Advanced Environmental Simulation for the In-Flight Characterization and Verification of FIS Aircraft Antennas

Maik Ritter

System Engineer
Aerodata AG
Braunschweig, Germany
Phone: +49 531 2359-246
E-mail: maik.ritter@aerodata.de

Frank Musmann

Project Manager
Aerodata AG
Braunschweig, Germany
Phone: +49 531 2359-341
E-mail: frank.musmann@aerodata.de

Dr. Mirko Stanisak

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

ABSTRACT

The accuracy of flight inspection results depends heavily on the precise characterization of the aircraft's installed antenna performance. While ground measurements provide a baseline, determining the full 4D antenna patterns (including elevation and frequency dependencies) requires dedicated in-flight calibration against known signal sources from the ground.

Ideally, these calibration flights require a controlled RF environment. In reality, however, terrain reflections, multipath effects, and variable ground properties introduce significant disturbances. This paper presents a newly developed sophisticated software framework designed to simulate these environmental factors with high fidelity. By combining high-resolution terrain data from a digital elevation model (DEM) with physics-based propagation models (such as ray marching and two-ray ground reflection), the tool predicts the exact Signal-in-Space (SiS) propagation for any given 3D volume-

This "digital twin" approach allows flight inspection organizations to validate real flight data against simulated baselines, ensuring the plausibility of derived antenna patterns. Furthermore, the simulation enables the pre-flight optimization of calibration profiles, identifying ideal flight paths to minimize unwanted interference and optimize the calibration accuracy. This paper will demonstrate the software's capabilities, compare simulation results with actual flight test data, and discuss how such tools significantly reduce antenna calibration effort while improving the overall measurement integrity.

INTRODUCTION

The required measurement accuracy of modern automatic flight inspection systems (AFIS) (as detailed in [1]) is increasingly limited by the complex interaction between the aircraft's antenna and its electromagnetic environment. For high-precision navigation aids (navaids), the antenna directivity pattern must be precisely known with high confidence to calculate the signal-in-space field strength based on the received signal power as determined by a receiver on board.

While theoretical 3D antenna modeling based on full-aircraft CAD data and material properties is possible, it remains a cost-prohibitive and labor-intensive process, requiring detailed internal analysis of antenna structures (e.g., via X-ray) and massive computational power. Similarly, measuring full-scale aircraft in anechoic chambers is practically unfeasible for most flight inspection organizations.

Consequently, the current industry standard concentrates on ground-based calibration of the antenna directivity patterns. Commonly, as shown in Figure 1, this involves a stable RF field at a certain position at an airfield. The RF signals are generated over the operationally required frequency bands using calibrated transmitters and directional antennas. To ensure a uniform RF field and to determine the absolute field strength, the intended area of the calibration is measured precisely at different test points. Only if the resulting field strengths of these test points differ only marginally over all frequencies, is the area suitable for calibration.

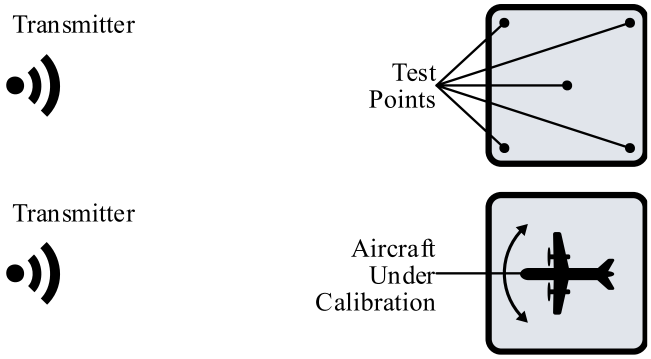


Figure 1: Antenna Directivity Calibration. Top: Test of Field Uniformity Bottom: Calibration of Aircraft Antenna

Once the area is measured and confirmed to be acceptable, the aircraft under calibration (AUC) is placed at the center point and rotated by 360°. This allows to generate high-precision absolute antenna directivity patterns as shown in Figure 2. While this procedure is essential for determining absolute gain and verifying installation symmetry, it inherently lacks elevation-dependent information. On the runway, the signal typically arrives at a near-horizontal elevation. In actual flight, however, the flight inspection aircraft receives signals from ground-based navigation aids at varying negative elevation angles (signals coming from below). Since the aircraft's fuselage and wings significantly shadow or reflect the RF signal depending on the angle of arrival, the ground-based pattern cannot be directly extrapolated to flight conditions. Furthermore, it is impossible to deploy a calibrated physical reference antenna in the air to establish a "reference volume."

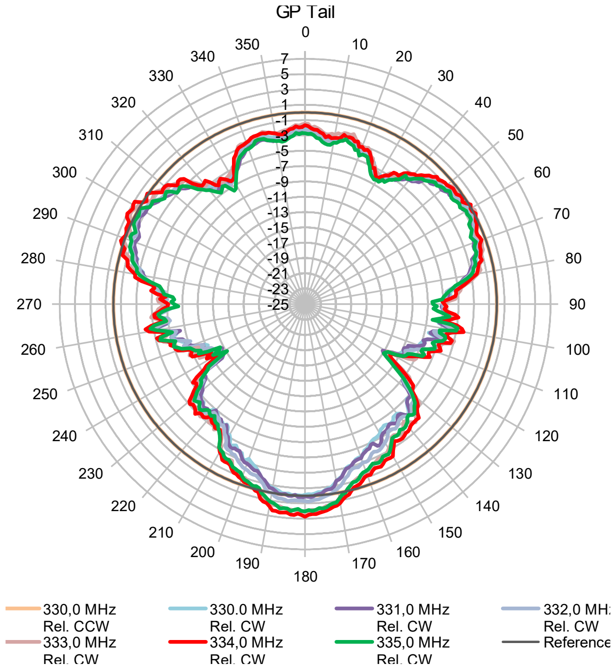


Figure 2: Example for Horizontally Calibrated Aircraft Antenna Directivity

This significant limitation in the derived antenna patterns served as the primary catalyst for the development of an environmental simulation framework, named "FIS-Antenna-Lab", which is presented in this paper. By simulating the Signal-in-Space (SiS) throughout a 3D volume, the software framework provides the necessary reference baseline that allows for the relative in-flight characterization of antennas under real operational conditions, effectively generating a digital twin of the RF environment.

ENVIRONMENTAL RF SIMULATION

Instead of relying on a physical reference point in the air, the proposed tool calculates the expected signal strength at any 3D coordinate within a modeled test area. The software integrates high-resolution digital elevation model (DEM) for terrain data and uses physics-based propagation models to account for the specific multipath environment.

When the flight inspection aircraft traverses this volume, its precisely recorded position is used to correlate the measured Received Signal Strength Indicator (RSSI) with the simulated field strength. By subtracting the simulated environmental effects, such as ground reflections and terrain shadowing, from the measured data, the aircraft's relative antenna characteristic can be isolated for any given elevation and azimuth.

Software Interface & Visualization

Before diving into the complex propagation physics (based on and implemented after the theories described in [2] and [3]), it is essential to understand the operational environment of the "FIS-Antenna-Lab" tool. This software provides a dual-perspective analytical interface designed for real-time interaction with the 3D signal volume.

The primary graphical user interface (as shown in Figure 3) consists of two synchronized views that allow for a comprehensive analysis of the signal-in-space.

All examples shown in this paper are for Braunschweig airport (EDVE) in Germany, as this airport is also used for the verification test campaign described later in this paper. Of course, any other location can be freely configured within the software.

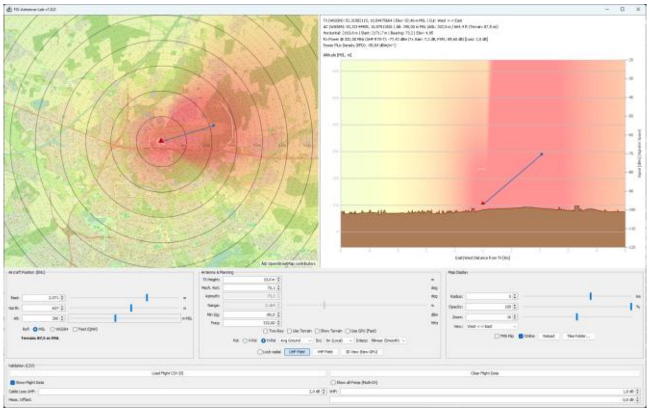


Figure 3: FIS-Antenna-Lab Interface

The top-down view on the top left (as detailed in Figure 4) provides geographic context for orientation. By default, it displays OpenStreetMap (OSM) tiles as background, but it can be toggled to a terrain rendering for visualizing the DEM data.

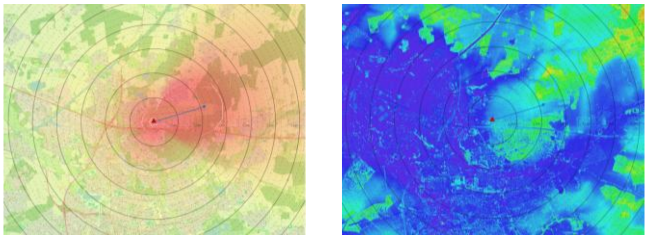
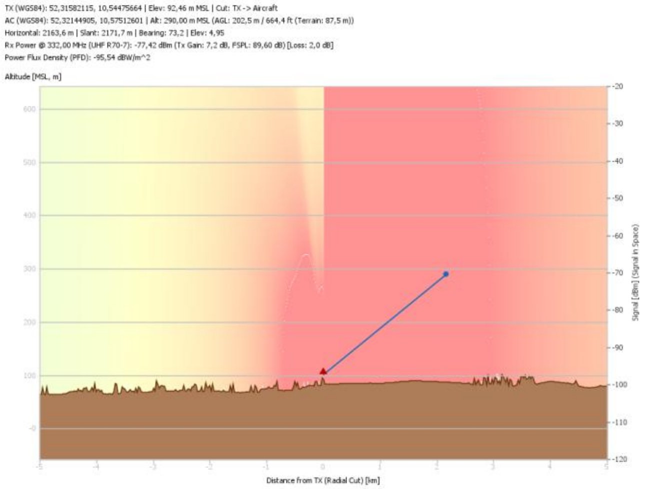


Figure 4: Top-Down-View
(left: OSM data, right: DEM data)

The vertical side view on the top right (detailed in Figure 5) is crucial for analyzing elevation-dependent effects. It displays a cross-section of the signal volume along the line-of-sight between the transmitter and the aircraft.

Both views allow to control the position of the aircraft. In both views, the transmitter (TX) is marked by a red triangle, while the aircraft (AC) is represented by a blue dot. A blue vector indicates the direct line of sight (LOS) between the transmitter and the aircraft. In the side view, the software displays various real-time parameters like path loss and the resulting geometry for the aircraft's current 3D position.



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TX (WGS84): 52,31582115, 10,54475664 | Elev: 92,46 m MSL | Cut: TX -> Aircraft
AC (WGS84): 52,32144905, 10,57512601 | Alt: 290,00 m MSL (AGL: 202,5 m / 664,4 ft (Terrain: 87,5 m))
Horizontal: 2163,6 m | Slant: 2171,7 m | Bearing: 73,2 | Elev: 4,95
Rx Power @ 332,00 MHz (UHF R70-7): -77,42 dBm (Tx Gain: 7,2 dB, FSPL: 89,60 dB) [Loss: 2,0 dB]
Power Flux Density (PFD): -95,54 dBW/m^2
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Figure 5: Side-View

The control suite at the bottom of the interface allows the user to manipulate the environment dynamically. Parameters such as TX antenna height, frequency, and mechanical tilt can be adjusted via sliders, resulting in an instantaneous recalculation of the signal volume. This interactivity allows for rapid "what-if" assessments, which are vital for identifying stable zones for in-flight calibration and for judging alternative areas if necessary.

The most intuitive way to understand RF challenges is by visualizing the RF environment. Instead of a simple surface plot, the software renders the SiS as a volumetric density map. As seen in Figure 4 and Figure 5, the RF signal's brightness decreases with distance, intuitively representing the free space path loss (FSPL).

An important feature is the visualization of a coverage volume given a certain minimum receiver sensitivity. Once defined by the user, the software dynamically visualizes the boundary where the predicted signal strength meets this limit with a white dotted line.

Once the analysis settings have been defined, more complex propagation models can be enabled, which simulate more physical effects than just the free-space path loss, but require higher computational processing.

Two-Way Propagation Model

The first improvement in simulation accuracy can be achieved by including interfering effects of direct and reflected signals. Depending on the phase relationships, these signal rays correlate constructively or destructively. With this two-way propagation model activated, the software outputs a signal distribution as shown in Figure 6.

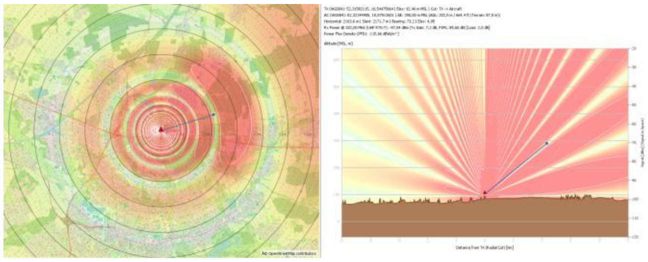

Figure 6: Simulation incl. Two-Ray Model

Compared to the previous outputs without this model activated, the homogeneous power distribution of the FSPL changes to various lobes, resulting in strong local power level fluctuations. This illustrates why an aircraft may experience signal drops at specific elevation angles, even at short ranges.

Terrain-Aware Propagation Model

For further improvements of the signal propagation simulation, an additional terrain-aware propagation model can be activated. Based on high-resolution elevation data (e.g. using a resolution of 1 meter and freely obtained at [4]), this model accounts for the actual surface topography, which includes buildings, hills, and forested areas. As illustrated in Figure 7, the high-resolution surface data reveals a significant contrast in the RF environment.

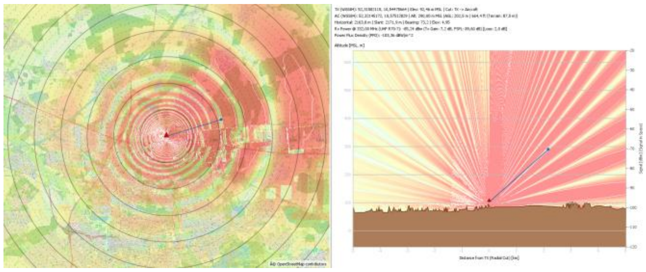

Figure 7: Simulation incl. Terrain-Aware Propagation Model

For the analyzed example, the southern sector of the airfield is characterized by dense infrastructure and airport buildings, which strongly influence the signal field and introduce complex interference. In contrast, the relatively flat areas surrounding the runway and taxiways in the North-East direction result in regions with highly predictable signal structures.

These stable zones were specifically identified through the simulation as the most suitable locations for performing elevation pattern characterization, as the environmental impact is mathematically consistent and can be effectively isolated from the aircraft antenna’s performance.

IN-FLIGHT CALIBRATION

For a validation of the developed software, a measurement flight was conducted using a typical flight inspection aircraft. The flight inspection system continuously recorded the actual RSSI from the antenna under test and the aircraft’s precise position.

Comparing the measurements with the simulated environment allows to analyze the antenna’s directivity pattern. Because these interference lobes are distributed across various elevation angles, a single flight leg at a constant altitude was sufficient to cover a broad range of the antenna’s vertical directivity. This approach effectively turns the airfield’s natural multipath environment into a calibrated test range, allowing for a high-resolution determination of the aircraft’s antenna pattern without the need for an idealized free-field environment.

While the theoretical framework provides a consistent model of the RF environment, an empirical validation is necessary to determine the accuracy of the simulated baseline. To verify the concept, a flight test was conducted at Braunschweig airport. The primary objective was to fly through the previously identified North-East sector to assess whether the simulated signal-in-space matches the real world measurements or if significant discrepancies exist.

For this initial validation, a rear-facing antenna was used on the aircraft. This way, a clear unobstructed line of sight between the antenna and the transmitter during outbound flight legs was ensured, reducing potential impact due to the aircraft’s fuselage.

The recorded flight trajectory, including the measured RSSI values, was subsequently overlaid within the software, as illustrated in Figure 8 and Figure 9.

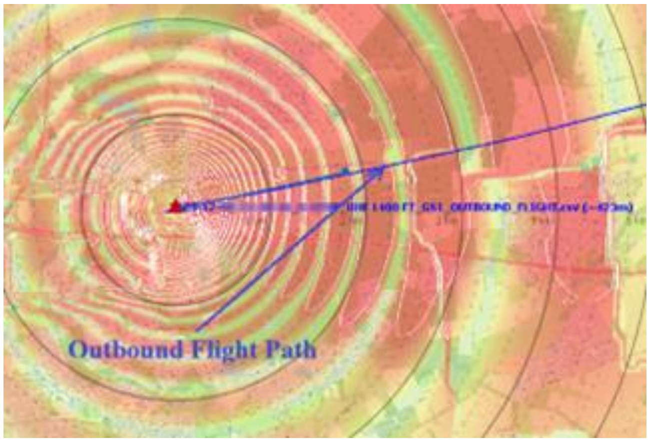

Figure 8: Top View of Flight Path

The software provides an intuitive visual correlation by color, coding the flight path based on the deviation from the model. As shown in the side view (Figure 9), segments with high correlation are rendered in green, while areas with larger discrepancies are highlighted in red. The static, blue dashed lines in the side view represent the theoretical propagation paths for each recorded position, allowing for a direct comparison between the simulated interference structure and the empirical data.

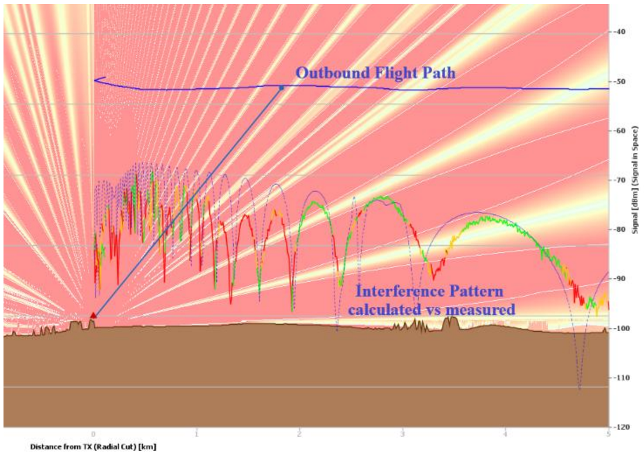

Figure 9: Side View of Flight Path

Despite minor discrepancies caused by the flight path slightly clipping building-induced interference zones rather than staying entirely within the unobstructed North-East corridor, the results are highly encouraging. The measured data exhibits interference rays and signal nulls at almost the exact spatial positions predicted by the developed software. This high degree of correlation confirms that the chosen approach of combining physics-based propagation models with high resolution DEM data represents a significant step toward creating a reliable digital twin of the RF environment, with various applications for flight inspections.

CONCLUSIONS & OUTLOOK

The initial results validate the prototype's capability to serve as a decision-making tool for antenna characterization. Since the software is location-independent and only requires the exchange of map and DEM data, the concept can be implemented globally. However, further verification is required to refine the transmit radiation pattern within the model. This can be achieved through dedicated flight campaigns at varying altitudes and radials, using the tool to plan optimized flight profiles that minimize the influence of the aircraft's own antenna characteristics.

Ultimately, the successful plausibility check during this initial flight test justifies the further development of the system. By integrating more complex antenna patterns for VHF, UHF, and L-Band frequencies, the software will provide a cost effective and highly accurate environment for the in-flight determination of antenna characteristics, reducing the reliance on idealized free-field environments and correspondingly the required flight time.

REFERENCES

[1] International Civil Aviation Organization (ICAO), *"Doc 8071, Manual on Testing of Radio Navigation Aids, Volume I – Testing of Ground-based Radio Navigation Systems"*, Fifth Edition, 2018

[2] Rappaport, Theodore S., *"Wireless Communications: Principles and Practice"*, Second Edition, Prentice Hall, 2002

[3] Seybold, John S., *"Introduction to RF Propagation"*, First Edition, John Wiley & Sons, 2005

[4] Landesamt für Geoinformation und Landesvermessung Niedersachsen (LGLN), *"Digitales Geländemodell 1 (DGM1)"*, Open-Data-Service, 2026