UAS-based NAVAID flight and ground inspection

Claus-S. Wilkens

Project Manager
Aerodata AG
Braunschweig, Germany
Phone: +49 531 2359-140
E-mail: wilkens@aerodata.de

Dr. Mirko Stanisak

System Engineer & Project Manager
Aerodata AG
Braunschweig, Germany
Phone: +49 531 2359-304
E-mail: stanisak@aerodata.de

Klaus Theißen

Director Economy Analyzer & Avionic Test
Rohde & Schwarz GmbH & Co. KG
Meckenheim, Germany
Phone: +49 2225 9997340
E-mail: klaus.theissen@rohde-schwarz.com

ABSTRACT

In recent years, small uncrewed aircraft systems (UAS) have become a valuable tool in flight and ground inspection of aviation navigation aids (NAVAIDs). The capabilities of these drones range from the calibration of radio NAVAIDs like ILS localizer and glide path transmitters, VOR, DME, or GBAS installations, to optical landing aids like VASI, PAPI, or runway lighting. This paper focusses on the inspection of radio navigation aids.

The institutions represented by the authors have developed a UAS-based system for flight and ground inspection of NAVAIDs. While the UAS-platform itself is commercially available off-the-shelf, the NAVAID inspection payload (receiver, antenna, ...), its software and some modifications to the UAS are based on the institutions' experience in the field of crewed aircraft-based measurement, calibration systems, and receiver technology.

This paper presents the UAS-based solution for complementing flight and ground inspection, with an emphasis on the VHF/UHF measurement system and the inspection software. Experience from the operation of the highly automated UAS at airports is shared. The commonality with crewed flight inspection is paramount to UAS-based measurements. For this reason, the proposed paper presents UAS-based results, and compares these to results from conventional, crewed flight inspection.

INTRODUCTION

A key factor in aviation safety is the reliable and accurate operation of navigation aids (NAVAIDs). Their safe operation needs to be guaranteed by a regular inspection and calibration in order to fulfil international standards and recommended practices (SARPs) of the International Civil Aviation Organization (ICAO) and national regulations. As clearly described in [1], ICAO Annex 10 [2] and the ICAO Doc 8071 [3] allow for the utilization of uncrewed/unmanned aircraft sytems (UAS) for flight and ground inspection of such ground-based navigation aids for aviation.

Small UAS close the gap between ground and flight inspection (FI). For ground inspection of NAVAIDs, small drones can utilize the same receiver technology already in use for these kinds of checks. Instead of being operated from the ground, vehicles, or high masts, the inspection receiver and its antenna can be directly positioned precisely at the location of choice for taking optimal measurements. In this way, all measurement locations necessary for NAVAID ground inspection and additional locations can be reached flexibly and conveniently.

Small UAS with take-off masses of less than 25 kg are no substitute for flight inspection with crewed aircraft. Flight inspection and procedure validation have to be oriented towards the human pilots and their use of NAVAIDs and procedures. Thus, a human pilot has to be in the loop. Furthermore, the endurance and measurement capabilities of small UAS are limited compared to crewed flight inspection aircraft and associated FI procedures due to their size and achievable payload, as described in [3]. Instead, specially equipped, small UAS can be a valuable supplement to conventional, crewed flight inspection.

The main benefit of using small UAS in order to support flight inspection is the reduction of crewed flight time. In this way, the noise and exhaust emissions, and expanses are minimized. Additionally, the flight crew spends less time exposed in the vicinity of the airport at low altitudes. The crewed flight time for calibration works is reduced by pre- or interim checks with small drones. As described in [1], frequent checks with drones at airports can ensure the correct operation of the NAVAID at certain intervals. In this way, the intervals for conventional, crewed flight inspections can be extended, so that in total fewer crewed calibration flights are necessary.

During commissioning or regular flight inspection missions, the drone can be used to gather measurements prior to crewed flights. In this way, the NAVAID can be adjusted if necessary based on the drone measurements. The subsequent crewed inspection then just has to ensure that the NAVAID operates within tolerance. In this way, crewed flights are not required for calibration work, and can focus on the check of the pre-calibrated NAVAID, thus reducing crewed flight hours. The application of the UAS-based pre-calibration of NAVAIDs is most useful during the commissioning of newly installed navigation aids, or if some environmental constraints change.

This paper introduces a small UAS complementing ground and flight inspection, describes its set-up, and shows results from measurement campaigns – especially in comparison to crewed flight inspection results. General considerations on using small drones for flight inspection missions are presented in [4]. Technical challenges like the propeller modulation and its effects on the measurements are described in [5].

AEROFIS® FLYBOT

The flight inspection system (FIS) manufacturer Aerodata has developed a small, uncrewed aircraft system for the (pre-) calibration of ground based aviation navigation aids. This small UAS is called AeroFIS® Flybot and capable of calibrating a multitude of radio and optical navigation aids. For the inspection of most radio NAVAIDs, Rohde & Schwarz has developed the EVSD1000 VHF/UHF nav/drone analyzer, which is tightly integrated into the AeroFIS® Flybot architecture. This paper focusses on the AeroFIS® Flybot with EVSD1000 payload, its operation, and the resulting measurement performance.

AeroFIS® Flybot Architecture

The general system architecture of the AeroFIS® Flybot is depicted in Figure 1. The complete system consists of the UAS remote control, the FIS operator laptop computer, the DGNSS/RTK ground station, the drone platform, and the task specific FIS payload. This modular payload covers two main tasks.

- The FI Core functionality includes recording, on-board processing, and transmission of flight/ground inspection measurements from the FI Sensor module.
- The FIS Sensor modules are easily interchangeable and provide the sensor specific to the measurement task. It can consist of radio NAVAID receivers and antennas like the R&S® EVSD1000 V/UHF Nav/Drone Analyzer, or optical sensors for the inspection of VGSI installations or infrastructure.

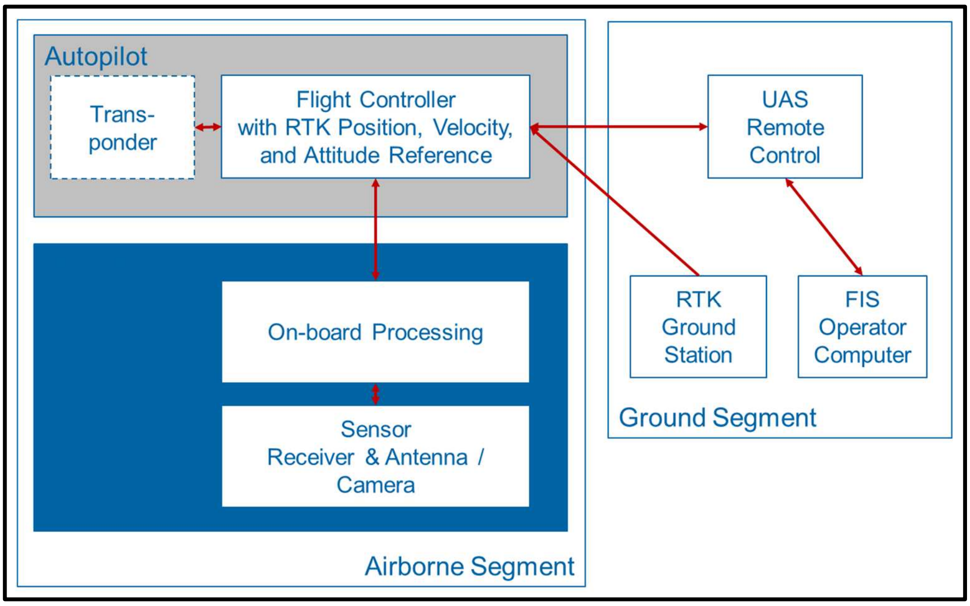

Figure 1. AeroFIS® Flybot architecture.

Figure 2 shows the AeroFIS® Flybot with EVSD1000 payload in flight and the UAS remote control running Aerodata's AeroFIS® Flybot Remote Control software. The FI payload and FIS operator computer are highly integrated with the professional UAS platform.

The drone's multi-constellation GNSS RTK-aided position, velocity, and attitude solution allows for a high accuracy FIS position reference. The FIS payload can use the drone's telemetry system to communicate with the remote control and the FIS operator laptop. In this way, the AeroFIS® software running on the FIS operator laptop provides the prepared flight procedures and tuning of the receiver to the drone pilot's remote control. The remote control runs the specialized AeroFIS® Flybot Remote Control software for the control and supervision of the inspection and calibration tasks.

Figure 2. Left: flight of the AeroFIS®® Flybot with ILS flight inspection payload R&S EVSD1000
Right: AeroFIS® Flybot Remote Control software running on the UAS remote control

The remote control software acts as a bridge between the UAS and the AeroFIS® software in order to ensure that the AeroFIS® software provides the same user experience to the FIS operator, as on board a conventional FI aircraft. In addition, the task distribution between the pilot and the FIS operator is identical compared to a crewed flight inspection operation. In this way, the FIS® operator can easily switch between crewed and uncrewed operation while benefiting from the well-established AeroFIS® user interface and flight inspection algorithms on both platforms. The results are also directly comparable in this way.

R&S®EVSD1000 VHF/UHF Nav/Drone Analyzer

Civil aviation requires accurate and reliable navigation receivers for optimizing air traffic control (ATC) and ensuring the essential public safety. Rohde & Schwarz is known for bringing future aviation technologies to the market, such as the CERTIUM program [6], which provides ATC infrastructure operators with all the equipment they need for their communications networks, including radios, direction finders, voice communications systems, network components and software. Those systems require unique test and measurement capabilities.

With the R&S®EVSG1000 and the R&S®EVSF1000, Rohde & Schwarz has two NAVAID receivers in the market that are mainly used for ground inspection and flight inspection. With the huge improvements on copters concerning payload versus flight time, more and more interest in measuring NAVAID signals with copters was registered.

Thus, Rohde & Schwarz developed a receiver for which size, weight and flexibility are optimized for copter measurements without reducing the outstanding performance of the existing Rohde & Schwarz ILS/VOR receivers. The outcome is the R&S®EVSD1000 VHF/UHF NAV/DRONE ANALYZER - a signal level and modulation analyzer suitable for medium sized drones with a compact / robust design and a weight of less than 1.5 kg [7]. The EVSD1000 is depicted in Figure 3.

Figure 3. R&S®EVSD1000 side view with connectors for the VHF/UHF antenna, the data link antenna, the GNSS and the two blue compartments for accessories like battery (R&S®EVSD1-Z1) and data link module (R&S®EVSD1-Z5)

The R&S®EVSD1000 offers high performance analysis capabilities on NAVAID signals like ILS, GBAS, VOR, MB and VHF COM, and fully complies with all ICAO requirements. Its high dynamic range and low noise floor allow measurements even in challenging situations and at low signal levels. The R&S®EVSD1000 has a very low noise figure and narrowband filters for outstanding receiver sensitivity. The analyzer performs high-precision signal analysis even with low signal levels. Its wide dynamic range and steep-edged preselection filters can reliably suppress potential interference sources, such as FM transmitters and radiotelephony signals. The R&S®EVSD1000 features high intermodulation suppression and interference resistance for reliable measurements even when near transmitting antennas [8].

One hundred recordings a second make R&S®EVSD1000 drone-based measurements accurate, reliable and highly reproducible. As shown in Figure 4, Rohde & Schwarz offers optional accessories like the GNSS module (R&S®EVSD1-Z6) and the GNSS antenna (R&S®EVSD1-Z7) for recording precise time and location stamps along with the gapless measurements.

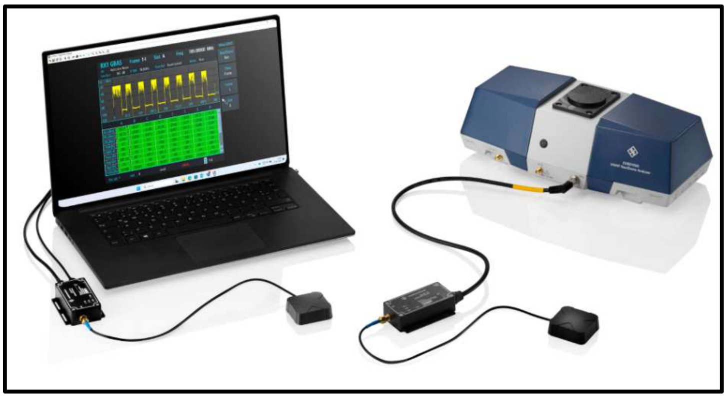

Figure 4. R&S®EVSD1000 with base and rover GNSS RTK device (R&S®EVSD1-Z6) and GNSS antenna (R&S®EVSD1-Z7)

All results are stored in the device, but can also be streamed to a different storage location via data link (R&S®EVSD1-Z5), ensuring that no data is lost and providing seamless real-time measurements and easy documentation of results.

The lightweight R&S®EVSD1000 can be attached to almost any mid-sized drone with a quick-release clamp – no tools required. The R&S®EVSD1000 is deeply integrated into Aerodata's AeroFIS® Flybot, both on the hardware and the functionality side. By also using Rohde & Schwarz's lightweight ILS/VOR antenna R&S®EVSD1-Z3 of just 150 g (see Figure 5), the Flybot benefits from the quick-release clamps of the antenna and the receiver for quick (de-) installations, their low overall weights, and the outstanding measurement performance.

Figure 5. Diverse accessories like the ILS/VOR antenna (R&S®EVSD1-Z3) are available and can be stored in the transport case (R&S®EVSD1-Z9)

AeroFIS® Flybot Operation

Two persons – a remote pilot and a FIS operator – usually operate the AeroFIS® Flybot. Similar to crewed flights, the remote pilot communicates with ATC, and controls and monitors the drone in flight. The FIS operator utilizes the AeroFIS® software of the FIS operator laptop for the set-up of the drone flight profiles and the recording, supervision, and interpretation of the measurements. The flight inspection measurements and parameters are visualized in near real-time at the FIS operator laptop.

The planed flight inspection procedures are directly transmitted into the AeroFIS® Flybot Remote Control software, which runs on the drone pilot's remote control. This software enables the pilot to get information on the planned procedures and their depiction in a map. In addition, the drone's flight controller can automatically follow these procedures precisely. The remote pilot can activate the automatic flight of these procedures by pressing a button, and can conveniently monitor the state of the UAS and the FIS components from the remote control. For this, the AeroFIS® Flybot Remote Control software provides a map showing the drone position and the selected flight procedure, and a first person camera view of the drone.

The operation of the AeroFIS® Flybot is highly automated. Departure and landing of the drone system can be performed automatically, and a press of the button activates the flight inspection procedures. The drone and the installed receiving antenna or camera are always automatically oriented towards the NAVAID under inspection during the flight. The inspection receiver is automatically tuned to the frequency of the NAVAID from the AeroFIS® facility database.

AEROFIS FLYBOT® PERFORMANCE

The main prerequisite for the operation of small drones in flight and ground inspection is the comparability of measurements with those of conventional, crewed flight inspections. For this reason, the AeroFIS® Flybot has been tested and validated during several measurement campaigns at different airports. The following paragraphs present results from a commissioning flight inspection for the new ILS of runway 01 at Košice International Airport in Slovakia in July 2023.

The AeroFIS® Flybot was used for a pre-calibration of the localizer and glide path signals. Right after the successful drone operation, the conventional, crewed commissioning flight inspection was conducted. As no adjustments in the ground installation were done in between, both systems measured exactly the same signals. The conventional flight inspection aircraft was operated by the Slovakian air navigation service provider (ANSP) and flight inspection service LPS SR. The LPS FI aircraft Let L-410 UVP-E-LW is equipped with an Aerodata AeroFIS® AD-AFIS-0115 flight inspection system and thus provides an ideal basis for the comparison of crewed and uncrewed FI measurements.

For both, the glide path and the localizer transmitter, maneuvers were flown by the AeroFIS® Flybot and by the Let 410 in order to measure the signal characteristics of the ILS ground transmitters. This included measuring the clearance and width as well as the alignment and structure of the signals with adequate procedures. In the following paragraphs and graphics, the AeroFIS® Flybot measurements are indicated by blue, and the Let 410 measurements by grey color.

Localizer

The measurements for the localizer alignment and structure runs are shown in Figure 6. Only the parts of the runs of Flybot and Let 410 from 900 m prior to the threshold to 2600 m behind the threshold are shown, which is the overlapping portion with measurements from both vehicles. Both systems performed standard 3° approaches with a subsequent overflight of the runway. Above the runway, the Flybot continued at exactly 15 m height above threshold (HAT), while the Let 410 flew at a lower HAT. This can also be seen in the plot at the top of the figure, where the signal in space (SiS) power density is shown. During the approach part, the measurements coincide precisely. Beginning with the flare maneuver of the Let 410 the SiS measurements begin to deviate from each other due to the height differences.

The second plot of Figure 6 shows the measured modulation depth of both inspection systems. The AeroFIS® Flybot measurements are as expected on point on the nominal value of 40 %. The Let 410 measurements are also close to the nominal value. The differences in the behavior of the measurements lies in the different types of receivers used by the systems. While the Flybot is equipped with a laboratory/scientific analyzer EVSD1000, the Let 410 AFIS utilizes receivers based on TSO certified aviation grade equipment, which are modified for additional FI functionality. Thus, the later receiver conditions the signal for application in avionics. The EVSD1000 instead provides a raw signal to the FIS.

The lower two plots of Figure 6 show the deviation and the deviation error in µA versus the distance to the threshold. In the deviation plot it can be well seen, that the AeroFIS® Flybot's flight trajectory precisely followed the 0 µA course line. This was possible due to the lower velocity compared to a crewed flight inspection aircraft, and due to the high accuracy of the RTK-based position and navigation reference. The Let 410 also flew close to the nominal course within ±10 µA. The deviation error plot clearly shows that the resulting measurements of AeroFIS® Flybot and Let 410 for the localizer are very similar, so that the commonality between crewed and uncrewed measurements is expected. The low velocity and high measurement frequency of at least 10 Hz of the AeroFIS® Flybot enable a detailed, high-resolution result.

Figure 7 shows the localizer clearance and width results of AeroFIS® Flybot and AeroFIS® equipped Let 410. The flight procedures for measuring the clearance and width of the localizer differed due to the different capabilities of the air vehicles and their operation. The Let 410 conducted a counter-clockwise partial orbit of ±35° in a distance of 17 NM from the localizer transmitter at 2 700 ft HAT. The Flybot flew ±35° partial orbits at a distance of 2 km from the localizer, at 50 m HAT in clockwise and counter-clockwise directions. For optimum reception quality, the multi-copter layout and the automatic flight guidance allowed the AeroFIS® Flybot to keep its receiving antenna pointed towards the localizer transmitter continuously.

The top plot of Figure 7 again shows the SiS power density of the received signal. All results are plotted versus the localizer azimuth. The quality of the SiS measurements is similar between both systems. Obviously, the power density measurement itself is different due to the significantly different distances from the localizer transmitter antenna array. The curves of the two AeroFIS® Flybot runs overlie, proving the high repeatability of these measurements.

The second plot of Figure 7 depicts the modulation depth. Again, the AeroFIS® Flybot measurements are as expected on point on the nominal value of 40 %. The Let 410 measurements are also around 40 %, but not as spot on due to the higher distance from the localizer, and due to the earlier mentioned reasons.

The last plot of Figure 7 shows the measured deviation versus the localizer azimuth. As expected, the course sector has a linear shape while crossing the 0° azimuth at 0 µA deviation. The clearance sector is well within the required tolerances. The deviation plot also confirms that the measurements of the two Flybot procedures and the one Let 410 flight are similar in shape and value, demonstrating the commonality between crewed and uncrewed measurements.

Glide path

Figure 8 presents the results of the glide path alignment and structure measurements (analog to Figure 6 for the localizer). For both systems, the results are plotted form a distance of 1900 m until the crossing of the runway threshold. Both aircraft followed the 3° approach, except for the flare manoeuver of the crewed aircraft.

The top graph of Figure 8 shows the SiS power density during the approaches. Both lines for the UAV and for the Let 410 are highly aligned until the point where the Let 410 starts to flare and the trajectories thus start to diverge. A similar behavior can be seen for the modulation depth in the second plot of Figure 8. Both lines are close to the nominal 80 % value as expected. The AeroFIS® Flybot measurement is again less noisy closer to the nominal value. Between 1500 m and 1600 m distance from the threshold, effects can be seen in the SiS power density of the AeroFIS® equipped Let 410. A similar effect is also noticeable on the deviation error in the third graph. It is assumed that a disturbing object like a ground vehicle was deflecting the signal during this part of the approach with the Let 410.

The lower two plots of Figure 8 again show the deviation and deviation error in µA versus the distance to the runway threshold. The deviation indicates, that the AeroFIS® Flybot follows the nominal 0 µA precisely thanks to the RTK-based position reference. The trajectory of the heavier and faster Let 410 naturally deviates from the 0 µA slightly – especially with decreasing distance to the threshold due to the flare maneuver. The deviation error is similar for both aircraft systems. Towards the threshold, the Let 410 measurements for the deviation significantly deviate from 0 µA, so that the linearity required for the calculation of the deviation error is not given. Thus, the deviation errors are not too similar close to the threshold.

The comparison of the measurements of the two systems show a good commonality between crewed and uncrewed NAVAID inspection.

Figure 9 shows the results of the clearance and width measurements of the both systems. Again, the flight maneuvers differed significantly. The AeroFIS® equipped Let 410 flew a standard level run from 12 to 0 NM at about 1200 ft HAT. The AeroFIS® Flybot instead flew a straight, vertical flight trajectory close to the middle marker at a distance of about 950 m from the threshold. In this way, both aircraft covered glide path elevations between 1° and 5.5°, as shown in the plots.

The top plot shows the SiS power density, which is again similar in quality for both airborne inspection systems. Due to the differences in distance and altitude, the measured values are off course different.

The modulation depth is depicted in the middle of Figure 9. Both systems agree on the 80 % nominal value in area around the glide path angle of 3°. The measurements of the Let 410 are impacted by the terrain at low elevation angles at a higher distance. At high elevation angles, both systems measure a deviation from the nominal value.

The final plot of Figure 9 shows the deviation measurements. Similar to the localizer clearance and width measurements presented in Figure 7, both inspection systems agree well – especially in the area around the nominal glide path angle of 3°. The clearance sector is well within the required tolerances in both measurement techniques.

As before, the measurements of the AeroFIS® Flybot and AeroFIS® equipped Let 410 show a good commonality for the glide path measurement.

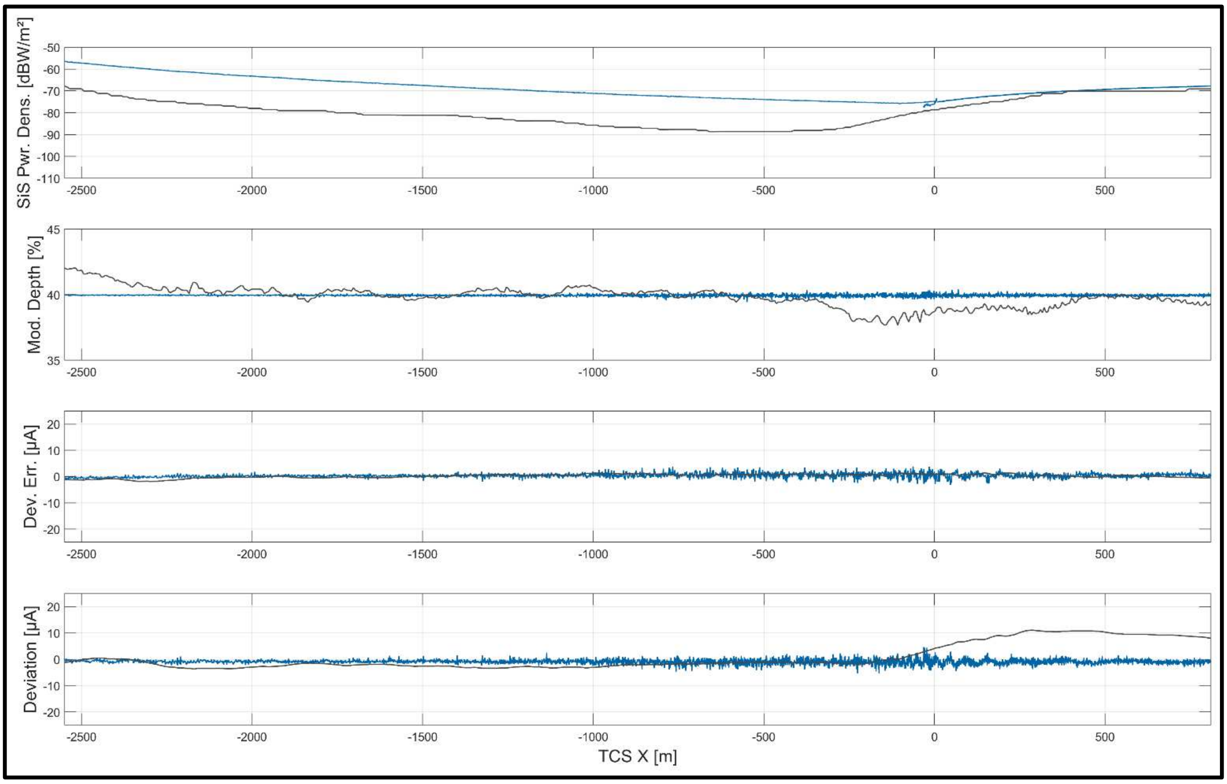

Figure 6. Localizer alignment and structure. (AeroFIS® Flybot in blue, AeroFIS® equipped Let 410 in grey color)

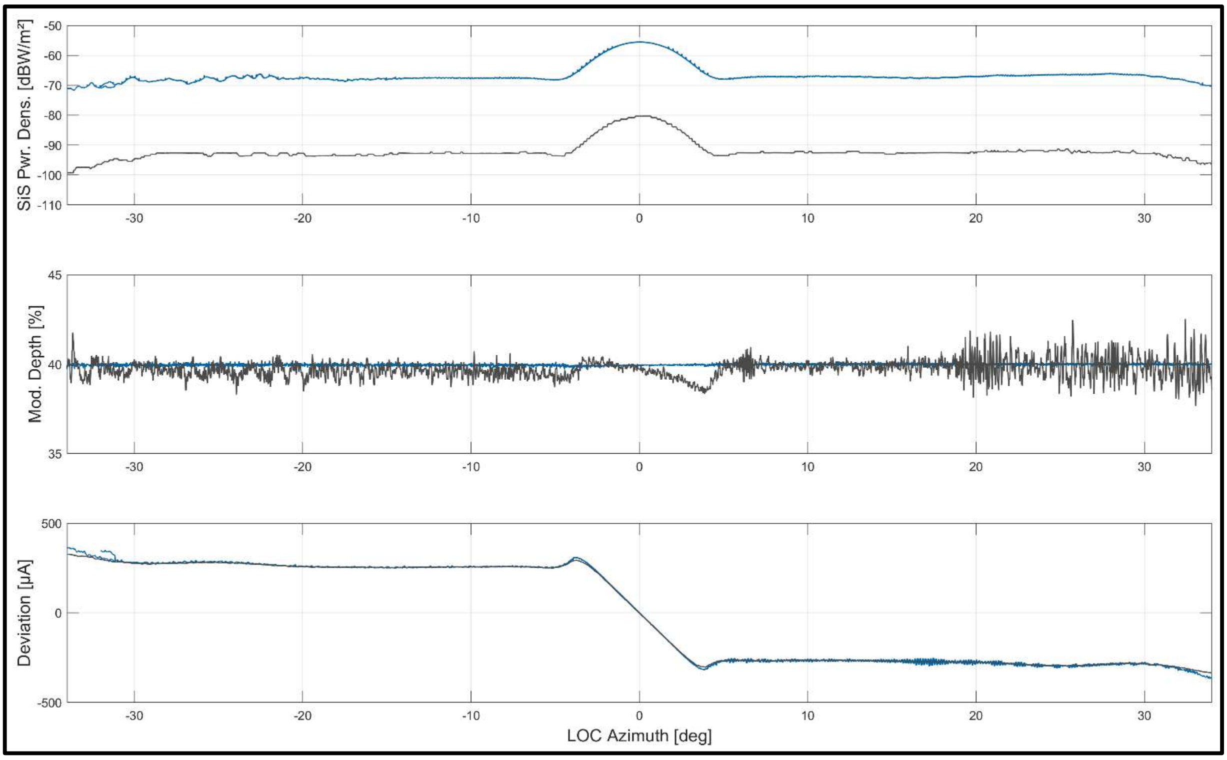

Figure 7. Localizer clearance and width. (AeroFIS® Flybot in blue, AeroFIS® equipped Let 410 in grey color)

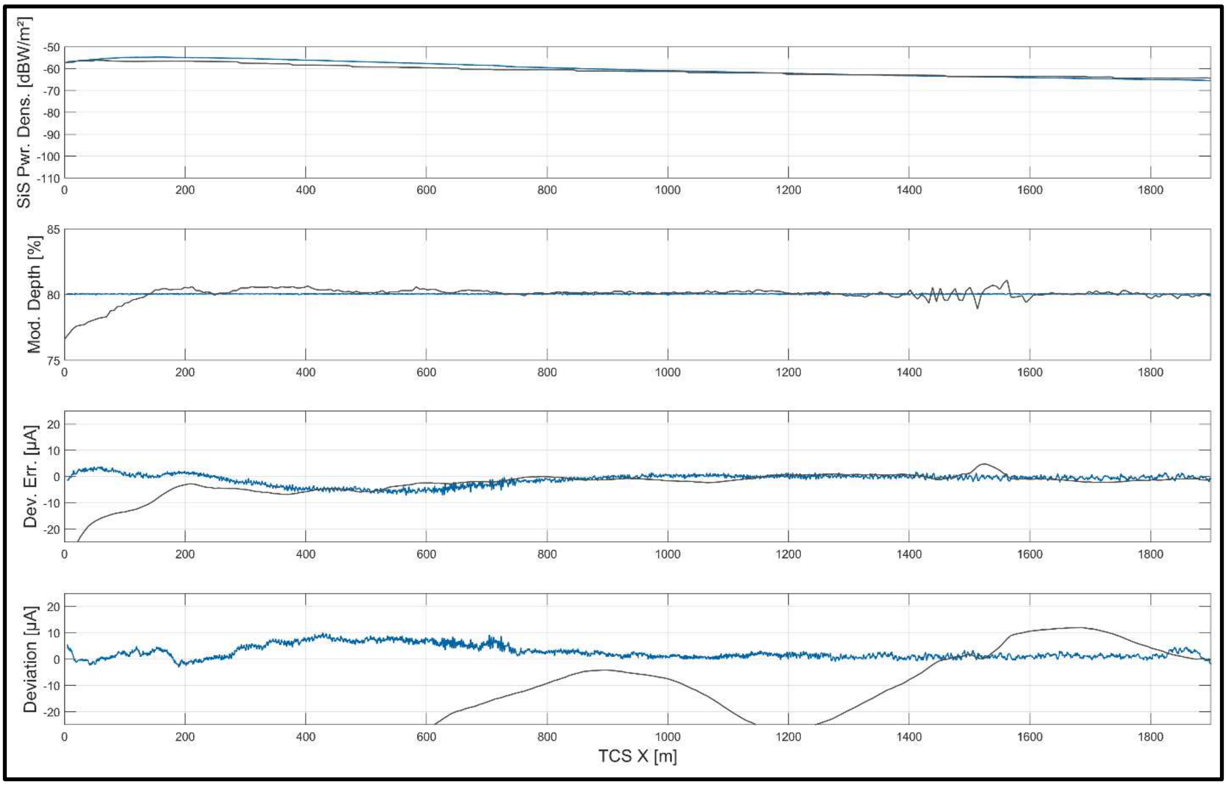

Figure 8. Glide path alignment and structure. (AeroFIS® Flybot in blue, AeroFIS® equipped Let 410 in grey color)

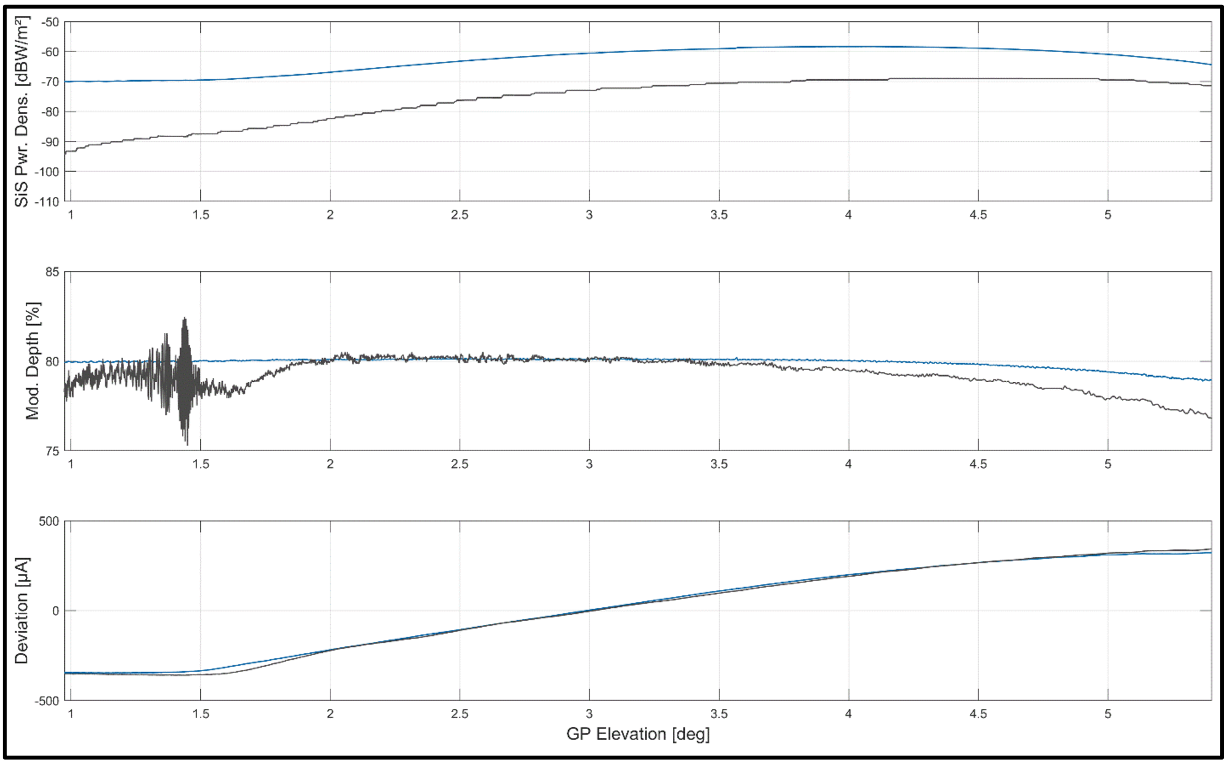

Figure 9. Glide path clearance and width. (AeroFIS® Flybot in blue, AeroFIS® equipped Let 410 in grey color)

CONCLUSIONS

The results presented in this paper prove that small, uncrewed aircraft like the AeroFIS® Flybot can be a valuable, accurate and convenient tool for NAVAID flight and ground inspection. This paper demonstrates the quality of these UAS measurements by comparing them with measurements of a conventional crewed flight inspection aircraft, using identical software, algorithms, and measurement techniques. The level of agreement of both systems demonstrates that both meet all requirements for flight inspections.

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