knowledge & development centre
Mainport Schiphol

Optimising Preferred Use of Schiphol runways through flexible ILS maintenance (OPUS)

J.J. Heijstek, J.H.G.J. Lansink Rotgerink, J.Verpoorte, A. Hulzinga, J. Bosch, A.A. Tervoort, J.C. Duringshof, M.Stuip

Date	8 december 2020
Version	V1.0
Document Nr	NLR-CR-2019-507
Executed by	NLR

Dedicated to innovation in aerospace

NLR-CR-2019-507 | December 2020

Optimising Preferred Use of Schiphol runways through flexible ILS maintenance (OPUS)

Final Report

CUSTOMER: Knowledge & Development Centre KDC

NLR – Royal Netherlands Aerospace Centre

Dedicated to innovation in aerospace

EXECUTIVE SUMMARY

UNCLASSIFIED

Optimizing Preferred Use of Schiphol runways through flexible ILS maintenance (OPUS)

Final Report

REPORT NUMBER
NLR-CR-2019-507

AUTHOR(S)
J.J. Heijstek
J.H.G.J. Lansink Rotgerink
J. Verpoorte
A. Hulzinga
J. Bosch
A.A. Tervoort
J.C. Duringshoff
M. Stuip

REPORT CLASSIFICATION
UNCLASSIFIED

DATE
December 2020

KNOWLEDGE AREA(S)
ATM and Airport
Simulation and Validation
Planning, advanced (sensor)information processing and control
Electronics Technology

DESCRIPTOR(S)
Instrument Landing System
Localizer
Glide Path
Calibration
Inspections

Problem area

The aim of the project is to assess the feasibility of additional permanent Instrument Landing System (ILS) signal quality monitoring, enabling a more flexible planning of ILS ground inspections at Schiphol.

Description of work

The general approach is to first develop a theoretical and numerical model of a ILS simulator for the signal in space (SiS) distribution, and use the simulator to correlate the SiS properties at the runway and the same SiS properties next to the runway. Taking into account measurement uncertainty and requirements from ICAO Annex 14, suitable locations next to the runway are selected to be used as Additional Field Monitors (AFM). Continuously monitoring the SiS properties, the AFMs indeed allow for improved assessment of the SiS properties and of the ground measurement periodicity.

Results and conclusions

The project’s approach leads to determining suitable AFM locations for both localizer (LOC) and glide path (GP) antennas.

Measurements for Schiphol localizer LOC 18R have confirmed the usefulness of one AFM at the corresponding glide path mast of GP 18R and one at its shelter.

For the glide path antenna the correlation of the SiS properties at the runway and the SIS properties at the AFM locations selected just outside the GP critical area is valid only under favourable conditions of the soil around the glide path mast which reflects the glide path signal. This document contains a list of soil types and its link to these conditions.

For Schiphol, the soil conditions are favourable most of the time. Therefore, the AFMs for the GP antenna will provide useful information more often than quarterly measurements or even monthly measurements (of approximately 20 minutes each) can provide. Consequently, the results enable a more flexible planning of ILS ground inspections than is currently the case.

Conclusion
In the project an approach for additional permanent ILS signal quality monitoring has been developed. It has been partly verified through measurements. LVNL and NLR are able to fully validate the approach and the results for operational ILS at any airport in The Netherlands. If the validation is successful there, the approach could be applied at Amsterdam Airport Schiphol.

Applicability

The approach is generic and applicable to flat runways with ILS of any category, in the absence of disturbance of the ILS signal in space, e.g. reflectors other than the ground. However, it is anticipated that it is applicable to hilly runways as well, e.g. to RWY 21 at Maastricht-Aachen Airport.

NLR
Anthony Fokkerweg 2
1059 CM Amsterdam, The Netherlands
p) +31 88 511 3113
e) info@nlr.nl i) www.nlr.nl

Dedicated to innovation in aerospace

NLR-CR-2019-507 | December 2020

Optimising Preferred Use of Schiphol runways through flexible ILS maintenance (OPUS)

Final Report

CUSTOMER: Knowledge & Development Centre KDC

AUTHOR(S):

J.J. Heijstek	NLR
J.H.G.J. Lansink Rotgerink	NLR
J. Verpoorte	NLR
A. Hulzinga	NLR
J. Bosch	LVNL
A.A. Tervoort	LVNL
J.C. Duringshoff	LVNL
M. Stuip	LVNL

NLR – Royal Netherlands Aerospace Centre

CUSTOMER	**Knowledge & Development Centre KDC**
CONTRACT NUMBER	**KDC2018005**
OWNER	**Knowledge & Development Centre KDC**
DIVISION NLR	**Aerospace Operations**
DISTRIBUTION	**Limited**
CLASSIFICATION OF TITLE	**KDC UNCLASSIFIED**

APPROVED BY :		
AUTHOR	**REVIEWER**	**MANAGING DEPARTMENT**
 J.J. Heijstek 2020.12.08 11:33:03 +01'00'	 Digitally signed by Jaco Verpoorte Date: 2020.12.08 11:36:24 +01'00'	 Henk van Dijk 2020.12.08 12:08:25 +01'00'

Summary

This document comprises the final report of the NLR OPUS project contracted by Knowledge & Development Centre March 29th, 2018, under contract number KDC2018005. The acronym OPUS stands for "Business Case - Optimising Preferred Use of Schiphol runways through flexible ILS maintenance". The aim of the OPUS project is *to assess the feasibility of additional permanent ILS signal quality monitoring, enabling a more flexible planning of ILS ground inspections at Schiphol*. This final report contains an overview of the approach, the results and limitations, and conclusions and recommendations. It is one of three reports delivered during the OPUS project. The first of the two other reports describes the theoretical assessment, leading to a proposed approach, and the second one describes the test period and its outcome. Both reports are summarized in this final report.

It is expected that the approach comprising the use of Additional Field Monitors (AFM), a monitor system next to the runway continuously measuring the ILS signal, allows to assess the quality of the ILS signal all the time for the localizer (LOC), and *most of the time* for the glide path (GP). This latter behaviour may be referred as *piecewise continuous assessment*.

Based on simulations, for the localizer suitable monitor positions have been selected which have been verified by corresponding measurements. As time progresses, the continuous monitoring of the localizer signal (drift) allows improved assessment of the time interval between each pair of successive ground based localizer calibrations. Moreover, using the localizer simulations, a first assessment of the impact of some aberrations of the antenna array is presented. The results obtained are promising but more work needs to be done before final conclusions can be drawn. It should be noted that the OPUS project is a feasibility study including safety case aspects, but it is not a complete safety assessment.

Based on simulations, for the glide path antenna, locations have been selected where AFM continuously measuring the glide path signal (drift) allows improved assessment of the time interval between each successive pair of ground based glide path calibrations. More specifically, for particular conditions of the reflecting ground plane near the glide path antenna array, the simulations indicate that AFM measurements suffice to evaluate the quality of the glide path signal in space above the (extended) runway. These particular conditions are linked to the reflection ground plane relative permittivity ε_r exceeding the value 10. These results are still to be verified by measurement.

The business case on optimisation of the preferred use of Schiphol runways through flexible ILS maintenance concentrates on two aspects: technical feasibility and return of investment. The first aspect has been concluded positively in the sense that implementing AFM to achieve more flexibility in the runway occupancy for ILS measurements appears to be feasible, although further confirmation by validation exercises still has to be done. The second aspect has been discussed on conceptual level, namely only in terms of runway occupancy time, providing for all stakeholders a basis to estimate their individual return of investment. Pending their individual business interest, the business case can be either positive or negative. Based on initial LVNL estimates regarding runway occupancy times before and after implementation of AFM, the business case is expected to be positive.

In this document, Chapter 1 contains an introduction to the project's goals, Chapter 2 describes an overview of the approach and the results, and Chapter 3 summarizes the conclusions and recommendations.

Contents

Abbreviations & acronyms

ACRONYM	DESCRIPTION
AFM	Additional Field Monitor
CSB	Carrier with Side Bands
DDM	Difference in Depth of Modulation
FFM	Far Field Monitor
FI	Flight Inspection
GP	Glide Path
ICAO	International Civil Aviation Organisation
ILS	Instrument Landing System
KDC	Knowledge & Development Centre
LOC	Localizer
LVNL	Luchtverkeersleiding Nederland (Air Traffic Control The Netherlands)
NLR	Koninklijk Nederlands Lucht- en Ruimtevaartcentrum (a.k.a. Royal Netherlands Aerospace Centre)
OPUS	Optimising Preferred Use of Schiphol runways through flexible ILS maintenance
PMP	Project Management Plan
ReFI	Reduced Flight Inspection
SBO	Side Bands Only
SiS	Signal in Space
THD	Threshold centre: the centre point of beginning of that portion of the runway usable for landing [1]

1 Introduction

The usefulness of an Instrument Landing System (ILS) for precise guiding of aircraft approaching the runway is illustrated in this online video[1]. How an ILS works can be viewed in this online video[2]. The performance requirements for a runway's Instrument Landing System are specified in ICAO annex 10 "Aeronautical Telecommunications" [2], while the guidance for calibrating an ILS is given in ICAO DOC 8071 [3]. Measurements for calibration of the ILS are usually carried out by flight tests, ground tests on or near the runway, and equipment tests. While these calibrations are taking place, the runway has to be closed, which may impact airport capacity.

In order to minimise the impact of the ILS measurements on the capacity of busy Schiphol Airport, LVNL and NLR have since 2006 carried out a number of projects aiming to reduce the number of ILS flight tests without compromising safety (see references [4], [5], [6], [7]). In these projects, NLR performed the analysis and justification of LVNL's conjecture on predicting (up to certain accuracy) specific ILS flight tests by ground measurements. The results allowed LVNL to reduce the total number of ILS flight test runs at Schiphol from 29 to 3, that is, by about 90%. This reduction of inspection flights contributed to the abatement of noise by measurement flights as well. Consequently, the ILS ground measurements then became the dominant factor in runway occupancy time.

The project "Business case - Optimising Preferred Use of Schiphol runways through flexible ILS maintenance", for brevity referred to as "OPUS", aimed to assess the feasibility of additional permanent ILS signal quality monitoring, enabling a more flexible planning of ILS ground inspections at Schiphol. This document is the final report of OPUS. It contains an overview of the project's theoretical and practical approach, the expected results and limitations, the actual results, and finally conclusions and recommendations.

It should be noted that the project was a feasibility study including some safety case aspects, yet a complete design and safety assessment were out of scope.

[1] https://youtu.be/sOokXvNaJdI
[2] https://www.youtube.com/watch?v=PziW3iKF5GI

2 Overview of study

2.1 Customer requirements

The customer Requirements and Product Specifications as defined in the Call for Tender [8] were the following:

1. Perform a theoretical assessment of permanent ILS monitoring configurations, in terms of antenna types and positions as well as expected measurement quality.
2. Provide a proof of concept for permanent ILS monitoring by building a test setup in a controlled environment, that is representative for ILS at Schiphol and perform tests that reveal measurement quality and stability.
3. Determine the operational benefits: provide a rationale to what extent ground inspection deadlines can be reconsidered based on the permanent ILS monitoring data.
4. Consult LVNL on the practical implementation of permanent ILS monitoring at Mainport Schiphol, in terms of optimal antenna types and positions, data distribution and software processing.

2.2 Desired results

Usually, due to the high traffic density at Schiphol Airport, time slots to perform ILS calibrations are quite small. Having improved insight in the evolution of the ILS signal quality allows moving the calibration time slots without compromising safety. The desired result is an affirmative answer to all four requirements in the form of a practical approach using ILS performance monitors permanently placed near the runway at allowed locations and able to continuously and independently from the ILS system provide adequate information on the quality of the transmitted signal in space. The information provided by the monitors should be helpful to decide if, and if so to which extent, current ground measurement time slots may be moved.

2.3 Approach

In sections 2.3.1, 2.3.2 and 2.3.3 below, a summary of the theoretical assessment in the OPUS project is presented. More details of the results are provided in the separate OPUS project report [9], in which several AFM methods are discussed which could be brought further towards validation.

2.3.1 General approach

As already mentioned above, the general approach is described in detail in the Theoretical Assessment Document [9]. The basic idea is to determine suitable positions next to the runway for Additional Field Monitors (AFM) continuously measuring the ILS Signal in Space (SiS), particularly its property Difference in Depth of Modulation (DDM), and to determine “new” SiS requirements, particularly DDM limits, just above these AFM locations corresponding one-to-one to DDM limits just above THD, the threshold centre, i.e. the point of intersection of threshold and the runway centreline.

After confirming that the ILS performs according ICAO requirements [2], it is expected that the following correlation statement holds.

2.3.2 Correlation statement ("Rule of thumb")

For all prescribed limits on the DDM at the measurement locations at the runway, there exist "new" limits at the AFM locations, such that if the DDM is in between the "new" limits at the AFM locations, then it is in between the prescribed limits at the measurement locations at the runway.

Note that the complement is not necessarily true, that is, even if the SiS is outside limits at the locations next to the runway, it may still be in between limits at the measurement locations at the runway.

2.3.3 Approach details

Prescribed DDM limits at measurement locations at the runway, say at threshold centre THD, could for example be defined by applying the parameter ratios (implied alarm ratio, and adjust and maintain ratio) appearing in [4], [5] and [7] to the ICAO limits on DDM at THD. Assuming the correlation statement in section 2.3.2 is true, it would follow that if the SiS satisfies the "new" limits at the AFM locations, then the SiS would satisfy the ICAO limits along the entire final approach path. Hence, as long as the SiS satisfies the "new" limits at the AFM locations, ground measurements with the measurement car at the runway can be postponed. Note that the converse is not necessarily true: the SiS can be within ICAO limits along the approach path even if it is outside the prescribed DDM limits at THD, and it can be inside the prescribed limits at THD even if it is outside the "new" limits at an AFM location.

The location of the AFM as well as the "new" DDM limits can be constructed using the DDM static iso-surfaces determined numerically by a sufficiently accurate ILS simulator. For any given DDM value just above THD, one can use the corresponding DDM iso-surface to search for an AFM location next to the runway where that iso-surface passes above at a for measurements usable height. This way, a mapping Γ can be defined which has properties similar to the identity. Choosing appropriate AFM locations next to the runway is an important part of the project. Reference [10] provides requirements on the AFM locations, which limit the freedom of selection.

A partially validated ILS simulator was used to study the properties of the mapping Γ from the DDM values just above such an AFM location and the corresponding DDM values just above threshold centre THD. The mapping Γ depends on both locations and on the DDM iso-surface which in turn depends on the transmitted signal in space, which in turn depends on the transmitting system and (primarily for the glide path system) on the environmental circumstances.
The mapping Γ may change if the DMM changes, which happens for instance by changes in the SiS as a result of variations in transmission parameters or the environmental circumstances. Such changes of Γ are allowed as long as the mapping remains smooth, invertible, and in some sense monotonic.

More precisely, in mathematical terms, Γ is a continuously differentiable one-to-one mapping uniformly with respect to the model parameters *h*, *SBO/CSB*, ε_r, and σ, where *h* stands for the antenna height above ground, *SBO/CSB* for the ratio of the level of the transmitted Side Bands Only signal and the level of the simultaneously transmitted Carrier with Side Bands signal, and ε_r respectively σ stand for the relative permittivity and absolute conductivity of the signal reflecting part of the ground near the mast supporting the ILS glide path antenna elements. These parameters, including their corresponding intervals of applicability, represent operational circumstances. Monotonicity of Γ is required in the sense that any increase (resp. decrease) of DDM at an AFM location due to a change of a model parameter, corresponds to an increase (resp. decrease) of DDM at the runway measurement location due to the same change. The sign of monotonicity (increase or decrease) must be the same irrespective the choice of parameter. The ICAO requirements on DDM and the abovementioned requirements on mapping Γ lead to limits on the range of the parameters. Using the inverse of mapping Γ, one can determine for each set of DDM limits above threshold centre THD a corresponding set of “new” DDM limits, also called “OPUS implied” limits, just above the AFM location.

In past projects Reduced Flight Inspection Phase 1 and Phase 2, a mapping similar to Γ was used to link the DDM at a location along the glide path and the DDM at THD. Details on the mathematical description of this similar but not precisely the same mapping as Γ are in references [4], [5]. The mappings are not the same, because here Γ is defined transversal to the runway centreline, whereas in references [4] and [5], the mapping is defined along the extended runway centreline. However, both mappings are based on the DDM iso-surfaces. Similar to expression (17) in [5], one can introduce for a measurement point R at the runway (more precisely, the threshold centre THD) and a point A at an AFM location, the parameter sensitivity ratio $\Pi_{p_0,R,A}$ at parameter value $p_0 \in \{p \mid p = (h, SBO/CSB, \varepsilon_r, \sigma)\}$ as follows:

$$\Pi_{p_0,R,A} \equiv \frac{\partial \Gamma}{\partial p}(p_0;R) \bigg/ \frac{\partial \Gamma}{\partial p}(p_0;A) \approx \frac{DDM(p;R) - DDM(p_0;R)}{DDM(p;A) - DDM(p_0;A)} \quad (p \approx p_0) \tag{1}$$

The ranges around the nominal values p_0 of the parameters *h, SBO/CSB,* ε_r and σ are chosen such that $DDM(p_0;R)$ complies to the ICAO requirements and $\Pi_{p_0,R,A}$ has the same sign for all values of the parameters p_0 in the range. Numerical values of $\Pi_{p_0,R,A}$ for LOC 18R as well as GP 18R have been described in the OPUS test report [11].

Two methods to determine the mapping Γ numerically were investigated, the so-called *indirect method* and the *direct method*. The *indirect method* relies on constructing the DDM iso-surfaces using the ILS simulator and *measured input* to the simulator, particularly the model parameters *h*, *SBO/CSB*, ε_r and σ. Measurement of *h* may be done visually, electromagnetically, or otherwise. The ratio *SBO/CSB* is measured continuously by the near field monitor.

For the localizer, parameter *SBO/CSB* suffices. Validating the indirect method means making sure that given sufficiently accurate measurements of this model parameter, the simulated DDM represents the actual DDM sufficiently accurate.

For the glide path, the situation is more complicated as the antenna height *h* and the relative permittivity ε_r of the soil in front of the antenna do influence the signal in space. Measuring relative permittivity ε_r could be done using capacitance probing [12], but it is impractical due to its limited domain of application: the probe may be unusable during e.g. the winter season (frost). Applying as an alternative an electromagnetic method using a spare frequency near the GP frequency, proved to be problematic due to lack of allowed antenna locations [10]. Measuring soil conductivity may be done as in [13]. It appears, just as in the Reduced Flight Inspection projects, that the conductivity σ plays a minor role and could be neglected.

The relative permittivity of the soil depends on the type (sand, clay, etc.). It also depends on the water content of the soil. Moreover, a layer of snow on the soil will not only affect the reflection of the GP signal due to its relative permittivity, but also reduce the distance *h* between the reflection surface and the GP antenna elements. More specifically, the skin-depth of the soil at the GP frequency may be in the order of 1 to 10 m, hence for an accurate assessment of the actual relative permittivity, the relative permittivity should be applied at the correct reflection surface, which is below the soil surface [14].

Several methods are available to measure the permittivity of the soil. One method is to use a set-up with a capacitor which has the soil as medium. The capacitance will vary proportionally to the permittivity. After calibration with a known dielectric (or air), other dielectric values can be measured. It should be noted that this method often uses a single frequency for the measurement. However, the permittivity may be frequency dependent so an assessment should be made of the applicability of the measured value to other frequencies. The best measurement frequency is the one which is also used in the application (e.g. the GP system).

The limitations of the indirect method for the glide path antenna lead to the decision to consider *the direct method*, in which a DDM iso-surface is selected based on a (theoretical) DDM measurement at threshold centre THD, while AFM sensor locations next to the runway are searched for, allowing to measure the DDM value of the same iso-surface at a practically feasible height.

2.4 Results and limitations

In sections 2.4.1 and 2.4.2 below, a summary of the technical results of the OPUS project is presented. More details of the results are provided in the separate OPUS project report [11] containing the verification test plan, test description and test results.

2.4.1 Results for the localizer

For localizer, the approach works if AFM locations are selected at two already allowed locations: the GP mast of the same runway and the shelter of that GP antenna (see both locations indicated in Figure 1). The direct method is applied. At each location additional horizontally polarised antennas have been installed to measure the localizer DDM, e.g. the value corresponding to angle 1.97 degrees from CL.

Figure 1: View on the location of GP 18R and its shelter (©Google Earth)

The expected DDM value is indicated in blue font in Table 1, the measured values in Figure 2 (the blue graph).

Table 1: Position of LOC measurement location and expected DDM

LOC 18R	*Distance along runway*	*Distance across runway*	*DDM*	*Angle with respect to CL*
AFM	3480 m	120 m	**19.1%**	1.97°

Similar results were obtained for the AFM at the shelter of GP 18R. The measurement accuracy suffices to link the ICAO requirements on LOC 18R DDM one to one to the measured values. More details can be found in OPUS test report [11].

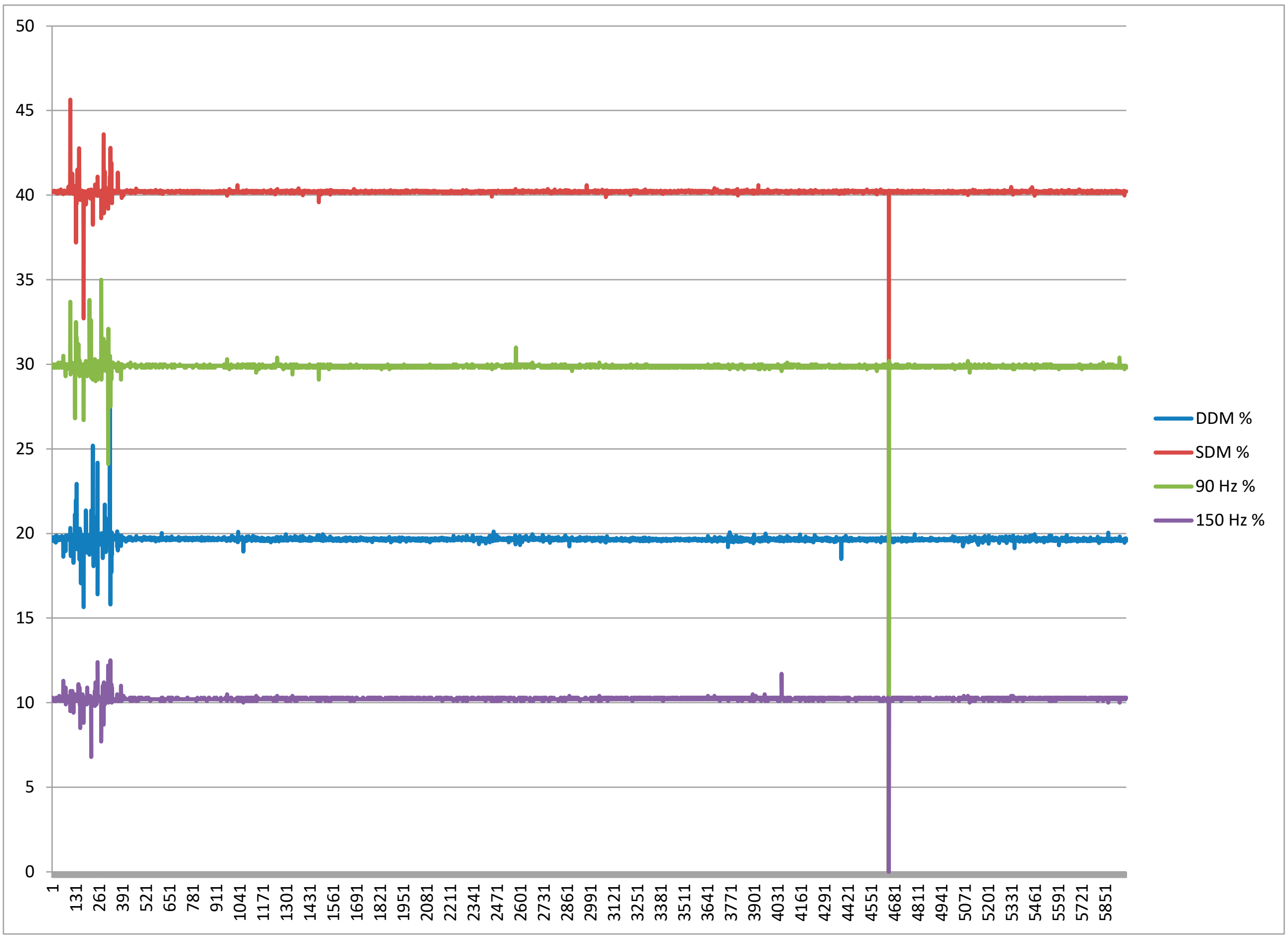


Figure 2: Measurements at Schiphol LOC 18R with EVS200 analyzer and antenna at GP mast 18R

An impression how for the localizer a DDM interval above the runway is mapped to a similar interval next to the runway is given in Figure 3, which is taken from the OPUS theoretical assessment document [9], figure 5. The red interval between half-width DDM tolerance limits at the runway is mapped to the green interval at the GP mast located next to the runway. Note that the orientation of the green interval is inverted compared to the red one, which illustrates the fact that the partial derivative of the mapping Γ with respect to parameter *SBO/CSB* is negative.

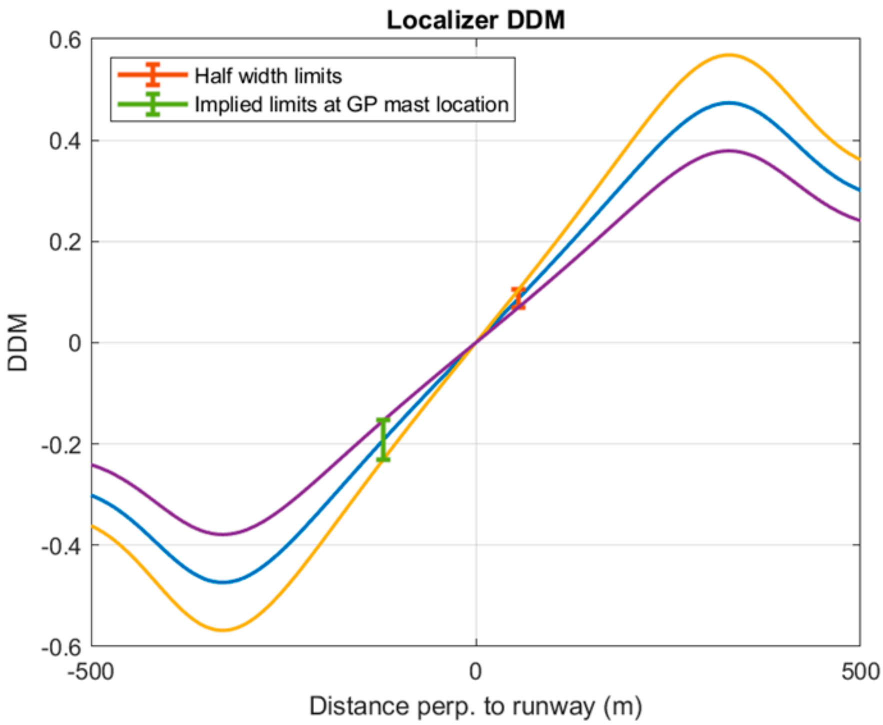


Figure 3: Indication of localizer half-width DDM tolerance limits at the runway mapped to similar limits at the GP mast. The blue line corresponds to SBO/CSB value for which the simulated DDM curve passes through the nominal DDM half-width points, the yellow and purple lines indicate the DDM curve associated with the half-width tolerance limits

As time progresses, the continuous monitoring of the localizer signal (drift) allows improved assessment of the time interval between each pair of successive ground based localizer calibrations.

2.4.2 Results for the glide path

For the glide path antenna, several candidate AFM locations were considered, of which the most promising ones (in front of the runway, approximately 120 m from runway extended centreline, 300 m from the GP mast, height approximately 15 m) were proposed to the authorities (EASA, represented by Schiphol Group) for approval. Unfortunately, these locations could not be allowed, because, by interpretation of the EASA certification specifications for aerodromes design [10], the AFM mast was not considered to be an object essential for navigation or aircraft safety.

Using the DDM iso-surfaces, the search for suitable AFM locations eventually led to candidates just outside the GP critical area, which appear to fulfil all requirements. Five of these suitable locations are indicated by coloured dots in Figure 5. The locations were determined using the DDM iso-surfaces of width, half-width and course, that is, for the DDM values 0.175, 0.0875, 0.0, -0.0875 and -0.175. See Figure 4. At these locations, according to [10], AFM masts of height 1 meter are allowed.

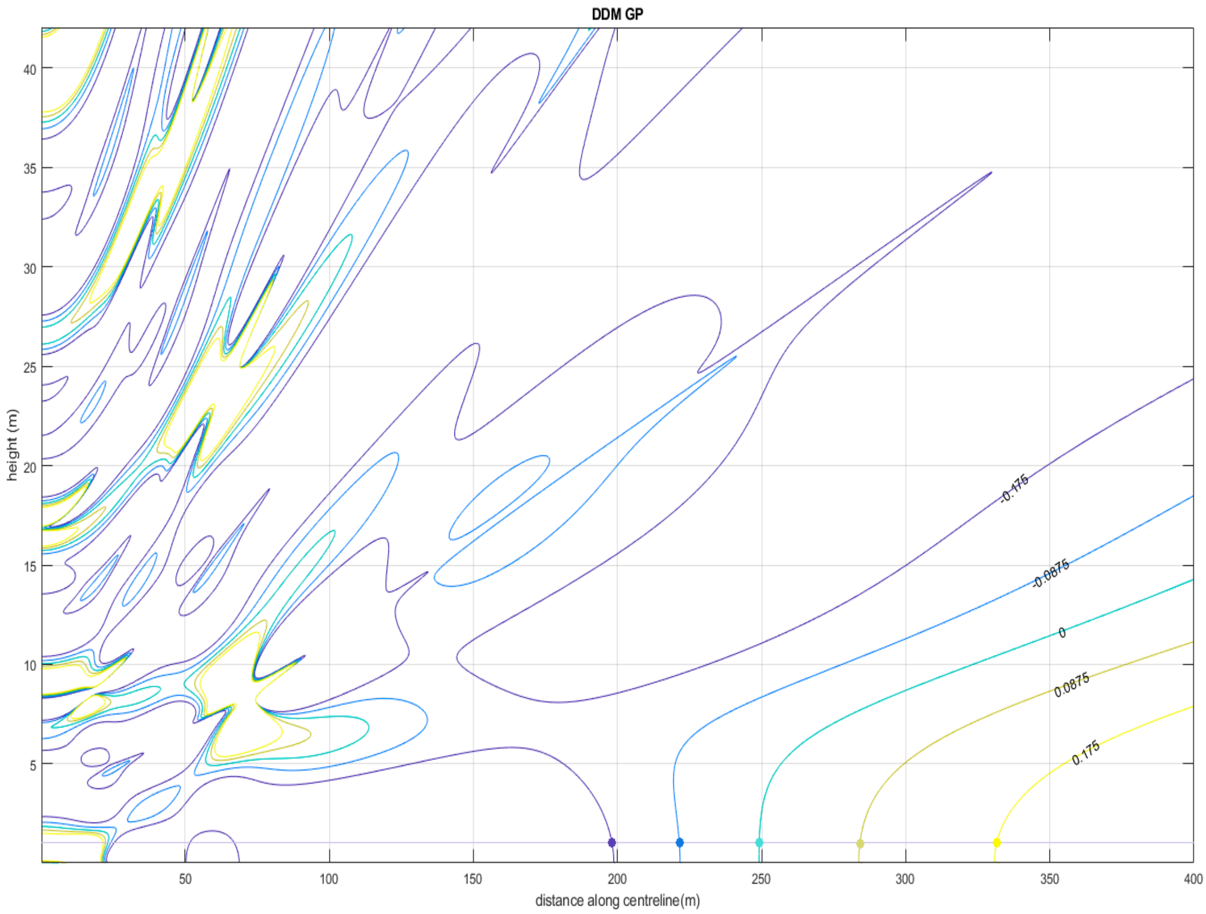


Figure 4: Simulated DDM in vertical plane parallel to the centreline at 157 m distance from centreline (at the same side of the runway as the GP antenna)

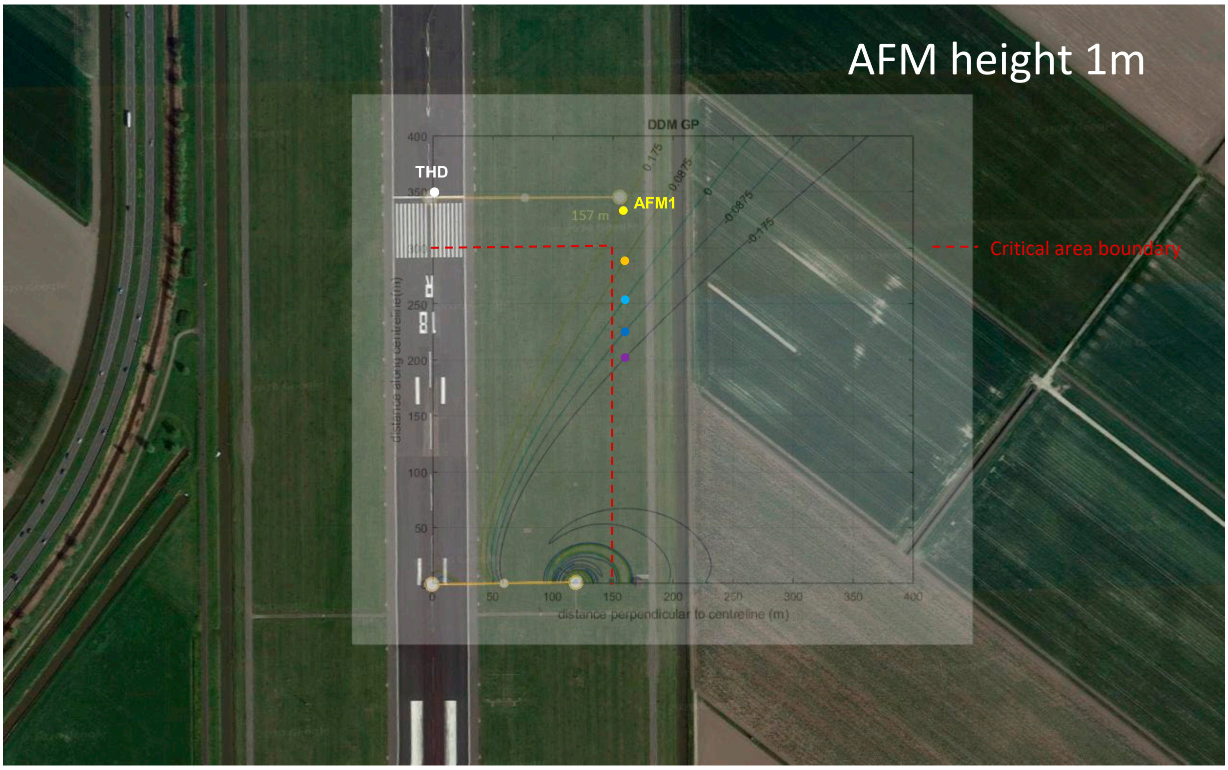
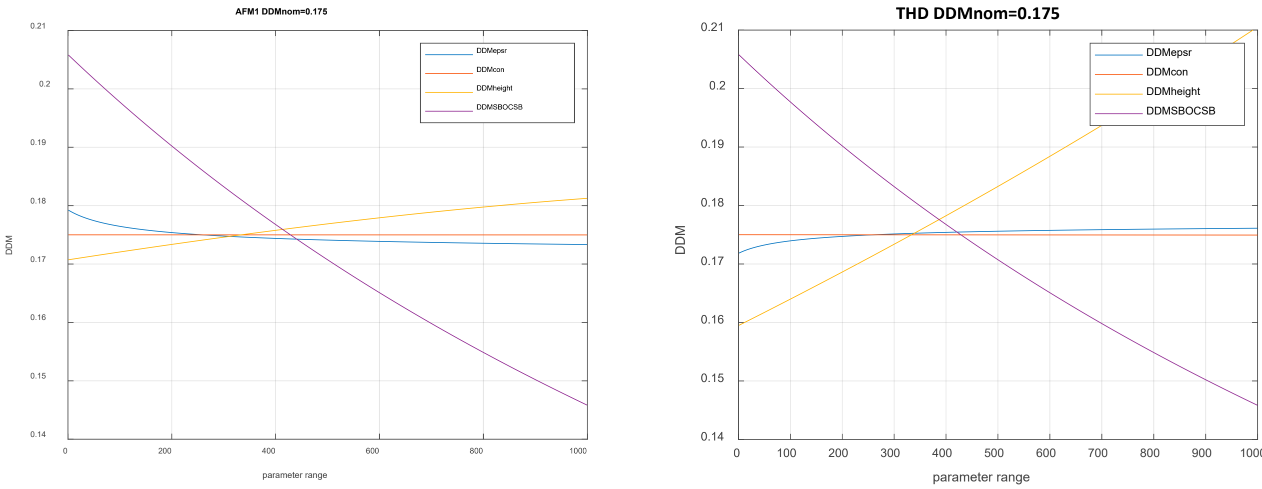


Figure 5: AFM locations near runway 18R indicated by the coloured dots just outside of the critical area

The influence of variation of the model parameters *h*, *SBO/CSB*, ε_r and σ on the DDM has been evaluated. At the first AFM location (say AFM1, indicated by the yellow dot in Figure 5), the variation in DDM as a result of variation of the model parameters *h*, *SBO/CSB*, ε_r and σ is shown in Figure 6. In this figure the parameter range has been normalized between 0 and 1000 in order to have a common axis for all four parameters.



Epsr=10 (variations 3 to 30)
Conductivity = 0.01 S/m (variations 0.001 to 0.03)
Height = 0 m (variations -0.15 to +0.30)
SBO/CSB=0 (variations 0.85 to 1.20)

Figure 6: DDM variations as a result of variation in relative permittivity, conductivity, ground plane height and SBO/CSB ratio for both AFM1 and THD (nominal DDM value is +0.175)

From this simulation (Figure 6) the sensitivity and the sign of the partial derivatives of the DDM for variations in the parameters can be derived. It is clear that the sensitivity of the DDM for variations in conductivity is limited.
It can also be observed that there is an almost linear relation between SBO/CSB and DDM. The sign of the partial derivative of DDM for these parameters is given in Table 2.

Table 2: Sign of partial derivatives of DDM for the parameters relative permittivity, conductivity, ground plane height and SBO/CSB ratio

Derivative	AFM				THD			
	epsr	con	height	sbocsb	epsr	con	height	sbocsb
DDM=0.175	-	-	+	-	+	-	+	-

Figure 6 and Table 2 indicate that DDM is a monotonically decreasing function of *SBO/CSB* both at THD and at AFM1. Further, DDM is monotonically increasing as a function of the height parameter *h* at both locations THD and AFM1. This implies, based on expression (1) that the parameter sensitivity ratio $\Pi_{p_0,\,THDC,\,AFM1}$ is positive for parameters $p_0 \in \left\{ p \mid p = (h, SBO/CSB, \sigma) \right\}$ for any fixed value of relative permittivity ε_r (in its range). However, DDM as a function of ε_r is (slightly) decreasing at AFM1 while it is (slightly) increasing at THD, which implies that $\Pi_{\varepsilon_r,\,THDC,\,AFM1}$ is negative for fixed values of *h*, *SBO/CSB*, and σ. In general the sign of the partial derivative of the mapping Γ is the same at the AFM compared to the sign at THD, except for the partial derivate for the relative permittivity. This behaviour makes it more difficult than in [4], [5] and [7] to predict the relation between the DDM at the AFM and the DDM at THD.

Indeed, the total DDM variation for a combination of parameter variations at AFM1 can include a cancelling effect, whereas at THD they can include a cumulative effect (or vice versa). Using the fact that variation of parameter ε_r leads to small DDM variation of at most approximately 0.7 %DDM at AFM1, respectively 0.5 %DDM at THD (see Figure 6), one finds for values of $\varepsilon_r \geq 10$, these DDM variations reduce to approximately 0.3 %DDM, resp. 0.2 %DDM. Note that these values are of comparable size to the measurement uncertainty which is approximately 0.19 %DDM (for expanded uncertainty k=3). See Table 4 in [11]. One can include the DDM variations induced by ε_r in the measurement uncertainty and use only one fixed value of ε_r in the mapping Γ, say $\varepsilon_r = 10$ (its nominal value).

As time progresses, the continuous monitoring of the glide path signal (drift) allows improved assessment of the time interval between each pair of successive ground based glide path calibrations.

More details can be found in the test report [11].

2.5 Business case

The ILS inspections at Schiphol Airport are performed periodically by monthly, quarterly and yearly ground measurements. Furthermore each ILS installation is checked by flight inspections twice each year.

Figure 7: Preparation at Schiphol Airport of a ground measurement of the ILS GP signal in space

The quarterly and monthly ground inspections take up most of the time; the average runway occupancy time of each inspection is presented in Table 3 and Table 4. The values in these tables are based on information of ground measurements performed between the years 2017 and 2020. The runway occupancy time depends on the type of ILS installation. It appears, measurements on older types of ILS generally require more time that those of newer types.

Table 3: Average duration of runway occupancy time due to LOC ground measurements

Measurement type	Average runway occupancy time	Frequency of ground measurements per year per LOC	Total average runway occupancy time per year per LOC
Quarterly LOC	1h40’	4	6h40’
Yearly LOC	2h15’	1	2h15’
Total LOC		*5*	*8h55’*

Table 4: Average duration of runway occupancy time due to GP ground measurements

Measurement type	Average runway occupancy time	Frequency of ground measurements per year per GP	Total average runway occupancy time per year per GP
Quarterly GP	1h30’	4	6h00’
Yearly GP	2h25’	1	2h25’
Total GP		*5*	*8h25’*

For safety reasons the periodic ILS ground measurements must be completed within a specific limited maintenance time window (of a few weeks). These measurements are necessary to either maintain confidence that the transmitted ILS signal in space meets the ICAO requirements, or are a trigger to make adjustments to the system so as to meet those requirements (again) and restore confidence.

Most of the time, the landing operation on the runway is given priority and the ILS ground maintenance is rescheduled to a later moment within this window. Consequently, as the end of the maintenance window is nearing, the priority of the ILS ground measurements has to be increased, in order to prevent the ILS be declared unserviceable which happens once the deadline has been passed. So at some point in time, the ILS ground maintenance must take place.

Because AFM measurements take place frequently, any drift of the monitored parameters (e.g. course position) in the far field as a result of changing circumstances (e.g. weather conditions), can be better detected than using the ground measurement facility. This allows to more accurately estimate the future moment that the signal in space could violate the ICAO requirements, which in turn can be used to justify to which extent maintenance can be postponed in lieu of normal operation. However, from the OPUS feasibility study it also became clear that the OPUS concept does not allow for measurement of the complete set of ILS parameters that are measured by ground inspections. For instance, the current OPUS concept of AFM does not include measurements of the ILS course structure (as it would require a large amount of AFM sensors).
Table 5 shows the duration of LOC ground measurements which can be scheduled in an extended maintenance window with the aim to avoid conflicts with the operational use of the runway. Taking into account *Table 4*, this means that on average only approximately *8h55’-6h40’ = 2h15’* conflicting runway occupancy time per LOC per year remains.

Table 5: Estimation of LOC ground measurements duration for which the maintenance window could be extended

Measurement type	Estimated duration allowing for conflict free planning	Frequency of ground measurements per year per LOC	Estimated total average runway occupancy time per year per LOC
Quarterly LOC	1h20’	4	5h20’
Yearly LOC	1h20’	1	1h20’
Total LOC		*5*	*6h40’*

For GP the analysis is more complex than for LOC, since the validation of the theoretical approach for GP still has to be performed. It is assumed, that similar results will be obtained. An example based on assumed figures including those in Table 3, Table 4, and Table 5, is in Appendix B. The reader may replace the figures with relevant ones to obtain a realistic value of RoI.

Assuming realistic values for runway occupancy times in Appendix B lead for all stakeholders to an acceptable RoI, the implementation could be performed stepwise per ILS, where the corresponding runways are ordered according usage density (frequency), since for these runways the use of AFM is most beneficial. Thus, as Schiphol runways 18R and 06 are used most frequently, the ILS for those runways could be treated first. Depending on the results, including the actual RoI, it could be decided whether or not to implement AFM for the runway next on the priority list.

2.6 List of deliverables

The OPUS project started in March 2018 and finished December 2020. The deliverables are:

D1. Theoretical Assessment Report, providing the theoretical basis for the OPUS approach.
D2. Simulation Results report, providing the basis for verification and validation steps.
D3. Verification Test Plan and Verification Test Description, providing detailed descriptions of the tests.
D4. Verification Test Report, including a comparison of LOC field measurements and simulation results.
D5. Final Report, including a summary of the approach, conclusions and description of potential ways forward.

Deliverable D1 is in reference [9], deliverables D2, D3 and D4 are combined in one document, reference [11], and deliverable D5 is this document.

2.7 Comments

The project team investigated first the indirect method, in which the applicable parameters (*h*, *SBO/CSB*, ε_r, σ) of mapping Γ are measured and fed to the simulator in order to predict the DDM values. After the details of the indirect method became clear, including the limitations to determine the relative permittivity ε_r of the soil in the first Fresnel zone of the GP signal, it was decided to switch to the direct method, which meant using AFM measuring the transmitted signal in space.

The decision to switch to the direct method meant loss of considerable time and budget, which was partly compensated by performing the direct method verification measurements concerning the localizer on site at Schiphol Airport, thereby avoiding the necessity to set up a scaled localizer measurement at NLR Flevoland.

Because the first selection of AFMs for glide path at Schiphol Airport was rejected based on ICAO Annex 14 requirements, instead of preparing scaled measurements for these AFMs at NLR Flevoland, the search for alternative AFM locations for GP continued via simulations. The result was a set of five locations just outside of the GP critical area, which according to the simulation results should be suitable for AFM of GP. However, due to budget limitations this result could not be verified by measurements within the OPUS project.

With only limited information on the business aspects of required runway usage and runway occupancy time, the description of return of investment remained on conceptual level. However, the description provided may be used by the stakeholders as a basis to estimate their individual return of investment.

3 Conclusions and recommendations

3.1 Conclusions and recommendations on technical level

The customer requirements listed in section 2.1 are fulfilled to the extent that a generic and robust approach has been developed which shows additional field monitoring of localizer is possible allowing continuous assessment of localizer transmission quality, and assessment of the glide path transmission quality is well possible if the following condition is fulfilled: the relative permittivity ε_r of the soil in the first Fresnel zone of the glide path antenna exceeds 10. Moist ground and pastoral soil have this property. For Schiphol Airport, which is located in a polder and only about 17 km from the west coast of The Netherlands, experiencing fog and precipitation, it is usually the case that ε_r exceeds 10. However, for dry sand and asphalt, the value of ε_r may drop to 2.7 to 5, so for the glide path antenna the approach may lead to practically unusable “new” limits. A mitigating measure could be to try and apply the indirect method for such values of ε_r. Due to budget limitations, this mitigation could not be further explored in OPUS, and may be researched in a potential follow-up project.

The extent to which the Customer requirements and product specifications from section 2.1 have been fulfilled are indicated in Table 6.

Table 6: Customer requirements

Requirement	Compliance
1. Perform a theoretical assessment of permanent ILS monitoring configurations, in terms of antenna types and positions as well as expected measurement quality.	Done. See [9] and section 2.3.
2. Provide a proof of concept for permanent ILS monitoring by building a test setup in a controlled environment, that is representative for ILS at Schiphol and perform tests that reveal measurement quality and stability.	Not fully done. See [11] and section 2.7 for an explanation.
3. Determine the operational benefits: provide a rationale to what extent ground inspection deadlines can be reconsidered based on the permanent ILS monitoring data.	See section 2.4.
4. Consult LVNL on the practical implementation of permanent ILS monitoring at Mainport Schiphol, in terms of optimal antenna types and positions, data distribution and software processing.	Done.

It is recommended to continue measuring the localizer and the glide path SiS according the proposed approach, e.g. in a new project based on the feasibility shown here. One AFM for the localizer antenna (at the corresponding GP mast), and one AFM for the glide path antenna (at the location marked by the yellow dot in Figure 5) may suffice, but if necessary the accuracy of the measurements can be increased by adding suitable AFMs.

3.2 Conclusions and recommendations on the business case

From the runway occupancy times by ILS ground measurements before and after implementation of AFM, one can determine a first estimate of the return of investment RoI similarly to Appendix B. For each stakeholder, this estimate of RoI should be replaced by a realistic value. This could be done by translating occupancy time to slot time, to number

of slots (which may vary as a function of time of day or season), and finally by taking into account the value of each slot (which may also vary as a function of time of day or season) to euros.
It is obvious, the decision to invest in AFM depends on the need to reduce runway occupancy time, the investment in implementing AFM, and the return of investment.

3.3 Recommendations

It is recommended to consider these follow-up activities:

- Perform validation measurements for GP at the suggested AFM locations.
- Design and implement data collection solutions (e.g. wireless).
- Develop applicable AFM data processing, display, and control, preferably using a graphical user interface.
- Validate a complete OPUS AFM facility at an airport The Netherlands.
- Adapt the current ILS ground measurement manuals according the OPUS results.

4 References

[1] ICAO, "International Standards and Recommended Practices, Annex 14 Volume I Aerodrome Design and Operations, Fifth Edition," International Civil Aviation Organization, Montréal, 2009.

[2] 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, 2006.

[3] 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, 2000.

[4] J. Heijstek, A. Tervoort, R. Hooijenga, J. Verpoorte, G. v. Baren, J. Duringshoff, H. Haverdings, M. Stuip, C. Tool and J. Bosch, "Reduction of flight measurements for ILS calibration at Amsterdam Schiphol Airport Phase 1, NLR-CR-2007-038," NLR, Amsterdam, May 2007.

[5] J. Heijstek, A. Tervoort, R. Hooijenga, J. Verpoorte, J. Duringshoff, M. Stuip, C. Tool and J. Bosch, "Reduction of flight measurements for ILS inspection at Amsterdam Schiphol Airport Phase 2, NLR-CR-2008-571," NLR, Amsterdam, April 2009.

[6] M. Stuip, W. v. Zutphen, J. Heijstek, A. Tervoort, J. Duringshoff, C. Tool and J. Bosch, "Rationalisation of ILS ground inspections intervals at Amsterdam Airport Schiphol, P1522 Phase III, NLR-CR-2009-311," NLR, August 2012.

[7] J. Heijstek, M. Stuip, J. Duringshoff, J. Bosch, C. Tool and A. Tervoort, "Reduction of flight measurement for ILS inspection at Maastricht-Aachen Airport, NLR-CR-2013-274," NLR, December 2013.

[8] KDC, "Call for Tender "Business Case - Optimising preferred use of Schiphol runways through flexible ILS maintenance"," Knowledge & Development Centre, Amsterdam, 28th September 2017.

[9] J. Heijstek, A. Tervoort, R. Hulzinga, J. Verpoorte, J. Duringshoff, M. Stuip, J. Bosch and J. Lansink-Rotgerink, "NLR-CR-2018-186 OPUS Theoretical Assessment," Netherlands Aerospace Centre NLR, Marknesse, 2018.

[10] EASA, "Certification Specifications and Guidance Material for Aerodromes Design CS-ADR-DSN Issue 4 (Annex to ED Decision 2017/021/R)," 8 December 2017. [Online]. Available: https://www.easa.europa.eu/sites/default/files/dfu/Annex to EDD 2017-021-R - CS-ADR-DSN Issue 4_0.pdf. [Accessed 30 10 2020].

[11] J. Verpoorte, J. Lansink Rotgerink, A. Hulzinga and J. Heijstek, "Optimising Preferred Use of Schiphol runways through flexible ILS maintenance (OPUS) - Verification Test Plan, Test Description and Test Results, NLR-CR-2019-490," KDC, Amsterdam, 2019.

[12] T. Dean, "The IH capacitance probe for measurement of soil water content," Institute of Hydrology, Wallingford, 1994.

[13] D. L. Corwin and J. Rhoades, "Establishing soil electrical conductivity - Depth relations from electromagnetic induction measurements," *Communications in Soil Science and Plant Analysis,* vol. 21, no. 11&12, pp. 861-901, 1990.

[14] R. Severns, "Skin Depth And Wavelength In Soil," 10 2006. [Online]. Available: https://www.antennasbyn6lf.com/files/ground_skin_depth_and_wavelength.pdf. [Accessed 28 10 2020].

Appendix A Relative permittivity of some materials

Table A.1 contains the relative permittivity or dielectric constant of some materials which may be situated in the vicinity of the GP mast.

Table A.1: Relative permittivity of some earth type materials at the indicated temperature (if specified)

Earth type	Temperature t (°C)	Relative permittivity ε_r
Vacuum		1
Polar ice cap		1
Air	0	1.00059
Magnetite Soil - Dry		1.09
Rubber (vulcanized)		2 - 3.5
Oil, kerosene	21	2.1
Clay Soil - Dry		2.38
Loamy Soil - Dry		2.47
Sandy Soil - 2.18% Water		2.5
Sandy Soil - Dry		2.55
Tree	18	2.2 - 3.7
Wood (depend on moisture content)		2 - 6
Asphalt	18	2.7
Polar ice		3
Sand		3 - 5
Ice	-18	3.2
Snow		3.3
Loamy Soil - 2.2% Water		3.5
Glass	18	3.7 - 10
Sea ice		4
Asphalt mixtures		4 - 10
Sandy Soil - 3.88% Water		4.5
Rock salt	20	5.6
Concrete		5 - 9
Magnetite Soil - 4.8% Water		9
Dry, Sandy, Flat (Coastal Land)		10
Fertile Land		10
Rocky land, steep hills		10 - 15
Marshy Land, Densely Wooded		12
Mountainous/Hilly (to about 1000 m)		12
Pastoral Medium Hills and Forestation		13
Pastoral Hills, Rich Soil		14 - 20
Rich Agricultural Land (Low Hills)		15
Clay Soil - 20.9% Water		20
Sandy Soil - 18.8% Water		20
Loamy Soil - 13.77% Water		20
Humid soil		30
Highly Moist Ground		30
Magnetite Soil - 11.0% Water		30
Sea water	20	73
Sea water	10	80
Fresh water		80
Sea ice		81

References

[A1] https://infotables.com/physical-tables/96-dielectric-constant-of-liquids-gases-and-solids-table.html (retrieved 10 Sep 2020).

[A2] Peter N Saveskie: *Earth constants*, TAI Inc Consuletter International, Vol. 6, No. 5, 1977.

[A3] https://pe2bz.philpem.me.uk/Comm/-%20Antenna/Info-905-Misc/soildiel.htm (retrieved 10 Sep 2020).

[A4] Arthur R. von Hippel (Ed.), Dielectric Materials and Applications, M.I.T. Press, 1954.

Appendix B Example of RoI estimate

The example below illustrates a Return of Investment calculation based on assumed data. Only the data for LOC [hr] may be assumed to be reasonably accurate.

Current situation

Yearly runway occupancy for LOC ground inspection	**hr**
Average total cost of ground measurements per ILS per year	8.9
Number of ILS installations to be inspected	7
Total LOC ground inspection costs per year	**62.4**

Yearly runway occupancy time for GP ground inspection	hr
Total cost per runway per year	8.4
Number of ILS installations to be inspected	7
Total GP ground inspection costs per year	**58.9**

Current yearly costs for ILS inspections	hr
Total yearly costs for ILS measurements	**121.3**

Future situation

Single investment to implement AFM	**hr**
Please enter the expected cost to implement the AFM Inspections (acquisition and installation of AFM equipment, integration into your maintenance systems and organisation).	400[3]

Estimated yearly runway occupancy for LOC ground inspection using AFM	hr
Average total cost per runway per year	2.3[4]
Number of ILS installations to be inspected	7
Total LOC ground inspection costs per year	**15.8**

Estimated yearly runway occupancy cost for GP ground inspection using AFM	hr
Total cost per runway per year	4.2[5]
Number of ILS installations to be inspected	7
Total GP ground inspection costs per year	**29.5**

Future yearly costs for ILS inspections	hr
Total yearly costs for ILS measurements	**45.2**

RoI **3.8** **year**

[3] Assumed investment to achieve AFM functionality in terms or runway occupancy hours (which can be translated to euros per stakeholder).
[4] Remaining for LOC: an estimated average total value of 2^{H}15' per LOC per year. Pending future improvements, the average total value may reduce further.
[5] Remaining for GP: None to full set of measurements remain (8.4 hours per GP per year), depending on the result of future AFM validation tests. Anticipating 50% success, an average value of 4.2 hours per GP per year has been chosen.

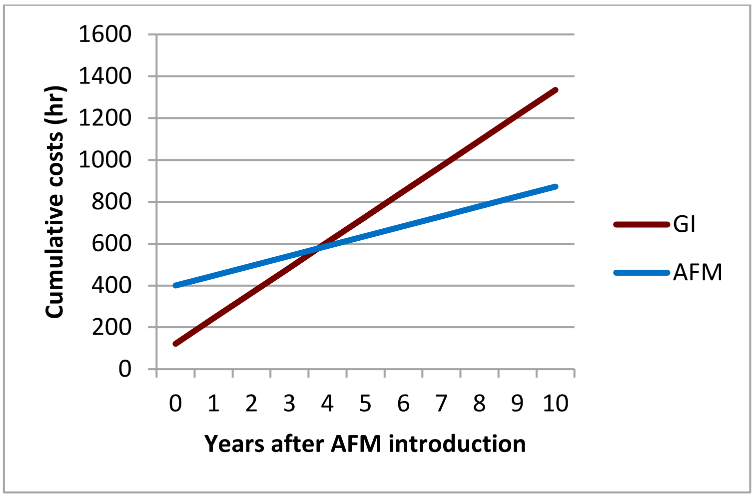


Figure B.1: Cumulative cost graph (hours) based on the assumed data above in this Appendix B

Dedicated to innovation in aerospace

NLR - Royal Netherlands Aerospace Centre

Royal NLR operates as an unaffiliated research centre, working with its partners towards a better world tomorrow. As part of that, Royal NLR offers innovative solutions and technical expertise, creating a strong competitive position for the commercial sector.

Royal NLR has been a centre of expertise for over a century now, with a deep-seated desire to keep innovating. It is an organisation that works to achieve sustainable, safe, efficient and effective aerospace operations.
The combination of in-depth insights into customers' needs, multidisciplinary expertise and state-of-the-art research facilities makes rapid innovation possible. Both domestically and abroad, Royal NLR plays a pivotal role between science, the commercial sector and governmental authorities, bridging the gap between fundamental research and practical applications. Additionally, Royal NLR is one of the large technological institutes (GTIs) that have been collaborating since 2010 in the Netherlands on applied research as part of the TO2 federation.

From its main offices in Amsterdam and Marknesse plus two satellite offices, Royal NLR helps to create a safe and sustainable society. It works with partners on numerous (defence) programmes, including work on complex composite structures for commercial aircraft and on goal-oriented use of the F-35 fighter. Additionally, Royal NLR helps to achieve both Dutch and European goals and climate objectives in line with the Luchtvaartnota (Aviation Policy Document), the European Green Deal and Flightpath 2050, and by participating in programs such as Clean Sky and SESAR.

For more information visit: **www.nlr.org**

Postal address
PO Box 90502
1006 BM Amsterdam, The Netherlands
e) info@nlr.nl i) www.nlr.org

NLR Amsterdam
Anthony Fokkerweg 2
1059 CM Amsterdam, The Netherlands
p) +31 88 511 3113

NLR Marknesse
Voorsterweg 31
8316 PR Marknesse, The Netherlands
p) +31 88 511 4444