REDUCED FLIGHT INSPECTION OF ILS USING RPAS

Jaap Heijstek, Ivo Wilmes, Jaco Verpoorte, Martijn Stuip, Adri Tervoort, Jacco Bosch

Royal Netherlands Aerospace Centre NLR
Anthony Fokkerweg 2, 1059 CM Amsterdam, The Netherlands
e-mail: jaap.heijstek@nlr.nl, ivo.wilmes@nlr.nl, jaco.verpoorte@nlr.nl

ATC The Netherlands LVNL
Stationsplein ZuidWest 1001, 1117 CV Schiphol, The Netherlands
martijn.stuip@lvnl.nl, a.a.tervoort@lvnl.nl, j.bosch@lvnl.nl

ABSTRACT

This paper summarizes the Reduced Flight Inspection approach applied in The Netherlands, which is periodic flight inspection with some measurements moved from the aircraft to the ground. The paper contains the justification of the ground measurements being performed using a measurement car with an extensible antenna mast, and outlines the development in The Netherlands of the alternative ground measurement approach based on Drone Flight Inspection.

Keywords: Instrument Landing System; ILS; Flight Inspection; Ground Measurement; Drone

1. INTRODUCTION

In The Netherlands Instrument Landing Systems (ILS) are operated at a number of civil airports, including Amsterdam Airport Schiphol. Most of these systems are of the highest ICAO ILS category, Cat. III, which allows landing of suitably equipped aircraft under low visibility procedure conditions.

Traditionally, the periodic calibration of the ILSs was performed by flight tests. Figure 1 shows the flight inspection aircraft used for this purpose by The Netherlands Aerospace Centre NLR.

Figure 1 NLR Cessna Citation II flight inspection aircraft equipped with Garmin/Aerodata Flight Inspection System

Nowadays, the periodic calibration of the ILSs is carried out by a well-considered combination of flight tests and ground tests, designed by the NLR, in which the accurate flight measurements of up to six specific ILS parameters are replaced by accurate ground measurements and some slightly less accurate flight measurements of the same parameters. This approach, referred to as *Reduced Flight Inspection runs* (ReFI), can be applied safely only if the ILS signal-in-space (SiS) is of high quality and free from disturbances.

If ReFI is applicable, it allows to reduce the number of flight inspection runs with approximately 90 percent, which leads to a significant reduction of cost (up to 65%) and environmental impact (less noise and emissions from periodic inspection flights). As a result, it improves runway availability, allowing more regular traffic to take-off or land, but there should be a balanced trade-off between improved airport capacity and environmental impact.

In The Netherlands, Luchtverkeersleiding Nederland (LVNL), the Dutch Air Navigation Service Provider (ANSP), has brought ReFI into operation in phases since May 2007. That is, the flight tests were carried out by NLR using a manned aircraft (see Figure 1) supplied with a Flight Inspection System (FIS), and the ground tests were done by LVNL using a measurement car with an ILS receiver and on-board processing equipment. Figure 2 shows the ground measurement equipment operated by LVNL in front of a localizer antenna array.

Figure 2 LVNL measurement car with LOC antenna on top, and towing a lorry with extensible mast having on top the receiving GP antenna.

In 2019, The Netherlands offered the ReFI approach to the ICAO Navigation Systems Panel for adoption in Doc 8071 as an example of good practice. The discussions at ICAO are ongoing and look promising.

2. SCOPE AND OBJECTIVE

In recent years, NLR has been developing Drone Flight Inspection (DFI), which is essentially calibration of navigational aids using a remotely piloted aircraft system (RPAS), equipped with suitable sensors and adequate onboard data processing capabilities. Figure 3 illustrates the NLR drone being prepared for testing by an NLR pilot in command.

Figure 3 NLR DFI drone and pilot with remote controller

DFI is aimed to supplement the capabilities of the measurement car, and potentially replace it. This paper summarizes the ReFI approach and discusses the two different options for the ground tests: the measurement car, and the DFI system. The advantages and the disadvantages of both options for ground testing are indicated. Investigations on replacing the piloted aircraft with an RPAS are ongoing as well worldwide, and are not discussed here.

3. MOTIVATION

The performance requirements for Instrument Landing Systems (ILS) are specified in ICAO annex 10 [1], while the guidance for calibrating ILS is given in ICAO Doc 8071 [2]. Measurements for calibration of ILS do not only involve the flight tests and the ground tests, but also equipment tests. While the measurements are taking place, the runway has to be closed for some time, which may impact busy airport capacity. As mentioned in the introduction, the ReFI approach leads to reducing the number of periodic flight measurements while maintaining the periodic ILS calibration objectives.

4. PARAMETERS OF INTEREST

The ILS parameters which are considered to be calibrated by ground measurements instead of flight measurements are localizer and glideslope *displacement sensitivity* and *change in displacement sensitivity*, *change in localizer course shift*, and *change in glideslope angle shift*. These six parameters can all be determined directly or indirectly from the measurement of the *Difference in Depth of Modulation* (DDM).

The advantage of measuring the abovementioned ILS parameters on the ground is illustrated by the following table showing an example of standard periodic calibration campaign and the ReFI campaign.

Table 1 shows an example of a full flight inspection program for LOC and GP in which the measurements of all six parameters of interest are moved to the ground. In this case, the total number of flight calibration runs is reduced from 29 to only 3, which is a reduction of almost 90%. However, the user may choose to move the measurements of only a subset of these parameters to the ground. Of course, the number of runs then may exceed 3, but may still be interesting.

Table 1 Example of a modified flight inspection programme for ReFI

Periodic ILS calibration		**Periodic full flight inspection program**	**ReFI program**
LOC/GP	***ILS parameter***	***number of runs***	***number of runs***
LOC	Course alignment accuracy	2	1
LOC	Course structure		
LOC	Polarisation		
LOC	Identification		
LOC	Modulation depth SDM		
GP	Angle alignment		
GP	Structure		
GP	Height of reference datum		
LOC	Off-course clearance[1]	1	1
GP	Clearance[2]	2	1
LOC	Displacement sensitivity	2	-
LOC	Monitoring of course shift	4	-
LOC	Monitoring of change in displacement sensitivity	4	-
GP	Displacement sensitivity	4	-
GP	Monitoring of angle	2	-
GP	Monitoring of change in displacement sensitivity	8	-
	Total	*29*	*3*

5. DUAL TRANSMITTER ILS

In case of an ILS facility with dual transmitters, flight inspections may be performed for only one of the transmitters, provided that the difference between the electrical signals produced by both transmitters is sufficiently small and can be maintained on the ground.

6. REFI PREREQUISITES

For the abovementioned six parameters to be predicted sufficiently accurate along the entire approach path, certain disturbance limitation conditions on the SiS, called *ReFI prerequisites*, need to be satisfied:

1) The ILS has successfully passed a commissioning program,
2) the ground measurement quality is sufficiently high,
3) the ILS facility is adequately safeguarded against disturbances stemming from the operational environment,
4) one-to-one correspondence between ground and airborne measurement results is established, and

[1] May include a measurement of the LOC course and displacement sensitivity.
[2] May include a measurement of the GP angle and displacement sensitivity.

5) DDM upper and lower limits along the approach path exist and are determined using either a representative set of measurements, or adequate ILS simulations, such that if the DDM measured near the ground is within certain more stringent limits than the ICAO limits from Annex 10, called *ReFI limits*, then the DDM is within the corresponding ICAO limits everywhere along the approach path.

If these criteria are not fulfilled, ReFI should not be applied.

Prerequisite 1) implies that at the time of commissioning, the ILS transmission is of good quality and without external disturbances. If, at some time after commissioning, the transmission is still of good quality, but there are external disturbances of the SiS present, the three ReFI flight inspection runs (*an arc for localizer clearance, a level run for glide path clearance, and a nominal approach run for several parameters*) should suffice to detect those external disturbances, which are to be removed before proceeding because of prerequisite 3).

Assuming no external disturbances, which potential transmission aberrations could be detected by a full periodic flight inspection, and not by ReFI? The measurements taking place in the three ReFI flight inspection runs are included in the full periodic flight inspection as well. Therefore, it remains to consider the DDM ground measurements.

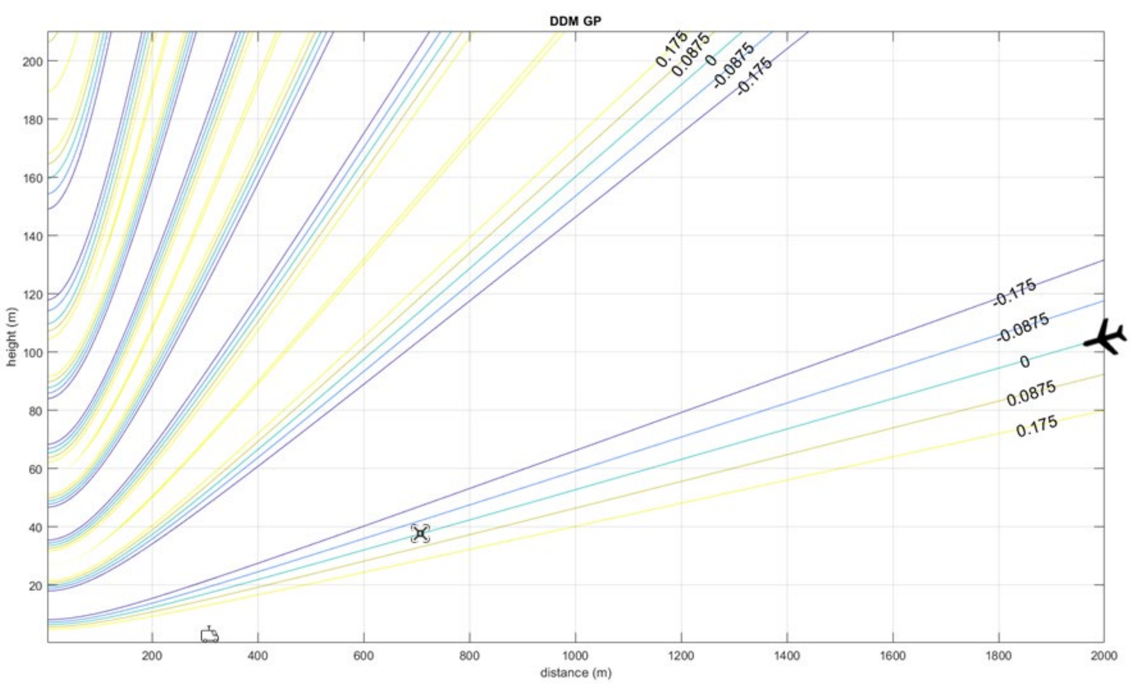

Figure 4 Simulated glideslope DDM iso-curves along extended centreline and ReFI measurement positions

If one uses a multi-copter near threshold (THR) flying up the glide path and sufficiently far from the transmitting antennas, then the DDM behaves nearly the same as in the far field, and prerequisite 4) is fulfilled with the one-to-one correspondence being given by the identity or a slight aberration thereof.

In other words, one has established correlation between the DDM values near THR and at 'FAR'.

If one uses a measurement car at or near THR, then for the localizer the measurement is taking place in the far field. But for glideslope, one is measuring in the near field, and hence care must be taken.

A discrepancy occurring between the DDM measured at THR and the expected value set at commissioning, indicates a potential transmission error. Corrective action should be taken before proceeding. If there is no discrepancy between the DDM measured at THR from the expected value set at commissioning, there can still be a discrepancy between the DDM measured at 'FAR' from the expected value set at commissioning. For detecting any such discrepancy, the three ReFI flight inspection runs are used, particularly the localizer off-course clearance measurement, and the glideslope clearance measurement. If the measured DDM differs from the expected value, corrective action on the transmission should be performed before proceeding.

From the above, it appears that in ReFI, the three remaining flight inspection runs should be performed before the ground measurements. If the flight measurement of the DDM are satisfactory, and no external disturbances are detected, then the ground measurements can be done. They should be performed soonest after the flight inspection runs, to ensure the environmental and transmission circumstances for the flight measurements and the ground measurements are practically the same.

7. REFI INTERVAL

For each of the aforementioned ILS parameters, the corresponding ICAO limits, be it adjust-and-maintain limits or alarm limits, translate to ReFI limits applicable in a ground measurement, performed at the same time or nearly the same time as the flight measurement. Clearly, these ReFI limits depend on the ICAO limits from Annex 10, the ILS configuration, the ground measurement performance (including accuracy), and the runway and environment characteristics.

In order to fulfil prerequisite 5), the ReFI limits, and the ReFI interval bounded by each corresponding pair of lower and upper ReFI limits, can be determined in several ways, of which we describe two.

The first one is to start with the DDM results from a preferably large set of the commissioning quality level flight measurements along the approach path under different environmental circumstances: check that prerequisite 3) is fulfilled, and then determine the intersection of the intervals of DDM values above THR, for which the corresponding DDM values along the approach path for all these flight measurements are (just) inside the ICAO interval, the interval bounded by the lower ICAO limit and upper ICAO limit, respectively. More measurements lead to more accurate results.

The second way to determine the ReFI limits is to model the ILS, the environment (ground, runway, weather, disturbances), and the transmission, acquire or develop based on this model an ILS simulator, use the simulator to calculate the DDM distribution along and in the vicinity of the approach path, and perform similar calculations as described above for measured DDM data in order to determine the ReFI interval. It goes without saying, that measurement uncertainty needs to be taken into account.

Prerequisite 2) implies that the calculations and measurements need to be of sufficiently high quality[3].

---

[3] The flight measurements are expected to meet or exceed the quality level set by ICAO DOC 8071.

8. REFI CORRELATION STATEMENT

Assuming the ReFI prerequisites above are fulfilled, the construction of the ReFI interval readily leads to the statement that DDM measured above THR and found inside the ReFI interval implies that the corresponding DDM along the entire approach path will be inside the ICAO interval.

9. ReFI GROUND MEASUREMENTS

9.1 Ground inspection using a measurement car

Using a measurement car and extensible mast for periodic ILS ground measurements provides high measurement accuracy, but requires a relatively long time of operation, compared to DFI, to achieve the results. It is well known, that for the localizer, one can measure the far field at THR. For the glideslope this is not the case, and the near field behaviour has to be taken into account, as described in section 6 above.

The radiation pattern and the DDM of the glideslope depend on the height of the GP antenna elements above the reflecting ground plane. This height can vary, e.g. due to changes in the ground water level or due to snow fall. In Figure 5 an example is given of the change in course angle (DDM=0) resulting from a change in antenna height of -30 cm or +30 cm of antenna 2 of an M-array.

For simplicity, the DDM is calculated at four discrete distances: at threshold (THR), ICAO Point B, ICAO Point A and a distance of approximately 18 km (‘FAR’) from threshold. As a result, the graphs are quite crude, but due to the monotonic behaviour of the DDM hyperbolic isolines the graphs suffice to serve the purpose of linking the DDM values at THR to values along the approach path, the hyperbole asymptote.

Note that the changes of the antenna height lead to the (simulated) GP course angle DDM shifting in the same direction at all distances. Moreover, from measured DDM changes at threshold one can estimate the DDM changes further away along the approach path. This allows the fulfilment of prerequisite 5) with quantified ReFI limits. In this particular case, one finds that the upper ReFI limit is slightly less than the ICAO limit minus the ground measurement uncertainty, and similarly, the lower ReFI limit slightly exceeds the ICAO lower limit plus the ground measurement uncertainty. This illustrates that better measurement accuracy yields a larger ReFI interval.

The radiation pattern and the DDM of the glideslope depend also on the phase of the CSB and SBO signals on the antenna elements. Figure 6 shows the influence of the phase of the CSB signal on antenna 2 of the GP antenna for the width below of the GP signal (DDM=0.0875). Also, here we observe that for variations in phase, the DDM shifts in the same direction at THR and at locations further away.

This relationship between DDM at THR and DDM at point B, point A and far away can also be shown for variation in ground permittivity and ground conductivity and for the amplitude of the SBO/CSB ratio. This supports the ReFI procedure of replacing specific flight measurements by ground measurements.

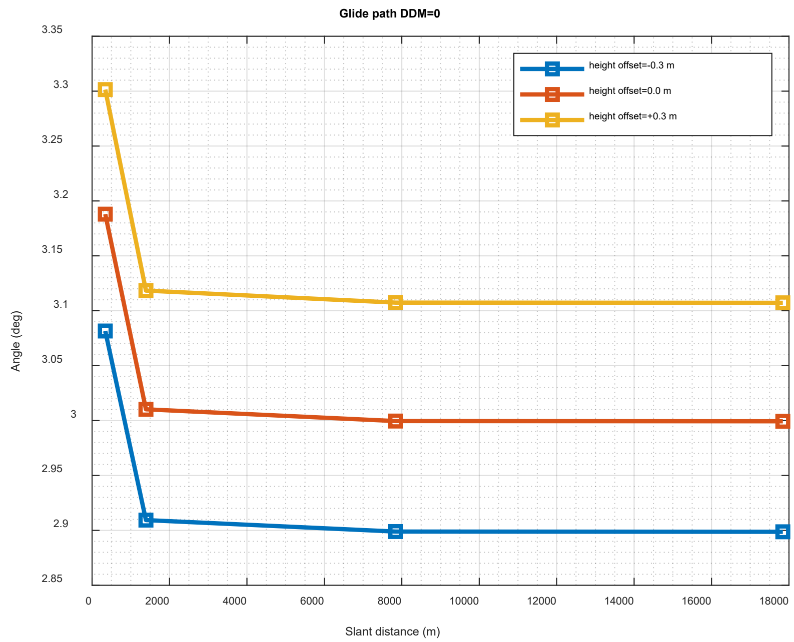

Figure 5. Course angle (DDM=0) as function of distance to the GP antenna for variations of the antenna height above ground plane (-30 cm to + 30 cm).

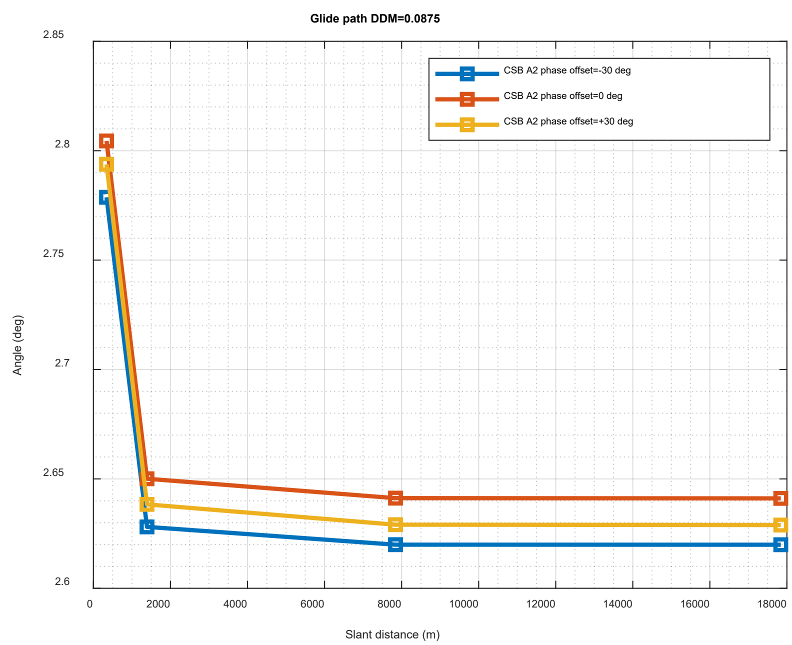

Figure 6. Width below angle (DDM=0.0875) as a function of distance to the GP antenna for variations of the phase of CSB on antenna 2 (-30 to +30 degrees).

9.2 Ground inspection using a DFI drone

NLR has started DFI system development in 2020 according the standard waterfall methodology:

- User Requirements elicitation based on FI operational requirements and use cases
- System Requirements elicitation based on user requirements and NLR experience
- System Design (Hardware, Software)
  - Drone selection, adaptation
  - Software selection, adaptation
  - Integration design
- Hardware components procurement and manufacturing, e.g.
  - "Large" drone ready to fly, equipped with ILS sensors and analyzer, for operational DFI runs
  - "Small" drone equipped with a camera, for run preparation, and training
  - Inhouse creation of integration support components
- Software acquisition, and in house development
  - ArduPilot (GPLv3 license)
  - GUI, data flow, control software development
- System integration
  - Drone, sensors, Rohde & Schwarz EVSF1000 analyzer, processor
  - Ground station (see Figure 7), remote control, data link
- Pilot and flight inspector training
- System verification and validation testing (NLR Drone Centre, and civil/military airports) is ongoing.
- Take care of the legal and procedural aspects of DFI operation at airports

As already mentioned above, an advantage of using DFI for periodic ILS ground measurements is that measurements are possible in or close to the far field of both the localizer and the glide path antennas. Also, the flexibility of the DFI system allows relatively short operation time to complete a measurement, which improves the runway availability compared to the measurements using the measurement car. Moreover, DFI measurements can be highly automated, and accurately repeated. DFI measurements of different ILS components can be easily combined.

The DFI system can easily be extended to other navigation aids, e.g. VOR, and to other application areas by using appropriate sensors, e.g. a camera for visual inspection of runway lighting and surface. A disadvantage is the potentially relatively lower position accuracy of the ILS measurement compared to the accuracy which can be obtained using the car with slowly extensible mast. Increased accuracy can be achieved by using hyperbolic DFI trajectories, and/or automatic run repetition followed by regression.

Figure 7 NLR DFI ground station

Referring to Figure 4, a simulated drone measurement at constant height 16.5 meter above centerline yields Figure 8:

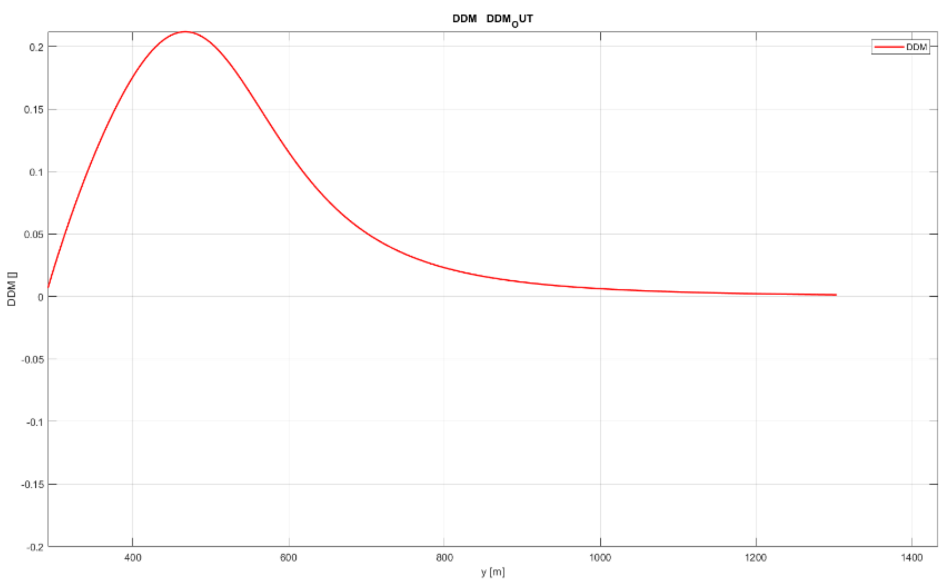

Figure 8 Simulated DDM measurement along extended centreline at constant altitude of 16.5 meter

If the DDM measurement is performed by a DFI drone flying an almost hyperbolic track close to the DDM=0 iso-curve, the resulting DDM-graph will look like the essentially constant function depicted in Figure 9. In practice, the measurements contain errors, and hyperbolic regression is required to obtain a similar result.

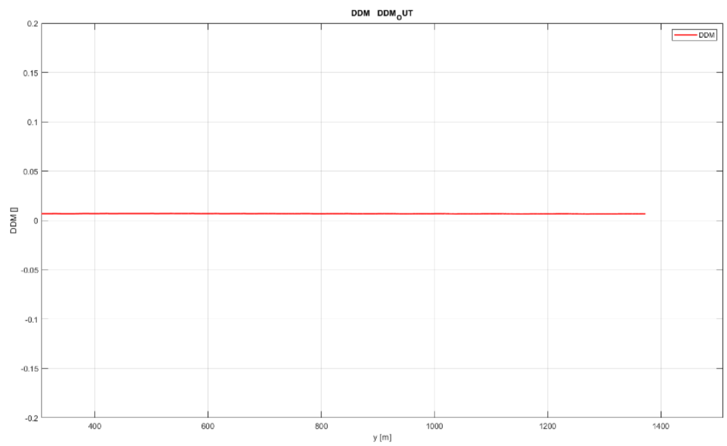

Figure 9 Simulated DDM measurement by an aircraft flying along the DDM=0 isoline (a hyperbole) above extended centerline

10. CONCLUSION

Using the classical approach of a measurement car and extensible mast for periodic ILS ground measurements is still a feasible way to perform ground measurements in the ReFI context. In recent years, drone flight inspection has been developed providing several advantages compared to measuring with a car and extensible mast, most prominently the ability to measure in or close to the far field of the ILS. However, there are some disadvantages as well, most notably its inability to detect some transmission errors in the far field.

11. REFERENCES

[1] International Civil Aviation Organization (ICAO), "ICAO Standards and Recommended Practices, Annex 10 to the Convention on International Civil Aviation, Volume I, Radio Navigation Aids," ICAO, 2018.

[2] International Civil Aviation Organization (ICAO), Doc 8071, Volume I, Manual On Testing Of Radio Navigation Aids, Testing Of Ground-Based Radio Navigation Systems, Fourth Edition, ICAO, 2018.