

## ANTENNA PATTERN CALIBRATION

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### ABSTRACT

ICAO Annex 10 defines coverage requirements for all navigational aids: Within the defined coverage volume a certain Field Strength (or Power Density) value must be measured. Field Strength and Power Density are used in equivalence as both parameters describe the 'strength' of an electromagnetic field. In contrast to Field Strength, Signal Level, which is used otherwise to define coverage requirements, describes an RF level measured after the antenna.

It is a challenging task, if Field Strength shall be measured correctly and with the level of uncertainty, which is defined in [2]

Polarisation, frequency range, cables losses, antenna and aircraft characteristics need to be taken into account as these have a non-negligible influence. Only then the electromagnetic field of a navigational aid can be assessed correctly. Accurate and aircraft independent Field Strength values can be calculated on board a modern flight inspection aircraft in real-time due to the computing power available today. However, this is realised only in very few systems.

This paper discusses precise Field Strength measurements to achieve the uncertainty as required by [2]. Different techniques are highlighted, such as the automatic correction of the antenna pattern, taking into account frequency dependency.

Methods for improving receiver accuracy and how to realise precise Field Strength measurements are discussed and practical examples are given for both techniques. The paper concludes with an outlook towards future developments.

### BACKGROUND

A navigational aid (NavAid) produces an electromagnetic field. Signals travel a certain distance until they form a stable electromagnetic field. But we can readily assume, that aircraft always operate in the 'far field' of a NavAid beam, where signals have stabilized. The strength of the electromagnetic field can be expressed as either Power Density [dBW/m<sup>2</sup>], electrical Field Strength [μV/m] or magnetic Field Strength [A/m]. All these quantities are equivalent and can be converted into each other. ICAO uses Field Strength in μV/m, to define coverage requirements, but quotes the equivalent Power Density in dBW/m<sup>2</sup>, too.

A Flight Inspection Aircraft should measure this electromagnetic field with best possible accuracy.

The antenna of a Flight Inspection Aircraft picks up the electromagnetic signal and converts it into a Radio-Frequency (RF) antenna signal. The value of this signal can be expressed as RF Power Level [dBmW] or RF Voltage Level [μV or dBμV]. Again these quantities are equivalent. RF Power can be converted into RF Voltage knowing the impedance of the antenna line, typically 50Ω.

Coverage requirements, which are defined in μV, relate to an RF Voltage Level, which is measured behind the antenna.

The performance of the antenna when converting electromagnetic Field Strength into an RF signal, influences the magnitude of the RF signal. The term that describes antenna performance is the 'Antenna Gain'. Antenna gain is composed of a constant gain factor as well as direction and frequency dependent parts. The frequency, on which a signal is received, and the orientation of the antenna influence the antenna gain and consequently the magnitude of the RF signal.

The magnitude of the RF antenna signal is still related to electromagnetic Field Strength, but due to the influence of the antenna gain, two different

antenna installations produce different RF levels, if the antenna gains are not exactly the same. In other words: The same electromagnetic field is measured differently in Flight Inspection aircraft #1 and #2.

When the signal travels to the receiver, cable losses and losses in dividers and relays reduce its magnitude further.

The receiver converts the RF signal into an output voltage. The output voltage is measured in a receiver circuit with acceptable linearity, which is typically the Automatic Gain Control (AGC) section of a receiver. The AGC voltage has a certain time constant and reacts smoothly to changes of the RF input signal.

AGC can be expressed as Signal Strength in dBmW or Signal Level in μV, both effectively being equivalent quantities: One expresses a power, the other a voltage measured across a 50 Ω resistance.

Standard receivers output AGC as an ARINC 429 label. And if this AGC parameter is not processed further, it can be displayed straight away on the screen of a flight inspection system.

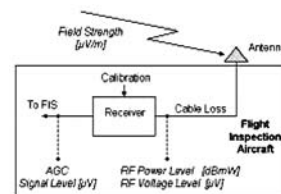
But usually the AGC voltage (or power) is corrected through calibration of the receiver itself or with software, that modifies the output AGC voltage such that it relates to the magnitude of the RF input signal with best possible accuracy.

This paper does not discuss receiver calibration. It assumes that receivers are calibrated.

One can see that many parameters influence the magnitude of the AGC output signal, which is used as a measure for the Field Strength of the electromagnetic field in which the Flight Inspection Aircraft operates.

Usually receivers are calibrated and losses in cables and dividers are considered. The influence of the antenna however is often neglected and an ideal characteristic assumed. This shall be discussed in the following.

AGC (Signal Level)	μV
RF Voltage Level	μV
RF Power Strength	dBmW
Field Strength	μV/m
Power Density	dBW/m <sup>2</sup>



**Fig. 1: From Field Strength to Signal Level**

RF Power Level, RF Voltage Level and AGC are relative quantities, their values depending on the measurement environment. Field Strength and Power Density are absolute quantities, their values expressing the electromagnetic field in which the Flight Inspection aircraft operates.

### FAA REQUIREMENTS

FAA document [3] specifies coverage requirements with an RF Voltage Level in μV that needs to be existent in the coverage volume. But this is not the only criterion; other additional coverage requirements exist. A NavAid conforms, if no flags or other indications of an invalid signal are present within the coverage volume. It conforms, if signals, e.g. clearance and structure of a Localiser, are within tolerance and if interference does not cause an out-of-tolerance situation.

A Flight Inspector will be aware, that the measured RF Voltage Level depends on the antenna gain,

i.e. on the specific installation in the flight inspection aircraft. He could use conversion tables, which are aircraft-specific, to convert RF Voltage Level into Field Strength and then be aircraft independent.

Still the decision, if a navigational aid conforms when coverage is marginal, is always based on other criterions. A NavAid does not fail due to an out-of-tolerance Signal Level measurement alone.

### ICAO REQUIREMENTS

Annex 10 and Doc 8071 Rev. 4 specify coverage of NavAids in terms of Field Strength and Power Density. As those quantities are equivalent, the term 'Field Strength' shall be used from now on.

'Field Strength' is an independent quantity, which manufacturers of NavAids and airborne systems can adhere to when designing their systems. Manufacturers of NavAids are allowed to manipulate transmitter power, types of antennas or antenna arrangements as needed, provided their equipment produces the Field Strength values set up by ICAO. Manufacturers of airborne avionic systems need to design their equipment that it functions in the Field Strength environment defined by ICAO. They are allowed some latitude in the design, provided that ICAO standards are met.

By specifying coverage through Field Strength values the design process of ground installations and airborne systems was made independent from each other. F

light Inspection must be able to check the Field Strength values set up by ICAO.

Receivers used in Flight Inspection output AGC (Automatic Gain Control) voltage in  $\mu\text{V}$  or basic power in dBmW. The relationship between these receiver output values and the Field Strength of the electromagnetic field needs to be found. Then the Flight Inspector is able to make an informed judgement, if coverage requirements are met or not. ICAO also specifies the uncertainty with which a field strength value needs to be measured. The  $\pm 3\text{dB}$ , which are specified in [2], are a challenge to meet, as these are absolute measurement requirements. Without more advanced measuring techniques, the antenna pattern correction as described below is such an example, the ICAO measurement requirement can hardly be met.

### FLIGHT CHECKING OF FIELD STRENGTH

According to ICAO document [1] Field Strength of localiser and glide path needs to be measured with an absolute accuracy of  $\pm 3\text{dB}$ .

Some installations have marginal field strength at the edges of coverage. If it were not possible to measure Field Strength accurately enough, the Flight Inspector – being aware of the measuring performance of his equipment – would revert back to other criteria, which tell him that the facility works all right. If the measurement equipment does not show flags and if other signals look okay, the Flight Inspector may issue a conformance statement, even if the field strength tolerances are not met.

If relying solely on RF Voltage Level or AGC, it will be even more difficult to say, if coverage requirements are being met or not. Now the characteristics of the Flight Inspection aircraft are unknown parameters in the measuring chain. If cable losses and other losses are taken into account, there is still the antenna, which – if its characteristics are unknown – contributes to an uncertainty about the true Field Strength value.

One has to admit, that uncorrected equipment simply does not measure Field Strength accurately enough. Wouldn't it be better, if Field Strength could be measured with improved accuracy? The Flight Inspector had Field Strength values on which he could rely. Wouldn't it be good, to know the characteristics of the receiving antennas? Provided the antenna manufacturer issued a statement about antenna performance, how does the performance change when this antenna is installed on an aircraft fuselage?

### TAKING THE ANTENNA CHARACTERISTIC INTO ACCOUNT

The characteristics of an antenna depend to a crucial degree on the installation on the fuselage of the Flight Inspection aircraft.

In Flight Inspection, standard aircraft antennas are used in a most unusual way. Drift during the approach leads to variations in the received RF signal strength. And when coverage is measured during orbits, antennas look sideways and measured field strength can grossly deviate from the true value. The ideal antenna for Flight Inspection does not exist.

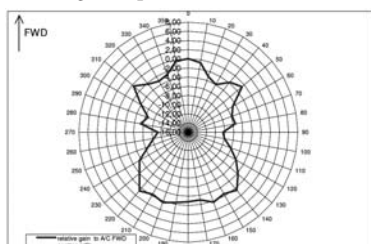


Fig. 2: Horizontal Pattern, FIS Localiser Antenna

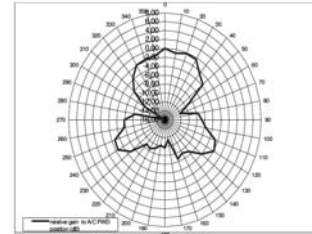


Fig. 3: Horizontal Pattern, FIS Glide Path Antenna

The pictures above depict the horizontal antenna diagrams of a FIS localiser and glide path antenna. These pictures contain more valuable information than the antenna diagrams issued by the antenna manufacturer, as they show the diagram of the antenna after being installed on the fuselage. The Flight Inspection System manufacturer measured both diagrams.

It is apparent in the glide path antenna diagram that accurate field strength measurements are difficult, when the aircraft tracks at a  $90^\circ$  angles to the ILS course. Uncorrected, this antenna would produce low RF Voltage Level readings when used in a glide path coverage orbit. Parts of the antenna diagram show a gain, which is more than 10dB lower compared with the forward direction.

But if the antenna diagram is known, a software algorithm can compensate this effect and produce an antenna, which is more ideal.

This is one example for the virtues of antenna pattern correction. If antenna patterns are known, the Flight Inspection aircraft can fly extraordinary calibration profiles and still measure accurate Field Strength. Compensating horizontal antenna patterns is mandatory for a FIS to comply with ICAO.

It shall be noted, that antenna diagrams change with varying frequency. Antenna pattern correction should take this also into account.

### ANTENNA PATTERN CORRECTION

The received signal strength depends on:

- The antenna itself
- The transmitter frequency
- Angle between transmitter and receiving antenna (= Angle of Incidence)
- Polarisation

If excluding the receiver and the cable and divider losses, the remaining variable is the antenna.

We shall assume that the transmitting and receiving antenna are equally polarised. The reception characteristic of the antenna then depends on the gain, which the receiving antenna has at a given frequency and at a particular angle.

For ease of calculation, frequency and direction dependent components shall be split from an absolute antenna gain. Listed separately we have the following antenna characteristics:

- Directional antenna pattern (Relative characteristic)
- Frequency dependent antenna behaviour (Relative Characteristic)
- Antenna gain (Absolute Characteristic)

Flight Inspection System manufacturers with precise Field Strength measuring capability, calibrate a range of antennas, including localiser, glide path, Marker and L-Band antennas, but seek to find a balance between an academic and a practical solution. The following example explains the calibration of localiser and glide path antennas:

The horizontal directional antenna pattern is measured with a resolution of one measurement point every  $1^\circ$ . On the overview in figure 2 are only shown 36 steps.

Such a horizontal pattern can be determined in a ground test. Braunschweig airport is used as a test site, which nicely meets the following requirements:

- No obstacles in the line of sight between aircraft under test and transmitter
- A homogeneous electromagnetic field inside the test area
- No multi-path effects

- The traffic is not too dense, so that times can be found to carry out the measurements

The antenna is tested when it is mounted on the aircraft to show the original operating environment.

Frequency dependency is measured by changing the frequency in steps within the frequency bands. Example values are chosen, which represent the behaviour in the band.

Once the directional and frequency dependent characteristic of the antenna has been determined, the absolute gain is measured through a reference measurement on the test-site using a reference antenna with known characteristics.

Subsequent to the measurements on the test-site, the results are analysed. This result is a table of correction values, which is loaded into a database. The contents of this database differ, not only for the different types of aircraft, but also for each particular flight inspection system in a particular aircraft.

Knowing the correction values, the Flight Inspection software is able to perform a correction of the antenna characteristics in real-time. The software compensates all losses and creates an antenna with virtually ideal performance. The figure below depicts the complete measurement chain, starting with the electromagnetic field, that shall be accurately measured, and finishing with the Field Strength value, that appears on the screen of the Flight Inspection system. The two pictures below are one diagram, which was divided into two, to fit into the available space:

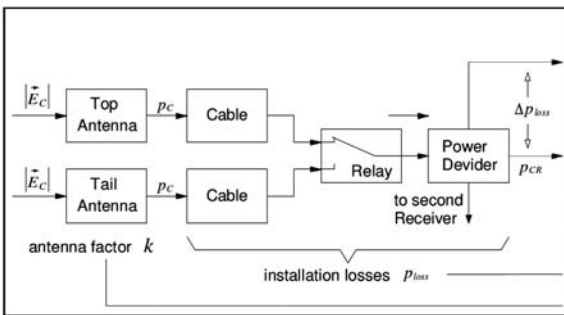


Fig. 4: AGC to Field Strength Conversion in AeroFIS Flight Inspection Systems, Part I

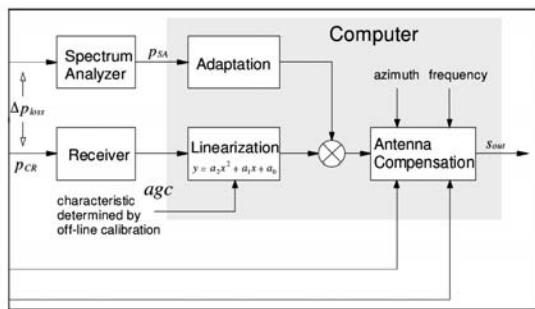


Fig. 5: AGC to Field Strength Conversion in AeroFIS Flight Inspection Systems, Part II

With the computing power available in modern Automatic Flight Inspection Systems (AFIS), Field Strength can be calculated in real-time from AGC. The great advantage of this method is that two different Flight Inspection aircraft produce identical Field Strength readings, provided all losses and antenna patterns are correctly measured and the compensation is done in real-time. The Flight Inspector can read required quantities from the screen and can directly verify the values in the books, independently from the aircraft in use.

It is relatively easy to incorporate fixed conversion parameters such as cable losses or losses in power dividers and relays. But it shall be noted that correction of the antenna gain for the directional and frequency dependent component is more difficult. An Inertial Navigation System (INS) or accurate gyroscopes are needed, to accurately know about the

attitude and heading of the Flight Inspection aircraft in relation to the NavAid under inspection, to determine the angle of incidence. Only if attitude and heading are known in real-time, the correct pattern correction values can be applied.

To be compliant with the FAA world, the Field Strength value can be transformed back into an RF Voltage Level  $\mu\text{V}$  using an ideal antenna gain of 1. This effectively is an aircraft-independent RF Voltage Level.

This method has proven to be reliable and to deliver accurate and satisfactory results for almost 10 years now. Measuring antenna characteristics has become routine and Flight Inspectors using such a system are used to accurate Field Strength values.

### ONLINE AGC CORRECTION

Other techniques to improve Field Strength measuring accuracy have been tried. A standard navigation receiver used in flight inspection – the Bendix King RNA-34-AF navigation receiver – struggles to meet the +/3dB uncertainty requirement given by ICAO.

Modern receivers, such as the AD-RNZ-850, have a much better measuring uncertainty. When combined with antenna pattern correction, they already make an excellent tool for Field Strength measurements.

Spectrum analysers with excellent measuring accuracy are an integral part of most modern Flight Inspection systems. Why not use it to crosscheck the Field Strength measuring performance of the navigation receiver.

If navigation receiver output and spectrum analyzer grossly disagree, the Field Strength value is corrected. This effectively is a continuous calibration of the navigation receiver while the Flight Inspection aircraft is flying a calibration.

### USER DEFINABLE ANTENNA PARAMETERS

At the beginning, antenna parameters – after the Flight Inspection System manufacturer had determined them – were written into a file and then compiled into the software. This worked well, but customers demanded to be more flexible.

In today's flight inspection world, a change of software often results in the need to re-certify the flight inspection equipment with the aviation authorities.

New software must allow authorised users to modify their antenna patterns without having to re-compile the software. This allows Flight Inspection Service Providers, to make their own Field Strength investigations.

A safety function is installed on top, that antenna patterns cannot be changed unknowingly. And a viewing function helps the Flight Inspector to view antenna characteristics for trouble-shooting purposes, even while being on a mission.

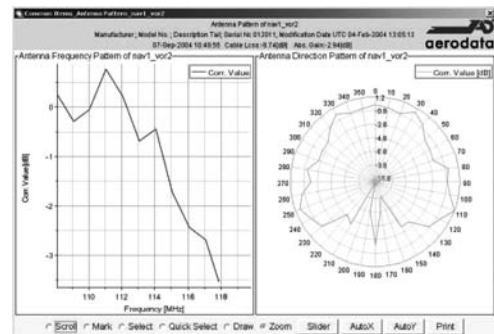


Fig. 5: Antenna Pattern viewed in modern Graphical User Interface

### CONCLUSION

This paper's aim was to demonstrate a practical approach towards measuring Field Strength, by emphasizing the importance of measuring it accurately, but also trying not to exaggerate the importance of this measurement.

In today's dense aviation environment, with new systems being installed in frequency bands, which are already full, it is necessary to define coverage areas carefully. Nobody can afford to install a NavAid that simply outputs 'a lot of power'.



Employing antenna gain correction, Field Strength (Power Density) can be measured with improved accuracy assisting the Flight Inspector to better classify the installation.

Compensating antenna installation characteristics like

- Cable Loss
- Horizontal Antenna Pattern
- Frequency Dependent Antenna Pattern
- Absolute Gain

is mandatory to comply with requirements of ICAO and to obtain aircraft independent measurement results according to FAA practice.

#### **OUTLOOK**

Currently under investigation are 3-dimensional antenna patterns, taking into account the horizontal AND vertical characteristic of an antenna. An accurate vertical antenna pattern will minimise the influence of pitch and roll on Field Strength measurements.

If frequency dependency is counted as an additional parameter, this effectively leads to 4-dimensional antenna patterns.

The measurement routines are to be simplified. Each change of an aircraft antenna might require a fresh antenna calibration. This process can be costly. A balance must be found between what is theoretically possible and what is useful in terms of accuracy. Nobody is going to pay for accuracy that is not needed. And calibration procedures must therefore aim to have a high degree of automation.

Practical experiences and measurements at the actual aircraft will improve our theoretical models of antennas. Maybe in the future the characteristics of antennas installed on a given airframe may simply be taken from a numerical simulation.

#### **REFERENCES**

- [1] ICAO Annex 10
- [2] ICAO Doc 8071, Rev. 4 of 2000
- [3] FAA United States Standard Flight Inspection Manual, Order 8000.1C