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(06/2014)

Airborne verification of antenna patterns of broadcasting stations

SM Series

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REPORT ITU-R SM.2056-1

Airborne verification of antenna patterns of broadcasting stations

(2005-2014)

1 Executive summary

This Report describes the measurement procedures, the equipment required, and the reporting procedures for antenna radiation pattern measurements using an aircraft. This Report is independent of the airborne platform chosen and it can be used regardless of the broadcasting system used. However, additional suggestions are given for specific airborne platforms and specific broadcasting systems, so that it can be tailored to anyone's specific needs.

The Report is divided into three Annexes:

– Annex 1 introduces the different antenna pattern types that can be distinguished, and the measurement procedures to measure those. The equipment needed to perform such measurements is described. This description is sufficiently detailed to assemble one's own system, without limiting the choice of equipment. The post flight analysis, important for evaluating the measurement accuracy, is described, followed by a reporting standard.

– Each broadcasting type and each frequency range requires its own settings and has its own points of attention. Annex 2 is dedicated to these items.

– Annex 3 describes the specific problems encountered when choosing a specific aircraft type, and proposes solutions when possible.

Annex 1

Airborne verification of antenna patterns of broadcasting stations

1 Introduction

This Annex describes the measurement procedures, the equipment required, and the reporting procedures for antenna radiation pattern measurements using an aircraft. The structure of the Annex is as follows:

Section 2 describes the different antenna pattern types that can be distinguished. Section 3 introduces the measurement method in general. Section 4 defines the different measurement flights types. Section 5 describes the equipment needed to perform these measurements. This description is sufficiently detailed to enable assembling one's own system, without limiting the choice of equipment. Section 6 describes the measurement procedures involved. Sections 7 through 9 deal with the different aspects of data processing, measurement uncertainty calculation and reporting.

The recommendations in this Annex are independent of the type of aircraft chosen and it can be used regardless of the broadcasting system used. Annexes 2 and 3 will give additional recommendations for specific airborne platforms and specific broadcasting systems.

2 Antenna pattern types

The radiation pattern of any antenna is three-dimensional. Measured antenna patterns are generally two-dimensional cuts of that three-dimensional pattern. Common cuts are the "vertical antenna pattern" and the "horizontal antenna pattern". The vertical antenna pattern is a vertical cut of the antenna pattern through the antenna and a specific azimuth direction. The horizontal antenna pattern is a horizontal cut of the antenna pattern through the antenna and a specific elevation or down tilt angle. See Figs. 1 and 2. The coordinate systems used are described in Recommendation ITU-R BS.705.

FIGURE 1

Vertical antenna pattern

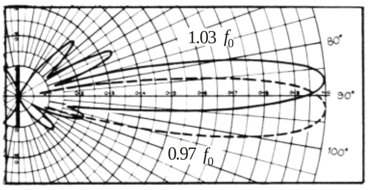
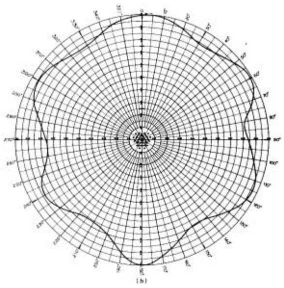


FIGURE 2

Horizontal antenna pattern



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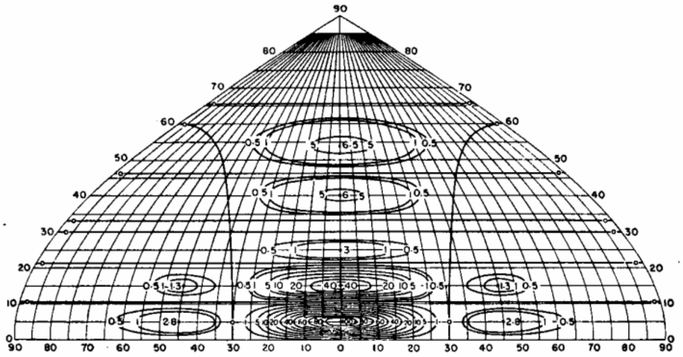
In certain cases a lot of emphasis is put on one specific sector of the antenna. For highly directional HF broadcasting antennas, the exact form and position of the main lobe, as well as the effective radiated power (ERP) in that main lobe determine the footprint on the targeted area, and are therefore very important. A specific antenna pattern measurement could chart that part of the antenna pattern. An example of such an antenna pattern, the Sanson-Flamsteed projection, is given in Fig. 3.

FIGURE 3

Main lobe antenna pattern



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Antenna pattern measurements can be repeated for different azimuths or different elevation angles to obtain more information on the complete three-dimensional antenna pattern. Those azimuths or elevation angles can be strategically chosen based on the geometry of the antenna, simulations and experience from previous measurement campaigns.

Measuring any of these antenna pattern types requires its own set of measurement flights, but the measurement procedure is very similar if not the same.

3 Method of measurement

An antenna pattern measurement is basically a series of field-strength measurements, each taken at an exactly known distance from the antenna to be measured. With these two values the absolute EIRP in that point can be calculated. If we measure the EIRP at a series of points positioned on a circle around the antenna, the horizontal antenna pattern emerges. Other diagram cuts can be measured at will. The formula for calculating absolute EIRP is, in linear form:

$$p_{EIRP} = \frac{p_{RX} . R^2}{g_{RX}} . \left(\frac{4 \pi f}{c} \right)^2 \tag{1}$$

where:

p_{EIRP}: power relative to an isotropic radiator (W)

p_{RX}: power at the receiver input terminals (W)

R: distance (m) between the receive and transmit antennas

g_{RX}: gain (linear value) of the receive antenna relative to an isotropic radiator

f: frequency (Hz)

c: speed of light (m/s).

Care must be taken to measure position and p_{RX} at exactly the same time. If this condition is not met, the resulting EIRP-value is not correct. In this formula p_{EIRP} and g_{RX} are expressed relative to an isotropic radiator. Additional losses such as cable losses, antenna alignment loss or polarization loss should be included in the value for G_{RX}. Generally, using a logarithmic version of the same formula is more practical:

$$P_{EIRP} = P_{RX} + 20 \log (R) - G_{RX} + 20 \log (f) + 20 \log (4\pi / c) \tag{2}$$

In formula (2) P_{EIRP} and P_{RX} are expressed in dBW, G_{RX} in dBi.

Depending on the broadcast application and the broadcast band used, the standardized reference antenna may differ from the isotropic radiator, e.g. a half wave dipole or a short lossless monopole. To calculate ERP (half wave dipole reference), the following formula may be used:

$$P_{ERP} = P_{EIRP} - 2.15 \, \text{dB}, \tag{3}$$

as the antenna gain of a half wave dipole is 2.15 dBi.

4 Measurement flight types

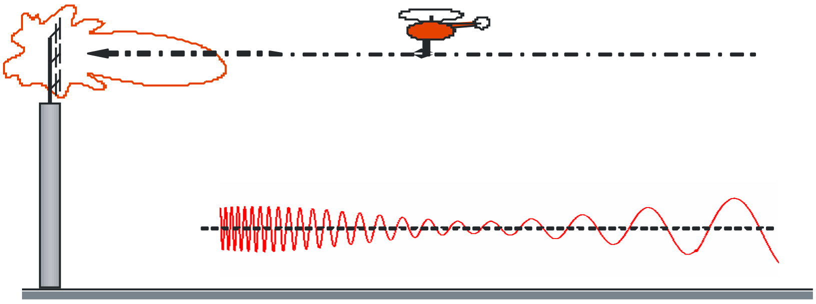
The type of measurement flights conducted depend fully on the antenna situation and the aircraft used. For example, for the measurement of the diagram of a VHF broadcast antenna with a helicopter, a different approach is needed than for the measurement of a medium-wave array with an aeroplane. The different measurement flight types and their application are described in this Section.

4.1 Propagation flight

To determine the optimal measurement distance, a propagation flight can be performed. This is a flight in a straight line towards the transmit antenna, at exactly the height of the transmit antenna. That way the angular position of the measurement antenna as seen from the transmit antenna is constant, and therefore the transmitted ERP in that direction is constant. If no reflections are present, the measured ERP during the propagation flight will be constant too. If ground reflections or scattering off buildings is present, their influence will show as deviations from that straight line, as shown in Fig. 4.

FIGURE 4

Propagation flight



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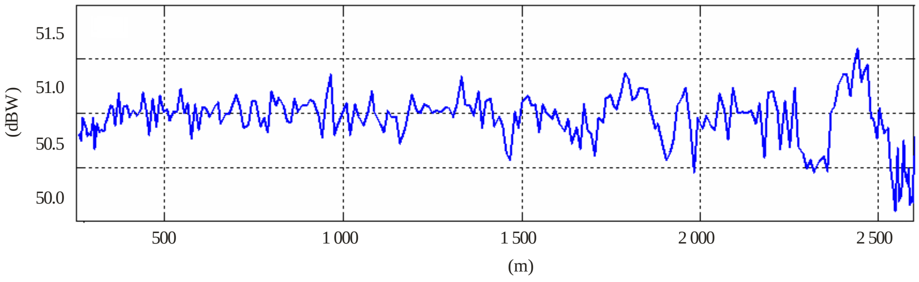
The suggested measurement direction for a propagation flight is in the direction of the main lobe in the antenna pattern. Multiple propagation flights are recommended on antennas with multiple radiation directions and in cases where ground conditions and thus ground reflections differ.

In addition to the theoretical graph of Fig. 4, an actual measurement result is given in Fig. 5. This graph is made of a 50 kW VHF FM broadcast transmitter. The transmit antenna consisted of an array of vertically polarized log-periodic dipole antennae mounted on tower approximately 150 m above the ground. The circle indicates the distance that was selected for a subsequent circular flight.

FIGURE 5

Actual propagation flight result



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From the result of the propagation flight an optimum distance is selected for subsequent measurements. The optimum distance is the distance where:

– the amplitude of the reflections is least, and

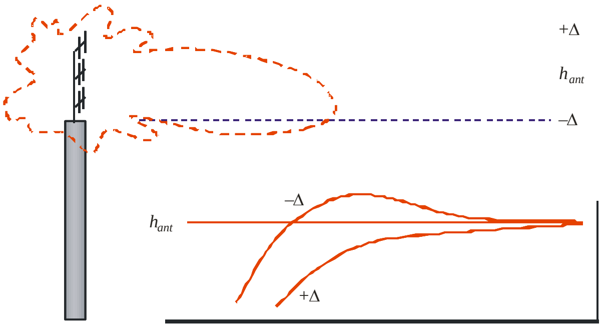
– the minima and maxima are closest together.

The first criteria is obvious, the second may require explanation. If the minima and maxima caused by ground reflections lie far apart, and the ground is flat and homogenous, e.g. a complete circle flight could be conducted at a distance where the minimum or maximum occurs. This would result in the biggest measurement error achievable, while the problem would show the least as variations in the measurement result. So this situation should be avoided. With the example shown, the optimum measurement distance would lay around 1 300 m. This distance is marked with a circle in Fig. 5.

If the height at which the propagation flight is performed differs from the actual height of the antenna, the graph will drop when the aircraft comes close to the antenna. When flying too low and measuring a transmit antenna with downtilt, the graphs may show a temporary rise before this drop in value occurs. This effect is illustrated in Fig. 6.

FIGURE 6

Effect of incorrect height during the propagation flight



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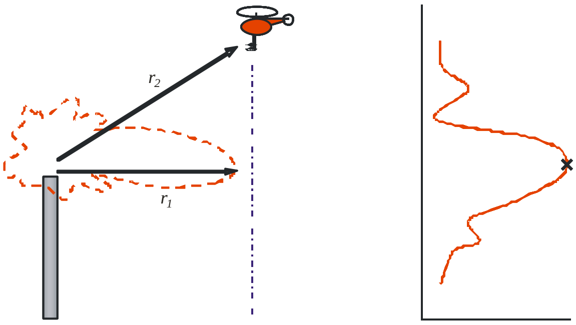
Prior to the propagation flight, the pilot display assists the pilot by showing the actual position of the aircraft relative to the transmit antenna, as well as the desired start-position of the propagation flight. This position can be described with the desired azimuth angle with respect to the transmit antenna and the desired height. During the propagation flight, the pilot display assists the pilot by showing the offset in metres from the desired flight path. A propagation flight is easier to perform with an aircraft that maintains good control and manoeuvrability at low speed, such as a helicopter. One can fly in a straight line up to 200 m of the tower, then stop and fly away. This is not possible with all other aircrafts. A minimum distance to the transmitting antenna(s) should be kept at all times, to avoid excessive electromagnetic exposure. If the transmit antenna is mounted directly on the ground, as in the case with most long-wave, medium-wave and short-wave antennas, a propagation flight is not possible.

4.2 Vertical flight

To obtain the vertical antenna pattern of a broadcast antenna in a specific azimuth direction, a vertical flight can be performed. Measuring the vertical antenna pattern can be necessary to determine the optimum flying height for measuring the horizontal antenna pattern, as indicated in Fig. 7.

FIGURE 7

Vertical flight



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To perform a vertical flight, the pilot first moves to the desired azimuth direction, then descends to the desired start height. The pilot display assists the pilot by showing the actual position of the aircraft relative to the transmit antenna, as well as the desired start position for the vertical flight. The pilot then starts ascending in a straight vertical line, trying to retain his horizontal position as good as possible. If a helicopter is used, maximum stability is obtained when the flight is performed flying from a low altitude to a higher altitude at full throttle.

During the vertical flight, the pilot display assists the pilot by showing the offset in metres from the desired flight path. This could be done representing the aircraft as a dot on a circular display. The centre of the circle represents the desired horizontal position, the circle itself shows the maximum allowed horizontal offset. The pilot should keep the dot within the circle while flying upward. The circular display can be connected to a compass to align its orientation with that of the aircraft. This makes steering easier, as the wind dictates where the nose of the aircraft is pointing.

When no aircraft is available for vertical flights, the vertical diagram cannot be obtained this way. It has then to be estimated by interpolating measurement points of subsequent horizontal flights.

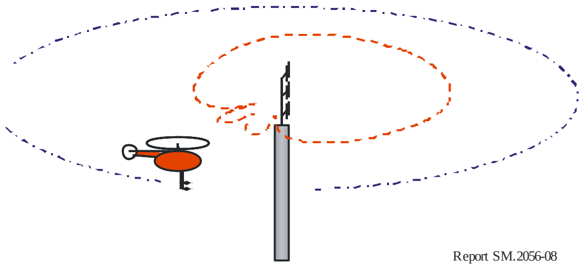
During the vertical flight the two correction factors need to be applied. A compensation for the difference in gain in the vertical antenna diagram of the measurement antenna and a compensation for the difference in distance (r_1 and r_2 in Fig. 4).

4.3 Circular flight

To obtain the horizontal antenna pattern of a broadcast antenna, the pilot starts flying a circle around the transmit antenna while correcting his altitude and distance to the transmit antenna until the target values are obtained. The measurement is then started, and the pilot continues flying along a circle around the tower, until the measurements are completed. During this process, the pilot is assisted with information on the pilot display. It shows the actual position of the aircraft relative to the ideal path around the transmit antenna in real-time. During the circular flight, the pilot display assists the pilot by showing the offset in metres from the desired flight path (distance and altitude). Generally it is necessary to fly part of a circle to enter the required flight path so the definition of a predetermined start azimuth is not practical. In most cases the pilot likes to see the object he or she is flying around so the layout of the aircrafts cockpit dictates if the circle is flown clockwise or counter clockwise. The software and antenna system should be adapted to this. Best stability is obtained when the aircraft flies with a steady and not too slow speed. As the aircraft flies around the antenna the relative wind direction changes with the azimuth angle, as a result of this the part of the aircraft pointing to the antenna changes during the flight. It is therefore in most cases necessary to steer the antenna during flight.

FIGURE 8

Circular flight



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4.4 Other flight types

Antenna radiation pattern measurements around ground-based antennas like, e.g. HF curtain arrays and medium-wave towers or arrays require a different approach than tower-based TV or FM broadcasting transmitters. For example: circular flights at other heights than the height of the main lobe can give the measurement points needed to construct a 3-dimensional picture of the radiation pattern, straight flights at low heights in the azimuth of the main lobe can give an impression of the vertical radiation pattern.

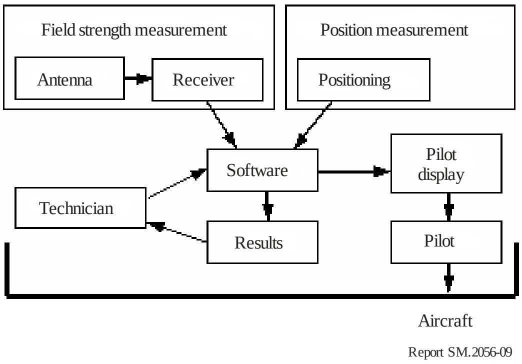
As long as the 3-dimensional position of the measurement point is known exactly, and the ERP is calculated in that measurement point, there are no limits to the actual flight path used, as long as the engineer that interprets the measurement data has a profound knowledge of the matter.

5 Measurement equipment

As shown in § 3, ERP can be measured by exactly measuring position and field strength. Position can be measured using any positioning device that gives fast and accurate 3D position information. Field strength can be measured with a free space calibrated antenna and a calibrated measurement receiver. The position and field-strength values are recorded and processed by a computer. It calculates ERP and the position of the measurement point relative to the antenna under test, and displays the results in an appropriate form to the technician. The technician controls the measurement system and takes decisions based on the results shown on the screen. The software also generates information for the pilot, to assist his navigation around the antenna site. The pilot is responsible for the flight itself and all related security issues. A simplified schematic presentation of a typical measurement set-up is shown in Fig. 9, subsystems of which will be discussed in the following paragraphs.

FIGURE 9

Schematic presentation of an airborne antenna pattern measurement system



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5.1 Positioning equipment

As the distance used in the formulae is 3D distance, the position of the measurement and the position of the transmit antenna have to be known along three axes, e.g. latitude, longitude and height. The difference of the 3D position of the measurement antenna relative to the positioning device should be taken into account.

The positioning system used should in any case meet the criteria for accuracy and update rate. The accuracy depends on the application but is typical ±1 m in all directions. Requirements for the update rate can be found at the end of this section and in § 5.5 of this Annex. Hybrid positioning systems using reference beacons can be used. Coverage of such beacons may limit the flexibility. The position accuracy determines the accuracy of the calculated distance to the antenna under test.

This in turn determines the accuracy of the calculated ERP-value and relative position. Measurements close to the antenna under test require a higher position accuracy than measurements at a larger distance. The optimum measurement distance depends on the wavelength, the dimensions of the antenna under test and environmental conditions that cause reflections. Required position accuracy is in the order of 2 m.

The update rate of the positioning device needs to be sufficient to generate enough measurement points along the curve flown. This is a function of the angular ground speed of the aircraft. Also the update rate of the pilot display should be near real-time. An update rate of 2 Hz is an absolute minimum, 10 Hz or more would be advisable.

5.2 Measurement antenna

5.2.1 Gain

To measure the absolute field strength the antenna has to be free space calibrated. Gain has to be expressed relative to the appropriate reference antenna. The calibration accuracy of the antenna is one of the main factors influencing the total measurement accuracy. A calibration accuracy of 0.5 to 1 dB is achievable and advisable.

The actual value of the antenna gain is not critical as long as it is exactly known. However, an antenna gain lower than −20 dBi will make the unwanted pickup of the antenna cable dominant. And a directivity above about 6 dBi will result in lower accuracy due to alignment errors.

5.2.2 Diagram of the measurement antenna

The measurement antenna only exhibits its calibrated gain figure when aligned bore sight to the antenna under test. Exact alignment of the measurement antenna during the flight is rather difficult, therefore it is preferable to use a measurement antenna which has as little as possible gain variation around the main lobe. That way alignment becomes less critical, improving the measurement accuracy.

When a flight is made on a different height than the antenna under test, e.g. during a vertical flight, the gain of the measurement antenna will vary with the angle of the incoming wave. When the vertical pattern of the measurement antenna is known, one can compensate for this in the measurement software. To be able to do this the measurement antenna should have a smooth antenna pattern.

It is not necessary to design a measurement antenna that has a high front to back ratio. The antenna under test is relatively close to the wanted antenna and other broadcast transmitters on the same frequency are relatively far away. As the signal strength is inversely proportional to the distance, the wanted signal is several magnitudes stronger than the signal of other broadcast transmitters received from other broadcast towers. There is generally no need to suppress them any further using the directivity of the measurement antenna.

5.2.3 Alignment of the measurement antenna

In most cases, the measurement antenna has directivity. So during flight, the measurement antenna has to be kept as close to bore sight to the antenna under test as possible. This can be done using some mechanical or electromechanical rotator controlled by the technician. Some indication of the actual antenna position is necessary in all cases, to roughly aim the antenna at the antenna under test. To adjust the direction more precisely, some aiming device is necessary. A small camera mounted on or near the antenna and looking in the same direction is a good and cost effective solution. Some sunlight filtering is needed to prevent overloading of the camera chip.

Omission of any means to direct the measurement antenna towards the antenna under test will result in incorrect results. Stabilizing the aircraft at a fixed angle towards the antenna under test is generally not possible, the wind direction will induce a pitch on the flight path. Alignment in the vertical plane is generally not feasible.

Misalignment and the resulting measurement error should be accounted for in the uncertainty analysis of the measurement.

5.2.4 Suppression of ground reflections

To get an accurate representation of the antenna pattern, only the direct waves from the transmit antenna to the measurement antenna should be measured. However, any object within sight of both antennas may cause transmitted waves to reflect. One should be aware that if no measures are taken, both direct and reflected waves are measured, generating some sort of unwanted “modulation” on the antenna diagram measured and presented.

This problem is very much dependent on the vertical directivity of the transmit antenna and of the receive antenna, and of the height of the transmit antenna versus the measurement distance. For example, low gain VHF FM antennas on low sites offer a much higher challenge in this respect than high UHF TV sites with high gain antennas. Also reflection of the received signal against parts of the aircraft must be considered. As ground reflections are amongst the major contributors to the total measurement uncertainty, this item is worth paying extra attention to.

Proper design of the measurement antenna can make the measurement system less vulnerable to disturbance by ground reflections. This can be done by designing an antenna that suppresses directions from which reflections are expected and favours the direct wave. This is illustrated with a practical example in Figs. 10 and 11:

FIGURE 10

Actual measurement using a simple measurement antenna

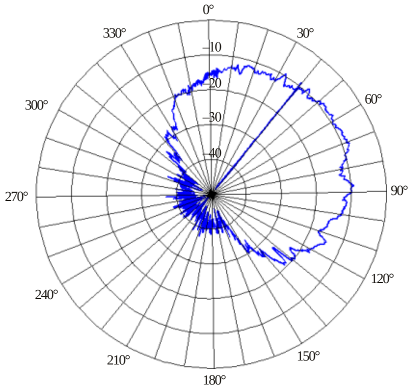
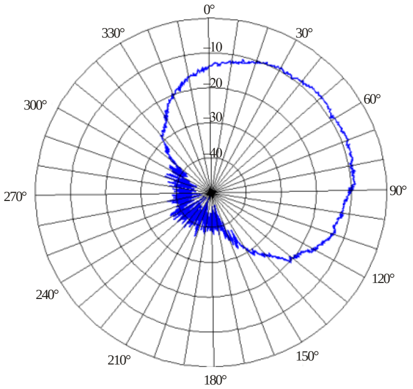


FIGURE 11

Same measurement, now using a specially designed measurement antenna



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In this example, a VHF FM broadcasting antenna was measured twice, once with a simple measurement antenna, and again with an antenna specially designed for airborne antenna pattern measurements. The reflections are shown as “modulations” in the first measurement. The advantage of the second specially designed measurement antenna is obvious.

Another way of attenuating reflections could be the deployment of multiple measurement antennas followed by multiple receivers and using DSP software. This software can use an algorithm for example MUSIC to extract only the direct signal from the sum of the reflected and direct signal. Whatever method is used to eliminate reflections, care must be taken to assure that the reproduced signal level is still an accurate representation of the signal level of the direct wave.

Simulations can be used to estimate the impact of ground reflections in specific cases. The model should contain measurement height, measurement distance, height of the antenna under test, expected vertical antenna pattern, the known vertical pattern of the receive antenna and a realistic ground model with the actual ground parameters. Using these, a good impression can be obtained of the particular difficulties that may be encountered in a specific measurement situation. However, simulations can never replace real measurements.

5.2.5 Polarization

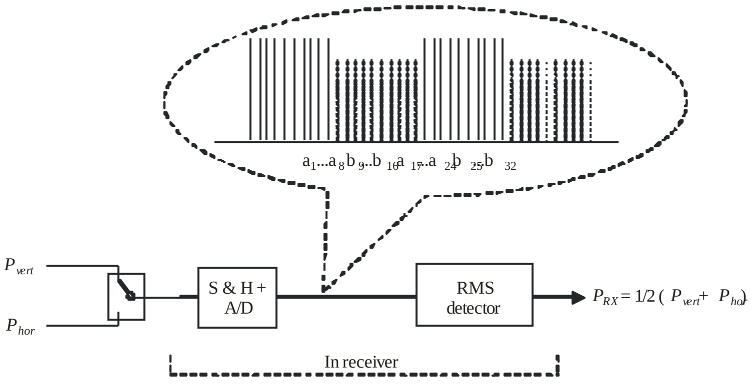
The polarization of the measurement antenna needs to be adapted to the polarization of the antenna under test. At VHF and UHF frequencies non-linear polarized antennas have become common. With these antennas the actual polarization varies with the position relative to the antenna. Therefore it is an advantage to measure polarization independently. There are two ways to achieve this:

- Use two measurement antennas with perpendicular polarizations and two measurement receivers. Both receivers are synchronized. Adding the values of the power measured with each receiver will give the total received power independent of the polarization of the transmitted signal. With this set-up it is possible to present the diagrams for the horizontal and vertical polarization planes separately, as well as the combined antenna pattern independent of polarization.
- Use a single receiver and the same two measurement antennas. The receiver is switched between both antennas and the RMS detector of the receiver sums the power of both paths. This is a low-cost method.

Using the latter method, each polarization plane is measured during 50% of the measurement time, and the end result is exactly 3 dB lower than the actual value, see Fig. 12. Switching time and measurement time should be chosen based on the properties of the modulation of the measured signal and the bandwidth of the receiver. With proper engineering this can be as accurate as the first method.

FIGURE 12

Principle of low-cost polarization independent system



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When for one switching period of the antenna switch: $p_{VERT} = \dfrac{\sqrt{\sum_0^T {a_k}^2}}{z_0}$ and $p_{HOR} = \dfrac{\sqrt{\sum_0^T {b_k}^2}}{z_0}$, then:

$$p_{RX} = \frac{\sqrt{\sum_{0}^{T/2} a_k{}^2 + \sum_{T/2}^{T} b_k{}^2}}{z_0} \approx \tfrac{1}{2}\frac{\sqrt{\sum_{0}^{T} a_k{}^2}}{z_0} + \tfrac{1}{2}\frac{\sqrt{\sum_{0}^{T} b_k{}^2}}{z_0} \approx \tfrac{1}{2}\,(p_{VERT} + p_{HOR})$$

Where (in linear values):

z_0: system impedance

p_{VERT}: RMS input power from vertical polarized antenna

p_{HOR}: RMS input power from horizontal polarized antenna

p_{RX}: power measured by the receiver, using a RMS detector

a_n: voltage amplitude of one measurement sample from the vertical antenna

b_n: voltage amplitude of one measurement sample from the horizontal antenna

T: period time of the antenna switch.

5.2.6 Dimensions

The wind load of the antenna is proportional to the effective surface of the antenna and the speed of the aircraft during the measurement. Therefore the dimensions and weight of the measurement antenna allowed depend very much on the type of aircraft used and the individual solution for the antenna mounting on that aircraft. For example, in the case of an antenna at the end of a line dragged behind an aeroplane, the wind load of the line should be small to prevent the aeroplane from stalling because of the drag of the line. And in the case of an antenna mounted on an antenna mast extended below a helicopter, the antenna should not interfere with the tail rotor when the mast is collapsed. The maximum allowable weight also depends on the manner of mounting. On an extendable mast, for example, an antenna which is too heavy can prohibit proper extension of that mast.

5.2.7 Safety

Because the antenna is mounted on the outside of the aircraft, a safety certification by the aeronautical regulatory organization is necessary. During the safety evaluation by this authority, the antenna and mounting are considered as a single unit. In many cases there is a conflict between the optimal electrical and the optimal mechanical design of the antenna. It is therefore advisable to consult specialists on aircraft design during the development of the antenna.

5.3 Receiver

The receiver used in this type of environment can be a normal measurement receiver, it is however advisable to use a receiver that is light and resistant to shock and vibration. Some modern receivers use mechanical hard drives to store data. When using this type, it is better to replace these receiver drives with solid-state versions.

5.3.1 Dynamic range

The dynamic range of the receiver should be sufficiently large. First of all, the front-end of the receiver should not be overloaded by all the signals (not only the wanted signal) within the pass band of the receivers front-end. The total amount of power of these signals sets the attenuation that is required at the receiver input. As the power increase with decreasing distance, the attenuator has to be set for the minimum distance expected. Do not use automatic attenuators, hysteresis can cause blocking of the receiver as well.

With this attenuator setting sufficient dynamic range should be left to accurately measure the wanted antenna pattern. In the case of a horizontal antenna diagram, the variation in ERP can easily exceed 30 dB. If distance varies, this variation increases accordingly. To accurately measure the lowest signal level occurring, the noise floor of the receiver should be 10-20 dB lower than that level.

5.3.2 Selectivity

The selectivity of the receiver should be such that the power of measured signal is completely passed on to the detector, while adjacent channel signals are sufficiently rejected at the same time. If too small a filter is chosen, the modulation of the wanted broadcast transmitter will cause variations in the signal, degrading the measurement accuracy. If the filter is too wide, power from adjacent channels is added to the power of the wanted channel, if present.

Rejection of adjacent channel transmitters on the same tower will become difficult in cases where the broadcast antenna uses less ERP than the adjacent channels and both antennas have highly directive antenna patterns. In that case proper planning of flights and attenuator settings are critical. The dynamic range and the quality of the filters of the receiver are the limiting factors for getting good results.

The receiver should be equipped with a detector that corresponds with the modulation of the broadcast station, so that the power density of the signal is measured correctly. Preferred detector type and relevant receiver settings are described in Annex 2. If only a sample detector is available, this detector type can be emulated in the measurement software provided the measurement speed of the receiver is fast enough and provided the measurement computer is fast enough.

5.4 Software and computing equipment

The most practical way to control the equipment is with a small remote control unit, e.g. a laptop or tablet pc. This unit is connected to the rest of the equipment with a single string of cables. This way the set-up is not optimized for just one operator but all operators can find the most comfortable way to sit in the aircraft. Since space is limited in most aircraft the unit should be small. If possible, using the built-in computer of the measurement receiver saves weight and interface cables and also limits EMI from the computer.

A mouse or trackball is very unpractical in an aircraft, so all software functions should be operable with the keyboard. Shortcuts and function keys are a way to do this. One should be careful in choosing the colours for the user interface, one should optimize the screen colours to make the information readable in both sunlight and dark conditions. One should not display multiple traces in one screen; it will cause confusion. Display raw data only, processed or smoothed data makes it difficult to estimate the quality of the measurement.

The software should contain all information necessary for calculating ERP during the flight and displaying the relative position of the aircraft, like tower position, antenna height, planned antenna pattern and ERP, frequency, etc. Preplanned flight paths and optimum heights and distances should be stored as presets. Other information to assist the technician could be stored too, like frequency, power and antenna height of other transmitters on the same tower. The practical situation always differs slightly from the planned one, so it should be easy to change parameters during the flight.

The software should contain an automated integrity test that checks the whole set-up and performs a quick calibration of the equipment. This integrity check can be started manually and is also automatically performed before each measurement.

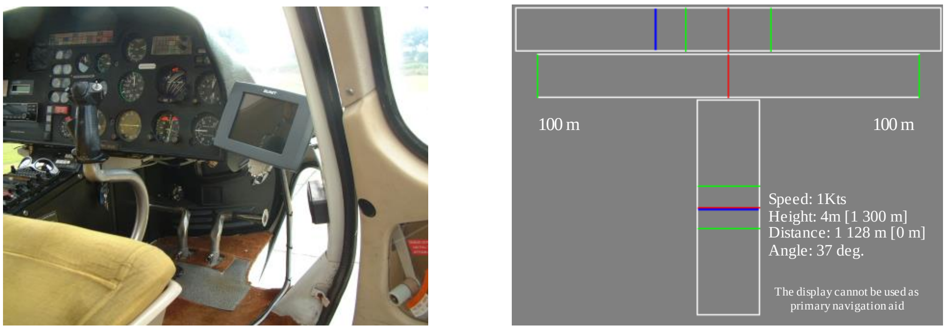
5.5 Pilot display

The pilot display is a small display mounted in front of the pilot. Before the measurement starts it guides the pilot to the position from where the measurement should start. During the measurement it gives real-time information about the diversion from the planned flight path. For different types of measurements different screen layouts can be used.

Small displays used in the automotive industry are robust and small and the interface cables can be longer than standard computer interface cables like VGA.

FIGURE 13

Pilot display and screen layout



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In the example screen layout of Fig. 13, the blue line in the upper horizontal bar represents the actual horizontal position of the aircraft. The blue line in the vertical bar represents the actual vertical position of the aircraft. The green lines represent the maximum allowable deviation from the ideal line represented by the red lines. The lower horizontal bar is a magnification of the part between the green lines in the upper bar. Experiments have shown that an update rate of 5-10 Hz is needed to provide the pilot with enough data for a smooth flight.

5.6 Technicians

The measurements should be performed by two technicians and a pilot. One technician performs the measurement and the other one takes care of aiming and extending the antenna and general matters like communication with the ground. The technicians should be able to analyse the data while measuring and adapt the measurement plan to the actual situation. It is therefore necessary for them to have extensive knowledge about antennas and antenna measurements. Detailed knowledge about the broadcasting systems to be measured is needed too. As this type of measurement is expensive and stressful, the technicians should be able to function well as a team in order to take the necessary decisions in time.

5.7 Pilot

The pilot should fly within preset flight path limits but accurate keeping to the flight path is not the most important factor. A stable flight is just as important. The pilot should have sufficient knowledge of the measurements to be performed to advise alternative flight paths in case the chosen flight paths cause practical or safety difficulties.

5.8 Aircraft

The choice for a specific aircraft depends on many factors, and also generates specific possibilities and restraints for the measurement system and the measurement flights. It is therefore advisable to design the measurement system on the aircraft that will be used. More information on these differences between aircraft can be found in Annex 3.

6 Measurement procedures

This Section describes the measurement procedures that have to be followed subsequently, in order to obtain high quality measurement results from airborne antenna pattern measurements:

6.1 Site survey

Before any measurement flight can be performed or even planned, a lot of information about the targeted broadcast site has to be collected:

- The 3D position of the broadcast antennas phase centre has to be known accurately. All orientation is done relative to this position and the distance used in the ERP calculation is relative to this position as well. Both horizontal position and height have to be determined using the positioning device of the aircraft, to minimize calibration differences. The phase centre of the antenna has to be measured rather than the position of the antenna tower. Values for antenna height and position on paper should not be trusted without verification by measurement.
- The antenna pattern limits (expressed in ERP) of the broadcasters license must be known beforehand. They can be input in the measurement software to assist the technician.
- The broadcast antenna type, its orientation and dimensions are necessary to estimate the influence of ground reflections and to plan the measurement flights.
- Ground type and morphology have to be known to take obstructions and potential reflection problems into account.
- The RF power and antenna patterns of other transmitters on the same site must be known to estimate degradation of the antenna pattern measurement due to adjacent channel signals and to calculate optimum receiver attenuator setting. Also, a minimum distance from the tower has to be calculated, to prevent personal and aircraft overexposure from electromagnetic fields.
- The occupied bandwidth and spectrum shape of the wanted transmitter has to be checked to assure the receiver filters are set appropriately. The occupied bandwidth of adjacent channel transmitters has to be checked to assure sufficient protection.

As most of this information is collected at the broadcast site, we call this data collection phase the *site survey*.

6.2 Measurement planning

An airborne measurement campaign has to be planned well to achieve the best results. Often several broadcast sites have to be measured subsequently, and in many cases more than one antenna pattern is to be measured at the same location. Proper planning combines these measurements in an efficient way.

Measurement planning includes calculation of flight time to and in between broadcast sites, and time needed to perform all desired flights. The necessary flights types and optimum flight heights, distances and paths can be determined using information collected during the site survey. It is generally, but not always, possible to measurement of multiple diagrams where more transmitters use the same antenna. Refuelling moments and locations and other flight related items should be discussed with the pilot, who remains responsible for a safe flight.

6.3 Pre-flight testing

As flight time is the most expensive component of the measurement time, all equipment has to be tested thoroughly after assembly in the aircraft and before taking off. That way surprises during the measurement flights can be avoided.

6.4 Measurement flights

The type of measurement flights conducted depend fully on the antenna situation and the aircraft used. For example, for the measurement of the diagram of a VHF broadcast antenna with a helicopter, a different approach is needed than for the measurement of a medium-wave array with an aeroplane. The different measurement flight types and their application are described in §§ 6 and 7. During the measurements, the signal coming from the antenna under test needs to be monitored on the ground, ensuring the transmitted signal remains sufficiently stable.

6.5 Post-flight equipment evaluation

Directly after the measurement flight, the pre-flight test has to be repeated to assure that all equipment still functions as expected. Any anomalies should be logged to assist post-processing.

6.6 Data processing and analysis

During flight all raw measurement data has been recorded. Combining this data with known values as measurement antenna gain, transmit antenna position and other correction factors the desired antenna patterns are produced in real-time, giving the technician a good impression of the measurement during flight. A more detailed analysis can only be made in the ground, where more time is available. Statistical information derived from the measurement data and calibration information of the equipment is used to estimate the measurement accuracy. And duplicated or intersecting measurement paths can be used to correlate measurement data. These items are described in § 7.

6.7 Reporting

A standardized reporting format, using standard report components, standardized graphs and scaling of graphs makes fast interpretation and comparing of different measurements much easier, and is therefore recommended. These items are addressed in § 9. A measurement uncertainty analysis is an essential part of this Report, without it the measurement report would be of little use. An example of such a calculation is given in § 8.

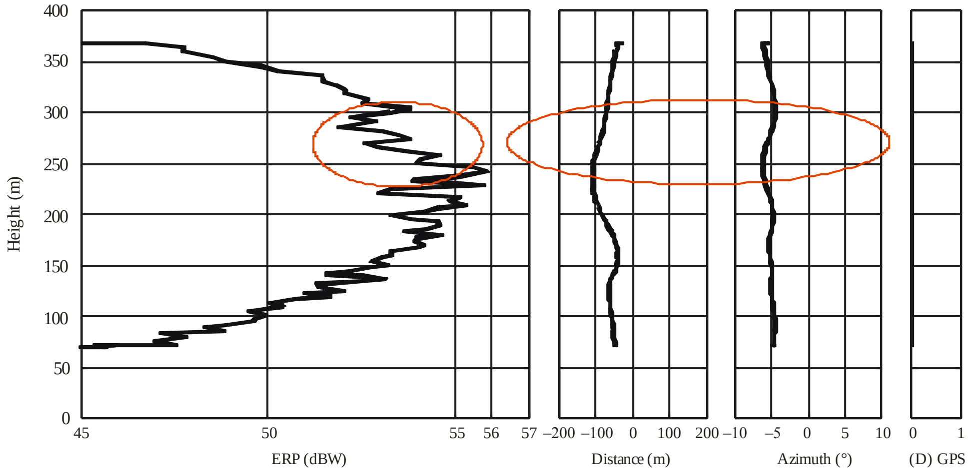
7 Processing the measured data

7.1 Examining the data

After finishing the measurements the data has to be analysed in order to determine if the accuracy criteria are met. To do this, several plots are made, showing all individual measurement points collected. Extra information such as altitude and path errors should be plotted in the same graph as the measurement results to make it possible to correlate for example flight errors to anomalies in the measured results. An example is given in Fig. 14. This is a vertical antenna diagram combined with three additional diagrams. From left to right the diagrams indicate ERP, offset from target distance, offset from target azimuth and position device error. The parts of the diagram that are marked are possibly unusable due to a combination of distance and azimuth errors. This first analysis can be used to exclude certain parts of the diagrams or to decide to measure these parts again. The same process should be performed for circle and horizontal flights.

FIGURE 14

Vertical diagram with flight information



Vertical flight			LOPIK 2004-05-11 LPs 94.3 MHz Radio 4				
Height			Distance	Azimuth	Date	Time	Measurement data file
From	To					10:14 uur	
70 m	367 m		950 m	314°	12 May 2004	10:15 uur	LOPIK 2004-05-11 LPs.M01

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7.2 Correlating different flights

When performing different flights on one transmitter it is often possible to correlate these measurements. This can be done when the same flight type is repeated, but also when different flight paths intersect. By taking a sufficient number of points of each flight around that intersection, mean and standard deviation values can be calculated. These can be evaluated to assess correlation and estimate the achieved accuracy.

7.3 Processing the data

Measurement accuracy requirements dictate that more measurement points are made than need to be presented. It is therefore possible to use data reduction. This augments the end accuracy per presented point, and the presented diagram becomes smoother and is more easily compared with other diagrams or reference curves.

For example: if one measurement point per degree azimuth is required for a horizontal radiation pattern and 20 measurements per degree are made, averaging over a one degree interval will result in a presented value that will be closer to the actual value.

The most common way to do this is to use a windowed average over an interval. The window shape and length should be adapted to the interval over which significant changes in value are expected. The preferred method is to use a sliding windowed average over an interval. Beside the mean value also the standard deviation over the window can be calculated. The size and shape of the window has significant influence on the final results and should be chosen with care. For the same reason, the amount and type of smoothing should be mentioned in the final measurement report.

8 Measurement uncertainty calculations

Every measured antenna pattern should be accompanied by a measurement uncertainty calculation. Without this, the measurement is useless for verification purposes.

8.1 Typical measurement uncertainty

A generalized measurement uncertainty calculation can be used to characterize the typical measurement accuracy of the measurement system. All uncertainty sources that are normally present in the measurement system and during the measurement are identified and estimated and an overall uncertainty calculation is then made, which we call the *typical measurement uncertainty of the system*. This figure gives a general idea of the accuracy of the measurement system for the average measurement situation. A typical measurement uncertainty between 1.5 dB and 2.5 dB for a 95% interval can be considered a good achievement. This can only be achieved when all main contributing error sources are minimized and when the measurement is conducted very precisely.

8.2 Actual measurement uncertainty

For every individual measurement, however, an individual measurement uncertainty calculation must be made, taking specific circumstances as they occur during the actual measurements into account. For example, variations due to reflections and flight errors will differ per measurement and per transmit site and transmit antenna configuration. Only by taking these differences into account can a correct measurement accuracy figure for each individual measurement be presented.

A good way to do this, is to start with the generalized measurement accuracy calculation, examining all values in that calculation and correcting them for the specific circumstances that occurred during the measurement. Analysis of the measurement data as described in § 7 will give important input to this process. The value calculated this way is called the *actual measurement uncertainty*, and is unique for every measurement. This figure has to be mentioned in the measurement report, *not* the typical value.

8.3 Methodology

The measurement uncertainty calculation should be performed and presented conforming to applicable international standards, e.g. ISO “Guide to the Expression of Uncertainty in Measurements”.

When using this method, each measurement is described first, followed by the mathematical formula with which the end result is calculated from the individual variables involved. Then all these variables are described with their uncertainties, and their weighting factors of their influence on the final result is established. When the source variables are expressed logarithmically, they first have to be converted to linear values. With this information, the uncertainty of the end result is calculated and is presented in the standardized form. Also the main contributors to the overall uncertainty are identified.

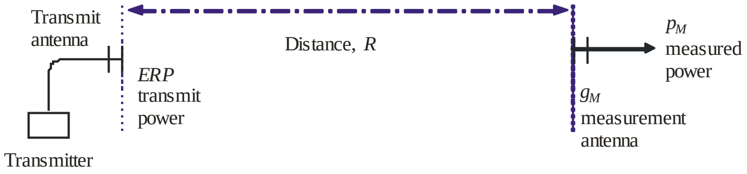
8.4 Example of a measurement uncertainty calculation

In this section, a practical example is given of an actual uncertainty calculation for an antenna pattern measurement system. The example illustrates the influence of different error sources, and is meant to assist the making of one’s own measurement uncertainty analysis. The values used in this example are arbitrary, and could in practice be better or worse depending on the effort made to optimize the design.

The example describes a fictitious helicopter-based measurement system measuring the horizontal antenna pattern of a VHF FM broadcasting transmitter, expressed in ERP, and starts with the measurement of the EIRP, if expressed in dB, or eirp otherwise. The power, p_M, is measured at a distance, R, from the transmit antenna. This is done using a measurement antenna with antenna gain, g_M, and a measurement receiver (see Fig. 15):

FIGURE 15

EIRP measurement



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In each measurement point the following calculation is performed using formula (1):

$$eirp = \frac{16\pi^2}{c^2} \cdot \frac{p_M . R^2 . f^2}{g_M}$$

where:

p_{EIRP}: power relative to an isotropic radiator (W)
p_{RX}: power at the receiver input terminals (W)
R: distance (m) between the receive and transmit antennas
g_{RX}: gain (linear value) of the receive antenna relative to an isotropic radiator
f: frequency (Hz)
c: speed of light (m/s).

The above formula only calculates the measured EIRP in that particular point in space. There are some additional factors that may cause the measured EIRP to differ from the actual EIRP of the transmit antenna. When including those factors in the formula, the formula reads as follows:

$$p_{EIRP} = \frac{16\pi^2}{c^2} \cdot \frac{p_M . R^2 . f^2}{g_M} \cdot a_{REF} . a_H$$

where:

a_{REF}: reflections: interference of direct and reflected wave
a_H: influence of incorrect flying height.

The EIRP obtained is converted to ERP using formula (3). As that formula contains only one theoretical constant, its contribution to the combined measurement uncertainty is nil. The measurement uncertainty of ERP is a result of the measurement uncertainty of the input parameters. Some of these parameters again have multiple error sources creating their uncertainty. The error sources relevant in this example are discussed hereafter.

Constants The formula contains the constants 16, π and the speed of light (c). As they are completely invariable and absolutely known, their contribution to the overall uncertainty of the system is nil.

Frequency The frequency f used in the formula is that of the carrier frequency, in this example 100.1 MHz. In reality not all the power components measured are on that frequency due to the modulation of the transmitter. Assuming that most of the power is concentrated within 100 kHz from the carrier, the relative uncertainty Δf is about 0.1%. The error distribution is assumed uniform.

Distance The uncertainty of the distance is caused by the measurement uncertainty of the 3D position of the transmit antenna and of the measurement antenna on the aircraft. In this example a circle is flown at almost the same height as the transmit antenna, with a downtilt of 5°. Therefore the horizontal errors have a much greater influence on the resulting accuracy than the vertical ones, so sensitivity coefficients are calculated and used. Additionally, the position of the electrical phase centre of the transmit antenna, the difference in horizontal and vertical position of the measurement antenna and the positioning device on the aircraft, are sources of uncertainty. The uncertainty of distance R is calculated separately to be used as an input for further calculations. (The calculation of the uncertainty of R is normally part of the report but omitted in this example.) The resulting uncertainty is 6 m, normally distributed, 95% probability. In this example, where a circle is flown at a distance of 1 100 m, this is an uncertainty of 0.56%.

Antenna gain The uncertainty of the antenna gain is caused by the calibration uncertainty of the antenna, the RF cables, the residual polarization mismatch, and the horizontal and vertical misalignment of the antenna. In formula (g_M as linear value, G_M in dB):

$$g_M = g_{CAL} \cdot a_{CBL} \cdot a_{HOR} \cdot a_{VERT} \cdot a_{POL}$$

RX power The uncertainty of the received power is caused by the calibration uncertainty of the receiver, mismatch between antenna and receiver, IF filter losses due to excess bandwidth of the transmitter and leakage of adjacent channel transmitters. In formula (p_M as linear value, P_M in dBW):

$$p_M = p_{M-CAL} \cdot a_{MIS} \cdot a_{FILT} \cdot a_{NABU}$$

Reflections One of the main contributors to the overall measurement uncertainty is the ground reflection. The relative amplitude of the reflections depends on the reflectivity of the ground and the objects built on it. The reflection is attenuated by the relative path length difference between direct wave and reflected wave and by the vertical pattern of transmit antenna and receive antenna. The amount of ground reflection in this example has been derived from analysis of the actual measurements, which is 1.7 dB in this case.

Height error Flying at a height that differs from the height where the diagram should be measured, the presented ERP differs from the transmit antenna ERP. The height error is caused by the uncertainty of the antenna height measurement during site survey, the measurement uncertainty of the positioning device in the aircraft and the flying error during measurement. The resulting ERP error depends on the distance from the transmit antenna and the vertical directivity of the transmit antenna.

In the example, the combined height error was 23 m, with a normal distribution and 95% confidence. At 1 100 m distance, this corresponds with a vertical angle of 1.2°. The vertical antenna pattern of a 4-layer broadcast antenna is such that the resulting error in ERP is around 0.1 dB.

The calculation of the total measurement uncertainty in this example is shown in Table 1:

TABLE 1

Total measurement uncertainty calculation

Symbol	**Source**	**Uncertainty**		**Distribution**	**Divider**	**Sensitivity coefficient** c_i	**Standard deviation of source** $u_i(a_x)$ **(%)**	**Degrees of freedom** ν_i **or** ν_{eff}
		(±dB)	**(%)**					
Speed of light								
c	Speed of light	Nil						
Frequency								
f	RF frequency		0.1	Uniform	1.7321	2	0.1	∞
Distance								
R	Distance between transmit and receive antenna		0.6	Normal	2	2	0.6	∞
Antenna gain								
$g_{M\text{-}CAL}$	Antenna gain calibration	1.0	26	Normal	2	1	12.9	∞
a_{HOR}	Horizontal misalignment	0.2	4.7	Uniform	1.7321	1	2.7	∞
a_{VERT}	Vertical misalignment	0.3	7.2	Uniform	1.7321	1	4.1	∞
a_{POL}	Polarisation loss	0.3	7.2	Uniform	1.7321	1	4.1	∞
Power measurement								
$p_{RX\text{-}CAL}$	Receiver calibration	1.5	41	Normal	2	1	20.6	∞
a_{MIS}	Mismatch	0.09	2.1	U-shape	1.4142	1	1.5	∞
a_{FILT}	Energy falling outside filter bandwidth	0.15	3.5	Uniform	1.7321	1	2.0	∞
a_{ADJ}	Adjacent channel interference	Negligible						
Reflections								
a_{REF}	Influence of reflections	1.7	47.9	Uniform	1.7321	1	27.7	∞
Height error								
a_H	Influence of height error	0.1	2.3	Normal	2	1	1.2	∞
$UERP$	Combined standard uncertainty			Normal			38	∞
U	Expanded standard uncertainty (95% conf.)			Normal (k=2)			75	∞

The actual measurement uncertainty for this example is therefore $10 \log_{10} (1 + U) = 2.4$ dB.

9 Reporting

The antenna radiation pattern should be reported in a report containing the measured diagram, completed with a summary and conclusions. It is preferable that a standardized format be used, this enables comparison of different measurements. This format should be kept as compact as possible, without omission of principal parameters.

9.1 Standardized report

The standardized report is easiest described by the following example report. The chapters of the report delete are presented in ***cursive***, the information that should be filled in to match the specific situation are underlined. Depending on the outcome or specific events during the measurements, text could be adapted. The general structure remains the same:

9.1.1 Summary

On 12 and 14 September 2003 the radio agency of Country A performed airborne antenna pattern measurements around the transmitting tower in City B. During this measurement campaign measurements were performed on the signal of Radio C on 102.2 MHz. By means of these measurements the antenna diagram of the used antenna system was determined.

9.1.2 Conclusions

The effective radiated power of Radio C in City B, transmitting on 102.2 MHz, exceeds the licence limits with up to 15 dB in the direction of 210-270° azimuth. In the direction of 340-0° azimuth the effective radiated power is up to 7 dB lower than was planned.

9.1.3 Introduction

Complaints about the reception of Radio C in the area around North of City B initiated this investigation. The results of mobile field-strength measurements gave the impression that the antenna diagram of Radio C was not optimal, therefore airborne antenna pattern measurements were performed. On 12 September 2003 the radio agency of Country A performed airborne antenna measurements around the transmitting tower in City B. During this measurement campaign, measurements were performed on the signal of Radio C on 102.2 MHz. From these measurements, the antenna diagram of the used antenna system was determined. The measurements were repeated on 14 September 2003 to prove the reproducibility of the measurements. This Report only expresses the results of the measurements but could be used as input for inspection activities or corrective actions.

9.1.4 Measurement results

On 12 September 2003 the horizontal antenna radiation pattern of Radio C in City B, transmitting on 102.2 MHz was measured twice. Both diagrams were almost identical proving the reproducibility of the measurement. On 14 September 2003 the same diagram was measured twice again. The measurement points of all flights correlated so much that it was not possible to distinguish between the diagrams. So the reproducibility is very high.

The antenna radiation pattern is given in Fig. 16. Effective radiated power in the different azimuthal directions is expressed on the radial axis (dBW). The red line displays the limits as given in the licence. The blue line is the measured antenna radiation pattern.

9.1.5 Measurement accuracy

The accuracy of the absolute effective radiated power measurement is 1.5 dB for 95% confidence for this specific measurement. The description of the measurement system and measurement uncertainty calculation is available as a separate report.

9.1.6 Violation of licence conditions

The measured results are compared with the license limits in Table 2. The horizontal diagram exceeds the limits for effective radiated power given in the licence in the azimuth directions between 210° and 270° with up to 15 dB. In the azimuth directions between 340° and 360° the effective radiated power is up to 7 dB lower than given in the licence.

FIGURE 16

Antenna radiation pattern of Radio C – City B – 102.2 MHz

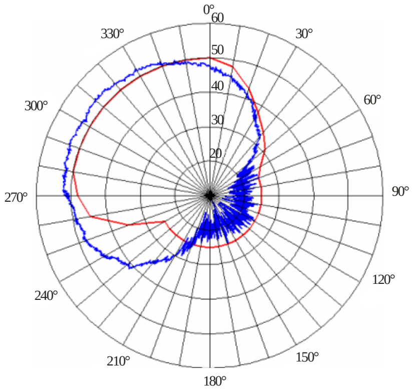

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TABLE 2

ERP data and licence data in tabular form

Azimuth direction	Licence	Measured	Difference
	(dBW)		
0°	50	43	–7 dB
10°	48	41	–7 dB
20°	43	37	–6 dB
30°	38	32	–6 dB
40°	34	29	–6 dB
50°	31	20	–11 dB
60°	27	18	–9 dB
70°	25	18	–7 dB
80°	25	17	–8 dB
90°	25	16	–9 dB
100°	25	18	–7 dB
110°	25	17	–8 dB
120°	25	19	–7 dB
130°	25	18	–7 dB
140°	25	17	–9 dB
150°	25	17	–8 dB
160°	25	19	–6 dB
170°	25	18	–8 dB
180°	25	17	–6 dB
190°	25	18	–7 dB
200°	25	20	–5 dB
210°	25	25	–0 dB
220°	25	31	+5 dB
230°	26	37	+10 dB
240°	25	41	+15 dB
250°	35	44	+8 dB
260°	45	45	–1 dB
270°	48	47	–1 dB
280°	50	48	–2 dB
290°	50	49	–1 dB
300°	50	48	–2 dB
310°	50	49	–1 dB
320°	50	48	–2 dB
330°	50	48	–3 dB
340°	50	47	–4 dB
350°	50	45	–6 dB

9.2 Standardization of reported antenna patterns

Changing the scale of the antenna pattern shown, will drastically change the optical appearance of the reported form. Therefore it is advisable to establish some preferred formats, this way it is easier to compare the results from different campaigns and even between different administrations. A few preferred formats for the most common flight types are given here:

9.2.1 Horizontal radiation pattern

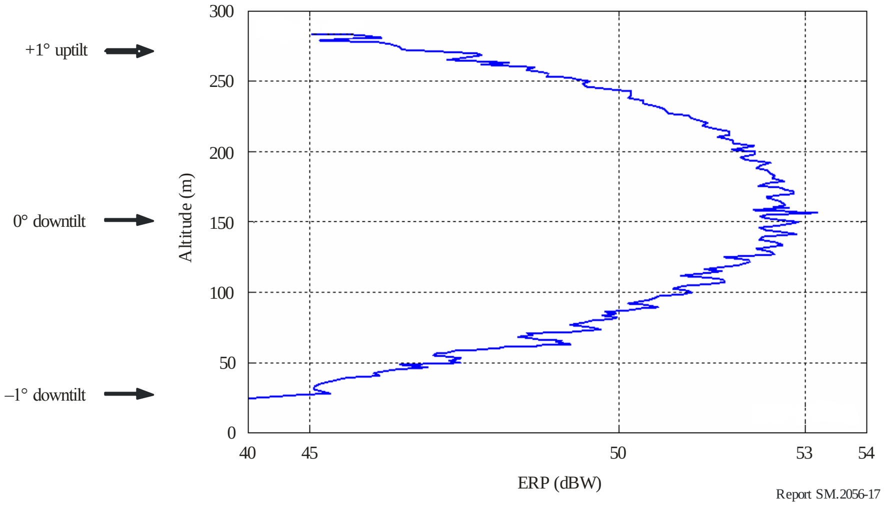
For the horizontal radiation pattern as shown in the example, the radial scale should be linear logarithmic with a range of 50 dB. More than 50 dB is not useful since even large arrays do not have a front to back ratio of more than 50 dB. It is also unlikely to have notches of more than 50 dB in the diagram.

9.2.2 Vertical radiation pattern

In the example report the vertical flight diagram is not reported, although it was actually performed to establish the correct measurement height before performing a circle flight. In certain situations, the vertical radiation pattern is of particular interest and therefore to be reported. In that case a range of 10 dB is sufficient. With that scale it is easiest to determine the tilt angle of the main lobe and the vertical beamwidth of the antenna. Figure 17 shows a vertical diagram with about 3 dB variation due to ground reflection. If suppression of, e.g. high angle radiation is researched, the scale should have a range of 50 dB, as with the horizontal radiation pattern.

FIGURE 17

Vertical diagram 10 dB range



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In the example diagram the vertical scale is in metres relative to ground level.

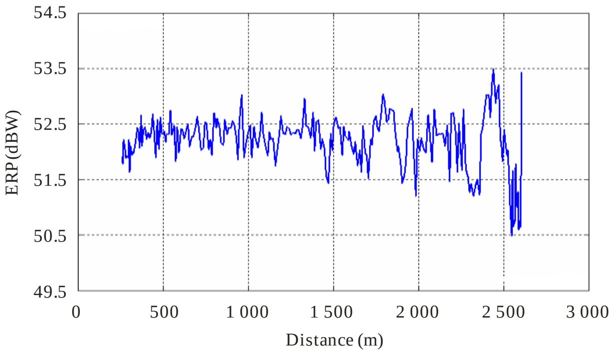
With the actual mechanical antenna height and flight distance it is also possible to express this scale in degrees tilt angle.

9.2.3 Propagation diagram

Diagrams of horizontal flights that are performed to determine a point of minimal ground reflection should have vertical axis of about 5 dB. This is sufficient to have an idea of the power deviation in the point of minimal reflection because ERP should be constant over the whole flight path.

FIGURE 18

Propagation diagram 5 dB range



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9.2.4 Other diagrams

Other diagrams for specific purposes can be adapted at will, but the preferred diagrams should be used whenever possible.

Annex 2

Applications

1 Introduction

In Annex 1 the recommended measurement procedures, the equipment required, and the reporting procedures for antenna radiation pattern measurements using an aircraft have been described. These recommendations are independent of the type of aircraft chosen and it can be used regardless of the broadcasting system used.

This Annex will give additional recommendations for some specific broadcasting systems, e.g. what measurement flights to perform, what measurement antennas to use and what receiver settings to choose. The broadcasting systems mentioned are meant to function as examples, no attempt is made to be complete. The flight types mentioned in this Annex are described in more detail in § 4 of Annex 1. In practice the recommended measurement flights types are depending heavily on the aircraft used as well, but aircraft specific recommendations will not be covered here as they are treated in Annex 3.

2 VHF FM broadcasting

The following recommendations are valid for frequency or phase modulated sound broadcasting in the 87.5-108 MHz band:

2.1 Radiation pattern

In VHF FM broadcasting a horizontal antenna radiation pattern is measured at the maximum of the vertical radiation pattern. The measured antenna pattern is expressed in ERP, with a half wave dipole antenna as the reference antenna.

2.2 Measurement flights

The maximum of the vertical radiation pattern is determined by performing a vertical flight at one or more azimuth directions. This maximum determines the height at which a circular flight is performed. As VHF antenna pattern measurements are especially sensitive to ground reflections, the measurement distance is chosen at which reflections are acceptable. This distance can be determined by performing a propagation flight. Knowing optimum height and optimum distance, a circular flight is then performed, yielding the desired antenna radiation pattern. At least two circle flights need to be made at the predetermined height and distance to check the reproducibility. The sequence of measurements is: propagation flight(s), vertical flights(s), circular flight(s).

2.3 Measurement antenna

The measurements are done with matching polarization. When transmit polarization is elliptical or changing with the azimuth angle, the measurement has to be performed for both horizontal and vertical polarization simultaneously, or with a polarization independent method, as described in Annex 1, § 5.2.5.

A good measurement antenna for this application has a vertical opening angle small enough to suppress ground reflections in an adequate way, combined with a reasonable constant gain in both vertical and horizontal planes around the main direction to easy alignment. The measurement antenna need not have high gain, even gains as low as –15 dBd are still useful. Full size antennas are not very practical at this frequency range, considering wind load and other mechanical issues.

2.4 Receiver settings

The setting of the receiver filter is a trade-off between adjacent channel interference and unwanted AM generated by the filter. The bandwidth of FM broadcasting signals are limited by regulations but should be checked before the measurement using the mask method of Recommendation ITU-R SM.1268. When the signals are too wide with respect to the used filter, unwanted AM is generated on the measured signal. This causes an increased measurement uncertainty. If adjacent channel occupation allows it, a wide filter with a high shape factor (Gaussian) should be chosen.

An RMS detector is the choice for polarization independent measurements but when this technique is not used an average detector can be used. A peak or sample detector can be used when a sufficient number of measurement points to perform averaging afterwards is available. The latter can be necessary to limit the effects of small measurement errors caused by interference from adjacent channels or the receivers filter bandwidth in relation to the measured signal.

3 MW (AM) broadcasting

The antenna systems used in MW broadcasting are large. From a mechanical perspective the far field condition starts, in the case of large arrays, sometimes further than 1λ from the antenna. Generally the power is high, therefore small, less efficient antennas can be used for the measurement. Polarization is vertical in most cases. MW broadcasting stations are often designed to serve relatively large regional areas and do not use pencil or fan beams. The bandwidth is more or less constant so a channel filter with low shape factor (channel filter) can be used. The modulation type is A3E so the preferred detector is AVERAGE. During the measurement power saving schemes like dynamic amplitude modulation (DAM) should be switched off. MW antennas are generally ground-based, they have a very low vertical radiation angle. They are generally omnidirectional, or only slightly directive: a directivity of more than 8 dB is exceptional. To get a good picture of the 3-dimensional radiation pattern of the antenna, several circular flights around the antenna can be made at different heights, completed with some flyovers. From these measurement points the actual 3-dimensional radiation pattern can be constructed, using the knowledge that the actual antenna pattern cannot vary much over small increments of angle.

4 HF (AM) broadcasting

The antenna systems used in HF broadcasting are large. From a mechanical perspective the far field condition starts, in the case of large arrays, several wavelength from the antenna. Generally the power is high so small, less efficient, antennas can be used for the measurement. Polarization is horizontal in most cases. The bandwidth is more or less constant so a channel filter with low shape factor (channel filter) can be used. The modulation type is A3E so the preferred detector is

AVERAGE. During the measurement power saving schemes like dynamic amplitude modulation (DAM) should be switched off.

HF broadcasting antennas exist in all possible forms, from omnidirectional high angle radiators up to pencil beams to serve particular areas of the world far away. Depending on the antenna diagram expected, the measurement strategy has to be determined. In the case of a low angle HF curtain array, a combination of vertical flights and horizontal flights can be made in the area around the main beam. These measurements points can be used to chart the radiation pattern in the sector around the main lobe and the first secondary lobes. Several circular flights at different heights could give a more general impression of the radiation outside the main beam.

5 T-DAB broadcasting

T-DAB is generally deployed in single frequency networks. To obtain accurate results and measure only the wanted transmitter it is necessary to use directional measurement antennas with a high front-to-back ratio. The bandwidth is 1.5 MHz and constant so a channel filter can be used. Transmit antennas with a small vertical opening angle and a down tilt are often used and the horizontal diagram is generally omnidirectional. The types of flights mentioned in the FM-broadcasting paragraph are valid here. The requirements for the measurement antenna are similar to that for FM broadcasting for VHF T-DAB. T-DAB is a digital system employing OFDM so an RMS detector is the correct choice.

6 DVB-T broadcasting

Digital TV can work in a synchronized single frequency fashion and most of time this is the case. To obtain accurate results and measure only the wanted transmitter it is necessary to use directional measurement antennas with a high front-to-back ratio. The bandwidth is 2 or 8 MHz and constant so a channel filter can be used. Transmit antennas with a small vertical opening angle and a down tilt are often used and the horizontal diagram is generally omnidirectional. The types of flights mentioned in the FM-broadcasting paragraph are valid here. The measurement antennas for this frequency range generally have enough vertical directivity to suppress reflections. A too narrow beamwidth should be avoided, as correct alignment of the antenna may become difficult.

Annex 3

Aircrafts for antenna pattern measurements

1 Introduction

The recommendations in Annex 1 are independent of the type of aircraft chosen and it can be used regardless of the broadcasting system used. The choice for a specific aircraft depends on many factors, and also generates specific possibilities and restraints for the measurement system and the measurement flights that are possible. These issues are addressed in this Annex.

The structure of this Annex is as follows: Section 2 addresses general issues that should be considered for all of the aircraft types. Sections 3 and 4 are dedicated to two of the most common aircraft used for antenna pattern measurements, respectively the helicopter and the aeroplane. Section 5 considers other aircraft that are less common.

2 Concerning all aircraft types

Some issues concerning all aircrafts in relation to the measurement equipment are summed up here:

- Vibration can damage components of the measurement system. In particular hard disks in computers and in modern receivers, relays in receivers and the pilot display are susceptive. The measurement set-up should be mounted on shock-mounts, and the characteristic mechanical resonance of the whole set-up should be outside the vibration frequencies of the aircraft during flight.
- RF is generated by equipment in the aircraft such as inverters and gyro's compasses. Take care of this by placing the antennas, including those used for navigation, in a position where they pick up minimum RF. Install chokes and ferrite clamps around cables radiating RF. This can be difficult, but every aircraft needs to be opened for service at regular intervals, use the opportunity.
- The power supply of an aircraft is generally instable, always use a separate inverter/stabilizer.
- A rack fixed to the aircraft must be used to fix the equipment to the aircraft. The easiest way to do this is using existing mounting points in the aircraft, they are already certified for a specified load.
- Maximum allowable flight time, as it is not always possible to land and refuel near the objects to be measured.
- Payload: the aircraft should be capable to carry the equipment and engineers.

3 Helicopter

A helicopter is often chosen for this kind of measurements. The reason for this may be its manoeuvrability and the possibility to conduct vertical flight or to move very slowly to a specific position. It has very specific setbacks as well: vibration is much more an issue than with other aeroplanes and the flying time is relatively expensive. When choosing a helicopter as an airborne platform for measurements, the following factors should be given extra attention.

3.1 Manoeuvrability

The biggest advantage of a helicopter is its manoeuvrability. A helicopter can easily correct its position along three axes, making it suitable to fly propagation flights, circle flights and vertical flights. It is worth mentioning that the ability to fly vertically is unique. In addition, a helicopter can fly at very low speeds, enabling very accurate positioning, if desired. When flying along a predefined path, the low airspeed, the number of measurements per covered distance, is relative high. The low airspeed has negative side effects when wind sensitivity is considered, however.

3.2 Wind sensitivity

A helicopter has a relatively low airspeed making it sensitive to wind. Its orientation with respect to the antenna tower will vary with changing wind direction and force, making it more difficult to keep the measurement antenna aligned. The measurement antenna therefore has to be aligned in real-time during the flight.

When performing a circle flight, any aircraft will have a groundspeed that varies with the azimuth angle. Opposite sections of the circle have tailwind instead of headwind. This results in a varying number of measurements per covered azimuth angle over the complete circle. This effect is much stronger when using a helicopter because of the low airspeed.

3.3 Cost

Flying a helicopter is relatively expensive. This can be considered the main setback when choosing a helicopter. Some costs are lower than for an aeroplane however: landing costs can be reduced because airfields with airstrips are not always necessary.

3.4 Flexibility

Take off and landing, and even refuelling can be done practically anywhere provided enough free area is available. This is very practical where several sites are to be measured subsequently. The flying range is limited, and the frequent need of landing and refuelling is one of the setbacks of the helicopter.

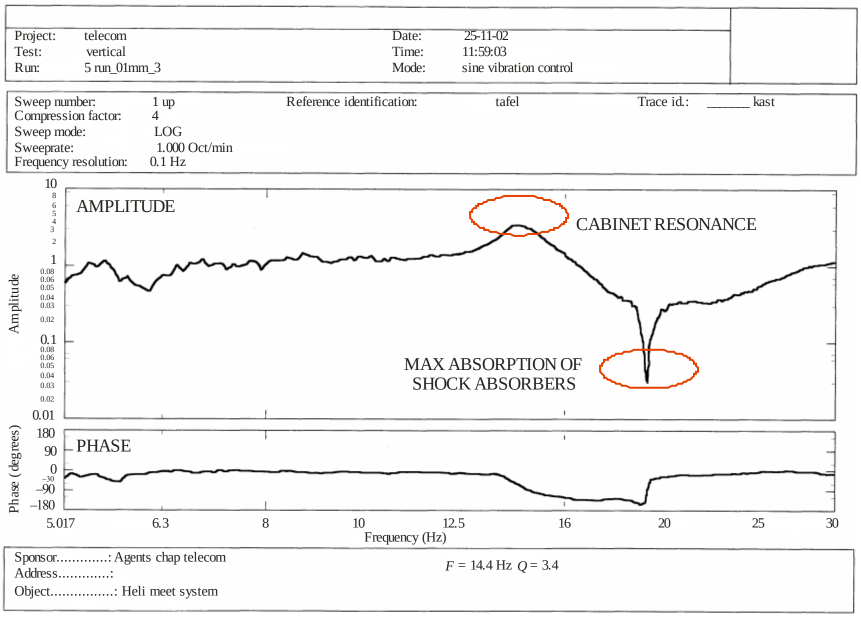
3.5 Vibration

A helicopter produces heavy mechanical vibration that is destructive for the measurement equipment. This vibration is mainly produced on the rotor blade frequency of the main rotor. This frequency lies around 10 Hz and depends on the type of helicopter and the number of rotor blades. Components susceptible to vibration are relays, non-locking connectors like printed circuit boards in slots and computer hard drives. If the resonance frequency of a component of the measurement system corresponds with the vibration frequency of the helicopter, the vibration is amplified. The individual components of the measurement system have relatively high resonance frequencies. The resonance frequency of the complete assembled rack however may approach that of the rotor blade frequency.

To solve this problem, the rack should be made rigid to increase its resonance frequency. Additionally the rack can be mounted on shock mounts to further suppress the vibration caused by the rotor blades. The shock mount therefore should have their maximum dampening on the rotor blade frequency. Despite these measures, individual components of the measurement system can still be susceptible to remaining vibrations. Individual solutions per component should be considered. It is advisable to test your set-up on a vibration test stand after building the prototype. Figure 19 shows a mechanical frequency sweep of a rack with its resonance frequency around 13 Hz.

FIGURE 19

Test results of a vibration test



Project: telecom
Test: vertical
Run: 5 run_01mm_3
Date: 25-11-02
Time: 11:59:03
Mode: sine vibration control

Sweep number: 1 up
Compression factor: 4
Sweep mode: LOG
Sweeprate: 1.000 Oct/min
Frequency resolution: 0.1 Hz
Reference identification: tafel
Trace id.: ______ kast

Sponsor.............: Agents chap telecom
Address.............:
Object................: Heli meet system

F = 14.4 Hz Q = 3.4

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This measurement helped to explain the severe vibration problems encountered during the initial test flights. After that the rack was modified to increase the resonance frequency and the shock mounts were replaced by other types with a lower damping frequency, curing the problems.

3.6 Mounting of antennas

When mounting an antenna on the helicopter, several factors have to be considered. Electrically we want the antenna to perform as if in free space, so care should be taken to avoid reflections off the body of the helicopter or the rotor blades. An extendable mast under the helicopter can provide extra separation between the measurement antenna and these reflectors, and design the antenna's radiation pattern with vertical opening angle that is as small as practical. The low airspeed and vertical take-off make it possible to extend an antenna mast below the helicopter. As the antenna is mounted on the end of the mast, wind load is still an issue, and the antenna must be designed accordingly. The antenna and antenna mast are outside parts of the aircraft, and need to comply with all aircraft safety regulations.

3.7 Regulatory factors

Specific restrictions are in vigour for helicopters, depending on the country in which the measurements are made. Sometimes extra restrictions are in place for foreign helicopter companies operating outside their country of origin. Restrictions may concern minimum flying height, no fly zones, or the restriction to fly over cities with a single engine aircraft. The helicopter company should be able to provide detailed information on these issues, and should best be charged with the regulatory affairs involved with the antenna pattern measurements. Regulations that favour helicopters over other aircraft exist too: a low flight with a helicopter over a city is often more accepted than with an aeroplane, and landing on an improvised landing patch is often allowed.

4 Aeroplane

When choosing an aeroplane as airborne platform for measurements, the following factors should be given extra attention:

4.1 Manoeuvrability

It is impossible to make a stable vertical measurement flight with an aeroplane. Also flying in a straight line towards an antenna tower and breaking off at close range is not feasible. Its inherent stability makes it very suitable for straight and circular flight paths however.

4.2 Wind sensitivity

Because of its high airspeed an aeroplane is less sensitive to wind. Flying a perfect circle in windy conditions is no problem. Of course the pilot should be experienced and equipped with proper navigation equipment. Because of the high airspeed the number of measurements per covered distance is relative low, but they are relatively even distributed even when wind speed is high.

4.3 Cost

Flying time using an aeroplane is relatively cheap. This advantage is smaller in areas where landing fees are expensive.

4.4 Flexibility

The flying range of an aeroplane is relatively large. This can be very practical when measuring multiple sites, or sites that are located far away. Take-off and landing requires an official airstrip however, limiting flexibility.

4.5 Mounting of antennas

The measurement antenna has to be mounted close to the fuselage of the aircraft because of the airspeed or a drag antenna has to be used. The latter is an antenna on a line behind the aircraft, this causes an additional position error but is sometimes unavoidable.

4.6 Regulatory factors

In densely populated countries it is often not allowed to fly low over cities using an aeroplane. In those situations antenna patterns of transmitters located inside urban areas cannot be measured.

5 Other aircraft

Other solutions can be imagined also. Other aircraft like mean airships and unmanned drones could be good solutions in specific circumstances. Also inverse measurements could be considered, like flying around antenna tower with a model aeroplane equipped with a RF source and measuring received signal on the transmit antenna itself. For each application the particular requirements and the specific possibilities of the aircraft have to be assessed, and the measurement system has to be adapted to the aircraft.