Using UAV multicopters as a complement of ILS/VOR ground and flight measurements: our feedback and experience after more than four years of successful operations

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BIOGRAPHIES

Hervé Demule, navigation engineer and senior project leader at Skyguide, is an engineering graduate of SUPAERO (Ecole Nationale Supérieure de l'Aeronautique et de l'Espace, Toulouse/France) and has accumulated extensive experience with ILS troubleshooting, commissioning and optimization. As project manager of many navaid replacements as well as with development and commercialization of a mobile bench for ILS measurements (ground and air) he has proven his great expert skill in these fields. On the educational side, he is also a certified instructor and a technical speaker. The Skyguide CNS Drone is one of his innovations.

Klaus Theißen leads a software lab with focus on economy analyzers and avionic testers at Rohde & Schwarz in Germany. At the same time, he is the product manager for all R&S air navigation analyzers.
After his diploma degree in electrical engineering (Dipl.-Ing.) at the Technical University of Aachen he started his career in 1994. He worked on different software development projects and for digital signal processing of NavAids analyzers like R&S®EVS200 and R&S®EV300. He became project leader for several development projects and then took over the product management for the R&S air navigation products - like R&S®EVSG1000.
He is now team leader for the software development of economy analyzers and air navigation receivers.

Vagel Argyrakis, Technical director, RPAS/UAV flight instructor.
Co-founder of Amphios srl (AltiGator) in 2008, one of the first UAV manufacturers in Belgium, Vagel has been manufacturing model aircraft since 1999 on all types of models (helicopters, airplanes and multirotors).
He is the Technical Director of the company, mastering industrial design, micro-mechanics, electronics, IT programming and tuning of all the RPA peripherals and subsystems.
Vagel is a remote pilot and instructor for multirotor and fixed wings UAVs.
Responsible for the technological development, he is leading the Research and Development department at AltiGator.

ABSTRACT

End 2015, Geneva, the first successful trials with an UAV multicopter carrying an ILS receiver concluded the first stage of the feasibility study. Indeed, these very promising first ILS measurements provided skyguide engineers many positive answers to their initial questions. Yes, it is possible and very worthful to measure ILS signal in the far field region with a multicopter. Yes, the stability and accuracy of the flight with a heavy and expensive payload were very acceptable. Yes, the accuracy and repeatability of the measurements fulfilled the expectations, and even much more. Yes, a very good level of correlation with flight checks had already been achieved.

In 2016 and 2017, Skyguide (the swiss air navigation service provider), Rohde&Schwarz (the manufacturer of the R&S®EVSF1000 VHF/UHF Nav/Flight Analyzer) and AltiGator (the UAV manufacturer) have developed a customized "drone check" solution, which fits the initial expectations and specifications. By putting a lot of importance in ILS/VOR ground and drone measurement techniques, the goal is to achieve the best possible repeatability and correlation with flight checks, as recommended by ICAO Document 8071.

January 2018, the so-called "Drone for CNS Maintenance" was mature and ready for deployment and regular operations on Swiss international airports: for preventive and corrective maintenances of ILS and VOR, as well as initial preparation of commissioning flight checks for new ILS.

April 2018, our first IFIS paper described this development project, the multicopter based measurement system and its first good achievements in winter 2018 in terms of repeatability and accuracy.

June 2022, after more than four years of successful operations of ILS/VOR measurements (as well as VDF commissioning preparation), this paper presents our experience and the system performances in terms of repeatability and correlation with flights check and monitor data: real facts and figures, curves and quantitative analysis of the results.

Our so-called "Drone for CNS Maintenance", based on its extensive experience and its high level of achievements, opens new horizons in terms of ILS/VOR measurement techniques: for preventive and corrective maintenances, and also for new ILS commissioning. Moreover, as mentioned by ICAO Document 8071 and based on the very good correlations, it has been playing a key role in the reduction of the ILS flight check in Switzerland from 2022.

Figure 1: The CNS Drone

INTRODUCTION AND BACKGROUND

ICAO DOC 8071 and its Recommendations with Regards to ILS

ICAO Document 8071 [1] "Manual on Testing of Radio Navigation Aids" provides general guidance on the extent of testing and inspection carried out to ensure that radio navigation systems meet the standards and recommended practices (SARPs) specified in ICAO Annex 10 [2]. However, Document 8071 specifically states in the introduction, that it does not have the status of SARPs. It is therefore, and by its own definition, only guidance material, "representative of best practices existing in a number of experienced States with considerable experience in the operation of these systems" [1].

The document describes the ground and flight testing in terms of periodicity, tolerances (in reference to the SARPs) as well as the respective relevant methods. Moreover, it suggests a nominal schedule, as a basis for the determination of an appropriate inspection intervals. However, it also raises the question of a possible extension of these intervals based on several criteria, such as for example a "good correlation between concurrent ground and airborne results". The next two figures show the relevant sections of Document 8071.

Determination of test/inspection intervals

1.15.4 Many factors influence the choice of appropriate intervals for both ground and flight tests. These include the reliability and stability of operation of the equipment, the extent of ground monitoring, the degree of correlation between ground and flight measurements, changes in the operating environment, manufacturer recommendations, and the quality of maintenance. The complete programme of ground and flight inspections should be considered when determining test intervals.

Figure 2: Extract from document 8071 [1], Paragraph 1.15.4 "Determination of test/inspection intervals"

Correlation as the basis for extending periodicity

1.15.10 A typical basis for extending the interval between required measurements without degrading ILS integrity is correlation. Any individual measurement is normally expected to be repeatable over time without adjustments to the equipment. Correlation between ILS measurements made both on the ground and in the air at the same or nearly the same time is also expected. This places equal responsibility on ground and airborne personnel and helps identify common-mode measurement errors. An additional requirement to extend flight inspection intervals is the influence of near- and far-field environments on the signals. These effects can be determined with a flight inspection aircraft. The following paragraphs give illustrations of the correlation technique.

Figure 3: Extract from Document 8071 [1], Paragraph 1.15.10 "Correlation as the basis for extending periodicity"

Based on the above presented extracts, one can conclude that, in accordance with the recommendations given by ICAO in DOC 8071, the achievement of good correlation places the same, or at least similar weight on both, ground and airborne testing.

Motivated by this, skyguide developed a set of very accurate and repetitive ground measurement tools and techniques, such as the ILS checker software. This software is in use in over twenty countries across the world. A more detailed description can be found in the IFIS 2010 presentation "R&S®TS6300 ILS Test System, The modern automatic mobile bench for ILS ground measurements" [3]. Following up from the 2010 publication, the 2012 IFIS paper "How to get a good correlation between ILS ground measurements and flight checks?" [4] further documents good correlation results achieved with a mobile automatic test bench for ground based measurements, which was developed by skyguide.

Going one step further, Document 8071 [1] states in Section 1.15.7, that "The correlation of air and ground measurement records have allowed some States to extend the interval between flight inspections. This is supported by the use of routine monitor readings, strict environmental safeguarding and closer tolerances on flight inspection results to ensure operational stability is maintained." It continues in the same section with a reference to example criteria, laid out in sections 1.15.8 and 1.15.9 respectively, which can be applied to extend the flight inspection intervals. The criteria are as follows:

1. proven stability of the ILS equipment:

a. no transmitter adjustment needed across four consecutive flight checks

b. tolerances narrowed to 75% of the standards

2. good correlation between ground and flight measurements (which can be complemented with a good correlation of ground monitor data)

3. a record of independent monitor calibration results

4. a record of monitor readings (at least monthly)

5. evidence of the high quality of maintenance

6. safeguarding measures against change in the operational environment, such as but not limited to, new building, cranes, and landscaping.

Furthermore, the latest update of document 8071 [1], published in 2018, opens up the possibility to use drones (RPAS / UAVs) for ILS measurements, in order to reduce the flight check periodicity. The next figure shows an excerpt of the relevant section from the latest revision of document 8071 [1].

1.18.2 Remotely piloted aircraft systems (RPAS) or unmanned aerial vehicles (UAV) should be assessed to determine that they provide the payload capability, speed and range necessary to conduct a flight inspection for navigation aids as recommended herein in a cost-effective manner. RPAS can and have been used for special and advanced measurement applications which are difficult to achieve with traditional ground and flight measurement capabilities. Nothing in this manual is intended to prevent the development of such capabilities. Some States are studying how the use of RPAS can help in making more regular measurement checks with the aim to reduce the periodicity of a full flight inspection with a typical flight inspection aircraft. These studies should take into account the guidance in section 1.15.

Figure 4: Extract from document 8071 [1], Paragraph 1.18.2, on the use of UAVs for flight inspections

The Project Drone for ILS Maintenance

Skyguide started systematic comparisons between the results of ILS ground measurements and flight checks in 2002. By using a vehicle equipped with special measurement tools as well as a 22 m high telescopic mast, a high degree of correlation between flight checks and these ground-based measurements was demonstrated. The results were especially good for localizer measurements. However, for glide path measurements, these ground based measurements, conducted at the runway threshold (approximately 300 m from the glide path), were found to be in the near field of the radiating elements and therefore too close. The resulting correlation of these glide path measurements was thus not satisfactory. This led to the idea to conduct these measurements much further away, ideally at a minimum distance to the threshold of around 1 to 1.5 km. As a consequence, the glide path measurements at theses distances must also be taken much higher from the ground, approximately at a height of 100 m. This is the same altitude a plane is in short final at the same distance from the threshold. The first idea, to use a very high mast of around 100 m, aligned with the runway centerline, was given up quite quickly. Another idea was to use a balloon, in order to conduct "elevator flights" to measure elevation profiles. But due to the logistic difficulties to set up such a system, and its sensitivity to wind, this idea was also given up. The third idea was to use a powerful drone, which is able to lift and carry the payload of ILS and GPS receivers. This idea was seriously considered and studied since summer 2015 onwards, and subsequently led to this project.

The study and concept phases

After successful feasibility tests with subsequent proof of concept in October 2015, skyguide decided to launch a formal project. The goal was to enable a deployment of this new measurement technique to be used for future preventive and corrective ILS maintenance and also for support during ILS commissioning. A key part of the first study phase was a costbenefit-analysis, which demonstrated, that a business case for a deployment of this drone for ILS measurements will become positive, as soon as a fraction of periodic flight check hours with an aircraft can be substituted by ILS checks with a drone. But it was clear from the start that it cannot be the aim of this project to replace the flight checks with a plane entirely by drone checks. At this stage it would be impossible from a technical as well as a legal perspective. The idea is to complement flight checks and thus to reduce the frequency and the program of periodic preventive flight checks, while adhering to the standards and recommendations set out in document 8071.

The development, test and training phases

After it was decided to realize the project, the goal was to have an operational system, ready to be deployed by the end of 2017. During this realization phase, skyguide has played a central coordinative role between the different stakeholders, especially between the UAV supplier AltiGator and the ILS receiver supplier Rohde&Schwarz. The schedules of three separate development sub-projects and their respective outcomes had to be synchronized and coordinated.

During this phase, several tests of the new UAV features, the new ILS receiver and the new measurement software were necessary. Parallel to the technical development, five drone pilots had to be trained, in order to be able to conduct autonomous operation of the UAV from November 2017 onwards. Subsequently, and after another round of test flights and validation measurements, the maintenance procedures were adapted to include drone measurements.

The deployment and operational phases

The use of the UAV multi-copter for regular preventive ILS maintenance has been successfully deployed on both international airports Geneva and Zurich from January 2018 onwards (with a total of 6 ILS). In a second step, from spring 2019 onwards, these drone checks have also been deployed at Bern-Belp airport. In a thirst step, from 2021 onwards, they have been gradually deployed to nearly all Swiss regional and military airports and ILS, maintained by skyguide. (with a total of 12 ILS in 2022). Skyguide decided to set a monthly periodicity for CAT III ILS and a quarterly periodicity for CAT I ILS. The goal was to collect as much data as possible and document any seasonal effects (temperature, humidity). Thanks to an intensive phase of data collection, a systematic evaluation of the collected data against the criteria set out in document 8071 (stability, correlation between ground, flight and monitor measurements) was conducted. The results of this evaluation has been presented to the Swiss regulator from Summer 2020, and then regularly discussed with the flight check services in 2020 and 2021.

Figure 5: Drone Check at a Regional Airport

THE CNS DRONE SYSTEM

The CNS Drone system is composed of three subsystems:

1- The drone which carries the payload and provides accurate positioning and power supply to the payload

2- The ILS/VOR receiver: the R&S®EVSF1000 VHF/UHF Nav/Flight Analyzer

3- The Preflight Checker software for data collection, display and analyses

1- The Drone

The Hydra drone from AltiGator is the result of multiple years of research and development in unmanned aviation. It combines the latest technologies in matter of navigation, flight precision, positioning accuracy and automation. Hydra is compact, robust, adaptable and future-proof. Associating high precision sensors together with redundant flight sub-systems, as well as versatility and infinite customization possibilities, Hydra is the unmanned aircraft tailored for CNS Maintenance, following Skyguide's requirements:

- A robust structure was designed to be able to embark the Rohde & Schwarz receiver, while still keeping an optimized aircraft size for transportation;
- Its airframe has been engineered in order to provide enough ground clearance to embed the ILS receiver with its antennas;
- Ensuring the best stability during the landing phase was essential in this application, involving this kind of equipment;
- A specific mounting system has been designed to secure the whole set of the embedded instruments and antennas;
- The high-performance propulsion system of the aircraft, combined with strong batteries provides sufficient power to carry the payload while still having enough flight time to perform the measurements;
- Special care has been taken to protect the electronic parts of the UAV, to ensure mission fulfillment under demanding operational conditions;
- The navigation is based on GPS RTK positioning in accordance with the accuracy and repeatability requirements of the project.

Figure 6: The UAV multicopter OnyxStar® Hydra

The OnyxStar® Hydra is navigating automatically, based on a preconfigured waypoint flight that precisely follows a programmed path. While it is always possible for the pilot to take on manual control at any moment of the operation, the automation concerns all the phases of the flight, including take-off and landing. This makes the measurements process much easier and precise as repeatability is not affected by the human factor. Each specific navigation needs to be configured once and then stored in order to be loaded and repeated at will.

2- The R&S®EVSF1000 VHF/UHF Nav/Flight Analyzer

The R&S®EVSF1000 is a two-channel signal level and modulation analyzer (e.g. for simultaneous Localizer and Glidepath measurements). It is designed to be installed in flight inspection aircraft, a measurement car or aboard of a drone. It performs measurements on ILS, VOR and marker beacon ground stations e.g. during startup, maintenance and servicing and is also able to analyze ATC COM signals.

The R&S®EVSF1000 delivers precise, high-sensitivity analyses in the frequency range from 70 MHz to 410 MHz. Its hardware and software are largely identical to that of the R&S®EVSG1000 VHF/UHF Airnav/Com Analyzer, which is designed for ground measurements. The identical performance of the two instruments ensures that results obtained in flight, aboard of a drone and from the ground are comparable, as stipulated by the ICAO standards.

Figure 7: The R&S®EVSF1000 VHF/UHF Nav/Flight Analyzer

The R&S®EVSF1000 offers an extremely wide dynamic range that is achieved by means of switchable preamplifiers and selectable attenuators in combination with a high-level mixer. An integrated calibration generator with high long-term stability ensures accurate level measurements.

Due to its high sensitivity, low noise figure and narrowband filters, the R&S®EVSF1000 is able to deliver highly precise results even at large distances from the transmit system with the resulting low levels. The R&S®EVSF1000 also offers a wide input level range and steep-edged preselection filters that provide optimized interference rejection for ILS, VOR, marker beacon and COM measurements. As a result, the instrument features high intermodulation suppression and immunity to interference and can deliver reliable measurements even in the immediate vicinity of FM transmitters.

By using digital signal processing, the R&S®EVSF1000 offers outstanding accuracy during modulation analysis. The input signal is sampled at the IF using a high-precision analog-to-digital converter. FPGA technology is used to process results in realtime with the highest degree of reproducibility.

The R&S®EVSG-K1 option makes it possible to measure both carriers of a dual-frequency (2F) ILS system independently and simultaneously. The IF bandwidth of the adaptive filters for the carriers can be set down to 1 kHz to optimize the signal to noise ratio. The level and modulation values of each carrier (course and clearance) are measured and analyzed at the same time. This means that each carrier can be measured without switching off the other carrier. This approach also allows users to determine the phase relationship between the 90 Hz and the 150 Hz AF tones of the single carriers.

Its compact dimensions (95 mm × 177 mm × 360 mm) and low weight (3.7 kg) make the R&S®EVSF1000 ideal for integration to a measurement drone. The mechanical design of the R&S®EVSF1000 meets the requirements of RTCA DO 160G/Section 7.0 with respect to shock and the requirements of RTCA-DO160G 8.5.2 with respect to random vibration. The robust mechanical design and the excellent sensitivity of the two signal processing units make it ideal for parallel measurements of Localizer and Glide Path.

The R&S®EVSF1000 can be directly connected to the on-board system's DC power supply (11 V to 32 V). The instrument comes with an integrated power supply that bridges short-term interruptions (RTCA DO 160G, Section 16, Category A, DC power interruptions up to 200 ms) and fluctuations in the on-board supply voltage, so that they will not affect the mission or measurement accuracy.

The R&S®EVSF1000 can process up to 100 data records per second, making it possible to determine and analyze effects such as scallops and bends. Using an external (RTK) GPS, the instrument automatically links each data record to the correct GPS time- and location-stamp. The R&S®EVSF1000 records all measured data with the internal data recorder and is able to transmit this data at the same time via its LAN interface (streaming).

Thus the R&S®EVSF1000 base configuration includes all functions essential for drone and flight inspection and can determine characteristic system parameters – such as modulation depth, DDM and SDM – with high precision at a rate of 100 data records/s. Additionally it measures and decodes the identifier of the station under test and returns the ID pulse repetition rate, the ID code and the dash, dot and gap lengths. Spectrum and signal analysis options are available in addition.

For smaller drone types R&S is currently working on a much smaller receiver that will be called R&S®EVSD1000 VHF/UHF NAV/DRONE ANALYZER. The R&S®EVSD1000 hardware, software and performance will be largely identical to that of the R&S®EVSG1000 VHF/UHF Airnav/com analyzer, which performs the same measurements from the ground.

The R&S®EVSD1000 will feature a highly compact, robust mechanical design. Spectrum and signal analysis options as well as a time domain analysis option will be available in addition. At 1.4 kg, the instrument's weight allows usage of a medium-sized drone to perform measurements on ILS/VOR systems in line with the ICAO standards.

Figure 8: The future R&S®EVSD1000 VHF/UHF NAV/DRONE ANALYZER

3- The Preflight Checker Software

During the last fourteen years, skyguide engineering and maintenance teams have gained experience and trust in its ground measurements system, composed of an ILS vehicle, a telescopic mast and its associated software ILS Checker. This in-house developed software enables the compensation of the vehicle trajectory in 2D along the runway centerline.

In 2014, the first version of the so-called Preflight Checker software with 3D trajectory compensation has been also internally developed, in order to enable pre-commissioning measurements of Glide Path. Indeed, it has been then possible to measure LOC and GP signals in the farfield aboard of a general aviation airplane for example. This has been the basis of the next software versions with the use of an UAV from 2015.

After the successful trials with an UAV in October 2015 and the decision of project realization in March 2016, an intensive phase of software development took place in spring and summer 2017. Thanks to this major upgrade, the latest version 3.0 of the Preflight Checker software enables now the following measurement modes associated to the UAV:

- Vertical Profile of the Glide Path:

Positioned in the farfield region of the Glide Path, at a distance to the threshold of at least 1 km or 1.5 km, the UAV multicopter simply follows a vertical trajectory up to a height of approximately 80 m to 120 m. The idea is to reach an elevation angle of at least 4°, for a 3° Glide Path. The principle of this measurement mode is the same as the old one with the telescopic mast at the runway threshold. The only, but major, difference consists in conducting the measurement in the farfield instead of in the nearfield, which is very worthful for correlation purposes.

Figure 9: Picture of an "elevator" flight for a Vertical Profile measurement

Thanks to these "elevator" flights, the Preflight Checker software enables to calculate and display in live the following curves for Glide Path: DDM, SDM and RF Level versus Elevation Angle. Without any post-processing time, it also immediately computes the significant GP parameters:

- Glide Path angle: 3.02° for the example below
- Displacement Error: -4.3 µA
- Both ¼ sector widths: -73.6 µA on the 150 Hz side and 74.7 µA on the 90 Hz side
- SDM: 80.0%
- and RF Level on centerline: -35.0 dBm

Figure 10: The Preflight Checker software in the Vertical Profile mode

As illustrated below by Figure 11, the Vertical Profile mode also enables to conduct the required measurements in alarm conditions:

- o Lower and upper angle alarm conditions
- o Narrow and wide alarm conditions of the ¼ sector widths

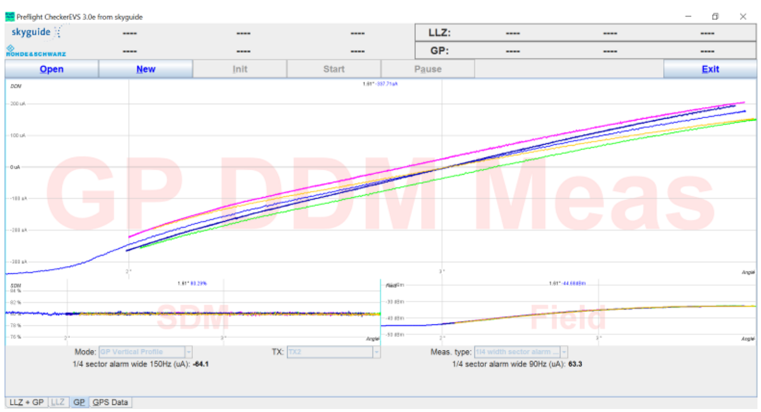

Figure 11: Vertical Profile mode in alarm conditions: lower, upper, narrow and wide alarms

- Mini Approach for simultaneous Localizer and Glide Path measurements

After the successful development and tests of the Vertical Profile mode, the second idea has consisted in flying a segment of the approach path and measuring simultaneously the Localizer and Glide Path signals, like any conventional flight check systems. Depending on the sites, the lengths of this approach segment vary today from 400 m to 800 m, in the short final region (typically in the area of point B, 1 km before the threshold). The length of these "Mini Approaches" flights may be increased in the future, depending on the battery autonomy, the UAV speed and of course the need for longer measurements. Better than the "vertical slice" measurements of the Elevation Profile, the Mini Approach mode computes **averaged** values of the key parameters, and thus enables an excellent correlation with the averaged flight check results in the same region.

Figure 12: Picture of a Mini Approach flight of the UAV

As illustrated below, the Preflight Checker software displays in live DDM course structures for both Localizer (in the upper part of the window) and Glide Path (in the lower part). For accuracy and repeatability reasons, it compensates of course the trajectory errors in 3D. Without any post-processing time, it also immediately computes and averages the following parameters for LOC and GP:

- DDM displacement error
- SDM
- RF level
- Course / Clearance ratio
- ICAO percentage of the course structures
- Glide Path angle and RDH (Reference Datum Height above the runway threshold)

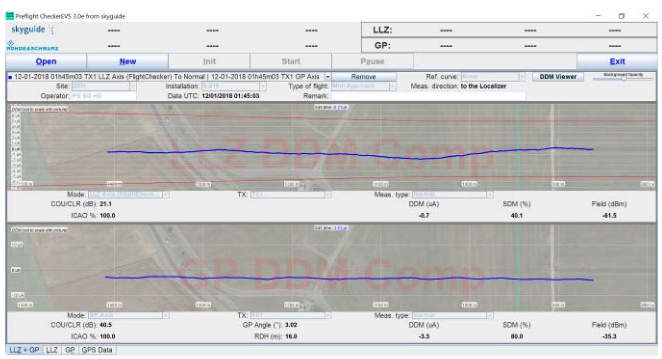

Figure 13: The Preflight Checker software in the Mini Approach mode (LOC in the upper part, GP in the lower part)

These averaged parameters such as DDM, GP angle, Course / Clearance ratio RDH are the ones, which can be compared and assessed for correlation with flight check, because they are measured in the same conditions. Finally, as illustrated below by Figure 16, the Mini-Approach mode also enables to conduct the required measurements in (simultaneous) alarm conditions:

- Left and Right alarm conditions for the Localizer
- Lower and upper angle alarm conditions for the Glide Path

- Lateral Orbit of Localizer
  The software also offers the possibility to measure the linearity coverage of the Localizer in its farfield region. The UAV follows a circular or "orbit" trajectory centered on the LOC. Without any post-processing time, it immediately computes the following parameters for LOC:

- Displacement Error: -0.1 µA below
- Both ¼ sector widths: -72.8 µA on the 150 Hz side and 73.2 µA on the 90 Hz side

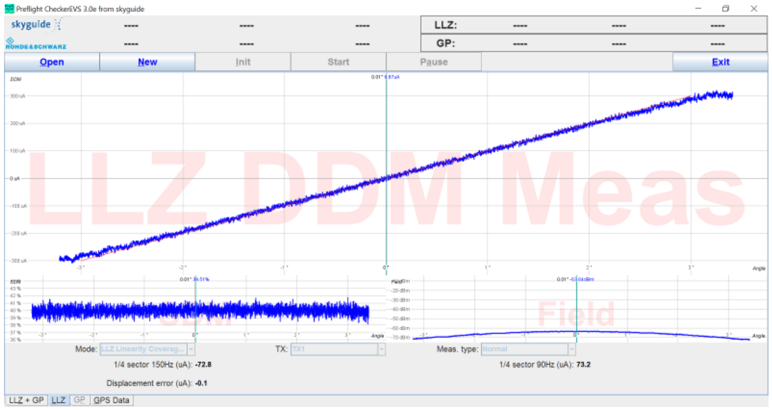

Figure 14: The Preflight Checker in the Lateral Orbit mode

The Lateral Orbit mode also enables to conduct the required measurements in narrow and wide alarm conditions of the Localizer ¼ sector widths.

RESULTS

This section presents the results of the ILS ground, drone and flight checks for ILS14 Localizer and ILS16 Glide Path at Zurich airport LSZH. Such results and analysis have been computed for all ILS in Switzerland, documented, and presented to the Swiss regulator. ILS 14 and 16 in Zurich have been taken as examples for this technical paper. The results are represented in the form of graphs and a summary in the form of tables.

LSZH14 LOC axis normal

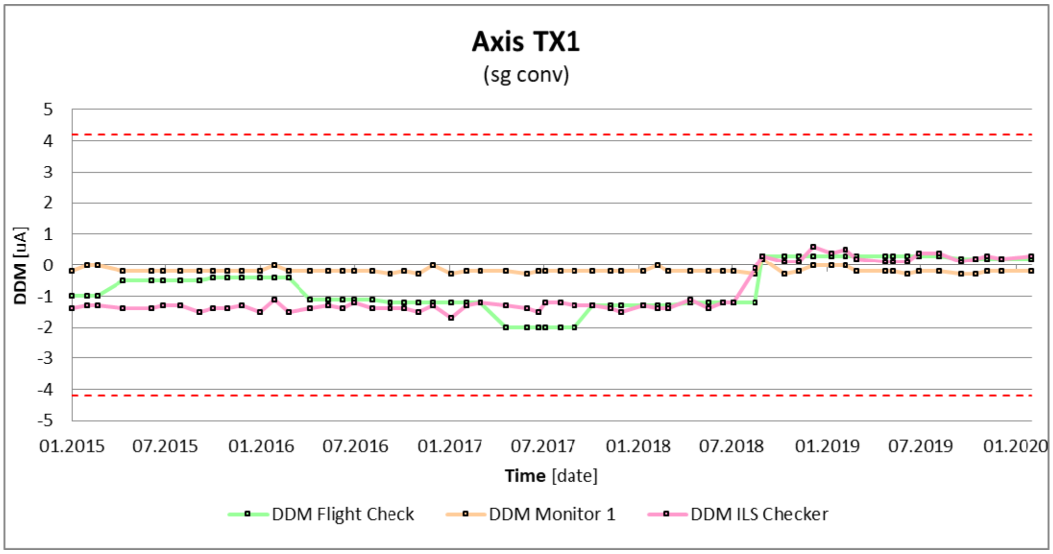

Figure 15: Ground Check of LOC Axis Normal (flight = green, monitor = orange, ground = pink)

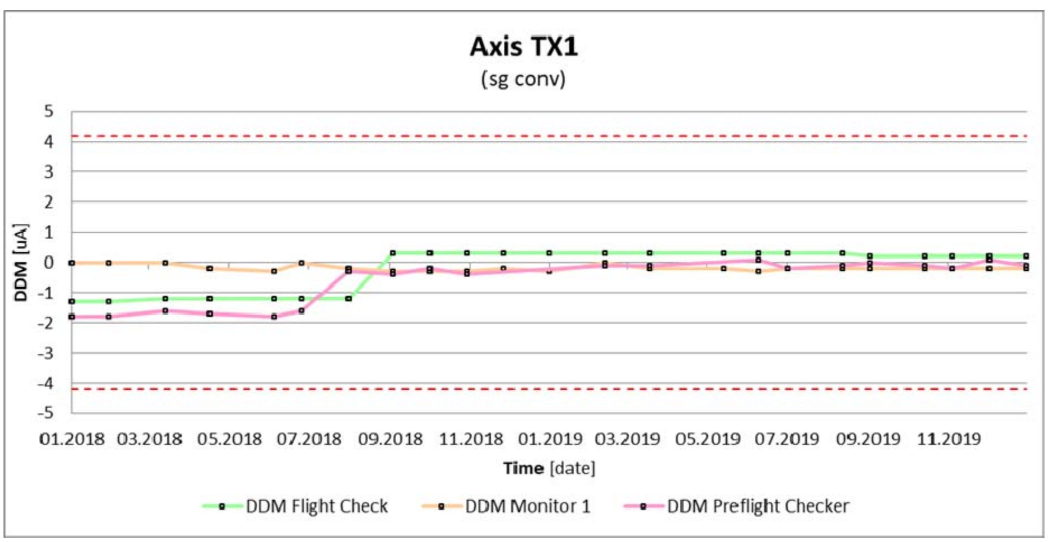

Figure 16: Drone Check of LOC Axis Normal (flight = green, monitor = orange, drone = pink)

It has to be noted that a signal correction (realignment of the LOC axis) has been conducted in August 2018. This correction is well shown by the graphs for flight, ground and drone checks, whereas the monitor data remains stable. This is due to the fact that a monitor calibration was conducted at the same time (monitor was realigned to zero). This demonstrates the strong correlation between ground, drone and flight checks.

LSZH14 LOC width normal

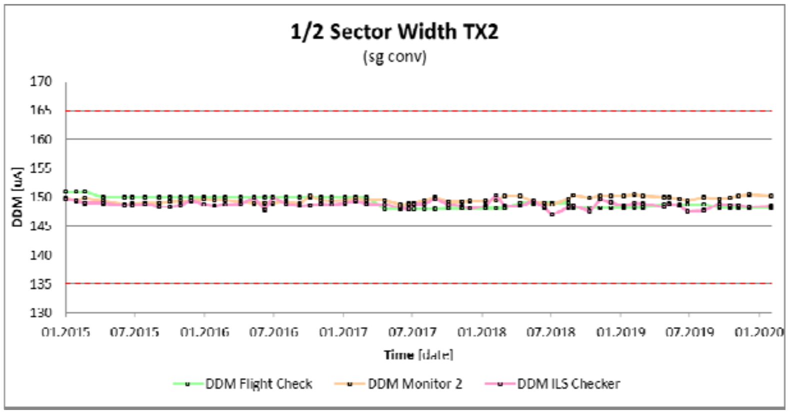

Figure 17: Ground Check of LOC Width Normal (flight = green, monitor = orange, ground = pink)

These systematic comparisons between monitor data, ground and flight checks demonstrate the strong correlation between these measurement methods, also for the width parameters of the Localizer.

Localizer ground and drone check correlation statistics

To quantify the degree of correlation between the different measurements and their respective methods, two tables are presented: the first table AVG and the second table σ respectively, represent the averages and the standard deviations of the subtraction between:

- flight check and monitor data,
- flight and ground (or drone) checks,
- ground (or drone) check and monitor data,

across all measurements conducted from January 2018 until April 2020. These averages and standard deviations have to be compared to their corresponding ICAO limits, shown in the second column. They are also illustrated by the red bar chart in every cell. (Full cell width = 100 % of the ICAO limit)

AVG	ICAO-Limit	FCS-MON	FCS-DRO	DRO-MON
Axis TX1	4.3 uA	0.1 uA	0.4 uA	0.5 uA
Axis TX2	4.3 uA	0.2 uA	0.5 uA	0.5 uA
Axis 90Hz dom TX1	8.6 uA	0.5 uA	0.9 uA	0.1 uA
Axis 150Hz dom TX1	8.6 uA	0.3 uA	0.3 uA	0.1 uA
Axis 90Hz dom TX2	8.6 uA	0.0 uA	0.1 uA	0.0 uA
Axis 150Hz dom TX2	8.6 uA	0.0 uA	0.1 uA	0.0 uA

Table 1: Averages for LSZH14 LOC Drone Checks

σ	ICAO-Limit	FCS-MON	FCS-DRO	DRO-MON
Axis TX1	4.3 uA	0.7 uA	0.2 uA	0.8 uA
Axis TX2	4.3 uA	0.9 uA	0.3 uA	0.8 uA
Axis 90Hz dom TX1	8.6 uA	0.5 uA	0.0 uA	0.1 uA
Axis 150Hz dom TX1	8.6 uA	0.1 uA	0.0 uA	0.0 uA
Axis 90Hz dom TX2	8.6 uA	0.2 uA	0.3 uA	0.1 uA
Axis 150Hz dom TX2	8.6 uA	0.0 uA	0.1 uA	0.0 uA

Table 2: Standard Deviations for LSZH14 LOC Drone Checks

In normal conditions (axis and width normal), the monitor and drone correlations with flight check represent respectively in **average 6% and 7% of the ICAO limits**. In alarm conditions (axis and width alarms), the monitor and drone correlations with flight check represent respectively **in average 2% and 3% of the ICAO limits**. For LSZH LOC 14, this statistical quantitative analysis documents and demonstrates the high degree of correlation of monitor data and drone checks with the flight check (especially in alarm conditions).

LSZH16 GP Axis Normal

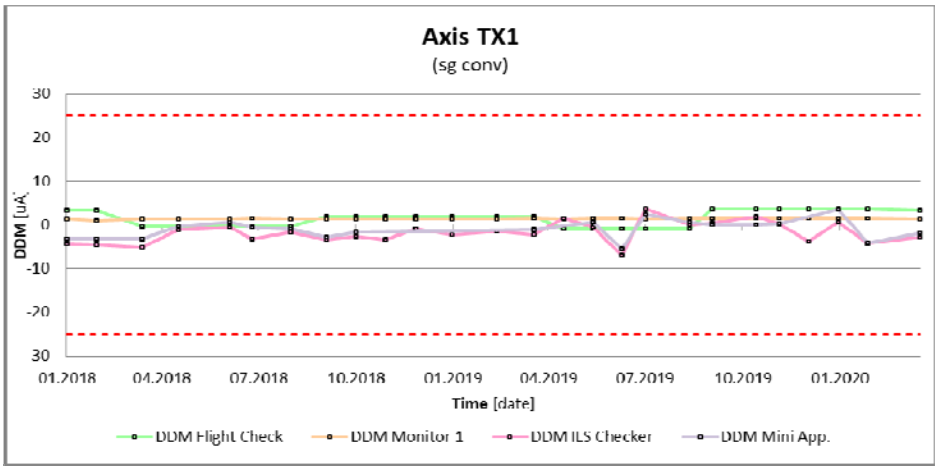

Figure 18: Drone Check of GP Axis Normal TX 1 (flight = green, monitor = orange, drone = pink & purple)

LSZH16 GP Width Normal

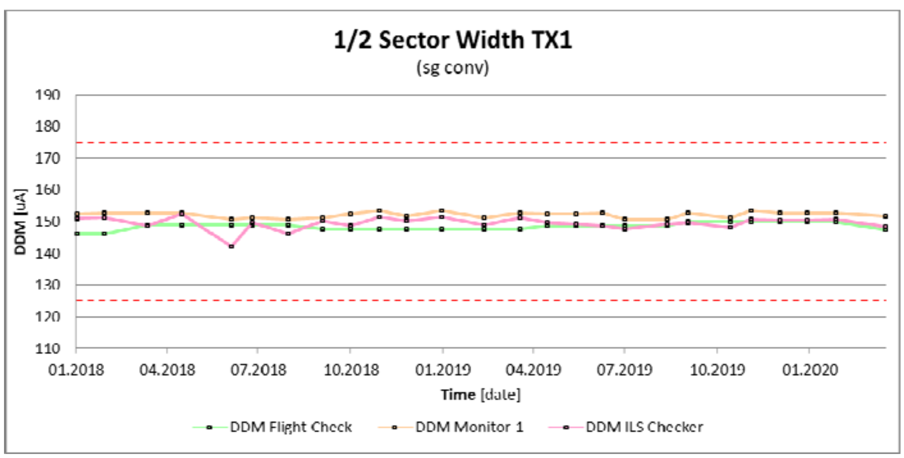

Figure 19: Drone Check of GP Width Normal TX 1 (flight = green, monitor = orange, drone = pink & purple)

These systematic comparisons between monitor data, drone and flight checks demonstrate the strong correlation between these measurement methods for the axis and width parameters of the LSZH16 Glide Path.

Glide Drone Check Correlation Statistics

To quantify the degree of correlation between the different measurements and their respective methods, two tables are presented: the first table AVG and the second table σ respectively, represent the averages and the standard deviations of the subtraction between:

- flight check and monitor data,
- flight and drone checks,

- drone check and monitor data,

across all measurements conducted from January 2018 until April 2020. These averages and standard deviations have to be compared to their corresponding ICAO limits, shown in the second column. They are also illustrated by the red bar chart in every cell. (Full cell width = 100 % of the ICAO limit). The third and the fourth columns "VP" document the Vertical Profile (VP) methods, whereas the sixth and seventh columns "MA" document the Mini Approach (MA) methods.

AVG	ICAO-Limit	FCS-MON	FCS-DRO	DRO-MON	FCS-DRO	DRO-MON
			VP	VP	MA	MA
Axis TX1	25.0 uA	0.2 uA	2.8 uA	3.0 uA	3.8 uA	3.3 uA
Axis TX2	25.0 uA	0.1 uA	4.3 uA	4.2 uA	3.8 uA	3.2 uA
Axis 90Hz dom TX1	46.9 uA	0.3 uA	2.5 uA	2.2 uA	1.5 uA	0.9 uA
Axis 150Hz dom TX1	62.5 uA	0.3 uA	0.4 uA	0.1 uA	1.0 uA	0.4 uA
Axis 90Hz dom TX2	46.9 uA	0.4 uA	0.8 uA	0.4 uA	2.0 uA	1.3 uA
Axis 150Hz dom TX2	62.5 uA	0.4 uA	1.1 uA	0.6 uA	0.8 uA	0.8 uA
Width TX1	22.5 uA	3.5 uA	0.8 uA	2.7 uA		
Width TX2	22.5 uA	4.5 uA	2.3 uA	2.2 uA		
Width narrow TX1	37.5 uA	0.3 uA	0.4 uA	0.6 uA		
Width wide TX1	37.5 uA	1.8 uA	2.1 uA	0.3 uA		
Width narrow TX2	37.5 uA	0.1 uA	0.4 uA	0.3 uA		
Width wide TX2	37.5 uA	1.5 uA	1.2 uA	0.3 uA		

Table 3: Averages for LSZH16 GP Drone Checks

The difference in correlation for the drone axis measurement of approximately 3 µA to 4 µA is again explained by the fact that the GP drone check axis measurements are conducted at the border of the "mid field" region (the transition zone between nearfield and farfield), whereas the flight check and the monitor measurements are taken in the farfield of the GP Antenna system.

σ	ICAO-Limit	FCS-MON	FCS-DRO	DRO-MON	FCS-DRO	DRO-MON
			VP	VP	MA	MA
Axis TX1	25.0 uA	1.8 uA	3.1 uA	2.7 uA	0.8 uA	1.4 uA
Axis TX2	25.0 uA	1.6 uA	1.8 uA	1.3 uA	1.2 uA	1.5 uA
Axis 90Hz dom TX1	46.9 uA	0.0 uA	2.3 uA	2.3 uA	0.0 uA	0.9 uA
Axis 150Hz dom TX1	62.5 uA	0.2 uA	0.0 uA	0.2 uA	0.0 uA	0.7 uA
Axis 90Hz dom TX2	46.9 uA	0.2 uA	0.5 uA	0.4 uA	0.2 uA	0.6 uA
Axis 150Hz dom TX2	62.5 uA	0.3 uA	0.6 uA	0.3 uA	0.7 uA	1.0 uA
Width TX1	22.5 uA	0.3 uA	1.1 uA	1.1 uA		
Width TX2	22.5 uA	1.7 uA	2.9 uA	1.6 uA		
Width narrow TX1	37.5 uA	0.3 uA	1.0 uA	0.7 uA		
Width wide TX1	37.5 uA	0.2 uA	1.2 uA	1.0 uA		
Width narrow TX2	37.5 uA	1.2 uA	0.9 uA	0.3 uA		
Width wide TX2	37.5 uA	0.0 uA	1.0 uA	1.0 uA		

Table 4: Standard Deviations for LSZH16 GP Drone Checks

In normal conditions (axis and width normal), the monitor and drone correlations with flight check represent respectively in **average 9% and 12% of the ICAO limits**. In alarm conditions (axis and width alarms), the monitor and drone correlations with flight check represent respectively **in average 2% and 3% of the ICAO limits**. For LSZH GP 16, this statistical quantitative analysis documents and demonstrates the high degree of correlation of monitor data and drone checks with the flight check (especially in alarm conditions).

ANALYSIS OF THE ACHIEVEMENTS

Glide Path Drone Checks: Reproducibility

One of the key questions was how consistently a drone measurement can be reproduced. In order to proof the reproducibility, we repeated the same measurement 29 times in a row. The results were very good and are discussed in this section.

GP Vertical Profile

Over 29 measurements, taken under the same conditions, using the same TX, the same time slot of +/- 45 minutes, the same drone, the same receiver, the same antenna, in the same measurement direction, were used to assess and quantify the reproducibility of the measurements and the flight trajectories. The measured standard deviations [σ] for 15 UP measurements (in the ascending direction) and 14 DOWN measurements (in the descending direction) are as follows:

- maximum 1 µA for the GP angle parameter (0.005°)
- maximum 0.5 µA for the ¼ sector widths 90Hz and 150Hz parameters

When comparing these results to the given tolerances by ICAO Annex 10 [2], we get:

- a maximum of 3% of the given ICAO tolerance for the Axis parameter
- a maximum of 2% to 4% of the given ICAO tolerance for the ¼ sector widths 90Hz and 150Hz parameters

These standard deviations of 1 µA and 0.5 µA, respectively, not only demonstrate but also quantify the excellent reproducibility we were able to achieve with the drone measurement system. They document a smaller and therefore better integrated performance than the certified receiver accuracy, which is +/- 1 µA. Additionally, we would like to point out, that these very small fractions of 2% to 4% of the ICAO tolerance, also further demonstrate the excellent measurement reproducibility that was achieved with this system. The key factor to achieve such excellent results is the very good flight path reproducibility, which for this data set was found to me accurate to a maximum of a mere +/- 22 cm in the horizontal plane.

UP measurements	ICAO-Limit		σ	uA	σ	%
Axis	25.0	uA	0.8	uA	3	%
1/4 sector width 150 Hz	11.3	uA	0.5	uA	4	%
1/4 sector width 90 Hz	11.3	uA	0.3	uA	2	%

Table 5: Reproducibility of GP Vertical Profile UP Measurements (15 identical measurements within 45 min)

The next figure shows a screenshot of the pre-flight checker software which is used to analyze the data coming from the drone in real time. It shows the flight profile of the above discussed UP flights, as well as the measurement results of all 15 flights superimposed. The results are so good that the graphs are barely distinguishable from each other.

Figure 20: Pre-flight checker software screenshot for fifteen UP measurements

GP Mini Approach

For the glide path axis measurements during mini approaches, a similar reproducibility check as done for the glide path vertical profile, was conducted. Again, the reproducibility across 14 measurements under the same conditions, using the same TX, during same time slot of +/- 15 minutes, using the same drone, the same receiver, the same antenna, and in same measurement direction, and using the same the flight trajectories, was assessed and quantified. The measured standard deviations σ across 7 FROM mini-approaches (opposite to the landing direction, FROM the runway) and 7 TO mini-approaches (in the landing direction, TO the runway) were found to give the following results:

- A maximum of **0.4 µA** for the axis parameter (**0.002°**). Which represents:
- A maximum of **2%** of the given ICAO tolerance for the axis parameter

This standard deviation of 0.4 µA demonstrates the excellent reproducibility of the drone measurement system. It is, for the integration across these results, in fact twice as good as the certified guaranteed receiver accuracy of +/- 1 µA. We would like to argue that the extremely small fraction of only 2% of the relevant ICAO tolerance further illustrates the excellent measurement reproducibility in a quantifiable manner. As discussed previously, the key factor to produce such good results is the excellent reproducibility of the flight path, with a maximum of +/- 50 cm in a horizontal plane and +/- 70 cm in a vertical plane.

FROM measurements	ICAO-Limit		σ	µA	σ	%
Axis	25.0	µA	0.4	µA	2	%

§Table 6: Reproducibility of seven FROM mini-approaches (opposite to the landing direction)

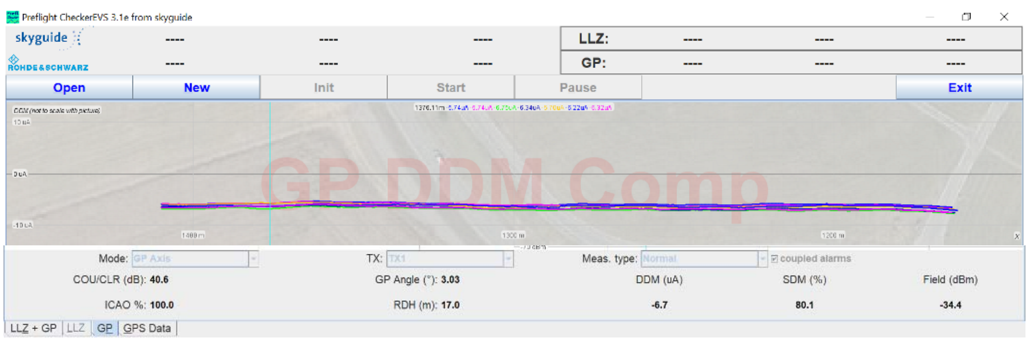

Figure 21: Pre-flight checker screenshot for seven FROM mini-approaches (opposite to the landing direction)

Localizer ground checks: repeatability and Localizer stability

LOCALIZER Course Structure

The next figures below illustrate all LOC Course Structure measurements (24 measurements) conducted with the ground vehicle over two years for the LSZH16 Localizer, in both normal and alarm conditions.

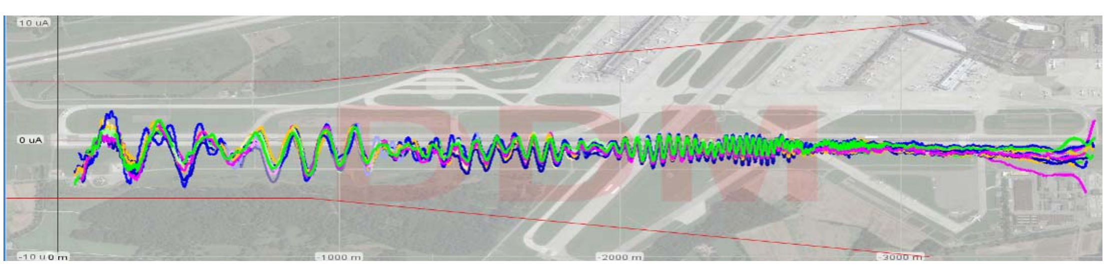

Figure 21: LSZH 16 LOC Course Structures over two years (24 measurements in normal conditions)

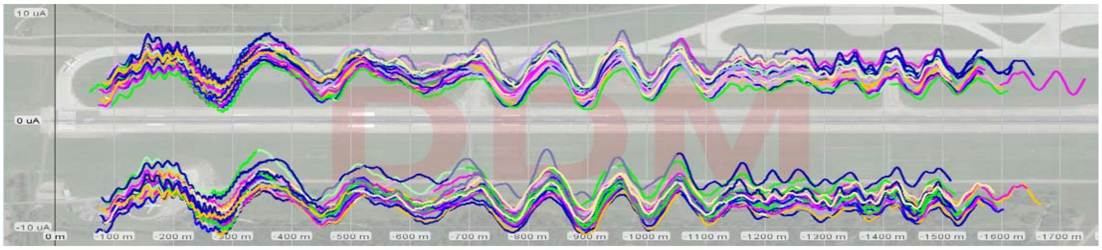

Figure 22: LSZH 16 LOC Course Structures over two years (24 measurements in alarm conditions)

LOCALIZER Linearity Coverage

As for the LOCALIZER Course Structure, the next figures below illustrate all LOC Linearity Coverage measurements conducted with the ground vehicle over two years for the LSZH16 localizer, in both normal and alarm conditions.

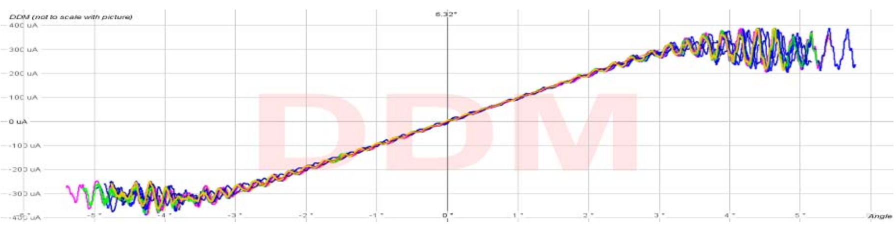

Figure 23: LSZH 16 LOC Linearity Coverage over two years (24 measurements in normal conditions)

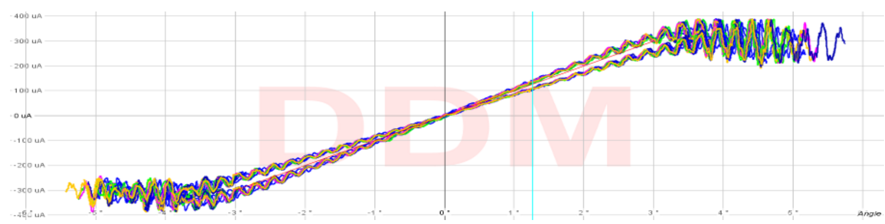

Figure 24: LSZH 16 LOC Linearity Coverage over two years (24 measurements in alarm conditions)

LOCALIZER Coverage

The next figure below illustrates all LOC Coverage measurements conducted with the ground vehicle over two years for LSZH16 Localizer, in normal conditions.

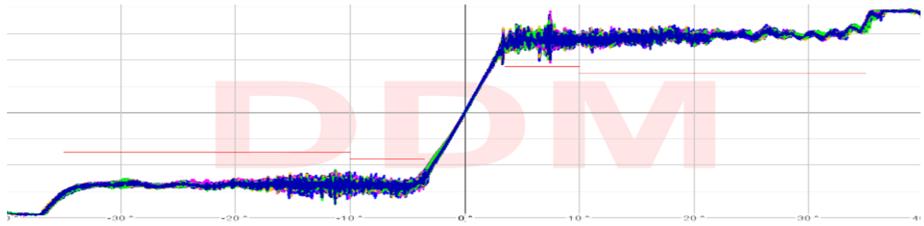

Figure 25: LSZH 16 LOC Coverage over two years (24 measurements in normal conditions)

For each measurement modes (course structure, linearity coverage and coverage), as all 24 curves are well superimposed, this is proofing both, the good stability of the equipment as well as the excellent repeatability of the measurements. Such data collection and analysis increase our trust in our Localizers and LOC ground check methods. Consequently, any small drift can be detected with a high level of confidence.

<u>Drone check: repeatability and ILS stability</u>

Glide Path Vertical Profile

The next figures illustrate the plots of all GP Vertical Profile measurements conducted with the drone in over two years for the LSZH16 GP, in normal and alarm conditions (90Hz and 150Hz dominant + narrow and wide).

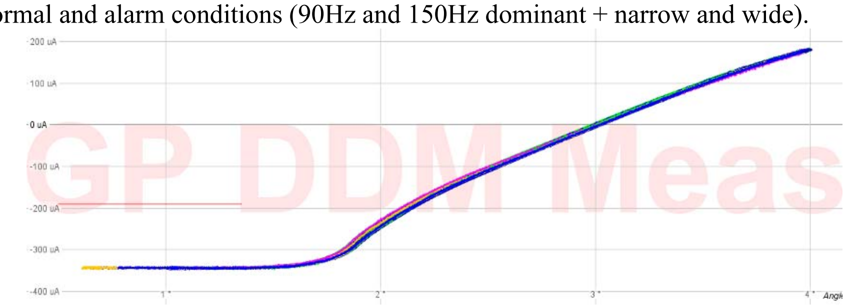

Figure 26: LSZH 16 GP Vertical Profiles over two years (24 measurements in normal conditions)

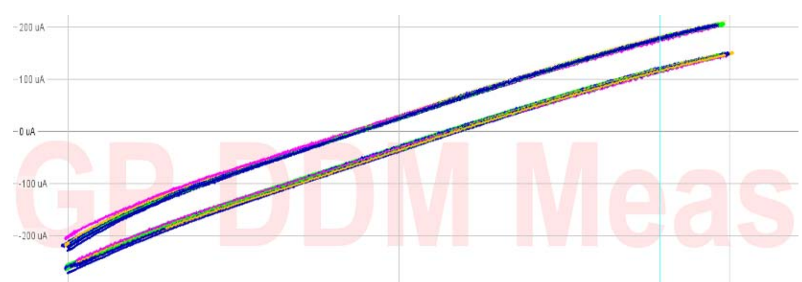

Figure 27: LSZH 16 GP Vertical Profiles over two years (24 measurements in alarm conditions 90Hz and 150Hz)

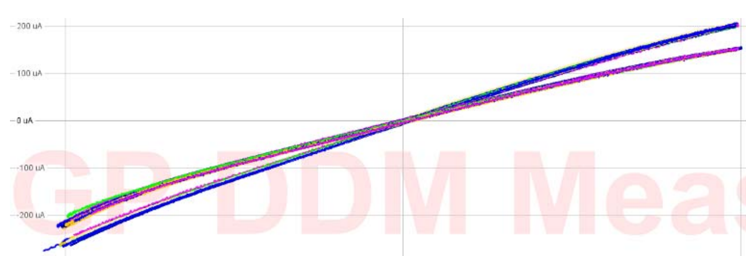

Figure 28: LSZH 16 GP Vertical Profiles over two years (24 measurements in alarm conditions narrow and wide)

Localizer and Glide Path Mini Approach

The four next figures illustrate all mini approach measurements conducted with the drone over two years for the LSZH16 ILS (LOC and GP), in normal and alarm conditions (90Hz and 150Hz dominant, left and right, high and low angles).

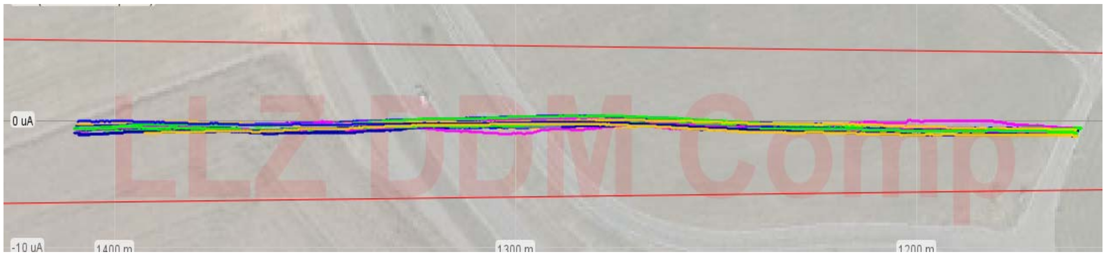

Figure 29: LSZH 16 LOC Mini Approaches over two years (24 measurements in normal conditions)

Figure 30: LSZH 16 LOC Mini Approaches over two years (24 measurements in alarm conditions 90Hz and 150Hz)

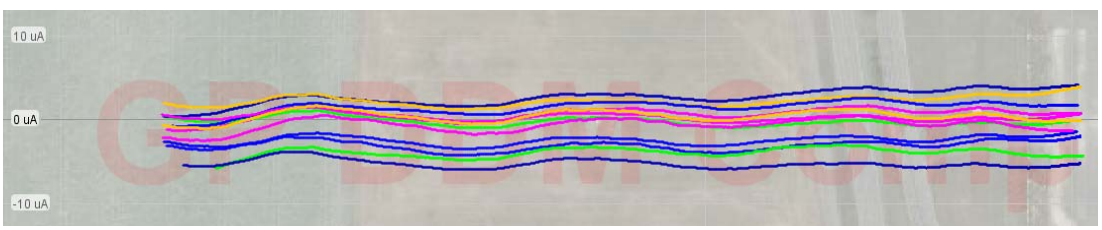

Figure 31: LSZH 16 GP Mini Approaches over two years (24 measurements in normal conditions)

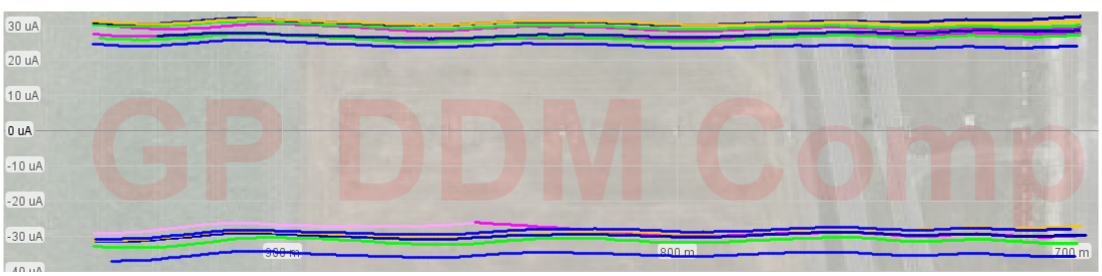

Figure 32: LSZH 16 GP Mini Approaches over two years (24 measurements in alarm conditions 90Hz and 150Hz)

As illustrated for each measurement modes (in normal and alarm conditions), all 24 curves are well superimposed. This as a clear demonstration of both the good stability of the equipment, as well as the excellent repeatability of the measurement system. Consequently, any small drift in any of the measured parameters would be detected with a high level of confidence. Another benefit is, that with such an accurate measurement system, we are able to document and understand seasonal effects on the ILS. This is especially true for the influence of environmental effects on the GP angle, as shown in figure 31," LSZH 16 GP Mini Approaches over two years (24 measurements in normal conditions)".

Correlation

As mentioned previously in the introduction, according to ICAO DOC 8071 [1], the **correlation** between ground, drone and flights checks and between monitor and flight checks, are key to demonstrate equipment integrity, which could be used to argue for a change of the flight check periodicity and program.

Averages

Table 7 summarizes the **averages** of the **subtraction** between:

- flight check and monitor data (third column FCS – MON),
- flight and ground + drone checks for LOC, flight and drone check for GP (fourth column FCS – DRO) for:
- normal conditions (left table NORMAL),
- and alarm conditions (right table ALARM).

The figures in the third and fourth column do not represent as absolute correlation in µA as how it was presented in the results in chapter 7. To show how much margin there is with regards to the threshold defined by ICOA, we present them as relative values (in %) compared to their respective ICAO limit, calculated as shown in Equation 1.

$$\textit{relative value in \%} = \frac{\text{absolute correlation in } \mu A \times 100}{\textit{ICAO limit in uA}}$$

Equation 1: relative value

This ratio is a good indicator of the degree of correlation compared to the ICAO limit. It enables us to assess and quantify the quality of the measurement system (ground, drone and monitor).

Finally, the last row (AVG-ALL) of the tables presents the "average all", which is the average for all averages, across all measured ILS, over more than two years of data collection:

- AVG-ALL NORMAL is the "average all" for all measurements in normal conditions
- AVG-ALL ALARM is the "average all" for all measurements in alarm conditions

AVG	NORMAL	FCS-MON	FCS-DRO
LSZH14	LOC	6%	7%
LSZH14	GP	8%	21%
LSZH16	LOC	13%	11%
LSZH16	GP	9%	12%
LSZH28	LOC	9%	6%
LSZH28	GP	9%	14%
LSZH34	LOC	8%	3%
LSZH34	GP	3%	6%
LSGG04	LOC	4%	11%
LSGG04	GP	5%	5%
LSGG22	LOC	4%	17%
LSGG22	GP	8%	25%
LSZB14	LOC	4%	6%
LSZB14	GP	6%	10%
AVG-ALL	NORMAL	7%	10%

AVG	ALARM	FCS-MON	FCS-DRO
LSZH14	LOC	2%	3%
LSZH14	GP	1%	2%
LSZH16	LOC	4%	2%
LSZH16	GP	2%	3%
LSZH28	LOC	3%	3%
LSZH28	GP	8%	8%
LSZH34	LOC	3%	3%
LSZH34	GP	4%	3%
LSGG04	LOC	3%	4%
LSGG04	GP	2%	3%
LSGG22	LOC	4%	4%
LSGG22	GP	2%	2%
LSZB14	LOC	5%	5%
LSZB14	GP	1%	3%
AVG-ALL	ALARM	3%	3%

Table 7: "average all" across all the averaged results from all ILS (more than two years of data collection)

In normal conditions, the "averages all" of the monitor and drone correlations are 7% and 10% respectively of the ICAO limits. These low values are a very good result and quantify the very high level of correlation between the different measurement methods in normal conditions.

In alarm conditions, the "averages all" of the monitor and drone correlations are even better, on average only 3% of the relevant ICAO limits. Again, these excellent results quantify the excellent level of correlations also for measurements in alarm conditions.

Increased level of confidence

In order to increase the level of confidence in our results, we computed another indicator: average + 2 σ. According to statistics and the Empirical Rule, which is based on a normal distribution, 95.5% of the data falls within two standard deviations of the mean (or between the mean – 2 times the standard deviation, and the mean + 2 times the standard deviation). The mathematical notation for this is: $\mu \pm 2\sigma$ [7]. This is illustrated below by Figure 33.

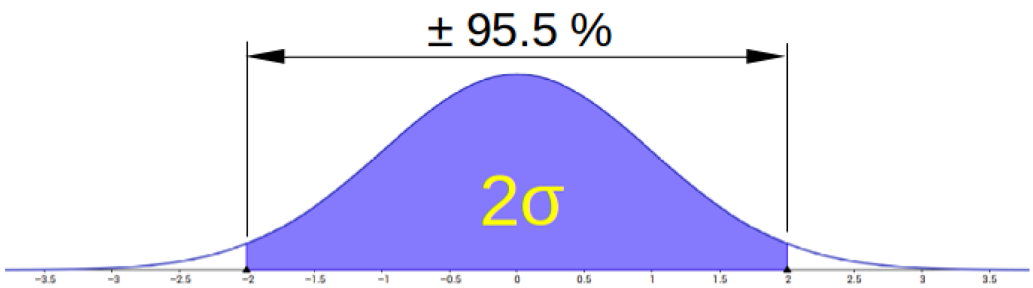

Figure 33: the 95.5 % and 2 σ normal distribution rule

AVG+ 2σ	NORMAL	FCS-MON	FCS-DRO
LSZH14	LOC	36%	22%
LSZH14	GP	17%	31%
LSZH16	LOC	33%	25%
LSZH16	GP	20%	27%
LSZH28	LOC	16%	16%
LSZH28	GP	13%	25%
LSZH34	LOC	15%	9%
LSZH34	GP	11%	18%
LSGG04	LOC	24%	31%
LSGG04	GP	14%	21%
LSGG22	LOC	26%	42%
LSGG22	GP	21%	48%
LSZB14	LOC	11%	13%
AVG+ 2σ-ALL	NORMAL	21%	24%

AVG+ 2σ	ALARM	FCS-MON	FCS-DRO
LSZH14	LOC	8%	9%
LSZH14	GP	2%	6%
LSZH16	LOC	12%	10%
LSZH16	GP	3%	6%
LSZH28	LOC	7%	11%
LSZH28	GP	10%	12%
LSZH34	LOC	9%	9%
LSZH34	GP	7%	8%
LSGG04	LOC	10%	15%
LSGG04	GP	8%	9%
LSGG22	LOC	11%	15%
LSGG22	GP	5%	4%
LSZB14	LOC	9%	13%
AVG+ 2σ-ALL	ALARM	8%	10%

Table 0: average + 2 σ for all measured ILS all ILS from more than two years of data collection

In normal conditions, 95% of all correlation indicators are within 21% and 24% of the ICAO limits for the correlation between flight checks and monitor measurements and between flight checks and drone measurements, respectively. These results further strengthen the evidence that we can demonstrate an excellent correlation between measurement results from the drone and the monitor, when compared to the flight checks.

The same conclusion can be drawn for the statistics of the measurements in alarm conditions. At least 95% of all results fall within only 8% and 10% of the ICAO limits for the correlation between flight checks and monitor measurements and between flight checks and drone measurements, respectively. Once more, these results prove that we can demonstrate an excellent correlation between measurement results from the drone and the monitor, when compared to the flight checks. It is actually 2.5 times better than the results achieved in normal conditions. This is due in fact that measurements taken on an ILS in alarm condition are always in relation to the value for the normal condition of the same measurement.

To summarize, when correlating monitor and drone measurements with flight check measurements, in more than 95% of all cases, we still have on average a **margin of approximately:**

- **75% to the relevant ICAO limit for measurements in normal conditions,**
- **90% to the relevant ICAO limit for measurements in alarm conditions.**

<u>Seasonal and environmental effects</u>

Experience and field measurements show, that ILS in general, but in particular Glide Path systems, are influenced by external environmental conditions, such as:

- Temperature: change in phase and attenuation of RF cables
- Humidity of the terrain, especially for Glide Path, as it uses the ground as a reflector for beam forming
- The height of the grass, or the depth of possible snow in front of the Glide Path antenna

<u>The blindness of integral monitor to external conditions</u>

Integral monitor measurements, which are based on internal antenna probes, are not able to detect any possible change of external environmental conditions. They are dedicated to characterize the signal emission at the antenna output level, but they can be considered as blind to external factors. This is the reason why flight, ground and drone checks are required to detect seasonal and environmental effects.

Figures 34 and 35 for LSZH GP 16, figure 36 for LSZH 28 GP and figure 37 for LSGG GP 04 below illustrate the seasonal changes in the GP angle. These changes are well detected by drone and flight measurements, whereas the integral monitor (orange curve) remains constant and does see any influence.

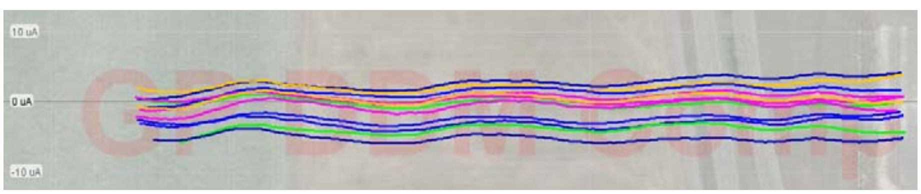

Figure 34: LSZH 16 GP Drone Mini Approaches over two years (normal conditions)

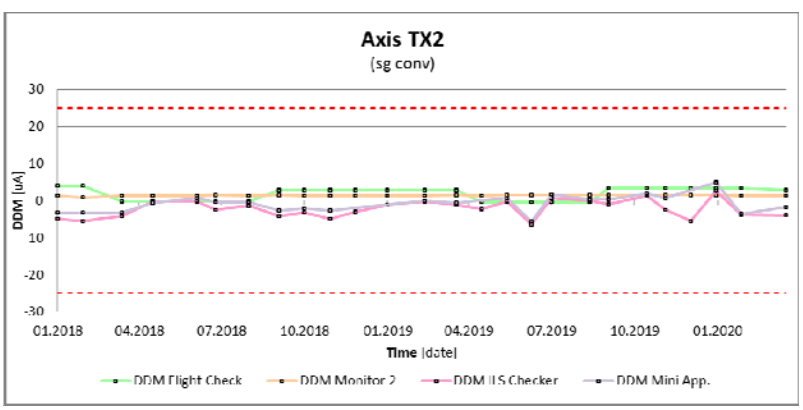

Figure 35: LSZH 16 GP Axis results for monitor, flight and drone checks

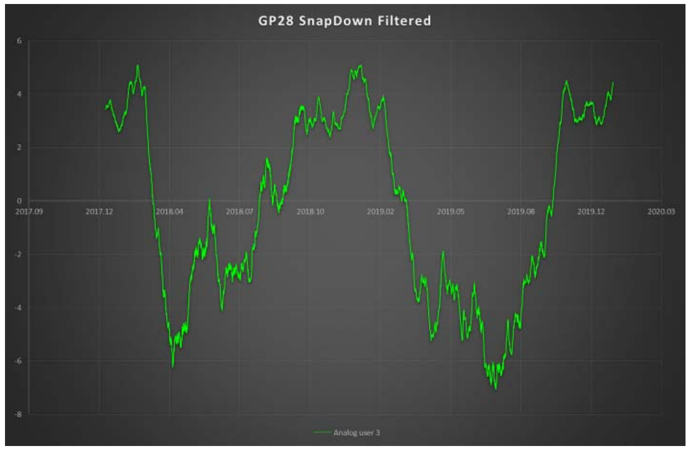

Figure 36: Seasonal effects on LSZH 28 GP Axis

<u>The drone ability to detect environmental effects</u>

As illustrated by Figure 37 below, drone checks are able to detect very accurately the seasonal and environmental effects (pink and grey curves, "DDM ILS Checker" and "DDM Mini App"), thanks to their high accuracy and reproducibility, but also thanks to their short periodicity. Indeed, their nominal periodicity is one month for CAT III (or every second month in case of bad weather conditions or limited internal resources), and three months for CAT I systems.

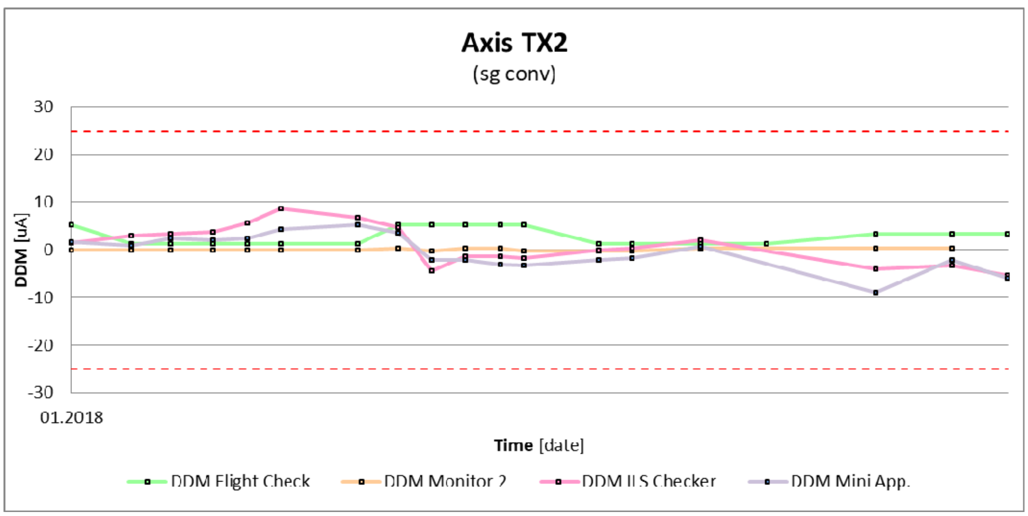

Figure 37: LSGG 04 GP Axis results for monitor, flight and drone checks

As the current flight check periodicity is currently 6 months, normally conducted during spring and fall, the flight checks of ILS are not able to detect some of the more severe seasonal influences, such as snow, or very wet or dry ground conditions. Thus, the drone checks offer further advantages over flight checks in respect to the quality of the measurements in terms of accuracy and reproducibility as well as the higher periodicity of the measurements, which are currently monthly for CAT III and quarterly for CAT I systems.

VOR DRONE CHECK

As the R&S®EVSF1000 VHF/UHF Nav/Flight Analyzer can also measure VOR signals at a high sampling rate of 30 Hz, the CNS Drone is also capable to conduct VOR measurements in the air at a larger distance than its nearfield monitor antennas. Skyguide has then decided to develop and deploy a complementary software for VOR measurements: the VOR Checker software.

Figure 38: The CNS Drone Conducting a Drone Check

The VOR Checker Software

It is possible to conduct two different measurement modes:

- Orbit: a circular flight with a typical radius of 200 m (even 300 m or more, if possible). The measured and displayed parameters are the following ones: azimuth error in degrees, the AM 30Hz and 9960Hz modulation depths in %, the 9960 Hz frequency in Hz, the FM deviation in Hz and the RF Level in dBm

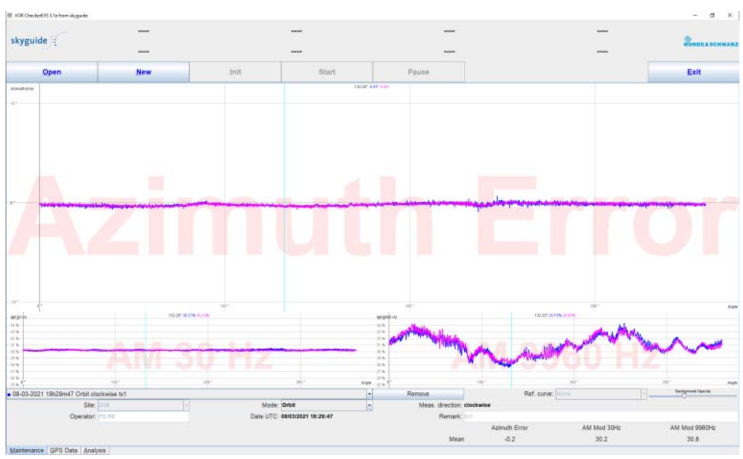

Figure 39: The Orbit Mode of the VOR Checker (azimuth error, AM 30Hz and 9960Hz modulation depths)

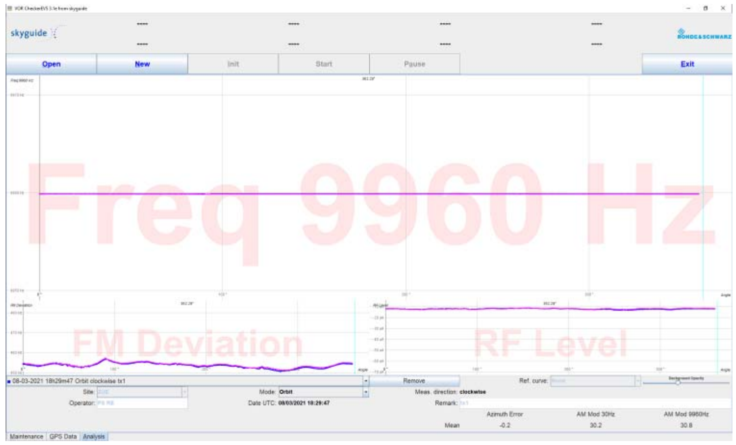

Figure 40: The Orbit Mode of the VOR Checker (9960 Hz frequency, FM deviation and RF Level)

- Radial: a converging (TO) or diverging (FROM) flight along a straight line radial, with a typical distance of 250 m (even 300 m or more, if possible) from the VOR center

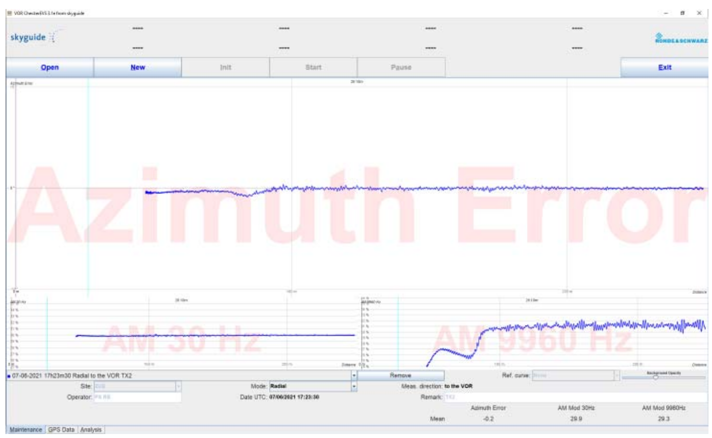

Figure 41: The Radial Mode of the VOR Checker (azimuth error, AM 30Hz and 9960Hz modulation depths)

Repeatability and Sensitive Area Tests

As the Preflight Checker for ILS measurements, the VOR Checker also demonstrates a high degree of repeatability, as illustrated below by Figures 42 for a CVOR and 43 for a DVOR.

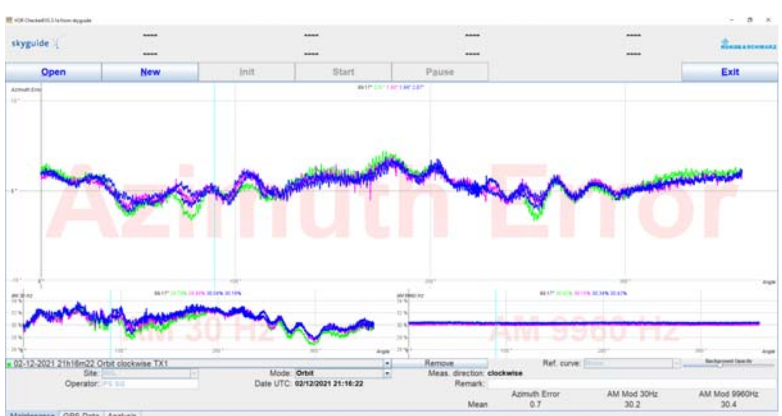

Figure 42: CVOR: Illustration of the Repeatability during Preventive Maintenance (4 orbits every 6 months)

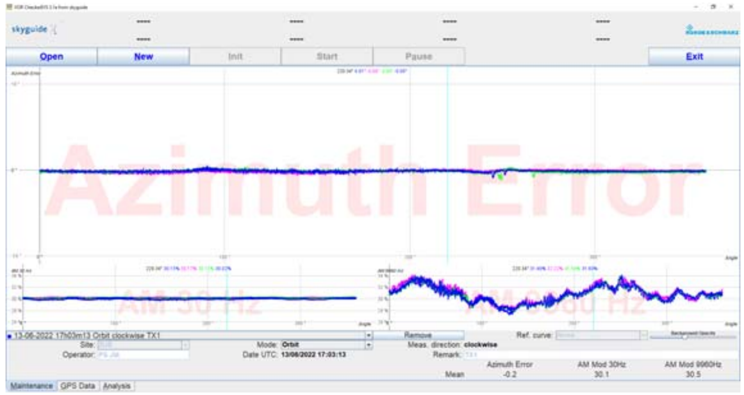

Figure 43: DVOR: Illustration of the Repeatability during Preventive Maintenance (4 orbits every 6 months)

It has also been possible to demonstrate and document the influence of external reflectors in the surroundings of the VOR and thus conduct sensitive area tests. These special tests have also been used to valid the correlation with our simulation tool.

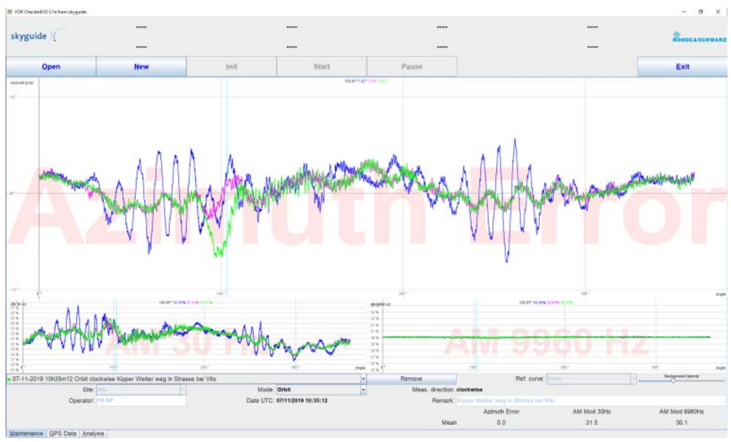

Figure 44: Influence of an External Reflector (different positions)

<u>Preventive and Corrective Maintenances</u>

Not only for preventive maintenance (with a typical periodicity of 6 months), such VOR Checker measurements can also be used for corrective actions purposes. As illustrated below, in the frame of a CVOR antenna replacement in 2021, skyguide has already prepared and pre-tuned the system thanks to VOR Checker measurements. The achieved goal was to reduce and simplify the re-commissioning flight check. Figure 44 below illustrates this pre-tuning action: from an initial raw situation in blue to a final situation "ready for flight check" in pink (with an azimuth error of 0.1°, confirmed by flight check)

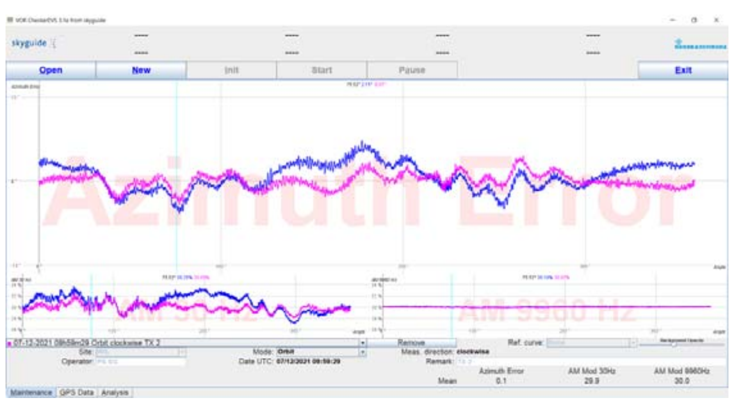

Figure 45: Flight Check Preparation (initial situation in blue, final situation "ready for flight check" in pink)

FROM TECHNICAL PEFORMANCES TO OPERATIONAL, ENVIRONMENTAL AND FINANCIAL BENEFITS: ILS FLIGHT CHECK REDUCTION

Figure 46: LSGG 04 LOC flight check

Over the last four years, the NAV services of skyguide collected data with ground as well as drone-based ILS measurements. It can be clearly concluded that this data collection and analysis demonstrate the ability to produce repeatable and quantifiable results, which not only correlate very well with the results from the flight checks, but also stay well within the tolerances set by ICAO. It has also been demonstrated that ground and drone checks are able to detect environmental effects and that, overall, they are as reliable as the results from flight checks. As proposed by ICAO Document 8071 and as the criteria mentioned in sections 1.15.8 and 1.15.9 are fulfilled, the Swiss regulators (civilian FOCA and military MAA) agreed to reduce the ILS flight check program. The principles of this reduction are the following ones:

- The general periodicity of flight checks remains 6 months: especially for strict environmental safeguarding reasons (to keep a good control of any external change in the environment: influence of possible new buildings, cranes, tree growth, wind turbines …)
- For LSGG, LSZH and LSZB (drone checked since 2018 and demonstrated correlations for four years): a very reduced flight check during the second slot 2 in Fall (only 3 measurements: one LOC and GP course structure, one LOC short orbit, one GP level run)
- As the good harmonization between both TXs has been demonstrated, it has been decided and agreed to measure only one TX per measurement slot. (uneven year: TX1, even year: TX2)
- As an excellent correlation in alarm conditions (also for monitor) has been demonstrated, it has been decided and agreed to measure the alarm parameters every other flight check

Airports	Justification	Measure	Details
LSGG, LSZH and LSZB	Drone / flight correlation	Very reduced program during slot 2	Only 3 measurements during slot 2: LOC+GP course structure, LOC 7NM orbit GP level run
All airports	Good harmonization TX1 / TX2	Only one TX will be measured	TX2 in 2022, 2024 ... TX1 in 2023, 2025 ...
All airports	Excellent monitor correlation for alarm parameters	Alarm parameters every other flight check	Alarms periodicity: - 2 years for LSGG, LSZH and LSZB (slot 1 2023, 2025, 2027 ...) - 1 year for all other airports (slot 1 every year)

Table 9: The Principles of the ILS Flight Check Reduction

OUTLOOK AND CONCLUSION

After more than four years of successful operation and the subsequent ILS flight check reduction, the use of the UAV multicopter already represents a major step in the domain of the ILS maintenance. However, its current concept of operation and measurement is not frozen and is still evolving with new ideas and future developments (increase of the range, autonomous flights, new features …). This first concrete step opens new horizons in term of CNS measurement techniques.

ACKNOWLEDGMENTS

I would like to express my special thanks to Pascal Schmid and Christoph Brem for their work and efforts done in the frame of the analysis of the ILS maintenance data and the redaction of the report "Drones for ILS Measurements. Proposal to Reduce Check Flights" (Reference [6]). I am also thankful to the NAV maintenance teams of skyguide, who contributed to the deployment of the CNS Drone and to the collection of the excellent maintenance data since 2018.

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