Combining Full Wave Electromagnetic Simulations with UAV Multicopter Measurements to improve VOR signal quality monitoring and interference prevention

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ABSTRACT

VOR systems (VHF omnidirectional radio range) still play an indispensable role in air traffic management. With the decommissioning of some of the VOR's, even a higher number of conventional flight procedures employ the remaining ones in the medium term. In order to maximize the availability of its VOR's, Skyguide performs inspections of the signal quality in the frame of preventative and even corrective maintenance as well as preventive engineering assessments of potentially interfering obstacles.

Obstacles in the vicinity of VOR's, such as buildings, towers, wind turbines, vegetation or machines can create strong interferences of the VOR-signal due to multipath reflections and therefore render it and its associated flight procedures unusable. Hence it is crucial to detect potential harmful interferences from planned obstacles in advance to be able to either prevent or mitigate them. Furthermore, it helps to be able to determine the source of once detected interferences with a high certainty. For these reasons Skyguide and DFS have invested into the strengthening of its numerical electromagnetic simulation capabilities. A full 3D electromagnetic simulation platform allows a high flexibility in analyzing potential interferences of CNS Systems.

In 2018 Skyguide has established regular signal-in-space inspections for ILS by a UAV multicopter as an extension of ground checks as presented in [1]. Meanwhile this platform has been enhanced to perform VOR inspections as well. Typically, an orbit flight at a radius of about 180 meters and a height above ground of 40 meters is performed to assess the

signal quality, which provides clearly superior information compared to a traditional ground check. If needed the platform is easily configured to perform measurements on arbitrary flight paths.

The combined use of measurements and simulation allow a rigorous validation of the simulation model and therefore a high confidence for the preventative obstacle assessments. Predicted interferences by simulation can be rapidly verified with measurements.

INTRODUCTION

Obstacles in the vicinity of VOR’s, such as buildings, towers, wind turbines, vegetation or machines can create strong interferences of the VOR-Signal and therefore render it and its associated flight procedures unusable. Hence it is crucial to detect potential harmful interferences from planned obstacles in advance to be able to either prevent or mitigate them. Furthermore, it helps to be able to determine the source of once detected interferences with a high certainty. For these reasons skyguide and DFS have invested into the strengthening of its numerical electromagnetic simulation capabilities. A full 3D electromagnetic simulation platform allows a high flexibility in analyzing potential interferences of CNS systems. With the introduction of drone flight checks for VOR since 2019 a very versatile measurement tool is available providing comprehensive VOR signal measurements. Next to its use in the frame of preventative and corrective maintenance ad-hoc measurements can be made, serving as validation measurements for the simulation platform. The combination of both helps to improve the simulation modelling and in return allows a fast measurement confirmation of predicted interferences.

VOR Signal Quality Management

ANSP's must assure that they operate their VOR's in compliance with ICAO Annex 10 [2]. They therefore perform preventative maintenance on regular time intervals. Conventionally this is done with a mixture of ground tests as well as flight tests. With the introduction of drone checks for VOR stations in 2019, Skyguide has added a new powerful method, extending the quantity and quality of the test data compared to a classical ground check. It can be performed at reasonable costs and requires limited administrative effort compared to a classical flight inspection.

CNS Safeguarding

In addition to the regular signal monitoring VOR operators must prevent unacceptable interferences that could potentially be caused by new buildings, growing vegetation or the planned presence of machines in the vicinity. Typical examples of such potentially harmful obstacles are large buildings, wind turbines, cranes, power lines, agricultural or construction machines. The ICAO EUR DOC 015 [3] provides guidance allowing to identify potentially harmful objects. The impact assessment, quantifying the interference to be expected, is done by a "Specialist Engineering Analysis". Latter can be performed using numerical electromagnetic simulations or approximative analytical formulas.

UAV MULTICOPTER VOR MEASUREMENT PLATFORM

In 2019 the UAV Multicopter platform originally developed for ILS testing [1] has been extended for VOR testing within Skyguide. The platform, named CNS Drone, makes use of the R&S®EVSF1000 VHF/UHF nav/flight analyzer which performs measurements on ILS, VOR and marker beacon ground stations e.g. during startup, maintenance and servicing and is also able to analyze ATC COM signals. The UAV measurements are performed by the Skyguide ATSEP personnel, which oversees the NAVAID maintenance. They have been qualified to operate and maintain the system. This makes it easy to integrate its use in the frame of the preventative and corrective maintenance.

Figure 1: VOR Drone Check

VOR preventative and corrective maintenance measurements

Conventionally at Skyguide CVOR ground checks comprised counterpoise edge measurements, where a monitor dipole antenna is placed in specific locations with the help of positioner brackets, as well as far field measurements at 150m. These have now been replaced by UAV orbit measurements at 180 meters with an angular resolution of about 0.01degrees. The measurements are performed within minutes. An orbit flight at 180m radius, e. g., takes approximately 3 minutes. The results can be monitored during the flight with the VOR Checker graphical interface as shown in Figure 3. They comprise precise position information as well as the entire signal information measured by the R&S®EVSF1000 VHF/UHF nav/flight analyzer including azimuth error, AM 30Hz, AM 9960Hz, Freq 9960Hz, FM Deviation and RF level. This provides more comprehensive information than conventional ground checks.

In the case of Doppler VOR, no specific ground check measurement is mandatory during the preventative maintenance as the system is monitored automatically. Nevertheless occasional drone checks are done as they provide a much more comprehensive overview of the signal quality allowing to detect potential degradations in an early stage.

Drone checks are especially helpful during corrective maintenance, where causes of signal degradations need to be detected and modifications of the system have to be validated. They allow a fast and iterative real time measurements faciliating system tuning and adaptations. The final drone check pre-validation ensures that the signal parameters are compliant.

VOR Commissioning

The commissioning of a Navaid is especially delicate, as the proper setup of the system must be tuned and validated meticulously. Skyguide had to do an unanticipated major repair of its conventional VOR Willisau (VOR WIL) due to a failure in the antenna feed system. The repair had to be done on a tight schedule in wintertime. The entire antenna system was replaced and taken into operation by the navigation maintenance and engineering team (Figure 2) within 6 days. Thanks to the availability of the CNS drone the configuration of the system parameters could be validated iteratively during the setup. This allowed a correct tuning of all signal parameters, which was confirmed by one final flight check. Figure 3 shows the flight check results before and after the pre-tuning. An initial maximum azimuth error of 0.5 degrees was reduced to 0.1 degrees. In summary the drone checks proved very beneficial as they are fast, provide instantaneous comprehensive results, can be scheduled flexibly without requiring administrative planning effort and reduce the required flight inspection effort.

Figure 2: Emergency Replacement of Antenna System of VOR Willisau (VOR WIL). Left: Lifting of new Antenna System onto VOR; Middle: Preparation of CNS Drone by ATSEP personnel; Right: Onsite instantaneous Monitoring of Measurement Results with VOR Checker Software.

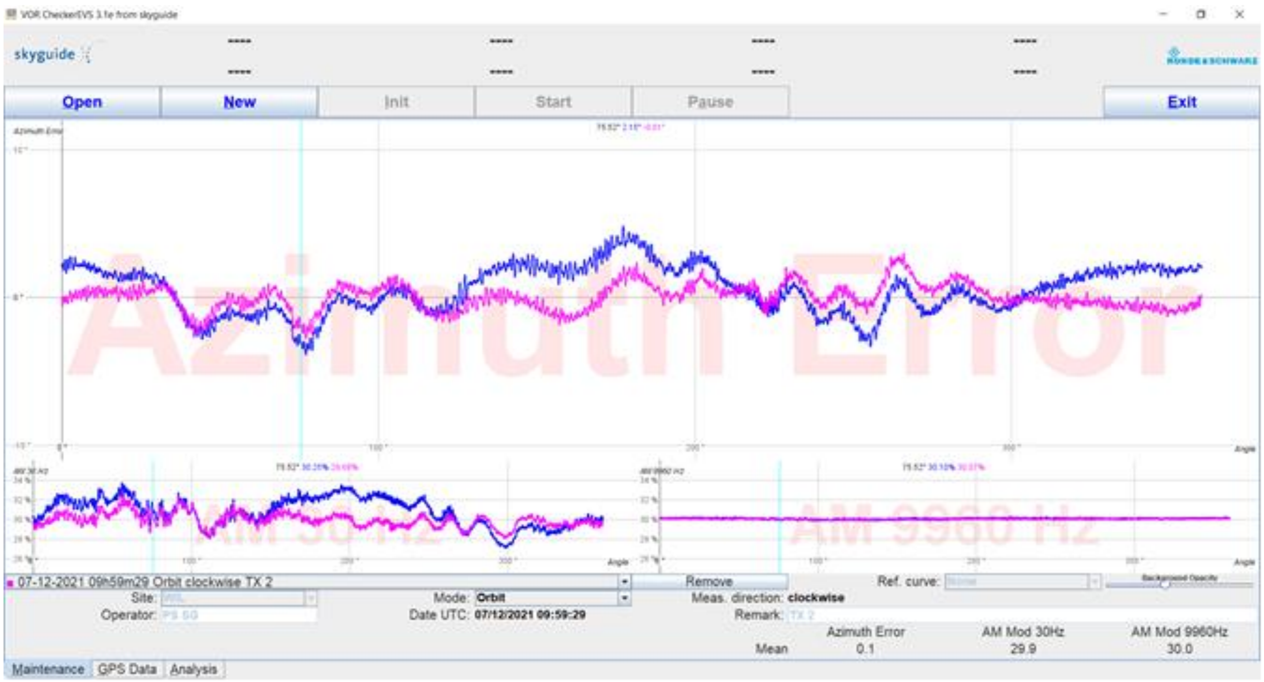


Figure 3: VOR Checker Graphical Interface displaying Measurement Results during Drone Check of VOR WIL after replacement of Antenna System. Blue Line: Results before Ground Pre-Tuning ; Pink Line: Results after Ground Pre-Tuning.

Ad-Hoc Measurements

Ad-Hoc Measurements have been proven very helpful for the assessment of signal interferences as well as for the validation of electromagnetic simulation models. The ability to configure arbitrary flight paths and the quick deployment have helped to provide measurement data allowing to validate simulation models and interference models.

ELECTROMAGNETIC SIMULATION PLATFORM

The impact prediction of multipath effects on VOR's has originally been done by analytical modelling [4] which only allowed a coarse estimation. Round about the beginning of this century the performance of numerical electromagnetic simulations has become sufficient to model multipath impacts on navaids [5], [6], [7]. Since then, the efficiency of the simulation algorithms as well as the computation power have been continuously improving. Today's commercially available electromagnetic simulation suites offer a variety of methods such as Method of Moments (MoM), Physical Optics (PO), Geometrical Optics (GO), Uniform Theory of Diffraction (UTD), etc. They are well suited to simulate the impact of large structures such as wind farms or buildings in a reasonable time frame with a high precision.

Figure 4 shows an example of a simulation of a conventional VOR using MoM. The left picture shows the surface currents of the directional antenna. The pictures in the middle and on the right side show the three-dimensional radiation pattern for the omnidirectional part of the signal as well as the one of the directional signal components of this VOR-type.

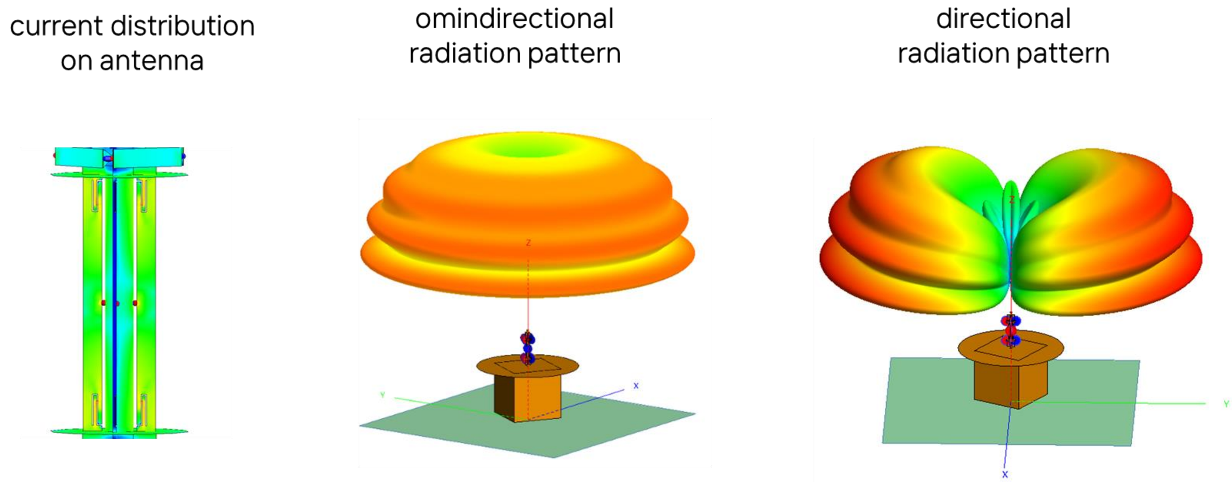


Figure 4: Electromagnetic Modelling of Conventional VOR (Thales 431)

Simulation Process

Figure 5 illustrates the simulation process. It is subdivided in three major steps, the Modelling of the Simulation Scene, the Numerical Electromagnetic Simulation and the Calculation of the VOR Parameters.

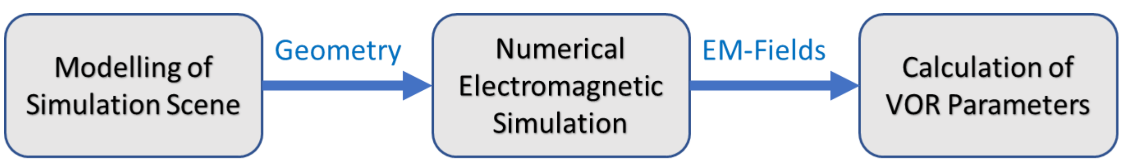


Figure 5: Simulation Process

The quality of CNS signal modelling depends on all these three steps. The modelling of the simulation scene, meaning the mechanical model used for the VOR as well as the interfering obstacles are hereby critical in simulation. On the one hand, one must simplify the model to be able to use it in a simulation, but at the same time small details in the model can significantly alter the result. Hence, developing a trustworthy model requires experience and a solid know how in electromagnetic modelling. Measurement validation is commonly used to confirm the quality of one's simulation model. With the UAV measurement we have now a powerful tool allowing to perform specific ad hoc measurements for the validation of the simulation model.

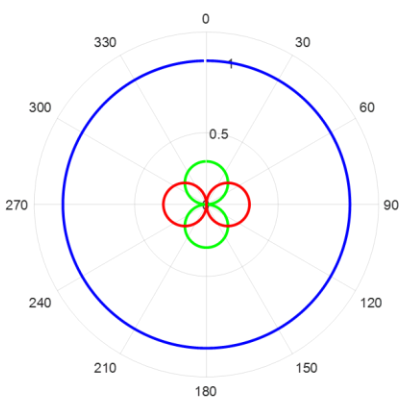
Regarding the numerical electromagnetic simulation step the most important parameter is the used calculation method. For VOR simulations two methods were used, the Method of Moments (MoM) and Physical Optics (PO). In some applications a combination of both is used. Physical Optics significantly reduces the required computation power and memory usage but can lead to important deviations of the results. During the modelling phase careful attention must be given when choosing which parts can be modelled by Physical Optics.

In the last process step, named Calculation of VOR Parameters, the signal-in-space VOR parameters are derived from the simulated electromagnetic fields. This is done with MATLAB or MATHEMATICA. The calculation method used for CVOR and DVOR, respectively have been co-developed between Skyguide and DFS.

Bearing Error Calculation for Conventional VOR

Conventional VOR's are much more susceptible to multipath reflections caused by obstacles than Doppler VOR's. This is the case for large obstacles such as buildings towers and wind turbines but even more so for smaller, close-by objects such as vegetation, vehicles and machines. Skyguide and DFS, operating the conventional VOR type 431 from Thales, have developed a simulation model for it allowing to predict the impact of multipath reflections with high precision at a reasonable computational cost [8]. The bearing angle error is usually the most critical VOR parameter affected by multipath reflections. Therefore, a particular focus is put on it in impact prediction simulations.

The conventional VOR type 431 from Thales produces the AM signal using three sub-signals: an omnidirectional signal emitted by two Alford-Loop antennas and two orthogonal directional signals emitted by 2 slot antennas. Figure 4 shows the slot antenna as well as the radiation patterns of the omnidirectional and one of the directional signals. A mathematical model illustrating the three different idealized signal components is described in Figure 6 below.



Omnidirectional signal

$$U_{omni} = A_0 \cos \Omega t \qquad (1)$$

Directional signal 0-degree direction

$$U_{Dir0} = 0.3\, A_0 \cos \Omega t\ \cos \omega t \cos \varphi \qquad (2)$$

Directional signal 90-degree direction

$$U_{Dir90} = 0.3\, A_0 \cos \Omega t\ \sin \omega t \sin \varphi \qquad (3)$$

where:
Ω : carrier frequency
ω: modulation frequency (2π 30Hz)
φ : azimuth angle

Figure 6: Mathematical model of AM-signal components of conventional VOR

In reality, the field sub-components are non-ideal and have therefore to be described more generalized as proposed in Equation 4 below. Assuming a product demodulation and an ideal low pass filtering, isolating the 30Hz AM component, the demodulated signal can be described according to Equation 5. Using the trigonometric identity described in Equation 6, the phase of the AM signal can be determined by Equation 7. The amplitudes and phases of the three signal components *Omni*, *Dir0* and *Dir90* respectively, are dependent on the location. Their values are determined with three independent electromagnetic simulations, modelling the three sub-signals. The results for each simulated sub-signal and location can then be inserted into Equation 7 to determine the resulting bearing angle error.

With this approach only three individual sub-signals have to be modelled and no approximations with regards to the signal in space have to be done. The determination of the AM-phase and the modulation depth are straight forward. Provided that the VOR model as well as the modelling of the obstacles is correct, a high accuracy can be achieved as even large obstacles can be simulated using method of moments.

Figure 7 illustrates the method. Here the impact of a cylinder, having a radius of 4m and a height of 100m, has been calculated. The cylinder is located in a distance of 2000m and an azimuth of 90 degrees. On the left side the radiation pattern, which is affected by the scattering of the cylinder, is shown for the three sub-signal components. The upper right side shows the magnitude of the E-Field calculated on an orbit at 5000m. The interference created by the multipath reflection is clearly notable. The resulting bearing angle error is shown in the graph below.

$$
\begin{aligned}
U_{AM} &= A_{Omni}(\varphi)\cos(\Omega t - \theta_{Omni}(\varphi)) \\
&\quad + A_{Dir0}(\varphi)\cos\big(\Omega t - \theta_{Dir0}(\varphi)\big)\cos\omega t \\
&\quad + A_{Dir90}(\varphi)\cos(\Omega t - \theta_{Dir90}(\varphi))\sin\omega t
\end{aligned} \tag{4}
$$

After AM-demodulation and filtering:

$$
\begin{aligned}
U_{Demod} &= A_{Dir0}\ \cos\omega t\ \cos(\theta_{Dir0} - \theta_{Omni}) \\
&\quad + A_{Dir90}\sin\omega t\ \cos(\theta_{Dir90} - \theta_{Omni}) \\
&= r\cos(\omega t - \phi)
\end{aligned} \tag{5}
$$

The phase of the AM signal can then be determined using the trigonometrical identity:

$$
\mathrm{a}\cos\mathrm{x} + \mathrm{b}\sin\mathrm{x} = \mathrm{r}\cos(\mathrm{x} - \phi) \quad \rightarrow \quad \phi = \operatorname{arctan2}\left(\frac{\mathrm{b}}{\mathrm{a}}\right) \tag{6}
$$

$$
\boldsymbol{\phi} = \mathbf{arctan2}\left(\frac{A_{Dir90}\cos(\theta_{Dir90} - \theta_{Omni})}{A_{Dir0}\cos(\theta_{Dir0} - \theta_{Omni})}\right) \tag{7}
$$

where

- Ω : carrier frequency
- ω : modulation frequency
- φ : azimuth angle
- ϕ : AM-Phase
- A_{Omni}: amplitude of Omni-signal
- θ_{Omni}: rf-phase of Omni-signal
- A_{Dir0}: amplitude of Dir0-signal
- θ_{Dir0}: rf-phase of Dir0-signal
- A_{Dir90}: amplitude of Dir90-signal
- θ_{Dir90}: rf-phase of Dir90-signal

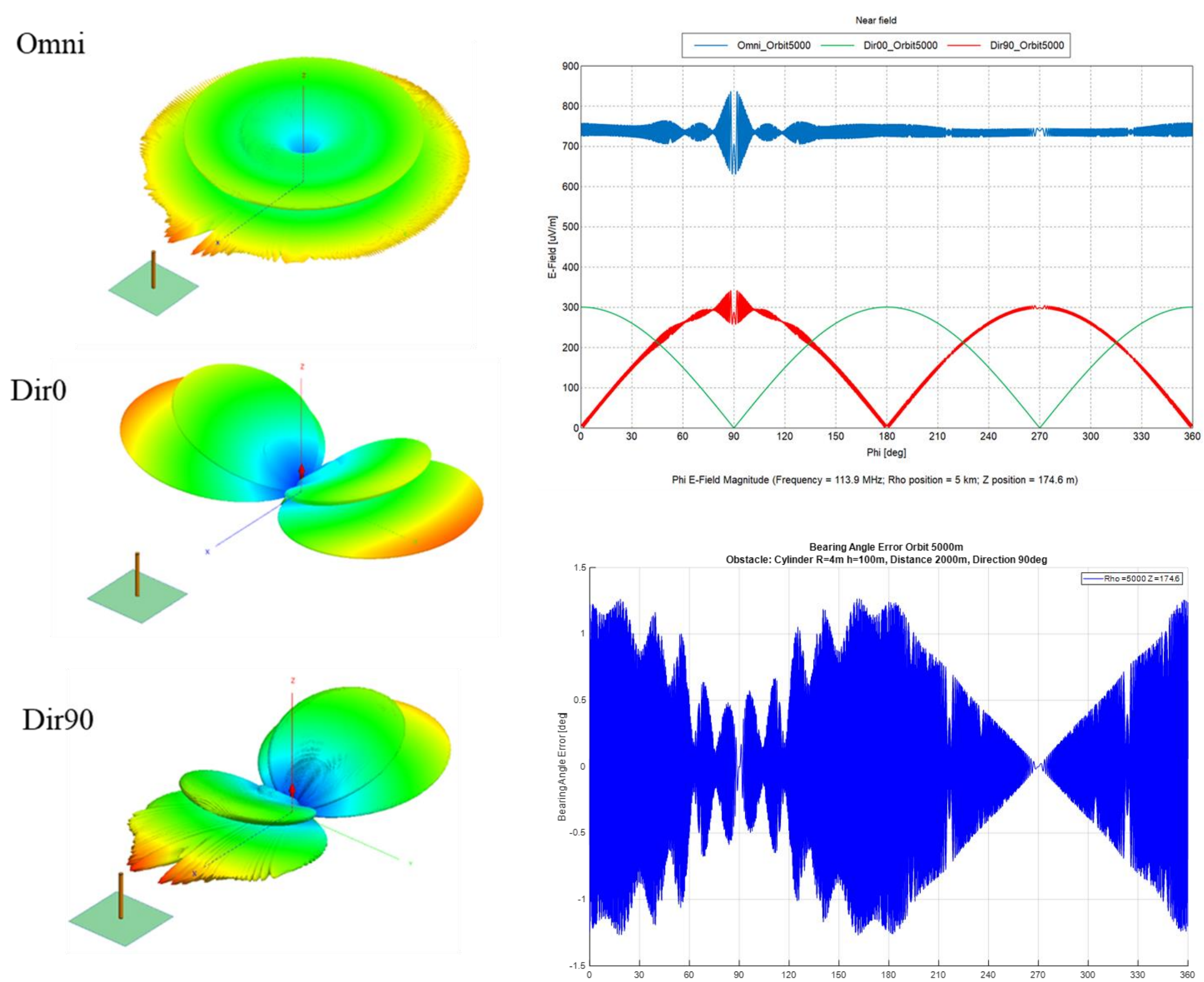


Figure 7: Simulation of Bearing Angle Error for CVOR in Presence of reflecting Cylinder (Distance 2000m, Direction 90deg, Radius 4m, Height 100m), Left Side: Simulation of Sub-Signal Field Components, Upper Right Side: Magnitude of Sub-Signal Components on Orbit at 5000m, Lower Right Side: Resulting Bearing Angle Error

Bearing Angle Error Calculation for Doppler VOR (CVOR)

In the case of the Doppler VOR, the FM signal, which is produced by the 50 side band antennas, has to be modelled for the calculation of the bearing angle error. In order to determine the FM phase, we use a similar approach as presented in [9], where the FM signal is analyzed in the time domain. The computational effort for the electromagnetic simulation is considerably higher compared to the CVOR case, as 50 sideband signals at 2 frequencies each, have to be simulated instead of only 3 single frequency simulations. The calculation of the bearing angle error is more complex as well. However the required calculation time is negligible compared to the electromagnetic simulation.

VALIDATION

The quality of simulation assessments depends on a cautions verification of each one of the three steps shown in Figure 5. This can partly be done by comparison to other simulation assessments. The most convincing validation however stays the comparison to a measurement. One source of such validation data are flight inspections measurements. In the case of VOR however, where flight inspection measurements are usually taken at great distances, they do include a multitude of multipath sources such as terrain, buildings, power lines as well as close-by obstacles. Many of these multipath sources cannot be properly modelled in a simulation, either due to their complexity or due the to the high computational effort required.

The availability of UAV measurements facilitates the validation in two aspects. It allows to make measurements close to the VOR, eliminating the multipath effects from further-away difficult to model multipath sources. This is especially helpful when validating the simulation model of the VOR itself and when studying the impact of close-by obstacles. Secondly it allows to make measurements in the vicinity of obstacles where their impact is better visible [10].

Impact of Tipper Wagon

A specific ad-hoc validation measurement was set up to verify the CVOR simulation model [11]. For this purpose, an agricultural tipper wagon was placed in the vicinity of the VOR Willisau (VOR WIL) at approximately 15m distance. The tipper wagon is an ideal validation obstacle as its geometric shape is well defined and simple to model. Precise position measurements have been taken in order achieve a good agreement of the measurement setup and the simulation model.

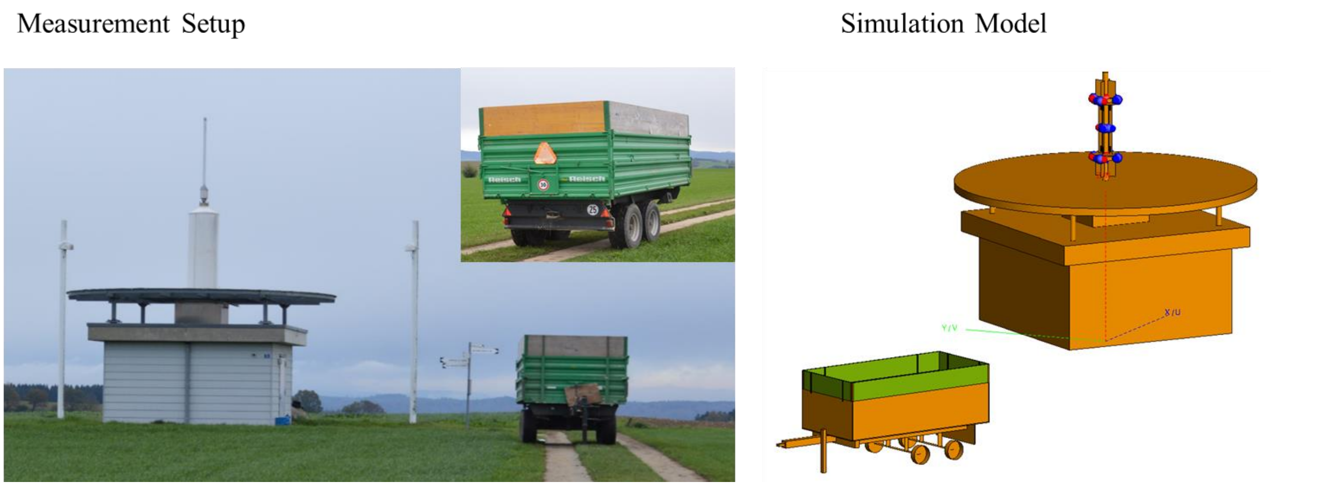


Figure 8: Measurement set and Simulation Model for Validation Measurement with Tipper Wagon in the Presence of a CVOR (VOR WIL).

The UAV measurement was then performed on an orbit with a radius of 180m and a height of 40m above ground level as well as on Radial 255 at a distance between 50m and 280m and a height of 40m above ground level. The results are shown in Figure 9. The measurement was performed twice, once without the presence of the tipper wagon and once with its presence. The impact of the tipper wagon on the bearing angle error was derived by taking the bearing angle error difference of the two measurements.

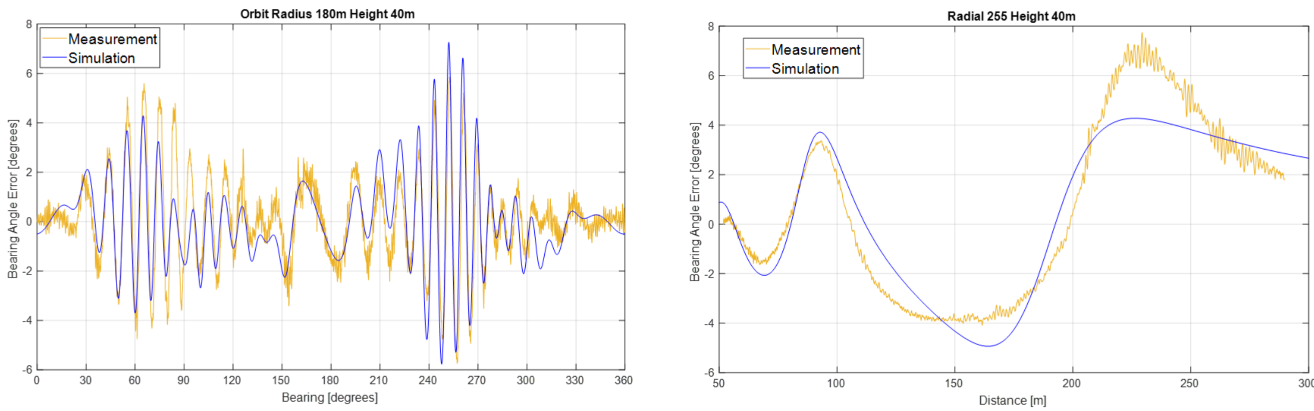


Figure 9: Comparison of UAV Measurement and Electromagnetic Simulation of Bearing Angle Error caused by Tipper Wagen.

A good agreement between measurement and simulation can be seen. On both comparisons the variation of the bearing angle error as well as the order of magnitude are well matched. The agreement is however not perfect, which can be explained be the non-flat terrain and the presence of other obstacles in the surroundings. In conclusion the simulation model for the CVOR 431 from Thales has been validated.

<u>Impact of Guidepost</u>

During the tipper wagon assessment, the guidepost shown in Figure 10 was modelled by simulation in an effort to capture the impacts of the close by obstacles. To our surprise the simulation indicated an impact on the bearing angle error up to 1.5 degrees. A UAV measurement of the bearing angle error with and without the presence of the guidepost yielded a difference up to 1.5degrees as well, confirming the order of the magnitude predicted by the simulation. This underlines the susceptibility of a CVOR to multipath reflections created by obstacles in its close vicinity.

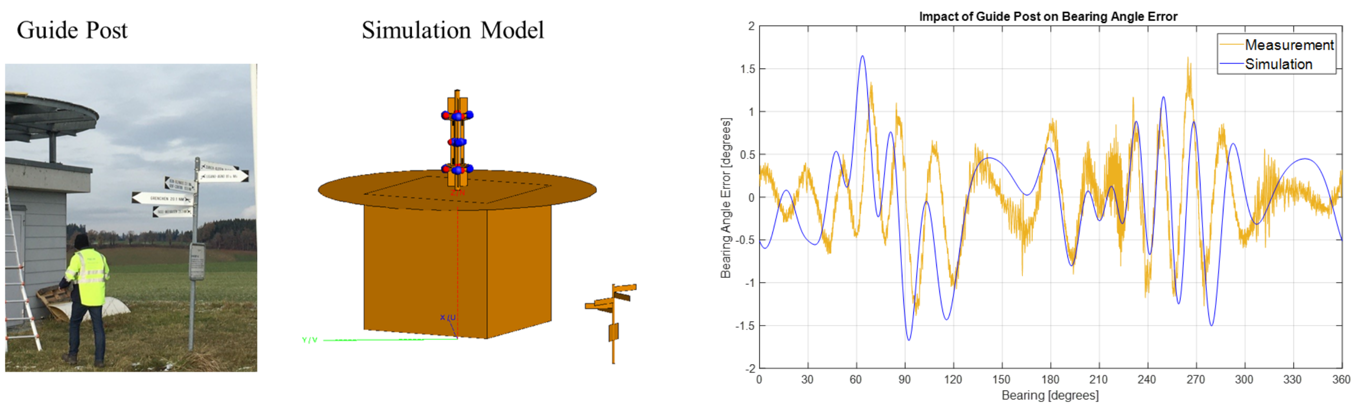


Figure 10: Guidepost Impact Assessment. Comparison of Measurement and Simulation on Orbit (Radius 180m, Height 40m)

<u>SIMULATION ASSESSMENT OF OBSTACLE IMPACTS</u>

Once validated, the electromagnetic simulation platform, allows a fast and expedient impact prediction facilitating the CNS safeguarding. In the following a few examples are presented:

<u>Impact of Excavator</u>

In this example, an existing conventional VOR is to be replaced by a Doppler VOR. The groundwork, in particular digging out foundations, shall be done, if possible, while the CVOR is in operation. Therefore, the impact of an excavator near the

VOR was assessed. The results shown in Figure 11 show a bearing angle error up to 1.2 degrees at an 10Nm-Orbit caused by the presence of the excavator. Also, in close proximity at the location of the monitor antennas, the bearing error angle risks to increase beyond the specified limit.

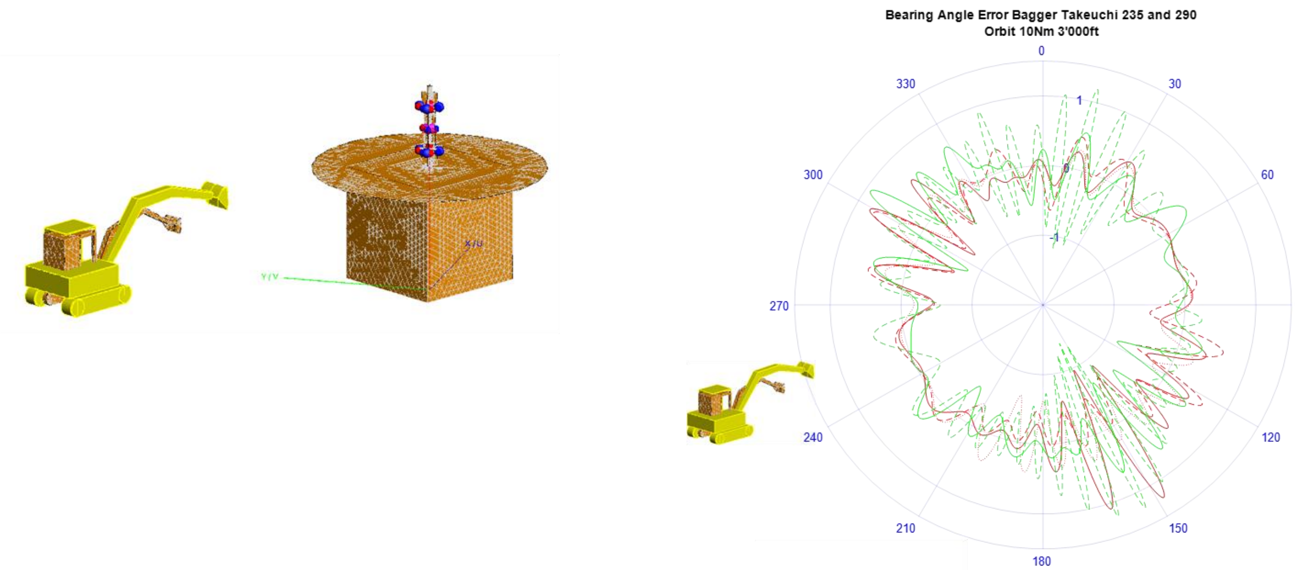


Figure 11: Bearing Angle Error caused by Excavator in the Proximity of a Conventional VOR. Three orientations of excavator are modelled.

Impact of Truck Mounted Crane on a Conventional VOR

This assessment has been done for a truck mounted crane being used at an airport site. The 39m high crane is used behind a terminal building surmounting it by 19m. Only the surmounting part of the crane is modelled, which yields a maximum impact of 0.5degrees on the assessed radial. Adding this error to the existing Bearing Angle Error, using the root sum square method shows that the maximum bearing angle error increase, caused by the crane is 0.15degrees and therefore negligible.

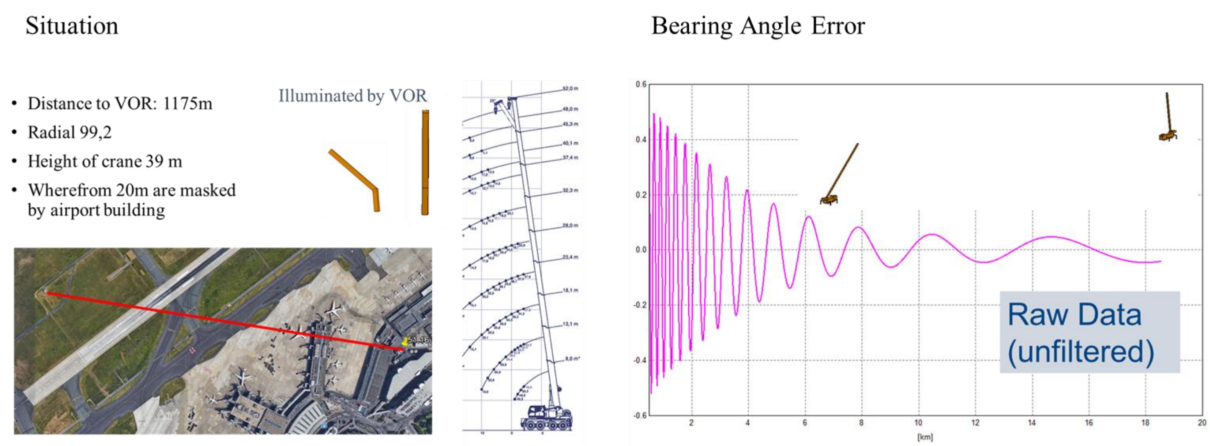


Figure 12: Impact Assessment of Truck mounted Crane of Conventional VOR

Wind Farm Impact

In this example the impact of a wind farm on a VOR was studied. The wind farm consists of 5 wind turbines having a hub height of 165m and a blade length of 75m. They are located in a distance between 3.1km and 4.6km to the VOR at an azimuth between 355 degrees and 20degrees. Currently a conventional VOR is being used. It will be replaced with a Doppler VOR. The assessment shall evaluate if a wind park in such proximity, which has not been possible up to now, will be acceptable once the Doppler VOR will be in operation. Figure 14 shows the results for an orbit and a radial. The assessment demonstrates that while this wind park is critical for the conventional VOR its impact is well tolerable for a Doppler VOR as the maximum error stays below 0.1degrees.

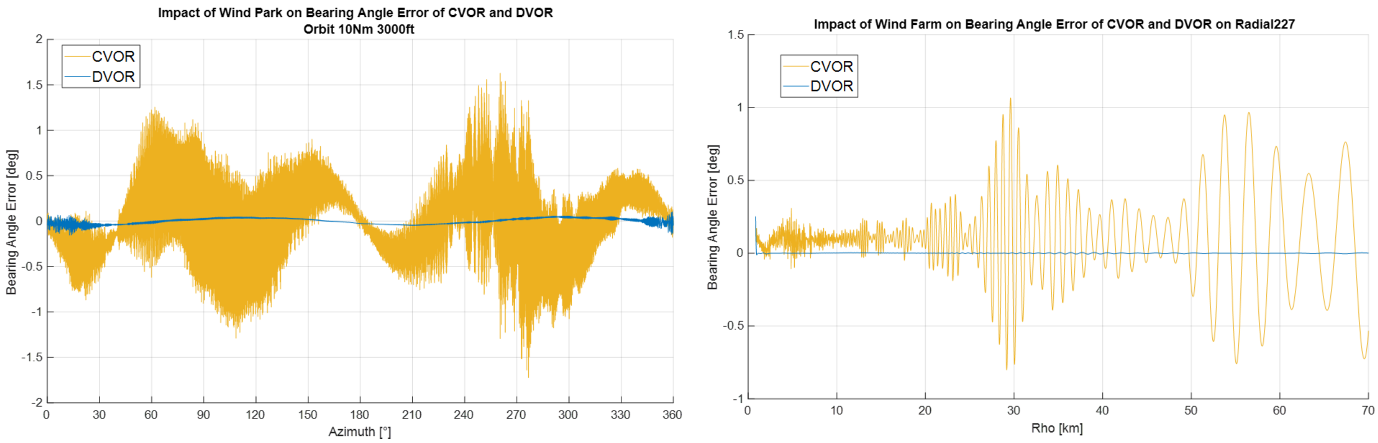


Figure 13: Impact of Wind Farm on Bearing Angle Error for CVOR and DVOR, resp. Results are shown on Orbit (Radius 10Nm, Height 3'000ft AGL) and on Radial227. Wind Farm Parameters: 5 Wind Turbines, Hub Height 165m, Blade length 75m, Distance between 3.1km and 4.6km to VOR, Azimuth between 355 Degrees and 20 Degrees.

CONCLUSION

With the introduction of a UAV measurement platform (CNS drone) and development of an electromagnetic simulation assessment platform, Skyguide has introduced two powerful tools for VOR signal monitoring and safeguarding. The application field of the CNS drone introduced in 2018 has been extended to VOR measurements for the use during preventative and corrective maintenance as well as for ad-hoc measurements. The flexibility in usage and the state-of-the-art measurement receiver prove to be very beneficial. The electromagnetic simulation platform has been developed in collaboration with DFS. It allows an accurate prediction of multipath effects caused by obstacles on VOR parameters. UAV measurements help to validate and solidify the underlying simulation models. Simulation assessments, on the other hand, are helpful to determine critical areas of a CNS system in terms of multipath reflections.

ACKNOWLEDGMENTS

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REFERENCES

[1] H. Demule, K. Theissen, "Using UAV multicopters as an extension of ILS ground measurements: This innovative idea has already become reality in Switzerland!," in International Flight Inspection Symposium (IFIS) 2018, Monterey CA, USA, 2018.

[2] ICAO Annex 10 Volume I: Radio Navigation Aids, 6th Edition, Amendment 86, 2011-07-18., ICAO, 2011.

[3] European Guidance Material on Managing Building Restricted Areas, Third Edition, 2015 (ICAO EUR DOC 015), ICAO, 2015.

[4] S. R. Anderson and R. B. Flint, "The CAA Doppler Omnirange," *Proceedings of the IRE,* pp. 808 - 821, 1959.

[5] G. Greving, "Latest Advances and Results of complex numerical Simulations for Navaids and Landing Systems," in *12th International Flight Inspection Symposium (IFIS)*, Rome, 2002.

[6] S. A. Odunaiya, "Wind Farms and their Effect on Radio Navigation Aids," in *Internationial Flight Inspection Symposium IFIS*, Toulouse, 2006.

[7] Christophe Morlaas M. F. B. S., "Wind Turbine Effects on VOR System Performance," *IEEE Transactions on Aerospace and Electronic Systems,* pp. 1464-1476, 2008.

[8] M. Fries, R. Eichhorn, "Full wave simulation based assessment methodology for conventional VOR," *EMWT21*, Zürich, 2021.

[9] S. Sandmann , J. Bredemeyer, T. Schrader u. H. Garbe, "A Numerical Time Domain Method for Calculation of the Indicated DVOR Bearing in Dynamically Disturbed Scenarios," *IET Microwave Antennas & Propagation,* no. August, p. pp 8, 2019.

[10] Schrader, T.; Bredemeyer, J.; Mihalachi, M.; Ulm, D.; Kleine-Ostmann, T. et al, "High-resolution signal-in-space measurements of VHF omnidirectional ranges using UAS," *Advances in Radio Science 17 (2019), S. 1-10.*

[11] M. Fries, R. Eichhorn, "Simulation and Validation of Signal Interference of a Conventional VOR," *EMWT19*, Toulouse, 2019.