

Practical experiences using drones for reduced Flight Inspection on an operational airfield.

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ABSTRACT

In The Netherlands Instrument Landing Systems (ILS) at civil airports are periodically inspected through a combination of flight checks and ground inspection. This approach, designed by NLR, is called Reduced Flight Inspection (ReFI). ReFI has reduced the required number of flight checks by almost 90%. Furthermore, the ReFI approach is being considered by ICAO for adoption in Doc 8071 as an example of good practice.

On top of ReFI NLR has developed an experimental drone flight inspection (DFI) system which replaces the ground measurements with multi-copter drone flights in the near-field, close to the runway. DFI amplifies the benefits of ReFI by providing improved flexibility and higher execution speed, while maintaining equivalent accuracy.

In this paper we will present the operational experience and results of using the DFI system at two Dutch airports for periodic inspection and pre-commissioning. The gathered results clearly show that DFI produces measurements with good correlation to ReFI ground measurements as well as traditional Flight Inspection measurements. Furthermore,

the results have proven to be very efficient for the initial alignment process in a pre-commissioning.

The ambition for the current year is to develop a fixed-wing DFI capability to also perform the far field measurements.

INTRODUCTION

Instrument Landing Systems (ILS) are operated at many civil and military airports around the world. These systems, depending on their category, allow for landing of suitably equipped aircraft under increasingly bad visibility conditions. Traditionally, all periodic inspections of the ILSs are performed by flight checks.

In the Netherlands, these flight checks are performed by The Netherlands Aerospace Centre (NLR) using their flight inspection aircraft PH-LAB shown in Figure 2. To increase efficiency, since 2007, NLR has been using a well-considered combination of flight checks and ground inspection to do ILS inspection for Luchtverkeersleiding Nederland (LVNL)¹, the Dutch civil Air Navigation Service Provider (ANSP). This approach, referred to as Reduced Flight Inspection (ReFI) [1] [2] [3], allows to reduce the number of flight check runs by up to 90% by performing regular ground inspection using a measurement car with ILS receivers and processing equipment, as shown in Figure 2.

¹ For the purpose of this research, LVNL has provided us with one dataset from their ground measurements at EHGG ILS23. The involvement of LVNL in this research

was limited only to providing this dataset. There was no further involvement of LVNL in this research.



Figure 2 left: NLR Cessna Citation II flight inspection aircraft right: LVNL measurement car with localizer antenna on top, and towing an extensible mast with glide path antenna.

In recent years, NLR has been developing Drone Flight Inspection (DFI) for inspection of navigational aids using a drone equipped with suitable sensors and data processing capabilities. DFI is aimed to supplement the capabilities of the measurement car, and potentially replace it. [2] The advantage of using DFI for the ReFI ground measurements with respect to the measurement car, is that measurements are possible closer to the far field of both the localizer and the glide path antennas. Furthermore, the flexibility of the DFI system allows relatively short operation time to complete a measurement, improving runway availability. Also, DFI measurements of different ILS components can be easily combined.

Different versions of DFI have also been researched and deployed by other organisations. E.g. since 2018 Skyguide has deployed DFI on Swiss international airports to extend the period between flight checks of ILS and VOR, as well as in preparation of commissioning flight checks for new ILS [4]. Also, two flight inspection system providers have experimented with DFI, namely Aerodata with their AeroFIS Flybot [5] and Norwegian Special Mission using the PRIMICO One 150 with a UNIFIS based fixed wing DFI system [6].

The approach presented in this paper stands out from the abovementioned DFI solutions in the fact that it combines DFI with ReFI to directly reduce the number of runs required per flight check, while only performing near field measurements with the drone.

In this paper we will present the operational experience and results of using the DFI system at two Dutch airports for periodic inspection and pre-commissioning, as shown in Figure 1. The gathered results clearly show that DFI measurements have good correlation to ReFI ground measurements as well as traditional Flight check measurements. Furthermore, an insight will be given into the first steps NLR has taken to extend DFI to also replace the remaining flight checks within the ReFI approach.

To this end, first a brief summary of the ReFI approach, as well as the current ground measurements is given. Then the DFI system and its operation is introduced as an alternative to the ground measurements. Lastly, the results of the experimental DFI measurements performed on two Dutch airports are presented to show the usability of DFI for ILS inspection and pre-commissioning.



Figure 1 NLR DFI drone operational on a Dutch Civil airport

ILS INSPECTION WITH REFI

ReFI is an inspection approach that combines ground measurements with limited flight checks to verify the accuracy of ILS signals. The method involves measuring the ILS signal-in-space (SiS) at specific locations on the ground and using this data to predict the signal's behavior along the approach path. By establishing a correlation between ground measurements and flight check data, ReFI enables the reduction of flight checks while maintaining the required level of accuracy.

The primary motivation behind ReFI is to reduce the number of flight checks required for ILS inspection. By leveraging ground measurements and advanced data analysis techniques, ReFI aims to minimize the need for frequent flight checks, thus reducing costs, environmental impact, and airport congestion. Additionally, ReFI enables more efficient use of airport resources, allowing for increased runway availability and reduced delays. [1]

The performance requirements for Instrument Landing Systems (ILS) are specified in ICAO annex 10 [7], while the guidance for calibrating ILS is given in ICAO Doc 8071 [8]. Measurements for inspection of ILS involve the flight checks and the ground inspection. While the measurements are taking place, the runway has to be closed for some time, which may impact busy airport capacity. As mentioned before, the ReFI approach leads to reducing the number of periodic flight measurements while maintaining the periodic ILS inspection objectives.

ReFI parameters of interest

Within the ReFI framework six ILS parameters can be fully inspected by ground measurements. As shown in Table 1 these are localizer and glideslope (change in)

displacement sensitivity, and localizer and glide slope course shift. These parameters can all be determined directly or indirectly from the Difference in Depth of Modulation (DDM) measurement.

Table 1 shows an example of a full ILS inspection program compared to a program in which ReFI is fully utilized. Here it can be seen that in this case the total number of flight check runs is reduced from 29 to only 3, which is a reduction of almost 90%. While the exact reduction depends on the original flight test program, by measuring the ILS parameters on the ground, the number of flight check runs for ILS inspection can always be reduced. Additionally, the user may also choose to only utilize ReFI for a subset of the possible parameters.

Table 1 Example of a modified ILS Inspection program for ReFI (LOC=localizer; GP=glide path)

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	-
<i>Total</i>		29	3

Before ReFI can be applied for ILS inspection, the following additional prerequisites must be met [1].

1. A one-to-one correspondence between ground and airborne measurement results is established.
2. The near-ground measurement quality is sufficiently high.
3. DDM upper and lower limits along the approach path exist and are determined using either a representative set of measurements or adequate ILS simulations.

If these criteria are not fulfilled, ReFI should not be applied. In applying ReFI at all civil Dutch airports, we have shown that these criteria are achievable.

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 [7], the ILS configuration, the ground measurement performance (including accuracy), and the runway and environment characteristics.

ReFI ground measurements

Currently a measurement car and extensible mast is used for the periodic ILS ground measurements. Typical measurement profiles performed with this car are:

1. Vertical slice with the extendable mast at threshold for glide slope near field course and width measurements.
2. Arc at threshold for localizer far field course and width measurements.
3. Arc close to localizer for near field course and width measurement at larger angles.
4. A run from the threshold over the full runway for localizer structure measurement.

Note that for the localizer, one can measure the far field at threshold. [4] [5] For the glideslope near field behavior has to be taken into account for measurements at the threshold.

This method generally provides a high measurement accuracy. However, during the driving maneuvers data also shows some oscillations in the mast, which are introduced due to the driving over the ground. Additionally, the measurement car requires a relatively long time of operation to achieve the results. Furthermore, as the car can only take measurements on pavement, the possible measurement positions are limited to the airport’s paving, which differs per airfield. Additionally, the measurement height is limited to the extension capacity of the mast with glide path antenna.

DRONE FOR REFI GROUND MEASUREMENTS

Drone flight inspection (DFI) has been developed at NLR in order to improve efficiency, flexibility and accuracy of the ground measurements of ReFI by supplementing, or fully replacing the measurement car. [2] This section first describes the expected benefit of using DFI, followed by a description of the developed DFI system and its typical operation.

Expected benefits of DFI

By using the DFI drone for the ReFI ground measurements, they are no longer restricted to the available pavement on an airport. This, for example, allows to measure glide path signals closer to the far field, and at higher localizer angles. Furthermore, the DFI approach has the flexibility to adjust the exact flight per ILS to optimize the measurement effectiveness. E.g. in an environment with more obstacles, measurement further from the glide path antenna might be necessary, while in environments without obstacles it may be possible to get sufficient measurements closer by, making the flight shorter and therefore more efficient.

An additional benefit is that drones can be piloted remotely and/or allow for a highly automated operation. This may be

used to increase operational efficiency by e.g. enabling DFI flights at short notice and at times convenient to suit the airport traffic flow. Furthermore, the flights can be performed quickly with runs taking at most 4 minutes, minimizing required closure of the runway.

Lastly, DFI allows for higher accuracy of measurements as the drone can precisely follow the reference and is not disturbed by imperfections in the pavement and the consequent oscillations of the measurement mast.

DFI system description

For the test program, the Freespace Callisto 50, equipped with the DFI payload as well as the required avionics to operate on active airports, has been used to perform the ReFI ground measurements. Additionally, the Tarot 650 quadcopter, a smaller drone with the same avionics but without the ILS inspection payload, was used to test and validate the DFI maneuvers. In this way ATC procedures and operational runs can be tested more conveniently and the runs can be validated for obstacle clearance. In this section only the Freespace Callisto 50 with DFI payload, shown in Figure 3 and Figure 4, will be further described.

The Freespace Callisto 50 specifications can be found in Table 2. Notably, the drone is capable of operations up to 52 kg take-off mass, with an endurance of about 20 minutes. Furthermore, the drone allows for full single propulsion fault tolerance. To assure the NLR DFI drone can be used to perform the ILS measurements, several modifications have been made.

Table 2 Specifications of Freespace Callisto 50

Outer dimensions	1812 x 1805 x 1076 mm
Max Take-off Mass	52 kilograms
Mass in DFI configuration	41.5 kilograms
Endurance in DFI configuration	20 minutes

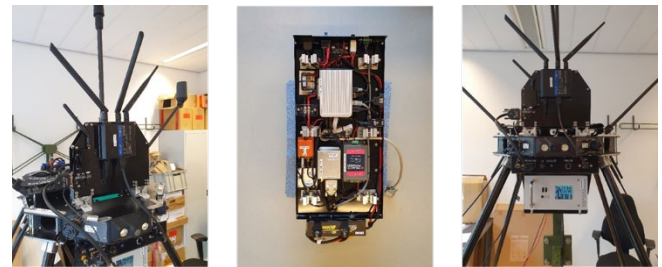


Figure 3 The NLR developed DFI payload.

Secondly, NLR designed a 3cm accurate RTK reference system, shown in Figure 5, for localization based on ArduSimple RTK modules, which use the well-known u-blox ZED-F9P GPS modules. The RTK reference system navigation accuracy has been statically and dynamically evaluated on the Tarot 650 using an optical verification method comparing the RTK with known marker positions.



Figure 4 Freespace Callisto 50 in the DFI configuration

Firstly, the Rohde & Schwarz EVSF1000 ILS receiver has been mounted on the drone, allowing for ILS measurement performance and accuracies required by ICAO Doc 8071. The EVSF1000 is able to provide all required ILS parameters such as DDM, SDM, course/clearance ratio, and field strength such that we can perform all ground measurements and checks required for ReFI.



Figure 5 The NLR RTK ground station

Thirdly, the propellers of the Callisto 50 were replaced by glass fiber propellers. Glass fiber is a non-reflective material, such that no propeller modulation issues should occur. Additionally, various antenna configurations, namely Dipole, Butterfly and Yagi antennas, were tested for their accuracy, resistance to propeller modulation and handling quality. All antennas were developed specifically for DFI in collaboration with an antenna design house. The antenna configuration in Figure 3 was the lightest antenna configuration and performed very well. Therefore this antenna configuration has been used in all experiments.

The DFI ground station consists of two parts shown in Figure 6, a hand transmitter for the safety pilot and a ruggedized laptop for the flight inspector running an in-house developed GUI containing the FIS database, which can be used to generate mission plans that can be loaded to the pilot's transmitter. This allows the flight inspector and pilot to both monitor the mission. The GUI also allows to configure the EVSF1000, can be used to start and stop the measurement, and monitor the measurement data in real time. After the flight, the data is transferred to a separate data processing station to generate flight inspection reports.



Figure 6 DFI ground control station

DFI system operation

The NLR DFI drone is operated by a crew of two persons, a drone safety pilot, and a flight inspector. The flight inspector loads the required runs into the drone and monitors the DFI results in real-time as they come in. The safety pilot initiates and stops each run, and continuously monitors the flight during runs. If necessary the safety pilot can intervene at all times. The safety pilot or flight inspector (as long as they have an RT license) is in constant contact with ATC using a specific Unmanned Aircraft System (UAS) RT procedure.

The DFI runs are also equipped with several safety features. Firstly, all DFI runs are validated for safety of flight and obstacle clearance by performing them with the smaller Tarrot drone first. Secondly, geofencing as well as a start position check prohibits automated flight from an erroneous start-up position.

Furthermore, stringent regulation applies for drone flights to be carried out within an airport's control zone (CTR). NLR is a drone operator and is allowed to operate the DFI drone within Dutch civil and military CTRs, and the DFI measurements are all performed under the Operational Authorization that the Dutch CAA has granted NLR based on an approved Specific Operations Risk Assessment (SORA) for Visual Line of Sight (VLOS) flights, Extended Visual Line of Sight (EVLOS) flights, and Beyond Visual Line of Sight (BVLOS) flights with UAS in segregated airspace (such as CTR, or restricted area). For details on the ground area considered for the risk assessment see [3].

Flight preparations include developing an operational plan describing all the details of the operation, including the definition of the DFI runs. The plan is first internally approved by NLR Operational Authorization office. Then

detailed arrangements are made with the local air traffic control and LVNL's Operational Helpdesk (OHD). Operational details of the drone flights are communicated to the OHD by phone and via the GoDrone app, which is the standard in the Netherlands. Also the definition of each DFI run is delivered to local air traffic control before operation commences to facilitate efficient communication about the planned maneuver.

During operation local ATC treats the DFI flights as normal traffic. Thus, the NLR team receives ATC clearances with reference to the DFI runs as specified in the operational plan, and the DFI flights are performed in-between other operational traffic.

Typical DFI runs

In our experiments various options for DFI runs have been tested, utilizing the increased flexibility of DFI with respect to the measurement car. Below the most used DFI runs are presented in comparison to the measurement car runs. These runs take at most 4 minutes each.

With DFI the vertical slice for glide slope near field course and width measurements can be performed at the threshold as well as in the area before the threshold. At the experiment locations a distance of 200m-300m before the threshold has shown to provide good measurements while still being above the airport controlled ground area.

Additionally, the arc for localizer far field course and width measurements can be performed at a higher altitude. While this did not seem to significantly affect the measurements, this does allow for a larger angle to be covered. For the DFI experiments typically an angle of around $\pm 3^\circ$ has been used to stay within the airport controlled ground area. With DFI no arcs have been performed closer to the localizer yet. This will however likely be required if DFI is used to fully replace the measurement car.

The DFI run for localizer structure measurement is a centerline approach, also allowing for measurements of the glide path structure. This centerline approach is currently not flown all the way to the localizer antenna, but for CAT II and III ILS this will be required if DFI is used to fully replace the measurement car.

To ensure repeatability of the results, all DFI runs are flown in automated flight mode. Standard DFI inspection runs can be chosen for any runway available in the FIS database. Adding runway and ILS data to the database requires executing a validation procedure to ensure safe and correct DFI measurements using that data.

EXPERIMENTAL EVALUATION

To test the DFI system's ability to perform the ReFI ground measurements as well as the proposed operational procedures, tests were performed at Deelen air base and

Groningen airport Eelde. The initial tests were performed at Deelen air base while no other traffic was present, allowing to do extensive testing of the sensitivity and accuracy of the DFI system. Then flight checks were performed at Groningen airport Eelde between other traffic. Here also reference ground and flight measurements are available, allowing for a direct comparison. Lastly, we returned to Deelen air base to perform a pre-commissioning of their new ILS. While the final commissioning results are not available to us yet, initial corrections to the ILS signal could be performed and verified based on the DFI measurements.

Below, the performed experiments and gathered results are presented for all three phases of the DFI evaluation.

Initial experiments at Deelen air base

During the experiments at Deelen air base, variations of the DFI measurement program have been performed to assess which runs give the cleanest reproducible measurement results. These tests have allowed us to determine runs where ground reflections and other disturbances in the ILS measurement are reduced, while staying within operational limits of the airfield.

As stated before, a typical DFI measurement program will include a vertical slice maneuver, an arc maneuver and a centerline approach.

For the vertical slice maneuver we always cross the glide path range twice, flying down and back up again. This results in two measurements for each location, allowing to increase accuracy. Furthermore, we have performed flights at the threshold as well as 200m before the threshold, as visualized in Figure 7. Results show that from measurements taken at 200m before the threshold, the far-field glide path angle can be accurately determined.

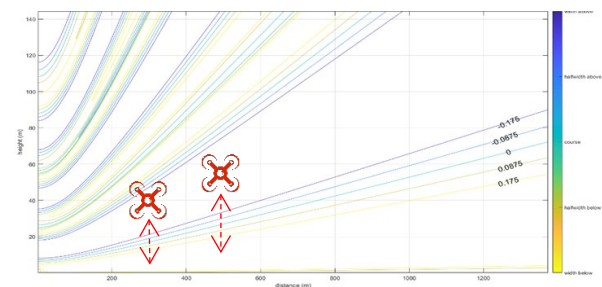


Figure 7 Vertical slice manoeuvres at threshold and 200m before threshold visualised in simulated glidepath iso-lines.

Furthermore, experiments have been performed with level run maneuvers to determine glide path course and width instead of the vertical slice. A glide path level run from 250m before threshold to the glide path antenna was performed. Results, shown in Figure 8, indicate that this

maneuver can be prone to ground reflections. Therefore, such maneuver is not recommended for further use.

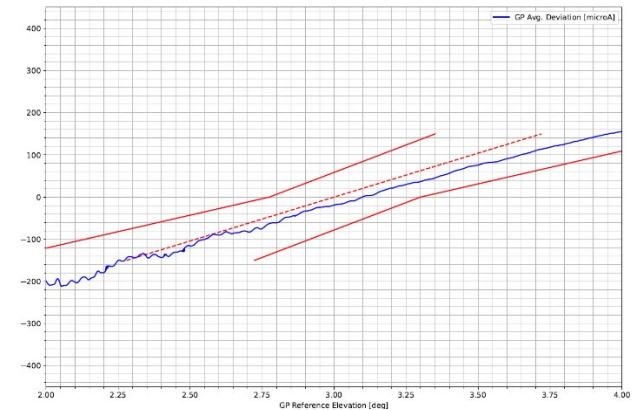


Figure 8 Glidepath course and width measurements based on a level run maneuver.

Experiments at Groningen airport Eelde

The objectives of the tests at Groningen airport Eelde were twofold. Firstly, we aimed to verify and validate the DFI measurements with recent ground and flight check measurements. Secondly, we aimed to test and refine the DFI operation on an active airport.

On various occasions, multiple runs were flown with the Callisto 50. The RTK navigation solution provided consistent and precise position data throughout the tests.



Figure 9 Manned aircraft waiting for ATC clearance while a DFI flight is performed at Groningen airport Eelde.

A vertical glide path slice and $\pm 2.4^\circ$ arc on 15m altitude (see Figure 9) were performed at the threshold to obtain measurements which are directly comparable with the ReFI ground measurements taken by LVNL with their measurement car. The results can be seen in Figure 11 and show that the measurements are practically identical.

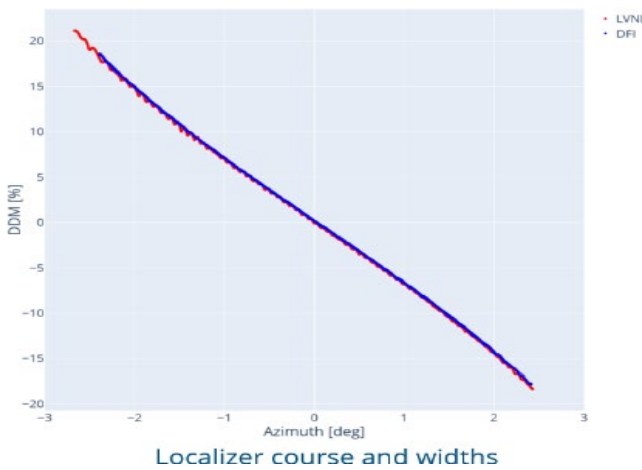
However, we see that for the localizer measurement, the DFI measurements have less oscillations than the measurements from the measurement car.



Figure 11 Arc manoeuvre ground track with ground control station and RTK reference position at Groningen airport Eelde.

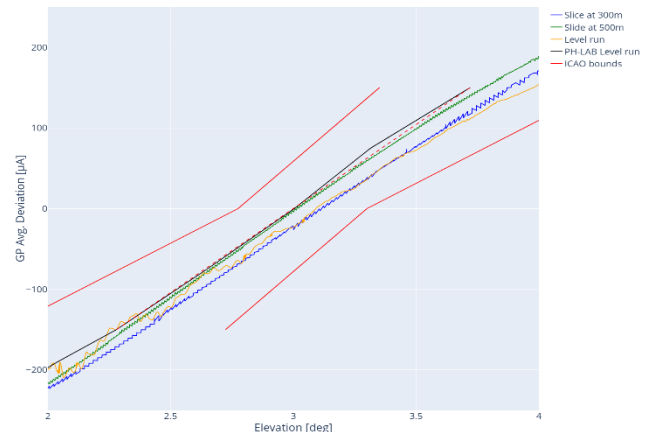


Glidepath course and widths

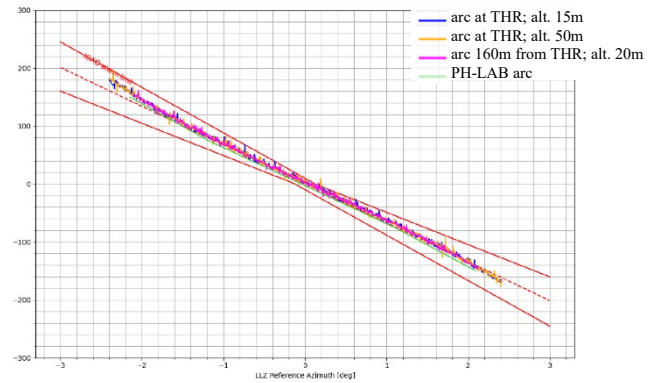


Localizer course and widths

Figure 10 Comparison of course and width ReFI ground measurements between DFI and LVNL measurement car.



Glidepath course and widths



Localizer course and widths

Figure 12 Comparison of DFI course and width measurements with flight check measurements. (THR = threshold)

A comparison of DFI measurements with the flight checks can be found in Figure 12. Here measurements from several variations of the DFI runs are shown. For the glidepath the following measurements are shown:

- Two vertical slices at 300m and 500m from the glide path antenna.
- A level run starting 550m from the glidepath antenna at 20m altitude.
- A level run from the flight check performed by the PH-LAB research aircraft.

It can be seen that all DFI measurements show the same trend as the flight check data and all stay within the ICAO bounds. However, clearly the vertical slice at 500m from the glide path antenna shows the results which are most consistent with the flight checks. The vertical slice at 300m from the glide path antenna shows a small offset. Additionally, the level run measurement shows more oscillations in the further part of the run, where glide path angles are low.

In [4] Skyguide has shown that they also routinely perform Glideslope Vertical Slice measurements in the far field, at

least 1.3km from the glide path antenna, and find a good correlation with flight checks. In the near field Skyguide has never reached an acceptable level of correlation for glide path measurements with flight checks. In our results the drone glide path measurements are already comparable to flight checks at 500m from the glide path antenna.

For the localizer measurements from several arcs are shown:

- Two arcs at the threshold at 15m and 50m altitude with a $\pm 2.4^\circ$ width
- An arc 160m before the threshold at 20m altitude with a $\pm 2.1^\circ$ width
- The arc from the flight check performed by the PH-LAB research aircraft.

It can be seen that all arcs produce nearly identical results and that they are also equivalent to the flight check measurements. For localizer measurements, also Skyguide has shown good correlation between flight checks and measurements at the threshold.

The performed manoeuvres were all coordinated with Eelde TWR, with whom we agreed on an RT phraseology similar to standard RT. In this RT reference was made to run numbers corresponding to an operational plan that was shared with ATC before operation. Initially such operation took some getting used to, but confidence in the operation was quickly gained. This allowed us to operate in-between take-off and landing of aircraft, getting cleared for a run in the same way a manned aircraft is cleared for take-off. Figure 10 shows a situation where the DFI operation is cleared for a run while another aircraft is waiting for its clearance to enter the runway. To allow for such operation, ATC indicated that for each run they needed to know where the drone would be flying, and how long the run would take.

The DFI flight checks at EHGG successfully collected a consistent dataset for verifying DFI measurements and algorithms. The tests demonstrated the effectiveness of using drones for ILS inspection measurements and highlighted areas for improvement in the DFI ground station software

Pre-commissioning at Deelen air base

Most recently, NLR performed pre-commissioning measurements using our DFI system for a new ILS at Deelen air base. These measurements allowed the ILS technicians to better adjust the ILS for the upcoming Commissioning flight check with a flight inspection aircraft. This demonstrated the potential of DFI for Pre-Commissioning work.

The following DFI manoeuvres were flown:

1. Vertical slice for glide path course and width at 300m from the threshold (600 meter from the glide path antenna)
2. $\pm 3.4^\circ$ arc above the threshold at 50 meters altitude for localizer course and width
3. Centreline approach from 250 meter before the Threshold until the glide path antenna.

The specific locations and ranges of the measurements were chosen based on the maximum possible given the controlled ground area and obstacle clearance requirements at Deelen airbase. Given the results obtained at Groningnen Airport Eelde, these runs are expected to give results consistent with flight checks.

Unfortunately, the flight check results of the commissioning flight are not yet available to us, so we cannot present this comparison here. Instead, we will present the measurement results before and after adjustments performed during the pre-commissioning.

Initially, the three runs above were performed giving the results in Figure 13 and Table 4. Figure 13 shows that both the localizer course sector and the glide path course sector are too wide and there are small offsets in the localizer course and the glide path course. After adjustments by the ILS technicians, a new set of measurements was performed using the same three runs giving the results in Figure 14 and Table 3. This shows that after the adjustment the course and width measurements are now much improved.

Furthermore, these results show that the adjustments performed based on the initial DFI measurements had the expected outcome, namely a nearly perfect course measurement and width for both localizer and glide path. Assuming the technicians performed the correct adjustment, this shows that at least the sensitivity of the DFI measurements is correct. In other words, the DFI measurements correctly reflect the change in localizer and glide path signals. Whether an offset in the measurements exist can only be determined when the flight check results are available.

Additionally, during the pre-commissioning we also performed measurements in alarm conditions for the first time. These measurements are not presented here, but showed a change in signal width as expected.

In conclusion, the DFI pre-commissioning clearly showed the advantage of DFI. If the ILS is already aligned and possible antenna position errors have been solved before the actual commissioning takes place, little to no adjustments are necessary anymore during the commissioning flights. In this way the commissioning flights can be flown more efficiently.

Table 3 DFI pre-commissioning measurements before adjustments

Localizer	Unit	Value	Glidepath	Unit	Value
Modulation Depth SDM	%	40.0	Modulation Depth SDM	%	79.8
Sector width	deg	4.74	Sector width	deg	1.61
Width ¼ sector 90 Hz	µA	68.2	Width ¼ sector 90 Hz	µA	0.39
Width ¼ sector 150 Hz	µA	66.5	Width ¼ sector 150 Hz	µA	0.41
Displacement Error	µA	1.21	Displacement Error	µA	3.06

Table 4 DFI pre-commissioning measurements after adjustments

Localizer	Unit	Value	Glidepath	Unit	Value
Modulation Depth SDM	%	40.0	Modulation Depth SDM	%	79.8
Sector width	deg	4.38	Sector width	deg	1.49
Width ¼ sector 90 Hz	µA	73.1	Width ¼ sector 90 Hz	µA	0.37
Width ¼ sector 150 Hz	µA	72.2	Width ¼ sector 150 Hz	µA	0.37
Displacement Error	µA	0.27	Displacement Error	µA	3.01

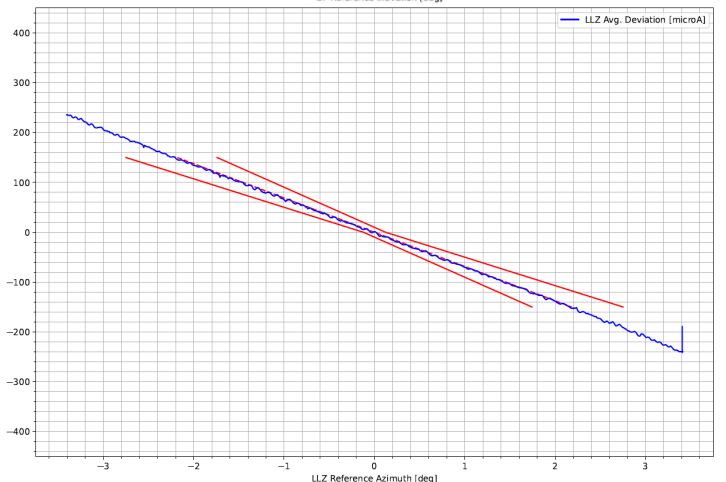
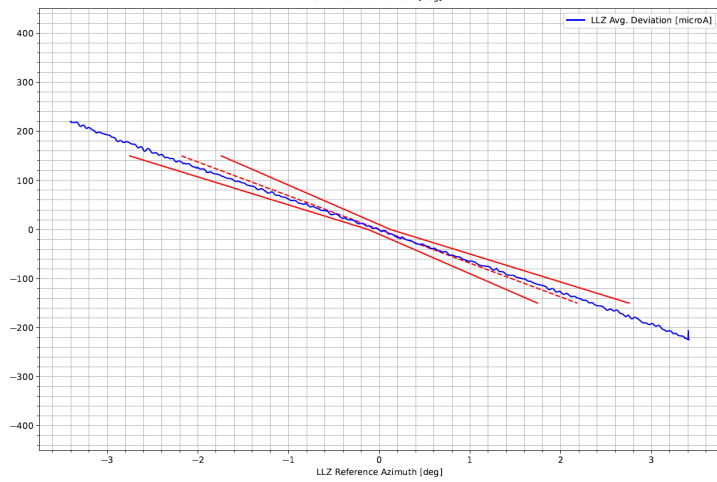
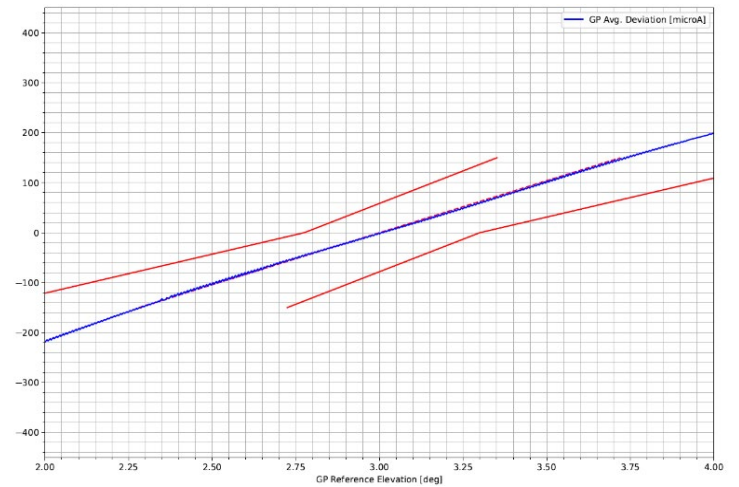
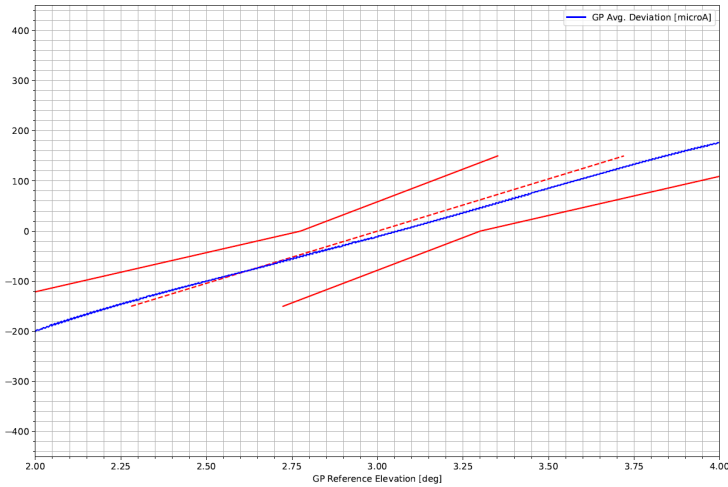


Figure 14 localizer and glide path clearance and width before adjustment, with ICAO limits

Figure 13 localizer and glide path clearance and width after adjustment, with ICAO limits

RECOMMENDATIONS & FUTURE WORK

In the research presented in this paper, it has been shown that DFI has the potential to replace the ground measurements in ReFI. As not all ground measurements have been replicated in the performed experiments, it is recommended that additional tests are performed to also show the effectiveness of DFI in the remaining runs.

Furthermore, to take full advantage of the intended benefits of DFI, the operational efficiency should be increased and a clear operational concept should be developed. One of the challenges in designing such an operation will be to include more automation, while still maintaining the high safety standards expected for (drone) operation in an airport environment.

Furthermore, the paper has shown that DFI has potential uses apart from the ground measurements of ReFI, such as for pre-commissioning. By measuring slightly further away, but still within the airport controlled ground area, measurements can be gained which show good correlation with flight checks.



Figure 15 Fixed-wing drone operation by NLR

Therefore, NLR intends to further develop DFI to allow for full ReFI, including both the ground and flight measurements. To this end, also experiments will be performed with a fixed-wing drone, such as the one shown in Figure 15, which can perform the necessary far field measurements. NLR is currently developing the system, payload and operational plan for the first experiments. Furthermore, NLR is developing an integrated ReFI-DFI operational concept, where a multi-rotor and a fixed-wing drone will perform a full flight inspection.

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