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Flight Plan to Innovation

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IFIS 2014

Flight Plan to Innovation

Session 1
Flight Inspection of VOR

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Measurement Effects on VORs – 9960 Hz Modulation Depth & Roughness Assessment

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ABSTRACT

Compared to conventional VORs, Doppler VORs (DVOR) provide a much more stable bearing signal in multipath environments. However, the technical operation principle introduces a flight inspection specific problem: While measuring the DVOR 9960 Hz amplitude modulation depth in flight, it often occurs that the result is out of tolerance while the bearing indications are perfect. The FAA and ICAO have widened the VOR tolerances in the past caused by this circumstance.

The paper discusses the physical and electrical background. It provides examples of real DVOR measurements including in-depth signal analysis, comparison to ideal VOR signals and analyses the effects on the flight inspection measurement. A technical solution for a VOR receiver with improved modulation measurement uncertainty and reproducibility under multipath conditions is presented.

Additionally, the aspect of receiver internal signal filtering on the assessment of "roughness" is considered. While filter characteristics for bends/roughness have been considered and presented at previous IFIS, the influence of the receiver characteristics on the system level frequency response is analyzed here.

A technical solution to align the results with the concept of a "typical VOR installation" through characterizing the frequency response of a receiver and using post-processing to consider different filters is presented from a system level perspective.

MEASUREMENT OF 9960 Hz MODULATION DEPTH

Introduction

The DVOR has the advantage that it brings more accurate bearing readings to the pilots of commercial and private airplanes in multipath prone areas such as mountains or cities with man-made reflecting structures.

This improved bearing behavior of the DVOR is based on the fact that the "free space" modulated signal carrying bearing information is not the amplitude-modulated 30 Hz AM of the signal (like the CVOR operates) but the 30 Hz derived by the frequency modulation on the 9960 Hz center frequency of the VOR baseband signal.

In simple terms a “free space” frequency modulation is attained by a circular antenna array with a number of single antennas that are electrically switched in a manner so that the “rotation” of the antenna switching implements the frequency modulation for a distant receiver by using the Doppler shift effect. The source of the signal is observed by the receiver to be moving away when the antenna switching occurs on one side of the transmitting circular antenna array, and approaching when the switching occurs on the other side of the array causing an apparent shift in frequency through the Doppler shift.

The mechanical dimensions, switching times and baseband signals are such that the VOR specifications for the 9960 Hz FM with a frequency modulation deviation ratio of 16 (480 Hz frequency deviation / 30 Hz baseband signal) and a modulation depth of 30% are met.

However, in flight inspection not only the bearing is interesting but additional parameters such as modulation depths. In basic terms the modulation depth is determined by measuring the amplitude of a signal and as experience shows, the amplitude of a free space modulated signal is sensitive to multipath effects.

The DVOR introduced some problems for the modulation depth measurement to the flight inspection community. These problems were deeply discussed by members of the International Committee for Airspace Standards and Calibration (ICASC) [1]. It also lead to new tolerances for the VOR modulation depth in [2].

This paper approaches the problem by looking at the flight inspection receivers’ behavior while measuring the DVOR and how its internal filters handle the disturbed amplitude modulated signals. Since the receiver is the primary measurement device for the flight inspection, it is important that receivers give consistent results on all parameters, including the modulation depths, in particular when two or more receivers are used in the AFIS.

It will show the “weak” spots in the signal processing chain that influence the results of the measurements and that contribute to the ongoing discussion around the measurement of modulation depth signals.

The receivers discussed in this paper are the Bendix/King RNA34AF (hereafter referred to as RNA34AF) and the Aerodata AD-RNZ850-0100 (hereafter referred to as AD-RNZ850).

While the RNA34AF is superseded by the RNA34BF it is not thought to be the subject of active development, and therefore will most likely not see any improvements in its signal processing. The Honeywell RNZ850 based AD-RNZ850 is routinely updated with the latest findings including those presented in this paper.

Receiver Internals

The most important receiver circuit affecting 9960 Hz modulation depth measurement is the 9960 Hz band-pass filter. It is used for rejecting signal components such as ident, audio and 30 Hz AM. An example of such a band-pass filter is shown in Figure 1.

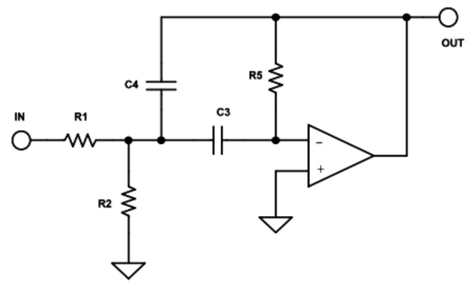

Figure 1: Analog band-pass filter circuit

This kind of band-pass filter is used both in the RNA34AF and the AD-RNZ850 flight inspection receiver. It is of the type “2nd order Multiple Feedback” which is a standard analog bandpass filter circuit. However, it has two properties that are considered weak spots for use in a flight inspection receiver:

The first is that it is comprised of analogue components such as resistors, capacitors and an operational amplifier. These analogue devices are subject to small but noticeable deviations from their nominal values which shift the exact pass through frequency of the filter. These deviations are based on production limitations, temperature changes during operation and aging over the life of the receiver.

The second adverse property of this multiple feedback band pass filter is the filter pass band. Being a 2nd order filter means that the filter has a narrow, single frequency pass band and all other frequencies are attenuated. This is not desirable if one tries to filter a frequency modulated signal that has a nominal frequency deviation of ±480 Hz. It means that in the best possible scenario only the 9960 Hz center frequency of the frequency modulated signal is passed through without attenuation while all other frequencies are attenuated, even the ones that belong to the signal of interest.

Figure 2 shows the effect of these characteristics on the possible filter responses of the analog band-pass filters.

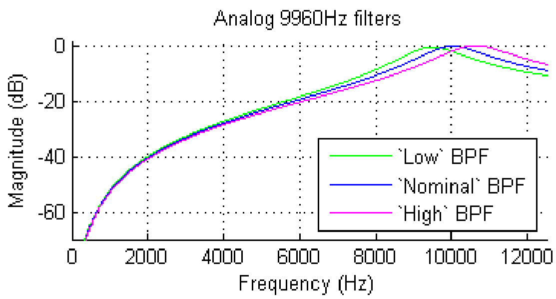

Figure 2: Analog Filters

An important finding is that in the area around 9960 Hz where the signal of interest is located, the 'Low' BPF filter response (based on analogue components at the lower end of their production/performance tolerance) and 'High' BPF filter response (based on analogue components at the high end of their production/performance tolerance) are not centered on the nominal frequency, rather on the lower/upper limits of the FM signal.

As we intend to measure the energy in the filtered signal and to derive the modulation depth from it, this is not initially thought of as being critical. After receiver calibration using a signal generator, producing a signal similar to that from a CVOR, a look up table (LUT) is determined that correlates modulation depth values to energy measurements of the filtered signal.

Figure 3 shows the examination results of the analog band-pass filters of two flight inspection receivers after this calibration. The center frequency of the 9960 Hz FM signal was varied in order to determine the filter characteristics. One can see that these receivers will show an accurate modulation depth of an ideal signal.

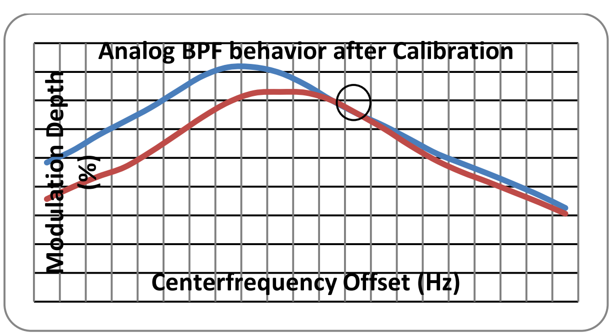

Figure 3: Analog band-pass filters of two VOR receivers after calibration

However, these receivers have problems measuring modulation depth from a DVORs signal, especially under multipath conditions. In this case both receivers will show different modulation depths, dependent on their varying filter characteristics.

Development of a DVOR/Receiver Model

The tools Matlab and Simulink are well known and ideal for the modeling and simulation of the DVOR, multipath and the receiver. Hence, they were used to simulate different effects in both the DVOR signal and the receiver and to see how these influence the measurement of modulation depth.

Since the whole system of a DVOR transmitter, the free space FM modulation, multipath conditions and receiver characteristics are complex, many simplifications and assumptions have been used for the simulation in this case. One important assumption for the simulation is that the free space FM modulation of the DVOR is sensitive to multipath - superposition of its own, delayed signal. Multipath is simulated in the model by simply adding an attenuated/delayed version of the original signal to itself.

Additionally, only the baseband signal of the VOR is simulated, as the cause for the 9960 Hz modulation depth measurement problems were expected to be in the baseband signal processing of the flight inspection receivers and not in the RF path.

The Simulink model used for the simulation of the multipath distortion and the receiver internal baseband processing is shown in Figure 4.

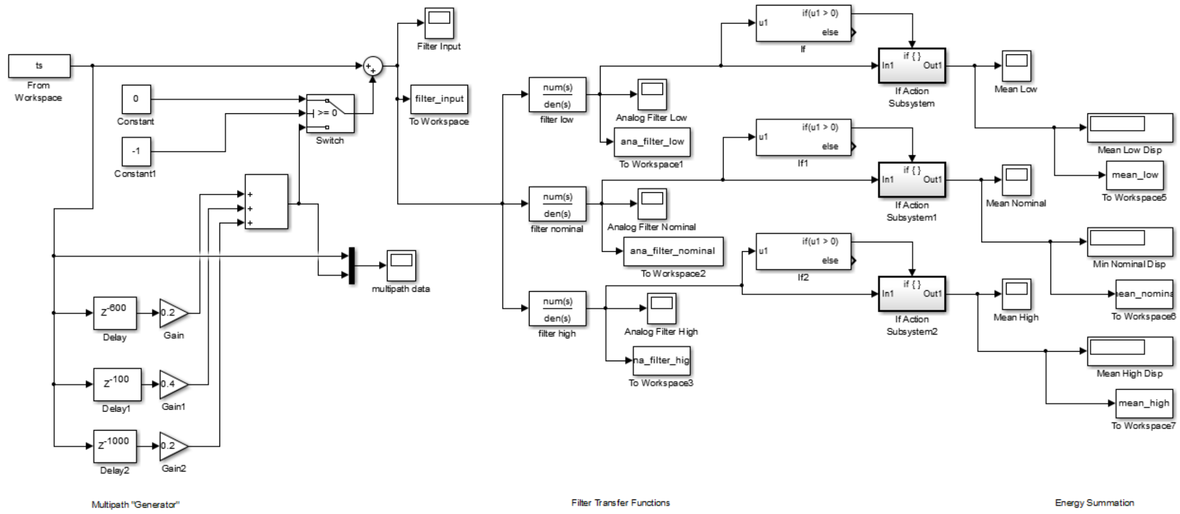

Figure 4: Simulink Model of Multipath Transmission Line and Receiver Filters

The multipath distortion can be switched on/off as required. It is switched "off" in order to "calibrate" this simulation system with a clean VOR baseband signal just like a real receiver would be calibrated.

The filters themselves are modeled as transfer functions in the s-domain defined by the resistor and capacitor values that are within the tolerances of the specified parts is the flight inspection receiver's schematic and parts list.

The FM test signal is generated in a Matlab script based on the FM formula:

$$Sig_{FM}=A_c*cos(2*pi*F_c*t+beta*cos(2*pi*F_{sig}*t));$$

Where:

Ac	Carrier Amplitude (0.3 for 30% Mod Depth)
Fc	Carrier Frequency (9960 Hz)
beta	Modulation Index (FMDR, 16)
Fsig	Signal Frequency (30 Hz)

<u>Examination of the Analog Band-Pass Filter Performance Under Multipath Conditions</u>

To verify the look up table after calibration, an undistorted nominal FM signal is used. The signal presented to the filter transfer function is shown as Figure 5.

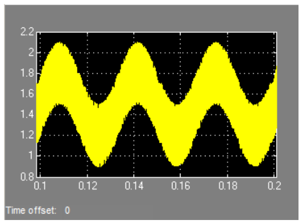

Figure 5:
Nominal VOR Signal

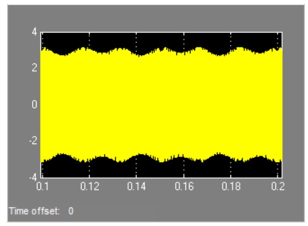

Figure 6:
Signal after nominal BPF

The signal after the nominal filter is shown in Figure 6, the modulation depth of all filters after this test is processed to:

Low Filter Mod Depth (%)	29.99 %
Nominal Filter Mod Depth (%)	30.00 %
High Filter Mod Depth (%)	30.00 %

This result is as expected given an ideal signal without distortion.

However, this test already reveals one of the drawbacks of the analog filter circuitry - the envelope of the filtered signal has varying amplitude, which is to be expected from a filtered FM signal, but which will vary amongst the different filters that are possible due to the analog design.

Figure **7** shows the envelope of the signal after the “high” BPF. The effect is much stronger because the input signal is on the edge of the filter response where each increment of frequency change has a much greater effect than it would in the center of the nominal filter response.

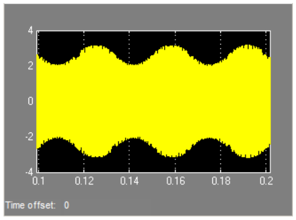

Figure 7: Signal after high BPF

By switching the multipath generator “on”, the signal is distorted by its own delayed and attenuated “copies” and we can investigate the effect on modulation depth measurement with a disturbed input signal. Figure 8 shows the signal presented to the filter, where Figure 9 shows the signal after the nominal BPF. The effect of the filter on the disturbed signal is easily seen in comparison to the signal shown in Figure 6.

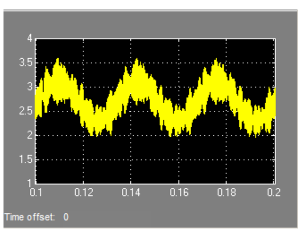

Figure 8: Multipath Distortion on Baseband Signal

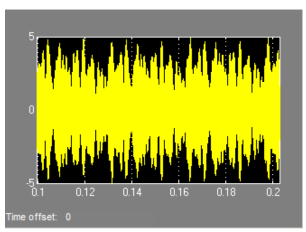

Figure 9: Baseband Signal after nominal Filter

The modulation depths determined by the filters are now:

Low Filter Mod Depth (%)	31.19 %
Nominal Filter Mod Depth (%)	30.77 %
High Filter Mod Depth (%)	30.31 %

These values now vary by 0.9% between the min and max value. It shows that multipath can change modulation depth readings if the BPFs of flight inspection receivers are as presented here. This makes it hard for a flight inspector to determine which receiver is giving the “correct” modulation depth result.

Another aspect of signal distortion is caused by the multipath effect: The absolute value of the modulation depth increased because the superposition of the original signal with its delayed signals is an addition in free space. Depending on the phase shift and strength of the reflected signal the value can vary significantly.

Experiments with this Simulink model show that there are many different modulation depth measurements possible by changing only the parameters of the multipath generator.

Additionally, it is possible to approximate real world signals using this model, refer to Figure 10 and Figure 11, comparing the simulated signal with the oscilloscope trace of a real DVOR. If modulation depths are calculated from this signal, then it can be seen that the simulated variation in modulation depth measurement is consistent with the observed variation between two receivers measuring the real signal.

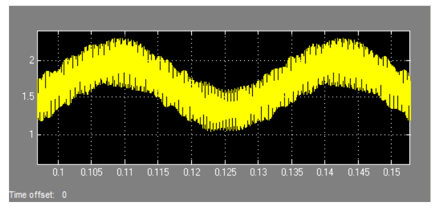

Figure 10: Modeling approach of a Real World Signal

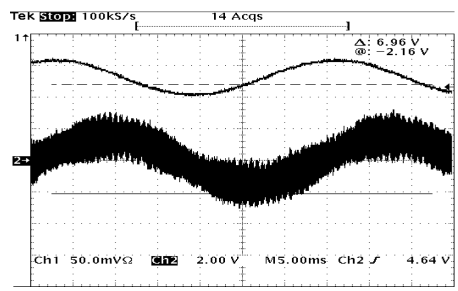

Figure 11: Oscilloscope Trace of a Real World Signal

Low Filter Mod Depth (%)	30.11 %
Nominal Filter Mod Depth (%)	29.98 %
High Filter Mod Depth (%)	29.85 %

The modulation depth difference is not very big, but is measurable and represents the real world behavior well. This further confirms – in an empirical way - that the simplified model works well for this analysis. It also shows that it is not suitable for flight inspection receivers to use analog band-pass filtering on the 9960 Hz FM base band signal if consistent results between receivers are desired.

<u>Implementation of a Digital Band-Pass Filter</u>

The flight inspection VOR receiver is a measurement device where one can expect consistent readings between devices. To achieve this it is desirable to change the BPF behavior such that external influences such as multipath have the same effect across individual receivers so that all receivers give similar, if not the same, results.

In order to align the signal processing of the VOR 9960 Hz FM baseband signal one has to change the following aspects of the filter performance:

1. Remove effects of analogue component tolerances on the filter response
2. Increase the filter order so that all of the energy within the signal to be measured is within the filter response
3. Additionally improve the filter roll-off in order to ensure that the measurement covers only the defined range of interest.

With a digital BPF all aspects listed above can be achieved. Certain prerequisites such as the presence of a digital signal processor and hardware that performs the analog to digital conversion of the VOR baseband signal without affecting the correct behavior of the original receiver circuitry must be fulfilled.

Both prerequisites are implemented in the AD-RNZ850 flight inspection receiver.

The magnitude response of a digital BPF, like that implemented in the latest generation AD-RNZ850, is depicted in Figure 12. It is an 8th order elliptic filter with the pass-band designed such that all 9960 Hz FM signals that are valid with respect to the ground station tolerances in Annex 10 [2] pass through it without attenuation.

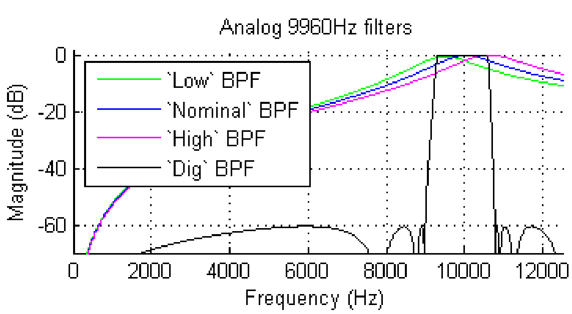

Figure 12: Addition of the digital BPF Magnitude response

The elliptic filter has ripple on both the pass-band and the stop-band, however it was determined that the minimal pass-band ripple is acceptable for two reasons:

1. The signal will be calibrated by using the previously described LUT and as long as the filter parameters do not differ from device to device they should present the same behavior under the same conditions.
2. The ripple on the pass band is a trade-off for a faster stop-band attenuation which was one of the desired improvements over the analog filters.

It is apparent that the improvements with the digital BPF are significant; the filter response is now designed to pass the whole FM signal without attenuation and all receivers can be made to have comparable filter curves as implementation is independent of the analogue components in the receiver's 9960 Hz band-pass filter.

Figure 13 shows the digital BPF implemented in the same two VOR receivers that were shown in Figure 3.

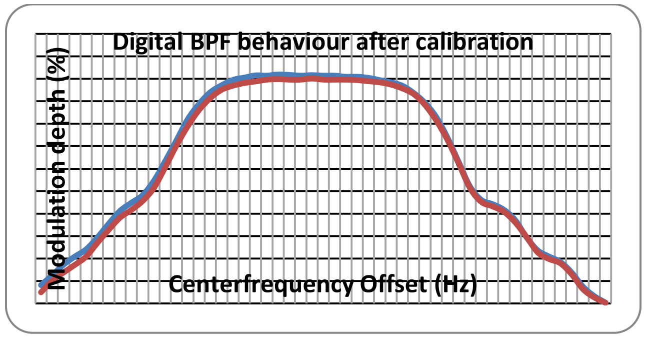

Figure 13: Digital BPF Behavior of Two VOR Receivers After Calibration.

There are small differences, traceable to the fact that not all analogue components in the receiver have been bypassed with digital means, only the base band processing, however test flights have shown that these difference are negligible under real-world conditions.

ASSESSMENT OF ROUGHNESS

Introduction

In a Flight Inspection application it is common and desirable to use standard/certified receivers as part of the measurement system. ICAO DOC 8071 makes reference to a "typical VOR receiver and antenna system" (§3.3.41 of [2]) to be used for VOR assessment. While this is commonly interpreted to be a TSO approved receiver and antenna system, the definition should be considered in a broader sense to ensure that the characteristics of the "typical VOR receiver and antenna system" are reflected in the AFIS performance and measurement results.

Previously in use at AeroPearl was an AFIS equipped with the RNA34AF navigation receiver for VOR measurements. In late 2008, the AD-RNZ850 was introduced for some tasks, later used for all tasks from late 2012. With the introduction of the new system/receiver combination it was seen that some VOR sites previously considered to be radiating within tolerance were now failing due to out of tolerance roughness results.

Research and investigation focused on the differences in receiver performance and differences in software algorithms. The outcome was a greater understanding of the "system level" filtering – the combination of the receiver bearing output frequency response and software algorithms - and the influence on the calculation of bends and roughness.

Presented here is the methodology used to investigate the receiver performance and calculate the system level frequency response for roughness to understand the results that were being observed in the field. Additionally an alternative method for assessing roughness is considered.

Receiver Frequency Response

When the discrepancies were first identified the focus was initially on the difference in receiver performance. Lab testing was completed in an attempt to characterize the frequency response of the bearing output.

By software control of a signal generator it was possible to create an input signal with oscillating bearing and vary this oscillation at rates of 0.1 Hz to 5 Hz. The raw bearing output from the receivers was recorded and analyzed, using Fast Fourier Transform (FFT) techniques to approximate the frequency response of the receiver.

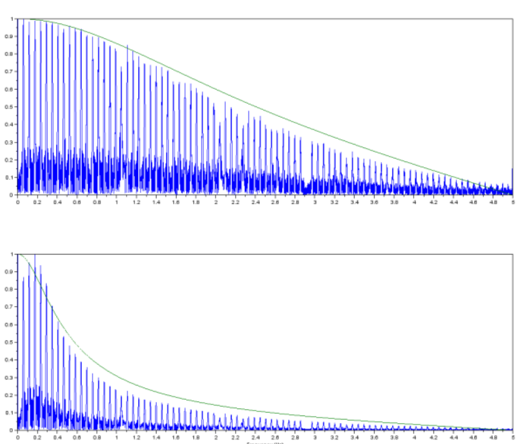

Figure 14: AD-RNZ850 (top) & RNA34AF (bottom) Raw Bearing Output Frequency Response With Approximate Filter

The frequency response of the AD-RNZ850 shows a typical low-pass response, but one that is quite linear. It can be approximated by a 1st order low-pass filter with corner frequency of 1.6 Hz as shown with the green trace in the upper section of Figure 14. The frequency response of the RNA34AF shows a stronger low pass filter characteristic. It can be approximated by a 1st order low pass filter with corner frequency of 0.35 Hz as shown with the green trace in the lower section of Figure 14.

The comparison shows that the AD-RNZ850 has a much wider frequency response and the ability to "see" roughness that would not normally be passed through the receiver in a typical aircraft installation. Whilst this is a desirable characteristic in a flight inspection receiver for reasons such as correlation with simulations and the ability to see degradation in the VOR guidance before normal aircraft may, it is important that the roughness algorithms are designed accordingly to meet the intent of the "typical VOR receiver" described in DOC 8071 [2].

Roughness Algorithms

In modern AFIS digital signal processing techniques can be used to determine roughness. Typically a low pass filter is used for determination of bends and a high-pass filter is used to determine the components of the signal which are un-flyable and hence fall into the category of roughness.

In both the previous and current AFIS used by AeroPearl the roughness filter is implemented without any roll-off at higher frequencies. Without an upper limit on the filter the upper frequency limit of the roughness result is defined by the receiver rather than the filter algorithm.

In comparison, the roughness filter proposed by NAV Canada at the 2012 IFIS [4] uses a high-pass filter cascaded with a low-pass filter to provide an upper frequency limit to the roughness result.

The system level frequency response for bends/roughness can be considered to be the frequency response of the receiver further filtered by (or cascaded with) the bends/roughness filter.

System Level Frequency Response for Roughness

The calculated system level frequency response for roughness in the AD-RNZ850 based AFIS and the RNA34AF based AFIS are shown in Figure 15.

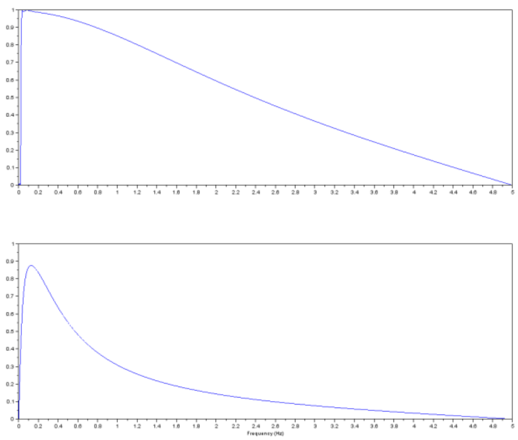

Figure 15: System Level Frequency Response AD-RNZ850 AFIS (top) vs. RNA34AF AFIS (bottom)

With a system level frequency response such as that in the AD-RNZ850 based AFIS it is likely that the AFIS is seeing more roughness than would be observed by a typical aircraft installation.

However in the previously used RNA34AF based AFIS the response is dominated by the receiver characteristic and not the filter itself. While this is likely to give a response similar to a typical aircraft installation, it can not be guaranteed - any filtering that may exist in the aircraft CDI/EFIS indications is not considered.

If a receiver with a wide frequency response is combined with a roughness algorithm with an upper limit, the outcome is more favorable for flight inspection purposes. The response is easily controllable through the filter definition.

For example, the AD-RNZ850's wide frequency response when combined with the Nav Canada defined roughness filter gives a result similar to the RNA34AF based AFIS but one that is "tuneable" through software to give a typical VOR response.

It can be seen that the combination of the receiver frequency response and the software algorithms can lead to three distinct outcomes with respect to the system level frequency response for roughness:

1. A system that over-measures roughness in the case of a receiver with a "wide" frequency response and a roughness algorithm with no upper frequency limit

2. A system that under-measures roughness in the case of a receiver with a "damped" frequency response and a roughness algorithm with an upper frequency limit (that causes the already damped output of the receiver to be further attenuated)

3. A system that can be made to accurately measures roughness in the case of a receiver with a "wide" frequency response and a roughness algorithm with a defined upper frequency limit.

With respect to the ICAO Guidance and consideration of a "typical VOR installation" it can be seen that outcomes 1 & 2 are unlikely to give the desired performance.

Outcome 3 gives a good balance between the TSO based hardware available and the software algorithms to be implemented in the AFIS or in post-processing.

<u>Impact of System Level Frequency Response for Roughness</u>

During the commissioning of a new VOR using the AD-RNZ850 based AFIS a roughness issue was observed on the approach. While the VOR was new, the site was not, and analysis of previous flight inspection data, recorded with the RNA34AF based AFIS, did not show severe roughness. Figure 16 compares the two results.

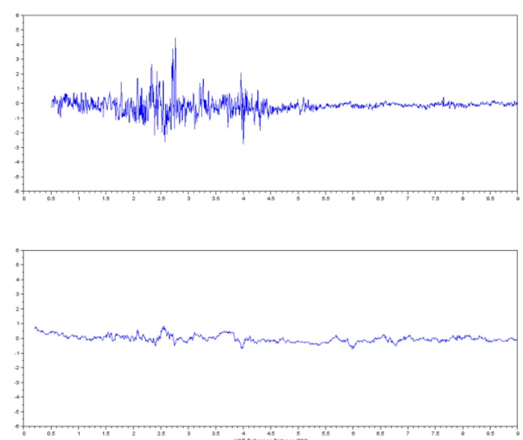

Figure 16: Bearing Error as Measured by AD-RNZ850 AFIS (top) vs. RNZ34AF AFIS (bottom)

After changes in the environment were excluded the analysis focused on the receiver/AFIS performance. Investigation of the roughness signal in the frequency domain, refer Figure 17, showed the expected outcome that the new AFIS had a wider system level frequency response for roughness and as such more roughness was being "seen".

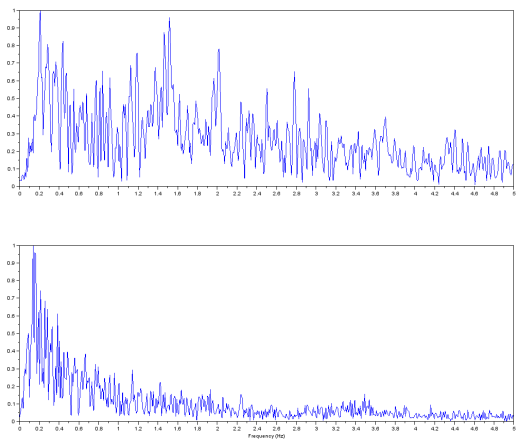

Figure 17: FFT of Roughness as measured by AD-RNZ850 AFIS (top) vs. RNA34AF AFIS (bottom)

Another parameter that was available for analysis was bearing data from the primary VOR system. The parameter recorded by the AFIS is the bearing displayed to the pilot on the EFIS of a Proline 21 (PL21) King Air, which could be considered as a typical installation.

A VOR bearing error was calculated on the information provided, while un-calibrated the parameter is useful for analysis, after being filtered, to provide roughness data. A simple roughness filter (high-pass, no upper limit) was used for comparison purposes as it was considered that the data had already been subjected to some form of low-pass filtering before presentation to the pilot on the EFIS.

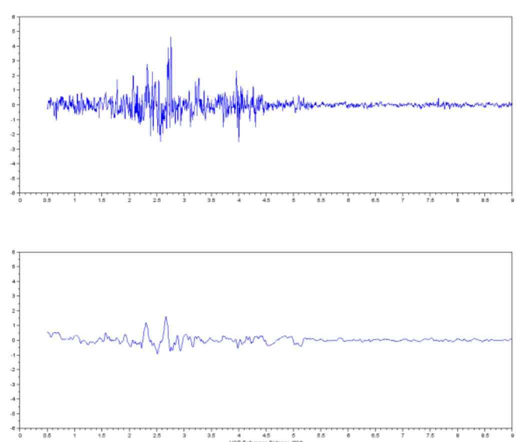

Figure 18: Roughness as Measured by AD-RNZ850 AFIS (top) vs. PL21 with HPF (bottom)

The data confirmed that the new AFIS was over-measuring roughness and that it was very likely that the previous system was under-measuring roughness. A solution somewhere between the two was required to bring the roughness result more in-line with that seen from the primary avionics, refer to Figure 18.

Proposed Solution

Using the Nav Canada defined roughness filter as a basis, the raw data from the AD-RNZ850 based AFIS was filtered with a so-called "CDI Filter". This filter has the same form as the Nav Canada filter, HPF cascaded with a LPF, but the LPF has a corner frequency of 0.375 Hz instead of 0.125 Hz as proposed by Nav Canada.

By using this filter the system level frequency response for roughness can be made similar to that from the PL21, as can be seen in Figure 19.

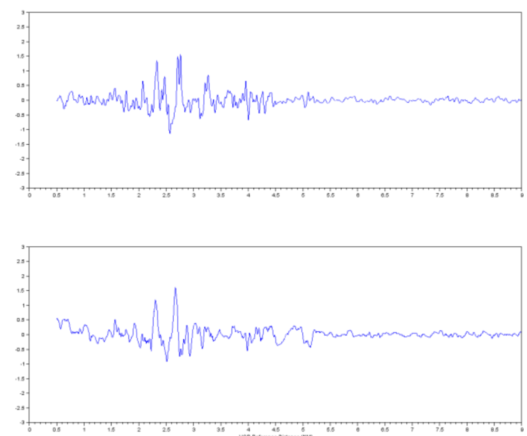

Figure 19: Roughness as Measured by AD-RNZ850 with CDI filter (top) vs. PL21 with HPF (bottom)

Alternative Solution

An alternative solution, and one that is in use in Australia in the interim, is based on consideration of VOR roughness as a measure of structure rather than absolute performance. With this approach a measure such as "percentage time in tolerance" is a more suitable measure.

From the ICAO material on LOC/GP structure assessment (§2.13, 2.14 of ATT-C to [2]) the following tolerance and post analysis framework has been developed in conjunction with Airservices Australia:

1. Use the existing "roughness" parameter to assess against the ± 3.0° tolerance, if the tolerance is not exceeded then no further analysis is required.

2. If the tolerance is exceeded use a "40 second sliding window" to assess the time that the signal is in tolerance and calculate the "minimum percentage in tolerance". If the aid fails to meet a "minimum 95% in-tolerance" criteria it will be classified as restricted.

Note that only the preceding 40 seconds of data is taken into the analysis, not ± 20 seconds as recommended by ICAO. This is based on the thinking that a pilot will judge the quality of the guidance based on current performance with respect to previous performance. The pilot can't see the next 20 seconds of data and as such it is not appropriate to consider it as part of the analysis.

This leads to a more practical assessment of roughness, where momentary excursions beyond the tolerance can be assessed to be of no significance as in Figure 20.

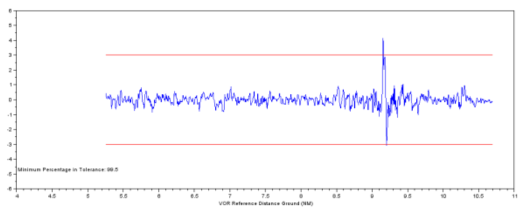

Figure 20: Example of Site, 99.5% in Tolerance After Sliding Window Analysis

However sites with poor performance are restricted accordingly, as in Figure 21.

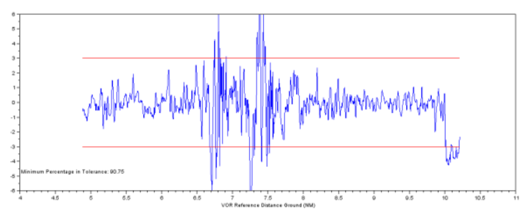

Figure 21 Example of Site, 90.75% in Tolerance After Sliding Window Analysis

With this approach the existing receiver/software combination remains (receiver with a "wide" frequency response and a roughness algorithm with no upper frequency limit) and the roughness parameter takes the role of an engineering parameter.

This method has been used successfully on several occasions and provides a suitable interim method for VOR roughness assessment until the desired characteristics of a roughness filter are more thoroughly understood, defined and implemented in the AFIS. Once the filter is defined it is expected that roughness assessments will be made on the "CDI filter" based results, but that the un-damped roughness results will remain accessible for engineering purposes.

CONCLUSIONS

Relating to the investigation into VOR 9960 Hz Modulation Depth Measurements the following conclusions are made:

a. It has been shown that for solving signal processing problems it is always best to fully understand the cause of the problem. The use of a Simulink model to simulate and understand the issues associated with measurement of distorted DVOR signals using receivers with analog filter circuitry was very beneficial and allowed initial solutions to be implemented and tested digitally with hardware/firmware modification.

b. The exchange of analog filter circuitry with a digital complement has led to better flight inspection results and as no fundamental modifications were completed in receiver circuitry itself this intervention has no effect on other signals like the VOR Bearing. This is important as changes in these signals, while maybe leading to "better" results, would also remove the ability to correlate flight inspection results with the performance observed by aircraft using standard TSO approved receivers.

Relating to the investigation into VOR Roughness assessment, the following conclusions are made:

a. Software algorithms used to filter VOR Error to produce a result for Roughness must consider the frequency response of the receiver and be adapted to give the desired "typical VOR receiver" system level response for application of the roughness tolerances.

b. A VOR receiver with an un-damped frequency response is useful for seeing a more complete picture of the VOR performance for engineering purposes.

c. Further development of a "CDI filter" is required such that the system level frequency response for roughness represents that of a "typical VOR receiver" allowing straightforward application of the DOC 8071 roughness tolerances.

FUTURE WORK

Relating to the investigation into VOR Modulation Depth measurement performance there are some aspects that warrant further investigation and work:

a. The performance of the 30 Hz AM filter should be investigated to determine if it also has a response that is adverse to its use in flight inspection measurements in a multipath environment and if a digital filter may be applied to resolve any identified performance issues.

b. The in-field performance of the latest generation AD-RNZ850 with the digital BPF implemented will be monitored at sites with known multipath issues and where measurements using previous generations of the AD-RNZ850 suggested poor VOR performance.

c. The complexity of the DVOR/Receiver Simulink model should be expanded and simplifications and assumptions removed to provide a more advanced theoretical simulation for future analysis. This should include a more complex model for multipath, that allows for phase shift in the reflected signal and more VOR signal components like 30 Hz AM, Identification and Audio to be added to the test signal in order to simulate a more complete VOR.

Relating to the investigation into VOR Roughness there are some aspects that warrant further investigation and work:

a. Deeper investigation of the RTCA/DO standards on VOR receiver performance with respect to filtering of the bearing output and similarly standards on CDI/EFIS filtering of bearing/deviation indications towards development of a "CDI Filter" to better represent a "typical" VOR installation when filtering the bearing error to assess roughness.

b. The system level frequency response of the PL21 VOR/EFIS system should be measured/analyzed for completeness and for reference in any future investigations.

ACKNOWLEDGMENTS

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Evolution of Terrestrial Navigation Aids as Consequence of PBN Implementation

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ABSTRACT

With the broad implementation of Performance Based Navigation (PBN), GNSS (satellite navigation, e.g., Global Navigation Satellite System) is becoming an essential infrastructure. Consequently, the role of terrestrial aids is evolving from supporting conventional procedures on a primary and exclusive basis to one that has a complementary function in the context of PBN. Current work in various SESAR (Single European Sky ATM Research) projects revolves around the use of DME/DME (Distance Measuring Equipment) as a redundant reversionary capability to maintain continuity of operation and the use of a VOR/DME back-up network to maintain safety for all airspace users during a GNSS outage. The paper will present the current thinking on the future operational roles of terrestrial NAVAIDS and the associated expected evolution in Europe. Extensive simulations have been conducted in order to identify the rationalization potential for conventional NAVAIDS (especially VOR, VHF Omnidirectional Range) and the expected evolution of the DME/DME network, and how these different aspects interact, in particular the mix of airport / terminal area use and en-route use of facilities. The paper will discuss open issues and implementation challenges that may be useful for flight inspection organizations to understand. A brief overview will also be given on how current NAVAIDS can support some aspects of Alternate Positioning, Navigation and Timing (A-PNT).

INTRODUCTION

When speaking of “network management” in Air Traffic Management circles, the immediate association is with route networks, sector loads and demand / capacity balancing. Even if in many parts of Europe and other places today, the route structure is still supported by VOR stations at most nodes (with station coverage extending to half the length of the supported route plus some buffer), the underlying infrastructure has often disappeared from the general operational conscience. Conversely, in the navigation service provision world, terrestrial facilities are normally seen in a very modular fashion, supporting a particular procedure for a particular airport. Understandably, current flight inspection is set up to verify signal in space performance one facility at a time. There is, however, a notion of “network” that is now emerging due to the introduction of PBN, e.g., the notion of a network of terrestrial navigation facilities to support PBN. While this brings potential improvements in the efficiency of navigation service provision, it also introduces a number of complexities, such as cross-border aspects, considerations of avionics constraints, and more. These complexities may thus endanger the required transition of conventional navigation aids to a terrestrial, complementary PBN support network, because “business as usual” (meaning a one by one replacement of aging facilities) is typically easier than having to embark on a coordinated project efforts that pulls together not only neighboring states but also the Air Navigation Service

Provider (ANSP)-internal disciplines of airspace planning, procedure design, navigation engineering, Aeronautical Information Management (AIM) and State-internal actors such as the Civil Aviation Authority (CAA) / National Safety Agency (NSA) and airspace users of all different flavors. This paper explains the target facility network envisioned to support the future PBN environment in Europe.

ROLE OF GNSS: FROM SUPPLEMENTAL TO PRIMARY SERVICE INFRASTRUCTURE

PBN is comprised of several "Navigation Specifications". There are two main groups of these specifications, Area Navigation (RNAV) and Required Navigation Performance (RNP). RNP specifications are also based on the RNAV principles of coordinate-referenced navigation, except that avionics meeting RNP specifications must provide "On-board Performance Monitoring and Alerting (OPMA)". It is essential to understand that the numbers that typically identify a particular navigation specification do not only link to a navigation accuracy performance requirement, but also to a set of navigation functionalities. For example, the new Advanced RNP specification requires not only a ±1NM (95%) accuracy performance for terminal area operations and an OPMA integrity function, but also the ability for the avionics to execute Radius-to-Fix (RF) turns. Such specific functionalities play just as essential of a role in PBN airspace improvements as do improvements in path keeping performance.

Amongst the current set of published navigation specifications in the International Civil Aviation Organization (ICAO) PBN Manual [1], the only infrastructure that supports all of them is GNSS. With the inclusion of RNP approaches into the PBN concept, the type of GNSS sensor can now also have an impact. Whereas a first generation Technical Standard Order TSO-C129 [2] avionics receiver met all navigation specifications, this is no longer the case when wanting to support RNP approaches to LPV (Lateral performance with vertical guidance) minima, which requires Space Based Augmentation System (SBAS)-capable avionics. In other high-navigation performance areas, such as Automatic Dependent Surveillance Broadcast (ADS-B), the first generation of TSO C129 avionics is also encountering some limitations. While it is not the intention of this paper to enter into these discussions, the point here is that GNSS in the form of GPS L1 receivers has already been around for a long time, is implementing its second generation with broader use of differential augmentation systems and working towards its third generation with multi-frequency, multi-constellation services. Already today, the use of GPS L1 avionics with Receiver Autonomous Integrity Monitoring (RAIM) has become the primary mode of operation for the large majority of aircraft, even if the avionics box certification still carries a "supplemental" label. Given the unique qualification and positive service record of GNSS, it is clear that GNSS as the primary enabling infrastructure for PBN and other operations is here to stay and increase in the long term.

Addressing GNSS Vulnerabilities

Despite the fantastic navigation utility provided by GNSS, concerns about vulnerability need to be addressed. In many ways, conventional terrestrial systems are just as vulnerable to a targeted attack as GNSS despite higher signal powers and more diverse frequencies. It can also be argued that the concerns over disturbances due to solar activity and the potential impact of unintentional Radio Frequency Interference (RFI) and intentional RFI not targeted at aviation are often overstated. The third major potential vulnerability of GNSS next to solar impacts and RFI, constellation weakness, does not evoke much concern either given the potential availability of four core constellations in the future, some of whose provider states are contemplating issuing mandates that would then need to be supported even more firmly by suitable minimum service commitments. Nonetheless, with GNSS supporting so many aircraft and multiple applications at the same time, it is necessary to be able to answer the question of "what happens when GNSS fails?" with a clear, simple and workable plan. Given all the warning voices about GNSS vulnerability, it would be irresponsible to not have such a response. To this end, a number of activities of EUROCONTROL and other aviation actors aim at reducing and managing vulnerabilities of GNSS through a whole range of measures.

When it comes to the impact of solar activity on GNSS, this can only be mitigated by better performing systems. Despite the sun having been "kind" during the current solar maximum, significant outbursts could still occur even during periods of low solar activity – the ability to predict such outbursts ahead of time and estimate its impact accurately is not an easy undertaking, and comparable to weather forecasting. Luckily, most of the European region, with the exception of some high latitude regions and the Canary Islands, is not exposed to a significant risk even to standard GPS L1 operations. EUROCONTROL is operating a dedicated monitoring network to assess vulnerabilities to solar activity [3], and initial estimations are that risks to operations are tolerable while awaiting the further robustness that will be provided by future dual frequency GNSS. When it comes to RFI mitigation, EUROCONTROL is developing a mitigation plan [4] that combines a number of preparatory and reactionary measures with the aim to reduce the probability of occurrence of RFI, to reduce the impact of RFI events on operations, and to be able to deal with any remaining impacts effectively. The catalog of mitigation activities spans from regulatory measures to public awareness and the investigation and deployment of possible ground and airborne monitoring and intervention systems. One concept that has been but forward, for example, is to use ADS-B performance indicators (NACp and NIC parameters) to detect a large scale GNSS outage in order to support a timely and coordinated reaction by Air Traffic Control (ATC) services.

The plan of what to do when GNSS fails in a large area is also being developed from the operational point of view. Real time, human in the loop simulations are being carried out in summer 2014 to address these aspects and develop corresponding operational procedures [5]. The difficulty to quantify the probability of occurrence with its associated geographic extent and duration is just as much a challenge for the operational world as it is for infrastructure provisions, where the residual level of vulnerability theoretically should determine the effort to be expended in providing alternate infrastructure. If a large area GNSS outage would happen, in a particular TMA, on a once a year basis, operational staff could become proficient and familiar with the associated reversionary procedures. If on the other hand, such an event is on the order of every ten years or less, then it will be quite difficult for anyone involved to remember if there are particular procedures to follow if such an event would happen. This challenge does provide an additional argument to ensure that at least in high-density traffic areas, terrestrial infrastructure should be in place such that in the event of an area GNSS outage, the large majority of aircraft will continue navigation normally, with only a very few of them requiring navigation assistance. Given the currently envisaged PBN performance requirements in Europe to remain at the 1NM accuracy level even in complex TMA airspaces, this naturally points to the existing and broad base of DME equipage, both air and ground.

REVERSION SCENARIOS AND ASSOCIATED INFRASTRUCTURE

Europe is in the process of developing a PBN Implementing Rule (IR). The IR foresees the broad use of the Advanced RNP (A-RNP) specification, which includes turn functionalities which are valuable from an airspace point of view. An issue that has been raised, however, is the question of what happens when GNSS is not available, because it implies a loss of RNP and its associated OPMA function. If the improved path keeping performance of RNP is exploited operationally through reduced route spacing, this could create capacity or even safety issues if left unaddressed. This has led to a reevaluation of the ability of DME to support RNP [6]. Part of the argumentation is that while GNSS relies on RAIM to remove faulty satellites which will not stop broadcasting by themselves, this is not true for DME, where executive monitors cause the station to stop radiation if a corresponding monitor is triggered – implying that such fault detection by avionics as is done in GNSS is not necessary for DME-based RNP. While the qualification of DME to support RNP requires further work, the use of DME as a PBN support infrastructure remains the primary alternate capability to GNSS today regardless of the outcome. This is because the key benefit of PBN is to enable airspace organization and route design free from facility constraints, in line with operational needs. Once the transition to a PBN-based route network has occurred, it will no longer be feasible to provide a conventional-based, non-RNAV route network as a shadow network behind the normal RNAV network. Even a partial conventional route structure still supported by some VOR with RNAV overlay is not considered advisable in the long term. This is important to recognize because it means that VOR has only a minor residual role in a PBN environment. In the near to mid-term, that leaves DME/DME as the only feasible alternative to GNSS. Fortunately, equipage levels of DME both in the air (97% of flights are DME/DME capable, while some may lack operational approvals) and on the ground are very high in Europe [6]. Of course, some state aircraft and general aviation may not ever have such a capability, and will need to be catered to as well.

When looking at a future PBN environment where all airspace users will have GNSS, the role of the DME network will also change. Today, the DME network caters to airspace users which are not GNSS-equipped, e.g., it enables a diversity of avionics capabilities. From an infrastructure robustness point of view, this is inefficient since two sets of infrastructure are required which are both single-string for those avionics which base their PBN capability on either GNSS or DME/DME, but not both. Once all airspace users will have GNSS and most will have a DME/DME, then the DME network truly becomes a redundant reversion infrastructure.

To cater to users not equipped with DME/DME, or to airspaces where DME network coverage is marginal (mainly at low altitudes), the use of a VOR/DME back-up network is proposed. A few states have begun to proactively rationalize their aging VOR infrastructure. In doing so, a consensus emerged that going directly to not having any VOR in a single step would be too ambitious. Most of these states have identified a reduced VOR/DME network that comprises about 50% of their current facility inventory. Those remaining facilities will be renewed and remain in the system another 20 years – by which time a mature, multi-constellation GNSS should be available to consider further infrastructure evolutions.

The combination of GNSS with various augmentations, a DME redundant network as well as a back-up VOR/DME infrastructure is not necessary or even feasible in all types of airspace. In low-density, low complexity airspace it may be perfectly acceptable to rely on GNSS alone as a navigation infrastructure, while providing ATC assistance through the classical communications and surveillance redundant capabilities. The primary objective is to provide safety by ensuring safe extraction and landing capabilities, through back-up capabilities that may have a lower level of performance and capacity. Once that is achieved, layers of redundant capability providing equal or similar performance to GNSS can be added to maintain continuity of operations, as a function of the economic business risks associated with such an outage. The VOR/DME back-up network can provide an emergency back-up capability, while the DME redundant network can support most airspace applications up to at least a ±1NM accuracy requirement. Whether operating in an RNAV mode or not, having a basic positional awareness, including navigation map displays that keep updating, is essential for aircrews to manage their flight, even if they are receiving vectoring instructions from ATC.

VOR/DME BACK-UP NETWORK AND FACILITY RATIONALIZATION

As mentioned previously, the role of VOR in PBN is quite limited. Despite VOR/DME being an eligible sensor to support RNAV 5 operations as implemented on a broad scale in all European upper airspace, and a large number of aircraft having such an RNAV capability, its actual use for this purpose is very limited. The first reason is that in most airlines equipped with standard multi-sensor Flight Management Systems (FMS) that have the "all sensor" fit of GNSS, DME/DME and VOR/DME, further supported by Inertial Navigation Systems (INS), VOR/DME has the lowest priority and is thus rarely used. The second reason is that even among those aircraft that use VOR/DME to support RNAV5, the actual use of it in terms of FMS tuning criteria is not harmonized. Some systems only use VOR/DME out to a 25NM distance from the station, others will only use them in a range from 10 to 60NM. This makes a consistent infrastructure provision practically impossible. Consequently, even if VOR/DME is an eligible sensor for RNAV5, the practical utility of it is so limited that the VOR cannot really be considered as having a primary role in PBN. The only PBN role of VOR that remains is in RNAV1 operations for aircrew cross-checks as an optional, additional quality control mechanism.

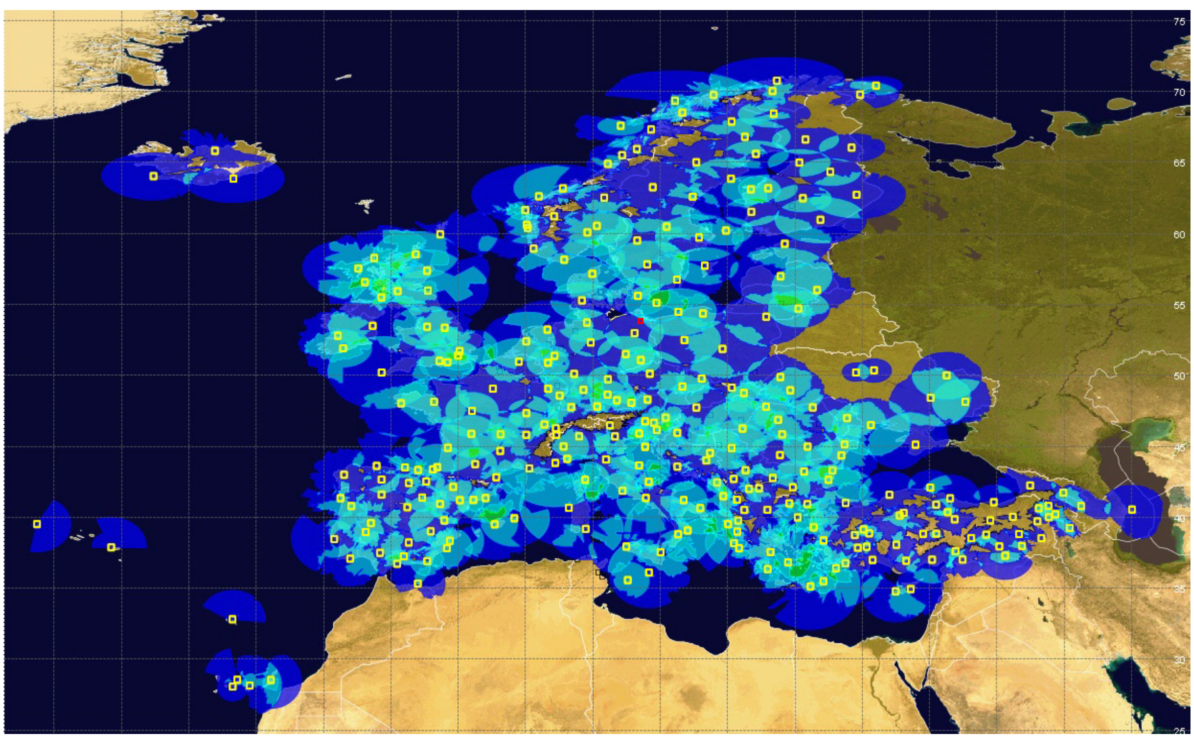

Figure 1: Proposed European VOR/DME Back-Up Network Cumulative Coverage

So what then is the role of VOR in a PBN environment, if any? If single step down to no VOR stations is too challenging, then it is necessary to define the interim operational role of VOR during the transition. The SESAR 15.3.2 project has investigated the different approaches to VOR rationalization. Given the resources required for either a facility replacement or for removing a facility from the operational environment, it is necessary to define a target infrastructure. It should not be forgotten that VOR/DME does provide a relatively quick and intuitive rho-theta navigation capability, which can be seen as sort of a "manual RNAV". Also, among non-precision approaches which aviation aims to eliminate [ICAO Assembly Resolution 37-11], VOR/DME approaches are certainly better than NDB approaches, especially if there is no ILS, and the VOR/DME often supports the ILS in intercept or missed approach operations. A VOR is typically used in many multiple ways, terminal and en-route, both documented (in procedures) and undocumented, including its use by general aviation outside of controlled airspace. Among the undocumented uses are aircrew contingency procedures, or the use of a particular guard-radial by general aviation to avoid airspace infringements.

In defining the future role of VOR, it is also instructive to look at the limitations of the DME network. While DME/DME supports RNAV1, which is used for TMA operations below MSA (which VOR/DME cannot support with RNAV-5), this is also where DME/DME coverage is most difficult to achieve. DME network coverage gets increasingly better with higher altitude. Meanwhile, the low altitude TMA or airport environment is also where vulnerabilities to GNSS RFI are greatest. In light of these issues related to DME and GNSS, as well as the fact that most of the residual roles of VOR are in the terminal area, the recommended approach is to give priority to single VOR/DME facilities installed at airports. Even if they may be more difficult to support than off-airport sites in an evolving airport obstruction environment, they are normally at least easier to support (shorter maintenance paths).

The U.S. FAA is pursuing a VOR "Minimum Operational Network" or VOR MON [7]. The aim is to provide coverage to general aviation pilots nationwide to at least 5000ft above terrain, to permit pilots to proceed to the nearest airfield with a non-GNSS landing capability in case there is a wide-area GNSS outage. A similar network is also proposed for Europe, but subject to implementation decisions by individual States. Obviously, if a certain VOR is identified for retention, then it makes sense to also preserve the collocated DME. Even if the current VOR is a standalone facility, it would make sense to equip it with a DME as an element of the DME network. The DME network design can then build on top of the residual VOR/DME back-up network and identify either existing or new facilities which complement those locations to provide an efficient DME network.

An optimized VOR/DME back-up network proposed for Europe is shown in figure 1. The analysis was done at 9'500ft AMSL (Above Mean Sea Level). A similar analysis was done over mountainous regions at 15'000ft AMSL (Alps, Northern Scandinavia, and near-Eastern regions). Some gaps remain over northern Finland, Belarus (those navigation aids have not been taken into account because Belarus is not a member of the European Civil Aviation Conference, ECAC), as well as the Ukraine (which has primarily NDB) and some Balkan States which would need to be addressed in further detail. What is important to note is not which individual facility has been retained – trade-offs will of course be necessary based on local conditions. The analysis aims rather to identify a "rationalization potential", e.g., to provide a target of how many VOR facilities could be eliminated while still providing a useful back-up network. The study identified that from the current 754 facilities, a reduction down to a network of 304 stations should be possible by using this back-up network approach giving priority to a single facility at airports, in line with the currently installed base. This represents a reduction target of 60%.

<u>VOR Rationalization Planning</u>

The first thing that needs to be said about VOR rationalization is that it is NOT primarily an engineering project, but rather, an airspace change project. Because the VOR is linked to many different procedures (including in some areas procedural control), all uses of the facility need to be analyzed and replaced with alternate means – in other words, the associated airspace needs to be "PBN-ized". This is best done when the VOR facility is at the end of its normal service life. Another important aspect is the need for broad consultation with airspace users. This is essential to determine the actual uses of the facility, and to prepare airspace users for the change such that the transition can be carried out safely. Finally, early regulatory support and interaction is another key to make rationalization a success. Detailed guidance on rationalization planning has been generated by the SESAR 15.3.2 project [8]. The business case for this activity is rather simple (which is extremely rare in aviation): a facility replacement, including the refurbishment of the site, costs on the order of 1 Million (in currencies such as the Euro, British Pound or US Dollar). A small PBN implementation and airspace change project to avoid this expense supported by expert staff (procedure design, etc) and associated consultation and documentation efforts on the other hand should normally not exceed 0.5 Million, even if that effort is a complex, multi-year matter. This gives a robust and low risk 2:1 cost avoidance to project cost ratio, without even counting the cost avoidance in the post-rationalization years on maintenance and flight inspection.

Obviously, people involved in the production and maintenance of VOR facilities may have difficulty in embracing such changes. Nonetheless, it would be irresponsible to stand in the way of PBN benefits of airspace capacity and efficiency, especially since there remains a minor but still essential role for VOR that will last another 20 years minimum, and there is no shortage of other infrastructure work to make those PBN benefits a reality. Even for an individual involved in "turning-off" facilities, this is normally not seen as a very exciting activity. Building and implementing new stuff is more attractive. This is why it is important to see "VOR rationalization" as one element in a broader transition or evolution towards a new, optimized and more network-based infrastructure provision to support PBN that will help improve the cost base of both the ANSP and airspace user.

REDUNDANT DME NETWORK

Traditionally, the DME has been an addition to a VOR. Standards, procedures and even facility design are still built around that logic. However, given the changed role of VOR, the DME takes on a much more standalone role. Even if the VHF tuning frequency remains an essential part of making the DME usable, standalone DME are perfectly feasible even if not collocated with a VOR. About 150 such stations are already in operation in Europe, typically with the purpose to fill RNAV coverage gaps. This new function brings with it new opportunities for DME sites. While with a VOR, there are significant challenges to find a good site, the demands of the DME are simpler to satisfy. From an RNAV geometry point of view, it is also better located not directly under where the traffic is, but rather off to the side by some distance. This leads to potential synergies with existing COM or SUR facilities, or even non-aviation telecommunication sites. A number of such installations have been realized without encountering significant challenges.

The SESAR 15.3.2 project has also carried out extensive infrastructure assessments of first the individual states and then the overall European area [9]. The premise of the work was to optimize DME/DME coverage with reasonable, small scale changes, without increasing the count of DME stations dramatically. The result of this optimized DME network analysis, carried out with the EUROCONTROL DEMETER tool, is shown in figure 2.

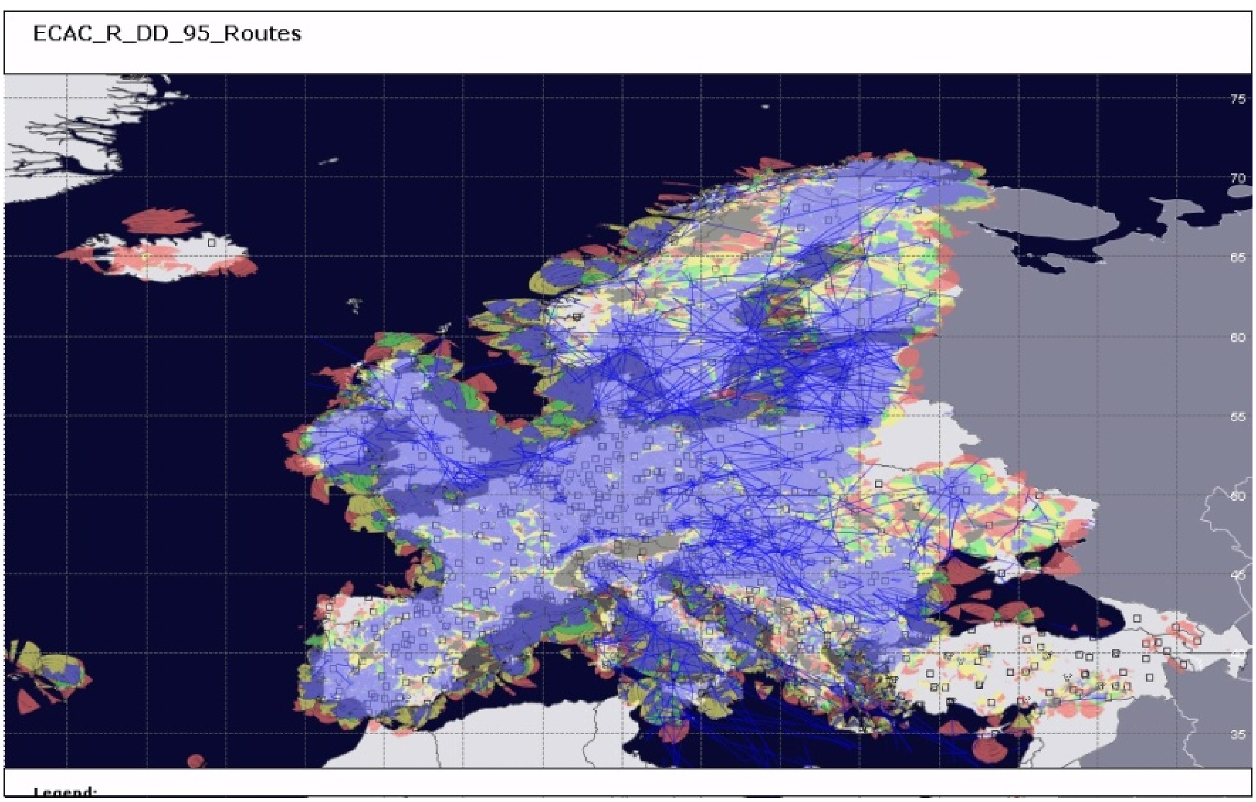

Figure 2: Optimized European DME Network RNAV1 Performance at 9'500ft AMSL

The green and blue colors in figure 2 stand for redundant and excessively redundant coverage, respectively. Yellow and red represent either limited or no redundancy, meaning that critical DME facilities are present. A critical DME is a facility where RNAV coverage will not be provided anymore if that station is inoperable. The acceptability of critical DME is subject to State decisions and local safety assessments, however it needs to be remembered that when looking at the DME network as a redundant capability to GNSS, the failure of a critical DME represents a double failure scenario of a failure with already a low probability of occurrence, coupled with normally the presence of COM and SUR capabilities with significant inherent redundancies also.

Figure 2 shows the impressive extent of Europe-wide DME network coverage, based on an optimized network of 754 facilities instead of the current 793, e.g., a slight reduction of 5%. Current navigation aid distribution is highly linked to traffic density, e.g., over-redundancies only exist in those areas where many conventional procedures need to be supported. With the transition from conventional procedures to PBN-based airspace, it will be feasible to eventually reduce the number of DME stations in such areas. In other words, as long as no lengthy transition of both conventional and PBN operations needs to supported simultaneously for many years, the density of the current spectrum congestion DME “hotspot” can be reduced. The DME “hotspot” and its compatibility with future dual frequency GNSS is the subject of another paper to this conference [10]. Of course, in other, low traffic density areas of Europe, more gap-filling DME are needed, which balances out the net effect.

While not shown in the interest of brevity, the same DME network produces a highly redundant, almost fully continuous coverage over all of Europe when evaluated at 19’500ft AMSL. In other words, for most European En-Route traffic, the DME network provides a highly reliable RNAV1 service. On the other hand, when looking at lower altitudes, DME network coverage is much more difficult, especially for airports surrounded even by moderate terrain. A quick look analysis of the 50 busiest airports in Europe revealed that some DME infrastructure improvements would be necessary at about half of these airports to achieve a suitable DME network coverage, requiring about 30 additional DME stations. When designing DME network coverage for terminal areas (TMA), the most important infrastructure aspect is to determine from which altitude upwards coverage is required. While normally, coverage provision to the final approach intercept waypoints on Standard Arrival Routes (STAR) is quite feasible, it is a lot more difficult for Standard Instrument Departures (SID) that begin at the take-off end of the runway. One solution to alleviate the coverage requirements is to require airspace users to be equipped with Inertial Navigation Systems (INS) capable of runway updating. In this way, the initial part of the RNAV SID can be flown on INS coasting until entering DME network coverage, to allow the FMS to establish an associated position fix before the RNAV1 accuracy error budget is exceeded. While there is a need for more analysis in this area, it is estimated that relaxing the DME network coverage requirements to a lower limit of about 3’000ft above airport elevation should be feasible.

A rather unfortunate aspect of DME network provision is the fact that Instrument Landing System (ILS)-associated DME cannot be used. It is common practice in Europe to use DME to provide a continuous range to threshold function rather than the discrete markers. ILS-associated DME cannot be used because some, but not all FMS use them in RNAV tuning. So from a minimum infrastructure baseline point of view, these DME should not be used, even if in some cases they could provide value especially at low altitude. Some states have re-published ILS DME as en-route facilities in the AIP, however, as long as the VHF tuning frequency remains an ILS frequency, the FMS non-use will not change.

PERSPECTIVE ON NDB

Despite a broad agreement that NDB are no longer needed in current operations, many are still in operation and more continue to be procured. The primary problem of the NDB is that they are too cheap, e.g., since the facility has a cost which is comparable to a procedure redesign, it is often easier to just buy an NDB. The primary current use of NDB is to support non-precision approach procedures, or as Locators associated with ILS approaches, often in areas where there may still be low levels of GNSS equipage. Luckily, the use of NDB as en-route markers has largely disappeared. To overcome the financial hurdle in NDB decommissioning, it should be remembered that the ICAO goal is to provide vertically guided approaches to all instrument runway ends by 2016. This favors the introduction of GNSS-based RNP approaches, especially at runways without ILS. Even in areas outside of SBAS coverage at airports with user fleets with limited Baro-VNAV equipage, a regular GPS-based Non-Precision Approach is considered to provide better safety for airspace users than an NDB-based approach.

So how can NDB be rationalized out of the aviation system? While the low cost of those facilities reduces the incentive to do so, it also reduces the urgency. It is unfortunate that the NDB spectrum is not very desirable for other uses. But even if a stronger motivation can be found, what will remain as an obstacle is the training issue. As long as it is a requirement to be able to fly an NDB approach to obtain an instrument pilot rating, these facilities standardized in ICAO Annex 10 and referenced in many other formal publications will remain part of the system. It is noted that current pilot training is still built on conventional procedures, with PBN coming as an addition on top of that. It is likely to still take considerable time until PBN implementation penetrates to the training level such that RNP approaches are the first and core content, whereas conventional procedures would be trained more as a contingency function.

PERSPECTIVE ON FUTURE ALTERNATE POSITIONING, NAVIGATION AND TIMING (A-PNT)

The 12th ICAO Air Navigation Conference recommended for ICAO and States to assess the "need for and feasibility of an A-PNT system" [11]. In this context, "alternate" PNT means alternate to GNSS. In the short to medium term, at least alternate positioning and navigation (e.g., not time) is provided by currently established navigation aids, as explained and proposed in this paper. However, does it make sense to use these well-established facilities for the foreseeable future? Both SESAR and NextGen expect that more advanced airspace and 4D trajectory based applications will need to be supported, while cost and spectrum pressures will not go away. Those cost pressures are also a significant obstacle to any transition to new technology in aviation, with its lengthy equipment cycles; however, the evolution of conventional navigation aids significantly beyond their original purpose to a complementary PBN support infrastructure does have its limitations, especially at the low altitudes of terminal areas where airspace related capacity limitations are the most significant. Can space-based navigation ever be made sufficiently reliable to provide navigation exclusively, even with multi-frequency, multi-constellation GNSS? For sure, the physics of space based ranging sources will always provide the most suitable, cost effective and high performance positioning capability to support PBN and other CNS/ATM applications, including ADS-B. But those same physics also dictate that such signals can easily be overcome by terrestrial RF sources. Similarly, while the wide-area network aspect of GNSS provides significant system-of-system redundancy, that same aspect raises increased concern if ever there are significant performance issues of such global systems affecting many airspace users at the same time. Conducting a reliability analysis at such a scale is unlikely to be conclusive, given the number of unquantifiable assumptions and apples versus oranges comparisons required. Thus the issue is ultimately more of an emotional or human acceptance kind of decision, constrained by what is economically supportable.

From the above it can be deducted that research on any future, new terrestrial A-PNT system should meet the following constraints:

- Overcome the limitations of VOR and DME, especially at low TMA altitudes while providing a level of positioning performance similar to GNSS, including vertical guidance, if possible;

- Provide significantly higher spectrum use efficiency than DME in particular, while providing significant robustness against RFI;

- Low facility installation requirements, including a low number of sites required to provide low altitude coverage;

- Low overall navigation service provision cost, in particular to not hinder the introduction of multi-constellation GNSS;

- Low aircraft integration cost, ideally enabling implementation together with other CNS/ATM capability upgrades in a single package, for all types of airspace users.

A number of technology candidates for A-PNT systems are being investigated in the U.S. and Europe. These include enhancements to DME, the use of ground based ranging sources similar to GNSS but not in the same area of L-Band spectrum, the use of a future L-Band digital avionics communication system (LDACS1) to provide a navigation function, as well as SSR Mode N, where N stands for navigation using a similar signal structure than is currently being used by secondary surveillance radar. Advantages and disadvantages of those and other candidate systems will have to be evaluated carefully in light of the above constraints.

In any GNSS-vulnerability related discussion, the topic of eLORAN is likely to come up as well. While this is certainly another A-PNT candidate system that should not be overlooked, it is the private opinion of the authors that LORAN is a highly recommendable A-PNT system for the maritime community, but for aviation applications in Europe, given the current state of implementation its utility would be limited to niche applications, such as air traffic in extended overwater areas with limited radar coverage, for example the North Sea. It will be interesting to see how all the technology options mentioned in this section will develop towards meeting stated the high level objectives and constraints.

Finally, the need for time and time distribution or synchronization between airspace users and ATM systems in the context of trajectory based operations is not addressed in this paper and will be the subject of future work.

CONCLUSIONS

This paper gave a comprehensive, facility-specific overview of developments in navigation infrastructure towards supporting the global implementation of PBN. The key emphasis is on the evolution from a modular conventional infrastructure to one that needs to be seen as a terrestrial, cross-border network. This shift in focus brings opportunities for rationalization and optimization that can only be brought about by a proactive cooperation of all actors as an integral part of PBN implementation planning. What is proposed is a VOR/DME back-up network to provide safe extraction and landing for all users, and a GNSS-redundant DME network providing business continuity to equipped users supporting at least RNAV1 operations en-route and in major terminal areas. The VOR/DME network gives priority to existing airport VOR/DME installations in line with its residual use, enables significant VOR rationalization and provides a basis to build the DME network in a complementary manner. While this proposal provides a sufficient near term A-PNT capability, it is also considered a necessary effort to investigate other long term options taking the constraints of cost and spectrum into account.

While there is relatively broad acceptance of these plans through fora such as the EUROCONTROL Navigation Steering Group (NSG), the key challenge is to reach the decision makers of individual facility renewals. Many NDB are probably being renewed simply because the decision makers are not aware of RNP approach options available today. Similarly, many ANSP may shy away from the expert project effort required to realize facility savings by defining a target terrestrial PBN infrastructure and engaging in extensive consultation. The goal of this paper is to help convince decision makers that such efforts are feasible and worthwhile starting right now, which is essential especially when considering the fact that infrastructure optimization is strongly linked to facility life-cycles, making such an evolution by definition a slow one.

The hope is that neighboring States will work together to turn the infrastructure networks described herein into reality, by making planned and coordinated changes to individual facilities that will, over the years, add up and converge towards the desired terrestrial PBN network. Corresponding guidance has been proposed for inclusion into ICAO Annex 10 [12]. Finally, it is also hoped that these proposals will find acceptance in the conventional navigation infrastructure provision community, e.g., equipment manufacturers, ANSP and flight inspection organizations. Significant work will continue to be required to make these evolutions a reality. Embracing the additional complexities derived from the PBN-network perspective described herein will be essential for success and will continue to require the professional support of this community.

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DISCLAIMER

The views expressed in this paper are those of the authors only. None of the statements contained in this paper represent an official policy statement of the EUROCONTROL agency or of the SESAR Joint Undertaking.

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Recent Issues in Performance Prediction and Flight Inspection Measurements

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ABSTRACT

This paper continues a series of discussions and papers by the authors on flight inspection measurements and facility issues. It presents investigations into current technical problems encountered during simulations and ground/airborne measurements.

This paper analyzes recent experiences during flight inspections on a variety of ground-based navaids, using several current Flight Inspection Systems. The paper maintains neutrality by not mentioning location or equipment manufacturers. The paper addresses common problems such as measured GS performance in the presence of unusually deep snow cover on the ground plane, problems with non-metallic GS masts, CVOR/DVOR performance (predicted and measured results for on-airport scatterers, many close, large wind turbines), and discussion of continued application of roughness/scalloping tolerances and the 95% rule. The paper concludes with recommendations for more detailed guidance material and further harmonization of flight inspection practices and measurements.

INTRODUCTION

Short case-studies for various ground-based navigation facilities and related issues will be presented.

GLIDE PATH CASES

Glide Path Facility and Snow - A Practical Example

The effects of snow cover on the Glide Path (GP) reflection plane have been addressed many times. As a very general statement, snow cover will increase the path angle, although the effects of melting and refreezing can complicate predicting the results. Most service providers have implemented policies to assure that the depth of an accumulated snow cover of the ground plane does not exceed a specified amount in critical beam-forming areas - a common maximum might be 2' or 0.7m.

During an indoor training session for the maintainers of a recently-installed arctic installation, a user complaint was received that the "...threshold crossing height is twice what it should be." While that specific claim is not technically credible, the crew observation that the aircraft was "floating 800' beyond the normal touchdown point" was much more credible. This would suggest a steeper-than-normal descent leading to a strong flare maneuver near threshold A visit to the site revealed that a snow drift approximately 10' (~3m) deep immediately in front of the GP mast had accumulated. (The moisture content of the snow was very low.) Figure 1 is a photo showing the drift within perhaps 40' of the mast - the snow is nearly the same level as the lower antenna, which is normally approximately 14-15' (3m) above the active reflection surface.

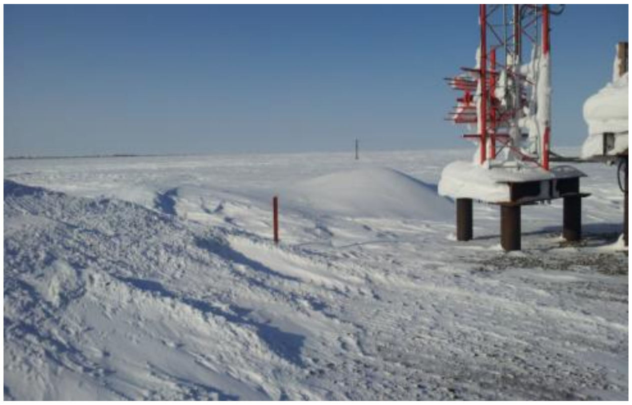


Figure 1. Snow Drift and Lower GP Antenna

The GP was promptly removed from service, and efforts began to remove much of the snow drift using a tracked vehicle. The area addressed was approximately 250' x 120' (~80m x 35m) immediately in front of the mast. Figure 2 shows the work in progress, as viewed from the lower antenna.

Figure 2. Removing Snow Drift

Ultimately, the snow depth was reduced to approximately 3' (1m) and a special flight inspection was requested by maintenance personnel. The resulting measurement produced a 3.16 degree path angle (normally 3.00º), with 2, 3, and 4 microamperes (µA) of roughness in Zones 1, 2, and 3 respectively. While the initial user-experienced GP angle was likely out of tolerance on the high-angle side, it was apparently operationally usable although an abnormal amount of the touchdown zone was used.

Non-Metallic GP Mast and its Effects

The application of a non-metallic GP mast recently focused attention on the effects of asymmetrical mast hardware on the antenna patterns, and a corresponding effect on path angle and achieved Threshold Crossing Height (ATCH).

Figure 3 shows at left a non-metallic mast installation. Near the top, a metallic triangular brace is installed between the tower legs. For some installations, the brace height may coincide with an antenna's height, as occurred recently. At right in Figure 3, the metallic brace (with two triangular sections) is shown behind the upper antenna, which is supported by hardware connecting only the front two tower legs.

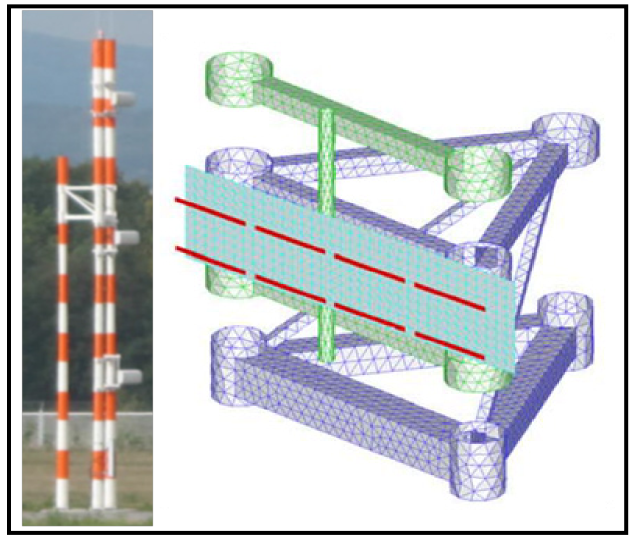


Figure 3. Non-Metallic Mast with Metallic Bracing

It is intuitive that asymmetric metallic tower bracing near only one of the GP antennas can produce pattern variations between antennas. Rigorous Method-of-Moment (MoM) Simulation of the metallic bracing structure, using numerous triangular patches as shown in Figure 3, resulted in the vertical antenna patterns shown in Figure 4. The almost-circular patterns for (1) the antenna only and for (2) the antenna plus its own mounting hardware nearly overlay one another.

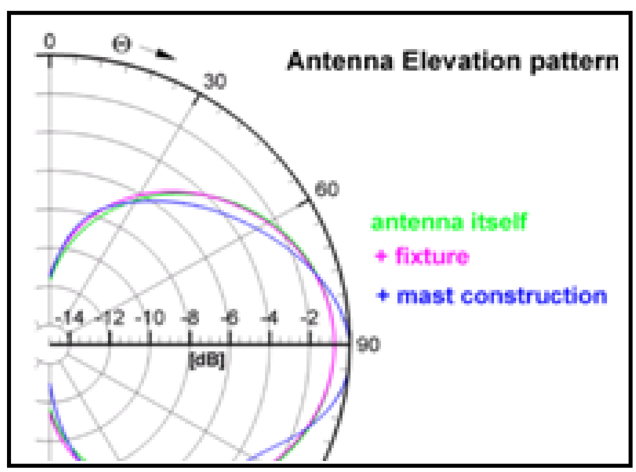


Figure 4. Predicted Antenna Patterns

However, the more irregular pattern with a larger maximum at the horizon results from the presence of the metallic tower brace, introducing approximately ± 1 dB of amplitude variations. Similar variations occur in the azimuth pattern as well. When one antenna in the GP array has these effects and the other two do not, it can be expected that parameters sensitive to the differences between the antennas, such as the Difference in Depth of Modulation (DDM), will be affected.

Two DDM parameters are GP angle (nominally 3.00 degrees) and TCH. Figure 5 shows flight inspection measurements on a non-metallic mast GP with the metallic bracing behind the upper antenna only. Although the path in the last two miles prior to threshold (THR) is reasonably straight, it trends downward in the figure beginning at approximately 0.5 nautical mile (NM), followed by a major upward flare near threshold.

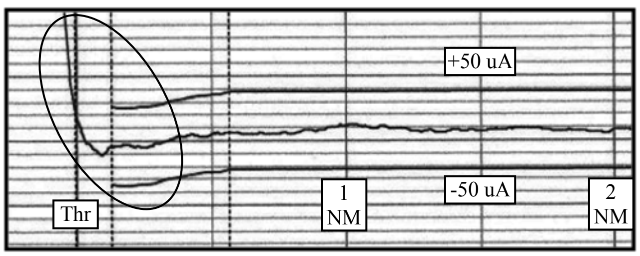


Figure 5. GP Results, Asymmetrical Mast Hardware

Beginning at approximately 0.5 NM, the aircraft is beginning to move laterally off the antenna bore sight axis. As this occurs, differences in the azimuth pattern of the antennas become more visible, resulting in the flare behavior - i.e., the upper and lower antenna amplitudes no longer cancel at the nominal path angle.

To partially mitigate this flare, the upper antenna was rotated in azimuth. Figure 6 illustrates the effects on GP structure and lists the numerical effects on path angle and TCH for rotation amounts of 2-7 degrees of the upper antenna. Variations in GP angle of 0.05 degrees and in TCH of approximately 3' result. It is clear that as the rotation angle approaches zero degrees (not shown), the shape of the structure closely matches that in Figure 5.

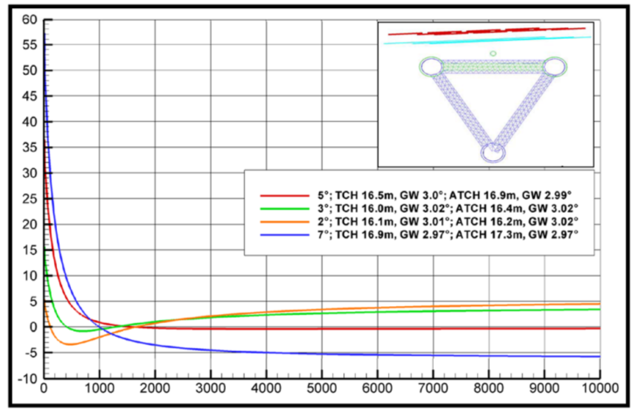


Figure 6. Ideal GP with Upper Antenna Rotation
(Horizontal - m from THR; Vertical - DDM µA)

VOR CASES

CVOR and Control Tower

A new ~100' (30m) Airport Traffic Control Tower (ATCT) was built on an airport with an existing CVOR that supported opposite-end approaches to the primary runway. The distance between the two facilities is approximately 3000' or 915m. Figure 7 depicts the general geometry of the CVOR, ATCT, and approach radial. Although a study was done to best locate the new tower, the eventually constructed ATCT was not positioned in the same way as it was studied. The approach from the south was removed from service following a flight inspection not long after the ATCT was completed.

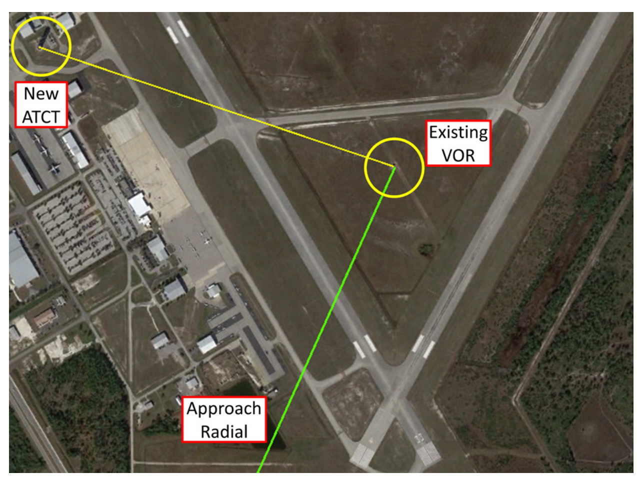


Figure 7. Geometry of Existing CVOR & New ATCT

To assure that potential solutions were addressing the correct problem, the ATCT was modeled for its effect on the approach, using 3-D techniques. Figure 8 shows the model and a photograph of the ATCT.

From the high-resolution 3-D model, the scattering pattern of the ATCT was computed. Figure 9 shows that a major lobe of the pattern is directed toward the south such that the primary reflection crosses the approach radial at a shallow angle. Figure 10 shows the resulting predicted VOR crosspointer error in an orbit at 10 NM and 1600' above the site. The maximum error on the 201 degree approach radial is approximately 4-5 degrees.

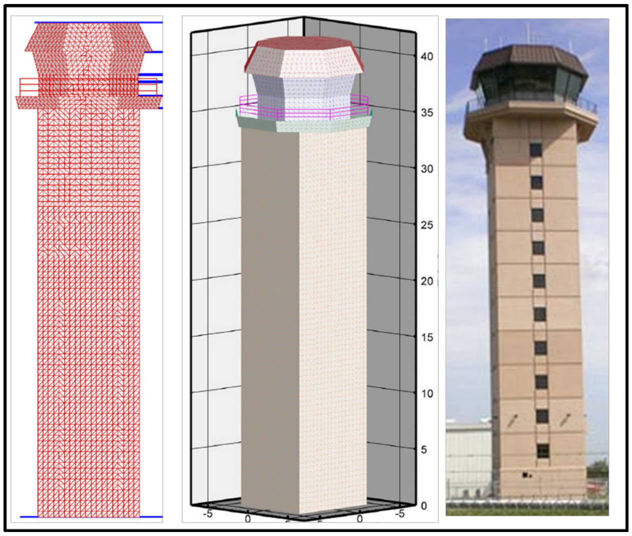


Figure 8. 3-D Model and Photo of New ATCT

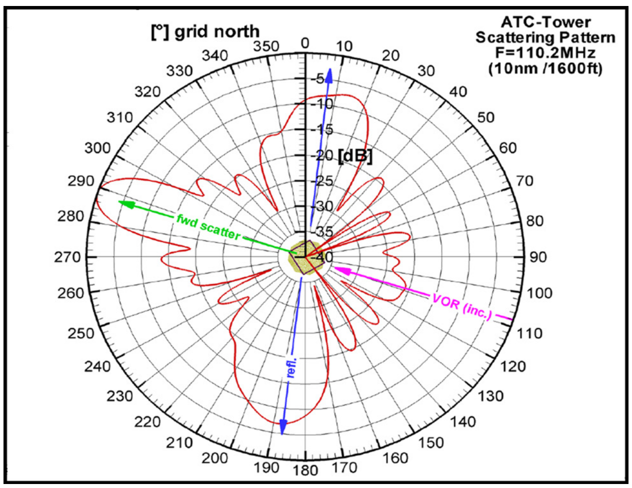


Figure 9. Scattering Pattern of ATCT

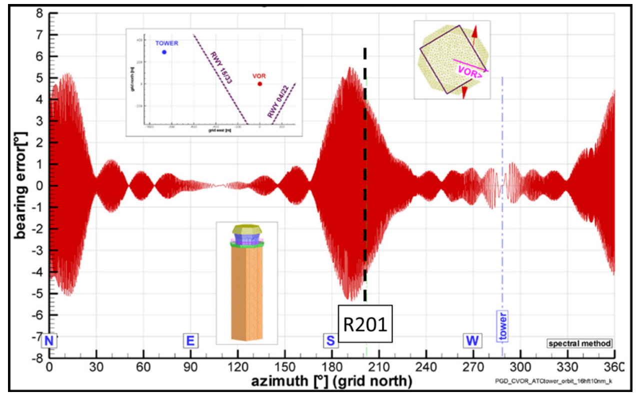


Figure 10. Predicted VOR Bearing Error from ATCT

Figure 11 presents a flight inspection measurement of the approach radial and the predicted errors from the ATCT, overlaid from 10 to 2 NM. The measured crosspointer trace is highlighted; its amplitude is generally ± 5-6 degrees in the 10-5 NM range and diminishes at closer ranges. The predicted errors have a similar magnitude and frequency from 10 to 5 NM. Although the agreement is reasonable, it is not as good as achievable in many simulation cases, because the actual descent path of the aircraft is very likely not flown at a constant rate and also not known with good resolution.

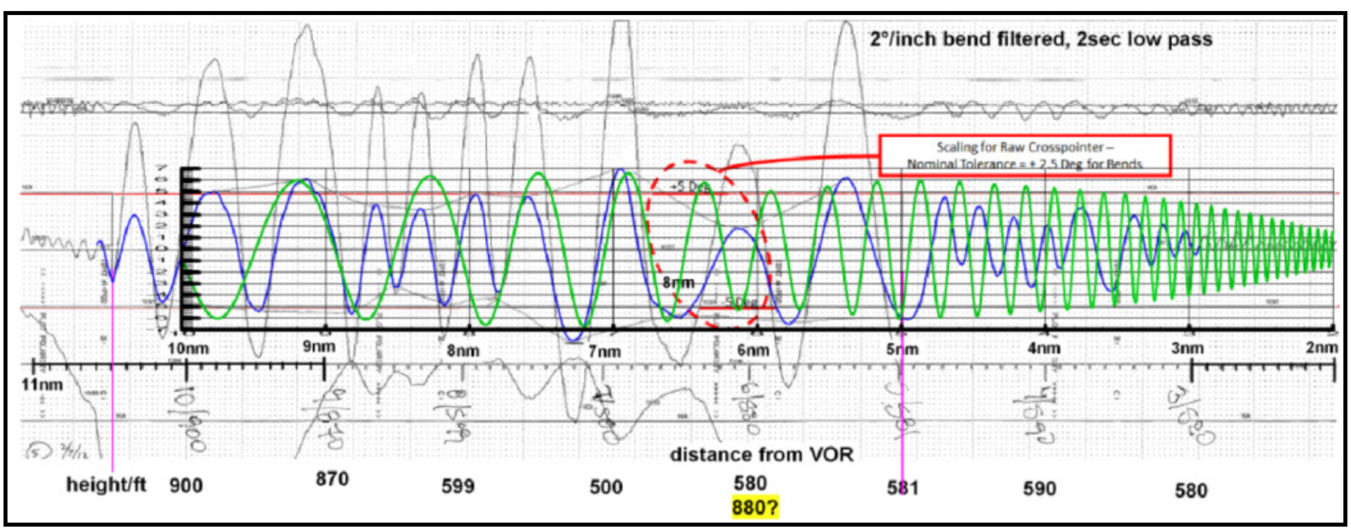


Figure 11. Measured and Predicted VOR Crosspointer Error for ATCT-affected Approach

DVOR and Wind Turbines

In late 2008, a developer proposed approximately 125 wind turbines (WT) of 400' (122m) height near a CVOR with TACAN. Figure 12 shows the originally proposed locations with respect to the VOR planned for installation in rows occupying approximately from radial 260 clockwise through radial 120, and ranging in distance from the VOR between 0.6 and 4.8 NM. After initial resistance to the plan from the appropriate regulatory authorities, the WT developer indicated willingness to engage in a "build a little, test a little" activity, during which the farther WTs would be installed first and their effects flight tested. Then closer WTs would be erected and another flight test of the VOR conducted. This would continue until all the planned WTs were erected, as long as flight test results continued to be acceptable. This test activity was based on first converting the VOR to the Doppler configuration at the developer's expense and the application of a WT placement algorithm negotiated between the developer and the regulators. The algorithm was a simple one (although very difficult to negotiate!):

- No WTs within 1 NM of the VOR
- No WTs in the 1.0 to 2.5 NM range if within...
    - 5 degrees of an instrument approach radial,
    - 10 degrees of a low altitude airway radial
- No constraints beyond 2.5 NM from the VOR

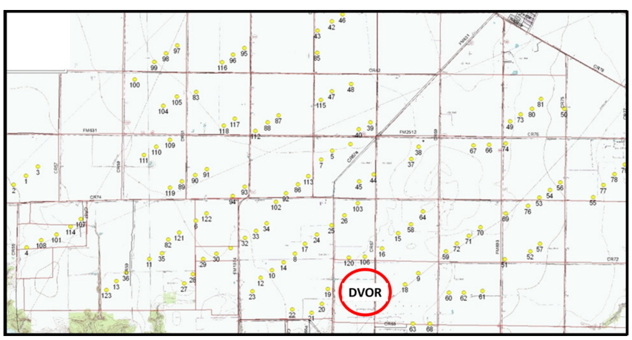


Figure 12. Proposed Wind Turbines near VOR

Presumably, the WT developer would benefit by obtaining approval for most of the WTs (if the algorithm was suitable), while the regulator could not only protect the airspace uses but also gain detailed flight inspection data with WTs in fairly close proximity to the DVOR. The plan was implemented, and flight inspections on both the DVOR and a temporary CVOR nearby (for data gathering purposes) occurred for the turbine configurations listed in Table 1.

Table 1. Flight Testing of Wind Turbine Development

Date	Number of WTs	WT Configuration	Facilities Tested
5/18/09	22	No rotor blades	DVOR
7/15/09	66	No rotor blades	DVOR
8/4/09	109	Rotors present, not turning	CVOR & DVOR
9/2/09	109	Rotors present, not turning	CVOR & DVOR
12/3/09	109	Rotors turning	CVOR & DVOR

The following measurement in Figures 13-18 were extracted from a report [1] published by the relevant regulatory authority. Flight inspection results for 10 NM and 40 NM orbits at 1000', for DVOR and nearby CVOR, are shown for the various WT configurations. Important radials were also flown, but for brevity only one is included here. Vertical scaling is one degree per major horizontal line.

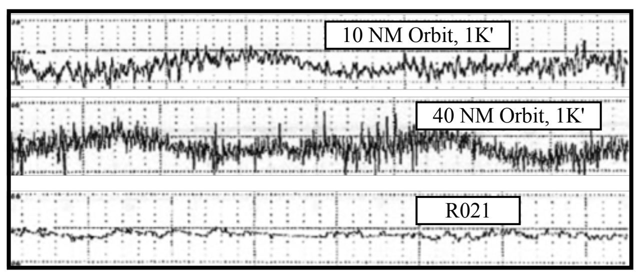


Figure 13. DVOR, 22 WTs, No Rotor Blades

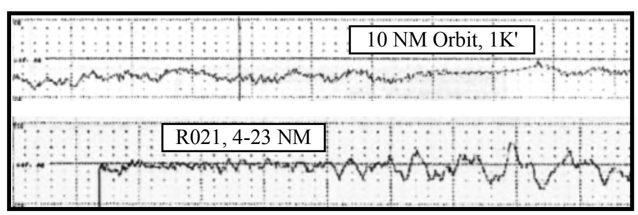


Figure 14. DVOR, 66 WTs, No Rotor Blades

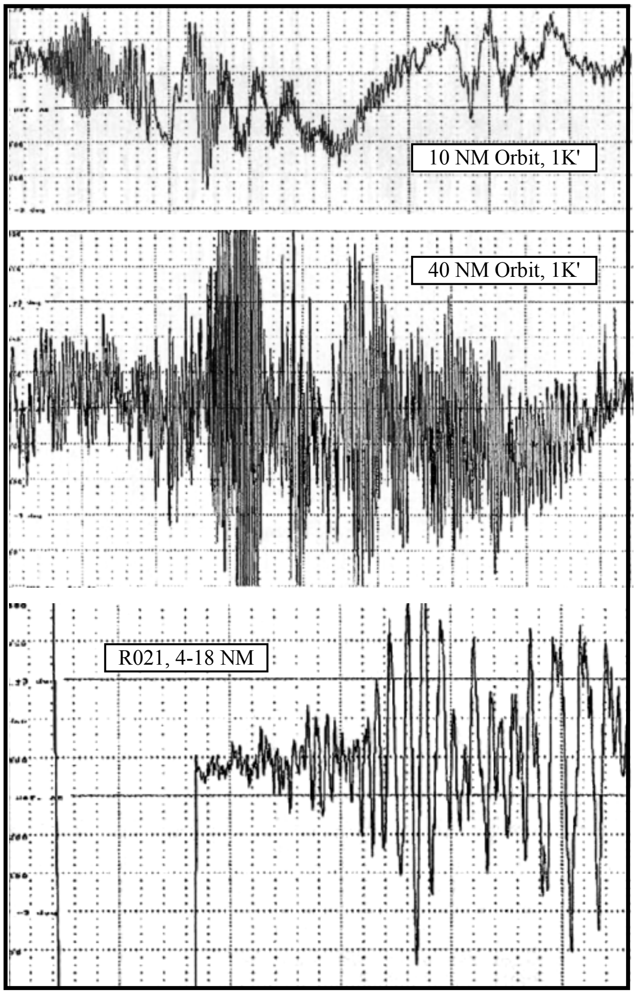


Figure 15. CVOR, 109 WTs with Stationary Rotors

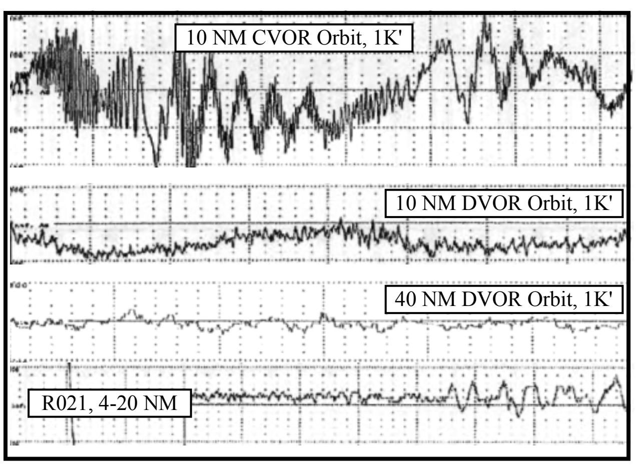


Figure 16. 109 WTs, Rotors Stationary

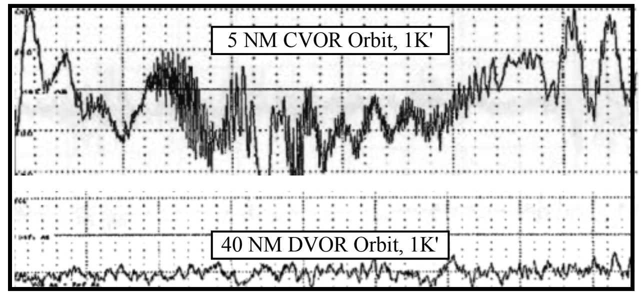


Figure 17. 109 WTs, Rotors Turning

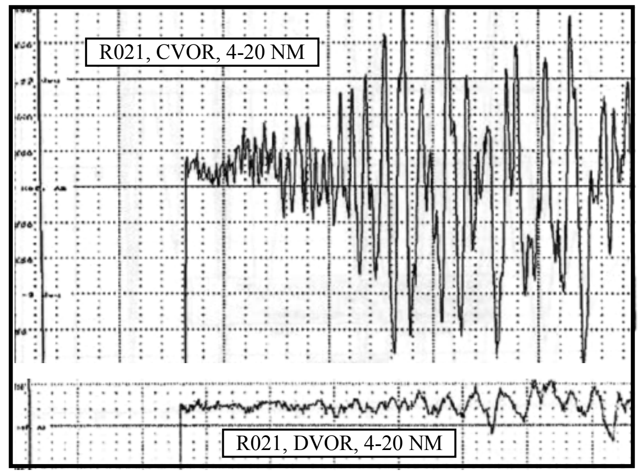
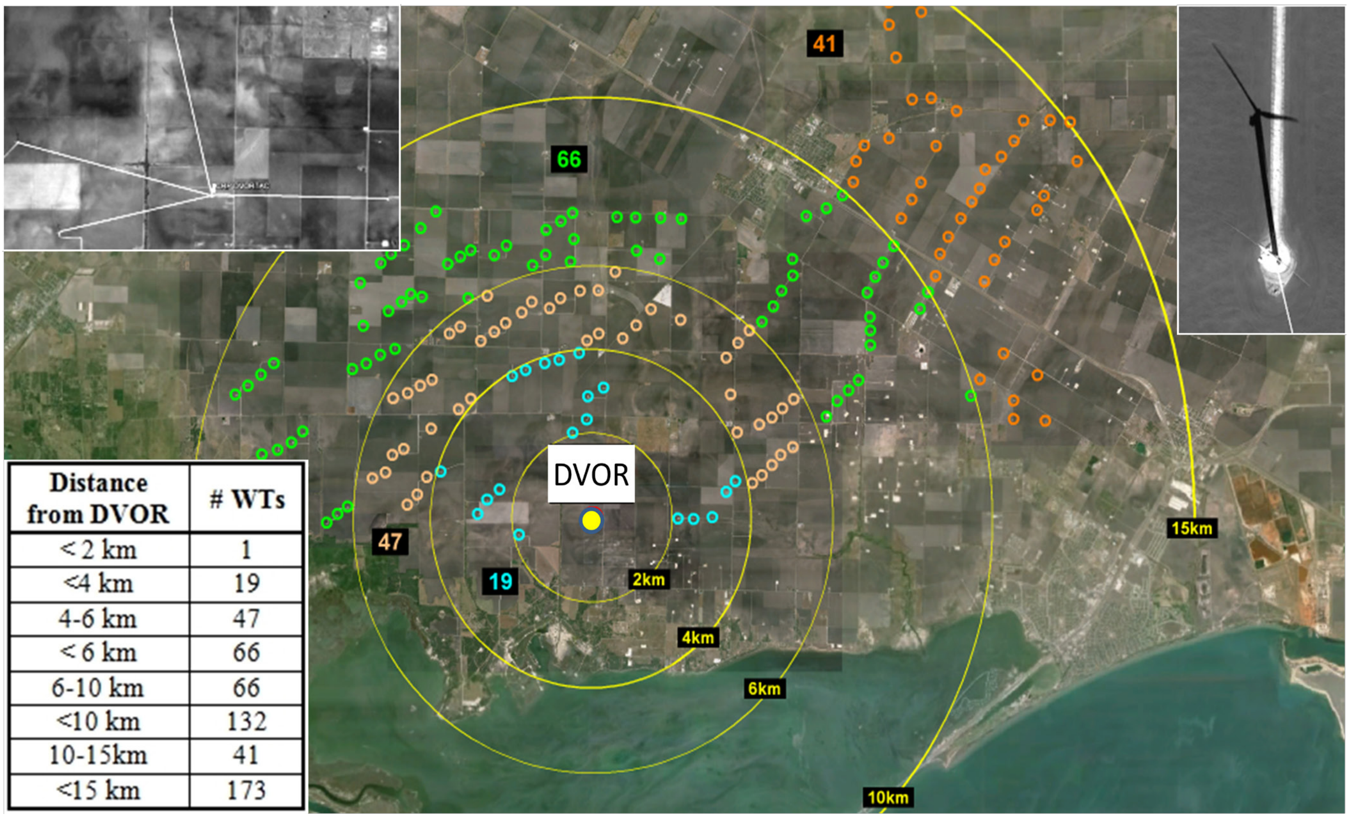


Figure 18. 109 WTs, Rotors Turning

After the DVOR was placed in service with the initial 109 WTs, the developer continued to add outlying turbines, as allowed by the algorithm. Within two years after the flight testing, approximately 175 WTs were located within 8 NM or 15 km of the DVOR. Figure 19 is a late 2011 photo showing the location of the WTs and a few statistics about their distances. Four of the 400' (122m) turbines (upper left inset) are within 1 - 1.3 NM or 1.8 - 2.4 KM.



Distance from DVOR	# WTs
< 2 km	1
<4 km	19
4-6 km	47
< 6 km	66
6-10 km	66
<10 km	132
10-15km	41
<15 km	173

Figure 19. DVOR with 173 Wind Turbines within 8 NM or 15 km

SPECIFICATIONS

Do we Need Roughness and Scalloping Tolerances?

From a conceptual standpoint, guidance errors seen by a user from most ground-based navigation stations may be divided into static or long-term, low-frequency, and high-frequency components. These are often referred to using terms such as Alignment (A), Bends (B), and Roughness and Scalloping (R/S), respectively. Often these error components are collectively referred to as "structure."

This concept of dividing errors by frequency does not consistently appear in the International Civil Aviation Organization's (ICAO's) Annex 10 [2]. For example, tolerances for VOR errors from the ground station are limited to an overall ± 2 degrees regardless of frequency. Similarly, tolerances for Instrument Landing System (ILS) Localizer and Glide Path facilities are limited to overall values such as ± 30 microamperes. In contrast, Microwave Landing System (MLS) tolerances are categorized by frequency of error, but use the terms path following error, path following noise, and control motion noise in lieu of A, B, and R/S.

Tolerances for A, B, and R/S have been applied separately by the flight inspection community to VOR flight testing results for decades. Although the Standards and Recommended Practices (SARPS) in ICAO's Annex 10 do not mention them, they appear in ICAO's Doc 8071 manual [3], at least in part because the current manual during its 1999 rewrite was patterned heavily on the contents of FAA's Order 8200.1C, *United States Standard Flight Inspection Manual* [4]. Doc 8071 defines VOR tolerances of ± 2 º (A), ± 3.5 º (B), and ± 3 º (R/S). Figure 20 shows an artificial sample of alignment errors (horizontal dashed line), bends errors (sinusoidal dashed line), and roughness (irregular) and scalloping (periodic) high-frequency errors.

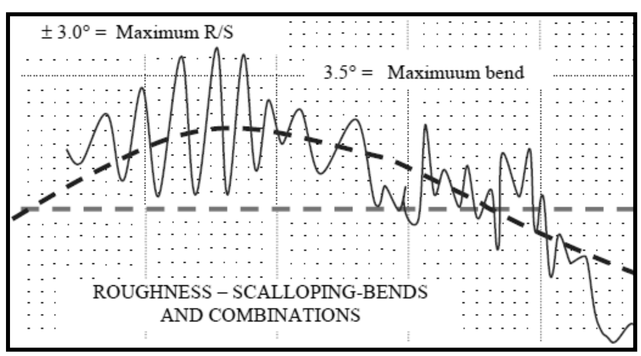


Figure 20. Alignment, Bends, and R/S Errors

R/S can be described in general terms as high-frequency errors (from VOR facilities), or as errors that are sufficiently fast that the aircraft cannot be maneuvered to follow them - ie, the ground track is unaffected by R/S. For modern automatic flight inspection systems (AFIS), however, it is necessary to mathematically define the frequency content. One system uses four-pole filters to separate A, B, and R/S, and defines R/S as errors with periods between 2 and 10 seconds (0.1 to 0.5 Hz) [5]. Errors of longer periods are separated into A and B components; errors of shorter periods are generally removed by the navigation receiver, are not sent to the AFIS, and cannot be seen by the user pilot.

Based on the authors' VOR experiences, both in the field and multipath simulation environments, many VOR performance issues relate to R/S errors, typically from power lines, wind turbines, and other reflectors at some distance from the ground facility. In other words, many VOR restrictions that result in the loss of an airway or approach, or in raising the relevant minimum altitudes, arise from R/S errors. Since such errors by definition cannot result in the aircraft changing its ground track, why is it necessary to restrict or penalize the benefits of operating the facility solely for R/S reasons?

For many years, the answer usually offered was "...to protect the autopilot from disconnecting." It very likely was true that older autopilots (circa 1960s, 1970s) were prone to disconnect from noisy signals, but this issue has surely been greatly attenuated by modern systems with improved filtering, microprocessor-augmented tracking, etc. But more importantly, taking the position that autopilot operation must be protected violates a common principle of flight inspection organizations - that the mission is to measure the signal-in-space, rather than addressing equipage, especially the less-elegant avionics.

Perhaps the flight inspection community might again choose to revisit defining the goal of applying R/S tolerances, especially when this action results in many facility restrictions and reductions in usable service, without the user aircraft's ground track being affected. If a consensus develops that this is unnecessary, the appearance of R/S tolerances in Doc 8071 (often used as the basis for flight inspection contracts) but which do not appear in Annex 10 can surely be addressed.

Implementation Issues with the 95% Rule

Various ICAO documents address the statistical nature of measured parameters and state that the signal-in-space Standards are 95% or 2-sigma values. A few examples include, from Annex 10, Volume 1:

- 3.1.3.4 & 3.1.5.4, Localizer & Glide Path Bends
- 3.5.3.1.3, DME System Accuracy
- 3.7.3.1.1.1, GPS Positioning Accuracy
- 3.11.4.9, MLS System Accuracy

Annex 10, Volume 1, Attachment C further discusses Course Bends and states in paragraph 2.1.5, Application of localizer course/glide bend amplitude Standard, *"The 95 per cent maximum amplitude specification is the allowable percentage of total time interval [emphasis added] in which the course/path bend amplitude must be less than the amount specified in Figure C-1 for the region being evaluated."*

Attachment A of Annex 11 states in paragraph 3, Determination of protected airspace along VOR-defined routes, *"The word "containment" ... is intended to indicate that the protected airspace provided will contain the traffic for 95 per cent of the total flying time (i.e., accumulated over all aircraft) for which the traffic operates along the route...it is implicit that for 5 per cent of the total flying time traffic will be outside the protected airspace." [emphasis added two places]* From this Annex 11 statement (explicitly about VOR routes), it is inferred that although the two-sigma concept is defined in Annex 10 for time (for ILS, DME, GPS, and MLS, but notably not for VOR), its purpose is related to spatial deviations of the aircraft from the desired course.

The general application of a two-sigma value is certainly conceptually helpful for the treatment of some measurement anomalies, such as outliers in sampled data, which is commonly processed in today's receivers and flight inspection systems [5]. However, a number of unaddressed issues cause questions or debate to arise when analyzing flight measurements and recordings of navigational aids.

- Bends, specifically their frequency content characteristics, are not formally defined in the SARPS.

- The quoted references in general address only bends (presumably low frequency error) amplitude, or they state that structure (presumably A, B, and R/S) is defined at a two-sigma probability. There is no mention in any of these documents of applying a two-sigma analysis process to high frequency errors (R/S).

- Localizer and Glide Path structure tolerances do not make a distinction between bends and R/S. If a 95% analysis is applied to structure measurements, does it apply only the bends component (which does not have an individual tolerance), or to the composite DDM measurement which generally contains A, B, and R/S errors?

- There is no mention or definition of bends or R/S in the VOR SARPS, and Doc 8071 [7] does not mention two-sigma or 95% in the VOR chapter (only in the ILS chapter). Yet, many flight inspection organizations apply two-sigma analysis to VOR recordings (for both bends and R/S components). Some, for example, apply a sliding window in which to measure the per cent of time that signals exceed the tolerance, where the window length (in feet or NM) varies with the altitude of the measurement [4].

Collectively, these unaddressed points again, as in the previous topic (whether R/S tolerances are even needed), illustrate challenges in the application of tolerances.

CONCLUSIONS

From the case studies presented here, the following conclusions may be drawn.

a. An extreme example of dry snow accumulation (within 3-4' of the lower antenna height, directly in front of the GP mast) resulted in a glide path that, although abnormally high in angle, was successfully flown by a user jet aircraft. When the snow depth was reduced by approximately two thirds, the measured GP angle was within tolerance at 3.16º (normally 3.00º).

b. Service maintainers must remain diligent in monitoring and limiting the depth of snow accumulation in the near proximity of the GP mast, since flight measurements occur too infrequently to serve as any form of monitoring.

c. Small metallic bracing components in non-metallic GP masts can affect radiation patterns if the bracing is near any of the antennas.

d. GP antenna pattern distortions can introduce undesirable effects near the runway threshold, such as changes in TCH.

e. TCH can be modified somewhat by small differential rotations of the GP antennas in a CEGS array.

f. Reflections from a 100' high ATCT ~3000' from a CVOR can exceed instrument approach procedure flight inspection tolerances.

g. A DVOR on flat terrain with numerous nearby 400' (122m) wind turbines was extensively flight tested and found in tolerance. (At least 173 turbines are located within 1-8 NM (1-15 km) of the DVOR.)

h. Roughness and Scalloping tolerances do not serve a safety purpose, given that R/S does not affect the ground track of the aircraft.

i. R/S tolerances should not be used to disqualify procedural uses of navigational aids.

j. The application of two-sigma values is inconsistent or poorly addressed in various international documents.

k. While not stated explicitly in the ICAO documents, the two-sigma concept is intended to address containment of the aircraft within known or defined boundaries.

l. The two-sigma concept should be applied only to bends (frequencies), not to R/S (frequencies).

m. If R/S tolerances were deleted, many of the issues with two-sigma application would disappear.

n. The two-sigma concept should be applied consistently to all navigational aids types - i.e., ILS, VOR, DME, MLS, GPS, etc.

RECOMMENDATIONS

The following recommendations are made from the topics presented.

a. Ensure that snow depth monitoring occurs for GP facilities in snow-prone areas.

b. Exercise caution when rotating GP antennas to lower TCH, as this technique causes downward trends in the flight path close to the runway.

c. Do not include out-of-tolerance time from high frequency R/S errors when applying the two-sigma concept.

d. Do not use R/S tolerances to restrict the operational benefits of navigation facilities.

e. Improve the consistency between various international documents for definition and application of the two-sigma concept.

REFERENCES

[1] Source: *[Organization Deleted to Retain Neutrality - contact authors]*, 2012, ...Signal Interference in VOR Systems Caused by Wind Turbine Farms

[2] ICAO, July 1996, International Standards and Recommended Practices, Annex 10 to the Convention on International Civil Aviation, Volume 1, Radio Navigation Aids, 5th Edition, http://www.icao.int

[3] ICAO, October, 2002, Manual on Testing of Radio Navigation Aids, Volume 1, Amendment No. 1, http://www.icao.int

[4] U.S. Federal Aviation Administration, October, 2005, Order 8200.1, United States Standard Flight Inspection Manual, Change 8, Order 8200.1

[5] Greving/Spohnheimer, June, 2006, Recent Issues in Demanding ILS Ground and Flight Measurement Environments, 2006 IFIS, Toulouse, France

[6] ICAO, July 2001, Air Traffic Services, Annex 11 to the Convention on International Civil Aviation, 13th Edition, http://www.icao.int

[7] ICAO, 31/10/02, Manual on Testing of Radio Navigation Aids, Volume 1, Testing of Ground-based Radio Navigation Systems, 4th Edition, Amendment 1

IFIS 2014
Flight Plan to Innovation

Session 2

Flight Inspection of RFI and Related Concepts

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Investigation of VHF Omni-Range (VOR) Signal Interference

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ABSTRACT

Signal interference is a fairly common occurrence during flight inspection work. The flight crew's first priority when dealing with interference is to identify its source. Once found, other helpful pieces of information about the interference could be measured. This was made evident in a case study involving interference to a Very High Frequency Omni-Range (VOR) facility.

This paper presents a case study involving interference to a VOR facility. This study includes 1) a description of the interference problem, 2) troubleshooting steps taken by the flight crew, and 3) lab test procedures used in hopes of duplicating the problem. An overall analysis is presented along with conclusions regarding the true nature of this problem: does the problem stem from inadequate performance by the flight inspection equipment or is it a facility performance/interference issue?

DESCRIPTION OF INTERFERENCE PROBLEM

An aircraft equipped with two RNA-34BF flight inspection navigation receivers flight inspected the Very High Frequency Omni-Range/Tactical Air Navigation (VORTAC) facility in Hattiesburg, MS. This facility identifier is LBY and operates at 110.6 MHZ. Large bearing errors were recorded at 2.1 miles from the facility on the 355 "from" radial. The VOR status changed states from normal to no computed data (NCD) during this time on at least one run. Figure 1 illustrates the flight inspection aircraft path using Google Earth. Figure 3 shows the flight inspection recording illustrating the VOR error and status trace fluctuations during the interference.

The flight inspection crew made radio contact with the facility maintenance personnel and described the anomaly. Ground maintenance did not report anything out of order, but did say that a localizer antenna is located about 2.1 miles from the VORTAC on the 355 radial. This localizer uses 109.5 MHZ. Figure 2 shows a close up view of the interference area with begin and end points of significant bearing errors taken from the flight inspection log files for this run.

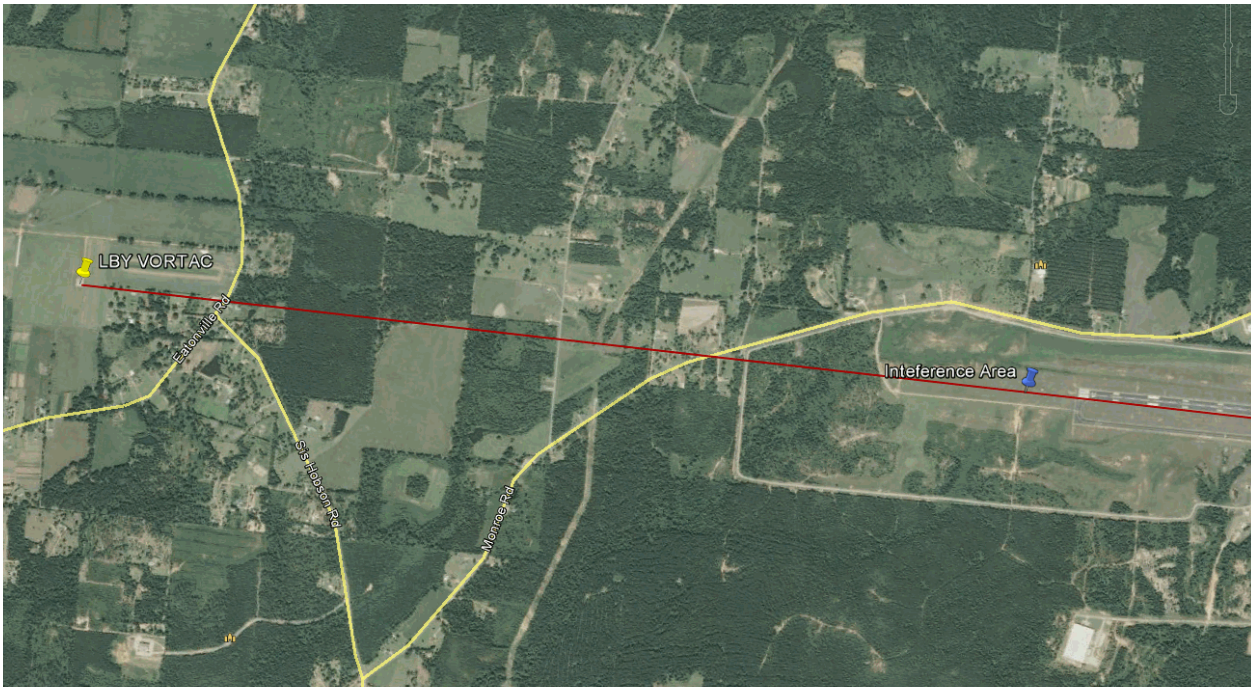

Figure 1. Flight Inspection Aircraft Path

Figure 2. Close Up View of Interference Area

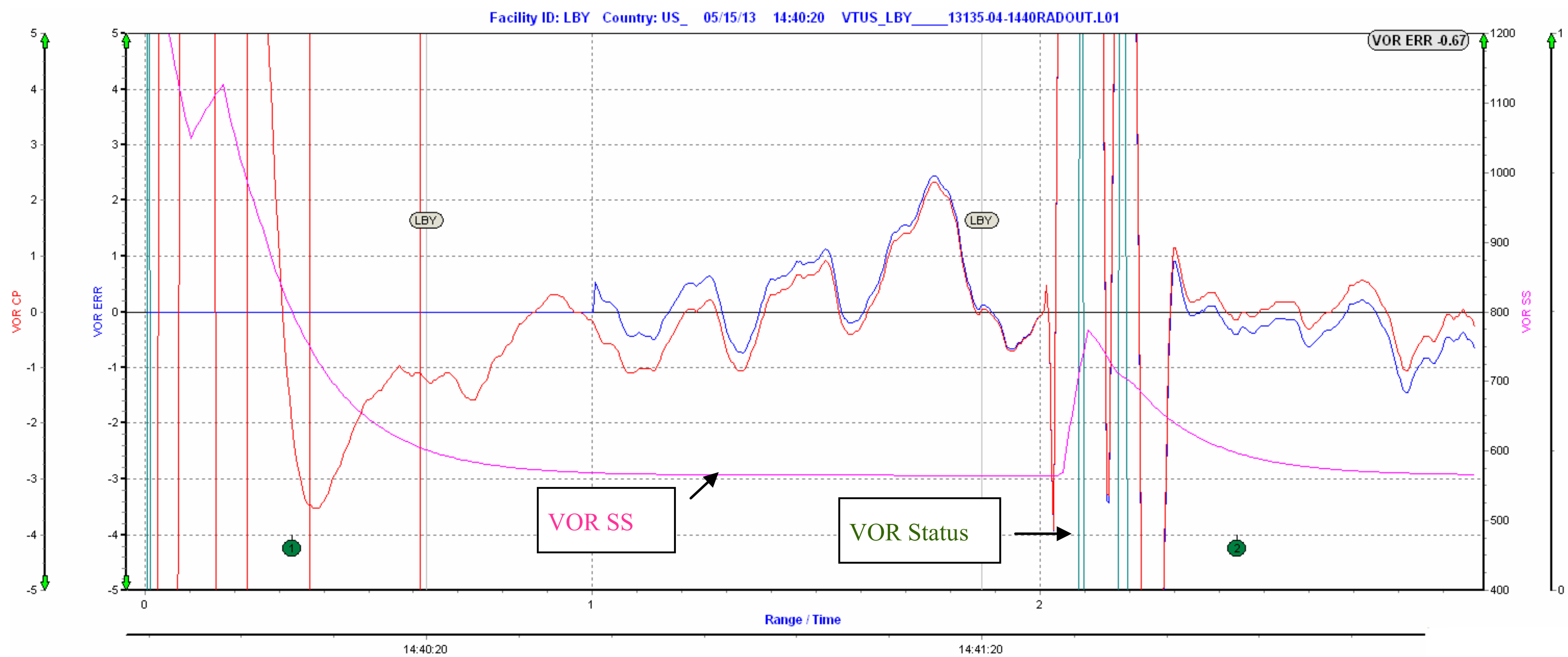

Figure 3. Flight Inspection Recording

FLIGHT INSPECTION DIAGNOSTIC STEPS

The crew reported that the front-end receivers of this aircraft did not experience any problems during the same time period.

The flight inspection crew coordinated with ground maintenance personnel to temporarily turn off the suspect localizer. The VOR radial run was repeated, and the bearing errors were no longer present.

Several days later the VOR radial inspection was repeated with an aircraft equipped with RNA-34AF flight inspection receivers. Interference problems were not experienced with either the front end or the flight inspection navigation receivers.

SECONDARY RNA-34BF RECEIVER INDICATION

In these aircraft the primary flight inspection navigation receiver provides the indications to the mission specialist and also records data to log files. The secondary navigation receiver records data as well but was not set up to provide secondary indications on this flight. The data recorded from the secondary RNA-34BF navigation receiver was examined later and found to contain the same interference measurements as displayed in Figure 3 above.

LAB TESTING

With two other models of navigation receivers performing without interference indications, the investigation turned to evaluation of the RNA-34BF receiver. Since test equipment for both the RNA-34BF and RNA-34AF receivers were available at our repair station, experiments were performed with each model to try and duplicate the disparate interference performance for these receivers. Also, sensitivity and selectivity tests were performed on the RNA-34BF to help evaluate its performance in the presence of interference.

RNA-34BF Receiver Interference Testing

Lab tests were performed with the RNA-34BF bench test equipment to duplicate the problem seen during flight inspection. To simulate the interference signal, a second signal generator was used to generate the interfering localizer signal, and the two signals were combined using a radio frequency (RF) combiner as in Figure 4.

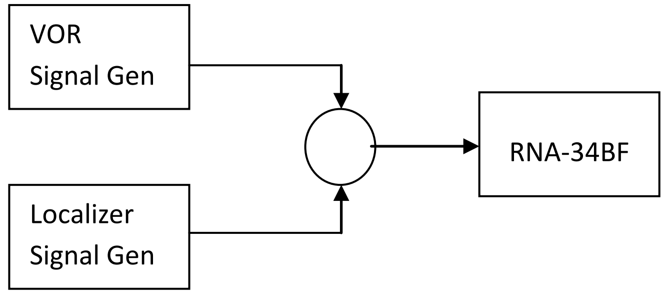

Figure 4. Interference Testing Block Diagram

Figure 3 shows the LBY VOR signal strength was approximately 550 uV at the interference area. For a 50 ohm system this is equivalent to approximately -52 dBm.

The interfering localizer signal strength was not recorded during the flight inspection runs since VOR mode was in use. The localizer signal strength was estimated by obtaining localizer signal strength from a log file recorded during an inbound low approach maneuver over the RGR localizer in Oklahoma City. In this log file, the RGR localizer signal strength over the localizer antenna at 70 feet above ground was 1303.57 uV. The LBY VOR radial flight path altitude was 300-350 feet above the interfering localizer antenna. From this data, a worst case signal strength estimate of 1000 uV was used for the interfering localizer signal. This is equivalent to -47 dBm for a 50 ohm system.

During the lab tests, VOR signal strengths stronger and weaker than -50 dBm were tested. Similarly, a range of localizer signal strengths around -47 dBm were tested. The resulting data is presented in a table format shown in Table 1. For each combination of VOR and localizer signal strength, bearing and receiver status was monitored.

The same lab testing procedure was repeated with an RNA-34AF receiver. See Table 2.

Table 1. RNA-34BF Interference Lab Test Results

RNA-34BF Lab Test Results VOR 110.6, Localizer 109.5						
VOR SS \ LOC SS	-15	-25	-35	-45	-55	-65
-40						
-45						
-50	OK	OK	OK	OK	OK	OK
-55	OK	OK	OK	OK	OK	OK
-65	OK	OK	OK	OK	OK	OK
-75	OK	OK	OK	OK	OK	OK
-85	OK	OK	OK	OK	OK	OK
-95	unstable bearing status = NCD	bearing +/-1 deg normal status	OK	OK	OK	OK

Table 2. RNA-34AF Interference Lab Test Results

RNA-34AF Lab Test Results VOR 110.6, Localizer 109.5						
VOR SS \ LOC SS	-15	-25	-35	-45	-55	-65
-40	OK	OK	OK	OK	OK	OK
-45	OK	OK	OK	OK	OK	OK
-50	OK	OK	OK	OK	OK	OK
-55	OK	OK	OK	OK	OK	OK
-65	OK	OK	OK	OK	OK	OK
-75	OK	OK	OK	OK	OK	OK
-85	bearing +/- 2 deg normal status	OK	OK	OK	OK	OK
-95	+/- 6 deg status = NCD	bearing +/- 3 deg status = NCD	OK	OK	OK	OK

In these tables OK means the bearing indication from the receiver is stable and within one degree of what the lab equipment was set to transmit, and the receiver indicates normal status. The colored cell represents the actual VOR signal strength and the estimated interference signal strength as calculated above.

Plainly, these lab tests failed to duplicate the interference problem at the worst case estimated interference signal strength. More discussion regarding these lab tests will be presented in the analysis section.

RNA-34BF Receiver Sensitivity Testing

Receiver sensitivity is defined to be the minimum input signal required to produce a specified output signal with a certain signal to noise ratio. For the RNA-34BF the sensitivity is defined as the minimum signal required for full flag down operation. A lab test was performed to confirm the RNA-34BF sensitivity figure of 2uV or less.

Again, the RNA-34BF test setup was utilized. The receiver was allowed to warm up. The signal generator was set up for VOR mode with a frequency of 110.00 MHZ. Additionally, the signal generator was setup with the chosen heading and a signal identification type set to tone. Lastly, the signal generator was set to a RF level of 5uV.

The correct bearing and a normal status was observed on the navigation receiver test set indicator (computer monitor). The RF level was then gradually decreased until the status changed from normal to no computed data (NCD). The signal generator RF level at this point was 1.11uV. The sensitivity specification of 2uV or less was confirmed.

RNA-34BF Receiver Selectivity Testing

After the sensitivity testing was performed, the RF level of the signal generator was gradually increased until the navigation receiver test set indicator showed a 6 dB stronger signal than the sensitivity threshold.

To gather selectivity curve data, the signal generator frequency was increased to 110.010 MHZ. The VOR signal strength reported by the bench test receiver indicator did not change. The signal generator frequency was then increased to 110.015 MHZ. The signal generator RF level was then adjusted to maintain the VOR signal strength at the center frequency signal strength. This process of increasing the frequency away from the center and then adjusting the RF level of the signal generator was repeated until data points for +/- 40 KHZ around the center frequency was obtained. The data obtained is plotted in Figure 5.

The OEM specifies that for +/- 17 KHZ around the center frequency, the attenuation shall be less than 6 dB. The data curve confirms this specification.

The OEM specifies that for +/- 31.5 KHZ around the center frequency, the attenuation shall be greater than 60 dB. Data points at +/- 31.5 KHZ delta around the center frequency were not collected. The data points at +/- 35 KHZ were -60.9 dB and -53.2 dB, respectively. This data indicates that the receiver performance is a little deficient for that specification.

The OEM specifies that for +/- 40.0 KHZ around the center frequency, the attenuation shall be greater than 80 dB. The data curve in Figure 5 shows that this specification is somewhat deficient as well.

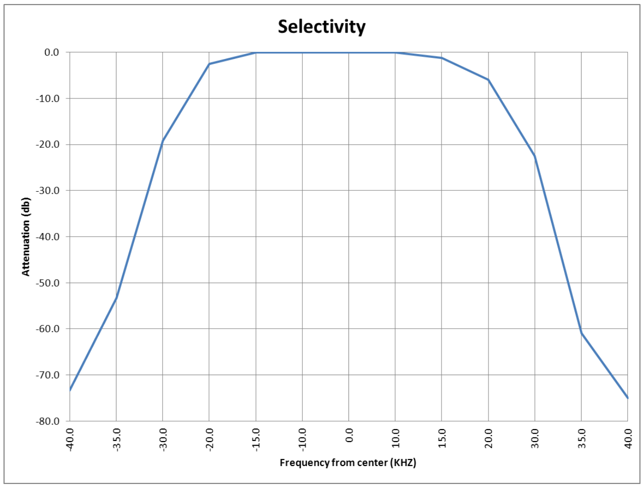

Figure 5. Data Curve for Selectivity Experiment

ANALYSIS

Interference Source

The interference signal causing problems for the RNA-34BF receiver was demonstrated to be the localizer signal (identification code IPIB) from data collected during VORTAC flight inspection runs with the localizer on and off.

RNA-34BF Interference Susceptibility

During the flight inspection runs, the RNA-34BF receiver was shown to be more susceptible to the localizer interference signal since neither the front-end receivers nor the RNA-34AF receiver experienced the interference problem. The fact that the second RNA-34BF flight inspection receiver experienced the same bearing and status problems rules out a problem with one particular receiver. Both receiver models use the same navigation antenna mounted at the same location.

However, the lab tests did not duplicate the interference problem at the estimated localizer signal strength. In fact, the lab test shows that the RNA-34BF does not lose normal status until the VOR signal strength is very weak (-95 dBm) and the interfering localizer signal is very strong (-15 dBm). This lab test evidence would tend to indicate that the interfering localizer signal strength estimation may not be very accurate or that some unexpected signal is present.

Sensitivity and selectivity lab tests show that the RNA-34BF is operating within its sensitivity specification, but a little deficient in its selectivity specification. The sensitivity and selectivity specifications for the RNA-34BF and the RNA-34AF receivers are identical.

The behavior of the RNA-34BF receiver in the presence of the strong localizer signal may not simply be due to insufficient out of channel rejection. Receivers can also be plagued by front end overload which manifests itself when the sensitivity of the radio is greatly reduced in the presence of strong nearby signals. Solid state radios that operate on small voltages characteristic of transistors may turn on or saturate in the presence of strong nearby signals and thus lose its sensitivity for the desired signal. Some evidence for front end overload may be present in the flight inspection recording in Figure 3. Notice the signal strength increase reported by the receiver when the flight inspection aircraft is over the localizer antenna. Obviously, the VOR signal strength is not getting stronger, but the strong localizer signal may be causing the automatic gain control to reduce sensitivity and thus lose the intended signal.

Not only will strong nearby signals cause solid state devices to turn on or saturate and thus reduce sensitivity, but, in addition, these devices may also operate in their non-linear regions. Some receivers purposely operate solid state devices in their non-linear region as a method of frequency conversion to produce sum and difference frequencies. Filters are employed immediately after this type of frequency conversion to eliminate the unwanted frequencies. However, when devices in the front end of a receiver operate in this manner, frequency conversion of nearby unwanted signals occurs causing their modulating signals to appear in the audio along with the intended signal. This behavior is known as intermodulation distortion.

Certainly the 355 radial out path from LBY VORTAC which positioned the aircraft right over the localizer antenna could have created conditions for either front end overload or intermodulation distortion for receivers prone to those issues.

However, the interference lab tests conducted with both the RNA-34BF and RNA-34AF showed the two receivers operate nearly the same in the presence of interference.

Spectrum Planning Concerns

Improper frequency assignment was a concern that was also checked. Both VOR and Localizer systems use the same band of frequencies. VOR is assigned 108.0 to 117.95 MHZ. Localizer systems are assigned 108.1 to 111.95 MHZ. In this case, LBY VORTAC uses 110.6 MHZ and the IPIB localizer uses 109.5 MHZ. This is 1.1 MHZ separation which should be plenty for a VOR signal using a 9960 subcarrier and localizer carrier modulated only by 90 and 150 Hz. An engineer at the Spectrum Testing and Engineering Analysis office confirmed that the frequency assignments for the LBY

VORTAC and IPIB Localizer were appropriate and that these frequency assignments had been in use since 1971. That engineer also stated that some VOR and Localizer assignments are as close as 500 KHZ apart.

CONCLUSIONS

a. Flight inspection data collected during the LBY VORTAC inspection shows that the RNA-34BF is more susceptible to interference than the RNA-34AF or the front end navigation receivers.

b. Laboratory testing indicates the RNA-34BF receiver is not operating within its selectivity specifications.

RECOMMENDATIONS

The following recommendations are made for the benefit of flight inspection efficiency.

After the interference source has been identified (a notable achievement in and of itself sometimes), measurement of the interference signal strength provides helpful information. In this situation a good way to do that would be by tuning the second flight inspection receiver to the localizer frequency. However, the best way would be to use a spectrum analyzer to obtain a complete picture of the signal situation, including any spurious signals that might be present.

FUTURE WORK

a. Repeat the “from” radial run for LBY with the RNA-34BF receivers to confirm the interference issue is still present. Repeat the “from” radial run once again using a spectrum analyzer to measure the signal strength of the localizer and to identify the existence of any spurious signals. This data will allow conclusions to be made regarding proper IPIB Localizer performance.

b. Perform laboratory selectivity testing of the RNA-34AF receiver and compare results with the RNA-34BF selectivity testing.

ACKNOWLEDGMENTS

I would like to acknowledge and thank Dale Rhoads for passing on his knowledge about laboratory receiver testing from his past troubleshooting experiences. Dale is the Branch Manager for the Engineering Group at the FAA’s Mike Monroney Aeronautical Center.

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Aeronautical Interferences Detection, the Spanish Case

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ABSTRACT

Radio Frequency interferences (RFI) are a major concern for aviation safety, since modern aircraft rely on radio spectrum for navigation and communication in all phases of flight. These interferences affect to the different services in the aeronautical mobile band (i.e. radio location, radio navigation, and radio communications). In the case of Spain, in 2013 a total of 100 cases were officially reported.

Some of these incidents can be solved by the dedicated ground units of the Telecommunications National Authority, but many others, given the wide area affected and the fly levels involved, must be addressed from the Air.

Certain RFI episodes may even lead to the closure of a runway which in the case of complex TMA (Terminal Control Area), like Madrid-Barajas may be critical for the National Airspace Safety.

In this context the Flight Inspection Unit of Aena International, after several field trials to set up its RFI detection equipment has been requested by AENA (the Spanish CNS services provider), to find the origin of some radio frequency interferences, along the year 2013.

This paper we will present some representative RFI cases of different nature that were successfully solved as well as the equipment and methods used.

INTRODUCTION

Since the Flight inspection Unit of Aena Internacional was established, our aircraft Beechcraft King Air 350 was equipped with a RFI detection system.

In brief it consists of a "Direction Finder", formed by a Cubic receiver 4400, integrated into the AFIS (Automatic Flight Inspection System). Its sensitivity ranges from 0.1 MHz to 2.0 GHz. This receiver is connected to several antenna arrays in L-band (800 MHz to 2000 MHz), VHF (30 to 300 MHz) and UHF (300 MHz to 3 GHz) bands. These groups of antennae array can be connected in flight to a spectrum analyzer and/or oscilloscope to allow the assessment of the spectrum in the affected geographic area in, the domains of frequency and time."Playing" with the phase differences of the signals reaching the arrays, allows locating the direction of the tuned signal. Moreover the intersection of successive received courses

(DF cross-bearing) on the plane, allows estimating the distance. The figure below shows the graphical interface controlling the DF.

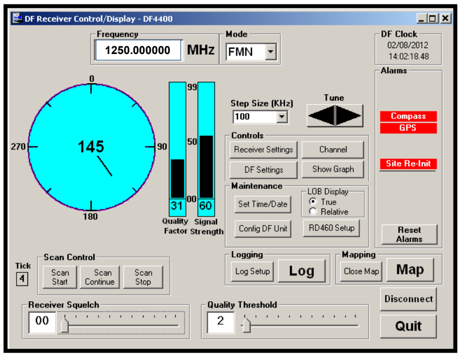

Figure 1. Graphical Interface of Direction Finder

RF Interferences may come from several sources as electronic and telecommunications systems that are operating in adjacent bands, such as harmonics of FM, TV, AM stations and mobile networks that may leak radio signals.

Interferences in the in the Mobile Aeronautical Service in Spain

In Spain an average of 100 RFI are reported per year. The table below shows the statistics for Spain in the last 4 years [1]. It shows that the most frequent events are the ones related with Radio Communications. However the interferences affecting navigation and radiolocation systems although few (only 6 cases in 2013), they are a priority for the potential risk they pose to the safety of air navigation and human life.

Table 1. Mobile Aeronautical Service Interferences in Spain

	2010	2011	2012	2013
Mobile Aeronautical Service	94	109	74	100
Radio Navigation	3	4	1	5
Radio Communications	77	104	70	94
Other	14	1	3	1

The following chart represents the distribution of the Mobile Aeronautical Service RFI's in Spain in 2013, classified by its origin.

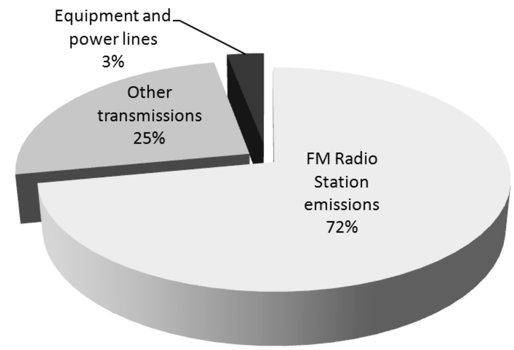

Figure 2. Identified origin of RFI's in 2013

Since 2010 Aena Internacional has carried out several RFI detection test flights in the L, VHF and UHF bands, using known sources such as FM radio stations, aeronautical communications radio stations and L band test emitters.

Once the equipment was properly set up and calibrated and the operational procedures defined, AENA called the Unit to intervene in three cases along 2013.

Two of them affected the radio communications and a third a ILS/DME signal.

INTERFERENCE SEARCH CASES

Interference in the 32 R DME of the Adolfo Suarez-Madrid Barajas Airport

In early July of 2013 an interference was reported by several commercial traffics in the localizer of the runway 32R from mile 17 to mile 3 of DME.

The flight check took place the 3rd of July. The following manoeuvers were carried out:

- Two orbits ±35º (one for each TX LOC) at 15NM DME from THR of RWY 32R (16,6NM DME from Localizer (LOC) at 5000ft MSL.
- 3 ILS approaches from 17 NM from THR in RWY 32R (18,6NM DME from LOC) at 5000ft MSL; two approaches for each TX and a third approach with the ILS equipment switched off.

A poor Clearance signal below 150µA beyond ±15º of the LOC was measured. The nominal width for both TX was correct

Possible oscillations in the LOC axis were also observed, as Seem in the two figures below for the LOC course structure and the coverage orbit.

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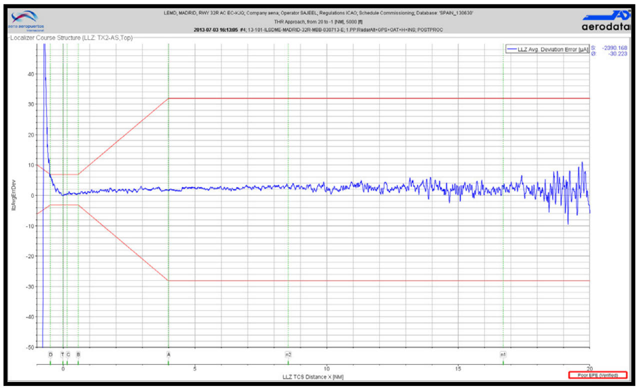

Figure 3. Oscillations in LOC course structure due to interference

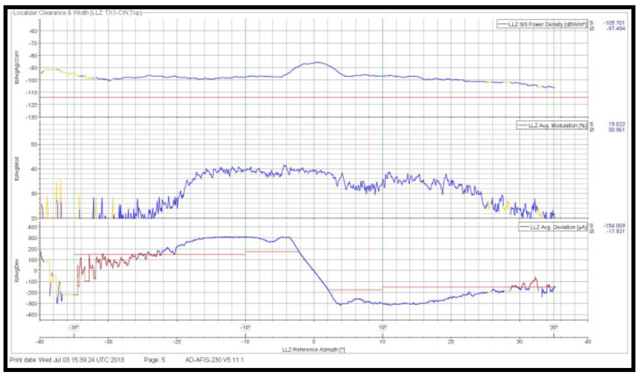

Figure 4. LOC coverage 17NM TX1 at 5000ft MSL

By monitoring the LOC-DME frequency 109,1 Mhz identification codes a commercial radio station was audible in both TX

The signal was so low that the direction finder was unable to provide a clear location.

However the audio file provided enough clues as to identify a radio local FM station situated in the nearby province of Toledo.

The interference was produced by an harmonic of the 107.4 Mhz nominal frequency of the FM station, superimposed in the 109.1 Mhz LOC frequency.

The FM station was located as far as 45 NM southwest from the runway 32R.

The information was passed to the Telecommunications Authority that enforced the cease of emissions until adequate filters were implemented.

A Flight was executed 3 days later to verify the signal was correct again. See figure below showing a correct LOC signal.

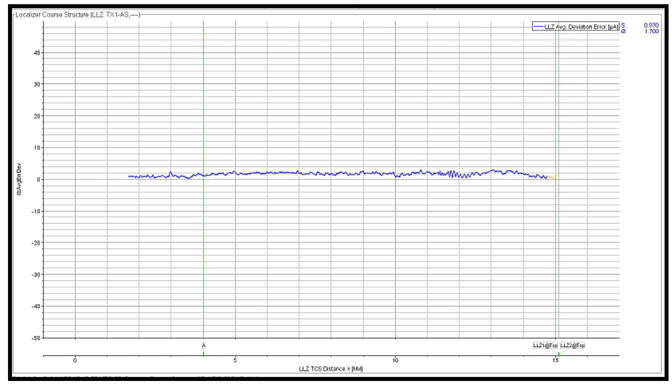

Figure 5. LOC signal after the interfering emissions were canceled

<u>Interference In The DME IVC Of Valencia Airport</u>

Multiple DME unlocks were reported by commercial traffics in Valencia airport Runway 30 approach. An interference seemed to affect the response of ILS/DME IVC that had been observed in previous calibration flights.

The origin was suspected by the maintenance staff as produced by multipath.

The flight tests were conducted the 18th of July in the Valencia airport, consisting of:

- THR Approach, from 12 to -1 [NM], 3000 [ft]
- IVC DME Orbit 10 [NM] CW, 3500 [ft]

The main purpose of the flight was to monitor with the oscilloscope the DME answer channel 38X at 999 Mhz signal .

As can be seem in the figure below, a replected response pulse pair is recived, separated just 7 µs of the direct one.

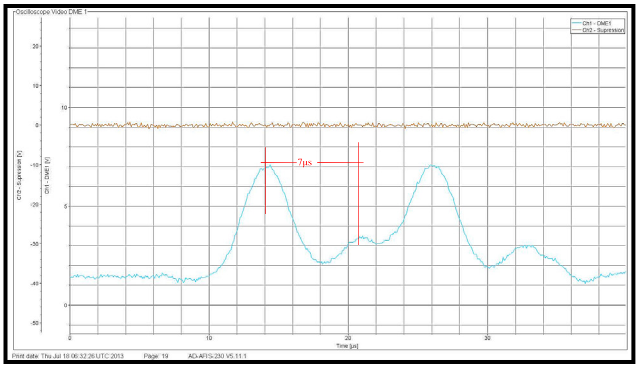

Figure 6. Multipath Pulses in DME IVC response

These values were used by the AENA experts to draw ellipses of constant delay at 7μs to help in finding the potential sources of multipath [2].

This allowed identifying the responsible new infrastructures in the approach area.

The implementation of a more directive DME antenna has been deemed the most reasonable solution.

<u>Interference In The Aeronautical Communications Band Second of the Alicante Area</u>

A discontinuous interference was detected in the 124.750 MHz operations communications frequency by several commercial and military traffics since early June of 2013. It affected a wide area of more than 85 NM in diameter in west provinces of Alicante, Albacete, Murcia y Valencia (see figure below), at high altitude, from flight level 120 to 200.

After multiple measurements at various locations at ground level through mobile units the Telecommunications Authority could not detect the source of interference.

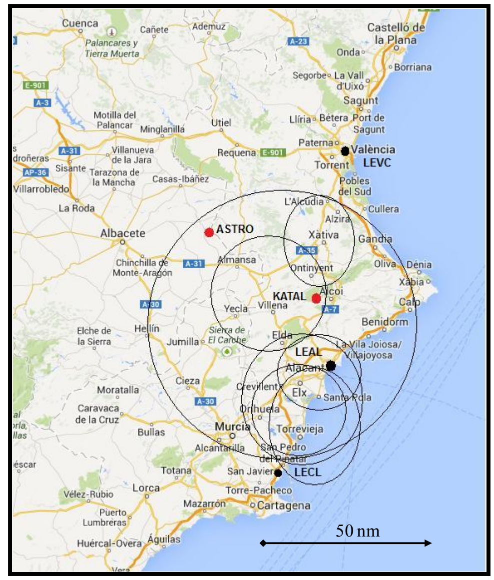

Figure 7. Map with the area of influence of the RFI

Operational approach

In order to search the interference the aircraft was positioned at Valencia airport the 17th of August. When the first interference occurrences in 124.75 Mhz frequency were reported, it stopped to be used for operations and the three remote stations. (Valencia-Aitana-Alicante), were switched off to avoid mislead the search.

Then the aircraft took off and once in the air the RFI was detected in the KATAL point and tuned in the DF in the FMW (FM wide) mode. The guiding was past to the cockpit, leading to an approximate point around which a orbit was made at 2000ft MSL to refine the result (see figure bellow)

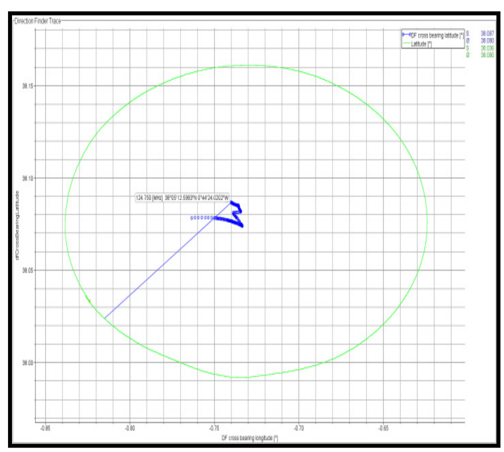

Figure 8. Orbit around the Suspected Point

The point 38º 05' 12.5983" N / 00º 44' 24.0202" W, was obtained with a positioning error of 0.9NM.

The same pattern was followed the next day starting again from Valencia airport, when the interference was noticed by commercial traffics and flying at FL 170. This time the RFI was not detected until the Alicante approach.

Using the same strategy the point 38º 05' 01.6150" N/ 00º 43' 56.9963" W, near the previous one) was obtained with a positioning error of 0.8NM (See figure below).

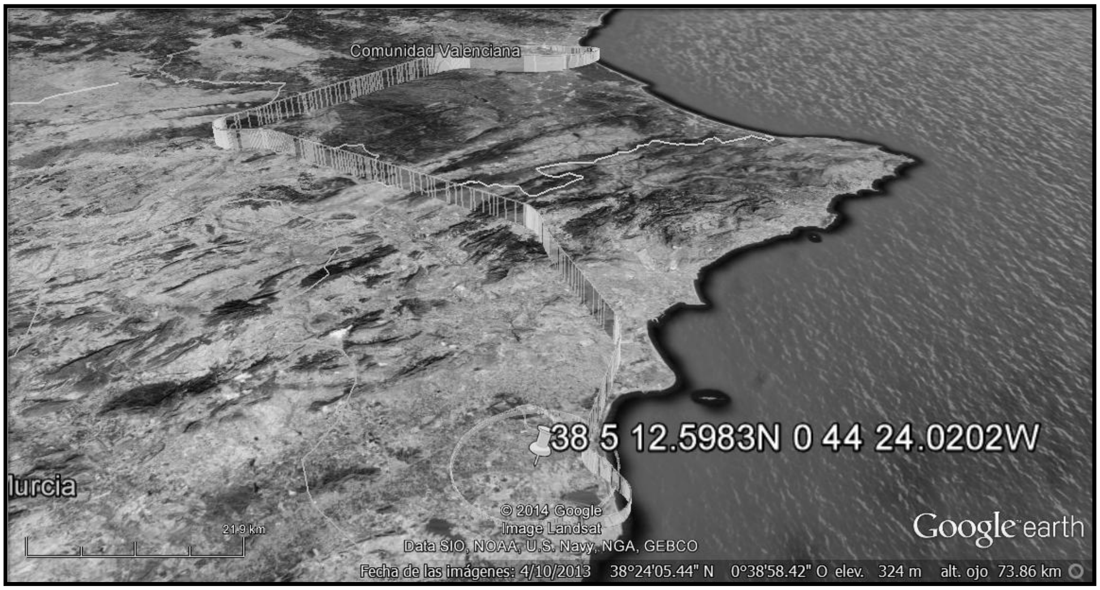

Figure 9. Map Showing the Trajectory.

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The spectrum in the first figure below shows the operations frequency free of interferences, and the second one when in presence of the RFI:

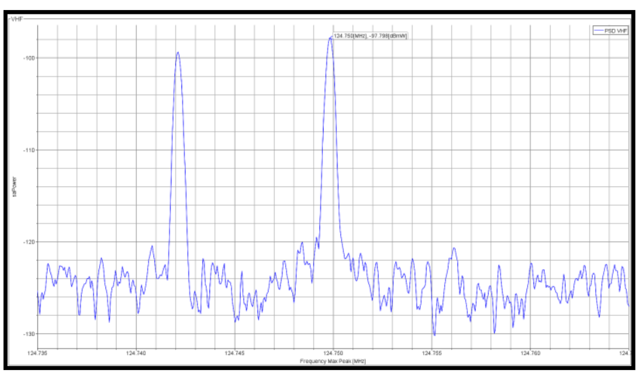

Figure 10. Spectrum with frequency free of RFI

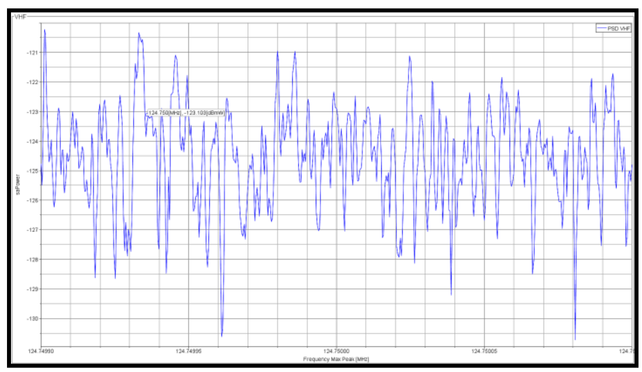

Figure 11. Spectrum of Ops frequency in presence of RFI

The point was situated in an industrial park. Out of band emissions of two radio stations were detected by the mobile ground units of the Spanish Telecommunications Authority.

CONCLUSIONS

The RFI detection system onboard the Flight Inspection aircraft has shown to be a powerful tool to detect RF perturbations in the Aeronautical Mobile Service, when affecting wide areas. In some cases the audio and recordings can give us direct clues when the signal comes from commercial radio stations, in other cases the geo-location gives a reduced area where the ground mobile units systems can complete the work at a cheaper cost.

FUTURE WORK

The Division of Communications of the Systems Direction of AENA Navigation is developing a collaboration agreement with the Spanish Telecommunications Authority on interference detection, in order to offer the services of the Unit. To this end, a technical report was sent in March 2013 describing the technical means available in the Unit.

ACKNOWLEDGMENTS

We want to thank Dr. Rolf Seide from Aerodata, for his advice and support in setting up the DF equipment and helping us in defining our RFI search procedures.

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http://icasc.co/sites/faa/uploads/documents/resources/15th_int_flight_inspection_symposium/qualifying_dme.pdf

Advanced Theory and Results of Classical System Simulations and Related Flight Inspection

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ABSTRACT

Typical actual tasks of (new) system installations or new objects close to existing systems are:

- Design, installation and flight check of systems (ILS, VOR/DVOR etc.)
- Design and approval, construction and flight check of large objects (e.g. terminals, wind turbines WTs).

The system simulations play a major role during the design phase in both cases, but also in case of detected system distortions in flight checks by analyzing and explaining these effects. This cannot be achieved by flight checks often due to time/cost constraints.

This paper will give first an overview by actual examples about most modern system simulation techniques, such as 3D-simulations under difficult near-field conditions and including Doppler effects for VOR/DVOR which cannot be handled by standard methodology, e.g. effects of large aircraft taxiing in a distance of 110m only to a terminal DVOR or large objects such as WTs close to a VOR/DVOR. The latter are an actual conflicting problem in many countries. Latest methodology and results will be shown for the tolerance analysis for parameter variations (wind, rotor) and large wind-farms. Statistical evaluation of the bearing errors is shown in the context of ICAO-specifications. Flight check results are discussed in this context mainly during the conference itself.

INTRODUCTION; SYSTEM SIMULATIONS

Building applications (**Fig. 1**) have to be approved when the locations of the applied objects are in some critical distance to radiating systems, such as navigation-, landing- or radar systems. ICAO EUR DOC 015 ([2]) describes a scheme how to process such an application procedure: If the objects do not penetrate a 3D-surface template unique for each system reaching up to 15km for VOR/DVOR, the building application can be approved directly by non-experts in the first formal "step 1". If the objects penetrate this template surface, the effects have to be analyzed in "step 2" by an appropriate engineering analysis and experts, i.e. as defined by adequate and real ***computer simulations*** according state-of-the-art SOA methodology (Fig. 1, Fig. 4). ***It does not mean explicitly that the application is automatically rejected if the template is penetrated.*** The approval criteria are the applicable specifications, i.e. ICAO Annex 10 ([1]) and associated applicable ICAO-documents (i.e. DOC8071 e.g. in case of CVOR/DVOR systems which are mainly evaluated in this paper).

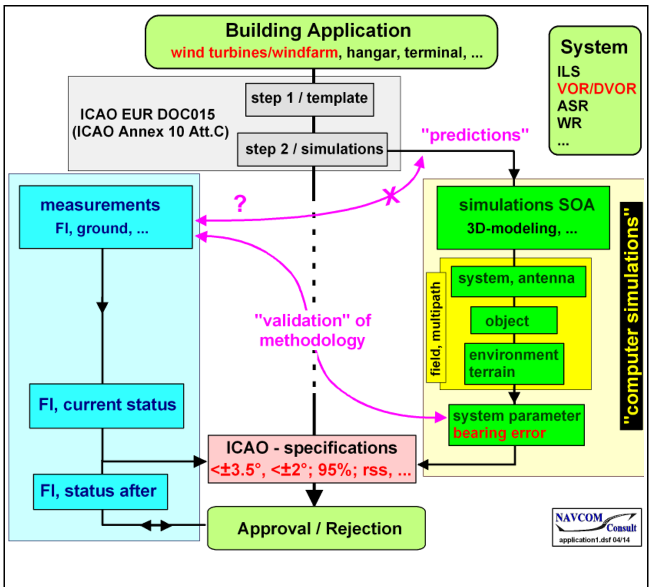

Fig. 1: Process of a building application; role of flight inspection and numerical simulations

The “building applications” are plans for future buildings which are not yet realized and which have each time unique features and different geometrical and electrical characteristics, e.g. for the

- detailed layout of a taxiway and type of taxiing aircraft very close to a DVOR/DME (**Fig. 2**; [4]),
- large wind farm of very large WT close to a DVOR/DME (e.g. example of a layout **Fig. 3**).

By that, whatever type of measurements cannot help in principal in the approval process for future developments because the real field measurements show always the status quo without the future unique plans. However, the measurements, e.g. flight check measurements are very useful in the validation process of the applied simulation methodology and for the final results (**Fig. 1**).

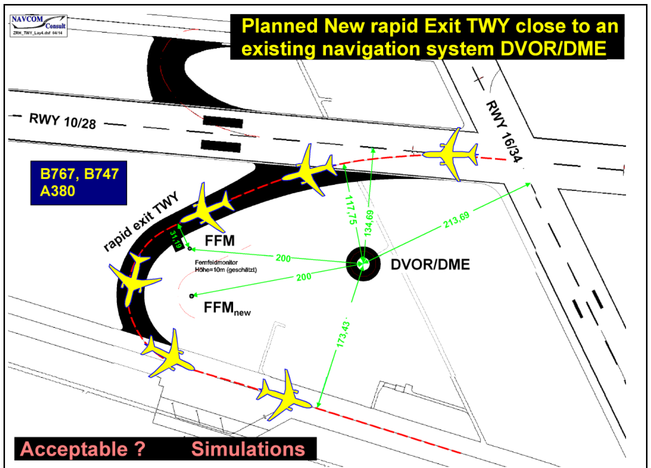

Fig. 2: The rapid exit TWY and DVOR system scenario in detail

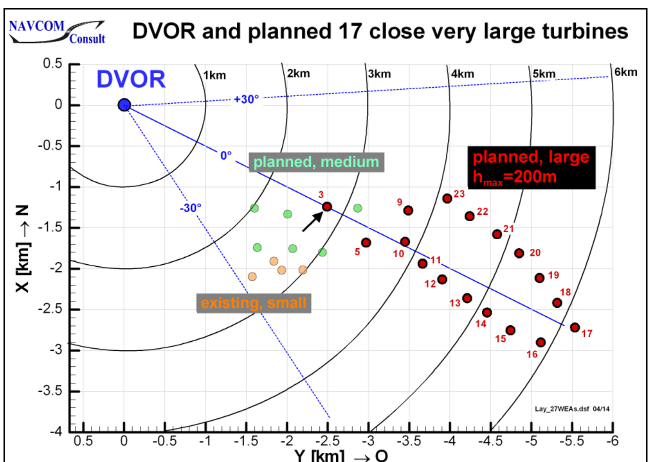

Fig. 3: Planned wind farm in close distance to a DVOR

Modern numerical systems simulations (**Fig. 1**, **Fig. 4**) integrate the most modern sufficiently proven electromagnetic scattering and wave propagation methods with the system specific aspects, such as receiving principles and adapted signal processing schemes. These general methods comprise the more general complex near-field capabilities as well as the far-field approximations for simplicity if justified. The modeling of the scattering and of the wave propagation is in a way safely established in the electromagnetics community that no surprises have to be expected for experts.

The boundary conditions (e.g. antennas, objects, ground/terrain) are stable and well defined for each field point to be considered in space on the orbits, radials etc. The superposition of the direct and the scattered signals at the distributed objects and at the ground forms the ***total interference field*** where the amplitudes and phases vary in space accordingly in a well-defined deterministic way. No undetermined processes, e.g. “noise” or other “dynamic effects” appear in the radiation field itself, but may appear tentatively in the receivers at low power levels or in the signal processing as unwanted and artificial “additional” bearing errors or spectral components. The dynamic of the aircraft movement on the orbits or radials can be sufficiently and well founded treated as a successive sequence of stationary cases for different field points. If all these facts would not hold sufficiently ***on the field level***, a good agreement between (flight check) measurements and numerical simulations could not be achieved at all (see **Fig. 9**, **Fig. 10** as validation examples). The following details of some decisive practical aspects in the IHSS-simulation-methodology (**Fig. 1**, **Fig. 4**) are listed

- 3D-modeling of the decisive system components to the extent required for accurate results , e.g. the radiating antennas, in case the pattern rotation
- 3D-modelling of the distorting objects, e.g. aircraft, WT again to the extent required for sufficiently accurate results
- selection of the adequate scattering and wave propagation methodology,
- application of the adequate signal processing, i.e. for the bearing error in case of the VOR/DVOR.

If the objects are very close to the VOR/DVOR, i.e. in the mutual near-field, and if the geometrical extension $\delta\varphi$ is large (**Fig. 6**), the standard simulation schemes cannot be applied for these cases. The IHSS (**Fig. 4**) contains a highly special and effective scheme, namely the so-called “near-field spectral” scheme which is rigorous and which treats the mutually coupled object as part of the system antenna resulting finally in the bearing error after an adapted modern signal processing. The impact of the objects on the 30Hz-FM is simulated and interpreted as the “bearing error” according to the basic DVOR-definition. Almost arbitrary objects and counterpoises can be handled above ground.

The validation results in **Fig. 9** and **Fig. 10** have been obtained with this "near-field spectral" simulation scheme.

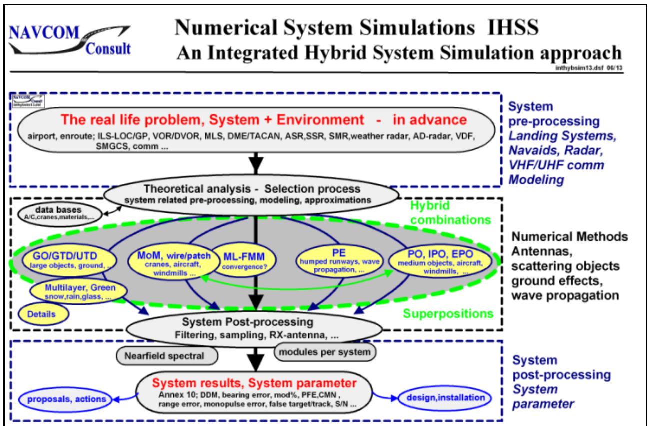

Fig. 4: Flow chart of the general IHSS simulation tool

VOR-SYSTEM; SPECIFICATIONS, VALIDATIONS

Some VOR Basics for a Multipath Environment

The VOR/DVOR-system is operated satisfactoryy already since more than 55 years ([5], [6]). It provides the used relative azimuth angle in the receiver by the phase comparison of the omni-directional 30Hz-reference to the variable 30Hz (**Fig. 5**, **Fig. 6**).

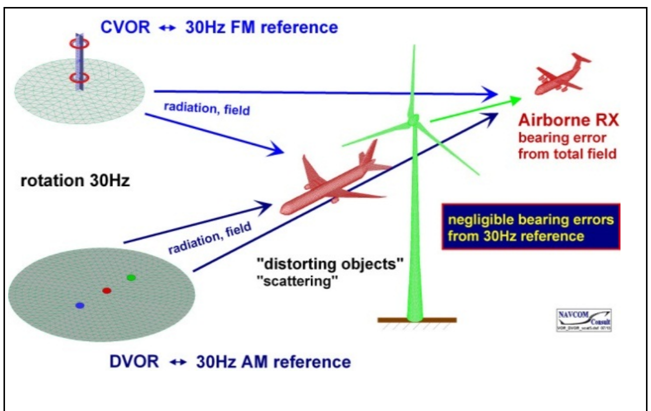

Fig. 5: General distortion scenario of the VOR/DVOR

The well-known basic conceptual system bearing errors of the VOR/DVOR are shown in Fig. 7. It shows the theoretical envelope of the real scalloping bearing errors for an idealized omni-scatterer of -20dB amplitude positioned at the azimuth 90°.

The possible theoretically large improvement of DVOR compared to VOR can be deducted from **Fig. 7** which depends on the difference angle. It can be seen as well that in the DVOR-case the bearing error is reduced at ±30° already to less than 50% while for the VOR-case an angular sector of ±90° has to be evaluated to find the maximum bearing error by some scatterer.

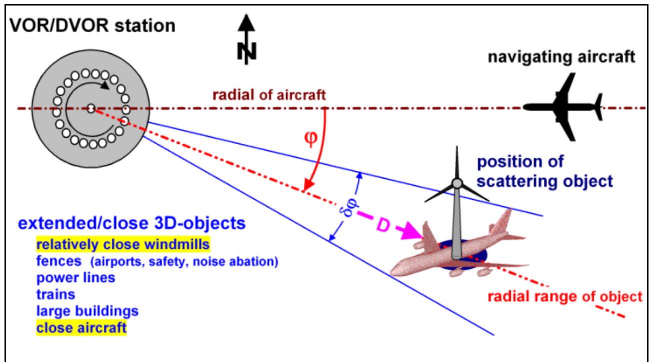

Fig. 6: VOR/DVOR Distortion Scenario for very Close and Extended Objects

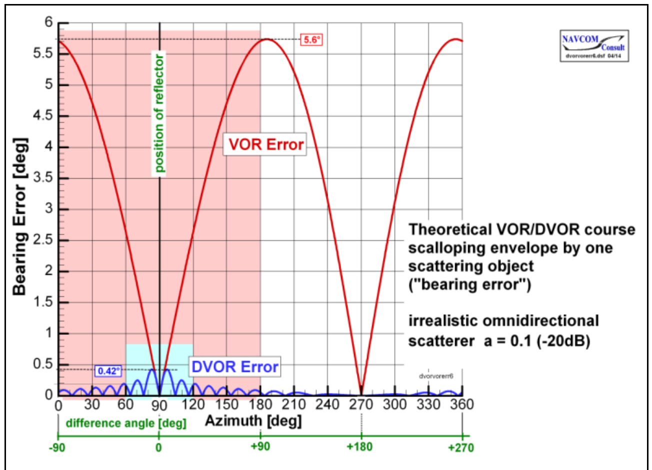

Fig. 7: Conceptual system bearing error of the VOR/DVOR for an idealized -20dB omni-scatterer

Some VOR Specifications; Comments, Interpretations

The applicable VOR-**specifications** are defined in principle by ICAO Annex 10 SARPs, but unfortunately not for the important multipath scattering case. These missing specifications are defined in DOC8071 for flight inspection acceptance purposes. The following table shows the most important spec parameters and some aspects. DOC8071 can be treated as a "quasi-SARP" being referenced throughout many ICAO Annexes and DOCs, e.g. ICAO Annex 10,ICAO Annex 11.

The ground station error ε_g(except the north alignment ε_n) is part of the "bends" in the statistical rss-sense based on dynamic field characteristics (**Fig. 8**), namely the

- dynamic movement of the navigating aircraft,
- the electrically wide distribution of the scattering objects and of the VOR/DVOR.

By that, the error components (ε_g, ε_b) cannot be added or subtracted linearly, but have to be processed by the rss-scheme if not assessed by the simulations directly.

ICAO DOC	Parameter / errors	value	SARPS
Annex 10	ground station ε_g (incl. north alignment ε_n)	±2°	yes
8071	bends ε_b	±3.5°*)	no
8071	R/S (short time, high frequ.)	±3°	no
8071	Sum: bends + R/S	6.5°*)	no
Attc.C/8071 Annex 11	Probability	95%	~yes

(*) north alignment to be considered

Approximately, several scatterers can be taken into account by its components ε_{bi} in the rss-scheme (1).

$$\varepsilon_{bends} = \varepsilon_n + \sqrt{\varepsilon_{b1}^2 + \varepsilon_{b2}^2 + \cdots + \varepsilon_{bi}^2 + \varepsilon_{g'}^2} \leq 3.5° \quad (1)$$

If the VOR/DVOR is well adjusted, the north alignment error is small and $\varepsilon_g \approx \varepsilon_{g'}$.
The pure ground station error $\varepsilon_{g'}$ of modern VOR-systems can be kept small as well ([5]), typically around 0.5°.

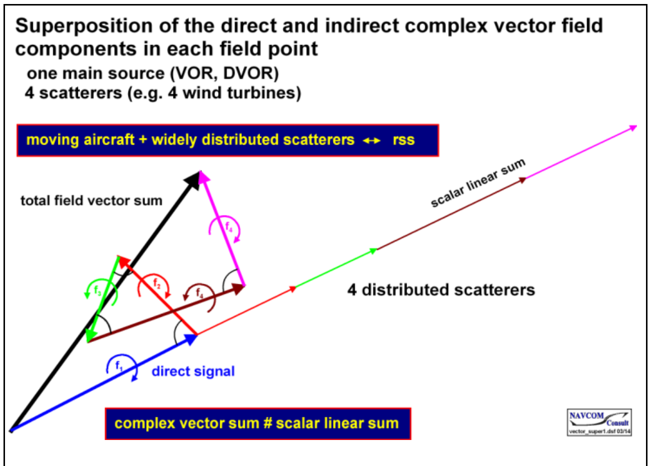

Fig. 8: Superposition of Complex Field Components

Some Validation Results for the VOR-Simulations

Two validation DVOR-examples for the IHSS-methodology are shown in **Fig. 9** and **Fig. 10** for very close and large building complexes which can be adequately simulated only by the above mentioned near-field spectral scheme of the IHSS-methodology. This scheme simulates the change of the 30Hz-FM-phase by the scattering object which is per fundamental VOR-definition the "bearing error". An excellent agreement of the IHSS-results with the flight inspection results can be seen despite the challenging scenarios. This applies for the larger maximum distortions of up to 4.5° (**Fig. 9**) as well as for the much smaller ones up to 0.9° in **Fig. 10**. This good agreement validates as well the modeling and verifies the completeness of the simulations and in turn validates the measurements too by the mutual agreement.

Examples for comparable and clearly identifiable flight check measurement results for WTs do not exist for the VOR/DVOR-system because

- first, simply, the WTs so far are not located in sufficiently close effective distances.
- second, the simulations are done for fully metallic worst case models as proposed in [1], [2] which exaggerates the effects.

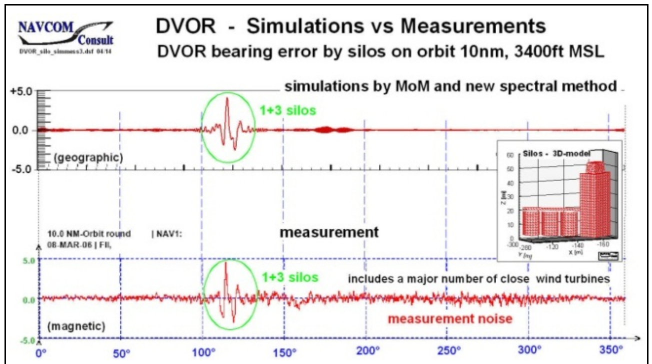

Fig. 9: Validation of Simulations by Flight Inspection (1)

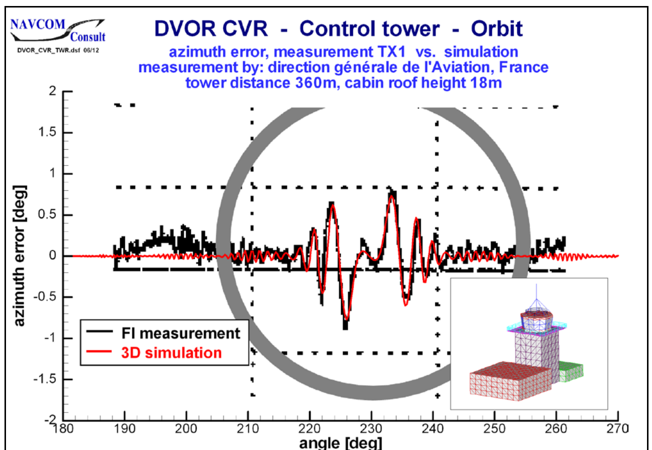

Fig. 10: Validation of simulations by flight inspection (2)

WIND TURBINES/FARMS AND DVOR-SYSTEMS

3D-modelling of Wind Turbines

A wind turbine is a widely "normal" scattering object within the IHSS and has to be modeled according to the established simulation rules.
Fig. 11 shows the 3D-model of an extremely large turbine of the 200m-class; left the standard worst case metallic 3D-model and right the substitution of the mostly dielectric rotor by the lightning protection system.

The 3D-model (**Fig. 11** left) consists of a large number of metallic triangles (about 51000 triangles)

- describing sufficiently the geometry of the turbine and its 3D-components and also
- support sufficiently the induced current on the surface.

This procedure is modern, but along well established electromagnetic theory ([3] etc.) for solving boundary value problems. The wave propagation part assumes in a first step that a flat ground is effective which is often fully sufficient for the horizontal polarization of the VOR-system and the VHF-frequency. If the ground is not flat by valleys and hills or mountains, the integrated method of Parabolic Equation PE is applied in a 2nd step (**Fig. 4**).

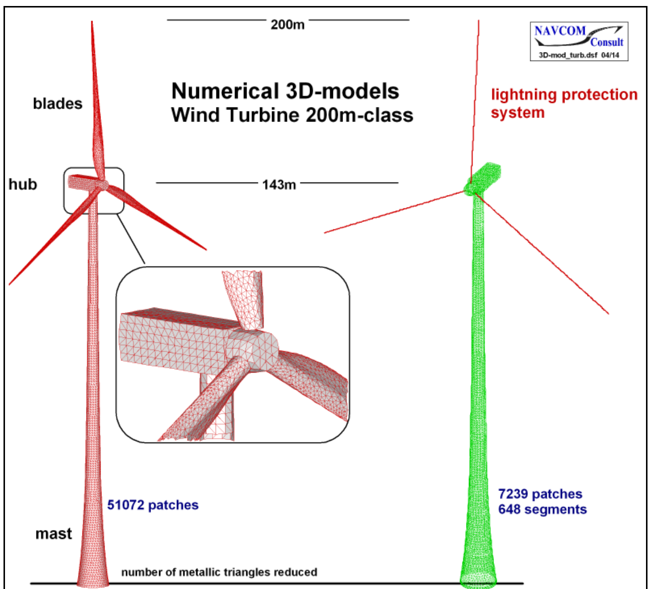

Fig. 11: Numerical 3D-models, worst case fully metallic (left); with lightning protection system (right)

Numerical Results for DVOR and Wind Turbines

The following numerical results (bearing error, statistics) are presented first for a single turbine in a close distance.

It is argued and suspected ([1],[2]) that the maximum bearing error would depend very sensitively and seriously on the wind direction and rotor orientation.

Single Wind Turbine and 3D metallic blades

To clarify this aspect, systematic evaluations of a relatively close large wind turbine (**d=2783m**) for a DVOR are carried out. The wind direction and the rotor orientation are varied systematically in steps of 15°, i.e. 192 combinations in total. The bearing error is calculated for each combination in a ±30° sector (**Fig. 7**, **Fig. 13**) up to a distance of 40nm for an operationally relevant height, i.e. 5100ft MSL for the evaluated DVOR.

Fig. 12 shows the graphical 3D-presentation of the maximum bearing errors of each of the 192 sector calculations. The absolute maximum bearing error is 0.46° out of 192*72057=13834944 field points in total. It is obvious that the numerical effort is very large to achieve these results.

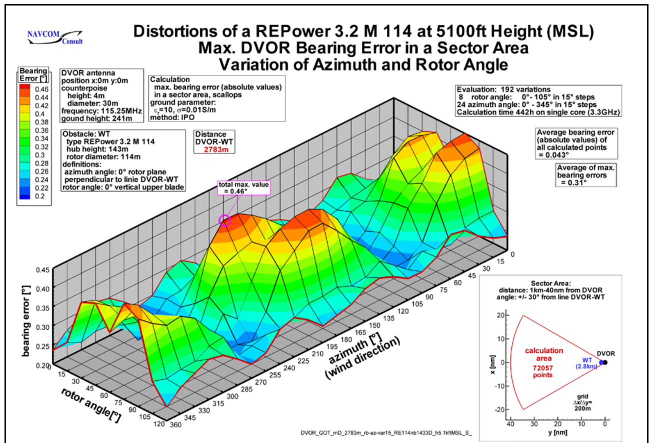

Fig. 12: Max bearing error for 192 combinations of wind direction and rotor position; full metallic rotor

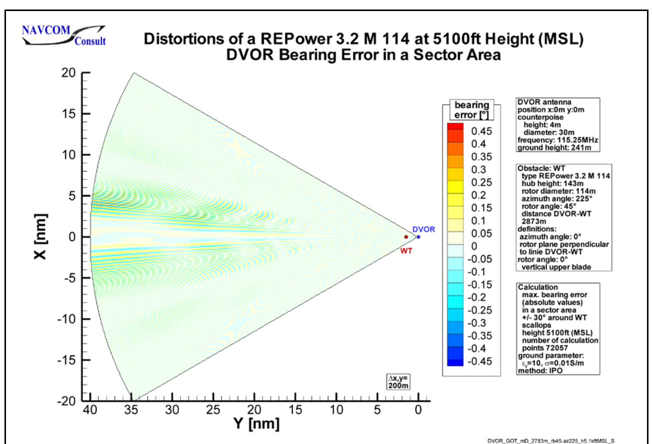

Fig. 13: Bearing error in a ±30° sector for one large turbine for the worst case combination of **Fig. 12**

It is important to note that the ±30°-sector (**Fig. 13**) contains the color coded bearing errors of ***all radials and orbits*** in that sector in the analyzed height. Also, it can be seen that the bearing errors for the DVOR are negligible outside the ±30° sector by the small figures at the outer azimuthal sector borders. The largest bearing errors are roughly at the region of the DVOR-peaks shown in **Fig. 7**.

A related statistical histogram of all the 13834944 individual bearing error values is shown in **Fig. 14**. It can be clearly seen that the maximum bearing error of 0.46° is extremely rare. The 95%, 99% and 99.9% error levels are marked. While in the ICAO-docs a 95% probability is used, it is suggested to treat the 99% threshold as a safe representative figure to characterize the bearing distortions of the simulated scenario. In this case, the 99% error is ±0.23° while the 95%-figure is only ±0.15°. These small error figures cannot be measured uniquely by flight inspection. At lower input power levels typical VOR-receivers show larger random bearing errors even for a high performance VOR-signal-generator input.

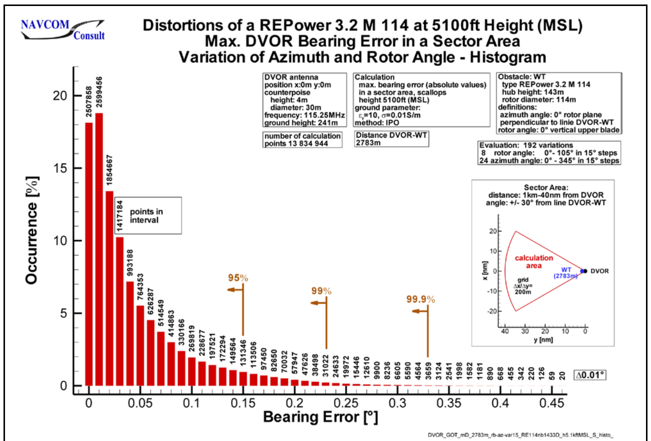

Fig. 14: Statistics of the max bearing errors (**Fig. 12**)

Wind farm of 17 Wind Turbine

The bearing error impacts of the total windfarm of 17 WTs (**Fig. 3**; 200m WTs) has been analyzed for several scenarios, such as the general wind directions. **Fig. 15** shows the case where the closest turbine has been setted for the worst case determined by the results in **Fig. 12** and **Fig. 14**. The other 16 WTs are oriented in azimuth ±5° random hereto and the rotor position is random. The resulting maximum worst case extremely rare bearing error is 1.32° and the 99% error is 0.64° respectively. **Table 1** shows the bearing errors for comparison for the different probabilities. It can be seen that the rss-superposition would be clearly result in larger bearing errors.

Bearing error /°	95%	99%	99.9%	max
Single turbine	0.15°	0.23°	0.33°	0.46°
17 turbines	0.36°	0.64°	0.92°	1.32°
ratio	2.4	2.8°	2.8	2.9
Single; lightning	0.15°	0.19°	0.22°	0.25°

Table 1: Statistical bearing errors (rss: √17=4.1)

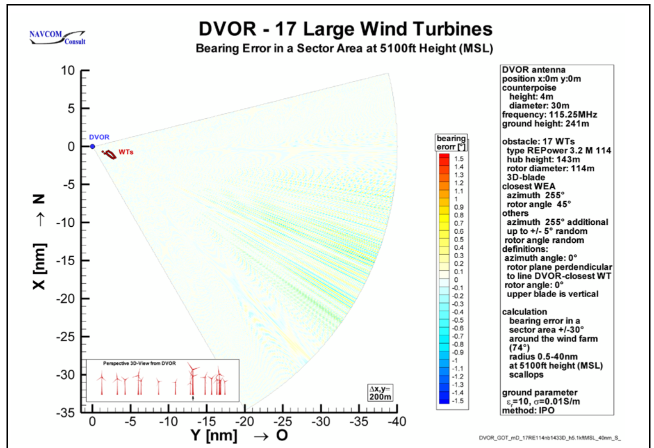

Fig. 15: Bearing error in a 74°-sector for 17 large WTs

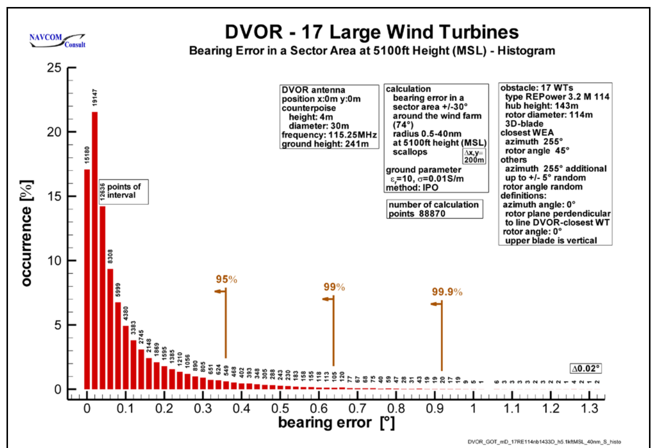

Fig. 16: Statistics of the sector bearing errors (**Fig. 15**)

Single Wind Turbine and lightning protection system

The results in Fig. 17 and Fig. 18 show the bearing errors for the same single wind turbine if the fully metallic 3D-blades are substituted by the integrated metallic wire-type lightning protection system. The resulting bearing errors are clearly smaller than for the fully metallic voluminous case as expected.

When comparing **Fig. 17** and **Fig. 12**, clear differences can be seen. The 3D-metallic blades do have much more impact than the wire-type lightning protection system as expected. Also, by comparing in addition the statistical histograms (**Fig. 18**, **Fig. 14**) it can be clearly seen that the maxima are reduced from 0.46° to 0.25°, but the 95% figures are the same (0.15°) in both cases.

The real bearing errors in the field will be in between, but clearly smaller than the worst case figures as requested by the ICAO recommendations ([1],[2]).

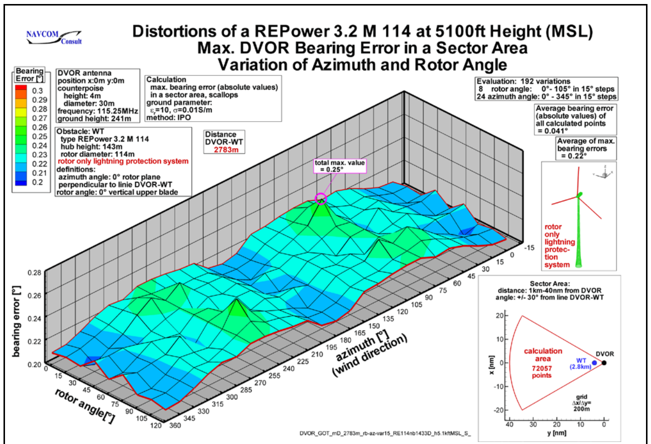

Fig. 17: Max bearing error for 192 combinations of wind direction and rotor position; lightning protection system

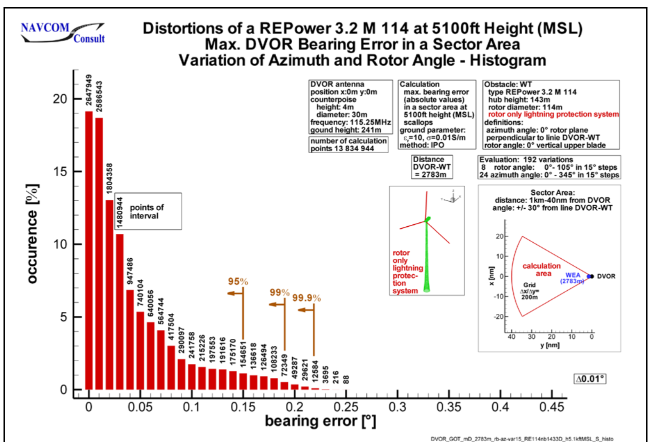

Fig. 18: Statistics of the max bearing errors in **Fig. 17**

Doppler effect by the rotating blades

The DVOR relies in its variable 30Hz FM phase on the Doppler frequency effect by the rotating DVOR sidebands. It is suspected that the rotating blades could generate 30Hz components which might affect significantly the bearing error of a DVOR.

While the sidebands are rotating with 30Hz, the blades rotate in space with its own turning rate. Within a rotation period of the DVOR (1/30sec) the blades have turned somewhat according to the rotation rate.

The developed near-field spectral approach within the IHSS (**Fig. 4**) enables the numerical simulation of these effects. **Fig. 19** shows some of the discrete rotation steps of the blades. The radial speed of each of the triangles of the blades is different, but contributes according to the scattering pattern to the complex field components scattered to the field point under consideration on the orbit or on the radial.

Fig. 20 shows the ***additional** bearing error* generated by a medium sized wind turbine for rotation rates from 0rpm to 30rpm. The blade circle is assumed to be oriented by 45° relative to the radial from the DVOR to the turbine. It can be seen that the resulting bearing error depends on the rotor angle, but its amplitude is negligible.

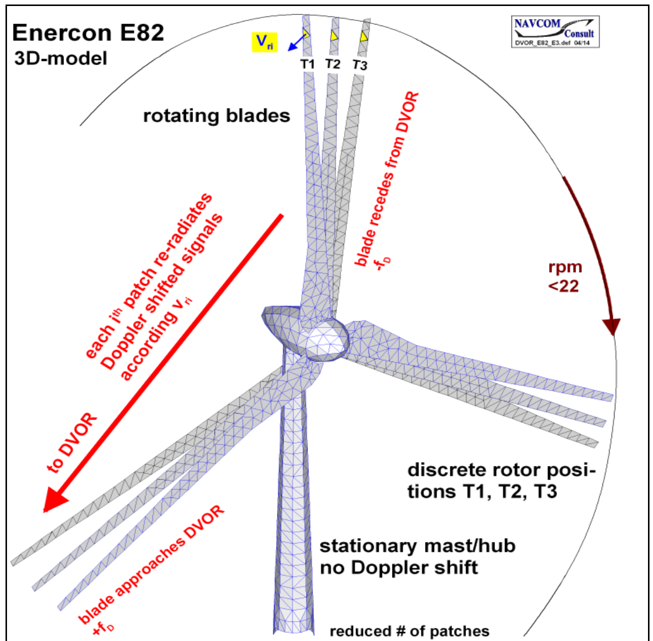

Fig. 19: Approximate discrete blade rotation

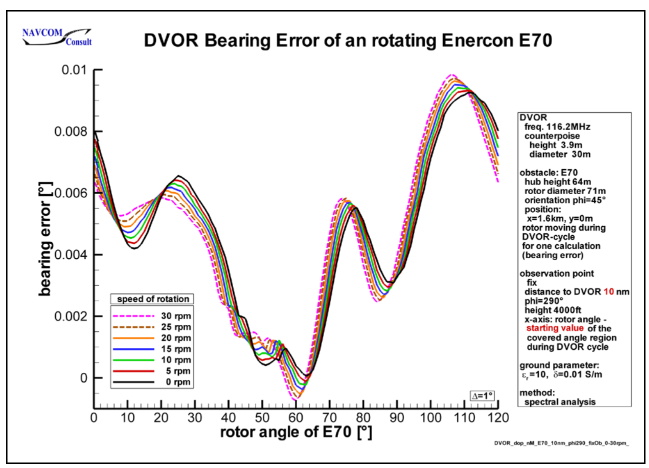

Fig. 20: Additional DVOR angle bearing error caused by rotating blades and different rotation rates (0rpm - 30rpm)

Some generic results for large close wind farms

Wind farms consist normally of irregularly distributed WTs. Also often different types of WTs are installed in the same wind farm. However, it is of relevant for the approving organizations to have available some systematic generic simulations of the worst case effects to be expected. **Fig. 21** shows an example of a large number of WTs in some distance around the DVOR CRP. More than 130 WTs are installed in a distance up to 10km, more than 170 up to 15km without compromising the DVOR performance shown by flight inspection.

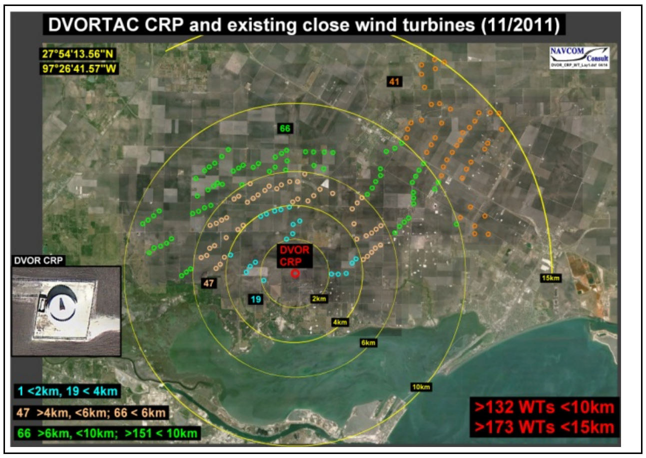

Fig. 21: Example of a large number of WTs located on an irregular pattern around the DVOR CRP

Adequately powerful simulation tools (**Fig. 4**) allow systematic simulations of the impact of increasing number of WTs in some distance assuming certain grid constraints and illumination conditions.

Fig. 22 shows such an example where up to 9*9 WTs on a regular grid (dx=dy=300m) are simulated for the minimum distance of 5000m to a standard DVOR. The evaluated sector is ±30° up to 40nm in the low height of 3000ft. The rotor circle is randomly facing (±5°) the DVOR. The orientation of the rotor is random. It can be seen that the very rare maximum error would be hardly acceptable for the larger arrays, but the 99%-errors seem to be acceptable even for 81 WTs (<±1.1°).

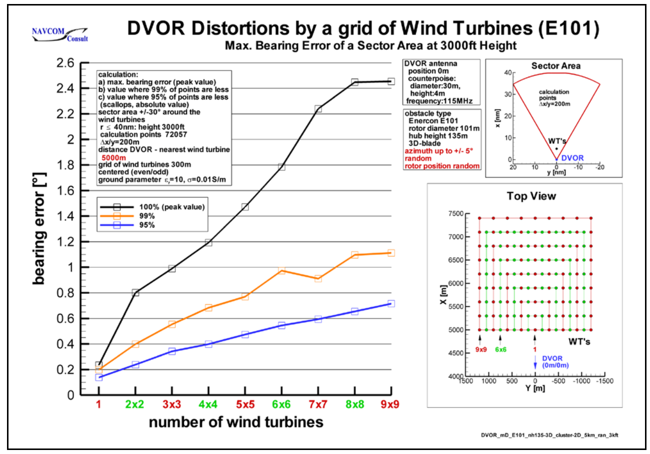

Fig. 22: Systematic generic simulation of the DVOR bearing error for large WTs on a regular grid; random orientation of rotor and wind direction ±5°; d_{min}=5000m

Other relevant generic examples and results will be presented on the conference.

CONCLUSIONS; RECOMMENDATIONS

The system theory, the general applied electromagnetic theory and the basics of the numerics of the simulation of large WTs in some distance to a DVOR have been outlined. Simulation details of the advanced methodology and of the advanced new nearfield spectral approach have been referenced. Validation examples have been shown with an excellent agreement between the simulations and the flight check measurements. This mutual agreement confirms that the 3D-modelling of the DVOR-system, of the WT and of the propagation channel is correct and complete and that the presented simulations comprise the relevant effects.

It can be concluded from the systematic simulations as a recommendation that the test radius up to 15km ([2]) can be safely generally reduced for DVOR easily down to 10km. In most cases a distance of 5km is safe for DVOR or even closer down to 2km. However it depends on the number and size of the distributed WTs, on the given performance and on the use of the installed DVOR. A reliable computer simulation according validated SOA-methodology has to be applied which is available today.

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IFIS 2014

Flight Plan to Innovation

Session 3

Flight Inspection of ILS

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ILS Simulation for Flight Inspection

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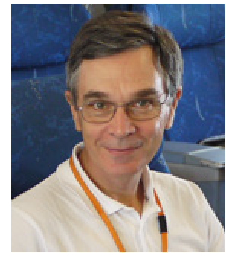


ABSTRACT

Flight inspection of the Instrument Landing System (ILS) can sometimes be quite challenging. ATOLL (Localizer) and LAGON (Glide path) ILS simulation software packages are designed to help flight inspectors for a better and quicker analysis of the recorded plots and thus reduce the number of flight hours during commissioning and routine flight checks. All important settings on the real equipment can be simulated: Transmitter adjustments, antenna positions and feeding, diffraction of the radiated signal from surrounding objects, as well as settings in the Flight Inspection Systems (FIS). All these features are well suited for initial and continuous training for flight inspectors.

It is also possible to import plots from different flight inspection systems as well as from ground inspection systems. It is thus very easy to compare plot records with simulations and determine which maladjustments led to the errors on the flight inspection records. ATOLL and LAGON can thus help flight inspectors to track down equipment and antenna errors in their daily job.

This presentation will show a few examples of plot analysis using ATOLL and LAGON and how terrain slopes and FIS settings change the shape of the plots for a correctly adjusted GP.

INTRODUCTION

Providing a good understanding of the ILS system to technicians, engineers or flight inspection crews proves to be difficult because a lot of parameters have an impact on the radiated and measured signal. It is not often possible to "play" with an ILS station just to provide training to the ground or flight inspection staff. The French Civil Aviation University (ENAC) decided therefore by the end of the 90^{th} to develop an ILS simulation tool in order to help ILS instructors explaining the principles and the adjustment procedures of the ILS and to facilitate the understanding of the different problems that can affect the system.

Over the time a lot of features have been added and the tool is now well suited for:

- Initial training
- Continuous education
- Tracking down equipment and antenna errors
- Training for flight inspection crews
- Assessing the impact of buildings and taxiing aircrafts using the method of Physical Optics
- Illustrating errors coming from the Flight Inspection System (FIS) itself

This paper will present some of the features implemented in the software packages and how they can be used from the flight inspector point of view.

LOCALIER SIMULATION

The localizer simulation program is called ATOLL for Advanced Training On LocaLizer. It consists of a main panel from which you can access all features available in the software.

Most of the space on this panel is used for the graphical representations of the simulations. The graph displays the simulations in a similar way as what you can see on Flight inspection system screens.

Three simulation modes are available:

- Orbit mode
- Approach mode
- Sensitive area mode

In this paper we are going to put the focus on the 2 first modes.

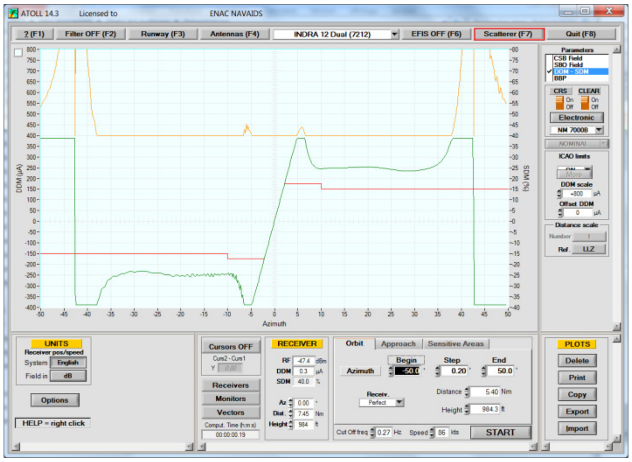


Figure 1. Main panel of ATOLL

Orbit flights simulations

On the Orbit tab one can set the parameters of the track followed by the aircraft.

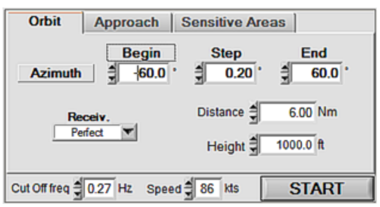
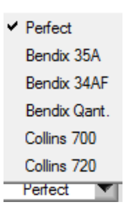


Figure 2. Orbit tab

- Begin and end azimuth of the track
- Computation step
- Distance and height of the track
- Selection of some kind of commercial receivers showing sometimes non-conventional behavior of the DDM



- Speed of the receiver. This will automatically adjust the low pass filter according ICAO recommendations

A click on the START button will start the simulation and display the plot on the graph.

Approach flights simulations

On the Approach tab one can set the parameters of the flight path for an approach

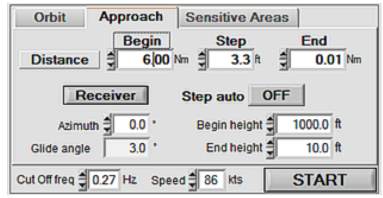
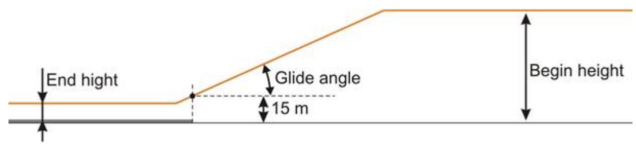


Figure 3. Approach tab

- Begin and End distances of the track
- Computation step
- Approach azimuth
- Vertical approach profile



Runway layout panel

Before starting a simulation one must set the runway parameters. A click on the Runway button opens the runway panel.

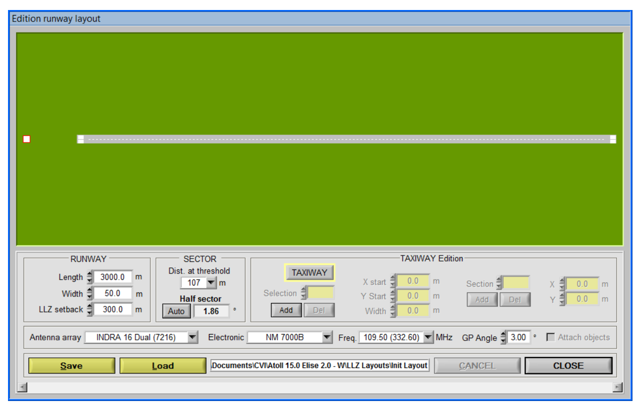


Figure 4. Runway panel

From this panel one can set:

- Runway length
- Localizer setback
- Sector width, manual or computed from the 2 above inputs
- Antenna array
- Transmitter type
- Localizer frequency

- GP angle for setting point C on the approach plots

These settings can be saved and recalled later if one wants to perform new simulations on a given localizer station.

It is also possible to define a complete layout including the taxiways. This feature is interesting when computing sensitive areas.

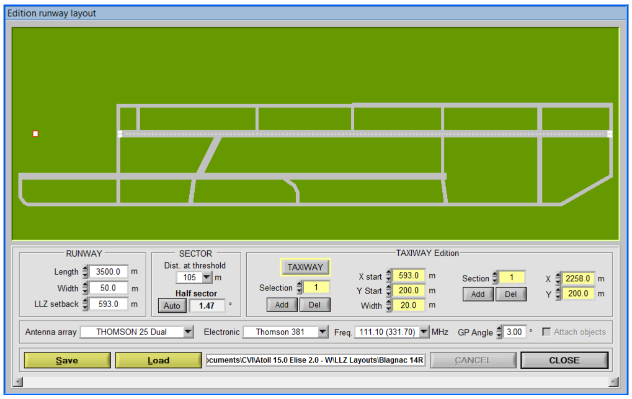


Figure 5. Runway panel with taxiways layout

Antenna settings panel

The antenna setting panel has 2 tabs, one for the mechanical setting and the other for the electrical settings.

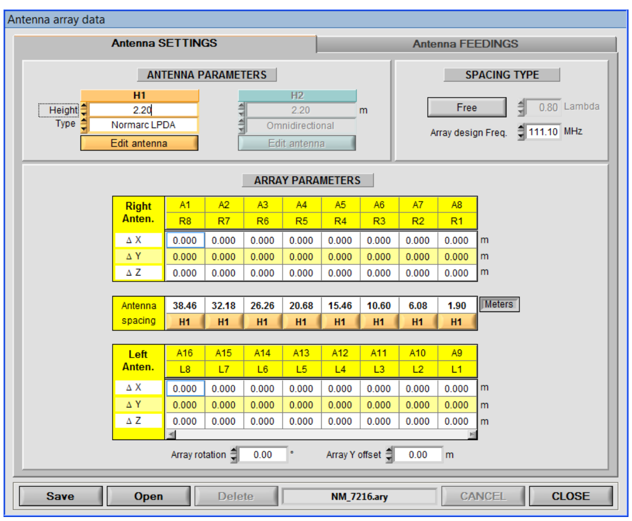


Figure 6. Mechanical settings tab

From the mechanical settings tab one can select the antenna type, the spacing between the antennas. It is also possible to add some antenna placing errors.

The antenna feedings tab permits to set the amplitude and the phase of the feedings of the signals to the antennas. Antenna feeding errors coming for example from bad soldering or some moisture in the connectors can also be added.

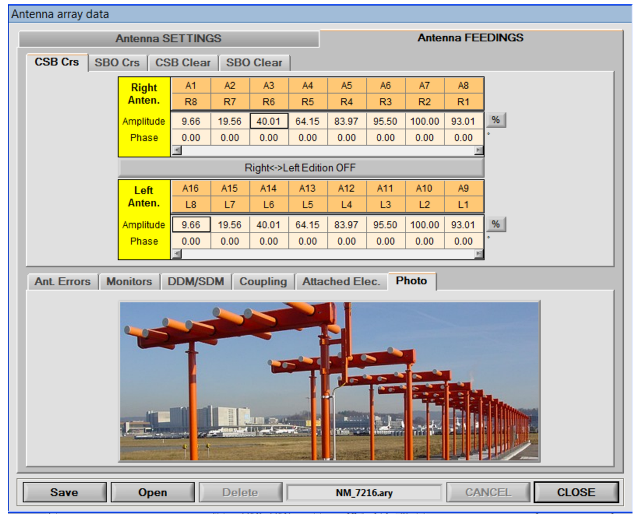


Figure 7. Electrical settings tab

Example of ground plot analysis

In order to analyze and compare measurements with simulations it is possible to import ground or flight inspection measurements.

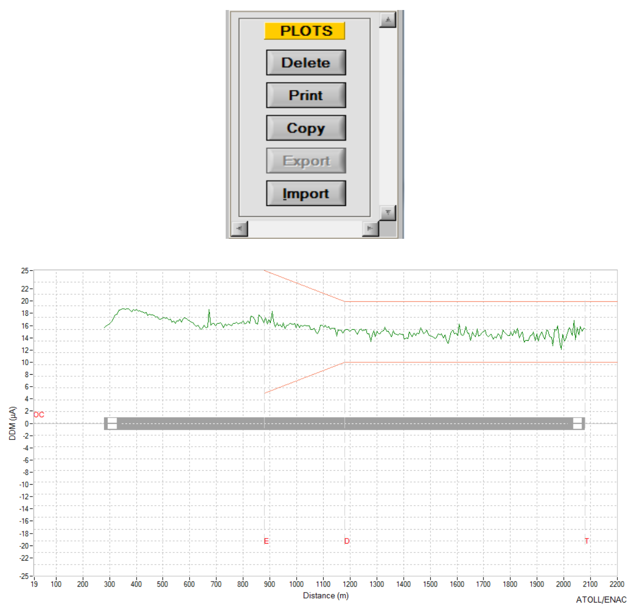


Figure 8. Ground inspection plot example

In this imported ground measurement file we can see a strong offset of the DDM along the runway centerline (15µA). We are now going to analyze this plot in order to identify the possible origins of this error.

DDM Modulation Balance error

The basic transmitter adjustment panel gives access to the adjustments available on all kind of transmitters and permits to test some transmitter maladjustments.

If we set the DDM modulation balance to +15µA we get the following plot.

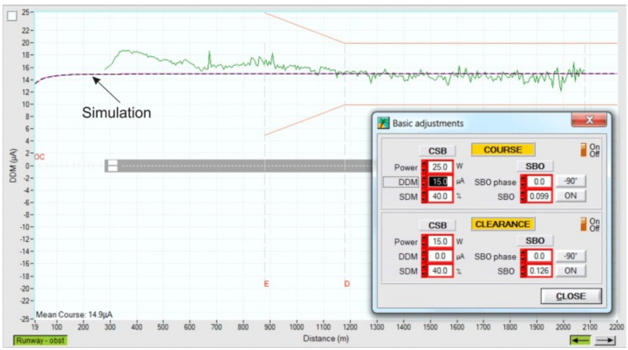


Figure 9. Basic adjustments panel

Figure 9 shows that a wrong DDM mod balance can in fact bring a similar effect as the recorded one.

For some ILS systems the complete block diagram with all the adjustments available on the real equipment can be displayed.

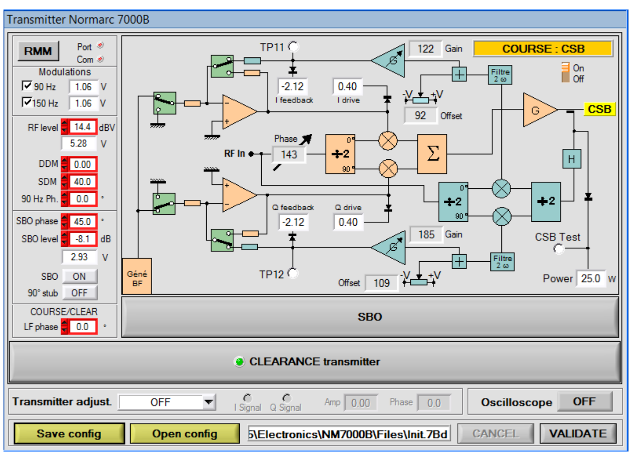


Figure 10. Example of transmitter panel

It is therefore possible to simulate more transmitter specific maladjustments and see how they can change the recorded signal in space.

Coming back to the DDM offset from the example we are looking at, it is easy to check on the ground if the DDM mod balance is not correctly adjusted and correct it. So we need to see if some other errors can lead to the same effect.

Sideway shift of the antenna array.

In the antenna panel it is possible to simulate a sideway shift of all antennas. This could happen if the middle of the antenna array is not aligned with the runway center line.

The simulation shows that a sideway shift of 1m (3.3ft) gives a completely different shape of the DDM as compared to the measured one.

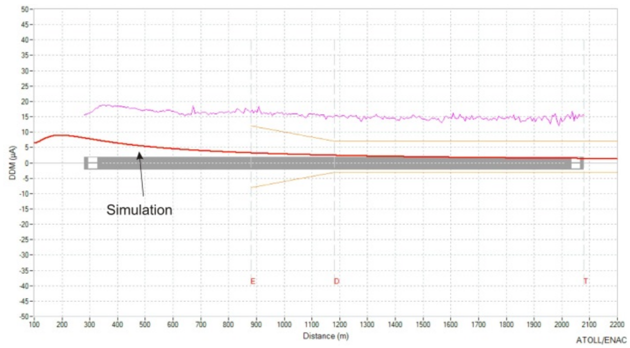


Figure 11. Sideway shift of antenna array

We can conclude that this error cannot be the cause of the recorded behavior.

Angular alignment error of antenna array

In the antenna panel it is possible to simulate an angular alignment error of the antenna array. Let's introduce a rotation of -0.29°.

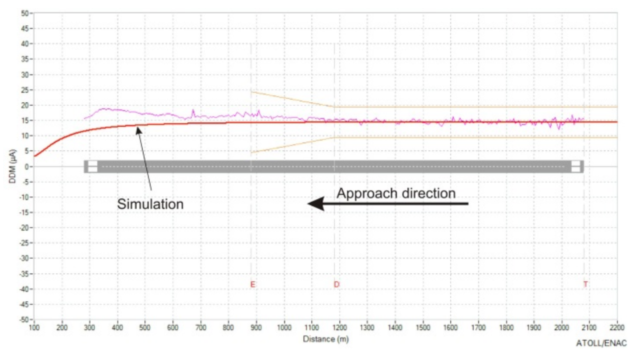


Figure 12. Rotation of antenna array

One may note that we get a behavior close to the measurement. This illustrates how accurate an antenna array has to be setup in order to get a correct radiated signal. If the mechanical alignment cannot be corrected it may be necessary to trim the feeding cables to the antennas. This can also be simulated in the antenna panel.

It can be seen on Figure 12 that the simulated plot is diverging from the measurement after point E.

A closer look at the antenna array in this case shows a sideway slope of the terrain in front of the antennas.

Figure 13. Terrain slope in front of antenna array

Introducing this terrain slope in the simulation gives the following result.

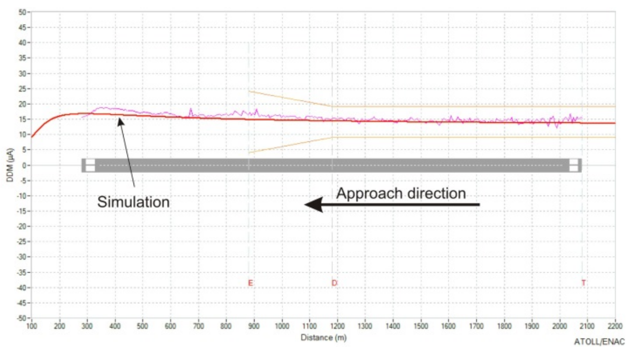


Figure 14. Simulation with terrain slope in front of antenna array

We can now see that the simulation is very similar to the record and that we found the reason of the strange behavior of the DDM.

Scattering objects panel

Obstacles, such as taxiing aircrafts, cranes or buildings present in the vicinity of the runway can produce unwanted multipath signals, thus degrading the performance of the ILS.

The method of Physical Optics (PO) on a rectangular plate is used to simulate the objects that may disturb the ILS signal.

One can add these objects and set their location and size from the Scattering objects panel.

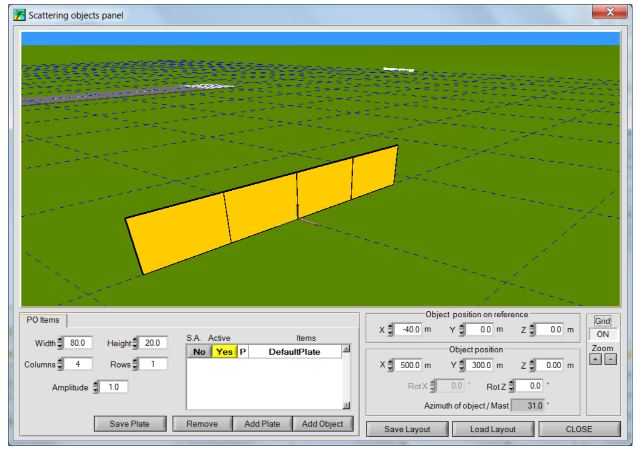


Figure 15. Scattering objects panel

With this feature it is easy to demonstrate what flight inspectors could expect to see on a measurement if there is a reflection from the course signal or from the clearance signal and thus determine the location of the disturbing object.

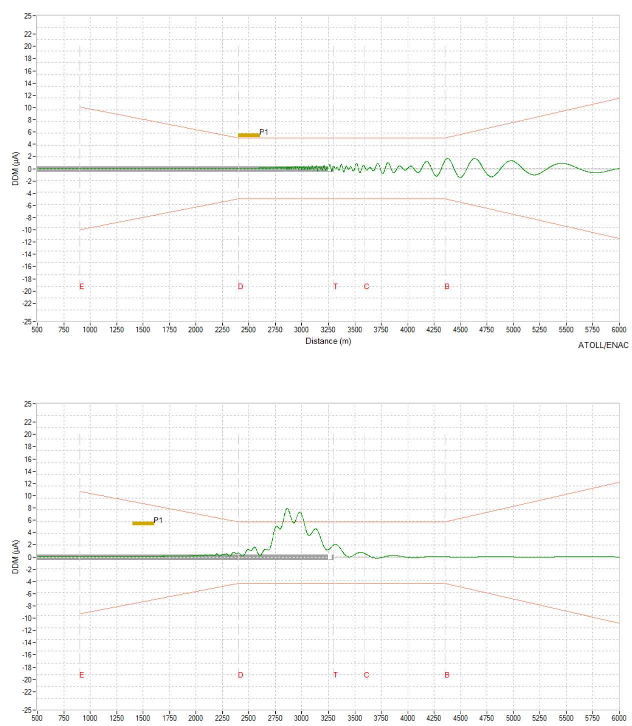


Figure 16. Example of a course reflection (top) and a clearance reflection (bottom)

Correlation tests between measurements and simulations show good agreement.

Here is an example from an airport with 3 major objects: the control tower, the terminal and a hangar on the opposite site of the runway.

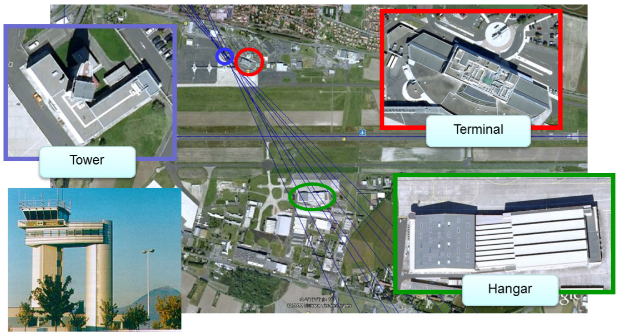


Figure 17. Example of object scattering: Airport layout

On the graph below we can see in green the simulation of the field strength recorded along the runway center line and in blue the measurement. The upper plots are related to the course signal and the bottom plots are related to the clearance signal.

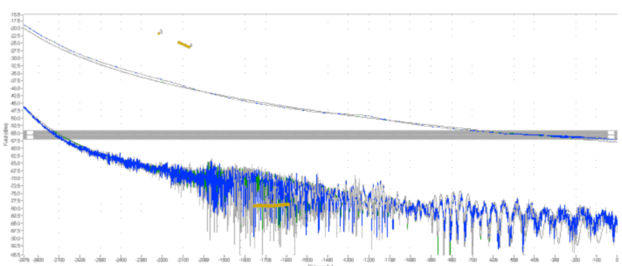


Figure 18. Example of object scattering: Field strength correlation

We can see quite good agreement between simulations and measurements.

GLIDE PATH SIMULATION

The glide path simulation program is called LAGON for Learning About Glide for Overall Needs. It consists of a main panel from which you can access to all features available in the software. The user interface is similar to the one in ATOLL.

They are much more receiver track options available in LAGON than in ATOLL. Some of them are similar to flight inspection trajectories and some others are more useful for training purpose, checking adjustment methods and troubleshooting of the system.

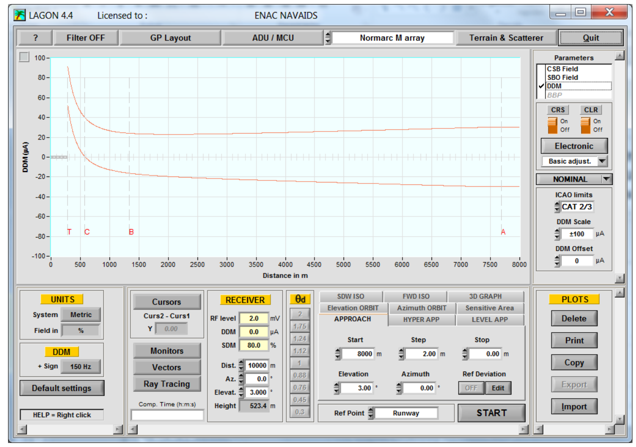


Figure 19. LAGON main panel

For flight inspection simulation the following modes are the most useful:

- Approach mode
- Level Approach mode
- Azimuth orbit

GP Layout Panel

In this panel one can set:

- Terrain parameters (slopes and height)
- Aiming point height
- Antenna positions
- Near field monitor position
- GP type
- Frequency
- Published approach angle
- Theoretical RDH (Reference Datum Height). This value will be used for computing the setback of the GP mast.

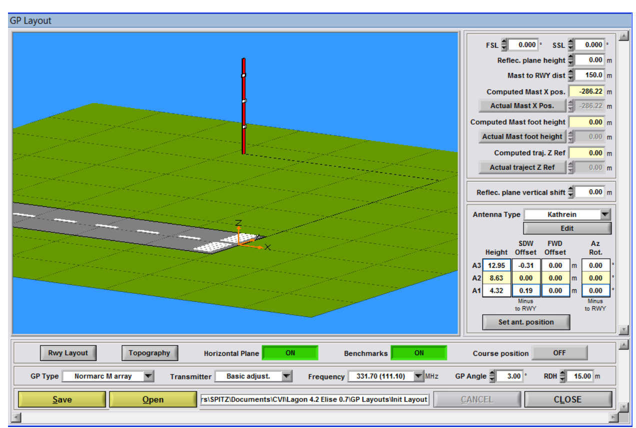


Figure 20. GP Layout panel (1)

It is also possible to display the theoretical approach path and the real locus of DDM=0µA as shown below.

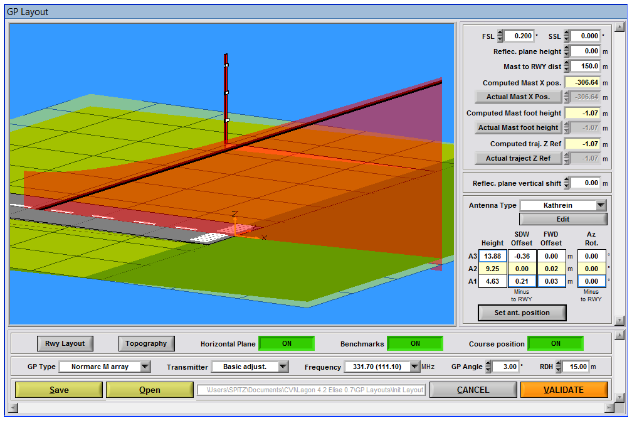


Figure 21. GP Layout panel (2)

From this panel one can open the Topography panel which can be used to compute the average reflection plane from terrain survey data.

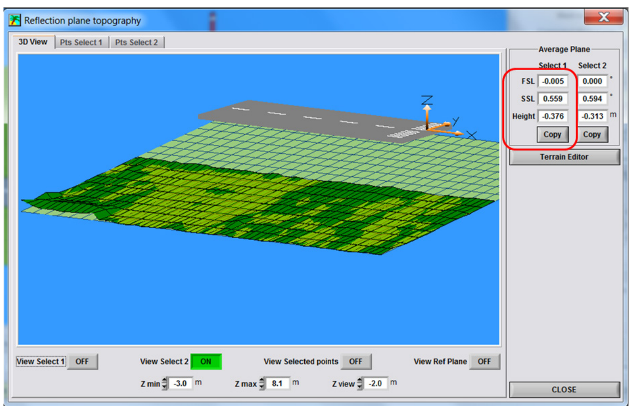


Figure 22. Topography panel

<u>Example of flight plot analysis</u>

In this example we are going to analyze the impact of the setting of the aiming point height in the flight inspection system (FIS) on the measured DDM on an approach at the nominal GP angle.

First we simulate an approach with all parameters set to nominal and no terrain slopes.

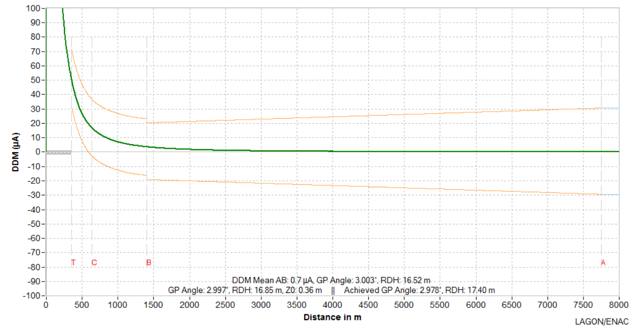


Figure 23. Nominal approach

We see the normal flare of the plot when coming closer to the antennas because of the hyperbolic shape of the DDM=0µA position points.

Let's now introduce a Forward Slope (FSL) of the terrain of +0.3° LAGON calculates the height of the theoretical Aiming Point: -1.83m.

After setting the correct antenna heights and using this value for the reference flight path we get the following plot.

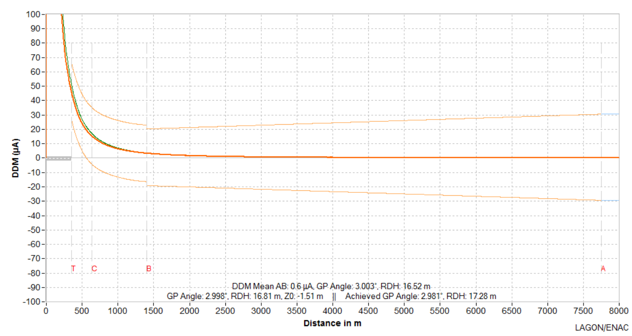


Figure 24. Nominal approach with FSL=+0.3°

One may note that we get a similar shape as without FSL if everything is correctly adjusted.

If we set now the Aiming Point to 0.0m with regard to the threshold we get the following plot.

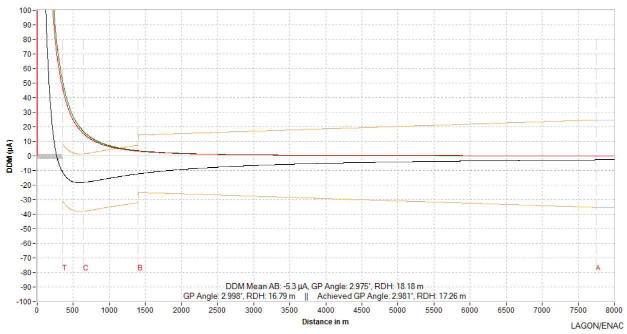


Figure 25. FSL=+0.3°, Aiming Point height =0.0m

We can see that without any change in the GP parameters settings we get a completely different picture. The average approach angle and the Threshold Crossing Height (TCH) computed from the recorded data have changed even if the signal in space did not change. This is a good illustration on the importance for the flight inspection crew to find and set correctly the Aiming Point height in the FIS.

Antenna Distribution Unit

This panel gives access to all the adjustments available in the Antenna Distribution Unit of the real equipment (phase shifters and power dividers).

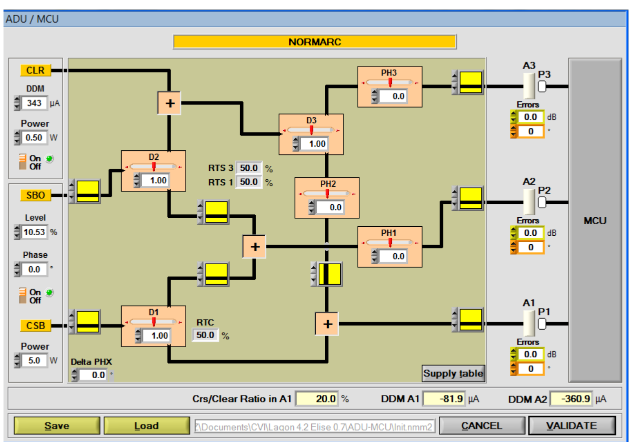


Figure 26. Antenna Distribution Unit

It is possible to simulate antenna errors as well as special settings needed during flight inspection like disconnecting some signals to given antennas or adding quadrature stubs. The main adjustments from the transmitter are also available from this panel. The button on the right opens the Monitor Combining Unit (MCU).

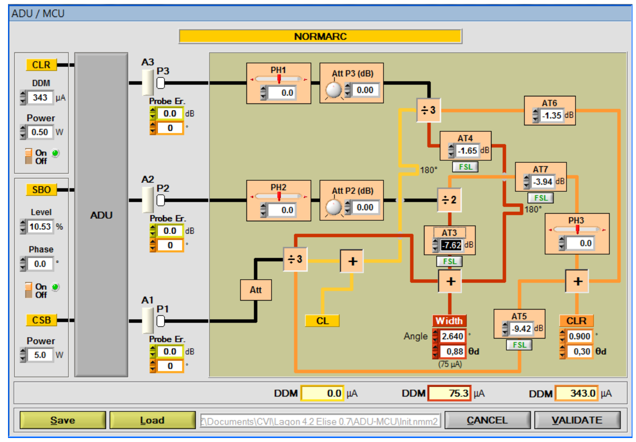


Figure 27. Monitor Combining Unit

This panel simulates accurately the real MCU and features the same adjustment devices. It is also possible to add some errors to the probes coupling and cabling. At the bottom the monitor readings are displayed. These values are also available in the signal measurement panel.

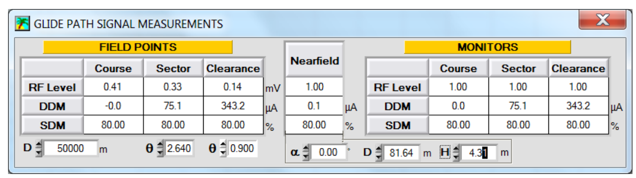


Figure 28. GP signal measurements panel

The Signal Measurement panel is very useful because it displays simultaneously the far field readings as seen by the flight inspection receiver, the monitor readings and the near field monitor readings. It is therefore easy to see how some maladjustments or errors are seen from the ground in comparison of what is seen from the air.

Scattering objects and terrain panel

This panel features 2 tabs, one for the scattering objects and the other for adding some terrain unevenness.

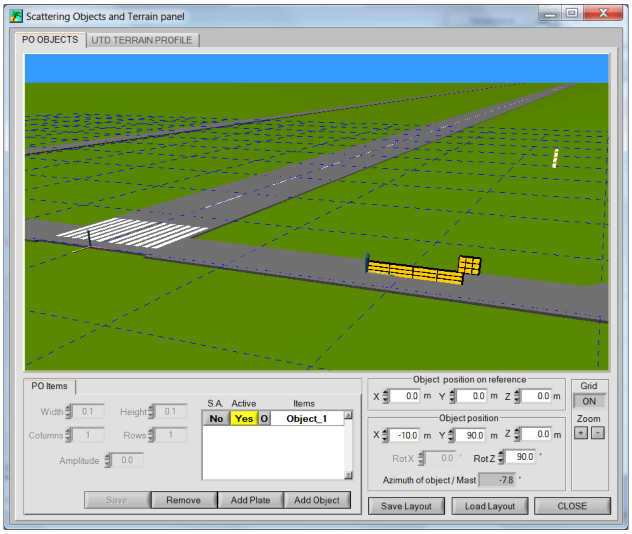


Figure 29. Scattering objects and terrain panel

The method of Physical Optics on rectangular plates is used for simulation the scattered signals from objects around the antenna system.

Even if the model looks very simplified it can give results quite similar to real measurement. Here is an example.

Example: B737 in front of GP mast

Lest first import the results from the flight inspection system using the importation panel.

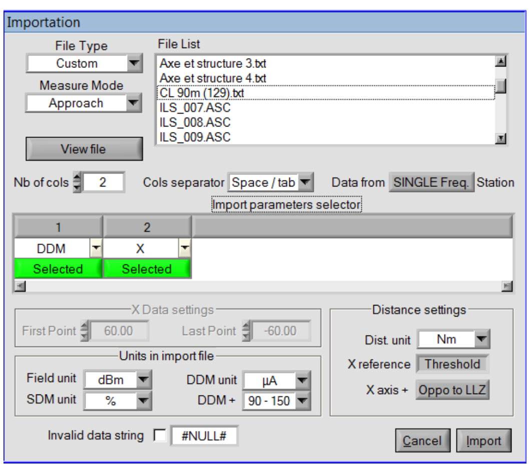


Figure 30. Importation panel

With this panel one can customize the importation of any data format from different flight inspection systems.

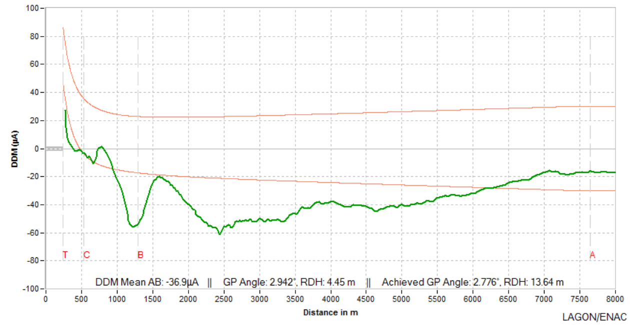


Figure 31. Imported plot from FIS data

Simulating the aircraft with 2 plates as shown in figure 29 gives the following result.

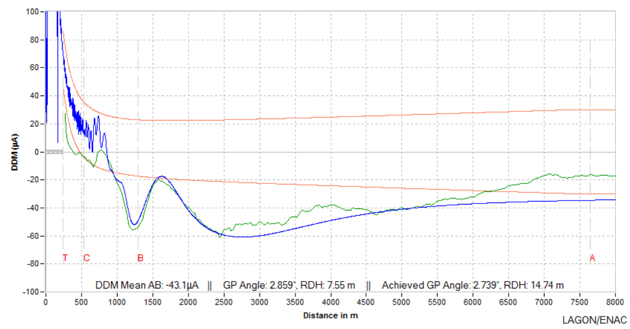


Figure 32. Imported data and simulation

We can see a quite good agreement.

Terrain features tab

With this panel it is possible to add some terrain unevenness in front of the antennas.

The real terrain is approximated by a set of rectangular plates simulating the terrain profile and the scattered signal is calculated using the method of Unified Theory of Diffraction (UTD).

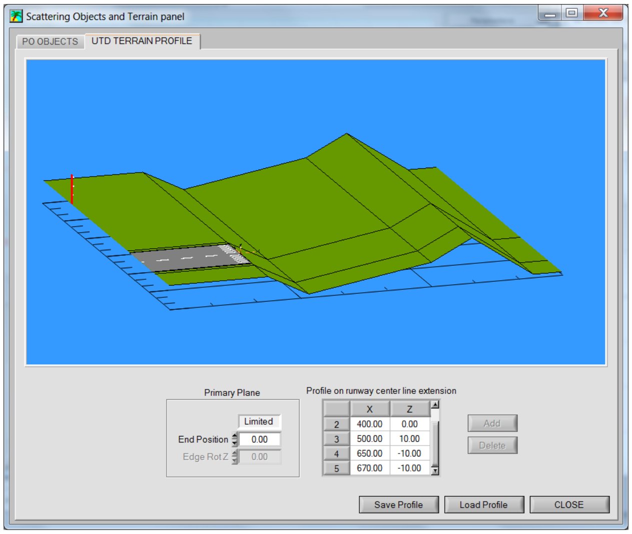


Figure 33. Terrain features tab

Workshop mode

LAGON features a workshop mode. In this mode it is possible to introduce some adjustment errors and hide them to the end user. It is then possible to simulate a complete flight inspection procedure and realign the GP in the same way as one would do it on the real equipment.

CONCLUSIONS

This paper gives an overview of the main features available in the ATOLL and LAGON software packages and how they can be used for flight inspections.

One may note that following points are of special interest for flight inspection:

- Initial and continuous training of flight inspection crews
- Solving issues arising from wrong settings in the flight inspection system or from ground equipment maladjustments
- Assess the impact of changes in the surroundings of the antenna systems

The use of the software packages may help to reduce flight inspection cost by

- Reducing initial setting issues
- Playing scenarios to solve some issues before flying the most relevant ones
- Analyzing more quickly the plots featuring some issues
- Improving communication between ground and flight staff

The software packages are already used by some flight inspection companies, by major ILS manufacturers as well as major Aviation Navigation Service Providers (ANSP's) all over the world.

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[3] FAA, 31 October 1995, Siting Criteria for Instrument Landing Systems, Order 6750.16C

An Emitting Reference Antenna Concept for Aircraft Antenna Calibration

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ABSTRACT

Navigations systems such as the instrument landing system (ILS) or the glide slope (GS) have to be calibrated after installation and later on on a regular base in order to ensure for instance required absolute field strength values. Hence measuring the absolute field strength of navigation systems is an important task of flight inspection. Within this scope recent advancements of aircraft antenna calibration have been presented at the last IFIS and proved to be a topic of high interest.

In this contribution we propose the concept of an emitting reference antenna. The radiated field strength of the former can be calculated analytically and reliably in full free space. This way a well-known field strength value is provided and can serve as a calibration normal to aircraft in-flight or on ground.

Such reference antennas, e.g. standard gain horns and open ended waveguides, are well established in near field antenna measurements. Whereas for higher frequencies the dimensions of such reference structures are easy to handle, standard gain horns for ILS or VOR frequencies are of considerable much larger size.

A design study including manufacturing aspects of such a reference antenna is presented. The study can be applied for arbitrary frequencies including the ones for the ILS localizer at 108 MHz, which are the most challenging. Additionally, the antenna placement on a ground is discussed.

INTRODUCTION

Since absolute field strength measurements are an important part of flight inspection, the calibration of aircraft mounted antennas is mandatory. At the last IFIS 2012 this topic was further investigated using calibrated receiving antennas to determine an absolute field strength value in free space that is the basis for the actual aircraft antenna calibration [1, 2]. Two different approaches were proposed. On the one hand a calibrated antenna was obtained with gain measurements that of course imply the assumption of an ideal propagation model. Another approach was to perform true field strength measurements. However, both methods require at any rate two measurements: one with the reference antenna to have a known field strength, and a following measurement with the actual measuring aircraft that refers to the obtained known field strength. These receiving reference antenna concepts consequently require two measurements with corresponding larger measurement uncertainties.

In this contribution we propose a concept of an emitting reference antenna which consequently requires only one single measurement with the actual measuring aircraft.

This however requires that the field strengths in space emitted by the reference antenna can be calculated traceable, analytically and to a high degree of accuracy. Such a class of antennas are rectangular waveguide structures comprising both simple open waveguides and horn antennas. Unlike any other class of antennas waveguide structures are easy and accurately scalable in frequency to cover the large frequency spectrum of navigation systems for flight inspection. Additionally, they are known to have only a very weak coupling with the environment that still allows their analytical description in the later measurement setup.

This contribution is organized as follows. In the first section the analytical description of rectangular waveguides is briefly recalled. The second section gives two measurement examples at glideslope and DME frequencies that demonstrate the accuracy and scalability of the emitting reference antenna concept. Finally, we discuss some issues of the antenna placement in the later measurement setup and manufacturing aspects.

WAVEGUIDE AND WAVEGUIDE ANTENNAS

Waveguides are used in order to have electromagnetic fields travel along a predefined path. A well-known structure to do so is the rectangular waveguide as depicted in Figure 1. Due to its geometry it allows for describing the electromagnetic fields by analytical expressions. For the TE_{10}-mode these expressions take the following form

$$\boldsymbol{E_y = -\frac{j\omega\mu a}{\pi} H_{10}\, sin\left(\frac{\pi}{a}x\right) e^{-j\beta z}} \quad \textbf{(1)}$$

$$\boldsymbol{H_x = \frac{j\beta a}{\pi} H_{10}\, sin\left(\frac{\pi}{a}x\right) e^{-j\beta z}} \quad \textbf{(2)}$$

$$\boldsymbol{H_z = H_{10}\, cos\left(\frac{\pi}{a}x\right) e^{-j\beta z}} \quad \textbf{(3)}$$

$$\boldsymbol{E_x, H_y = 0} \quad \textbf{(4)}$$

whereas H_{10} denotes the amplitude constant depending on the power fed into the waveguide, ω the angular frequency, μ the permeability, β the propagation constant in z direction and a the waveguides dimension in x direction [3]. The cutoff frequency of the TE_{10}-mode, which is the lowest cutoff frequency of all modes in a rectangular waveguide, is given by

$$\boldsymbol{f = \frac{c}{2a}} \quad \textbf{(5)}$$

with c the velocity of light.

Even though the equations stated above are derived for an unlimited waveguide they constitute a fairly well description of the fields on the aperture of an open ended waveguide. This yields a big advantage of aperture antennas in comparison to many other radiating elements which do not allow for such a description of their near field: the far-field can be calculated by the Fourier transform of the near-field.

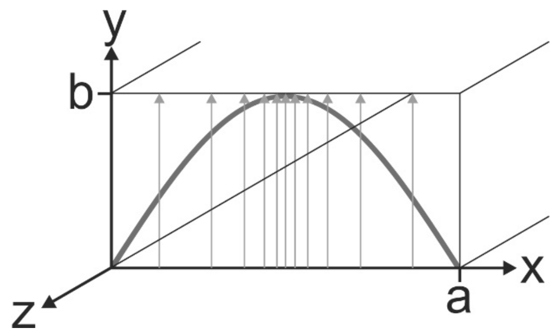

Figure 3: Rectangular Waveguide with E-Field Distribution of the TE_{01}-Mode.

In order to improve the radiation of an open-ended waveguide and to account for impedance mismatch the cross section of the open end is widened smoothly with only a slight change of the field distribution. By such a modification of a rectangular waveguide a horn antenna is built as shown in Figure 5.

EMITTING REFERENCE ANTENNA EXAMPLES

In the following two measurement examples of emitting reference antennas are presented. Generally, measurement results are performed on the two dimensional apertures of respective antennas. According to Huygens principle this is sufficient for a full description of the antenna's far field which is a simple spatial Fourier transform of the aperture's field distribution.

For measurements of the aperture field distribution an electro-optical sensor system is used. A detailed description of the measurement system and its calibration is given in [4] with first measurement results.

As a first example measurements are done for a rectangular waveguide, the cross section of which has a width of 259 mm and a height of 129 mm.

Figure 2 shows a view inside the waveguide structure with the coaxial feed and additional matching stubs. Figure 3 depicts the field strength measurement setup measurement with the waveguide placed in front of an anechoic environment.

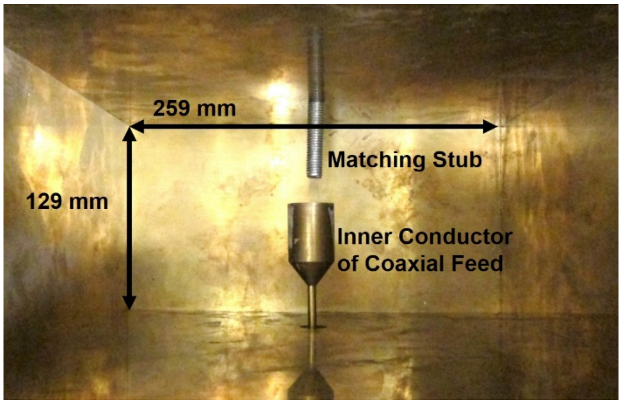

Figure 4: Inside View of Rectangular Waveguide.

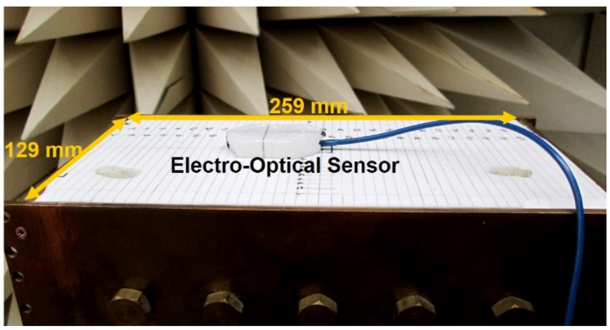

Figure 5: Field Strength Measurement Setup with Electro-Optical Sensor on Aperture of Waveguide.

The following figure shows measurement results for the electric field distribution at 1 GHz. As a comparison the analytical expression given in the preceding section of this contribution is also displayed and emphasizes the applicability of purely analytical, thus traceable formulation of fields to this waveguide antenna concept.

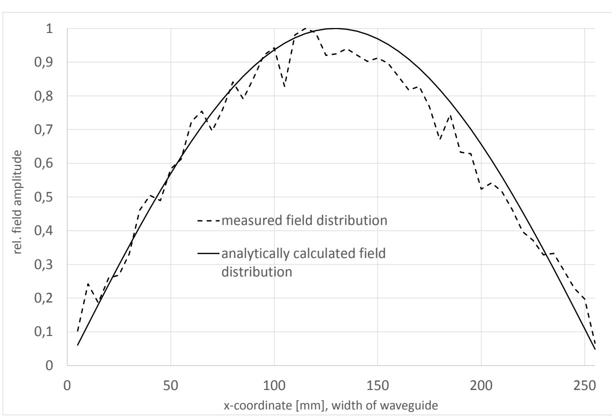

Figure 6: Comparison between Analytically Calculated and Measured Field Strength Distribution.

As a second example a double-ridged horn antenna is presented in the following at ILS glide slope frequencies, here 300 MHz. Figure 5 and Figure 6 show the actual emitting reference antenna as well as the setup for measuring the aperture field distribution.

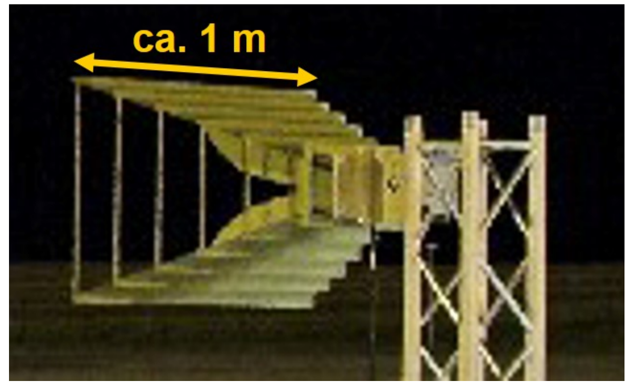

Figure 7: Double-Ridged Horn Antenna Mounted to a Mast

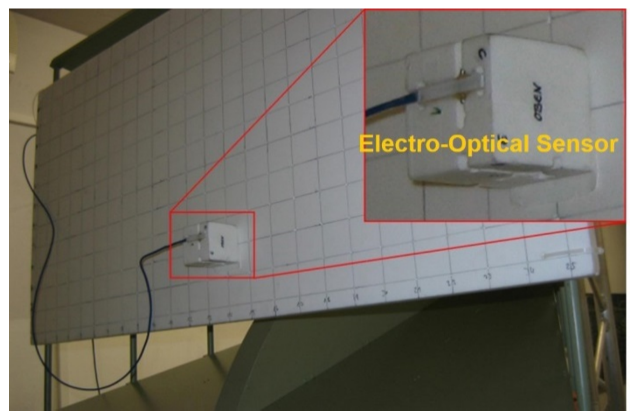

Figure 8: Electro-Optical Sensor Placed Along the Aperture of the Horn Antenna on a Sheet of Styrofoam.

The analytical expressions for the field distribution on the horn's aperture are not given here. It is referred to [5, 6]. However, like the field distribution of the waveguide structure only a sinusoidal shape fulfills the boundary condition of the tangential electric field to be zero at the boundaries of the horn. Figure 7 shows the measured electric field at 300 MHz within the antenna's aperture.

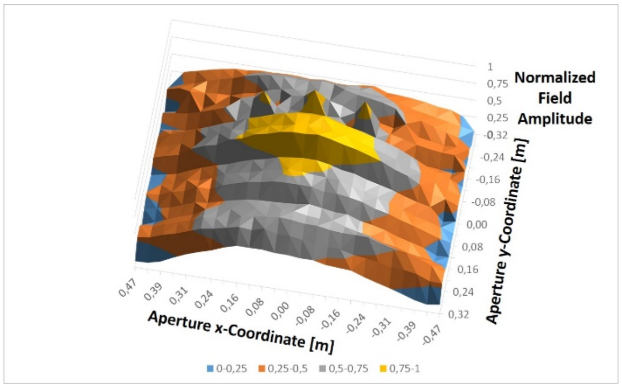

Figure 9: Sinusoidal Field Distribution at the Horn Aperture.

Basically, the sinusoidal field distribution on the horn aperture can be observed. Usually, the exact analytical description refers to standard gain horns whereas the double-ridged horn used here is a particular enhancement of the standard gain horn design with respect to bandwidth. For a better readability the following figure shows the field distribution along the middle of the horn antenna for y equal zero. As a comparison the analytically calculated values for the sin-function are also displayed.

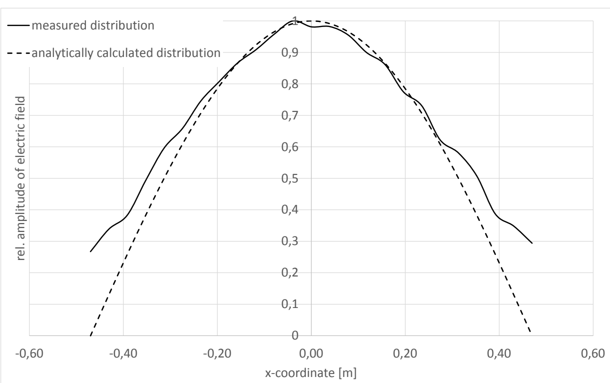

Figure 10: Analytically Exact and Measured Field Distribution in the Middle of the Horn Aperture.

A good agreement between analytical field solutions and measured field strength is observed. Though, slight deviations at the edges of the horn antennas are perceived. However, for the main lobe of the horn antenna these effects can be considered to be negligible. Thus, the analytical expressions for the field distribution are representative enough as a measure to calculate the electric field in the far field of the antenna.

Since the concept of waveguide antennas can be considered to be applicable as emitting reference antennas, some aspects of antenna placement in a later setup for aircraft antenna calibration are discussed in the following.

SCALING, ANTENNA SETUP AND SITE EFFECTS

Since the cutoff frequency as well as the radiation pattern merely depends on the dimension of the waveguide / horn measured in the wavelength of the operational frequency, once designed, antennas of this kind can be scaled according to the desired frequency. For instance, by applying a scaling factor of 22.6 on Flann Microwave's standard gain horn model 08240-10, which is designed to operate in the frequency band from 1.7 GHz up to 2.6 GHz, one receives a horn with single mode operation within the frequency band from 75 MHz to 115 MHz. This range covers the frequency of the marker beacon, 75 MHz, as well as of the localizer, 108 MHz up to 112 MHz. The cross section of the feeding waveguide equals 122 cm by 244 cm and the aperture is the size of 260 cm by 362 cm.

In order to get a first insight of how a conducting ground plane influences the radiation pattern of the horn, two sets of simulations are conducted in CST Microwave Studio [7]. The horn is orientated so that it emits the electric field strength horizontally polarized. Figure 9 depicts the scenario schematically.

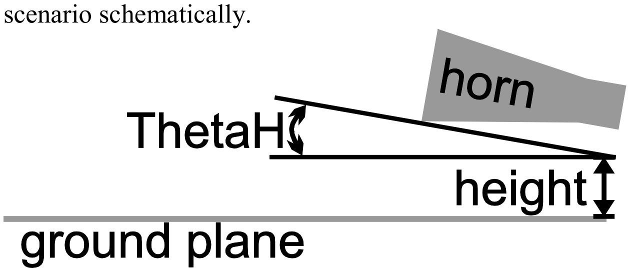

Figure 11: Simulation Scenario to Investigate the Influence of the Position of the Horn with respect to the Ground Plane.

In the first set the elevation angle of the horn with respect to the ground plane has been varied from 0° up to 20° in steps of 1° while keeping the height of the horn above the ground at 2 cm. In the second the height of the horn above the ground has been varied from 0 m to 0.5 m, which is a reasonable range for the placement of the very large horn antenna. A reasonable height for a good pattern without too much disturbing influence of the ground is 0.5 m. However, even the influence of the ground can be taken into account analytically applying the image theory. The installed antenna should be considered individually for later measurements.

The graphs plotted in Figure 10 depict the simulated directivity versus the elevation angle for different values of the parameter ThetaH. ThetaH is the elevation angle of the horn antenna with respect to the ground. The graphs given in Figure 11 show the variation of the antennas directivity versus the elevation angle for different heights of the antenna above the ground.

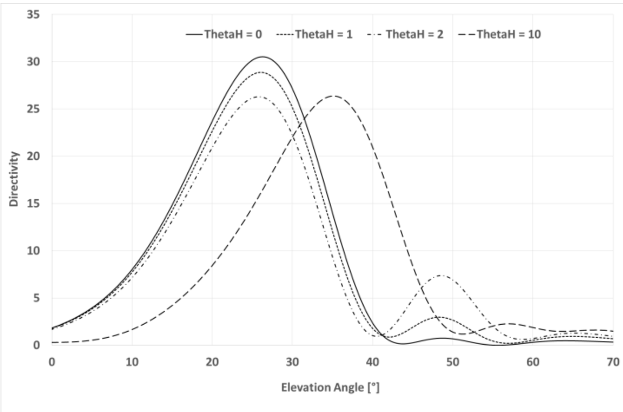

Figure 12: Simulated Directivity for varied Elevation Angles of the Horn with a constant height.

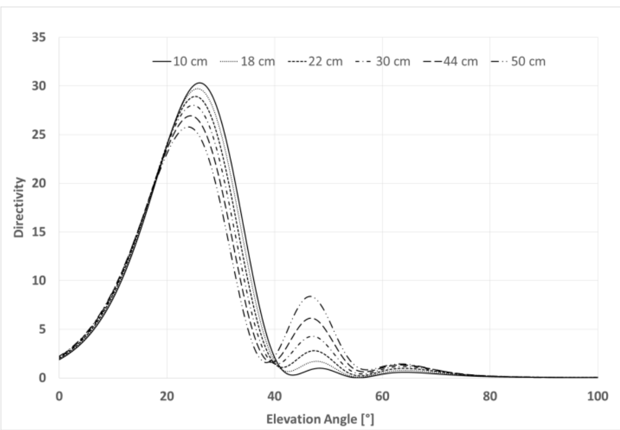

Figure 13: Simulated Directivity for Various Heights of the Antenna Placement.

As can be seen from the graphs in Figure 10 and 11 the beam width of the horn antenna is sufficient to illuminate the measuring aircraft. In order to check for sufficient link budget prior to calibration the Friis transmission equation can be applied:

$$\frac{E^2}{Z_0} = \frac{P_e G_e}{4\pi r^2} \quad (6),$$

with E the electric field strength, Z_0 the impedance of free space, Pe the power the emitting antenna is supplied with, Ge the gain of the emitting antenna and r the distance between the emitting antenna and the point of interest. Otherwise or instead the Fourier transform may be used for this purpose.

MANUFACTURING ASPECTS

Due to the frequencies in question the horn antenna is of considerable size. Nevertheless it needs to allow for an easy transportation. Therefore a modular construction consisting of a supporting wood structure covered on the inside with chicken wire is suggested. Using chicken wire instead of solid metal shields reduces the weight drastically and may be used as long as the mesh size is sufficiently small with respect to the wavelength. See also the double-ridged horn depicted in Figure 5.

CONCLUSION

In this contribution the feasibility of the waveguide antenna concept has been shown with measurement examples: at DME and glide slope frequency.

Furthermore the down-scaling of a standard gain horn to frequencies used by the marker beacons and ILS-localizer has been presented including numerical studies with respect to the placement of the antenna on ground.

Future work includes building and measuring antennas for VHF frequencies as for the above shown examples as well as further studies on the placement of the antenna.

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New ILS Localizer Ultra-Wide Antenna System Reduces Traffic Restrictions

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ABSTRACT

The introduction of large aircraft like the Airbus A380 and Boeing 747-8 could result in air traffic restrictions due to the ILS Localizer Critical and Sensitive Area (CSA) size for the current antenna systems. The introduction of the ultra-wide NORMARC 32-element antenna system avoids such restrictions by its smaller CSA and is an important part of the sustainable ILS.

ILS CAT III Zurich runway 14 is such case where traffic on the de-icing platform else could limit landing aircraft using the runway. The paper presents the simulations of the Zurich 14 ILS scenario using the advanced 3D modelling ILS prediction software ELISE developed by AIRBUS and ENAC, the antenna system's design with suppressed clearance radiation and measurement data, plus the commissioning flight inspection results.

AIRBUS ProSky has simulated A380 traffic at major airports with use of NORMARC 32-element antenna system compared to other systems on the market. This demonstrates operational benefits as less separation between approaching aircraft and holding positions closer to runway.

INTRODUCTION

The increased air traffic volume and introduction of very large aircraft like theA380 or the B747-8 have resulted in a more demanding situation for handling of the traffic flow. However, restrictions given by the ILS Localizer Critical and Sensitive Area (CSA) size could result in traffic constraints, which would be avoided if a smaller CSA were implemented.

The width of the Localizer antenna system is the only factor, which can be applied to reduce the size of the CSA. The purpose of this paper is twofold: First, it demonstrates that significant improvements in airport operations can be gained by replacing existing Localizer antenna systems with a Ultra-wide antenna system. Secondly, it shows that an airport site-specific analysis of the CSA using advanced airport environment simulation tool like ELISE could also significantly reduce the size of the CSA and bring operational benefits.

TYPES OF TRAFFIC LIMITATIONS

Examples of possible traffic and airport restrictions due to the CSA are:

- Limitations in use of the whole or part of the taxiway system

- Increased separation between approaching aircraft
- Autopilot decoupling under CAT I conditions
- Restrictions on number of large aircraft to line up for take-off
- Extended taxiing route
- Restrictions in new airport constructions and parking area due to multipath

The introduction of larger aircraft like the A380 and the B747-8 has resulted in larger ILS Localizer Critical and Sensitive Areas (CSA). Assessments of the existing Localizer (LOC) antenna systems CSA show that for many runways CSA for large aircraft (A380 and B747-8) could cover parts of runway and taxiways and hence give restrictions on the air traffic movements.

DEFINITIONS AND SIZE OF CSA

Definitions

The current ICAO Annex 10 definitions of Critical and Sensitive are [1]:

The ILS critical area is an area of defined dimensions about the localizer and glide path antennas where vehicles, including aircraft, are excluded during all ILS operations. The critical area is protected because the presence of vehicles and/or aircraft inside its boundaries will cause unacceptable disturbance to the ILS signal-in-space.

The ILS sensitive area is an area extending beyond the critical area where the parking and/or movement of vehicles, including aircraft, is controlled to prevent the possibility of unacceptable interference to the ILS signal during ILS operations. The sensitive area is protected against interference caused by large moving objects outside the critical area but still normally within the airfield boundary.

This paper addresses only the sensitive area. However, CSA is used in this paper as it is the common international recognized term.

Normally, the CSA is defined for a specific runway based on generic calculations. These generic calculations are based on 2D object modeling and on Physical Optics. However, this simplified method usually results in an excessive CSA. To have a more optimized size of CSA it is necessary accurately model the specific airport site by taking into account the real airport environment (ground profile, existing buildings, operational aircraft orientation, trees, etc.). AIRBUS ProSky in collaboration with ENAC developed an advanced ILS simulation software namely ELISE using exact methods of resolution of ILS propagation equations (Method of Moments) applied on the entire 3D object modeling.

Size of CSA

The size of the CSA for a specific runway is given by the following parameters:

- Width of the antenna system
  - A Localizer antenna system with a larger width (aperture) will give a narrower radiation beam which gives a narrower sensitive area than a system with less width
- Localizer Course Sector
  - A longer runway, resulting in a narrower Localizer course sector will have a larger sensitive area than a shorter runway
- ILS Category
  - The operational category of the runway has a large impact on the size of the sensitive area: The higher category, the larger sensitive area. For the same Localizer antenna installation, the CAT I sensitive area will be much smaller than the CAT II or CAT III sensitive areas. In most cases, the CAT II and CAT III sensitive areas will be of approximately the same size.
- Maximum aircraft type using the airport
  - A larger aircraft will result in a larger sensitive area than a smaller aircraft. Consequently, the size of the sensitive area should be determined by the size of the largest aircraft operating at the airport in question.
- Taxiway pattern
  - The general "worst-case" sensitive area calculation is based on the worst-case orientation of the tailfin of the aircraft leaving the runway after landing, and taxiing. The size of the CSA could be optimized by taking into account the "operational" worst-case scenario on each taxiway.
  - The proximity between the LOC and the runway end might also be a constraint as the CA might cover a part of the RWY end.

DESIGN GOALS.

- The main lateral coverage region, ± 35° shall be 100% compliant with existing ICAO Annex 10 specifications (e.g. 25NM within ± 10° 2000' and 17NM from ± 10° to ± 35° 2000').
- The Clearance signal shall be radiated from the same antenna system as the Course signal.
- The Clearance CSB field strength shall have a large negative gradient from +/- 10° to +/- 15° (reduction of field strength by approx. 6dB), in order to optimally fit the lateral coverage region and especially the difference in range between 25 NM within ± 10° and 17 NM within ± 35.°
- From +/- 15° to +/- 35° the Clearance field strength shall be mainly constant.
- The DDM pattern from ± 5° to ± 35° shall be mainly flat.
- The width of the CAT III sensitive area shall be 20% less than for the NORMARC 20-element Localizer antenna system for an A380 aircraft.

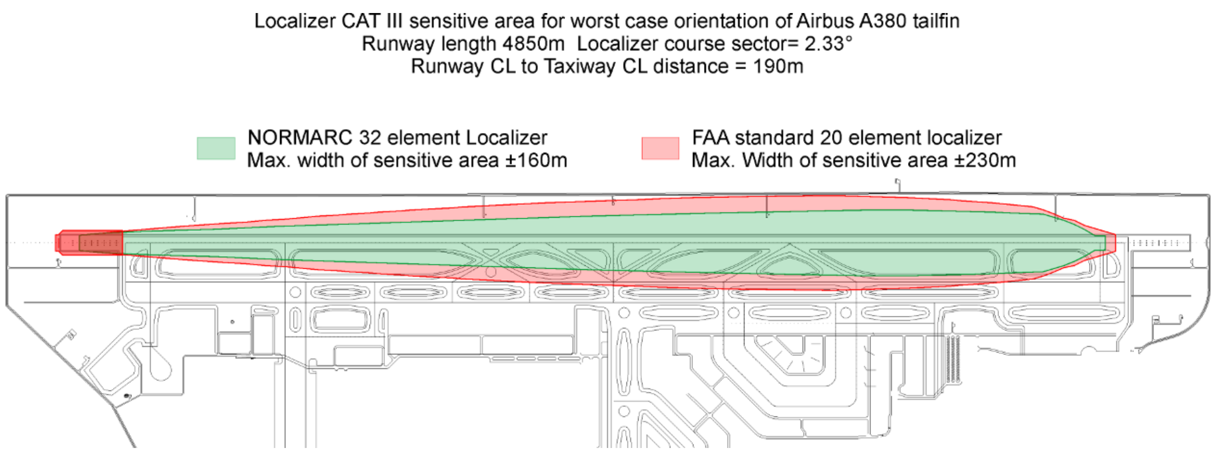

Figure 1 Example of generic CSA.

Key figures

Number of antenna elements:	32
Physical aperture:	75m
Course CSB Beam Width:	±1.4°
Design Course CSB Side lobe level:	~ -50 dB
Design Course SBO Side lob level:	-30dB
Course SBO first maximum:	1.6°
Course SBO first null:	4.3°

Design of antenna feeding

A proprietary antenna array design tool developed within Indra Navia AS was used for the synthesis phase of the design. The design was finally tested by modeling the complete array (32 Log-periodic dipole antennas (LPDA)) with the Method of Moments. The NEC 4.1 program from Lawrence Livermore National Laboratory was used for this purpose.

The radiation patterns are shown in Figure 3 for CSB and Figure 4 for SBO pattern.

The effect of production tolerances in the antenna distribution unit is shown in Figure 5 and Figure 6 Measured values on the distribution unit for Zurich Localizer 14 are used.

Calculated DDM/SDM patterns based on the design feeds and the measured feeds for Zurich RWY 14 are shown in Figure 7 and Figure 8 respectively.

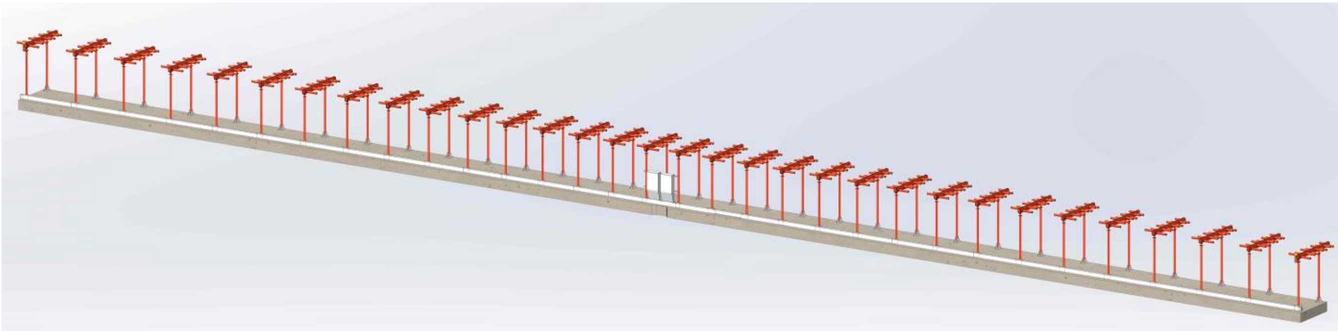

Figure 2 NORMARC 7232A 32-element Localizer antenna system

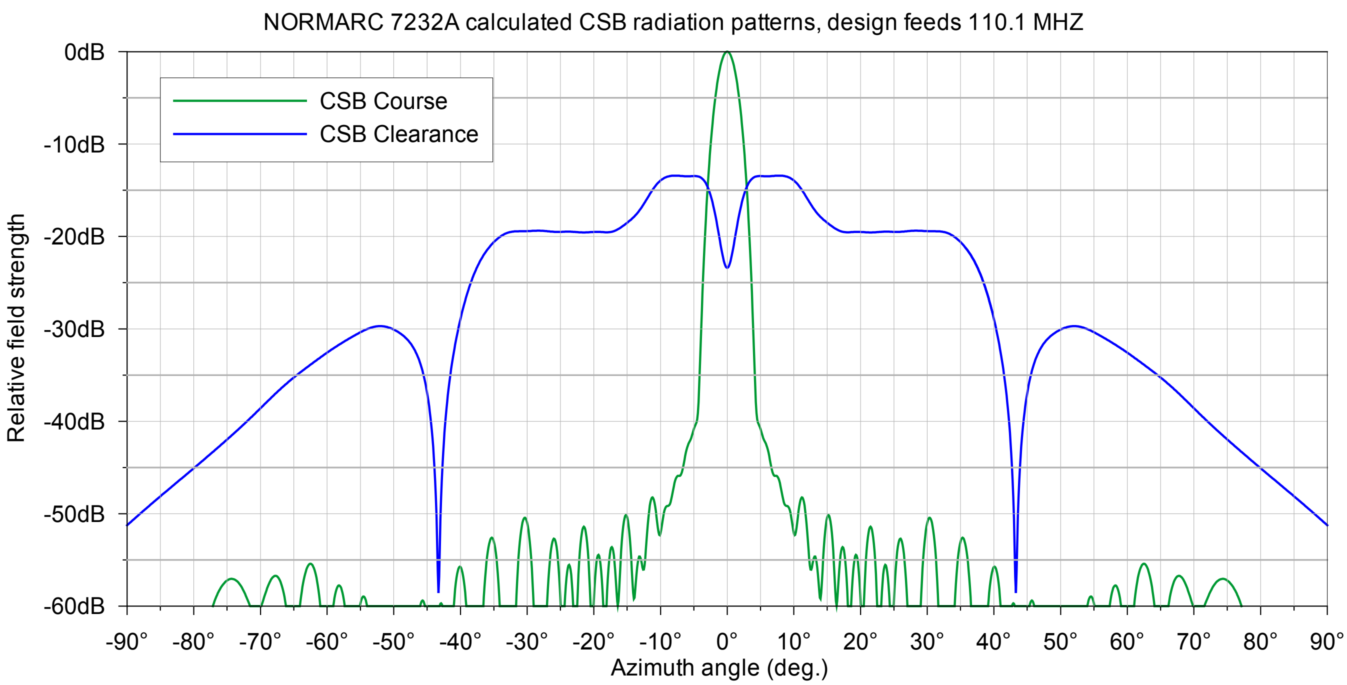

Figure 3

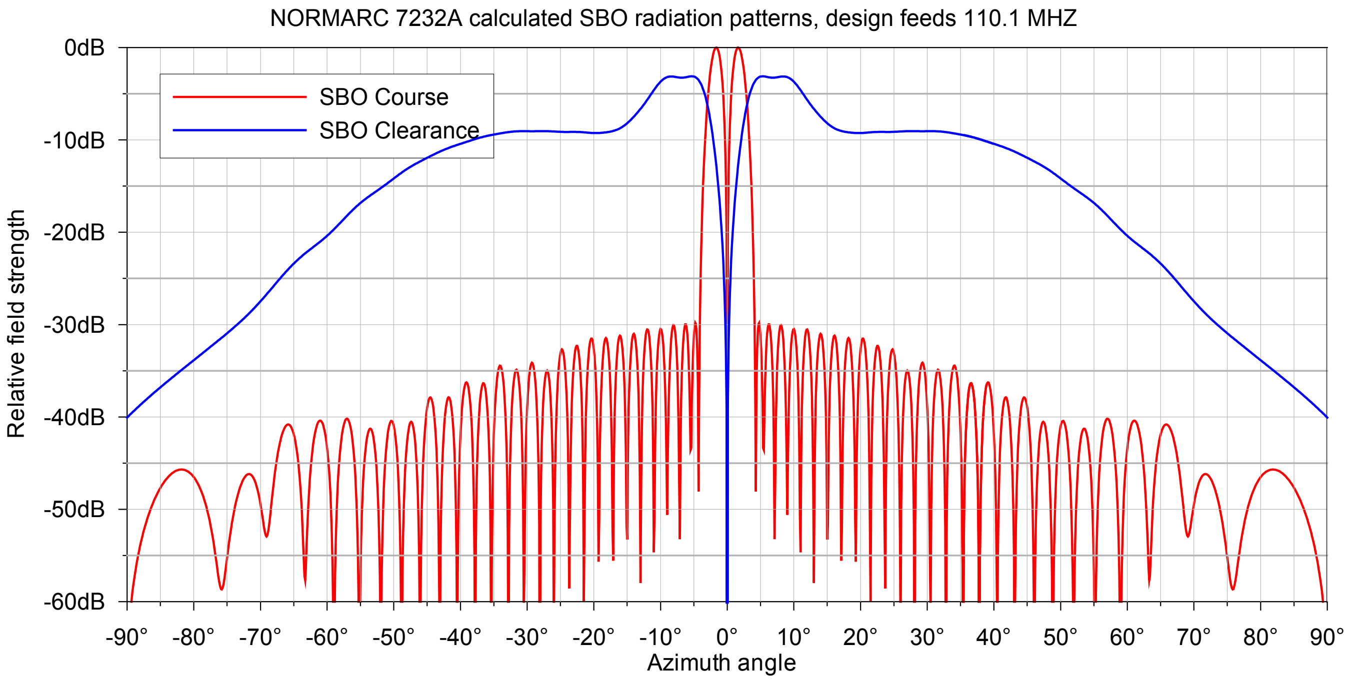

Figure 4

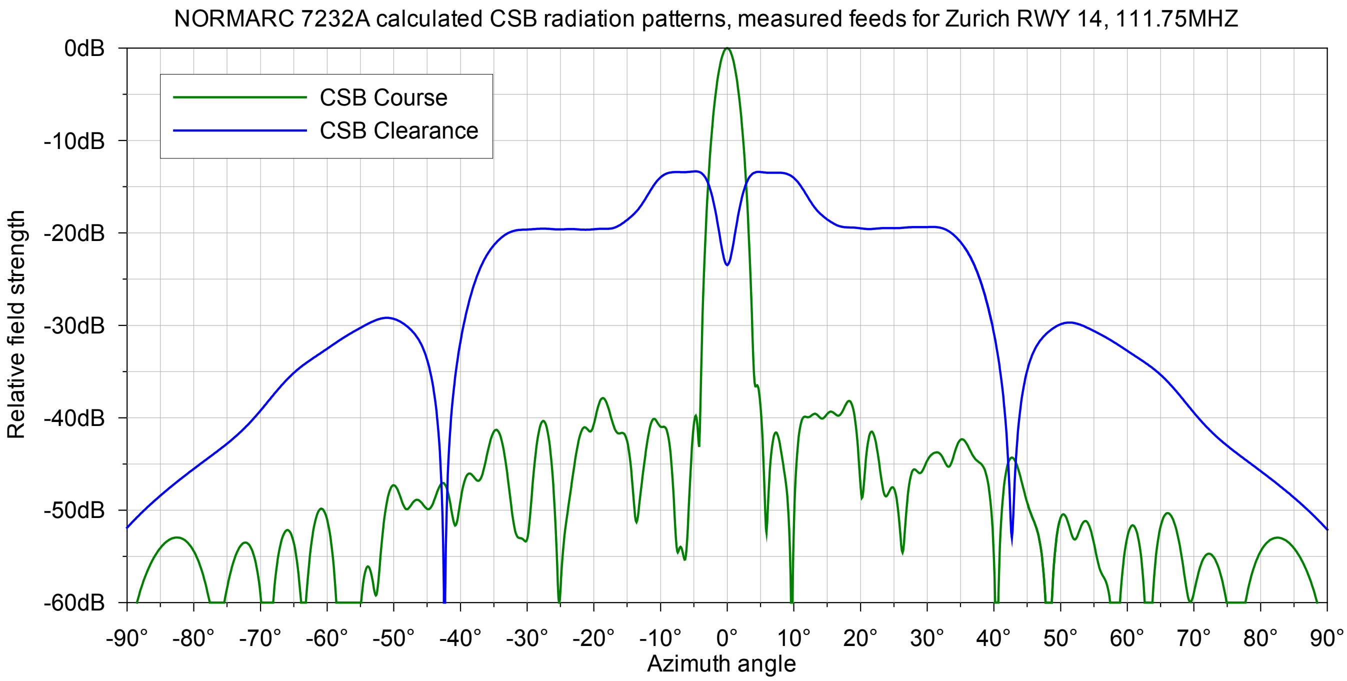

Figure 5

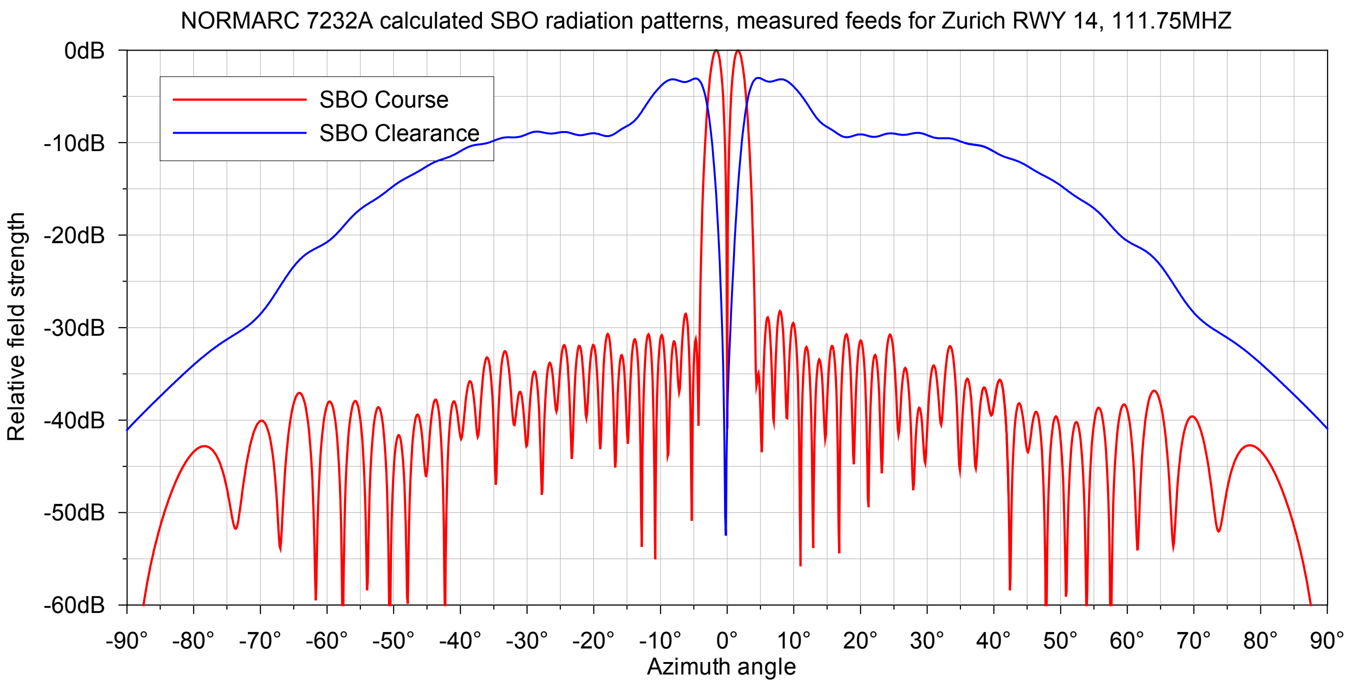

Figure 6

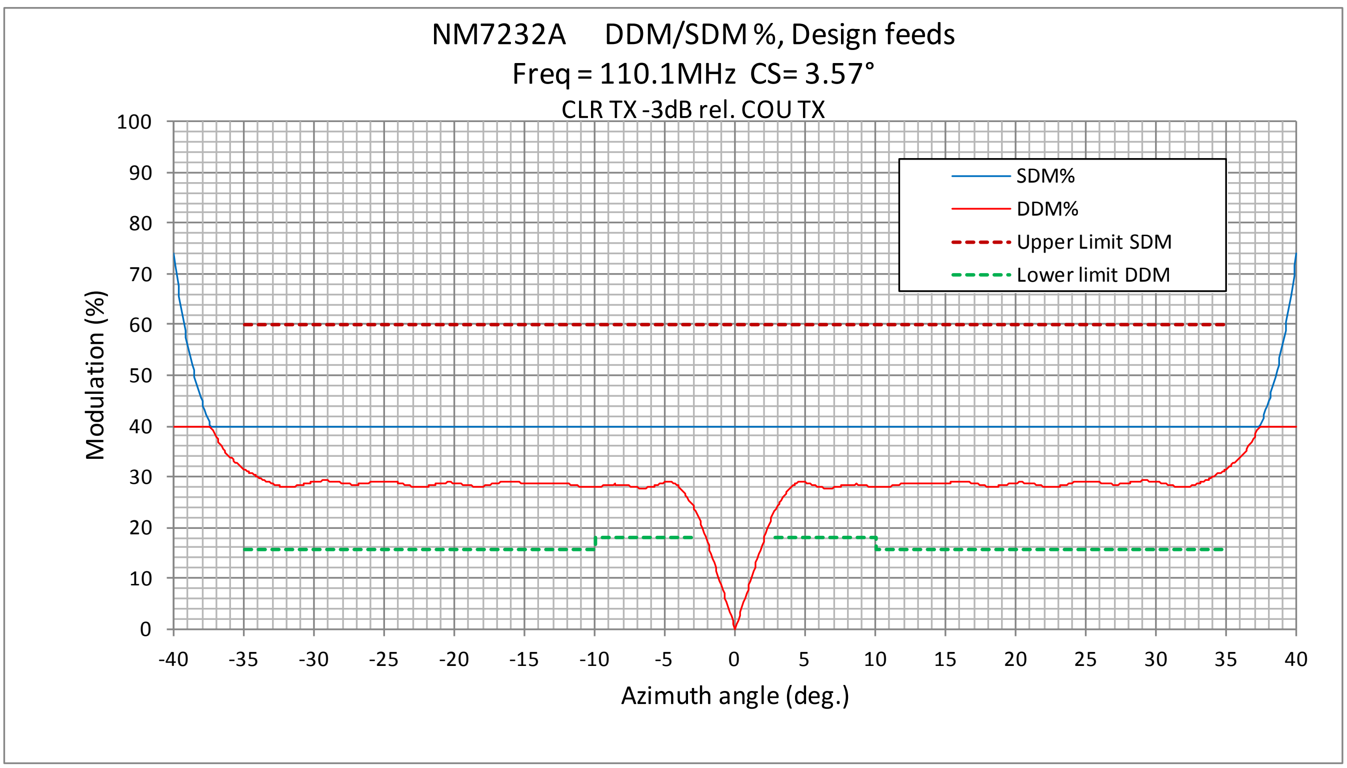

Figure 7

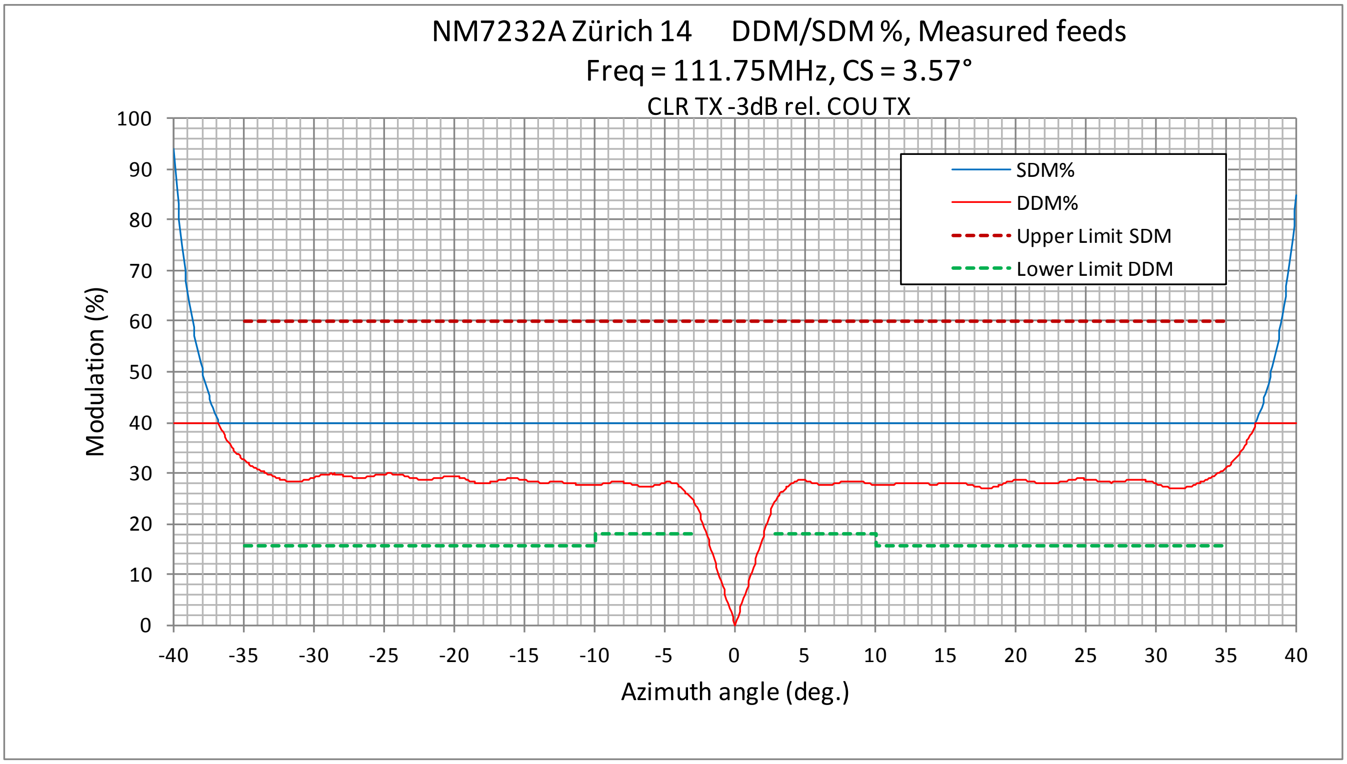
NM7232A Zürich 14 DDM/SDM %, Measured feeds
Freq = 111.75MHz, CS = 3.57°
CLR TX -3dB rel. COU TX
SDM%
DDM%
Upper Limit SDM
Lower Limit DDM
Modulation (%)
100
90
80
70
60
50
40
30
20
10
0
-40
-35
-30
-25
-20
-15
-10
-5
0
5
10
15
20
25
30
35
40
Azimuth angle (deg.)

Figure 8

Mechanical and Electrical design

Design based on well-proven technology that complies with CAT III integrity and continuity of service requirements:

- Same LPDA antenna elements as in other NORMARC antenna systems
- Same Antenna Distribution Unit (ADU) technology
- Same Monitor Combining Unit (MCU) technology

The ADU is shown in Figure 9 and the MCU in Figure 10.

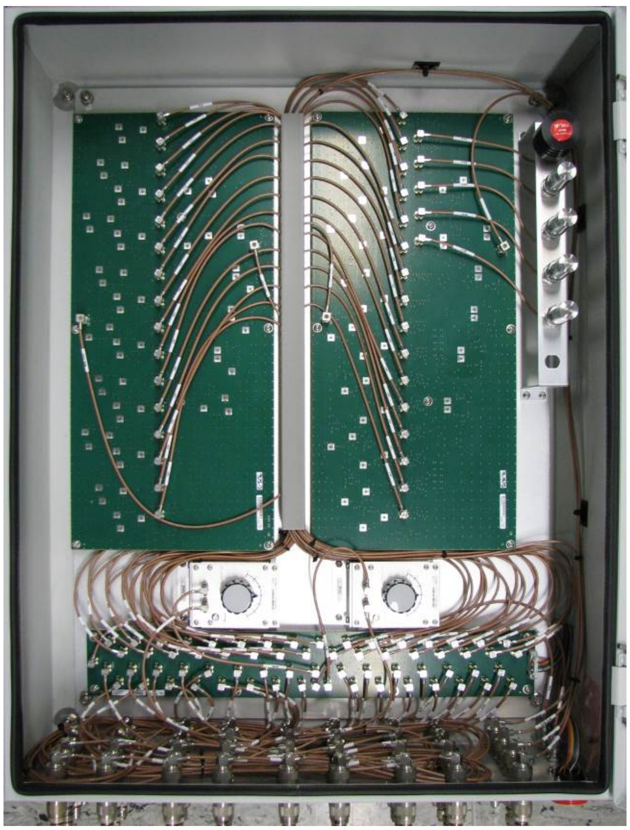

Figure 9 (ADU)

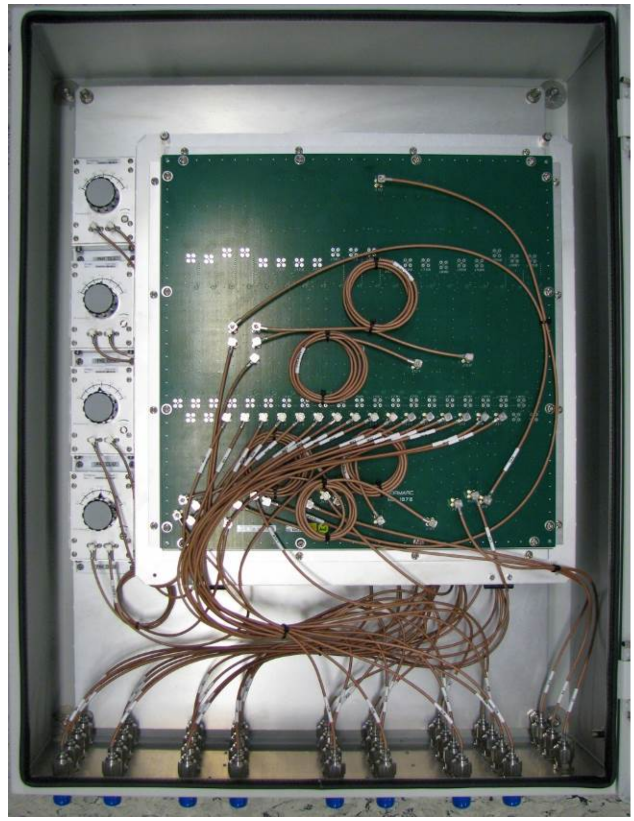

Figure 10 MCU

Beam Bend Potential (BBP)

The probably best method for comparing localizer antenna systems with regard to immunity of course bends caused by course SBO signal reflected into the course line, is to compare the Beam Bend Potential (BBP) for the different systems. The BBP is a measure of how large bends could be caused by course SBO reflected into the course line, if 100% of the radiated SBO signal for each calculated angle was reflected. The smaller the BBP is, the less sensitive to course SBO reflections the localizer is.

The BBP for the NORMARC 7232A Localizer antenna system compared to two other common Localizer antenna systems, the NORMARC 7220A 20-element system and the FAA standard 20-element system are shown in Figure 11.

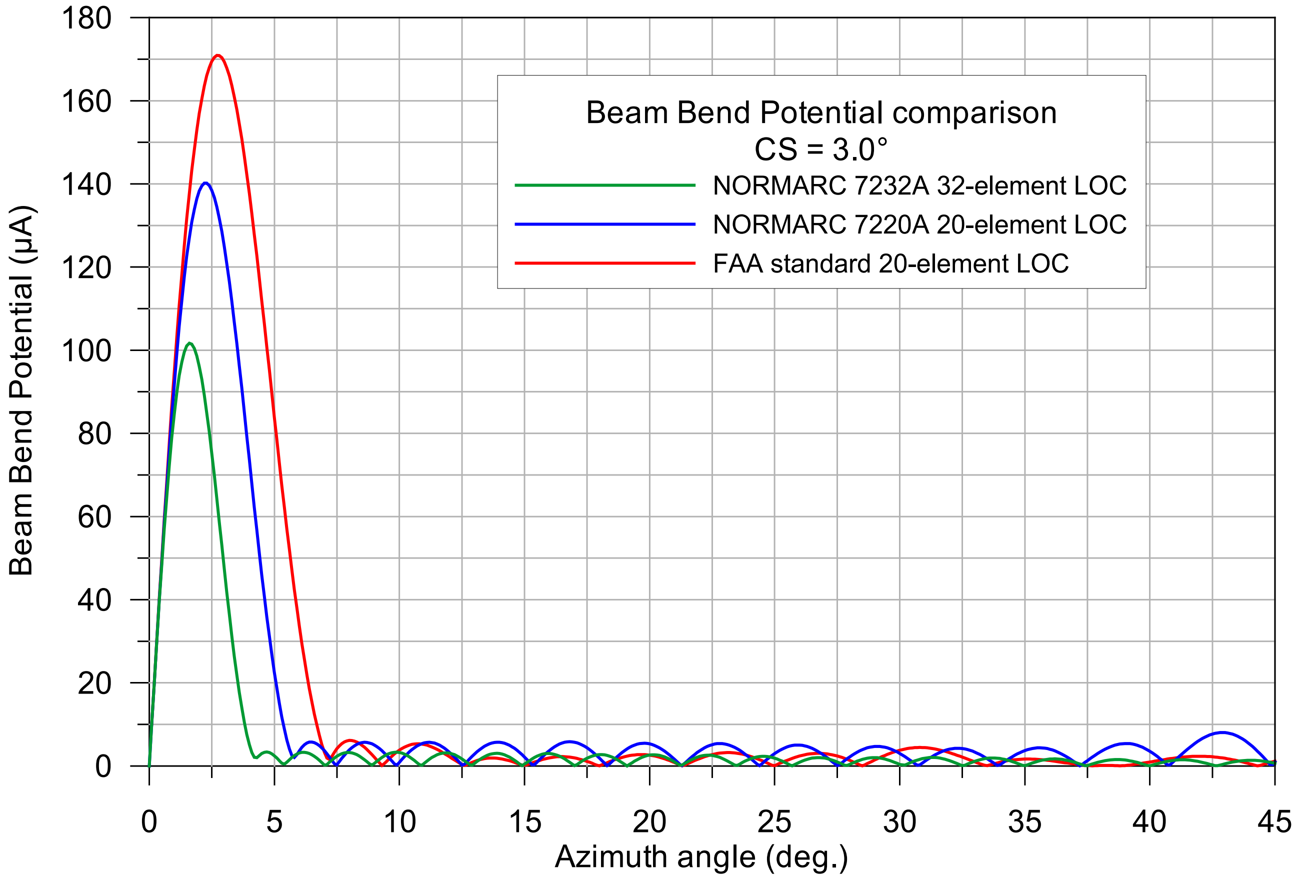

Figure 11

SUPPORTING TECHNICAL VALIDATION

The installation of the NM 7232A in Zurich, RWY 14

In collaboration with AIRBUS ProSky and Indra Navia AS, Zurich airport (FZAG) and skyguide launched in 2013 a feasibility study in order to assess the size of the CSA of the new localizer 14 Zurich (in particular the new NM 7232A), and evaluate the potential gain for airport operations. Among several localizer types (and different antenna heights), the results of the ELISE study clearly showed the benefits of the NM 7232A, with an antenna height of 3 meters. Thus, the replacement project has been launched for a realization phase in 2014, according to the following the schedule:

- Building phase in February and March 2014
- Mechanical installation in April 2014
- Ground commissioning in May 2014
- Flight check in June 2014 (till 13.06.14, just before IFIS 2014)

Figure 12 and Figure 13 show pictures of the brand new installed localizer NM 7232A in Zurich, RWY 14.

Figure 12 Picture of the NM7232A, seen from the side

Figure 13 Picture of the NM7232A, seen from behind

<u>An ILS replacement with (nearly) no service interruption</u>

Moreover, the other challenge of this project is to minimize the ILS service interruption, or even to have nearly no service interruption (only 2.5 days without ILS service). Based on the future layout of the airport and the new taxiways distribution, the new LOC has to be positioned 120 meters **in front of** the current one, which represents a tough configuration with possible multipath and/or screening effects. Figure 14 and Figure 15 illustrate this situation. In order to assess the impact of the new LOC on the current one, another ELISE study has also been conducted by AIRBUS ProSky. According to these simulations, the influence on course structures and coverage (orbits) will be marginal and will be CAT III compatible. These results confirmed skyguide in the choice of the NM 7232A (with a height of 3 meters) and a project realization in parallel with the CAT III operations of the current ILS.

In order to support this special "double ILS" situation (one operating and one in building phase), the following conditions have been required and applied:

- The new ILS radiates on another (compatible) frequency.
- Only night work for the building, installation, tuning and ground commissioning phases.
- After the mechanical installation of the new ILS, the flight check from FCS has confirmed on 10.04.2014 the non-impact of the new ILS on the current one. Thus, the current ILS has been then released for normal operations, after a 3 day service interruption. (because of the 3 night installation phase)

Figure 14 Picture of the current LOC and the NM 7232A, seen from the side

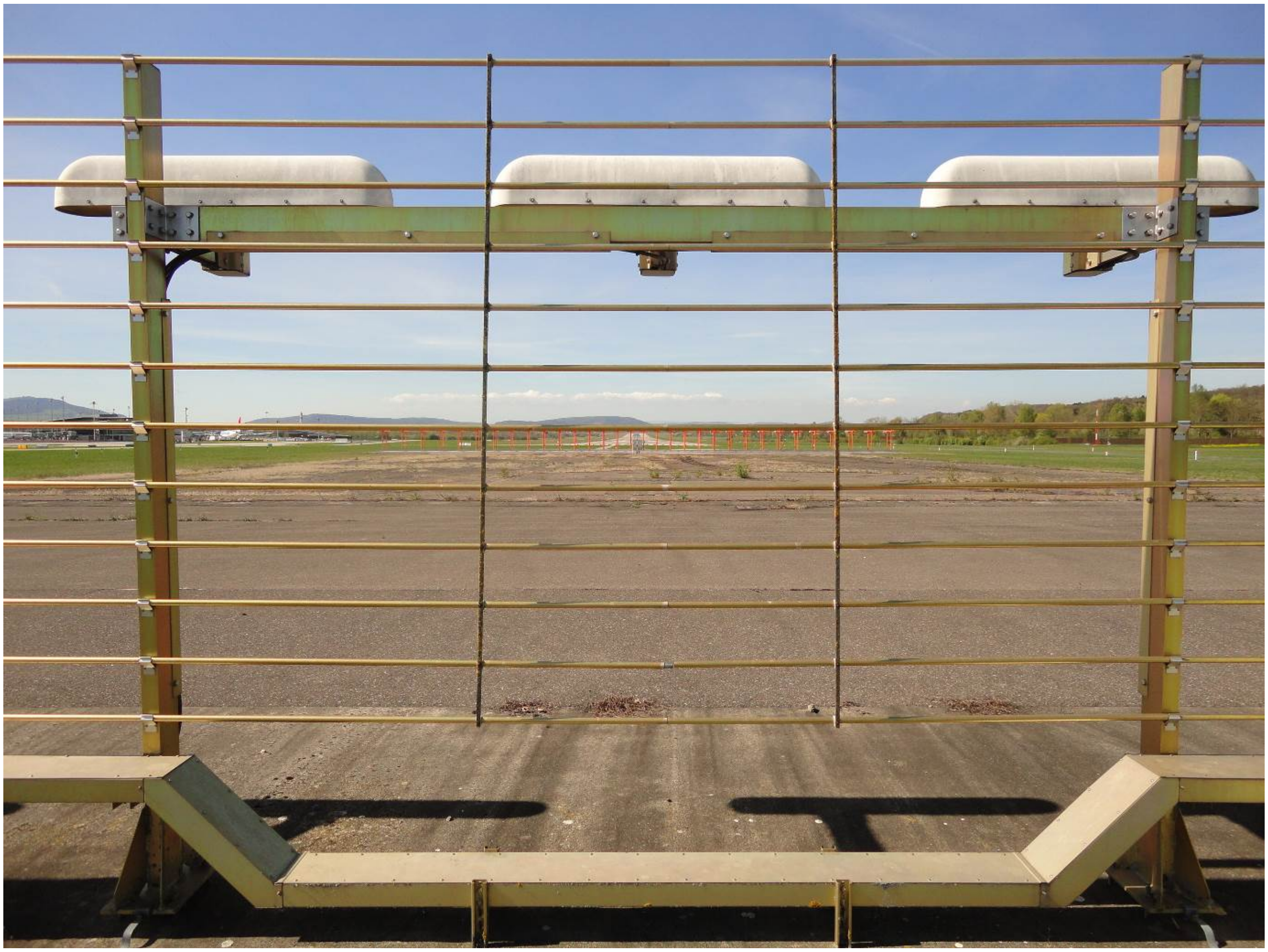

Figure 15 Picture of the current LOC and the NM 7232A, seen from behind

Figure 16 and Figure 17 show the non-impact of the new
ILS on the current operating one.

Figure 16 Picture of the flight check from FCS, confirming the non-impact of the new ILS

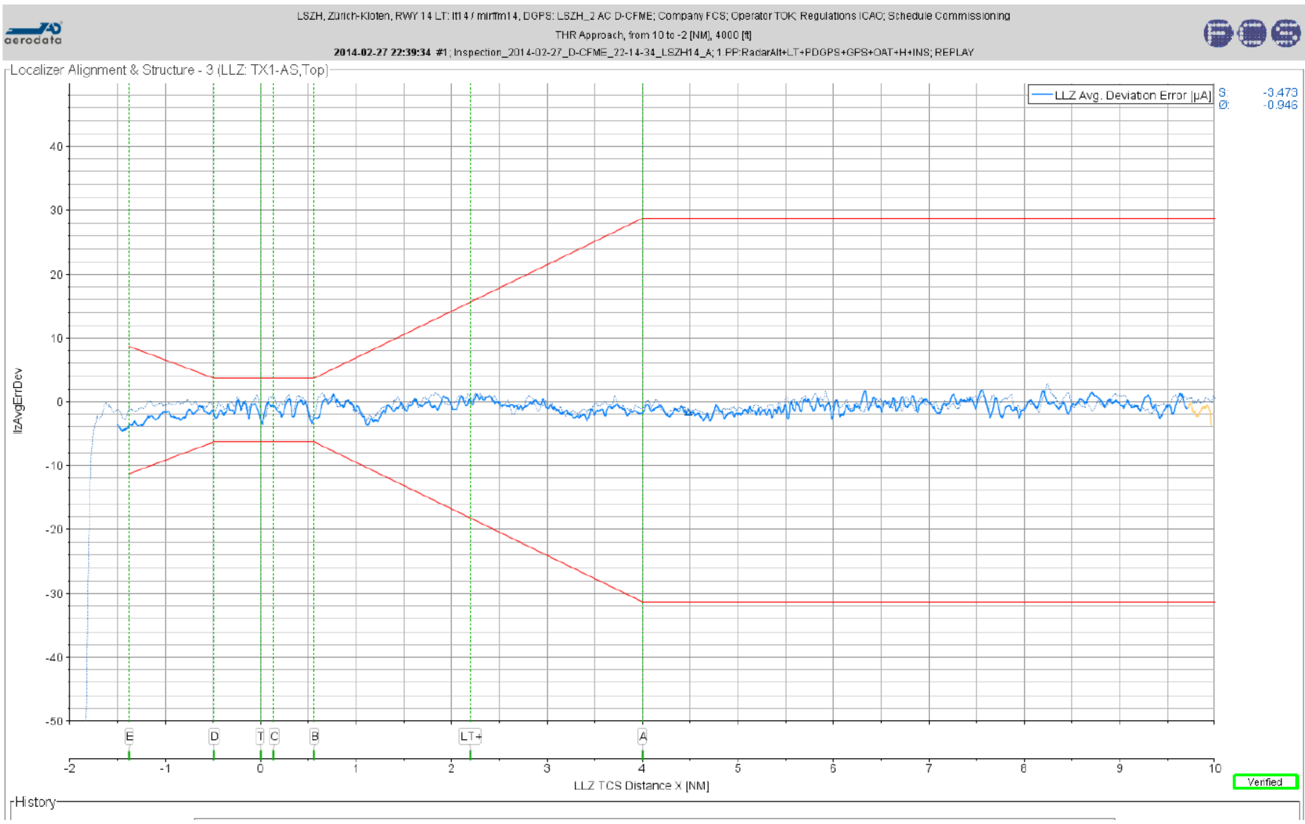

Figure 17 Current LOC 14 Course Structure: before and after the installation of the new LOC

Ground commissioning and measurements

Just after the completion of the installation of the new NM 7232A, the first part of the ground commissioning phase has been conducted. The following figures of the ground measurements illustrate the promising results, produced by the ILS Checker software. Figure 18 shows the DDM, SDM and RF Level azimuth profiles (coverage) at a distance of 1300 meters from the LOC.

They correlate very well with simulations. Besides, the deep analysis of these curves (Course only and Clearance only), illustrated by Figure 19, also correlates very well with theory. Finally, the antenna diagrams (Figure 20) measured on ground in the near field region fit also the expected / theoretical results.

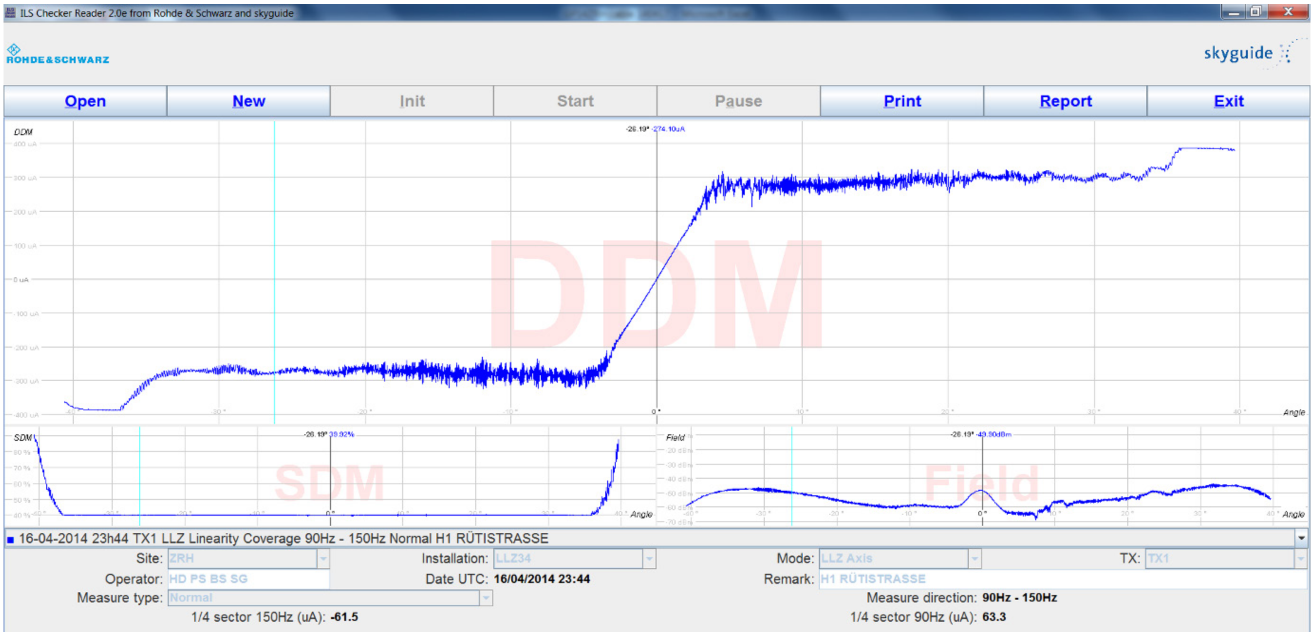

Figure 18 Ground measurements Course + Clearance in the near field (at a distance of 1300 from the LOC)

Figure 19 Ground measurements Course only (in pink) and Clearance only (in light blue) in the near field

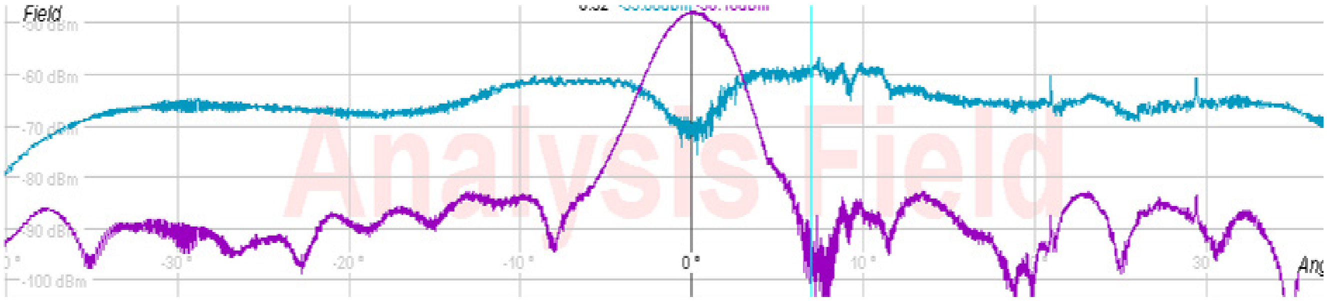

Figure 20 Ground measurements of the antenna diagrams Course only (in pink) and Clearance only (in light blue) in the near field

Commissioning flight check

As the date of writing this paper (April 2014) is prior to the commissioning flight check (June 2014), no flight check result can be shown in this version of the document. However, the presentation during IFIS will integrate the detailed analysis of the flight check results:

- Signal in space performance confirmation
- Correlation between simulations and flight measurements for DDM, SDM and antenna diagrams

CONCLUSIONS

Airport operations, especially for very large aircraft like the A380 and the B747-8, could be affected due to the size of the existing Localizer antenna systems ILS Critical and Sensitive Areas (CSA).

Indra Navia has designed an Ultra-wide Localizer antenna system, which has a significant smaller generic CSA. With advanced ELISE software, AIRBUS ProSky computed the optimized CSA of Zurich 14 runway taking into the specific airport environment. The association of the two competencies therefore results in less restriction on the air traffic and an increased traffic flow.

The NORMARC 7232A 32-element antenna system is now installed at Zurich Airport and supports the following technical validations:

- The results of the ELISE study clearly showed the operational benefits of the NORMARC 7232A 32-element ultra-wide Localizer antenna system
- An ILS replacement with nearly no service interruption (only 2.5 days) thanks to accurate and reliable simulations and flight check confirmation.
- The ground measurements correlate very well with the simulations, conducted in the frame of the feasibility study.
- Such good ground results are very encouraging for the coming commissioning flight check (in June 2014), which should confirm all the assumptions about signal in space performance and CSA.

REFERENCES

[1] ICAO, July 2006, International Standards and Recommended Practices, Annex 10 to the Convention on International Civil Aviation, Volume 1, Radio Navigation Aids, 6th Edition, Attachment C para. 2.1.9.1 http://www.icao.int

The Algorithm to Accurately Obtain the Glide Path Reference Point (Aiming Point) Elevation in Flight Inspection

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ABSTRACT

For the flight inspection of ILS Glide Path, the most difficult challenge is to correctly determine the Glide Path Reference Point (Commonly known as the Aiming Point) elevation by Automatic Flight Inspection System (AFIS).

Using the correct Glide Path reference point (Aiming Point) is critical to get correct results for the Glide Path structure, the Glide Path angle. The ILS Reference Datum Height (RDH), also referred to as TCH .

Some flight inspection agency use the base of the Glide Path antenna as Glide Path Reference Point (Aiming Point), which is a violation of ICAO Annex 10 definitions for ILS Glide Path. And some flight inspection agency use ground simulation supplemented by numerous flight inspection verification methods. The results determined by these two methods are often not satisfactory in practice.

Flight Inspection Center of China and BUAA have studied the related algorithm, and have been applied in CFIS fight inspection system (which is made by China). Using the algorithm, flight inspector can accurately obtain the Glide Path Reference Point (Aiming Point) elevation by only one approach, using this algorithm, On the one hand it can get the accurate Glide Path Reference Point (Aiming point) elevation result. On the other hand it can save the cost of flight inspection.

This article will publish the algorithm in this meeting, and show its actual effect in practice.

KEYWORDS

Flight Inspection, Glide Slope, Best Fit Straight Line, Glide Path Reference Point, Aiming Point.

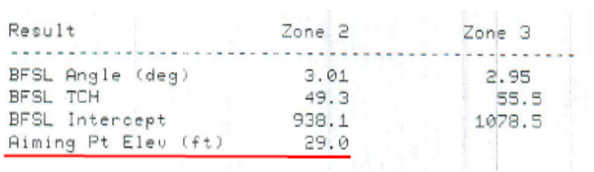
INTRODUCTION

The concept of Glide Path Reference Point (Aiming Point) is a very critical concept in flight inspection theories on Glide Slope of ILS, and has been widely used and adopted in the field of international flight inspection. We can find the detail description about aiming point concept on international standards and literature, like FAA 6750.16D, FAA 8240.47C, etc.

According the description from FAA 8240.47C: Aiming point is a location which is programmed into the automated flight inspection system (AFIS) from which glide path measurement results are referenced. The Aiming point may not be coincident with the Glide Slope origination point [1].

Usually, we call the optimal Aiming Point determined by flight inspection and use in facility database as Glide Path Reference Point. The elevation of the Glide Path Reference Point is usually an important data in facility database to involve in the calculation on the related parameter of Glide Path.

In fact, the concept of Aiming Point has been used for a long time in flight inspection field. As flight inspection technology advances, and AFIS system appears, it becomes increasingly important. As shown in Figure 1, it is a part of flight check drawings which printed from Sierra 9205 AFIS System (This system has been in service for over 20 years in China).



Result	Zone 2	Zone 3
BFSL Angle (deg)	3.01	2.95
BFSL TCH	49.3	55.5
BFSL Intercept	938.1	1078.5
Aiming Pt Elev (ft)	29.0	

Figure 1. Flight Inspection Drawings of AFIS Sierra 9205

The drawings shown in Figure 1 shows the data associated with BFSL (Best Fit Straight Line) result during Glide Slope flight inspection practice. We can see the data of Aiming Pt Elev (Aiming Point Elevation), the value is 29ft.

Why the data of Aiming Point Elevation appears in BFSL result? If Aiming Point Elevation is related to BFSL? To understand these questions, we need to understand how the data of Aiming Point Elevation is determined.

DETERMINATION OF AIMING POINT

As we know, for image Glide Slope antenna, the Glide Path zero DDM signal radiates as a "cone" with the top point at the base of the Glide Path antenna mast (As shown in Figure 2)[2].

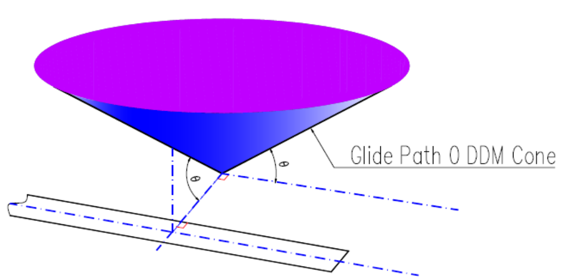


Figure 2. Glide Path zero DDM "cone"

Generally, the image glide path antennas are located on the side of the runway for safety reasons. So the actual Glide Path is formed as a vertical plane cut through the zero DDM "cone" along the runway centerline and its extension, eventually forming a hyperbolic shape of the Glide Path. (As shown in Figure 3)[3].

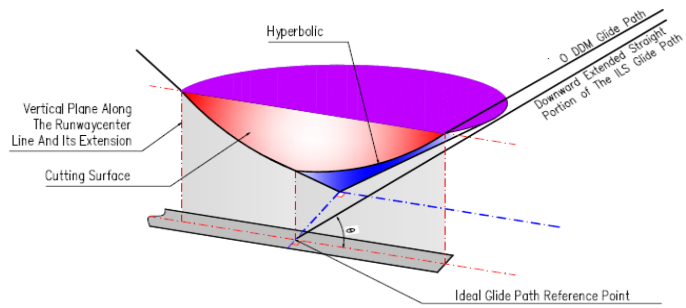


Figure 3. Formation Of Glide Path

Affected by factors such as reflection sites, obstructions, antenna, equipment commissioning status, in many cases, the Glide Path is not a smooth hyperbolic but a curve with bend, skew and roughness. Theoretically, we can not directly depend on the curve configuration to determine the data such as Glide Path angle in different segments, RDH and ARDH, etc. So we need to use linear approximation method to characterize the Glide Path. (As shown in Figure 4)[4]

In flight inspection theories, Best Fit Straight Line (BFSL) is used to characterize hyperbolic Glide Path. According the description from FAA 8240.47C: Best Fit Straight Line (BFSL) is a straight line segment of the Glide Path derived by using a least squares mathematical technique. The slope of this straight line defines the height of the Glide Path angle relative to the approach surface baseline and threshold.

Using Best Fit Straight Line (BFSL), AFIS can calculate some important data such as Glide Path Angle on ILS Zone2 and Zone3, RDH ARDH, and Aiming Point Elevation, etc. Flight inspectors often use these data to assess the quality of Glide Path.

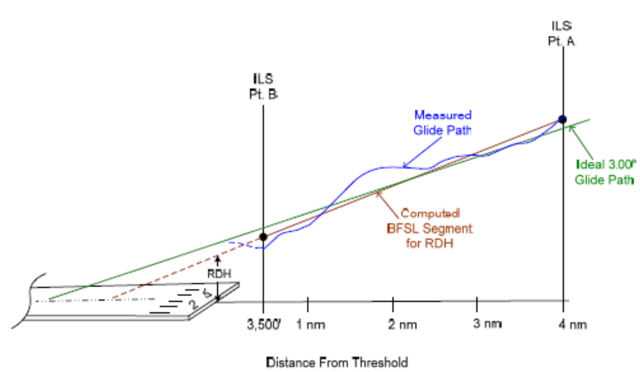


Figure 4. Best Fit Straight Line

Aiming Point is the product calculated by BFSL. Ideally, correct Aiming Point is a point on the runway, the Best Fit Straight Line (BFSL) is down toward extending through this point (As shown in Figure 5, Figure 6).

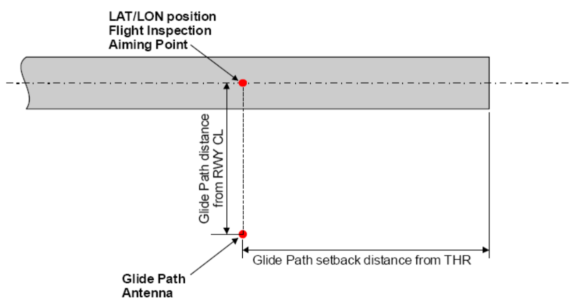


Figure 5. Aiming Point (Top View)

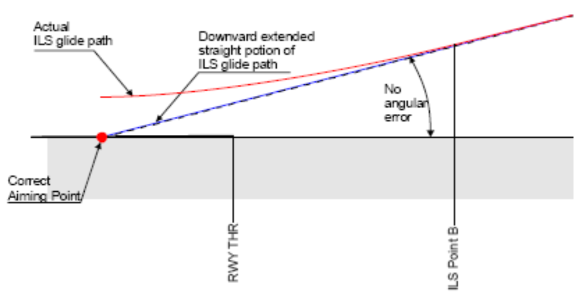


Figure 6. Ideal Aiming Point (Lateral view)

Since the Glide Path is not a smooth hyperbolic but a curve with bend, skew and roughness, the computed Best Fit Straight Line (BFSL) is often inconsistent with the ideal Glide Path or designed Glide Path. This will cause changes in the position of Aiming Point (As shown in Figure 7).

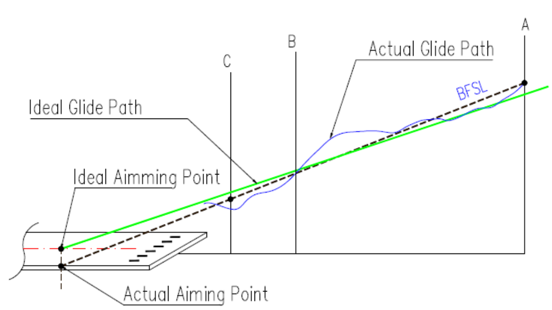


Figure 7. Best Fit Straight Line

As shown in Figure 8, the actual position of Aiming Point is below or above the theoretical position of the Aiming Point. So the Aiming Point is an intersection of BFSL and the plane which contains the base of the Glide Path antenna mast and perpendicular to the Runway centerline.

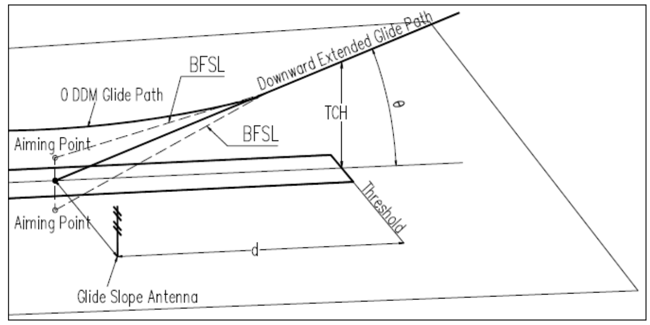


Figure 8. The Actual Aiming Point

THE PRACTICAL SIGNIFICANCE OF GLIDE PATH REFERENCE POINT (AIMING POINT)

From the above, we understand the concept of Aiming Point and Glide Path Reference Point, but what is the practical significance of Glide Path Reference Point (Aiming Point)?

In early 2012, a flight inspector from China Flight Inspection Center (CFIC) was sent to the Duncan Aviation Inc. in Nebraska, United States, for the acceptance of modification on new flight inspection aircraft. In acceptance process, flight inspector used CFIS flight inspection system to carry out a series of tests to verify the effect on Glide Path which caused by change of Glide Path Reference Point (Aiming Point).

In the tests, flight inspector respectively used 362.38 m, 366.19 m and 363.54m as the elevation of Glide Path Reference Point (Aiming Point) in ILS facility data base, and run three approaches along the Glide Path of 05#ILS in Lincoln airport, and got the results and Glide Path Deviation Error curve as below.

Figure 9. Results And Glide Path Deviation Error Curve Using 362.38m as Glide Path Reference Point Elevation

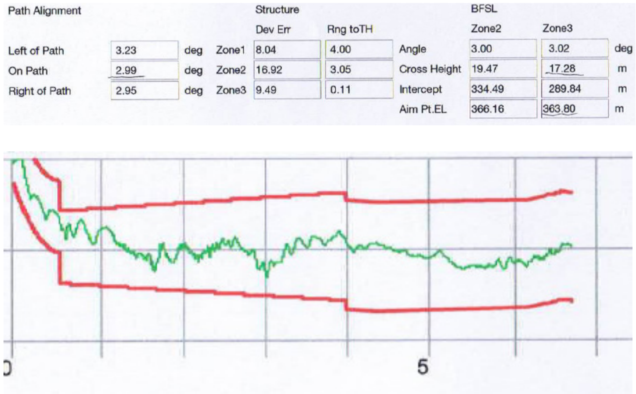


Figure 10. Results And Glide Path Deviation Error Curve Using 366.19m as Glide Path Reference Point Elevation

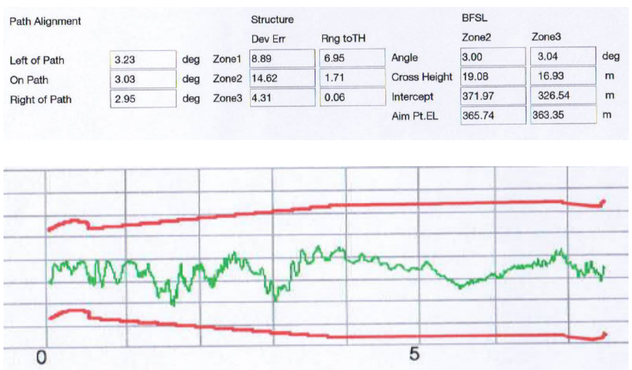


Figure 11. Results And Glide Path Deviation Error Curve Using 363.54m as Glide Path Reference Point Elevation

From Figure 9, we can see the Glide Path Deviation Error Curve present bend downward shape. From Figure 10, the Glide Path Deviation Error Curve present bend upward shape. From Figure 11, the Glide Path Deviation Error Curve tends to be straight.

Table 1 is an important data summary of Figures 9, 10, and 11. From Table 1, we can see: with changes on Glide Path Reference Point (Aiming Point) elevation, the Glide Path results such as Glide Path angle, structure, RDH and ARDH changed accordingly. In particular, significant changes occurred in the value of Glide Path angle, and structure.

Seen from above, the data of Glide Path Reference Point (Aiming Point) elevation will produce significant impact on flight inspection results of Glide Path. If we use incorrect Glide Path Reference Point (Aiming Point) elevation in flight inspection database, we will get incorrect flight inspection results of Glide Path. In severe cases, it may lead to erroneous conclusion which made by flight inspector for assessing the quality of Glide Path.

Table 1. The Glide Path Results under different Glide Path Reference Point elevation

Glide Path Reference Point Elevation (m)	362.38	366.19	363.53
Glide path Angle(°)	3.05	2.99	3.03
Structure Zone1(μA)	11	8	9
Structure Zone2(μA)	15	17	15
Structure Zone3(μA)	19	9	4
RDH (m)	19.49	19.47	19.08
ARDH (m)	17.09	17.26	16.93

In addition, the elevation of Glide Path Reference Point (Aiming Point) in facility database is used as a necessary known data to calculate the Best Fit Straight Line (BFSL) by using a least squares mathematical method. The calculation results of Best Fit Straight Line (BFSL) will be directly affected by correctness of Glide Path Reference Point (Aiming Point).

CURRENT METHODS TO DETERMINE GLIDE PATH REFERENCE POINT (AIMING POINT) ELEVATION

Currently, there are two methods to obtain the Glide Path Reference Point (Aiming Point) elevation.

One method is to use the base elevation of Glide Path antenna mast as the original Glide Path Reference Point elevation in ILS facility database. In commissioning flight inspection of ILS, flight inspector will continually correct the elevation of Glide Path Reference Point (Aiming Point) in facility database, until the acceptable glide path data and curves are obtained. The final elevation determined by flight inspector may be different with the original Glide Path Reference Point elevation, and will be used in periodic flight inspection in the future. Using this method, it largely relies on individual's technical ability and experience of flight inspector, and will spend more flight inspection costs.

Some flight inspection agency directly using the base elevation of the Glide Path antenna as Glide Path Reference Point (Aiming Point) elevation in commissioning and periodic flight inspection practices is not correct and is a violation of ICAO Annex 10 definitions for ILS Glide Path.

Another method is prior to actual flight inspection using ground simulation software to calculate the original Glide

Path Reference Point (Aiming Point) elevation. In actual flight inspection, flight inspector need to adjust the Glide Path Reference Point (Aiming Point) elevation until obtaining ideal glide path data and curves in flight inspection. This method can improve the accuracy and cost savings to a certain extent.

Due to the difference between ground simulation and actual flight inspection conditions, the acquisition of ideal Glide Path Reference Point elevation still relies on individual's technical ability and experience of flight inspector; The result is still not precise enough; In special cases, this method can not save the cost of flight inspection.

So it is significant to find a method to automatically calculated by AFIS, with high accuracy, and not relying on ability experience of flight inspector.

ALGORITHM

The flight inspection engineers from China Flight Inspection Center together with the software engineers from BUAA have found a method to accurately determine the Glide Path Reference Point (Aiming Point), which is called as "straighten method".

The algorithm of "straighten method" is based on the "square sum of deviations" and "arithmetic iteration".

As previously mentioned, the Glide Path Reference Point (Aiming Point) in facility database is used as a necessary known data for the calculation of Glide Slope parameters. Different Glide Path Reference Point (Aiming Point) in facility database will result in different inspection results, especially for the glide path angle, structure, RDH or ARDH which are calculated by BFSL.

From above, we know, the Best Fit Straight Line (BFSL) is used to characterize the actual Glide Path. Since different Glide Path Reference Point (Aiming Point) in facility database may result in different Best Fit Straight Line (BFSL), then which BFSL is correct and has the best fit of the actual Glide Path?

We think if we can find a Glide Path Reference Point which can make the square sum of deviations for Glide Slope deviation error data tends to be minimum, then we can determine a correct Best Fit Straight Line (BFSL).

In summary, the algorithm will be carried out by the following steps:

1. Flight inspection aircraft approach along the Glide path. Flight inspection system gather the Glide Slope deviation data , combine with precise positioning data and get the data of Glide Slope Deviation Error.

2. After a flight inspection approach, an iteration scope and interval should be set based on the Glide Path Reference Point (Aiming Point) information in facility Data.

3. Flight inspection system automatically iterates the Glide Path Reference Point (Aiming Point) elevation in facility Data in accordance with a predetermined iteration scope and interval, and continually calculates the corresponding the sum of squares of data of Glide Slope deviation error from zone2 to zone3.

4. Square sum of deviations will be:

$$S^2 = \frac{\sum_{i=1}^{n}(X_i - \bar{X})^2}{n-1}$$

Where the X represents the Glide Slope deviation error sample value;

$\bar{X}$ represents mean value of X;

n represents the sample number;

S represents square sum of Glide Slope deviation error.

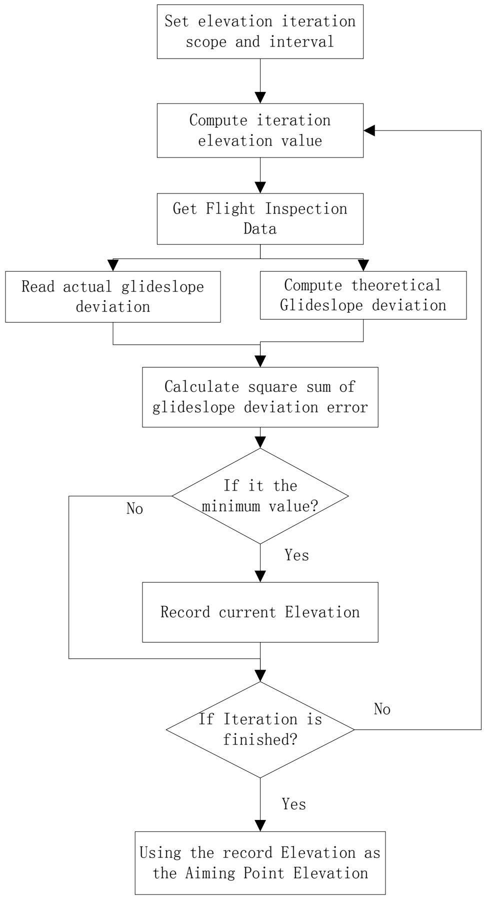


Figure 12. the algorithm flow chart

5. Flight inspection system automatically compare all the data of square sum of deviations and determine the minimum value of square sum of deviations.

6. The related Glide Path Reference Point elevation which make square sum of deviations minimum is the optimal elevation which will be used to calculate the correct Best Fit Straight Line (BFSL).

The detail flow-process diagram is shown as Figure 12

EXAMPLES OF APPLICATION OF THE ALGORITHM

In September 2012, Flight Inspection aircraft B-9300 equipped with CFIS system executed 17L ILS (category III) flight inspection mission in Shanghai PUDONG International Airport.

The elevation of Glide Path Reference Point in facility database is 4.07m. After a low pass approach ,we set the elevation iteration scope as ±5m (i.e. 4.07m-5m to 4.07m+5m) and the interval as 0.1 m(as shown on figure 13), then we calculated the optimal elevation of Glide Path Reference Point elevation , which is 6.07m.

During this procedure, 100 times calculation of square sum were done automatically by the flight inspection software.

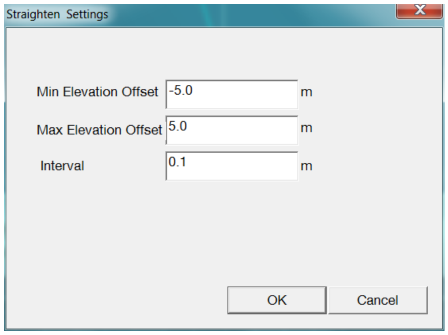


Figure 13. Iteration scope and interval select window

Figure 14 shows the relationship between elevation of Glide Path Reference Point and the square sum of the Glide Slope deviation error, from which the best elevation can be seen clearly.

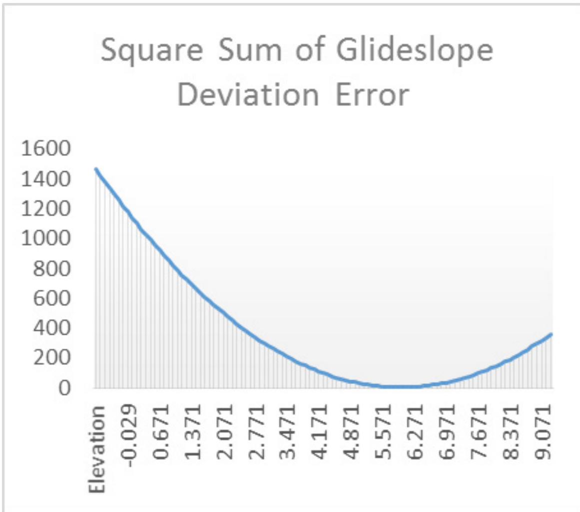


Figure 14. Square sum vs Aiming Point Elevation

Let us look at the effect of "straighten method" in flight inspection practices.

Figure 15 shows the actual Glide Path deviation error curve and results when the original Glide Path Reference Point elevation is 4.07m in facility database. We can see the actual Glide Path deviation curve presents bend downward shape.

Glide Path Reference Point Elevation (m)	4.07	6.07
Glide path Angle(°)	2.97	2.95
Structure Zone1(μA)	1	3
Structure Zone2(μA)	11	3
Structure Zone3(μA)	14	7

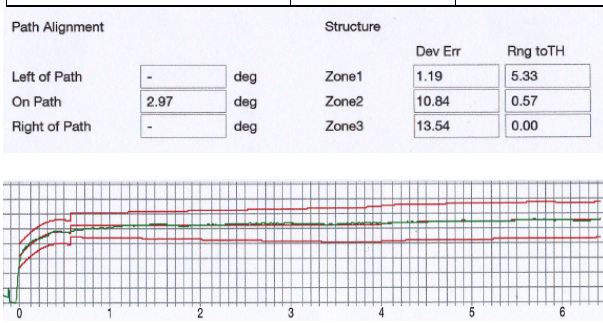


Figure 15. Results And Glide Path Deviation Error Curve Using 4.07m as Glide Path Reference Point Elevation (17L ILS Of PUDONG Airport)

Using "straighten method", CFIS calculated the Glide Path Reference Point elevation, the value is 6.07m. Flight inspector corrected the Glide Path Reference Point elevation to 6.07m in facility database.

Figure 16 shows the actual Glide Path deviation error curve and results when Glide Path Reference Point elevation in facility database change to 6.07m.We can see the actual Glide Path deviation curve has been made a great improvement. The curve presents ideal straight shape.

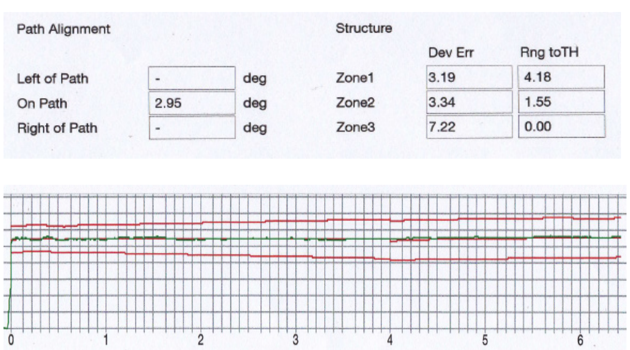


Figure 16. Results And Glide Path Deviation Error Curve Using 6.07m as Glide Path Reference Point Elevation (17L ILS Of PUDONG Airport).

Table 2 shows the comparison between the result of Glide Path shown on figure15 and figure16.we can see it is made a great improvement in structure of Glide Path.

Table 2 The comparison Between The Result Of Glide Path shown on figure15 and figure 16

From the above, using "straighten method" can accurately obtain elevation of Glide Path Reference Point, and can improve results of Glide Path significantly.

APPLICATION OF ALGORITHM

This algorithm can bring the flight inspector great convenience.

1. Using this algorithm can accurately obtain the elevation of Glide Path Reference Point in commissioning and periodic flight inspection practices ;

2. Using this algorithm can obtain the ideal Best Fit Straight Line which have consistent with actual glide path and obtain the correct result of Glide Path.

3. Using this algorithm can find the problems caused by incorrect determination of Glide Path Reference Point , such as the Glide Path angle is not correct, structure is out of tolerance, RDH or ARDH is out of tolerance, the shape of Glide Path deviation error curve occurs serious curved upward or downward, etc.

For example Figure 17 shows flight inspection drawings of 02#ILS in LIJIANG airport, southwest china. The elevation of original Glide Path Reference Point is 2226.3m.

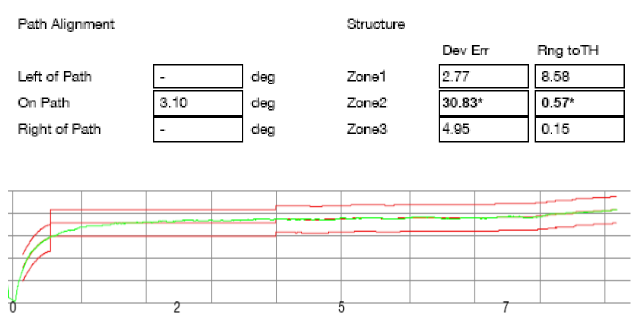


Figure 17. Results And Glide Path Deviation Error Curve Using 2226.3m as Glide Path Reference Point Elevation (02# ILS Of LIJIANG Airport).

From drawings, we can see the Glide Slope deviation error curve bend downward severely and the structure of ZONE 2 is out of tolerance. Maintenance staff considered it maybe have some trouble happened on equipment of Glide Slope or reflection site. But after using "straighten method", flight inspector obtained the elevation of Glide Path Reference Point is 2230.6m. After recalculating the Glide Slope deviation error curve and flight inspection results(shown as Figure 18), we can see all the flight inspection results and configure of curve are particularly satisfying, it is obvious that the reason resulted in problems is due to incorrect Glide Path Reference Point in facility database.

Path Alignment			Structure	Dev Err	Rng toTH
Left of Path	-	deg	Zone1	2.64	8.58
On Path	3.02	deg	Zone2	4.53	0.63
Right of Path	-	deg	Zone3	2.12	0.16

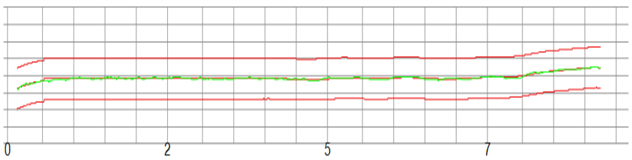


Figure 18. Results And Glide Path Deviation Error Curve Using 2230.6m as Glide Path Reference Point Elevation (02# ILS Of LIJIANG Airport).

4. Using this algorithm can provide guidance for equipment commissioning installation and parameters adjustment on periodic, such as the installation of Glide Slope antenna, phase adjustment on Glide Slope equipment.

CONCLUSION

Glide Path Reference Point (Aiming Point) elevation is a critical parameter for ILS Glide slope flight inspection and it is very difficult to be determined exactly.

The straighten method based on iterative calculation only needs one approach run to determine the Glide Path Reference Point (Aiming Point) elevation. Using this method, amount of problems happened on Glide Path have been solved in flight inspection practice. It is proved that the algorithm is accurate and effective.

This algorithm overcomes the shortcomings of existing methods to determine the Glide Path Reference Point (Aiming Point) elevation, and significant cost of ILS flight inspection can be saved in practice.

We hope this algorithm can be promoted, and constantly be improved, and hope this algorithm may solve more practical problems in international flight inspection field.

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Strategies for Accurate Field Strength Measurement

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ABSTRACT

The measurement of field strength to assess navigation aid signal coverage is one of the most challenging tasks faced by flight inspection organizations. An absolute accuracy goal of 3 dB is typically set, but in practice is extremely difficult to achieve. If ground reflections are not properly controlled when calibrating aircraft antennas, errors in excess of this target can be introduced. Furthermore, the gain patterns of aircraft antennas are far from omnidirectional; failure to account for this in flight can result in a further inaccuracy of several dB.

NAV CANADA has commissioned mathematical models to describe the antenna patterns on its aircraft. These models are being employed to develop and implement improvements to the ground calibration methodology to minimize errors. They are also being used to correct antenna gains as a function of aircraft attitude and the horizontal and vertical angles to navigation aids.

This paper describes these initiatives and their effect on RF measurement accuracy.

INTRODUCTION

ICAO requires flight inspection organizations to verify minimum navigation aid field strengths at specified locations. For example, Annex 10[1] requires a field strength of 40 µV/m for localizers and 90 µV/m for VORs at the limit of operational coverage.

Two challenges face us:

1. to convert measured power data, usually in terms of dBm into a 50-ohm device, to an electrical field strength;
2. to do #1 as accurately as possible.

Most of us strive for a target of ±3 dB for these measurements[1], and that's certainly a noble goal.

However, I maintain that the flight inspection community isn't achieving anywhere close to this. Depending on how we do our antenna calibrations and compute our field strengths, the errors could be in the 6-8 dB range. We perform calibrations and are quite pleased when we achieve antenna factor[2] repeatability of a couple of dB, but accurately measuring the absolute magnitude of a signal in the air is another matter.

The unfortunate reality is that few of us realize how badly we're doing. Or, maybe we suspect that we're falling short of the mark but don't admit it. In this paper, I look at a couple of significant sources of error and share some of the strategies that we at NAV CANADA are implementing to address them.

THE ANTENNA GAIN PROBLEM

The primary issue that affects accuracy is the gain pattern of the antennas on flight inspection aircraft. The response of the antenna in a given direction is influenced by nearby structures, e.g. wings, fuselage, engines, and control surfaces. The resulting directionality – which is often quite complex – manifests itself in two ways: first, errors in the ground calibration; and second, errors in power measurements as a result of aircraft attitude and position relative to the navigation aid.

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[1] 3 dB is the uncertainty specified in Doc 8071[2] for coverage (field strength) measurements.

[2] Antenna factors are essentially measures of gain, where a higher factor implies a lower gain. Their unit is dB/m.

Effect of Antenna Gain on Calibration

Let's start by looking at the calibration of the aircraft antennas. For simplicity and cost control, many of us use the ground substitution method: one generates an RF field, measures it using a calibrated reference antenna, positions the aircraft so that its antenna of interest is situated in the same place previously occupied by the reference antenna, and then measures the signal received by the aircraft antenna. From the two power measurements and the reference antenna gain, one can calculate the gain of the aircraft antenna. Typically, the same procedure is repeated with the aircraft aligned to give antenna factors in the forward, aft, port, and starboard orientations.

However, this relatively straightforward procedure and calculation is complicated by the fact that the field that we're measuring is composed of the sum of the direct signal and that reflected off the ground. Our studies have shown that the latter is only a couple of dB lower than the direct; clearly its effect cannot be ignored.

For most reference antennas, there is no appreciable difference in gain between the horizontal and the relatively small (6-12°) vertical angles at which the reflected signal arrives. Thus, the response to the direct and reflected signals will be essentially equal (see Figure).

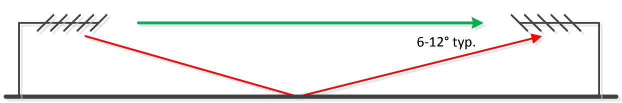

Figure 1 – Direct and Reflected Signals During Calibration

Provided that the behaviour of the antennas mounted on aircraft is similar, we may expect to compute the antenna factor accurately. Unfortunately, this is not the case. We have obtained 3-D simulation models for the gain patterns of the antennas on our flight inspection fleet, and validated them by cross-checks against anechoic chamber measurements using scale models of the aircraft. The models show significant gain variation across a small range of vertical angles above and below the horizon[3].

As an example, consider the tail-mounted VOR/LOC antenna on one of our aircraft, used for most field strength measurements on ILS and VOR. Its vertical pattern is shown in Figure 2. In the forward direction, the gain can be seen to roll off at a rate of approximately 0.8 dB per degree as the vertical angle decreases from the horizontal. (The different lines on the plot are for various yaw angles.)

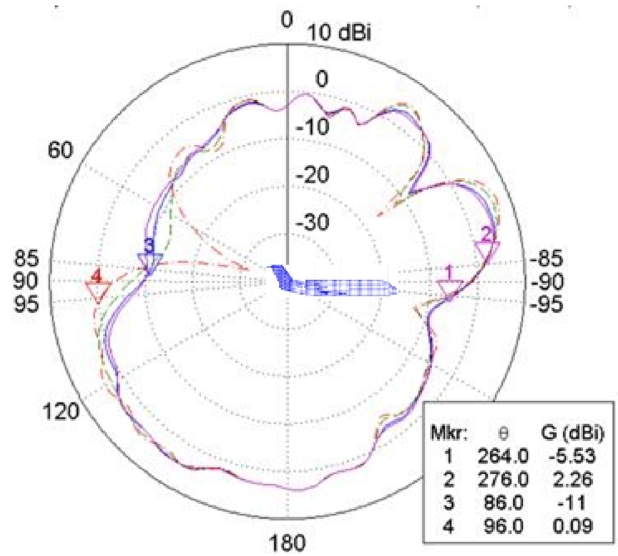

Figure 2 - ILS/VOR Tail Antenna Pattern (113 MHz)[3]

Revisiting the ground calibration, and referring now to Figure 3, we see that the substitution method is no longer valid, since the response to the reflected signal arriving from below is different from the response to the direct (horizontal) signal.

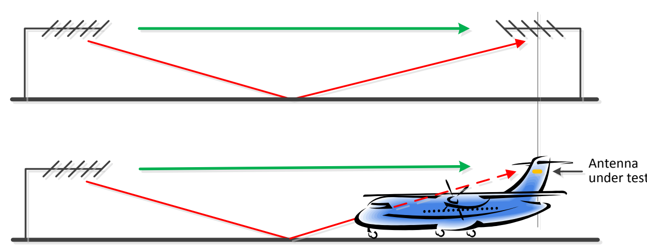

Figure 3 – Effect of Antenna Pattern on Calibration Factors

When the aircraft is in flight, ground reflections still occur, but the direct and reflected paths are so very nearly parallel that the aircraft sees what appears to be a single signal from a point source.

To get an idea of the magnitude of this effect, consider a range set up to calibrate the tail antenna referred to in Figure 2 in the forward direction. The transmit and

[3] Variations in gain also occur for non-zero roll and yaw angles, but the effect in the vertical is of greatest interest to antenna calibration.

reference antennas are set to the same height as the antenna on the aircraft: 4.95 m. The distance between the transmit and receive antennas is somewhat arbitrarily selected to be 45.5 m. At mid-band (113 MHz), the direct and reflected signals arrive at the measurement point 325° out of phase, and the reflected signal arrives at the receive antenna at an upward angle of 12°. (Basic geometry is used to calculate the path lengths of the direct and reflected signals while making the assumption that the incident and reflected angle are the same. We then convert their difference to degrees of phase at the selected frequency, keeping in mind that the signal undergoes a 180° phase reversal upon reflection.)

For this phase relationship, and assuming that the ground signal is 2 dB less than the direct (this was validated experimentally), the interference between them is constructive, and by vector addition we can determine that the combined signal is 1.9 dB higher than the direct signal alone. This is the level that we would measure with the reference antenna.

However, the aircraft antenna gain at a vertical angle of -12° is about 10 dB less than in the horizontal; the reflected signal will be attenuated by this amount. The effect is that the aircraft antenna is now in a field that is only 0.2 dB higher than if there had been no ground-reflected signal. The difference between the two pairs of combined signals will result in an antenna factor that is 1.7 dB too high, and all subsequent field strength measurements will therefore be in error by this amount.

So how do we deal with this? The best way would be to eliminate the reflected signal altogether. We put some effort into exploring this option by constructing a fence measuring 5 x 1.8 metres out of ABS pipe, covering it with wire mesh having 25-mm hexagonal holes, and placing it between the transmit antenna and the measurement area. It was supposed to scatter the reflected signal while allowing the direct one to pass unaffected over the top. However, in spite of several design evolutions, it had no discernable effect in the VHF band and seemed to act as a re-radiator in the glide path band. Nevertheless, we believe that the fence concept still has merit and warrants further investigation.

In the meantime, we decided that if we couldn't prevent the reflection from the ground, we might be able to manage it by manipulating the phase relationship between the direct and reflected signals so that the amplitude of their sum was the same as the direct signal alone. Thus, while the reflected signal still existed, it wouldn't affect the measured amplitude of the combined field. It was determined that a phase difference of 252° would accomplish this. For the antenna height on our aircraft, this would require the aircraft to be situated 91 metres from the transmit antenna for a frequency of 113 MHz. Unfortunately, the size of our test range did not permit this, and we were limited to a distance of 85 metres.

Theoretically, this would result in a phase difference of 257° and a field 0.2 dB greater in amplitude than the direct signal alone. The incident and reflected angle would be 6.6°, and from Figure 2 we can see that the reflected signal is attenuated a further 3.7 dB as a result of the vertical pattern of the antenna. Recomputing, we determine that that combined signal that the aircraft antenna sees is 0.1 dB weaker than it would have been had there been no reflected signal. Thus, the resulting antenna factor, although still in error by 0.3 dB (partly because of our distance limitation), has improved from the 1.7 dB error that resulted from ignoring the effect of the reflection and antenna pattern entirely. (The next time we perform calibrations, we'll ensure that the equipment is set up to avoid space constraints.)

Effect of Gain Pattern on Airborne Measurements

We have now considered the effect of the ground reflection and gain pattern on the basic antenna factor computed during ground calibration. Of equal importance is how the same gain pattern affects airborne field strength measurements.

Ground calibrations are typically done with a zero-degree elevation angle, i.e. the signal arrives at the aircraft antenna on the horizontal. However, this is seldom the situation encountered during normal flight inspection operations.

For most ILS inspection runs, the vertical angle is approximately three degrees below the horizon. For a VOR used for an instrument approach, this figure may be even greater.

Consider one of our CRJ aircraft confirming the Minimum Enroute Altitude (MEA) on an airway where the vertical angle to the VOR is one degree down. The CRJ level-flight pitch is approximately 1.7° nose up. Thus, the combined vertical angle is around 2.7° below the horizon when flying inbound, resulting in a measured field strength 2.2 dB too low. By a similar logic, we can see that the measurement will be about 1.1 dB too high when travelling outbound[4] (refer again to Figure 2[5]). These differences will be more pronounced as the vertical angle to the facility increases negatively.

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[4] This is why we have observed different results depending on which direction we were flying.

[5] It's likely difficult to see in black-and-white, but the trace with the "4" marker on it corresponds to a yaw angle of 0°.

If we're lucky, the calibration and attitude errors will cancel; more likely, though, these two issues alone could cause inaccuracies in our field strength measurements that exceed our target tolerance.

Evaluation of the New Techniques

The final consideration in this paper is to assess how well we have understood the issues, and whether our modified calibration technique and antenna model will improve the accuracy of our data.

We flew one of our aircraft past a specific point on a VOR airway, inbound and outbound, and measured the received signal. The vertical angle to the VOR was -2.0°, and the pitch angle was maintained at 0.1° or less. The raw received power was -63.8 dBm inbound and -65.5 dBm outbound.

To determine if these figures are reasonable, we need to estimate the gains in the forward and aft directions for a vertical angle of -2°, at 115.5 MHz, the frequency of the VOR of interest. We refer to Figure 2 and Figure 4 and interpolate for the desired frequency.

Frequency	Rel Gain, Fwd	Rel Gain, Aft
113 MHz	-2.9 dB	-2.8 dB
118 MHz	-2.8 dB	-6.1 dB
115.5 MHz	-2.9 dB	-4.5 dB

Thus, we should expect the raw signal strength outbound to be about 1.6 dB lower than inbound, which agrees well with the 1.7 dB observed. Thus, if we were to incorporate corrections in flight to the signal amplitude as a function of the vertical angle, we would compute the same field strength regardless of the direction of flight, as we should expect from a flight inspection system.

Next, we consider a wider range of vertical angles by varying the pitch of the aircraft during flight. Figure 5 shows a few seconds of flight on an outbound radial from the same VOR, during which the aircraft pitch moves from 5° nose down to 7° nose up. The vertical angle to the VOR remains at -2°; the sum of this and the pitch angle is shown in the "Total Vert Angle" trace. The raw RF power can be seen to decrease as the combined vertical angle increases.

Taking two points, where the vertical angle is -5 and +5 degrees (20.05 NM and 20.35 NM, respectively), and again referring to Figure 2 and Figure 4, we have relative gains as follows:

Freq	113 MHz	118 MHz	115.5 MHz
Gain -5°	-0.6 dB	-4.4 dB	-2.5 dB
Gain +5°	-10.0 dB	-6.9 dB	-8.5 dB
Delta Gain	--	--	6 dB

Thus, the measured power is expected to decrease by 6 dB as the vertical angle increases from -5° to +5°. The actual measured values are -63 and -71 dBm, for a difference of 8 dB, comparing reasonably (although not perfectly) with the expected figure.

Finally, we compare actual antenna factors from a recent ground calibration with values from the polar plots of gain.

Frequency	AF, Fwd	AF, Aft	Delta
113 MHz	31.6	32.3	-0.7 dB
118 MHz	31.7	37.6	-5.9 dB

Frequency	Rel Gain, Fwd	Rel Gain, Aft	Delta
113 MHz	-1.5 dB	-3.5 dB	-2.0 dB
118 MHz	-1.5 dB	-8.6 dB	-7.1 dB

The differences agree within slightly over 1 dB, which gives us a measure of confidence in both the calibration technique and the antenna model[6].

[6] It should be noted that the problem of ground reflection is not resolved by the management of phase for this aircraft in the aft direction (see General Observations). Thus, some error in the aft antenna factor remains.

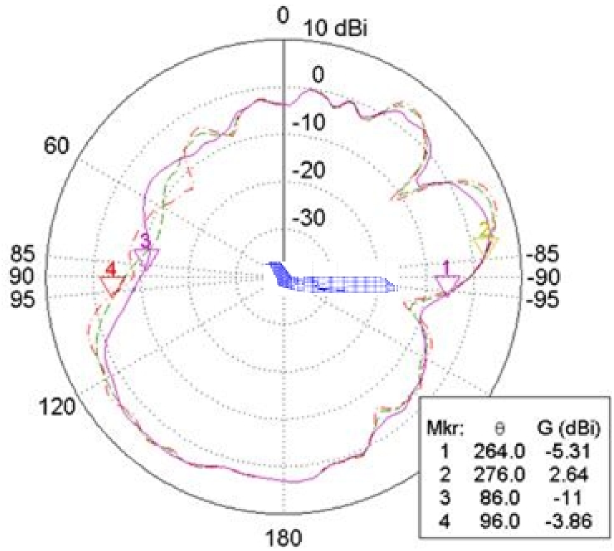

Figure 4 - ILS/VOR Tail Antenna Pattern (118 MHz)

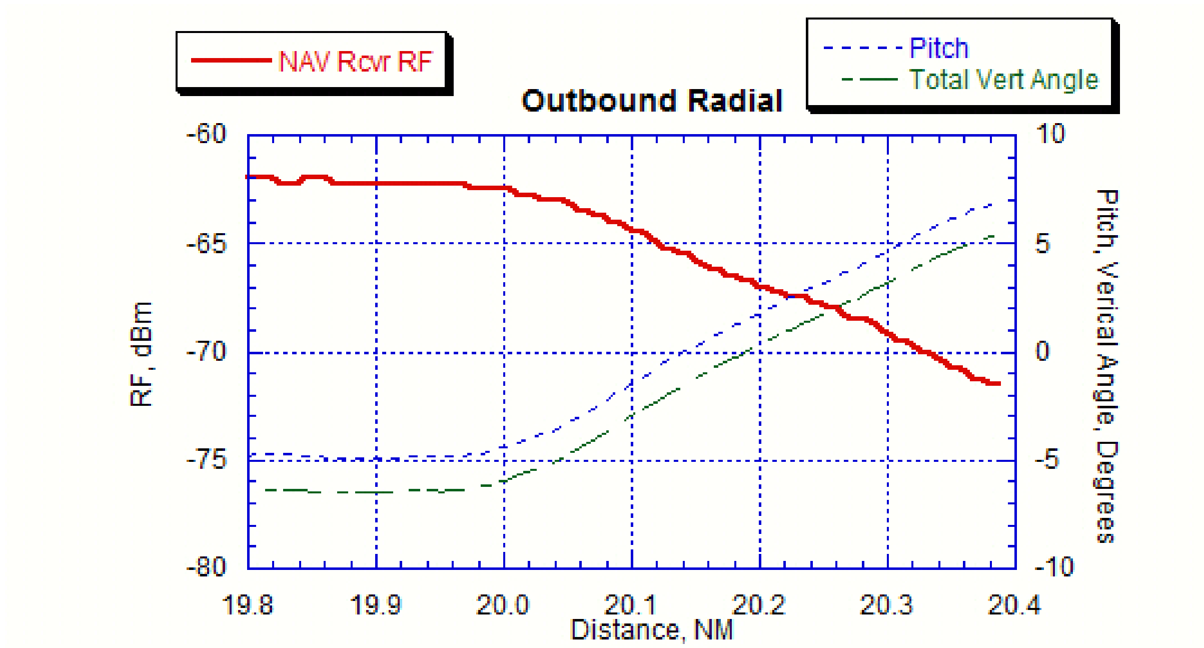

Figure 5 – Variation of Received RF with Vertical Angle

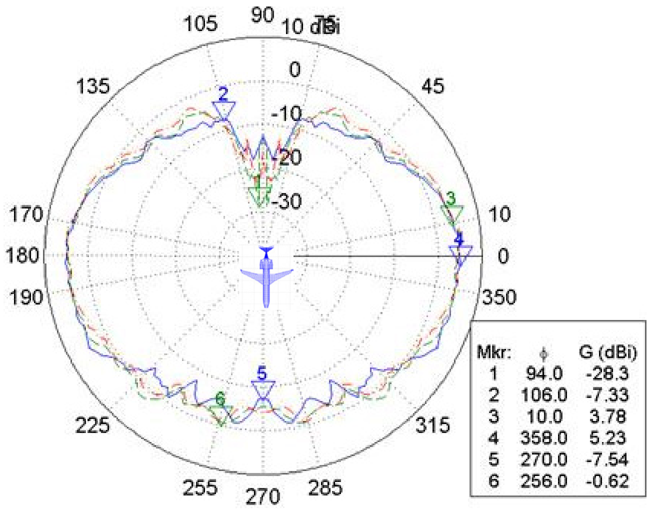

Figure 6 - GP Tail Antenna Pattern (329 MHz)

GENERAL OBSERVATIONS

- Sources of error associated with these techniques include:
  - Actual ground reflection coefficients. These can be estimated empirically by making field strength measurements over a range of phase shifts by varying the height of the transmit or reference antenna. However, once the reflected signal is attenuated by more than a few dB, the amplitude of the combined signal is relatively insensitive to further reductions;
  - Geometry. Generally, antenna calibrations are done by sweeping a signal generator across the band of interest. Selection of antenna heights and separation will only yield the desired result at one frequency at a time. A certain error will be introduced as one moves away from that frequency unless the geometry is readjusted;
  - Limited data points. Our antenna models were computed for edge and mid-band frequencies and a limited number of pitch-roll-yaw combinations. Some of the plots show significant discontinuities with the change of a single variable, making interpolation less than ideal.
- We briefly considered the possibility of making glide path field strength measurements while flying outbound from the facility as well as inbound, thinking that we might gain some flight efficiency. However, the model (see Figure 6) showed a very erratic response aft. Since this instability made it unlikely that we would obtain accurate measurements, we abandoned this concept in favour of one where we collect RF data during an arc, where the response is much cleaner;
- Note that the strategy for managing ground calibrations by manipulating their relative phase is valid only when the aircraft antenna gain in the direction in which the reflected signal arrives is less than the gain in the horizontal (direct) direction. Otherwise, the resulting antenna factor would in fact represent the gain in the below-horizon direction. Calibration in the aft orientation is an example where this would not work (refer again to Figure 2); further pursuit of the fence concept is warranted;
- Compensation for antenna response must also be made to account for non-horizontal incident angles. Yaw has a similar effect (when crabbing into the wind, for example) but was not addressed specifically in this paper;

CONCLUSIONS

a. Flight inspection organizations are likely not achieving the desired 3 dB absolute accuracy for field strength measurements;

b. Without proper design to manage reflected signals, antenna factors obtained on the ground using the substitution method can be erroneous;

c. If compensation is not made for the response of the aircraft antenna in the horizontal and vertical planes, airborne measurements of field strength will be inaccurate.

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IFIS 2014

Flight Plan to Innovation

Session 4
Flight Validation and Related Concepts

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Verification of Final Approach Segment Data Prior to SBAS Flight Inspection

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ABSTRACT

Precision Satellite Based Augmentation Systems (SBAS) inflight procedures are becoming a vital part of our everyday aviation lives. Precision inflight SBAS procedures consist of multiple data points that help an aircraft navigate from one point to another along a specific bearing.

The Final Approach Segment Data Block (FAS Data Block) contains 20 different data points providing precise navigational guidance to the runway or a predetermined point in space. The FAS Data must be aligned with the Final Approach Course (FAC) within tenths of degrees in order to provide proper navigation, and prevent unwanted guidance changes when transitioning from the terminal to precision approach modes of the approach.

This paper will discuss the importance of FAC and FAS data alignment and what will happen if the data is not aligned properly. The paper will also discuss the theory and method of verifying the FAC is aligned properly with the FAS Data.

INTRODUCTION

Satellite based approaches or Area Navigation (RNAV) approaches are becoming increasingly popular for runways located at airports that are limited on what kind of instrument approaches can be used.

As stated in the Aeronautical Information Manual (AIM), Area Navigation (RNAV) is a method of navigation that permits aircraft operation on any desired flight path within the coverage of ground or space based navigation aids (Federal Aviaiton Administration, 2014). With these navigational aids there are large amounts of data located in the aircraft avionics telling the aircrafts' avionics where to go and how to get there.

In late 2011, I helped develop a program called Coding Preflight Validation (CPV), which is an extensive desktop review of the ARINC 424 Coding associated with each instrument flight procedure. CPV compares specific data provided in the source ARINC 424 coding to the instrument flight procedures procedural data.

The ARINC 424 Coding is not an avionics database; rather it is an international standard file format for aircraft navigation data maintained by Airlines Electronic Engineering Committee and published by Aeronautical Radio Inc. The ARINC 424 Coding specification provides specific guidance on how to arrange each piece of data in an instrument approach procedure, so the same data can be made available to any avionics manufacture for processing into their avionics equipment. Each dataset of ARINC 424 coding is 132 characters long, each row and column within the ARINC 424 coding has a specific meaning. The ARINC 424 coding format contains information for airport, heliports, airports navaids, waypoints, runways, arrivals, and departures. ARINC coding consist of alpha character, numeric characters, and plus and minus signs. No decimal points or special characters are allowed within the ARINC Coding.

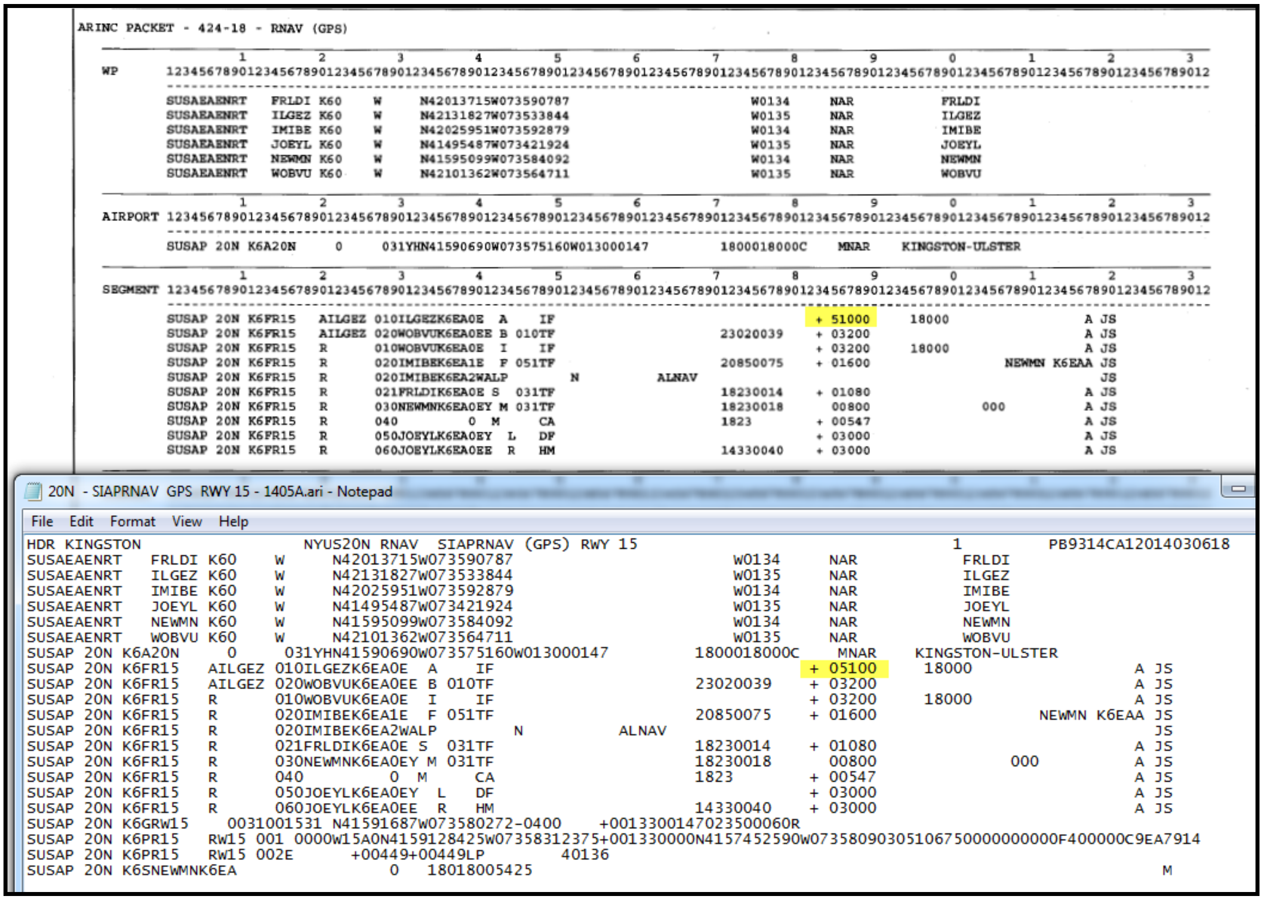
The Coding Preflight Validation (CPV) process reviews any instrument flight procedure developed by the Federal Aviation Administration, or a Non-FAA developer. Each applicable instrument flight procedure is manually reviewed for data accuracy and integrity before it is sent to flight inspection for validation with an aircraft. There are numerous data points reviewed in the Coding Preflight Validation (CPV) process, including but not limited to, airspeed, altitude, waypoint names, transitions, waypoint latitude/longitude, Threshold Crossing Height (TCH), turn direction, and bearing alignment.

If there are any data discrepancies found during the Coding Preflight Validation (CPV) process, the instrument flight procedure package is returned to the procedure design specialist for review and correction. The instrument flight procedure is returned with a description of the discrepancies and any other information that may help the procedure design specialist correct the discrepancies. Once the instrument flight procedure has been corrected by the procedure design specialist, it is returned to the flight inspection, rechecked in the Coding Preflight Validation process, and then either sent on to flight inspection or returned to the procedure design specialist for any additional corrections.

EXAMPLES OF CODING PREFLIGHT VALIDAITON ERRORS

Numerous discrepancies have been identified by the Coding Preflight Validation (CPV) process. Each discrepancy carries the same weight as the next. If a waypoint is not spelled correctly between the instrument flight procedure package and the ARINC 424 coding, it is sent back to the procedure design specialist who created it for correction. This statement is the same for any other discrepancy that is found, for example altitude, airspeed, leg type, and bearing. (Figure 1)

Each discrepancy that is found is recorded, evaluated, and discussed with the procedure design specialist who created it. Each discrepancy is also evaluated, and put into a report to show how much flight time was saved by finding the errors early, rather than later.



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ARINC PACKET - 424-18 - RNAV (GPS)

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        ------------------------------------------------------------------------------------------------------------------------------------
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        SUSAEAENRT  ILGEZ K60   W    N42131827W073533844                   W0135   NAR       ILGEZ
        SUSAEAENRT  IMIBE K60   W    N42025951W073592879                   W0134   NAR       IMIBE
        SUSAEAENRT  JOEYL K60   W    N41495487W073421924                   W0135   NAR       JOEYL
        SUSAEAENRT  NEWMN K60   W    N41595099W073584092                   W0134   NAR       NEWMN
        SUSAEAENRT  WOBVU K60   W    N42101362W073564711                   W0135   NAR       WOBVU

                 1         2         3         4         5         6         7         8         9         0         1         2         3
AIRPORT 1234567890123456789012345678901234567890123456789012345678901234567890123456789012345678901234567890123456789012345678901234567890012
        ------------------------------------------------------------------------------------------------------------------------------------
        SUSAP 20N K6A20N    0    031YHN41590690W073575160W013000147      1800018000C  MNAR   KINGSTON-ULSTER

                 1         2         3         4         5         6         7         8         9         0         1         2         3
SEGMENT 1234567890123456789012345678901234567890123456789012345678901234567890123456789012345678901234567890123456789012345678901234567890012
        ------------------------------------------------------------------------------------------------------------------------------------
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        SUSAP 20N K6FR15   AILGEZ 020WOBVUK6EA0EE B 010TF              23020039  + 03200                     A JS
        SUSAP 20N K6FR15   R      010WOBVUK6EA0E  I   IF                         + 03200   18000             A JS
        SUSAP 20N K6FR15   R      020IMIBEK6EA1E  F 051TF              20850075  + 01600          NEWMN K6EAA JS
        SUSAP 20N K6FR15   R      020IMIBEK6EA2WALP      N       ALNAV                                         JS
        SUSAP 20N K6FR15   R      021FRLDIK6EA0E S  031TF              18230014  + 01080                     A JS
        SUSAP 20N K6FR15   R      030NEWMNK6EA0EY M 031TF              18230018    00800           000       A JS
        SUSAP 20N K6FR15   R      040          0  M   CA               1823      + 00547                     A JS
        SUSAP 20N K6FR15   R      050JOEYLK6EA0EY  L  DF                         + 03000                     A JS
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20N - SIAPRNAV GPS RWY 15 - 1405A.ari - Notepad
File Edit Format View Help
HDR KINGSTON               NYUS20N RNAV  SIAPRNAV (GPS) RWY 15                    1        PB9314CA12014030618
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SUSAEAENRT   ILGEZ K60    W     N42131827W073533844              W0135     NAR      ILGEZ
SUSAEAENRT   IMIBE K60    W     N42025951W073592879              W0134     NAR      IMIBE
SUSAEAENRT   JOEYL K60    W     N41495487W073421924              W0135     NAR      JOEYL
SUSAEAENRT   NEWMN K60    W     N41595099W073584092              W0134     NAR      NEWMN
SUSAEAENRT   WOBVU K60    W     N42101362W073564711              W0135     NAR      WOBVU
SUSAP 20N K6A20N    0    031YHN41590690W073575160W013000147    1800018000C   MNAR   KINGSTON-ULSTER
SUSAP 20N K6FR15   AILGEZ 010ILGEZK6EA0E  A    IF                          + 05100   18000              A JS
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SUSAP 20N K6FR15   R      010WOBVUK6EA0E  I    IF                          + 03200   18000              A JS
SUSAP 20N K6FR15   R      020IMIBEK6EA1E  F 051TF               20850075   + 01600           NEWMN K6EAA JS
SUSAP 20N K6FR15   R      020IMIBEK6EA2WALP       N        ALNAV                                          JS
SUSAP 20N K6FR15   R      021FRLDIK6EA0E S  031TF               18230014   + 01080                      A JS
SUSAP 20N K6FR15   R      030NEWMNK6EA0EY M 031TF               18230018     00800           000        A JS
SUSAP 20N K6FR15   R      040          0  M    CA               1823       + 00547                      A JS
SUSAP 20N K6FR15   R      050JOEYLK6EA0EY  L   DF                          + 03000                      A JS
SUSAP 20N K6FR15   R      060JOEYLK6EA0EE  R   HM               14330040   + 03000                      A JS
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SUSAP 20N K6PR15   RW15 001 0000W15A0N4159128425W0735831237 5+001330000N4157452590W07358090305106750000000000F400000C9EA7914
SUSAP 20N K6PR15   RW15 002E      +00449+00449LP        40136
SUSAP 20N K6SNEWMNK6EA              0    18018005425                                                    M
```

Figure 1. Altitude Discrepancy between Instrument Flight Procedure and ARINC 424 Coding.

ALIGNMENT ISSUE

Within an RNAV instrument flight procedure with Localizer Performance or Localizer Performance with Vertical guidance minima, there is Final Approach Segment (FAS) data associated with those procedures. The Final Approach Segment as defined in the Aeronautical Information Manual is the segment of an instrument approach in which alignment and descent for landing are accomplished. The data that is associated with the Final Approach Segment provides precision guidance from the instrument flight procedures Precision Final Approach Fix (PFAF) to the Landing Threshold

Point (LTP) or Fictitious Threshold Point (FTP). Within this information, there are 20 data points that provides precise navigation. The Cyclic Redundancy Check (CRC) is a method that ensures the Final Approach Segment data is transmitted correctly from one place to another.

In 2013, a user flying the RNAV GPS approach into runway 35 at Salt Lake City, Utah, experienced a full-scale, left deflection of the Course Deviation Indicator (CDI) needle. This deflection of the needle occurred just prior to crossing over the Final Approach Fix (FAF), as the avionics in the aircraft were switching from terminal mode to approach mode. Switching from terminal mode to approach mode triggers the avionics to verify it has adequate GPS satellite coverage, and change to the Final Approach Segment data block guidance.

This approach was designed as an offset approach with Localizer Performance (LP) minima. The Final Approach Course (FAC) that was designed crosses the extended centerline of the runway 2999' from the threshold on a published bearing of 341 degrees. The Final Approach Segment data block that was attached to the end of the Final Approach Segment was designed down the centerline of runway 35, and not on the same 341 degree bearing as the Final Approach Course. The misalignment of the Final Approach Course and Final Approach Segment data block caused the course deviation indicator to go full scale deflection to the left.

This was most likely one of the first times this approach had been flown using the Final Approach Segment data since it was designed and flight validated in 2011. Due to the limited experience of validating RNAV GPS offsets with Localizer Performance (LP) minima at the time, the procedure was commissioned with the misalignment issue.

The users' complaint caused a safety alert to be issued from the avionics manufacturer. The users' complaint was then forwarded to the Technical Services Division of the Federal Aviation Administrations' Flight Inspection Operations group, where a NOTAM was issued to not authorize the approach. This prompted the database supplier to issue an alert for the approach in their database.

Once the approach was NOTAMed, a process needed to be designed and put in place to make sure that the Final Approach Course and the Final Approach Segment data block for any existing or newly developed WAAS procedure with Localizer Performance (LP) or Localizer Performance with Vertical guidance (LPV) minima is aligned properly.

THE PROCESS

Coming up with a process to verify the Final Approach Course (FAC) to the Final Approach Segment (FAS) data alignment was not a simple task. We need to figure out what data is needed, where the data is located, and a method on how calculate the data.

The data needed to verify the bearing alignment between the Final Approach Course and the Final Approach Segment data block can be found in the ARINC 424 coding record, as well as the procedural data from the instrument flight procedure package.

It was determined the data that was need was:

1. Precise Final Approach Fix (PFAF) latitude and longitude
2. Landing Threshold Point (LTP) or the Fictitious Threshold Point (FTP) latitude and longitude
3. Final Approach Course (FAC) determined by the procedure designer
4. Magnetic Variation used in the development of the procedure
5. Flight Path Alignment Point (FPAP) latitude and longitude

A geodetic calculator that has the ability to calculate the inverse between two waypoints is also required for this process.

The table below provides a representation of the steps associated with the process. (Figure 2)

Step	Function	Result
1	Enter PFAF and LTP/FTP Coordinates into IAPA Calculator	
	Bearing from PFAF/FAF to the LTP/FTP	
	Bearing from LTP/FTP to the PFAF/FAF	
2	Enter -3 FAC (Convert to True)	
3	Compare PFAF/FAF to the PFAF/FAF bearing to 8260-3 FAC in True (Tolerance = +/- 0.03)	
4	Determine the INVERSE (180° opposite) of PFAF/FAF	
5	Enter FAS Data LTP/FTP and FPAP Coordinates into IAPA Calcualtor	
	Bearing from LTP/FTP to FPAP	
6	Compare Results from Inverse Bearing from LTP/FTP to FPAP (Tolerance = +/- 0.10)	

Figure 2. FAS Data Alignment Verification Worksheet

Method for Verification of Alignment

The first portion of the verification of Final Approach Course (FAC) and Final Approach Segment (FAS) data block alignment is to determine the bearing from the Precise Final Approach Fix (PFAF) to the Landing Threshold Point (LTP) or the Fictitious Threshold Point (FTP).

The latitude and longitude of the Precise Final Approach Fix (PFAF) or Final Approach Fix (FAF) are located in the waypoint section of the ARINC 424 Coding. The latitude and longitude for the Landing Threshold Point (LTP) or the Fictitious Threshold Point (FTP) are located in the Path Point Record of the ARINC 424 Coding as well.

1. Input the PFAF Latitude and Longitude into the first coordinate section of the geodetic calculator.

   Note the bearing from the PFAF/FAF to the LTP/FTP.

2. Input the LTP/FTP latitude and longitude into the second coordination section of the geodetic calculator.

   Note the bearing from the LTP/FTP to the PFAF/FAF.

Step	Function	Result
1	Enter PFAF and LTP/FTP Coordinates into IAPA Calculator	
	Bearing from PFAF/FAF to the LTP/FTP	355.20
	Bearing from LTP/FTP to the PFAF/FAF	175.20

Figure 3. PFAF/FAF to LTP/FTP Coordinate Calculations

3. Locating the Final Approach Course that was calculated by the procedure design specialist.

4. Use the Magnetic Variation to calculate the Final Approach Course to TRUE degrees.

    a. Add for a East Magnetic Variation to the Final Approach Course designed in the instrument procedure package.

    b. Subtract for a West Magnetic Variation from the Final Approach Course designed in the instrument procedure package.

5. Note the Final Approach Course bearing in TRUE.

6. Compare the bearing from the PFAF/FAF to the LTP/FTP to the Final Approach Course Bearing in TRUE.

    This comparison must be within +/- .03 degrees.

7. Determine the reciprocal of the bearing from the LTP/FTP to the PFAF.

    Note this bearing.

2	Enter -3 FAC (Convert to True)	354.72
3	Compare PFAF/FAF to the PFAF/FAF bearing to 8260-3 FAC in True (Tolerance = +/- 0.03)	-0.48

Figure 4. Comparison of data

The second portion of the verification of the Final Approach Course (FAC) and Final Approach Segment (FAS) data block alignment is to determine the bearing from the Landing Threshold Point (LTP) or the Fictitious Threshold Point (FTP) to the Flight Path Alignment Point (FPAP).

The latitude and longitude for the Landing Threshold Point (LTP) or the Fictitious Threshold Point (FTP) are located in the Path Point Record of the ARINC 424 Coding. The latitude and longitude for the Flight Path Alignment Point (FPAP) are also in the Path Point Record of the ARINC 424 Coding.

1. Input the LTP/FTP Latitude and Longitude into the first coordinate section of the geodetic calculator.

    Note the bearing from the LTP/FTP to the FPAP

2. Input the FPAP latitude and longitude into the second coordination section of the geodetic calculator.

3. Compare the reciprocal of the bearing from the LTP/FTP to PFAF to the bearing from the LTP/FTP to FPAP.

    This comparison must be within +/- .10 degrees

4	Determine the INVERSE (180° opposite) of PFAF/FAF	355.20
5	Enter FAS Data LTP/FTP and FPAP Coordinates into IAPA Calcualtor	
	Bearing from LTP/FTP to FPAP	359.99
6	Compare Results from Inverse Bearing from LTP/FTP to FPAP (Tolerance = +/- 0.10)	4.79

Figure 5. Final Comparison of Alignment Data

CONCLUSION

ARINC 424 data plays a vital part in every instrument flight procedure that relies on space-based and ground-based augmentation system. Coding Preflight Validation (CPV) ensures that all data is accurate prior to any flight inspection or flight validation mission.

Having a final approach course and final approach segment data misaligned was a costly discrepancy. Costly to the point that the Federal Aviation Administration (FAA) flight inspection was required to go back to the same location and evaluate the same approach multiple times. This not only delayed the cancelation of the NOTAM that was issued, but it cost time, money, fuel, and air traffic delays to revisit the same place

The solution to this issue was to develop a process by which the Final Approach Course bearing is evaluated and compared to the Final Approach Segment data block. This process must be performed prior to any mission that has a RNAV instrument approach with Localizer Performance or Localizer Performance with Vertical guidance minima associated with it. The ultimate conclusion is no matter how subtle the discrepancy is, the discrepancy can cause major navigational guidance issues if not caught.

FUTURE WORK

The Federal Aviation Administration (FAA) Technical Services Division is working on a way to make the Coding Preflight Validation process totally automated. This will eliminate the need for an individual to manually examine all the required documentation for Coding Preflight Validation (CPV).

The automation of this process will not only include the validation of all key items, but will incorporate the Final Approach Course (FAC) and Final Approach Segment (FAS) data block alignment check into its process.

REFERENCES

[1] FAA, April 2014, Aeronautical Information Manual, PPG A – 12, Area Navigation, 5th Edition

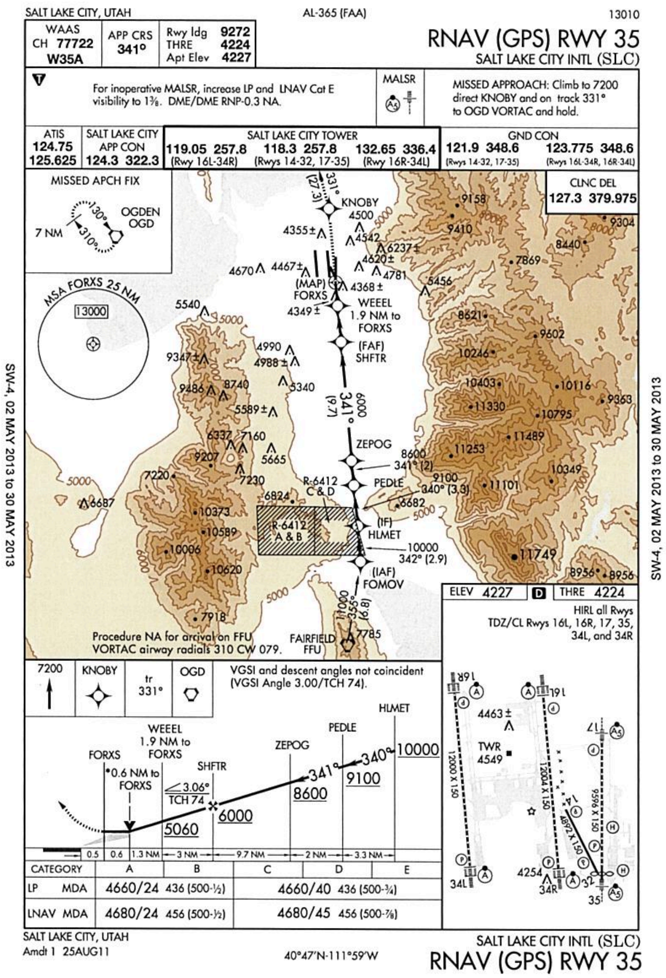
APPENDIX 1

Final Approach Segment (FAS) data block Alignment Verification Worksheet

	FAS Data Alignment Verification Worksheet	
	** Note: **All IAPA Calculators bearings will be in True degrees** **	
	** Note: **Verify/Select IAPA Inverse Function** **	
Step	Function	Result
1	Enter PFAF and LTP/FTP Coordinates into IAPA Calculator	
	Bearing from PFAF/FAF to the LTP/FTP	______
	Bearing from LTP/FTP to the PFAF/FAF	______
2	Enter -3 FAC (Convert to True)	______
3	Compare PFAF/FAF to the PFAF/FAF bearing to 8260-3 FAC in True (Tolerance = +/- 0.03)	______
4	Determine the INVERSE (180° opposite) of PFAF/FAF	______
5	Enter FAS Data LTP/FTP and FPAP Coordinates into IAPA Calcualtor	
	Bearing from LTP/FTP to FPAP	______
6	Compare Results from Inverse Bearing from LTP/FTP to FPAP (Tolerance = +/- 0.10)	______

APPENDIX 2

Instrument Flight Procedure Package for KSCL



TL 11-18

US DEPARTMENT OF TRANSPORTATION
FEDERAL AVIATION ADMINISTRATION

RNAV - STANDARD
INSTRUMENT APPROACH PROCEDURE
TITLE 14 CFR PART 97.33

Bearings, headings, courses, and radials are magnetic. Elevations and altitudes are in feet, MSL, except HAT, HAA, TCH, and RA. Altitudes are minimum altitudes unless otherwise indicated. Ceilings are in feet above airport elevation. Distances are in nautical miles unless otherwise indicated, except visibilities which are in statute miles or in feet RVR.

TERMINAL ROUTES

FROM	TO	COURSE AND DISTANCE	ALTITUDE
FFU VORTAC	FOMOV (FB)	354.89 / 6.82	11000
FOMOV (IAF)	HLMET (FB)	341.75 / 2.90	10000
HLMET (IF)	PEDLE (FB)	340.30 / 3.32	9100
PEDLE	ZEPOG (FB)	340.54 / 2.00	8600
ZEPOG	SHFTR (FB)	340.95 / 9.68	6000
SHFTR (FAF)	WEEEL/1.90 NM TO FORXS (FB)	340.72 / 2.95	
(SEE FORM 8260-10)			

MISSED APPROACH

LP: FORXS
LNAV: FORXS

CLIMB TO 7200 DIRECT KNOBY AND ON TRACK 331.39 TO OGD VORTAC AND HOLD.

ADDITIONAL FLIGHT DATA:
HOLD NW, RT, 130.00 INBOUND.
CHART FAS OBST: 4349 TOWER 404435N/1115744W
CHART FAS OBST: 4368 T-L TWR 404523N/1115656W
CHART R-6412 A & B.
CHART VDP AT 0.64 MILES TO FORXS*
SHFTR TO RW35: 3.06/74.
WAAS CHANNEL # 77722
REFERENCE PATH ID: W35A
FAC CROSSES RWY C/L EXTENDED 2999 FROM THLD.
LTP HAE: 1270.4 M

1. PT ____ SIDE OF COURSE ____ OUTBOUND ____ FT WITHIN ____ MILES OF ____ (IAF)
2. PROFILE STARTS AT HLMET
3. FAC: 340.72 FAF: SHFTR DIST FAF TO MAP: 4.85 THLD: 5.35
4. MIN. ALT: HLMET 10000, PEDLE 9100, ZEPOG 8600, SHFTR 6000, WEEEL/1.90 NM TO FORXS 5060
5. DIST TO THLD FROM OM: ____ MM: ____ IM: ____ 150 HAT: ____ 100 HAT: ____ GS ANT: ____
6. MIN GS INCPT: ____ GS ALT AT: ____ OM: ____ MM: ____ IM: ____
7. GS ANGLE: ____ TCH: 34:1 IS CLEAR
8. MSA FROM: FORXS 13000

MAG VAR: 14E EPOCH YEAR: 1995

MINIMUMS

TAKEOFF: SEE FAA FORM 8260-15A FOR THIS AIRPORT
ALTERNATE: N A
STANDARD

CATEGORY =====>	A			B			C			D			E		
	DH/MDA	VIS	HAT/HAA	DH/MDA	VIS	HAT/HAA	DH/MDA	VIS	HAT/HAA	DH/MDA	VIS	HAT/HAA	DH/MDA	VIS	HAT/HAA
LP MDA	4660	2400	436	4660	2400	436	4660	4000	436	4660	4000	436	4660	4000	436
LNAV MDA	4680	2400	456	4680	2400	456	4680	4500	456	4680	4500	456	4680	4500	456

NOTES:
CHART NOTE: FOR INOPERATIVE MALSR, INCREASE LP AND LNAV CAT E VISIBILITY TO 1 3/8.
CHART NOTE: DME/DME RNP-0.3 NA.
CHART PROFILE NOTE: VGSI AND DESCENT ANGLES NOT COINCIDENT.
CHART NOTE: PROCEDURE NA FOR ARRIVAL ON FFU VORTAC AIRWAY RADIALS 310 CW 079.

CITY AND STATE	ELEVATION: 4227 THRE: 4224 / AIRPORT NAME:	FACILITY IDENTIFIER:	PROCEDURE NO./AMDT NO./EFFECTIVE DATE:	SUP:
SALT LAKE CITY, UT	SALT LAKE CITY INTL	RNAV	RNAV (GPS) RWY 35, AMDT 1 — 25 AUG 2011	AMDT: ORIG-A / DATED 03/22/2001

FAA FORM 8260 - 3 / April 2006 (computer generated)

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US DEPARTMENT OF TRANSPORTATION - FEDERAL AVIATION ADMINISTRATION

RNAV - STANDARD

INSTRUMENT APPROACH PROCEDURE - TITLE 14 CFR PART 97.33

Bearings, headings, courses, and radials are magnetic. Elevations and altitudes are in feet, MSL, except HAT, HAA, TCH, and RA. Altitudes are minimum altitudes unless otherwise indicated. Ceilings are in feet above aiport elevation. Distances are in nautical miles unless otherwise indicated, except visibilities which are in statute miles or in feet RVR.

TERMINAL ROUTES, (CONT.):

FROM	TO	COURSE AND DISTANCE	ALTITUDE
WEEEL/1.90 NM TO FORXS	FORXS (MAP) (FO)	340.71 / 1.90	
FORXS (MAP)	4627 MSL	340.71	
4627 MSL	KNOBY (FB)		
KNOBY	OGD VORTAC (FO)	331.39 / 27.26	7200

CITY AND STATE	ELEVATION: 4227 THRE: 4224	FACILITY IDENTIFIER:	PROCEDURE NO./ AMDT NO./EFFECTIVE DATE:	SUP:
SALT LAKE CITY, UT	AIRPORT NAME: SALT LAKE CITY INTL	RNAV	RNAV (GPS) RWY 35, AMDT 1 25 AUG 2011	AMDT: ORIG-A DATED: 03/22/2001

FAA FORM 8260-10 / April 2006 (Computer Generated)

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U.S. DEPARTMENT OF TRANSPORTATION - FEDERAL AVIATION ADMINISTRATION

RNAV STANDARD INSTRUMENT APPROACH PROCEDURE
FLIGHT STANDARDS SERVICE - FAR PART 97.33

Bearings, headings, courses, and radials are magnetic. Elevations and altitudes are in feet, MSL, except HAT, HAA, TCH, and RA. Altitudes are minimum altitudes unless otherwise indicated. Ceilings are in feet above aiport elevation. Distances are in nautical miles unless otherwise indicated, except visibilities which are in statute miles or in feet RVR.

FAS DATA BLOCK INFORMATION

DATA FIELD	DATA
OPERATION TYPE	0
SBAS SERVICE PROVIDER IDENTIFIER	0
AIRPORT IDENTIFIER	KSLC
RUNWAY	RW35
APPROACH PERFORMANCE DESIGNATOR	0
ROUTE INDICATOR	
REFERENCE PATH DATA SELECTOR	0
REFERENCE PATH IDENTIFIER (APPROACH ID)	W35A
LTP/FTP LATITUDE	404624.4900N
LTP/FTP LONGITUDE	1115743.4400W
LTP/FTP ELLIPSOIDAL HEIGHT	+12704
FPAP LATITUDE	404756.1000N
FPAP LONGITUDE	1115743.4600W
THRESHOLD CROSSING HEIGHT (TCH)	00073.8
TCH UNITS SELECTOR (METERS OR FEET USED)	F
GLIDEPATH ANGLE (GPA)	03.06
COURSE WIDTH AT THRESHOLD	106.75
LENGTH OFFSET	0000
HORIZONTAL ALERT LIMIT (HAL)	40.0
VERTICAL ALERT LIMIT (VAL)	0.0
CRC REMAINDER	017DF208

ADDITIONAL PATH POINT RECORD INFORMATION

ICAO CODE	K2
LTP ORTHOMETRIC HEIGHT	+12874
FPAP ORTHOMETRIC HEIGHT	+12874

CITY AND STATE	ELEVATION: 4227 THRE: 4224	FACILITY IDENTIFIER:	PROCEDURE NO./ AMDT NO./EFFECTIVE DATE:	SUP:
SALT LAKE CITY, UT	AIRPORT NAME: SALT LAKE CITY INTL	RNAV	RNAV (GPS) RWY 35, AMDT 1 25 AUG 2011	AMDT: ORIG-A DATED: 03/22/2001

FAA FORM 8260-10 / April 2006 (Computer Generated)

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RNAV STANDARD INSTRUMENT APPROACH PROCEDURE
FLIGHT STANDARDS SERVICE - FAR PART 97.33

Bearings, headings, courses, and radials are magnetic. Elevations and altitudes are in feet, MSL, except HAT, HAA, TCH, and RA. Altitudes are minimum altitudes unless otherwise indicated. Ceilings are in feet above aiport elevation. Distances are in nautical miles unless otherwise indicated, except visibilities which are in statute miles or in feet RVR.

ARINC PACKET - 424-18 - RNAV (GPS)

```
                 1         2         3         4         5         6         7         8         9         0         1         2         3
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        SUSAD        OGD   K2011570VTLW N41132675W112055367     N41132675W112055367E0140042231    NAROGDEN                              I

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WP      1234567890123456789012345678901234567890123456789012345678901234567890123456789012345678901234567890123456789012345678901234567890123456789012
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        SUSAEAENRT   FORXS K20     W     N40455485W111574343                           E0121     NAR          FORXS                     I
        SUSAEAENRT   HLMET K20     W     N40260788W111552004                           E0121     NAR          HLMET                     I
        SUSAEAENRT   KNOBY K20     W     N40515355W111582710                           E0122     NAR          KNOBY                     I
        SUSAEAENRT   PEDLE K20     W     N40292601W111554593                           E0121     NAR          PEDLE                     I
        SUSAEAENRT   SHFTR K20     W     N40410470W111570815                           E0121     NAR          SHFTR                     I
        SUSAEAENRT   WEEEL K20     W     N40440120W111572960                           E0121     NAR          WEEEL                     I
        SUSAEAENRT   ZEPOG K20     W     N40312555W111560091                           E0121     NAR          ZEPOG                     I

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                 1         2         3         4         5         6         7         8         9         0         1         2         3
SEGMENT 1234567890123456789012345678901234567890123456789012345678901234567890123456789012345678901234567890123456789012345678901234567890123456789012
        ----------------------------------------------------------------------------------------------------------------------------------------------
        SUSAP KSLCK2FR35   AFFU    010FFU   K2D 0V        IF                                                    18000               A JS   I
        SUSAP KSLCK2FR35   AFFU    020FOMOVK2EA0E  A 020TF                        35490068     + 11000                              A JS   I
        SUSAP KSLCK2FR35   AFFU    030HLMETK2EA0EE B 010TF                        34180029     + 10000                              A JS   I
        SUSAP KSLCK2FR35   R       010HLMETK2EA0E  I   IF                                      + 10000      18000                   A JS   I
        SUSAP KSLCK2FR35   R       011PEDLEK2EA0E S  051TF                        34030033     + 09100                              A JS   I
        SUSAP KSLCK2FR35   R       012ZEPOGK2EA0E S  051TF                        34050020     + 08600                              A JS   I
        SUSAP KSLCK2FR35   R       020SHFTRK2EA1E  F 051TF                        34100097     + 06000                   FORXS K2EAA JS   I
        SUSAP KSLCK2FR35   R       020SHFTRK2EA2WALP          N          ALNAV                                                          JS   I
        SUSAP KSLCK2FR35   R       021WEEELK2EA0E S  031TF                        34070030     V 0506005060       -306              A JS   I
        SUSAP KSLCK2FR35   R       030FORXSK2EA0EY M 031TF                        34070019       04441            -306              A JS   I
        SUSAP KSLCK2FR35   R       040            0  M     CA                     3407         + 04627                              A JS   I
        SUSAP KSLCK2FR35   R       050KNOBYK2EA0E          DF                                                                       A JS   I
        SUSAP KSLCK2FR35   R       060OGD   K2D 0VY   010TF                       3314         + 07200                              A JS   I
```

CITY AND STATE	ELEVATION: 4227 THRE: 4224	FACILITY IDENTIFIER:	PROCEDURE NO./ AMDT NO./EFFECTIVE DATE:	SUP:
SALT LAKE CITY, UT	AIRPORT NAME: SALT LAKE CITY INTL	RNAV	RNAV (GPS) RWY 35, AMDT 1 25 AUG 2011	AMDT: ORIG-A DATED: 03/22/2001

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RNAV STANDARD INSTRUMENT APPROACH PROCEDURE
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Bearings, headings, courses, and radials are magnetic. Elevations and altitudes are in feet, MSL, except HAT, HAA, TCH, and RA. Altitudes are minimum altitudes unless otherwise indicated. Ceilings are in feet above aiport elevation. Distances are in nautical miles unless otherwise indicated, except visibilities which are in statute miles or in feet RVR.

```
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      ------------------------------------------------------------------------------------------------------------------------------------------
                 1         2         3         4         5         6         7         8         9         0         1         2         3
RUNWAY  1234567890123456789012345678901234567890123456789012345678901234567890123456789012345678901234567890123456789012345678901234567890123456789012
        ----------------------------------------------------------------------------------------------------------------------------------------
        SUSAP KSLCK2GRW35     0095963460 N40462449W111574344-0100     +12704042240324531501                                          I
      ------------------------------------------------------------------------------------------------------------------------------------------
                 1         2         3         4         5         6         7         8         9         0         1         2         3
PP      1234567890123456789012345678901234567890123456789012345678901234567890123456789012345678901234567890123456789012345678901234567890123456789012
        ----------------------------------------------------------------------------------------------------------------------------------------
        SUSAP KSLCK2PR35    RW35 001 0000W35A0N4046244900W11157434400+127040306N4047561000W111574346001067500000000738F400000017DF208I
        SUSAP KSLCK2PR35    RW35 002E      +12874+12874LP        77722                                                              I
      ------------------------------------------------------------------------------------------------------------------------------------------
                 1         2         3         4         5         6         7         8         9         0         1         2         3
MSA     1234567890123456789012345678901234567890123456789012345678901234567890123456789012345678901234567890123456789012345678901234567890123456789012
        ----------------------------------------------------------------------------------------------------------------------------------------
        SUSAP KSLCK2SFORXSK2EA                0    18018013025                                                                   M   I
      ------------------------------------------------------------------------------------------------------------------------------------------
```

CITY AND STATE	ELEVATION: 4227 THRE: 4224	FACILITY IDENTIFIER:	PROCEDURE NO./ AMDT NO./EFFECTIVE DATE:	SUP:
SALT LAKE CITY, UT	AIRPORT NAME: SALT LAKE CITY INTL	RNAV	RNAV (GPS) RWY 35, AMDT 1 25 AUG 2011	AMDT: ORIG-A DATED: 03/22/2001

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Utilization of ARINC 424 Database in Performing Flight Inspection

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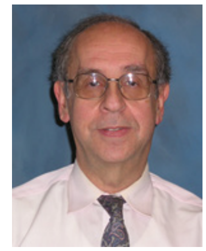

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ABSTRACT

It has long been desirable to have the Flight Inspection System be aware of the flight procedures that are being flown by the flight crew to support a current flight inspection mission. Flight procedures are displayed to the mission specialist for situational awareness. This has become a requirement for RNAV modes such as non-precision GPS inspection, SBAS/WAAS and GBAS/LAAS inspection modes and for procedure validation by the flight inspection crew. These new flight inspection modes have placed additional demands on maintaining the integrity of the database from the development of the procedure through distribution to the facility and flight inspection aircraft.

This paper will review the methods used by the Flight Inspection System to obtain the FMS procedure being flown by the crew. Some problems have arisen with the current FAA aircraft cockpit upgrades that have made it difficult to obtain accurate procedure information, and in some cases, not being able to retrieve FMS procedure information.

Ideally it would be desirable for the flight inspector to retrieve the database parameters directly from the FMS to assure that the procedure flown matches what the flight inspector is verifying. However, the data available from the FMS does not provide in some cases all required parameters and the accuracies needed for flight inspection. In view of this constraint, the paper raises the question of the significance of having the identical flight plan and database for the pilot and the flight inspector.

INTRODUCTION

A few years ago the FAA introduced the term "Gold Standard", which is a process of automation in developing a flight procedure, validating the procedure, coding the procedure in ARINC 424 format, and electronically packing the coded procedure into a navigation database for use in the Flight Management System (FMS) on the flight inspection aircraft[3]. The initiative is to use only source ARINC 424 coding for the inspection and validation of RNAV procedures.

Since that time much progress has been made toward achieving this "Gold Standard", however a number of issues still need to be addressed. The RNAV precision approach modes require a procedure validation consisting of flying over specified waypoints and verifying the critical data elements that provide the course and glide path deviations to the pilot. These parameters are contained in the FAS data block that are transmitted by the GBAS/LAAS station and must be verified by the flight inspector.

The paper will describe how NXT's flight inspection system currently decodes the FAA's (US) continental Coded Instrument Flight Procedures (CIFP) ARINC 424 coded database (or FAA's tailored ARINC 424 coded procedure database) in performing RNAV inspection modes including:

- GPS-NP
- SBAS/WAAS - LNAV/VNAV and LPV approaches
- GBAS/LAAS
- DME/DME (flight plan is optional but not generally used)

At this point we need to provide a brief summary of the database parameters required to perform flight inspection of the above modes.

This paper first addresses the current mechanism for loading the flight plan and data base parameters into the FMS and AFIS. The interface between the FMS and AFIS is discussed, describing the limitations of the GAMA (General Aviation Manufacturers Association) format that the FMS outputs. A brief overview of the various ARINC 424 versions is discussed below, describing the increased capability of the latest version.

The final question to be raised is the importance of having the identical flight plan and database used by the pilot and flight inspector. Prior to flying a RNAV procedure the pilot may manually edit the flight plan in the FMS after it was loaded from the ARINC 424 file. The changes may include adding waypoints, but this modification to the flight plan will not be automatically relayed to the flight inspector. Therefore, what would be the significance of having the pilot's and inspector's flight plans not being necessarily identical? Any changes to the waypoints introduced by the pilot may affect the AFIS data collection starting points, and therefore could lose a portion of the collected data.

FLIGHT INSPECTION USING ARINC 424

In the flight inspection mission, the primary purpose of decoding the ARINC 424 database is to retrieve flight plan waypoints to a runway to support LNAV, LNAV/VNAV inspections and to retrieve FAS data to support SBAS/GBAS LPV inspections.

Using information supplied by the operator, such as airport name and runway, the flight inspection software interfaces with the ARINC 424 database to decode and build all possible flight procedures to the runway, and if available, to retrieve the FAS data associated with the runway. The operator may select from a list of procedures. The software then retrieves and builds the flight plan using all defined waypoints and/or navaids.

The interface to the ARINC 424 database assists the FAA on aircraft that have FMS's that do not provide the flight inspection system with flight plan information.

The non-precision GPS flight inspection was the first mode that required waypoint information, typically starting at the FAF waypoint and continuing to the runway threshold. The waypoint information may be entered by the mission specialist by hand. However, this method is prone to errors. Some FMS's can output the current flight plan that is being flown in the GAMA (General Aviation Manufacturers Association) format, usually on an ARINC 429 data bus. The GAMA flight plan output from the FMS provides an accurate means of obtaining flight plan data for the non-precision GPS inspection and insures that the mission specialist's flight procedure is the same as the cockpit is. The waypoint information is used by the AFIS to define the start and stop of data collection as well as defining the course bearing necessary in the computation of along-track, cross-track and waypoint displacement errors due to GPS errors.

While the GAMA flight plan is suitable for non-precision GPS flight inspection, it does not provide sufficient waypoint accuracy for SBAS/WAAS and GBAS/LAAS inspection. These inspection modes require waypoint accuracy that is beyond the data resolution provided by the GAMA format. The GAMA format for waypoint latitude and longitude provides 20 bits of resolution equal to approximately 0.000172 degrees or about 60 feet of resolution[4]. This is not enough resolution for WAAS/LAAS flight inspection, where we typically require data resolution to 1 foot or better. In addition to this limitation, GAMA does not provide waypoint altitude.

Figure 1 was received in 2007 from the Japanese Civil Aviation Bureau who marked 3 positions in google earth image. These are:

1) Published
2) FMS indicated
3) AFIS FMS indicated (from GAMA flight plan)

This shows that even the FMS displayed position is off from the published position, but what is interesting is the difference between the FMS and the AFIS threshold position. The AFIS position comes from the GAMA output and if you were to measure distance, you would find that it falls within the 62 feet (both in latitude and longitude). Since both Latitude and Longitude can be off by up to 62 feet, the total error can be some combination of latitude error and longitude error, resulting in a total error of more than 62 feet.

The FAA's flight inspection fleet of Challenger, Learjet and Beechcraft aircraft is comprised of two types of FMS's. The FMS on the Beechcraft does not support a GAMA flight plan output. However, the FMS used on the Learjet has modified the GAMA 429 output bus to include three new ARINC 429 labels that extend the latitude/longitude precision and provide waypoint altitude. While this is acceptable for the Learjet aircraft, it did not resolve the issue for the FMS used on the Beechcraft. A more universal solution across all flight inspection aircraft would be more desirable.

The ARINC 424 database is supplied to AFIS by a text file or files. This file is loaded onto a media, usually a USB thumb drive. The AFIS reads the file as specified by the operator, usually on the FACILITY selection page. AFIS parses the file using the facility and runway identifiers as input search parameters.

Figure 1. Difference Between Published, FMS and AFIS Indicated Position

The least desirable method is to manually enter each required waypoint from the procedure to allow the mission specialist to conduct procedure validation. This is always a fallback mode of data entry when no other means of data acquisition is available, but clearly this is not desirable.

ARINC 424 BRIEF DESCRIPTION

The ARINC 424 specification was first developed in the mid 70's to meet the more complex requirements of embedded navigation systems including FMS's. The first specification was officially published in 1975 and has been continuously updated to support the evolving requirements. The latest specification is ARINC 424-20, published in 2011[1].

From Wikipedia, **ARINC 424** or **ARINC 424 Navigation System Data Base Standard** is an international standard file format for aircraft navigation data maintained by Airlines Electronic Engineering Committee and published by Aeronautical Radio, Inc.. The ARINC 424 specifications are not a database, but a "standard for the preparation and transmission of data for assembly of airborne navigation system data bases”.

ARINC 424 specifies a 132-byte fixed-length record format. Each record consists of one piece of navigation information such as an airport, heliport, runway, waypoints, navaids, airways, arrival routes, and departure routes. The Appendix shows an extract from an ARINC 424 procedure record for the KOKC approach plate.

ARINC 424 contains several sub-specifications for different data formats. New formats have been introduced as capabilities of equipment have increased and new classes of equipment (such as GPS) have been introduced. The sub-specifications are indicated by a format number. The three sub-specifications currently in use are ARINC 424-13, ARINC 424-15, and ARINC 424-18.

The ARINC 424 datasets are assembled by commercial data suppliers based on the public sources (also named ‘standard data’). Custom data (also named tailored data) is specific to the end-user. The input ARINC 424 dataset can be adapted to meet the specific requirements of a target Flight Management System or flight inspection system.

APPROACH PLATE FOR OKC RWY 17L

As an example, the Oklahoma City Runway 17L, as depicted in Figure 2, will be used to show the capability of decoding the ARINC 424 file and display on the AFIS monitor all information pertinent to this approach. In this case the facility inspection type is SBAS/WAAS.

There are five (5) approach transitions defined for the approach into runway 17L. They are:

1) DAROO
2) FLAPP
3) GULLI
4) HIPES
5) DECKK

After loading the ARINC 424 data for RWY 17L into the AFIS, the information is shown on the console display, identifying all waypoints for each of the five approaches, as shown in Figures 3 and 4.

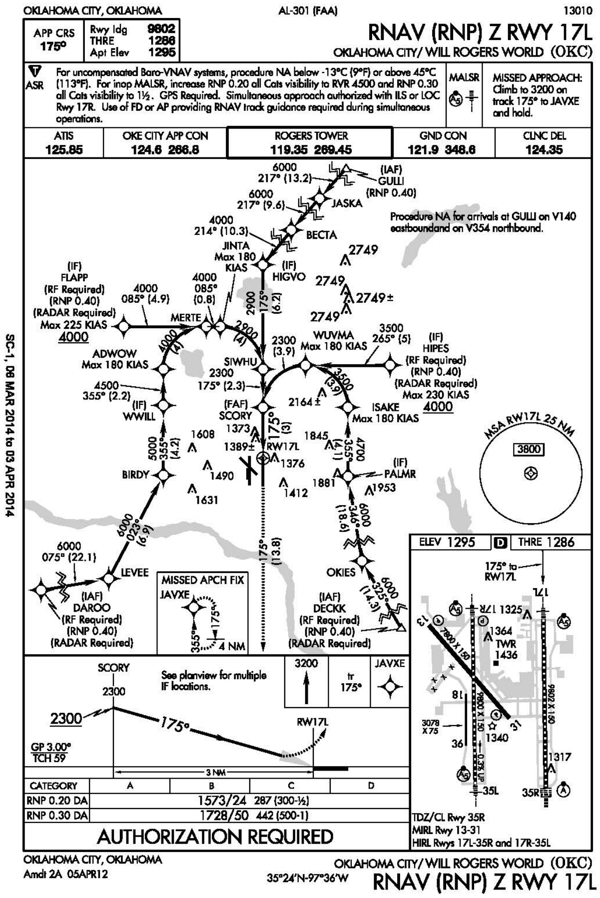

Figure 2. Approach Plate for OKC RWY 17L

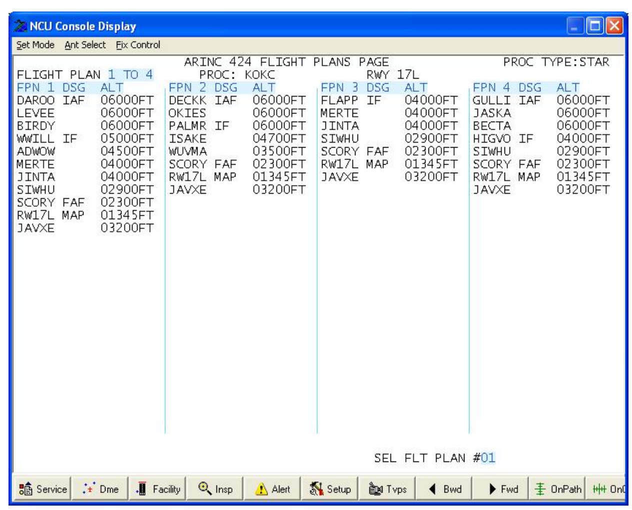

Figure 3. Flight Plans 1 to 4

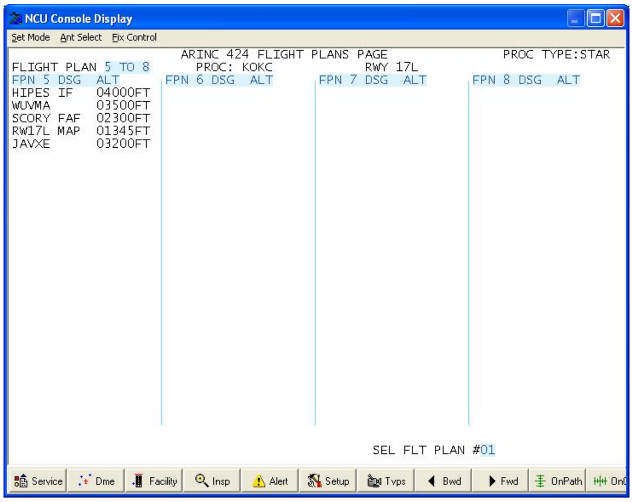

Figure 4. Flight Plan 5

The next display identifies the Runway data which is displayed in Figure 5. Upon selecting the approach to be inspected, the operator enters in this example the DAROO approach transition, which is copied to the AFIS facility page and automatically appears on the console display, as shown in Figure 6.

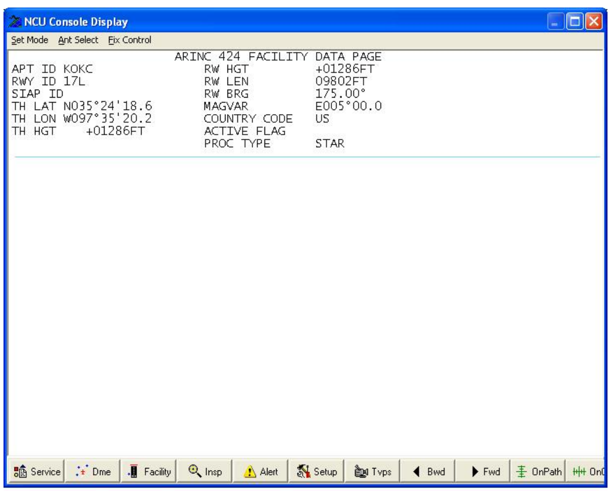

Figure 5. RWY 17L Runway Data

In Figure 7, the approach waypoints have been decoded displaying the bearing/range, latitude and longitude data. The facility data as read from the AFIS database is displayed in Figure 8. Figure 9 shows the FAS data block, which has been decoded from the ARINC 424 or FAA binary file for the OKC RWY 17L. Figure 10 is a graphic representation showing google earth with all the waypoints of the DAROO procedure and the runway threshold.

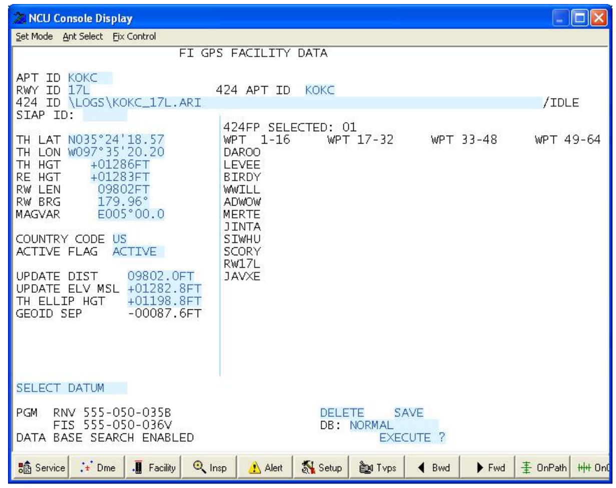

Figure 6. DAROO Approach Flight Plan

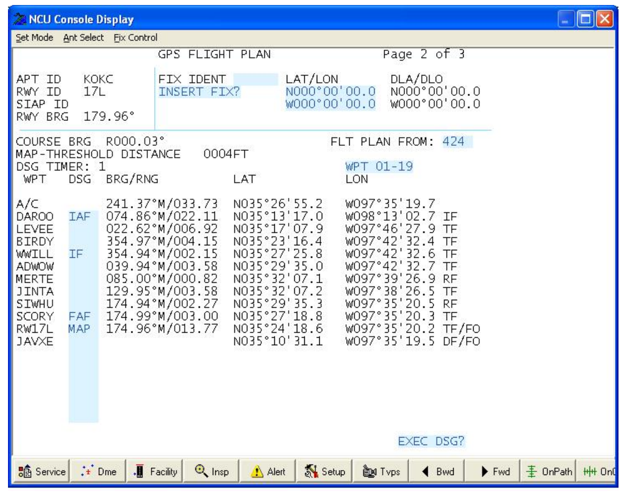

Figure 7. Decoded waypoints for DAROO approach

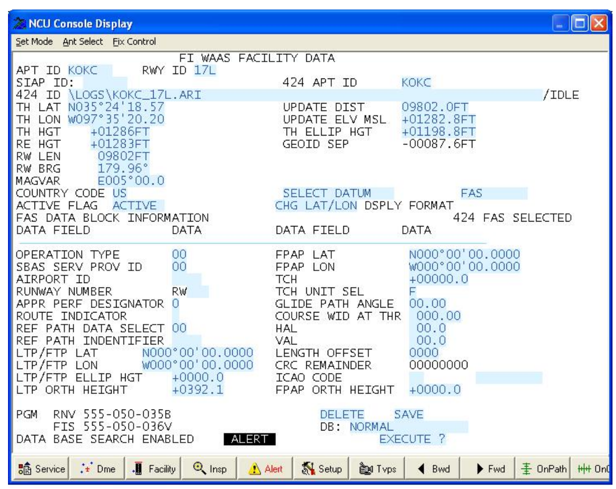

Figure 8. SBAS/WAAS Facility Data

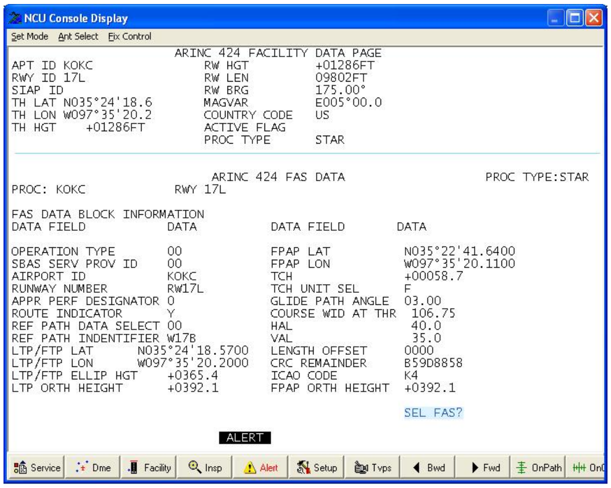

Figure 9. Facility FAS Data Block

Figure 10. Google Earth image showing DAROO Procedure

FAS DATA BLOCK

Due to the fact that the FAS data block is a critical element in performing SBAS/WAAS and GBAS/LAAS facility inspections, a brief overview on how it is applied is presented here. For KOKC the FAS data information is as follows:

Data Field	Data
Operation Type	00
SBAS Service Provider ID	00
Airport Identifier	KOKC
Runway Number	RW17L
Approach Performance Designator	0
Route Indicator	Y
Reference Path Data Selector	00
Reference Path Identifier	W17B
LTP/FTP Latitude	N035°24’18.5700
LTP/FTP Longitude	W097°35’20.2000
LTP/FTP Ellipsoid Height	+0365.4
LTP Orthogonal Height	+0392.1
FPAP Latitude	N035°22’41.6400
FPAP Longitude	W097°35’20.1100
Threshold Crossing Height	+00058.7
TCH Unit Selector (Meters or Feet)	F
Glide Path Angle	03.00
Course Width at Threshold	106.75
HAL	40.0
VAL	35.0
Length Offset	0000
CRC Remainder	B59D8858
ICAO Code	K4
FPAP Orthogonal Height	+0392.1

For SBAS/WAAS and GBAS/LAAS facilities the FAS data block is loaded into the AFIS as a binary file supplied by the FAA. This file is only used to load the AFIS and its content is derived from ARINC 424. Its parameters define the precision approach, which include the critical path elements that provide the course and glide path deviations to the pilot. When an LPV inspection is performed the AFIS computes the FAF waypoint at a distance of five miles from the threshold point. During the facility inspection after getting a position fix at the threshold and runway end, the flight inspection data acquired is back-corrected between the FAF and the threshold. The FAS data block CRC is used by AFIS to verify the integrity of the data. AFIS computes its own CRC on the decoded FAS data and compares it to the file CRC. This ensures the integrity of the data and a ‘bad’ CRC alerts the operator of compromised data.

For a GBAS/LAAS facility, the FAS data block is loaded into the GBAS facility, which transmits the data to the aircraft. The same FAS data is loaded into the ground station, FMS and AFIS. During the flight inspection several of the FAS data block parameters are measured and verified. The Landing Threshold Point (LTP) and Flight Path Alignment Point (FPAP) are stored in the FAS data block as longitude/latitude coordinates. The bearing from the LTP to the FPAP defines the approach course. This course must match the runway bearing and final approach course. GBAS FAS files only contain 38 bytes of real data while SBAS files have 40 bytes of real data. The difference being that there is no HAL/VAL data in the GBAS file.

The LTP ellipsoid height and the threshold crossing height are parameters that define the GNSS elevation that the glide path will terminate above the runway threshold. Corruption of this data will skew the glide path forward or aft along the inbound course. This condition may lead to the aircraft being below or above the designated glide path[2].

CONCLUSIONS

The application of the ARINC 424 database in performing flight inspection has not been standardized and its future use raises several questions:

1) Is it necessary to have an exact copy of the procedure being flown?

    a. No. However it is necessary to have the FAF and RDP/LTP waypoints that are required starting/stopping points in AFIS. For LPV, it is necessary to have the FAS data for the runway being inspected.

2) Is the ARINC 424 database the only solution?

    a. No. Any database format may be used. This may be a simple text based formatted database or a complex XML formatted database. The ARINC 424 format provides a universally accepted format that can be shared by the FMS and AFIS.

3) Are there other solutions?

    a. Yes, The GAMA format can be expanded to include the additional information and accuracy required by the AFIS. However, it may be very hard to update the GAMA specification and have it implemented in current FMS's in a timely fashion.

    b. The AFIS database may be expanded to include the necessary information. However the AFIS database is a proprietary format.

    c. Define a new AFIS database format for procedures that would supplement the existing databases.

In the future, if there will be plans to standardize the use of the ARINC 424 database for flight inspection, the following disadvantages should be considered:

1) Requires verbal coordination with flight deck to select the same procedure as is entered into the FMS. No guarantee that the flight plans are the same and it may be difficult to verify.

2) FMS may insert pseudo waypoints. Different FMS's may result in different pseudo waypoints or none at all.

3) Crew may add or delete waypoints. These would not be seen by the AFIS.

4) The ARINC 424 database may require a significant coding effort.

RECOMMENDATIONS

Due to the fact that ARINC 424 is a globally accepted format by most FMS's and GPS receivers, its content and use could be adopted by the flight inspection community to achieve the "Gold Standard" in terms of procedure accuracy and repeatability.

One possibility is to expand the use of ARINC 424 beyond the RNAV modes to include VOR, ILS, and MLS inspections, which is currently being supported. With this approach there would be a possibility to eliminate the AFIS database and rely only on ARINC 424. Further expansion could be considered in the future to support other inspection modes.

For future revisions of the ARINC 424 Specification, it may be desirable for the flight inspection community to have inputs for inclusion of specific flight inspection parameters not normally required for aeronautical applications.

REFERENCES

[1] Aeronautical Radio, Inc. Navigation System Database, ARINC 424 Specification.

[2] Flight Inspection Symposium, June 2012, Paper by Dan Burdette, "Flight Inspection of the Ground Based Augmentation System (GBAS)/ Local Area Augmentation System (LAAS)".

[3] Flight Inspection Symposium, June 2008, Paper by Dan Burdette, "Electronic Coding/Packing Process of RNAV Approach Procedures for Flight Inspection".

[4] ARINC 424 GAMA Specification, Version 5.0 dated September 19, 2007

APPENDIX 1

Extract for an ARINC 424 procedure record for KOKC approach plate

```
HDR          KOKC         RWY 17L

TUSAEAENRT   ADWOW K40    W  R  N35293496W097423268  E0044     NAR  ADWOW  002751202

TUSAEAENRT   BECTA K40    W  R  N35434542W097272011  E0042     NAR   BECTA 023251202

TUSAEAENRT   BIRDY K40    W  R  N35231638W097423236  E0044     NAR  BIRDY  027181202

TUSAEAENRT   DAROO K40    W  R  N35131701W098130274  E0047     NAR  DAROO  072661202

TUSAEAENRT   DECKK K40    C  RB N34522212W097165192  E0041     NAR  DECKK  293181202

TUSAEAENRT   FLAPP K40    W  R  N35320678W097452566  E0044     NAR  FLAPP  119071202

TUSAEAENRT   GULLI K40    C  RL N36004302W097083963  E0040     NAR  GULLI  315101202

TUSAEAENRT   HANGS K40    C     N35285310W097352043  E0043     NAR  HANGS  143911202

TUSAEAENRT   HIGVO K40    W  R  N35354775W097352079  E0043     NAR  HIGVO  157301202

TUSAEAENRT   HIPES K40    W  R  N35294935W097260916  E0042     NAR  HIPES  159041202

TUSAEAENRT   ISAKE K40    W  R  N35271889W097291254  E0043     NAR  ISAKE  189801202

TUSAEAENRT   JASKA K40    W  R  N35505407W097192943  E0041     NAR  JASKA  198571202

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Flight Inspection of Helicopter Procedures in a Challenging Topographic Environment

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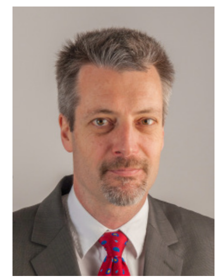

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ABSTRACT

Switzerland will introduce a "low flight network" (LFN) in mountainous terrain with Point-in-space (PinS) procedures to hospitals. Topographical constraints require on the one hand a detailed flight inspection for Global Navigation Satellite System (GNSS) interference and communication coverage but preclude on the other hand the flight inspection with a fixed wing flight inspection aircraft.

Today's demand for flight inspection of helicopter procedures is still limited, requires adapted system installations, and is therefore costly. An efficient solution must be found. The combination of flight inspection and flight validation is a major requirement for economical and ecological reasons. A high end flight inspection system is required to fulfill international and national standards.

This presentation will focus on the current installation and operation of an existing fixed wing flight inspection system in an IFR certified helicopter usually used for Helicopter Emergency Medical Services (HEMS). The description will highlight the different requirements concerning mechanical installation, certification, the quick install and removal possibilities and the independent position determination system. Finally, the benefits of a high quality helicopter flight inspection system for future applications, such as company mobile radio network calibration or flight guidance system certification, will be discussed.

INTRODUCTION

The special topographic situation in Switzerland often faces helicopter operators with inversion layers, especially in winter. While ski resorts have best weather conditions, hospitals can only be reached in marginal visual metrological conditions due to the compact cloud layer.

Since the early seventies of the last century the Swiss Federal Office for Civil Aviation (FOCA) may approve helicopter departure in fog (HDF). Technical and operational requirements for HDF are minimal. Neither a helicopter full Instrument Flight Rules (IFR) certification nor an entire IFR pilot qualification is required.

While departure cloud breaking is today routinely performed, the unavailability of an approach cloud breaking procedure remains a major problem.

For this reason the Swiss Air Navigation Services (skyguide), Swiss Air-Rescue (Rega) and the Swiss Air Force (SAF) started a project to implement a low flight network (LFN) with Point-in-Space (PinS) and Helicopter Approach in Fog (HAF) procedures to hospitals and operational bases.

Once fully implemented, the LFN will cover Switzerland entirely, including a route crossing the Alps and linking over 30 PinS procedures. Required Navigation Performance (RNP) is 0,3NM and PinS procedures are mainly Approach Procedures with Vertical guidance (APV) with Space Based Augmentation System (SBAS).

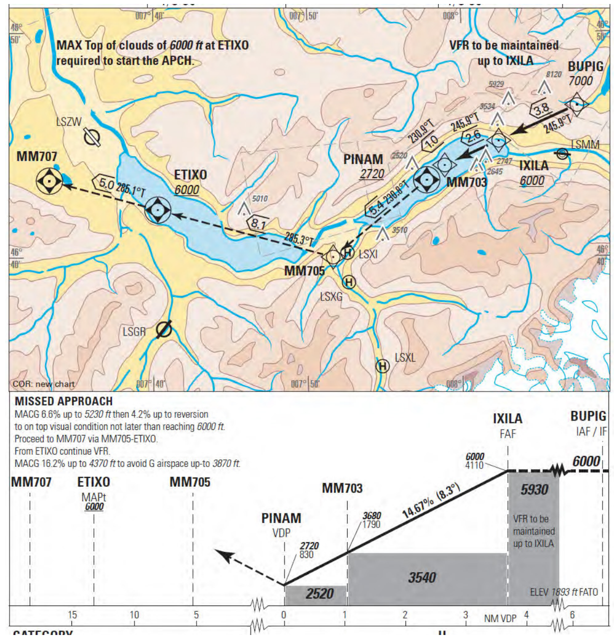

Figure 1. HAF Example

LFN and all PinS procedures are subject to a commissioning flight inspection and a commissioning flight validation. Routine flight inspections may be required due to the special topographic situation.

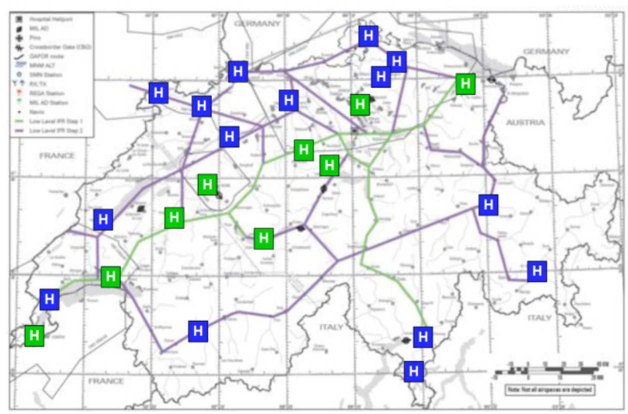

Figure 2. Low Flight Network with PinS to hospitals

FLIGHT INSPECTION OF HELICOPTER PROCEDURES WITH A KING AIR 350

Background

In 2010 FCS Flight Calibration Services GmbH (FCS) first started flight inspecting helicopter procedures with a King Air 350 equipped with an Aerodata AD-AFIS-220 flight inspection system (FIS). FCS King Air 350s are approved for steep approaches up to 6,65° through a supplemental type certificate (STC). Of course, a risk assessment took place prior to each mission, effectively excluding all safety-critical or non-flyable legs from the inspection mission.

The extent of flight inspection of helicopter procedures in Switzerland was limited to one or two approach procedures per year.

The flight inspection was focused on GNSS behavior, interference detection and communication coverage.

Operational problems encountered with King Air 350

Helicopter procedures can generally not be flown by fixed wing aircraft mainly due to the limited turn radius and due to the excessive approach angles. Flight inspection was only possible with workarounds, e.g. flying each leg separately one after the other with a new line up in between, creating additional flight time and costs.

Flight inspection with the King Air on the Berne city hospital procedure led to massive complaints from the population despite a prior radio and newspaper information campaign.

Two other HAF procedures had approach angles of 8,3° and 7° respectively, which are beyond our King Air 350 limitations for approaches.

Flight inspection of the LFN at low levels in valleys and over mountain passes is not possible for safety reasons with a King Air 350. Furthermore, the King Air 350 does not fulfill RNP 0,3 requirements.

For the flight validation task, all procedures were flown in parallel with an IFR certified helicopter by an approved helicopter flight validation pilot, thus increasing costs and environmental impact.

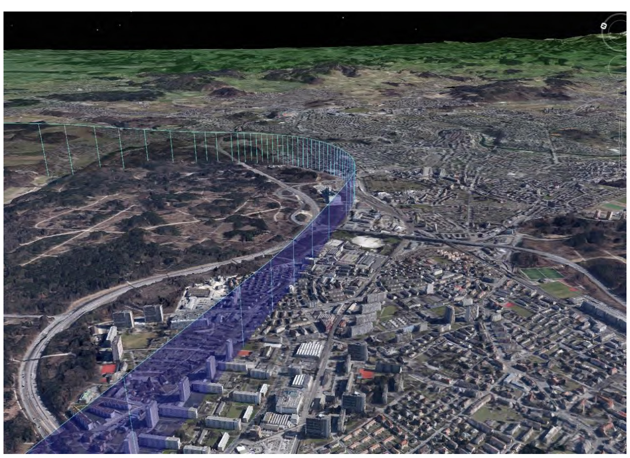

Figure 3. Approach Berne hospital AeroFIS recording presented in Google Earth

GNSS interference

Up to now no GNSS interference was detected on any helicopter procedures. As expected, the GNSS Space Vehicles coverage is limited, especially in valleys oriented in East-West and North-South directions [5]. A GNSS performance analysis in very narrow valleys and with possible multipath effects from cliffs was not yet performed, as a King Air is hardly a suitable platform for these flights.

Figure 4. Typical mountain valley *(Jungfrau Region / Jost von Allmen)*

VHF/UHF communication coverage

VHF/UHF communication coverage is generally calculated prior to the flight inspection. In critical regions coverage must then be verified by flight inspection. Experience showed that communication coverage frequently is a major issue for helicopter procedures. Normal procedures to airports lead from a marginal to a nearly perfect communication infrastructure, whereas helicopter procedures to hospitals typically lead from a good to a poor communication infrastructure.

INSTALLATION OF A KING AIR FLIGHT INSPECTION SYSTEM IN A HELICOPTER

Motivation

Safety issues and the increased demand for helicopter procedure inspections motivated all partners to review the currently applied practice. Despite increasing demand for flight inspection of helicopter procedures, the number is still limited, requires an adapted flight inspection system and is therefore costly.

Feasibility Study

In 2013 FCS Flight Calibration Services GmbH (FCS) carried out a feasibility study in close cooperation with Rega, Aerodata, DFS and skyguide. The goal was to conceive a flight inspection system fulfilling international and national requirements while increasing the safety of the flight operations. The combination of flight inspection and flight validation was also a major objective for economical and ecological reasons.

The study showed that the installation of an existing Aerodata FIS, normally installed in a King Air 350, in an IFR certified Agusta AW109SP of Rega would be the best solution regarding fulfillment of requirements and low costs under the given circumstances.

Requirements

National requirements call for the analysis of the navigation solution error also for GNSS procedures which means that the position accuracy must be in the sub-meter range for APV SBAS.

Beside basic GNSS data such as position information several additional parameters such as carrier to noise ratio for each received space vehicle signal are required for further analysis.

The targeted VHF/UHF field strength measurement uncertainty was 3dB .

In order to combine the flight validation with the inspection it was necessary to install the system in an IFR certified helicopter, preferably equipped with dual instrumentation and commands. The helicopter must be capable to fly RNP 0,3 and approach angles up to 9°.

For the flight inspection system a GNSS L1/L2 antenna outside the rotor disk, a VHF/COM antenna, a power interface and a quick installation and removal unit was mandatory.

For safety and technical reasons a 'loose equipment' installation, e.g. with laptop and a mobile GNSS antenna, was excluded from the beginning.

Selection of helicopter

Rega operates 11 Agusta AW109SP and 6 Eurocopter EC145 for HEMS in Switzerland. The complete fleet is IFR equipped.

One of the Agusta AW109SP is completely dual IFR equipped and normally operated as a backup and training helicopter. Advantageous for this helicopter was an existing VHF/UHF antenna interface, the existing mission power interface with load shedding and the retractable gear for economical ferry flights. A stretcher base with a quick locking device for the stretcher is standard equipment.

The helicopter is already equipped with 2 primary GNSS receivers including data recording with a quick access recorder. A service bulletin for the installation of a third GPS antenna (L1/L2 for the flight inspection system) retaining platform on the vertical stabilizer is currently implemented by AgustaWestland. The installation of the antenna, wiring and connecting interface in the cabin is developed and certified by Rega's own engineering department under their privileges as an approved European Aviation Safety Agency (EASA) design organization (EASA.21J.489).

Figure 5. Agusta AW109SP (Rega)

Flight inspection system design

Due to the stringent requirements for positioning and field strength measurements it was decided to use both design and components of the Aerodata AFIS-220 for the helicopter flight inspection system.

The AFIS-220 was designed for an installation in King Air 350s and is equipped with a large number of sensors not required for a helicopter flight inspection system. The system was reconfigured to a standard basic helicopter configuration with

a. a real time computer for the data acquisition and a display computer with one monitor

b. a hybrid position solution with an inertial navigation system, a GNSS carrier phase solution and an Omnistar wide area augmentation system

c. a Novatel OEM3 GNSS receiver, a TSO approved Collins GPS-4000S GNSS receiver and a Rohde&Schwarz EB200 monitoring receiver

d. a telemetry link for a local DGPS station.

Additionally the following provisions are integrated

e. an interface for a Collins GNLU-930 GBAS receiver

f. an interface for an AD-RNZ-850 NAV/ILS/DME/MKR flight inspection receiver

g. an interface for a Rohde&Schwarz EVS300 measuring receiver

h. an interface for FCS SISMOS (Signal in space monitoring system)

i. an interface for LASER tracker positioning update

The system allows an online evaluation of all results and also permits post flight evaluations with a lab system or a King Air system.

The software remains exactly the same as for the FCS King Air 350s. Aircraft typical configuration files (e.g. for lever arms, antenna positions, antenna data and cable losses) are included in the standard software distribution kits and are automatically detected and applied by a hardware coding.

As the helicopter flight inspection system remains identical with the King Air flight inspection system for the operation, the effort for documentation, training and certification remains minimal.

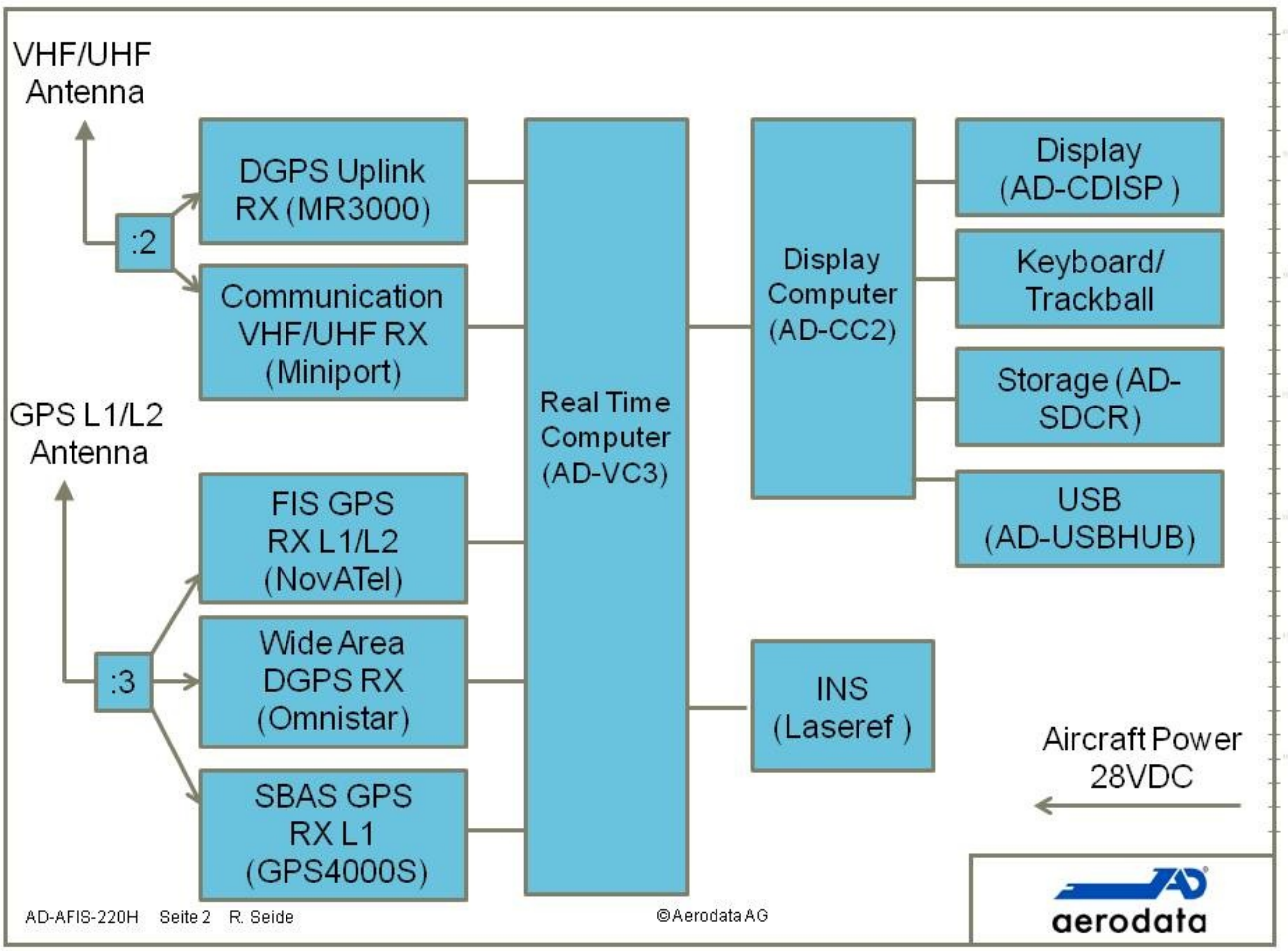

Figure 6. HeliFIS block diagram

Mechanical integration

The main difference between the helicopter flight inspection system (HeliFIS) and the King Air flight inspection system is the mechanical integration.

The FIS in the King Air 350 is a 3 console system with a weight of approx. 400kg, 3500W maximum power consumption and FAR part 23 certified.

Figure 7. Stretcher base Agusta AW109SP (Rega)

To comply with the quick install and removal requirement we decided to install the helicopter flight inspection system on the existing stretcher base with the quick locking device. In fact, the stretcher will be replaced by the HeliFIS.

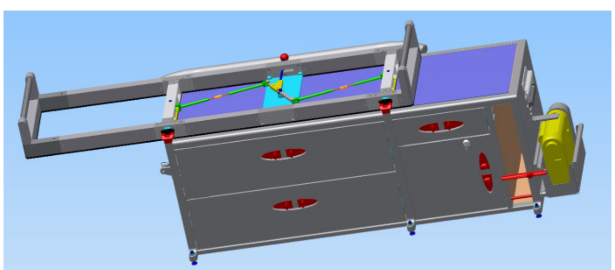

Figure 8. Stretcher base with mounting frame

Subsequently the weight of the HeliFIS was reduced to approximately 80kg. At the same time power consumption was reduced to below the 800W available, and a form factor compatible with emergency exit clearance requirements was determined.

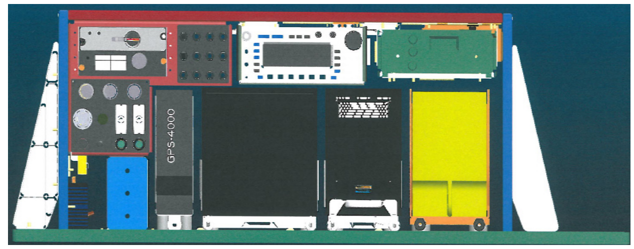

Figure 8. HeliFIS rack front view

A major requirement was the certification according to specification CS 27 with respect to crash loads of 16g forward, 20g downward and 8g sideward, compared to the crash loads of the King Air with only 8g forward.

Aerodata designed and built a new rack complying with these requirements. The rack is fixed on a mounting frame designed by Rega for the existing quick locking device.

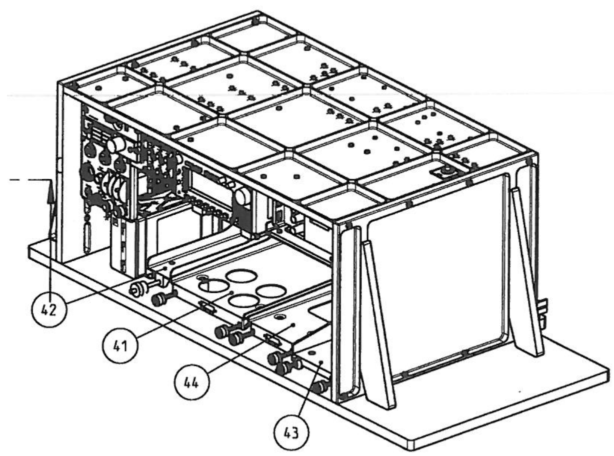

Figure 9. HeliFIS rack

The airworthiness certification is performed by Rega's in-house European Aviation Safety Agency (EASA) design organization.

Commissioning

Laboratory and ground tests will be completed by end of June 2014. The helicopter installation with ground and flight tests is planned in the beginning of July 2014 with a release to service in August 2014.

Figure 10. HeliFIS installed in AW109SP

FUTURE APPLICATIONS

The integration of a high level flight inspection system with an inertial navigation system and GNSS carrier phase solution position accuracy offers a wide spectrum for future applications outside the classical flight inspection tasks.

Approach lighting systems

The HeliFIS basic capability also covers the calibration of visual approach slope indicators (VASI), precision approach indicators (PAPI) or helicopter visual segment approach lighting systems (HALS).

Precision approach RADAR

Precision approach RADAR (PAR) calibration could be a future application for the HeliFIS without any additional modification. This could be of special interest for some high angle PAR approaches to airports in the mountains.

Verification of flight guidance systems

The HeliFIS may be used for the airworthiness verification of flight guidance systems. All flight parameters are available with 10Hz, e.g. angles, position and acceleration. Position accuracy will be better than 0,2m and angular uncertainty is 0,1°.

Verification of mobile land communication system

Rega operates an emergency radio network on 160MHz covering the whole of Switzerland. Coverage in mountainous terrain is ensured by over 40 communication relays. To verify the calculated coverage in critical regions the HeliFIS may be used to verify the simulations comparable to VHF/UHF coverage flights for airborne communication.

Signal in space monitoring

For several years FCS has been operating signal-in-space monitoring system (SISMOS) for RF signal analysis for PSR/SSR and conventional navaids. Up to know the SISMOS operation was limited to measurements on King Air flight profiles and ground measurements. With the HeliFIS this gap could be closed and measurements close to terrain or during hover will be possible.

CONCLUSIONS

The installation of a flight inspection system designed for fixed wing aircraft was successfully adapted for a combined flight inspection and flight validation operations in a rotary wing aircraft.

Weight and high crash loads that need to be considered pose a substantial challenge in the mechanical design that should not be underestimated.

A HeliFIS was derived from a standard flight inspection system in order to minimize project risk, certification and training cost. Despite a limited demand for helicopter flight inspection, this can be a cost effective solution while maintaining a high level of safety for flight operations.

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IFIS 2014

Flight Plan to Innovation

Session 5

Flight Validation of ADS-B and Datalink

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ADS-B
A New Mission for Flight Inspection

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Abstract

New technologies in regard to safety requirements are arising due to expanding capacity in civil air traffic. One important keystone of new techniques comprised in SESAR, NextGen or CNS/ATM is Automatic Dependent Surveillance Broadcast (ADS-B). It has been developed further and has been upgraded in the past years to fulfill more and more its intended function of supplying situational awareness for safety reasons. ADS-B is used in all new commercial air transport and most general aviation aircraft. The schedule for its mandatory use in aircraft is defined and the final dates are coming closer. The worldwide implementation of ADS-B ground stations for area-wide coverage is steadily increasing and the basic rules for it are set.

The deadlines for the enforcement of ADS-B integration are defined, but the rules for necessaries in-flight verification are not. What needs to be tested and what are the requirements to flight inspect such data in accordance to its sensitivity for flight safety during surveillance? What kind of flight checks have to be performed to uphold the accuracy, integrity or procedure workflow resulting out of the ADS-B technology?

This paper summarizes experiences, practices and requirements regarding the flight inspection of ADS-B systems. It evaluates hard- and software requirements to flight inspect the ADS-B service and it discovers new potentialities in flight inspection missions in regard to the ADS-B technology, while considering the importance for flight safety. The corresponding procedures are examined in detail and evaluated in regard to accuracy, integrity and process workflow.

Introduction

All modern commercial airplanes are equipped with capable transponders using the ADS-B transmission. In the past three different ADS-B techniques were used, explored and analyzed in regard to their advantages and disadvantages.

The first ADS-B technique is the transmission via a separate VHF data link, which requires special equipped VHF radios to fulfill the requirements according to MOPS ED108A. The second technique focuses on the dedicated Universal Access Transceiver (UAT) working in the 978 MHz band. Each aircraft has to be equipped with such unit which complies with RTCA DO 282B and TSO C154c. This technique is mainly used for the lower airspace in the United States. The third method for transmitting ADS-B signals is the extended squitter technique in the 1090 MHz band. It complies with RTCA DO 260B and TSO C166b. The extended squitter method is suitable for the lower and upper airspace and used by all commercial airplanes.

This paper focuses on the extended squitter method for ADS-B as the prevailing system and describes in regard to it new possibilities in flight inspection. It displays the scheduled implementation in aviation in different countries around the globe. The necessary diverging expansion stages are examined in regard to its intended function. The possible new procedures for flight inspection are highlighted and discussed.

Regulations for the implementation of ADS-B

The regulations for the implementation of the extended squitter method for ADS-B are defined and the schedule for its incorporation in commercial air transport is announced in most of the countries with frequent regular commercial air traffic. As an example three implementation deadlines of different civil aviation authorities are listed:

- EASA: NPA 2012-19 defines the mandatory extended squitter implementation for all new aircrafts certified after the 8th of January 2015
- FAA: FAR 91.225/91.227 defines the mandatory extended squitter implementation and/or universal access transmitter implementation for all aircrafts until the 1st of January 2020
- CASA: CAO 20.18 defines the mandatory extended squitter implementation for all aircrafts above flight level 290 until December 2013 (only RTCA DO260).

All implementation schedules defining variable stages of introductory phase but in general all focusing on ADS-B as one of the key pillar for surveillance safety in commercial air traffic. This illustrates the important role of flight inspecting this ADS-B technique.

Requirements for ADS-B flight inspection

The general requirement to establish an ADS-B link is to have an airborne segment, which encodes and transmits the necessary data in a special format and a ground segment which receives the data and decodes it. The newest flight inspection systems, like the AeroFIS©, are equipped with state of the art transponders, which are capable to transmit the required data to the ground station. In addition the necessary capable software is included to comply with the newest changes of the defined signal type to manipulate individual transmitted data for flight inspection reasons. The ground stations are equipped with ADS-B receivers to display such data to the radar or ADS-B display operator, dependent on the development stage.

Figure 1: AeroFIS© capable to perform ADS-B flight inspection missions

The flight inspection system comprises a latest revision Rockwell Collins TDR 94 supporting the transmission of elementary and enhanced surveillance and ADS-B messages. Therefore the aircraft is equipped with an additional L-Band antenna for the transponder transmission. Only the newest revision of this transponder complies with TSO C166b and due to this to RTCA DO260B capable for the transmission of ADS-B.

Figure 2: Suitable ADS-B Transponder latest revision

To operate a non primary transponder on an airborne system special rules have to be followed according to airworthiness standards. The special and advanced design of the certified aircraft installation ensures that not two targets are visible for the ATC controller. The airborne flight inspection transponder is fully controlled by the flight inspection operator, which enables him to submit special test data via the data-link. This assures proper decoding at the ground segment and/or allows the ground station to perform fully autonomous checks with such specialized data. The AFIS computer is connected to the transponder through a digital data connection. The computer submits automatically the necessary dataset required by the transponder for transmitting the desired and requested ADS-B data.

Different stages of expansion

Since the implementation of ADS-B several different stages have been passed through according to its specification. The basic specification in RTCA DO260 was update to DO260A, further to Change 1 and 2 of DO260A and finally to RTCA DO260B, which is now the current specification. Its deadlines are mentioned above in this paper.

Capability	DO-260	DO-260A	DO-260B	Comments
NUC (Navigation Uncertainty Code)	✓			Baseline
Mode A Code		✓	✓	Support legacy ATC infrastructure
NACp (Navigation Accuracy Code for Position)		✓	✓	Replaced NUC
SIL (Surveillance Integrity Level)		✓		Replaced NUC
NIC (Navigation Integrity Code)		✓	✓	Replaced NUC
Revise SIL to become Source Integrity Level & add: SDA (System Design Assurance)			✓	Clearly separates the reporting to reflect equipment certification levels and navigation source fault detection capability
Revise NIC/NAC/SIL and add GVA (Geometric Vertical Accuracy)			✓	To improve vertical accuracy, decouple vertical from NIC/NAC/SIL and add GVA
Add ADS-B IN bits			✓	Enhancement to show both UAT IN and 1090ES IN receiver equipage
Changes to the Target State Report			✓	To better align with available aircraft data
Offer non-diversity antenna options for small aircraft			✓	Lower cost of equipage for General Aviation
Revise latency requirement (limit extrapolation)			✓	Enhancement
New guidance on how to determine NACv			✓	Fix
New guidance on how to select the best position/state vector sources			✓	Fix
Changes to the Mode A Code transmission rates			✓	Improvements and squitter efficiencies
Redefine TCAS status bits			✓	Fix
Fixes and improvement to NIC reporting and modified surface movement field for airport surface			✓	Improvements for Surface applications

Figure 3: Changes in stages of expansion

Figure 3 shall highlight the tremendous changes in each development stage of the specification of ADS-B. The data, which are transmitted via ADS-B in the last development stage, are grown enormously and influencing more and more the flight safety segment of each aircraft. Therefore the data content of ADS-B becomes further critical for the aircraft itself and for the receiving parties of the signal.

In the past flight inspection missions have focused on three main tasks, while inspecting the receiving ADS-B ground segment:

- Coverage Checks
- Interference Checks
- Data Continuity and Integrity Checks

The flight checks were most likely performed together or in accordance to the regular radar flight inspection tasks.

Nowadays a new mission for flight inspection is conceivable, which investigates the safety critical nature of the complete ADS-B system in regard to its future use in programs like SESAR, NextGen or CNS/ATM.

Dataset transmitted according to ADS-B RTCA DO260B

The ADS-B dataset which is transmitted via extended squitter specified according to RTCA DO260B is very extensive. The complex design enables future upgrades and further enhancements. Today the mentioned below data are transmitted, at which only the most important datasets are listed. The data list is separated according to known terms of aircraft implementation stage. The terms are described in detail in the EASA certification specification for airborne communication, navigation and surveillance:

ELS – Elementary Surveillance:

- Squawk
- Altitude
- On Ground Status
- Aircraft Identification (Flight Plan or Registration)
- Special Position Indication (IDENT)
- Emergency Status
- Data Link Capability
- Common Usage GCIB Capability
- ICAO 24-bit aircraft address
- ACAS report

EHS – Enhanced Surveillance (Data in addition to ELS):

- MCP/FCU Selected Altitude
- Roll Angle
- True Tack Angle
- Ground Speed
- Magnetic Heading
- Indicated Airspeed or Mach Number
- Barometric Altitude Rate or Inertial Altitude Rate
- Barometric Pressure Setting (QNH)
- Track Angle Rate or True Airspeed

ADS-B Out (Data in addition to ELS and EHS):

- Horizontal Position (fine and course)
- Horizontal Position Quality (NIC, NAC_P, SIL, SDA)
- Pressure Altitude Quality (NIC_{BARO})
- Velocity over Ground (East/West, North/South)
- Velocity Quality (NAC_V, SIL, SDA)

- Geometric Altitude (WGS84)
- Geometric Altitude Quality, respectively Accuracy (GVA)
- Extended Squitter Version
- Emitter Category
- Length and Width of Aircraft
- GPS Antenna Offset

Not all aircrafts are capably of transmitting the complete information. Either this is induced by missing sensors, not connect sensors or due to an old standard of the transponder itself. Nowadays only a few of those transponders in general aviation are fully certified according to TSO C166b. But of course the availability of such units is growing as we are coming nearer to each individually deadline.

Flag	Code	Callsign	Country	Altitude	Speed	Track	Vert Rate	Squawk	Latitude
	[redacted]	[redacted]	Germany	9.800 ft	291.1 kts	282.7°	-512	1453	52.396°
			Germany	30.025 ft	415.4 kts	51.3°	-1088	5016	52.395°
			Germany	21.650 ft	367.1 kts	1.1°	-3072	5015	53.020°
			Germany	27.750 ft	455.1 kts	161.3°	1472	1361	52.609°
			Norway	32.000 ft	457.6 kts	198.5°	0	0770	52.471°
			Norway	36.975 ft	483.1 kts	178.7°	0	3535	52.333°

Figure 4: Alpha page of the ground receiver with ADS-B information

This real data example in Figure 4 shows that not all information is transmitted. This can be caused by reasons mentioned earlier in this paper or by intention from the aircraft operator respectively airline operator.

ADS-B and flight inspection

In the past the main aspects for flight inspection was to fulfill its tasks according to coverage, interference, continuity and integrity. Modern flight inspection systems are capable to transmit the complete dataset as listed above and can modify this critical data set. This data respectively modified data can be transferred to the ground station to assure correct decoding of the signal and to adjust settings during commissioning. An example of the flight track on which the desired ADS-B check is monitored and recorded is shown in Figure 5. This graphic and its alphanumeric values are compared automatically to the graphics and recordings of the ground station.

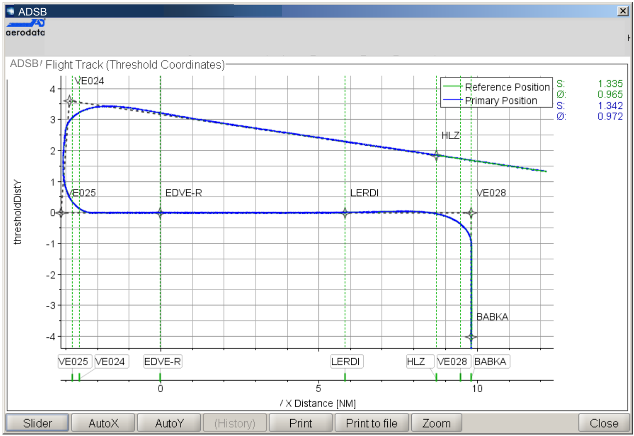

Figure 5: Flight track of flight inspection mission with monitored ADS-B information

In Figure 6 to 10 examples from the AeroFIS© of control pages of the graphical user interface are shown for the ADS-B management. For testing purposes all values can be modified to a defined value or to the actual pertinent value derived from the primary avionic of the aircraft.

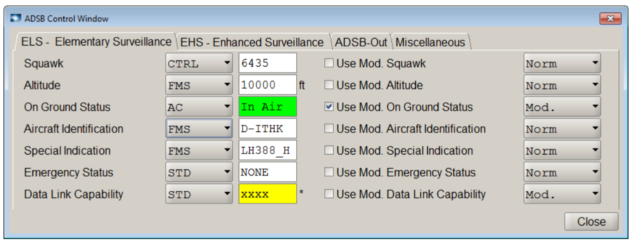

Figure 6: Control page of ADS-B elementary surveillance

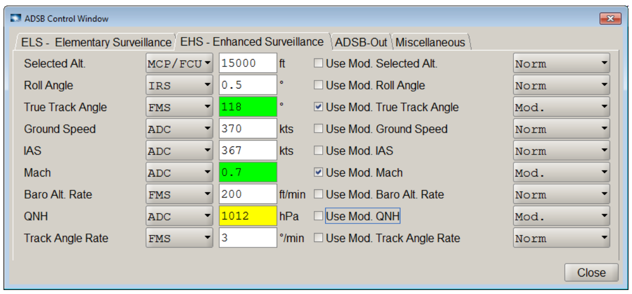

Figure 7: Control page of ADS-B enhanced surveillance

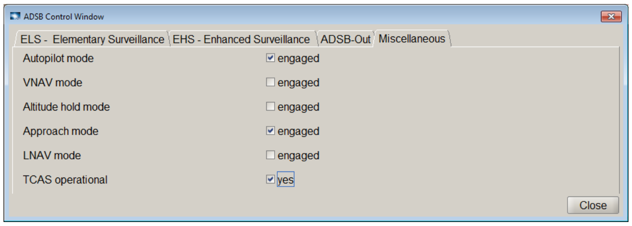

Figure 8: Control page of ADS-B miscellaneous parameter

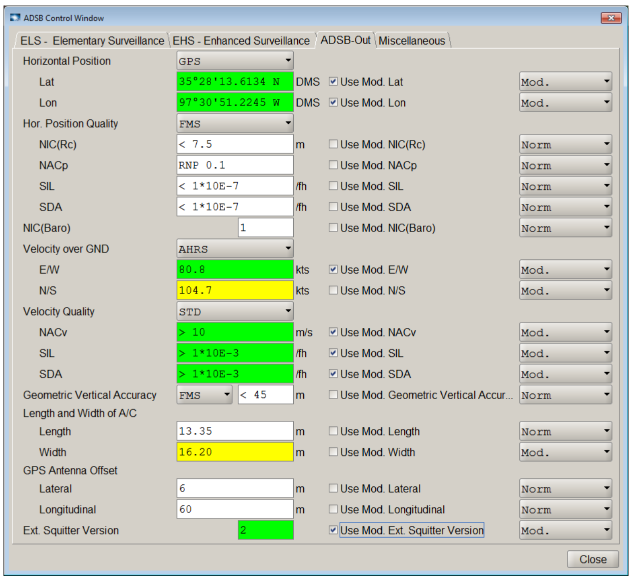

Figure 9: Alpha page of flight inspection system with ADS-B information

Of course modified ADS-B transmission has to be communicated in advance with ATC and has to follow the regulations of each country. A closer look into the sensitivity of this data and into the growing influence on secure air traffic management and surveillance reveals the growing field of flight inspection regarding ADS-B. All data sets of the above displayed figures could be easily modified by the flight inspection operator, either through a predefined procedure or by simply choosing the typed in value in the text field. Also position critical data can be modified in the airborne flight inspection system. This will allow the receiving ground base to simulate the procedures which are caused by an integrity problem or any other problem of an airliner. Not only the value can be verified, also the routine, the process behind it and the action, which is required to assure the dedicated safety or integrity. As visible in Figure 9 the Source Integrity Level (SIL), the System Design Assurance Level (SDA) in conjunction with Navigation Accuracy Category (NAC_P) for the position can be manipulated in parallel. This enables air traffic control to cross check the dedicated recovering procedures. The complete internal path at air traffic management starting with recognizing the error, initiating dedicated procedures and the required action can be verified in regard to its correct function.

Conclusion

Because of the required and intended improvements for the surveillance of aircrafts in aviation regarding air traffic control, and the growing capability of the ADS-B and its key function regarding large programs like SESAR, NextGen or CNS/ATM, it is mandatory to flight inspect the ADS-B ground segment. Flight check of these data including simulate special procedures will become compulsory, if ATC has to relay on these data safety wise and if this safety relevant data is steadily increasing.

The future development for this surveillance, situation awareness and information technique is not easily foreseeable yet. The growing capacity in conjunction with possibilities for ATC improvement will definitely require flight inspection for these new procedures in the future.

References

[1] ICAO Annex 10, Vol IV – Surveillance and Collision Avoidance Systems, Fourth Edition, 2007

[2] ICAO Doc 9871 – Technical Provisions for Mode S Services and Extended Squitter, Second Edition, 2012

[3] EASA Web Page – http://easa.europa.eu

[4] FAA Web Page – http://www.faa.gov

[5] CASA Web Page – http://www.casa.gov.au

[6] Eurocontrol Web Page – https://www.eurocontrol.int

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What We Have Learned About ADS-B and How Do We Stay Under the RADAR

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ABSTRACT

Automatic Dependent Surveillance – Broadcast (ADS-B) is a critical component in successfully implementing the United States Federal Aviation Administration's (FAA) Next Generation Air Transportation System (NextGen) initiative for addressing the growing concerns of an aging U.S. National Airspace System (NAS) infrastructure. The advent of ADS-B provides a necessary stepping stone to propel the FAA into a new era in aviation, utilizing Global Navigation Satellite Systems (GNSS) as the foundation for advancement. ADS-B is a satellite based surveillance technology that employs two separate broadcast link technologies; 1090 MHz Extended Squitter (ES) and 978 MHz Universal Access Transceiver (UAT) along with ground infrastructure technologies to improve the position accuracy interface between aircraft to aircraft and aircraft to air traffic control, providing an enhanced level of safety both airborne and during ground movement.

This paper presents a descriptive view of the current FAA flight inspection methodology for evaluating both *Critical* and *Essential* ADS-B services.

This paper also provides an overview of ADS-B concepts, the interoperability of various components within ADS-B and the enhanced features ADS-B provides in comparison to a legacy radar system.

INTRODUCTION

The Federal Aviation Administration (FAA) has been developing the Next Generation Air Transportation System (NextGen) with the initiative of addressing the growing concerns of an aging National Airspace System (NAS) infrastructure.

As part of the NextGen development, the FAA has determined that it is essential to move from ground-based surveillance and navigation to a more robustly dynamic and accurate airborne-based system utilizing GNSS as the foundation for advancement.

Automatic Dependent Surveillance-Broadcast (ADS-B) is a critical component in the successful implementation of the FAA's NextGen long-term modernization initiative. ADS-B equipment is an advanced surveillance technology that combines an aircraft's positioning source, aircraft avionics, and a ground infrastructure to create an accurate surveillance interface between aircraft and Air Traffic Control (ATC). ADS-B is a performance-based surveillance technology that provides a more precise position reference achieved through higher updates rates and enhanced accuracy of surveillance information over the current radar-based system consisting of Primary Radar and Secondary Surveillance Radar (SSR).

ADS-B is expected to provide air traffic controllers and pilots with a more accurate representation of an aircraft's three-dimensional spatial position; to improve terminal and en route aircraft separation services and during ground movement; minimizing potential runway incursion incidents.

The inclusion of ADS-B into the NAS will inherently promote an environment of increased safety by enhancing the situational awareness for the both the airline and general aviation communities and air traffic operations. In conjunction to the increased level of safety introduced by ADS-B, improved efficiency in operations and enhanced 'visibility' will allow the NAS to be expanded to contend with current and future airspace congestion concerns. As a result of ADS-B's improved position accuracy and increased surveillance services, ATC will be able to move aircraft to and from congested airport environments with smaller separation standards; increasing the NAS' capacity, reducing delays associated with vectoring for spacing, holding times, and reducing operating costs with more efficient flight profiles resulting from improved surveillance services into areas where none currently exist. With the increased efficiency, the economic and environmental impact can be lessened by reducing fuel consumption and costs, CO_2 emissions, and noise.

ADS-B consists of two differences services: ADS-B Out and ADS-B In. ADS-B Out broadcast messages contain specific aircraft information such as; identification, both horizontal and vertical Position Velocity & Time (PVT). The information broadcast by the aircraft is received by appropriately equipped aircraft within line of sight of the broadcast signal and also by the ground infrastructure network; which will process and provide a target and pertinent identifiable information to ATC automation for display and tracking. ADS-B In refers to an appropriately equipped aircraft's ability to receive and display another aircraft's ADS-B Out broadcast message as well as the ADS-B In services provided by the ground system, including Automatic Dependent Surveillance-Rebroadcast (ADS-R), Traffic Information Service-Broadcast (TIS-B), and Flight Information Service-Broadcast (FIS-B).

Although ADS-B technology is being deployed in support of ground operation surface vehicles in conjunction with aircraft, the discussions of this paper will primary focus on ADS-B equipage and usage pertaining to aircraft and not include specific references to surface operations.

BACKGROUND

The Federal Aviation Administration maintains a certification process that is an integral quality control method to ensure that air traffic control systems, subsystems, and services directly affecting the flying public are safe and function as intended. FAA has historically owned and operated all key air traffic control systems in the NAS but has recently been transitioning more of them to the private sector. Under the contract terms, the FAA owns the design and configuration of ADS-B and also the ADS-B surveillance data transmitted, but Exelis maintains ownership of the hardware and ground infrastructure used by FAA's ATC facilities.[2]

The FAA has adopted a policy of using monitoring rather than certification to ensure the ADS-B ground infrastructure meets FAA's standards. The FAA developed a monitoring system called the Surveillance and Broadcast Service (SBS) Monitor. Two SBS monitors have been installed; one is located at the FAA Technical Center in Atlantic City, NJ, and the other one at the FAA Mike Monroney Aeronautical Center in Oklahoma City, OK.[2] These SBS monitors receive ADS-B Reports in FAA All Purpose Structured EUROCONTROL Surveillance Information Exchange (ASTERIX) CAT033 Report format, TIS-B Reports in ASTERIX FAA CAT033 format, FIS-B in a non-ASTERIX or FSPEC format, Service Status Reports in the ASTERIX FAA CAT023 format, ADS-R Acknowledgment/ Negative Acknowledgement (ACK/NACK) according to field specification (FSPEC) format, Wide Area Multilateration (WAM) Reports in ASTERIX FAA CAT010 format, and WAM Service Status Reports in ASTERIX FAA CAT019 format. These reports are used to monitor, confirm system performance, and validate contractor compliance and system service status by an FAA Operational Control Center (OCC). The OCC coordinates with the service provider's Network Operations Center (NOC) to report any abnormal facility status indications. The NOC has control access to all Surveillance and Broadcast Services Subsystem (SBSS) components to continuously monitor the 'health' and performance of the system.

Table 1. Broadcast Services Data Unit ID Byte Values [3]

Application Elements	Value (decimal)	Direction (To/From SBSS)
ADS-B Reports	033	From
TIS-B Reports	033	From
FIS-B Reports	032 (assigned by Exelis)	From
Service Status Reports	023	From
ADSR ACK/NACK Reports	002 (assigned by Exelis)	From
WAM Reports	010	From
WAM Service Status Reports	019	From

ADS-B DESCRIPTION

On May 28th, 2010 the FAA issued a final rule mandating ADS-B equipage and performance standards, listed in Title 14 of the Code of Federal Regulations (14 CFR) part 91, § 91.227, for aircraft usage within the airspace defined in Title 14 of the Code of Federal Regulations (14 CFR) part 91, § 91.225. The aircraft equipment must be installed and meet the requirements set forth in TSO-C166b for the 1090ES broadcast link technology; and TO-C154c for the 978 MHz UAT broadcast link technology. Effective January 1st, 2020, any aircraft operating in current Mode C required airspace, will also be required to carry an ADS-B Out transmitter. At the time of this writing, the FAA Final Rule is not mandating the requirement for ADS-B In.[1]

ADS-B stands for: Automatic – it's always on and requires no operator intervention nor is an interrogation necessary to activate the system and broadcast. Dependent – the spatial accuracy of the aircraft's position is reliant upon a valid and accurate GNSS signal, Flight Management System (FMS), or inertial/multisensory navigation system for positional updates that are broadcast to other similarly equipped aircraft and the ground surveillance infrastructure. Surveillance – the system provides satellite based surveillance "radar like" services to determine and aircraft's position. Broadcast – an aircraft will automatically transmit, without interrogation, squitter messages at a 1 Hz rate; relaying its calculated PVT and other pertinent aircraft specific information.[4]

ADS-B Surveillance service falls under the purview of Surveillance and Broadcast Services (SBS). The ground-based portion of ADS-B falls under the Surveillance and Broadcast Services Subsystem (SBSS). The SBSS portion contains the ground radio station (RS) that provides both an uplink and downlink coverage interface to all ADS-B equipped aircraft in the NAS; receives and decodes ADS-B Messages while performing reasonable test and then forwards the messages to the Control Station. Control Stations process ADS-B reports, radar/sensor reports and meteorological/aeronautical data, perform validity checks and provide a low-latency feed of surveillance information to designated FAA SDPs. Service Delivery Points (SDP) are the demarcation points that serve as the interface to ATC Automation and the FAA SBS monitor that routes received target data and delivers ADS-B target reports and other data to the appropriate services, and the associated communications network that provides the connectivity for the processing/exchanging of data.

ADS-B is currently divided into two separate service specifications; Separation/ Critical and Advisory/ Essential. Contained within the two service specifications there are four distinct services provided; Automatic Dependent surveillance-Broadcast (ADS-B), Automatic Dependent Surveillance-Rebroadcast (ADS-R), Traffic Information Service-Broadcast (TIS-B), and Flight Information Service-Broadcast (FIS-B). The Separation service specification currently only encompasses ADS-B services. ADS-R service originally fell under the Separation service specification, but has since been relegated to advisory level surveillance only and will be addressed once the requirements and design for Critical services mature. TIS-B and FIS-B services fall within the Essential services specification and are considered as advisory only. "It should be emphasized that there is no delegation of separation responsibility from controllers to pilots as a result of SBS Essential Services. Furthermore, pilot responsibilities for see and avoid and obtaining the requisite weather and aeronautical information regarding their flight are unchanged." [5]

Operators have two broadcast link technologies for aircraft equipage used to broadcast the aircraft's State Vector and other pertinent identifying information; 1090 MHz Extended Squitter (ES) and/or 978 MHz Universal Access Transceiver (UAT). The 1090ES is an extension of the Mode S technology and is the internationally agreed upon broadcast link technology for ADS-B and is intended to support applications used by carriers and other high-performance aircraft. 1090ES will be required for aircraft flying at or above 18,000 feet mean sea level (MSL). 1090ES will include the ability to obtain ADS-B In services; ADS-R and TIS-B services but will preclude receiving FIS-B due to bandwidth congestion. The 1090 MHz broadcast link technology is currently being employed for other services such as; Mode A/C and S transponder, Air Traffic Control Radar Beacon System (ATCRBS) for aircraft replies to an interrogation from the ATCRBS ground sensor on 1030 MHz and the on-board Traffic Collision Avoidance System (TCAS). The 978 MHz UAT wideband multi-purpose broadcast link technology will have the capability to receive ADS-B In services; ADS-R, TIS-B, and FIS-B. The structure of the UAT frame protocol uses Time Division Multiple Access (TDMA) in the Time Division Duplex (TDD) mode with regular time slotted access or random access protocols. There are two types of transmissions on the UAT broadcast link; the ADS-B message and the Ground Uplink Message. The ADS-B message is used to broadcast the aircraft's State Vector and other identifiable information to other ADS-B In equipped aircraft and ground stations within radio line of sight. The ground uplink message contains the services provided by the ground station.

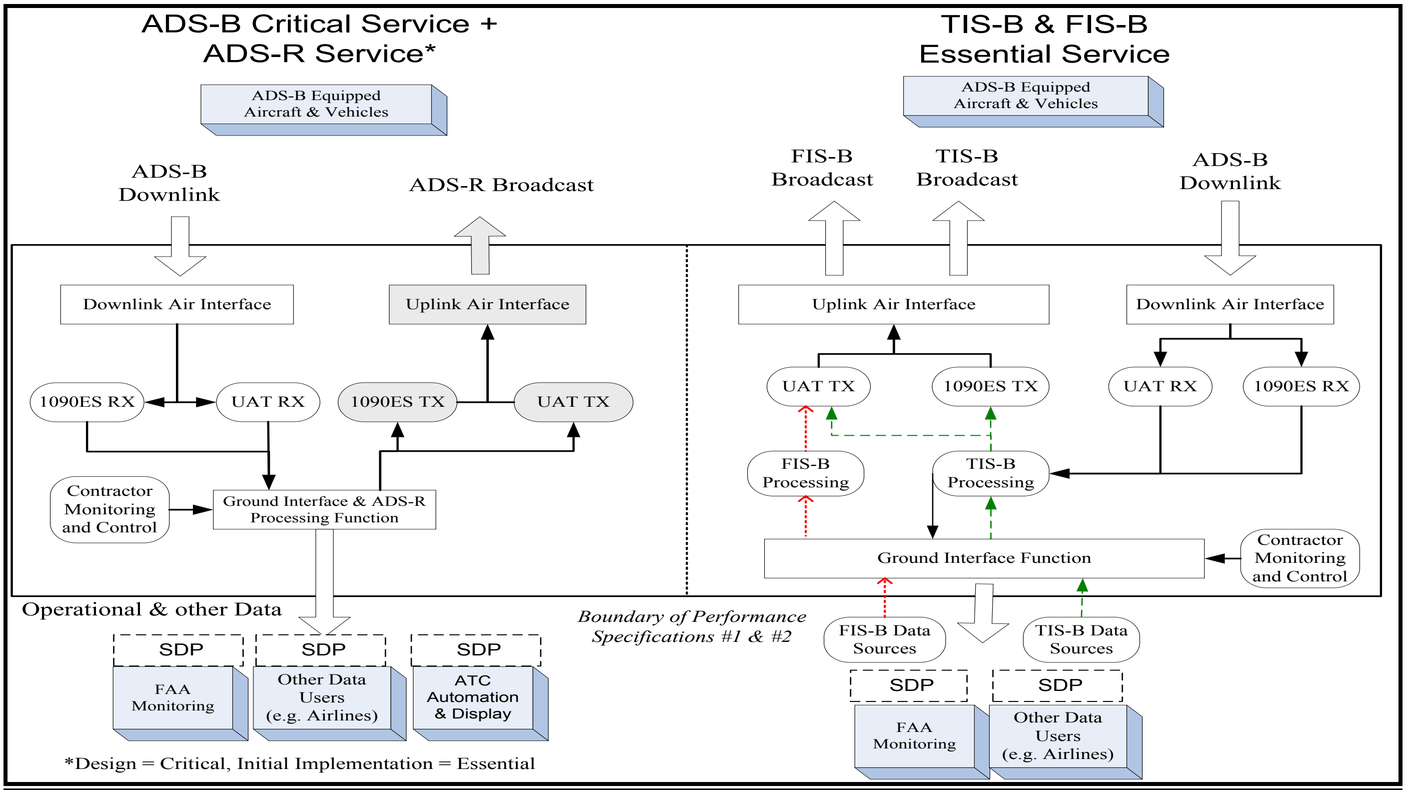

Figure 1. Surveillance and Broadcast Services Partitioning.[5]

Except for specifically selected operational service areas, the SBSS automation filters out all broadcast link technologies that are not RTCA DO-260B and DO-282B compliant. 1090ES broadcast link versions are 0, 1 or A spec., 2 or B spec. UAT broadcast link versions are 1 or A spec. and 2 or B spec. The A or B spec. is synonymous with the corresponding version of RTCA DO-260 and DO-282 documents. The RS decodes the broadcast link technology version from the ADS-B Out payload from each target. Only link technologies that are version 2 will be sent to the ATC display as an ADS-B target.

Client Aircraft Equipage	Proximity Target Aircraft Equipage				
	Non ADS-B Radar (Mode C/Mode S)	1090ES (Version 0, Version 1)	1090ES (Version 2)	UAT (Version 1)	UAT (Version 2)
UAT (Version 2)	TIS-B Service	TIS-B Service	ADS-R Service	ADS-B Air/Air	ADS-B Air/Air
1090 ES (Version 2)	TIS-B Service	ADS-B Air/Air	ADS-B Air/Air	TIS-B Service	ADS-R Service
Dual UAT (Version 2) /1090ES (Version 2)	TIS-B Service (on UAT)	ADS-B Air/Air	ADS-B Air/Air	ADS-B Air/Air	ADS-B Air/Air

Note: Only 1090ES Version 2 (defined in DO-260B), and UAT Version 2 (defined in DO-282B) are supported. The 1090ES as defined by DO-260, often referred to as Version 0, is not supported.

Figure 2. Target Provision to ADS-B In Aircraft [7]

Automatic Dependent Surveillance-Broadcast

ADS-B equipped aircraft broadcast their state vector (horizontal and vertical position, horizontal and vertical velocity) and other information through the use of a 24-Bit address assigned to the aircraft avionics, over either 1090ES or UAT broadcast link technology. This 24-Bit address may be either an ICAO address or a self-assigned address (applicable to UAT only). The ADS-B messages are received by other properly equipped ADS-B In aircraft with the same link technology and ground stations within radio line of sight. The ADS-B ground system processes the ADS-B messages (also referred to as payloads) and formats them into a common ADS-B Report format. These ADS-B Reports are delivered to ATC for use in separation assurance and other services. Latency is the measurement of the reception of the last bit of an ADS-B Message containing State Vector to the receipt of the first bit of the corresponding ADS-B report at the SDP. The maximum delay or latency must be less than or equal to 700 ms. ADS-B Reports are output to the SDPs using FAA CAT033 format. Each specific element within the FAA CAT033 ADS-B Report is identified with a Field Reference Number (FRN).[5, 6]

Table 2. ADS-B Position Update Intervals [7]

ADS-B Position Update Intervals	
Surface	On average; at least 1 per second at the SDP
Terminal	< 3 seconds at the SDP
En Route	< 6 seconds at the SDP
En Route High Update (HU)	< 3 seconds at the SDP

Automatic Dependent Surveillance- Rebroadcast

ADS-R is a client service provided by the SBSS that allows aircraft with single link technology ADS-B In the capability to interact with other aircraft that are broadcasting on a different broadcast link technology. An aircraft that is an active ADS-B user and is receiving ADS-R service is known as an ADS-R Client. An ADS-B equipped aircraft on the opposite link as the ADS-R Client that has its messages translated and transmitted by the SBSS is known as an ADS-R Target. ADS-R service is not offered in all service volumes, but if the service is provided the ADS-R Client must be ADS-B Out equipped, have broadcast a valid position report within the last 30 seconds and received by a ground RS and must be ADS-B In on only one link.[5] Aircraft that are dual link technology equipped will not receive an ADS-R uplink message, they will receive a single ADS-B target. ADS-R targets for an aircraft are determined by the SBSS which populates a list of all active ADS-B equipped aircraft and their respective technologies via received ADS-B reports. The SBSS determines which ADS-B In technology the aircraft is requiring and will broadcast an ADS-R report to the receiving aircraft identifying which other aircraft are within its client proximity 'hockey puck'. Each ADS-R target aircraft may have one or more client aircraft that need to receive an ADS-R report. If there is more than one client, there could be multiple service volumes needed to provide the ADS-R report. The SBSS determines the ADS-R transmission rate required by the client and also determines which ground RS or set of RSs are necessary to transmit ADS-R reports. An aircraft may also be in range of a ground RS that is transmitting reports required by other aircraft. When this is the case it will receive reports of aircraft that are outside the altitude and horizontal range of its vicinity.[5]

As depicted in Figure 3. ADS-R En Route and Terminal Airspace Client Proximity Determination, all aircraft within a 15 NM horizontal range and ± 5000 feet of the ADS-R client aircraft will have their ADS-R target reports uplinked.

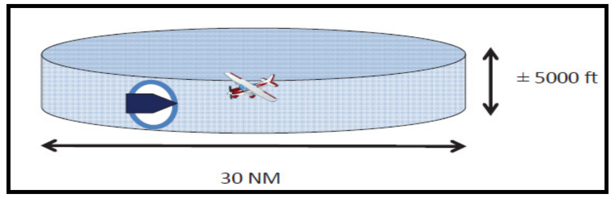

Figure 3. ADS-R En Route and Terminal Airspace Client Proximity Determination[5]

The cumulative number of messages transmitted by all SBSS RS within reception range of any aircraft in the NAS will not exceed 1,000 1090ES messages per second. This limit applies to both the ADS-R and TIS-B services combined (although ADS-R transmission are prioritized over TIS-B when approaching capacity limits). The cumulative maximum number of UAT messages received by an aircraft will not exceed 400 messages per second. These limits are achieved through a combination of the client proximity filter size, the density of radios, radio transmit power, the required update intervals, and the best radio selection algorithm.[5] The maximum latency delay between the Time of Message Received (TOMR) of an ADS-B Message that results in the generation of an ADS-R uplink message and the transmission of the first bit of any corresponding broadcast message on the opposite link technology must be less than 1 second.[7]

Table 3. ADS-R Position Update Intervals [7]

ADS-R Position Update Intervals	
Surface	≤ 2 seconds for each client
Terminal	≤ 5 seconds for each client
En Route	≤ 10 seconds for each client

ADS-R and TIS-B Service status shall be provided to a client with ADS-B In availability; to indicate whether the services are currently available to each link technology. The services status provides users with a near real-time indication of the availability of a complete surveillance picture. ADS-R Service status will not be provided to clients that are equipped to receive ADS-B In on both link technologies.

Traffic Information Service-Broadcast

TIS-B is a client service provided by the SBSS that allows ADS-B In equipped aircraft to receive ground-based surveillance systems sensor data in digitized form.[5] These ground-based systems include FAA and Department of Defense (DoD) radar systems and FAA multilateral systems. The TIS-B service provides a low-latency stream of position reports from non-ADS-B equipped aircraft. An aircraft ADS-B user receiving TIS-B service is known as a TIS-B client. To be considered a TIS-B client an aircraft must be ADS-B Out, provide a valid position report within the last 30 seconds received by a RS, and must be ADS-B In on at least one link.[5] TIS-B latency is the difference between the time of measurement of the source position data and the time of transmission of the TIS-B message. Latency must be ≤ 1.5 seconds; as measured from the SDP to the start of the TIS-B message transmission.[7]

As depicted in Figure 4. TIS-B En Route and Terminal Airspace Client Proximity Determination, all aircraft within a 15 NM horizontal range and ± 3500 feet of the TIS-B client aircraft will have their TIS-B target reports uplinked.[5 7]

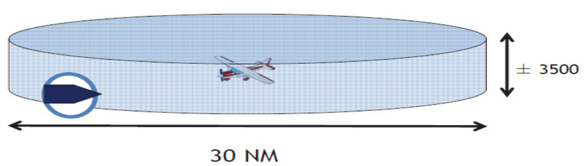

Figure 4. TIS-B En Route and Terminal Airspace Client Proximity Determination[5]

The SBSS fuses multiple surveillance sources into a singular aircraft tracks. The tracks are then cross matched with a list of active ADS-B users, if the track does not correlate to an ADS-B user the track is then handled as a TIS-B target. TIS-B has a service ceiling of 24,000 feet MSL, above which TIS-B client will not be provided TIS-B service (targets will be provided up to 27,500 feet).[5]

The TIS-B service must assign a unique target address to each target. The address may come from the 24-Bit ICAO address included in an ADS-B message or self-assigned by the TIS-B service. Once a target address has been assigned, it must remain constant to ensure user updates can associate the change in state vectors to a particular target.

Table 4. TIS-B Position Update Intervals [7]

TIS-B Position Update Intervals	
Surface	≤ 2 seconds for each client
Terminal	≤ 6 seconds for each client
En Route	≤ 12.1 seconds for each client

TIS-B service updates for target position and velocity data is dependent on the availability of source sensor input. In the event an updated sensory input has not been received, it may be necessary to transmit the same report multiple times in order to ensure the required update and probability of detections specifications are met.[5]

Flight Information Service-Broadcast

FIS-B is a broadcast service and not considered client based. FIS-B supports the Weather and NAS Status Information Situational Awareness Application.[7] FIS-B service for weather and aeronautical information is broadcast over the UAT link technology only, regardless if there are any SBSS clients within the Service Volume. Some of the FIS-B services provided: Airmen's Meteorological Information (AIRMET), Significant Meteorological Information (SIGMET), Convective SIGMET, METAR, TAF, Continental United States (CONUS) Next-Generation Radar (NEXRAD), Regional NEXRAD, Notice To Airmen (NOTAM), Pilot Report (PIREP) and winds and temperatures aloft.

FIS-B services are not broadcast from every RS, but rather with the concept that a single radio station within a service volume will provide a specified set of data products. Radio stations that provide FIS-B services are configured in a tiered design and the products received from the designated RSs will vary depending on the tier classification assigned to the RS.

Table 5. FIS-B Radio Station Tiers [7]

Tier	Altitude range	Description
High-altitude	surface - 24,000' MSL	This altitude band extends up to the upper limit of FIS-B service (24,000' MSL). These ground stations serve some higher-performance general aviation aircraft (turbocharged or turbine) operating in an En Route environment, and also serve commercial aircraft in climb/descent (and some En Route).
Medium-altitude	surface - 14,000' AGL	These ground stations serve the majority of general aviation aircraft operating in an En Route environment. The upper band of 14,000' was chosen as this would typically be above the service ceiling of the world's most-produced aircraft (Cessna 172: over 43,000 built), thus this band includes the largest quantity of aircraft. It also includes some commercial aircraft in climb/descent (and some En Route).
Low-altitude	surface - 3,000' AGL	These ground stations serve the majority of aircraft (of all types) operating in a Terminal environment.
Surface	surface	These ground stations consist of Surface Service Volume radios which serve aircraft in the immediate vicinity of major airports.

FIS-B is required to work up to FL240, but it is expected that the services will be available for higher altitudes. In its current product design station, an estimated 90% of the areas will have FIS-B coverage up to FL400.[7]

Table 6. FIS-B Product Transmit Intervals [7]

FIS-B Product Transmit Intervals	
AIRMET, SIGMET, AND METAR	5 minutes
CONUS NEXRAD	15 minutes
Regional NEXRAD	2.5 minutes
NOTAM, PIREP, and Wind and Temp Aloft	10 minutes
TIS-B Service Status	10 seconds

Service Volumes and Composite Traffic Volume

A Service Volume (SV) is a defined volume of airspace in the NAS; which ADS-B Services are provided and the required performance criteria are met. A Composite Traffic Volume (CTV) is the aggregation of reports from multiple SVs. The reports within a CTV are filtered spatially according to a specified polygon and to eliminate radio station duplicates. SVs are classified into three different domains; En Route, Terminal, and Surface. At the time of this writing, there have been 40 CTVs and 272 SVs inspected; these figures include the deployment of 619 radio stations.

Each SV has an 'assigned' horizontal and vertical boundary, of which, specific ADS-B services are provided by the SBSS. SVs and CTVs are designed to ensure the applicable domain is within the horizontal boundaries of ADS-B service via software masking. Radio Stations within each terminal SV are designed to operate in approximately 60 NM radiuses usually centered over the ASR or airport and En Route SVs are directly correlated to the Air Route Traffic Control Center (ARTCC) Area of Responsibility (AOR) orthogonal boundaries. SVs and CTVs are independently configurable with software automation and filtering. Dependent upon the service domain, the SVs or CTVs are automated to provide the level of service required and to define the service volume boundaries. The SBSS automation software delineates what RSs are associated with a SV or CTV and only those RSs are used to provide ADS-B payload information to both ATC and aircraft. All other RSs within line of sight will be filtered out. Radio Stations can be used to support multiple SVs or CTVs. The data that is forwarded on to ATC or aircraft is derived on the Best Radio concept. The Best Radio concept is the taking of duplicate reports received by all the radio stations, and sorting/ranking them in a weighted ranking list based upon completeness of the report and the Signal Quality Level (SQL). This helps alleviate the large amount of bandwidth requirements that would be necessary if all the radio stations information were processed.

Unless it is needed to clearly distinguish between SV or CTV, this paper will use SV to imply both SV and CTV applications.

FLIGHT INSPECTION OF ADS-B

This paper does not cover the ADS-B implementation processes, such as; Service Integrations Tests (SIT), Service Acceptance Testing (SAT), Implementation Service Acceptance Testing (ISAT) and Initial Operating Capability (IOC). There has been much debate as to the requirement for flight inspection. The topics of those debates are not contained within the scope of this paper. The discussions contained within this paper will focus on the role of flight inspection and the flight inspection practices that are being currently employed.

The advent of ADS-B and similar technologies; and their integration within the NAS has resulted in an enigma of what role flight inspection plays in the certification process. There are those who believe the initial testing of the ADS-B system, the architecture of the ground infrastructure, SBS monitor capabilities, targets of opportunity (TOO)s, and math modelling of the service is sufficient in determining the implementation of ADS-B without the requirement for flight inspection and validating the signal in space. FAA Flight Inspection Services enlisted assistance form academic experts, Ohio University Avionics Engineering Center (AEC), to help develop FI requirements for ADS-B. Ohio University AEC recommended flight inspection of ADS-B services. "The intended use of ADS-B system data in the provision of aircraft separation services by FAA ATC necessitates flight inspection of the system to ensure that the ADS-B signal-in-space (SIS) is present, useable, and safe with aircraft operating at a minimum transmission power. Additionally, flight inspection of the SIS can identify areas in the service volume(s) where: interference sources may exist, there is SIS blockage by terrain and buildings, obstacles (new or temporary) exist in the intended flight operations area, etc. There is no independent monitoring of the ADS-B SIS (i.e., external sampling of the ADS-B SIS broadcast by the ground facilities) as have been the case in previous navigation and landing systems." [9, 12]

Because the ground infrastructure is owned and maintained by a service vendor, the concept of flight inspection needed to shift to a validation of the Separation Services reports used by ATC rather than a certification of the equipment. An Ohio University AEC study commented "a recurring question has arisen regarding whether the development of flight inspection criteria for ADS-B needs to be approached in a different fashion since the service to be tested in not provided by equipment that the FAA owns. Instead the FAA uses the service from equipment built and maintained by the ADS-B service provider." [9]

"While Service Acceptance Tests (SATs) are performed for the initial service volumes, and may be performed for each new service volume, it is important to understand that they are not a substitute for commissioning flight inspections as SAT flight test are primarily concerned with verification that the vendor has met contractual requirements. Flight Inspection is part of the Implementation System Test (IST). IST is done after and separate from the ISAT. This test incorporates the services delivered by the service provider and the integration with FAA automation. The purpose of a commissioning flight inspection is to provide a means (i.e., data) for FAA Technical Operations Engineering and air traffic services to verify and quantify the extent to which the service meets ATC operational requirements." [9]

Although within the ADS-B Flight Inspection Order, the use of TOO(s) are permitted, Flight Inspection Services (FIS) provides a means to efficiently evaluate and confirm ADS-B Out reporting for each SV on both broadcast links simultaneously. Because there are so few aircraft equipped with the UAT broadcast link, the FI aircraft provides the only viable means to validate ADS-R coverage and performance in specific areas and routes. Additionally, FI aircraft have the capability to data log and preserve the integrity of ADS-B In services provided by the ADS-B ground infrastructure. The archived data log files can be validated through post-flight analysis to ensure the level of services meet the requirements without requiring additional flight inspections.

ADS-B Flight Inspection Order

A FAA Order for the Flight Inspection of ADS-B is in the final review status. In the Order, it is described that the flight inspection should be used as a means to be an end-to-end inspection of the ADS-B based ATC Surveillance and Separation Services.[10] As described in previous paragraphs, the current concept of a commissioning flight inspection is for certifying ADS-B Out Separation Services only, but in conjunction with evaluating the Separation service the Advisory services should be data logged and evaluated for validity. The objective of the commissioning inspection is to evaluate system performance, determine and document whether the coverage meets Air Traffic requirements, and provide a baseline for the detection of a deterioration of performance.[10]

Although the Flight Inspection Order has not been finalized and is still in a draft status, Engineering Services and the SBS Program Office have agreed to apply the Order as a baseline in the development of flight inspection plans and also as a reference for the type of conditions that must be documented during the course of the inspection. The checklist in Figure 6 provides the conditions and aircraft settings that should be used when conducting flight inspections. When developing the flight inspection plan, Engineering Services should ensure that each condition listed in flight inspection checklist is incorporated into the flight plan.

At the time of these writings, dedicated periodic flight inspection of ADS-B is not required. It was agreed upon during the system design, which after 3-5 years of operational status a series of special surveillance inspections will be conducted at select sites. The select sampling will be representative of the various automation platforms and SVs.

Flight Inspecting a SV, where do we begin?

The mental model of what needs to be flight inspected and how the flight inspections plans are compiled has matured since initial testing. The maturation process has evolved from the lessons learned and an increased availability of avionics. Initially flight inspections entailed flying the boundaries of the SVs and areas of known gaps in radar coverage and/or areas of predicted ADS-B coverage gaps based upon math modelling. In addition, a sampling of airports and approaches were included to observe how well the ADS-B services were 'actually' performing as compared to the prediction modelling tools. During the initial phases of ADS-B, specialized tests were performed utilizing FAA flight inspection and Ohio University Avionics Engineering Center (AEC) aircraft. These initial tests provided Flight Inspection and Technical Operations Engineering with a blueprint of what requirements were needed to validate the ADS-B services.

FAA Technical Operations Engineering creates a flight inspection plan for each SV to be inspected. Utilizing the FAA ADS-B Flight Inspection Order as a baseline, Engineering Services will use information derived from the ISAT testing and gather specific information from local air traffic services to compile the flight inspection plan. The flight plans identify a sampling of routes and airways along with specific areas requested by ATC for inclusion. The plans also contain all of the pertinent SV information such as: predicted coverage, both vertically and horizontally, for each radio station, all the applicable radio station identifiers and their respective latitudes/longitudes. The flight inspection crew reviews the proposed plan and provides any amendments to the proposed routing that will maximize the overall efficiency, while still maintaining the integrity of the flight inspection plan.

On average, Terminal Radar Approach Control Facilities (TRACON) will take approximately 3-5 hours to complete, while En Route and larger TRACON facilities nominally average 3-4 days.

FLIGHT INSPECTION AIRCRAFT

Flight Inspection Aircraft Equipage

FAA Flight Inspection Services utilizes a fleet of Lear Jet 60s to conduct ADS-B inspections. The LJ60s have been equipped with dual broadcast link Version 2 capabilities for both ADS-B Out and ADS-B In data logging capabilities. Both broadcast link technologies are equipped with dual antenna diversity (top and bottom antennas). In addition, each aircraft has been equipped with a supplemental truth positioning reference system used in conjunction with the flight inspection system.

The 1090ES equipage is comprised of an ACSS XS-950 Air Transport Data Link transponder and a Honeywell TPA-100B Surveillance Processor. The 1090ES ADS-B Out, for flight inspection purposes, is passed through an attenuator to produce approximately 125 Watts/ A1H classification as required by the Final Rule, selectable via an on-board low power switch.

The 978MHz UAT broadcast link equipage is comprised of a Garmin GDL 88 transceiver and Garmin Touch Navigation (GTN)-725 Multi-Function Display (MFD). The GDL 88 transceiver provides ADS-B Out on the 978 MHz broadcast link only and is ADS-B In capable on both broadcast link technologies. Figure 5, is a screen view of the GTN-725 MFD. The MFD is a remote interface to the GDL 88 for configuration changes and fault monitoring; and also provides the user a display of ADS-B traffic information, approach information, and weather and traffic data relative to their position on a moving map.[11]

The FI aircraft are configured to operate both broadcast link technologies independently. Because there isn't a digital interface between the GDL 88 and the 1090ES transponder, the GDL 88 is configured to utilize self-interrogation. The GDL 88 transceiver has a built in low power 1030 MHz transmitters that interrogates the 1090ES transponder. This interrogation is similar to the interrogations from the ground based radar systems and the 1090ES transponder replies with the Mode 3/A codes, IDENT and emergency statuses. The GDL 88 receives the replies and sets the corresponding UATADS-B Out messages to reflect the same data.

Figure 5. GTN-725 Display

UAT Version 2 link technology is comparatively a new technology and as a result, approved vendor ground test equipment is not yet available. Because of the unavailability of ground test equipment, the GDL 88 transceiver output power is not currently being attenuated to the Final Rule requirement of 16 Watts. Although discussions with vendors have resulted in assurances the output power levels meet the required A1H class power and sensitivity level, an accurate measurement uncertainty assessment; including line loss values is currently not available.

In addition to the flight inspection system's truth position reference system, the ADS-B inspections use a supplemental Truth Position Reference System, an Ashtech ProFlex 800 which outputs National Marine Electronic Association (NMEA) and Ashtech Optimized Messaging (ATOM) data formats.

The FI aircraft is equipped with multiple VHF radios which allows for communication and monitoring of multiple frequencies. The flight deck will monitor and communicate on the normal ATC frequencies for the area of operations, while the Mission Specialists will work directly with Engineering Services and ATC Operations on dedicated frequencies when performing ADS-B inspections. This direct communication is essential in relaying timely information pertaining to the status of the inspection, coordinating the various checklist conditions, and maximizing efficiency without causing congestion on ATC frequencies. It is important to establish communication between the FI aircraft and Engineering Services before any maneuvers that deviate from the flight plan or configuration changes that would cause results to differ from the expected values. During certain checklist items, the aircraft's configuration is changed to conditions that are non-standard. For these configuration changes it is important that communication with Engineering Services is established to coordinate the changes and to confirm system settings. A contingency plan should also be used if communications with ATC and Engineering Services have been lost. These practices ensure the flight inspections are completed with the greatest efficiency and maximum cost savings.

Flight Inspection Configuration

The flight inspection (FI) aircraft are configured to operate simultaneously on both broadcast link technologies, improving the overall efficiency of the inspections and allowing for ADS-R Services to be evaluated. Because the FI aircraft are operating on two different links concurrently, special 'test' automation adaptations are normally utilized to prevent the system from issuing conflict alerts to the controller; indicating two separate targets are within close proximity to one another and to allow the FI aircraft to appear as two different targets types.

Flight Inspection Services along with Engineering Services developed six sets of FI test ICAO addresses and correlating Flight IDs, used only with the UAT broadcast link, which triggers a prescribed altitude offset factor applied to the ATC display. As depicted in Table 6, each pair of ICAO addresses and Flight IDs have a specific resulting altitude offset factor.

The altitude offsets range from plus 1000 feet to minus 1000 feet. If an altitude offset factor is desired, the GDL 88 must be configured with the ICAO address and Flight ID from the table that correlates to that specific altitude. As an example, the flight inspection plan requests a UAT altitude offset of plus 1000 feet. The user would configure the GDL 88 to broadcast an ICAO address of FAAFC1 and a Flight ID of FLTCK1U, the pseudo altitude seen by ATC would be equivalent to the pressure altitude plus 1000 feet. Each pseudo altitude offset factor has two paired ICAO addresses and Flight IDs associated with it. A user cannot mix an ICAO address and a Flight ID from a different row in Table 6 to achieve an altitude offset. Each row in Table 6 is a separate condition and the rows cannot be used interchangeably.

Table 6. 978 MHz UAT Altitude Offset Configuration [10]

ICAO Address HEX	ICAO Address Octal	Altitude Offset Feet	Flight ID
FAAFC1	76527701	+1000	FLTCK1U
FAAFC2	76527702	-1000	FLTCK2U
FAAFC3	76527703	-500	FLTCK3U
FAAFC4	76527704	+1000	FLTCK4U
FAAFC5	76527705	-1000	FLTCK5U
FAAFC6	76527706	-500	FLTCK6U

It is important to understand if two separate ADS-B flight inspections are being conducted simultaneously, proper coordination must transpire between the crews to ensure that the same matched pair is not utilized for both aircraft. The SBS Monitor may see the two separate aircraft with the same ICAO address and disregard reports because of the conflicting PVT information received in the ADS-B Out messages.

Exelis built a configuration file into the automation software, whenever the ground system receives an ADS-B Out message containing one of the designated test ICAO addresses and paired Flight IDs, the altitude offset factor associated with that matched pair will be applied to the altitude provided to the ATC automation. The pseudo altitude is only provided to the ATC automation and for the sole purpose of preventing continuous conflict alerts. The altitude offsets cannot be seen by any other receiving aircraft; they are specifically designed to be applied to the ATC displays only.

FLIGHT INSPECTION GUIDANCE

The FI crews will adhere to the guidance as described in the ADS-B Flight Inspection Order. The checklist in Figure 6 provides the conditions and aircraft settings that should be used when conducting flight inspections.

	Inspection Type			
	Para Ref	C	RS Ant or Radio Change	Transponder Setting (1)
Modes/ Codes	8a	X		E
Transition with Radar-only	8b	X (3)		E
General Coverage	8c	X	X (2)	L
Airways/ Route Coverage	8d	X	X (2)	L
MSAW	8e	X		E
Fix/ Map Accuracy	8f	X (2)		E

Footnotes:
(1) Settings for 1090 Transponder: E = Either Normal or Low Power; L = Low Power. In Low Power setting, the 1090 ADS-B transponder approximates power and sensitivity of A1 class 1090ES transponder. The UAT transponder is fixed at an A1H class power and sensitivity level.
(2) May be completed using targets-of-opportunity. Flight inspection aircraft at engineering request only.
(3) Only applicable when SV is adjacent to radar-only airspace.

Figure 6. ADS-B Flight Inspection Checklist

The flight inspection aircraft flies the flight profiles pre-determined by the flight inspection plan. En Route SVs should be flown at the floor of radar coverage, but no lower than minimum obstruction clearance altitude (MOCA). However, in practice, coverage in En Route SVs is often verified at altitudes well below radar coverage when the ADS-B infrastructure supports it. During Visual Flight Rules (VFR) conditions the FI aircraft may go lower than the radar coverage altitude if the predicted coverage model of ADS-B indicates reception of the SIS at the lower altitudes, but still ensuring not to go below the applicable Obstruction Clearance Altitude (OCA). In a Terminal SV, coverage should be flown 500' below the minimum en route altitude (MEA)/ minimum vectoring altitude (MVA), but no lower than the applicable OCA.

Modes/Codes checks ADS-B Out for proper operation when changing Mode 3/A codes. The check verifies that the controller reads the entered code. The flight deck changes the 1090ES transponder Mode 3/A code to 1200 and another discrete code containing the number 7, (e.g., 0707, or 7070). There is no requirement to check any of the emergency codes. Along with the codes, ensure that the ATC altitude readout is within ±125 feet of the indicated aircraft altitude. [10]

Minimum Safe Altitude Warning (MSAW) functionalities are performed as an end-to-end check of MSAW features activated solely by an ADS-B only target, thus verifying a target processed through the ADS-B network will trigger a low altitude alert correctly. There are two different components of MSAW: General Terrain Monitor (GTM) and Approach Path Monitor (APM). An APM check can be accomplished at any airport with an APM adaptation. The GTM must be in an area away from any airports and not in a MSAW inhibited area.[10] Because both broadcast link technologies are independent systems in the FI aircraft, difficulties were encountered when conducting MSAW checks. The GDL 88 uses interrogation replies from the 1090ES to provide the UAT ADS-B Out with a Mode 3/A squawk code. MSAW checks are performed to ensure applicable alerts are generated through the ADS-B system and not induced by the legacy radar system thus it was important to develop a method that would ensure only the ADS-B target prompted the alert. The simplest method to ensure the MSAW alert is generated from an ADS-B target is to isolate and perform the inspection on the UAT broadcast link only, but because the GDL 88 sets its Mode 3/A via an interrogation of the 1090ES system; a method was developed that permitted the 1090ES transponder to remain on and not influence an MSAW alert from the legacy radar system. The flight deck switches off the altitude encoding function (Mode C) of the 1090 transponder while transmitting the proper Mode 3/A code on UAT. The FI crew should change to the UAT Flight ID to something other than the Flight ID listed in Table 6. This will cause the automation to reflect the actual altitude the aircraft is flying and not introduce the offset factor. Proper attention to the correct configuration on the ATC automation system is required, including selecting the proper Mode-3/A code and associating the aircraft with an instrument flight rule (IFR) flight plan.

<u>Data Logging ADS-B Out and ADS-B In Messages</u>

Data logging is a critical component in the flight inspection of ADS-B. The aircraft must have the ability to data log both ADS-B Out and ADS-B In messages for both broadcast link technologies and the Truth Position Reference System. Each broadcast message must also be accurately time stamped in order for the PVT information to be used in the post flight analysis to confirm the latency requirements are met. Additionally, it is necessary for the data logging software to have monitoring capabilities so the FI crew can assess the SIS in real-time. The real-time monitoring indications are provided by the uplink messages containing the systems status for the various report types and the individual message reports. Real-time monitoring provides the flight crew the ability to discern coverage for ADS-R, TIS-B, and FIS-B services along with monitoring the ground radio stations for reception. For every SV flight plan, the radio stations are included with their SV Identification and their respective latitudes/longitudes. The FI crews should track and monitor which radio stations are being observed to ensure the adaptation files have been correctly installed in the automation.

Flight Inspection Services solicited Garmin and Honeywell requesting additional interface capabilities for each respective processor specifically for flight inspection data logging capabilities. The additional interfaces provide the capability to port the unfiltered ADS-B message directly via Ethernet to a stand-alone device for data logging and monitoring of the ADS-B services. Each processor has the capability to filter out messages that are not within a calculated service area around the aircraft. It is necessary for the FI aircraft to be able to display and data log all the incoming ADS-B messages.

The GDL 88 has been modified to accommodate a *pass-through* interface utilized for flight inspection services only. The *pass-through* interface uses the Transmission Control Protocol (TCP) and Internet Protocol (IP), commonly known as TCP/IP, to provide packet routing, connectivity, and data streaming between a GDL 88 and a data logging/processing computer. The GDL 88 hosts a TCP/IP server that listens for a connection over a static IP address. When a TCP/IP client, only one client permitted to connect at a time, connects to the server the GDL 88 will begin to pass through the data stream. The *pass-through* interface enables all the unfiltered ADS-B Out and ADS-B In messages to be sent to a peripheral device to data log and display real-time information. The data stream from the GDL 88 to the peripheral device is not bi-directional, i.e.; the user cannot use the connection to remotely configure the GDL 88.

The Honeywell TPA-100B 1090ES surveillance processor utilizes a maintenance port to allow the 1090ES ADS-B Out messages to be data logged by vendor software called MonTPA. A problem has been identified with using the maintenance port as a source for data logging the 1090ES ownship ADS-B Out messages. The

ADS-B Out messages sent to the transmit antennas are split off and stored in a buffer, this buffer delays sending the ADS-B Out messages to the recording software. When the ADS-B Out messages are sent from the buffer to the recording software; a pseudo time stamp is applied but it isn't the actual time the ADS-B Out message was broadcast but the time it was sent to the recording software. The pseudo time stamp varies approximately ±1.5 seconds, resulting in an unknown variable; preventing the file to be used in determining latency and using the 1090ES ADS-B Out ownship data as an end-to-end evaluation of the ADS-B system.

As a result of the limitations imposed by the MonTPA software and the time stamp skewing, the 1090ES ADS-B In data received on the GDL 88 transceiver is used in the post-flight analysis of the 1090ES ownship data. Because of the close proximity of the GDL88 to the broadcast antenna of the 1090ES, the amount of time delay in the received message is very minimal; resulting in a negligible impact to latency calculation.

Flight Inspection Software Suite

Original testing included using software provided by vendors to capture and display each broadcast link technology separately. Problems arose in gaining support from vendors for modification to the software programs when the link technologies progressed to Version 2. This required the FAA to begin development of their own software suite to use for data logging and displaying the information in a real-time environment. Flight Inspection Services with the help of the FAA Technical Center Office of Advanced Concepts & Technology Development Surveillance Branch have developed software which provides the capability to data log and display ADS-B Out and ADS-B In payloads for both broadcast links and the truth positioning reference data into a single source. The FAA software currently has full data logging and monitoring capability but is still in beta testing for the development of additional features. Until such time the FAA software is fully vetted, vendor supplied software continues to be additionally employed to ensure data logging redundancy.

The FI crew uses the software suite to monitor the real-time status of the ground infrastructure and the signal in space (SIS). The FI crew coordinates with Engineering Services during the inspection and identifies any SIS discrepancies. If anomalies are noted by either the FI crew or observed by the Engineering Services monitoring the flight inspection on the ATC display, the entities will discuss a means of resolution. Although the ADS-B In messages are not considered a Critical Service and some entities feel they should not be flight inspected, the vast experience and knowledge of Flight Inspection Services and with the technical assistance from Ohio University AEC has concluded these services should in fact be validated for accuracy and SIS during flight inspection of ADS-B SVs.

The FI crews maintain a Flight Inspection Log for each SV inspected. Contained within the Flight Inspection Logs are the applicable details for the facility under inspection, aircraft equipment configuration, and a summary of the conditions noted during the inspection. The logs should contain enough detail for the post flight analysis to conclude; the corresponding time of the condition, a general description of the aircraft's location, any anomalies encountered, and changes in the aircraft's configuration that would cause an inspection parameter to vary. Aircraft configuration changes would be encountered when completing checklist items, such as; an evaluation of the ADS-B processing of the Minimum Safe Altitude Warning (MSAW) system and Modes/Codes.

Engineering Services and ATC tracks the ADS-B Out targets of the flight inspection aircraft on a scope that has been adapted with the ADS-B automation platform. Engineering Services will monitor and *score* the flight path of the flight inspection aircraft and annotate any anomalies encountered during the inspection, such as; loss of one or both of the broadcast links, incorrect aircraft tracking information, altitude discrepancies, etc. *Scoring* is an Engineering Services function that is similar to our FI inspection log. S*coring* is the process of annotating the results as a Pass/Fail criterion for the various checklist conditions that are performed during the inspection.

Figure 7 is a screenshot of the FAA data logging software providing a real-time graphical display of the ADS-B Out and ADS-B In messages processed by the GDL 88. The target displayed is the flight inspection aircraft with a tail number of N55. The gray box to left of the targets is a pop up window which allows the user to select specific message fields they want to observe.
The message fields are derived from Field Reference Numbers (FRN). The FRN establishes the order of the items in the FSPEC, and along with the Category codes, serves to uniquely identify each data item.[3] The FRNs included in the payloads vary depending on the context being reported, but each Service Report is delineated in a consistent FRN format for simplicity and standardization processes.

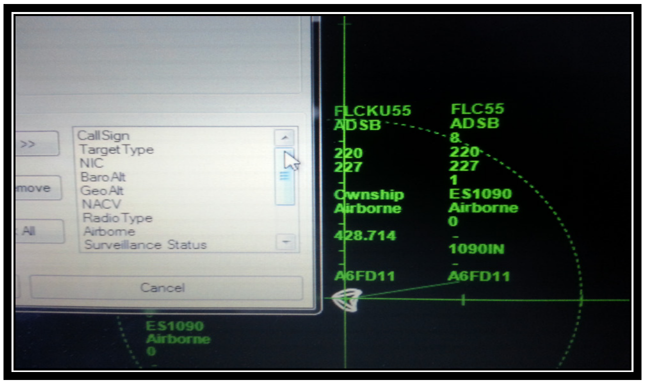

Figure 7. FI Software Suite Display

The FAA software allows the user to filter out particular target types, i.e., ADS-B, ADS-R and TIS-B. Figure 7, is filtered to only display the ADS-B targets. Each target is displayed graphically, with the ability to view the targets broadcast information textually.

Figure 8, Data Logging / Traffic Display, provides another snapshot of the recording software. In this snapshot, Flight Check 56 is being used for the ADS-B inspection. For this inspection, the UAT broadcast link is employing the pseudo altitude offset factor. This is indicated by the hexadecimal ICAO address of FLTCK4U and Flight ID of FAAFC4, this combination results in a plus 1000' offset factor applied to the altitude displayed on the ATC display. Also included in Figure 8, are additional ADS-B targets being observed and a ground radio station. The ground radio station will be shaded orange when it is providing uplink messages to the FI aircraft.

The GDL88 has been filtered to include ADS-B and ADS-R message for display. Notice two targets are being displayed for each broadcast link, the aircraft is receiving an ADS-B message and an ADS-R message for each link. Keep in mind the GDL 88 is a dual link ADS-B In receiver, so why are we receiving an uplink for the ADS-R? This example is an indication of the importance of flight inspection. Without the use flight inspection and the validation of SIS, this automation flaw could have possibly gone unnoticed. Without delving further into the fundamentals of the ground infrastructure, the ground system is designed to track ICAO addresses and the link technologies associated for each target and only uplink messages applicable to the target type. The ground infrastructure is not properly identifying the targets and their associated aircraft equipage; and is broadcasting unnecessary information to the aircraft to process and display.

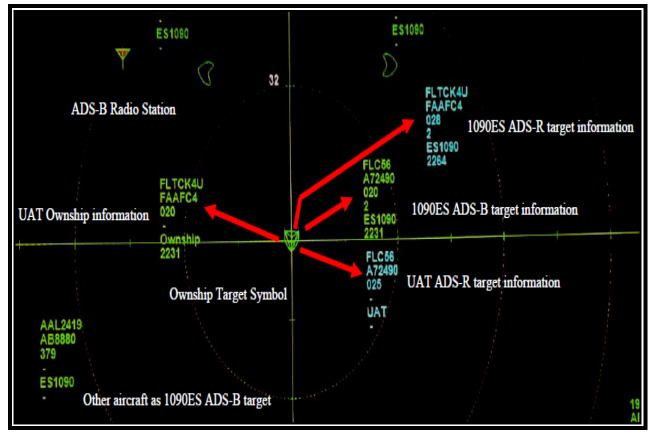

Figure 8. Data Logging / Traffic Display

POST-FLIGHT ANALYSIS

During the course of the inspection, the FAA Technical Center in Atlantic City, NJ is parsing hourly reports from the SBS Monitor. Although the Technical Center does not yet have the corresponding FI aircraft data to compare positional information, they can compare reports from the SBS Monitor pertaining to the FI aircraft and other TOOs in the area and perform preliminary gap analysis. These preliminary reports are beneficial during the inspection as they can provide early identification of coverage problems while the aircraft is onsite and modifications to the flight plan can be addressed.

Upon completion of the flight inspection, all of the FI data files are uploaded to a FAA network. These files include: flight inspection logs, 1090ES ownship data from the MonTPA (used solely for ADS-R validation, because of the time delay), GDL88 transceiver ADS-B Out and ADS-B In of both broadcast links, and ProFlex 800 truth position in NMEA and ATOM data formats. FAA Technical Operations Engineering Services parses all of the corresponding message reports from the FAA Technical Center's SDP.

A flight inspection report is generated by the flight crew for each SV inspected. The flight inspection report will only reflect a record of what was accomplished during the inspection and will not list the facility status. Also included in the report are any abnormal findings encountered during the inspection. Engineering Services will document the initial test results of the flight inspection in a quick look report and the finalized results in the Flight Inspection Analysis Report. The analysis reports are used by local Air Traffic and Technical Operations to determine if the performance of the ADS-B system is satisfactory

Common Errors Encountered and Areas of Concern

The use of flight inspection in the IST process has consistently yielded beneficial results and identified areas that are problematic for future applications. Multiple flight inspections have discovered errors in the automation software, such as: the broadcast of ADS-R messages for an aircraft that is dual linked ADS-B In; missing radio stations from the adaptation files for a SV; incorrectly registering an aircraft as an TIS-B target instead of an ADS-B target; and has confirmed predicted coverage based upon math modelling shouldn't be the sole basis for discerning coverage.

Although rare, instances have occurred where flight inspection has identified problems with the ground infrastructure and should have been identified in the ISAT process. Oversights in ensuring the ground system is tied to and synced with a valid GPS timing source has resulted in loss of target tracking ability and system failures.

Consideration should be given to barometric pressure impacts and the effects it poses on the flight inspection results when evaluating the service volume floor and ceiling. Altitudes reported over the 1090ES and UAT data links provided the aircraft's "standard day" or uncorrected altitude. The aircrew uses the aircraft's altimeter, which uses local barometric corrections for altitudes below 18,000' MSL. In most case, when the barometric pressure is close to the standard day of 29.92 mb, the difference does not affect the ADS-B ground system. However, when large enough changes in the barometric pressure are present due to weather fronts, there can be significant differences in the aircraft's displayed and transmitted ADS-B altitudes.[9]

CONCLUSIONS

The concept of ADS-B and dual link technologies has proven to be difficult to apply. As expected with each new technology there will be some difficulties in transitioning from the design concept to the application phase. As explained in the initial paragraphs of this paper, ADS-R is not considered a Critical Service, something that may change in the future when more knowledge and experience is gained on the system. Overall the ADS-B system's coverage has met or exceeded ATC expectations in many areas and the additional coverage in areas has added an extra layer of safety within the NAS. Continued advancements in technology and aircraft equipage will further enhance the system's capability and prove to be a formidable cornerstone in the development of NextGen. Flight Inspection should continue to be an invaluable component in the assessment of ADS-B Services. Future work and expansion of technologies will continue to benefit from the end-to-end performance evaluation and data collection flight inspection can provide.

ACKNOWLEDGMENTS

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Experiences with Inspection of FANS-1/A Data Link

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ABSTRACT

As the congestion of air traffic rises, there is a greater strain put on air traffic control (ATC) to safely manage an air space.

The Future Air Navigation System (FANS) technology is implemented in both oceanic and domestic airspace around the world and the LINK 2000+ programme in Europe will soon expand the use of domestic Aeronautical Telecommunication Network (ATN) based data link. These technologies assist in significantly reducing pilot and ATC workload whilst increasing safety and efficiency.

The positioning of an aircraft by ATC is reliant on messages it receives from the aircraft. Considering that ATC messages are not given priority over other data link messages that are delivered by the same path e.g. Aeronautical Operational Control (AOC) flight plan uplinks, there is a need to verify that the transit time of ATC messages meet the requirements for current reduced separation standards. Additionally it should be evaluated that the data link performance is correct throughout its service volume.

HISTORY OF FANS

In 1983 the ICAO Council established the Special Committee on FANS as a strategy to counter global increases in air traffic and an aging worldwide infrastructure. The role of the Committee was to study, identify and assess new technologies, including satellite technology, and to make recommendations for the future development of navigation systems for global civil aviation. The proposal developed by the FANS Committee came to be known as the Communication Navigation Surveillance/Air Traffic Management (CNS/ATM) concept. The CNS/ATM system is based on global communications systems, global navigation systems, and Automatic Dependent Surveillance (ADS). Air Traffic Management (ATM) is a result of these integrated systems being used to provide a range of Air Traffic Services (ATS).

The Controller Pilot Data Link Communications (CPDLC) and Automatic Dependent Surveillance Contract (ADS-C) data link applications were designed for transportation across the then future ATN. Until the ATN became available, Boeing and Honeywell built a FANS application to run on the existing Aircraft Communications Addressing and Reporting System (ACARS). This avionics package became known as FANS-1. Airbus created an equivalent system known as FANS-A. Collectively, these systems are known as FANS-1/A.

CPDLC versus ADS-C

CPDLC is a communications application that allows for the direct exchange of text-based messages between ATC and an air crew. The controller is provided with the capability to issue level assignments, crossing constraints, lateral deviations, route changes and clearances, speed assignments, radio frequency assignments, and various requests for information. The air crew is provided with the capability to respond to messages, to request clearances and information, to report information, and to declare/rescind an emergency. A ‘free text’ messaging option is also provided to both parties so that information not conforming to defined formats may be exchanged.

ADS-C is a surveillance application that provides ATC with accurate surveillance reports from an aircraft in remote and oceanic regions. Reports are sent automatically in accordance with the parameters of a contract that an air traffic controller has set up. Under normal circumstances ADS-C requires no pilot interaction: the pilots can turn the ADS-C application on and off, or when a contract is in place can initiate and cancel an emergency reporting mode.

CPDLC Necessity

Before CPDLC, the standard method of communication between ATC and an air crew was voice radio: VHF bands for line-of-sight or HF bands for long-distance communication.

A major problem with voice radio communication is that all pilots being handled by a particular controller are tuned to the same frequency. This raises the chance that one pilot will accidentally override another, thus requiring the transmission to be repeated.

ADS-C Necessity

Before ADS-C, aircraft flying in remote areas were managed by ATC using procedural control: aircrafts are separated using generous separation standards based on inertial or GNSS position that are routed to ATC via HF relay stations.

The introduction of ADS-C has provided ATC with a means of managing a whole airspace more efficiently. Not only can they track an aircraft more accurately whilst receiving a greater amount of information than was previously sent via a non-ADS-C equipped aircraft position report, they can also be alerted immediately if an aircraft deviates from its predefined flight track.

INTRODUCTION

Norwegian Special Mission (NSM) have been working with the Brazilian flight inspection organisation - Grupo Especial de Inspeção em Vôo (GEIV), to assist with improving their role in the application and inspection of FANS-1/A data link services to meet air traffic projected demand for the Europe/South America corridor and improve ATC capacity and efficiency.

The ADS-C functionality in ACC-Atlantic (Brazil) has been operationally available since 23rd October 2008. The CPDLC functionality has been operational since 30th July 2009.

Figure 1. ACC-Atlantic Airspace

Considering that FANS data links are used for ATM communication and safety purposes, who makes sure that the data link is flyable, and who ensures that it is commissioned and inspected, either routinely or in special cases of antenna replacement or accidents?

For many years the Brazilian Air Navigation Service Provider (ANSP) - DECEA - asked questions like these to the international flight inspection community. The conclusion was that there were no flight inspection requirements, there was not much data to get access to, and very often verification tests of data link performance are carried out by the data link service providers.

Concluding that this was not by any means compatible with proper quality aviation ATM safety standards, DECEA decided to study this and a brief requirement for flight inspection was discussed. DECEA wanted to verify that all data messages were transmitted from the ground station (Air Traffic Services Unit (ATSU)) correctly and that this could be documented properly.

As the right quality way to do this is always by the flight inspection organization, their first task was to enable GEIV to have FANS data link capability on board their flight inspection aircrafts. A contract was awarded to NSM in 2008 to outfit four Hawker 800XP aircrafts with UNIFIS 3000 Flight Inspection Systems (UNIFIS 3000) equipped with the functionality to access the data received and transmitted via the FANS data link.

4 x FANS Installations for the Brazilian Air Force.

The following equipment has been installed and is operational in four Hawker 800XP flight inspection aircrafts.

Aircraft Components:

VHF Antenna

SATCOM Antenna

Universal NCU Flight Management System (FMS)

Universal Multi-function Control/Display Units (MCDU)

UNIFIS 3000 Components:

Simulated FMS and DM Software

Flight Inspection System Software

Rockwell Collins CMU 900 (CMU)

Rockwell Collins VHF 4000 Data Radio

Rockwell Collins SRT 2100B SATCOM Transceiver

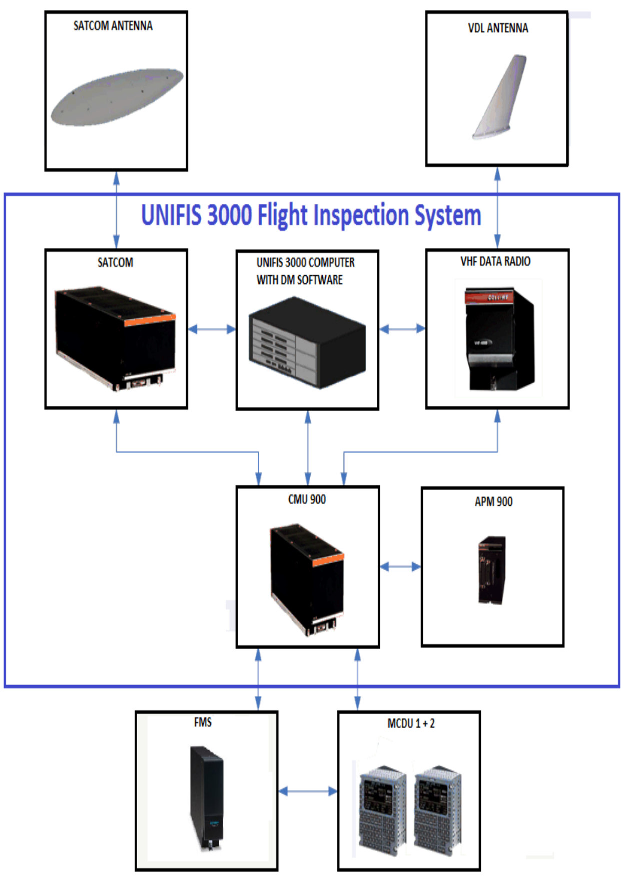

Figure 2. GEIV H800 XP Equipment Configuration

Both cockpit MCDU's and the UNIFIS 3000 'simulated' MCDU can display and control the CMU. All MCDU's can view different pages of the CMU application menu simultaneously.

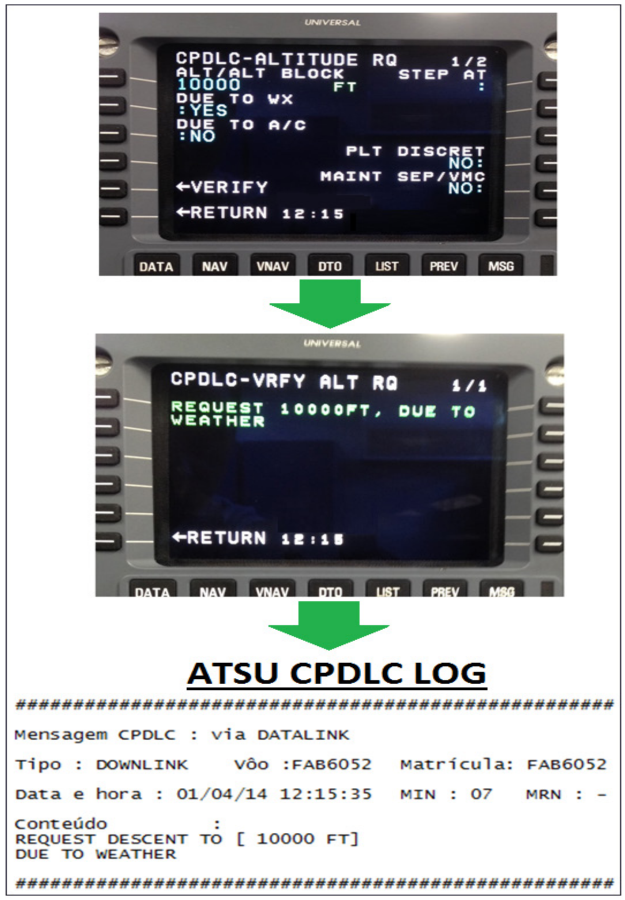

Figure 3. CPDLC Message from MCDU to ATSU Log

GOLD STANDARD REQUIREMENTS

ICAO has for many years worked for a common global standard for data links. The Global Operational Data Link Document (GOLD) is the result of the progressive evolution of the ICAO Asia-Pacific (APAC) Initial Future Air Navigation System Operations Manual, the North Atlantic (NAT) Guidance Material for ATS Data Link Services in North Atlantic Airspace, and the Eurocontrol LINK2000+ Guidance Material for the aeronautical telecommunication network baseline 1 (ATN B1). Each of these founding documents provided guidance on a regional basis. However, in recognition of the need to provide globally harmonized guidance on data link operations, the GOLD, First Edition, merging initially the APAC and NAT guidance material, was adopted by the APAC and NAT Regions in 2010. The Second Edition of the GOLD enabled integration of the LINK2000+ guidance material. [1]

The GOLD addresses data link service provision, operator readiness, controller and flight crew, procedures, performance-based specifications and post-implementation monitoring and analysis. Although it does not directly address any kind of flight inspection of FANS data links, it does make the following recommendations for monitoring their performance:

1. To enable adequate system performance monitoring the ANSP should at minimum perform a monthly analysis of CPDLC Required Communication Performance (RCP) and ADS-C performance data. This monitoring will verify system performance and also enable continuous performance improvement by detecting where specific aircraft or fleets are not meeting the performance standards. [2]

   The recommendation for analysis of CPDLC transit times only states to use uplink messages that that receive a single DM 0 WILCO response. The transit times of uplink messages that receive other responses: DM 1 UNABLE, DM 2 STANDBY, DM 3 ROGER, DM 4 AFFIRM or DM 5 NEGATIVE are not used as they will skew the observed data because of the longer response times from the flight deck. [3]

   It should be noted that assessing transit times does not verify that all uplink and downlink messages can be sent and received correctly, just that certain messages are transmitted and a response is received within an acceptable time frame.

2. The ANSP should conduct trials with aircraft to ensure that the system meets the requirements for interoperability such as is defined for FANS-1/A in RTCA DO-258A. [4]

   RTCA DO-258A defines the requirements for FANS-1/A ATS applications. It covers the ATS Facilities Notification (AFN), ADS-C and CPDLC.

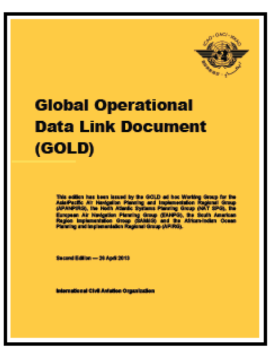

Figure 4. ICAO GOLD Document

TEST OF FANS -1/A GROUND STATION

Although the requirement to monitor transit times according to the GOLD is written as 'should', not 'must', the recommendations for periodic monitoring intervals, calculations and graphical analysis of RCP are well defined, as are the procedures and report forms for non-conformances. In addition to the monitoring of transit times, SITA, who are the air data service provider in Brazil, have a support team that continuously monitors the quality of the air-ground communication.

The GOLD does not define how to fulfill the requirement that the ANSP should conduct trials with aircraft to ensure that the system meets the requirements for interoperability such as is defined for FANS-1/A in RTCA DO-258A. This scope is quite large and covers the testing of all possible CPDLC downlink and uplink messages to assess if they can be sent or received correctly. It should be noted that an incorrectly configured ground station can transmit an automatic response to a received CPDLC downlink that will alert a flight crew that a service is not available. This message usually takes the form: MESSAGE NOT SUPPORTED BY THIS FACILITY.

Figure 5. ADS-C Setup Screen

Flight and ground tests were conducted using VDL Mode 0/A, VDL Mode 2 and SATCOM. During testing, after an AFN logon was established, both the flight inspector and an air traffic controller would follow a scripted dialogue of various CPDLC messages and responses. Additionally, tests were also performed to verify that all types of ADS-C contracts could be initiated.

RESULTS

The UNIFIS 3000 contains software that can simulate an FMS Data Manager (DM). The DM is the FMS application that generates the Arinc labels that the ACARS computer - Rockwell Collins CMU 900 - requires in order to provide FANS services. This software is capable of generating all possible FANS FMS data labels. An optional simulated MCDU can also be enabled which provides a flight inspector the ability to monitor or participate during FANS-1/A testing.

The DM software provides the option to for the flight inspector to send static data to the CMU, this allows a flight inspector the ability to perform a more controlled test and is particularly useful not to mention timesaving when analyzing numerous pages of log files that have been recorded using live data.

The DM software creates a time stamped log of all uplink and downlink messages. The ATSU creates the following logs:

1. Report of AFN logon activity.
2. Report of CPDLC activity.
3. Report of ADS-C activity.

Additionally, the UNIFIS 3000 has the ability to decode the CMU information intended for the aircraft Flight Data Recorder, and can generate a maintenance log that contains all raw data messages.

By comparing the ground station logs to the UNIFIS 3000 logs, it is possible to verify with evidence whether or not all uplink and downlink messages can be received correctly.

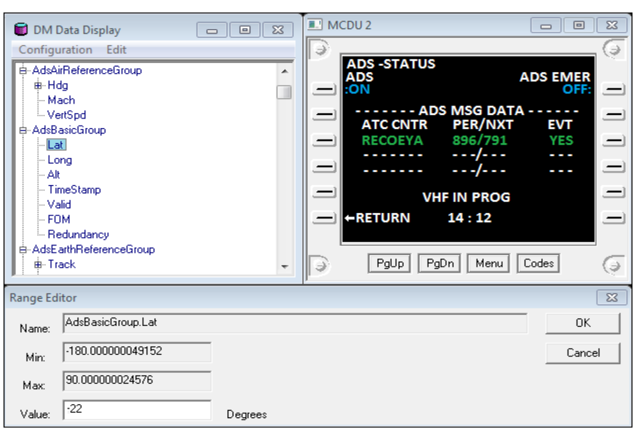

Figure 6. FANS DM and Simulated MCDU.

```
##################################################################
#                    Mensagem ADS - UPLINK                       #
##################################################################
Data da gravação :  01/04/2014 - 12:57:50
Indicativo (Flight Id) : E40088
Matrícula (Tail Number) : FAB6052
Número da Pista Local : 13
::Mensagem Automatica::
Posição :  STA01          Operador :  N/A
Cancelamento de Contrato :  N/A
##################################################################

##################################################################
#                    Mensagem ADS - DOWNLINK                     #
##################################################################
Data da gravação :  01/04/2014 - 12:57:54
LATITUDE: -43.000          LONGITUDE: -22.000
ALTITUDE: 1500    TIME STAMP: N/A
Data de Envio:     01/04/2014 - 00:00:00
Ultima Atualização:     N/A
---------------------------------
Número de Contrato :  5
---------------------------------
##################################################################
```

Figure 7. Extract of ATSU ADS-C Log

```
##################################################################
#                    UNIFIS 3000 CMU LOG                         #
#                        - 01/04/2014                            #
#                        - FAB6052                               #
##################################################################
<12:57:51> Request message received
Contract # 5
Trigger: Periodic 640
Request elements:
    AdsBasicGroup

<12:57:51> Output message triggered
Contract #: 5
AdsBasicGroup

    FOM:                            None
    Lat:                            -43.000000
    Long:                           -22.000000
    Alt:                            1500
    Redundancy:                     None
    Valid:                          Valid
    TimeStamp:                      0.000000
```

Figure 8. Extract of UNIFIS 3000 Log

During several test periods over 1000 uplink and downlink messages were exchanged between the UNIFIS 3000 and the FANS ATSU. As these were controlled tests where the flight inspector was informing ATC of the required dialogue to be exchanged before an uplink message was generated, it could be verified in real time that the ground station was performing correctly. A post-test analysis of the UNIFIS 3000 logs and the ATSU logs was performed which also consistently confirmed this.

CONCLUSION

The testing performed so far in Brazil allows the ANSP to be confident that the FANS communication and surveillance functionalities are operating correctly. They can now verify that not only does the FANS ground station meet the requirements for ADS-C and CPDLC transit times, but also fulfills the requirement to conduct trials with aircraft to ensure that the system meets the requirements defined for FANS-1/A in RTCA DO-258A. [3]

The flight inspection organization can now produce reports backed up by evidence that can be used to certify the following:

- ADS-C Periodic, Event and Demand contracts uplink correctly according to the parameters stipulated by ATC.
- All ADS-C downlink messages are received and archived in the ATSU logs correctly.
- ATC is assured that all CPDLC requests downlinked to them by an aircraft are received correctly and that no downlinked message generates an incorrect automatic response.
- Transition of messages between VDL (Mode 0/A and 2) and SATCOM, and transition of messages between VDL stations operates correctly.

Testing with ATC is definitely more efficient when both parties have been fully briefed and have agreed to a scripted dialogue. Although it is possible to complete all testing using VHF data links within a relatively short time frame (circa fifteen minutes), test times for SATCOM can be significantly longer. With SATCOM in particular it is beneficial to perform testing in the most efficient manner possible, as SATCOM data is charged by the byte: this means that cost is a consideration to keep in mind during testing.

Since all VHF and SATCOM data link information is routed to the ATSU via the air data service provider's computer network, it is reasonable to assume that if the ATSU can correctly uplink and receive downlinks of all FANS applications via VHF data link without a problem, then with it will also be able to do the same via a SATCOM data link. Although further investigation of this is required, testing of the communication capability of the ATSU could be achieved by performing the majority of the testing using a VHF data link, and concluding it with a basic SATCOM communication verification test.

It was observed during testing that it was more efficient if the flight inspector performed the testing as he/she could visually assess the data that is being both uplinked and downlinked in real time using the UNIFIS 3000 live data log. Having the flight inspector perform this testing also allows the pilot to concentrate on flight operations whilst still having the ability to monitor the test.

Although the GOLD states that trails by aircraft are required, is this because the avionic equipment required to perform this testing is usually found inside an aircraft? It is of course possible to carry out this testing via a lab setup, or by using a specially configured aircraft on the ground.

During testing that took place with the aircraft on the ground, it was agreed beforehand with ATC that a flight plan did not need to be submitted before initiating an AFN logon. Also, for all ground tests, the reported altitude was set to 0ft using the UNIFIS 3000 DM software.

Testing on the ground can not only save money for a flight inspection organization, it can also assist in overcoming the difficulty of scheduling a time that both testing can take place with ATC, and that a flight crew can be airborne.

ACKNOWLEDGMENTS

This paper was only possible because of the cooperation and support from the Brazilian ANSP, DECEA and flight inspection organization, GEIV. The author would like to thank them for their continued partnership and hard work during the implementation and testing of FANS-1/A equipped flight inspection systems.

The author would like to thank Rockwell Collins, Universal Avionics, Arinc Direct and SITA for their continued support and assistance during development and testing of FANS and ATN (CPDLC) equipped flight inspection systems.

Also, Craig. J. Roberts of ATC Data Link News hosts a website that provides detailed and informative content on the operational use of FANS-1/A data link technology. [5]

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Session 6
ICAO (IFPP Summary) and Enhanced Vision

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State Responsibility for Instrument Flight Procedures: ICAO IFPP's Challenges

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ABSTRACT

The implementation of PBN (Performance-Based Navigation) means that even small errors in data can lead to catastrophic results. This significant change in data quality requirements has led to the need for a systemic quality assurance process, including flight validation, of instrument flight procedures. Under such circumstances, ICAO (International Civil Aviation Organization) developed requirements on quality assurance of instrument flight procedures and related guidance material. However, many States are still struggling with the implementation of the quality assurance process. For instance, some States have not implemented proper scheme for flight validation. In a worst case, instrument flight procedures may be even out of control by States. Background behind this is the lack of standardized ICAO regulatory framework for such services. To solve such problem, ICAO decided to develop SARPs material governing the responsibility by States on instrument flight procedures and related guidance material.

This presentation aims at providing latest information on the activities and challenges by ICAO IFPP (Instrument Flight Procedure Panel) on the development of the SARPs (Standards and Recommended Practices) and a guidance material. Especially, a focus is made on the States' responsibility related to flight validation of instrument flight procedures, one of the most important tasks for the safety and quality of instrument flight procedures.

IMPORTNT NOTICE

Note that the intention of this paper is to introduce general overview of discussions within IFPP, as an opportunity to encourage the readers to consider the issue. Also note that conclusion within IFPP has not been reached yet, and that the contents here are NOT an ICAO formal statement.

INTRODUCTION

PBN (Performance-Based Navigation) is a powerful tool that can improve airspace safety and efficiency. Therefore, ICAO developed PBN Manual (Doc 9613) [1] to support PBN implementation by States. As a result, PBN has been implemented by many ICAO member States in these several years [2].

IMPACT BY TRANSITION TO PBN

However, the implementation of PBN means that even small errors in data can lead to catastrophic consequences in actual flights.

Transition from conventional navigation to PBN is a transition from analog navigation to digital (data-dependent) navigation. Under conventional navigation, most types of errors of conventional Navaid and onboard navigation system can be estimated and controlled through "Quality Control" like an industrial product. In addition, these analog (systematic) errors can be regarded to behave in accordance with Normal Distribution (Gaussian distribution). Therefore, the probability of deviation from the tolerance can be estimated quantitatively.

On the other hand, under PBN, small error in a pilot action and/or navigation data stored in FMS (Flight Management system) may make catastrophic consequences. In addition, it is difficult to estimate the distribution of error and its consequences statistically. See Figure 1. If, upon inputting latitude on CDU (Control & Display Unit), a pilot presses "3" instead of "6" which are adjacently located, then, the location of the target waypoint to which aircraft is flying results in the difference of 3 minutes (approx. 3 NM).

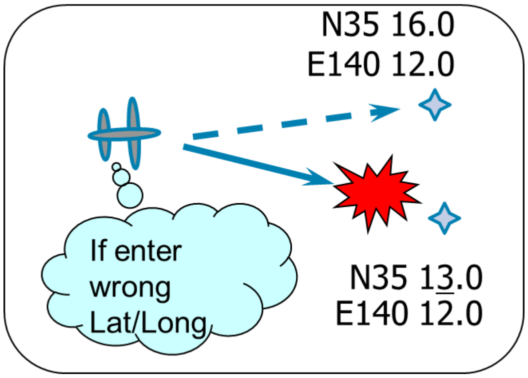

Figure 1. Possible consequence by small error in data input under PBN

It is to be noted that, under PBN, the relationship between the magnitude of error and that of consequences are not in linear function. Of course, various mitigations to reduce such risk have been implemented. For example, avionics have been designed and crew procedures have been established to eliminate such possible errors [1].

However, countermeasures in the air are not sufficient. Such significant change in the impact by error can be found not only during the flight but also during other phases. Error in flight procedure design, data processing and database coding may result in severer consequence as the impact spread out to all users of such flight procedure and related data. Hence, it is also necessary to take appropriate measures to eliminate possible errors during work processes on ground which may degrade the data quality.

IMPORTANCE OF QUALITY UNDER PBN

This significant change in data quality requirements has led to the need for a systemic quality assurance process, including flight validation, of instrument flight procedures. Under such circumstances, ICAO developed requirements on quality assurance of instrument flight procedures and related guidance material.

ICAO Doc 8168 PANS-OPS vol. II, Part I, Section 2, Chapter 4 provides basic requirements for quality assurance process applicable to Instrument Flight Procedure Design Service (IFPDS) [3]. In addition, various volumes of ICAO Doc 9906 provide guidelines as a support for the States and other parties in meeting the requirements of PANS-OPS. Among these volumes, Volume 1 provides guidelines for the establishment of quality assurance process applicable to IFPDS [4], and, Volume 5 provide guidelines for the provision of flight validation [5].

CURRENT ISSUES

However, many States are still struggling with the implementation of the quality assurance process. For instance, some States have not implemented proper scheme for flight validation. In a worst case, instrument flight procedures may be even out of control by States. Background behind is the lack of standardized ICAO regulatory framework for such services.

One of the most significant issues is the absence of ICAO provision on the responsibility by States for instrument flight procedures in Annex (SARPs) level. PANS-OPS Vol. II provides some related requirements. However, most part of PANS-OPS Vol. II is just flight procedure design criteria [3].

IFPP'S CHALLENGE (1): SARPS ON STATE RESPONSIBILITY FOR IFPDS

Under circumstances mentioned above, ICAO IFPP is tackling with two challenges. Firstly, ICAO IFPP, as tasked by ICAO ANC (Air Navigation Commission), is developing SARPs provisions addressing the responsibility by ICAO contracting States, etc. (second challenge is the development of guidance material, which is discussed in the next section).

Introducing SARPs concerning the responsibility by State for instrument flight procedure design service will lead to the improvement of flight safety by the implementation of instrument flight procedure design service by States in a uniform way.

While discussions are still under way within IFPP, general direction of discussion on the contents of SARPs is as follows.

General Responsibility by States

First of all, as a principle, ICAO contracting States, where instrument flight procedures exist, have the responsibility for the provision of "Instrument Flight Procedure Design Service" (IFPDS). Provision of this service, or a part of this service, may be delegated to one or more other Contracting State(s) as a joint service; and/or to non-governmental agency(s).

It is to be noted that, in all cases in the paragraph above, the State concerned shall still remain responsible for all instrument flight procedures for aerodromes and airspace under the responsibility of the State. In other words, a State is responsible for all instrument flight procedures for aerodromes and airspace under the responsibility of the State no matter who design or own the flight procedure.

The statement above on the final responsibility by State looks simple and clear. However, there are some cases where the situation is complicated. One special case may be found in the following situation. Imagine which State is responsible for this RNP AR APCH (Required Navigation Performance - Authorization Required Approach) in the following case.

a. RNP AR APCH is established in an aerodrome in State A.

b. Operator (Airline) in State B flies the procedure (Sometimes, the operator leads the project for the implementation of RNP AR APCH).

c. The RNP AR APCH was designed by a design organization in State C.

Final conclusion has NOT been reached. However, general direction within IFPP is that State A, which is responsible for the aerodrome/airspace the flight procedure serves to, is responsible. This is because State A is responsible not only for the operation itself, but also for overall impact caused by the operation on entire society around the aerodrome.

This philosophy is valid for both of these two cases, where the RNP AR APCH procedure is published on the State A's AIP (Aeronautical Information Publication) as "public procedure", and, where the procedure is not published (special procedure).

In reality today, such situation may exist where State A has NO clue about the design criteria which the design provider applied. This situation should NOT be left. The RNP AR APCH must be regulated by State A, no matter whether it is published on the AIP or not. For this purpose, State A must have appropriate function to oversee this operation including the approach procedure itself in order to complete its responsibility for the overall safety.

Design Criteria

Instrument flight procedure shall be designed in accordance with State-approved design criteria. This "State-approved design criteria" should be based on ICAO Doc 8168 (PANS-OPS) [3]. However, deviation is possible. In case of the deviation, the difference should be published in the State AIP in accordance with the provision in ICAO Annex 15 (Appendix 1) [6]. Such information on the difference will facilitate operators to know how flight procedures they are going to fly have been designed.

Oversight

States must ensure that an instrument flight procedure design service provider intending to design an instrument flight procedure for aerodromes or airspace under the responsibility of the State meets the requirements established by an appropriate regulatory framework.

Safety Management

No one will disagree with the idea that IFPDS is a significantly safety-related activity. Therefore, general consensus by IFPP is that Safety Management System (SMS) should be applied to IFPDS in some way. However, situation is not so simple. This is because of the fact that there are varieties of schemes for the provision of IFPDS. Followings are examples of existing scheme.

a. State may design flight procedures for aerodromes under their responsibility

b. ANSP(s) (Air Navigation Service Provider(s)) may design flight procedures for aerodromes within airspace under their service (Note that there exist multiple ANSPs in some State!)

c. Aerodrome operator(s) may design flight procedures for their own aerodromes

d. Third party (independent) design organization(s) may design flight procedures under contract with State, ANSP, aerodrome operator, airline, etc.

e. Combination of above.

Due to such diversity, and resulting difference in the size of organization, it is not easy to establish one single Standard, Recommended Practice, or even guidelines for SMS by design provider. For example, assume the case d. above. In some location, the entire risk associated with aircraft and air traffic management operation may be better managed by aerodrome or ANSP level than within single design organization. However, in another location, this is not true. A State-certified third party design organization and an ANSP may be competing with each other for flight procedure design activities. In this case, "SMS at ANSP level" will not work well.

Noting the facts such as above, IFPP, coordinating ICAO Safety Management Panel (SMP), will continue the discussion on how to implement SMS to IFPDS which is applicable to various schemes.

Quality Assurance

States shall ensure that an instrument flight procedure design service provider utilizes a properly organized quality assurance system at each stage of the instrument flight procedures design process. This shall be made demonstrable for each stage of the process, when required.

Continuous Maintenance

One important aspect of quality assurance of instrument flight procedures are their continuous maintenance and periodic review.

Upon continuous maintenance, significant changes to obstacles, aerodrome, aeronautical and Navaid data are assessed for their impact on the instrument flight procedure. Especially, assessment of the impact by newly-proposed construction on the published procedures are getting more and more important, as more and more new construction such as mobile phone antenna, wind power mill, etc. are planned.

States must ensure that continuous maintenance of promulgated instrument flight procedures be properly conducted. This requirement can be, and must be, met through appropriate oversight system on the sponsor / owner of the flight procedure. For example, where an aerodrome operator is responsible for the flight procedure, requirements for continuous maintenance may be included in the conditions for an aerodrome certificate.

Periodic Review

Upon periodic review, in addition to continuous maintenance, all changes to obstacles, aerodrome, aeronautical and Navaid data are assessed. In addition, impact by changes to design criteria and user requirements are assessed upon periodic review. If action is required, the design activity returns to the start of process.

State must establish the interval for the periodic review according to the needs of the State (but, no longer than five years) [3]. Then, States must ensure that periodic review of promulgated instrument flight procedures is properly conducted. This requirement can/must be enforced through appropriate regulatory framework like that for continuous maintenance as discussed above.

IFPP'S CHALLENGE (2): GUIDANCE MATERIAL ON THE REGULATORY FRAMEWORK FOR IFPDS

Development of SARPs is not a final goal. Many States recognize that they need more detailed guidelines to meet the requirements in SARPs. Therefore, IFPP is also trying to develop a guidance material which supports States in meeting the responsibilities mentioned above. This is the second challenge by ICAO IFPP.

Outline of the Manual

IFPP developed the TOR (Terms of Reference) of the guidance material. The material is titled as *"Manual on the Development of Regulatory Framework for Instrument Flight Procedure Design Service"* (tentative). Main points within the TOR are as follows:

[Scope] This manual is a guidance material for the development of regulatory framework by States, including legislation, regulations and technical standards for the oversight and provision of IFPDS (Instrument Flight Procedure Design Service). It also aims at providing guidelines for service providers to develop their process, procedures and organizations, under States' legislation.

[Assumed Reader] Considering the scope above, it is assumed that the primary reader is State Regulators responsible for regulating IFPDS. However, this guidance material also regards IFPDS as assumed readers.

[Harmonization] Harmonization will be made as much as possible with existing ICAO documentation, such as PANS-OPS vol. II [3], Doc 9906 [4][5], as well as proposed SARPs provisions as discussed above.

The guidance material consists of three chapters, Introduction (Chapter 1), Regulator Issues (Chapter 2), and Provider Issues (Chapter 3).

Regulator Issues

States shall ensure that an instrument flight procedure design service provider utilizes a properly organized quality assurance system at each stage of the instrument flight procedures design process.

Chapter 2 of the Guidance Material provides guidelines for regulators (State) on the development of regulatory framework to oversee IFPDS. Original intention is to supplement the proposed SARPs as discussed above. ICAO Safety Oversight Manual (Doc 9734) [7] was referred to upon developing the basic framework. Based on the sample legislation in Doc 9734, contents were supplemented in order to meet the requirement specific to IFPDS.

In addition, Protocol Questions (PQs) were referenced, which were asked about by ICAO USAOP (Universal Safety Oversight Audit Programme) auditors. Some of current PQs are not directly derived from existing ICAO regulations (Annex or PANS), but just applied from good practices in successful States.

In the future, PQs will be revised reflecting the new Annex provisions and the guidance material which IFPP is developing.

Provider Issues

Chapter 3 will provides guidelines on the development of processes and procedures to be established by service providers. For example, this chapter will include sample contents of Operations Manual by Instrument Flight Procedure Design Provider and Flight Validation Service Provider.

Note that existing ICAO Doc 9906 ([4][5]) focus on the work process and quality assurance process applicable to services. The new guidance material rather focuses on the "framework" needed to establish and operate the work process such as described in Doc 9906.

Flight Validation

As widely recognized, Flight Validation (FV) is one of the most important steps within quality assurance process of instrument flight procedures. Hence, it is implied that State must ensure that "a flight validation provider" (though not clearly defined) intending to validate an instrument flight procedure for aerodromes or airspace under the responsibility of the State meets the requirements established by an appropriate regulatory framework.

ICAO IFPP has contributed to the development of guidance material for FV activities. ICAO Doc 9906, vol. 5 [5] provides guidance for conducting validation of instrument flight procedures, including safety, flyability and design accuracy. ICAO Doc 9906, vol. 6 [8] provides guidance for the establishment of flight procedure validation pilot training.

Intention of new guidance material is to supplement these guidelines. Focus by the new guidance material is on the establishment of organization and working frameworks within FV provider, while Doc 9906 vol. 5 [5] focuses on the work process itself. For example, it may provide sample Table of Contents of an Operations Manual for FV provider.

The author recognizes that many providers have established excellent working organizations with good framework. On the other hand, it is to be noted that the main target reader of the new guidance material is those who are going to develop all from scratch. To accomplish this, the author request input from the audiences on their good practices, etc.

CONCLUSION

For the improvement of safety related to flight operations with instrument flight procedures, it is important that State must establish a well-organized regulatory framework and conduct oversight of providers in accordance with the framework.

Now, ICAO IFPP is making effort for this purpose, by developing (draft) SARPs and supporting guidance material.

RECOMMENDATIONS

It is recommended that the participants of IFIS 2014 should

a. note the importance of quality assurance process of instrument flight procedures, including flight validation,

b. support the activities by ICAO IFPP to develop SARPs and related guidance material, especially by providing input to the guidance material.

ACKNOWLEDGMENTS

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Enhancement of Flight Inspection System Using Visual Information

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ABSTRACT

In conventional flight inspection system (FIS), inspection conclusion is based on mainly signal data (AGC, angle, range, etc.), voice quality (VHF inspection, for example), eye observation (VASI/PAPI), plus pilot/inspector's intuitive feelings and subjective judgment, especially during flight procedure validation. Evaluation of procedure obstacle clearance and maneuvering area design remains some degree of uncertainty under cover, on account of different experience/ability level of pilots/inspectors. The paper proposes to use visual information to enhance flight procedure inspection: three-dimensional virtual environment based GIS technology, video information from airborne cameras and EVS, digital charts. The visual information solution provides additional, repeatable, more intuitive, diverse views during inspection flight. It supports procedure inspection with a more convincible, accurate conclusion.

In this solution, flight inspection system collects video data from airborne nose and tail cameras, as well as EVS video bus. All the data are recorded real time with epoch tags obtained from GPS receiver. In post-processing module of FIS, aircraft position and attitude information is imported into three-dimensional GIS virtual environment rendered by actual terrain and image data. Aircraft position is plotted in the digital chart with protection area indication, meanwhile the recorded video can be replayed. The visual information from three sources is synchronized by GPS UTC time tag, therefore by this solution, in the meantime, live scenes outside the cabin are seen from different views, while the three-dimensional geographical feature is visible and aircraft track is shown in the chart. Inspectors and procedure designers can evaluate the obstacle clearance and protection area design more accurately with the repeatable video, flight track in chart and GIS environment.

The key elements of the special visual post-processing module of FIS are described in this paper and its successful application in Collaborative Flight Inspection System is presented in detail.

INTRODUCTION

Flight validation is essential before one flight procedure is published, which should confirm the coded ground track and the identified lateral/vertical protection boundaries [1] at least. Besides, obstacles assessment is a critical part in flight procedure validation in air, which includes controlling obstacle verification, obstacle evaluation and missing obstacle identification.

Mainly, the obstacle is assessed via the pilot's intuitive judgment [2, 3, 4] and depends on subjective factors largely. The tool or equipment supporting objective or numerical analysis is lacking, as well as the way to record, playback the process of obstacle assessment which is a one-time activity in current procedure validation work. The assessment result highly relies on the experience of pilots. This can lead to different conclusions for a same obstacle. With no any record support, the result cannot be confirmed by other groups when different opinions appear, unless a new flight is arranged. All the above concerns expose the potential risk of present obstacle assessment mode.

The paper presents a way to enhance procedure flight validation introducing multiple visual information: terrain and image data in Geographic Information System (GIS), real-time video data from airborne cameras and Enhanced Vision System (EVS) and digital chart. The fusion among multiple visual information, flight track data, procedure chart and flight inspection outcome provides inspectors and procedure designers an outstanding panoramic view of the whole flight, with controllable playback ability. The projection of actual flight path in the digital chart makes an accurate evaluation of obstacle clearance. These improvements offer more reliable validation of procedure, especially for obstacle assessment.

POSTPROCESSING PLATFORM IN CFIS-G450

Collaborative Flight Inspection System for Gulfstream 450 (CFIS-G450) is designed to perform PBN flight procedure validation via Gulfstream 450 jet. Onboard data from ADC, IRS, FMS and HUD etc., are brought into CFIS-G450 to support procedure validation, plus video data from onboard cameras and EVS which makes visual inspection possible.

A special platform are developed to process all the data further in ground after flight activities. The system block diagram of this postprocessing platform is shown as Figure 1. Control and Data Processing Module manages the whole processing steps, processes the original data recorded during flight, and synchronizes all the processed data into GPS UTC system. GIS Module renders a virtual, 3D, full-view scene by rendering terrain data, integrating images, applying Digital Elevation Model (DEM) information. Chart Module integrates flight track and obstacle clearance information, points out relative position among the actual path and clearance area intuitively. Multiple Video Module displays the videos from cameras and EVS synchronously with active flight path and inspection/validation outputs. Inspection Data Module outputs inspection/validation results as tables, curves on the screen, such as Navigation System Error (NSE), Required Navigation Performance (RNP), Dilution of Precision (DOP), etc.

All the data, including flight track, video from cameras and EVS, inspection outcomes, are labeled with GPS UTC flag to achieve information fusion in time domain. The operator can pause the playback at any epoch and check all the information at specific timestamp. When an obstacle shows in the video clip, GIS Module helps to check it from multiple views while Chart Module provides obstacle location.

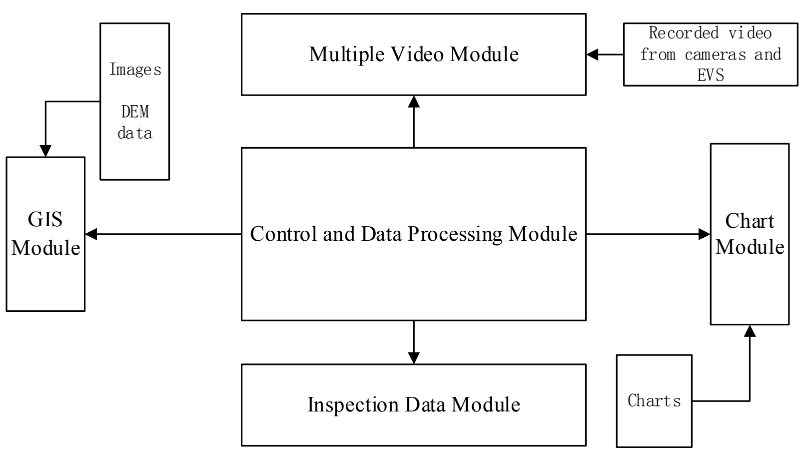

Figure 1. Postprocessing Platform of CFIS-G450

CORE DESIGN IN POSTPROCESSING PLATFORM

GIS Module

The classical Pyramid pattern (Figure 2) is applied to manage and display all the data in this module. In this pattern, a couple of layers are generated by copying the original data with decreasing levels of resolution, for example the original layer (No. 0) with the highest resolution while the coarsest layer (No. n) with the lowest resolution. The advantage is that drawing speed can be maintained since fewer pixels are needed to draw a successively areas as the user zooms in. The coarsest level of resolution is used to represent the entire area quickly.

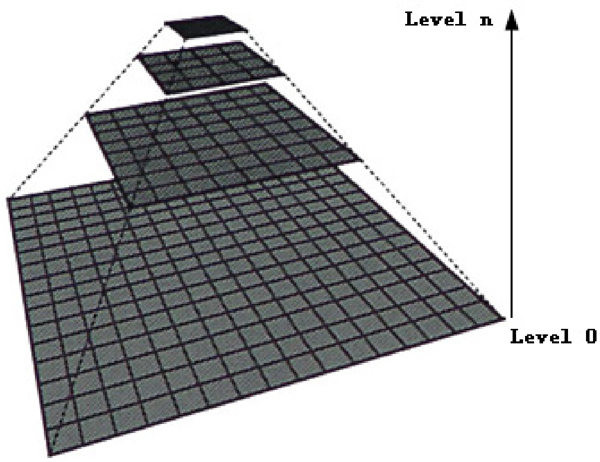

Figure 2. Pyramid Pattern in GIS [5]

In this module, bilinear interpolation method is employed to sample the original dataset (DEM) and obtain "data tiles" for various levels in the Pyramid. Taking the DEM values at points $Q_{11}(x_1,y_1)$, $Q_{12}(x_1,y_2)$, $Q_{21}(x_2,y_1)$, $Q_{22}(x_2,y_2)$ as known, the DEM value of point P (x,y) in the area of four known points is calculated by two steps [5]:

1) Linear interpolation in X direction

$$f(R_1) \approx \frac{x_2 - x}{x_2 - x_1} f(Q_{11}) + \frac{x - x_1}{x_2 - x_1} f(Q_{21}) \quad (1)$$

$$f(R_2) \approx \frac{x_2 - x}{x_2 - x_1} f(Q_{12}) + \frac{x - x_1}{x_2 - x_1} f(Q_{22}) \quad (2)$$

2) Linear interpolation in Y direction:

$$f(P) \approx \frac{y_2 - y}{y_2 - y_1} f(R_1) + \frac{y - y_1}{y_2 - y_1} f(R_2) \quad (3)$$

The DEM data tiles are stored in advance, so do the image data. The real 3D terrain scene is rendered automatically by loading the sampled data when drawing the flight track.

Chart Module

The Chart Module is designed to not only use digital chart directly, but also be able to digitalize the charts in PDF or image format (jpg, bmp, etc.). Two known position points in the chart, for example way points or navaid facilities, are taken as the references. The position of other points in the chart can be calculated via the map scale, pixels, and relative location. The position mapping in chart frame and Earth frame for all the points in the chart is stored in a XML file which is loaded. The file is loaded with the chart to match flight track projection.

Figure 3 shows the example to process a chart with PDF format. Figure 4 displays the 2D map with loaded chart. Measurement tool can be used to evaluate the distance between actual flight track and obstacle clearance boundary.

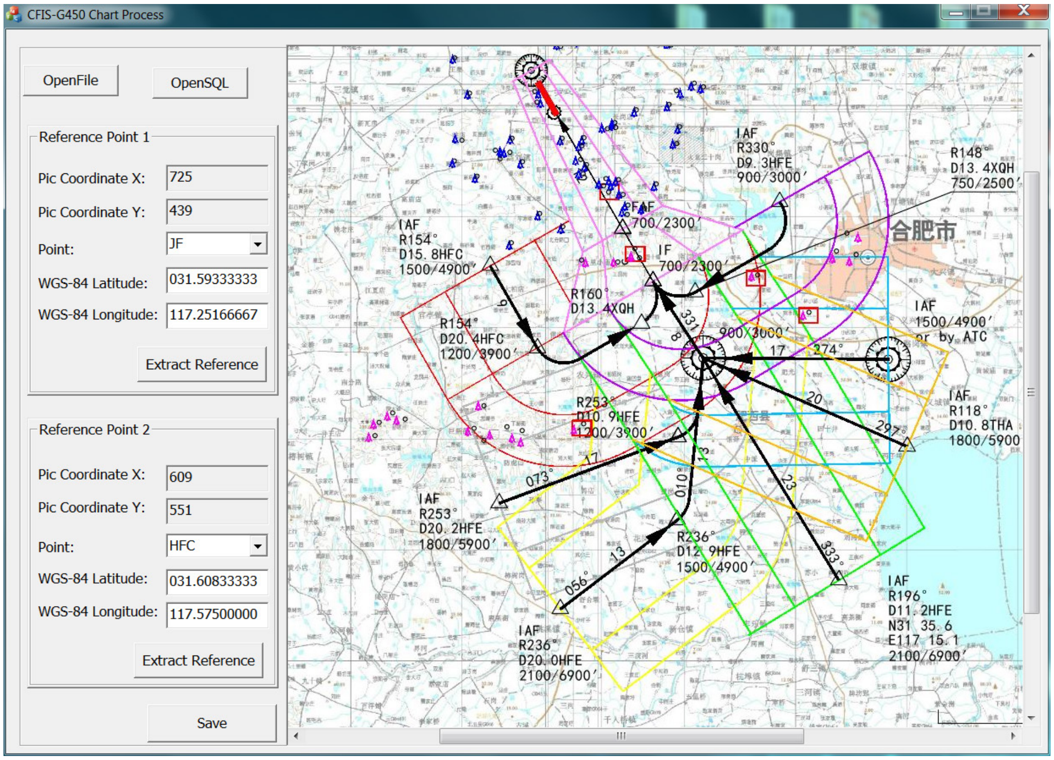

Figure 3. Chart Process Example

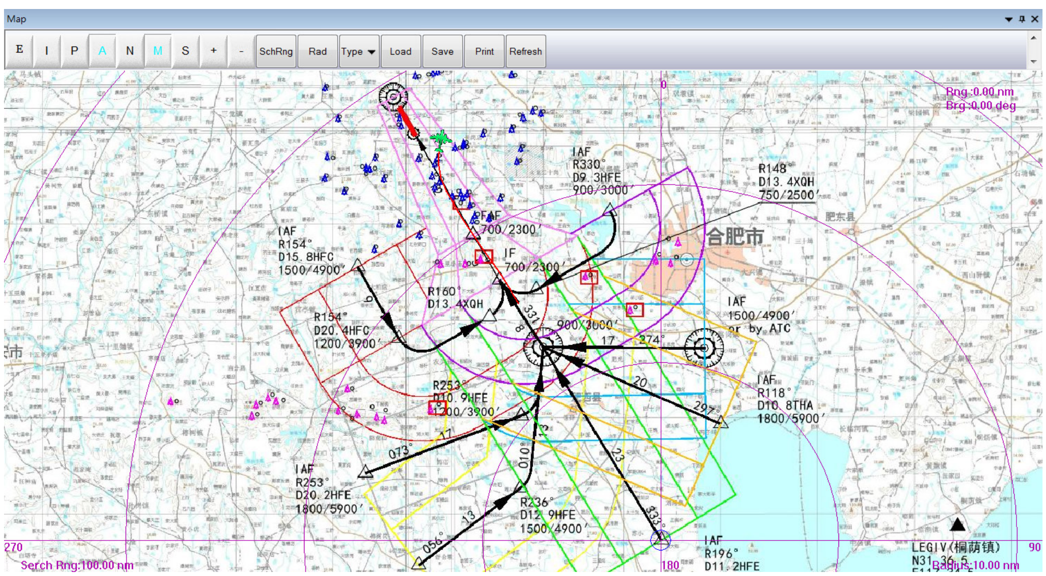

Figure 4. 2D Map with Chart Loaded

The purple, green and yellow lines refer to the protection boundaries for different approach procedures. The black line is the approach path while the red one shows flight track. This visual mode offers plenty of information for the protection design assessment.

Multiple Video Module

The videos are introduced from four onboard cameras:

1) two locating on the belly: record the obstacles during approach

2) one on the tail: record the attitude and full view during flight

3) one camera for EVS: record the view in the nose direction and information from onboard instruments

A commercial off the shelf (COTS) rugged digital video recording and distribution system, GRIP DVR is used to store the videos and process 3D position + time with GPS receiver output.

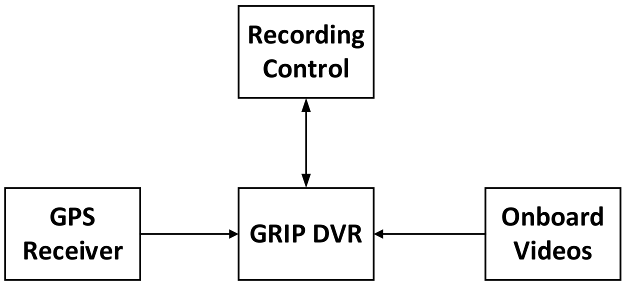

Figure 5. Video Processing

GRIP DVR starts to record videos after receiving control command, meanwhile GPS receiver outputs position and time information (4 dimensions, 4D) to DVR via serial port. The 4D information is overlaid in the original videos. The video frame for any GPS UTC epoch can be located by the known starting time and frame rate. The synchronization among videos and other modules is achieved at the same time.

APPLICATION IN PROCEDURE VALIDATION

The Postprocessing Platform was used to process flight procedure validation performed at Palm Spring International airport, CA, an experiment to test the CFIS-G450, October 30, 2013. Figure 6 shows an overview of the platform. The active inspection data, 3D GIS visual scene, 2D chart and real videos are displayed simultaneously to provide procedure validation results with multiform numerical and visual information.

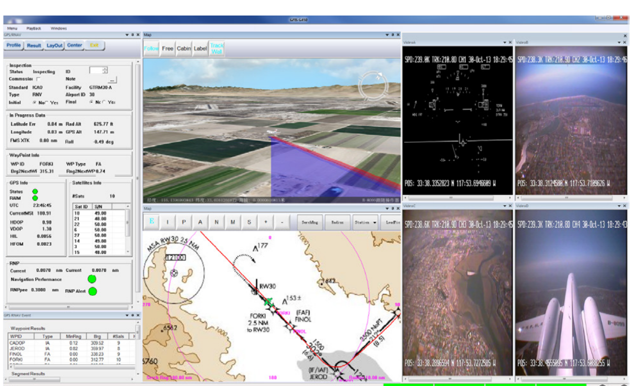

Figure 6. Postprocessing Platform Overview

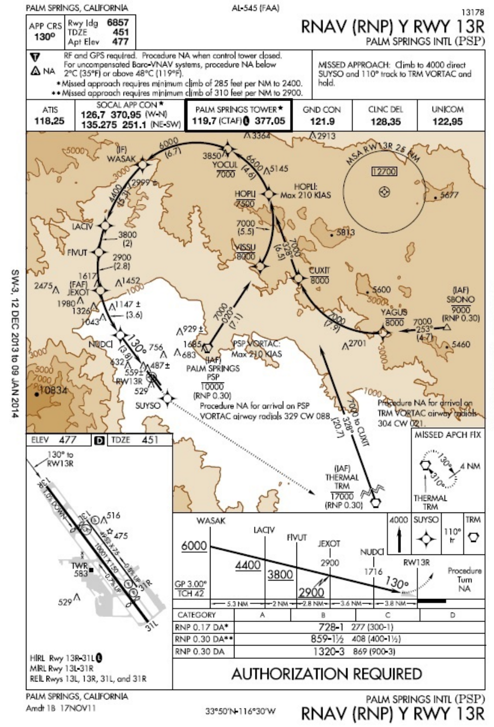

Figure 7. The Validated Procedure

Figure 7 is the flight procedure validated which is actually a published one, but was used for experimental purpose here. Figure 8 presents the Altitude 'Wall' in GIS visual scene to describe the variation of altitude. The hyacinthine track surface provides an intuitive view of altitude variation.

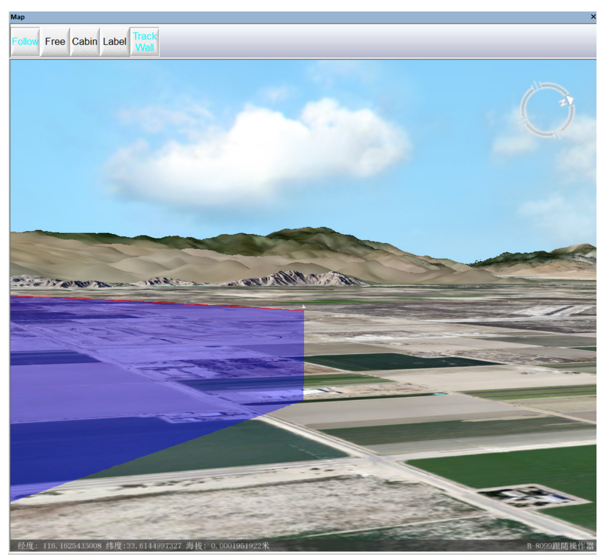

Figure 8. Altitude 'Wall'

Figure 9. Multiple Video Display

When the 2D chart indicates the deviation of actual flight track and expected route, Figure 9 offers real views of altitude, terrain, and instrument information.

CONCLUSIONS

Multiple visual information: 2D charts, 3D GIS virtual scene, onboard videos are employed to enhance flight procedure validation, especially provide a controllable playback platform to support obstacle assessment. All the visual information is labelled with GPS UTC time flag for synchronization in temporal domain. The postprocessing of the experimental flight data in Palm Spring Intl airport outputs a multiform validation result: numerical and visual, which supports procedure validation with more reliability.

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Session 7

Flight Validation of SBAS & GBAS

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SBAS and its Roles in Flight Inspection

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ABSTRACT

Space Based Augmentation Systems (SBAS) for GNSS/GPS navigation are operational in many areas in the world today. Some systems are already fully certified for approaches with vertical guidance and for Safety of Life (SoL) applications. Many countries have successfully implemented SBAS based Localizer Performance procedures with Vertical guidance (LPV) for approach already.

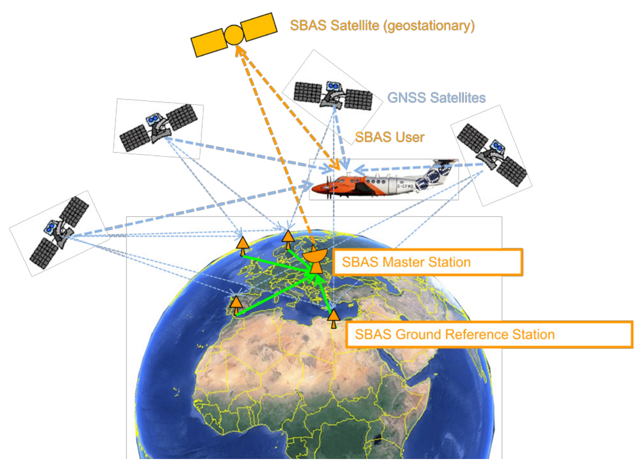
Even if the supporting SBAS itself is fully certified, each new approach procedure needs to be flight checked/validated before it is promulgated for public use. During the flight check, SBAS coverage, accuracy and integrity along the procedure as well as the final approach construction data are the central points of interest. SBAS capable flight inspection equipment provides automatic evaluation and recording of these parameters.

In addition to SBAS procedure checks, where SBAS is subject to inspection, SBAS can also serve to improve the accuracy of the position reference of the flight inspection system. By this SBAS lead to higher accuracy without additional costs for ground equipment or service subscriptions.

This paper describes the requirements for flight inspection of SBAS based procedures and shows a procedure oriented way of in-flight data analysis and evaluation to comply with these requirements. Further it describes the implementation and experience of using SBAS as position reference during flight checks.

INTRODUCTION

An SBAS augments core GNSS satellite constellations by providing ranging, integrity and correction information via geostationary satellites. The system comprises a network of ground Ranging and Integrity Monitoring Stations (RIMS), Master Control Centers (MCC) and Uplink Stations. The RIMS monitor satellite signals and send the data to the Master Control Centers (MCC) that collect and process the data and generate SBAS messages. The Uplink Stations send the SBAS messages to geostationary satellites that broadcast the SBAS messages to the SBAS user.



SBAS Elements

SBAS PRINCIPLE

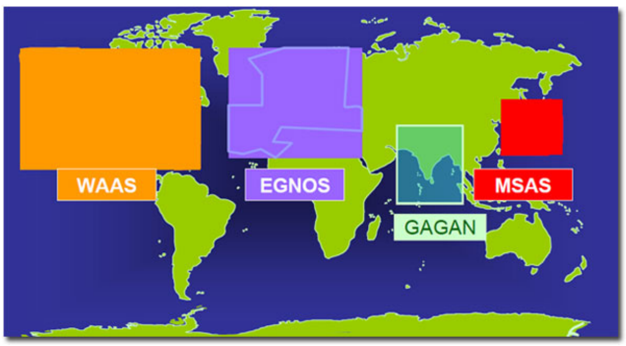
Aircraft receivers using SBAS for navigation acquires the ranging and correction data and applies this data to determine the integrity and improve the accuracy of the derived position. Four certified satellite augmentation systems are available today:

- WAAS (North America)

- EGNOS (Europe)
- MSAS (Japan)
- GAGAN (India)

Other SBAS services are under construction:

- SDKM (Russia)



SBAS Service Areas

The SBAS corrections and integrity data is transmitted by a geostationary satellite as a GPS-like signal modulated with a PRN code and can be received and processed by any SBAS capable GNSS receiver. A secondary geostationary SBAS satellite serves as backup.

The SBAS service is specified to provide at least the following accuracies (conservative 95% limit) within its service volume:

- Horizontal Accuracy: 3 m
- Vertical Accuracy: 4 m

Besides an improved position solution the SBAS also provides integrity service for detection of e.g.:

- GNSS satellite errors
- Ionosphere propagation errors
- Satellite clock errors

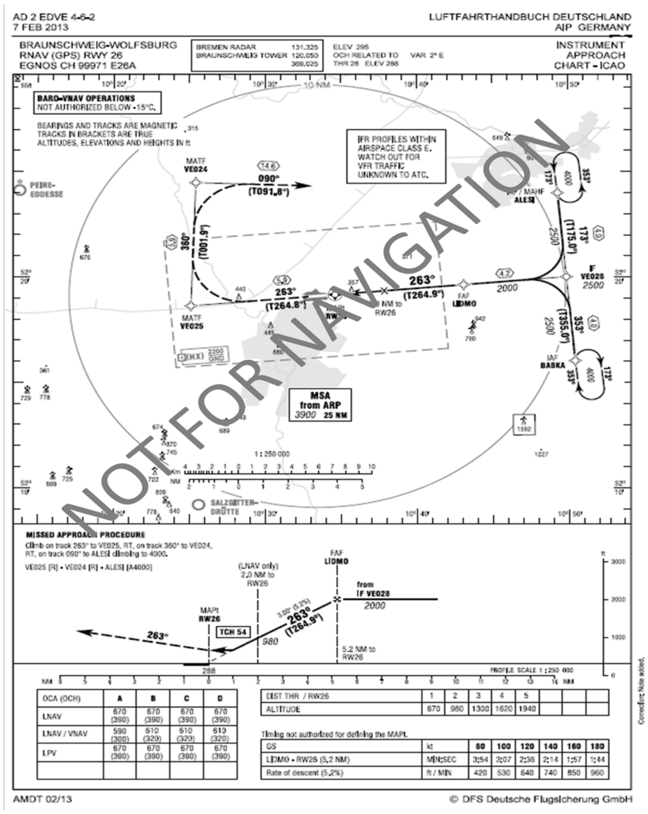
The geostationary satellite broadcasts this information via different message types. 20 different message types are defined so far.

Type	Contents
0	Don’t use for safety applications
1	PRN mask assignments, set up to 51 of 210
2-5	Fast corrections
6	Integrity information
7	Fast correction degradation factor
9	Geo Navigation message (X,Y,Z, time, etc.)
10	Degradation parameters
12	SBAS Network time / UTC offset parameters
17	Geo satellite almanacs
18	Ionospheric grid points masks
24	Mixed fast corrections/long term satellite error
25	Long term satellite error corrections
26	Ionospheric delay corrections
27	SBAS Service message
28	Clock Ephemeris Covariance Matrix message
62	Internal test message
63	Null message

The Message Types 2-5 contain the data for fast correction of each satellite.

Urgent integrity information is transmitted by Message Type 6 alerting the SBAS using receiver within 6 seconds after occurrence of an alert condition. The occurrence of Message Type 6 can be seen as the first indication of a tendency to integrity loss.

On 2nd March 2011 EGNOS performance (within EGNOS Service Area) was certified for Safety-of-Life (SoL) application in aviation. Approach procedures with vertical guidance (APV) are implemented in many countries as LPV (Localizer Performance with Vertical guidance) with descent minima down to 200 feet, today.



Example: LPV Approach Braunschweig EDVE

Avionic for SBAS Precision Approach

The main elements of the aircraft navigation equipment for flying SBAS LPV approaches consist of:

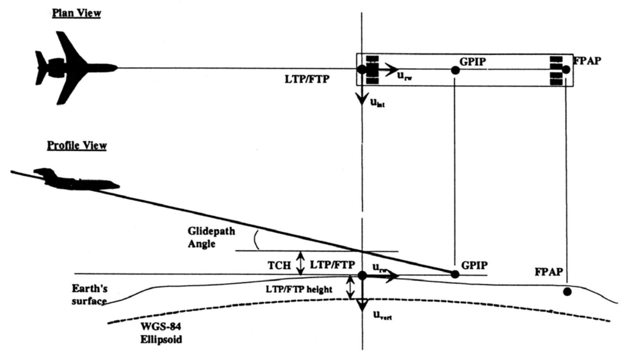
- SBAS capable GNSS receiver
- SBAS LPV capable FMS
- Navigation Database
(with Final Approach Segment (FAS) Data Block)

DATA FIELD	DATA
OPERATION TYPE	0
SERVICE PROVIDER IDENTIFIER	1
AIRPORT IDENTIFIER	EDVE
RUNWAY	26
APPROACH PERFORMANCE DESIGNATOR	0
ROUTE INDICATOR	
REFERENCE PATH DATA SELECTOR	0
REFERENCE PATH IDENTIFIER (APPROACH ID)	E26A
LTP/FTP LATITUDE	521913.0605N
LTP/FTP LONGITUDE	0103432.5010E
LTP/FTP ELLIPSOIDAL HEIGHT	130.4
FPAP LATITUDE	521906.9805N
FPAP LONGITUDE	0103243.8325E
THRESHOLD CROSSING HEIGHT (TCH)	54
TCH UNITS SELECTOR (METERS OR FEET)	0
GLIDEPATH ANGLE (GPA)	3.00
COURSE WIDTH AT THRESHOLD	107
LENGTH OFFSET	72
HORIZOLTAL ALERT LIMIT (HAL)	40
VERTICAL ALERT LIMIT (VAL)	50
CRC REMAINDER	65CB4D53

GNSS/GPS receiver	Flight Management System (FMS)	Navigation Database (FAS Data Block)

The airborne GNSS/GPS receiver applies SBAS range correction data to the GNSS pseudo range data and calculates a corrected position.

In order to fly an SBAS approach the pilots selects the approach via the FMS CDU. The nominal geometry of the approach to be flown is stored in the FMS navigation database. The Final Approach Segment (FAS) Data Block for the selected approach contains the coordinate of the threshold, the flight path alignment point, glide path angle and threshold crossing height.



Approach Definition by FAS Data Block

Based on the SBAS corrected position the FMS calculates ILS-lookalike lateral and vertical deviations that guide the aircraft on the precision approach. The correctness of the FAS data block is essential, since all guidance is calculated according this data. A CRC checksum allows detection of corrupted FAS Data.

Typical errors in a FAS data block are:

- Incorrect LTP height or coordinates:
Typically caused by a wrong coordinate datum e.g.: NAD-83 instead of WGS-84 or during conversion between different datums.
- Flight path is not aligned with the runway
Incorrect coordinates of FAF or FPAP or by mixing up these two points.

Integrity on SBAS approach

The availability of integrity information is essential for applications in aviation in order to minimize the risk of Hazardous Misleading Information (HMI). The requirements for integrity and alert limits for particular operations are laid down in ICAO SARP’s:

Operation	Integrity requirement	Horizontal Alert Limit (HAL)	Vertical Alert Limit (VAL)
NPA	$1x10^{-7}$/h	0,3 NM	N/A
LPV DH ≥ 250ft	$1\text{-}2x10^{-7}$/Appr. (per 150 seconds)	40 m	50 m
LPV DH < 250ft 200ft ≤ DH	$1\text{-}2x10^{-7}$/ Appr. (per 150 seconds)	40 m	35 m

High Level Integrity Requirements for SBAS Approaches

The integrity limits for precision approaches are specified per approach (per 150 seconds).

Definition of Integrity Parameters:

HPL/VPL (Horizontal / Vertical Protection Limit): is a horizontal/vertical distance around the indicated position that assesses the risk to be 10^{-7} for every 150 seconds that true position is outside of that distance. The geometry described by HPL and VPL is a cylinder around the indicated position.

HAL/VAL (Horizontal / Vertical Alert Limit) is the allowable limits for HPL/VPL depending on the phase of flight.

The horizontal and vertical alert limits (HAL/VAL) are directly specified for the particular operation. During the approach the airborne receiver calculates actual Protection Level (HPL/VPL) based on the actual satellite constellation (DOP), and the remaining differential range error and other error characteristics for residual troposphere delay and receiver errors. If the computed xPL exceeds the xAL (HPL > HAL or VPL > VAL) for a particular operation SBAS integrity is not adequate forcing the navigation system to flag the guidance output.

SBAS AS SYSTEM UNDER FLIGHT INSPECTION

Although EGNOS and WAAS themselves are certified for Safety-Of-Life applications the GNSS/SBAS system and the procedures FAS data block needs to be flight checked during commissioning of SBAS based Instrument Procedures. The aim is to check:

- Continuity of GNSS (Signal to Noise)
- Continuity of primary and secondary SBAS satellite (Signal to Noise)
- Integrity
  (HPL/VPL)
- Accuracy
  (DOP, Positioning Error)
- Navigation Database
  (FAS Data Block)
- Procedures Design
  (Flyability, Obstacle Clearance)

In the following the implementation of SBAS capability to a flight inspection aircraft and to its flight inspection system is described.

Flight Inspection Aircraft

Inspection of an SBAS approach procedure with vertical guidance (LPV) requires an appropriately equipped flight inspection aircraft. Alternatively, if no LPV capability can be installed to the aircraft avionic the AFIS can provide the required guidance to fly the LPV approach. AFIS guidance can also be used with flight director and autopilot.

> **Note:**
> AFIS guidance can be used to fly the aircraft according to the desired flight path during flight validation, if the weather conditions permit flight validation (typical daylight VMC). It does not enable the aircraft to fly SBAS LPV approaches for navigation in IMC down to the published minima!

AFIS Equipment for SBAS Checks

The implementation of SBAS capability to the AFIS followed a simple rule:

Any SBAS parameter that may provide an indication of marginal performance, interference, loss of integrity or other anomalies shall be recorded by the AFIS to allow further analysis:

- GNSS Time
- For the primary and secondary SBAS satellite(s):
  - SBAS PRN being tracked
  - Signal-to-Noise Ratio (SNR)
  - Elevation
  - Azimuth
- SBAS Integrity Alerts
  (e.g. occurrence of Message Type 6)

- Number of GNSS PRN being tracked
- For each individual GNSS satellites:
  - GNSS PRN being tracked
  - Signal-to-Noise Ratio (SNR)
  - Elevation
  - Azimuth
- Position Dilution of Precisions (PDOP)
- Horizontal Dilution of Precision (HDOP)
- Vertical Protection Level (VPL)
- Horizontal Protection Level (HPL)
- Vertical Dilution of Precision (VDOP)
- For each segment, the maximum and minimum altitude, ground speed, climb rate, and climb gradient
- The flight track flown referenced to the desired track of the approach procedure, including procedure fixes

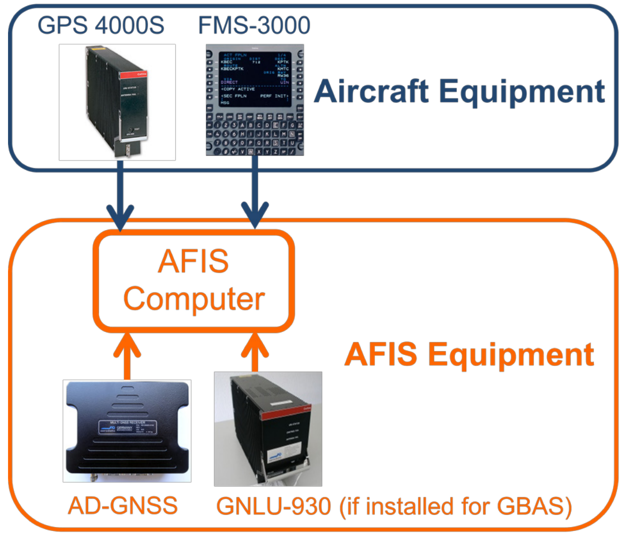
To provide the above data the AFIS must be interfaced with suitable SBAS receiver(s) to acquire the relevant data.

Interface Considerations:

It is desirable to interface with the aircraft SBAS receiver (TSO C145a) as source of data, however many TSO SBAS receiver do not provide detailed analysis of SBAS Messages or detailed access to individual satellite parameters like Signal to Noise ratio. The AFIS integrated GNSS/SBAS receiver (mainly installed as position reference sensor) typically provides all this data and fills this gap. Each SBAS Message received is provided by this receiver and can be recorded in fully length together with other flight inspection data. In case of anomalies all data required for its analysis can be found in one common recording.

It has been observed that different receivers sometimes differ in their behavior during short period anomalies. It could happen that some anomalies might not be shown by one of the receivers. Sometimes the one receiver is more sensitive sometimes the other(s). For that reason every available SBAS receiver is interfaced by AFIS.

The AFIS interfaces the following SBAS receivers:



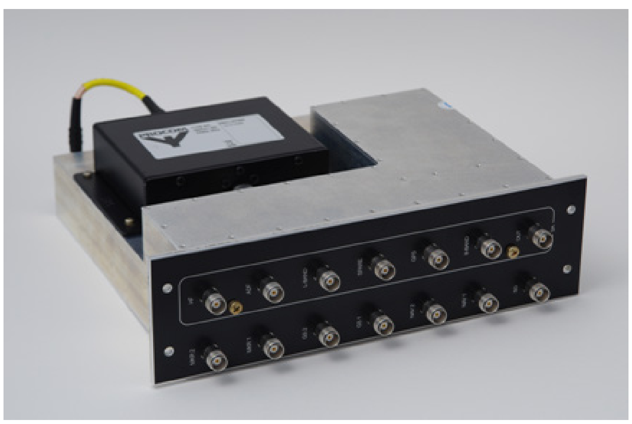
The following data is provided by the different SBAS receiver:

Sensor	Data
AD-GNSS	GNSS satellite data (Az, Elev, S/N) GNSS data (DOP etc.) SBAS satellite data (Az, Elev, S/N) SBAS messages (MT 6 etc.) SBAS corrected position HPL/VPL
GPS-4000S	GNSS satellite data (Az, Elev, S/N) GNSS data (DOP) SBAS corrected position HPL/VPL
GNLU-930	GNSS satellite data (Az, Elev, S/N) GNSS data (DOP) SBAS satellite data (Az, Elev, S/N) SBAS corrected position HPL/VPL
FMS-3000	Lateral deviation Vertical deviation Flight Plan (waypoints)

For interference checks the use of a digital Spectrum Analyzer is required. A typical Spectrum analyzer installed as part of the AFIS is the Rohde&Schwarz FSV4:

Spectrum Analyzer R&S FSV4)

User configurable measurement programs are available to remote control the spectrum analyzer to perform GNSS measurements. Since the source of interference to GNSS/SBAS is likely based on ground, the use of a GNSS antenna installed on the lower fuselage of the flight inspection aircraft is required (instead of a normally installed GNSS antenna on top of the fuselage). Automatic antenna switching according to the selected measurement program is provided by the antenna switching unit:



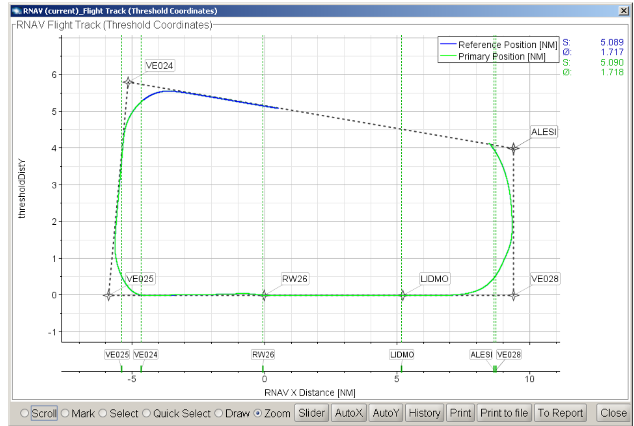
Integrated Antenna Switching Unit AD-ARBO

The measured spectrum data is recorded time synchronized with all other flight inspection data. This allows spectrum analysis during replay of flight inspection data.

AFIS Software Functions

In order to enable and support the SBAS flight checks the following features have been implemented to the AFIS software:

For documentation of the horizontal flight track the AFIS displays the nominal procedure transformed in a local threshold coordinate system:



Procedure Track in Threshold Coordinates

The LTP is at the origin of this coordinate system, the x-axis represents the desired approach path aligned with the runway. Such plot simplifies to check runway alignment, since any waypoint that appears not the x-axis is obviously not aligned with the runway.

Whenever a procedure fix is passed a vertical event line is displayed, labeled with the waypoint identifier. By this each leg switching along the procedure is marked.

This graphic provides a good overview about the resulting flight track in relation to the nominal procedure. But how can other data like GNSS Signal to Noise be plotted in a procedure oriented way? During conventional flight inspection typical graphics use the distance to the facility or the azimuth angle as x-axis parameter, but this doesn’t make sense for flight procedure oriented analysis. Especially if the procedure is complex the proper selection of the x-axis is essential.

In the initial implementation data was simply plotted versus time. The event marking with the waypoints allows correlation with the procedure legs:

Signal to Noise Evaluation vs. Times

The disadvantages of using time as x-axis are:

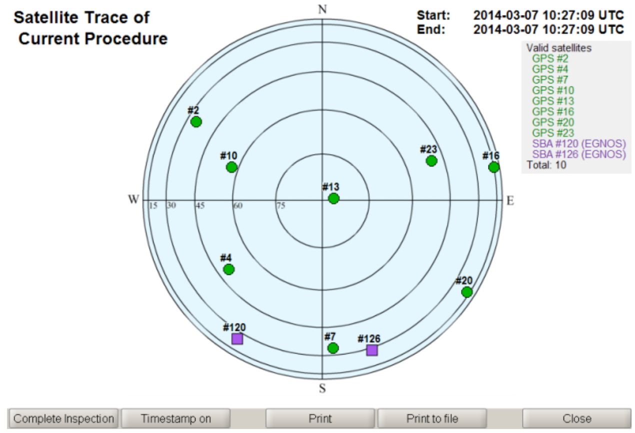
- Every time the measurement is repeated the x-axis is different
- ground speed variation does not allow precise location of certain points of interest related to the procedure

For solving this dilemma a new parameter “Along Track Distance” was defined. This parameter counts the distance from the first waypoint of the procedure under inspection along the procedure track to the last waypoint of the procedure. By this new parameter each point on the procedure can be precisely addressed. The following example shows GNSS Signal to Noise versus Along Track Distance:

Signal to Noise Evaluation vs. Along Track Distance

By the event marking of passed waypoints the correlation of the plot with each procedure leg becomes obvious.

The satellite constellation and the satellite trace are also visualized by the AFIS in a sky-plot format:



Satellite Sky Plot

The position of each GNSS satellite as well as its movement (trace) during the flight inspection procedure is displayed. The display also includes the geostationary primary and secondary SBAS satellite.

The SBAS augmentation status (healthy/unhealthy/unmonitored) of each GNSS satellite is displayed in a tabular format:

SBAS Solution | SBAS Monitor

Channel	PRN	Azim [deg]	Elev [deg]	S/N [dB/Hz]	GPS Status	SBAS Status
1	24	316	20.3	47.8	Healthy	Healthy
2	2	231	21.4	40.8	Healthy	Unmonitored
3	28	0	0.0	31.8	Weakly	Unmonitored
4	0	0	0.0	0.0	N/A	N/A
5	13	86	34.4	48.0	Healthy	Healthy
6	25	60	44.1	48.9	Healthy	Healthy
7	7	76	65.3	49.1	Healthy	Unmonitored
8	8	194	63.8	50.0	Healthy	Healthy
9	0	0	0.0	0.0	N/A	N/A
10	10	292	54.5	48.7	Healthy	Healthy
11	4	203	7.3	42.5	N/A	Unmonitored
12	120	212	25.5	41.0	N/A	Unmonitored

Satellite Augmentation Status

The following display allows direct comparison between Single GNSS and SBAS solution:

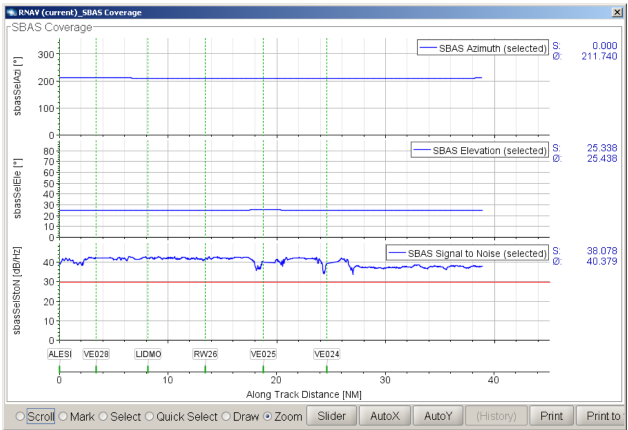
SBAS Solution | SBAS Monitor

	GPS		EGNOS (Receiver)	
Solution Mode	Single		WAAS	
Date	2013-12-03		2013-12-03	
UTC Time	10:29:42.0		10:29:41.0	
Latitude	52° 24' 14.38" N	[deg]	52° 24' 17.09" N	[deg]
Longitude	10° 49' 07.50" E	[deg]	10° 49' 06.66" E	[deg]
Altitude	1243.0	[m]	1237.8	[m]
HFOM | VFOM	3.9 | 6.7	[m] | [m]	0.9 | 1.5	[m] | [m]
HPL | VPL	78.1 | 136.4	[m] | [m]	41.1 | 69.4	[m] | [m]
Track	170.1	[deg]	169.1	[deg]
GSpeed | VSpeed	87.2 | -0.1	[m/s] | [m/s]	87.3 | -0.1	[m/s] | [m/s]
HDOP | VDOP	0.8 | 1.4		0.8 | 1.4	
Channel Indicator	oooo-ooooooo----1---		oooo-ooooooo----1---	
Solution Lost Time	0	[s]	0	[s]
Fault Alarm Time	0	[s]	N/A	[s]
WAAS MSG Quality	N/A		Pretty Good	
Measurement Condition	Not Bad		Good	

NovAtel SBAS Configuration: PRN | Enable Correction | NONE | Test Mode | Send & Save | Send

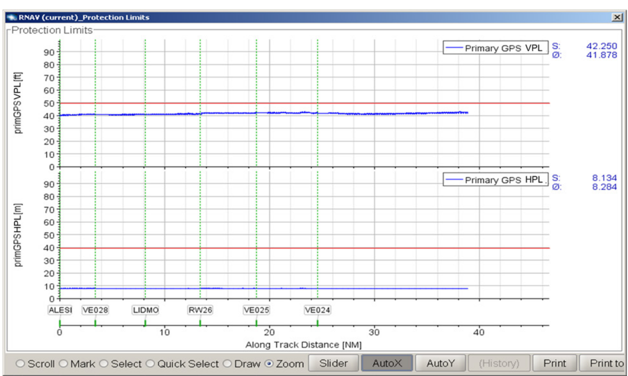
Comparison GNSS/SBAS Solution

For SBAS continuity and coverage checks the AFIS provides detailed analysis of the primary and secondary SBAS satellite in alphanumeric and graphical format:



SBAS Continuity/Coverage

Any violation of HPL/VPL against HAL/VAL becomes obvious in the following graphic:



SBAS Protection Limits

The overall evaluation for the SBAS based procedure is summarized in the Result Page:

SBAS Result Page
RNAV: RNAV;FMS#4; FlightPlan: ALESI, VE028, LIDMO, RW26, VE025, VE024, ALESI,Operator: Musmann;Company: Aerodata;
Regulations: IGS; Date: 2014-04-14 Start: 13:19:56, Stop: 13:41:13; Software: AD-AFIS-X
Inspection: Inspection_2014-04-14_D-DEMO_LPV_EDVE;

Parameter	Value		Parameter	Value
GNSS			SBAS	
HDOP max	1.0		HPL max	8.2 [m]
VDOP max	1.4		VPL max	41.2 [m]
No. SV min	8		SBAS (primary) SNR min	42.6[dB/Hz]
SNR min	41.8 [dB/Hz]		SBAS (secondary) SNR min	41.7[dB/Hz]
HFOM max	9.8[m]		FMS	
RAIM Alarm	0.000 [s]		ATK Error max	0.02 [NM]
			XTD Error max	0.00 [NM]
			XTD max	8.17 [NM]

Wpt #	Name	Latitude	Longitude	Distance to next WP	True Course to next WP	Vert. Path Angle
		[deg]	[deg]	[NM]	[deg]	[deg]
1	VE028	52°20'03.1200"N	10°49'47.5000"E	4.17	264.99	0.00
2	LIDMO	52°19'41.1500"N	10°43'01.3100"E	5.22	264.89	-1.13
3	RW26	52°19'13.0600"N	10°34'32.5000"E	5.85	264.78	-3.00
4	VE025	52°18'40.8500"N	10°25'02.5200"E	5.85	1.87	5.88
5	VE024	52°24'31.4300"N	10°25'21.3100"E	14.63	91.78	0.00
6	ALESI	52°24'01.8800"N	10°49'13.3300"E			

SBAS Result Page

The result page also indicates the following data for each leg of the procedure:

- Distance to next waypoint
- True Course to next waypoint
- Vertical Path angle

This data allows easy verification of waypoint correctness by comparison to the published procedure chart.

Since all navigation during an SBAS LPV approach is done with reference to the FAS data block the check of its correctness is imperative.

The AFIS allows direct import of FAS data block in electronic format (ARINC424) to avoid errors by manual database preparation.

The contained CRC checksum of the FAS data block is verified by AFIS, a CRC checksum error is highlighted by immediate alert.

A first verification of the imported FAS data block is possible through Google-Earth visualization prior to flight:

FAS Visualization in Goolge Earth

Errors in the FAS data block that occurred by incorrect or mixed coordinates of Final Approach Fix (FAF) and Flight Path Alignment Point (FPAP) would result in a wrong path that can be easily identified in Google Earth.

Other typical error is incorrect height datum of LTP/FTP resulting in a forward or aft displacement of the intended flight path. Such error can likely occur by mixing coordinates with different reference datum (e.g. NAD-83 with WGS-84) or during coordinate conversion. Such FAS data error will be detected during flight check since the Threshold Crossing Height determined in flight does not match the TCH in the FAS data block.

SBAS AS FLIGHT INSPECTION REFERENCE POSITION SENSOR

Due to the good experience during inspection of SBAS the idea of using SBAS as Position Reference sensor for flight inspection came up.

The SBAS receiver for that purpose is the Standard Flight Inspection GNSS receiver that is an integral part of each AFIS:

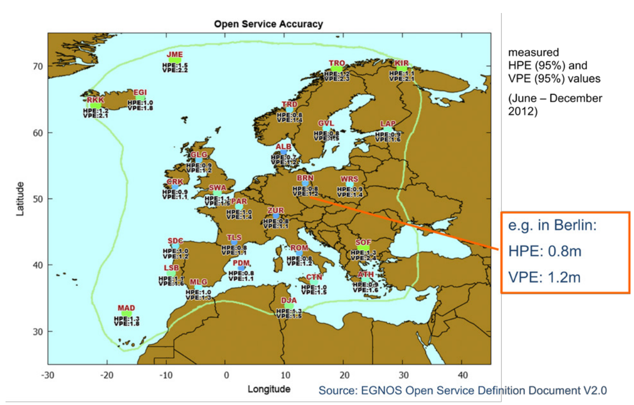
AD-GNSS Multi GNSS/SBAS Receiver

Features of the AD-GNSS receiver:

- Multi GNSS capability (GPS, GLONASS, Galileo…)
- 120 channel
- SBAS capable (WAAS, EGNOS, MSAS, GAGAN …)
- 10 Hz SBAS position output
- Ruggedized for airborne application
- Interfaces: Ethernet, RS232, USB

No additional hardware in AFIS for using SBAS as Position Reference is required.

The accuracies of the SBAS open position service are permanently monitored by the Ranging and Integrity Monitoring Station (RIMS):



SBAS Accuracy in Europe [2]

The Horizontal and Vertical Position (95%) Errors (HPE/VPE) in Berlin were measured over a 6 month period in the year 2012:

- HPE: 0.8 m
- VPE: 1.2m

The user directly gains from the benefits of SBAS as Position Reference:

- Improved accuracy during En-route Navaid and RADAR inspection without PDGPS Ground Reference Station
- Wide Area Coverage
- No costs for Service Subscription (Open Service)
- Reliable position reference data due to high level of integrity
- Proven availability and accuracy within Coverage Area

For that reason SBAS Position Reference became a standard feature for all new AD-AFIS!

All existing AD-AFIS can easily be upgraded.

CONCLUSIONS

a) Many SBAS LPV approaches are in service today

b) The AFIS features described in this paper provide detailed SBAS LPV inspection of all involved elements

c) SBAS is an ideal, free of charge Reference Position Sensor for improved accuracy during En-route and RADAR flight inspection.

REFERENCES

[1] User Guide for EGNOS Application Developers, ED. 1.1, 07/30/2009

[2] EGNOS Open Service Definition Document, Ref : EGN – SDD OS, V2.0

[3] RTCA, "Minimum Operational Performance Standards for Global Positioning System/Wide Area Augmentation System Airborne Equipment", RTCA-DO 229 D, 12/13/2006

[4] ICAO Annex 10, Vol. I Radionavigation Aids, Chap 3. 6th Ed. July 2006, Amdt 85

A Flight Inspection Perspective on Satellite Based Augmentation System Performance Monitoring

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ABSTRACT

The use of the Global Positioning System (GPS) and Satellite Based Augmentation Systems (SBAS) has become increasingly prevalent within the Airspace System. Is it the goal of a Flight Inspection Service (FIS) to inspect the accuracy, availability, continuity, and integrity of these GPS and SBAS signals?

For the Federal Aviation Administration's (FAA) Wide Area Augmentation System (WAAS), these metrics are continuously monitored and reported. This paper presents an overview of WAAS, the monitoring that is performed, and the resources and reports that are available. In addition, specific examples are provided that illustrate the usefulness of WAAS in the application of flight inspection activities.

INTRODUCTION

This paper is not intended to be an authoritative reference on the subject of Satellite Based Augmentation System or Flight Inspection Activities. It is aimed at providing a general knowledge of SBAS functionality and the data and tools that are available that can aid in flight inspection activities.

This paper is limited in presenting the FAA's GPS WAAS augmentation system. However, many of the same tools and techniques are applicable to other SBAS systems, such as the European Geostationary Navigation Overlay Service (EGNOS), Multi-functional Satellite Augmentation System (MSAS), GPS and Geo-Augmented Navigation (GAGAN), etc., that are operational or as they become operational.

WAAS OVERVIEW

Like GPS, WAAS contains three segments; a Ground Segment, a Space Segment, and a User Segment. An overview of each of these segments is provided.

WAAS Ground Segment

The Ground Segment consists of thirty-eight Wide-Area Reference Stations (WRS), three WAAS Master Stations (WMS), one pair of Ground Uplink Stations (GUS) per WAAS geostationary (GEO) satellite, and two Operations and Maintenance (O&M) Stations. The ground segment also includes a network that enables communication between the ground stations. Refer to Figure which shows the distribution of the Ground Segment locations.

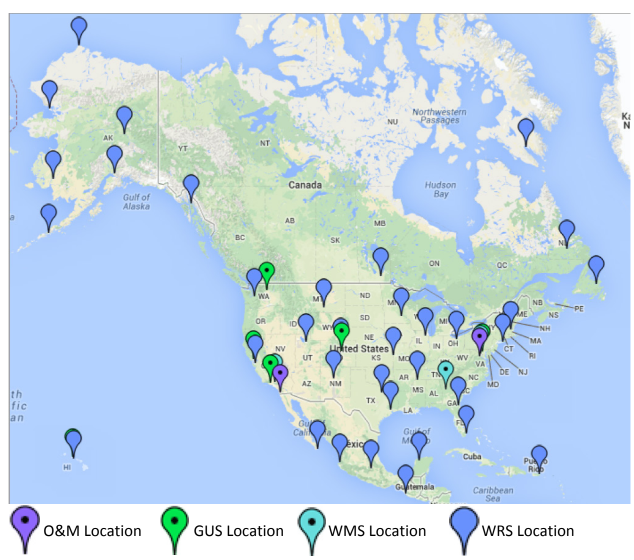

Figure 1. WAAS Ground Segment Locations

There are thirty-eight WRSs located throughout North America including Alaska, Canada, the Contiguous United States (CONUS), Mexico, Puerto Rico, and Hawaii. A WRS contains three systems, referred to as Wide-Area Reference Equipment (WRE). A WRE includes separate antenna, reference clock, receiver, and processor. Refer to Figure 2 which illustrates the equipment located at each WRS. Once a second, each WRE receives and forwards GPS and WAAS GEO satellite data to each WAAS Master Station, independent of the co-located WREs.

Each antenna location at a WRS has been precisely surveyed and is updated on an annual basis as required.

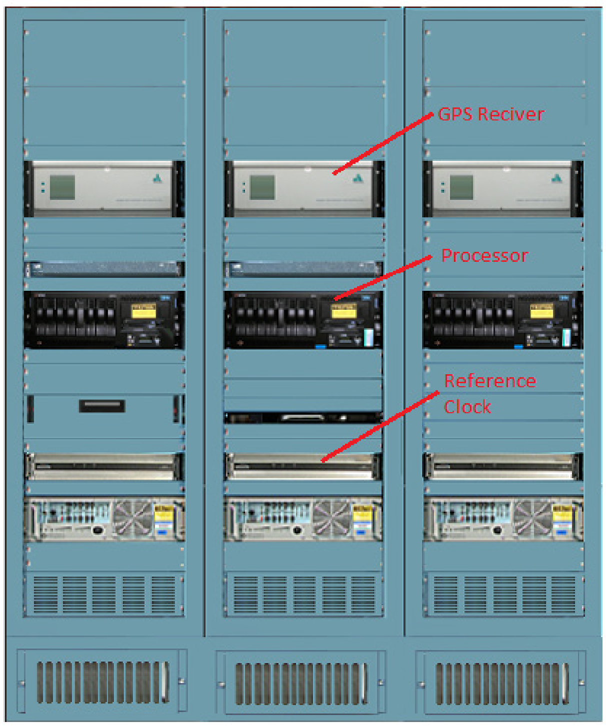

Figure 2. WRS Equipment

There are three WMSs located at FAA Air Route Traffic Control Centers (ARTCC) in geographically diverse locations; Washington D.C., Atlanta GA, and Palmdale CA. Each WMS receives data from every WRE located at one of the thirty-eight WRS sites. A WMS is comprised of two Correction Processors, which calculate clock and ephemeris corrections, and Safety Processors which calculate ionospheric corrections and integrity data, which includes error bounds for clock, ephemeris, and ionospheric corrections. The resulting corrections and integrity data are sent from the WMS to the GUS.

A GUS is comprised of a Signal Generator Subsystem (SGS) and a Radio Frequency Uplink (RFU). The SGS receives the calculated corrections and integrity data from the WMS and creates the WAAS correction message. Refer to Table 3 which lists the WAAS Correction Message Types. The WAAS correction message is uplinked via a C-Band frequency from the SGS to the GEO satellite by the RFU.

Each GEO satellite is served by two GUS sites. One GUS serves as the primary uplink and transmits the WAAS correction message to the GEO satellite. The second GUS serves as a back-up in the case of a primary failure. The backup is held in hot standby by transmitting into a dummy load. This reduces the time required to bring the backup GUS on-line if the primary GUS faults.

Table 3. WAAS Correction Message Types

Type	Title
0	System under test. Do not use for safety applications
1	PRN mask assignments
2-5	Fast clock corrections
6	Integrity information
7	Fast correction degradation
9	WAAS satellite navigation message
17	WAAS satellite almanac
18	Ionosphere Grid Point (IGP) mask
24	Fast and long term clock corrections
25	Long term clock corrections
26	Ionospheric delay corrections
27	WAAS service message
28	Clock-Ephemeris covariance matrix

WAAS is an automated system that does not require considerable operator involvement. When periodic operator interaction is required, it is performed at one of two O&M locations. A graphical user interface is used by the operator to perform controlling functions as well as periodic and corrective maintenance activities. Refer to Figure 3 which shows a typical graphical topology display used by the operator. In addition to providing an operator interface, both O&Ms continuously monitor and record the status of WAAS.

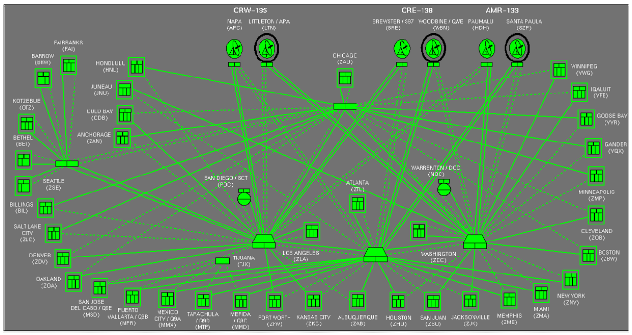

Figure 3. O&M Graphical Topology Display

Space Segment

The WAAS space segment is comprised of the GEO satellites. WAAS currently utilizes three GEO satellites with Pseudo-Random Noise (PRN) codes 133, 135, and 138. Refer to Figure 4 which shows the respective footprints for the WAAS GEO satellites with five degree elevation angles.

1. PRN 133 – AMR/Inmarsat 4F3, located at 98° W
2. PRN 135 – CRW/Galaxy 15, located at 133° W
3. PRN 138 – CRE/Anik F1R, located at 107.3° W

Since the WAAS corrections message is transmitted by the GEO as a GPS-like L1 signal, the GEO may be used by the user's receiver as an additional satellite ranging source. This increases the number of satellites in view that may be used by a receiver when computing a position solution within the footprint of the GEO satellite.

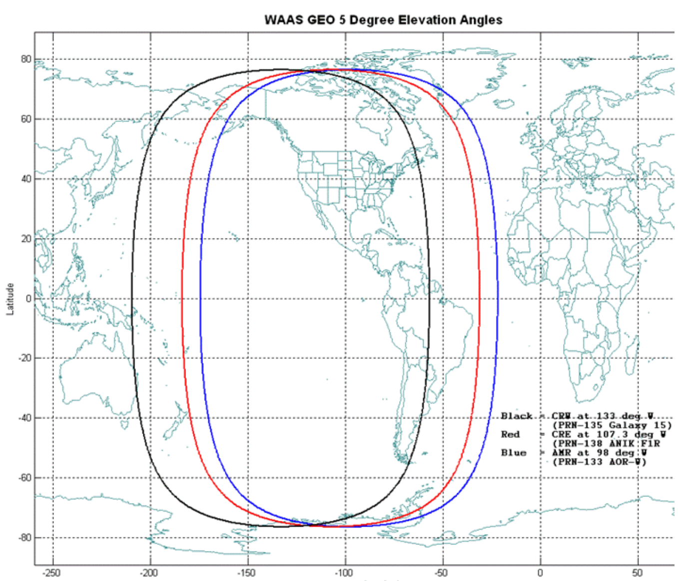

Figure 4. WAAS GEO Footprints

User Segment

The User Segment of WAAS is any receiver that is compliant with FAA Technical Standard Order (TSO) C145/146. The receiver obtains the WAAS correction messages from a WAAS GEO satellite. The receiver applies the correction information to its position solution. In addition, the integrity data is used by the receiver to compute a Horizontal Protection Level (HPL) and a Vertical Protection Level (VPL). These protection levels are compared to the Horizontal Alert Limit (HAL) and the Vertical Alert Limit (VAL) and alerts if the limit is exceeded. The HAL and VAL limits vary depending on the flight operation. Refer to Table 4 which lists the HAL and VAL corresponding with the flight operation.

Table 4. Alert Limits for Flight Operation

Flight Operation	HAL	VAL
En Route	2 nmi	N/A
Terminal	1 nmi	N/A
LNAV	556 m	N/A
LNAV/VNAV	556 m	50 m
LPV	40 m	50 m
LPV200	40 m	35 m

WAAS PERFORMANCE

GPS WAAS is continuously monitored and reports are available on the performance. The system level performance requirements are expressed in terms of accuracy, integrity, continuity, and availability. The following will provide the definition, as defined by the WAAS Performance Standard, of each of these performance requirements and some examples of reports that are available.

Accuracy

From the WAAS Performance Standard, "Accuracy is defined to be the statistical difference between the estimate or measurement of a quantity and the true value of that quantity. For the purposes of this WAAS Performance Standard, accuracy is expressed as either as 95th percentile (95%) differences or as rms differences."

Accuracy is further divided into Horizontal Accuracy and Vertical Accuracy requirements, depending on the flight operation. Refer to Table 5 which lists the accuracy requirements corresponding with the flight operation. These accuracies are expressed in terms of 95% differences. In the case of Horizontal Accuracy for LPV flight operations, the horizontal accuracy must be less than or equal to 16 m 95% or the time.

Table 5. Horizontal and Vertical Accuracy Requirements

Flight Operation	Horizontal Accuracy (95%)	Vertical Accuracy (95%)
En Route	0.4 nmi	N/A
Terminal	0.4 nmi	N/A
LNAV	220 m	N/A
LNAV/VNAV	220 m	20m
LPV	16 m	20 m
LPV200	16 m	4 m

The WAAS Test Team at the William J. Hughes Technical Center provides a WAAS Performance Analysis Report (PAN) on a quarterly basis. In this report, the accuracy is reported for the WAAS reference stations and the National Satellite Test Bed (NSTB) network for that quarter. The current PAN report, in addition to previous quarterly reports, is available from the www.nstb.tc.faa.gov website. The executive summary provides a table for a quick reference to the CONUS/Alaska Site maximum/minimum accuracies for 95% horizontal and 95% vertical. The executive summary table for report #47 is duplicated in Table 6. Additional accuracy information, plots, and real time data for all WAAS reference and NSTB network locations are available in section 2 of the WAAS PAN Report.

Table 6. WAAS PAN Report #47 Executive Summary Accuracy and Availability

Parameter	CONUS Site/Maximum	CONUS Site/Minimum	Alaska Site/Maximum	Alaska Site/Minimum
95% Horizontal Accuracy (HPL <= 40 meters)	Washington D.C. 1.341 meters	Arcata 0.582 meters	Juneau 0.864 meters	Anchorage 0.666 meters
95% Vertical Accuracy (VPL <= 50 meters)	Houston 1.627 meters	Salt Lake City 0.888 meters	Barrow 1.739 meters	Bethel 0.945 meters
LP Availability (HPL <= 40 meters)	Multiple Sites 100%	Multiple Sites 100%	Bethel 100%	Barrow 99.98%
LPV Availability (HPL <= 40 meters & VPL <= 50 meters)	Multiple Sites 100%	Washington D.C 99.99%	Bethel 99.99%	Barrow 99.47%
LPV 200 Availability (HPL <= 40 meters & VPL < =35 meters)	Multiple Sites 100%	Arcata 98.66%	Anchorage 99.91%	Cold Bay 94.38%
99% HPL	Oakland 17.177 meters	Memphis 11.314 meters	Cold Bay 29.399 meters	Fairbanks 14.198 meters
99% VPL	Arcata 34.311 meters	Memphis 19.413 meters	Cold Bay 37.542 meters	Anchorage 23.875 meters

Availability

As defined in the WAAS Performance Standard, “Availability is defined as the percentage of time that a particular WAAS service is available to the WAAS user.”

Like accuracy, availability is dependent upon the flight operation. Availability is further divided into zone coverages. The zones are defined as; Zone 1 – CONUS, Zone 2 – Alaska, Zone 3 – Hawaii, Zone 4 – Caribbean Islands, and Zone 5 – United States territory excluding zones 1 through 4. These zones are depicted in Figure 9 through Figure 13 located in Appendix 1. The requirements for each of these zones, depending upon the flight operation, are listed in Table 7. These requirements are expressed in the percent of time available across a percentage of the coverage area.

WAAS is determined to be available at a particular point in time, if the HPL and VPL are within the HAL and VAL for a particular flight operation. For example, for Zone 2 LPV availability, the HPL must be <= 40 meters and the VPL <= 50 meters for 95% of the time across 75% of the Zone 2 coverage area.

The WAAS PAN Report availability information is reported in number of ways. One measure of availability is reported as the Protection Limit value in meters, which contains 99% of the Protection Limit values over a given period. This is shown as the 99% HPL/VPL and can be referenced in Table 6 Executive Summary table from WAAS PAN Report #47.

Section 3 of the WAAS PAN Report also provides additional information on the number of LP, LPV, and LPV 200 outages, outage rates, and percent available for each WAAS reference and NSTB network locations. The specifics on the calculation of these results are provided within the report.

Historical and real-time data, plots, and videos are available on the www.nstb.tc.faa.gov website to include RNP, LNAV/VNAV, LP, LPV, and LPV 200 service levels.

Table 7. Availability Requirements

	Availability (Zone Coverage)				
Flight Operation	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5
En Route	0.99999 (100%)	0.999 (100%)	0.999 (100%)	0.999 (100%)	0.99999 (100%)
Terminal	0.99999 (100%)	0.999 (100%)	0.999 (100%)	0.999 (100%)	0.999 (100%)
LNAV	0.99999 (100%)	0.999 (100%)	0.999 (100%)	0.999 (100%)	0.999 (100%)
LNAV/ VNAV	0.99 (100%)	0.95 (75%)	N/A	N/A	N/A
LPV	0.99 (80-100%)	0.95 (75%)	N/A	N/A	N/A
LPV200	0.99 (40-60%)	N/A	N/A	N/A	N/A

Continuity

Continuity is defined in the WAAS Performance Standard as "… to be the probability of time that a particular WAAS service will continue to be available over an hour time interval for en route through LNAV operations, over a 15 second interval for LNAV/VNAV and LPV operations, given that it was available at the beginning of the interval and that an outage was not announced in a prior notice to airmen (NOTAM)."

The continuity requirement for WAAS is only applicable to Zone 1 and varies by the flight operation. Refer to Table 8 which shows the continuity requirements corresponding with the flight operation. These requirements are expressed in the probability that a loss of continuity will occur within a window of time.

The WAAS Performance Standard explicitly states the "Continuity is not tracked." However, monitoring of Late Messages are provided within the WAAS PAN Report. Late messages is a possible cause for a loss of continuity.

Table 8. Continuity Requirements

Flight Operation	Zone 1 Continuity
En Route	$1 - 10^{-5}$ per hour
Terminal	$1 - 10^{-5}$ per hour
LNAV	$1 - 10^{-5}$ per hour
LNAV/VNAV	$1 - 5.5 \times 10^{-5}$ per 15 seconds
LPV	$1 - 8 \times 10^{-6}$ per 15 seconds
LPV200	$1 - 8 \times 10^{-6}$ per 15 seconds

For continuity and proper user operation, WAAS messages must be broadcast and received within a specific time frame. Delay of broadcasting WAAS messages can be caused by GEO outages, GUS switchovers (change from primary to backup GUS), and broadcast alerts. Reports on message rates are provided on a per GEO basis. Table 9 provides an example of Fast Correction and Degradation Message Rates for CRW (PRN 135) included in WAAS PAN Report #47.

Table 9. Fast Correction and Degradation Message Rates

Message Type	On Time	Late	Max Late Length (seconds)
1	109228	6	131
2	1325724	56	19
3	1324376	305	19
4	1324599	274	18
7	100989	30	137
9	93108	0	0
10	100947	39	137

Integrity

The WAAS Performance Standard defines Integrity as, "Integrity is a measure of the trust which can be placed in the correctness of the information supplied by the total system. Integrity includes the ability of the WAAS Signal In Space (SIS) to provide timely alerts (alarms and warnings) to receivers when the WAAS service HPL or VPL no longer bound the horizontal position error (HPE) or vertical position error (VPE) or a GPS satellite should not be used as part of the WAAS augmentation solution."

In order to better understand the integrity monitoring that is performed within WAAS, a further discussion of the Alarm Limits (HAL/VAL), Protection Levels (HPL/VPL), and Position Error (HPE/VPE) and how these interrelate is provided. The WAAS Performance Standard provides an excellent illustration which is reproduced in Figure 5. The figure illustrates four important features: 1. The aircraft's calculated position which is shown at the center of the cylinders. 2. The protection level cylinder (shaded) which is centered on the aircraft's calculated position. The size of this cylinder is based on the HPL and VPL which are calculated from the WAAS integrity data. 3. The alert limit cylinder (clear) which is also centered on the aircraft's calculated position. The size of this cylinder is determined by the flight operation (LPV 200, LPV, LP, etc.). 4. The aircraft's true position. The difference between the aircraft's true position and the calculated position is comprised of a Horizontal Position Error (HPE) and a Vertical Position Error (VPE).

As discussed earlier, WAAS is considered to be available when the protection level cylinder (shaded) is contained within the alert limit cylinder (clear). In other words, HPL <= HAL and VPL <= VAL.

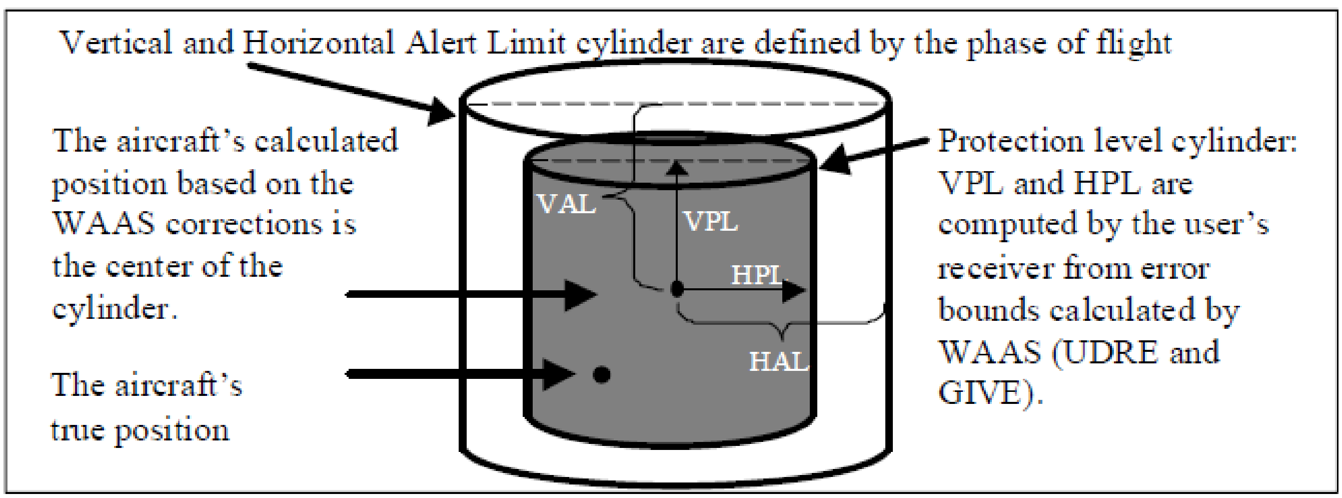

Figure 5. Integrity Protection Cylinder

For integrity, the magnitude of the position error is considered against the size of the protection level cylinder. Specifically, the protection level cylinder must encompass the aircraft's true position, HPE <= HPL and VPE <= VPL. If the aircraft's true position is outside of the protection level cylinder, and the time that it remains outside the cylinder exceeds the Time To Alarm (TTA) requirement, there exists a condition termed Hazardously Misleading Information (HMI).

Therefore there are two performance requirements for WAAS associated with integrity, TTA and HMI. These requirements are listed in Table 10 corresponding with the flight operation.

In the WAAS PAN report, HMI is reported in terms of a safety index for each of the WAAS reference and NSTB network locations. The safety index is the ratio of the protection limit to the maximum observed error. This index is calculated for both horizontal and vertical. If the safety index is greater than one, the protection limit cylinder encompasses the true position. If the safety index is less than one, the true position is outside the protection cylinder. However, this condition must persist for greater than the TTA, 6.2 s, to be deemed an HMI event.

Table 10. TTA and HMI Performance Requirements

Flight Operation	TTA	Probability of HMI
En Route	15 s	10^{-7} per hour
Terminal	15 s	10^{-7} per hour
LNAV	10 s	10^{-7} per hour
LNAV/VNAV	10 s	2 x 10^{-7} per approach
LPV	6.2 s	2 x 10^{-7} per approach (150 s)
LPV200	6.2 s	2 x 10^{-7} per approach (150 s)

For the WAAS PAN Report #47, the lowest safety index reported was 3.12 for the horizontal safety index at Fairbanks, AK. However, no HMI event occurred for this site or any other. The report states that since WAAS was made available to the public in August 2000, there has not been an HMI event.

FLIGHT INSPECTION AND WAAS

Presented previously was an overview of WAAS and the WAAS Performance in terms of accuracy, availability, continuity, and integrity. In addition, the metrics that are monitored and reported to measure WAAS performance were given. In terms of flight inspection activities, this information has little use. So what information or tools are available that would aid flight inspection activities?

Consider the issue of trying to perform a flight inspection for a GPS WAAS procedure, and the flight inspection receiver is incapable of achieving the required protection levels (HPL and/or VPL) for the flight operation. This is not an indication of a problem with the GPS WAAS procedure, but rather an indication of a problem with the flight inspection equipment or with GPS WAAS.

Considering the flight inspection issue presented, the problem can be divided into one of four categories; Intentional fault with advanced notice, Intentional fault with no advanced notice, Unintentional fault with advanced notice, or Unintentional fault with no advanced notice. Refer to Table 11 which presents a fault matrix that categorizes some possible problems into each of these four categories.

Table 11. Fault Matrix

	Advanced Notice	No Advanced Notice
Intentional Fault	• WAAS issues • GPS issues	• RFI / Jamming
Unintentional Fault	• Ionospheric Activity	• Receiver Fault • RFI • Ionospheric Activity

Unintentional Fault – No Advanced Notice

In this particular category, three possible problems are listed, Receiver Fault, Radio Frequency Interference (RFI), and Ionospheric Activity.

If an additional TSO-C145/146 receiver(s) is installed on the aircraft, and is capable of achieving the required HPL and VPL for the flight operation, this could indicate that the flight inspection receiver could have a fault. Another issue may be not allowing sufficient time for the receiver to acquire, calculate, and apply the WAAS augmentation.

If RFI is present, it is likely that all TSO-C145/146 receivers on the aircraft would not be capable of achieving required protection limits for the flight operation. A quick check of the spectrum centered on the L1 1575.42 MHz may prove helpful. Since GPS signal are spread spectrum Code Division Multiple Access (CDMA) signals, the signals are essentially buried in the noise floor and will not be discernable within the spectrum. However, a strong interfering signal may be present and identifiable.

Ionospheric activity that affects WAAS availability may occur without advanced notice. If it is believed to be a WAAS availability problem that prevented a successful flight inspection, a review of the WAAS availability can be accomplished. The NSTB website, www.nstb.tc.faa.gov, provides real-time and historical data and plots, as well as availability videos for the previous 24 hour period.

Figure 6 shows an example of a real-time plot for WAAS LPV Vertical Navigation Service. The color scale represents the VPL across the coverage areas. Contour lines are included which indicate the level of service available. For example, the yellow contour line signifies a VPL of 35 meters. Any point located within this contour signifies a VPL < 35 meters, LPV 200 service available. Outside of the yellow contour line signifies a VPL > 35 meters, LPV 200 service not available. Additional contour lines for LPV and LNAV/VNAV are also included.

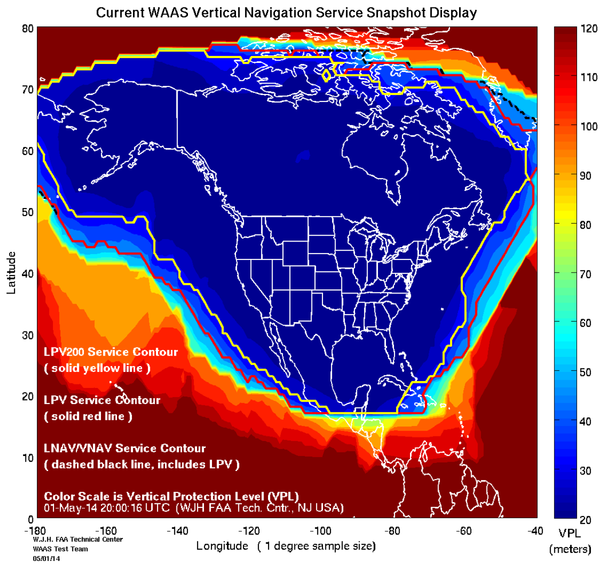

Figure 6. WAAS LPV Vertical Navigation Service

This plot is also available in 24 hour video. If the flight inspector notes that a receiver is incapable of achieving the required protection levels for a flight inspection, this video may be reviewed to determine if the level of service was unavailable at the time of, and the location of, the inspection.

In addition to the real-time plots, a 24 hour coverage plot is also available for different levels of service. Figure 7 shows an example of a RNP 0.3 (HPL <= 556 meters, VPL = N/A) coverage plot. In this plot, the coverage area (Zone 5) is outlined and the color scale represents the service level percent available for the previous day. Similar plots are available for LPV 200, LPV, LP, and RNP 0.1 service levels.

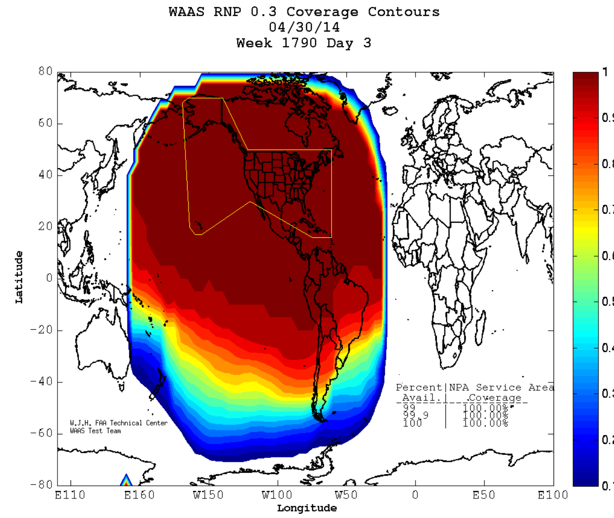

Figure 7. RNP 0.3 Coverage Contours

<u>Unintentional Fault – Advanced Notice</u>

The ionization level in the ionosphere depends primarily on the sun and its solar activity. Since the ionosphere can affect the availability of WAAS, advanced notice of solar flares or knowledge of the sunspot cycle may provide an indication for the availability of the WAAS augmentation.

One source of information regarding solar activity is http://spaceweather.com/.

<u>Intentional Fault – No Advanced Notice</u>

A common concern regarding WAAS reference stations as well as GBAS installations, has been the use of GPS jamming devices. While these devices are illegal to market, sell, or use in the United States, incidents still have occurred. These have primarily been used by individuals who operate a commercial vehicle equipped with a GPS fleet tracking device. The primary intent of these individuals is tracking prevention of their movements, not to jam WAAS users or reference stations. Since the output power of these devices is not high, the area around the device that prevents GPS WAAS reception will be quite isolated. Therefore, movement away from the jamming device and allowing the receiver to reacquire GPS and the WAAS augmentation will restore the receiver's operation.

Intentional Fault – Advanced Notice

This category contains issues for GPS and/or WAAS that are known or planned for in the future. These planned service interruptions may be caused by testing, training activities, or military exercises. Refer to Figure 8 which shows planned military GPS testing that could affect GPS WAAS availability.

APPROVED GPS TESTING (UPDATED April 30th, 2014)

TEST PERIOD APPROVED BY DEPARTMENT OF DEFENSE., EXACT DATES AND TIMES OF TESTING, DURING APPROVED PERIOD, WILL BE DETERMINED BY TEST RANGE EVENT PLANNERS.

Area	Range	Testing Dates	BNM
White Sands Missile Range, NM WSMR 14-04	468NM	28 APR – 28 MAY 14	No
White Sands Missile Range, NM WSMR 14-05	260NM	28 APR – 18 MAY 14	No
China Lake Range, CA CHLK 14-04	210NM	29 APR, 01 MAY, 28-29 MAY 14	No
Dugway Proving Ground, UT NAFC 14-05	335NM	2-18 MAY 14	No
Eglin AFB, FL GAFC 14-03	32NM	1-2, 5-9, 12-16, 18-23, 27-30 MAY 14	Yes

Figure 8. GPS Testing

Notification for these types of issues is available through Notice to Airmen (NOTAM) or Notice Advisory to NAVSTAR Users (NANU). These notices may be checked prior to a flight inspection to determine the likely interference with the flight inspection. In addition, these should be checked after

NOTAMs are available through https://pilot.nas.faa.gov. An example NOTAM for the Albuquerque Air Route Traffic Control Center (ARTCC) ZAB is provided.

ZAB ALBUQUERQUE (ARTCC),NM.

!GPS **04/149** ZAB NAV GPS (INCLUDING WAAS, GBAS, AND ADS-B) MAY NOT BE AVAILABLE WITHIN A 483NM RADIUS CENTERED AT 401840N1133428W (BVL 147026) FL400-UNL DECREASING IN AREA WITH A DECREASE IN ALTITUDE DEFINED AS: 429NM RADIUS AT FL250, 348NM RADIUS AT 10000FT, 355NM RADIUS AT 4000FT AGL, 335 NM RADIUS AT 50 FT AGL. 1405031500-1405031730

NANUs are normally issued three day prior to a change in the operation of a GPS satellite and are available through www.navcen.gov, GPS Constellation Status. An example NANU is provided. This site also provides the status for the entire GPS constellation including the plane, slot, Space Vehicle Number (SVN), PRN, Type, and Clock for each satellite in the GPS constellation.

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2014018 -------------------------
SVN64 (PRN30) LAUNCH JDAY 052
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NOTICE ADVISORY TO NAVSTAR USERS (NANU) 2014018
SUBJ: SVN64 (PRN30) LAUNCH JDAY 052
1. NANU TYPE: LAUNCH
NANU NUMBER: 2014018
NANU DTG: 210207Z FEB 2014
SVN: 64
PRN: 30
LAUNCH JDAY: 052
LAUNCH TIME ZULU: 0159

2. GPS SATELLITE SVN64 (PRN30) WAS LAUNCHED ON JDAY 052.
A USABINIT NANU WILL BE SENT WHEN THE SATELLITE IS SET ACTIVE TO SERVICE.

3. POC: CIVILIAN - NAVCEN AT 703-313-5900, HTTP://WWW.NAVCEN.USCG.GOV
MILITARY - GPS OPERATIONS CENTER AT HTTPS://GPS.AFSPC.AF.MIL/GPSOC, DSN 560-2541, COMM 719-567-2541,GPSOPERATIONSCENTER@US.AF.MIL , HTTPS://GPS.AFSPC.AF.MIL/GPSOC/GPS
MILITARY ALTERNATE - JOINT SPACE OPERATIONS CENTER, DSN 276-3514. COMM 805-606-3514. JSPOCCOMBATOPS@VANDENBERG.AF.MIL

CONCLUSION

The FAA employs an extensive monitoring network to measure the performance of WAAS in terms of Accuracy, Availability, and Integrity. The data and analyses are readily available and can be a useful tool in support of flight inspection activities.

RESOURCES

WAAS Resources
William J. Hughes Technical Center WAAS Test Team
http://www.nstb.tc.faa.gov/

EGNOS Resources
http://www.egnos-pro.esa.int/index.html

Indian Space Research Organisation
www.isro.org

Notice to Airmen (NOTAM)
https://pilotweb.nas.faa.gov/PilotWeb/

Notice Advisory to NAVSTAR Users (NANU)
http://www.navcen.uscg.gov/?Do=constellationstatus

GPS Operations Center
https://gps.afspc.af.mil/gpsoc/

Solar Activity
http://spaceweather.com/

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Brad Snelling, Flight Inspection Operations, for his assistance regarding flight inspection activities.

AJW-14B WAAS Engineering, for their assistance regarding WAAS.

REFERENCES

[1] Federal Aviation Administration, October 2008, Global Positioning System Wide Area Augmentation System (WAAS) Performance Standard, First Edition, http://www.gps.gov/technical/ps/2008-WAAS-performance-standard.pdf

[2] Federal Aviation Administration/William J. Hughes Technical Center, January 2014, Wide-Area Augmentation System Performance Analysis Report, Report 47, www.nstb.tc.faa.gov

[3] FAA/Technical Standard Order, September 2002, Airborne Navigation Sensors Using the Global Positioning System (GPS) Augmented by the Wide Area Augmentation System (WAAS)Airborne Navigation Sensors Using the Global Positioning System (GPS) Augmented by the Wide Area Augmentation System (WAAS), TSO-C145a, www.airweb.faa.gov

[4] FAA/ Technical Standard Order, September 2002, Stand-Alone Airborne Navigation Equipment Using the Global Positioning System (GPS) Augmented by the Wide Area Augmentation System (WAAS), TSO-C146a, www.airweb.faa.gov

[5] U.S. Department of Transportation/FAA, August 2001, Specification for the Wide Area Augmentation System (WAAS), FAA-E-2892c Change 2,

[6] FAA, Interactive Electronic Technical Manual for the Wide Area Augmentation System, TI 6882.1

Appendix 1

WAAS Coverage Area

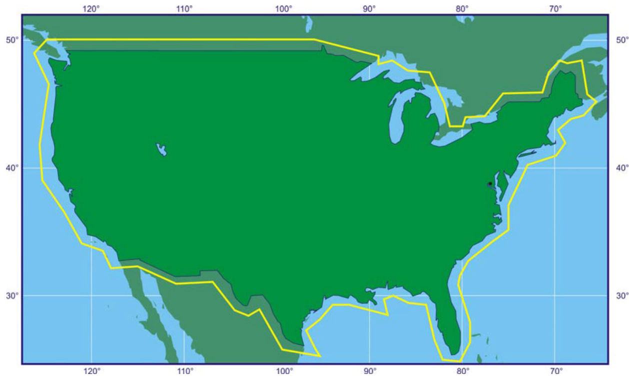

Figure 9. Zone 1 - CONUS Coverage Area

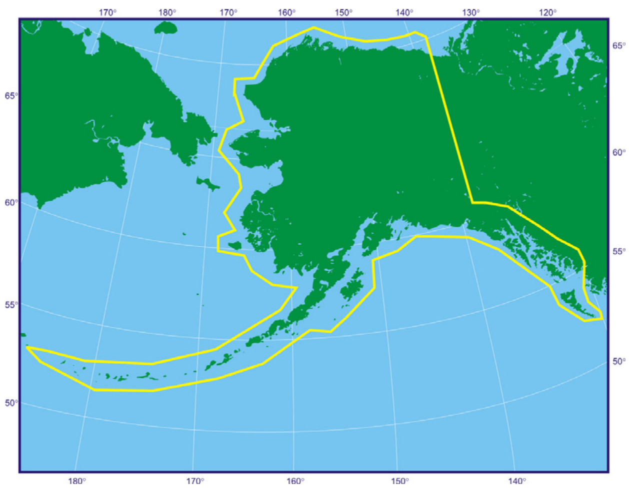

Figure 10. Zone 2 - Alaska Coverage Area

Figure 11. Zone 3 - Hawaii Coverage Area

Figure 12. Zone 4 - Caribbean Islands Coverage

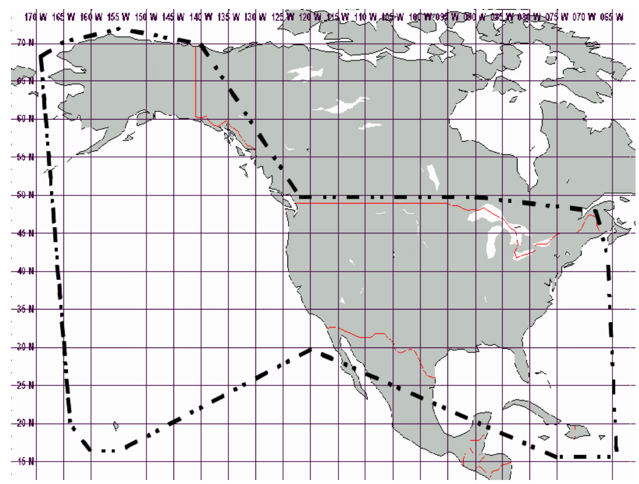

Figure 13. Zone 5 - US Territory Coverage Area

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DME and GNSS L5/E5 Compatibility Prediction and Measured Data

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ABSTRACT

The planned modernization of the existing Satellite Navigation Systems (GPS and GLONASS) and the ongoing development of new constellations, GALILEO (Europe) and BEIDOU (China) will bring more accurate and robust positioning performance to current and future air navigation applications. While in particular the use of dual frequency GNSS signals brings significant benefits, compatibility with current primary services such as DME needs to be ensured. Previous theoretical studies have shown that if the "pulse blanking technique" is used by the receiver, the carrier to noise post-correlation degradation is within the GNSS link budget margin for GPS and Galileo even over the European and US DME hotspots. This paper will present the results of a new theoretical study carried out for the Europe region that takes into account the current network of DME stations and terrain screening (not implemented in previous simulations). The simulation results will be compared to real data measured in a dedicated flight test campaign conducted by DLR. The paper then describes the issues involved in ensuring continued compatibility between GNSS L5/E5/G3[7] and DME in the light of an evolving DME environment to support PBN.

INTRODUCTION

Regarding the compatibility between DME/TACAN and the GNSS L5 signals, the ICAO GNSS Manual [1] states:

5.2.5 The additional GNSS signals in the band 1,164-1,215 MHz to be broadcast by second-generation core satellites share the band with DME and Tactical Air Navigation system (TACAN). ITU rules require that DME/TACAN must be protected from interference. Compatibility studies based on the current DME/TACAN infrastructure concluded that the impact of interference on the processing of the new GNSS signals is tolerable. The studies also concluded that a high density of DME/TACAN facilities operating in or near the new GNSS band could result in interference with GNSS signals at high altitudes. States should assess whether an increase of the DME/TACAN infrastructure is compatible with expanded use of GNSS and if necessary reallocate DME assignments away from GNSS frequencies.

While the potential to "reallocate DME assignments away from GNSS frequencies" is quite easily stated as a concept, the practical implementation and feasibility of

[7] G3 stands for the GLONASS G3 band, extending from 1189 to 1214 MHz, e.g., above the range of GPS L5 and Galileo E5a. The future use of E5b, as well as G3 and potentially BeiDou B2 by aviation still requires the resolution of antenna issues. Consequently, this work has focused on the range of 1164 to 1189 MHz supporting GPS L5 and Galileo E5a.

that recommendation has not been tested. While changing a DME frequency may not be that difficult, the potential complexities of also changing the paired VOR frequencies could lead to significant costs. Even if avionics equipage with dual frequency GNSS receivers has not yet begun, significant lead time would be needed to develop associated frequency management processes if a more proactive assignment practice would be needed to better accommodate GNSS. Consequently, it is necessary to verify if such frequency management is required, and if so, study how this could be implemented. This study aimed to verify that need and test the methods available to do so in an evolving DME/DME environment to support current and future PBN operations. This paper presents the results of an initial theoretical assessment of the L5 carrier to noise degradation factor, taking into account the current navaids infrastructure in Europe and the natural screening (by terrain) of the radiated signals. A discussion on the need to validate these simulations by flight tests and the potential validation solution are included as well.

The simulation were performed using the theoretical model of the RFI caused by DME/TACAN station in GNSS L5 band that is described in various standards and guidance materials. The new implementation of the model was "validated" by comparing the outputs of the hotspot analysis with the results of previous studies, using the same input data (as presented in these reference documents).

STANDARDS AND GUIDANCE MATERIALS

The issue of the radio frequency interference in L5/E5A Band is assessed in detail in RTCA DO-292 [2]. This document identifies all potential sources of interference, describes theoretical models to estimate the impact on the GPS receivers and also defines a mitigation technique at the receiver level in order to minimize the impact. The document also presents the results of the software simulations aimed at estimating the interference hotspots over US and Europe and evaluating the degradation of the GNSS signals over these hotspots. The same issue is also addressed in the following ITU documents:

- Report ITU-R M.2220 [3]
- Recommendation ITU-R M.2030 [4]

All these documents are consistent in what regards the potential sources of interference, the mitigation technique and the theoretical model of GNSS signal degradation. These elements are shortly presented below:

Potential sources of interference

L-Band pulsed RFI sources (960-1215 MHz) geometrically distributed within the radio line-of-sight (RLoS):

- in-band ground DME/TACAN beacon transponders;
- near-band airborne DME/TACAN interrogators (on-board and nearby aircraft);
- out-of-band (OoB) ATC surveillance systems (ground, on-board and nearby aircraft elements);
- CNI[8] (Communication, Navigation and Identification) system networks (ground and nearby airborne terminals).

Continuous wideband RFI from:

- intra- and inter-RNSS system satellite signal cross-correlation;
- unwanted and unintentional wide- and narrow-band RFI from ground-based sources.

Note that the present report will only analyse the interference from the DME/TACAN beacon transponders, the other potential sources are out of the scope of this analysis, but illustrate the need for extra margin in the link budget.

Mitigation Technique

The RF interference mitigation solution proposed for next generation aviation GNSS receivers is called pulse blanking: the receiver will employ rapid digital pulse blanking as soon as the signal level exceeds the blanking threshold – the corresponding data and desired signal will be lost during this limited time while still preserving enough of the GNSS signal to maintain operations. Given potential technological progress over the years, other techniques could also be used but must achieve equivalent performance in a high pulsed RFI environment.

Figure , (extract from [3]) shows how digital pulse blanking might be implemented ahead of the signal correlators in an RNSS receiver.

Theoretical model

The theoretical equation to compute the effective C/N0 for a pulse blanking receiver is:

$$(C/N_{0,EFF}) = (C/N_0)\frac{(1-PDC_B)}{1+\frac{I_{0,WB}}{N_0}+R_I} \qquad (1)$$

where:

C: post-correlator (interference-free) RNSS satellite carrier power (W);

[8] Some administrations authorize a system that utilizes spread spectrum techniques for terrestrial communication, navigation and identification (CNI) to operate within the 960-1 215 MHz band. This CNI system, which is utilized on surface and airborne platforms within a network, is a frequency-hopping system that operates on 51 different carrier frequencies (3 MHz increments) between 969 MHz and 1 206 MHz.

N_0: receiver system thermal noise density (W/Hz);

$I_{0,WB}$: total wideband equivalent continuous RFI power spectral density (PSD) (W/Hz) (in case that other RNSS interference is included, spectral separation coefficient (SSC) should be properly taken into account);

PDC_B: (pulse duty cycle-blanker) is the net aggregate duty cycle of all pulses strong enough to activate the blanker (unitless fraction); and

R_I: unitless post-correlator ratio of total aggregate below-blanker average pulsed RFI power density to receiver system thermal noise density N_0.

PDC_B and R_I are computed using formulas (2) and (3):

$$PDC_{B,DME/TACAN} = 1 - e^{-\lambda w} = 1 - e^{-(2700 N_{DME} + 3600 N_{TACAN}) E\{2PW_{eq}\}}$$

(2)

where:

N_{DME}: total number of DME stations within RLoS

N_{TACAN}: total number of TACAN stations within RLoS

$E\{2PW_{eq}\}$: above-blanker pulse width averaged over the total DME and TACAN received pulses.

$$R_I = \frac{1}{N_0 \cdot BW} \sum_{i=1}^{N} (P_i \cdot dc_i) \qquad (3)$$

where:

N: total number of pulsed emitters that generate received pulses (i.e. pulses or pulse portions) below the blanker threshold;

Pi: peak received power (W) of the i-th pulse emitter (referenced to the passive receive antenna output) with peak level below the blanker threshold;

BW: pre-correlator IF bandwidth (for spreading effect) (Hz); and

dci: duty cycle (unitless fraction) of the i-th below-blanker pulsed emitter exclusive of pulse collisions.

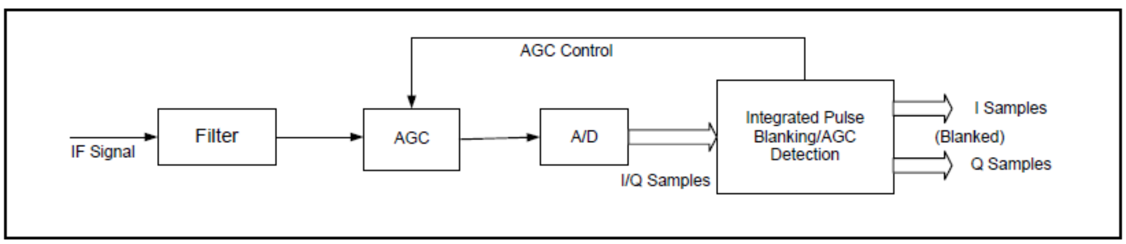

Figure 1. Block Diagram of a Typical Digital Pulse Blanking Receiver

To help streamline the necessary pulsed RFI impact calculations, an additional term has been defined: "effective noise density ratio", $N_{0,EFF}$, which combines the pulsed RFI effects on thermal noise density, wideband continuous RFI density, and signal loss. This term is defined algebraically as:

$$N_{0,EFF} = (C/N_0) \frac{(1 - PDC_B)}{1 + \frac{I_{0,WB}}{N_0} + R_I} \qquad (4)$$

Then, using the above formulas, the effective post-correlation C/N_0 degradation (equivalent to $N_{0,EFF}$ degradation) is computed in logarithmic form as:

$$Deg(C/N_0)_{[dB]} = 10\log(1 - PDC_B) - 10\log(1 + \frac{I_{0,WB}}{N_0} + R_I) \qquad (5)$$

For the purposes of the current study, in order to estimate only the impact of the pulsed interference generated by DME/TACAN stations, the wideband continuous interference is disregarded (I0,WB = 0) and the final formula for computing the carrier to noise degradation becomes:

$$Deg(C/N_0)_{[dB]} = 10\log(1 - PDC_B) - 10\log(1 + R_I) \qquad (6)$$

PREVIOUS ASSESSMENTS

The RTCA and ITU documents mentioned in the previous section ([4] and [5]) present also the results of the software simulation aimed at estimating the L5 carrier to noise degradation over US CONUS and over Europe. Two different dedicated software tools were created for this purpose:

- GREET – GPS RFI Environment Evaluation Tool developed by MITRE's Center for Advanced Aviation Systems Development (CAASD)
- PULSAR – PULSe Assessment Routine

The description of both tools is presented in [4]. Note that both tools simulate the pulsed environment in the L5 band. However, PULSAR also implements a full signal processing simulation inside the receiver in the presence of RFI while GREET calculations are based mainly on the theoretical model.

This compatibility issue has been addressed in many conferences and PhD thesis in the past. One of the most comprehensive pieces of work was presented by Frederic Bastide (et al.) at the ION Conference in 2004, which compares the PULSAR results with the theoretical model results [5].

All these simulations estimate the location of the degradation hotspot in Europe for FL 400 at the geographical coordinates: 50N/9E. The graphic results of these simulations are extracted from [2] and presented below in Figure 2 and Figure 3. Note that the GREET map presents the overall degradation due to all RFI sources while the PULSAR map takes into account only the impact of DME/TACAN. The results related to the degradation over the hotspot due only to DME/TACAN are summarized in Table 1, to allow an easy comparison with our results (blank cells indicate that the data is not presented in the reference documents).

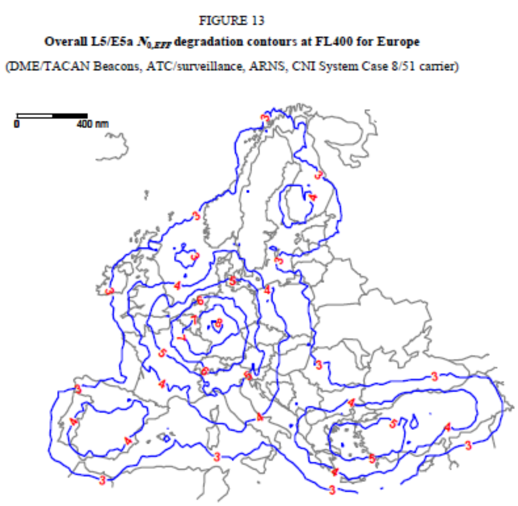

Figure 2. C/N_0 degradation map (GREET)

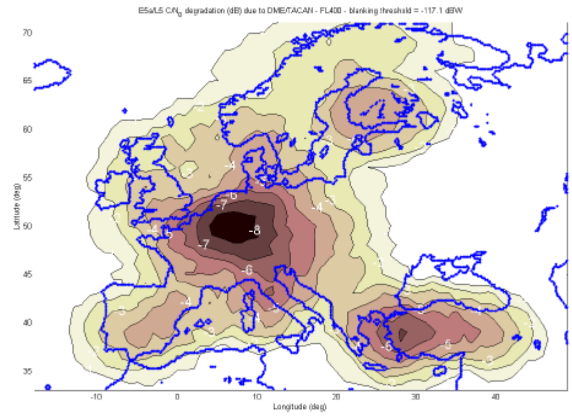

Figure 3. C/N_0 degradation map (PULSAR)

NEW ASSESSMENT

By analyzing the previous simulations, several issues are identified:

- The full list(s) of Navaids that were used for these simulations are not presented in any document
- Although there is an agreement on the estimated location of the hotspot at 50N/9E, the optimum blanking threshold identified is not the same for all simulations (ranges between -117.1dBW and -120dBW)
- The carrier to noise degradation estimation over the hotspot ranges between -7dB and -8.1dB. The largest discrepancy is noted for a blanking threshold of -120dBW
- The studies are about 10 years old, while the DME environment continues to evolve.

In order to clarify the above issues, several attempts were made to contact the authors of these assessments. Although some additional information was obtained, this effort was not completely successful because it was not possible to identify the Navaids database used for simulations and find a solution for re-running the simulations using the initial database or an updated database. In this context it was concluded that an up to date analysis of the L5/DME compatibility cannot be done only based on the previous assessments. One reason that leads to this conclusion is the recent clean-up of the ICAO assignments database in L band, i.e. ICAO Table COM3, on which occasion approx. 30% of the DME frequency assignments were found to be not in operational use and consequently, they were deleted. As such it is expected that the initial simulations returned conservative results. Taking into account the requirements of the ICAO GNSS Manual [1], it is considered important to have the possibility to estimate the L5 C/N_0 degradation due to the current and future configurations of the DME/TACAN network. To meet this need, a new software application was created (using the LabVIEW program suite). Due to the limited amount of effort available within the project the main objectives of the new application were to:

- generate a preliminary analysis of the L5 C/N_0 degradation over Europe considering the current DME/TACAN infrastructure and taking into account terrain shadowing
- assess the complexity of the theoretical model and the potential solutions and issues related to the implementation of the L5/DME compatibility analysis in existing EUROCONTROL tools e.g. DEMETER (Distance Measuring Equipment Tracer) [10] or MANIF AFM (Advanced Frequency Manager) [11].

The new application uses only the theoretical model in line with the existing ITU recommendations, whereas a Signal-in-Space replica is not generated and the receiver signal processing chain is not modeled.

Before proceeding to the actual degradation assessment it was considered important to validate the implementation of the theoretical model by comparing the results with those generated by the previous simulations. This was possible only for the hotspot (50N/9E) thanks to the availability of the list of received DME/TACAN signals on this location, produced by PULSAR. This list which was provided by courtesy of ENAC is also presented (with minor differences) in Table B-3 of the EUROCAE GALILEO MOPS v 3.0 [6]. The results returned by the LabVIEW application when using this list of signals are presented together with the previous simulation results in **Error! Reference source not found.**1.

Table 1. Hotspot simulation results

	DO-292 [2]		ION [5]		New
	PULSAR	GREET	PULSAR	Theory	(Theory)
-117.1 dBW					
PDC_B	0.3		0.29	0.28	0.32
R_I	3.6				3.4
Deg [dB]	-8.1		-7.9	-7.8	-8.1
-118.4 dBW					
PDC_B			0.34	0.33	0.38
R_I					2.7
Deg [dB]			-7.5	-7.5	-7.7
-120 dBW					
PDC_B		0.57	0.4	0.4	0.47
R_I		1.18			1.8
Deg [dB]		-7	-8	-7.4	-7.2

From this table it can be observed that in terms of C/N_0 degradation, the new results are reasonably close to the previous results, notably to the previous theoretical evaluations presented in [5]. It is also noticed that for all thresholds considered, the new results estimate a higher value for the PDC_B. This can be explained by the slight difference in the theoretical models considered in [2] (implemented in the new application) and [5]. The difference refers to the blanking technique: while in [2] the blanking applies to the envelope of the DME pulse, [5] considers that a fast digital blanking can be applied at the A/D sample level. Blanking the individual digital samples leads to a smaller blanking duration but at the same time to an increase of the noise power density. Note that for the purposes of this study it was decided to use the model described in [2] (RTCA DO-292).

Considering that the results obtained for the hotspot simulation are reasonably close to the previous simulations results it was concluded that the new software application can be used to estimate the C/N_0 degradation over Europe in the current ground infrastructure configuration. For this purpose, first a database of the DME and TACAN stations currently in operation was prepared. This database contains only the stations using channels between 70X and 126X for which the transponder frequency is in or near L5 band (see the DME/TACAN frequency allocation plan in Figure 4 [3] and the GNSS frequency bands allocation in Figure 5 [12]). The database was obtained in the following steps:

- Export all assignments for 70X to 126X channel from SAFIRE database (Table COM 3 assignments)
- Remove the assignments that are currently not operational (using the information published in States AIPs)
- Replace the coordinates exported from SAFIRE with the coordinates published in AIP/EAD which are more accurate (also used by DEMETER tool)
- Insert the ground station elevation from DEMETER database

The above steps were performed in order to:

- Optimize the quality of the input data and of the simulation results
- Allow comparison with real data recorded in Flight Inspection campaigns
- Allow using the coverage calculations performed by DEMETER, which take into account the terrain screening

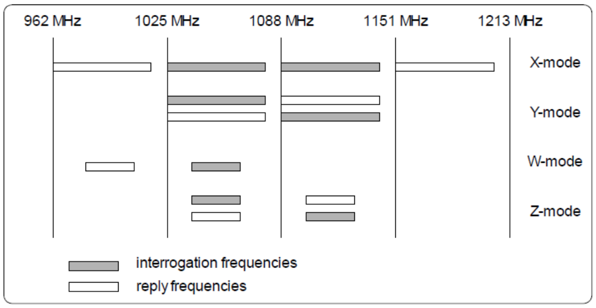

Figure 4. DME/TACAN mode and frequency plan

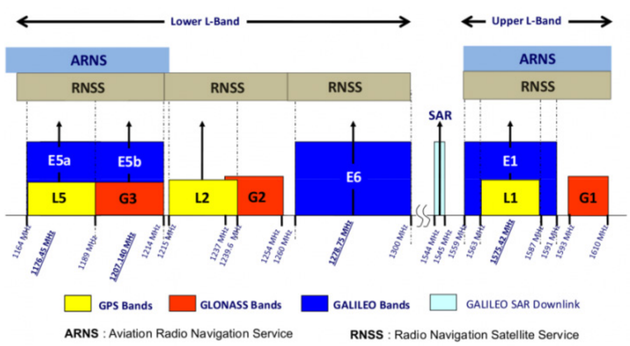

Figure 5. GNSS Frequency Bands Allocation

For the area simulations, the application computes two main results for a grid of geographic locations:

- Visibility (number of stations in radio line of sight)
- C/N_0 degradation [dB]

It is important to note that all previous simulations were performed in a "Flat Earth" scenario, meaning that for determining the ground station visibility only the Earth curvature was taken into consideration (signal screening by terrain was disregarded). For the new simulations it was considered important to take a terrain model into account, because the work was conducted with more of a focus on frequency management rather than spectrum compatibility only, e.g., before deciding on measures to reallocate DME assignments (and associated complications for VOR) to improve GNSS compatibility, a clear need would need to be confirmed.. As such the simulations were performed in two scenarios:

1. Flat Earth (no terrain) scenario
   In this scenario only the Earth curvature is considered in order to determine the ground stations visibility. This scenario allows the comparison with the previous simulations.
2. Radio Line of Sight scenario
   This scenario uses a DTED 1 terrain model to determine the visibility of each ground station, and is expected to provide more accurate results by excluding the sites for which the radiation towards the analyzed location/altitude is screened by terrain.

In both scenarios an effective Earth Radius of 4/3 of the real radius was used ("k factor"=4/3) to take into account atmospheric refraction.

The C/N_0 degradation is computed by formula (5), using the following inputs and assumptions:

- Updated Navaids database as described above
- A constant PRF (Pulse Repetition Frequency) of 2700 ppps (pulse pairs per second) for all DMEs and 3600 ppps for all TACAN stations
- A Link Budget based on the standard DME and TACAN ground stations antenna radiation patterns, the airborne GPS antenna pattern ([2]) and the FSPL (Free Space Path Loss) propagation loss. Note that multipath and diffraction effects are not considered.
- Blanking Threshold at -118.4dBW

All simulations presented in this paper were performed for an altitude of 40.000 feet AMSL (FL 400), which is the same altitude as has been considered in the previous assessments.

The large area simulations (all Europe) were performed in increments of 1 degree of arc for both latitude and longitude coordinates. For the hotspots identified in these large scale simulations the increment was reduced to 0.1 degrees or arc in order to increase the accuracy. The results are presented in a graphic format using a GIS software (GlobalMapper) which interpolates the incremented results and creates a smooth representation. The same software was used to create contour levels for both visibility and degradation maps.

Flat Earth Scenario

In this scenario the visibility hotspot is located around 49N/9.6E, where 76 stations are received at FL 400.
Figure 6 presents the C/N_0 degradation map which shows a large area over Central Europe where the estimated degradation exceeds 5dB. Figure 7 shows detail plots of this area when using the high resolution increment (0.1 arc deg.). It can be observed that the maximum degradation level is estimated at -6.53dB for a slightly different geographical location: 48.5N/8.7E.

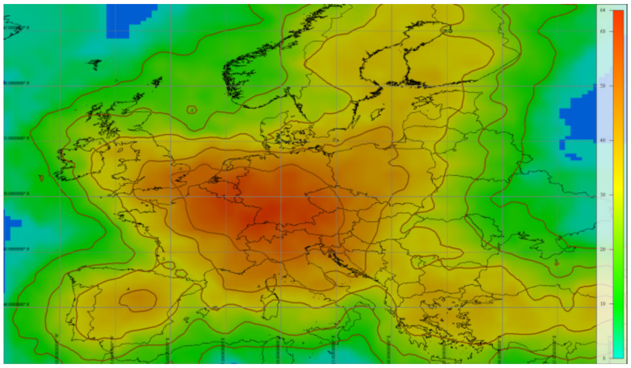

Figure 6. C/N_0 degradation map – Flat Earth

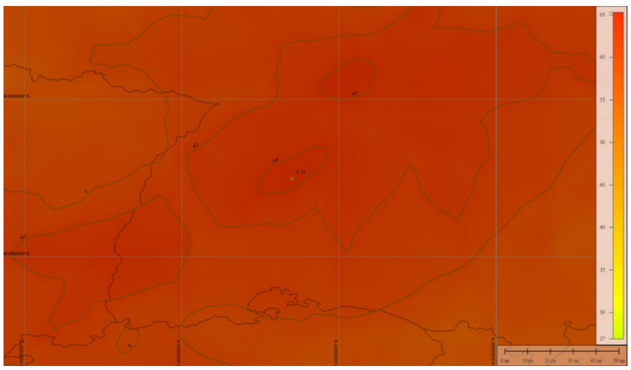

Figure 7. C/N_0 degradation map detail – Flat Earth

When comparing the above results with the results obtained in previous simulations it is noted that:

- The degradation hotspot locations are slightly different 48.5N/8.7E vs. 50N/9E
- The maximum degradation in the new simulation is approx. 1dB lower than the previous estimations: 6.5dB vs 7.5dB. This difference (and also the different hotspot locations) appear to be justified by the lower number of stations in the new database, so that at the degradation hotspot only 72 stations are in radio line of sight compared to 117 as determined by previous simulations. Note that visibility and degradation hotspots are relatively close but not identical (justified by the fact that the C/N_0 is computed based on a series of parameters of the received signals, not only based on the number of stations in line of sight).

<u>Radio Line of Sight Scenario</u>

In this scenario the visibility of each ground station is determined based on the results of the coverage simulations performed with DEMETER (Distance Measuring Equipment Tracer), the EUROCONTROL tool for the assessment of DME/DME coverage and performance.

In order to validate that the LabVIEW application reads the DEMETER coverage plots correctly, the visibility plot of the hotspot area was created and compared to a DEMETER cumulative coverage plot. A hotspot detail that combines both sets of results is shown in Figure 8. In this plot the visibility level contours and peaks created by Labview are overlaid with the DEMETER cumulative plot. It can be seen that the LabVIEW application contours match well with DEMETER coverage polygons. There are two peak areas identified by LabVIEW application where the number of received stations is 47 (50.2N/8.6E and 52N/10.6E). These peak areas match relatively well with the red polygons generated by DEMETER, although the received number of stations estimated by DEMETER appears to be slightly higher (49). Unfortunately, the current version of DEMETER does not allow the identification of the stations that cover each polygon, and as such the list of stations returned by the LabVIEW application cannot be validated (but such a capability will be considered in future versions of DEMETER).
The slight discrepancies identified in this plot can be explained by:

- The lower resolution of the LabVIEW simulation i.e. 6 arcmin. vs. 0.5arcmin of DEMETER
- The simplified geographical calculation algorithms used at this stage by the LabVIEW application.

However, the above discrepancies are rather minor and consequently it is considered that the accuracy of the visibility calculations achieved by the new application is fit for the purposes of this study.

Figure 9 presents the C/N_0 degradation map for the RLoS scenario. This plot shows a large potential hotspot area located over north-east of France, Belgium and west part of Germany. For a more accurate estimation of the degradation hotspot(s), the higher resolution simulation (0.1 arc deg. increments) was performed for the above areas, see Figure 10. In this plot, four different areas in which the estimated C/N_0 degradation exceeds -5dB are identified. However, the peak degradation value -5.27dB is still recorded in the Frankfurt area at the location: 50.5N/8.7E.

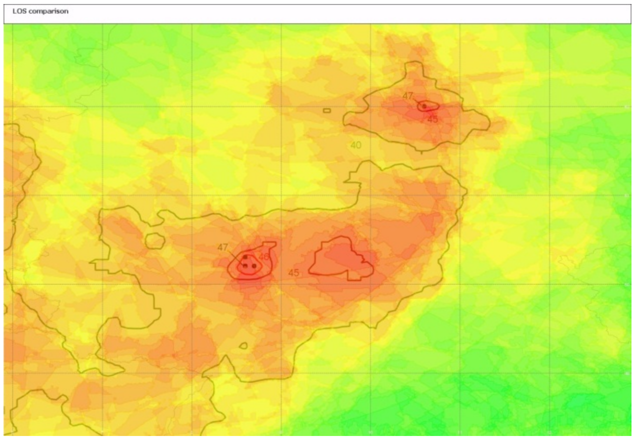

Figure 8. Visibility Plot Comparison - RLoS

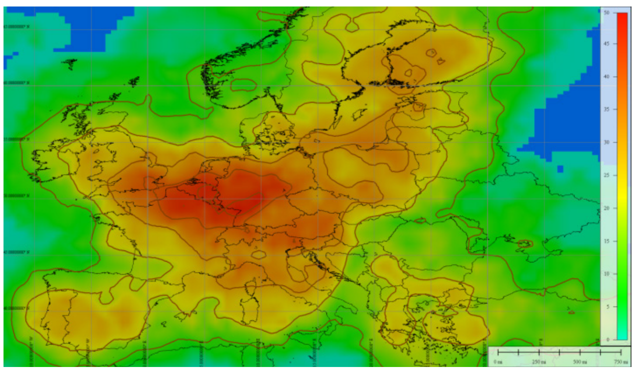

Figure 9. C/N_0 degradation map – RLoS

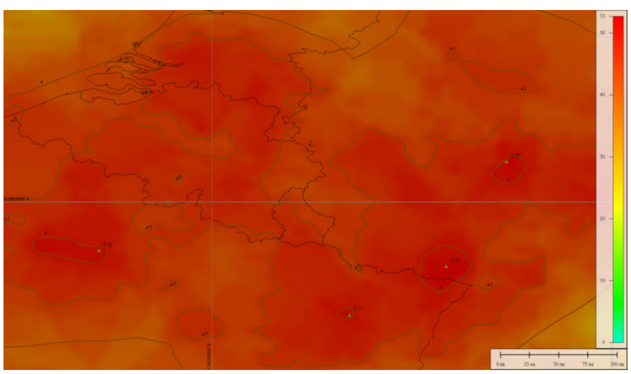

Figure 10. C/N_0 degradation map detail – RLoS

ASSESSMENT CONCLUSIONS

The results of the theoretical study can be summarized as follows:

- The maximum L5 post–correlation C/N_0 degradation due to the DME/TACAN systems currently in operation in Europe is estimated at:
  - **6.7 dB (48.6°N/8.9°E) – Flat Earth scenario** (no terrain)
  - **5.3 dB (50.5°N/8.7°E) – RLoS scenario** (DTED 1 terrain model)
- An additional degradation margin of at least **1dB** is predicted compared to the previous assessments which computed a degradation of **7.5 dB** or higher at the hotspot.
- This difference can be explained by the lower number of GS received (predicted) that is due to:
  - the updated Navaids database following the Table COM3 cleanup
  - taking into account the terrain screening when determining the RLoS
- Considering these simulation results it can be concluded that in the current configuration of the Navaids infrastructure, a reallocation of the DME channels in order to ensure the L5 compatibility may not be required, subject to further validation.

ASSESSMENT LIMITATIONS

We need to stress the fact that the above results are based on the implementation of a theoretical model of the impact of the DME/TACAN pulses on the C/N_{0eff} in GPS L5 band. Although an up to date Navaids database and the DTED1 terrain model were used for the simulations, there are a number of assumptions and limitations related to the parameters input into the model, such as:

- Assume the published EIRP (not measured)
- Assume maximum PRF (DME-2700ppps, TACAN-3600ppps)
- Simple propagation model: FSPL (propagation effects, e.g. multipath, diffraction, are not considered)
- Aircraft attitude (which impacts the effective antenna gain) and the fuselage effects are not considered

All these assumptions and limitations lead to the need for the validation of the simulation results. From our perspective the validation refers to the validation of the parameters input in the degradation model (notably ground stations received and corresponding power level and PRF), not to the validation of the model itself.

DME FLIGHT INSPECTION DATA

DEMETER Validation

A flight inspection campaign aimed at validating the DEMETER coverage prediction (not related to DME/L5 compatibility) showed a good correlation between the recorded data and the predicted RLoS ([7]). However it should be noted that in the data analysis process the recorded signal levels were compared to the minimum power density required for the DME signal in space i.e. $-89dBW/m^2$, which roughly corresponds to a level of -110dBW at the receiver input, when using the DME

dedicated antenna. The minimum power density would produce a power level at the GNSS receiver input close to the blanking threshold (negative GNSS antenna gain is considered in this case). Even if the signals with a power density below this threshold may not trigger the blanking of the GNSS receiver they would still increase the in-band noise and have an impact on the C/N_0 degradation. Consequently, it might be necessary to also take into account the ground stations which are out of the radio line of sight (i.e. consider the diffraction effects).
Furthermore, the DEMETER validation effort did not make an analysis of the signals above the -89dBW/m^2 threshold and does not offer any indication on the correlation to the level predicted using the FSPL model.

DLR Flight Inspection Campaign

The lack of real measured data related to DME/TACAN interference in L5/E5 band has led to the setup of a dedicated flight inspection campaign over the hotspot estimated by the initial studies performed by EUROCAE and RTCA (Frankfurt area). This campaign was organized and carried out by DLR (German Aerospace Center) and the details regarding the flight path, the aircraft and the measuring and recording equipment used are provided in [8]. The following paragraph describes the setup of the measurement and data recording equipment:
To record the DME interference two different systems were used:
• An Agilent E4443A Spectrum analyser. This System was configured so that it recorded 150 ms every 30s to a PC. The recording bandwidth was set to 80 MHz the centre frequency was 1188MHz. In this configuration the spectrum analyser recorded band from 1148 to 1228 MHz covering the complete E5 band.
• Furthermore a data grabber was used to continuously record the signal. This system was sampling the E5 band with 100 Msamples/s and at the same time the L1 and E1 band with 50Msamples/s.
Since this data grabber recorded the signal continuously, the amount of recorded data is enormous. This system generates 300 Mbytes/s and transfers this data stream in real time on 32 hard disks. In this mode the system records 1TB/hour. During the whole campaign 18 TB of data were recorded.

The initial findings of this measurement campaign are found in the presentation given at the EUROCAE WG 62 meeting held in December 2013 ([9]). Two of the diagrams that summarize the results have found to be of interest for the purposes of our study. Figure 11 shows the flight path followed during the recordings, the different estimations of the hotspot location and the location of the measured hotspot (note that the original source picture does not include the EUROCONTROL hotspot estimation). The results of various studies are consistent in what regards the location of the hotspot in the Frankfurt area (although the exact position is not the same) and the results of the flight measurements confirm the existence of the hotspot in the same area.

From the initial analysis of the recorded data performed by DLR it was seen that the number of stations received may change significantly as a function of aircraft bank angle. While in a level flight configuration about 57 stations were received, the number increased to 65 stations when the aircraft was performing a turn in the hotspot area; this “worst case” situation is illustrated in Figure 12. The DLR analysis also confirms that some of the stations within the radio horizon range were not received (most likely shadowed by terrain) while signals from a number of stations beyond the radio horizon were detected. This appears to confirm the need for taking into account the diffraction effect in the simulations.

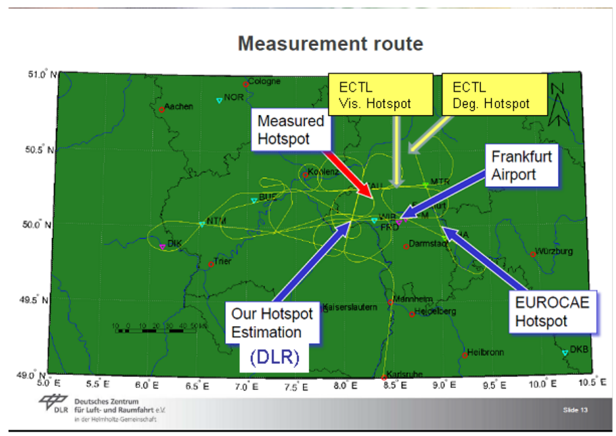

Figure 11. Flight Path and Hotspot Location

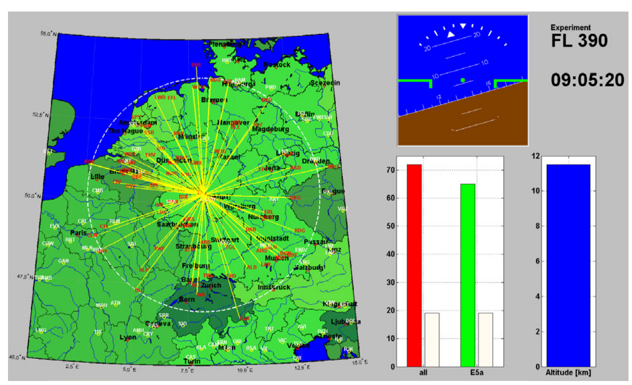

Figure 12. Ground Stations Received – Worst Case

Unfortunately more detailed information regarding the DLR recorded data was not yet published. As described in the above excerpt from [8], an impressive amount of raw data was recorded during the flight tests campaign. In order to retrieve the detailed information related to the individual ground stations in L5/E5 band, an important post processing effort is needed. Due to unforeseen events, this effort could not be completed at the time this paper was written. Consequently, the analysis of the flight recorded data aiming at validating and refining the DME/L5(E5) compatibility simulations will be the subject of further work.

FUTURE WORK

As mentioned in the previous sections, several assumptions were used in the assessment of the impact of current DME/TACAN network in EUROPE on the GPS L5 carrier to noise degradation. These assumptions and the results of the assessment need to be validated before any actions (or no actions), such as specific frequency assignment planning measures, are taken to ensure the DME/L5 compatibility in the hotspot areas. The main validation data source identified so far is the measured data recorded by DLR in the dedicated flight measurements campaign. The authors of this study are continuously coordinating with the technical staff involved in the DLR tests and plan to use the results of the recorded data post processing in order to:

- Evaluate the impact of the assumptions on the final C/N_0 degradation figures
- Improve the assumptions and the assessment methodology so that this impact is minimized

Another line of action aimed at improving and refining the assessment methodology is the cooperation with the specialists from ENAC France (l'Ecole Nationale de l'Aviation Civile) where a similar study has been started. The scope of ENAC project is broader and will include studies on various implementations of the blanking technique and also on other mitigation techniques proposed, e.g. Frequency Domain Interference Suppressor (FDIS).

Depending on the results of the validation exercise, and after refining the theoretical model implementation and the input data assumptions in collaboration with ENAC, the following actions will be considered:

- Extend the assessment to E5 band
- Integrate the assessment model in one of the EUROCONTROL software tools (AFM-MANIF or DEMETER).

This integration would support the analysis of the potential solutions to minimize the RFI impact in the hotspot area (if found necessary) and would allow evaluating the impact of new X channel assignments in the upper DME band in Europe.

CONCLUSIONS – INCLUDING IMPLICATIONS FOR FUTURE FLIGHT INSPECTION CAPABILITIES

EUROCONTROL exercises the role of "Network Manager" in Europe, which includes the management of scarce resources, such as frequencies. This radio frequency management function is carried out in coordination with member states and the ICAO European Region. Prompted by statements in the ICAO GNSS Manual, the EUROCONTROL network manager asked if such frequency management is necessary and how it would be implemented. Consequently, a SESAR project undertook to investigate this question in further detail, and the results of this work are presented herein. The preliminary result, based on updated theoretical studies that take terrain screening as well as an updated database of operationally used DME assignments into account, is that no such measures are needed. In related studies carried out by SESAR on navigation infrastructure evolution, it is estimated that the implementation of a DME/DME network to support PBN alongside GNSS would lead to a more even distribution of DME compared to today. Consequently, provided the theoretical studies can be verified appropriately by actual measurements, it is estimated that no significant frequency management mechanisms are needed to ensure the continued compatibility of DME and dual-frequency GNSS.

While it will remain necessary to keep an eye on the evolution of the DME hotspots and ensure that appropriately validated tools are available for that purposes, it appears to be sufficient to only limit the assignment of new DME channel assignments in the GNSS bands as much as possible, e.g., by simply giving priority to DME assignments that are not in that sub-band, if such channels are available. This will also reduce the common mode between GNSS and DME in terms of vulnerability to interference, even if susceptibility levels between DME and GNSS are dramatically different.

The larger issue that is relevant for flight inspection organizations is that navigation service provision in the PBN context will shift more and more away from an individual facility assessment logic to more of a network management function. The theoretical models need to make many assumptions about the signal in space, and normally revert to worst case assumptions. Here, flight inspection data can have a role to ensure that those conservatisms remain within realistic bound, which is essential to ensure that aviation can retain credibility in spectrum defense activities.

Normally, ANSP know quite well how their facilities operate. However, even there, surprises may appear on for example, actual pulse pair repetition rates at which stations operate. Likewise, accurate measurements of received signal strength, from multiple stations at large distances (often from cross-border) are another key input into compatibility models.

It is recommended that flight inspection organizations develop their capabilities to ensure that frequency management aspects such as the one discussed in this paper can be supported in the future PBN environment.

ACKNOWLEDGMENTS

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To SESAR project 15.1.6 which supported this work.

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GBAS Calibration

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ABSTRACT

By flight inspection it shall be ensured that navigation aids conform to international standards according to their specification. During flight calibration of Ground Based Augmentation Systems (GBAS), the VHF Data Broadcast (VDB) signal in space (power density) needs to be checked very accurately.

The signal in space measurements of the VDB uplink are depending on aircraft antenna, polarization, bearing of aircraft to ground transmitter, frequency, the way the signal level is detected and the time slot it is transmitted in. The signal is transmitted in a special digital format, with differential phase modulation, synchronized to a time standard in short bursts. Several stations can transmit on the same frequency (TDMA).

Standard equipment for power level measurements cannot be used for determination of field strength, since the measurement depends on parts of data contents of the telegram and the time slot in use. A special GBAS receiver following the standards of RTCA DO-246 has to be installed in the flight inspection aircraft for measuring field strength.

The calibration of the GBAS receiver itself has turned out to be a critical part in the measurement chain. Various techniques using laboratory test transmitters and receivers as well as in-service GBAS ground stations have been analyzed to develop a calibration procedure for the airborne GBAS receiver.

This presentation shows the background and technical solutions.

INTRODUCTION

The Ground Based Augmentation System (GBAS) is a system to support approaches, landing, departure and ground surface operations.

A dedicated ground station provides locally relevant pseudo-range corrections, approach segment data as well as integrity monitoring information.

One critical path is the data link from ground to the aircraft. This link is discussed in detail in this paper.

GBAS FLIGHT INSPECTION

The following components are subject of flight inspection:

Contents	can be checked also on Ground
Data	can be checked also on Ground
GNSS Signal	Must be checked in flight
VHF Signal	Must be checked in flight

- **Coverage of VDB Ground Station (This paper)**

Additionally the frequency Spectrum of the VDB Frequency ±100 kHz either side in case of suspected interference should be checked

SYSTEM COMPONENTS

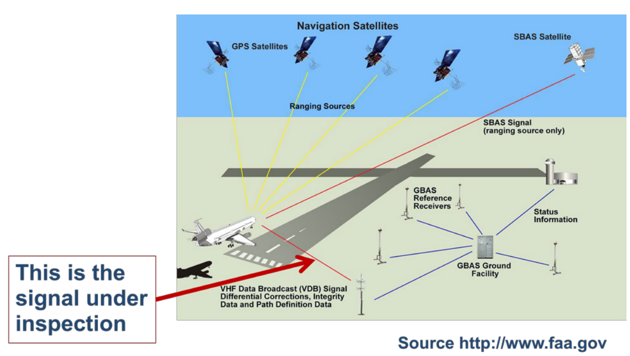

Figure: GBAS System overview

REGULATIONS

The main information about GBAS technical details and operation are found in:

- ICAO Aeronautical Telecommunications, Annex 10, Volume I, Radio Navigation Aids, Sixth Edition, July 2006
- RTCA DO-246C, GNSS-Based Precision Approach Local Area Augmentation System (LAAS) Signal-in-Space Interface Control Document (ICD), April 2005

TECHNICAL DETAILS OF THE DATA LINK

The VHF data link is a pulsed signal, which cannot be measured regarding signal level with a standard analog receiver.

Figure: Analog receiver with analog and digital readout

Some mechanism is required, to „freeze“the signal level readout according to [2].

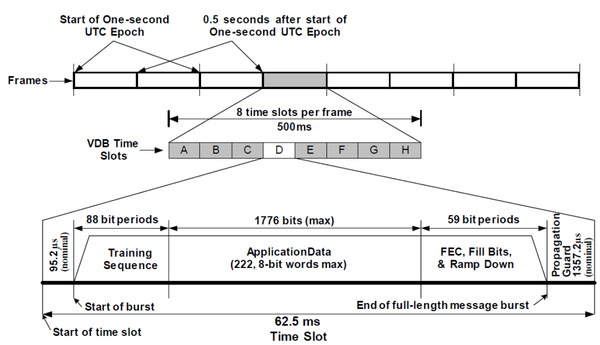

Figure: Definition of the timing

Table 2-6 Training Sequence Format

Segment Sequence	*Training Sequence Description*	*Number of Bits*
1	Power Stabilization	15
2	Synchronization & Ambiguity Resolution	48
3	Station Slot Identifier (SSID)	3
4	Transmission Length	17
5	Training Sequence FEC	5
	TOTAL	88

Figure: Training sequence formats

According to [2], DO-246C, 2.1.3, Field Strength:

<u>The VDB Field Strength Measurement is averaged over the period of the synchronization and ambiguity resolution segment in the training sequence of the VDB message</u>

A typical plot showing signal level versus time with x-axis (time) and y-axis signal level (logarithmic, in dBm) looks like:

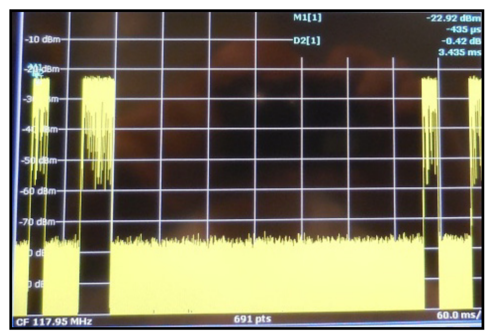

Figure: Signal level versus time, x-axis set to 600 ms, showing 10 time slots

To determine this specified signal level in the defined timing and slot, a time- and/or data synchronized test system has to be used.

If the „Time slot“ is known (A to H), test equipment can be synchronized with an appropriate system to the UTC one-second epoch.

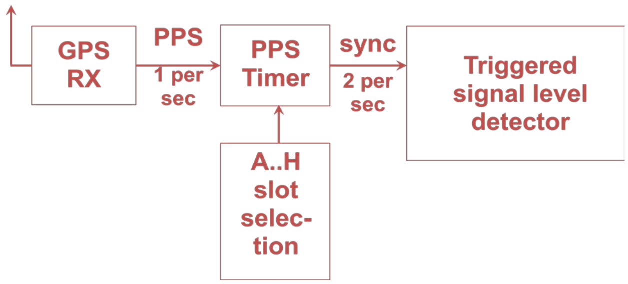

Figure: Synchronization of the signal level detector to the "UTC one-second-epoch" (PPS)

A unit „PPS Timer" has been developed to be input-triggered by a GPS PPS pulse and send an output sync signal to a receiver detecting the „averaged signal level over the period of the synchronization and ambiguity resolution".

With the synchronization unit the following plot is taken showing the signal level versus time. The x-axis is set to 2 ms, showing only the „synchronization and ambiguity resolution" data field. This shows 48 bits, equivalent to 16 symbols of 8PSK modulation. Each symbol has 8 different possible stages, holding the information of 3 bit.

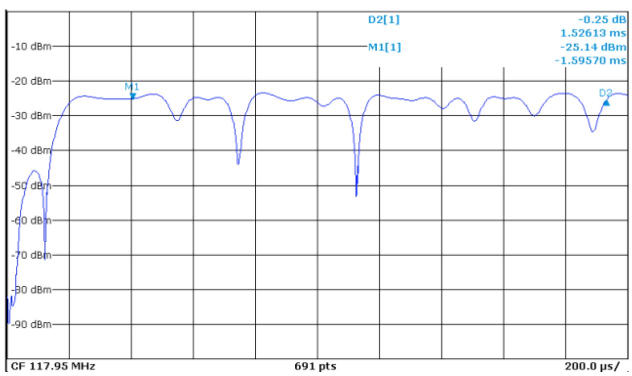

Figure: only the synchronization and ambiguity resolution is shown, synchronized to UTC one-second epoch at relevant time slot number.

The field strength of the VDB Signal according to [2] is the average of all signals between 476 us and 2000 us after start of the burst.

COVERAGE, SIGNAL IN SPACE

The coverage area to receive a valid signal is defined in [2] as:

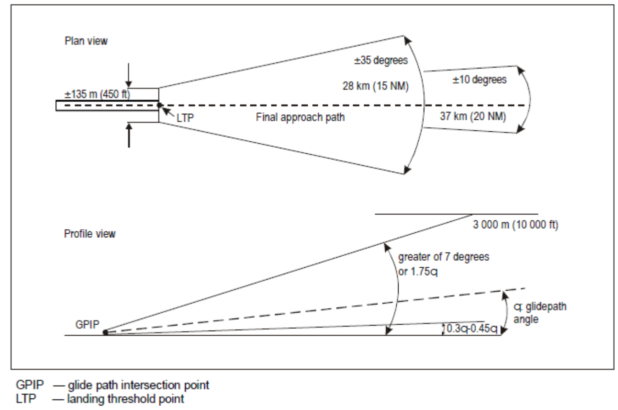

Figure: Coverage area in approach

A signal in space is not easy to set up in a perfect way, so one typical problem with transmit antennas close to ground are multipath effects.

To show this, real flight data of a "level-run" in 10,000 ft from 21 NM to 12 NM and a simulation of the same run show the effect of a "null", when the VDB signal is transmitted by a single antenna, close to ground are shown.

Definition: A null is an area of an antenna radiation pattern where the signal cancels out almost entirely.

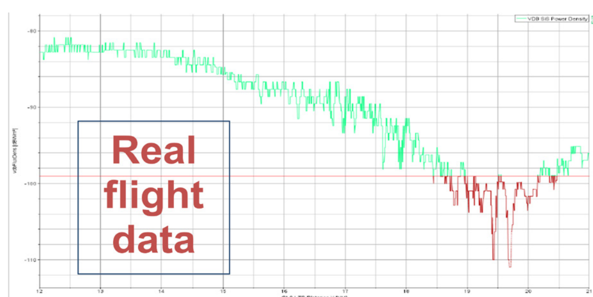

Figure: Real flight data level run

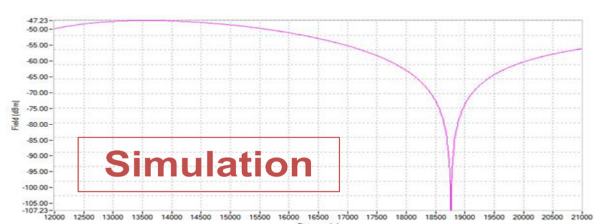

Figure: Simulated data level run

A typical signal in space of a single horizontal TX antenna close to ground with different heights has been simulated to explain this. The results depend on frequency, height and ground reflections.

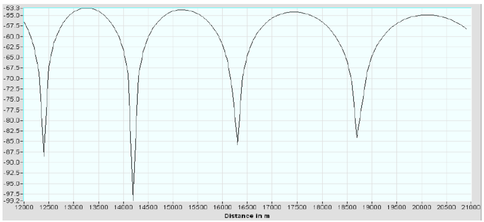

Figure: TX antenna installed high above ground

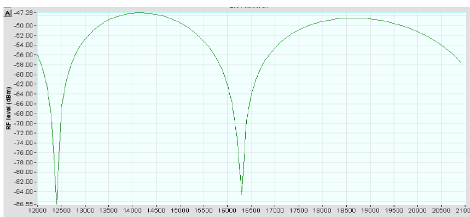

Figure: TX antenna middle height above ground

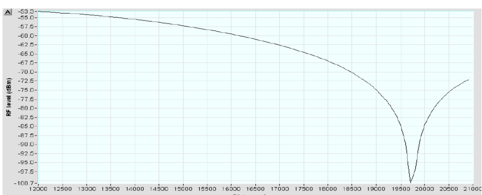

Figure: TX antenna low above ground

Low installation height has less „Nulls“, but lower signal level.

<u>GROUND ANTENNAS, POLARIZATION</u>

ICAO Annex 10, Attachment D, 7.12.4, – “Use of multiple transmit antennas to improve VDB coverage” allows more than one antenna for transmitting:

“7.12.4.2 One example of the use of multiple antennas is a facility with two antennas at the same location but at different heights above the ground plane. The heights of the antennas are chosen so that the pattern from one antenna fills the nulls in the pattern of the other antenna. The GBAS ground subsystem alternates broadcasts between the two antennas, using one or two assigned slots of each frame for each antenna”

This leads to a complex measurement in flight, synchronizing the switching algorithm of the ground antenna with the data collected in flight.

A more simple solution is to build a complex antenna, avoiding ground illumination, but this not always possible.

Figure: Typical multi-element TX antenna optimized to avoid ground illumination.

The specification [2] allows two different polarized transmissions:

- Horizontal polarization (GBAS/H) or
- Elliptical polarization (GBAS/E), consisting of horizontal (HPOL) and vertical (VPOL) components

Annex10 (3.7.3.5.4.4.2.1) recommends: „An elliptically polarized signal should be broadcast whenever practical“

A note in Annex10 (3.7.5.4.4) states: „Aircraft using VPOL component will not be able to conduct operations with GBAS/H equipment“

The Signal level limits are:

	Min	Max
Horizontal	-99 dBW/m2	-35 dBW/m2
Elliptical		
- Vertical	-103 dBW/m2	-39dBW/m2
- Horizontal	- 99 dBW/m2	-35 dBW/m2

Annex 10, 7.2.5: In order to ensure that an appropriate received power is maintained throughout the GBAS coverage volume during normal aircraft maneuvers, transmitting equipment should be designed to radiate HPOL and VPOL signal components with an RF phase of 90 degrees.

Real-life data from GBAS Station, EDVE, Braunschweig with antenna Rohde & Schwarz HE300:

Figure :Polarization check of real-life data with hand-held antenna

Readout horizontal:	-30.4 dBm
Readout vertical:	-35.4 dBm

CHANNEL AND FREQUENCIES

Each GBAS approach transmitted from the ground subsystem is associated with a channel number in the range of 20 001 to 39 999. If provided, the GBAS positioning service is associated with a separate channel number in the range of 20 001 to 39 999. The channel number is given by:

Channel number = 20 000 + 40(F – 108.0) + 411(S)

where

F = the data broadcast frequency (MHz)

S = RPDS or RSDS

RPDS = reference path data selector for the FAS data block

RSDS = reference station data selector for the GBAS ground subsystem.

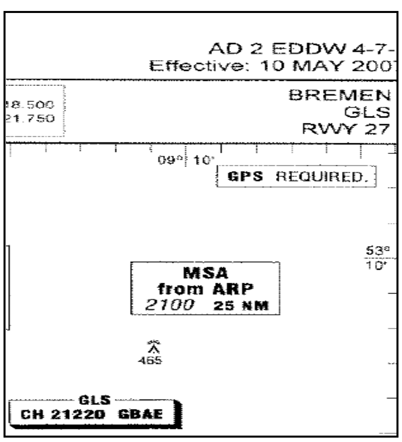

Figure: Map with GLS channel "GBAE 21220"

DO-246C [2] explains: …RSDS is a numerical identifier that is unique on a frequency in the broadcast region and used to select the station for the differential positioning service….

8 bits are used, but only 49 different identifier possible (0 .. 48).

The formula to determine the frequency of the GBAS transmitter is:

F= 108.0 MHz + ((Ch# -20000) mod 411) x 0.025 MHz

Examples:
Bremen EDDW Freq. 117.950 MHz, S=2 → Ch# 21220

Braunschweig EDVE
Freq. 117.950 MHz, S=21 (G26A) → Ch# 29029

Freq. 117.950 MHz, S=23 (G08A) → Ch# 29851

This channel number has to be set when tuning the GBAS-RX in the cockpit or the AFIS

LINK BUDGET

The GBAS Link Budget for the data link from ground transmitter up to the airborne receiver is:

Table D-3. Nominal VDB link budget

VDB link elements	Vertical component link budget at coverage edge	Horizontal component link budget at coverage edge
Required receiver sensitivity (dBm)	–87	–87
Maximum aircraft implementation loss (dB)	11	15
Power level after aircraft antenna (dBm)	–76	–72
Operating margin (dB)	3	3
Fade margin (dB)	10	10
Free space path loss (dB) at 43 km (23 NM)	106	106
Nominal effective radiated power (dBm)	43	47

The aircraft implementation loss is the critical factor in the aircraft installation.

AVIONIC / TEST EQUIPMENT

To flight check GBAS ground station and detect the exact signal level the following avionics and test equipment can be used:

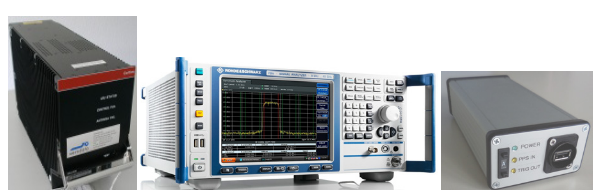

Figure: Collins GNLU-930, spectrum analyzer and UTC time synchronization box

ABSOLUTE LEVEL MEASUREMENT

The following signal levels have been measured at GBAS EDVE, using the antenna signal on ground and a switchable attenuator in line with different receivers:

Signal	Spectrum Analyzer, UTC-second-sync., averaged	R&S EVS 300	Collins GNLU-930, raw Output data
Direct	- 44.4 dBm	- 42.0 dBm	- 38.0 dBm
-10 dB ATT	- 54.2 dBm	- 52.0 dBm	- 48.0 dBm
-20 dB ATT	- 64.2 dBm	- 62.0 dBm	- 58.0 dBm
- 30 dB ATT	- 74.2 dBm	- 72.0 dBm	- 68.0 dBm
-40 dB ATT	- 84.3 dBm	- 82.0 dBm	- 79.0 dBm
-50 dB ATT	- 93.6 dBm	- 92.0 dBm	- 89.0 dBm

Which one is correct?

SOFTWARE PRESENTATION

A software screen showing all relevant data in a complex GBAS environment shows the following information with an update rate of 500 ms:

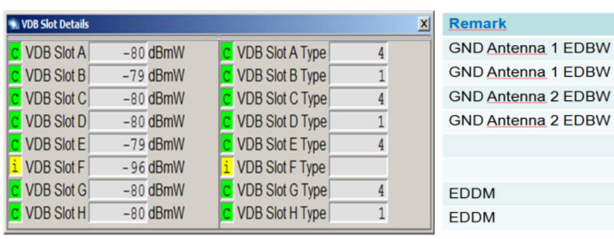

Figure: numerical presentation of signal level per slot and decoded message type

CONCLUSION

Measuring GBAS VDB Signal levels is not a simple task as in analogue modulation.

To perform a full analysis, special equipment is necessary to detect a signal level at each time slot.

Absolute calibrations with different available systems show different results.

Currently only simple ground TX installations are performed, measuring correct signal levels in a complex installation with several stations overlapping will be a challenge in the future.

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[4] Implementation and Operational Use of Ground-Based Augmentation Systems (GBASs)—A Component of the Future Air Traffic Management System, Proceedings of the IEEE, December 2008

Experiences and Analysis with Flight Inspection of GBAS

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ABSTRACT

The traditional purpose of a flight inspection have been to calibrate and evaluate the performance of aircraft navigation and landing aids to ensure conformance to specifications. With the new GNSS augmented landing systems, the flight inspection is moved from the traditional analyses of “signal-in-space” towards flight validation, verification of associated procedures and the radio environment in which the navigation signals are received. The only exception is Ground Based Augmentation System (GBAS), where in additional to validation and verification, the VDL coverage is also verified using traditional procedures.

In this paper we present the flight testing experience with Ground Based Augmentation System. It is focused on how to best aid the pilot and the FIS-operator during the in-flight inspection. With the right information, at the right place, at the right time. Keywords for topics that are covered are; situational awareness, anomaly analysis, interference, position fixing, coverage, fault detection and isolation.

INTRODUCTION

These days almost all phases of the flight can be performed by satellite navigation systems. The most challenging phase of flight is the approach and landing phase. The Ground Based Augmentation System (GBAS) allows precision approaches to be performed using satellite navigation. GBAS is a safety critical system composed of both hardware and software that improves the Standard Positioning Service (SPS) of GNSS (currently GPS and GLONASS, but potentially any constellation in the future), providing better service levels and supporting precision approach in the coverage area. It uses a VHF data link to broadcast differential GNSS corrections, integrity information and approach definitions to aircrafts. The aircraft combine the differential corrections with their own GNSS measurements, calculate a corrected position solution and determine path deviations based on the selected approach.

GBAS SYSTEM

GBAS is composed of three subsystems: the satellites, the ground and the aircraft subsystems. The ground subsystem comprises a set of fixed-based reference receivers that constantly collect data from the GNSS satellites, which form the satellite subsystem. This data is afterwards used to compute corrections which are then transmitted via a VHF Data Broadcast (VDB) link. The VDB operates in the VHF band (108 – 117.975 MHz) and uses time-division multiple access (TDMA) to allow the operation of multiple VDB transmitters on a single frequency. The separation between channels are 25kHz.

The information transmitted on the VDB that the flight inspector will mostly care about is the Final Approach Segment (FAS) data block in Message Type 4 and facility station and integrity information in Message Type 2.

The FAS data block contains the definition for a single precision approach. This includes the data elements that provides the glide path and course deviations. These are parameters that the flight inspection will be measuring.

FLIGHT INSPECTION

GBAS flight tests are used to confirm procedure design, final segment alignment, GNSS signal reception and data link reception within the coverage volume.

The focus of GBAS flight inspection is the coverage of the VDB correction signal, complementing extensive measurements on the ground. As typical for all GNSS-based procedures, commissioning checks only are carried out.

Some states perform periodic check of GBAS systems while other only perform commissioning and special checks.

Typical Flight Inspection procedures for GBAS are:

- VDB coverage arc +/- 10 deg @ 20NM.
- VDB coverage arc +/- 35 deg @ 15NM.
- VDB coverage orbit @ 23NM / Dmax
- VDB coverage Level runs from 21NM @ 10000ft.
- VDB coverage Level runs from 21NM @ 2000ft
- Final Approach path.
- Missed Approach.

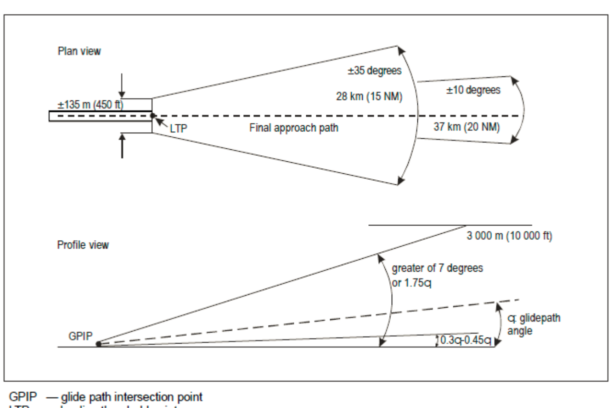

Figure 1. Minimum GBAS coverage (Annex 10, vol. 1, fig. D-4)

FAS DATA VERIFICATION

For GBAS systems the FAS data are uplinked as a type 4 message on the VDB. The received FAS data from the GBAS ground station is extracted from the GNLU and logged by the flight inspection system.

The received FAS data block is then compared to the FAS data stored in the flight inspection facility database and any mismatch are announced to the flight inspector.

The FAS data should be checked for consistency against the original procedure design and the calculated CRC should be checked for consistency with the expected CRC.

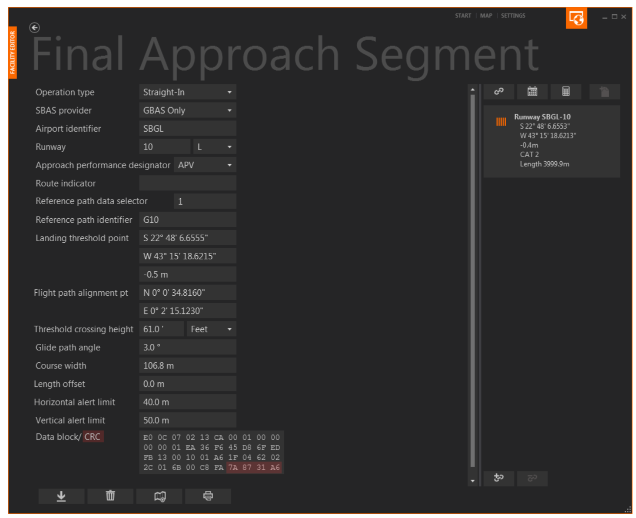

Figure 2. Example of FAS data-block as stored in Flight Inspection system Facility database.

Like for SBAS procedures the FAS data stored in the flight inspection facility database can be inserted manually or automatically.

For manual inserted FAS data the hex code representation of the data-block and CRC is calculated by the flight inspection system and presented.

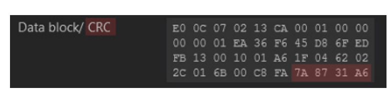

Figure 3. FAS data-block and CRC

Direct automatic ARINC 424 import of the FAS data is the best solution to prevent data corruption caused by human manipulation. ARINC 424 is the industry standard for transmission of navigation data.

If FAS data-block is published in hex format, as we see done by many states, the hex values can also be cut and pasted directly into the facility database to automatically populate the FAS data and calculate correct CRC. The ease of this procedure will save the operator time and it will also reduce the risk of inputting wrong data.

The generated facility database including the FAS data-block can be opened in Google Earth for easy visualization and as an initial reasonability check. The accuracy of Google Earth is not at all sufficient for final assessment of FAS data, but errors in manually input data can often be eliminated by a quick check in Google Earth.

When the inspection starts, the flight inspector can validated the FAS data block received on the VDB in message type 4 and facility information in message type 2.

Errors in the FAS can lead to the aircraft being offset from the desired path and may provide inadequate obstacle clearing. A flight inspection system analysis is required to validate the FAS data for lateral alignment, threshold crossing height and glide path angles. Since the flight inspection facility database also contains data for the runway this analysis can be performed automatically.

GUIDANCE

For flyability checks of GBAS it is required to provide GBAS guidance to the flight inspection pilot. ICAO DOC 8071 Vol II specifies the requirement to check flyability and to verify that the defined final approach course deliver the aircraft to the desired point.

GBAS receivers are so far only available for large air transport category aircrafts and the smaller aircrafts typically used for flight inspection does not have this capability.

In order to provide GBAS flight inspection capabilities and guidance to pilots the easiest solution certification wise is to install the GBAS receiver as part of the flight inspection system and interface the GBAS receiver either to dedicated FIS guidance displays in cockpit or directly to aircraft flight displays.

Tuning of the GBAS receiver can be performed by the flight inspection system. The GBAS receiver output ILS lookalike deviation signals which normally can be shown on standard EFIS systems with little or no modification.

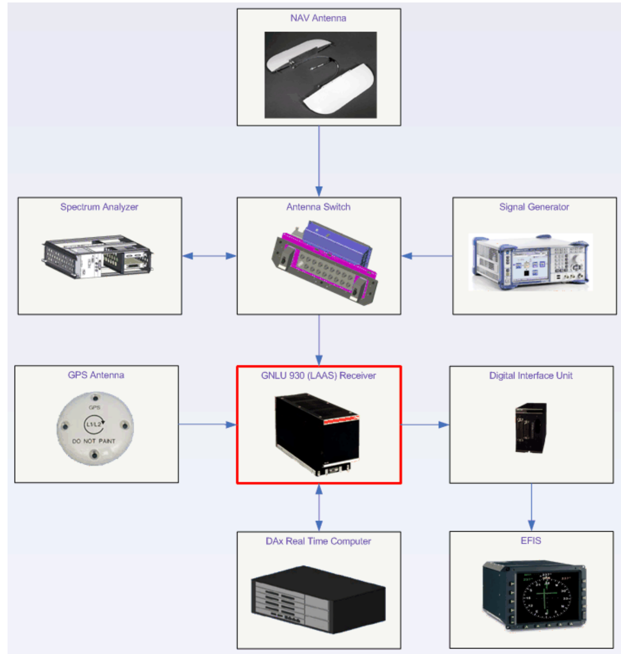

Figure 4. GBAS interface

Situation awareness is essential to ensure a safe and effective execution of any flight inspection mission. This is especially important for GBAS stations with flight patterns less common than the well-known flight patterns of conventional NAVAIDS.

To ensure good situation awareness for the pilots and crew it is recommended to have a flight inspection system capable of generating, presenting and exporting the required flight patterns.

Direct upload of flight patterns from the flight inspection system to aircraft Flight Management Systems (FMS) will ensure that each flight profile is flown efficiently as defined with the lowest crew workload.

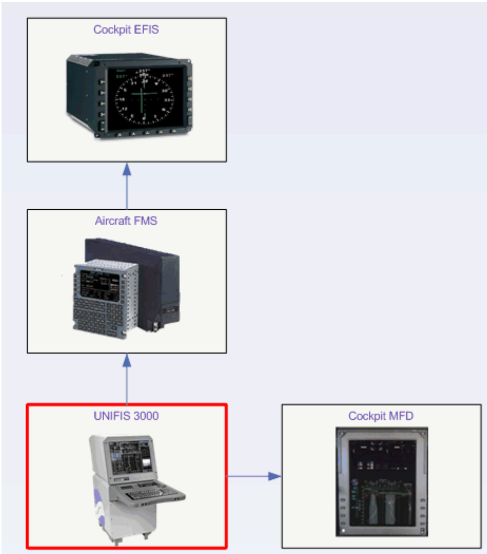

Figure 5. FMS Interface

Graphical presentation of the flight patterns to the system operator can be shown on the flight inspection system screen and also to the pilots if a dedicated FIS cockpit display is installed or interfaced to cockpit MFD video.

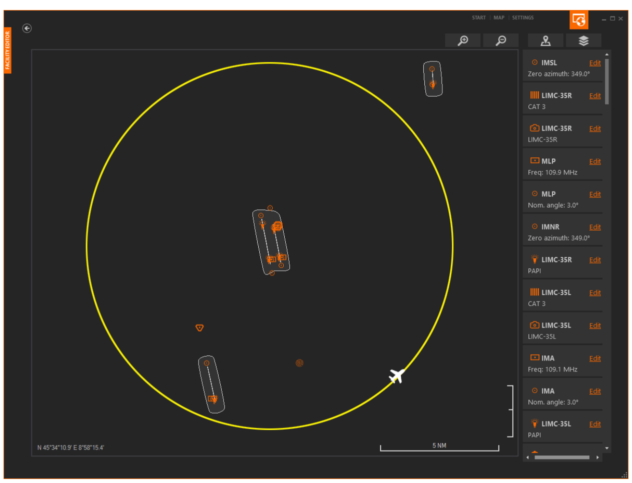

Figure 6. Facility map with flight pattern

CALIBRATION

One of the main flight inspection requirements for GBAS is to check the coverage of the VHF Data Broadcast Station.

The Rockwell Collins MMR GNLU-930 GBAS receiver used in the UNIFIS 3000 flight inspection system has a specialized firmware for flight inspection of GBAS which will output the signal strength information from the built in VDB receiver.

The signal strength can be calibrated in the flight inspection system software by the use of special signal generators capable of simulating a GBAS VDB broadcast.

The calibrated signal strength signal can be used for accurate signal strength measurements. In order to obtain correct field strength measurement the antenna gain pattern and the cable loss for the VDB receiver antenna must be known.

Flight inspection antennas are far from ideal isotropic receptors and variation of the antenna gain can be more than 10dB over various angles and frequencies. Without advanced antenna gain compensation algorithms the required measurement accuracy simply cannot be met.

In most cases a horizontally polarized antenna (VOR/LOC antenna) is used as the VDB receiving antenna. The GBAS specification allows also vertical polarized VDB receiving antennas to be used since the VDB transmission is often performed by an elliptically polarized antenna.

For cases where vertical polarization is used, VDB vertical field strength measurements also has to be verified to be within given tolerances.

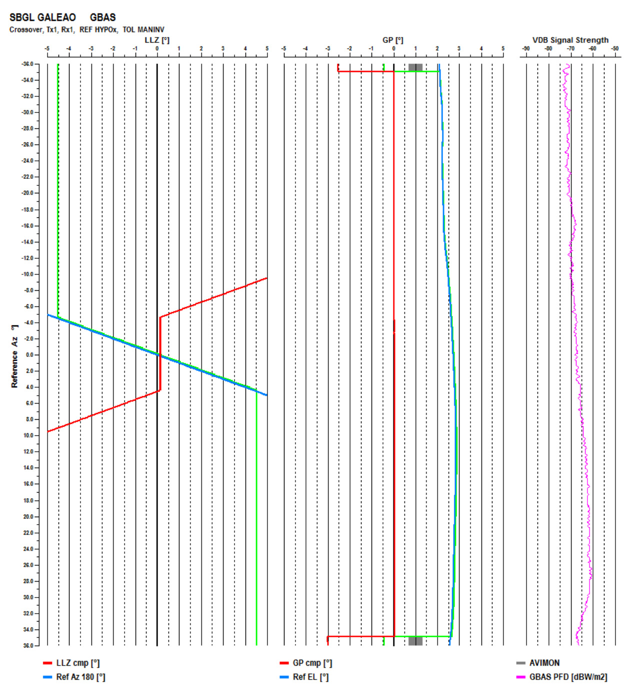

Figure 7. GBAS Crossover with VDB field strength measurement

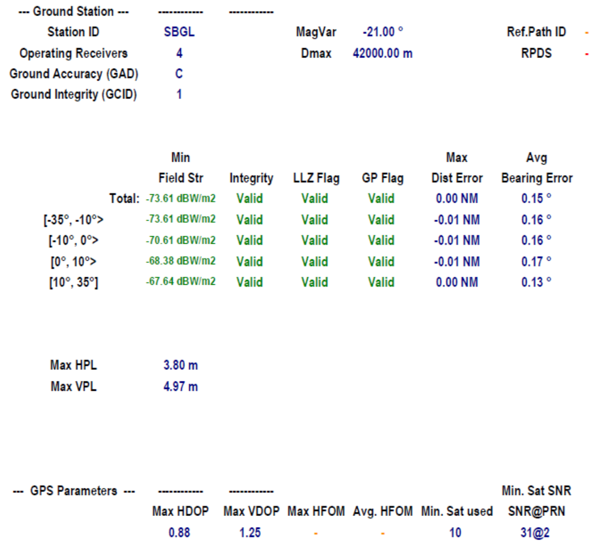

Figure 8. Example of GBAS Crossover results

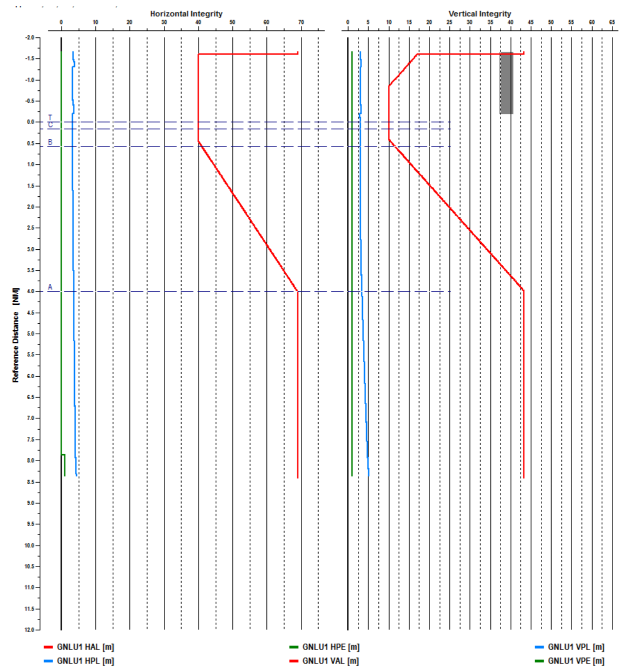

Figure 9. GBAS Integrity parameter recording

INTEGRITY AND INTERFERENCE TESTING

The integrity of the GBAS system is good and abnormalities are normally detected and announced by the GBAS ground station.

Interference may occur on either the ranging (GNSS) or VDB frequencies. Excessive ranging signal interference will therefore affect continuity and availability, rather than integrity. The loss of GBAS guidance or loss of GBAS correction signals are indicators of interference issues. Other indicators of interference are when integrity parameters are over the expected values.

FAA recommends to record and observe the following GBAS related satellite data:

Parameters	Expected values
Horizontal Protection Limit (HPL)	< 40m
Vertical Protection Limit (VPL)	< 10m
HDOP	< 4.0
VDOP	< 4.0
Horizontal Integrity Limit (HIL)	< 0.3nm
Figure Of Merit (FOM)	< 22 meters
Satellites Tracked	5 Minimum
Signal-to-Noise Ratio (SNR)	30 dB/ Hz minimum

If interference is suspected, further analysis should be performed. In this case the use of a spectrum analyzer or broadband receiver with ability to log data is recommended.

The spectrum analyzer or broadband receiver installed in the flight inspection system is able to connect both to the VDB antenna (NAV) for interference analysis of the VHF Data broadcast and to be connected to a passive GPS antenna mounted on the belly of the aircraft for interference analysis in the GNSS frequency band.

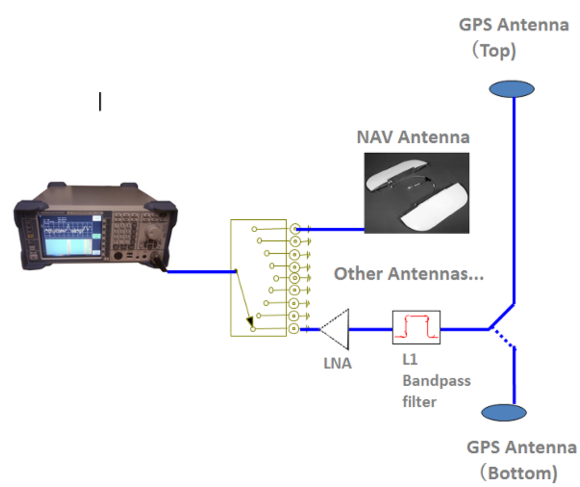

Figure 10. Interference test equipment.

ALIGNMENT WITH ILS

We all know about the importance about accuracy and verification of the FAS data that is used for GBAS. What we have also noticed is that the flight inspector sometimes also wants to see how the GBAS is compared to the ILS. This is due to that ILS will remain in operations for a long period (due to fleet renewal etc) and that in the mean time that precision approaches could be done with both ILS and GBAS. In addition, the ILS is a technology that is known, while the GBAS flight inspection is still in a learning curve.

When an ILS exists at the same approach as GBAS, it is recommended to align the GBAS with the ILS.

Doc 8168 says:

> *"At runways with an ILS it is generally desirable to align the GPA with the ILS glide path, both to ensure alignment with existing lighting systems and to provide consistency between the two approach systems."*

So based on the feedback we have got, many states wants to see the GBAS results compared to the already steablished ILS facility.

The possibility to also see the GBAS results in uA and to watch the ILS deviation while performing GBAS inspection has been added to the GBAS flight inspection procedures of the UNIFIIS 3000. In addition to the standard GBAS results, this can boost the confidence to the inspector that both landing systems are aligned.

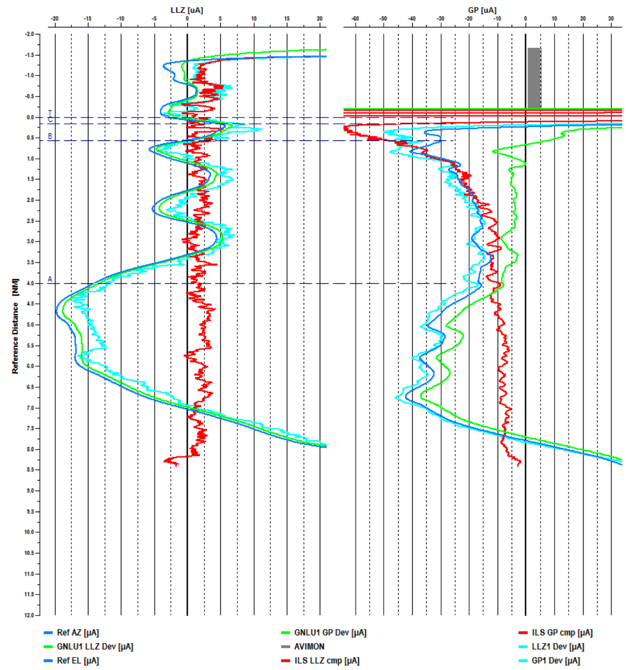

Figure 11. GBAS vs ILS

In this run we see that the ILS localizer is well aligned to the GBAS lateral guidance, while the ILS glide-path will deviate from the GBAS vertical guidance the closer you get to the threshold due to the position of the glide-path antenna.

POSITIONING FIXING

GBAS flight inspection can in theory be performed without a reference system, but optionally the position accuracy can be checked.

Doc 8071 says:

"1.11.4 For inspection of Category I GBAS procedures, a positioning system is not required, but may be used, depending upon regulatory requirements of individual States. Although no accuracy tolerances are defined, if a GNSS-based positioning system is used its independence should be demonstrated, i.e. there must be no common-mode errors between the GBAS and positioning system. For example, for code-based GBAS, a carrier-based position-fixing system may be used. Alternatively, a non-GNSS based position-fixing system may be used."

RTK carrier phase differential GNSS system or camera based position reference systems with sufficient accuracy to be used as reference for precision landing systems can be used for GBAS flight inspections.

The benefit of using a position reference system is that a running compare calculation between GBAS and the reference source can prove that the recommended accuracy of 4 m vertical and 16m lateral is met near decision height. It can also be used to identify periods where the GBAS accuracy is low.

CONCLUSIONS

(A) Flight inspection of GBAS procedures are more than just VDB coverage checks. Errors in FAS data or other issues related to flyability are easily seen during flight inspection / validation.

(B) Good import functionality of FAS data to the flight inspection system facility database increase the integrity.

(C) VDB coverage checks require calibrated antennas and sensors to achieve required accuracy.

(D) GBAS Guidance is important for the pilot to perform procedure validation and flyability check.

(E) Flying GBAS procedures with high accuracy reference systems is recommended.

ACKNOWLEDGMENTS

The authors would like to thank the Brazilian Flight Inspection division, GEIV for their support of data and the continued partnership.

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[2] ICAO, 2007, Doc 8071, Manual on Testing Radio Navigation Aids, Volume II – Testing of Satellite Based Radio Navigation Systems.

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IFIS 2014

Flight Plan to Innovation

Session 8

SBAS RFI and Related Concepts

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Mitigation of an RF interference on GNSS signal observed during Flight Inspection

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ABSTRACT

According to the ICAO, assessment that no RFI occurs in the GNSS band is a mandatory verification that has to be done during a commissioning flight inspection of an RNAV procedure.

Through an actual example of an RFI detected thanks to the flight inspection aircraft during the commissioning of an LPV procedure, the proposed presentation will show the effect of the RFI on the guidance signal observed in real time onboard, the conclusions that were drawn after this flight on the operational use of the procedure and the technical means deployed in order to identify and mitigate the interference.

Thanks to this well documented example of a real case of RFI, it will be possible to present some solutions and guidelines that could be used in order to reduce the threat of RFI on GNSS procedures.

INTRODUCTION

For several years now, the commissioning of procedures based on RNAV navigation means, especially GNSS, has become common in many countries. These procedures are used in addition to or instead of legacy navaids based procedures.

Flight inspection is the only way to ensure the conformity of these procedures. However, this activity has changed significantly from the control of a technical means to the validation of a complete procedure. In this process, the evaluation of the accuracy of navigation means is no longer relevant because of the nature of these means. It is actually not possible to give any conclusion on the accuracy of a GNSS system given that this accuracy is only related to the satellite constellation at a given time. Thus, it remains necessary to check appropriate reception of the GNSS signal all along the procedure and, in case of failure, identify the reason causing the degradation of the navigation solution.

It is now well established in the aviation community that radio interference (RFI) is a potential cause of degradation of a GNSS means. Several specific cases of intentional or unintentional interference affecting air navigation have been reported in different countries and have contributed to the awareness of the phenomenon by different actors.

Since then, numerous discussions and studies have been conducted on the subject. Opinions are divided on the criticality of RFI phenomenon from the point of view of air navigation, ranging from " *RFI have no impact*" to " GNSS *should no longer be considered as navigation means used by civil aviation* !"This is not the point to discuss here the future strategy even though one might think that a position between these two extreme views is, for the moment, desirable. This is, in any case, the position adopted by DSNA (Direction des Services de la Navigation Aérienne), the French ANSP, which continues its deployment plan of GNSS procedures while developing its capacity to fight against interference.

As with conventional navaids, service providing flight inspection should be a major player in the fight against interferences. The use of aircraft dedicated to this task makes it possible to detect these events where they actually may be encountered by users, and carry the equipment needed for detection and identification.

ICAO, through its publications, highlights the need to perform this task in the most relevant way possible.

Annex X Attachment D §10 and the document 8071 Vol. II Chapter 1 Appendix 3 provide elements allowing a better understanding of the activity that requires good knowledge of the problems encountered and an adapted equipment.

GNSS BAND INTERFERENCE

Frequencies that are concerned, at this time and for the civilian sector, are mainly limited to the L1 band, namely the frequency 1575.42MHz with a band of ± 20MHz. The introduction of new constellations (Galileo among others) will extend the frequency domain to EHF (Extremely High Frequency) bands dedicated to GNSS i.e. 1176.45 MHz (L5), 1227.60 MHz (L2), 1381.05 MHz (L3).

Civil aviation has always been confronted with RFI in most of its assigned frequency bands. The distinctive feature of the GNSS band is that civil aviation is not the only user of the systems in this band. GNSS positioning is used by a wide variety of users for various needs. For this reason, the interest of intentionally interfering with these systems is multiplied and no longer only targeting aviation. That said, the fact remains that many sources of interference are unintentional and result from dysfunction of various materials.

We thus find several categories:

- RFI due to technical faults : Faults affecting TV equipment are a good example and may be frequently encountered.
- RFI due to illegal use of the frequency band normally reserved for GNSS. Here we find equipment operating without authorization in L band, however, their purpose is not to interfere with navigation systems.
- RFI due to malicious use. This category includes equipment that are designed to intentionally jam GNSS (or spoof the receiver in the worst case).

The effect on the navigation solution is variable, ranging from a total loss of navigation means to zero impact.

- Total loss of the solution. The GNSS receiver is no longer able to calculate a position since it can no longer receive the satellites signals.
- Performance degradation. The GNSS receiver continues to provide position but its operation is degraded; the number of satellites received decreases while the signal to noise ratios are degraded.
- No impact. A signal other than the legitimate signal is present in the received band but does not disturb the operation of the receiver.

Obviously, the impact of the same interference can evolve from one to another of these categories in function of the time of the day, the geographical position of the receiver relative to the source, the receiver robustness to interference and the satellite constellation at a given time (DOP).

Spoofing is a separate phenomenon, necessarily intentional, whose impact is obviously critical since the goal is to distort the position provided by the receiver without the user's knowledge.

DSNA POINT OF VIEW AND METHODS

DSNA is pursuing a proactive policy of deployment of GNSS based procedures with stated objective to eventually equip all IFR airports with at least one LNAV, LNAV/VNAV or LPV procedure by 2016 (as targeted by 36th ICAO assembly).

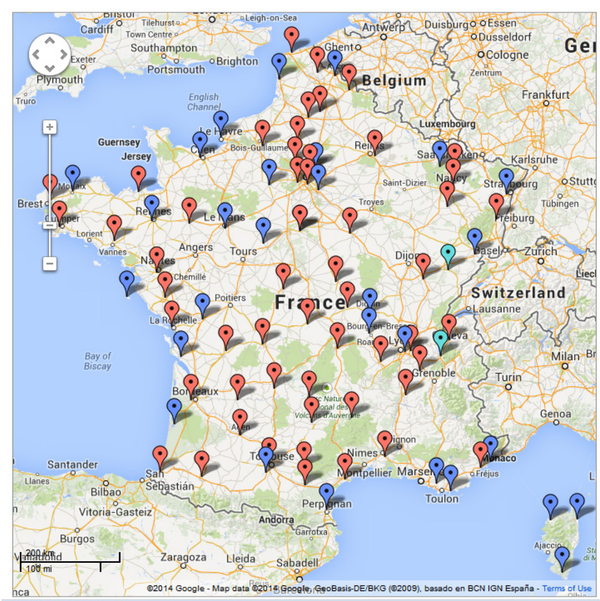

Figure 1 : Flight inspected RNAV(GNSS) Procedures on French mainland territory (As of 01/March/2014)
(Red : LNAV+LPV, Blue : LNAV only, Clear Blue : Trials)

Flight Inspection role

DSNA Flight Inspection Service (DTI/CNS/CEV) has an essential role in this policy by intervening before any publication or modification of a PBN approach procedure.

Its tasks are multiple: checking the consistency of data to be published, the draft chart, and validation of the procedure in flight. Verification of non-interference in the L1 band is systematic and made mandatory by the French reference document based on ICAO recommendations describing this activity.

RFI Aspects

Looking for RFI in the GNSS band is not necessarily an easy task if you want to do it effectively. The selected equipment must achieve noise levels low enough to allow detection of any potentially interfering signal to the GNSS signal received on the ground at about -130dBm. The noise floor of the measurement system must be of the same order.

DSNA FI Service, based on the experience gained in the VHF area, where research of interference is, since long ago, a recurring activity (refer to previous articles on this subject), has developed improved detection means in L band. Each flight inspection aircraft is equipped with a high performance receiver measurement associated with low noise preamplified antennas.

AiRFIndeR© software allows the operation of the equipment and data processing.

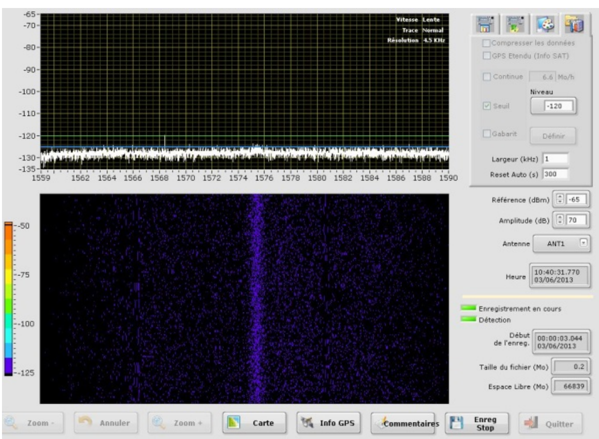

Figure 2 : L1 band analysis with AiRFIndeR©

Those devices and software allow real-time analysis with a scanning speed high enough to be compatible with use on board the aircraft in flight.

RFI detected in GNSS Band

During different RNAV procedures flight inspections, some cases of interference have been met:

Loss of GPS Position (Navigation Solution) on a large area has been reported by users on SID/STAR RNAV trajectories near Nice Côte d' Azur airport (LFMN). The use of a flight inspection aircraft helped identify and locate an RFI caused by an illegal TV transmission in a private house. It took 2 weeks between the first complaint and the stop of the transmission (especially because of the constraints related to international coordination)

RFI causing a degradation of performance of GNSS receivers (without total loss of solution) has been identified and localized during an LNAV commissioning flight inspection at Nimes Garons (LFTW). This RFI was caused by a malfunction of a TV transmitter. The case has been solved in a few days.

Two interference without impact on the operation of the airborne receivers have been identified and located during LPV commissioning flight inspections in Colmar Houssen (LFGA) and Le Castellet (LFMQ). In both cases, interference was due to malfunction of a receiving TV amplifier. Those cases have been solved in less than a week, thanks to coordinated actions of both civil aviation and spectrum management agency.

Finally, an RFI has been observed during the commissioning of two LPV procedures at Chateauroux Déols (LFLX) in 2012.

CHATEAUROUX DEOLS (LFLX) EXAMPLE

Presentation

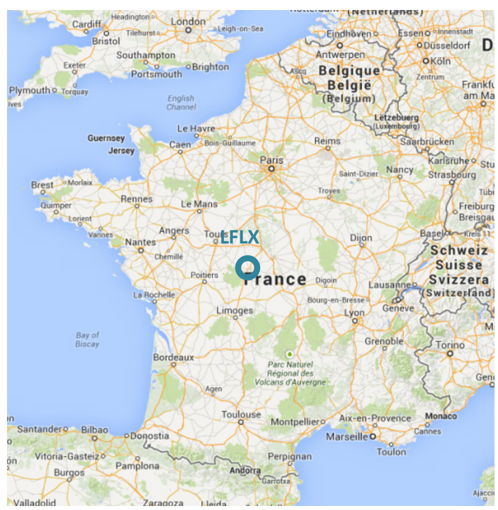

Figure 3 : LFLX Situation

At the end of 2012 it was planned to equip this regional airport with two LPV procedures in addition to the existing Cat I ILS procedure.

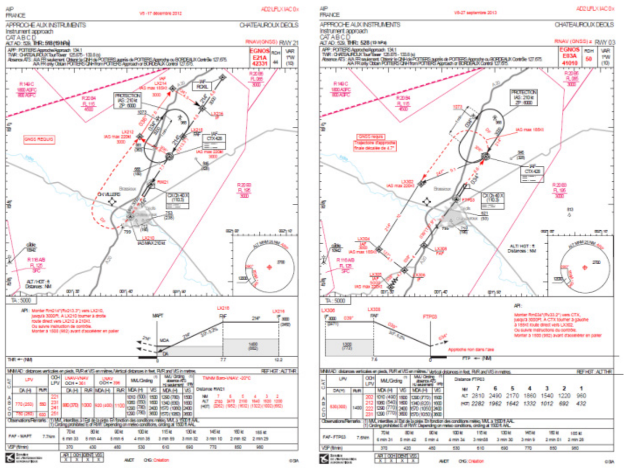

Figure 4 : LFLX RNAV Draft Charts

After the usual checks (FAS Data Block, Consistency of WP and path/terminators, etc. ...) flight inspection was undertaken in December 2012.

Flight Inspection

During the inspection, the CARNAC30© flight inspection software showed a complete loss of GNSS tracking by the Ashtech GG24 GNSS receiver. The loss was also seen by the crew on the receivers (Rockwell Collins GPS4000a) of the aircraft. At the same time, spectral analysis of the L1 band showed a spurious signal overlapping the GPS signal (see Figure 5). Loss of tracking due to this interference was observed over a distance of 2Nm along the first segment of the missed approach procedure on runway 21. The tracking was recovered when the signal disappeared.

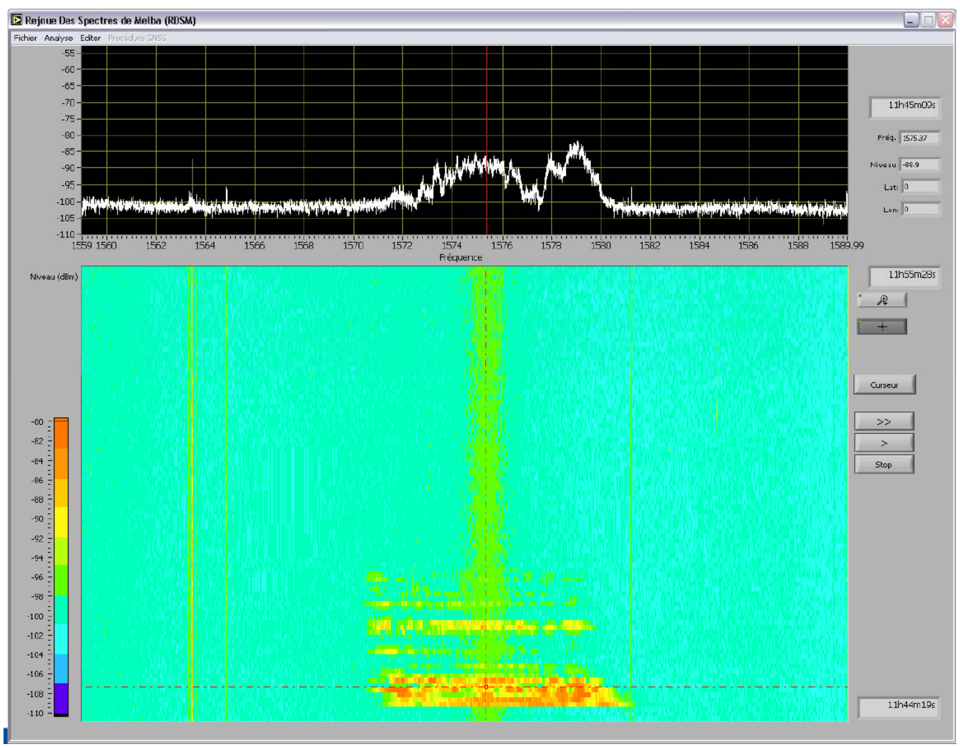

Figure 5 : Screen capture of the RFI software during the event

During the rest of the flight, the interfering signal was again seen but at much lower levels due to the increased distance of the plane from the zone of influence.

At the end of the inspection, a complementary detection flight failed to find the signal that caused the dead reckoning on the receivers.

Figure 6 clearly shows the sharp decrease in the number of satellites received and the raise of a receiver RAIM flag (red part of the curve). The gradual return of the acquisition of satellites back to normal after the disappearance of the source or the increasing distance between the plane and the source can also be seen.

Finally Figure 7 shows the geographical area in which the interference was seen with loss of the GNSS solution. The color of the path is the S/N ratio for a given satellite. We see that this ratio fells sharply below 30dB/Hz and that the position was maintained for a few moments before complete loss (aka ‘dead reckoning’).

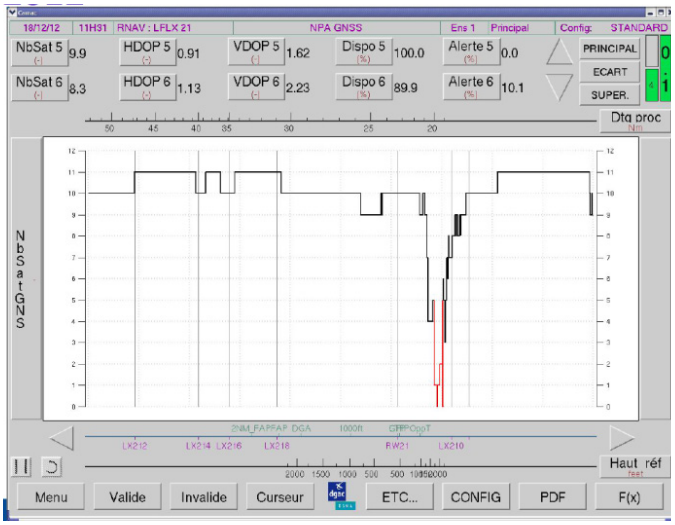

Figure 6 : Loss of GNSS tracking as seen on the Carnac30© Flight inspection system

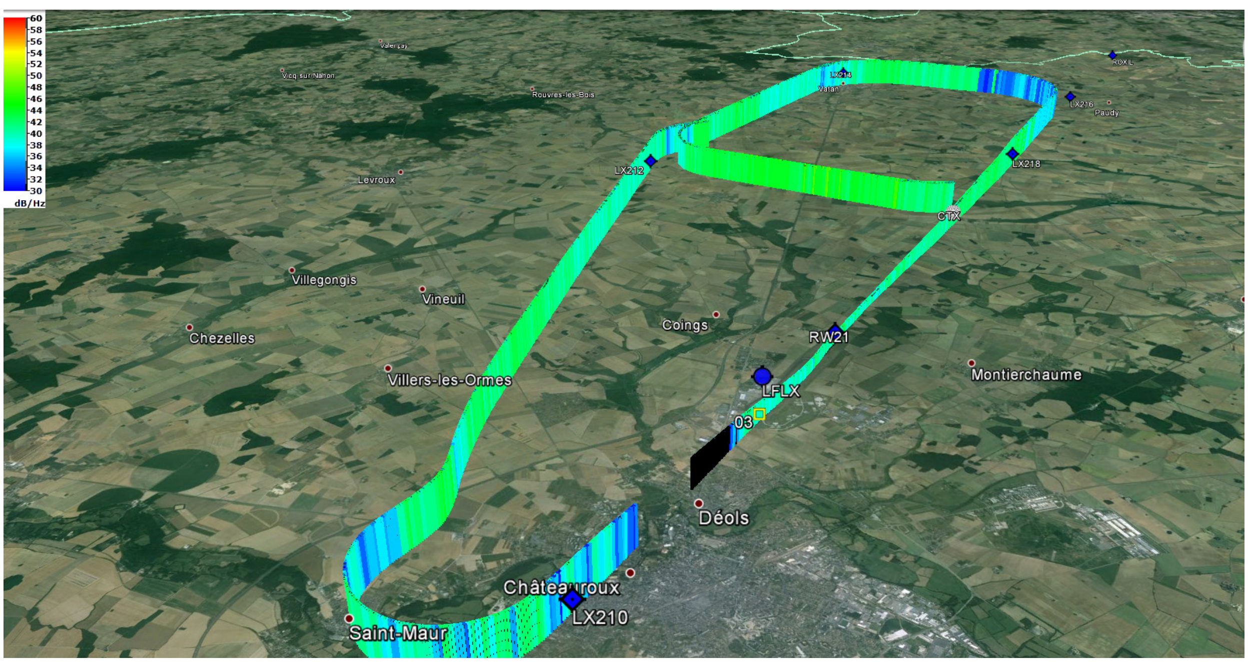

Figure 7 : View of the actual trajectory followed during LPV RWY21 inspection

Actions taken after the flight inspection

The spectrum observed during the flight is fairly typical, about 10 MHz wide and centered on 1575.42MHz. This kind of spectrum looks similar to the one radiated by PPD (Personal Privacy Device) equipment used to deliberately jam the GPS, GPRS, GSM and UMTS signals. These jammers, although banned for marketing and use in France, are quite widespread and used, particularly by professional drivers who use them to block the tracking systems used by transport companies to monitor their fleet of vehicles. They are also found in theaters, in prisons or exam rooms. These systems are very diverse in terms of power, shape and targeted frequencies. However the principle of generation of signals is frequently the same and generally consists of a fast frequency sweep in a saw-tooth law (often called 'linear chirp').

Figure 8 : GPS Jammers

The spectrum observed on one of these devices is given for comparison in Figure 9.

Figure 9 : GPS Handheld jammer spectrum

After this flight, Flight Inspection entity issued a negative conclusion on the procedure FI report due to the presence of intermittent interference causing loss of GNSS tracking. The interference case was further processed through the DSNA Interference Management Process which leads to the deposal of a complaint to the spectrum management agency (the ANFr Agence Nationale des Fréquences). A technical team of the agency visited the site twice without being able to identify any signal that may be similar to the one observed on board.

In addition, the maintenance staff of the airport was, at this moment, only equipped for RFI detection in the VHF band.

It was therefore decided to quickly design an autonomous 24/7 ground monitoring equipment of the L1 band and to deploy it on the top of the control tower of Châteauroux.

This site was chosen mainly because of the possibility to easily get a power supply, because it was secure and because it was the best location to have an increased radio-horizon

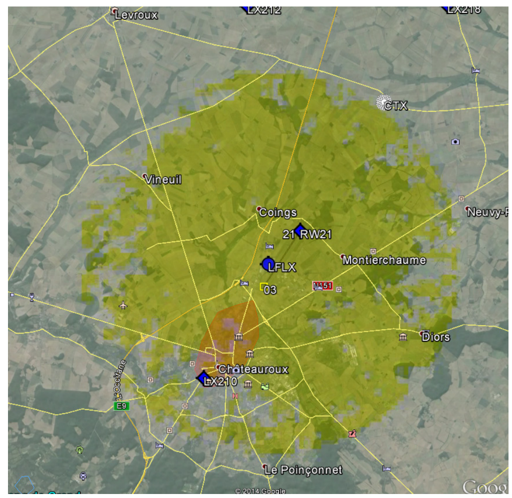

Figure 10 : Simulated radio-horizon of the ground system installed at Chateauroux Airport (Yellow), Dead reckoning area (Red)

This equipment (called later "PANDORE" Portable ANalyzer for Detection of Rfi Events) was intended to check if the signal seen in the flight inspection aircraft was also received on the ground and if so, with which recurrence. (see Figure 11 and Figure 12)

Figure 11 : Pandore system deployed at Paris Orly Airport (for further testing)

This equipment has been assembled from elements available and already used by the flight inspection service. Especially the same Airfinder© software that is used on board in real time, also allows to record events exceeding a given threshold. It was therefore installed in the laptop included in the detection beacon.

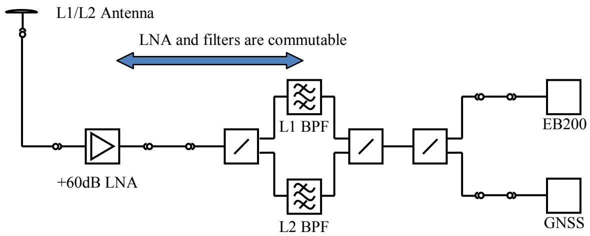

Figure 12 : Pandore system RF Architecture

The system was deployed for a month. The results revealed that the interference happened again several times during the observation period.

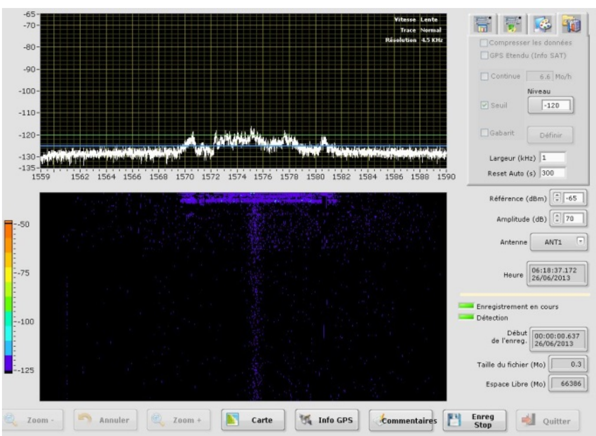

Figure 13 : RFI observed on top of LFLX TWR.

It has been established that a similar interference to what was observed onboard was repeated for about 4 hours (cumulative time) during a period of one month. Figure 14 shows for example the events identified during a single day the 6/26/2013.

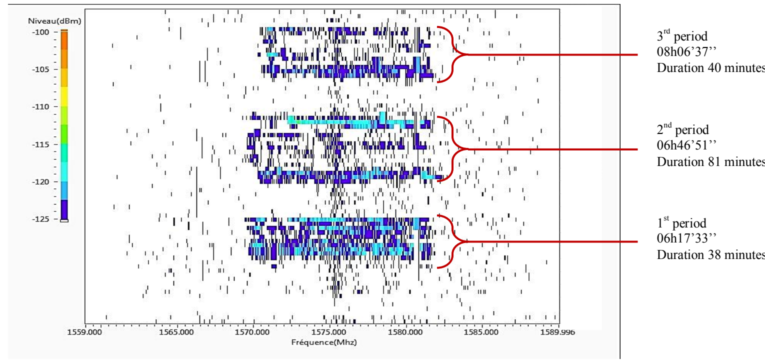

Figure 14 : RFI detection during the 06/26/13

This equipment has confirmed that the interference was indeed present regularly and could create the same problems as those encountered during the RNAV procedure flight validation. However it has also shown its relatively low recurrence.

Note also that these records do not say with certainty that this is the same interference that was causing the loss of signal onboard and the different detections on the ground. However, the observed spectra are sufficiently similar to assume that the signals encountered would have the same effects onboard GNSS receiver.

Procedure publication

Taking into account the flight inspection report and the findings of ground recordings, the regulation authority of the French Civil Aviation (DSAC Direction de la Sécurité de l'Aviation Civile) finally decided to authorize the publication of RNAV RWY21 of LFLX (procedures RWY03 were postponed for environmental reasons).

However, some provisional measures have been set up to mitigate the impact of this GNSS interference on safety.

- The DH (Decision Height) of LPV and LNAV/VNAV RWY21 has been increased from 250ft to 400ft.
- A NOTAM has been issued notifying this change in minima and the risk of RFI :

LFLX CHATEAUROUX DEOLS
B0138/14 - INSTRUMENTS APP CHART AD2 LFLX IAC 03, RNAV (GNSS) RWY 21 :
MINIMA PROCEDURES LPV AND LNAV/VNAV CHANGED :
DA(H)=920(400) RVR=1100
GNSS JAMING POSSIBLE. IN CASE OF LOSS OF RNAV/GNSS GUIDANCE SYSTEM,
USE THE EXTRACTION PROCEDURE DEFINED BY ACFT OPERATING AGENCIES. 06 FEB 00:00
2014 UNTIL PERM. CREATED: 13 JAN 14:10 201414:10 2014

This is reflected on the final chart by a specific insert.

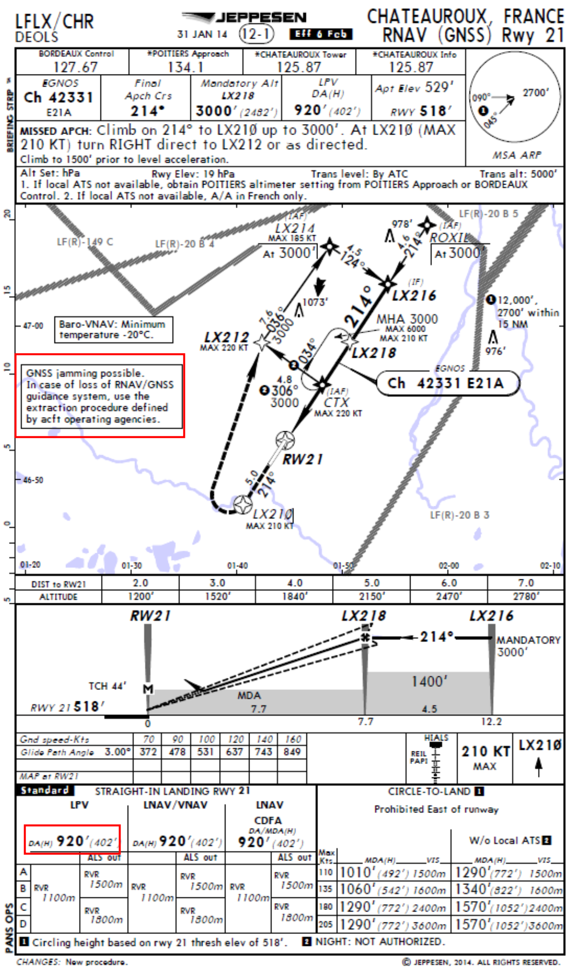

Figure 15 : LFLX RNAV Procedure RWY21

These measures are, of course, temporary and investigations continue in order to identify and stop the interference. The deployment of a specially equipped vehicle with direction finding capabilities is planned in the coming months. The Pandore system after several improvements (including a GNSS receiver and a more efficient antenna) will be re-installed and will send e-mail alerts in case of detection directly to the local technical team which has now been equipped with specific resources to perform RFI detection in the L-band.

CONCLUSIONS

The example of Châteauroux is currently the only case of a temporary interference detected in commissioning flight caused by a PPD in France. It shows how difficult it is to understand and deal with these phenomena. If continuous or intermittent interference with high recurrence are relatively easy to deal with, it is clearly not the same with this type of RFI. Several lessons can be learned from this example.

From a regulatory perspective, it is necessary to ensure that the rules are unambiguous and provide a legal tool on which to rely. The French regulation has been adapted in this direction, a few years ago, especially thanks to the intervention of civil aviation.

Below is the text as it appears in the French code of Posts and Telecommunications

> L33 – 3 -1 I. Importing, advertising, selling or free donating, commercializing, installing, owning and using devices aiming at interfering and stopping the use of electronic communication devices of any kind, in transmission or reception mode, is prohibited
>
> II. By derogation to paragraph I., these activities are authorized when needed by the forces in charge of maintaining law and order, defense and national security, or justice public service.

Nevertheless, although necessary, it is insufficient.

Regarding flight inspection, it is very important to be properly equipped with appropriate means to fight against interference, particularly in the GNSS band. In the majority of cases, the spectrum regulation agencies do not have the appropriate tools to deal with interference affecting aviation and it is the responsibility of flight inspection services to provide technical elements to understand and handle the phenomena on the ground. The equipment used, in particular the receiver and the antenna, must be carefully selected and adapted to the frequency bands and field strength levels that are to be reached.

Besides airborne assets, it is possible and desirable to enhance the detection means on the ground, at least to quantify interference that may affect users. In this context, DSNA has chosen to further develop the 24/7 detection system prototype presented here. It will be reproduced in some copies that could be installed on different airports if the need arises or in different places around the same area to facilitate the location of an RFI.

Information to the user is also critical and must be taken into account in the publications even if the drawback is to frighten users of GNSS approaches. The example of Châteauroux raised many questions about what to do for the publication of a procedure under these conditions of interference at low recurrence. Possibilities were ranging from outright cancellation of the proposed RNAV procedure to a publication regardless of the observation of a temporary interference. Although the choice in this case, to publish under NOTAM restriction can be discussed, it remains that this case should be considered and clear guidelines should be issued for the different actors.

GNSS RFI Detection in Switzerland Based on Helicopter Recording Random Flights

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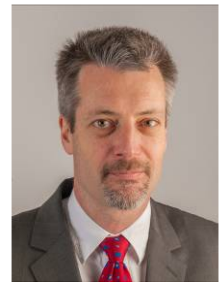

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ABSTRACT

In the framework of establishing Performance Based Navigation (PBN) in Switzerland a number of special issues have been identified. In conjunction with the implementation of Global Navigation Satellite System (GNSS) based rotary wing approaches, departures and low flight routes, special interest is on the probability of an aerial vehicle being affected by GNSS Radio Frequency Interference (RFI).

A project called Helicopter Recording Random Flights (HRRF) was launched, which objective is to install quick access recorders on board of three dozen helicopters operated by the Rega, the main Swiss Helicopter Emergency and Medical Service (HEMS), and the Swiss Air Force. Global Positioning System (GPS), Flight Management System (FMS) and Attitude and Heading Reference System (AHRS) data of every flight are recorded during a period of three years and under daily operation conditions. By this way large parts of Switzerland will be randomly covered. Common to all of these helicopter operations are low flight altitudes. Therefore it is expected, that the probability of them being exposed to RFI of GPS signal is higher than for fixed wing vehicles. Any exposure of this kind can be detected through the recorded GPS carrier to noise (CNo) measurements or position losses. The additional recorded data supports more in depth analysis of this kind of occurences.

INTRODUCTION

In the near future Switzerland's air space will primarily be managed by applying the performance based navigation concept. Therefore, the Swiss-wide Implementation Programme for SESAR-oriented objectives (CHIPS) has been initiated in 2008. In the frame of CHIPS a number of applied research and development efforts are undertaken in order to solve specific problems related to the peculiarities of Swiss air space.

A major topic is potential RFI impacting GNSS receivers used as primary navigation source. Different research studies are currently being conducted in this frame. One of them is called Helicopter Recording Random Flights (HRRF). Quick access recorders are being installed on board of roughly three dozen helicopters operated by Rega, the main Swiss Helicopter Emergency and Medical Service (HEMS), and by the Swiss Air Force. The objectives of this study are manifold: RFI detection, assessment of GNSS performance within a topographic challenging environment [1], assessing the potential of narrowed Required Navigation Performance (RNP) values and the quality of GPS performance and Receiver Autonomous Integrity Monitoring (RAIM) prediction tools.

It is of major interest that a large number of parameters from the onboard GPS receiver used for navigation as well as helicopter attitude and FMS data are recorded. These data sets allow to identify possible GPS RFI.

Data will be recorded randomly for a period of 3 years at each flight of each equipped aerial vehicle under normal operations conditions. Since most flights are carried out under Visual Meteorological Conditions (VMC) and have different missions, it is expected, that the lower part of the Swiss airspace will be randomly sampled.

This paper presents a model for RFI detection based on CNo and aerial vehicle attitude measurements.

TECHNICAL SOLUTION

The entire fleet of helicopters equipped with recording units consists of 11 AW109SP and 6 EC-145 operated by Rega, and 18 EC-635 (figure 1) operated by the Swiss Air Force. Due to the planned period of three years of data collection it was decided to have fixed installations. Figure 1 shows one of the Swiss Air Force's EC-635.

Figure 1. EC-635 of the Swiss Air Force (© VBS).

Installation

The technical solution is a mini Quick Access Recorder (mQAR) connected to the vehicle's ARINC bus, respectively RS-232 interface, depending on the architecture. The mQAR is a small size and small weight unit. Figure 2 depicts an installed mQAR.

As soon as the helicopter is powered up, the mQAR automatically starts recording the available data until the power is cut. Therefore no interaction by the pilot or ground crew is necessary.

Storage medium is a SD (Secure Digital) memory card which during normal operations can record several weeks of flight data. Ground crews at each helicopter base are instructed to download the recorded data periodically every 2 to 4 weeks and upload it to a common data storage.

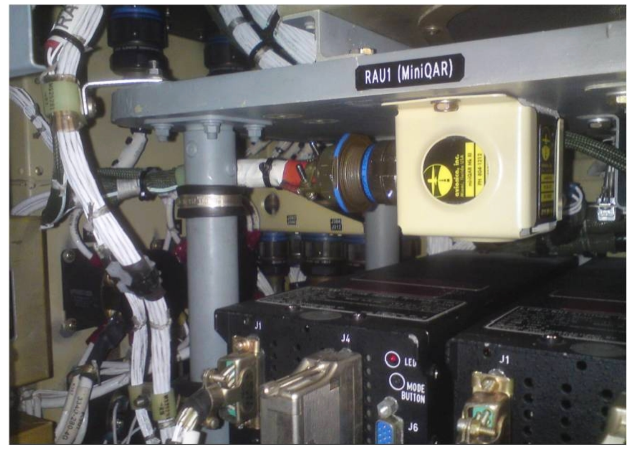

Figure 2. Installed mQAR, the gray Box on the Right Side of the Image.

Recorded Data

A large amount of data is available onboard. Basically, data from the three sensors GPS, AHRS and FMS are recorded on the EC-145/635 and GPS, FMS on the AW109SP.

GPS data on EC145/635 consist on GPS position, satellite vehicle position, pseudo range and pseudo range rate, horizontal and vertical integrity limits and figure of merits, carrier to noise ratio and different status parameters. Position domain data only is available on the AW109SP. AHRS data consist on roll, pitch and heading information. Finally the flight plan as well as the selected waypoints are available from the FMS. Sampling interval on GPS and AHRS is 1Hz.

RFI DETECTION

The main parameter used for GNSS RFI detection is the CNo of each tracked satellite. Any RFI would negatively affect all CNo.

RFI on a Static GPS Receiver

Assessing the CNo of each tracked satellite could give an indication on a possible RFI. Such an occurrence would decrease the CNo by a constant value at each single epoch because the entire GPS receiving antenna is affected by the same interference level. Figure 3 shows a real interference measured by a static GPS receiver. The interference appeared instantaneously and the CNo decreased by 5dB for all tracked satellites.

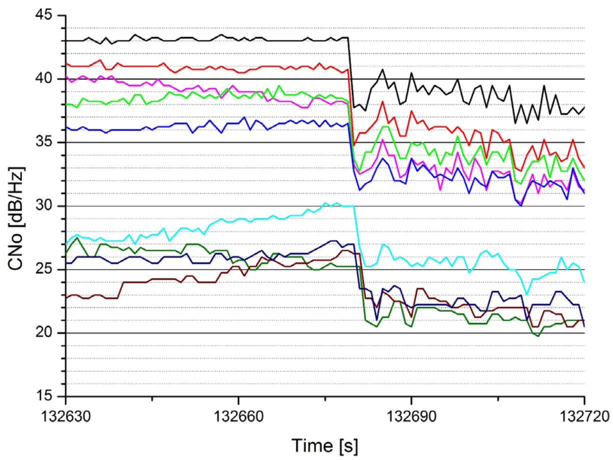

Figure 3. RFI on a Static GPS Receiver.

RFI Detection on a Dynamic GPS Receiver

RFI detection for a GPS receiver under dynamic conditions can be treated analogously, but two difficulties have to be taken into account. First a moving vehicle that approaches a RFI source would usually be gradually affected and the CNo would smoothly decrease in contrast to the example shown in figure 3. Second the positions of the satellites referred to the antenna have an impact on the CNo. Changes of attitude of vehicle affects the CNo values as shown as an example in figure 4.

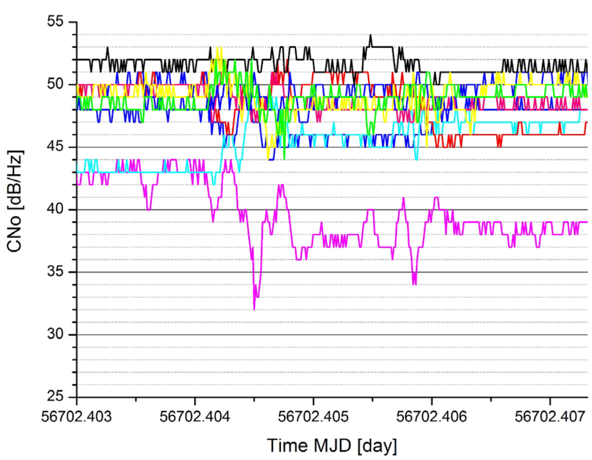

Figure 4. Helicopter Maneuver Affecting GPS Satellite's CNo.

The CNo alteration at the time of 56702.404, given in days within MJD (Modified Julian Date) calendar, cannot be attributed to a RFI as some satellites are negatively and some positively affected. The observed values of roll and pitch angles indicate that a maneuver has taken place at this moment (figure 5).

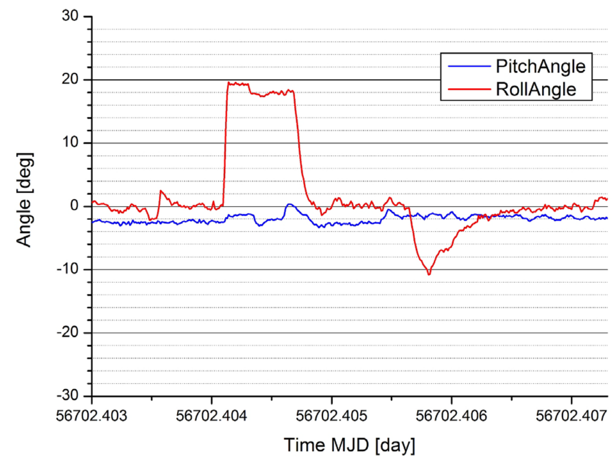

Figure 5. Pitch and Roll Angles Affecting the CNo Shown in Figure 4.

Following reasons apart from RFI might have an impact on the CNo measurements:

1. signal fading caused by multipath from environment outside the airframe
2. signal fading caused by multipath at the airframe
3. signal attenuation caused by the air frame (shadowing)
4. antenna gain pattern
5. variations in attenuation of cabling and gain of amplifiers (antenna and receiver)
6. troposphere
7. ionosphere

Reason 1 can be brought under control by limiting the measurements, where the helicopter has a minimum velocity over ground. By doing that it can be avoided that the geometry between satellite, reflector and GPS antenna remains constant over a longer period and therefore signal fading is very short and averaged.

Reasons 2 to 4 are always present and have to be taken into account. Common to these reasons is, that the signal attenuation depends mainly on the satellite position with respect to the local coordinate system of the antenna.

Reason 5 is neglected as these amplifications and losses are constant for all tracked satellites.

Reasons 6 and 7 are always present analogously to reasons 2 to 4, but are independent on the vehicle's attitude. In this case it is of interest to have an estimation on the signal attenuation due to troposphere and ionosphere. A major reason for the selection of the L-band for GNSS purposes is the low signal attenuation due to atmosphere. The tropospheric attenuation is far below 1dB for signal paths entirely within the troposphere [2], [3]. It is even lower for space-earth signal paths. The ionospheric attenuation is assumed to be negligible [4]. Particular care should be taken under ionospheric scintillation conditions, where the attenuation can be increased at levels over 20dB [5], [6]. Ionospheric scintillation is maximum near the geomagnetic equator and smallest in the mid-latitude regions [5]. Despite the location of Switzerland at mid-latitudes it is advantageous to avoid RFI detection recordings during ionospheric scintillation activities.

Finally only causes 2 to 4 are relevant for RFI detection. These impacts on CNo can be derived empirically by determining the CNo of the tracked satellites referred to the antenna over a long period. Figure 6 shows a polar plot of the mean CNo for bins of the size of 5° by 5° measured during 8 hours of flight for one helicopter type.

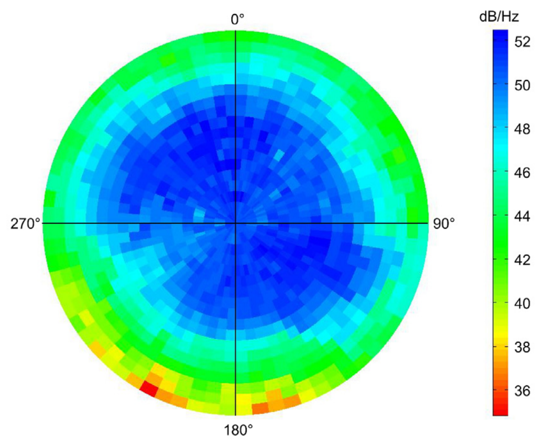

Figure 6. Polar Plot of Mean CNo Referred to the Antenna.

A CNo of roughly 50 dB/Hz is measured for satellites at the antenna zenith. The difference between this 50 dB/Hz and the measured CNo for satellites at other positions than the antenna zenith indicates the signal attenuation depending on the antenna azimuth and zenith distance. With the knowledge of these differences the measured CNo can be compensated to a nominal value of 50dB/Hz. Figures 7 and 8 show the effect of this compensation. The measured CNo are shown in figure 7 where the compensated CNo are represented in figure 8 (red lines).

A simple indicator for RFI is the mean value of the compensated CNo, which is represented as blue line in figure 8. This mean value is 50 dB/Hz with small noise. Because a RFI affects the CNo of every satellite signal by the same level, the mean value of the compensated CNo is affected by the same level too. Therefore a RFI reducing the CNo by only a few dB can be detected with this model.

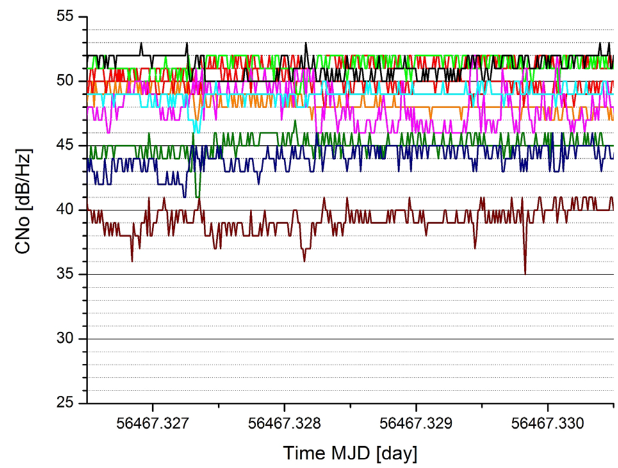

Figure 7. Measured CNo.

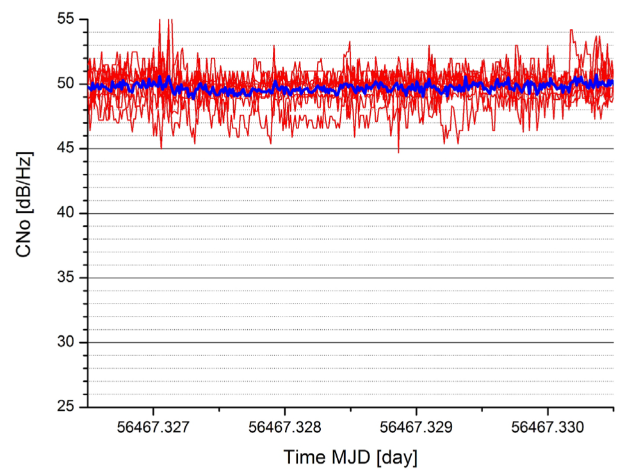

Figure 8. Compensated CNo (Red Lines) and Mean of Compensated CNo (Blue Line).

CONCLUSIONS

A model has been developed, which enables to detect potential RFI based on measurements of CNo and aerial vehicle attitude. CNo attenuation due to the antenna pattern and antenna environment is taken into account. RFI affecting the CNo by only a few dB can be detected with this model.

FUTURE WORK

Improvement of this RFI detection model can be achieved by refining the antenna CNo attenuation pattern. This is done by assessing a larger amount of data recorded on flight. Further it is expected that additional recorded parameters are also affected under RFI conditions. Taking these parameters into account will reduce the probabilities of missed and false RFI detection.

ACKNOWLEDGMENTS

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Session 9
Safety Concepts

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Common Standards in Flight Inspection Operations – The Way Ahead to Improve Safety?

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ABSTRACT

The following paper continues from the paper and presentation given on the last IFIS 2012 in Braunschweig by the same author, which covered flight safety on flight inspection missions, and ways to mitigate risks associated with flying these particular types of missions. The new paper represents the status of discussions the Operational Working Group within ICASC reached on this topic to this day.

After briefly re-visiting the specific risks involved in flying flight inspection missions, the paper continues with giving a detailed insight into a proposed structure of a flight operation dealing with flight inspection / flight validation. Aspects like the operational environment or set-up of the flight department, safety and risk mitigation strategies, equipment and training will be covered.

Although some topics are dealt with rather in detail – like Operation Manuals, Standard Operating Procedures (SOPs), Check Lists and Crew Coordination Concepts – the author is trying to strike a fine balance between over-regulating and laissez-faire, knowing very well from experience that a one-size-fits-all-approach simply does not work in the flight inspection industry.

In closing, the paper continues the discussion towards a common ground in flight inspection operations, by trying to establish a minimum standard for a flight inspection / flight validation department.

INTRODUCTION

Flight Inspection and Flight Validation represents a rather demanding operational environment in aviation. Its very nature translates into a certain amount of risk elements – which are covered in a following chapter - , that have to be identified, addressed and subsequently mitigated in order to achieve a safe and reliable flight operation.

The tools to mitigate these risks are wide and varied. This paper tries to identify these tools, concentrating on the organizational set-up and environment of a flight inspection entity. In each chapter, recommendations are given how to address certain aspects. The idea is to arrive at a common set of tools that might be useful in achieving the goal of a safe flight inspection flight operation. But prior to start the discussion on this tool-set, let us have a look at the flight inspection-specific risk elements again:

FLIGHT INSPECTION-RELATED RISKS REVISITED

International accident data show that a combined 56,6% of all accidents in aviation happen either on take-off, approach or landing - the very segments of the flight envelope the flight inspection community spends between 70 to 80% of all their flight time. [5]

Further challenges we encounter in our flight inspection / flight validation work:

- We have to fly low, sometimes very low.
- We fly in densely populated airspace, seeing and avoiding other traffic is absolutely paramount.
- We fly demanding missions with at times high crew workload, necessitating to liaise with ATC, ground engineers and the NavAid Inspector on board simultaneously.

- We might find ourselves in operationally harsh environments, both with regard to climate / weather, as well as infrastructure, ATC, etc.
- On commissioning flight checks, unknown terrain and obstacle data might pose a challenge.
- Working internationally, language barriers might hamper communications, both on the ground as in the air.
- Flying demanding missions, maybe on deployment for several days or even weeks in a row, ever poses the danger of crew fatigue.
- Regardless of working either for a government or for a private service provider, we most of the time face a certain commercial pressure, as flight inspection does tend to interrupt the usual routine at any airport, which might cause delays to (and in turn: generates pressure from) the airlines.
- To keep the aircraft being used for flight inspection and their respective systems technically up to date with current requirements at times poses a challenge, again in the light of ever present commercial pressure.

All these bullet points mentioned above form the mission related factors that govern the risk of our work. To put all this a bit more into perspective, let us re-visited a more generic risk model as described in the last paper of the IFIS 2012:

According to the standards of risk research, all aviation accidents fall under the category of the so-called low probability / high consequence events (lp/hc), were "The lp/hc problem domains are inherently ill-structured, multi-layered, and characterized by consequences with low likelihoods, high severities and numerous, pervasive uncertainties. Decision making is typically complex, multitiered and non-transparent with conflicting objectives and multiple perspectives" (Clement 1996) [1]

Translated into a much more simplified formula, it might be fair to say that risk is the product of probability multiplied by severity

$$\mathbf{R_{isk} = P_{robability} * S_{everity}}$$

To further refine our formula above we might break down probability into number of (flight) events multiplied by interfering factors – and these are all the things that might go wrong, like weather, ATC, crew performance, technical issues with airframe and systems, operational environment and circumstances, etc.

$$\mathbf{R_{isk} = P_{robability} * S_{everity}}$$

with $\mathbf{P = (E_{vents} * I_{nterfering}\ F_{actors})}$,

= $\mathbf{R_{isk} = (E * IF) * S}$

We can further break down the Interfering Factors into being mission-specific – all the bullet points above, which we can only influence to a certain degree – and operational aspects: how we set-up up our flight operation in terms of training, aircraft, equipment, operating guidelines, etc.:

with $\mathbf{IF = (M_{ission}\ s_{pecific} * O_{perational})}$

= $\mathbf{R = (E * (MS * O)) * S}$

= $\mathbf{R_{isk} = P_{robability} * S_{everity}}$

$$\mathbf{(E_{vents} * I_{nterfering}\ F_{actors})}$$

$$\mathbf{(M_{ission}\ s_{pecific} * O_{perational})}$$

In the light of this formula, it is quite obvious that the flight inspection community has to focus on the operational aspects (**O**) of our working environment, as this is the part of the equation we can directly influence; the other factors like Events (= number of flights) are dictated by the required flight inspection intervals and the Mission Specific factors are governed by the very nature of our mission profile.

How to address these operational aspects is dealt with in the following chapters.

OPERATIONAL SET-UP: GENERAL

Flight Inspection / Flight Validation organizations come in wide array of forms and shapes: they can be organized as a government body or come as a private enterprise. They might be a big organization with dozens of aircraft and hundreds of employees, or being a very small operator with just one aircraft and a handful of staff.

The regulatory oversight imposed on them might be fairly strict, or might be rather relaxed: in most countries, aerial work – under which domain flight inspection will fall – is governed by appropriate government rules and regulations, dealing specifically with the requirements of this specific activity in aviation.

Other countries do not have such a dedicated regulatory framework. Interesting enough, Germany is such a country, where aerial work is not subject to specific regulation.

Most customers, on the other hand, today require their flight inspection service provider to be subject to some form of regulatory oversight and to have an appropriate Air Operator Certificate (AOC).

With flight inspection organizations coming in all forms and shapes, flying a wide variety of flight inspection missions, it is quite obvious that a one-size-fit-all-approach simply will not work. Each organization is called upon to come up with a set-up and organizational framework that bests fits its individual work environment and requirements. In the interest of safety, and on top, a common standard in the flight inspection community, it is recommended, though, that whatever the organizational framework, whatever the size of any flight inspection organization, to give some consideration to some elemental requirements for a safe operation of the entity:

- A clearly defined mission profile:

  What kind of missions are expected to be flown? Where? With what kind of equipment?

- A clearly defined organizational set-up of the entity that reflects the mission profile above and clearly defines interfaces within the entity:

  Who is responsible for doing what within the organization, requiring what training, reporting to whom?

- A clearly defined set of rules, procedures and best practices, laid down in an appropriate set of company documents (best maybe combined in a single document like an Operation Manual (OM)):

  Who is doing what and when with what

Elements of this organizational set-up will be described more in detail in the following chapters. Prior embarking on that endeavor, though, some words on an underlying principle that should be part of the organization's philosophy: Keep it simple and stupid (KISS) ! It is very tempting to try and govern and cover every little detail of the organization: The result might be arriving at 400 procedures with 1200 related documents – the sheer volume of the work to maintain and support that level of governance will put even big organizations to the limit, and even more important: it will overwhelm the front-end crews, resulting in the end in a unsatisfactory performance in terms of quality and safety. It should be remembered that the final product of flight inspection is generated by a flight crew (cockpit and cabin), flying an already demanding mission. All aspects of internal governance and it related documents must therefore reflect that fact and thus be kept concise, clear and reduced to the maximum.

<u>Safety Philosophy / Safety Management System (SMS)</u>

Safety, as per ICAO, is defined as

"…the state in which the risk of harm to persons or of property damage is reduced to, and maintained at or below, an acceptable level through a continuing process of hazard identification and risk management"

ICAO Doc 9859, 1-1[3]

To arrive at that point, each flight inspection entity should define its own safety philosophy, identifying risks of its individual operation and strategies to mitigate them.

The ICAO Doc 9859 Safety Management Manual gives a very good oversight on the topic and provides valuable tools and procedures how to arrive at a safety philosophy, and how to implement it in one's own flight organization.

The Safety Management System (SMS) is the formalized approach of an organization on how to implement its safety philosophy, by describing risk identification methods and tools, risk communication and mitigation strategies, clearly defining lines of responsibilities and accountability.

As safety is a very complex topic, and Doc 9859 alone covers 290 pages, the reader is referred to that document for details. A number of topics shall be addressed in this paper, though, in more detail:

An essential part of any safety philosophy and its ensuing safety management system is the clear and unambiguous commitment of all stakeholders within the organization to safety. That always has to be a top-down-commitment: management of the organization has to encompass and support the safety concept of the organization with uncompromised rigor, otherwise it will ultimately fail. This commitment is easier said than done, as safety, more often than not, has cost implications – these cost implications notwithstanding, safety has to be communicated and lived up to! as the number one priority of any entity's leadership.

As part of the SMS, it is recommended to implement a **Reporting System**, allowing each member of the organization to give feedback on any issues that might be safety-related. Again, in the light of keeping the organization lucid, and depending on the size of the organization in question, a reporting system does not necessarily have to be formalized with sophisticated forms and lines of communication, some form of feedback should be established, though (i.e. in the shape of regular safety meetings, simple emails, etc.). That form of communication should, in any case, be encouraged by management.

An integral and essential part of any reporting system is the implementation of a so-called "**Just Culture**", which means that no repercussions or negative effects have to be expected by those individuals who report any issues, even when these issues have been caused by omission or error. Without this just culture, a viable form of feedback on safety issues cannot be established, and thus an important loop of communication on safety cannot be closed.

Finally, and again in line with the requirement of keeping organizational policies and documents light and lucid, it should be noted that a SMS does not necessarily have to be published as a stand-alone document; in an ideal world, the SMS is an integral part of the Operations Manual of the organization, thus keeping documents to be maintained, read and understood to a minimum. ICAO in Doc 9859 supports this approach.

Operating limits

An essential part of any safety philosophy should be the publication of Operating Limits applying to the individual organization.

Operating limits should cover all aspects of the flight operation, addressing topics like:

- Weather minima
- Minimum Equipment status and requirements
- Crew qualification, training and recurrency standards
- Flight and Rest Time Limitations (FTLs)
- Airport criteria
- Security aspects

These bullet points will be addressed to a certain extent in the chapters to follow. In general, though, operating criteria should be realistic in the light of the missions intended to be flown. Here, a balance between safety and operational requirements has to be struck: Minima with an excessively high threshold might enhance safety, but will limit the operation up to a point where providing a reliable service to the customer will be impossible.

Again, operating limits have to be accepted by all stakeholders from top down; raising minima and expecting the same productivity output, for instance, will not be a realistic prospect.

Therefore, operating limits should be set after careful study of the operational environment to be expected, equipment to be used and crew qualification considered. The limits have to be open, transparent, clearly communicated and no ambiguities must exist between the organization's ambitions and targets and its operating limits.

Again, for ease of operation and reference, the operating limits should be an integral part of the Operations Manual of the organization.

Equipment

One of the most important factors affecting safety on flight inspection / flight validation missions is the choice of the appropriate aircraft. Again, in the light of the wide variety of flight calibration missions and theatres of operation, there is no one-size-fits-all solution in picking the right aircraft. In general, the aircraft type should be able to fly the mission required without too many restrictions (i.e. fuel load, payload), in order not to pressure crews too much into accepting risks, just to get the mission done.

Under normal circumstances, the size of the equipment required to fulfill the role more or less dictates the size of the aircraft in use. With the advent of very small, low cost Flight Inspection Systems, using fairly small twin-engined piston aircraft became a viable option in the flight inspection world. A prominent example of this new breed is the Diamond DA42 Twinstar. Under defined circumstances (limited amount of flying required per year, moderate climate, moderate terrain, no high top speed required at busy airports) it is already clear that the combination of low cost FIS and low cost aircraft do work; it remains to be seen over the next years, though, how well this combination fares when pushed harder, both in terms of flying hours required and harsher external environments encountered.

With the advent of modern single-engine turboprops, like the Cessna Caravan, the Pilatus PC12 or the Socata TBM850, there are even projects envisioned to use these aircraft for flight inspection missions. It remains to be seen how the regulatory environment will react to this proposition; it would further be worthwhile to discuss within the community the use of single-engine aircraft for flight inspection work.

The flight inspection aircraft in use should be maintained and upgraded as best as possible to the current, mission-specific requirements.

Proper maintenance based on an appropriate maintenance program, by qualified staff, at the right intervals, is a must that goes without saying.

Providing a cockpit environment that offers a good support to achieve situational awareness is highly desirable. Today, this almost automatically translates into a glass cockpit with a suitable Flight Management System FMS, and moving map displays that goes with it.

Being able to depict the calibration mission (desired tracks, tracks to starting point of a run) as well in one way or the other to the cockpit crew is highly recommended as well , either by interfacing the Flight Inspection System FIS with the existing avionics (preferred option), or by providing an additional display.

It cannot be stressed enough that keeping situational awareness is absolutely paramount on flight inspection missions, any piece of equipment supporting that goal, therefor, is highly desirable.

When flying Procedure Validation missions, a FMS commensurate with the task is a must – the FMS must be capable of processing the ARINC424 formats used by the procedure designer / coder, for instance, and depicting them properly.

A Traffic Collision Avoiding System TCAS is a highly desirable piece of equipment to have on board, especially when flying in densely populated airspace. As TCAS is not really cheap (USD 250.00 – 500.000,- per aircraft), this might easily collide with the commercial pressures mentioned above. Nevertheless, as this is a very effective tool to enhance safety, it should be installed whenever possible. To benefit from it, proper training should be supplied; part of that training should be to raise awareness that TCAS might not be able to "see" all traffic, as some other targets might have switched off their transponders or do not have on to start with – like gliders, a major challenge in Germany at times, for instance. So the requirement for constant airspace surveillance remains.

There are other, low-cost TCAS-Look-alike solutions out there on the market. When installed, great care must be taken that the installation was done properly, otherwise false / nuisance indications might result, which effectively do more harm than good, as they distract the crew and undermine the confidence in the system.

Enhanced Ground Proximity Warning Systems EGPWS are another valuable safety feature. On flight inspection missions it does have its limitations, though, as it will cause false alarms when flying low approaches with gear / flaps up. As repetitive false alarms must be avoided, when EGPWS is installed on flight inspection aircraft, having a switch available to turn the system off and back on, when required, is paramount. For turning the EGPWS off and later back on after mission, an appropriate SOP has to be devised by the respective flight operation, and that SOP has to be reflected by the Normal Checklist in use.

In order to reduce stress for the crew as much as possible, all systems that provide cabin comfort should be operational and effective (heating in cold climate, air conditioning in hot climate). Notably an effective air conditioning is paramount in hot climates, as heat tends to foster the onset of fatigue considerably. Apart from issues affecting the crew, a functioning air conditioning in hot climates are paramount for the integrity of the Flight Inspection System (FIS) and its respective navigation receivers.

Crewing

Every operator will have his individual selection and hiring process. Great care should be spent on finding pilots that do have a professional attitude towards special mission flying – not too many per the classes that annually leave the flight schools, by this author's own experience, as the vast majority of the pilot community is striving for a job with the big airlines. Emphasis should be put on adjusting the candidates focus on the aircraft being merely a tool for a greater purpose; when in commercial flying the task is to fly safely from A to B, in our world the real job only starts at B.

ICAO Doc 9906 vol 6 gives a very good insight into initial qualification requirements for Flight Validation Pilots (FVPs). By and large, these criteria apply to a Flight Inspection Pilot as well. For Commanders on a flight inspection mission they read as follows:

- CPL or ATPL with IR
- Current type rating for the type to be flown on mission
- Total flight time > 1.500 hrs
- Command time > 400 hrs
- Flight Inspection Pilot for more than 2 years[2]

It is recommended to set up policies regarding initial and recurrent training, recency, and crewing in the light of mission requirements and individual qualification.

Again, it is recommended to keep this qualification matrix not overly complex, as it might hamper operations considerably otherwise.

Operational status

A number of flight inspection missions are outside the normal operating envelope of the aviation community. In many case this stipulates a requirement for official approval of these kinds of operations (i.e. flying below the Minimum Safety Altitude in some countries, night flying activities, etc.) Whenever possible, it is recommended that the affected flight inspection organization applies for this approval or "waiver" at the appropriate authorities, to minimize ambiguities and potential risk of violating rules and regulations, which in turn will reduce crew workload considerably.

Quality Management System QMS

A Quality Management System (QMS) should be an essential part of any flight inspection organization. Most regulatory frameworks address this requirement – an AOC holder is required to set up a QMS, for instance.

A QMS is highly desirable for tracking the performance of, and thus providing integrity for, the flight inspection mission itself.

Again, requirements on the side of the flight inspection regulator notwithstanding, a QMS can be an integral part of the overall OM of an organization, thus again reducing complexity in the organization's documentation.

OPERATIONS MANUAL

The Operations Manual (OM) can be viewed as the central document of an organization dealing with all aspects of the flight operation.

Its format, structure and extent, to a certain degree, will be driven by the individual requirements of the regulator being in charge of that particular entity.

Numerous layouts and templates for an OM exist with various regulators; it would be beyond the scope of this paper to name them in detail.

In general, what an OM should cover, are aspects as follows:

- Organizational set-up
- Responsibilities and accountabilities
- Aircraft related subjects (Minimum Equipment List MEL, navigation equipment, etc.)
- Limitations and Minima
- Crewing
- Operational Procedures, Normal and Abnormal
- All weather operations
- Flight and Rest Time Limitations
- Training
- Security

Again, as reiterated a number of times in this paper, the OM should be concise and limited to the absolute minimum necessary, in order to avoid over-complexity, which would only create a work atmosphere of ambiguity and double standards. An OM has to be workable under all operational circumstances the organization is operating under.

Some content of an OM shall be discussed in more detail in the following paragraphs.

Crew Resource Management (CRM) / Crew Coordination Concept (CCC)

Crew Resource Management is an essential part of any professional flight organization for many years now. It is highly recommended for any entity in flight inspection operations to take up the task of defining a workable CRM system and a Crew Coordination Concept that goes with it.

A CCC basically defines how a crew on task is to work together, laying down fairly in detail which crew member is doing what when and how. It clearly describes the communication involved in executing these tasks and should be backed-up by Standard Operating Procedures (SOPs) and Checklists (more to that below).

The CRM system, however, does not only define the cooperation between cockpit members, it also should encompass procedures and communication between cockpit and cabin, and it should define the interface between the flight crew and the rest of the company, like tasking / scheduling, management, etc. This rather holistic approach in CRM is of great importance to create a working environment that takes into account all requirements to accomplish the organization's mission profile safely and reliably.

Standard Operating Procedures (SOPs)

Standard Operating Procedures (SOPs) describe how certain aspects of the scope of work are handled by whom, at what time.

SOPs govern aspects like cockpit work, crew coordination, checklist philosophy, but also issues like how to execute certain calibration profiles, how to schedule tasks, write reports, etc.

Again, SOPs should be commensurate with the task at hand. They should be concise, transparent, and again, be an integral part of the OM.

Checklists

Checklists form an enormously important part of the operating environment. Again, the KISS approach is highly recommended: it is a well-known fact that the manufacturer's checklists, especially when the aircraft in question is certified for single pilot operations, are often useless in a normal aviation environment for reasons of over-complexity and length. These checklists reflect legal and liability issues, which might be well required to keep the manufacturer from harm in legal terms, however, focusing on these legal aspects unfortunately renders these checklists almost useless.

So every operator is called upon to design checklists that do reflect its individual needs. Depending on the regulatory environment it might be necessary to get the altered checklist approved by the respective regulator.

The checklists as well should reflect the operational environment the specific missions are flown in. Again, avoid over-complexity. The checklists have to be in line with SOPs and other procedures laid down in the OM, a very important aspect to keep in mind.

TRAINING

The importance of training in aviation in general, and in flight inspection in particular, cannot be overestimated.

Every flight inspection organization should set out and establish a training regime, covering both initial as well as recurrent training, and then stick to that training regime. This translates into a certain commitment from all stakeholders involved including management, as training inevitably has cost implications.

Again, that training regime shall be written down in a concise document, with that document being an integral part on the OM of the organization.

Whenever a suitable simulator for the type operated by the organization is in reasonable reach, it is strongly recommended to use that simulator both for initial as well as recurrent training.

As the standard type rating and recurrent training provided by the big training houses does not really reflect the particular aspects of flight inspection missions, it is further strongly recommended to introduce one's own training program / syllabus and own SOPs, checklists, etc. into the training, starting from initial training on. At least the two biggest training and simulator providers are more than happy to accommodate the individual needs of an operator, train according to their syllabus, checklists, etc, or even accept their instructors as co-instructors or even full-time instructors for that particular organization.

Special emphasis should be laid on the transition training once the initial training on the simulator has been passed, as in almost all circumstances the cockpit layout, interfaces etc. of the calibration aircraft in operation will differ significantly from the simulators standard layout.

RISK MITIGATION STRATEGY

Every flight inspection organization should embark on formulating a Risk Mitigation Strategy by identifying risks associated with specific missions, address them and come up with solutions how to mitigate these risks.

In an ideal world, this risk mitigation strategy is an integral part of the overall operating procedures of an organization and well described in its documents, preferably it's OM and as such, has been covered in this paper.

Some aspects of the risk mitigation strategy warrant a closer look, though, and shall be discussed here in more detail:

Any risk mitigation strategy shall address the **external circumstances of the operation:** where do we operate, doing what with whom? How is the terrain, how is the infrastructure (fuel / de-icing / hangar available)? How well is ATC organized, is radar coverage given? Who on a specific mission will be point of contact for the company? Who for the crew? How is the security situation on site / in country?

Giving all this a thorough consideration is even more important when doing commissioning flight checks at new airports.

Dealing with these questions effectively constitutes some sort of risk assessment prior embarking on the mission, something that is highly recommended. Whenever possible, these data should be collated prior bidding for a tender; marketing or management should try to find out as much information as possible prior committing to a task, in order to reduce pressure and stress to the crew on site later.

Avoiding crew fatigue is another major issue: Most AOC holders are regulated in terms of Flight and Rest Time Limitations (**FTLs)** by their respective regulator. However, as the trend in the regulatory regime goes more and more in the direction of operator-specific FTLs that have to be scientifically based and approved by the authority, and as standard FTL regime do not really reflect the special needs of a flight inspection organization, it is highly recommended for each flight inspection entity to come up with an individual FTL regime, reflecting and taking into account the specific operational requirements of that organization.

At what point fatigue hits will very much depend on the type of mission flown (ILS low level work, in general, being more stressful then airway work high up), the aircraft being used (Cockpit equipment being available, space available on board, susceptibility to turbulence, temperature control) and the environment operated in (poor ATC? Poor infrastructure, i.e. refueling a major undertaking? Night flying involved?). Thus, geographical and climatological conditions of theatre of operation, length of deployment, transit times and other factors, like aircraft and cockpit equipment mentioned above should be taken into account when designing a FTL scheme.

It is recommended to liaise as closely as possible with the crews affected when designing FTL schemes, as they might be able to provide valuable input as to what is both desirable and practicable as well.

It goes without saying that in the end, the proposed FTL scheme has to be approved by the authority in charge.

A very important consideration also is **accommodation** and **transportation** for crews, notably when away from base. It must be assured that a good rest and a good night sleep can be accomplished at the accommodation picked. Transits in and out of theatre of operation should be as efficient as possible, both to save on valuable duty time as well as avoiding fatigue on crews after a lengthy airline flight with various connections.

CONCLUSIONS

Managing risk in the very demanding flight inspection environment is achievable by applying a number of common standards covered in this paper

Applying these standards to all organizations dealing with flight inspection not only would provide a level playing field for all parties involved, it would undoubtedly foster and enhance safety in this sector of the aviation industry considerably.

RECOMMENDATIONS / FUTURE WORK

It is therefore recommended to continue the discussion on common standards in flight operation of our industry, with the ultimate goal of establishing a common set of standards that all parties involved could subscribe to.

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Study on Crew Resource Management in Flight Inspection of Localizer

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ABSTRACT

Compared with commercial flight, flight inspection has its own special characteristics. The flight inspection crew need to cooperate closely, and timely communicate with the ATC controllers and maintenance technicians, so that we can complete the flight inspection safely, high-quality, and efficiently. Because the Localizer (LOC) profiles need to cross the course, many factors will affect flight safety, inspection quality and efficiency.

Crew Resource Management (CRM) in LOC flight inspection is of great significance for improving the safety and quality of the flight inspection.

In this paper, combined with the actual flight inspection, the author analyses key factors affecting flight safety and quality, studies the major factors from CRM aspects, such as human, equipment, environment, and gives recommendation and proposal to improve the safety and quality of the flight inspection.

INTRODUCTION

Flight inspection is to calibrate, test and evaluate spatial signal quality of navigation, radar, communication and other facilities. Safe, reliable and accurate flight inspection is the basic premise of airport operation. Flight inspection is an important link to ensure the flight safety of civil aviation.

Compared with commercial flight, flight inspection has its own special characteristics. The flight inspection crew need to cooperate closely, and timely communicate with the ATC controllers and maintenance technicians, so that we can complete the flight inspection safely, high-quality, and efficiently.

Because the Localizer (LOC) profiles need to cross the final course, many factors will affect flight safety, inspection quality and efficiency. Therefore, Crew Resource Management (CRM) in LOC flight inspection has great significance for improving the flight inspection safety and quality. In this paper, combined with the actual flight inspection, the author analyses key factors affecting flight safety and quality, studies the major factors from CRM aspects, such as human, equipment, environment, and gives recommendation and proposal to improve the safety and quality of the flight inspection.

HUMAN FACTORS AFFECTING THE QUALITY AND SAFETY OF FLIGHT INSPECTION

During flight inspection, human factors such as communication process, inquiry and reply, will affect the quality and safety of flight inspection.

Communication Process

During fight inspection, provided effective communication process among crew members, the quality, efficiency and safety have been greatly improved. In contrast, poor communication can weaken the crew members' technical ability, arise some misunderstandings, and affect the quality, efficiency and safety.

The communication process involves the flight inspectors, pilots, ATC controllers and maintenance technicians. In order to avoid the misunderstandings and mistakes, closed-loop mode must be used during the communication process, as shown in Figure 1.

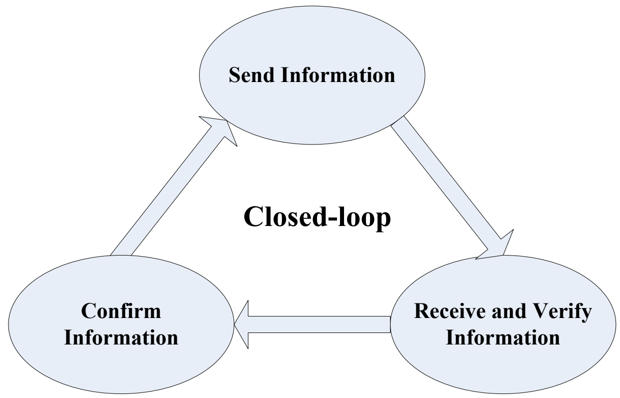

Figure 1. Closed-loop Communication mode

Inquiry and Reply

Research shows that inquiry and reply is the weakest link in modern crew resource management. For example, during one mission, the flight inspector required the pilot to perform ILS profile 4 (please see Appendix 1 for detailed ILS profile classification), but the pilot did not hear the instruction clearly due to interphone interference. What's more, the pilot did not confirm the instruction with the inspector and then apply for ILS profile 3 directly, which leads to the decrease of the flight efficiency.

There are many actual flight inspection cases all pointing to the weakness of inquiry and reply. Even if there are inquiries, the crew member may not take it through the end, and the communication process is not a closed-loop. The pilot's checklist is a formal inquiry and response forms, which contributes to define normal and abnormal situations. Inquiry and reply may not like to perform the checklist, but can learn its execution idea.

In addition, the captain has the responsibility to establish a beneficial inquiry atmosphere. If the captain does not establish such an environment, the other crew members should try to establish a beneficial inquiry atmosphere, and must be confident to inquiry.

EQUIPMENT FACTORS AFFECTING THE QUALITY AND SAFETY OF FLIGHT INSPECTION

During flight inspection, equipment factors such as interphone system, air-ground communication system and inspection console system, will affect the quality and safety of flight inspection.

Interphone System

Communication between inspectors and pilots is carried out through interphone system. As the most important link, communication between inspectors and pilots determines the flight inspection quality, efficiency and safety, to a certain extent. If interphone is abnormal, inspector cannot convey profile arrangement to pilot, and pilot cannot inform the air traffic situation to the inspector. Therefore, interphone system is the key factor to influence the crew resource management.

Air-ground Communication System

Inspectors use air-ground communication system to release facility adjustment command, confirm facility status and inform flight inspection data. Clear, accurate and readable communication is an important guarantee to convey the intention between the air and the ground timely and effectively.

Air-ground communication system between the inspection console and the cockpit should be completely isolated from each other to avoid mutual interference.

Inspection Console System

Many functions of inspection console system play a supporting role on flight efficiency and safety.

CAAC has installed a GARMIN200 display system on its inspection console, as shown in Figure 2. Combining the terrain database, GPS signal source, the UAT data, it can display the aircraft's status of selected region. Using this function, flight inspector can get terrain and all aircraft status of operation areas, and predict the terrain and other aircrafts influences on inspection aircraft.

Inspection software can display the flight trajectory, longitude, latitude, altitude and the relative location of calibrated facilities by computing the GPS positioning signal and calibrated facility database. In LOC profile, inspector can obtain the aircraft's relative location of LOC, such as distance, azimuth, left/right course, etc. For some profiles which are far away from the Instrument Approach Procedure (IAP) protected area, this function plays a supporting role on flight safety. For example, the LOC coverage profile must fly a 17 (25) nautical miles/±35 (10) degrees arc to check whether the LOC power can meet the tolerance in the Standard Service Volume (SSV) and Expanded Service Volume (ESV). Using this function, the inspector can accurately grasp the circumstances that the aircraft comes into marginal area such as 17 nautical miles/±35 degrees and 25 nautical miles/±10 degrees. In this case, the inspector should reasonably grasp the information resources, timely notify the pilot and observe the external terrain to grasp the aircraft's real-time status during maneuver turning.

Figure 2. GARMIN200 Display System

In addition, another important function of the console is to monitor the cockpit air-ground communication without tuning any frequency. The monitoring function can reduce the call volume between pilots and inspector, which will significantly reduce the crew members' workload.

ENVIRONMENT FACTORS AFFECTING THE QUALITY AND SAFETY OF FLIGHT INSPECTION

Because the LOC profiles need to cross the course line, the aircraft may fly beyond the IAP's protect area. The crew must follow the Visual Flight Rules (VFR) during LOC flight inspection. Considering the flight procedure and sample method, the information factors that affect the quality and safety is LOC course surrounding terrain, visibility, ceiling, air traffic flow and day-night flight, etc.

LOC Course Surrounding Terrain

LOC width, clearance and coverage inspections need to cross the course line. LOC course surrounding terrain has significant effect on the quality and safety of flight inspection. China has the most High Plateau Airports (HPAs) in the world. By April 2014, there are 11 HPAs with elevation over 8,000 feet in operation. Flight inspections in those HPAs are more difficult and risky. Therefore, flight inspection for HPAs in China is the most difficult and complicated operation all over the world.

Let's take Jiuzhai Huanglong Airport (Airport Code: ZPJZ) as the example; around the ILS course of RWY20, we can see many mountains. The inspection aircraft cannot fly over the Standard Service Volume (SSV) due to terrain restriction. The ILS of RWY20 will be classified as RESTRICTED, with the report annotated as to the limited coverage flown.[1] The published NOTAM will show the ILS of ZPJZ RWY20 as UNUSABLE in the areas where cannot be checked.

The flight procedure of LOC clearance in ILS of ZPJZ RWY20 is shown in Figure 3. There is a 4632-meter mountain located at the left side, 25 degrees from the front course line. According to the flight inspection rules, we need to check the LOC clearance in the QNH 4800 meters, but cannot meet the requirement of 300 meters Minimum Obstacle Clearance (MOC) in some areas. Considering the maneuver and turning radius after sampling, sampling area delineated within the 17 degrees. The area outside the 17 degrees is annotated as restricted due to terrain.

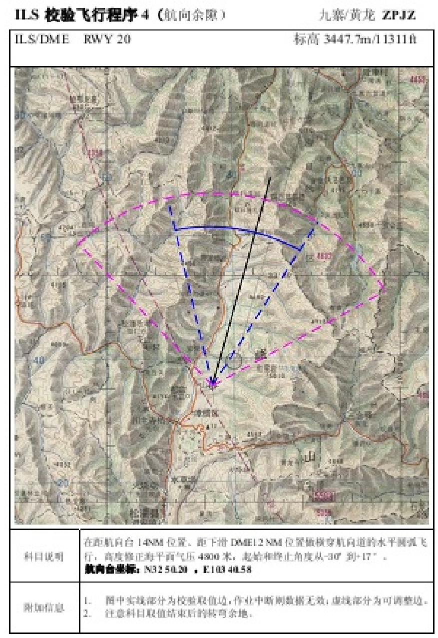

Figure 3. ZPJZ RWY20 LOC Clearance Flight Inspection Procedure

Visibility and Ceiling

During LOC flight inspection, a higher weather standard is required due to VFR. The ceiling must be higher than the inspection procedure altitude. The visibility must be high enough to ensure the pilots can see the ground. Flying into the cloud is prohibited during LOC inspections.

Air Traffic and Flight Flow

Nowadays, airport traffic and flight flow has increased rapidly in China. By the end of 2013, we already have ten airports with more than twenty million annual passenger capacities within Chinese Mainland. The conflicts between commercial flights and flight inspection have become more and more prominent. Therefore, how to coordinate the conflict of commercial flight and flight inspection is an urgent research topic.

Flight Inspection at Night

In some high-density airports, conducting flight inspection in daytime will put more pressure on controllers and may bring less safety and more delays. So, more and more flight inspection operators are seeking ways to conduct the flight inspections at night time to avoid interfering with normal flight operations. [2]

The inspectors should evaluate effect of night condition, and determine if there are any vital measurement differences between day and night operations, such as city background radio noise, reflecting obstacles, etc.

The pilots conducting night fight must operate above the Minimum Safe Altitude (MSA). Some profiles whose altitudes are lower than MSA should not be taken at night.

CONCLUSIONS

In this paper, combined with the actual flight inspection, the author analyses key factors affecting flight safety and quality, studies the major factors from CRM aspects, such as human, equipment, environment, and gives suggestions and proposal to improve the flight inspection safety and quality.

a. The latest consoles developed by CAAC can monitor the cockpit air-ground communication. This function can reduce the crew members' workload significantly.

b. Flight Inspection Center of CAAC has made Flight Inspection Procedure Manuals for every airports operating in China Mainland, as shown in Figure 4. These manuals specify the flight methods of each profile in different airports. The standard flight inspection procedures, such as altitude, range and sector angle, are described on the flight charts or terrain maps, in which way to improve the CRM among pilots, inspectors, controllers, and ground technicians efficiently.

Figure 4. Flight Inspection Procedure Manuals in Our Office

ACKNOWLEDGMENTS

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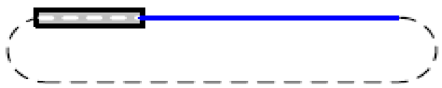
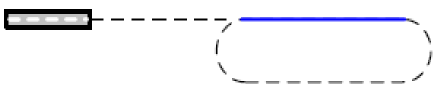
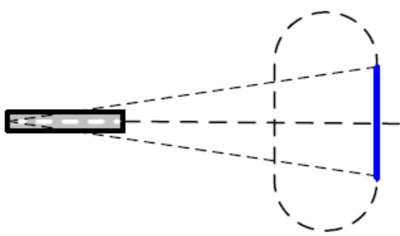
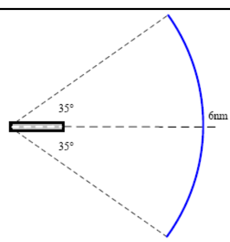
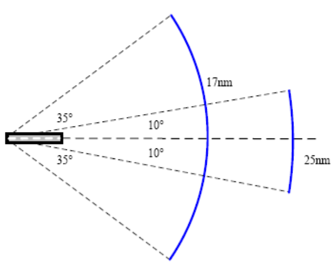
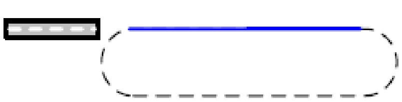
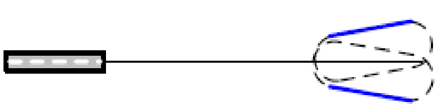
[2] ICAO, 31 October 2002, Manual on Testing of Radio Navigation Aids, Doc 8071, Volume 1, Testing of Ground-based Radio Navigation Systems, 4th Edition, http://www.icao.int

APPENDIX 1

ILS Profiles of China Flight Inspection

In order to improve flight quality, efficiency and safety, Flight Inspection Center of CAAC has classified the ILS inspection into seven profiles, as shown in Table 1.

Table 1. ILS Profiles Classification

Profile 1 Approach		**Parameters:** LOC: Alignment, Structure, Modulation, Polarization GP: Angle, Height of reference datum, Structure, Modulation
Profile 2 Level Run		**Parameters:** GP width/displacement sensitivity, Symmetry, monitor
Profile 3 Level Arc		**Parameters:** LOC width/displacement sensitivity, Symmetry, monitor
Profile 4 Level Arc		**Parameters:** LOC Clearance
Profile 5 Level Arc		**Parameters:** LOC Coverage
Profile 6 Level Run		**Parameters:** GP Clearance
Profile 7		**Parameters:** GP Coverage

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Efficient and Traceable Configuration Management – The Flight Inspection Service Provider's Perspective

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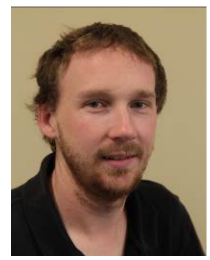

ABSTRACT

Taking a Systems Engineering approach to managing complex systems is not a new concept and formal Configuration Management Systems have been used successfully by organizations like NASA and Boeing for many years. Configuration Management and traceability to National and International standards is critical in regulated environments like Flight Inspection for Regulatory and Compliance purposes.

Application of the same Configuration Management principles and processes into a smaller operation presents some challenges, however the reward is effective management of the accuracy, integrity and traceability of the flight inspection results.

This paper will present the approach taken in developing, implementing and working to a formal Configuration Management System in a growing commercial Flight Inspection Service Provider. The benefits, pitfalls and lessons learned while transitioning to the formal Configuration Management System will be presented and discussed.

INTRODUCTION

With the introduction of a new Flight Inspection Service (FIS) contract in 2013 the structure for management of the Flight Inspection System (FISy) changed.

Previously the Air Navigation Service Provider (ANSP) was responsible for the Configuration Management (CM), change management and traceability of the FISy for certification purposes. Under the new system these tasks became the responsibility of AeroPearl. A new approach was required to provide the framework and necessary processes and procedures to ensure FISy CM and traceability to National and International standards. An Engineering Management System (EMS) was the solution.

Typically Engineering Management Systems and formal CM processes exist in organizations like NASA and Boeing. In this context the procedures are focused on large projects and complex systems, simply using an existing framework such as these would not have been appropriate, the overhead would have been far too great.

AeroPearl instead chose to develop and implement a tailored EMS, firmly based on Systems Engineering principles and the shared experiences of larger organizations.

The benefits of the EMS can now be seen by both AeroPearl and it's customers. They are discussed here for the benefit of other organizations facing similar CM challenges.

WHAT IS AN ENGINEERING MANAGEMENT SYSTEM (EMS)?

A simplistic view is that the EMS is a Quality Management System (QMS) for engineers, but the reality is that it is much more than that. While a QMS provides processes and procedures to drive a quality outcome for the business, the EMS is focused only on providing a basis for how engineering and CM activities are done in the organization.

In a way the EMS fills the gaps in the QMS, it is the basis for engineering authority, defines interfaces for change management through technical/contractual triggers and contains processes developed by engineers for engineers.

The EMS must become a way of life for those doing engineering work and seen as something that makes the job easier rather than a layer of administration.

The EMS is not a manual, it is a way to do work, a concept. How the concept is described and documented is in the Engineering Management Plan (EMP), a general structure is shown in Figure . The EMP itself provides an overview of the EMS and how associated Work Instructions (WI), which define specific processes, are to be followed for specific activities such as Review of a design. The Engineering Authority Matrix describes who is allowed to do what in the EMS.

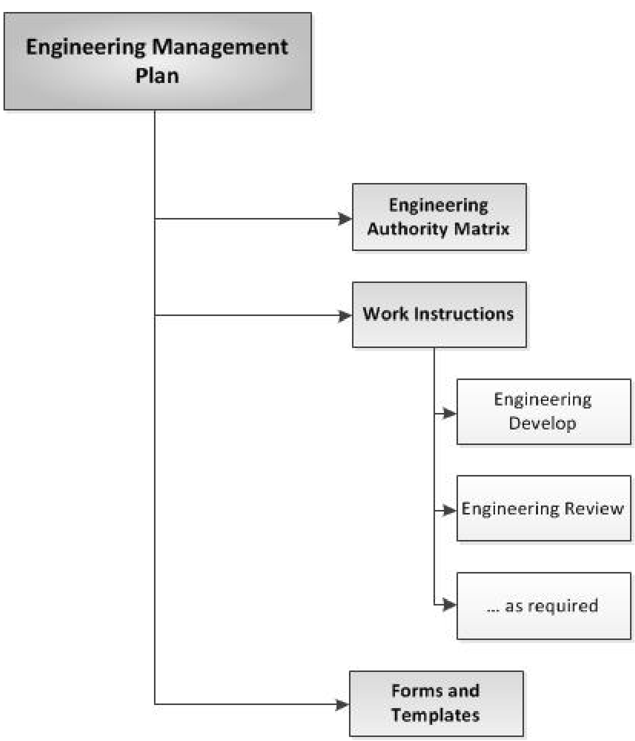

Figure 1: General Structure of an EMP

Formalizing Engineering Work

Formalizing engineering work within AeroPearl has resulted in better quality outcomes from engineering investigations and changes. Additionally, as both AeroPearl and customer confidence and experience in the EMS grows the customer role transitions to one that is more “hands-off”. This reduced level of day-to-day involvement by the customer in the technical aspects of the FISy allows the service based Flight Inspection model to function as intended.

One of the best outcomes is that work can be done once, something particularly beneficial in engineering investigations. When an issue is identified, investigated and resolved, this is fully documented and archived/catalogued. Should a similar issue develop in the future the investigation work has already been completed and the rectification can be implemented quickly.

Another useful outcome in this regard is that verification evidence is of high quality and can be re-used to provide justifications for deviations/dispensations. Taking existing evidence and re-packaging it ensures that workload is reduced which is beneficial as approval of dispensations is usually a time critical task. Furthermore, the evidence can be provided for audit/approval purposes to new customers as required for approval/acceptance of AeroPearl’s FIS.

DEVELOPMENT & IMPLEMENTATION

Key to developing and implementing the EMS was a clear understanding of where it would be applied and what it’s application was to achieve.

The EMS was envisioned to provide a basis for *the Mission System* and *Support Systems* to provide a *FISworthy* Flight Inspection Service. A breakdown of AeroPearl’s Flight Inspection System is presented in Figure 2 and the key elements are defined as follows:

The *Mission System* is defined as: *the aircraft platform fitted with the Flight Inspection Equipment including the Deployable Ground Equipment when required/used for the task.*

The *Support Systems* are defined as something less tangible: *systems, including engineering, configuration management, maintenance, supply, operations, quality, finance, information technology, training and facilities required to support the FISy in delivery of the Services.*

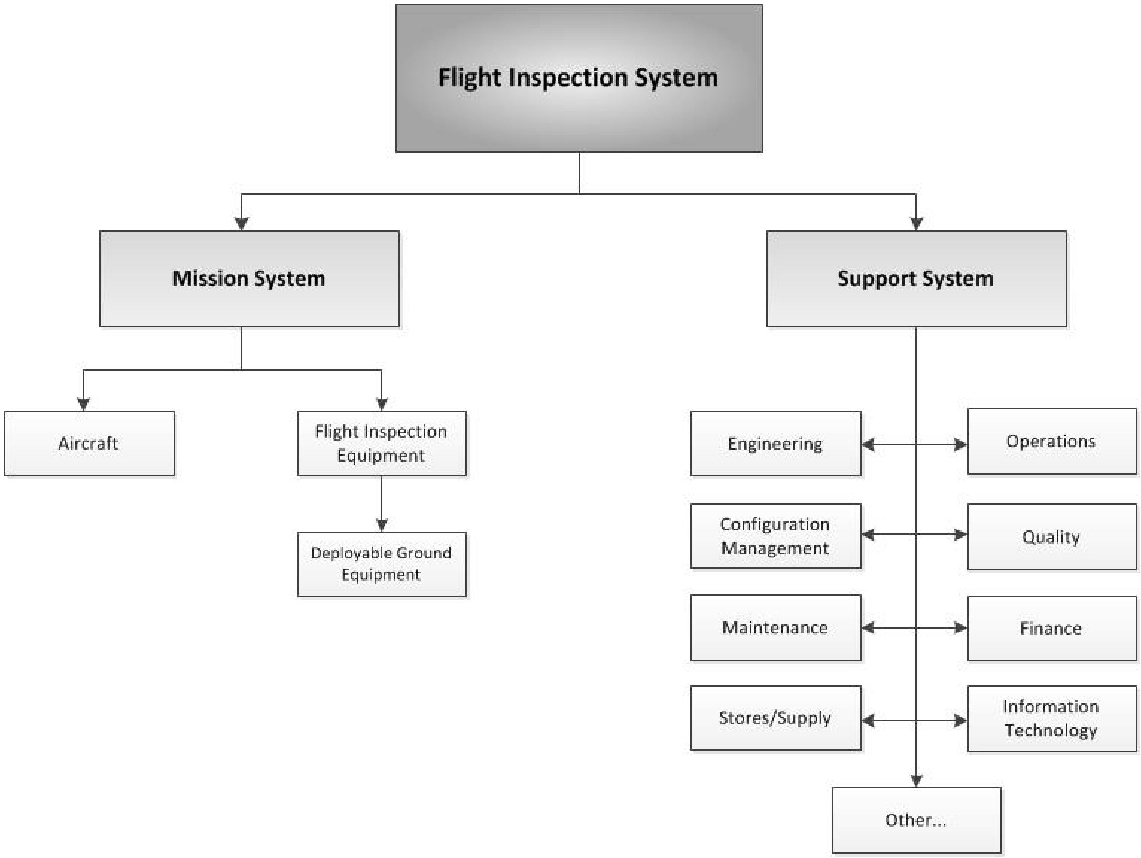

Figure 2: FISy, Mission System and Support System Breakdown.

FISworthiness has been defined by AeroPearl, analogous with airworthiness but focused on the output of the FISy (Flight Inspection results/reports), to be: *a concept, the application of which defines the condition of the FISy and supplies the basis for judgment of the suitability for use of the FISy in the FIS, in that it has been designed, constructed, maintained and is expected to be operated to approved standards and limitations, by competent and authorized individuals, who are acting as members of an approved organization and whose work is certified as correct.*

Traceability

The link between FISy performance and the required standards/requirements is made through verification and validation activities such as analysis, test, demonstration and inspection. Verification evidence is linked to the requirements through the Verification Cross Reference Matrix (VCRM) providing full traceability and auditability.

The VCRM exists and evolves for the life of the FISy, how changes are managed to ensure that the links between performance and requirements are maintained is the role of Configuration Management.

WHAT IS CONFIGURATION MANAGEMENT?

CM is more than keeping a record of which serial number receiver is installed in which aircraft on which day. A more complete definition of CM, taken from Military Handbook -Configuration Management Guidance [1] and adopted by AeroPearl, is: *A management process for establishing and maintaining consistency of a product's performance, functional, and physical attributes with its requirements, design and operational information throughout its life*.

In terms of Flight Inspection, maintaining the consistency of the FISy's performance is critical to both the ANSP and Flight Inspection Service provider. Establishing and maintaining proper CM of the FISy provides measurement results with a level of traceable and guaranteed performance which otherwise may not be easily achieved.

The traceability provided from the implementation of an EMS and formal CM processes ensures that the system state and its ability to produce *FISworthy* data is maintained and is auditable at all times.

MANAGING CONFIGURATION CHANGES

Establishment and management of configuration baselines is fundamental for ensuring continued traceability and guaranteed system performance.

In the Flight Inspection environment where technology changes over the life of the system, configuration changes will always be necessary to maintain the FISy with the latest technology and measurement capabilities.

Successful management of configuration changes ensures that baseline performance is maintained (or improved with the change where relevant), impacts on interfaces are addressed and that the system remains maintainable, during and after configuration changes.

Configuration Baselines

In order to manage the FISy's performance, functional and physical attributes, they must first be established. AeroPearl adopted standard CM methodology in establishing three configuration baselines, Functional, Allocated and Product, during the implementation of the new FISy.

The relationship between the three baselines is shown in Figure 3 (taken from [1]), and they are defined as follows:

1. The Functional Baseline defines the functional characteristics and performance requirements of the system. In the case of the FISy this is represented by the body of performance specifications such as Customer Requirements, ICAO Doc 8071 etc.

2. The Allocated Baseline defines the allocation of functional characteristics and requirements to specific elements/components within the system. It is typically more important during development stages to document how the proposed design will fulfill the requirements.

3. The Product Baseline completely describes the functional/performance and physical characteristics of the product. It is the collection of mechanical and electrical drawings, verification results, parts catalogues etc.

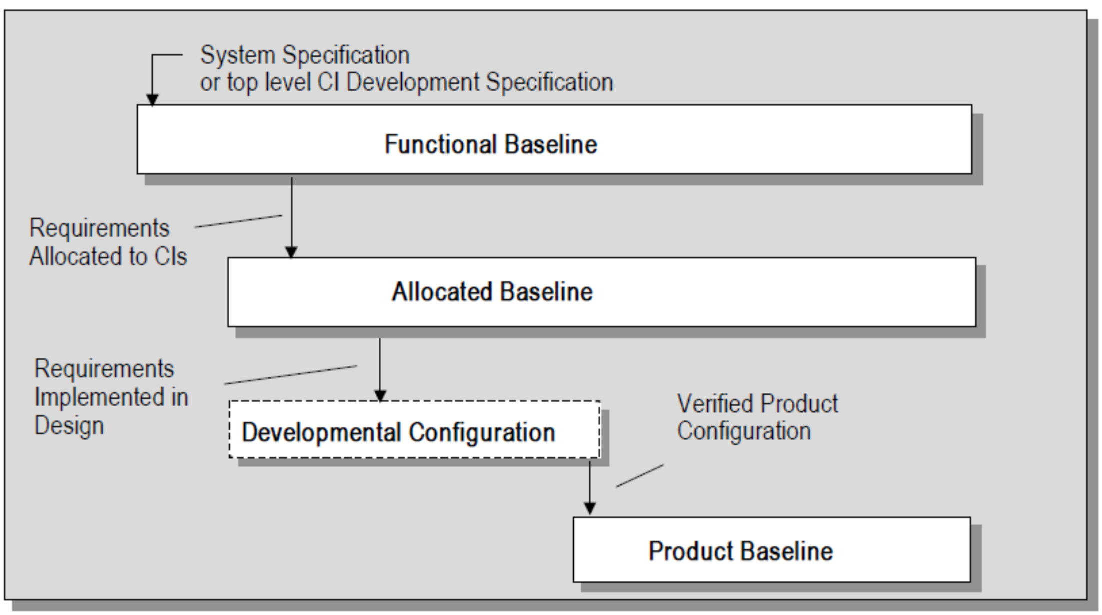

Figure 3: Baseline Relationship

Configuration Items

Configuration Items (CIs) are generally items which implement critical capabilities within the system or which require an exact reference to the item's configuration at any given time. Designation of an item as a CI enhances the level of control and verification required for the item. These items are specifically designated for CM, along with others items that may not fit the definition of CIs but need to have their configuration formally managed (ie. cabin layout).

CIs can be defined at a system level where control is managed with respect to performance or function, or defined to a lower-level such as a Line Replaceable Unit (LRU) like a computer, where control is based on part number, revision number and modification status. Both hardware and software items can be designated as CIs.

Specifying certain components of the system as CIs defines the scope of the change management processes to be applied across the system. This allows for more effort to be applied in change management of critical items and less effort for non-critical items within the system. This allows change control to be applied specifically and efficiently.

The selection criteria adopted by AeroPearl in identifying CIs is based on the criticality of the item/system with regards to the system's objective, *FISworthy* measurement results and compliance with national/international requirements.

By adopting this approach, it allows for appropriate levels of change management to be applied to various parts of the system. Importantly, it also allows for maximum distinction between change management of primary aircraft equipment, Flight Inspection Equipment and Support Systems.

Airworthiness/FISworthiness Interface

As part of any change to an aircraft, regardless of whether the change is to the Flight Inspection Equipment or primary equipment, airworthiness impacts need to be addressed and appropriately approved. However not all changes to the primary aircraft, have an impact on *FISworthiness*.

By defining CIs based on their criticality to *FISworthiness* the majority of changes to primary equipment are considered to involve non-critical items and as such can be completed with reduced involvement of the EMS. In these cases the EMS typically need only consider the impact of the change to the Flight Inspection Equipment and trigger any modifications or re-verification activities as appropriate.

Some items of the primary equipment do have an impact (or the potential to impact) on *FISworthiness* (e.g. Primary Air Data Computer that provides altitude information to the Flight Inspection Equipment). AeroPearl has identified these items specifically as CIs to ensure changes are managed appropriately.

Levels of Change Control

AeroPearl established three different levels of change control for appropriate application of CM processes:

1. Category A: Any change to an item designated as a CI. Changes such as a receiver modification (change to specification, part number, revision number or modification status) or software update falls into this category

2. Category B: Any change to Flight Inspection Equipment related items which do not directly affect measurement results (such as a printer) but provide a required system level functionality.

3. Category C: Any change that does not require engineering approval. Typically this relates to consumable items such as screws, capacitors, resistors, relays and cables where system level functionality is maintained as long as the new item meets the required specification.

Having varied levels of change control enables AeroPearl to effect changes with the appropriate amount of rigor, ensuring configuration baselines are maintained whilst ensuring the EMS is applied efficiently.

As part of AeroPearl's tailored EMS, two formal configuration change processes were established, a Major Engineering Change Proposal (ECP) and a Minor ECP.

The Minor ECP process is a scaled down version of the Major ECP process and involves fewer reviews and approvals external to the engineering department. Both processes still address the same CM considerations such as identification of new CIs and update of relevant CI documentation and baselines.

Typically a Major ECP is required for Category A changes, where as a Minor ECP is required for Category B changes.

Effecting a Change

Figure 4 depicts the main stages within AeroPearl's engineering change process. All proposed changes are made to a controlled configuration baseline.

Change initiators (such as obsolescence reports, defect reports or change requests from customers) come into the engineering department. They are assessed, and if determined that a change is required, an ECP is raised. AeroPearl engineering personnel process the change, using relevant design inputs from customers, manufacturers/suppliers, regulatory bodies, vendors, maintenance staff and end users.

The change progresses through various stages, including definition of requirements, design, verification and incorporation.

Before progressing to the next stage in the process, the ECP is presented to the Configuration Control Board (CCB) for assessment and approval. At the final stage of the ECP, after the change has been verified, the ECP is presented to the CCB for Incorporation Approval and Service Release.

This final gate ensures that all impacted interfaces have been considered and changes to applicable documents, such as operations manuals, are ready, training has or will be provided and that sufficient and correct evidence confirming that the modified system meets the requirements is available.

After Incorporation Approval and Service Release is granted, formal incorporation into the configuration baselines and any hardware/software changes can be effected as necessary.

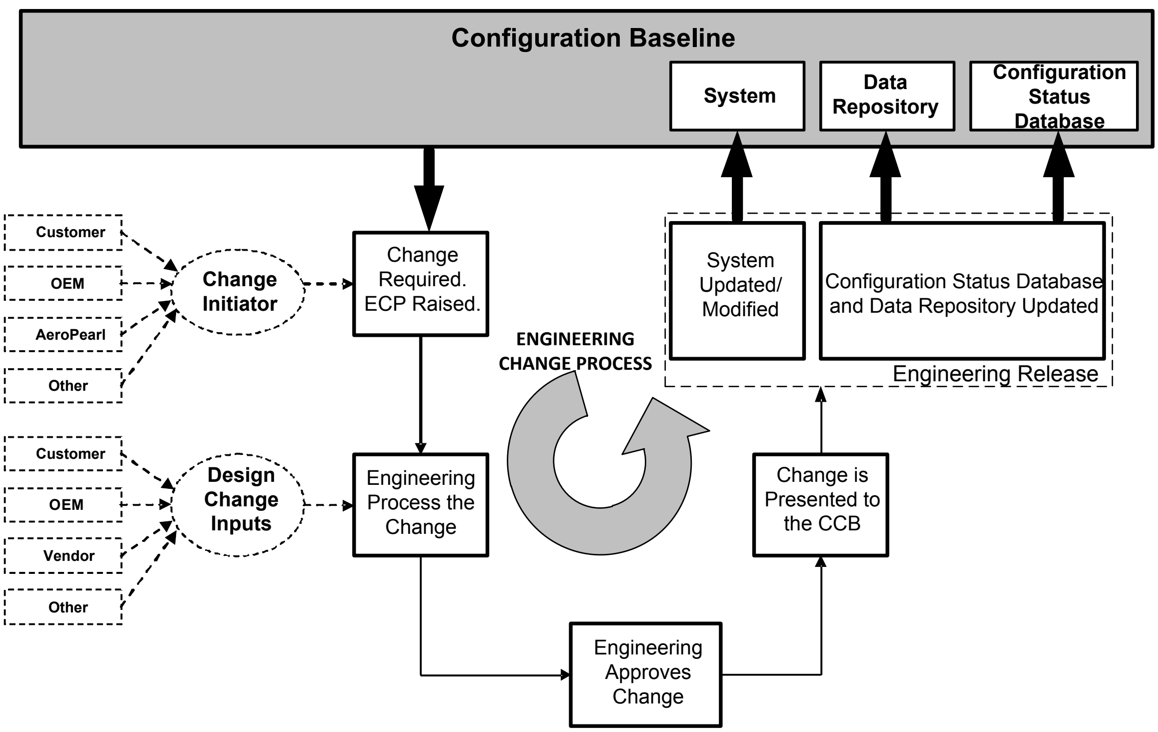

Figure 4: Overview of AeroPearl's Change Management Process

Configuration Control Board (CCB)

AeroPearl established a CCB as a means to harmoniously consider and agree changes to the configuration of the FISy. Each major business area of AeroPearl is represented on the CCB.

Additionally, customer representatives are invited to attend CCB sessions when relevant to them. Feedback from the customer and the CCB members is captured within this process, and if the change is not approved this feedback is considered in the rework cycle.

Changes to the primary aircraft and Flight Inspection Equipment are presented at the CCB for consideration. The CCB considers the change and data pack to ensure all aspects of the proposed change are addressed. This includes safety, airworthiness, *FISworthiness*, operations, maintenance, supply, CM (including such things as variations within the fleet), training and documentation updates.

LESSONS LEARNED

While AeroPearl can not claim to be experts on Engineering Management Systems and CM, there are some lessons that have been learnt whilst implementing and working to a formal EMS that should be considered if similar Engineering and CM processes are required to be implemented.

Getting the Balance Right

When implementing an EMS into a commercial operation, set the balance correctly. Two approaches are possible:

1. Start with higher level of control/process until confidence in the system and experience grows, then streamline processes as required. This approach was adopted by AeroPearl.

2. An alternative to be considered, if within the running system environment already, is to start with less formalized processes and build these up over time to increase functionality. This reactive approach typically requires trigger events (where things didn't work as expected) which may not be suitable in all scenarios.

CCB Participation

All key departments involved with the Flight Inspection Service should be represented in the CCB. The more people involved (within reason) when considering the change the more collective knowledge is available. This is especially important early in the change process or while the EMS has a low level of maturity/experience. This reduces the potential for rework when things aren't picked up early in the change process and improves the outcome.

Even if some people may have minimal involvement in a CCB, attendance is still important and assists in communicating changes throughout the change process.

Baseline Management

Actively and formally managing changes and maintaining the baselines is beneficial for both the Customer and the Flight Inspection Service Provider - both have an assurance of system performance at all times.

In cases where discrepancies are found between flight inspection results and expectations, the focus is on investigating the issue with the navigation aid rather than finding and excluding any possible faults in the Flight Inspection Equipment as its performance is thoroughly understood and documented as part of developing and maintaining the baseline.

EMS Rollout

Due to limited timeframe, AeroPearl implemented their EMS in one stage (rather than a progressive rollout) which was a significant change in how engineering was previously completed. Due to this, the implementation was initially met with reluctance, however after further training and experiencing the benefits of the EMS, the concept was accepted within the company.

In order reduce the reluctance towards the implementation of an EMS, a progressive rollout may be beneficial. A progressive rollout allows specific modules and processes to be trained/explained up front and as each process is embedded, another one can be rolled out.

Training

A significant amount of training was required for AeroPearl's engineers when the EMS was implemented. A small amount of organizational training was also conducted to make everyone in the company aware of its implementation and explain the impact on other business functions.

Recurrent training is also required, ensuring engineers are kept up-to-date on current practice and changes to the EMS. It also provides a forum to discuss scenarios encountered using the EMS, analyze how things were done and identify where processes can be improved.

Resources

Depending on the complexity and quantity of systems which are to be managed through the EMS, additional resources may be required.

AeroPearl found that appointment of a Configuration Manager was required to ensure that baselines, documentation and the configuration of the system were maintained. One of AeroPearl's engineers performs this duty along with normal engineering work. For a larger number of systems, a dedicated Configuration Manager may be required.

AeroPearl has also found that in some instances nominating an engineer to perform independent review was difficult due to the close working nature of the team and availability of engineers with appropriate engineering authority. Depending on how the organization is structured, additional engineers may be required to ensure independent reviews are possible. Use of external/contract resources on occasion to fulfill this requirement has proven beneficial to AeroPearl. For critical resources within the company, a level of redundancy is recommended to ensure coverage in design reviews or other engineering activities whilst they are not available.

The Golden Rule

Process and procedures are no substitute for knowledge and creativity.

The original source for this statement can't be located, but this is a sentiment expressed by many who have worked within an EMS framework.

Put simply, existence of an EMS will not automatically guarantee sound engineering design, rigorous review, fully managed configuration and traceability.

Only knowledgeable engineers, applying the processes, procedures and principles from an EMS into their everyday work will give the desired outcome.

CONCLUSIONS

Our experience implementing the EMS and CM processes into AeroPearl, has led to the following conclusions:

1. Implementation of an EMS is not limited to large organizations. There are benefits from applying formal Engineering and CM processes to small commercial organizations that go beyond the technical realm. Financial benefits will be seen in reduced levels of rework after configuration changes.

2. An EMS does not fundamentally change the way that work is done, it only formalizes processes and procedures that most likely already existed.

3. If the EMS is scaled appropriately, additional resources may not be required to achieve the appropriate amount of rigor and traceability.

FUTURE WORK

AeroPearl's EMS is a living system, it is subject to continuous review and improvement with a focus on streamlining processes while maintaining the required level of engineering rigor and CM traceability.

ACKNOWLEDGMENTS

It would be remiss of AeroPearl not to acknowledge Airservices Australia for providing the catalyst to develop and implement the EMS and providing the guidance which has allowed the system to mature very quickly in a short period of time.

REFERENCES

[1] MIL-HDBK-61A(SE), Military Handbook Configuration Management Guidance, 7 February 2001.

Proactive Flight Safety through FOQA & ASAP

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ABSTRACT

The flight inspection (FI) mission creates a unique and challenging flight environment. In addition to the flight risks associated with a typical air transport operation, FI crews face the additional risks created by frequent low altitude flight, operation against normal traffic flow in high density areas, a high degree of multi-tasking, and increased exposure to birds and conflicting traffic

Routinely operating in the higher risk FI environment can lead to a latent, flight crew complacency. A highly motivated crew may become so fixated on acquiring FI data that flight safety may be inadvertently compromised.

With the objective to increase safety, Flight Inspection Services (FIS) implemented the FOQA and ASAP programs.

FOQA is an onboard data acquisition system that records a large number of parameters in addition to those typically available in a flight data recorder. This data is "de-identified" and analyzed through post processing. Mitigating training and/or procedures are then implemented to improve safety.

ASAP is a voluntary safety reporting program where crew members can file reports of unsafe conditions or incidents without fear of retribution. A special committee reviews each report and then recommends procedures or training as needed to mitigate the problem in the future.

This presentation will share examples and particularly FI specific lessons learned since the inception of these programs in FIS. In addition, the infrastructure that has led to successful implementation of these programs will be examined.

INTRODUCTION

The study of many aircraft accidents has shown that it is not unusual for the cause to be at least partly the result of a trend of unsafe practices or a compromised safety culture. These safety threats may often remain undetected for long periods of time, sadly being exposed only after an accident.

Having a way to accumulate objective, safety critical data provides great insight into identifying unsafe trends before they become an incident or accident. Flight Operational Quality Assurance (FOQA) and the Aviation Safety Action Program (ASAP) are two programs that are designed to do just that.

Proper interpretation and use of data from these programs can uncover safety threats before they become another link in the accident chain. Recognizing the unique risks in flight inspection (FI), and with the goal of obtaining the highest level of safety, Flight Inspection Services (FIS) implemented both FOQA and ASAP programs in 2006.

REACTIVE VS PROACTIVE DATA COLLECTION

Reactive data is collected after an undesirable event has occurred. For example, the data obtained from a Flight Data Recorder (FDR) after an accident is reactive data. It can show what happened on a particular flight, but reveals nothing about operational trends that might have led to the accident. By the time reactive data is received, the only available action is often damage control.

Sometimes, reactive data can be found where we least expect or want it. Who hasn't seen newscasts of surveillance videos that have captured the final seconds of an aircraft accident? This is certainly not an ideal or pleasant way to find out that we may have missed an important unsafe trend that led to a disaster.

Proactive data, on the other hand, allows the methodical collection of critical data. We can analyze this data for trends at our convenience. Corrective action can be taken without having to deal with the pressures associated with an accident or incident. Most importantly, an unsafe trend can be broken before an accident/incident occurs.

Figure 1 – Jan. 18, 2014 Challenger Accident at KASE

The FOQA / ASAP PROCESS

FOQA and ASAP are methods for acquiring and interpreting safety critical data. FOQA is an onboard data acquisition system. It records a large number of parameters in addition to those typically available in a flight data recorder. Post processing software facilitates trend analysis.

ASAP is a voluntary safety reporting program where crew members can file reports of unsafe condition or incidents without fear of retribution. A special committee reviews each report and then recommends procedures or training as needed to mitigate the problem in the future.

Both programs share the same process (figure 2) which is:

1. Data Acquisition
2. Analysis & Validation
3. Reporting
4. Corrective Action
5. Monitoring

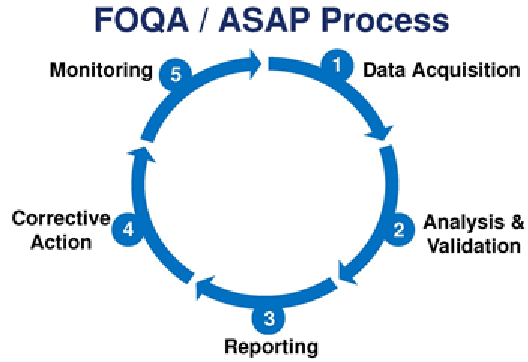

Figure 2 - The Process

1. Data Acquisition

FOQA data acquisition is through an onboard digital system. It records a large and comprehensive set of parameters. Examples include; acceleration and air data, autopilot status, flight control positions, electrical information, engines, fuel, oil temperature/pressure, flight instruments, landing gear position, navigation systems and communication status. This is later downloaded for post processing.

ASAP data acquisition relies on crewmember input. Crewmembers are encouraged to submit a report anytime an event occurs where a crewmember's actions or inactions causes or contributes to an unsafe condition. In addition, crew members may report any deviation from standard operating procedures, non-compliance with any Federal Aviation Regulation, or any safety of flight concern.

In FIS, ASAP submission can be made on-line on a secure server which contains an account for each crewmember. It is easily accessed through the internet. If a computer or internet is not available, a Facsimile form is available and may be submitted to a special phone number. Submission can also be made verbally over the phone if necessary.

2. Analysis and Validation

The **FOQA** program employs an operation tailored "event set". For FIS, this includes events specific to flight inspection maneuvers.

The voluminous aircraft acquired data is then filtered to show only the data that fits the event set. The following chart (figure 3) shows a sampling of these events.

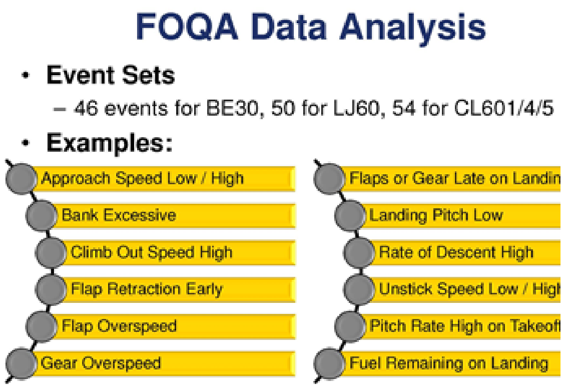

Figure 3

ASAP data is accumulated by compiling the user submitted reports and is held for later review by the Event Review Committee (ERC). These reports include things like course deviations, altitude deviations, traffic conflicts, airspace incursions, limitation exceedances, and even system failures. The following chart (Figure 4) shows the typical categories.

Figure 4

3. Reporting

Quarterly, **FOQA** tabular and graphical reports showing trends over years and quarters are presented to the FIS Flight Safety Committee. This committee includes the FIS Director, Senior Flight Safety Officer, Flight Safety Officers, Director of Operations, Chief Pilot, Director of Maintenance, and Principal Operations Inspector (POI).

The FOQA Steering Committee, which includes the FOQA Program Manager, Chief Pilot, Sr. Flight Safety Officer, Director of Operations, Maintenance Representative, and Union Representatives, also reviews the FOQA data. The committee determines actions like possible modification, addition, or deletion of events.

An **ASAP** Event Review Committee (ERC) reviews the submitted ASAP reports quarterly. This committee, comprised of a management representative, a union representative, and the principal operations inspector, meets as needed.

Both FOQA and ASAP data as well as other supporting information are published quarterly in the FOQA / ASAP Newsletter (Figure 5). The newsletter contains the same tabular and graphical FOQA event results that were provided to the Flight Safety Committee. In addition, it lists the top five occurring events. Regular safety related articles, usually based on FOQA results, are also included in the newsletter.

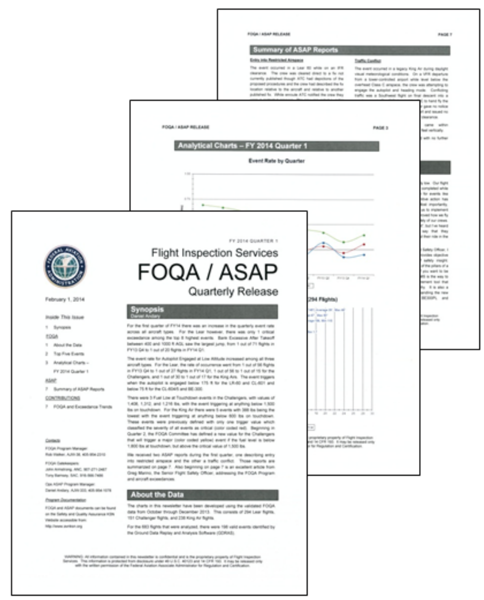

Figure 5 – FOQA/ASAP Newsletter

4. Corrective Action

For both FOQA and ASAP, corrective actions usually involve amending or adding operational procedures and training emphasis. For FOQA, these actions are usually initiated by the Flight Safety Committee. ASAP corrective actions are generally recommended by the ERC and reviewed for implementation by the Flight Safety Committee.

FIS FOQA Events That Invoked Change

1. High Rate of Descent

This was a recurring event where aircraft were descending at very high rates at altitudes close to the ground. This will be discussed in more detail later in this paper.

2. **Speed Below 10,000 ft.**

This was a trend where aircraft were occasionally exceeding the below 10000 ft., 250 kt. speed limit. Corrective action was crew education and procedural training emphasis.

3. **Stabilized Approach**

FOQA data showed that crews were making aggressive maneuvers and configuring late for landing. Data analysis showed that this generally occurred by continuing to a landing after completion of an FI maneuver, like an ILS holding pattern. In order to avoid rejoining the downwind for a stabilized approach, crews were descending to a landing about 2 miles from the runway threshold from 1500 agl. Corrective action was to review the FOQA data with crews, and emphasize the importance of a stabilized approach.

NOTEWORTHY FIS SUCCESS STORIES

1. **High Rate of Descent (ROD)**

FOQA data revealed some occurrences of descent rates greater than 2500 fpm below 1200 agl. Study of the data revealed that the High ROD events were occurring on Approach Path Monitor (APM) checks.

An APM is designed to generate an alarm to Air Traffic Control (ATC) if an aircraft descends, or is predicted to descend, below a safe limit above the ground while on an Instrument Flight Rules (IFR) clearance. Figure 6 shows the typical APM coverage area. Conducted in visual conditions, under Visual Flight Rules (VFR), the flight inspection maneuver requires a descent that is rapid enough to trigger the alarm on Air Traffic radar. Sometimes, ATC inadvertently disables the alarm during a flight check since it is normal procedure to eliminate nuisance alarms from VFR aircraft. Not hearing a “low altitude” call from ATC, and extremely motivated to complete the flight check, some FI crews were pushing over harder, hoping to get the alarm. In fact, we have seen one data set that shows a rate of descent in excess of 6000 fpm to 400 agl.

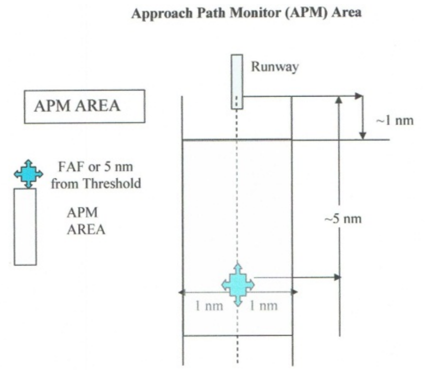

Figure 6

Corrective action involved educating the crews that a very high ROD was not necessary to set off the alarm. Figure 7 shows a representative profile of a typical APM flight check. The chart graphically shows the FOQA event limits, the APM alarm threshold and that a rate of 2000 fpm will set off the APM alarm without triggering a FOQA event.

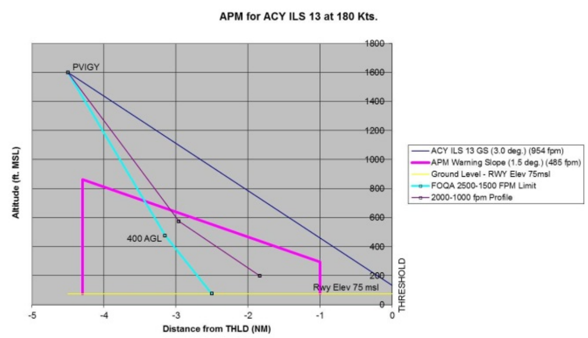

Figure 7

Another training aid we were able to derive from the data in this case was displaying an actual animation of a High ROD event through the use of X-Plane software loaded with FOQA data.

Event rates decreased drastically after this kind of training. It is a perfect example of how FOQA data uncovered a potential safety issue and facilitated corrective action. Armed with the data, a logical and convincing argument can be made for proactive change. Compare that to standing before an assembly of crews, with only your opinion that you *think* there is a high ROD issue. A positive change in crew behavior is certainly less likely.

2. **BE300 Propeller Anomaly**

FI began operating the first of its 18 Beech BE300 King Air Twin Turboprop aircraft in 1988. Over the years, we have experienced an intermittent condition where one propeller will move to a flatter position than it is supposed to in flight. With the opposite side propeller operating normally, a severe difference in thrust and drag occurs. This results in the aircraft making a sudden, nasty yaw towards the side of the malfunctioning propeller. To make matters worse, it is typical for this to happen during power reduction in the landing flare.

Once on the ground, the problem clears itself and maintenance is unable to duplicate the problem. Depending only on the crew's description, maintenance can only check to see if there is some defect or mis-adjustment in the configuration. Most of the time there is not and so much speculation takes place over what the crew actually experienced.

Over the last few years, FIS has been upgrading its King Air fleet with new Proline 21 avionics. Included in this upgrade is installation of FOQA recording equipment. Now we are able download the data from one of these events and see exactly what the propeller and engine parameters were when the event occurred. With this new information maintenance has been able to zero in on the problem and a solution is forthcoming.

After analysis of the FOQA data, we have also been able to provide the crews with better procedures to check for and deal with this event should it happen. In this case an Operations Bulletin was used to distribute the information.

Figure 8 shows an example of how we post processed the FOQA data to expose the propeller anomaly. It is an example of how FOQA can be valuable for more than just trend analysis.

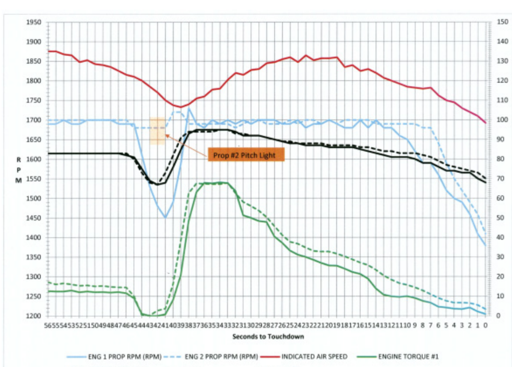

Figure 8

3. Loss of Radio Contact

A good example of an ASAP success story is one where radio communication with ATC was lost in a busy terminal environment under IFR in instrument meteorological conditions (IMC).

The flight, en-route to another facility, was not flight checking at the time. The mission specialist (MS) was at his station preparing for the next facility. During the process, the MS decided to check the Spectrum Analyzer, a device which is rarely used these days. Unfortunately, due to a peculiarity in the flight inspection package, enabling the spectrum analyzer disabled the #2 Communications radio on the flight deck. There was no annunciation on the flight deck nor at the MS station that showed this had happened. Of course, as luck would have it, the crew was using Com #2 for primary communications at that time. Unaware of the total loss of communication with ATC, the flight proceeded on its current course. Before long, the crew realized what had happened and reconnected with ATC. Fortunately the rerouting of some traffic was the only consequence.

The crew filed an ASAP report. This was a benefit to them, because it provided protection from a possible violation. It was a benefit to our operation because their submission allowed us to identify a safety risk that was not very obvious due to the infrequent use of the spectrum analyzer. Training emphasis resulted and the experience was also considered in the redesign of our later flight inspection equipment.

SAFETY MANAGEMENT SYSTEM (SMS)

FIS, like most operations these days, has a comprehensive safety management system. FOQA and ASAP are the perfect tools to provide measurable data to a SMS. Here are some key elements of our FIS SMS program. You can see how perfectly FOQA and ASAP fit into the SMS philosophy.

1. SMS is a comprehensive process with a focus on proactive management of safety risks.
2. All personnel will identify and report hazardous conditions
3. All reported hazardous conditions will be investigated to determine underlying causes.
4. Safety Promotion: Communication, Lessons Learned.
5. Performance Measurements.

CONCLUSIONS

FOQA and ASAP are extremely valuable tools in providing data to help establish and maintain a positive safety culture. In FIS, FOQA and ASAP have enabled us to uncover unsafe trends that may not have otherwise been apparent. We rely on the information provided by both programs to help us maintain the highest level of insight into how safely we are operating our aircraft.

ACKNOWLEDGEMENTS

Special thanks go to Daniel Andary, FOQA / ASAP Program Manager. Daniel has been instrumental in the implementation and maintenance of both programs, since their inception in FIS. His keen knowledge of the program has helped us to use the data in the most effective way. Daniel has contributed to this paper, as well as the associated presentation.

IFIS 2014

Flight Plan to Innovation

Session 10

Training and Certification Issues

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Training of DSNA/DTI Flight Inspectors

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ABSTRACT

Within the French Civil Aviation, it has always been considered that the flight inspector skills had to go beyond the use of a Flight Inspection Equipment (FIS) for the measuring of parameters. They shall obviously be able to ensure that the radio-navigation aids are working properly within ICAO tolerances, that new procedures can be validated. But, above all, they shall also be able to guide ground maintenance regarding the tuning of their ILS, VOR …, to advise on the adequate corrective action to take but also to discuss with procedure designer regarding incorrect implementation …

ICAO documents mention that flight inspector shall be adequately trained but no real recommendations are provided.

The proposed presentation will describe the training courses and steps that are required within French DGAC to be qualified as a flight inspector for different types of inspection.

INTRODUCTION

The French flight inspection unit was created in 1948, as air transport was growing rapidly after the Second World War. Since that date, the technical means (aircraft and flight inspection equipment), the measurement methods, and also the radio-navigation means have evolved tremendously. In parallel, standards, requirements, in terms of safety and quality, have dramatically increased. Some of the most significant examples are the mandates for States to develop standards for the commissioning and follow-up of radio-navigation equipment, to take into account the qualification of all personnel working on operational CNS (Communication, Navigation, and Surveillance) or ATM (Air Traffic Management) system. These two documents, at least, have had a major impact on the various activities conducted by flight inspectors, in their level of responsibility and therefore their training methods. In France, another criterion has been taken into account, when developing the training standards. DSNA.DTI considers that a flight inspector shall not only validate measurements. He/she should also have the ability to help the ground maintenance in solving issues so that the radio-navigation equipment works properly after the aircraft departure or, at a minimum, appropriate corrective action has been defined.

REGULATORY ASPECTS

Rules applicable to equipment

In accordance with the rules set out by the European Commission on system interoperability and on the provision of air navigation system, France has released, in 2008, decrees for every type of radio-navigation equipment (ILS, VOR, DME…) but also for the development of procedures (SID/STAR…). According to these regulatory documents, every ANSP (Air Navigation Service Provider), operating in France, shall develop safety, performance and interoperability requirements for radio-navigation equipment. In addition, ANSP shall also describe:

- Adjustments along with ground and flight inspections to be performed for the commissioning of equipment,
- Routine preventative action to be performed on equipment, once installed,
- Corrective action
- Routine ground and flight inspection
- Conditions and procedures to shut down the equipment operations.

As the main ANSP in France, DSNA (Direction des Services de la Navigation Aérienne) has developed documents, called PROMESS (PROcédures de Mise en Service et de Suivi – PROcedures for the Commissioning and the Follow-up), for each type of equipment in order to show compliance to the above mentioned French regulations. These procedures have been validated by DTA (Direction du Transport Aérien), the French Civil Aviation Regulator and are now in force on every French aerodrome (including overseas territories) managed by DSNA. As an example, the ILS PROMESS complies with the above mentioned requirements but also describes the air/ground correlation methods that have been implemented for most of the French ILS. These methods have allowed an increase in the flight inspection interval up to twelve months, with a four month due date window.

Regarding procedures, DSNA is currently developing a document, equivalent to the PROMESS for equipment, in order to show compliance with ICAO doc 9906. This document will be officially released in December 2014 and will describe how the verification and validation tasks are shared between procedure designers, flight inspectors and flight crew.

Rules applicable to personnel qualification

In Europe, the ESARR (Eurocontrol SAfety Regulatory Requirements) 5 was developed in order to complement and/or supplement requirements included in the ICAO Annex 1. This document has been validated by the European Commission and is applicable to every Member State. France has therefore released, in 2007, a regulatory material to comply with the European rules. This concerns each operational or technical civil aviation personnel, who perform tasks which have a potential safety impact.

This French decree defines notions such as:

- Minimum entry qualifications and requirements
- Initial qualification
- Qualification for different domains such as Communication, Navigation, Surveillance, data processing… with criteria to obtain such qualification
- Certification for people performing maintenance, or technical supervision tasks on operational equipment.

In order to get such Certification, it is required to have the minimum entry qualifications and requirements plus the appropriate field qualification.

This Certification is approved by the Departmental Head and has a maximum three year duration. It can be renewed only if the two following conditions are fulfilled:

- To be compliant with the Training Plan requirements and,
- To have practiced the related tasks during a minimum period (defined in the training plan).

INITIAL TRAINING ASPECTS

ENAC (Ecole National de l'Aviation Civile – French Civil Aviation Academy)

The air transport growth after the Second World War has led to the creation of a school dedicated to the training of the various aviation players. Initially located at Orly (Paris second aerodrome), ENAC moved in 1968 to Toulouse. This school welcomes about two thousands permanent students, and five thousands short course trainees per year in the following domains

- Flight crews
- Air Traffic Controllers
- Technicians and Engineers, both private or public, and working in every aeronautical area.

ENAC is the only French aviation school authorized to deliver training in accordance with ESARR 5 requirements.

Initial ENAC training

In order to fulfill DSNA needs, ENAC trains three engineer categories:

- Managers
- Air Traffic Controllers
- Electronic engineers

These last ones work in operational centers where they are responsible for ground maintenance or technical monitoring of radio-navigation equipment.

To be recruited by ENAC, future electronic engineer shall have a minimum level at electronic or data processing. Their three year training is equally divided into:

- Theoretical sessions which include teachings on data processing, antennas, frequency, micro-wave, networks…Such sessions obviously include initial learning on the CNS and ATM systems they will work on afterwards.
- Practical sessions where they start to work on various minor CNS or ATM related projects followed by one year on their first appointment.

At the end of these three years, people hold the electronic engineer grade along with the initial qualification. In the frame of their professional activities, and thanks to specific trainings, the electronic engineers will obtain further qualifications.

One of the main benefit of this initial ENAC training is that electronic engineers, whatever their future appointments, learn to know each other's and acquire similar methods and a common working culture. This is an obvious benefit when working together, ground staff on one side and flight inspection on the other.

FLIGHT INSPECTION TRAINING

As previously mentioned, flight inspectors shall first hold a Certification in order to work. Such certification encompasses all Communication, Navigation and Certification domains, whereas ground staffs are specialized in only one domain. For the past few years, flight inspectors have also had to perform procedure validation which is another qualification to obtain.

The certification is therefore composed of several degrees with different levels, which are summarized in the following table:

Table 1. Flight Inspector Degrees

	ILS	VOR	PBN	MLS	Other
Routine	x	x		x	x
Commissioning	x	x	x		x
Corrective	x	x			x

Each degree matches specific training and different levels of experience. In average, a new flight inspector is fully qualified after a two year period. The objective, within the French flight inspection unit, is that every flight inspector shall be fully qualified in order to facilitate the operational flight inspection program progress.

The following sections describe the required steps in order to hold every degree. Each of these training courses is associated to a specific taxonomy, derived from the Eurocontrol one:

- T1: A basic knowledge of the subject. It is the ability to remember essential points, to memorize data and retrieve it.
- T2: The ability to understand and to discuss the subject matter intelligently in order to represent and act upon certain objects and events.
- T3: A thorough knowledge of the subject and the ability to apply it with accuracy. The ability to make use of the repertoire of knowledge to develop plans and activate them.
- T4: Ability to establish a line of action within a unit of known applications following the correct chronology and the adequate methods to resolve a problem situation. This involves the integration of known applications in a familiar situation.
- T5: Ability to analyze new situation in order to elaborate and apply one or other relevant strategy to solve a complex problem. The defining feature is that the situation is qualitatively different to those previously met, requiring judgment and evaluation of options.

Module 1: Familiarization with the flight inspection unit and the technical means

A new flight inspector shall, at first, be familiarized with the flight inspection unit:

- Organization (laboratory, operations…)
- Technical means (aircraft, flight inspection equipment…)
- Other involved organizations (aircraft maintenance, flight crews…)

but shall also undergo medical exams.

He/she will then work with the laboratory staff in order to:

- Learn about the flight inspection system architecture,
- Acquire knowledge on the DGPS (Differential Global Positioning System) theory and installation, but also:
    - Aerodrome reference points,
    - How to install the DGPS ground station
    - How to proceed in case of DGPS failure

Taxonomy: T4

At last, and before to start flying with other flight inspectors, he/she shall follow several further training courses on:

- CNS equipment in order to supplement his/her knowledge on such system,
- Procedure design,

- And eventually obtain an electrical habilitation in order to be authorized to handle the flight inspection equipment and the various related sensors.

Module 2: DME

This module is only a theoretical one. The objectives are to know:

- The functional architecture of a DME ground station,
- How to perform fundamental measures on DME,
- The characteristics of a ground station,
- The possible tunings of the ground station.

Taxonomy: T3

Module 3: VOR/DME (Routine)

Module 3 starts with a theoretical training whose goals are to know:

- The functional architecture and the characteristics of a ground station (***Taxonomy T3***)
- The radiated signals and the potential tuning of the ground station (***Taxonomy T4***)

As soon as this training is completed, the flight inspector spends at least one week with an instructor in order to:

- Learn how to use the flight inspection equipment, for VOR inspection purpose,
- Know how to prepare a VOR flight inspection,
- Perform VOR simulation on the flight inspection ground station.

Taxonomy: T4

To validate the "Routine VOR/DME" degree, the flight inspection trainee shall then perform successfully and under the supervision of an instructor, at least five routine VOR/DME flight inspections.

Module 4: VOR/DME (Commissioning)

This module can only take place when module 3 has been successfully completed. The flight inspection trainee shall perform successfully and under the supervision of an instructor, at least two VOR/DME commissioning flight inspections.

Module 5: ILS/DME (Routine)

Module 5 starts with a theoretical training whose goals are to learn the functional architecture and the radiated signals of an ILS ground station (***Taxonomy T3***).

As soon as this training is completed, the flight inspector spends several weeks with an instructor in order to:

- Learn how to use the flight inspection equipment,
- Know how to prepare a Localizer flight inspection,
- Know how to prepare a Glide flight inspection,
- Perform Localizer simulation on the flight inspection ground station
- Perform Glide simulation on the flight inspection ground station.

To validate the "Routine ILS" degree, the flight inspection trainee shall then perform successfully and under the supervision of an instructor, at least ten routine ILS/DME flight inspections (or 10 Localizer and 10 Glide flight inspections).

Module 6: ILS/DME (Commissioning)

This module is the trickiest one in the flight inspector training and can only take place when module 5 has been successfully completed.

At first, the flight inspection trainee has to perform several training courses on:

- ILS system (Null ref and Type M)
- ILS from different manufacturers (INDRA, THALES …)

Taxonomy: T4

The flight inspector trainee shall then perform successfully and under the supervision of an instructor, at least two Localizers and five Glide commissioning's flight inspections.

Module 7: MLS (Routine &Commissioning)

Taking into account that there are a very limited number of operational MLS equipment in Europe and that no MLS training exists, this module is fully performed under the supervision of the DTI MLS specialist and a flight inspector instructor.

After a theoretical training, where the MLS functional architecture is described, the flight inspection trainee shall perform, successfully, one routine and two commissioning on the Toulouse Blagnac MLS to validate the MLS (Routine & Commissioning) degree.

Module 8: PBN (Performance Based Navigation) - Commissioning

Within the PBN module, the flight inspection trainee has to familiarize with the validation of procedures supported by different means. He/She shall therefore attend several trainings dealing with:

- LNAV procedures
    - LNAV Theory (***Taxonomy T3***)
    - Requirements on data to be validated for LNAV inspection (***Taxonomy T4***)
    - How to enter the procedure in the flight inspection system (***Taxonomy T4***)

Two LNAV procedures commissioning shall then be performed successfully under the supervision of an instructor.

- LPV procedures
    - LPV specificities compared to LNAV procedures (***Taxonomy T3***)
    - How to enter the procedure in the flight inspection system and requirements on data to be validated (***Taxonomy T4***)
    - Validation of FAS Data Block (***Taxonomy T4***)

Two LPV procedures commissioning shall then be performed successfully under the supervision of an instructor.

- DME/DME procedures
    - Information on the simulation tool used in order to define the DME/DME coverage and to identify critical DME (***Taxonomy T3***)
    - How to enter the procedure in the flight inspection system and requirements on data to be validated (***Taxonomy T4***)

Two DME/DME procedures commissioning shall then be performed successfully under the supervision of an instructor.

Module 9: Others

The flight inspector certification only addresses the previously mentioned equipment routine and commissioning checks. However, other inspections may have to be performed such as:

- VHF special or commissioning,
- Routine VOR high altitude
- PAPI routine or commissioning
- Direction Finder commissioning
- Radar routine or commissioning
- Radio Frequency Interference research (even if this activity is not really part of flight inspection, it is considered as a full DSNA/DTI flight inspector duty)

In order to be authorized to perform such flight inspection, the flight inspection trainee shall successfully perform one check per type of equipment, under the supervision of an instructor.

Module 11: Skill refresh

The maximum duration of a Flight inspector Certification is three years. In order to maintain each of the various degrees, it is required to perform at least:

- A minimum of 50 flight inspection hours per year,
- A minimum of 200 flight inspection hours between the certification issuance and its renewal,
- A minimum of one ILS commissioning between the certification issuance and its renewal,

In case of non-compliance with these minimum requirements, several flight inspections will have to be performed under the supervision of an instructor who will eventually decide whether the certification can be extended or not.

In addition to these minimum requirements, flight inspectors shall also attend the following trainings or meetings:

- One CRM (Crew Resource Management), per year, with the flight inspection crews addressing the importance of human factors during flight inspection.

- Internal bi annual meeting where return on experience, new technologies… etc. are discussed for methods harmonization.
- Aircraft safety and rescue procedures training (every two years)
- Electrical habilitation training every two year.

Module 10: Instructor qualification

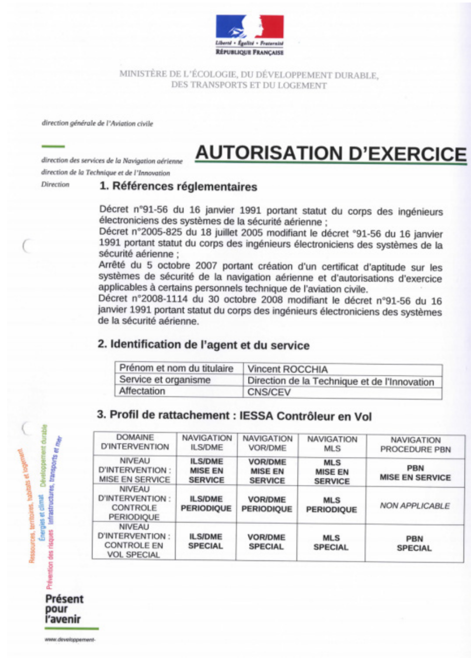
The ESARR 5 only addresses the instructor notion in the context of Air Traffic Controller. Within DSNA/DTI, this notion has also been extended to ground technical staff and flight inspectors.

At first, it should be clearly understood that training a new electronic engineer can be performed by every qualified flight inspector. However, the instructor is the only one who can validate the various degrees and, in case of doubt, who can decide if a Certification can be extended or not.

To become a flight inspector instructor, it is therefore required to:

- Hold a valid flight inspector certification,
- At least have a five year experience as flight inspector and have performed 500 flight inspection hours,
- Attend a specific training where the instructor tasks and responsibilities are defined, but also the way continuous checks have to be performed along with specific tests, if felt necessary.

Within the DSNA/DTI flight inspection unit, two flight inspectors, amongst the seven, hold the instructor qualification.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direction générale de l'Aviation civile

direction des services de la Navigation aérienne
direction de la Technique et de l'Innovation
Direction

AUTORISATION D'EXERCICE

1. Références réglementaires

Décret n°91-56 du 16 janvier 1991 portant statut du corps des ingénieurs électroniciens des systèmes de la sécurité aérienne ;
Décret n°2005-825 du 18 juillet 2005 modifiant le décret °91-56 du 16 janvier 1991 portant statut du corps des ingénieurs électroniciens des systèmes de la sécurité aérienne ;
Arrêté du 5 octobre 2007 portant création d'un certificat d'aptitude sur les systèmes de sécurité de la navigation aérienne et d'autorisations d'exercice applicables à certains personnels technique de l'aviation civile.
Décret n°2008-1114 du 30 octobre 2008 modifiant le décret n°91-56 du 16 janvier 1991 portant statut du corps des ingénieurs électroniciens des systèmes de la sécurité aérienne.

2. Identification de l'agent et du service

Prénom et nom du titulaire	Vincent ROCCHIA
Service et organisme	Direction de la Technique et de l'Innovation
Affectation	CNS/CEV

3. Profil de rattachement : IESSA Contrôleur en Vol

DOMAINE D'INTERVENTION	NAVIGATION ILS/DME	NAVIGATION VOR/DME	NAVIGATION MLS	NAVIGATION PROCEDURE PBN
NIVEAU D'INTERVENTION : MISE EN SERVICE	**ILS/DME MISE EN SERVICE**	**VOR/DME MISE EN SERVICE**	**MLS MISE EN SERVICE**	**PBN MISE EN SERVICE**
NIVEAU D'INTERVENTION : CONTROLE PERIODIQUE	**ILS/DME PERIODIQUE**	**VOR/DME PERIODIQUE**	**MLS PERIODIQUE**	*NON APPLICABLE*
NIVEAU D'INTERVENTION : CONTROLE EN VOL SPECIAL	**ILS/DME SPECIAL**	**VOR/DME SPECIAL**	**MLS SPECIAL**	**PBN SPECIAL**

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Au vu des modalités de délivrance des Autorisations d'Exercices à la Direction de la Technique et de l'Innovation, l'agent Vincent ROCCHIA détient les briques Mise en service ILS/DME, VOR/DME, MLS et PBN ; les briques Contrôle périodique ILS/DME, VOR/DME et MLS ainsi que les briques Contrôle spécial Mise en service ILS/DME, VOR/DME, MLS et PBN.
Les éventuelles restrictions sont mentionnées au paragraphe 5 de la présente Autorisation d'Exercice.

4. Visas et validation

Le Titulaire	Le Directeur de la DTI	Date : 08 Novembre 2011
Mr Vincent ROCCHIA	Le Directeur de la Technique et de l'Innovation, P. PLANCHON Mr Pascal PLANCHON	Expire fin : novembre 2014

5. Suivi des restrictions temporaires

Restriction	A compter du	Signature Directeur DTI	Levée le	Signature Directeur DTI
Toutes briques MLS	Le Directeur de la Technique et de l'Innovation,	P. PLANCHON		

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Figures 1&2: Example of Flight Inspector Certification

CONCLUSIONS

Having nearly seventy years' experience in flight inspection, the DSNA/DTI flight inspection unit has always tried to improve its methods and its performances in terms of equipment, technology. However, this is not enough if flight inspector training is not performed adequately. Also taking into account new regulations from ICAO, European Commission… very stringent and formalized requirements now apply regarding the qualification process of ground maintenance staff, air traffic controllers and flight inspectors. This is a major step towards aviation safety.

RECOMMENDATIONS

There are currently no detailed ICAO requirements or recommendations on flight inspector training. Taking into account the influence of flight inspection on air transport safety, it is recommended to issue minimum requirements on flight inspector training, qualification and skill refresh.

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Developing an Effective Training System for IFP Flight and Ground Validation of High-Performance PBN

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1. ABSTRACT

With increasing demand of ever growing air traffic, Japan Civil Aviation Bureau (JCAB) has implemented a large number of PBN Instrument Flight Procedures (IFP) in the last decade.

Simultaneously JCAB has established the IFP Validation Process consists of Flight and Ground Validation, in order to assure the quality of those implemented PBN IFPs.

IFP Validation requires the profound knowledge on Quality Assurance and Flight Procedure Design, and high skills of Programming and Database for processing Aeronautical Information such as AIXM, Navigation Database and ARINC424. JCAB has therefore established its own training system and curriculum for IFP Validation.

In recent years, the basic training for IFP Validation has been provided several Asian countries corroborating with Japan International Cooperation Agency (JICA). The aim of this training is to build up Flight Validation Pilots and Radio Engineers based on JCAB curriculum.

This paper presents the details of JCAB training system, designed to build up the personnel with a certain level of experience in Flight Inspection to become skilled at Flight/Ground Validation for High-Performance PBN.

2. INTRODUCTION

In 2007, JCAB formulated *"RNAV Roadmap"* in accordance with *ICAO Document 9613 "PBN Manual"* as the first step for PBN implementation in Japan. Following this roadmap, JCAB began to refurbish pre-existing RNAV route that had no prescribed RNP values.

All outdated routes have been replaced to RNAV5 in recent years, and JCAB has been aiming to expand RNAV5 route to cover furthermore airspace.

From 2008 to 2012, JCAB has promoted *"Sky-Highway Plan"* to allocate the airspace above FL290 as priority to the specified aircrafts approved for RNAV5.

Besides, a large number of PBN Terminal procedures have been implemented to the congested airports. RNAV1 SIDs and STARs for radar-controlled airport, and Basic RNP 1 SIDs, STARs, and RNP Approaches for non-radar airport have been established.

In 2011, JCAB has established a RNP-AR Approach in Tokyo International Airport (TIA) as the first high-performance PBN procedure. After the success in TIA, 19 RNP-AR procedures have been established in 11 airports around Japan.

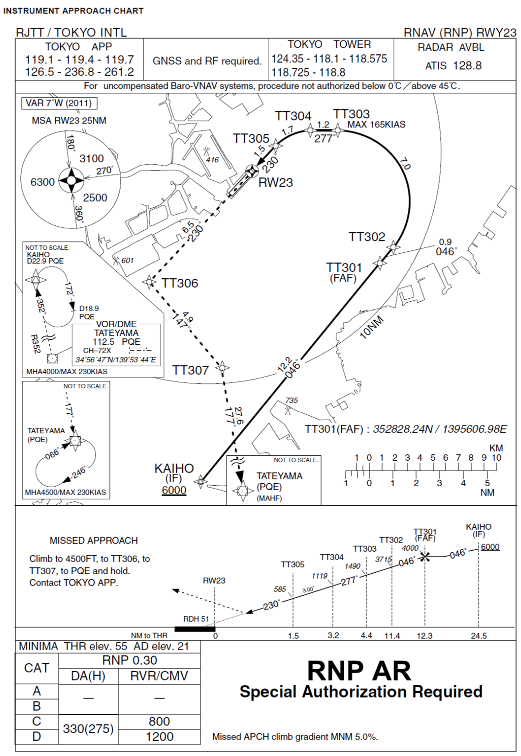

Fig. 1 Tokyo INTL (RJTT) RNAV（RNP）RWY23

Airports	Procedures
Hakodate	RNAV（RNP）Z RWY 30
Yamaguchi-Ube	RNAV（RNP）RWY 07/RWY25
Kitakyushu	RNAV（RNP）RWY 18/36
Kumamoto	RNAV（RNP）RWY Z/Y RWY25
Okayama	RNAV（RNP）RWY 07/25
Kochi	RNAV（RNP）RWY Z/Y RWY14
Miyazaki	RNAV（RNP）RWY Z/Y RWY09
Tottori	RNAV（RNP）RWY 28
Matsuyama	RNAV（RNP）RWY 14/32
Odate-Noshiro	RNAV（RNP）RWY Z/Y RWY29
Tokyo（Haneda）	RNAV（RNP）RWY 23

Table 1. RNP-AR IAP（04/01/2014）

Regarding the establishment of High-Performance PBN procedure, ICAO Document 9906 *"Quality Assurance Manual"* prescribes that state authority should assure the quality for all of the procedures, and the organized activities for that quality assurance are indispensable. JCAB therefore has a responsibility to protect the whole IFP process by constructing the robust Data-Chain from the IFP design draft through the IFP Validation, including Simulator Validation and actual Flight Validation, to the promulgation.

Above mentioned *"Validation"* requires the specialists having profound knowledge on Quality Assurance and IFP design, besides high-skill level of aeronautical information such as AIXM, Navigation Database and ARINC 424. JCAB has been established and developed its own training system in order to continuously produce sophisticated specialists for Flight Validation.

3. DEVELOPMENT OF TRAINING PROGRAM

Flight Validation specialists consist of Pilot and Radio Engineer are required to assure the safety of all of the IFPs. Detailed requirements contain some differences between Pilot and Radio Engineer, but required basic skills and knowledge are just same and essential.

To conduct Flight Validation, all personnel have to well understand the new concept added to the conventional Flight Inspection, such as IFP design (ref. ICAO Document 8168 *PANS-OPS*), basis of PBN (ref. ICAO Document 9613 *PBN Manual*), ARINC424 and Geodesy study. JCAB therefore has considered the method of training and effective curriculum.

3.1 Survey on International Standards

At first JCAB initiated the research on overseas situations and activities for High-Performance PBN. Besides, on the occasion of the first implementation of RNP-AR, JCAB dispatched two well-experienced pilots to FAA. They finished *"Flight Validation of satellite-based performance navigation IFPs"* course and were certified as Flight Validation Pilot. They learned following subjects.

- ✓ How to evaluate flyability of IFPs.
- ✓ What kind of tools are used in validation activities
- ✓ The data flow from procedure design to publication and the contents made by procedure designers
- ✓ How to prepare navigation database for FMS used in flight validation
- ✓ Training and check for flight validation pilots(FVPs)

ICAO	● Doc.8168（PANS-OPS） ● Doc.9906（QA Manual）
FAA	● N8260-67（FV of PBN and WAAS IFP） ● 8240.3B (Certification of Flight Inspection Personnel） ● 4040.3A(Flight Inspection Proficiency and Standardization Evaluation Program）

Table 2. International standards used as reference

Based on the FAA curriculum they completed, JCAB has established its own training system for Flight Validation. The syllabus is separated into Initial Training and Periodic Training. Experienced Pilots and Radio Engineers are thought to be already well familiar with IFP and its designs. JCAB therefore took account in personnel's experience and arranged the curriculum to be matched for individual abilities.

3.2 Understanding of Quality Assurance

Based on the preceding research and training in FAA, JCAB started to develop its own training subjects. The core concept of the training is to understand the importance of Quality Assurance in Flight Validation process. This is the prerequisite for both Pilots and Radio Engineers.

Drawing up the training syllabus especially on Quality Assurance, the undermentioned items as shown in Table 3 were picked up from mainly ICAO Document 9906 *"Quality Assurance Manual"* as the required subjects.

1	Importance of Quality Assurance in Flight Validation Process
2	Basis of Quality and Requirement
3	Activities regarding Quality Assurance
4	Quality Management and its component
5	Basis of Quality management, Quality Assurance and Quality Improvement
6	PDCA Cycle
7	Documentation and Preservation
8	Regulations on Quality Assurance
9	Flight Procedure Design and ICAO Annex 15
10	ICAO Doc 8168 PANS-OPS
11	ICAO Doc 9906 Quality Assurance Manual
12	ISO/RTCA Standards
13	Roles of Procedure Designer and Flight Inspector
14	Role of AIS
15	Role of Data house

Table3. Subjects for understanding Quality Assurance

3.3 Training Program for Pilots

Both Initial and Periodic training are partially common. The basic sections of them are practiced in ground school with Computer-Based Training (CBT). Regarding the subject *"Simulator Evaluation"*, participants use Boeing 737-800 Virtual Simulator (VSIM), which is used in the actual Simulator Validation.

After completion of Initial training, pilots with a certain level of experience in Flight Inspection would be certified to conduct Flight Validation for High-Performance PBN. Even the certified personnel should take periodic training to maintain their skills, moreover, to catch up with the latest IFP design and new CNS/ATM concept.

	Contents
1	Flight Validation and Inspection
2	AIS
3	WGS84
4	PBN concept
5	Geodesy
6	ATM
7	IFP design
8	Aerodrome
9	Quality Assurance
10	ARINC424 Coding
11	Aeronautical Chart
12	FOSA
13	Human Factor
14	Aircraft Operation and Performance
15	Simulator Evaluation
16	Documentation for the results of flight validation

Table 4. Subjects of Flight Validation for Pilots

Fig. 2 B737-800 VSIM (Desktop Simulator)

3.3 Training Program for Radio Engineers

Government Authority is responsible for quality assurance of all of the promulgating IFPs. For that purpose, the Authority also should preserve and manage complete the package including all the considerations regarding IFP process. Radio Engineers are responsible for data acquisition and preservation. In the conventional Flight Inspection scene, they analyzed data of aeronautical radio facilities with FIS.

Even in Flight Validation, their mission is basically same, i.e. Radio Engineer acquires and analyzes the data to confirm the performance of Navigation aids supporting IFPs such as GNSS and DME/DME. Besides, for the integrity of IFPs, Radio Engineer must preserve all related data they acquired and used. Hence they should learn following items;

- ➢ Quality Assurance
- ➢ Differences in Flight inspection and Flight Validation
  - ✓ Flight inspection is one of the items that are essential to flight validation, whereas the evaluation activities of air navigation facility alone, and flight validation is an evaluation activities containing aviation security facilities to be used in IFP, fly ability, and obstacle, comprehensive to ensure the quality of IFP.
- ➢ Aeronautical Information
  - ✓ Configuration of aviation information
  - ✓ RTCA document DO-200A & 201
- ➢ Knowledge on Information Technology
  - ✓ Knowledge on the following items that were based on the knowledge on programming and general database

    Knowledge on following items; ARINC424 & NDB coding

●	Quality of FMS NDB
1	Overall Process
2	AIRAC Delivery Cycle
3	Common Error
4	Quality Management of NDB
5	Compliance with DO-200A/201A

●	Outline of FMS NDB
1	Standard Data & Company Data
2	FMS Flight Planned Route
3	Old/New Cycle

●	Data Coding of IFP
1	Steps of Data Coding
2	ARINC424
3	FIX & Waypoint
4	Leg Type
5	Path Terminator Coding Rule
6	Coding Practice

  - ✓ Knowledge on XML (Extensible Markup Language) and analysis AIXM
  - ✓ Understanding on surveying various algorithms
- ➢ Knowledge of flight inspection for GNSS & DME / DME
- ➢ ICAO Doc.9849 (GNSS Manual)
- ➢ Application knowledge
  - ✓ Analysis of Tailored NDB
  - ✓ Knowledge of decoding ARINC424
- ➢ Method of data verification of validated Tailored NDB and AIP
- ➢ Knowledge on AIXM4.5 data handling
- ➢ Method of calculation for the DOP / protection level from the geometry of the GPS and determining the presence or absence of radio interference from the placement and the actual number
- ➢ Potential interference to the wireless device mounted on the aircraft

3.4 Tools and Aids for Radio Engineer Training

All trainees are required to acquire the several new knowledge and skills during the training. JCAB has developed some software designed for supplement of such new concepts. Those tools have been used for not only training but also actual Flight Inspection and Validation activity.

a) **Training tools for GNSS Flight Inspection**

FD/FDE Availability Monitor has been developed for education of GNSS and its Flight Inspection. It can calculate the availability of GNSS core-constellation including GPS and SBAS satellites.

Its world-wide coverage enables us the real-time calculation of GNSS satellite geometry from the present point to 6 hours into the future. The calculation is based on TLE (Two-Line Element set) provided by NORAD (North American Aerospace Defense Command). *FD/FDE Availability Monitor* processes this simple plane text and generates the visualized satellite status at the specified moment.

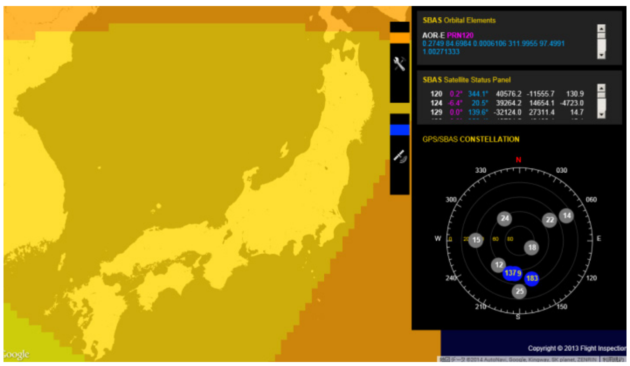

Fig.3 FD/FDE Availability Monitor

Trainees can learn how the satellite geometry affects the accuracy of aircraft's position estimation by this software. Furthermore, they can compare the actual and the simulated geometry in the flight, and find out the existence of the interference. As an indicator of GNSS Availability and performance, Dilution of Precision (DOP) is the one of the most important elements. Trainees are able to learn and understand visually the mathematic theory of DOP by the software designed for educational purpose.

JCAB Flight Inspectors are using those software and RAIM NOTAM provided by ATMC (Air Traffic Management Centre) as one of the basis for their decision-making.

b) **Tools for Database Validation**

For the quality assurance of Aeronautical Information, JCAB Flight Inspector is provided the Snapshot of Static Database in Aeronautical Information Service Center (AISC) every AIRAC. Those provided data are coded in the AIXM format, which is designed to enable the management and steady distribution of Aeronautical Information.

AIXM-NDB Parsing Program (ANPP) has been developed by Flight Inspector for the validation of that AIXM data. ANPP can decode and extract all of the information contained in the AIXM format, and display them visually like web interface. In addition, ANPP has two calculation methods in order to verify the difference of IFP design tool and FMS algorithm, and can display the calculation result on the map.

Not only trainees but also almost all of personnel are using ANPP routinely for data extraction. They can therefore understand the importance of IFP Data-Chain and Database Validation intuitively.

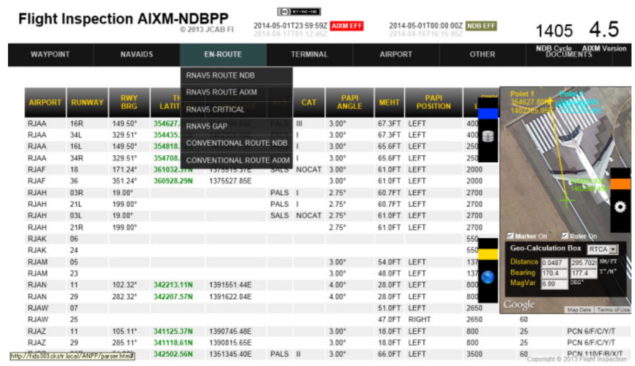

Fig.4 AIXM-NDB Parsing Program

As well as Pilots, Radio Engineers already have enough knowledge and experience on conventional Flight Inspection. Therefore, the main subjects of training for Radio Engineer are focused to the items as follows;

- ✓ Flight Inspection of Satellite-Based radio aids
- ✓ Quality Assurance and Database processing

At first, all trainees have to take 20-hour basic course on CBT. After completion of CBT, trainees who have basic knowledge on Quality Assurance would learn more advanced contents from certified instructors, and conduct actual Flight Validation to acquire the all requirements. With enough experience of Flight Validation, they proceed to final exam including oral test and practical skill test. After passing all of the examinations, they would be certified to conduct all activities regarding Flight Validation.

ICAO	● Annex 4 Aeronautical Charts ● Annex 6 Operation of Aircraft ● Annex10 Aeronautical Telecommunication ● Annex14 Aerodromes ● Annex15 Aeronautical Information Services ● Doc.8701 Manual on Testing of Radio Navigation Aids ● Doc.8697 Aeronautical Charts Manual ● Doc.8168 PANS-OPS ● Doc.9137 Airport Services Manual ● Doc.9613 PBN Manual ● Doc.9849 GNSS Manual ● Doc.9906 Quality Assurance Manual for Procedure Design
FAA	● N8260.67 Flight Validation of Satellite-Based Performance Based Navigation（PBN）Instrument Flight Procedures（IFP）-Current Guidance and Criteria ● FIM Order 8200.1C Flight Inspection Manual ● TI 8200-52 Flight Inspection Handbook ● AC90-113 Instrument Flight Procedure Validation（IFPV）of Satellite Based Instrument Flight Procedures（IFP）
RTCA	● DO-200A Standard for Processing Aeronautical Data ● DO-201A Standard for Aeronautical Information

Table 5. Documents referred in training of Radio Engineers

	Contents
1	Flight Validation and Inspection
2	AIS
3	WGS84
4	PBN concept
5	Geodesy
6	ATM
7	IFP design
8	Aerodromes
9	Quality Assurance
10	ARINC424 Coding
11	Aeronautical Chart
12	FOSA
13	Aircraft Operation and Performance

Table 6. Training syllabus for Radio Engineers

4. ACTIVITY OF FLIGHT VALIDATION PILOTS AND RADIO ENGINEERS

4.1 Participation for FOSA

The certified Pilots and Radio Engineers also take part in Flight Operational Safety Assessment (FOSA), the technical conference convened to identify all hazards and risks of the IFP, and ensure operational safety objectives. The participants are composed of several experts from Safety Department, ATC, ATM, Procedure Designer, ANSP, Airlines and Flight Inspector.

a) Process for Publishing RNP-AR IAP and the Position of FOSA in these sequences

Fig. 5 shows FOSA basic work flow in Japan. The safety of new High-performance PBN IFP should be evaluated from various aspects. After desktop-assessment by FOSA, actual Flight Validation would be conducted.

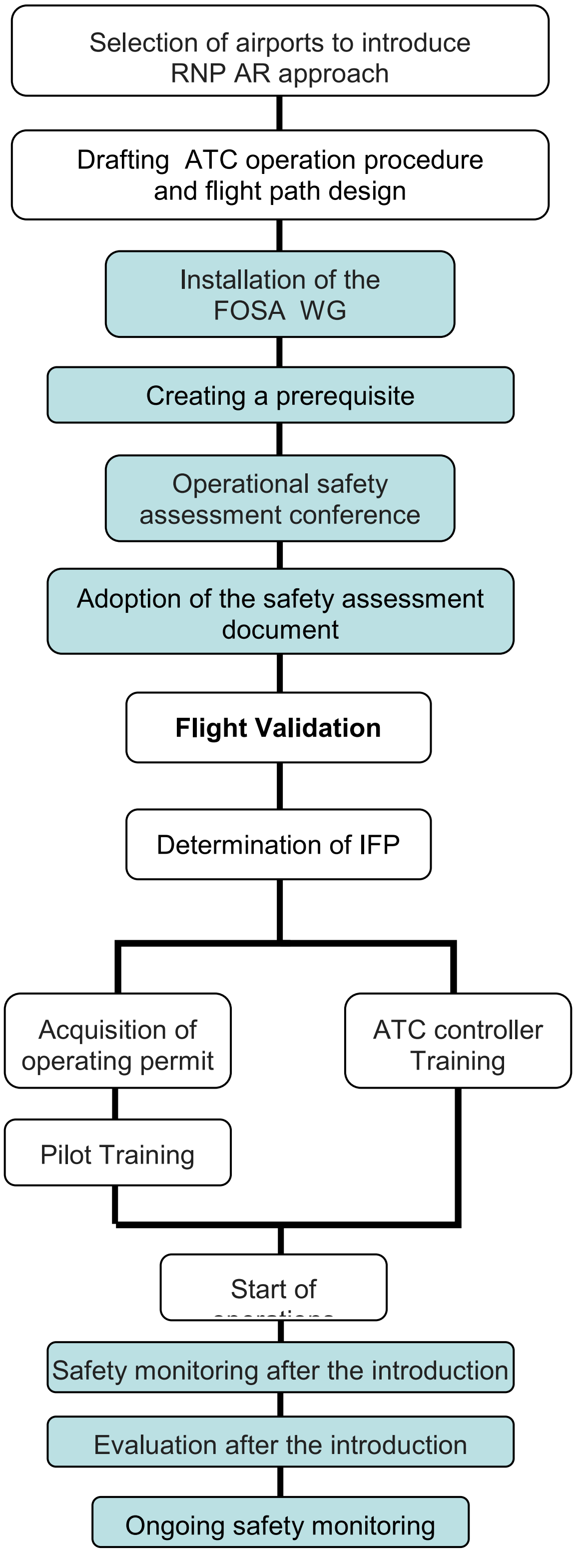

Fig. 5 Process for Publishing RNP-AR IAP and the Position of FOSA

So far FOSA has been held 16 times in Japan. Among them, the FOSA for RJFT RNP-AR in 2012 was especially good example that Flight Inspector played highly important role. During Flight Validation process of that IFP, an unexpected hazard was detected, and re-evaluation was requested by Flight Inspector.

b）Role of Flight Inspector in FOSA – Example of publishing Kumamoto RNP-AR

Kumamoto airport (RJFT) is located at the center of Kyushu Island, west of Japan. Neighboring Kumamoto city is the second largest city in Kyushu area, and this airport has relatively high demand for air transportation.

Around this area the dense fog is often formed, and Kumamoto airport has high-category (CAT-IIIa) ILS on Runway 07. On the opposite side (Runway 25), however, any proper conventional approach procedures could not be established with the present design criteria due to mountain range lies in the east side of the airport. In case of westerly wind, airlines had trouble to make landings on Runway 25, hence airlines had ever requested to JCAB to solve this problem.

Fig.6 Location of RJFT in Japan

In 2012, new RNP-AR approach was finally designed and accordingly FOSA was held for this flight procedure. During the subsequent Flight Validation process, a critical hazard was detected. The original design of the RNP-AR trajectory was considerably close to the specified 4 airspaces for Air-sports, such as hang gliding and paragliding. Flight Inspector proposed the solution against this hazard in FOSA, and the re-evaluation was conducted to analyze the risk in detail.

Hazard	Existence of sky sports area
Consequence	Closure to paragliding Airspace
Risk severity	Safety factor decrease Hazardous
Risk probability	Possibility Remote
Causes	Causes mitigation

Table 7. Risk management of FOSA

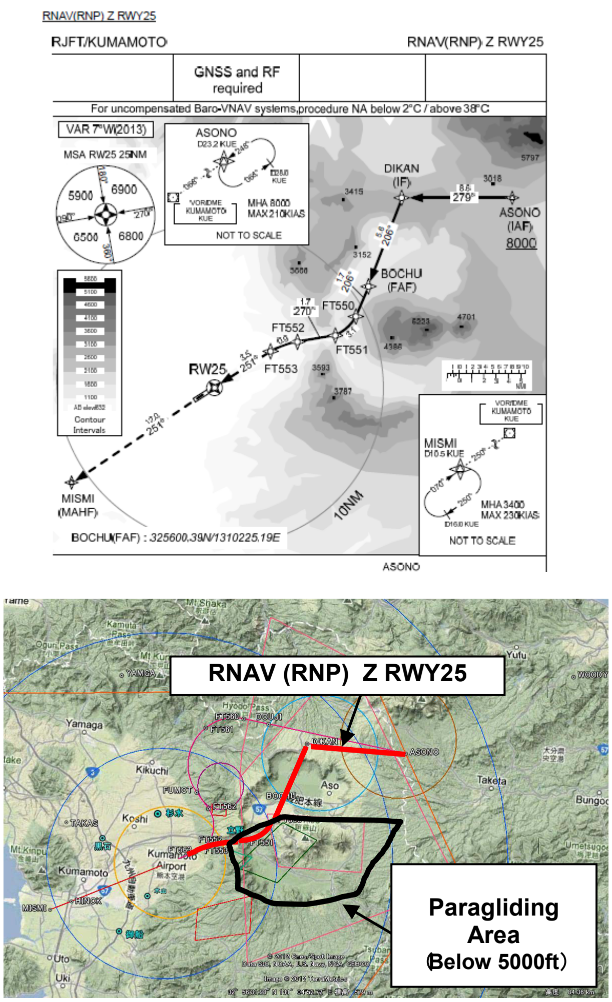

Fig. 7 Locational relationship of airspaces for Air-sports and planning route

As a result of the re-evaluation, this hazard was categorized as “Acceptable”, under condition of the following items;

(1) This approach procedure should be used only in night hours, and AIP approach chart should mention “Night operations only”

(2) Aircraft Operator can request this approach procedure during the specified periods as the condition;

- ✓ Estimated time of arrival to IAF should be within 30 minutes before sunrise
- ✓ Estimated time of arrival to IAF should be beyond 30 minutes after sunset

(3) Air Traffic Controller can give the permission for use this approach procedure during the specified periods as the condition;

- ✓ Estimated time of arrival to IAF should be within 30 minutes before sunrise
- ✓ Estimated time of arrival to IAF should be beyond 30 minutes after sunset

(4) Government Authority should provide proper safety instruction and materials including terrain and altitude information regarding this procedure.

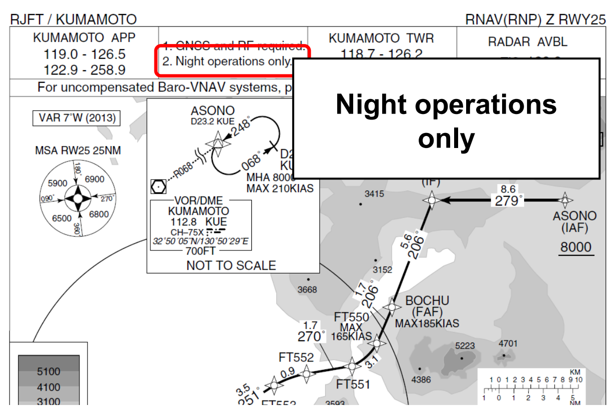

Fig. 8 Finally published RNAV(RNP) Z RWY25

Flight Inspector contributed to FOSA, and played the leading role to solve the problem by the knowledge skills and experiences acquired through the above-mentioned training.

4.2 Training Cooperation for Neighboring Countries

In recent years, JCAB has been corroborating with Japan International Cooperation Agency (JICA) to offer the basic program on Flight Validation to the neighboring countries.

Date of training	Contains of training
Sep 2012	● Air navigation system safety and efficiency improvement projects ➢ New CNS/ATM（RNAV）(in Japan)
Jan 2013	● Development projects related to the transition to the next generation aviation security system ➢ Flight inspection and validation training in accordance with the PBN IFP
Jan 2013	● Aviation safety policy improvement project ➢ The PBN IFP validation training for flight inspection personnel
Aug 2013	● Development projects related to the transition to the next generation aviation security system ➢ Flight inspection and validation training in accordance with the PBN IFP (in Japan)
Oct 2013	● Aviation safety policy improvement project ➢ Flight inspection and validation training in accordance with the PBN
Feb 2014	● Aviation safety policy improvement project ➢ Flight inspection and validation training in accordance with the PBN

Table 8. Training provided in neighboring countries in recent years

JCAB has prepared to offer such training program responding to several requests. It is expected that the training program will contribute to development of PBN in several countries arranging their circumstances.

5. CONCLUSIONS

As stated above, JCAB has developed the effective training system for Flight Validation via various researches on International Standards. Certified Pilots and Radio Engineers have contributed to the implementation of the large number of PBN procedures by taking part in IFP design process. Recently the know-how that JCAB has accumulated and the training program contributed to other countries to support their PBN implementation. The training program is expected to be hereafter demanded by both internal and external organizations.

The training program is designed to build up the personnel with a certain level of experience in Flight Inspection. The instructors are appointed among the skilled Flight Inspectors, and the personnel are continuously trained according the above mentioned syllabus, and stacking skills and experiences step by step.

However, the method of this training contains some problems.

First, at present, there is no International Standards or regulations concerning the level of achievement and its evaluation. The skill levels of each trainees and lecturer are considered separately, but both of them should be considered mutually for the proper evaluation of level of achievement. And the quality of training materials is critical element for the whole training too. JCAB has defined the original Goals of training for each subject as described above by itself.

Second, the proportion of each Flight Validation and Flight Inspection is changing, and its transition speed is accelerating. About both airway and terminal flight procedures, JCAB is planning to deploy high-performance PBN supported by new facilities e.g. GBAS. On the other hand, JCAB is also planning to withdraw the conventional navaids, especially VOR used for airways. Under these circumstances, it is very necessary to update the training program to catch up with the latest technology, e.g. GBAS and the other navaids for PBN procedures.

And finally, with the progress of the times, the more operational efficiency has been demanded. Education and training is no exception, therefore JCAB has ever made effort to achieve the required level of efficiency.

However, the present training scheme has to take too long time to grant the required skills and experiences as a Flight Validation specialist. It is desired to introduce a new training method that is capable of applying the higher capacity in more short term, so called "*Competency-Based Training*" method.

JCAB defined the required competency-level individually, but we have no criteria reflecting the global aviation industry. So it is necessary to define ideal figures, i.e. *what it should be for Flight Validation specialists* with a concrete description.

Therefore JCAB propose to sort out common definition of *"Competency Level"* for Flight Validation specialists. Besides, in order to introduce "*Competency-Based Training"*, it is essential to develop training method and materials such as Standard Training Package (STP). To make a scheme for each countries to share those method can contribute to the standardization of the quality of Flight Validation specialists of the world.

6. FUTURE WORK

In 1989, ICAO established "TRAINAIR Program" to meet the demand for Air transportation and increase in sophistication. And in 2006, PANS-TRG was published aiming to optimize the training for Pilots. It regulates all the required procedure in actual flight. Moreover, the "*Competency-Based Training*" concept was implemented into the Multi-crew Pilot License (MPL) training. On the other hand, Next Generation of Aviation Professionals (NGAP) Task Force was formed in 2009, and one of its Working Group (ATM-WG) stipulated the training manuals for Air Traffic Safety Electronics Personnel (ATSEP). Regulations and Manuals for Pilots and Radio Engineers have made steady progress.

Under the present circumstances, JCAB should adopt the concept of Competency-Based method and revise the Flight Validation training program.

As the long-range view, it is expected that required competency level of personnel will be considered in detail, and International Standard for Flight Validation will also be stipulated by ICAO.

Integrated CRM/TRM Concepts Applied to FIV Flights and Ground Activities

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ABSTRACT

Safety is paramount in any complex flight operation. Flight Inspection Validation (FIV) flying has an increased exposure to potential threats due to environmental factors (low level, high speed, turbulence, air traffic, birds and other factors). So thereby involving the entire crew to mitigate risk, not only the pilots, will increase safety and have benefits in terms of efficiency and the quality of the final results. Expanding this concept to the whole flight inspection operations group (Ops, Maintenance and Administrative personnel) has the potential for even greater benefits. ENAV's implementation of this concept, both in the experimental and operational phases are reviewed to highlight the advantages and discuss how to correct the drawbacks, if any, of this innovative approach to cooperative interaction of all the "players" involved.

The project was born to contribute to the achievement of high safety standards, through a structured training and checking method, and a continuous improvement of non-technical skills (NOTECHS), according to regulatory provisions.

Specifically the project has the following operational objectives: creation of an internal department that deals with CRM and NOTECHS development in order to provide training, evaluation and development tailored to Flight Inspection and Validation needs. Training and updating according to the latest Human Factor Concepts and Management of Just Culture, as foreseen by ICAO, and finally providing the required integrated CRM training to our Flight Inspection Validation Dept.

INTRODUCTION

Over the years, the concept of team integration has become the mainstay of any complex operation. When operating in an environment with a high technical content and a low tolerance to errors, it is important to manage all the available resources in the best way possible to mitigate risks.

More than just relying on technology and the efficiency of a procedure, the quality of the performance of the crew is fundamental. Operational performance is a result of integrating technical training and non-technical training thereby reflecting the ability of the crewmembers to integrate and collaborate, in other words, CRM – Crew Resource Management.

CRM IN AVIATION

CRM can be defined as "The efficient use of crew resources with the scope of maintaining an elevated level of safety". It is a flexible and systematic method for optimizing human performance through structured training of NOTECHS (Non-Technical Skills), learning about threat and error management techniques and promotion of a culture of safety (Just Culture).

The roots of CRM date back to the late ‘70s as the result of the investigation of aircraft accidents, which made it clear that the main cause was due to “human error” such as communication, leadership, decision making, etc. From this, CRM training was born. Its aim is to reduce error by making better use of human resources in the cockpit.

INTEGRATING CRM AND TRM FOR THE PURPOSE OF FIV OPS

In any type of flight operation, safety is a function of the quality of the human performance which comes from technical training and how it is applied.

It has been known for some time that human error is a contributing factor in more than 70% of aircraft accidents. The risk of human error increases in conditions where the flight operations take place in a complex and ever changing environment.

Flight Inspection operations take place in high-density traffic environments where a multi-pilot crew must integrate and coordinate their activities in order to complete the mission safely. Therefore, it is necessary for the crew to be prepared, not just in terms of technical training but also in the management of non-technical skills, which are crucial for flight safety.

Having noted how important it was for a full integration between the various players that are needed to plan, execute and make a FIV mission successful, ENAV started a project to develop a specific Integrated CRM Training Course for such missions. The goal of the 5-year project was to obtain CAA certification according to a plan specified below.

The CRM Training objective was to develop the NOTECHS on a cognitive, organizational, interpersonal and communicative non-specific technical expertise level, which are equally important for the success of a mission. When these standard behaviors are put to use by pilots, it makes flight operations safer. The behaviors specified in the NOTECHS training are practiced through the CRM and are evaluated together with the technical skills during simulator checks and on missions.

The need to create CRM Training dedicated to FIV Flying comes from the type of mission and the crew. These are differentiated from commercial airline flights in the following aspects:

-CREW: The Flight Inspection Crew is composed of two pilots and a systems engineer who works inside the aircraft.

-MISSIONS: The activity takes place in an environment of high density traffic. The performance of the aircraft, the objectives of the mission and the stress levels are much more elevated than commercial flight activities.

-TRAINING: The training of Flight Inspection Pilots is different compared to airline pilots. They are different when it comes to professional experience, previous training and previous profession (some were ATC, while others were airline pilots or commercial pilots) as well as experience in different types of aircraft and the type of operation flown.

-ORGANIZATION: In our case, the Flight Inspection Group is smaller than most airline companies and is incorporated within ENAV. The number of crewmembers is small and therefore there is a close daily contact between them.

The basic crew to perform a FIV mission is three: a captain, first officer and systems engineer. They all contribute to the safe outcome of a flight. They are all directly involved in the mission so they must contribute to the overall safety of that flight. Dispatchers are important and fundamental as well, because they are the first line of defense against operational errors (underestimation of weather conditions or airport/facilities status, for example) and they do an invaluable job in providing coordination with all the parties involved in a FIV mission. Furthermore, maintenance technicians are obvious involved in keeping the aircraft and systems in perfect condition. Safety and efficiency of the flight is in their hands as well.

The creation of a CRM and NOTECHS Training Dept. that is functional and efficient was made possible by involving the entire organization in an integrated safety approach. The change in management culture provided fertile ground for this study, which was approved in 2011, with the intent of reaching initial independent capability in providing training by the end of 2013.

THE MASTER PLAN

The ENAV project “Contributing Human Factors for the safety of flight inspection flights” was launched in October 2010 by the Human Factor department. It has the principle objective to contribute to achieving high standards of safety for flight inspection operations through the establishment of a standardized model of training, checks and continuing improvement of NOTECHS for the operational crews according to EU-OPS1.

To best reach the above objective (A), the program included two other objectives (B and C) as equally important to achieve the primary objective.

Objective A: Creation of an internal CRM structure

Objective B: Initial and Continuing Training on Human Factors and Just Culture for Middle Management (ICAO)

Objective C: Building and delivering CRM courses by integrating relevant professionals.

To achieve each of these objectives, three phases were laid out; an analysis, supervision and follow-up phase.

1. Development of Internal CRM/NOTECHS Training

This was the starting point for constructing a "matrix" for NOTECHS dedicated to flight inspection operations, which was in line with the standards and consequent development of a CRM ad hoc.

1.1 Building of NOTECHS

- Building a Matrix:

The NOTECHS Matrix was an integration between a matrix used for commercial aviation and behavioral indicators built from scratch based on flight inspection operations. To discover these indicators, Human Performance experts from ENAV observed operational tasks done by the crew inflight and in simulators to identify crucial NOTECHS. At the same time, pilots were interviewed singularly and as a group to analyze what were the distinctive NOTECHS needed for flight inspection operations. From this study, 4 skills were identified.

- Communication
- Interpersonal Relationships
- Workload Management
- Situational Awareness and Decision Making

Each of these skills were divided into 3 subcategories and a list of 20 behavioral indicators was created for each category. The behavioral indicators were subjected to the scrutiny of pilots through focus groups. The most significant indicators were selected. This led to the first draft of the NOTECHS Matrix which was trialed in 2012 during simulator checks. In 2013, Type Rating Examiner (TRE) and Human Performance experts validated the Matrix through validation checks. This led to the final draft of the matrix.

- TRE Training: The proceeding phase was dedicated to training of the TRE for observation, validation and feedback of the NOTECHS. The training process included theory and practical training based on the evaluation of NOTECHS. In particular, they were given methodological tools to independently perform the first evaluations of the NOTECHS in the simulator. ENAV Human Performance Experts were present during simulator sessions to supervise the evaluation activities and to give feedback to the TRE. It was followed by a debriefing on the NOTECHS and "coaching" for the TRE on their evaluation skills.

1.2 Construction of the CRM

The first step in individualizing the NOTECHS for CRM Training were determined during flight and simulator observations. A number of CRM discussion points were identified and submitted to working groups made up of our pilots. A focus group method was used and discussions were stimulated by:

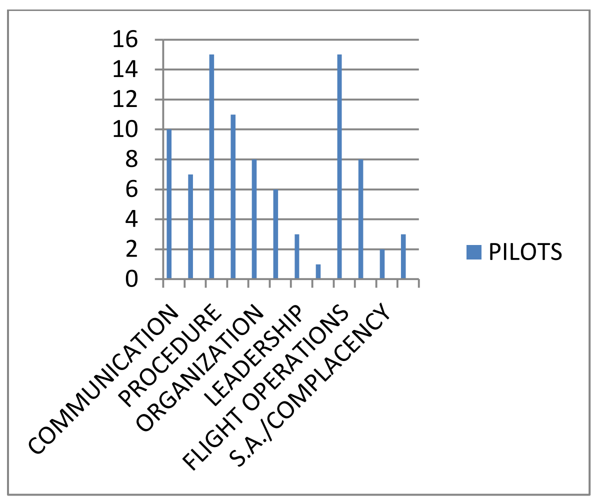
-Identifying the consistency of the content with respect to Flight Inspections;

-Identifying priority areas for intervention;

-Having any needs for CRM not highlighted to come out

The results of the working groups are shown below

Table 1 N=16



Pilots Total n= 16

The results showed that communication, teamwork and stress/workload management were the principle instructional needs. Other points such as procedure, organization and flight operations were not chosen as points to be covered in the CRM but were referred to management to improve the awareness of the potential problems perceived by the pilots for possible intervention.

-Case Studies: For effective analysis and reflection of the CRM, case studies were designed ad hoc based on flight inspection operations. Through the collaboration of pilots and ENAV Human Performance Experts, scenarios consistent with flight inspection operations were built and presented to the pilots in the flight simulator located at the ENAV Academy in Forli. The scenarios were videotaped and are now part of the CRM training.

From this, CRM Training was built reflecting real life operations of the ENAV Flight Inspection Dept. while complying with the requirements of the regulations currently in force.

-CRM Facilators: In line with the regulations, the pilot CRM facilitators were chosen (2 pilots and 2 captains) and for better integration in CRM Training, 2 FIOs were inserted.

The CRM facilitator training has 4 phases:

Participation in a CRM Flight Inspection Course;

Participation in a Train the Trainer Course for conducting classes (taught by the ENAV Academy);

Participation with the classroom in co-presence of a Human Performance Instructor;

Conduct CRM Recurrent Training Courses supervised by ENAV Human Performance Experts.

MANAGEMENT SUPPORT

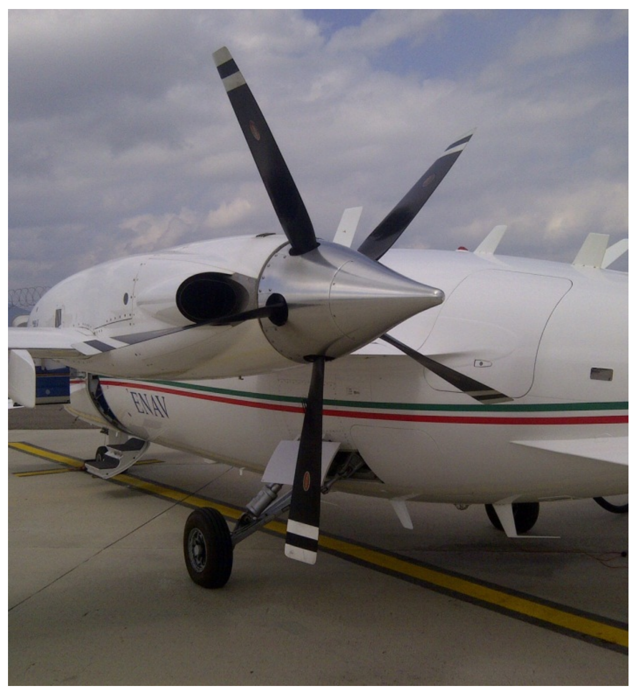
The training of management personnel for improvement of the Just Culture is an ICAO request and in our case, it is needed to support the management in a crucial moment of change. Human factors is inserted in during reorganization, recruitment of new resources and dismissal of others. The involvement of management in the project has the aim of not only contributing to the efficiency and effectiveness of the crew but the well-being, productivity and safety of the entire organization.

The training requirements for management in part was met through the NOTECHS Training as the role of the TRE was done by those who held managerial positions. At the ENAV Academy, we had the chance to get to know the entire training process, evaluation and the development of the NOTECHS for pilots and compare them to the role of management in the development and aid of the Just Culture. To accomplish this, there were individual interviews to discuss the points more in-depth and identify eventual training needs. Furthermore, the presence of the ENAV Human Performance Team at the flight inspection headquarters and during the various phases of training in the simulator enabled the implementation of coaching. Management is currently in the phase of being supervised.

INTEGRATION OF PROFESSIONS

With the objective of improving effectiveness and efficiency in organization not only front line personnel (pilots, technicians, mechanics) were involved in the project but everyone who contributed indirectly to producing a quality service and maintaining a high standard of safety. We proceeded in the first phase of an organizational analysis through field observation and personal interviews with them. Once the needs and critical issues were known, the first steps to integration were to insert them into the CRM Course along with the pilots. Successively, TRM – Team Resource Management courses were successfully integrated among the various professions with the aim of improving the integration between roles and diverse functions and improving everyone's awareness of how their work fits into others, affects safety and the final product.

Pic. 1 P180 Avanti II FIV Aircraft



RESULTS

Based on the applied methodology and thanks to the open collaboration between the various professions involved in the project, the results are as follows:

- NOTECHS MATRIX

The matrix is dived into 4 areas and each has 3 elements. Each element is a behavioral indicator.

Table 2 NOTECHS Flight Inspection Matrix

CATEGORY	***ELEMENTS***
COMUNICATION	• **ATMOSPHERE**
	• **TRANSMIT**
	• **MANAGEMENT**
INTERPERSONAL	• **LEADERSHIP**
	• **TEAMWORK**
	• **CONFLICT MANAGEMENT**
WORKLOAD MANAGEMENT	• **TASK**
	• **TIME**
	• **STRESS AND ERROR**
SITUATION AWARENESS & DECISION MAKING	• **SITUATION AWARENESS**
	• **PROBLEM SOLVING**
	• **DECISION MAKING**

- Building and Delivering a Flight Inspection CRM Course:

The basic CRM Course has the following modules:

Table 3 Basic CRM Modules

-Introduction
-Errors
-TEM-Threats and Error Management Method (adapted to Flight Inspection)
-Situation Awareness
-Decision Making
-Stress, Fatigue, Workload
-NOTECHS for Flight Inspection Operations
-Communication
-Teamwork and Leadership
-Safety Culture

- CRM facilitators Training:

The CRM Instructors have completed the training for instructors and are in the phase of copresence in the classroom. In the next step, they will be teaching autonomously.

- Integration of Professions:

The need of an integrated CRM Course, as mentioned in the third objective, to integrate the various professions includes an integrated CRM course for technicians with the pilots.

- Management Support:

Activities were carried out to support and coach management, which contributed to the improvement of the managerial skills for the new CRM, NOTECHS and integrated organizational activities. This improvement was not only determined by the increase in the level of self-efficacy satisfaction of the managers involved but also above all, by a constant improvement of the overall company performance and the quality of service offered by the ENAV Flight Inspection Group.

CERTIFICATION

The entire process was monitored by the national CAA, with regular meetings and reviewing of the material. The final stage of the certification involved the modification of the Operations Manual part D, Training Manual, to include the CRM training syllabus and the approved CRM Instructors/Facilitators. The joint effort of the Human Factor Department and that of the FIV Department was completed within the allocated timeframe.

ONGOING TASKS

Activities that will take place in the near future:

-CRM/NOTECHS: Building of CRM Recurrent Training with collaboration between instructors and Human Factor Experts, supervision of instructors, supervision of the TRE.

-Management Support: Supervision and coaching activities for Middle Management

-Integration of Professions: Develop TRM (Team Resource management) courses for maintenance personnel, operational and administrative office personnel. Supervision and continuous improvement of safety will be carried out by an Organizational Risk Assessment that is to say an analysis of organizational risks perceived by the operators directly (pilots, technicians, mechanics) rather than middle or upper management. The objective is to intervene in a focused and proactive way in the management of real risks. In addition, develop a method of analysis and error handling through the application of valid and reliable tools, utilization of successes in other fields and accredited in the aviation world

RESULTS AND CONCLUSIONS

There are four major points that we have to look at to trace the results. These points are Safety, Flexibility and Economics, Operations and Working Environment.

Safety: We are always looking for ways to maintain or improve the safety level of our operations. How much this will contribute to the overall safety is hard to define in numerical terms, but statistics are clear across the aviation industry, that a dedicated, operations specific, and integrated CRM is the right tool to work with.

Flexibility and Economics: We no longer depend on an external Training Service Provider since all the resources to provide the training are "in house" at no additional cost. This is a budget advantage, although not huge, but visible (about 2% of the direct training costs, or 1.25% of the total budget of the Flight Crew Training Office*).

Operations: An increase in mission efficiency has been noted. There are indications that this result is the natural byproduct of point number four below. We have metrics to define mission parameters, and those are closely monitored for any needed changes.

Working Environment: One the best results obtained and immediately visible without any need of a specific metrics, is the change in the general atmosphere. The possibility to freely express personal thoughts during the training (in the open) and in the initial interviews (privately) had the effect of solving some conflicts, smoothing out corners, lowering the overall stress level and, in general, made the working environment a more enjoyable place.

LIST OF ABBREVIATIONS AND ACRONYMS

CAA	Civil Aviation Authority
CRM	Crew resource Management
FIO	Flight Inspection Operator
	(Flight Inspection System Engineer)
FIV	Flight Inspection and Validation
ICAO	International Civil Aviation Organization
NOTECHS	Non-Technical Skills
TEM	Threat and Error Management
TRE	Type Rating Examiner
TRM	Team Resource Management

REFERENCE MATERIAL

ICAO DOC 9683 Human Factor Training manual

ICAO DOC 9824 Human Factors Guidelines for Aircraft Maintenance Manual

UK CAA CAP 1179 A strategy for human factors in civil aviation

ENAC (Italy) Safety Plan 2012-2015

EASA European Aviation Safety Plan 2013-2016

IFIS 2014

Flight Plan to Innovation

Session 11

Flight Inspection Standards

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Recommended Qualification Requirements for Flight Inspection Service Providers

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ABSTRACT

ICAO Annex 10 Volume 1 requires that Navigational Aids are routinely flight inspected. Doc 8071 provides guidance on how to conduct the flight inspection. DOC 8071 also provides some guidance on the make-up of flight inspection organisation. This includes People, Equipment and Procedures.

To date there are no internationally agreed standards for the oversight of flight inspection service providers, some states do provide oversight of the service providers through locally produced regulatory material. During the tendering stage for a flight inspection contract the Air Navigation Service Provider may require that the flight inspection service provider is approved by their CAA. This may cause problem for states which do not provide oversight of the flight inspection service providers.

As flight inspection is considered to be a maintenance activity there is a general requirement that the flight inspection arrangement should be fit for their intended purpose. As a result of feedback from several International Flight Inspection Symposia the ICASC has decided to provide guidance to the industry on the subject of Requirements for Flight Inspection Service Providers.

PURPOSE OF THIS DOCUMENT

The purpose of this document is to provide Recommended Qualification Requirements for Flight Inspection Service Providers for either a state CAA to implement into its own regulatory regime or for an individual flight inspection service provider to use for some form of self-declaration in the absence of any state requirement.

SCOPE

The scope of this paper covers measurement of the Signal in Space of a Navigational Aid. The paper does not include Procedure Validation as detailed in Doc 9906 Volume 5.

CAPABILITIES

A Flight Inspection Service Provider shall be capable of:

- Using flight inspection techniques to measure accurately the signals in space radiated by those navigational aids which they are intending to inspect.
- Evaluating the measured signals with respect to applicable standards and tolerances which should be established by the local regulator.

  Examples of typical standards are ICAO (Doc 8071 and Annex 10), or FAA 8200.1, or UK CAP 670.
- Communicating with ground engineers and technicians to advise if any adjustments are required to the equipment being inspected.

NOTE: The extent to which the Flight Inspection Service Provider provides information and guidance regarding the Navaid setting up to the ground engineer varies from state to state. This may mean that Flight Inspector *competence could be different from one organisation to another.*

- Providing a flight inspection report to the customer,

APPROVAL PROCEDURE

Applicants shall detail the overall Flight Inspection operation in an Exposition. The Exposition shall include evidence based demonstration that each of the requirements detailed below or set by the local regulator are adequately met.

A practical demonstration of the Flight Inspection Operation may be necessary to demonstrate the

Appendix 2

Accountable Manager

APPLICABLE STANDARDS

Doc 8071

The flight inspection should comply with the guidance and recommendations given in ICAO Doc 8071 to support the measurement of the parameters in ICAO Annex 10 Volume 1. Alternative methods may be proposed in the exposition as long as it is demonstrated that it meets the specific objective of Doc 8071.or Annex 10.

ICAO DOC 8071 provides tables with flight inspection requirements and tolerances for each type of navigation aid and a summary of the table headings is provided in Table 1.

Table 1. DOC 8071 Flight Inspection Tolerances

#	Facility	Flight inspection requirements in DOC 8071
1	VOR	Table I-2-3.Summary of flight inspection requirements — VOR
2	DME	Table I-3-3.Summary of flight test requirements — DME
3	ILS Localizer	Table I-4-7.Flight inspection requirements and tolerances for localizer Category (Cat) I, II and III
4	ILS Glide path	Table I-4-8.Flight inspection requirements and tolerances for glide path Categories (Cat) I, II
		and III
5	ILS Marker beacons	Table I-4-9.Flight inspection requirements and tolerances for ILS marker beacons
6	Non directional beacons	Table I-5-3.Summary of flight test requirements for non-directional beacons

performance of the Inspection Service. A practical demonstration does not replace the evidence based demonstration of the requirements. Details of a practical demonstration can be found in Appendix 1

The Exposition should include references to associated documentation as appropriate.

The exposition should address how the provider uses design, process monitoring, training and procedures to ensure the quality of the Flight Inspection results.

The Exposition should be Approval by the Accountable Manager. Details of the Accountable Manager can be found in

EXPOSITION

Content

The content of the Exposition should detail the overall Flight Inspection operation. The following sections provide some headings that would normally be included in an Exposition. The detail is not exhaustive and may vary from one flight inspection operator to another.

The headings assume that the flight inspection organisation does have a Quality Management System. The most appropriate headings that would normally be contained in a Quality Management System have been included.

SCOPE OF TASKS.

It is important that the exposition clearly identifies the scope of tasks that the exposition covers. This would include the types of navigational aids to be inspected, category of operation (For ILS) and the types of inspection e.g. routine or commissioning.

ORGANISATION

Organisation name

This should be the name that the flight inspection organisation trades under. This would normally be the legal entity.

Contact details

Address and Telephone Contacts.

Flight Inspection Organisational Chart

An organisational Chart should be provided detailing the roles that make up the flight inspection organisation. This should show the reporting lines up the accountable manager or board as appropriate. It is sometimes also necessary to show functions within the organisation this typically the case where several people perform the same task. For example surveying.

Interfaces with other internal departments and divisions

Where the flight inspection operation is part of a larger organisation it is important to ensure that all contributing departments, divisions or other organization involved directly or indirectly with the flight inspection operation comply with the flight inspection organisations exposition or quality management system as appropriate.

PERSONNEL RESPONSIBILITIES

Objective

The Organisation shall ensure that all personnel concerned with the flight inspection are competent to conduct their job functions.

Acceptable Mean of Compliance

The organization should establish a written procedure for determining required job competencies and continued competence checking of all personnel through regular assessment.

The procedure should consider all personnel directly engaged in the flight inspection operation, this includes but is not limited to the pilot (in terms of flying the correct flight inspection procedure), flight inspector, surveyor, documentation controller and auditor.

Flight inspection methods and strategies vary according to the type of equipment and procedure to be inspected. Consequently different types of qualification must be considered such as ILS, VOR, NDB, MLS, commissioning or routine inspection.

The organisation shall maintain records of competency including any on-going competency checking.

CHANGE PROCESS

Objective

The organisation shall ensure that all changes to the flight inspections operations are assessed and recorded.

Acceptable Means of Compliance

The organisation shall establish procedures for, assessing and documenting changes to all areas of the operation, this would normally include but is not limited to the:

- Organisational.
- System changes
- Procedure changes

Changes shall be identified and records maintained. The changes shall be reviewed, verified and validated, as appropriate, and approved before implementation. The review shall include evaluation of the effect of the changes on the flight inspection operation.

Records should be established to provide evidence of conformity to requirements and of the effective operation of the QM system shall be controlled, identifiable, stored, retrievable and protected according to procedure description (9001-4.2.4).

Documents required by the QM system shall be controlled according to established procedures to ensure proper handling of revision and changes (9001-4.2.3

Design and development changes shall be identified and records maintained. The changes shall be reviewed, verified and approved before implementation (9001-7.3.7).

Significant equipment modifications and renewal might still need approval by the principal or the CAA before implementation.

DOCUMENTATION CONTROL

Objective

The organisation shall ensure that all documents that support the flight inspection operation should be controlled so that the correct version of any document can be easily identified and used.

Acceptable Means of Compliance

A documented procedure shall be established to define the controls needed

- to approve documents for adequacy prior to issue,
- to review and update as necessary and re-approve documents,
- to ensure that changes and the current revision status of documents are identified,
- to ensure that relevant versions of applicable documents are available at points of use,
- to ensure that documents remain legible and readily identifiable,
- to ensure that documents of external origin determined by the organization to be necessary for the planning and operation of the quality management system are identified and their distribution controlled, and
- to prevent the unintended use of obsolete documents, and to apply suitable identification to them if they are retained for any purpose.

AUDITING

Objective

The organisation shall plan and implement the monitoring, measurements, analysis and improvement processed needed to ensure conformity of the QM system.

Acceptable Means of Compliance

To ensure consistent meeting of customer requirements and continual improvement of the QM system, the audit schedule must at least identify the following action items

- internal audits,
- customer satisfaction monitoring,
- management reviews,
- audits with independent certification body,
- external audits with sub-contractors, CAA and/or customer as appropriate.

CONTROL OF SUB-CONTRACTORS

Objective

The organisation shall ensure that sub-contractors are controlled.

Acceptable Means of Compliance

The organisation shall evaluate and select sub-contractors based on their ability to supply products and services in accordance with the organisation's exposition.

Criteria for selection, evaluation and re-evaluation shall be established.

Records of the results of evaluations and any necessary actions arising from the evaluation shall be maintained

The types of organisations that would be considered under this heading include:

- Test equipment calibration company.
- Other flight inspection organisations.
- Contracted Personal (e.g. Pilots, Flight Inspectors)

The same requirements for documents and records must be established and maintained by sub-contractors as appropriate, and verified by auditing. This task will normally be simplified if the sub-contractors have equal QM system

Monitoring of Subcontractor performance metrics covering areas such as reporting, testing and acceptance, issue resolution and mitigation and documentation version control.

A clearly written and well managed procedure defining all of the responsibilities associated with the role of a subcontractor or supplier will not only result in the success of the primary organization and their customer, but it will create a positive relationship with the other company or individual themself. This procedure must contain the following key components:

- A Source/Selection plan which establishes all guidelines beginning with first contact and issuance of initial documentation (eg. proposed SOW, RFI, etc), continuing through the proposal evaluation and selection criteria, and terminating with the communication of the final choice.
- Development of a work plan detailing key organizational reports , negotiation and management schedule, exit strategy details, expected milestones and deliverables.

Examples

OTHER FLIGHT INSPECTION ORGANISATIONS

If a service provider has limited recourses, like only one aircraft, or lack of capability to perform all sorts of required procedure tasks, it will make sense to establish a relationship with another such organization to make sure the inspections can be performed at all times without disruption. In such a case, the other organization should be described in the organizational details with adequate responsibility and performance. It is strongly recommended that such an addendum is applied for and approved by the principal, with all roles and responsibilities described, in due time before it may become required to use the additional service.

CALIBRATION EQUIPMENT SUPPLIERS

Instruments like Signal Generator need to be calibrated regularly as described by the instrument supplier. The service provider must make sure that all calibration tasks are fully described, like regular calibration intervals of the equipment as well as calibration of the signal sources.

TECHNICAL REQUIREMENTS

Flight Inspection System

Build State

The applicant shall maintain a build state document for the Flight Inspection System.

The build state document shall include the following for major components:

- Manufacturer
- Make
- Model
- Modification status

The build state document shall also include version numbers of all software and Firmware.

Details of all uses of software and firmware in the measurement system. Also details of software and firmware support.

The design authority for all equipment shall be stated

Doc 8071 Vol I, section 1.12.6 states "The build state of all equipment, including test equipment, should be recorded and the records should be updated whenever modifications or changes are made. All modifications should be accurately documented and cross-referenced to modification strikes or numbers on the equipment. After making any modification, tests and analyses should ensure that the modification fulfils its intended purpose and that it has no undesired side effects".

Functional description

Function block diagram and discussion of that diagram.

Technical specification

e.g. Data processing, storage capability, HMI

System Design

Physical block diagrams and discussion.

Manufacturer's type number for all major items of the flight inspection system.

Firmware and Software Design Description

Where the software or firmware is used within the system

Process ensuring that the software performs as specified.

Version control.

Algorithms for the measurements being made.

To a level to support the measurement uncertainty. Listing of source code is not required.

Recordings and Graphs

All recordings shall be time synchronised so that they can be correlated with the aircraft's position at the time of the measurement.

If recordings or graphs are used to derive figures for the inspection report, the scales shall be commensurate with the permitted measurement uncertainty limits.

All recordings or graphs shall have sufficient resolution.

Environmental Conditions

The operator shall define the environmental conditions (temperature range, humidity range, etc.). Evidence may be in the form of test results made by the operator, or manufacturer's specifications

If the measuring equipment requires any warm-up or cooling time, this shall be clearly indicated in the operating instructions.

Temperature dependent equipment may need to be fitted in a temperature controlled enclosure to maintain compliance with the performance standard.

An indicator/alarm may need be fitted to inform the operator of any change in temperature that may affect the accuracy of the system.

Consider monitoring of all parameter that influence the measurement uncertainty – provide examples.

Aircraft

Details of the aircraft used for flight inspection(make and type)

The aircraft with the installed flight inspection system should be airworthy and approved by the airworthiness authorities for the intended operation in the area it operates.

NOTE: aircraft type -preference should be given to multiengine turbine aircraft, for their reliability and performance. Pressurization and air conditioning should be available as a mean to reduce crew workload, increase safety and keep the FIS equipment within the technical specification. Standard avionics must match the airspace requirements.

Interference

The navigation aid measuring equipment shall not interfere with the operation or accuracy of the aircraft's normal navigation and general avionics equipment.

The Organisation still needs to ensure that all safety or regulatory requirements associated with the safe operation of the aircraft are met.

The flight inspection measurements shall be adequately protected against the prevailing EMC environment internal or external to the aircraft. Abnormal interference effects shall be clearly identified on the inspection Propeller Modulation

It shall be shown how propeller modulation can be avoided.

The formula below shows the propeller modulation frequency.

Propeller Modulation Frequency (Hz) =

Shaft Rotation Speed (RPM) x Number of Propeller Blades / 60

Examples:

3-blade propeller at 1800 RPM: 1800 x 3 / 60 = 90 Hz > BAD for ILS

4-blade propeller at 1800 RPM: 1800 x 4 / 60 = 120 Hz > OK for ILS

5-blade propeller at 1800 RPM: 1800 x 5 / 60 = 150 Hz > BAD for ILS

Independence from aircraft's operational avionics fit.

As far as is reasonably possible the flight inspection equipment, including associated aerials should be totally independent from the aircraft's operational avionics fit.

This is to protect both the integrity of the FI results and the operation capability of the aircraft avionics.

If not, show effect on measurement accuracy

If duplicated FIS navigation aid measuring receivers are used they may use a common aerial.

Location, characteristic and type of all measurement aerials on the aircraft

Consideration should be made to the aerials being positioned in such a manner that they are not obscured from the signal during any normal inspection flight profiles.

NOTE: To achieve this may require the use of more than one measuring aerial for one particular function.

Aircraft antennas are far from ideal isotropic receptors and the antenna gain will vary with both frequency and received angles (azimuth, elevation and bank).

Antenna characteristics for relevant sectors and frequencies must be compensated manually or automatically by the flight inspection system to obtain necessary accuracy for coverage measurements.

If duplicated navigation aid measuring receivers are used it may be possible to use a common aerial.

ICAO DOC 8071 Vol I, Attachment 1 to Chapter 1 describes recommended requirements for Flight Inspection Aircrafts.

Policy on Crew, Training and FTL (Flight Time Limitations)

Flight Inspection aircraft shall be employed as multicrew aircraft, with two pilots and a system operator. When a mission requires seating provision for other technical persons on board these should be available. E.g. training or observation.

Training shall be as such that initial and recurrent training and checking syllabi are approved by the CAA and clearly specified in the Operations Manual.

Policy on aircraft maintenance

Strict adherence to manufacturer and CAA technical requirements are mandatory.

MEASUREMENT UNCERTAINTY

The measurement uncertainty for any parameter must be small compared with the operational limits for that parameter.

Doc 8071 Vol I, section 4.3.86 includes a description of a 5^{th} of the value being measured.

The measurement uncertainty to 95% probability must be calculated for each of the parameters to be measured. The method of calculation and any assumptions made must be clearly shown. This includes all uncertainty contributions.

Where several measurements are combined to produce a single result, these errors should be added using a statistical model such as the RSS method (the square-root of the sum of the squares).

Example

An example could be calculation of localizer alignment error which is a product of the accuracy of the receiver, signal generator and position reference system:

Area of interest (worst case):
ILS point D.

NAV receiver error contribution:
Stated Accuracy: 0,0005DDM = 0,48 μA
Nonlinearity of receiver is eliminated in calibration procedure.

Signal Generator error contribution:
Stated Accuracy: 0,0003DDM + 2% of reading
0,0003DDM + 0,01DDM*2% = 0.0005DDM = 0,48 μA

Reference System error contribution
Assume a time stamped high accuracy position reference system is used with 5cm horizontal accuracy.
This will equivalent to an accuracy of about 0.10 μA @ ILS point D.

Total RSS Error:

$$LLZ\_Alignment\_RSS\_Error =$$

$$\sqrt{Receiver\_error^2 + Generator\_error^2 + REF\_System\_error^2}$$

$$= \sqrt{0{,}48\mu A^2 + 0{,}48\mu A^2 + 0{,}10\mu A^2} = 0{,}68\mu A$$

For measurements which can only be derived from recordings, the accuracy and resolution of the recording equipment shall be included in calculating the expected results.

Details of statistical methods or interpolative techniques which may be applied shall be described.

The flight inspection system shall include equipment which can determine and record the aircraft's position in space relative to the aircraft reference point.

The provider must clearly indicate the measures taken in order to reduce the budget errors in the positioning (e.g. : use of DGPS, geodesic database , care in setting up the positioning system on the ground,)

The aerials to be used for tracked structure measurements shall be positioned with due regard to the tracking reference on the aircraft. If the aerials and the reference are not in close proximity, this error must be addressed in the measurement uncertainty calculations and in setting the operational crosswind limit. Alternatively, the errors may be corrected using information from attitude and heading sensors to calculate the true position of the aerial's phase centre.

MAINTENANCE

Objective

Maintenance on all involved systems and equipment shall be performed.

Acceptable Means of Compliance

All equipment used in the maintenance and calibration process shall have traceability to national or international standards. e.g. ISO standards.

ICAO DOC 8071 Vol 1 describe requirements for calibration in Chapter 1.12.8 – 1.12.10. This requirements should be fulfilled.

Procedure for the control of Equipment used for calibrating the Flight Inspection system.

Procedures for maintenance and calibration of the Flight inspection System.

- Interval
- Description of the procedures
- Consider Who Where, What, When.

The flight inspection receivers of the system shall be calibrated at suitable intervals to maintain the system uncertainty within allowable tolerances between calibrations. The calibration interval recommended by the manufacturer should be monitored and adjusted if required in order to maintain system accuracy under the actual operational conditions.

The purpose of the calibration is the determination and compensation of non-ideal receiver characteristics for achieving the highest possible accuracy.

Reference signals from suitable, calibrated signal generator(s) shall be used as reference for the receiver calibration.

The receiver error shall be determined throughout the required measurement range of the receiver, in numerous steps.

The connection of the signal generator to the receiver under calibration should preferably be automatically (if technically feasible).

The calibration process shall compensate cable loss during calibration.

Due to the numerous signal generator settings during the calibration, the signal generator(s) shall preferably be steered automatically by the system.

Note: Incorrect settings of signal generators during calibration can be avoided to the highest extend by automatic control.

The determined receiver error shall be applied for compensation of receiver output in order to improve the measurement accuracy of the system during flight inspection.

The receiver output errors shall be checked against equipment specifications throughout the required measurement range. Automatic warning shall be given, if a receiver error is out of specified tolerance.

It is recommended to check the resulting performance of the calibrated receivers in the system against independent signal generator(s). This allows detection of errors during the calibration process or detection of a defective signal generator used for calibration.

The check of the calibrated receiver shall preferably also be automatically throughout the receiver's measurement range.

The result of the calibrated receiver check shall be recorded as evidence for the overall system performance.

Details of inspections, calibration and checks shall be recorded as evidence.

Operating Instructions

The Exposition should at least include concise details of:

a) Planning and scheduling process

b) The flight profile to be used for each individual measurement.

c) Pre-flight inspection of measuring equipment.

d) Siting of any necessary ground tracking or position fixing equipment.

e) Operation of the measuring equipment.

f) Production of the flight inspection report.

g) The method of calculating all results in the Flight Inspection Report. g) Pilot operating procedures

h) Cross wind limits - to allow measurement accuracies to be within the limits required.

i) ATC coordination

FLIGHT INSPECTION REPORT

The minimum information to be provided on the report shall be:

a) Station name and facility designation.

b) Category of operation.

c) Date(s) of inspection.

d) Serial number of report/Unique Identifier

e) Type of inspection. Routine/Annual?

f) Aircraft registration.

g) Manufacturer and type of system being inspected.

h) Wind conditions.
(To allow cross wind to be established)

i) Names and functions of all personnel involved in the inspection.

j) Method of making each measurement (where alternatives are available).These may be referenced to the operating instructions.

k) Details of associated attachments (recordings, etc.).

l) Details of extra flights made necessary by system adjustments.

m) An assessment by the flight crew of the navigational aid's performance. Comments by the navigation aid. inspector/equipment operator.

n) Details of any immediately notifiable deficiencies. q) Statement of conformance/non-conformance.

o) Signatures of appropriate personnel

p) Results and tolerance.

A confirmation of the status of the inspection should be provided immediately after the inspection.

RETENTION OF FLIGHT INSPECTION DATA

Flight inspection reports and data required to generate flight Inspection Reports shall be retained.

The flight inspection organisation shall have means to reproduce Flight Inspection Report

ICAO DOC 8071 Vol I, Attachment 2 to Chapter 1 section 5 states:

"Each flight inspection organization is responsible for ensuring that sufficient historical data are retained to legally establish the trends in facility performance over a reasonable interval of time. As a minimum, all commissioning inspection reports and data recordings should be retained in the facility file along with reports and data recordings from the last five periodic inspections. All special flight inspections carried out during this time period should be retained on file."

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John Mundy – NAV Canada

Larry Brady – Airfield Technology

Mike DiBenedetto – University of Ohio

Sigurd A. Bjelkarøy – Norwegian Special Mission

Sileno Goedicke – ENAV

REFERENCES

[1] ICAO, 2006, Annex 10 Aeronautical Telecommunications, Volume 1 – Radio Navigation Aids, Sixth Edition.

[2] ICAO, 2000, Doc 8071, Manual on Testing Radio Navigation Aids, Volume 1 – Testing of Ground Based Radio Navigation Systems, Fourth Edition.

[3] ISO 9001, 2008, Quality management systems – Requirements, Fourth edition.

APPENDIX 1

PRACTICAL DEMONSTRATION

In some cases the Regulator or ANSP may wish to observe the flight inspection operation first hand either on board the aircraft or on the ground.

During practical demonstration or flight inspection observation, repeatability of measurement results shall be demonstrated. The variation of results, measured by subsequent flights shall be within the measurement uncertainty as stated by the performance analysis. It shall be demonstrated that results are independent from external circumstances e.g:

Results independent from normal speed variation

Independent from direction to fly (CW/CCW or inbound/outbound)

The repeatability should be checked for the most sensitive parameters of the navigation aids under inspection.

Example: Typical parameters for demonstration of repeatability for ILS calibration could be:

- Course alignment accuracy
- Glide path angle
- Displacement sensitivity
- Height of reference datum

APPENDIX 2

ACCOUNTABLE MANAGER

The Accountable Manager has the overall responsibility to respond to the requirements. He is responsible to establish a Quality System for ensuring that all flight inspection activities are carried out according to the required standards.

In particular, he is responsible for ensuring that adequate contractual arrangements exist. This includes, amongst others, provision of facilities and sufficient competent and qualified personnel in relation to the work to be undertaken.

All of this with a view to ensure that all flight inspection activities are performed on time and in accordance with the applicable requirements, regulations and approved standards, and that all aircrafts have a valid Certificate of Airworthiness for all flights undertaken. activities.

Comparison of International Flight Inspection Standards and Procedures

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ABSTRACT

ICAO documentation provides recommendations for flight inspection standards and procedures for the member states. However, in practice there are differences among the various states around the world in the way the ICAO recommendations are interpreted and applied.

This paper presents a comparison and clarification of some of the more common differences with the goal of providing better understanding and improved consistency among regulators and flight inspection service providers.

INTRODUCTION

The International Civil Aviation Organization (ICAO) document Doc 8071, "Manual on Testing of Radio Navigation Aids" [1] provides guidance on ground and flight testing of radio navigation aids. ICAO Annex 10, Volume 1, "Radio Navigation Aids" [2] is the reference standard and contains additional guidance on ground and flight testing in Attachment C as well as general and supplemental information in Chapter 3.

All of the ICAO Contracting States agree under Article 38 of the Chicago Convention "to notify the Organization of any differences between their national regulations and practices and the International Standards contained in this Annex and any amendments thereto."

In actual practice there are many differences in interpretation and application among the various states. In a few cases the local standards may have been developed prior to the ICAO recommended standards.

Some states have published their own standards that generally comply with ICAO, some have adopted direct use of the ICAO documents, and others use the Federal Aviation Administration (FAA) Order 8200.1C, "United States Standard Flight Inspection Manual" [3].

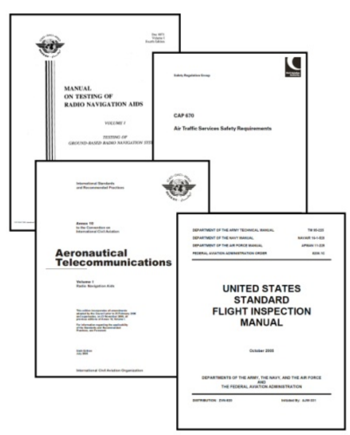
SCOPE

This paper examines and compares a few of the more commonly encountered differences between ICAO and FAA flight inspection standards and procedures. Certain specifications from the UK CAA [4] and Australia Airservices [5] standards are also referenced.

This paper is by no means a comprehensive comparison of the references; it only discusses a very few of the more common differences. Comprehensive references do exist in some cases and some from FAA are included in the References. [6] [7]

DISCLAIMER

The information in this paper is based on reference documents purchased from ICAO, downloaded from the FAA and UK CAA websites, and obtained by personal request. Some of the documents may have changed since this writing.



ILS LOCALIZER

Course Alignment

One of the most basic ILS flight inspection measurements is evaluation of alignment of the localizer zero DDM course with respect to the runway centerline. ICAO and FAA flight inspection measurement procedures for the Instrument Landing System (ILS) localizer course alignment differ as described below.

ICAO Procedure

ICAO Doc 8071, paragraph 4.3.26 specifies localizer course alignment should be measured "in the following critical region" (refer to table below).

FAA Procedure

FAA 8200.1C, 15.20g(4) specifies localizer course alignment should be measured "in the following areas" (refer to table below).

ILS LLZ Course Alignment Difference in Measurement Ranges		
Category	ICAO 8071 Table I-4-7 4.3.26	FAA 8200.1 15.60a 15.20g(4)
CAT I	"in the vicinity of ILS Point B"	1 NM to Threshold
CAT II	ILS Point B to ILS reference datum	1 NM to Threshold
CAT III	ILS Point C to ILS Point D	1 NM to Threshold *and* Threshold to Point D *and* Point D to Point E

As the table shows there are differences between FAA and ICAO procedures for ranges from threshold where the alignment is checked. This is the case for all ILS categories.

How should we interpret the phrase "in the vicinity of ILS Point B"? A definition for this phrase could not be found in the ICAO documents.

Does "in the vicinity" mean ±1000 m, ±100 m, or maybe only ±10 m?

The Merriam Webster online dictionary [8] defines "vicinity" as: "the area around or near a particular place". Does this mean we could measure alignment within some radius of Point B? Was the word "vicinity" intended to allow for slight aircraft variations from centerline?

It is suspected, as someone once said about another ICAO flight inspection parameter under discussion, "The answer is likely lost to history".

The FAA specified range from 1 NM to Threshold is certainly "in the vicinity of ILS Point B" as it roughly Point B ± 0.5 nautical mile.

Different flight inspection service providers and/or different flight inspection systems will not get the same results unless they all use the same calculation range (or the LLZ is perfect!).

CAT II - Course Structure Inside ILS Point B

It has been reported that this difference between ICAO and FAA standards caused a delay in regulatory approval for commissioning of a new ILS at a major airport.

The ICAO and FAA standards are summarized in the table below for comparison.

ILS Localizer Cat II Course Structure Tolerances		
Category	ICAO 8071 Table I-4-7	FAA 8200.1 15.60(a)
CAT I	± 15 μA Point B to Point C	± 15 μA Point B to Point C
CAT II	± 5 μA Point B to Reference Datum	± 5 μA Point B to Point D
CAT III	± 5 μA Point B to Point D ± 5 μA > ± 10 μA Point D to Point E	± 5 μA Point B to Point D ± 5 μA > ± 10 μA Point D to Point E

For Cat II localizers the ICAO tolerance inside Point B stops at the Reference Datum while the FAA tolerance continues to ILS Point D.

The localizer in question met all ICAO tolerances but had a short bend between the Reference Datum and Point D which exceeded the FAA structure tolerance.

ILS GLIDEPATH

Structure Inside ILS Point B

The analysis of glidepath structure (and other parameters) which reference the terms “mean curved path” (ICAO) or “graphical average path” (FAA) by computer-based flight inspection systems has always been troublesome.

The problem is that there is not a clearly defined mathematical equation published by ICAO or FAA on which to build a software algorithm.

The author has been advised that FAA began using the “graphical average path” method during implementation of the first generation of Automatic Flight Inspection System (AFIS-1) to compensate for flare in the glidepath indications. It is not known when ICAO adopted the similar term “mean curved path”.

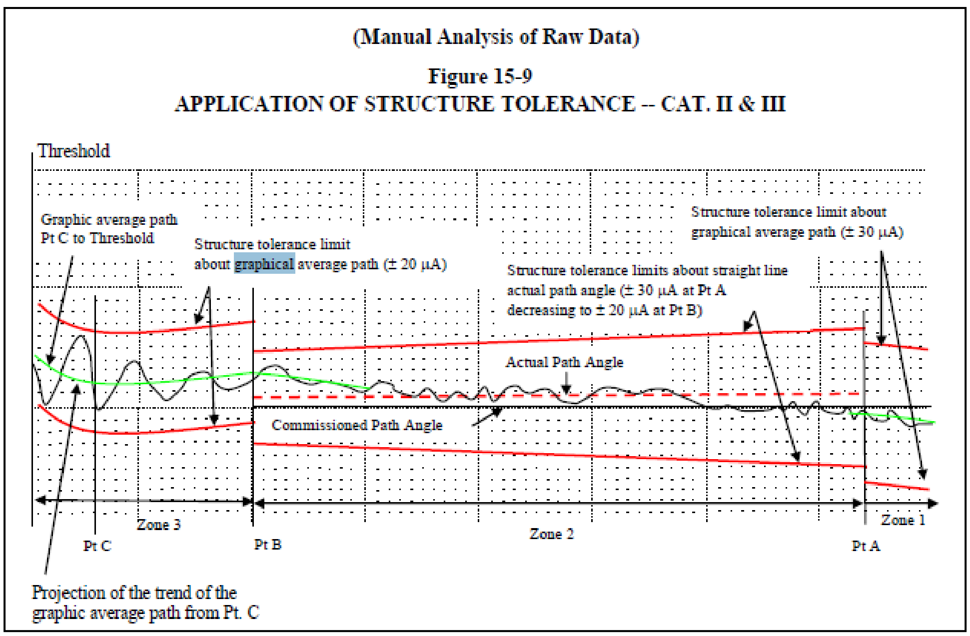
At that time in history it would have been a normal and everyday task for an experienced flight inspector to take a pencil to the glidepath chart recording, draw a curved line through what looked like a “graphical average path”, and evaluate the structure deviations around the “mean curved path”.

The example recording below is taken from FAA 8200.1. The table below compares the ICAO references and FAA definition for these terms.

The FAA definition “the mean of all crosspointer deviations” seems to indicate the average of the differential deviations. However that calculation would not result in the “curved path” as shown.

Correspondence with FAA around 10 years ago indicated their AFIS software was using a 6th order polynomial fitting algorithm to calculate the “graphical average” path inside Point B.

It is recommended that ICAO and FAA review this “standard” for glidepath and publish a clear, mathematical definition of these terms.



ILS GP Structure Between ILS Point B and C	
ICAO 8071 & Annex 10 References to GP “Mean Curved Path”	**FAA Definition of “Graphical Average Path”**
ICAO 8071Table I-4-7, Note 5: “Tolerances are referenced to the mean course path between Points A and B, and relative to the mean curved path below Point B.” ICAO Annex 10, Vol 1, 3.1.5.4.2, Note 2: In regions of the approach where ILS glide path curvature is significant, bend amplitudes are calculated from the mean curved path, and not the downward extended straight line.	FAA 8200.1: Graphical Average Path. The average path described by a line drawn through the mean of all crosspointer deviations. This will usually be a curved line which follows long-term trends (1,500 ft or greater) and averages shorter term deviations.

Glidepath Antenna Phasing

Background

While the phasing of a localizer antenna array usually can be tested and adjusted on the ground with good results, glidepath antenna phasing must be tested by flight inspection because the ground in front of the antennas forms the antenna patterns and therefore the signal in space.[9]

Any variation from an infinite size, perfectly flat, and perfectly conducting ground plane is detrimental to the optimum performance of an image-type glidepath.

Adjusting the antenna phasing for actual glidepath facilities is complicated because of several factors including:

1. The signals from each antenna reflect from a different area of the ground.

2. The area of ground which reflects the signals changes as the aircraft approaches the runway threshold.

In order to achieve the optimum antenna phasing for a glidepath on an imperfect ground plane it is commonly necessary to achieve a compromise by measuring the phasing over a region of the approach and adjusting for an average reading.

Some Practical Experience

Multipath from buildings, fences, and other objects can also create problems phasing the system. At one facility a water tower that seemed from a visual perspective to be insignificant caused major problems.

A close analysis will show the phasing of a glidepath antenna array is constantly changing by some amount, and the goal is keep the changes to a minimum.

One cause of phase change is variation in the length of the antenna cables with temperature. For best stability a glidepath installation should have equal lengths of cable feeding each antenna, especially the parts of the cables that are exposed to the outside environment. The cables also should be attached to the antenna mast so that they receive approximately the same amount of sunshine.

[9] After a flight inspection a ground test point is selected to use as a phasing reference point to help maintenance maintain correct antenna phasing between flight inspections.

Another cause of glidepath phasing change can be changes in the reflecting ground, such as geometry or shape changes by natural erosion or man-made causes, conductivity changes, and other factors.

FAA Phase Verification

FAA requires "Phase Verification" checks which consist of dephasing the glidepath from its normal settings in various ways to simulate phase shifts in the antenna distribution, antenna feed cables and antennas.

However, the ICAO standards do not require these phase verification checks.

Capture-Effect Glidepath

Phasing is especially critical for a Capture-Effect (CE) type glidepath, because dephasing from optimum can cause the angle to decrease and the width to increase beyond allowable limits.

For a CE glidepath the most critical antenna phasing is usually for the middle antenna. FAA requires that the middle antenna can be de-phased by ±15 degrees from the normal setting, and the equipment must still operate within flight inspection tolerances.

Finding a normal phasing setting which can meet the dephasing checks is easy when the ground plane is close to ideal, but can be a very challenging task when it is not. In some situations there can be so many variables that the only practical solution is trial and error.

It is also found that ±15 degrees of middle antenna phasing gives less DDM shift in the ILS width monitor than what will be found when adjusting SBO power for the wide alarm check. The integral width monitor of the CE glidepath for wide alarm is then set at the middle antenna dephasing limits

When the Phase Verification checks are not made it is possible for a CE Glidepath system to drift between flight inspections so that the middle antenna is dephased relative to the other antennas. If the drift is too much the angle can decrease below tolerances and the width can increase beyond tolerances... a bad combination.

The ICAO documents do not require the phase verification checks, and as a result not all regulators or service providers use the FAA or similar procedures.

There are known cases in which glidepath facilities have been found operating outside of tolerances. In one case the glidepath angle had decreased so low that users of the ILS were complaining. The problem was found to be non-optimum phasing.

It is recommended that ICAO should consider adding glidepath phase verification procedures to Doc 8071.

Glidepath Reference Point

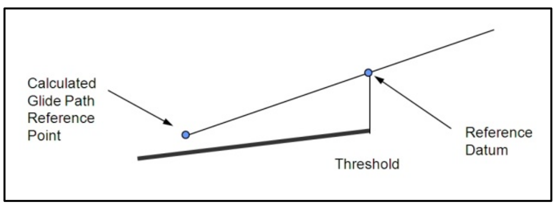
The issue of where to put the glidepath reference point has been debated for years. It has included theodolites, laser trackers, and now automatic DGPS based systems for which the reference point is only a set of coordinates.

The internationally recognized standards for flight inspection (ICAO Annex 10 and Doc 8071) do not specify a geometric reference point for flight inspection of image-type glide path facilities.

DGPS has almost universally replaced theodolites and laser trackers as the truth source for ILS flight inspection because of its accuracy and reliability.

In DGPS based flight inspection systems the reference elevation angle is calculated from the GPS coordinates of the aircraft glidepath antenna and the coordinates of the glidepath reference point. Therefore it is no longer necessary to tie the measurement reference to some point to the ground.

One proposed method that has been suggested by others [9] is to calculate the reference point from the reference datum and the commissioned path angle, as shown below:



With this method the reference point would always define a glidepath that passes through the Reference Datum.

This method could have potential as an acceptable international standard and it is recommended for consideration by ICAO and other regulatory agencies.

It is recommended that ICAO should establish and publish a standard for glidepath reference point as noted in a paper [10] presented at the IFIS 2006.

It is also recommended that FAA publish their method for establishing the glidepath reference point in 8200.1.

Glidepath Reversals

FAA has a tolerance for rate of change of slope of the glidepath for which there is no corresponding ICAO tolerance.

If the change of slope exceeds a specified tolerance it is called a “Reversal” and this can require the ILS procedure to have restrictions for coupled approaches. The details are provided in 8200.1, 15.51(b) and an example is shown in 8200.1 Figure 15-10.

It is believed this reversal tolerance came about from problems with one specific aircraft/autopilot combination many years ago.

The presence of restrictions on ILS approaches due to reversals can create economic impacts for the aircraft operators at the airport and also adds costs for additional flight inspection resources. It is suggested that FAA should consider making an evaluation as to whether this “reversal tolerance is still necessary.

DME MEASUREMENT UNCERTAINTIES

DME Range / Distance Accuracy

A comparison of the ICAO, FAA [11] and CAP 670 DME range accuracy measurement uncertainty tolerances are shown in the table below.

DME Range Accuracy Measurement Uncertainty Tolerances	
ICAO 8071 Table I-3-3	20 m 0.01 NM
FAA VN 8200.8	20 m 0.01 NM
UK CAP 670 FLI 02	60 m 0.03 NM

The CAP 670 specification of 0.03 NM is considered to be a more practical tolerance and it is recommended that ICAO and FAA consider adopting this tolerance.

DME Coverage

A comparison of the ICAO, FAA , CAP 670 and Airservices Australia [12] specifications for DME power density measurement uncertainty tolerances is shown in the table below.

DME Field Strength / Power Density Measurement Uncertainty Tolerances		
Reference	Tolerance	Notes from Reference
ICAO 8071 Table I-3-3	1 dB	Note 4: The uncertainty of 1 dB in coverage refers to repeatability of equipment calibration, not to absolute accuracy.
FAA VN 8200.8 Appendix 3	3 dB	Absolute Note 1. Approaches state of the art

DME Field Strength / Power Density Measurement Uncertainty Tolerances		
	1 dB	1 dB repeatability
UK CAP 670 FLI 02 7.14	2 dB (relative)	The word (relative) indicates repeatability
Airservices Australia AEI-2.1239	6 dB	

Since calculation of the measurement uncertainty for Field Strength or Power Density must also include the aircraft antenna pattern effects, a tolerance of 1 dB seems to be a very impractical value.

The Airservices Australia requirement of ±6 dB seems to be the most practical and it is recommended that ICAO and FAA consider adopting this tolerance.

SUMMARY

This paper has compared only a very few of the common differences between international flight inspection standards and procedures.

There are of course many more subjects to be considered, including VOR parameters, navaid coverage measurements (power density/field strength versus antenna signal level), and PAPI/VASI inspection procedures and tolerances, to name but a few.

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Carole Thompson, Radiola Aerospace

John Mundy, NavCanada

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IFIS 2014

Flight Plan to Innovation

Further Publications

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A Practical Guide to Datum Transformations

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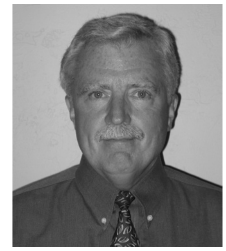

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ABSTRACT

As the role of flight inspection migrates from localized, ground-based guidance systems to global, satellite-based systems, we must become more focused upon data integrity, compatibility, and temporality. Within this paradigm, one area remains a challenge: relating various locations that have been described using differing survey datums.

This paper is an attempt to unravel the mystery and complexities surrounding the datum transformation process. Although this paper is based upon a National Geodetic Survey (NGS) tool, primarily focused upon North America, much of the information and many of the transformation techniques can be applied anywhere.

INTRODUCTION

The intent of this document is to add some understanding and clarity with regard to datum transformations, especially as they relate to NGS tool HTDP (Horizontal Time Dependent Position). [1]

BACKGROUND

Datum vs. Reference Frame

Within this document, the terms *datum* and *reference frame* are used interchangeably.

Local Datum vs. Worldwide Datum

Two major groups of datums are considered: NAD83-based (local) and WGS84-based (worldwide). Although the NAD83-based datums are not used worldwide, their corresponding coordinate systems do extend around the globe. Consequently, WGS84 Transit and NAD83 are often considered equivalent.

When transforming a location among these various datums, there is really no difference in how we deal with a NAD83 datum vs. a WGS84 datum. They are segregated below simply for convenience.

NAD83 Datums

- NAD83 (North America, considered equivalent to WGS84 Transit)
- PACP (Pacific Tectonic)
- MARP (Mariana Tectonic)

WGS84 Datums

WGS84 datums are typically paired with an ITRF (International Terrestrial Reference Frame) realization.

- WGS84 Transit (the "original" WGS84, considered equivalent to NAD83)
- ITRF88 → ITRF93

- ITRF94 (used as the "conduit" for transforming from one datum to another)
- ITRF96 → ITRF97
- ITRF2000
- ITRF2005
- ITRF2008

Coordinates: Ellipsoidal vs. Cartesian

A location may be described using either of two coordinate systems: ellipsoidal or Cartesian. When using ellipsoidal coordinates, a location is described as latitude, longitude, and height above the ellipsoid. Alternatively, Cartesian coordinates may be used, relative to the center of the earth. The Earth-Centered Earth-Fixed (ECEF) axes are defined as follows.

- X: inside the equatorial plane, in direction of 0° longitude (Prime Meridian – passes near the Royal Observatory in Greenwich, England)
- Y: inside the equatorial plane, in direction of E90° longitude
- Z: coincident with earth's axis of rotation, in direction of north pole

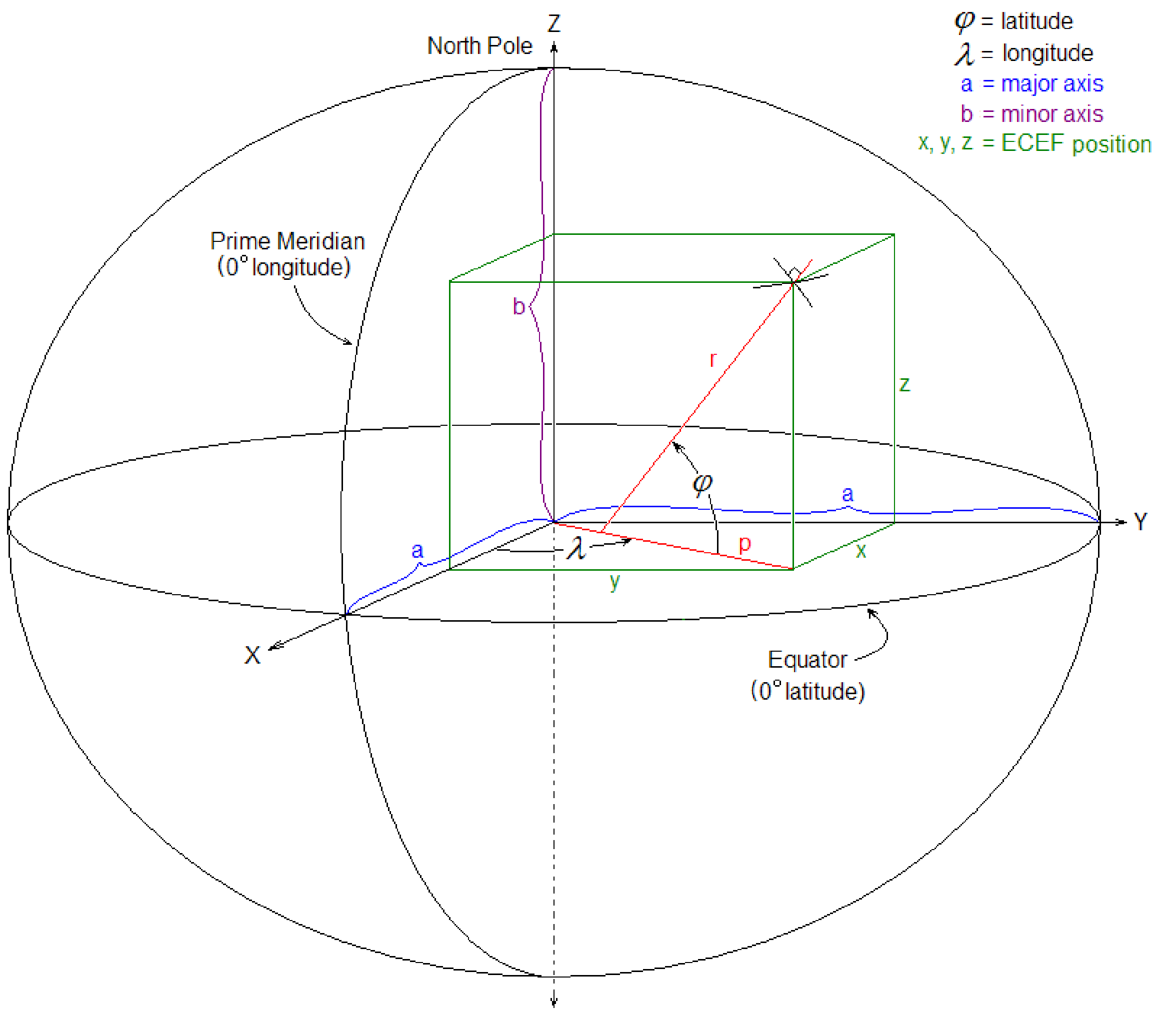

Figure 1. ECEF Coordinates in Relation to Latitude and Longitude

Converting Angular to Rectangular

Throughout the discussion that follows, angular XYZ displacement ($\Delta\boldsymbol{R}$) will be converted to linear XYZ displacement ($\Delta\boldsymbol{T}$). In short form:

$$\Delta\boldsymbol{T} = \Delta\boldsymbol{R} \times \boldsymbol{p}$$

Where,

$\boldsymbol{p}$ = XYZ location

Assuming the $\Delta\boldsymbol{R}$ angles are oriented such that a positive angle corresponds to a **CCW** rotation (as viewed from the axis' positive infinity), the formulas for this conversion are:

$$\Delta T_x = p_z \cdot sin(\Delta R_y) - p_y \cdot sin(\Delta R_z)$$

$$\Delta T_y = p_x \cdot sin(\Delta R_z) - p_z \cdot sin(\Delta R_x)$$

$$\Delta T_z = p_y \cdot sin(\Delta R_x) - p_x \cdot sin(\Delta R_y)$$

Since these are small angles, if the angles are expressed in radians, we can use sin ($\Delta\boldsymbol{R}$) ≈ $\Delta\boldsymbol{R}$, simplifying the equations:

$$\Delta T_x = p_z \cdot \Delta R_y - p_y \cdot \Delta R_z$$

$$\Delta T_y = p_x \cdot \Delta R_z - p_z \cdot \Delta R_x$$

$$\Delta T_z = p_y \cdot \Delta R_x - p_x \cdot \Delta R_y$$

The orientation of this transformation can be confirmed visually using figure 1.

The same formulas can be used for converting rotation rate ($\dot{\boldsymbol{R}}$) about XYZ to linear XYZ velocity ($\boldsymbol{v}$):

$$v_x = p_z \cdot \dot{R}_y - p_y \cdot \dot{R}_z$$

$$v_y = p_x \cdot \dot{R}_z - p_z \cdot \dot{R}_x$$

$$v_z = p_y \cdot \dot{R}_x - p_x \cdot \dot{R}_y$$

DISCUSSION

Transforming a Location from One Datum to Another

What Time is it?

If we want to visualize the relative position of the ellipsoids associated with two different datums, we must specify a point in time; the relative location between two datums changes over time. Fortunately, the rate of change is considered constant.

Was Einstein Right, is Everything Relative?

Einstein *was* right and, when it comes to datums, it's also difficult to come up with any absolutes. Estimates of the location of the earth's center continue to be refined and a datum's location relative to other datums is influenced by the corresponding set of landmarks and measurement techniques used to define it.

If we're going to catalog each datum by a standard transformation formula and a datum-specific set of coefficients, we must establish a standard by which all datums are to be measured. Within the NGS HTDP application, this is WGS84 ITRF94 (see "WGS84 Datums"). Consequently, all such coefficients for the ITRF94 datum are equal to zero

Relating One Datum to Another

When comparing one datum to another, we utilize the ECEF (Cartesian) coordinate system. Six parameters are used.[10] As stated within the previous section, these parameters are all relative to the ITRF94 datum.

- Linear Offset ($\boldsymbol{T}$): the inverted 3D origin offset from that of ITRF94 at datum epoch date[11]
- Rate of Change of Offset ($\dot{\boldsymbol{T}}$): the constant 3D rate of change of the linear offset
- Rotational Offset ($\boldsymbol{R}$): the non-inverted 3D origin CCW rotation from that of ITRF94 at datum epoch date[12]

[10] Within this document, it is assumed that all datums utilize the same ellipsoid (size and shape).

[11] By inverting the target origin offset (relative to ITRF94 origin), this vector can be directly *added* to the ITRF94 location to obtain the location referenced to our target datum. This is demonstrated in "A Location defined by a Datum: ITRF94."

[12] Since the rotational offset is not inverted, we must *subtract* the resultant vector from our ITRF94 location in order to obtain the location referenced to our target datum. This is demonstrated in "A Location defined by a Datum: ITRF94." Within NGS literature, this fact is hidden by their use of a non-standard matrix product (i.e. inverted from that provided in "Converting Angular to Rectangular").

- Rate of Rotation ($\dot{\boldsymbol{R}}$): the constant 3D rate of change of the angular offset
- Scale Offset (D): the difference in overall scale of the Cartesian coordinates as compared to ITRF94 at datum epoch date (scalar)
- Rate of Expansion ($\dot{D}$): the rate of change of scale offset (scalar)

In order to simplify this discussion, the last two parameters (scale and expansion rate) are not included within this discussion. All of these parameters have been measured and documented by NGS for each datum. As stated previously, these parameters are all zero for the ITRF94 datum.

Datum Epoch Date

Each datum is assigned an epoch date: the temporal baseline for applying associated velocities. On this date, the datum's velocity parameters can be ignored when transforming to ITRF94. No ITRF94 epoch date is used within this discussion.

What's Moving: the Location or the Datum, or Both?

As stated earlier, any given datum is moving in relation to any other datum (slowly yes, but still moving). This motion among datums certainly complicates the transformation process. But what are we trying to accomplish here? In order to address this one step at a time, two paradigms are presented: one from a datum's perspective and one from the ground's perspective.

A Location Defined by a Datum: ITRF94

In this paradigm, the location is *defined* by its coordinates within the ITRF94 datum. Within the ITRF94 datum model, time is not an issue (i.e. all velocities equal zero).

Although the location is *defined* by its ITRF94 coordinates, it's likely *described* using a different datum. Since coordinates change over time when described in any datum other than ITRF94, time must also be specified.

To convert a location from its *descriptive* datum (at $Date_{from}$) to ITRF94, the following formula is used. Refer to "Converting Angular to Rectangular" for a description of the matrix multiplication depicted below. The sign of the $\boldsymbol{R}$ and $\dot{\boldsymbol{R}}$ terms is opposite to that found in NGS literature; they utilize a non-standard matrix product, inverted from that documented in referenced section. As mentioned before, scale differences are not included within this discussion.

$$\begin{aligned} \mathrm{p_{ITRF94}} &= \mathrm{p_{from}} - \left(\mathrm{T_{from}} + \dot{\mathrm{T}}_{\mathrm{from}}(\mathrm{Date_{from}} - \mathrm{Epoch_{from}})\right) \\ &\quad + \left(\mathrm{R_{from}} + \dot{\mathrm{R}}_{\mathrm{from}}(\mathrm{Date_{from}} - \mathrm{Epoch_{from}})\right) \mathrm{p_{from}} \end{aligned}$$

$$\begin{aligned} \mathrm{p_{ITRF94}} &= -\mathrm{T_{from}} - \dot{\mathrm{T}}_{\mathrm{from}}(\mathrm{Date_{from}} - \mathrm{Epoch_{from}}) \\ &\quad + \left(\mathrm{I} + \left(\mathrm{R_{from}} + \dot{\mathrm{R}}_{\mathrm{from}}(\mathrm{Date_{from}} - \mathrm{Epoch_{from}})\right)\right) \mathrm{p_{from}} \end{aligned}$$

To convert from ITRF94 to a *target* datum (at $Date_{target}$), the following formula is used.

$$\begin{aligned} \mathrm{p_{target}} &= \mathrm{p_{ITRF94}} + \left(\mathrm{T_{target}} + \dot{\mathrm{T}}_{\mathrm{target}}(\mathrm{Date_{target}} - \mathrm{Epoch_{target}})\right) \\ &\quad - \left(\mathrm{R_{target}} + \dot{\mathrm{R}}_{\mathrm{target}}(\mathrm{Date_{target}} - \mathrm{Epoch_{target}})\right) \mathrm{p_{ITRF94}} \end{aligned}$$

$$\begin{aligned} \mathrm{p_{target}} &= \mathrm{T_{target}} + \dot{\mathrm{T}}_{\mathrm{target}}(\mathrm{Date_{target}} - \mathrm{Epoch_{target}}) \\ &\quad + \left(\mathrm{I} - \left(\mathrm{R_{target}} + \dot{\mathrm{R}}_{\mathrm{target}}(\mathrm{Date_{target}} - \mathrm{Epoch_{target}})\right)\right) \mathrm{p_{ITRF94}} \end{aligned}$$

Where,

$\boldsymbol{p}$ = location

$\boldsymbol{I}$ = unity matrix (i.e. one)

Note that, for ITRF94, parameters $\boldsymbol{T}, \dot{\boldsymbol{T}}, \boldsymbol{R},$ and $\dot{\boldsymbol{R}}$ are all equal to zero. Also note that no epoch, associated with ITRF94, is used anywhere within this discussion.

When transforming a location in one datum/time in to another datum/time, these two methods should be concatenated:

$$\boldsymbol{p}_{from}(Date_{from}) \rightarrow \boldsymbol{p}_{ITRF94} \rightarrow \boldsymbol{p}_{target}(Date_{target})$$

A Location Defined by a Spike in the Ground

Now comes the hard part, defining a location by a spike in the ground. This is the paradigm used by HTDP. Within this paradigm, we have a spike in the ground and nobody is allowed to touch it. How does this differ from the paradigm previously discussed?

Crustal motion. The basis for the datum paradigm above is that the location remains constant with respect to ITRF94. This *could* be the case if the earth's surface were stationary. Unfortunately, it's not and the HTDP tool takes this into account.

If we hammer a spike into the ground at some point in time, it will not remain fixed with respect to ITRF94, due to crustal motion. Except for earthquake effects (not addressed herein), NGS has measured and documented all crustal motion as a constant velocity for any given location. In some regions, this constant velocity is described as NS and EW. In other regions, it is described as a constant rate of rotation about the X, Y, and Z axes.

The easiest way to visualize this crustal motion would be to measure it with respect to our transformation standard, ITRF94. Unfortunately, it appears NGS elected to document each region of crustal motion using just about any datum other than ITRF94. HTDP version 3.1 utilizes 12 regions and 3 datums (ITRF2000, ITRF2005, and ITRF2008). In version 3.2, all regions are referenced to ITRF2008.

It should be apparent at this point that velocity plays a major role within this paradigm. When crustal motion is included, the simple conversions described in "A Location Defined by a Datum: ITRF94" must be augmented by intricate, less intuitive transformations. This process is described below.

Keep in mind that, throughout all of this, we're never moving the spike in the ground (at least as far as the ground is concerned).

Transforming Velocity

As stated above, within this paradigm, velocity plays a major role. In this section we provide the basic datum velocity transformation. In later sections, regional velocity is handled.

We transform velocity from one datum to another using a transformation similar to what we did for transforming a location in "A Location Defined by a Datum: ITRF94." To convert a velocity from its associated datum to ITRF94, the following formula is used. Since all velocities are considered constant, we have no need to include dates. [13]

$$\boldsymbol{v}_{ITRF94} = \boldsymbol{v}_{from} - \dot{\boldsymbol{T}}_{from} + \dot{\boldsymbol{R}}_{from} \times \boldsymbol{p}_{from}$$

To convert velocity from ITRF94 to a *target* datum, the following formula is used.

$$\boldsymbol{v}_{target} = \boldsymbol{v}_{ITRF94} + \dot{\boldsymbol{T}}_{target} - \dot{\boldsymbol{R}}_{target} \times \boldsymbol{p}_{from}$$

In theory, we should have used $\boldsymbol{p}_{ITRF94}$ in the second equation rather than $\boldsymbol{p}_{from}$. At a radius of about 6.4 million meters, a possible 2-meter offset will produce a velocity error of about 0.0003% within the $\dot{\boldsymbol{R}}$ term. This is insignificant. Within HTDP, the same location is used throughout the concatenation of several velocity datum transformations.

Combining the two equations:

$$\begin{aligned}\boldsymbol{v}_{target} &= (\boldsymbol{v}_{from} - \dot{\boldsymbol{T}}_{from} + \dot{\boldsymbol{R}}_{from} \times \boldsymbol{p}_{from}) + \dot{\boldsymbol{T}}_{target} \\ &\quad - \dot{\boldsymbol{R}}_{target} \times \boldsymbol{p}_{from} \\ &= \boldsymbol{v}_{from} + (\dot{\boldsymbol{T}}_{target} - \dot{\boldsymbol{T}}_{from}) \\ &\quad - (\dot{\boldsymbol{R}}_{target} - \dot{\boldsymbol{R}}_{from})\boldsymbol{p}_{from}\end{aligned}$$

Calculating Regional Velocity

In "What Time is it?" we transformed a location in one datum/time to another datum/time. In theory, we could concatenate this process indefinitely. Now we've introduced a regional velocity to this exercise. If we were to repeatedly change a location from one datum/time to

[13] As previously stated, the sign of the $\dot{\boldsymbol{R}}$ term is opposite to that found in NGS literature; they utilize a non-standard matrix product, inverted from that documented in "Converting Angular to Rectangular."

another, this regional velocity component would need to persist, continuing to influence the results of each conversion. In other words, since time *is* a variable within each conversion, the regional velocity cannot simply be compensated for once then forgotten.

In "A Location Defined by a Datum: ITRF94," we provide the formulas for location datum transformation without regional velocity; in "Transforming Velocity," we provide the formulas for velocity datum transformation. The first step in transforming a location with a regional velocity is to calculate the regional velocity as referenced to our source datum. HTDP provides regional velocity information in two different formats: arbitrarily, using sample grids (*weighted* regions) and uniformly, using a uniform rotation rate (*uniform* regions). Regardless of region type, all velocities are presumed to be constant with respect to time.

Weighted Regions

Within any *weighted* region, velocity data is provided as arbitrary NS and EW values assigned throughout a rectangular latitude/longitude grid. The grid coordinates are assumed to be referenced to the region's datum at the current date.[14, 15] The following steps describe this transformation.

- Weighted Region, Step 1: Transform Location to Region's Datum at Current Date

Using the transformation in "A Location Defined by a Datum: ITRF94":

$$\boldsymbol{p}_{from}(Date_{from}) \rightarrow \boldsymbol{p}_{ITRF94} \rightarrow \boldsymbol{p}_{region}(Date_{from})$$

Where $\boldsymbol{p}_{from}$ represents the location referenced to the source datum ($Datum_{from}$).

- Weighted Region, Step 2: Convert XYZ Position to Latitude and Longitude

Using a standard ellipsoidal transformation (not shown):

$$\boldsymbol{p}_{region}(X, Y, Z) \rightarrow \boldsymbol{p}_{region}(lat, lon, up)$$

- Weighted Region, Step 3: Interpolate Velocity

Using a two-dimensional linear interpolation (not shown), fetch velocity in terms of NS (v_N) and EW (v_E) components. No vertical information is included ($v_U = 0$).

$$\boldsymbol{v}_{NEU} = (v_N, v_E, v_U)$$

- Weighted Region, Step 4: Convert Velocity to XYZ Values

Use the standard conversion process, described below.

$$v_X = -v_{north} \cdot \sin(lat) \cdot \cos(lon) - v_{east} \cdot \sin(lon) + v_{up} \cdot \cos(lat) \cdot \cos(lon)$$

$$v_Y = -v_{north} \cdot \sin(lat) \cdot \sin(lon) + v_{east} \cdot \cos(lon) + v_{up} \cdot \cos(lat) \cdot \sin(lon)$$

$$v_Z = v_{north} \cdot \cos(lat) + v_{up} \cdot \sin(lat)$$

$$\boldsymbol{v}_{region} = (v_X, v_Y, v_Z)$$

This velocity is referenced to the datum specified for the region.

- Weighted Region, Step 5: Convert Velocity to Source Datum

Using the velocity transformation in "Transforming Velocity," convert the velocity from the region's datum back to the original source datum.[16]

$$\boldsymbol{v}_{from} = \boldsymbol{v}_{region} + (\dot{\boldsymbol{T}}_{from} - \dot{\boldsymbol{T}}_{region}) - (\dot{\boldsymbol{R}}_{from} - \dot{\boldsymbol{R}}_{region})\boldsymbol{p}_{from}$$

Uniform Regions

Within any *uniform* region, velocity data is provided as a constant rate of rotation about the X, Y, and Z axes:

[14] HTDP uses NAD83 for positioning inside a region instead of the region's reference datum. Per email from NGS Dr. Snay to FAA Dr. Zhong, region's reference datum would be preferred (and is reflected herein).

[15] The velocity is presumed to remain constant for each location within the region. Once time has elapsed and the "spike" has moved (with respect to region's datum), the spike's velocity will change to the velocity assigned to the new location. Consequently, for a given location (as described by region's datum), the velocity will remain constant, regardless of the date.

[16] As previously stated, the sign of the $\dot{\boldsymbol{R}}$ term is opposite to that found in NGS literature; they utilize a non-standard matrix product, inverted from that documented in "Converting Angular to Rectangular."

$\dot{\boldsymbol{R}}_{region}$. The following steps describe this transformation.

- Uniform Region, Step 1: Transform Location to Region's Datum at Current Date

This step is identical to the corresponding step (1) in the weighted region process.

$$\boldsymbol{p}_{from}(Date_{from}) \rightarrow \boldsymbol{p}_{ITRF94} \rightarrow \boldsymbol{p}_{region}(Date_{from})$$

- Uniform Region, Step 2: Convert $\dot{\boldsymbol{R}}_{region}$ to $\boldsymbol{v}_{region}$

Convert the rotational velocity about XYX to a linear XYZ velocity using the velocity formulas in "Converting Angular to Rectangular."

$$\boldsymbol{v}_{region} = \dot{\boldsymbol{R}}_{region} \times \boldsymbol{p}_{region}$$

- Uniform Region, Step 3: Convert Velocity to Source Datum

This step is identical to the corresponding step (5) in the weighted region process.

$$\boldsymbol{v}_{from} = \boldsymbol{v}_{region} + (\dot{\boldsymbol{T}}_{from} - \dot{\boldsymbol{T}}_{region}) - (\dot{\boldsymbol{R}}_{from} - \dot{\boldsymbol{R}}_{region})\boldsymbol{p}_{from}$$

<u>Applying Regional Velocity</u>

So far, all we've done is get the regional velocity (crustal motion) and transform it to our source datum. What next? In the most general sense, our goal is to convert a location described in one datum/time to a location described in another datum/time, taking regional velocity into account. In order to accomplish this, we're going to break it up into two major steps.

- <u>*Step 1: Integrating Regional Velocity*</u>

Our first step is to move the spike to its new location as a result of crustal motion and time. We achieve this by integrating the velocity over time. Our resultant location remains referenced to the source datum but corresponds to the target date.

$$\acute{\boldsymbol{p}}_{from} = \boldsymbol{p}_{from} + (Date_{target} - Date_{from})\boldsymbol{v}_{from}$$

Where,

$\boldsymbol{p}_{from}$ = location referenced to source datum at start time ($Date_{from}$)

$\boldsymbol{v}_{from}$ = regional velocity referenced to source datum (i.e. the output of "Calculating Regional Velocity")

$\acute{\boldsymbol{p}}_{from}$ = location referenced to source datum at target time ($Date_{target}$)

- <u>*Step 2: Transforming to Target Datum*</u>

The second step is nothing new. We simply transform the location from its current datum to the target datum using the formulas in "A Location Defined by a Datum: ITRF94," with no change in date.

$$\acute{\boldsymbol{p}}_{from}(Date_{target}) \rightarrow \boldsymbol{p}_{ITRF94} \rightarrow \boldsymbol{p}_{target}(Date_{target})$$

Where,

$\boldsymbol{p}_{target}$ = location referenced to target datum at target time ($Date_{target}$)

Although not needed to estimate the new location ($\boldsymbol{p}_{target}$), we would need the target velocity ($\boldsymbol{v}_{target}$) to move from our new location to another datum/time. From "Transforming Velocity":

$$\boldsymbol{v}_{target} = \boldsymbol{v}_{from} + (\dot{\boldsymbol{T}}_{target} - \dot{\boldsymbol{T}}_{from}) - (\dot{\boldsymbol{R}}_{target} - \dot{\boldsymbol{R}}_{from})\acute{\boldsymbol{p}}_{from}$$

Where,

$\boldsymbol{v}_{target}$ = regional velocity referenced to target datum

<u>*Concatenating Transformations*</u>

In "Calculating Regional Velocity," we stated that, if we performed these transformations properly, we should be able to jump from one datum/time to another without having to recalculate the regional velocity from scratch each time. Since "Applying Regional Velocity, Step 2" provides us with both location and regional velocity with respect to our new datum/time, we have all we need to feed these two values back into the process and derive a new location and regional velocity referenced to a new datum/time.

<u>Relating One Position to Another</u>

In "A Location Defined by a Spike in the Ground," we explained how we transform one location to a different datum/time, taking crustal motion into account. In this section, we want to transform a location to a local coordinate system. When using a local coordinate system, we must take into account the datum and survey date of the coordinate system's origin. Keep in mind that the local origin is likely moving due to crustal motion and at a rate that differs from our location of interest.

The only way we can compare two locations is to transform them into the same datum, same time. Once both locations are of the same datum/time, we can calculate the XYZ vector from the origin to the location of interest as follows.

$$\Delta\boldsymbol{p} = \boldsymbol{p} - \boldsymbol{q}$$

Where,

$\boldsymbol{p}$ = location of interest = (p_x, p_y, p_z)

$\boldsymbol{q}$ = local origin = (q_x, q_y, q_z)

$\Delta\boldsymbol{p}$ = location of interest in local coordinate system = $(\Delta p_x, \Delta p_y, \Delta p_z)$

We convert this relative location to NS, EW, and vertical components as follows.

$$\Delta p_E = -\Delta p_x \cdot sin(lon_q) + \Delta p_y \cdot cos(lon_q)$$

$$\Delta p_N = -\Delta p_x \cdot sin(lat_q)\, cos(lon_q) - \Delta p_y \cdot sin(lat_q)\, sin(lon_q) + \Delta p_z \cdot cos(lat_q)$$

$$\Delta p_U = +\Delta p_x \cdot cos(lat_q)\, cos(lon_q) + \Delta p_y \cdot cos(lat_q)\, sin(lon_q) + \Delta p_z \cdot sin(lat_q)$$

$$\Delta\boldsymbol{p}_{\boldsymbol{NEU}} = (\Delta p_N, \Delta p_E, \Delta p_U)$$

Where,

lat_q = latitude of $\boldsymbol{q}$

lon_q = longitude of $\boldsymbol{q}$

Conversion of $\boldsymbol{q}_{xyz}$ to lat_q, lon_q, ht_q is not shown herein.

Using What We've Learned

How does this relate to aircraft navigation? Does the location from a GPS receiver have crustal motion? How could it? The spike is traveling through the air. Three scenarios are addressed.

Scenario 1, Airborne GPS vs. NAD83 Landmark

In this scenario, the origin on the ground has been surveyed to NAD83 and the navigation system is providing GPS positioning referenced to WGS84 ITRF2008.[17] Let's assume that the ground survey was performed January 1, 2000 and the current date is January 1, 2013.

Since our goal is to measure the relative position of these two locations as they currently exist, we convert both locations to the current date.

- *Step 1: Convert Airborne GPS ITRF2008 Position to NAD83*

This requires a simple datum transformation IAW "A Location Defined by a Datum: ITRF94."

$$\boldsymbol{p}_{ITRF08}(Date_{current}) \rightarrow \boldsymbol{p}_{ITRF94} \rightarrow \boldsymbol{p}_{NAD83}(Date_{current})$$

- *Step 2: Convert Ground NAD83 Position to Current Date*

This requires calculation of the regional velocity ($\boldsymbol{v}_{regional}$) IAW "Calculating Regional Velocity."

$$\acute{\boldsymbol{q}}_{NAD83} = \boldsymbol{q}_{NAD83} + (Date_{current} - Date_{survey})\boldsymbol{v}_{regional}$$

If the survey date is unknown or precision better than ± 1 foot is not needed, use the current date. In this case, $\acute{\boldsymbol{q}}_{NAD83} = \boldsymbol{q}_{NAD83}$.

- *Step 3: Subtract Origin from Aircraft Location*

Subtract origin from aircraft location per "Relating One Position to Another."

$$\Delta\boldsymbol{p} = \boldsymbol{p} - \acute{\boldsymbol{q}}$$

Convert XYZ vector to NEU.

$$\Delta\boldsymbol{p}_{\boldsymbol{xyz}} \rightarrow \Delta\boldsymbol{p}_{\boldsymbol{NEU}}$$

Scenario 2, Using the Camera System

In this scenario, the origin on the ground has been surveyed to NAD83 and the navigation (camera or pilot fix) is providing positioning referenced to the runway threshold.[18] Since the navigation system and origin are

[17] Scenario 1 might occur within the position reference system (PRS) as well as the system under inspection. It comes into play when using GPS/WAAS as the PRS for ILS orbit, ILS radial, VORTAC orbit, VORTAC radial, DME/DME, etc. It also occurs during inspection of WAAS LPV approach procedures. The accuracy associated with regional velocity compensation would likely be required only for the inspection of WAAS LPV approach procedures.

[18] Scenario 2 would exist within the camera system PRS, typically used during the inspection of ILS and lighting systems.

referenced to the same datum/time, no conversion need be done.

- *Step 1: Subtract Origin from Aircraft Location*

Subtract origin from aircraft location per "Relating One Position to Another."

$$\Delta \boldsymbol{p} = \boldsymbol{p} - \boldsymbol{q}$$

Convert XYZ vector to NEU.

$$\Delta \boldsymbol{p}_{xyz} \rightarrow \Delta \boldsymbol{p}_{NEU}$$

Scenario 3, Using DGPS

In this scenario, the origin on the ground has been surveyed to NAD83 and the navigation (DGPS) is providing GPS positioning referenced to some variant of WGS84.[19] We can assume that the WGS84 positioning (based upon ground survey) corresponds to the same date as the origin's NAD83 position. Because of this, regional velocity is not an issue.

- *Step 1: Convert Airborne GPS WGS84 Position to NAD83*

This requires a simple datum transformation IAW "A Location Defined by a Datum: ITRF94." Let's assume that the WGS84 position is referenced to ITRF2000.

$$\boldsymbol{p}_{ITRF00}(Date_{survey}) \rightarrow \boldsymbol{p}_{ITRF94} \rightarrow \boldsymbol{p}_{NAD83}(Date_{survey})$$

If the survey date is unknown, use current date.

- *Step 2: Subtract Origin from Aircraft Location*

Subtract origin from aircraft location per "Relating One Position to Another."

$$\Delta \boldsymbol{p} = \boldsymbol{p} - \boldsymbol{q}$$

Convert XYZ vector to NEU.

$$\Delta \boldsymbol{p}_{xyz} \rightarrow \Delta \boldsymbol{p}_{NEU}$$

CONCLUSION

It is my hope that this paper eliminates some of the mystery surrounding datum transformations. It should become obvious, after reading this paper, that accounting for crustal motion involves a much greater effort than what is required for simple datum/time transformations.

[19] Scenario 3 would exist within the DGPS PRS, typically used during the inspection of ILS.

The good news:

- Crustal motion impacts only one of the three flight inspection scenarios described in "Using What We've Learned."
- Crustal motion compensation need be performed only for the ground reference point, not for each sample of navigational position.
- If the ground survey date is unknown or high precision is not needed (and we use the current date in its stead), crustal motion is not a factor.

Based upon the assessment in "Using what We've Learned," it appears that the only time crustal motion compensation would be needed would be during the inspection of WAAS LPV approach procedures. Even then, compensation can be performed only if the runway survey date is known or can be estimated.

REFERENCES

[1] National Geodetic Survey, Horizontal Time-Dependent Positioning,
http://www.ngs.noaa.gov/TOOLS/Htdp/Htdp.shtml

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An Automatic Workflow for RNAV Procedures Flight Validation

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ABSTRACT

The use of RNAV routes and approaches/departures increase the challenges of flight inspection teams. ENAV and IDS developed a workflow for the validation of RNAV procedure (both GNSS and DME-DME). This workflow is composed of 2 phases: an upstream phase regarding design and coding of the flight procedure, calculation of a list of DMEs segment by segment following RNAV criteria (for validation of DME DME procedures), and export of a data package ready to be automatically imported on the onboard NSM (Norwegian Special Mission) UNIFIS 3000 Console. A downstream phase regarding the flight check of the RNAV procedure is foreseen importing the radio-measures into the design environment to make a direct comparison between flight inspection and simulation. This is possible through the usage of FPDAM (Flight Procedure and Airspace Management) for the flight procedure designing phase and EMACS ASUV (Area/Airborne Signal Usability Verification) that is able to export this data package maintaining data integrity of the onboard facility aeronautical database starting from a set of information (flight procedure and/or navaids) stored into an AIXM 5.1 database.

INTRODUCTION

IDS and ENAV, in collaboration with NSM (Norwegian Special Mission) developed a workflow to validate RNAV procedures (GNSS and DME DME) starting from the flight procedure designing phase to the flight inspection itself. The workflow can be summarized as follow:

- Flight procedure designing using a computer aid design SW.
- Creation of a DME DME configuration of equipment (that are in the operational range of the flight procedure itself).
- Evaluation of Coverage/Visibility for each single DME.

- Evaluation of the DME DME performances taking into account the RNAV principles [2], [7].
- Calculation of the data package (optimized list of DMEs to be flight checked segment by segment).
- Export of the data package to the NSM UNIFIS 3000 Console (see Figure 1).

Figure 1. UNIFIS 3000 Consolle

- Automatic loading of the digital data package through simple plugin of a pen driver.
- Flight check and validation of the flight procedure through the ENAV Radiomisure P180 (see Figure 2).

Figure 2. ENAV Radiomisure P180

- Flight inspection measurement post-processing and comparison with EMACS ASUV simulations.

The workflow has been reported in Figure 5.

FLIGHT PROCEDURES DESIGN

The proposed workflow starts from the ANSP (Air Navigation Service Provider) Flight Procedure Designing Department through the usage of a computer aided design SW called FPDAM based on a set of aeronautical data AIXM 5.1 compliant (managed from the AIS department in a centralized mode). An example of flight procedure has been reported in Figure 3.

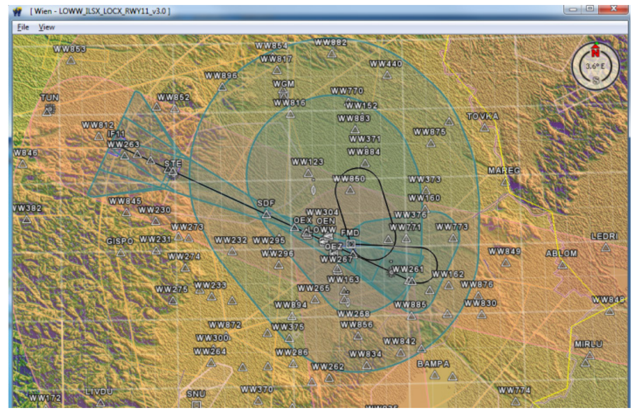


Figure 3. Example of FPDAM Flight Procedure

DME DME configuration of equipment

The second step consists in the creation of a DME DME configuration starting from published data and cross-checking them with the onboard database used for the flight inspections. The data to complete this set of data can be listed below:

- Antenna position (LAT., LONG., ALT.)
- Antenna pattern (an example of DME elevation pattern has been reported in Figure 4)

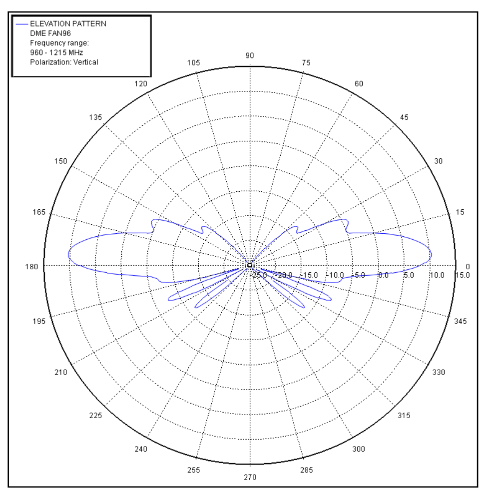


Figure 4. Example of DME antenna pattern

- Power
- Frequency
- DOC (Designed Operational Coverage) and sectorial limitations.

Once these parameters have been collected in a single equipment configuration, a preliminary coverage/visibility simulation can be performed.

Evaluation of coverage for each single DME

Coverage and visibility for DME equipment can be evaluated preliminarily. EMACS permits to evaluate:

- Optical visibility taking into account earth curvature (see Figure 7);
- Radio electric coverage (see Figure 6) taking into account the real antenna pattern, power and frequency of the navaid. EMACS provides a set of solvers using the following E.M. methods:
    - Deygout (see Appendix 1 for details)
    - IF77 (see Appendix 1 for details)
    - PE – Parabolic Equation (see Appendix 1 for details)

The user can also set and consider directly operational range and eventual published limitations for each equipment.

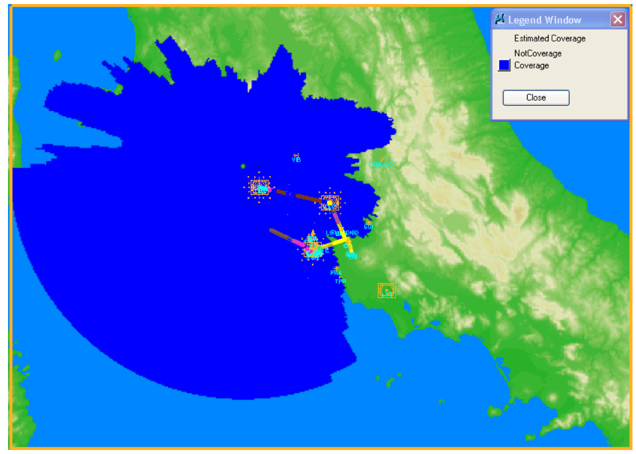


Figure 6. Example of DME coverage

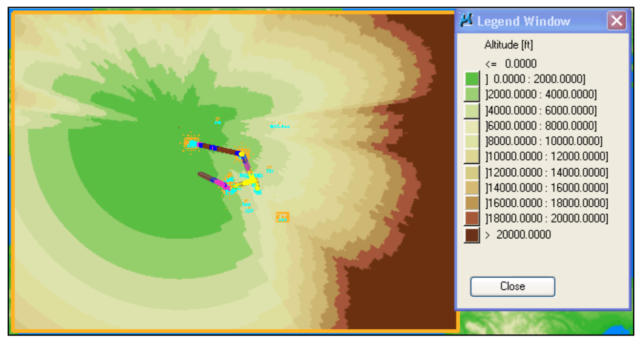


Figure 7. Example of DME visibility

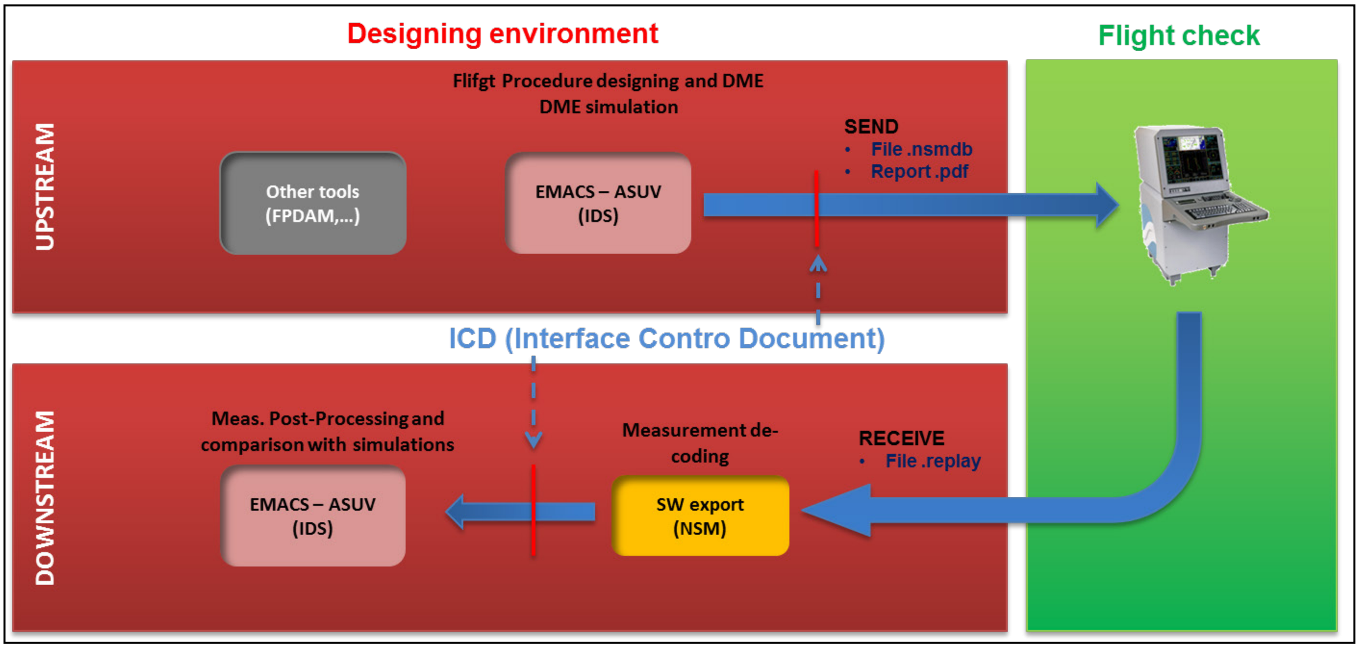


Figure 5. RNAV (DME DME and GNSS) flight procedures validation workflow.

DME DME Performances evaluation

For the evaluation of DME DME RNAV performances, a set of applicable exclusion logics can be applied (see Figure 8, 9):

- DME that see some points of the procedure with lower elevation angles to a definable value or exceeding a definable value
- DME that see some points of the procedure at distances less than or greater than 160Nm 3NM
- DME that see some points of the procedure outside the service volume stated in AIP
- DME and along the procedure are not tunable (in coverage for a period equal to Acquisition Time)
- DME and along the procedure form pairs that do not guarantee a given accuracy requirement of RNAV

The user can also:

- Exclude any DME
- Exclude all co-located DME with ILS (highlighted in green)

Selecting a DME the user can also check the following data:

- Error model
- Year of installation
- MTBF
- DOC (AIP)
- Limitations / Extensions to the DOC (AIP)

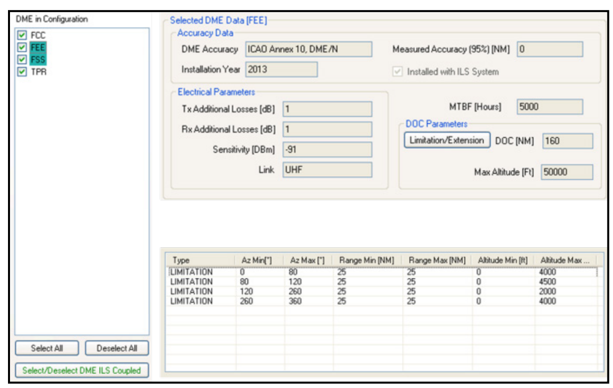


Figure 8. EMACS ASUV logic exclusions for RNAV performances evaluation.

Depending on the performance (see Figure 9) type the following calculations can be performed:

- Number of DME in coverage (see Figure 10,13),

- Number of DME pairs usable for RNAV (see Figure 11,12,14),
- Number of critical DME and identification of the critical site,
- Min. and max. Position Estimation Error (PEE).

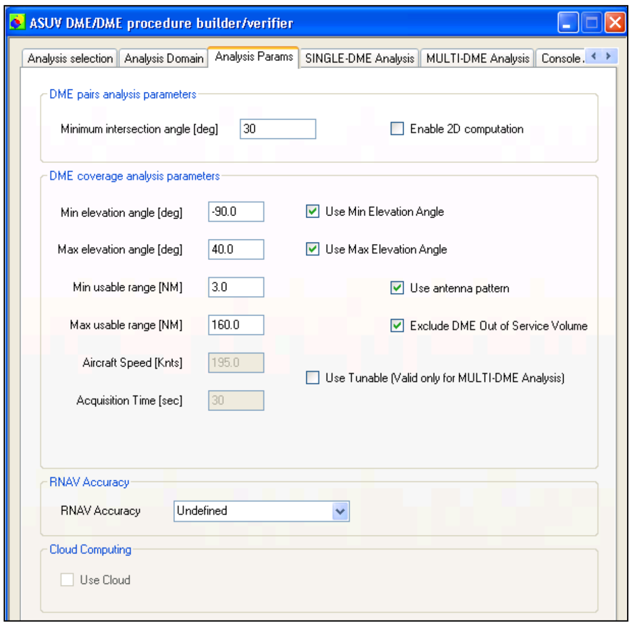


Figure 9. EMACS ASUV exclusion logics and RNAV parameters

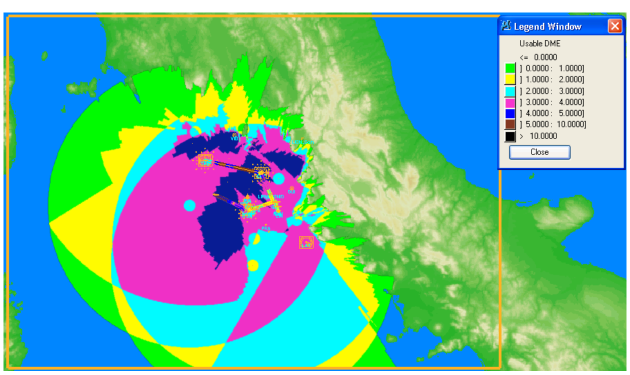


Figure 10. EMACS ASUV number of DME in coverage on area domain

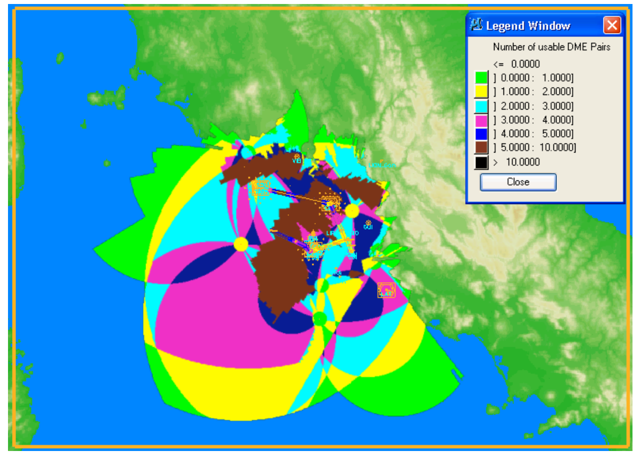


Figure 11. EMACS ASUV number of DME pairs in coverage and usable on area domain

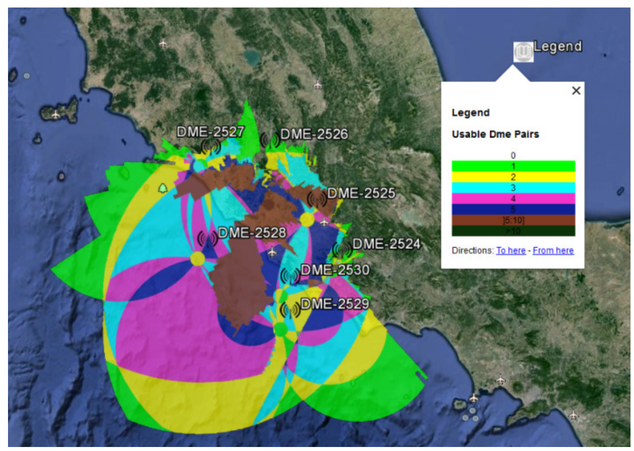


Figure 12. EMACS ASUV number of DME pairs in coverage and usable on area domain (Google view)

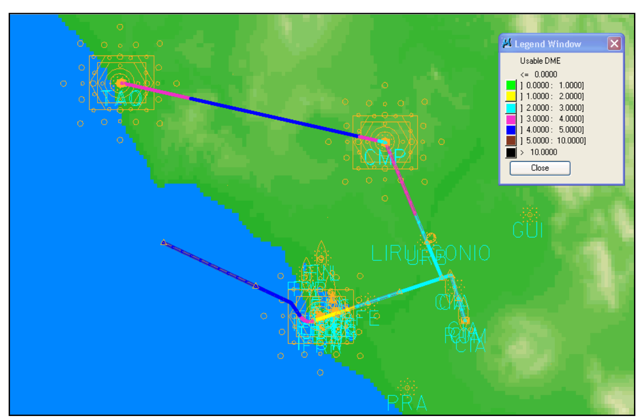


Figure 13. EMACS ASUV number of DME in coverage along a flight procedure

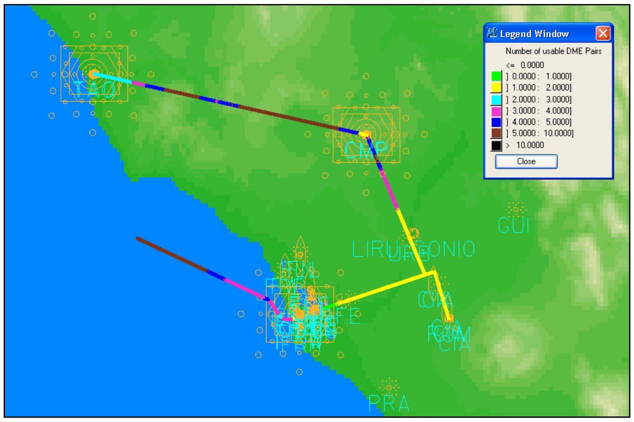


Figure 14. EMACS ASUV number of DME pairs in coverage and usable along a flight procedure

Calculation and export of the data package

Once the RNAV performances have been calculated, there is the possibility to export the optimized data package calculating the maximum number of equipment (DME and/or TACAN) measured simultaneously. Moreover there is the ability to:

- Define the maximum number of DME and the maximum number of simultaneously measurable TCN (see Figure 15)
- Minimize the number of COP (Change Over Point) of a flight procedure and reduce the DME receiver workload (see Figure 15).
- Display the result of the computation on a Cartesian graph or colored map
- Export the result of the computation to the UNIFIS 3000 (through the definition of an Interexchange Control Document format .nsmsql) and NXT (.txt file). An example has been reported in Figure 16.

The export panel has been reported in Figure 15:

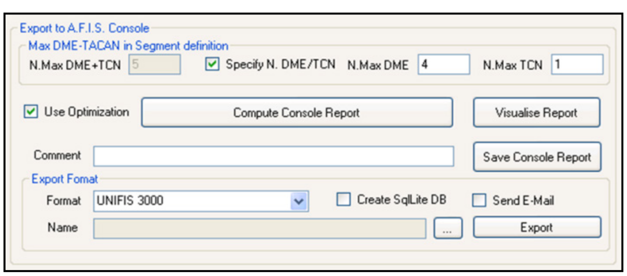


Figure 15. EMACS ASUV calculation and export of the data package.

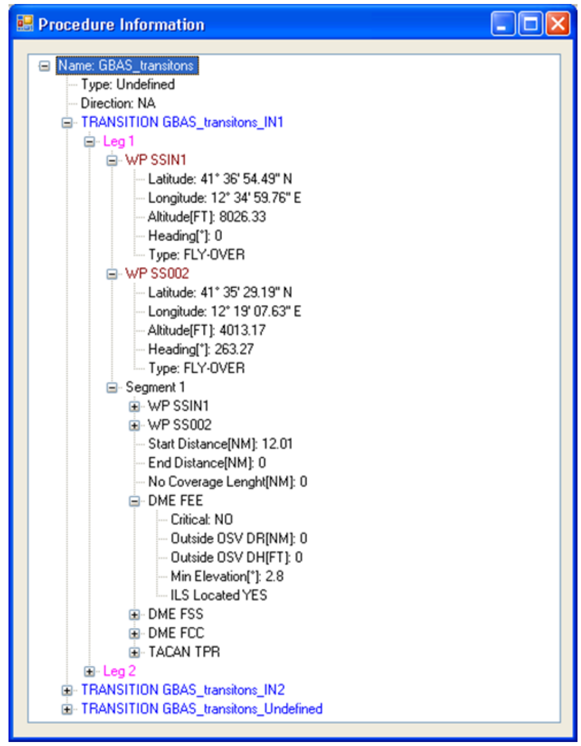


Figure 16. EMACS ASUV example of data package (open format)

In case of exports to the Console UNIFIS 3000, there is the possibility to automatically prepare a mail with the data to be sent to the Flight Inspection Department in the attachment. The data are listed below:

- File .nsmdb (data package to be automatically imported onboard plugging in a pen driver)
- File . nsmsql (sql script to populate the UNIFIS DB schema)
- A descriptive PDF file for crew briefing describing the number of DME to be checked segment by segment

DB data and examples of files have been reported in Figure 17:

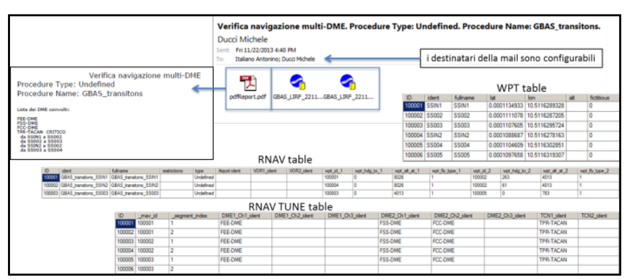


Figure 17. EMACS ASUV export and mail to the Flight Inspection department.

Loading of the data package and flight procedure validation

Once received from the Flight Inspection Department, the data package can be automatically loaded onboard to pilot the UNIFIS Console (and the DME receivers) and tune up the right sensors to acquire measurements for tuned DME (the ones listed segment by segment in the data package). The procedure validation will be completed and the measurement data package (for each DME segment by segment) will be acquired.

Each measurement file is converted into 2 files through a converter component provided by NSM:

- .Txt file with the identification of the number of the run
- .Dat file with the data measured during the run

The flight inspection measurements import panel has been reported in Figure 18.

The 2 files can be then automatically imported into EMACS ASUV in order to close the loop and compare flight inspection measurement vs numerical simulations. This has a double scope:

- Improve the calibration of the simulation
- Compare the logics of the aircraft FMS (Flight Management System) and the simulation results

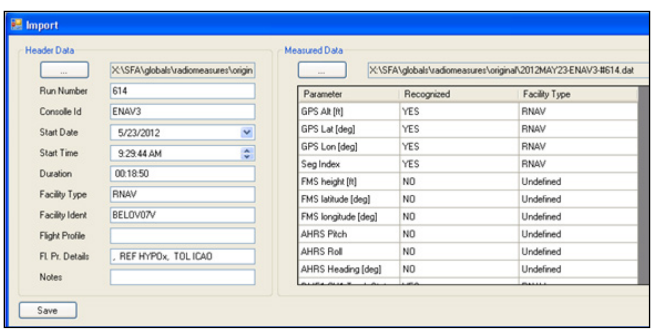


Figure 18. Data file coming from the flight inspection validation campaign (import interface)

Simulation vs Flight Inspection

Once the measures relating to a route/procedure have been imported into the DB, there is the possibility to make a comparison between measurement and simulation in a graphical way like reported below (Figure 19):

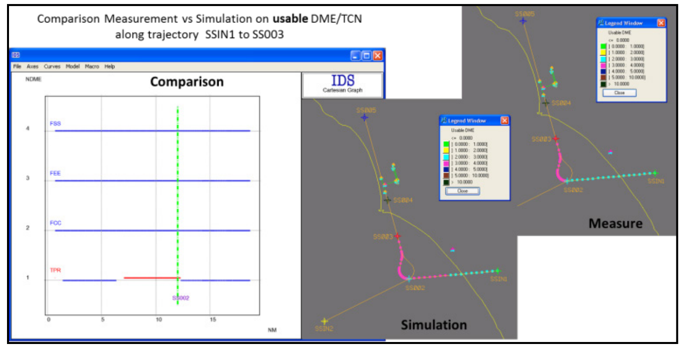


Figure 19. Data file coming from the flight inspection validation campaign

This means there is the possibility to compare the calculated number of DME in coverage segment by segment and check/correct eventual inconsistencies in the NSM Console/EMACS ASUV logics.

CONCLUSIONS

This report provides results of distance measuring equipment – area navigation (DME RNAV) flight inspection requirements, concepts, and implementation proposed for an automated flight inspection system. The DME RNAV route/procedures requires the availability of two or more DMEs although limited gaps in coverage are tolerated. RNAV route and procedure design is facilitated by the FPDAM/EMACS ASUV usage. The software determines if suitable DME coverage exists for the procedure based on inter-site geometry and predicted coverage characteristics. Flight inspection of the designed route/procedure is performed to assess actual DME coverage. The algorithm used in EMACS ASUV software is assessed and data is compared with measurements to ensure compatibility between procedure design/simulation and AFIS software logics. The final flight procedure validation workflow is reported below (Figure 20):

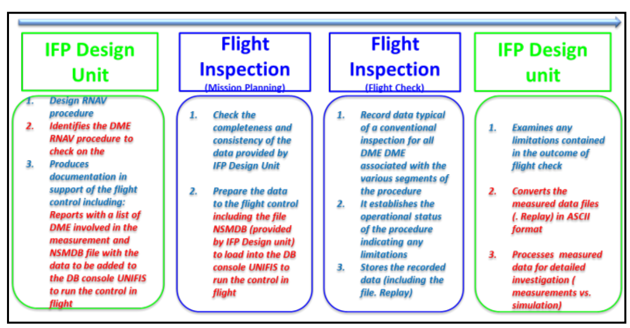


Figure 20. Summary of the ENAV flight procedure validation workflow

FUTURE WORK

The presented workflow has been already implemented and it is in phase of validation. Several activities have been planned through the Italian territory and abroad to make it fully operational. The next validation activities will regard the following airports:

- LIRF (Fiumicino Airport)
- LIPE (Bologna Borgo Panigale)
- LIRN (Napoli Capodichino airport), STAR RWY 06, 24, SID RWY 06 only

Next technological evolutions will regard integration between the UNIFIS 3000 and the onboard FMS (Flight Management System). The goal will be an automatic flight procedure dataflow from the UNIFIS to the flight management system.

REFERENCES

[1] International Civil Aviation Organization, July, 2006, Annex 10, Aeronautical Telecommunications, Volume 1, Radio Navigation Aids.

[2] International Civil Aviation Organization, 2000, Manual on Testing of Radio Navigation Aids [Doc 8071], Volume 1, Testing of Ground-Based Radio Navigation Systems (10/02 version).

[3] RTCA DO-196 "Minimum operational performance standards for airborne VOR receiving equipment operating within the radio frequency range of 108-117.95"

[4] RTCA DO-195 "Minimum operational performance standards for airborne ILS localizer receiving equipment operating with the radio frequency range of 108-112 MHz"

[5] RTCA DO-192 "Minimum operational performance standard for airborne ILS glide slope receiving equipment operating within the radio frequency range of 328.6.335.4 Megahertz"

[6] RTCA DO-189 "Minimum operational performance standards for airborne distance measuring equipment (DME) operating within the radio frequency range of 960-1215 Megahertz"

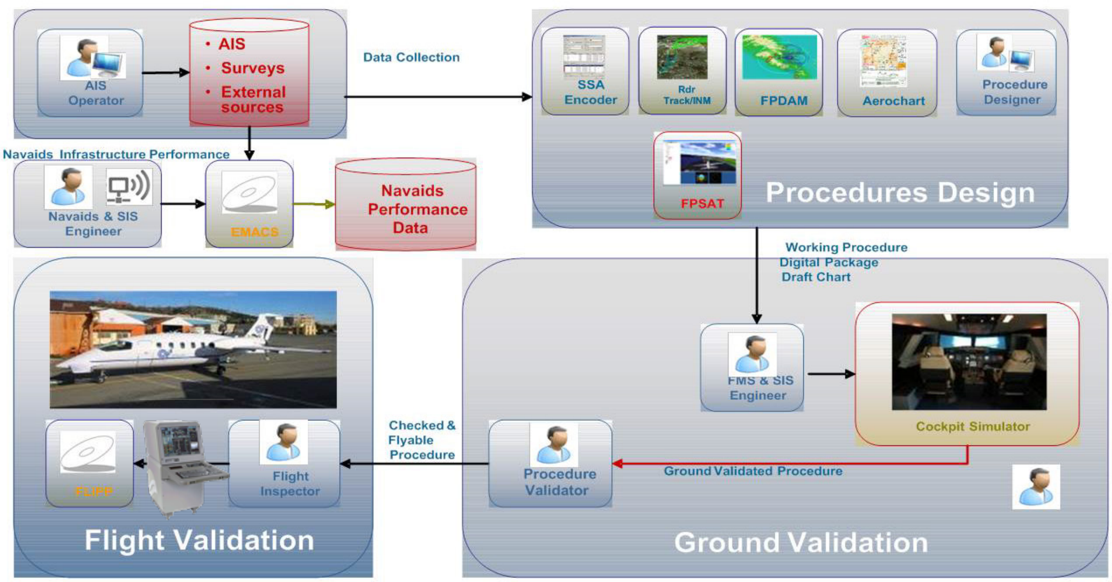
[7] Eurocontrol Guid 0114 "Eurocontrol Guideline for P-RNAV Infrastructure Assessment"

APPENDIX

From Data collection to procedure design and flight check

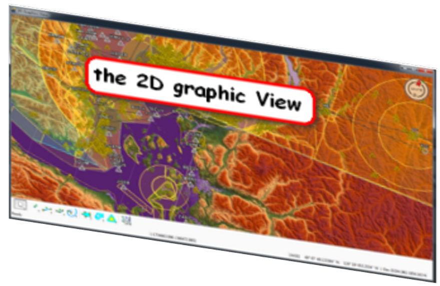
The entire workflow represented is a commonality of process and product that represent :

- An automated and workflow for the AIS data using a data quality controlled process
- Develop the flight procedures with current FPDAM
- Validate the flight procedures with current FPDAM
- SSA ARINC 424 coding with current FPDAM
- Electronic Packing the Coded Procedures in the NaV DB
- Flight Inspect and Validation using the Navigation DB
- Release quickly to the Airlines and DB suppliers

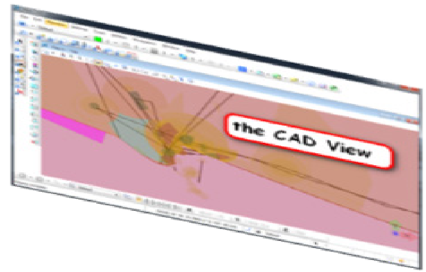


FPDAM covering TERPS .58 ICAO PANS/OPS 8168, DOC 9905,DOC 9906

Latest FPDAM version can natively manage the data with the AIXM5.1 schema model by providing an automatic coding to the IFP while the procedure gets designed. Procedures, routes, airspaces and all the features in the AIXM5.1 database can be imported and re-worked.



IDS solution for flight procedure design is the most sold and used in the world. The level of integration between IDS FPDAM system and IDS AIM system is strong in the sense that there is no need to define an exchange ICD format between the different subsystems. De facto, IDS is the only company in the world capable of offering and deploying a true and complete AIM solution as a single vendor. FPDAM will be able to read/write and submit the data changes directly connected to the central and unique database. There will be no need for any re-projection as it is done automatically on the fly; full open formats management for terrain and images will be also extremely easy. Drawing, checking and assessing more than one procedure will be possible and extremely useful in terms of procedure maintenance and procedure regulation check in case of new amendment/new criteria.



In other worlds, FPDAM can automatically:

- re-assess the obstacle clearance of archived procedure ”S” against new obstacles («**land-use assessment**»)
- re-assess the IFP vs Airspaces for containment analysis
- check consistency on ATS data
- re-draw protection areas
- re-assess obstacle clearance

of archived procedures against:

- new criteria amendments
- changes in the ATS scenario (e.g. **waypoint displacement**)

All of this in «**batch**» mode (without any user intervention).

Latest FPDAM version is also minimizing the number of human operations (often repetitive and without any “added value”), leaving to the user the responsibility about the most significant design choices.

CAD/GIS usage will not be any more a mandatory prerequisites because FPDAM uses CAD/GIS software as additional mere views. It is, as matter of fact, equipped with internal graphic capabilities to visualize the internal application domain and all the relevant metadata needed for procedure design, validation and verification.

CAD system as Microstation Bentley or GIS system as Intergraph Geomedia can be used for designing new geometries to be associated to the domain.

FPDAM provides a complete set of user-friendly tools for designing flight procedures either conventional than RNAV. In particular, the system allows to automatically creating procedures and procedural features in accordance with ICAO PANS-OPS including PBN approaches, departures and standard arrivals;

It allows to interactively modify the procedure by simply moving a leg or a waypoint in a new position or with a different track/bearing that the system will draw the relative flight path, the relative protection areas/surfaces the relative obstacles assessment.

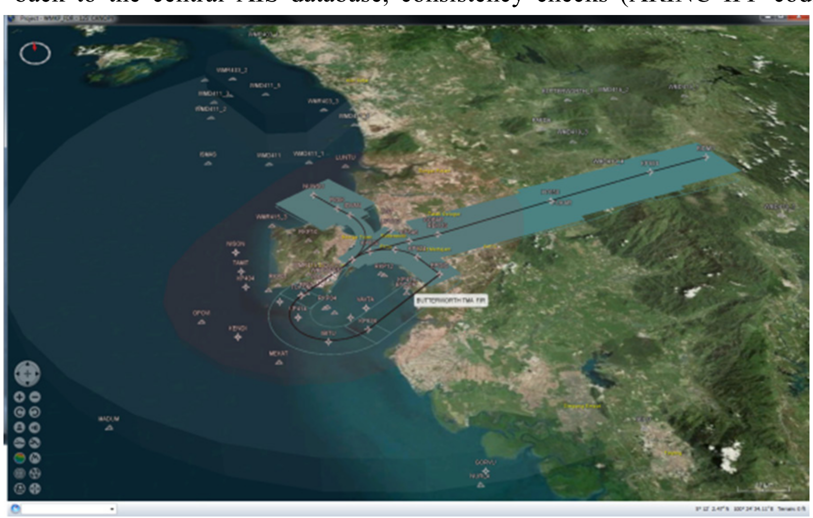
FPDAM allows a user to:

- Read Procedure Design information from an AIXM4.5, 5.1, ARINC 424 file or from AIXM5.1 database.
- auto-check, validate and adjust ARINC 424 coding; it loads the coding and checks the compliancy of the above mentioned legs/segments against the ARINC 424 rules in terms of sequence, starting/ending path & termination, the minimum set of parameters to be provided. Validation parameters settings based on some rules/checks done automatically by the system to take into account normative compliancy or user defined

compliancy. The checks are typically performed on leg length (according to the type of segment final, initial, initial missed approach and so on), track angle between two legs (according to the maximum value foreseen), leg gradient (according to the type e.g. final), minimum distance between waypoints, maximum ground distance for VOR/DME fixes, fixes tolerance area according to the type of fix (IAF,IF,FAF and so on). Also the optimum value is suggested by FPDAM system.

- Auto-code ARINC 424 while designing; when designing a new procedure, FPDAM assigns to each single leg/segment the related path & termination without user selection. If the P&T is selected, FPDAM will consequently draw the relative flight path, the protection areas related to that flight path and minima for that leg. Waypoints linked to the procedure, OCA/OCH values, MSA, SSA supplementary data can be maintained and committed at the same time. During the construction of the procedure the SSA data are automatically saved in the database or in the file AIXM, ARINC424 depending on the configuration. The user can add attributes to each feature of the working file. Once the coding process is finished and checked by the designer supervisor, the electronic package can be sent to the AIS for the final validation process. The final commit in the central AIS database can be carried out by the AIS responsible.

FPDAM allows a user to display in the geospatial based environment all the Aeronautical features coming from the ARINC file they need to use for the procedure construction and validation together with “what-if” data for design purposes. FPDAM can display as information layers as many vectors files as the user may require. SSA (SID, STAR, Approaches) data can be also displayed in different ways. The user may select to display the nominal track only, the nominal track and the protection areas at the same time (for lateral /vertical separation analysis) or the entire design project. Additional information layers such as noise sensitive areas, populated areas, geographical grids, airports layouts can be added from the user on request and switched on/off. Once the design has been completed, the user may select to propose top the AIS partial design projects, (single SSA for a complex SSA design project, for instance) or the whole project. When committing back to the central AIS database, consistency checks (ARINC IFP coding rules applied and verified) are performed in order to validate the data. FPDAM can:



- dynamically manipulate procedure design features in order to optimize an find the best OCA/OCH (e.g. FPDAM allows the user to draw and assess final protection areas in one step, in this way the user can just modify the final track approaching radial to compare which is the lowest minima);
- modify the design rules; each single FPDAM construction provides default values, for the parameters and equations, taking into account the most penalizing parameter stated in the reference criteria (indicated air speed, gradient, length, etc). Because FPDAM has been parametrically developed, the parameters of equations can be changed by the user (both the default and the single case). In case of great changes such as constructive equations and obstacle assessment formulas, a customization of the system is required by the IDS development team;
- highlight and display significant/critical changes to a generated procedure resulting from modifications in the Reference Data; every time one data has been changed, FPDAM will warn the user that the change affects one or more procedure if the procedure design has been developed using that feature.

The capability of providing automated assessments and reports for the purpose of obstacle assessment i.e. In FPDAM every obstacle assessment analysis on each specific procedure, leg/segment produce provides a list of the most penalizing obstruction that can be saved or printed, for legal recording purposes or for personal storage. link will have the capability of printing/plotting each function using different scales and paper formats.

EMACS E.M. methods for coverage calculations

EMACS description

EMACS is a family of electromagnetic 3D modeling and simulation tools, able to solve EMC (ElectroMagnetic Compatibility) and EMI (ElectroMagnetic Interference) issues in complex airport and air navigation scenarios.

The numerical tools are based on the most sophisticated and widely known computational electromagnetic techniques, such as (3-D methods):

- Geometrical Theory of Diffraction (GTD/UTD)
- Physical Optics (PO/PTD/ITD)
- Method Of Moments (MOM)

EMACS supports:

- Periodic flight calibrations and checks
- Feasibility analysis of new or upgraded airports/equipments
- CAA planning permissions
- Support ATC with radars and navaids systems siting
- Interference, PSR/SSR coverage and radar maps.

EMACS computes RNAV performances (described in detail in this article) taking into account the:

- Transmitted power (at the antenna input),
- Frequency of the antenna,
- Antenna pattern,
- Free space propagation losses,
- Earth Curvature (K-factor),
- Terrain effect,
- RNAV constraints specified on the configuration (Minimum and Maximum VOR and DME Range, Maximum Elevation Angle and the Cone of silence).

The radio coverage evaluations have been performed using a 2D algorithms called Deygout Method.

The radio coverage result is displayed using a 2D map, with colour contours distinguishing the different strength signal levels. It is possible to set a threshold level (i.e. receiver sensitivity) in order to predict the range of coverage.

The tool also gives the number of Navaids covering each area on the map using the cumulative coverage. A colour legend is then used allocating different colours to areas depending on the number of Navaids covering them.

The purpose of the RNAV performance calculation is to evaluate multiple performance parameters based on the available navaids on each point of the analysis domain. The user is able to select a domain of analysis using the CAD/GIS tools from EMACS, then select the list of navaids from their planned or existing position through locating them on the graphics or via the relevant co-ordinates. EMACS executes the performance calculation on the domain specified by the user.

Depending on the performance type (DME-DME or VOR-DME), some calculations are performed:

- Number of navaids in coverage,
- Number of DME pairs usable for RNAV,
- Number of critical DME and identification of the critical site,
- Min. and max. Position Estimation Error (PEE),
- Multi DME continuity of service,
- Compute altitude constraints for waypoints in order to meet requested precision and continuity goals.

For the VOR-DME performance, only the Number of navaids in coverage is calculated. For the DME-DME performance all the calculations are performed.

Deygout method description:

The Deygout algorithm is suggested in recommendation 715 from the former CCIR (now ITU), and represents the solution to the problem of multiple diffraction of radio waves (f>30 MHz) over knife-edge obstacles. The path loss is obtained directly and quickly by alignment of distances and heights adequately selected from a path profile.

The Deygout algorithm works as follows.

- Terrain profile is generated for the path between transmitter and receiver intersecting the vertical plane containing the antenna phase centre and the observation point with the digital terrain model. The use of digital terrain models with different resolutions can be used to describe the terrain within the area of interest.
- Terrain heights are then corrected to take into account the curvature of the earth.
- The terrain profile is processed to select the terrain points which would be touched if a string was stretched between the transmitter and receiver (the interfering peaks or knife edges)
- The field strength is computed by adding the free space losses to the extra losses caused by the interfering peaks.

When more than one knife edge obstacle is present along the terrain profile, the cumulative effect is evaluated.

Other algorithms used by EMACS for coverage simulations:

The radio coverage evaluations are performed using 2D algorithms (like Deygout already described). Thus, all the implemented numerical tools execute their computations taking into account the propagation mechanisms within the vertical plane passing through the antenna phase centre and the observation point. EMACS uses other algorithms for evaluating the signal strength:

1. IF77 method: this method is applicable to air/ground, air/air, ground/satellite, and air/satellite paths. It can also be used for ground/ground paths that are line-of-sight or smooth earth. Model applications are restricted to telecommunication systems operating at radio frequencies from about 0. 1 to 20 GHz with antenna heights greater than 0.5 m. In addition, radio-horizon elevations must be less than the elevation of the higher antenna. The radio horizon for the higher antenna is taken either as a common horizon with the lower antenna or as a smooth earth horizon with the same elevation as the lower antenna effective reflecting plane. At 0.1 to 20 GHz, propagation of radio energy is affected by the lower, non-ionized atmosphere (troposphere), specifically by variations in the refractive index of the atmosphere. Atmospheric absorption and attenuation or scattering due to rain become important at SHF (Super High Frequencies). The terrain along and in the vicinity of the great circle path between transmitter and receiver also plays an important part. In this frequency range, time and space variations of received signal and interference ratius lend themselves readily to statistical description.

2. GTD-2D method: this method is based on the use of a 2D formulation of the Geometric Theory of Diffraction (GTD) in its uniform formulation, also known as Uniform Theory of Diffraction (UTD). This theory is based on an asymptotic solution of the Maxwell equations which is obtained under a high frequency approximation. Such a formulation is applicable in the evaluation of the interaction between a radiating source and a scattering structure whose dimensions are much larger than the field wavelength.

The total scattered field can be described as the combination of discrete contributions from a number of 'hot points' distributed over the body according to relatively simple geometric laws relating to the propagation of rays.

3. Parabolic Equations method: the PE solution is a full wave solution (i.e. exact solution). This method is used to solve the two-dimensional (2-D) Helmholtz equation.

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Investigating Multipath Propagation for Navigation Systems in a Miniaturized Airport Environment – ILS and Extension to VOR

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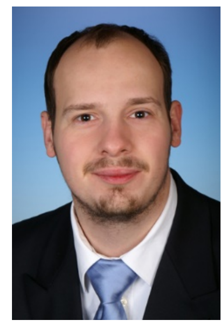

ABSTRACT

For various navigation systems, such as the instrument landing system (ILS), the VHF omnidirectional radio range (VOR) or radar, multipath propagation can degrade their performances and even crucially disturb their actual navigation information. Known scenarios for such disturbances are reflections from large taxiing aircraft near the runway influencing the localizer of the ILS and the scattering of signals from VOR or radar due to rotating wind turbines. Since such multipath propagation scenarios have impact both on the safety and on the capacity of an airport as well as the approval of wind farms, it is essential to accurately quantify the amount of performance degradation.

Since measurements at a real airport are very demanding and expensive, thus hardly can cover all relevant scenarios, we propose to scale down an airport's geometry and correspondingly rebuild scaled versions of relevant navigation systems to provide a measurement environment with nearly unlimited availability and flexibility.

In this contribution we present progress in the work with a scaled measurement setup suitable for optimizing ILS-protection areas individually for airports. Additionally, we show how to enhance this scaled measurement concept for the VOR and rotating wind turbines which is a timely topic in Germany.

INTRODUCTION

In ICAO Annex 10 [3] allowed tolerances for navigation systems are defined. E.g. for the ILS localizer, depending on the distance to the runway threshold allowed tolerances are 5 µA. For the VOR a maximum bearing error of 3° is given. Naturally, these tolerances take into account non-ideal environment where multipath propagation affects the ideal navigation signal. Whereas such tolerances are a reasonable measure for safe air traffic operation, a real physical connection between these tolerances and the size and shape of reflecting objects is not established at all. On the one hand this is due to the complexity and size of scattering objects like aircraft and wind turbines and due to the difficult boundary conditions such as a non-plane wave incidence. Up to now no validated simulation tools exist that can accurately predict course tolerances due to multipath propagation. In particular, a full validation of such a simulation tool cannot be provided with a single good agreement between measurement and simulation results. Moreover, most important is a sensitivity analysis, thus a statement on how do simulation results depend on a slight variation of input parameters, such as position and heading of an aircraft on a taxiway, which can hardly be more accurate as a few meters, respectively degrees. Such an analysis cannot be obtained by measurements at a real airport, simply due to the enormous effort.

To validate the scaled measurements technique, results are compared with those of measurements in real environments. In a reference study, which was made because of the introduction of the A380 [1], several scenarios are presented where the effect of a taxiing A380 or a B747 on the ILS localizer is investigated. Figure shows how the current overall concept for ILS protection areas does not take into account fundamental aspects of the scattering behavior of an aircraft.

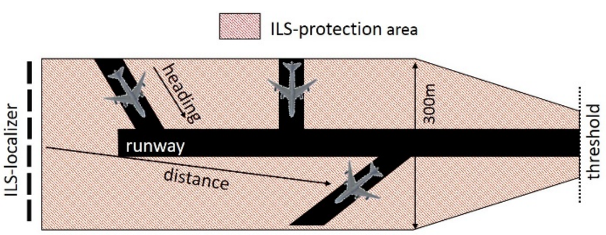

Figure 1: Overall Layout for ILS Protection Areas.

Though the current layout for ILS protection areas may be a pragmatic one, it is quite obvious that relevant parameters of such scattering scenarios are not taken into account at all such as the following. In nearly all cases this is a near-field scattering scenario as the distance of the aircraft to the ILS localizer is usually smaller than 4000 m. E.g. the so-called “antenna foot print” gives variations of more than 10 dB over the whole dimensions of a large aircraft compared to plane wave illumination approximations. Thus the illumination of the aircraft strongly depends on this distance as well as the heading of the aircraft itself. The latter is the main parameter that specifies both the incidence and the scattering angles into the direction of the landing aircraft. Consequently, the three examples depicted in Figure 1 must physically considered to be different. In particular, taking a sphere, the scattering behavior of which can be calculated analytically exact, gives a mathematical proof, that the current ILS protection area layout cannot accurately be valid for all three scenarios, thus does not sufficiently describe the scattering of aircraft themselves. Similar are current regulations with respect to rotating wind turbines. The actual scattering behavior of wind turbines is not discussed at all in corresponding ICAO documents [4]. The only question addressed is if a quasi-optical ray would reach wind turbines or not. There are no physical relations between the scattering behavior and existing tolerances for the VOR bearing error.

One reason for that, of course, is the current lack of data that describe the scattering behavior of aircraft (with respect to ILS) or wind turbines (with respect to VOR or radar) due to the missing validity and sometimes limited applicability of simulation tools and the enormous complexity of measurements in a real airport environment. An overview about that is described in more detail in [5].

Consequently, the technique of scaled measurements is proposed in this contribution to flexibly analyze the impact of reflecting objects on arbitrary navigation systems. Scaling makes use of the physical fact that the scattering properties stay the same for dispersion free objects if the ratio between objects’ dimension and the wavelength is kept constant. This actually is empirically familiar to anyone recalling the function principles of antennas. A dipole radiating at lower frequency requires a larger length and vice versa, but once the ratio of dipole length and wavelength is constant, the radiation characteristics stay the same.

In a scaled, respectively miniaturized measurement setup of navigation systems the complex airport environment is reduced to a compact, well controllable, and flexible measurement facility with nearly unlimited availability and manageable costs for operation.

The fundamental concept of scaling navigation systems and the major high frequency engineering aspects are described in detail in [2] as it would exceed the scope of this article. The main focus of this contribution is a validating comparison between results in the scaled environment and results obtained in an comprehensive ICAO study about large taxiing aircraft in ILS protection areas, conducted at Heathrow, Frankfurt and Toulouse airport in 2006 [1]. Additionally, the idea of scaled measurements is enhanced to apply also for the VOR and rotating wind turbines, a simple measurement example is given here.

SCALED MEASUREMENT SETUP FOR ILS

For the scaled measurements the ILS itself, the airport environment, the taxiing aircraft, and the receiver are re-built in the new scale. For VHF frequencies, where ILS localizer and VOR are operating at, this leads to a higher frequency of 16 GHz using a scale of 1:144. Thus a landing approach in 9 km distance to the ILS corresponds to a scaled distance of 62 m.

For the taxiing aircraft galvanized resin models are used that are commercially available. The scaled ILS localizer is built with a slotted waveguide antenna array as the key element of the scaled approach as it provides the same antenna pattern as the real ILS localizer. Moreover, the design is reconfigurable to even match arbitrary ILS patterns. The detailed description on that is given in [2].

In Figure 2 the measurement open area test site of the national institute of metrology (PTB) in Braunschweig is shown with the layout of Frankfurt airport in Germany and a taxiing aircraft as reflecting object, the influence of which on the ILS signal, is measured. At one end of the runway the scaled version of the ILS is located. At the other end, not shown on the picture, the receiver is mounted on a platform which is moveable in vertical direction. This unit is attached to a wagon that autonomously drives on rails made of PVC, resembling the actual landing approach. Both units are driven with electric motors. A microcontroller reads out the data of a distance measuring laser and controls the two motors in order to realize reproducible approaches with a defined glideslope angle.

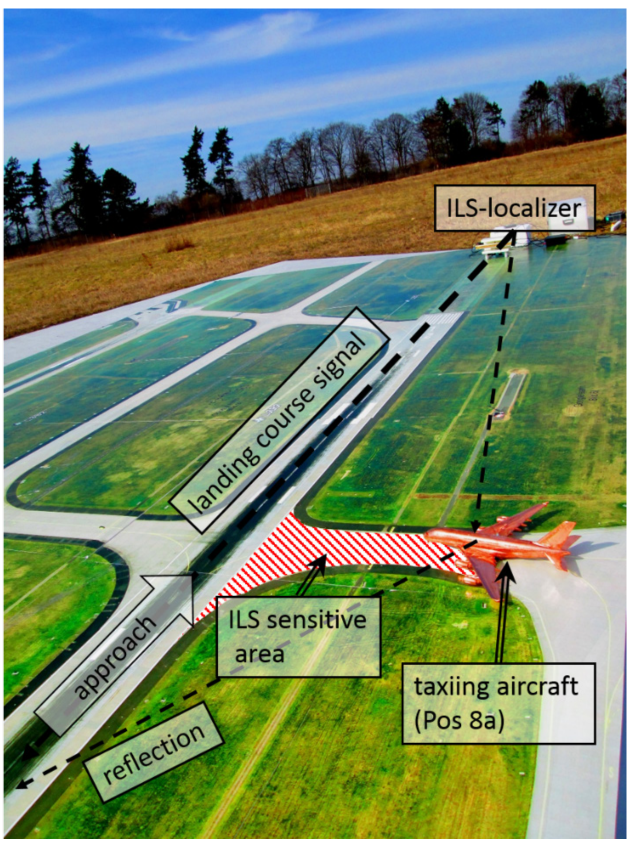

Figure 2: Mini-Airport Setup at Scale 1:144.

For the scaled approach, the wagon moves at constant speed of around 0.25 m/s towards the ILS, while the height of the receiver is successively reduced on the glideslope corresponding to a descent aircraft. It is also possible to perform measurements for an aircraft after touchdown rolling on the runway with just shifting the rails towards the ILS. Consequently, a whole landing approach is divided into descent phase and roll-off on the runway. It is even possible to calibrate the whole mini-airport environment by simple performing scaled landing approaches without any scattering objects. This is of course hardly feasible at real airport environments.

Definition of Tolerance Categories in Real Measurements

In the ICAO-study [1] measurement results of each landing approach are assessed with respect to allowed tolerance limits of the respective ILS categories. The applied classifications are displayed in Table 1.

Table 1. Tolerance Categories for the Reference Measurements.

Category	
IT	Fulfills CAT I-III
IT*	On CAT III tolerance
ATC3	Outside CAT III tolerances
ATC3*	On CAT II tolerance
ATC2	Outside CAT III tolerances
ATC2*	On CAT II tolerance
ATC1	Outside CAT I/II/III tolerances

According to that similar classifications are applied for the scaled airport environment which is explained in the following.

Definition of Tolerance Categories in Scaled Measurements

The mentioned ICAO study does not make statements about the expected positioning accuracy of the scattering aircraft, but in the scaled measurement setup it turned out that the resulting landing course disturbances strongly depend especially on its lateral distance to the middle of the runway. Thus equivalent categories are defined for the scaled measurement results referring to a percentage of measurement points exceeding ILS tolerances.

Table 2. Tolerance Categories Defined for the Scaled Measurements.

Category	Allowed percentage of measurement points	
	Outside ± 5 µA	Outside ± 15 µA
IT	0%	0%
IT*	2%	0%
ATC3	10%	0%
ATC3!	100%	0%
ATC3!*	100%	2%
ATC1!	100%	100%

Results demonstrate that the influence of positioning accuracy becomes larger the closer the landing aircraft gets to the ILS. This is where the tolerances are narrow. These narrow tolerances are applied for the whole measurements. The tolerance limits for CAT I (15 µA) and CAT III (5 µA) [3] are used and the category is determined by the number of points, if any, are exceeding these limits as it is shown in Table 2. If only 2% points exceed the tolerance limits, the lower category is used and marked with an asterisk which corresponds to the "on tolerance" categories of the real measurements.

In the following, the scattering scenarios of A380 and B747 conducted at Frankfurt and Toulouse as presented in mentioned ICAO study are compared.

COMPARISON OF MEASUREMENT RESULTS

Frankfurt Airport Scenarios

At Frankfurt Airport the positions of the taxiing, respectively scattering aircraft are shown in Figure 4 as conducted both in the original ICAO study and in the scaled measurement setup.

In the ICAO-study positions P1, P1.1 and P8 are realized by a fixed receiver and a moving taxiing aircraft. In the scaled measurements each of these positions are split up into three static positions on the trajectory of the movement allowing a measurement for the whole landing approach. Therefore the highest disturbance of the three scaled measurements has to be compared with the results of the Frankfurt airport measurement.

Measurement results at the real Frankfurt airport are not differentiated into approach (descent phase) and runway (roll-off), therefore only the maximal value from either configurations is taken for comparison with the scaled measurement results.

As an example Figure 3 shows measurement results obtained in the scaled environment.

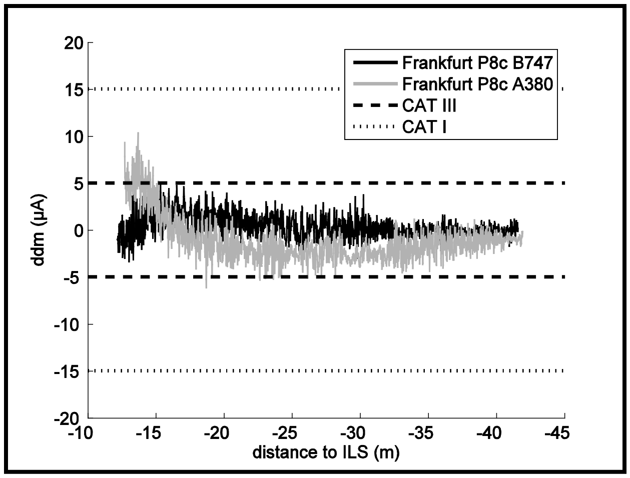

Figure 3. Measurement Example of a Scaled Landing Approach for the Movement on the Runway after Touchdown.

Measurements on the runway (roll-off) show a higher disturbance potential than measurements during the descent phase of the landing aircraft. This is especially visible at the crossing scenario (P8) which is within the ILS tolerances. The lower potential for disturbance effects of the B747 in contrast to the A380 is observed at the crossing scenario (P8) where only the A380 leads to severe disturbances as displayed in Figure 3 for the position P8c. This is likely due to the larger tailfin of the A380. This effect at this position is higher than at position 8a, as the tailfin is closer to the center of the runway.

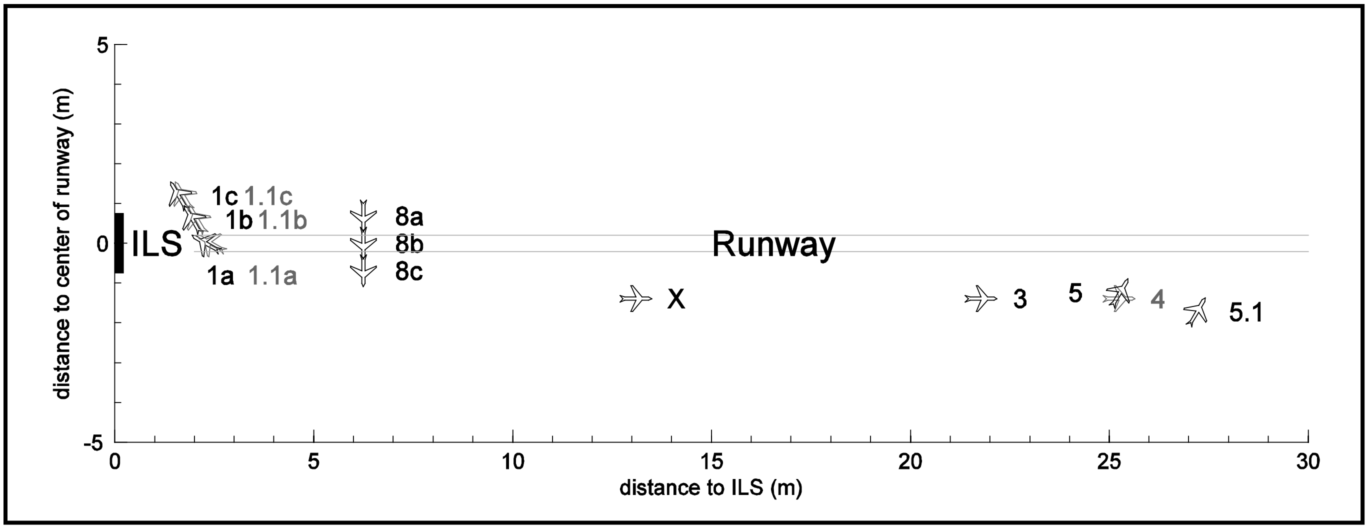

Figure 4. Scattering Aircraft Positions for Frankfurt Airport, Real Distances Have to be Multiplied with the Used Scaling Factor of 144.

Table 3 summarizes the comparison between measurements in the real and the scaled Frankfurt airport environment. It can be seen clearly that the scaled airport environment leads to the same classification with respect to ILS Cat tolerances.

Measurements on the runway (roll-off) after the threshold show more disturbances than in the descent phase of the landing approach. For example this is obvious for the crossing scenario where there is disturbing influence only during the movement on the runway after threshold. At position P1, where the taxiing aircraft leaves the runway, the disturbances for rolling off on the runway (**ATC1!**) are more severe than for the descent phase of the approach. For this particular scenario P1 the effect of an A380 is higher than for a B747: **ATC1!** instead of **ATC3!.** For position P1 the CAT I tolerances are exceeded both in real and in scaled measurements.

In the ICAO study the measured instrument current for aircraft at position P1 is likely wrong for the B747. The value is 5 µA, but the tolerance class is **ATC1.** For position P1.1 the current is 20 µA, thus much higher but the category is only **ATC2**. With the current for A380 at P1 being 30 µA, the correct current may probably be 25 µA for the B747. In addition to the scattering scenarios at Frankfurt airport measurement results are also shown for Toulouse airport in the following.

Table 3. Results for Frankfurt Airport Scenarios in Real and Scaled Measurement Environment.

Position	Reference				Scaled Measurement			
	A380		B747		A380		B747	
	Category	I (µA)	Category	I (µA)	Approach	Runway	Approach	Runway
P1a	**ATC1**	30	**ATC1**	5	**ATC1!**	**ATC1!**	**ATC3!**	**ATC1!**
P1b					IT*	IT*	IT	IT*
P1c					IT	IT*	IT	IT
P1.1a	N/A	N/A	**ATC2**	20	N/A	N/A	**ATC3!**	**ATC1!**
P1.1b					N/A	N/A	IT	IT*
P1.1c					N/A	N/A	IT	IT
P2	IT	3.5	IT	1	N/A	N/A	N/A	N/A
PX	IT	2.5	N/A	N/A	IT	IT*	N/A	N/A

Position	Reference				Scaled Measurement			
	A380		B747		A380		B747	
	Category	I (µA)	Category	I (µA)	Approach	Runway	Approach	Runway
P3	IT	2.5	N/A	N/A	IT	N/A	N/A	N/A
P4	IT	3	N/A	N/A	IT	N/A	N/A	N/A
P5	IT*	2.5	IT	1.7	IT	N/A	IT	N/A
P5.1	N/A	N/A	N/A	N/A	N/A	N/A	IT	N/A
P8a					IT	IT*	IT	IT
P8b	ATC2	20	ATC3	8	IT*	ATC3!	IT	IT
P8c					IT	ATC3	IT	IT*

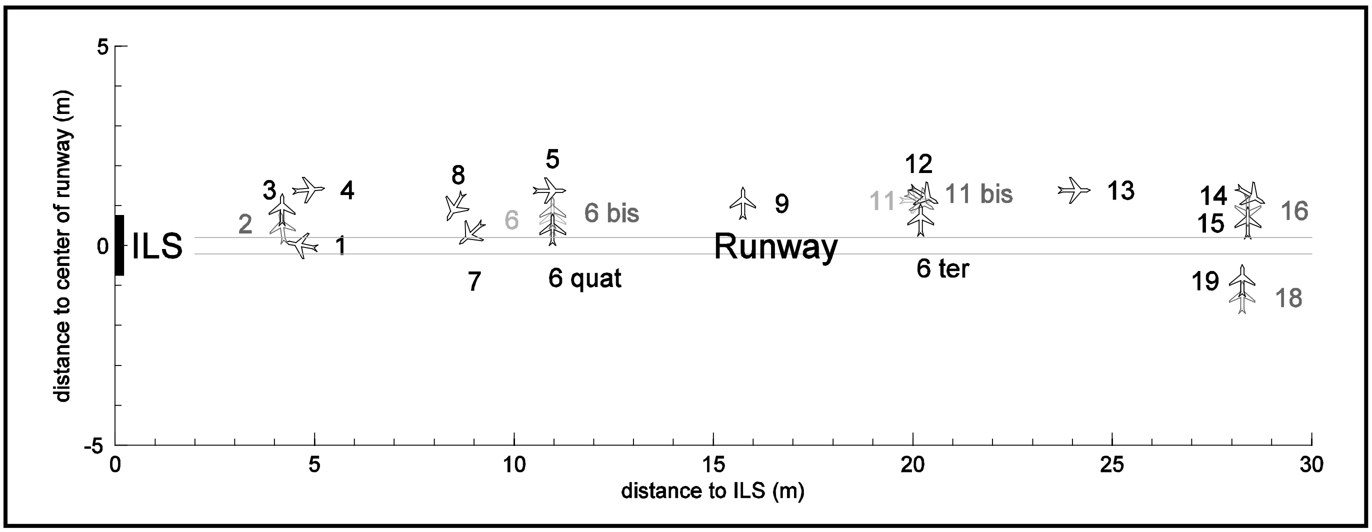

Figure 5. Scattering Aircraft Positions for Toulouse Airport.

Toulouse Airport Scenarios

At Toulouse Airport all positions are with a static scattering aircraft, and taxiing scenarios are already split into several positions. E. g. the positions P1-P4 correspond to the movement of an aircraft leaving the runway. Test positions, both in real airport environment and in the miniaturized airport, are shown in Figure 5.

The measurements at the real Toulouse airport as reported in [1] were done in two different configurations. Both measurement flights were conducted (for the descent phase of the landing aircraft) and measurements on the runway with a car (for the roll-off phase of the aircraft). Only some of these measurements are differentiated into these two phases. If not, the worst case of either of them is summarized in the ICAO study with the maximal value of the instrument current. The scaled measurements are also divided into descent and roll-of phase with a separate classification of ILS disturbances.

Measurements in the scaled and the real airport environment show significant disturbances in the descent phase of the landing aircraft only for position P2, while at the other position the results are within allowed ILS CAT tolerances.

At positions P6, P6Bis, P6Ter, P6Quat, P7, P8 and P9 measurements at the real Toulouse airport exceed the CAT-III tolerances, but not the CAT-II and CAT-I tolerances. In the scaled airport environment this is also the case for P6Quat, P7. For the other positions, the disturbances are either a category lower (IT*: P6Bis, P6Ter and P9) or in the real measurements the tolerances are only very slightly exceeded anyway (P8).

Furthermore there are contradictions within the real measurement results provided by the study. The values for the instrument current for the car measurements are much higher than for the runway measurements performed with an aircraft. Although if there are no disturbances measured these values are similar, for the more critical scenarios these are far too high. Especially at position P2 this value is unrealistically high with 90 µA. Therefore the real car measurements can only be used as a tendency but not as an allocation of a particular disturbance category.

The results of the Toulouse measurements are summarized and compared in Table 4.

Table 4. Results for Toulouse Airport Scenarios in Real and Scaled Measurement Environment.

Position	Reference					Scaled Measurement	
	Category		I (µA)			Category	
	Aircraft		Aircraft		Car		
	Approach	Runway	Approach	Runway	Runway	Approach	Runway
P1	IT		3		2	IT	N/A
P2	**ATC1**		20		90	**ATC3!**	**ATC3!**
P3	IT		3		3	IT	N/A
P4	IT		3		3	IT	N/A
P5	IT		2		3	IT	N/A
P6	IT	**ATC3**	2	7	50	IT	**ATC3**
P6 Bis	IT	**ATC3**	3	8	30	IT	IT*
P6 Ter	IT	**ATC3**	3	4	40	IT	IT*
P6 Quat	IT	**ATC3**	2	8	50	IT	**ATC3!**
P7	IT	**ATC3**	4	10	40	IT	**ATC3**
P8	IT	**ATC3**	2	6	3	IT	IT
P9	IT	**ATC3**	2	5	10	IT	IT*
P11	IT		2		3	IT	N/A
P11 Bis	IT	IT*	2		5	IT	IT*
P12	IT		1	N/A	2.5	IT	N/A
P13	IT		2		2.5	IT	N/A
P14	IT		2		2.5	IT	N/A
P15	IT		2		2.5	IT	N/A
P16	IT		3	N/A	2.5	IT	N/A
P18	IT		3		3	IT	N/A
P19	IT		3	N/A	2.5	IT	N/A

CONCLUSIONS FOR SCALED ILS SCENARIOS

A comparison is presented between measurements conducted at real airports and conducted in the scaled airport environment. It has to be mentioned explicitly that the presented good agreement between results obtained in the real and the scaled airport environment is only a part of the successful validation. Additional measurements were done with a metallic sphere as a reference scatterer, the scattering behavior of which can be calculated analytically exact, unlike any other scattering object such as an aircraft. These additional validation measurements are not shown in this contribution as the description would be beyond its scope. However, taking both the validation with the ICAO-study results from real airport environments and mentioned results of the reference scatterer the scaled airport environment can be considered fully validated.

Moreover, it has been demonstrated that the identification of crucial scenarios and especially its relevant parameters is possible giving the desired physical link between parameter space and CAT-classification

This mini-airport environment provides an individual, flexible and low-cost tool for optimizing the ILS protection area layout at airports for more safety and capacity. Moreover, all measurements can be realized, reproduced and demonstrated in a live-modus to anyone with a high degree of transparency and reproducibility. Especially with respect to transparency and accessibility this tool is superior to much more limited measurements in a real airport environment and simulation techniques.

SCALED MEASUREMENTS FOR VOR

Convincing validation results for the scaled ILS measurement environment were the motivation to adapt the idea of scaling also to the VOR and rotating wind turbines. In fact, since the operating frequencies of both systems are quite the same, nearly the same high frequency hardware can be used. Consequently, the scaled VOR operates at 16 GHz, too. For further details about the used hardware architecture refer to [2].

Like for the ILS it is necessary to individually assess the properties of the direct propagation path from VOR to a flying aircraft and the scattered path from VOR to rotating wind turbines to the aircraft as finally their ratio is the measure for bearing errors.

For measurements with the scaled VOR the main difficulty is that both a fast varying amplitude must be measured as well as a frequency spectrum due to Doppler-shifts. In the scope of this contribution only a feasibility of measurements with a scaled VOR and wind turbine is shown. A deeper discussion of additional measurements will be presented in future work.

Figure 6 shows a simple measurement configuration with a direct propagation path and a scattered propagation path. For this feasibility study only an angular section of the VOR with a generic four antenna arrangement is used. Measurements are done in an anechoic chamber.

Figure 7 presents resulting spectra of the direct and the scattered propagation path in the baseband. The scattered path clearly shows a resulting Doppler spectrum component due to the motion of the rotating blades. Of course, the Doppler spectrum is spread due to the different absolute motion speeds along the radius of the rotating blade. Additionally, the reflected path also contains a static component, which belongs to the mast of the turbine.

The interpretation of measured spectra in terms of bearing errors, like for the ILS the instrument current deviations, will be dealt with in future work. However, this first measurement example demonstrates the feasibility of scaled measurements for VOR and rotating wind turbines.

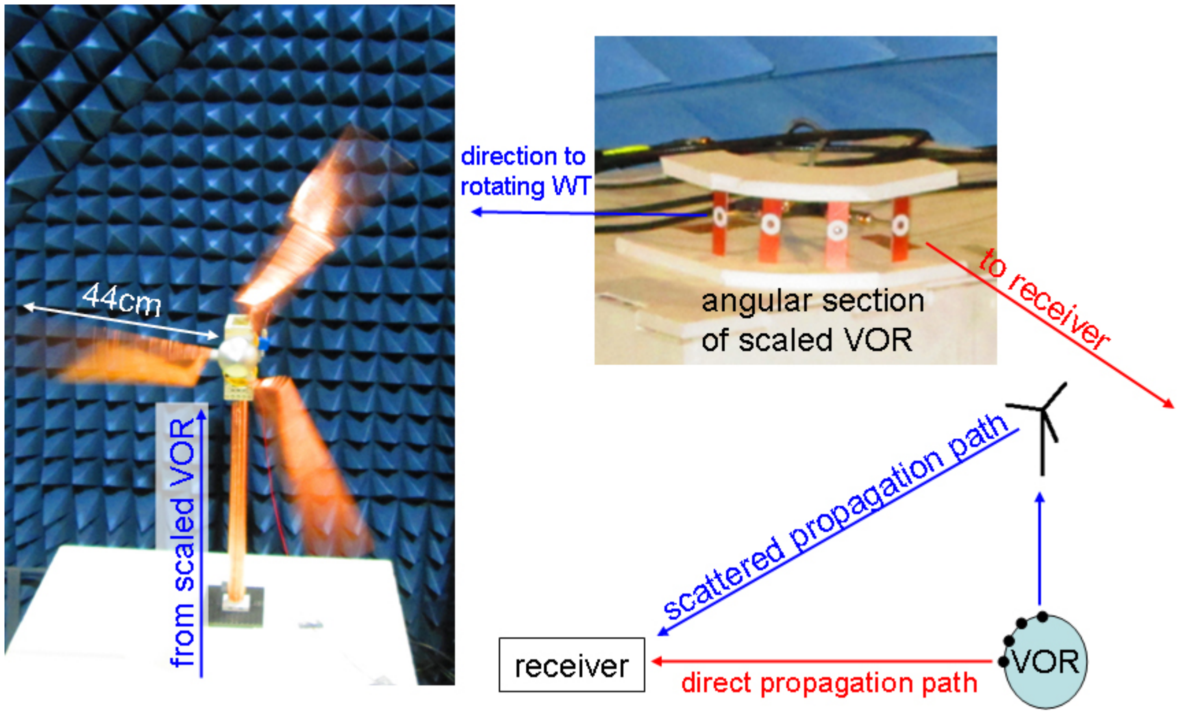

Figure 6. Measurement Configuration of Scaled VOR and a Rotating Wind Turbine.

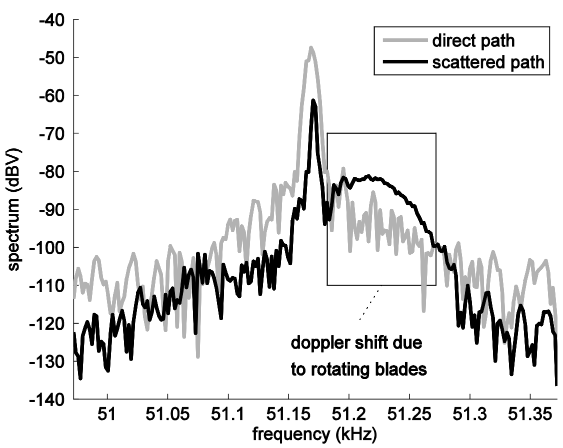

Figure 7. Measurement Results for the Direct and the Scattered Propagation Path.

CONCLUSIONS FOR THE SCALED VOR

With the proposed scaled measurement environment first measurement results demonstrate the feasibility to measure the relevant quantities for assessing bearing errors due to rotating wind turbines. Additionally, since the used high frequency hardware is the same for the scaled ILS and the scaled VOR, the successful validation of the ILS setup is a promising bases for a validation of the scaled VOR environment.

RECOMMENDATIONS

For assessing multipath propagation issues for navigation system authors propose a scaled measurement environment of reduced size that is well controllable and offers a very flexible and moderate cost tool that could enhance the current work of flight inspection and traffic management.

In particular, the miniaturized airport environment is an ideal tool for assessing planned construction measures at airports, respectively their impact on the integrity of involved navigation systems. Especially in the planning phase, no measurements in the real environment can be conducted and the scaled environment offers a much higher degree of transparency and accessibility than simulation tools.

As nearby application for ILS is the optimization of ILS protection areas for airports that currently suffer from insufficient capacity because of e.g. CAT induced taxiing restrictions. Changing the size of ILS protection areas is not an actual construction measure but only a repainting on corresponding taxiways after having analyzed the real physical scenarios like described here.

FUTURE WORK

Future work of the authors will deal with the direct application of the scaled ILS system on real airports, in order to improve their safety and capacity.

For the scaled VOR additional research is planned to assess the impact of even whole wind farms on the integrity of the VOR. Unlike for the measurements in a real environment this allows a detailed investigation of individual wind park states, with parameters such as synchronicity, wind direction, wind speed, or even terrain topology. These parameters for investigating worst case scenarios can only be varied and adjusted in the scaled environment but not for a real wind park.

Additionally, the idea of scaled measurements can also be adapted for other navigation systems, e.g. radar.

ACKNOWLEDGMENTS

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On Great Circle and Great Ellipse Navigation

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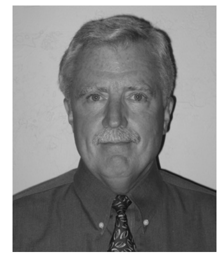

ABSTRACT

Sphere and ellipsoid are two common geometrical models for the Earth. Although great circle navigation has long been used, with satellite technology available for navigation based on the more accurate ellipsoidal model for the Earth, great ellipse navigation has been proposed. This paper compares the two types of navigation in terms of mathematical expressions and numerical results with the goal of providing guideline in practice.

I. INTRODUCTION

Sphere and ellipsoid[1] are two common geometrical models for the Earth. In the 17th and 18th centuries, people began to realize the necessity of using ellipsoid in geodesy to model the Earth [1]. Computations of the geodetic coordinates of points on the ellipsoid have a long history in geodesy. Such coordinates are usually specified as latitude and longitude[2]. Based on the knowns and unknowns, there are two geodetic problems – direct problem and inverse problem. By direct problem in geodesy, we mean that given the coordinates of a starting point, a distance and azimuth to a second point, we wish to compute the coordinates of the second point, as well as the azimuth from the second point to the first. On the other hand, given the ellipsoidal coordinates of two points, the inverse problem in geodesy is to find the distance and azimuths between them.

By calculus of variations it can be proved that the shortest distance between two points on the surface of an ellipsoid is a unique curve known as geodesic [1]. Except for a few special cases, in general, a geodesic on an ellipsoid has double curvature and is not a plane curve. The solutions for computing distance and longitude differences between points connected by geodesic are in the form of elliptic integrals [2]. This comes from the idea of using a sphere as an auxiliary surface and relating it to the ellipsoid which models the Earth[3]. However, these elliptic integrals do not have direct solutions, but instead have been solved by expanding them into trigonometric series and integrating term by term. This is the approach which dated back to the work of Bessel [3]

[1] The word ellipsoid used in geodesy is in fact an ellipsoid of revolution (an ellipsoid with two equal semi-diameters), which is also called spheroid. In this paper, we use the words ellipsoid and spheroid interchangeably. We also imply that the spheroid is oblate.

[2] In this paper, it is assumed that all points are on the surface of the Earth such that the ellipsoidal heights are always zero. This practice follows the convention in geodesy when dealing with direct and inverse problems.

[3] This is different from approximating the ellipsoid by a sphere to be discussed later in the paper.

in the 19th century. Still, the research has been very active. For the most recent work and tutorial presentation, the readers may refer to [4] and [2], respectively.

Because the algorithms for geodesic computation is so involved, there have been research to approximate geodesic of ellipsoid in simpler form -- great ellipse (GE) on the ellipsoid and great circle (GC) on the sphere for navigation applications. Great elliptic curve[4] and great circle are plane curves. Although a great elliptic curve between two points on the surface of ellipsoid does not give the shortest distance, it is still a good approximation to geodesic and has less computation.

To lay the foundation for discussion in this paper, in Section II, we provide the necessary information of the Earth reference ellipsoid. In Sections III and IV, we discuss the inverse problem in the context of GE on the ellipsoid and GC on the sphere, respectively. In Section V, we give a numerical example to show how close GC and GE distance are to geodesic. Finally, in Section VI, the conclusions are presented.

II. THE REFERENCE ELLPSIOD

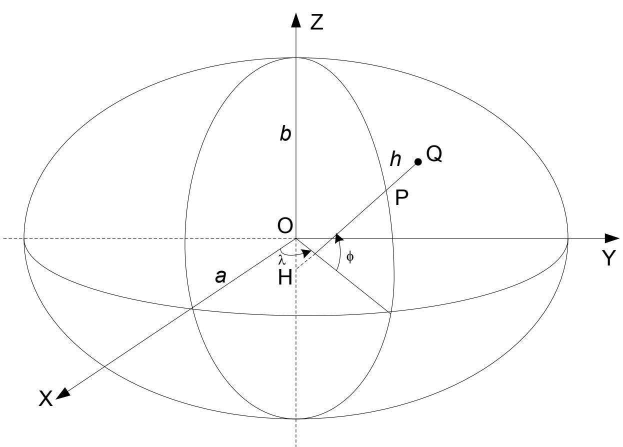

Fig. 1 Coordinate Systems of the Earth Reference Ellipsoid

The Earth reference ellipsoid is shown in Fig. 1. There are four commonly used parameters related to the size and shape of an ellipsoid: a and b are the semi-major and semi-minor axes, respectively, where $a > b$. f is the flattening, and e is the first eccentricity. They are related as follows

$$f \triangleq \frac{a-b}{b} \tag{1}$$

$$e \triangleq \frac{\sqrt{a^2-b^2}}{a} \tag{2}$$

A point P in a three-dimension (3D) space may be described either by Cartesian coordinates (x, y, z) or by the (curvilinear) geodetic coordinates (ϕ, λ, h) in the Earth-centered Earth-Fixed (ECEF) reference system. The origin of the ECEF reference system is at the Earth's center of mass (geocenter). The Z-axis passes through the Earth's axis of rotation, in direction of North Pole. The X-axis passes through the zero longitude locate on the equatorial plane. The prime meridian goes through this point is very near to the meridian of Greenwich although they are not coincident. The Y-axis forms a right-handed coordinate frame with the above X-axis and Z-axis.

All the three major 3D terrestrial reference systems, the North American Datum of 1983 (NAD 83), the World Geodetic System of 1984 (WGS 84), and International Terrestrial Reference System (ITRS) have been defined in this concept. They differ in their realizations. Different reference ellipsoids have been adopted for the above reference systems resulting different geodetic coordinates even with the same 3D Cartesian coordinates. In this paper, all the numerical examples are based on WGS 84 geodetic system, where a = 6378137.0m and f = 1/298.257223563 [1].

Now, we consider the meridian ellipse passing P in Fig. 1, which is shown in Fig. 2. In addition to the (geodetic) latitude ϕ, which is the angle between the normal to the ellipsoid at P and the equatorial plane, another type of latitude to be used in this paper, is the geocentric latitude ψ, which is the angle between the line (connecting P and the center of the ellipsoid) and the equatorial plane.

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[4] In this paper, we use the words great elliptic curve, great elliptic arc, and great ellipse interchangeably.

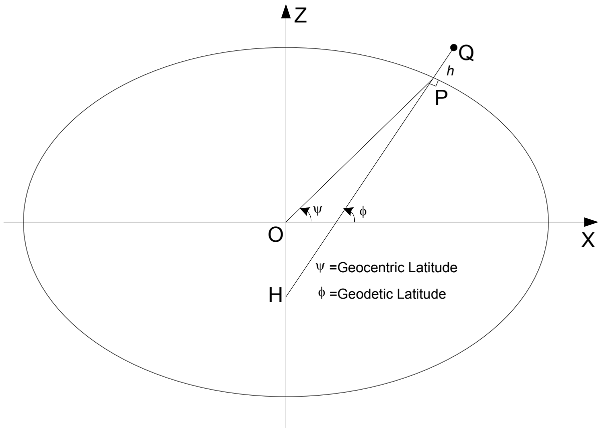

Fig. 2 Geodetic and Geocentric Latitudes in a Meridian Ellipse

Geodetic latitude ϕ and geocentric latitude ψ are related by [1]

$$\tan\psi = (1-e^2)\tan\phi \tag{3}$$

The ECEF coordinates (x, y, z) and geodetic coordinates (ϕ, λ, h) for an arbitrary point (Q in Fig. 2) in the 3D space is [1]

$$\begin{aligned} x &= (N+h)\cos\phi\cos\lambda \\ y &= (N+h)\cos\phi\sin\lambda \\ z &= \left[N(1-e^2)+h\right]\sin\phi \end{aligned} \tag{4}$$

where $$N = \frac{a}{\sqrt{1-e^2\sin^2\phi}} \tag{5}$$

shown in Fig. 2 as PH, is the radius of curvature in prime vertical section of the ellipsoid at P, which is a function of latitude ϕ, and $-\pi/2 \le \phi \le \pi/2$, $-\pi < \lambda \le \pi$. As mentioned previously, in this paper, we assumed that all points are on the surface of the Earth such that ellipsoidal heights h are always zero. In this case, (4) is simplified as

$$\begin{aligned} x &= N\cos\phi\cos\lambda \\ y &= N\cos\phi\sin\lambda \\ z &= N(1-e^2)\sin\phi \end{aligned} \tag{6}$$

which represents the coordinates of a point on the surface of the ellipsoid, such as P.

III. GREAT ELLIPSE ON ELLPSIOD

It can be proved mathematically that the intersection of an ellipsoid and a plane is an ellipse. When the plane passes through the center of the ellipsoid, the resulting ellipse is the biggest, i.e., the GE, compared with those obtained by planes not passing through the center.

The earliest work on GE started in 1984 by Bowring [5]. Recent work, such as [6], focuses on the vector solution approach initially proposed by Earle [7]. Our presentation here is also a vector solution approach.

Let $P_1 = [x_1, y_1, z_1]^T$ and $P_2 = [x_2, y_2, z_2]^T$ be two arbitrary points on the surface of an ellipsoid[5], where T represents transpose of a vector. In Fig. 3, the intersection of the plane containing P_1, P_2, and the center of the ellipsoid O, with the surface of the ellipsoid forms the GE while the arc connecting P_1 and P_2 is an elliptic curve/arc which is part of a GE. Clearly, there is only one such curve between P_1 and P_2, and thus a unique distance and an azimuth.

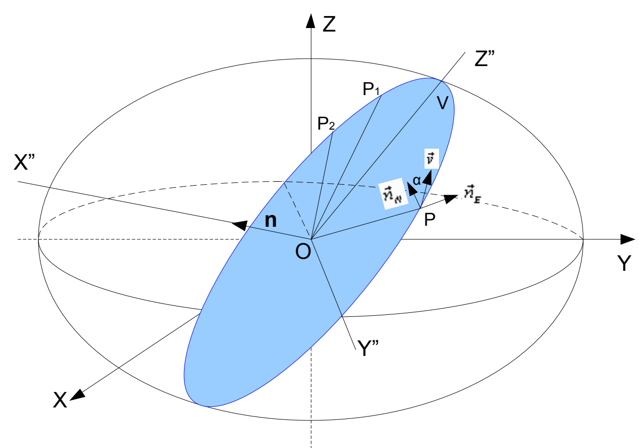

Fig. 3. Great Ellipse of an Ellipsoid

GE Equations

Given vectors $\overrightarrow{OP_1}$ and $\overrightarrow{OP_2}$, the angle between them is

$$\theta_{P_1P_2} \triangleq \angle P_1OP_2 = \arccos\left(\overrightarrow{OP_1}\cdot\overrightarrow{OP_2}\right) \tag{7}$$

---

[5] P_1 and P_2 can also be represented as $P_1 = (\phi_1, \lambda_1, h_1)$ and $P_2 = (\phi_2, \lambda_2, h_2)$. The two representations are related by (4) or (6) when $h = 0$. We will freely use these two forms at our own convenience.

The unit vector $\vec{n} = \left[n_x, n_y, n_z\right]^T$ normal to plane $P_1O\ P_2$ is

$$\vec{n} = \frac{\overrightarrow{OP_1} \times \overrightarrow{OP_2}}{|\overrightarrow{OP_1}||\overrightarrow{OP_2}|\sin\theta_{P_1P_2}} \quad (8)$$

where $|\cdot|$ is the magnitude of a vector. The equation of plane passing the center of the ellipsoid O has the following form

$$n_x x + n_y y + n_z z = 0 \quad (9)$$

where

$$\vec{n} = \begin{bmatrix} n_x \\ n_y \\ n_z \end{bmatrix} = \frac{1}{\sqrt{\left(y_1 z_2 - y_2 z_1\right)^2 + \left(z_1 x_2 - z_2 x_1\right)^2 + \left(x_1 y_2 - x_2 y_1\right)^2}} \begin{bmatrix} y_1 z_2 - y_2 z_1 \\ z_1 x_2 - z_2 x_1 \\ x_1 y_2 - x_2 y_1 \end{bmatrix} \quad (10)$$

Replacing (x, y, z) in (9) with geodetic coordinates (ϕ, λ, h) in (6), we obtain

$$n_x \cos\lambda + n_y \sin\lambda + n_z \eta \tan\phi = 0 \quad (11)$$

where $\eta = 1 - e^2$. Eq. (11) shows that given the longitude λ of a point P on the GE, we can compute its corresponding latitude ϕ, and vice versa,

$$\phi = -\arctan\left[\frac{n_x \cos\lambda + n_y \sin\lambda}{n_z \eta}\right] \quad (12)$$

or

$$\lambda = \arccos\left[-\frac{n_z \eta \tan\phi}{\sqrt{n_x^2 + n_y^2}}\right] + \arctan\left[\frac{n_y}{n_x}\right] \quad (13)$$

Eq. (13) denoted as λ_0 is only one of the two solutions of λ given ϕ; the other solution is one of $\lambda_0 \pm \pi$, such that $\lambda_0 \pm \pi \in (-\pi, \pi]$. The other alternative to (13) of computing λ is to solve the nonlinear equation of (11) using algorithms such as Newton–Raphson method [8] when ϕ is given.

We are also interested in the highest latitude in North or South reached by GE, which is a turning point known as vertex where $d\phi / d\lambda = 0$ [7]. We thus obtain the longitude as well as the latitude of a vertex,

$$n_x \sin\lambda_V - n_y \cos\lambda_V = 0 \quad (14)$$

But, when implemented algorithmically, λ_V should be

$$\lambda_V = \text{atan}\,2\left(-n_y, -n_x\right) \quad (15)$$

where $\text{atan}\,2(y, x)$ is the four quadrant arctangent.

The corresponding latitude is

$$\phi_V = \pm\arctan\left[\frac{\sqrt{n_x^2 + n_y^2}}{n_z \eta}\right] \quad (16)$$

Distance

Given P_1 and P_2 expressed as $P_1 = \left(\phi_1, \lambda_1, h_1\right)$ and $P_2 = \left(\phi_2, \lambda_2, h_2\right)$ [6]. The distance between them (on the surface of the ellipsoid) is

$$l(P_1, P_2) = a\int_{\lambda_1}^{\lambda_2} \sqrt{\frac{1}{1 + \eta\tan^2\phi}\left[1 + \eta^2 \frac{\left(1 + \tan^2\phi\right)^3}{\left(1 + \eta\tan^2\phi\right)^2}\left(\frac{d\phi}{d\lambda}\right)^2\right]}\, d\lambda \quad (17)$$

or

$$l(P_1, P_2) = a n_z \sqrt{\eta} \int_{\lambda_1}^{\lambda_2} f(\lambda) d\lambda \quad (18)$$

where

$$f(\lambda) = \frac{1}{n_z^2\eta + (n_x\cos\lambda + n_y\sin\lambda)^2} \cdot \sqrt{\frac{\left[n_z^2\eta + (n_x\cos\lambda + n_y\sin\lambda)^2\right]^2 + (n_x\sin\lambda - n_y\cos\lambda)^2\left[n_z^2\eta^2 + (n_x\cos\lambda + n_y\sin\lambda)^2\right]}{n_z^2\eta + (n_x\cos\lambda + n_y\sin\lambda)^2}} \quad (19)$$

Obviously, the integral for (18) does not have a close-form expression and is very complicated to compute.

In this paper, we propose an alternative method to compute $l(P_1, P_2)$ based on the concept of Cartesian coordinate frame rotation. First rotate about the Z-axis an angle ω_Z to obtain $X'Y'Z'$ frame[7], then rotate about the new Y'-axis an angle $\omega_{Y'}$ to obtain $X''Y''Z''$ frame. Therefore, the overall rotation matrix is

---

[6] $h_1 = h_2 = 0$

[7] A positive rotation ω is defined by the right-hand rule [1].

$$R = \begin{bmatrix} \cos\omega_{Y'}\cos\omega_Z & \cos\omega_{Y'}\sin\omega_Z & -\sin\omega_{Y'} \\ -\sin\omega_Z & \cos\omega_Z & 0 \\ \sin\omega_{Y'}\cos\omega_Z & \sin\omega_{Y'}\sin\omega_Z & \cos\omega_{Y'} \end{bmatrix} \quad (20)$$

And, the coordinates in the $X''Y''Z''$ frame is

$$\begin{bmatrix} x'' \\ y'' \\ z'' \end{bmatrix} = R \begin{bmatrix} x \\ y \\ z \end{bmatrix} \quad (21)$$

In order for the GE to be on the $Y''\sim Z''$ plane, Y'' and Z'' to be the major and minor axes, respectively, $\omega_Z = \arctan\left(\frac{n_y}{n_x}\right)$ and $\omega_{Y'} = -\left(\frac{\pi}{2} - \psi_V\right)$ where the geocentric latitude ψ_V and geodetic ϕ_V are related by (3). After the above rotations, the x'' coordinate of the Cartesian coordinates of P_1 and P_2 is zero. Now, the problem of computing the arc distance $l(P_1, P_2)$ of P_1 and P_2 on an ellipsoid has been transformed to computing the meridian arc distance $l(P_1, P_2)$ of P_1 and P_2 of an ellipse in the $Y''\sim Z''$ plane. The formula [1] for the latter is

$$l(P_1, P_2) = a\left(1-\varepsilon^2\right)\int_{\phi_1''}^{\phi_2''} \frac{1}{\sqrt{\left(1-\varepsilon^2\sin^2\varphi\right)^3}} d\varphi \quad (22)$$

where

$$\varepsilon = \frac{\sqrt{1-e^2}}{\sqrt{1-e^2\sin^2\phi_V}} e\sin\phi_V \quad (23)$$

is the first eccentricity of the GE. The other equivalent expression of ε is [9]

$$\varepsilon = \frac{e\sin\psi_V}{\sqrt{1-e^2\cos^2\psi_V}} \quad (24)$$

The proof of (23) or (24) is a little bit involved which is omitted here.

Azimuth

At any arbitrary point P there is a velocity unit vector $\vec{v}$ indicating the vehicle moving direction. The azimuth α is the angle between the meridian through P and the normal plane at P containing $\vec{v}$ [8] (measured from North towards $\vec{v}$ in clockwise direction). Then, $\vec{v}$ can be written as

$$\vec{v} = \sin\alpha\,\vec{n}_E + \cos\alpha\,\vec{n}_N \quad (25)$$

where $\vec{n}_E = [-\sin\lambda, \cos\lambda, 0]^T$ and $\vec{n}_N = [-\sin\phi\cos\lambda, -\sin\phi\sin\lambda, \cos\phi]^T$

are the unit meridian tangent vector (in the North direction) and the unit parallel tangent vector (in the East direction) at P, respectively. The velocity is vertical to the normal of the GE (i.e., $\vec{n}$) and the normal to the ellipsoid at P, which is [6].

$$\vec{n}_P = [\cos\phi\cos\lambda, \cos\phi\sin\lambda, \sin\phi]^T \quad (26)$$

$$\vec{v} = \vec{n}\times\vec{n}_P \quad (27)$$

By vector algebra,

$$\vec{n}\cdot\left(\vec{n}\times\vec{n}_P\right) = 0 \quad (28)$$

We have

$$\vec{n}\cdot\vec{v} = 0 \quad (29)$$

which leads to

$$\tan\alpha = \frac{n_z\cos\phi\left(1+\eta\tan^2\phi\right)}{n_x\sin\lambda - n_y\cos\lambda} \quad (30)$$

Algorithmically, $\operatorname{atan}2(\cdot,\cdot)$ should be used to obtain α and also $\alpha \in [0, 2\pi)$ should be taken into account.

IV. GREAT CIRCLE ON SPHERE

The practice of using a sphere to model the Earth in navigation has existed for centuries. As has been mentioned in Section I, the shortest distance between two points on the surface of an ellipsoid is a geodesic. As a special case, the shortest distance on sphere is a great circle, which is the intersection of the plane, formed by the above two points and the center of the sphere, with the sphere. Any other circle formed by the sphere and a plane in parallel with the above plane is called small circle (SC) in this paper.

When using a sphere to model the Earth, the first question is from which sphere to choose because there are various spheres to approximate the Earth. The navigation sphere [9] is used here, which has the radius of $R_E = 6366707.0m$.

[8] The normal plane containing $\vec{v}$ is slightly different from the GE plane at P [6].

GC Equations

When two points $P_1 = [x_1, y_1, z_1]^T$ and $P_2 = [x_2, y_2, z_2]^T$ are given on the surface of a sphere, the derivation of the equation of plane is the same as that of the case for GE equation except now $\eta = 1$ in (11) because the first eccentricity *e* is zero for sphere. Thus the equation is

$$n_x \cos\lambda + n_y \sin\lambda + n_z \tan\phi = 0 \tag{31}$$

In order to simplify the discussion, we assume the sphere has unit radius, and all the vectors from the center O to the sphere are unit vectors. The $[x, y, z]^T$ in (33) multiplied by R_E will give the coordinates of a point on the Earth's surface. Similar to (6), on a sphere, the Cartesian coordinates and the geodetic coordinates[9] are related by

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} \cos\phi\cos\lambda \\ \cos\phi\sin\lambda \\ \sin\phi \end{bmatrix} \tag{32}$$

From (32) $P_1 = [\cos\phi_1 \cos\lambda_1, \cos\phi_1 \sin\lambda_1, \sin\phi_1]^T$ and $P_2 = [\cos\phi_2 \cos\lambda_2, \cos\phi_2 \sin\lambda_2, \sin\phi_2]^T$, the normal vector $\vec{n}$ to the plane formed by vectors $\overrightarrow{OP_1}$ and $\overrightarrow{OP_2}$ is given in (8) as is shown in Fig. 4.

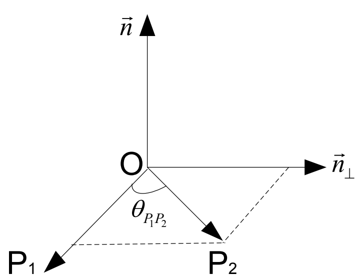

Fig. 4. Orthogonal Vectors

Now there are three mutually perpendicular vectors $\vec{n}$, $\overrightarrow{OP_1}$, and $\vec{n}_\perp \triangleq \vec{n} \times \overrightarrow{OP_1}$ making a right-handed Cartesian coordinate system, and vector $\overrightarrow{OP_2}$ can be expressed as

$$\overrightarrow{OP_2} = \cos\theta_{P_1P_2} \overrightarrow{OP_1} + \sin\theta_{P_1P_2} \vec{n}_\perp \tag{33}$$

[9] In this case, the geodetic latitude and geocentric latitude are one and the same. So in some references, they are called geographic coordinates.

Similarly, an arbitrary point P can be expressed as

$$\overrightarrow{OP} = \cos\theta_{P_1P} \overrightarrow{OP_1} + \sin\theta_{P_1P} \vec{n}_\perp \tag{34}$$

where

$$\theta_{P_1P} = \angle P_1OP = \arccos\left(\overrightarrow{OP_1} \cdot \overrightarrow{OP}\right) \tag{35}$$

and

$$\vec{n}_\perp = \frac{\overrightarrow{OP_2} - \cos\theta_{P_1P_2} \overrightarrow{OP_1}}{\sin\theta_{P_1P_2}} \tag{36}$$

Eq. (34) means that given $\angle P_1OP$ we can obtain the position P.

Distance

The arc distance $l(P_1, P_2)$ of P_1 and P_2 on a sphere is

$$l(P_1, P_2) = R_E \theta_{P_1P_2} \tag{37}$$

where $\theta_{P_1P_2}$ is given in (7).

Azimuth

The azimuth can be easily obtained by letting $\eta = 1$ in (30),

$$\tan\alpha = \frac{n_z}{\cos\phi\left(n_x \sin\lambda - n_y \cos\lambda\right)} \tag{38}$$

Intersection between Two GCs

In order to facilitate the following discussions, we use points A and B to replace the previous notation P_1 and P_2. Similar to (8), we can find another GC given another pair of points C and D on the sphere. The normal vector to the plane formed by vectors $\overrightarrow{OC}$ and $\overrightarrow{OD}$ is

$$\vec{n}_{CD} = \begin{bmatrix} n_{CD,x} \\ n_{CD,y} \\ n_{CD,z} \end{bmatrix} = \frac{\overrightarrow{OC} \times \overrightarrow{OD}}{\sin\theta_{CD}} \tag{39}$$

Let E be the intersection point of the two GCs (AOB and COD) as is shown in Fig. 5.

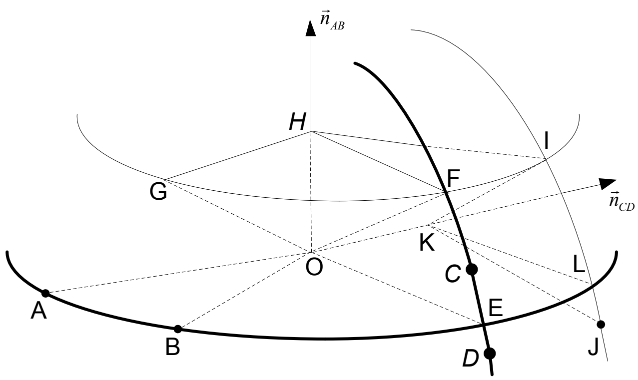

Fig. 5. Intersections of Great Circles and Small Circles

Since vector $\overrightarrow{OE}$ is both on the plane AOB and the plane COD, it is perpendicular to both $\vec{n}_{AB}$ and $\vec{n}_{CD}$,

$$\overrightarrow{OE} \cdot \vec{n}_{AB} = 0 \tag{40}$$

and

$$\overrightarrow{OE} \cdot \vec{n}_{CD} = 0 \tag{41}$$

With $\overrightarrow{OE} = [\cos\phi_E \cos\lambda_E, \cos\phi_E \sin\lambda_E, \sin\phi_E]^T$, we obtain a nonlinear system of equations about (ϕ_E, λ_E)

$$\begin{cases} n_{AB,x} \cos\phi_E \cos\lambda_E + n_{AB,y} \cos\phi_E \sin\lambda_E + n_{AB,z} \sin\phi_E = 0 \\ n_{CD,x} \cos\phi_E \cos\lambda_E + n_{CD,y} \cos\phi_E \sin\lambda_E + n_{CD,z} \sin\phi_E = 0 \end{cases} \tag{42}$$

Following (34), $\overrightarrow{OE}$ can be expressed

$$\overrightarrow{OE} = \cos\theta_{AE} \overrightarrow{OA} + \sin\theta_{AE} \vec{n}_{AB,\perp} \tag{43}$$

Then, plug it to (41),

$$\theta_{AE} = -\arctan\left(\frac{\overrightarrow{OA} \cdot \vec{n}_{CD}}{\vec{n}_{AB,\perp} \cdot \vec{n}_{CD}} \right) \tag{44}$$

Similarly, we can also express point E relative to point C by

$$\theta_{CE} = -\arctan\left(\frac{\overrightarrow{OC} \cdot \vec{n}_{AB}}{\vec{n}_{CD,\perp} \cdot \vec{n}_{AB}} \right) \tag{45}$$

Intersection between One GC and One SC in Parallel to the Second GC

Assume G is an arbitrary point on the parallel (the SC with H being the center) to the GC. Then,

$$\overrightarrow{OH} = |\overrightarrow{OH}| \vec{n}_{AB} \tag{46}$$

When $G = [\cos\phi_G \cos\lambda_G, \cos\phi_G \sin\lambda_G, \sin\phi_G]^T$ is given, $|\overrightarrow{OH}|$ can be obtained by

$$|\overrightarrow{OH}| = \overrightarrow{OG} \cdot \vec{n}_{AB} \tag{47}$$

Let F is the intersection point of this parallel to the second GC COD. The goal is to find the coordinates of F, or vector

$$\overrightarrow{OF} = \begin{bmatrix} \cos\phi_F \cos\lambda_F \\ \cos\phi_F \sin\lambda_F \\ \sin\phi_F \end{bmatrix} \tag{48}$$

We find that $|\overrightarrow{OH}|$ can be computed by

$$\overrightarrow{OF} \cdot \vec{n}_{AB} = |\overrightarrow{OH}| \tag{49}$$

It is noted that $\overrightarrow{OF}$ is also on the GC formed by C and D, therefore

$$\overrightarrow{OF} \cdot \vec{n}_{CD} = 0 \tag{50}$$

With known values of $\vec{n}_{AB}$ and $\vec{n}_{CD}$ obtained in eqs. (8) and (39), from (49), we have

$$\begin{bmatrix} n_{AB,x} & n_{AB,y} & n_{AB,z} \end{bmatrix} \begin{bmatrix} \cos\phi_F \cos\lambda_F \\ \cos\phi_F \sin\lambda_F \\ \sin\phi_F \end{bmatrix} = |\overrightarrow{OH}| \tag{51}$$

From (50),

$$\begin{bmatrix} n_{CD,x} & n_{CD,y} & n_{CD,z} \end{bmatrix} \begin{bmatrix} \cos\phi_F \cos\lambda_F \\ \cos\phi_F \sin\lambda_F \\ \sin\phi_F \end{bmatrix} = 0 \tag{52}$$

Putting (51) and (52) together, we obtain a nonlinear system of equations about (ϕ_F, λ_F)

$$\begin{cases} n_{AB,x} \cos\phi_F \cos\lambda_F + n_{AB,y} \cos\phi_F \sin\lambda_F + n_{AB,z} \sin\phi_F = |\overrightarrow{OH}| \\ n_{CD,x} \cos\phi_F \cos\lambda_F + n_{CD,y} \cos\phi_F \sin\lambda_F + n_{CD,z} \sin\phi_F = 0 \end{cases} \tag{53}$$

where $|\overrightarrow{OH}|$ can be computed by (47).

Intersection between Two SCs Which Are in Parallel to Two GCs

Assume J is an arbitrary point on the second parallel (the second SC with K being the center) to the GC COD, where

$$\overrightarrow{OJ} = \begin{bmatrix} \cos\phi_J \cos\lambda_J \\ \cos\phi_J \sin\lambda_J \\ \sin\phi_J \end{bmatrix} \quad (54)$$

The two parallels (i.e., SCs) intercept at I with the coordinate

$$\overrightarrow{OI} = \begin{bmatrix} \cos\phi_I \cos\lambda_I \\ \cos\phi_I \sin\lambda_I \\ \sin\phi_I \end{bmatrix} \quad (55)$$

The goal is to find (ϕ_I, λ_I). From Fig. 5, we know that

$$\overrightarrow{OI} \cdot \vec{n}_{AB} = |\overrightarrow{OH}| \quad (56)$$

and

$$\overrightarrow{OI} \cdot \vec{n}_{CD} = |\overrightarrow{OK}| \quad (57)$$

where

$$|\overrightarrow{OK}| = \overrightarrow{OJ} \cdot \vec{n}_{CD} \quad (58)$$

and $|\overrightarrow{OH}|$ can be obtained from (47). Putting (56) and (57) together, we obtain a nonlinear system of equations about (ϕ_I, λ_I)

$$\begin{cases} n_{AB,x} \cos\phi_I \cos\lambda_I + n_{AB,y} \cos\phi_I \sin\lambda_I + n_{AB,z} \sin\phi_I = |\overrightarrow{OH}| \\ n_{CD,x} \cos\phi_I \cos\lambda_I + n_{CD,y} \cos\phi_I \sin\lambda_I + n_{CD,z} \sin\phi_I = |\overrightarrow{OK}| \end{cases} \quad (59)$$

So far, we assume that G and J are known in advance such that $|\overrightarrow{OH}|$ and $|\overrightarrow{OK}|$ in (59) can be obtained in advance from (47) and (58), respectively. Sometimes, a SC may be specified by the arc distance from a GC. For example, given two GC AOB and COD, and the arc distance $\overset{\frown}{EF}$ and $\overset{\frown}{EL}$, then

$$|\overrightarrow{OH}| = |\overrightarrow{OF}| \sin\angle EOF \quad (60)$$

where

$$\angle EOF = \frac{\overset{\frown}{EF}}{|\overrightarrow{OE}|} \quad (61)$$

Similarly,

$$|\overrightarrow{OK}| = |\overrightarrow{OL}| \sin\angle EOL \quad (62)$$

where

$$\angle EOL = \frac{\overset{\frown}{EL}}{|\overrightarrow{OE}|} \quad (63)$$

V. A NUMERICAL EXAMPLE

Using the same data in [6] (Table 4), e.g., $P_1 = (\phi_1, \lambda_1) = (26^\circ 28'01.2", 130^\circ)$ and $P_2 = (\phi_2, \lambda_2) = (33^\circ 21'07.2", 140^\circ)$, we obtain $l(P_1, P_2) = 1229761.645$ m. The geodesic, which is the shortest distance on the ellipsoid, is computed to be obtained 1229761.635 m. This means that the distance along GE is only 0.010m longer and the relative difference is $8.05 \times 10^{-7}\%$. On the other hand, the result in [6] gives bigger difference of 4.40m, and the relative difference is $3.58 \times 10^{-4}\%$. Other numerical results of our method follow similar trend compared with those in [6]. Using GC in this case gives 832.810m difference compared with the geodesic, the relative difference is $6.78 \times 10^{-2}\%$. In general, the difference in using the sphere when compared to the ellipsoid is near 0.5% [9].

VI. CONCLUSIONS

In this paper, we have presented formulas for computing the distance and azimuth of two points on the surface of the Earth. For the ellipsoid model of the Earth, great ellipse distance and azimuth have been discussed and a new method of computing the distance based on the concept of Cartesian coordinate frame rotation is proposed. This method avoids computation of a complicated integral and is therefore more efficient. For great circle model of the Earth, we also provide formulas and algorithms for computing the intersections between great circles and/or small circles, which have found applications in navigation and flight inspection.

With numerical results we conclude that great ellipse distance has very close approximation to the geodesic (true distance of two points on the Earth) than the great circle distance. However, the sphere model to the Earth may still be acceptable for navigation purpose as long as it will be used consistently.

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APPENDIX

Solving Nonlinear Systems of Equations (59)

Eq. (59) is the most general form of a nonlinear system of equations among (42), (53) and (59). In order to simplify the notation, we rewrite (59) in the following general format,

$$\begin{cases} a_1 \cos\phi \cos\lambda + b_1 \cos\phi \sin\lambda + c_1 \sin\phi = d_1 \\ a_2 \cos\phi \cos\lambda + b_2 \cos\phi \sin\lambda + c_2 \sin\phi = d_2 \end{cases} \quad (64)$$

Let
$$\sin\phi = \frac{2s}{1+s^2}, \text{ where } |s| \le 1 \quad (65)$$

then,
$$\cos\phi = \frac{1-s^2}{1+s^2} \quad (66)$$

Similarly, let

$$\sin\lambda = \frac{2t}{1+t^2}, \text{ where } |t| \le 1 \quad (67)$$

then,
$$\cos\lambda = \frac{1-t^2}{1+t^2} \quad (68)$$

Now, (64) becomes

$$\begin{cases} a_1 \dfrac{1-s^2}{1+s^2}\dfrac{1-t^2}{1+t^2} + b_1 \dfrac{1-s^2}{1+s^2}\dfrac{2t}{1+t^2} + c_1 \dfrac{2s}{1+s^2} = d_1 \\ a_2 \dfrac{1-s^2}{1+s^2}\dfrac{1-t^2}{1+t^2} + b_2 \dfrac{1-s^2}{1+s^2}\dfrac{2t}{1+t^2} + c_2 \dfrac{2s}{1+s^2} = d_2 \end{cases} \quad (69)$$

Define

$$\vec{p}_1 = \begin{bmatrix} a_1 \\ b_1 \\ c_1 \\ d_1 \end{bmatrix}, \vec{p}_2 = \begin{bmatrix} a_2 \\ b_2 \\ c_2 \\ d_2 \end{bmatrix}, \text{ and } \vec{x} = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = \begin{bmatrix} s \\ t \end{bmatrix} \quad (70)$$

$$\vec{q}(\vec{x}) = \begin{bmatrix} (1-s^2)(1-t^2) \\ 2(1-s^2)t \\ 2s(1+t^2) \\ -(1+s^2)(1+t^2) \end{bmatrix} \quad (71)$$

then (69) becomes

$$\begin{cases} f_1(\vec{x}) = \vec{p}_1 \cdot \vec{q}(\vec{x}) = 0 \\ f_2(\vec{x}) = \vec{p}_2 \cdot \vec{q}(\vec{x}) = 0 \end{cases} \quad (72)$$

Solving (72) for $\vec{x}$ numerically using algorithms such as Newton-Raphson method, we will obtain (s,t) and thus (ϕ,λ).

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Operational Approval for New and Modified Flight Inspection Systems

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ABSTRACT

Following installation and regulatory certification of a Flight Inspection System (FIS), the aircraft is flyable, but what process is followed to obtain approval for operational flight inspection? Federal Aviation Administration (FAA) has recently instituted a formal operational test and evaluation (OT&E) program to obtain Operational Approval for each new or modified FIS. The OT&E includes detailed objectives and procedures to evaluate aircraft manuals, human factors, measurement uncertainty, operational considerations, data archival/ retrieval, and crew training. Following successful completion of this evaluation, an Operational Approval letter is signed by the Director of Operations and the specific flight inspection capabilities are published. This paper provides an overview of the OT&E and Operational Approval process for new and modified systems. The process provides significant benefit to the integration of standardization, human factors, inspection performance, training, and policy into the flight inspection operation.

The pace of evolving avionics, airspace changes, and flight inspection requirements drives constant modifications. In the last 5 years the FAA installed new FIS equipment and software in 6 different aircraft types and over 23 individual aircraft. Each new aircraft and modification is unique. The King Air 300 modernization (BE-300PL) project was so comprehensive that it quickly became more complex than a new aircraft installation. There came a point where everyone looked at each and asked “who is going to certify the final product for flight inspection?” That was the genesis of what is now an effective process the FAA uses to approve new and modified systems for flight inspection. First, the term Operational Approval will be defined. Then the Operational Approval process will be described. Finally, the flight inspection OT&E philosophy will be described with some representative examples.

DEFINING OPERATIONAL APPROVAL

Regarding the FIS, ICAO Doc 8071 states the importance of equipment calibration, testing, and analysis [5]. It further provides specific criteria for FIS measurement uncertainty. While Doc 8071 recommends certification of flight inspection personnel, there is no reference for certification of the FIS. FAA questioned whether certification was even the correct terminology. Perhaps a better term can be used to describe when a given aircraft/FIS configuration is ready for operational flight inspection? Is the system approved, accepted, certified, or should we say legal? The FAA now formally uses the term “Operational Approval” to identify that a given aircraft configuration and crew may take credit for its Operationally Approved flight inspection capabilities.

The term Operational Approval was intentionally chosen as analogous to FAA Part 135 or 121 Operational Approval. For example, it is one thing for aircraft equipment to be certified for RNAV(GPS) approaches. However, in order for Part 135/121 carriers to legally fly an RNAV(GPS) approach, an Operational Approval is required. Tables 1 and 2 show the relationship between capability, certification, and Operational Approval for some representative aircraft and flight inspection capabilities of the BE-300PL. Capability is something the aircraft or FIS can do, but capability does not define how well it performs. Certification implies we have met some required standard of performance. Note that from an aircraft certification perspective, the chief performance standard only requires that the FIS not interfere with other aircraft systems. Operational Approval means that we’ve checked everything from a performance, operational, and training perspective to use the system for its intended purpose. As in Part 135/121, Operational Approval simplifies things for everyone in the flight inspection organization by making the final call on whether or not a given capability may be used by the flight crew.

Table 1: Aircraft Capability Examples

	Answers this question	ILS Cat III	RNAV(GPS) LPV	RNAV(GPS) LP	GLS Approach
CAPABILITY	What can it do?		X	X	X
CERTIFICATION	Does it meet any specifications?		X		X
OPERATIONAL APPROVAL	What is the system approved to do?		X		

Table 2: Flight Inspection System Examples

	Answers this question	ILS Cat III	RNAV(GPS) LPV	RNAV(GPS) LP	GLS Approach
CAPABILITY	What can it do?	X	X	X	X
CERTIFICATION	Does it meet any specifications?	X	X	X	X
OPERATIONAL APPROVAL	What is the system approved to do?	X	X	X	Pending

OPERATIONAL APPROVAL PROCESS

System Requirements

The importance of establishing clear and specific system requirements cannot be emphasized enough. In fact, entire books exist on this topic alone. Hull states simply "Agreed requirements provide the basis for planning the development of a system and accepting it on completion" [2]. Too often, operations driven requirements are stated in such generic terms that they are almost useless. For example, requiring that a new FIS have ILS flight inspection capability is not nearly specific enough. Meaningful requirements include specifics such as "Measurement of Zone 2 glideslope angle must have a 95% measurement uncertainty no greater than .02° when using runway updates." Establishing clear and specific requirements for ensuring a well performing FIS is a laborious and specialized task that should not be overlooked, underestimated, or assigned only to engineering or only to operations.

Pilot and Flight Inspector Involvment in Development

In practical experience with installing and modifying most FIS, Developmental Test and Evaluation occurs in conjunction with OT&E. However, there can be an initial stage where requirements are worked by engineering and/or software developers. No matter the detail of written requirements, questions often arise about the intent or specific function of most requirements. The FAA has dramatically improved effectiveness and efficiency by including pilots and flight inspectors at the earliest stages of developmental work. The synergy and communication benefits to this approach are overwhelming. In one FIS software update, the FAA had over 70 individual requirements for modification. Dedicating a flight inspector to work on-site with the contractor was the best way to get the project completed correctly and on-time. Flight inspector involvement resulted in meeting expectations because any questions about functional intent were immediately answered. In addition, improvements from the initial request were implemented including several very useful features not originally envisioned. An example of one such improvement was a FIS screenshot tool. This was not part of the original requirement, but early flight inspector involvement during testing resulted in a very useful tool. The ability to quickly take a screenshot, saved with log files, provides a rapid method for sharing results with facilities maintenance, creating training documents, and documenting FIS issues.

Operational Test and Evaluation (OT&E)

The major process in preparation for Operational Approval is completion of an OT&E plan. Regarding OT&E from a military weapon system perspective, Giadrosich states:

"OT&E is conducted to estimate a system's operational effectiveness and operational suitability, and to identify needed modifications. It also includes tests for compatibility, interoperability, reliability, maintainability, logistics supportability, software supportability, and training requirements. In addition, OT&E provides information on organization, personnel requirements, doctrine, and tactics, and may result in changes to operation employment and maintenance concepts" [1].

This is an excellent description of OT&E on a new or modified FIS. It does little good to simply fly and test the FIS alone. A perfectly operating FIS is useless in the hands of an improperly trained crew, with no procedures for use, or no policy on how to flight inspect with it. In addition, it is possible to receive a perfectly operating FIS but with overly complex human factors issues. The FAA approach is to take all elements of organizational coordination and consolidate them into a single OT&E plan for execution. These elements include manuals, functional evaluation, measurement uncertainty, training, data logging, reporting, and any additional requirements unique to the project. A standardized test plan template provides ease of creation. Each plan is collaboratively authored, tracked, and archived on the FAA internal website.

The introduction of each test plan contains the overall OT&E objective, aircraft configuration, deliverables, flight test techniques, risk assessment, references, and milestones. For sections detailing the actual testing, a variety of test plan formats were studied to determine which best suited flight inspection OT&E. To achieve consistency and simplicity, all test plan sections formally contain the same four subsections: Objectives, Procedures, Data Requirements, and Evaluation Criteria. Objectives are necessary to define the intent of the test. Procedures provide the specific configuration and condition to achieve the objective. Data Requirements define which log files and/or additional information is required such as video recording of the test. Evaluation Criteria may identify specific pass/fail criteria or define when enough data has been collected to meet the objective. An executive summary and if required, a technical report, is compiled on the completion of each OT&E project.

Operational Approval Letter

A key deliverable from the OT&E process is the Operational Approval letter. The signing authority for FAA Flight Inspection Services is the Director of Operations (DO). Depending on the extent of testing required, there may be one or more briefings to organization stakeholders (e.g. policy, standards, training) prior to recommending signature to the DO. The first two pages of an Operational Approval letter (examples in Figures 1 and 2) define the exact aircraft and FIS configuration tested and approved.

The following Flight Inspection System (FIS) configuration is operationally approved. Test results may be reviewed in the listed test plans and reports. Any changes to this configuration must be evaluated for operational approval.

	Configuration	Test Plan(s)	Test Report(s)
Aircraft Type:	CL-605	TEP 13-09 **TEP 13-10**	*TR 13-09* ***TR 13-10***
NCU Software Version	V		
Workstation Software Version	J.2		
TVPS Software Version	H.3		
Other	*		

* See FIS Fleet Configuration Spreadsheet (Data Management tab) on KSN Fleet Configuration Management page for current Workstation Image date. In this configuration, JetLan is provisioned for cockpit mission display capability.

Figure 1: Operational Approval Letter (Page 1)

Ant Gain	dB
V/L	-02
GS	-02
TACAN	+08
MLS FWD	N/A
MLS AFT	N/A

Ant Norm	dB
0	-04
30	+04
60	+00
90	+02
120	+00
150	-01
180	-05
210	-01
240	-01
270	-01
300	+02
330	+06

Dimension	Feet
ACDLN47	012.52
ACDLN41	012.17
ACDLN24	028.96
ACDLN48	N/A
ACDHT07	006.73
ACDHT08	N/A
ACDHT48	N/A
ACDLN49	-015.17
ACDHT09	012.04
ACDHT49	007.42
ACDLN4A	-015.17
ACDHT4A	007.42

TVPS Page

TVPS	Feet
ACDLN34	036.00
ACDLT34	-002.00
Frame Delay	2

DME FIX Page

RADAR Altimeter	
Type	Digital
Lag	120

Figure 2: Operational Approval Letter (Page 2)

The third page contains a detailed matrix of specific Operational Approvals including which Position Reference Systems (PRS) may be used for each approval. An example from the current CL-605 Operational Approval is contained in Appendix 1. The final page contains limitations associated with the Operational Approval. Examples of typical limitations include:

- How long the previous configuration remains Operationally Approved
- Antenna selection or operational procedures not yet incorporated into the Flight Inspection Handbook
- Specific crew member approvals if training is incomplete

OT&E TEST PLAN FORMAT

In planning the level of testing for each new or modified FIS, many factors need to be considered including at a minimum: Have untested sensors been incorporated? Have previously tested sensors been added to a new aircraft type? Is the FIS software change comprehensive or is it an incremental change? What are the interrelated effects of multiple modifications including human factors interaction between the pilots and flight inspector?

Without formal guidance, the OT&E planners must use their best experience and judgment to integrate all available information into a plan that is effective, efficient, and appropriate. Two excellent resources to learn more are the Defense Acquisition University's *Test and Evaluation Management Guide [4]* and *Guidelines for Conducting Operational Test and Evaluation (OT&E) For Software-Intensive Increments [3]*.

When the OT&E is extensive, FAA test plans contain detailed estimates for office time, ground test time, and flight time required for completion. A common error in FAA program management was to evaluate OT&E progress by tracking flight hours. Flight hours are the incorrect metric for tracking OT&E progress. Providing the breakout of ground testing and office time required helps management visualize the scope of work required in addition to flight hours.

Following are typical sections of an FAA Operational Approval OT&E plan, a brief overview of considerations in each, and some representative examples.

Aircraft and FIS Manuals

"It is imperative that all system publications and manuals be completed, reviewed, and selectively tested under operational conditions…" [4]. While this may seem obvious, ensuring proper documentation is a difficult part of OT&E that is easy to overlook and undervalue. In a typical OT&E, Aircraft Flight Manual Supplements and Operator's Guides must be obtained and incorporated into the organization's manual system. In addition, flight inspection policy manuals must be updated to reflect new procedures based on the new or modified system. In many cases, this is a process of refreshing outdated guidance and changing existing procedures.

Example: During OT&E on the FAA's first graphics FIS, it became abundantly clear that existing manuals were insufficient for operational deployment of the system. As part of the OT&E process, a handbook [8] was created with operational procedures and diagrams necessary to successfully use the FIS for operational flight inspection. The handbook provides much needed standardization and serves as a primary training resource. The current version is 550 pages and contains dozens of action oriented procedures/checklists as in Figure 3 below.

Checklist 7. Challenger Power Up Sequence

	Action	Additional Information
1	CL605 Only – Toggle all unused passenger microphone jacks to "OFF".	This step is required to eliminate noise on the headsets. **Note:** Move around the cabin to accomplish this step when safe.
2	Select FIS POWER to ON	From cockpit.
3	CL604 - Select High Speed Data (HSD) to ON CL605 – (LAN) to ON.	From cockpit. Standard practice is to leave HSD on. Note: This step is mandatory for printer use!

Figure 3: Sample Checklist in FIS Handbook

Operational/Functional Performance

Assessing operational or functional performance of a FIS requires checking that all modes function as intended and that the desired flight inspection results are generated. This is not where the result accuracy is assessed. Result accuracy is assessed in the measurement uncertainty section. The operational/functional assessment simply assures that a reasonable result can be captured. Development of procedures should emphasize placing the test crew in the most realistic operational environment possible. Many times, the FAA OT&E team decided to accept compromises for efficiency and reduced flight hours only to realize that a FIS discrepancy was missed because "we didn't do it like a real flight inspection". Exposing the FIS to the most realistic permutation of inspection scenarios and facilities with the resources available is always the goal. During implementation of the FAA's first graphics system, hundreds of issues were identified during operational/functional testing. Early identification of issues provides an opportunity to fix them. Issues that cannot be fixed can be mitigated by integration into training.

Example: Rather than installing a dedicated TACAN flight deck display in the FAA CL-605, the cabin Wi-Fi system is used to send a FIS generated display to a portable electronic device on the flight deck. This required a minor modification to the FIS software. While extensive testing was conducted on a simulator, it was not discovered until OT&E flying that a programming error caused CDI reverse sensing on the missed approach segment. Coupled with this error was another unintended programming issue found when the aircraft heading transitioned between 359° and 001°. Detected early in OT&E, both of these errors were quickly communicated to the programmers and easily corrected.

Measurement Uncertainty

Measurement uncertainty testing determines how well the FIS captures, analyzes, and reports the correct result. Even though a flight inspection system produces believable results, the flight inspection operator must know the accuracy and/or measurement uncertainty of those results. In fact, internal FAA Order 8200.8 states "FAA must document the accuracies achieved by its measurements, showing that the uncertainties in the Appendices are not exceeded" [7]. While most flight inspectors are familiar with recommended ICAO Doc 8071 flight inspection tolerances, few are familiar with the associated measurement uncertainty requirements. They are different! See Figure 4, excerpt from Doc 8071, on VOR measurement uncertainty requirements. **The flight inspection tolerances are only valid if the FIS being used to evaluate them meets the measurement uncertainty requirements.** If the established measurement uncertainty requirements cannot be met (and some cannot) then additional analysis and/or engineering judgment is required. Without an established measurement uncertainty, application of any tolerance to a given FIS result cannot be considered meaningful.

There are many benefits realized during the measurement uncertainty evaluation. This activity undoubtedly results in greater understanding of the operator's FIS, learning which operational procedures are most effective for accurate measurement, and what improvements are needed in the requirements for future systems.

Parameter	*Measurand*	*Tolerance*	*Uncertainty*
Rotation	Clockwise	Correct	
Sensing	Correctness	Correct	
Polarization	Deviation	±2.0°	0.3°
Pattern accuracy	Deviation		
Alignment		±2.0°	0.6°
Bends		±3.5°	0.6°
Roughness and scalloping		±3.0°	0.3°
Flyability		Flyable	Subjective
Coverage	Field strength	90 µV/m	3 dB

Figure 4: Sample ICAO Doc 8071 Measurement Uncertainty Requirements [5]

In preparing for the BE-300PL OT&E project, attempts to determine methods for previous measurement uncertainty revealed that in most cases, none existed. Where estimates of measurement uncertainty did exist they were either a crude comparison to some previous system or a theoretical analysis estimate provided by the FIS vendor. Ideally, individual sensor uncertainties and operational variables are well known and a mathematical uncertainty can be derived for each measurand. Presently, the FAA does not have resources for this method so multiple measurements are used in an operational environment to statistically estimate most measurement uncertainties. In the opinion of the author, a true measurement uncertainty includes random and systematic errors caused by factors in addition to just those within the FIS, such as crew skill and technique. The general method is outlined in *Application of Signal Detection Theory to RNAV Flight Inspection Tolerances [9]:*

- All possible error sources are considered and discussed in the test planning process
- An independent truth estimation method is formulated for each measurand
- Following the truth estimation, the system is used normally for a goal of 30 measurements. Runs include parametric variations considered normal in day-to-day operation
- Comparison of the OVERALL system performance against a truth estimate based on a traceable standard is always the goal

Following the process above for each FIS reported value with an associated flight inspection tolerance results in dozens of individual tests. Brainstorming exercises amongst the subject matter experts are essential in designing valid, meaningful, and realistic test sequences. The following examples are representative of less than 2% of the work for a complete FIS measurement uncertainty. Each example requires extensive detail to fully describe. However, they are briefly described to demonstrate the overall nature of the work.

<u>Example #1:</u> Measurement uncertainty of VOR/LOC signal strength is normally accomplished simultaneously with establishing the antenna radiation patterns. The initial results and normalized results for the BE-300PL are shown in Figure 5 and 6 below.

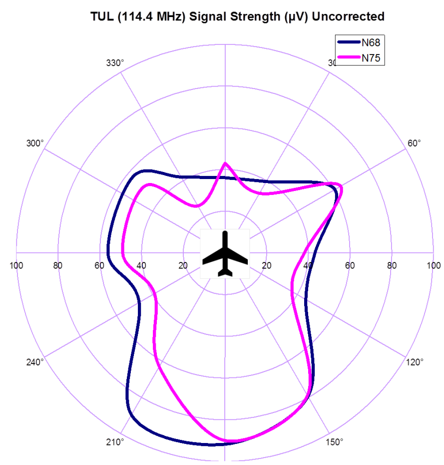
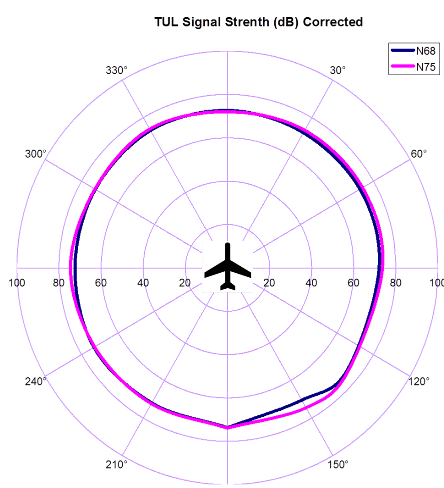


Figure 5: BE-300PL VOR/LOC Radiation Patter



Relative Bearing To Facility	Normalization Factor
0°	2
30°	3
60°	-2
90°	2
120°	2
150°	-4
180°	-5
210°	-3
240°	2
270°	0
300°	-1
330°	4

Figure 6: BE-300PL VOR/LOC Normalized

Once the normalization data is known, the overall gain to calibrate for true signal strength is needed. This is done by assessing the true field strength at a point in space and comparing it to multiple aircraft measurements. Since the current FAA system can only use a single gain, a complex analysis is used to determine the most appropriate gain to match intended uses and objectives for VOR/LOC signal strength evaluation. On completion of the process, the confidence interval is determined and plotted (Figure 7) using significant μV values. This helps flight inspectors recognize the relationship between varying μV confidence intervals based on a constant dB uncertainty. This test was repeated on the BE-300PL following addition of winglets; no change was found.

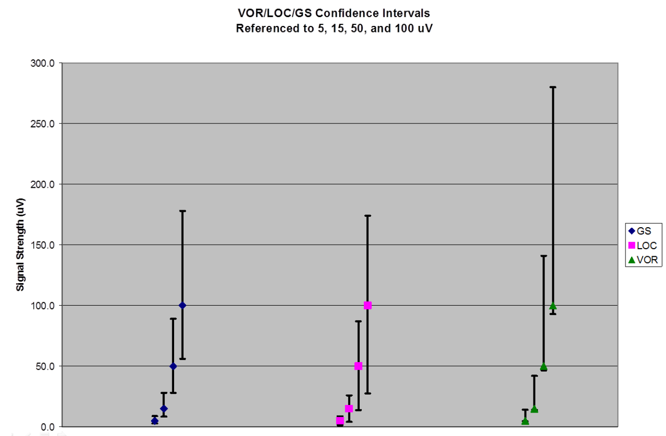


Figure 7: VOR/LOC Sig Strength Uncertainty (μV)

<u>Example #2:</u> In many cases, measurement uncertainty uncovers clear errors that need to be corrected. During testing of a major FIS software revision, angle data collected for measurement uncertainty in the ILS3 and PAR/VGSI mode showed significant angle measurement errors and their direct relationship to growing error in an IRU correction term (see linear relationship in Figure 8). A lengthy analysis was conducted to determine the source of error, the software algorithm was fixed, and the error is no longer observed!

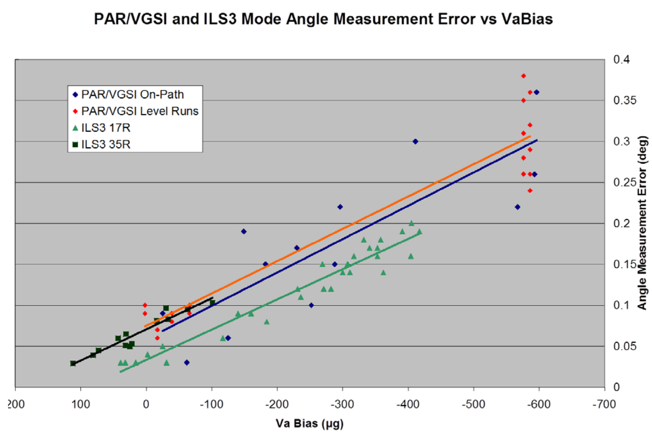


Figure 8: Analysis of IRU Correction Term Error

Example #3: During OT&E to obtain Operational Approval for GBAS inspection mode on the LR-60, a test was designed to assure the system's ability to detect Message Type 4 spatial data errors. Due to a different definition of the Flight Path Alignment Point (FPAP) in GBAS data, the results were unexpected. The OT&E revealed which data errors were detectable, which data errors were undetectable, and which procedures maximized the chances of detecting facility error in the Type 4 message. This activity resulted in defining the most effective GBAS inspection procedure and assuring that design requirements for the next FIS are written to increase spatial data error detection in RNAV approach modes.

Training

Well trained pilots and flight inspectors are required to successfully use flight inspection aircraft and the FIS to get the correct inspection result. While obvious, emphasis on quality training is difficult to sustain with the volume of operational inspection requirements. The goal of including training in the OT&E process is to ensure training personnel understand new systems, have developed appropriate training objectives, and developed acceptable training plans. Operational Approval for a new system frequently includes a limitation of required training for crew members.

Example: The BE-300PL differences training program initiated in OT&E is now a 3-week course that fully integrates pilot and flight inspector functions. The support from management, dedication of instructors, and quality of instruction was only possible through careful planning that started during OT&E. The course is frequently rated as "the best training in memory within FAA". One specific set of objectives identified for this training was unique to RNAV flight inspection. These objectives were used to develop an 8-hour course covering ARINC 424 coding as it relates to flight inspection/validation. In addition to supporting the BE-300PL training objectives, this course has been successfully used as refresher training by previously certified pilots and flight inspectors to increase their knowledge and effectiveness. By educating crews in RNAV/ARINC 424 appropriate language, FAA flight inspectors continue to improve operational effectiveness during RNAV inspections.

Reports/Data Logging/Archival/Retrieval

In addition to observing the flight inspection result, it is important to record, report, archive, and later retrieve the result. This section of OT&E focuses on that process. In the hustle of getting the operational flying and measurement uncertainty completed, this can be an easy task to miss or underestimate. It is worth the effort to get right because missed data causing repeated flight inspections is costly and inefficient.

Example: During initial measurement uncertainty testing for the DME/DME inspection mode, analysis revealed that DME range errors were not recorded anywhere in the three log files available for that mode. A software modification was made so that DME range error is now included.

CONCLUSIONS

A robust OT&E program and Operational Approval process is working well for FAA Flight Inspection Services. Management support for standardization of the OT&E process, the Operational Approval process, and fleet configuration management has been the key to success. The current FAA process ensures completion of all tasks required to integrate a new or modified FIS into the operational environment. There is synergy in this method as latent issues are found and corrected, training is developed and delivered, and improved requirements for future capabilities are identified.

RECOMMENDATIONS

FAA Flight Inspection Services is benefitting from the FIS Operational Approval concept and process. Where States are responsible for determining who or what is qualified to certify navigational aids and procedures in their airspace, a formalized process similar to this is recommended.

FUTURE WORK

The FAA has several legacy aircraft and systems used for flight inspection that have not completed the new OT&E for Operational Approval. They will remain in operation but will not be covered in the new process. The OT&E process is planned on each new and modified system operated by FAA. As part of this, the OT&E team strives to relay all suggestions for improvement to software developers of the next FIS. Areas of improvement for continued OT&E include increased collaboration from internal teams (e.g. training, standards, policy), improved methods for signal strength calibration, better analysis methods to decrease flight time for measurement uncertainty, and better documentation of OT&E results.

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APPENDIX 1

Example Operational Approval Matrix (CL-605: Jan 14, 2014)

FI Capability	Ops Approved	Operationally Approved Position Reference System (PRS)						
		RNAV				DGPS		RTT
		HYBRID (3)	GPS	FI DME	MAN/RN DME	FIXED/ FLOAT	DIFF	
Airport Lights	O							
VHF Comm	O							
UHF Comm	-							
NDB	O							
RNAV T Routes	O							
RNAV Q Routes	O							
RNAV DPs/STARS	O							
DME/DME Procs	O	O	-	-	-	O	O	-
RNAV(GPS) Approach	O	O	-	-	-	O	O	-
RNAV(GPS) w LPV	O	O	-	-	-	O (1)	O (1)	-
RNAV(GPS) w LP	O	O	-	-	-	O (1)	O (1)	-
RNAV(RNP)	O	O	-	-	-	O	-	-
GLS (GBAS)	-	-	-	-	-	-	-	-
ASR/ARSR	O (2)	O	-	-	-	O	O	-
PAR/VGSI	O	O	-	F	-	O	O	-
APM/GTM/MSAW	O							
VORTAC/DME	O	O	-	F	-	O	O	-
TACAN Procedure	O	O	-	-	-	O	O	-
ILS Cat I	O	O	-	F	-	O	O	-
ILS Cat II/III	O	O	-	-	-	O	-	-
MLS	-	-	-	-	-	-	-	-
RFI/DF VHF	-	-	-	-	-	-	-	-
RFI/DF UHF/GPS	-	-	-	-	-	-	-	-
Obstacle (ROC/Accuracy)	O	O	-	-	-	O	O	-
Obstacle Imaging	-	-	-	-	-	-	-	-
VFIP	O							
NASE	-	-	-	-	-	-	-	-
ASDE-X	O	-	-	-	-	O	O	-
ADS-B 1090ES Out	-							
ADS-B UAT In/Out	-							
1090ES In (Ethernet)	-							
ProFlex Data Log	O							

O Operationally Approved. Functional and Uncertainty Assessment Complete.
F Functional Assessment Only Complete.
- Not Tested or Not Equipped.

(1) Ops approval is for offset procedures only
(2) Unable Low Power / FI Sensitivity Select
(3) Includes TVPS or Pilot Runway Updates

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Notes: