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Uncertainty estimation of receiver antenna gain for UAV-based antenna measurements

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The article deals with the issue of estimating the measurement (receiver) antenna gain uncertainty for Unmanned Aerial Vehicle (UAV)-based radiation pattern measurement of large FM antenna system (AS). The ± 5° tolerance for the axis of UAV rotation (pitch, yaw, roll) is imposed, and the simulation of the measurement device, receiver antenna and UAV is verified by aerial and static semi-anechoic chamber radiation pattern measurements in a horizontal cut at theta = 90°. The simulation model is used to further estimate the gain deviation limited by the imposed rotation criteria, resulting in a measurement antenna gain expanded combined standard uncertainty of 0.44 dB for the given measurement system.

Keywords: unmanned aerial vehicle, antenna radiation pattern, uncertainty analysis, antenna measurement

1 Introduction

The radiation pattern of an antenna is one of its key parameters, crucial for many applications. In the telecommunication industry, more precisely terrestrial broadcasting services, the radiation pattern has a decisive role when it comes to the signal coverage and implicates legal obligations regarding the interference with other telecommunication providers. The radiation pattern of an antenna system (AS) usually refers to its horizontal cut [1-2], not to the full 3D pattern. The radiation pattern is usually measured after AS first installation, extensive repairs, or as part of a regular maintenance procedure. The in-situ radiation pattern measurement confirms correct AS installation and its working condition during its lifetime. An example of such an AS working in the FM frequency band from 94 MHz to 107 MHz that is mounted on a monopipe structure and supported by anchoring cables, is displayed in Fig. 1.

The in-situ radiation pattern measurement of large AS usually relied on a manned helicopter with a specialized measurement equipment on board. This is also well documented in an International Telecommunication Union (ITU) report [1] and in a locally enforced national regulation [2]. Nowadays, costly preparations and overall expenses render helicopter measurements obsolete. Although helicopter measurements were considered standard procedure, when it comes to the in-situ radiation pattern measurement of large AS, the exact methodology lacks several specifics and explanation of key aspects of the measurement, which is a result of limited capabilities of the helicopter itself. In recent years, Unmanned Aerial Vehicle (UAV) equipped with various measurement payloads have been widely experimented with, as a highly flexible and cost-effective alternative enabling rapid radiation pattern data acquisition [3] and in some cases diagnostics of defective antenna elements [4], requiring only a fraction of resources.

Fig. 1. Placement of a large antenna system on a monopipe structure

This article analyses the radiation pattern measurement of a receiver antenna for custom, specialized measurement device Pixla 1 mounted on a UAV (see Fig. 2), which was already used on multiple AS similar to the one seen in Fig. 1, utilized for: AS radiation

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pattern measurements [5], identification of faulty AS segments [4], investigation of far-field conditions for large AS [6-7] and further research focused on investigating systematic error reduction for UAV-based radiation pattern measurement [8]. The analysis is carried out by numerical calculations performed in a dedicated software, subsequent in-situ measurements and measurements in a controlled environment of a semi-anechoic chamber.

Fig. 2. Measurement device Pixla 1 mounted on a UAV (DJI Matrice 300)

2 Aerial radiation pattern measurement limitations

The use of UAV for AS radiation pattern measurement poses some additional challenges. These stem mainly from the design and placement of the measurement (receiver) antenna with respect to the UAV and measurement device Pixla 1. For measurements with a helicopter, usually a directional antenna is recommended [1-2], such as the Yagi-Uda antenna shown in Fig. 3.

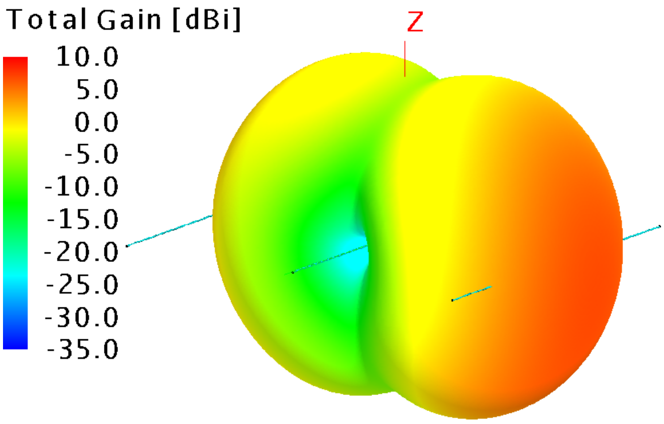

Fig. 3. Simulated radiation pattern of a Yagi-Uda antenna for FM band

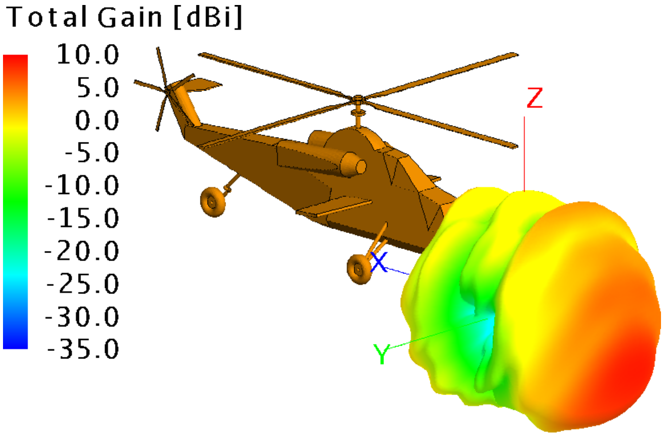

Fig. 4. Radiation pattern simulation of the Yagi-Uda antenna shown in Fig. 3 mounted under a helicopter

For frequencies at FM band (87.5-108 MHz), individual elements of the Yagi-Uda antenna are rather large, approx. 1.5 meters in length. Due to the antenna size and flight stability requirements, the antenna is placed under a helicopter and its radiation pattern is simulated in Fig. 4.

The proximity of the measurement antenna to the helicopter hull is influencing its radiation properties in comparison to the non-reflective (“free space”) environment the receiver antennas are originally calibrated in. Additionally, directional antennas (at these frequencies), such as Yagi-Uda, are not suited for a medium-sized UAV due to its size and weight.

As a result, a custom, specialized measurement device Pixla 1 was developed, using a short monopole over a conductive ground as a receiver antenna. A short monopole has a reasonably flat impedance response in the FM band but has a quasi-omnidirectional radiation pattern, which is not ideal as it can be influenced by the UAV hull. However, the UAV body has a significantly smaller profile compared to the helicopter and usually consists of composite materials. Hence, UAV influence on the receiver antenna can be expected to be lower.

Figure 5 illustrates horizontal flight measurement that is used to measure the horizontal cut of the radiation pattern of the measured AS. In addition to the helicopter / UAV influence on the receiver antenna radiation pattern, the helicopter / UAV is moving during the aerial AS measurement, causing slight rotation in all axes (pitch, yaw, roll). Rotation is also caused by the wind, to which the vehicle is responding by rotating, stabilizing itself. By rotating the vehicle, the receiver antenna rotates as well, changing its polarization plane and gain in respect to the measured AS. In this case, the omnidirectional properties of the short monopole antenna appear to be convenient. However, to minimize the measurement uncertainty caused by the rotation of the receiver antenna, the receiver antenna radiation pattern must be known and the movement should be restricted to the minimal possible angles.

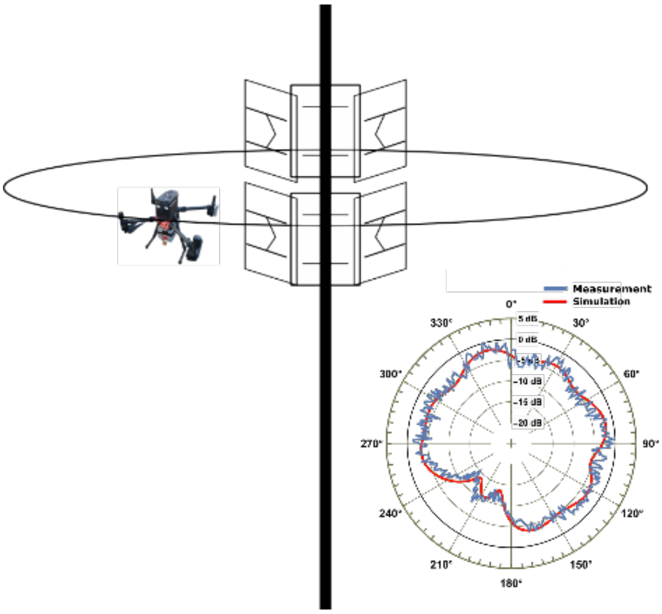

Fig. 5. Horizontal flight measurement with simulated and measured horizontal radiation pattern cut

3 Receiver antenna radiation pattern verification

During a horizontal flight measurement, the UAV is set to a circular flight path with the point of interest being the measured AS. The UAV is automatically rotating in yaw (phi) in a way that the UAV front and measurement antenna are always facing the AS. Small in-flight rotations caused by the wind, the UAV vibrations, or other influencing factors are well documented in the internal flight log. After practical considerations, the antenna movement (UAV rotation) is restricted to ± 5° in any axis from the nominal position during the flight. Any data that is measured with UAV rotated beyond this restriction is unfit for further evaluation and is excluded. The goal of further analysis is to establish the receiver antenna gain variation within this ± 5° restriction.

To define the receiver antenna radiation pattern deviation, a simulation model is created. A model is then verified in a horizontal cut using special aerial measurement – “pirouette“, and by experimental measurement in the EMC semi-anechoic chamber.

3.1 Simulation model

To define the radiation pattern of a receiver antenna, a simplified model of the utilized UAV with Pixla 1 and a short monopole antenna is created in Altair FEKO (see Fig. 6).

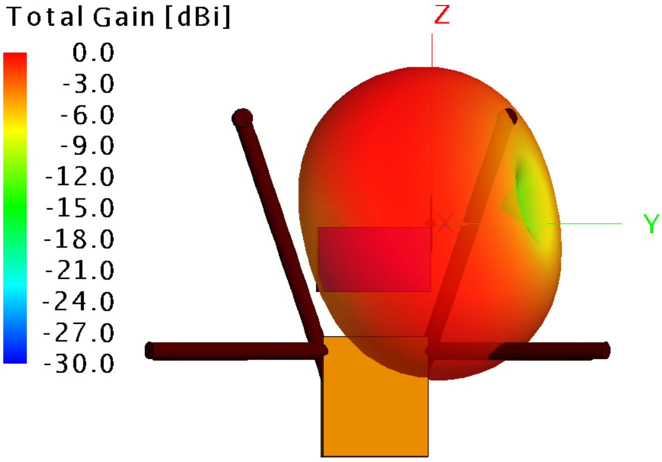

Fig. 6. Simplified radiation pattern simulated at 96 MHz of the measurement device Pixla 1 mounted on a UAV DJI Matrice 300

The UAV simulation model includes lossy carbon-fiber UAV arms / landing platform and a perfectly electrically conductive body. The real UAV body consists of various composite materials and many conductive elements, including batteries, which make up a large part of the UAV body. Therefore, modelling the body of the UAV as a fully conductive part is in this case sufficient without having a significant impact on the output results. The measurement device Pixla 1 body is simulated as pure aluminium, while the receiver antenna (short monopole antenna over reflective surface) is simulated as a single-side copper / FR4 laminate with a copper rod (short monopole), resembling the true nature of the used receiver antenna. The calculation method used to determine the radiation pattern of the receiver antenna is the Method of Moments (MoM).

As seen in Fig. 6, the radiation pattern of the receiver antenna is slightly rotated compared to the radiation pattern of the short monopole antenna in free space.

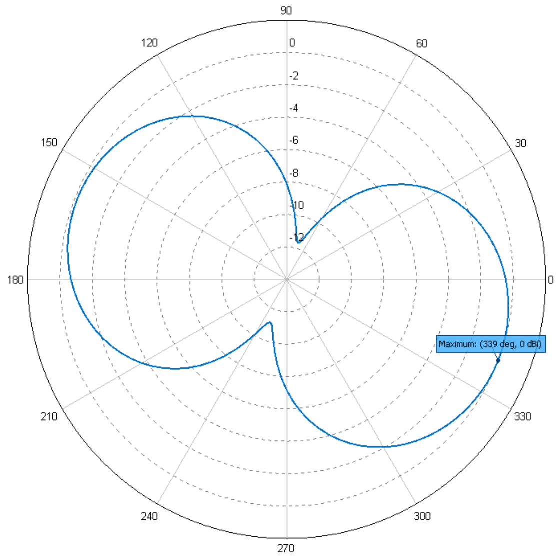

Fig. 7. Horizontal cut (theta = 90°) of simulated radiation pattern of measurement device mounted on a UAV from Fig. 6

The horizontal cut of the simulated radiation pattern in Fig. 7 shows that the measurement device and UAV are affecting the receiver antenna and the maximum of the antenna gain is shifted by approx. 21°.

3.2 In-situ measurement – "pirouette"

It is convenient to use the transmitting AS as a "constant" EM source and measure the received power during the full UAV yaw (phi) rotation. With this "pirouette" measurement it is possible to obtain only the horizontal cut of the receiver antenna radiation pattern. This is because additional pitch / roll of the UAV would cause its movement, changing the AS incident gain, polarization plane and overall distance from the AS resulting in a different measurement condition, invalidating the measurement. In Fig. 8, an AS with Pixla 1 mounted on a UAV before one of the aerial measurements can be seen.

Fig. 8. Pixla 1 mounted on a UAV – before the aerial measurement (illustrating in-situ measurement environment)

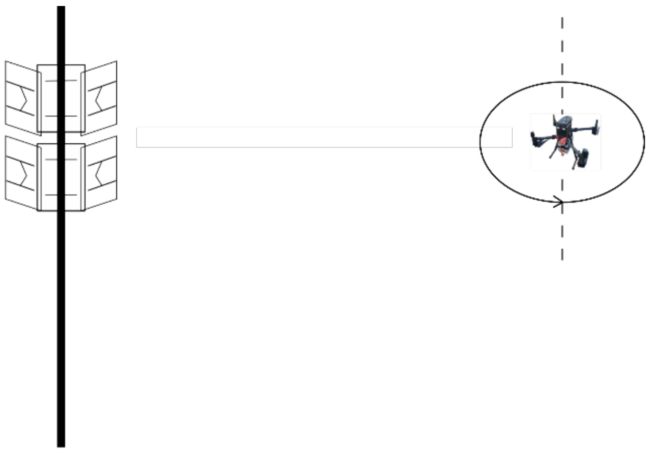

Fig. 9. "Pirouette" measurement of receiver antenna radiation pattern in horizontal cut

The pirouette measurement starts with the UAV ascending to the height of the geometrical centre of the AS and positioning itself in the far-field of the given AS. Minimal far-field distance is derived from [6] and in this case the UAV is positioned at a distance of 90 meters from the AS. Subsequently, the UAV performs slow yaw (phi) rotation around its z-axis as depicted in Fig. 9, while Pixla 1 is collecting samples at the transmit frequencies 98 MHz and 103.6 MHz of the AS.

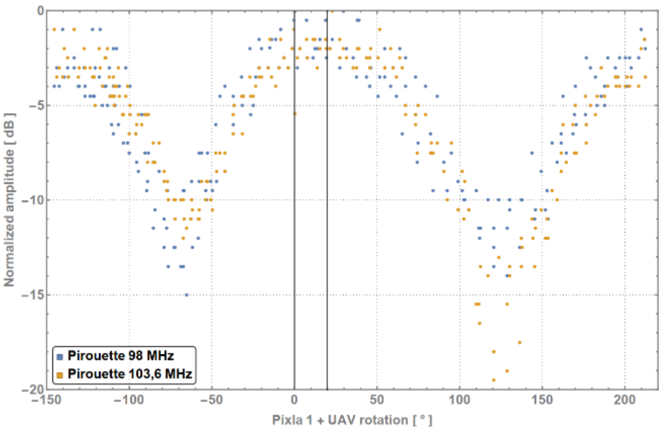

Fig. 10. Measurement results of a “pirouette” – aerial radiation pattern measurement of Pixla 1 receiver antenna

As seen in Fig. 10, the maximum of the receiver antenna radiation pattern in the horizontal cut is shifted, approximately by 20°. Deviation of the measurement samples in Fig. 10 is caused by the overall measurement uncertainty during the flight, including the Pixla 1 FM amplitude stability and amplitude linearity, but also AS transmitting power fluctuations, which are not subject of this article.

3.3 Measurement in EMC chamber

To potentially measure the radiation pattern of a receiver antenna also in other 2D planes, utilization of a semi-anechoic chamber is investigated. For aerial measurements of other than horizontal cut, the UAV needs to be tilted to angles at which it is not stable. Such measurements are, therefore, not possible in-flight, but could be performed with an idle UAV on the ground – fixed in a static position while tilted at various angles. Such measurements would provide additional verification for radiation pattern cuts at limiting pitch and yaw rotations.

Fig. 11. Experimental radiation pattern measurement of Pixla 1 mounted on a UAV in the EMC semi-anechoic chamber

In Fig. 11, the experimental setup for radiation pattern measurement (in horizontal cut) with Pixla 1 mounted on the UAV in an EMC semi-anechoic chamber is presented. During the measurement, a log-periodic antenna is used to create an EM field at constant amplitude and frequency. The semi-anechoic chamber itself is lined with ferrite tile absorbers to limit reflections at relatively low test frequency (100.2 MHz). The ferrite tile absorbers are not perfect, and their reflection and absorption properties differ with frequency and angle of arrival but should be sufficient for this experimental measurement. The measurement is performed with an angle increment of 3°, with five amplitude samples at each angle. Measurement device Pixla 1 is used for amplitude data acquisition, while angular information (yaw rotation) is obtained directly from the motor controller driving the rotating platform with the UAV.

A normalized comparison of radiation pattern measurement and simulation of receiver antenna in a horizontal cut (theta ~ 90°) is shown in Fig. 12. The comparison confirms that the radiation pattern maximum of the receiver antenna is shifted by approx. 20° in the horizontal cut. The overall comparison of the radiation pattern cut in Fig. 12 agrees within ± 30° from the global maximum but the simulation and measurements differ in other angles corresponding to the back lobe and global minima of the radiation pattern.

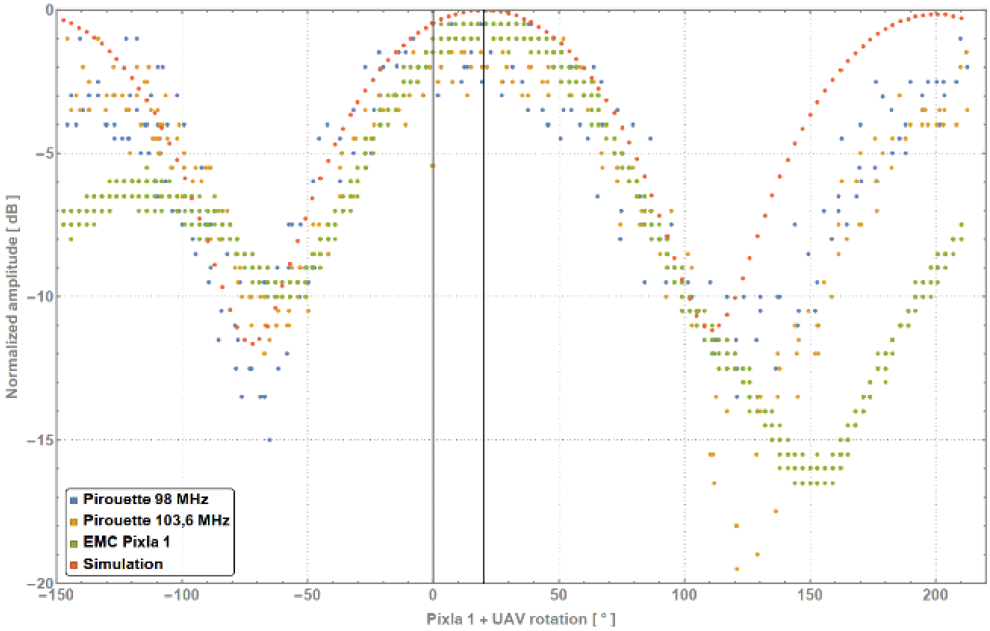

Fig. 12. Comparison of normalized receiver antenna radiation pattern measurements at horizontal cut (theta ~ 90°) acquired by aerial pirouette measurement, experimental EMC chamber measurement and simulation

It is also important to mention that simulation considers only one point for one angular position and is calculated for ideal conditions, whereas in an EMC chamber, the measurement points are subject to Pixla 1 stability as well as signal generator stability on transmitter side and properties of the quiet zone. The effects on measurements are the most severe in the case of outside in-situ measurements where environmental factors, quadcopter tolerances, Pixla 1 stability as well as FM transmitter stability play a significant role. Furthermore, the signal transmitter from the FM AS is frequency modulated, further introducing measurement point uncertainty. These factors, however, are not deeply analysed within this study, as the goal is to evaluate uncertainty caused by "outside maximum" measurements and for this purpose, even the outside conditions can be considered adequate, which is demonstrated in Figs. 10 and 12.

4 Results

A good match in shape and rotation of radiation pattern (horizontal cut) between the simulated and measured data verified the simulation model near the global maxima. Using a simulation model to further estimate the receiver antenna gain uncertainty is very practical due to the fact that precise in-flight rotations in other than theta ~ 90° planes are not possible and the EM field uncertainties in the EMC semi-anechoic chamber may increase the measurement uncertainties dramatically [9]. Using a verified simulation model, it is possible to simulate receiver antenna gain for possible rotations in yaw / pitch. Gain uncertainty caused by roll rotation shall be calculated simply as maximal polarization loss.

During a horizontal flight, UAV is usually statically rotated in yaw (phi) by approx. 5°. For that reason, Pixla 1 receiver antenna gain is simulated with a phi offset of –5° (for clock-wise horizontal flight). In Fig. 13, simulation of the receiver antenna gain is presented for yaw (phi) at 355° ± 5° and pitch 0° ± 5° (for theta it is 90° ± 5°).

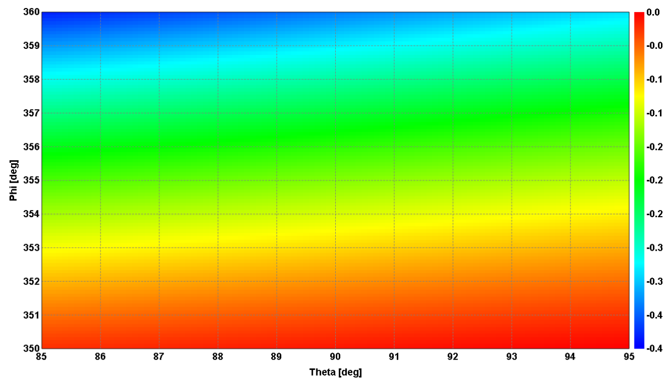

Fig. 13. Normalized gain for Pixla 1 receiver antenna according to model from Fig. 6 (for ± 5° yaw and ± 5° pitch tolerance from nominal rotation)

The simulated ±5° rotation in yaw and pitch in Fig. 13 represents any in-flight antenna gain deviation caused by wind, positioning error, vibration, or other influencing factors.

Table 1. Uncertainty sources of the Pixla 1 receiver antenna radiation pattern

Uncertainty source	Limits	Influence (dB)	Distribution	Standard uncertainty σ_i
Polarization loss (roll)	±5°	± 0.03	Rectangular ($k = \sqrt{3}$)	0.017 dB
Receiver antenna gain (pitch and yaw)	±5°; ±5°	± 0.44	Normal ($k = 2$)	0.220 dB
Combined standard uncertainty $\sigma_{comb} = \sqrt{\sum_{i=1}^{n} \sigma_i^2}$	-	-	-	0.220 dB
Expanded combined standard uncertainty (k = 2)	-	-	-	0.441 dB

According to the receiver antenna radiation pattern simulation from 88 MHz to 108 MHz at 2 MHz steps and restriction to ± 5° from the nominal UAV rotation, the maximal gain deviation is 0.44 dB. Given the random nature of UAV rotation during the flight, a normal distri-bution is selected and a combined standard uncertainty of 0.22 dB is calculated in Tab. 1.

5 Conclusion

The article presents an analysis of radiation pattern measurement of a large antenna system utilizing a UAV-based measurement device, specifically addressing the receiver antenna gain deviation due to random UAV movement. Radiation pattern deformation is presented for standardized helicopter measurements, but also for UAV-based measurements that are gaining popularity in recent years.

A simplified simulation model is prepared, including a specialized measurement device Pixla 1 with an electrically short monopole over a ground plane for the measurement (receiver) antenna, and a UAV represented by a simplified model of the DJI Matrice 300. Preliminary simulations showed that the radiation pattern of the receiver antenna was shifted due to the presence of a measurement device and UAV nearby the receiver antenna.

By performing in-situ "pirouette" aerial measurement and radiation pattern characterization (in horizontal cut) in an EMC semi-anechoic chamber, the simulation model was verified near the global maximum of the horizontal cut (theta ~ 90°) of the receiver antenna radiation pattern.

Based on the flight log data from previous UAV circular flights, it is established that ±5° movement freedom in yaw, pitch and roll rotation is sufficient in standard wind conditions. The simulation model at frequencies from 88 MHz to 108 MHz with a 2 MHz step was subsequently used for detailed gain simulation of ±5° in yaw and pitch rotations from nominal flight position, while roll rotation is associated with polarization losses.

The expanded combined standard uncertainty of the receiver antenna gain for the analysed UAV-based measurement system for large AS radiation pattern measurement is 0.44 dB.

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