PROBLEMS AND SOLUTIONS FOR NAVAIDS AIRBORNE AND GROUND MEASUREMENTS – FOCUS ON RECEIVER SAMPLING AND TCH

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ABSTRACT

This paper advances an ongoing discussion by the authors of challenging measurement issues faced by flight inspection organizations. Newly encountered problems are discussed, along with previous topics for which a deeper analysis and discussion are presented. The primary topics include airborne antenna patterns and resulting effects on common navaids measurements, flight inspection effects related to the trend of increasing digitization of airborne receivers, and the challenges of measuring Threshold Crossing Height (TCH) of the ILS Glide Path.

This paper discusses these issues in the context of a typical flight inspection organization's aircraft, antenna, receivers, and computations. Detailed airborne antenna pattern modeling is presented, and pattern effects on ILS and VOR measurements described. A brief tutorial on digital signal sampling and filtering concepts is included; simulation results are presented showing the importance of correct sampling and filtering design choices.

In a second major focus, the paper considers the TCH determination problem, and discusses typical contributions to differences between methods. A detailed analysis of TCH issues is given. Proposals for improving international definitions and the method for determination of TCH are provided.

BACKGROUND

Today's flight inspection organizations use a wide variety of airframes, antennas, receivers, and computational systems and software. Since each of these components affects the performance of the others, it is increasingly difficult to obtain similar measurement results from dissimilar measurement platforms. In some cases, it is even difficult to obtain similar results from the same platform used on repeated measurements.

In addition to measurement tool differences, challenges in navaids measurements also arise from incompletely defined requirements, widely varying interpretations of measurement goals, and the computations applied to airborne measurements.

Some of the parameters affecting these measurement challenges include:

- The airborne antenna pattern and its modification by the airframe (This topic is covered in more detail by a parallel paper in this conference.)
- Data sampling and filtering in the receiver and flight inspection computation system
- ICAO Annex 10 and Document 8071 definitions and recommendations
- Interpretation of flight inspection data
- Comparative accuracy of directly-measured and derived parameters

These parameters and their effects on common ILS and VOR measurements are discussed in the following sections.

NAVAIDS MEASUREMENT PROBLEMS

Flight Inspection Antenna Patterns.
A previous paper[1] by the authors presented a typical flight inspection aircraft's azimuth antenna pattern, showing significant distortion caused by the

airframe to the desired omni-directional shape. The paper also included examples of the effects of the poor pattern on measurements of ILS and VOR signals, such as significant differences in structure noted between inbound and outbound flights.

More recently, a detailed modeling capability has been designed which predicts both azimuth and elevation patterns on a variety of airframes using various antenna elements.[2] The detailed airframe model can consist of hundreds or thousands of triangular plates. Both polar plots and three-dimensional graphics of the pattern can be produced. Figure 1 is an example of the three-dimensional pattern of the rear navigation antenna on a LearJet Model 60, which is used by a major flight inspection organization.

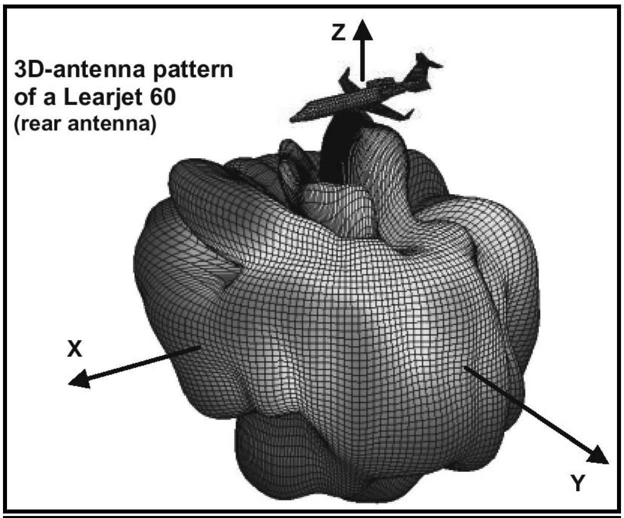

Figure 1. Lear Jet 60 Rear Antenna Pattern

Ideally, the antenna would exhibit a spherical antenna pattern, or if some minor forward directivity is desired, a smoothly-shaped surface whose volume is biased toward the front of the aircraft. [1] However, notice how the rear antenna exhibits a significant minimum in its pattern to the front and below the aircraft, while the response off the side of the aircraft is strong. This pair of characteristics will accentuate the effects of multipath signals arriving from the side of the aircraft, particularly when the desired signal is arriving from the front at a negative angle in the vertical plane. Clearly, this antenna will produce a very different structure measurement in the presence of multipath than one with a more desirable pattern.

Flight Inspection Receivers and Signal Processing.

In this section, trends in receiver design and digital signal processing techniques are presented, and their effects on flight inspection results are examined.

Trends in Navaids Receiver Design. For much of the 20th century, radio receiver design was based on strictly analog circuit techniques. Analog circuits are characterized by relatively bulky passive components such as coils and capacitors in filters, and by active devices such as transistors that operate in a linear mode (for which output signals are typically faithful replicas of input signals). Such circuits are heavy and require substantial space and current. As digital and programmable microprocessor circuits became common, manufacturers of avionics receivers in particular were eager to adopt the digital techniques, due to the intense demand for low power, size, and weight.

Figure 2 shows a simplified, typical receiver block diagram with common internal frequencies. Initially, digital circuits were suitable only for the low-frequency (post-detection) stages of the receiver, such as ILS and VOR crosspointer signal processing, as shown in the bottom half of the figure.

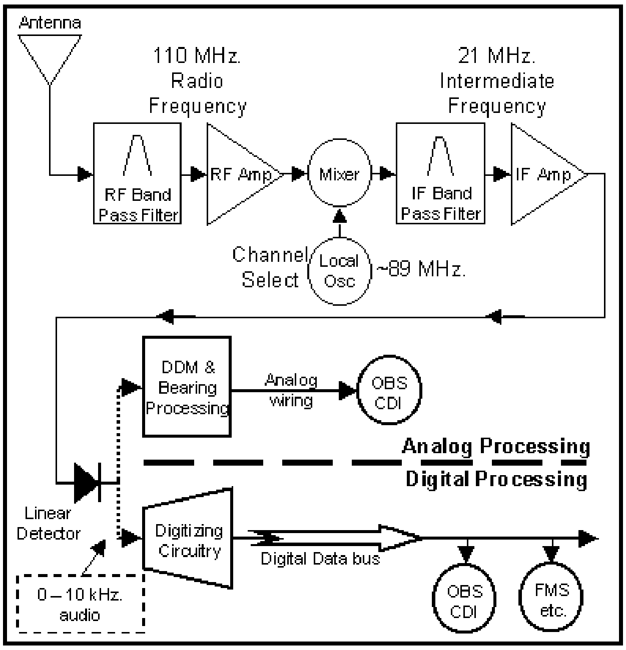

Figure 2. Simplified receiver block diagram

Flight management computer and display systems, as well as (automatic) flight inspection systems (AFIS), were ideal for digitized crosspointer input signals defined by industry data bus standards such as ARINC 429. As semiconductor devices became capable of operating at higher speeds, more of the receiver circuits could be digitized, and as a result the industry trend is to continually move the first digitizing process in the receiver block diagram toward the antenna.[3] Some current single-chip integrated circuits can provide digital outputs for input frequencies as high as 300 MHz.[4]

Digital Sampling and Filtering Review. The technique for digitizing an analog signal involves nearly-instantaneous, repetitive sampling of a complex waveform, such as an ILS crosspointer signal, in an Analog-to-Digital Converter (ADC) integrated circuit[5]. At each sample time, the voltage or current is converted to a numerical value, and the resulting string of numbers is processed as required. A block diagram of typical digitizing circuitry is shown in Figure 3. The figure includes the receiver digital circuits to the left of the first digital data bus, and a simplified AFIS consisting of storage and processing functions for the receiver's output, and a conversion of the signals back to analog format for presentation on a chart recorder.

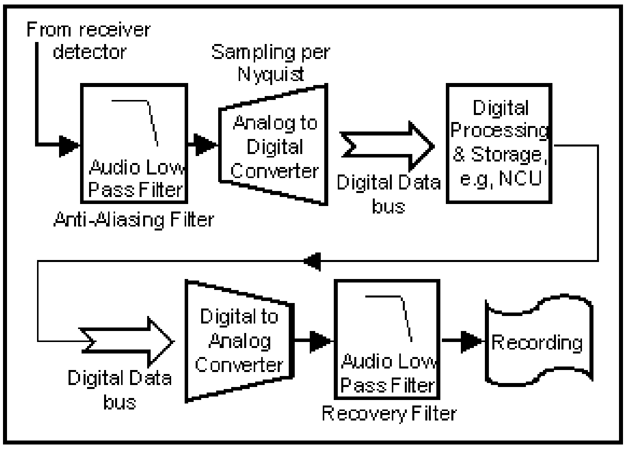

Figure 3. Typical Digitizing Circuitry

If the original information content in the analog waveform is to be fully recoverable from the digital data, the sampling rate must satisfy the *Nyquist Sampling Theorem*. This fundamental postulate requires that the digital sampling rate must be at least twice the highest frequency content of the analog signal. In practice, the actual sampling rate must be significantly faster than the theoretical Nyquist rate for good fidelity in the sampled data. For a consumer electronics example, consider digitized high-fidelity music as stored on common Compact Discs (CDs). To recover audio frequencies up to 20 kHz. (the upper range of human hearing) in a recorded symphony, a standardized sampling rate of 44 kHz. is used.

Digital sampling requires careful attention to filtering. See again Figure 3. Pre-sampling filtering is necessary to ensure that no frequency components higher than one half the sampling rate are fed to the ADC. Without this filter, unwanted higher frequency components will appear in the sampled data as lower-frequency components. This condition is known as *undersampling* or *aliasing*. This filter was often not included in analog receivers because cockpit Navigation displays such as CDIs or OBSs were not capable of reacting to the undesired high frequencies – the slow response of the displays acted as a "free" filter.

Figure 4 shows how an undersampled signal, such as a high-frequency *scallop* on an ILS signal, can appear on flight inspection recordings as a low-frequency signal or *bend*. The vertical lines illustrate the digitizing sample times, the small circles the digitized value of the analog scalloping waveform, and the smooth line between the circles the resulting recovered bend characteristic as it would appear on the recordings. If a second flight is made through this same scalloping, the sample times will almost surely occur at different points on the scalloping waveform, as in the lower part of Figure 4, and the resulting bend will appear in this case to occur in the opposite direction. This shows in general how a receiver or AFIS sampling rate can contaminate or completely change the character of the recorded results.

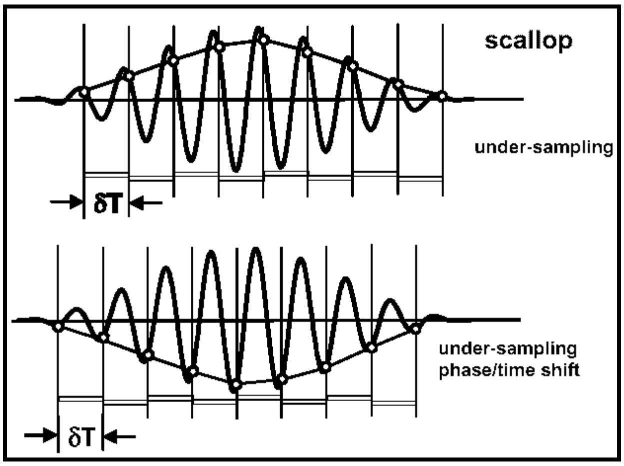

Figure 4. Effects of Undersampling (aliasing)

A second filtering problem applies to the recovered analog signal, such as the recorded traces of an AFIS. These are typically obtained from a Digital-to-Analog Converter (DAC) integrated circuit. Because the sampled numerical values are noisy by definition, the recovered signal will contain high frequency components that are multiples of the original analog signal. If these are not properly filtered out (by a low pass recovery filter, see again Figure 3), AFIS recordings will contain false data that will be analyzed against the roughness and scalloping tolerances for an ILS or VOR signal, resulting in inappropriate restrictions.

<u>Measurement Effects of Sampling Techniques.</u> The previous sections presented general digital sampling techniques, and discussed how the selection of sampling rate and filtering can affect results for a simple, fixed analog signal. In this section, the added complications of aircraft speed and multipath geometry are considered to place the discussion in a flight inspection context.

a. **<u>Undersampling Effects.</u>** Consider a common glide path (GP) reflection problem as shown in Figure 5. A 40m high hangar is located 700m off centerline and 500m prior to threshold. Its reflections contaminate the GP guidance in the region between 2000m and 1000m prior to threshold, in a predictable way.

The scallops from the hangar occur at fixed, known locations in space. However, for differing approach speeds, the frequency of the scallops, and the ratio of their frequency to the fixed receiver or AFIS sampling rate, varies.

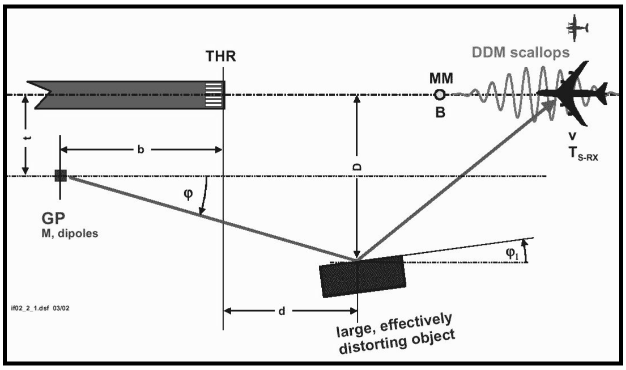

Figure 5. Geometry of a common GP reflection.

For some combinations of aircraft speed and sampling rate, the Nyquist Sampling Theorem will not be met and aliasing will occur. For reference, Table 1 shows various aircraft speeds, wavelengths (λ) traveled per second at that speed, and the distance traveled per digitized sample for various receiver or AFIS sampling rates. At the highest aircraft speeds, scalloping frequencies on LOC and VOR signals can be 30 Hz or more.

Aircraft Speed				**Distance traveled (m) for sample rate of:**			
Km/ hr	M/ sec	λ/sec LOC, VOR	λ/sec ILS-GP	4/ sec	8 / sec	10/ sec	16/ sec
600	167	61	NA	42	21	17	10
310	86	31	95	22	11	7	5
280	78	28	86	20	10	8	5
250	69	25	76	17	9	7	4
200	56	20	61	14	7	6	4

Table 1. Distances traveled vs. sampling rates.

Figure 6 shows in the lightest gray color the example hangar's scalloping results when digitized at a rate five times the scalloping frequency (Nyquist criterion easily **met**). The magnitude is about 50 microamperes (μA) between approximately 1600 and 1300 meters prior to threshold, and the frequency is sufficiently high (scallop period of 5m at 1600m) that individual scallops are very difficult to visually resolve.

Also shown with a dark line is the result from a digitizing rate equal to the scalloping frequency (Nyquist criterion **not met**). The very low apparent DDM frequency in the area between 1700 and 1500m prior to threshold is actually an artifact from aliasing (undersampling), and appears as a bend rather than scalloping to the flight inspector. As discussed previously, a second flight along the exactly identical flight path may well result in a completely different character to the DDM recording in this area. For example, it may appear as a bend in the opposite direction, depending on the relationship between the sampling times and the fixed spatial location of the scallops.

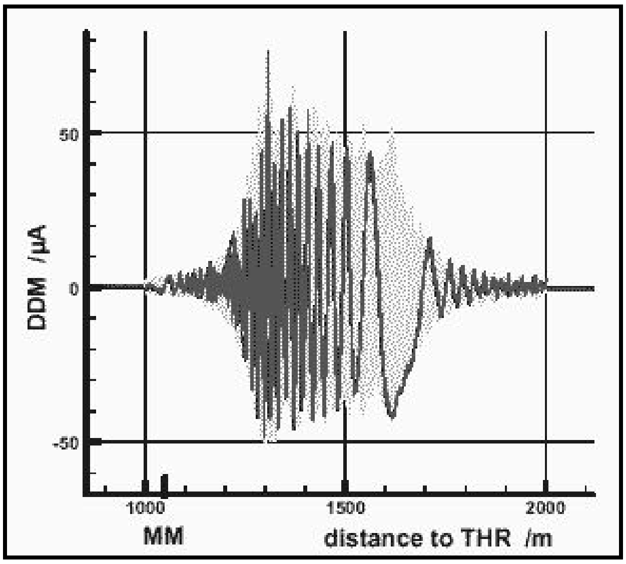

Figure 6. True and undersampled DDM results

b. **Modern Sampling Design.** As mentioned previously, modern receiver design is digitizing at ever-higher frequencies in the receiver block diagram. As the digitizing frequency increases, more attention must be paid to filtering. Figure 7 expands on the first two generalized blocks of Figure 3, and depicts the digitizing and filtering functions from a contemporary ILS/VOR receiver. Only the ILS signal processing is shown.

Because the highest frequency signal to be recovered is the 9960 Hz VOR FM signal, the anti-aliasing low-pass filter has a corner frequency of 12 kHz. The sampling rate of the ADC is at 64 kHz., easily meeting the Nyquist criterion.

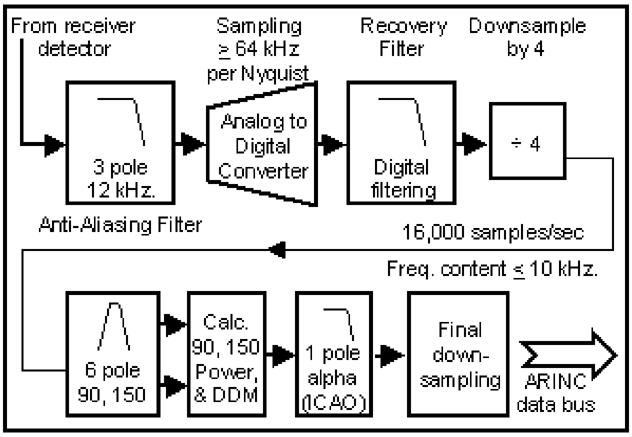

Figure 7. Modern Receiver Digital Section

All the blocks following the ADC are actually implemented in software. After the (software) recovery filter eliminates high-frequency artifacts of the sampling process, the data stream is decimated, or downsampled, by discarding three of every four samples, for an effective data rate of 16 kHz. Sharp 90 and 150 Hz (software) band pass software filters are followed by computations that determine the received power of the two ILS tones and calculate the Difference in Depth of Modulation (DDM) or crosspointer value. (Additional down-sampling is applied throughout this ILS processing section, but is not explicitly shown in the Figure.) Before a final downsampling to the receiver output bus update rate of approximately 16 Hz, a final (software) low pass filter removes higher frequency crosspointer characteristics that could be troublesome for avionics connected to the bus, such as autopilots or flight management systems.

c. **<u>Filtering Implementation Effects.</u>** If a digitally-sampled system is not well designed or fully implemented, various signal processing flaws occur. For example, if the anti-aliasing low pass filter is absent or poorly selected, high frequency crosspointer scalloping errors in the analog signal will appear as low frequency scalloping or even bends in the digitized data. A low pass filter does not change the frequency of the scalloping, but greatly attenuates the high frequency components, which then show up in the post-sampling data stream as very small variations in the numerical values.

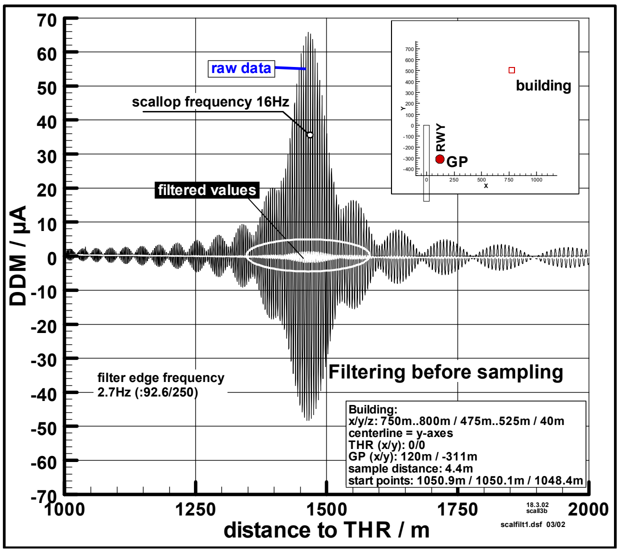

Figure 8. Sampling with/without aliasing

Figure 8 shows the large (up to 65 µA) raw data results from an unfiltered sampling of scallops from a building near an ILS GP. From Table 1, the scalloping rate will be higher than the selected 4.4 m sampling distance, which is equivalent to 16 samples per second. Therefore the Nyquist criterion is **not** met. With filtering according to the ICAO guidance material applied prior to the sampling (Nyquist criterion met), only a small residual DDM effect of approximately 3-5 µA is shown.

A second effect of filtering choices in a digital sampling design occurs when the recovery filter is absent or poorly selected. Its purpose is to remove high-frequency sampling artifacts in the numerical data, prior to conversion of the numerical data back to an analog signal, e.g, for application to a chart recorder. If not removed, this high-frequency content often will be above the frequency response capability of the recorder or other displays, resulting in a discontinuous or highly-distorted output. Isolated data points ("outliers") not connected to the nominal trace, or random-appearing high-frequency components that are not sinusoidal in nature are two indicators of this potential sampling problem.

A third filtering issue in the particular case of flight inspection systems is the final filter applied to the data before analysis and recording generation. To assure common results between different systems, it must comply with ICAO's guidance material[6] (Annex 10, Attachment C, paragraph 2.1.7) on recorded crosspointer frequency content:

Owing to the complex frequency components present in the ILS beam bend structures, measured values of beam bends are dependent on the frequency response of the airborne receiving and recording equipment. It is intended that beam bend measurements be obtained by using a total time constant (in seconds) for the receiver DDM output circuits and associated recording equipment of 92.6/V, where V is the velocity in km/h of the aircraft or ground vehicle as appropriate.

<u>Signal Processing.</u> A final category of navaids measurement problems introduced briefly here, in addition to the effects of antenna patterns and receiver digitization design choices, relates to choices in receiver signal processing.

a. **AGC Circuit Frequency Response.** Because the RF amplifier (Figure 2) must accommodate a large range of input signal levels, some form of Automatic Gain Control (AGC) is included in all receivers. If signal levels rise, as measured typically at the intermediate frequency (IF) stages, the gain of the RF amplifier is reduced to prevent distortion. However, because signal levels can fluctuate quickly in areas of multipath, the signal controlling the RF amplifier gain is filtered, producing an AGC response time of up to several seconds. The response time can vary depending on whether signal levels are rising or falling.

The AGC response time can have a negative effect on modulation percentage measurements. Modulation percentage is defined as a ratio between the modulating audio and the carrier levels. However, many receivers perform this "measurement" by merely displaying the post-detection audio signal levels, calibrated in per cent, rather than actually computing a ratio. This method works satisfactorily only if one assumes that the carrier level is constant. If the received signal varies more quickly than the AGC time constant, the measured audio voltage levels and the indicated modulation percentage will vary even when the received modulation level does not.[8]

This often results in flight restrictions, based on apparently out-of-tolerance modulation percentages, being inappropriately applied to navaids. An early indicator to this problem is a fluctuation in indicated percentage modulation that is faster than the AGC time constant of the receiver.

b. **DDM normalization.** Once software was added to receivers, it became attractive to process output signals to correct for problems such as temperature sensitivities elsewhere in the receiver. Crosspointer calibration is particularly challenging as the detector circuits are subjected to a wide range of temperatures. For recent-generation receivers with analog signal processing, a change in measured modulation percentages such as ILS Sum of Depth of Modulations (SDM) usually indicates a change in the gain of the amplifiers prior to the detector. These changes can miscalibrate non-zero DDM crosspointer values. As digital "back ends" were added to analog receivers to provide a databus output, some manufacturers used this change in modulation percentage to normalize or recalibrate the DDM output. For example, for a localizer output,

$$DDM = [m_{90} - m_{150}] \times [0.4 / SDM] \qquad (1)$$

Where m = modulation percent
SDM = sum of depths of modulation

This method works poorly if the transmitter is not set to 40%, or if the received SDM is high due to localizer antenna pattern characteristics that result in SDM > 40% (over-modulation; also known as "abnormal-case DDM"). (Note that a local SDM > 40% will typically appears in the course/clearance transition region of dual frequency ILS.)

THRESHOLD CROSSING HEIGHT (TCH)

Introduction.
The threshold crossing height (TCH) (also known as "RDH or Runway decision height" and "height of ILS point T above threshold") is one of the key parameters in the ILS. See Figure 9. Obstacle clearance surfaces are referenced to it, and therefore it is also a key safety parameter in the design and the installation of the ILS glide path.

Specification of TCH.
Due to its importance, the TCH is specified in Annex10 to be 15m (-0m,+3m). The inadequate tolerance limits shall not be discussed here, but in the design and realization process a reasonable, nominal TCH of 16m (16.5m) is assumed.

Definition. An (indirect) definition of the TCH can be found in Annex 10 [6] also via the *"ILS glide path"* and the *"ILS point T"*. It is defined and determined via *"the downward extended straight portion of the ILS glidepath"*. The ILS glide path is defined by "*the locus of points ... at which the DDM is zero...*". In the definition of the glide path angle one finds: *"... straight line which represents the mean of the ILS glidepath"*.

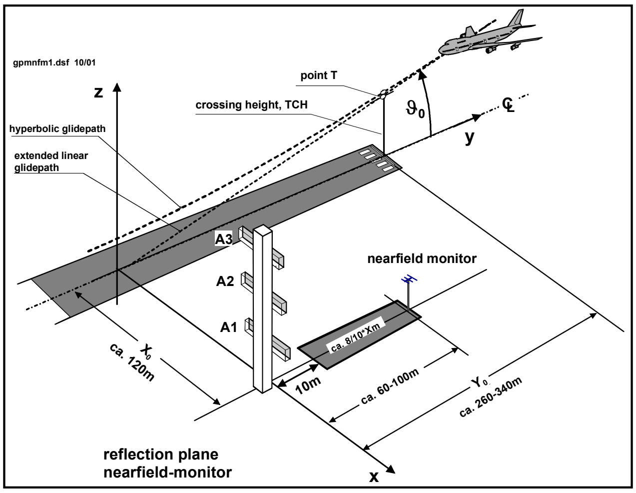

Figure 9. Coordinate system of classical GP (M)

Issues. Although this definition may seem to be unique, complete, and reasonable, there are a number of issues:

- Definition of the straight line. It is well known that close to the threshold the DDM = 0 curve in space is rarely straight.
- Definition of the averaging process *("mean")*. Which "averaging" and "linearization" process shall be applied?
- Range/region of the straight line on the glide path. Unfortunately the ICAO Standards and Recommended Practices (SARPs)[6] do not define where the straight line has to be taken -- between ILS points A and B according to the Recommendations, or between 1 NM and ILS-point C, resulting in the achieved TCH (ATCH).
- Adjustment and derivation of the TCH from operational needs irrespective of formal definitions. Is it really reasonable to take into account the DDM near point A?
- Potential update of the definitions by considering the modern landing schemes, i.e. the use of the radio altimeter in the final landing process (e.g. disregard the GP-structure between ILS Points C and T).

If applicable formal specifications exist, they have to be applied; if not they must be published in general by the member state or in a case-by-case manner for an airport.

Development of TCH.
TCH is not solely dependent on the glide path geometry, but in general is a time variant value.

Generation of Glide Path DDM in space. Consider the generation of DDM by assuming that the antenna feeds are stable and sufficiently controlled. The ground equipment antennas are radiating two vector field antenna patterns carrying the amplitude modulated signals (CSB, SBO). The CSB and SBO include all field distortions from any scatterers and the non-ideal ground, in case of the classical image type glide path. The DDM is derived in the receiver, and is a scalar field, i.e., in each field point one DDM-figure exists (Figure 10). Both the scatterers and the ground properties may be time variant, e.g., due to environmental effects such as snow or turning cranes.

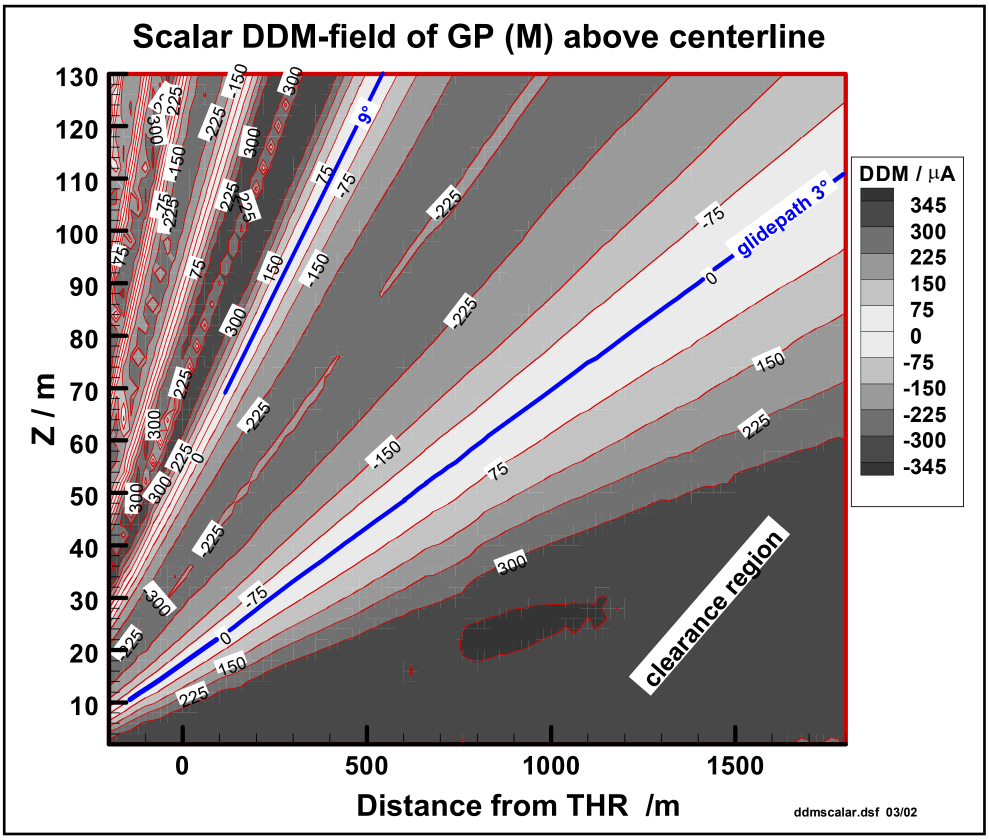

Figure 10. Scalar DDM-field above centerline of a GP(M) installed on a highly 3D reflection plane

Formation of TCH. Since TCH is a parameter dependent on DDM, its establishment and control are accomplished in multiple ways (see Figure 11):

- Careful design and optimization by numerical means[7], particularly when the ground is non-ideal, i.e. truncated and three-dimensional. In the design phase, target values for TCH and glide path angle are basic parameters to be optimized.
- Installation on the basis of the predetermined geometry data (position, heights etc.) and ground check
- Flight check (commissioning, routine)

Figure 11 shows that the analysis and design and the flight check should have similar or identical steps. Since TCH depends on the DDM and not solely on the geometry, a periodic flight check and TCH evaluation is mandatory if the stable scalar DDM-field cannot be safely guaranteed.

Determination of TCH.
Widely varying opinions exist for the appropriate method of determining TCH at a GP site. The primary issues in the flight inspection activity are removing flight path errors from measurements and the subsequent mathematical treatment of the data.

TCH and Flight Path Correction in FI. The aim is to find the locus in space for DDM=0. This can be obtained quite easily by numerical means. Any flight path deviation from this "unknown curve in space" has to be converted to a DDM correction. This inherently requires an iterative approach, and can require several flights. The correction is done via the displacement sensitivity, which is typically assumed to be nominal. To minimize errors in this correction process, the autopilot should be used during GP structure measurements whenever possible, although windy conditions or a very poor GP structure may prevent it. If the real DDM scallops are too large, or if major bends are encountered, the correction process may be unsuccessful and can even introduce artifacts.

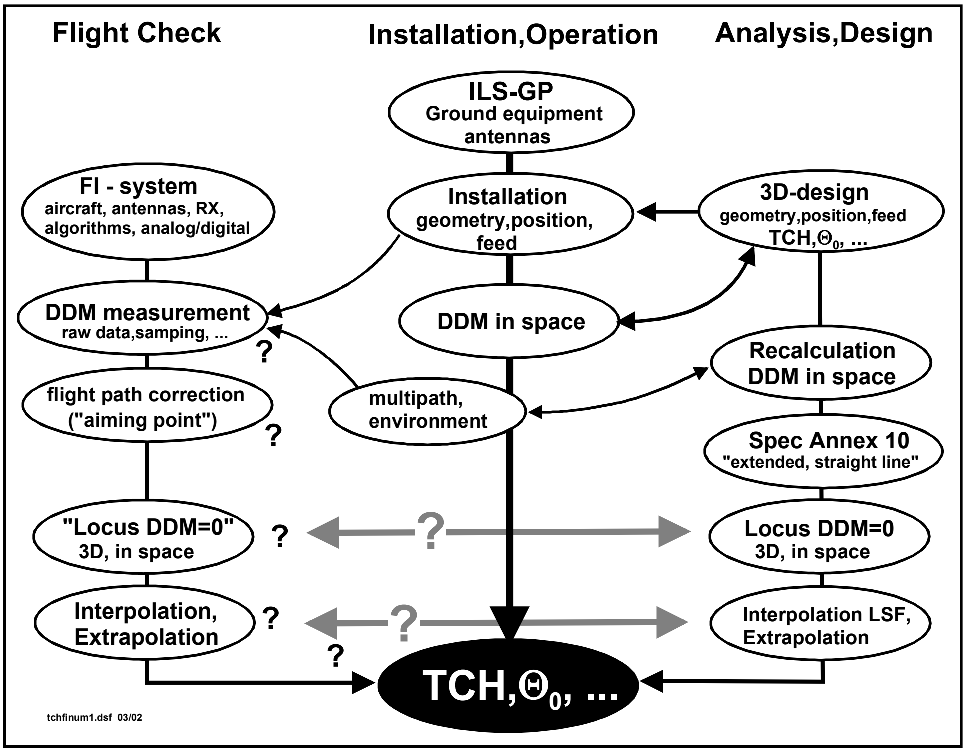

Figure 11. Flow chart of the GP installation, design and flight check

<u>TCH and "Aiming Point.</u> It is common to use a so-called special "aiming point" as a reference in the FI systems for eliminating the actual flight path errors induced in the measured raw DDM. However, this aiming point is not unique and must be deduced from geometrical data versus point T, the nominal TCH, and the path angle. Figure 12 shows the relationship between these two points.

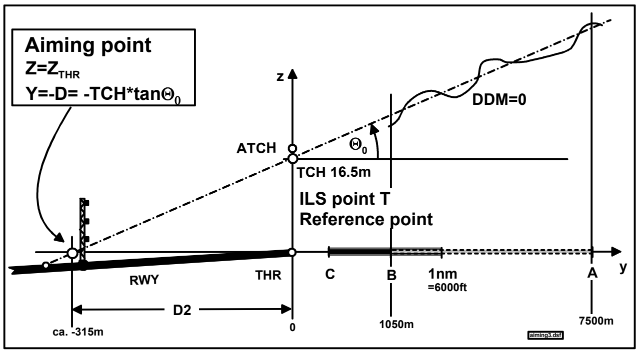

Figure 12. ILS Point T and the aiming point

Fortunately, it is not necessary to use an additional independent aiming point. Instead, it is proposed to use ILS point T as a natural reference point for the flight path error extraction. In any case, ILS point T and any special aiming point are only mathematically transformed points. If the design of the GP has been performed by modern 3D-means (Figure 11), the point T (i.e. the derived aiming point) is sufficiently accurately defined for FI measurements.

<u>TCH and Averaging Process.</u> As mentioned, the averaging process ("mean") is not defined in Annex 10. Also the term "mean" is not unique. Therefore reasonable and adequate mathematical algorithms should be applied to meet the formal specification requirements and the operational application. The authors claim that the least square fit linearization (LSFL) algorithm is the preferred candidate. It is a straight-forward mathematical "interpolation" with inherent smoothing characteristics. Using this method, the TCH is defined by the extrapolation of the interpolated LFSL straight line ("downward extended").

However, extrapolation processes must be used with caution, because they amplify characteristics of the function within the interpolation area. To address this, the specification and determination of the glide path angle and TCH can be improved by taking into account operational needs. For example, at IFIS 2000 the authors proposed a weighting scheme[1] to reduce the sensitivity of TCH determination to glide path variations near Point A. The scheme could include DDM changes (first derivatives close to ILS points B and C and T). Ideally, one or more preferred methods should be referenced in Annex 10.

<u>TCH and ICAO Formula.</u>

As discussed at IFIS 2000[1], the simple formula (equations 2 and 2') in ICAO's guidance material (Attachment C to Annex 10) for the siting of the ILS GP is not meant for the determination of the TCH.

$$D = (H+Y) / \tan(\Theta+\alpha) \quad (2)$$

$$H = TCH = D \tan(\Theta+\alpha) - Y \quad (2')$$

where α = forward slope
D =backset of glide slope antenna

The language in paragraphs 2.4.9 through 2.4.12 of Attachment C makes clear that the formula is used to position the GP mast from "geometrical abstractions", and that "the achieved ILS reference datum can only be ascertained by flight check." The formula may be used as a first approximation for siting the mast in simple cases on sufficiently flat ground, or in cases of large only longitudinally sloped terrain. Improved formulas have been developed for the two-dimensional case:

$$H_{TCH}=D\tan(\Theta+\alpha)+(H_{GP}-H_{THR})+d\tan\beta \quad (3)$$

where β = lateral slope
d =sideward distance to centerline

A comparison of (2') and (3) shows that the term $d\tan\beta$ is missing in (2'). This term is negligible if the lateral slope is sufficiently small. For realistic values of d=120m and β=2%, the missing term equals 2.4m. If the ICAO formula is then applied in a flight inspection process for TCH, an error of at least this amount is to be expected!

In the general 3D-case, or even in the simplified general 2D-case, the simple formula (2) is totally insufficient and may yield large errors depending on the actual situation. Based on this example and the ICAO text, all formulas based solely on geometry are insufficient, because they neglect DDM effects from ground plane truncations, scattering, and other siting challenges.

Measurement Uncertainty for TCH.

The expected accuracy for the TCH using a LFSL method depends on a number of individual measurement uncertainties, e.g. DDM and position measurement, as well as the algorithms used. It is estimated that for state-of-the-art individual measurements, a total typical TCH accuracy of 0.5m should be achievable (1m maximum). If the TCH has been determined reliably by 3D-methods to be 16.5m, the proposed airborne verification of the TCH to be >15m will have been sufficiently accomplished.

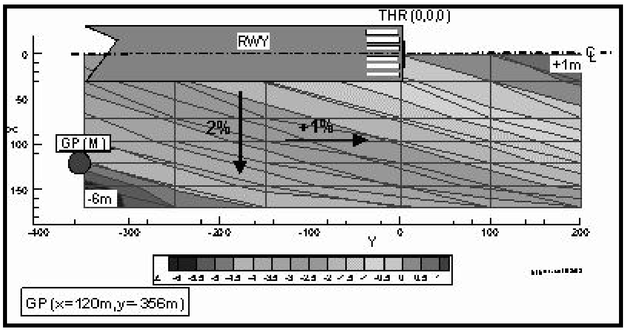

Figure 13. 3D-terrain for GP (M) with large lateral and forward slopes (42 points)

TCH Measurement Example.

A real example for a TCH-problem is discussed in the following. Figure 13 shows a GP 3D-terrain having simultaneously a large lateral slope of 2% and a forward slope of 1%. The optimized design was made in advance for 16.5m and a glideslope angle of 3.00°. After the site preparation was accomplished, the terrain was surveyed and the values recalculated. The results for the actual terrain were 16.7 m and almost 3.00° (Fig. 14).

The flight inspection result for TCH, determined by applying the ICAO-formula (2'), was 14.2m. The difference is 2.5m, which nearly equals the missing term ($d\tan\beta$ = 2.4m) of equation (3). If the ICAO Attachment C equation (2') were used, the glideslope system would have to be relocated back by about 46m – in fact creating a too large TCH. This is an obvious example where the simple formula completely fails.

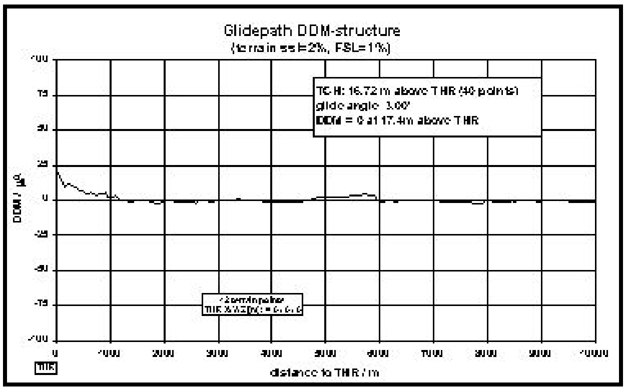

Figure 14. DDM structure on GP for the 3D-terrain of Figure 12

TCH Measurement Periodicity.

The periodicities of the measurements of TCH and glidepath angle are of course connected. It has been pointed out that both parameters are time-variant parameters in principle.

The prudent selection of the measurement periodicity depends on several factors:

- The type and number of (field) monitors installed
- The multipath environment of the local site (is it clean?)
- The nature and pace of construction activities
- The identification and supervision of the GP safeguarding areas (e.g., critical and sensitive areas).
- Additional ground measurements provided (e.g. DDM=0 above THR).

If time-variant environmental effects can be safely excluded or minimized, an extension of the periodic flight check to 1 year or longer for TCH and the GP-angle is justified from a technical point of view.

CONCLUSIONS

a. Airborne antenna patterns are rarely omni-directional or even smooth, and have a major effect on flight inspection results, particularly in areas of significant multipath.

b. Modern simulation techniques can produce faithful predictions of airborne antenna patterns.

c. Avionics receiver design will continue to emphasize digitization of the signals at higher frequencies.

d. Careful attention must be paid to implementation of digital sampling and filtering techniques to ensure fidelity to the original signal.

e. For flight inspection work, the application of filtering to digital sampling is most critical at the receiver output, where the data is transferred to the flight inspection system.

f. Poorly implemented digitization schemes can result in inappropriate navaids facility restrictions.

g. Crosspointer outputs on flight inspection systems must be filtered identically to achieve common results among different systems.

h. Some measurement schemes can falsely indicate large fluctuations in modulation due solely to differences between the signal strength's rate of change and the receiver AGC time constant.

i. TCH is a key safety parameter in the design and installation of a GP, because obstacle clearance surfaces are referenced to it.

j. TCH is not dependent solely on GP geometry, but in general is a time variant value.

k. The least square fit linearization (LSFL) algorithm is a good choice for use in GP measurements.

l. Some weighting scheme should be used to determine TCH, to minimize the sensitivity to distant GP errors of no operational consequence.

m. TCH formulas based solely on geometry are insufficient, because they neglect DDM effects from ground plane truncations, scattering, and other siting challenges.

RECOMMENDATIONS

It is referred generally to the remarks and recommendations made in the preceeding paper also [1].

a. Flight inspection organizations should model/measure their airborne antenna patterns, and disqualify or modify those that seriously impact good navaids measurements.

b. Flight inspection organizations should ensure receiver and AFIS circuits and software comply with good filtering and digitization principles.

c. Flight inspection personnel should identify evidence of measurement problems, such as substantially different results from inbound and outbound flights, data point outliers, and AGC-induced artifacts, and bring them to the attention of the responsible engineering organization.

d. All flight inspection organizations should implement the ICAO-recommended speed-dependent filtering function on recorded and analyzed crosspointer indications.

e. One-dimensional TCH formulas should not be used; two-dimensional formulas should be used only with caution where applicable.

f. Three-dimensional modeling and the least square fit method of determining TCH from the actual DDM field are generally applicable.

g. Flight inspection organizations should standardize on the ILS Point T as a reference point ("aiming point") for removal of flight path errors.

h. Design GP installations for a nominal TCH of 16-16.5 m (center of ICAO tolerance).

i. Calculate and protect obstacle clearance surfaces for the ICAO minimum TCH value of 15 m.

j. Use measured TCH values only for verification that the actual TCH is ≥15m and <18m.

k. Accept realistic measurement uncertainties for determination of TCH.

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