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Electromagnetic Characterization of Installed Antennas Through UAVs

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Abstract. The characterization of the radiation pattern of low-frequency antennas is a challenging problem that requires an advanced strategy to reach the expected measurement accuracy. A micro Unmanned Aerial Vehicle (UAV) has been used as a radio frequency test-source to perform such measurements with an innovative technique, obtaining outstanding results. In particular, a Differential Global Navigation Satellite System (DGNSS) based positioning has been introduced through the use of an external GNSS (Global Navigation Satellite System) receiver to obtain the UAV position during the flight with a high level of accuracy. The system has been experimentally tested since a challenging topic is to define all the issues that can occur in the combined use of unmanned aerial systems and electromagnetic components. For this reason, it was investigated to assess sensors problems (such as interferences and positioning troubles with the external sensor) and to define some best practices in the use of such system for this particular field of application to reach the expected result. Finally, an experimental case to demonstrate the suitability of the proposed system is presented in this paper. The radiation pattern of a log-periodic antenna at 250 MHz has been measured with good results.

Keywords: Antenna characterization · PPK positioning · Unmanned aerial vehicle (UAV) · Dual frequency GNSS (Global navigation satellite System)

1 Introduction

One of the current challenges of the international radio astronomical community is the Low-Frequency Aperture Array technology. This consists of a high number of low-cost low-frequency antennas with large field of view spread over several square kilometers. The antennas are mechanically fixed on the ground and the array beam is steered by

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electronically combining the signals received by each antenna. The most important example is the Low-Frequency Telescope of the Square Kilometre Array (SKA[1]), which is expected to be completed in the 2020s. The performance of these arrays critically depends on their electromagnetic characterization and calibration.

At low frequencies, (e.g. 10–100 MHz), an advanced tool is required to characterize both the elements and the whole array in their effective working conditions. In fact, besides the practical impossibility of using anechoic chambers for such a physical large instrument, the strong interaction of the antennas with the surrounding environment and other elements can be properly accounted at the final site of the telescope. For this reason, an innovative system to perform such measurements has been developed starting from the properties of Unmanned Aerial Vehicles (UAV) [10]. The system has been used for the calibration of demonstrative arrays [1–8]. This paper describes the implemented system and tests carried out on the sensors. Operative practices for the employment of such methodology are investigated providing also the application to a real case study. Since the system is experimental and innovative, it was necessary to study its limits and improvement activities for the application with millions of antennas.

2 Developed System

In order to have a flexible system for the pattern characterization of installed antennas, a solution through UAV was adopted for this topic. A customized Mikrokopter Hexakopter (Fig. 1) was used: it is a low-cost (~5000€) micro UAV which is able to perform autonomous flights through waypoints. Its maximum payload is 1.5 kg that can be placed in a dedicated servo-assisted support, which is made of carbon fiber.

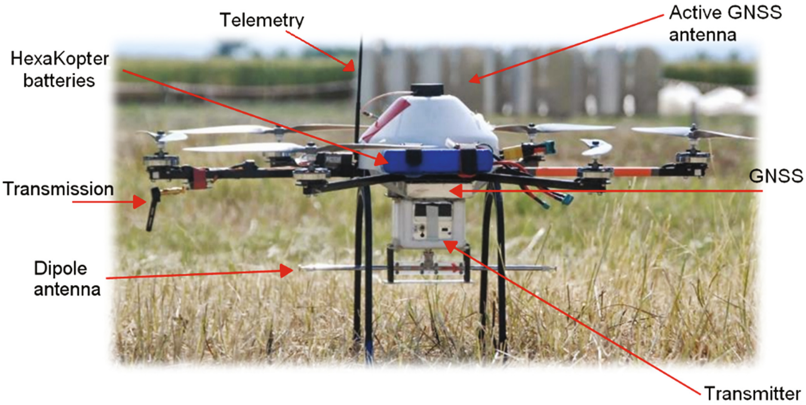

Fig. 1. Main components of the customized Mikrokopter

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[1] https://www.skatelescope.org/project/.

The main elements of the micro-UAV are:

- 6 brushless DC (Direct Current) electric motors;
- 6 brushless (BL) controllers;
- one Flight-Control (FC) that contains a pressure sensor and a 3-axis IMU (Inertial Measurement Unit) with 3D gyroscope and 3D accelerometer;
- the Navi-Control (NC) that is the autonomous navigation system of the Hexakopter. It is able to define the absolute position and attitude (X, Y, Z, Yaw, Pitch and Roll) of the UAV and to perform the autonomous flight using a low cost GPS receiver, a 3-axis magnetic field sensor and an internal 3-axis IMU.

As far as the radio frequency components are concerned, the UAV has been equipped with a programmable, continuous-wave RF (Radio-Frequency) transmitter. The output frequency can be set in the range from 4.3125 MHz to 4400 MHz, whereas the output power is programmable from 0 dBm to 8 dBm in four steps. The transmitter is battery-powered and completely shielded in a custom metal box with output connector. Finally, a balloon and a dipole antenna is connected to the transmitter output. Each monopole can be easily replaced with others having different length to achieve impedance matching and a proper radiation pattern at the various operative frequencies.

During the measurement, the output power signal at the AUT (Antenna under test) port is measured through a spectrum analyzer. The analyzer is configured in zero-span mode and centered at the operative frequency. With this configuration, the output trace of the analyzer corresponds to the received power versus time.

The spectrum analyzer acquisition is triggered using the Pulse Per Second (PPS) signal available from a GPS receiver u-blox EVK-6T [9]. A computer acquires both the trace of the analyzer and the GGA message from the GPS receiver [4, 5]. In this way, a common time reference is used for all the data that are required for the post processing, i.e. the received power, the position of the UAV and its orientation [11].

Since a precise (few cm) knowledge of the UAV position along the flights is required [6], a Differential Global Navigation Satellite System (DGNSS) was adopted. It is a dual-frequency (L_1 = 1575.42 MHz and L_2 = 1227.60 MHz) and multi-constellation (GPS and GLONASS) receiver (Novatel OEM 615) that was connected to an active antenna (able to receive GPS, GLONASS and Galileo constellations) installed on the cover of the UAV. The storage of the raw data has been realized making a direct connection between the DGNSS and a dedicated Ardulog data logger. The system was positioned above the transmitter and housed inside a shielded box (Fig. 2).

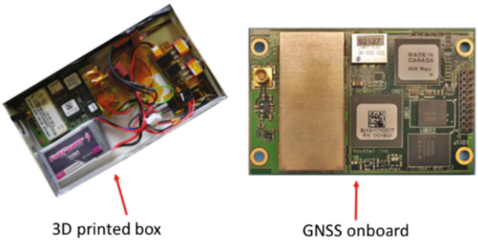

Fig. 2. Novatel OEM 615 external receiver and its shielded box

The telemetry was broadcasted from the UAV to the ground station through a wireless communication using two XBee Pro2 modules with a nominal range of 1 km. Different kind of antennas can be used to perform this communication. In particular, we used two solutions (Table 1) that can provide a good quality of the link.

Table 1. Antennas used for the telemetry broadcasting

Antenna	Model	Typology	Frequency range	Gain
Patch	D-Link DWL-R60AT	Micro-strip Patch	2.4–2.5 GHz	6 dBi
Log-periodic	Sirio SLP- 1.7:2.5-11	Directional	1.7–2.5 GHz	11 dBi

3 Analysis of the Performance of the Proposed System

Before using the developed system, it is fundamental to test the accuracy of the installed sensors and to define some operative procedures for the correct use of the system during the flights and the processing of the data. Moreover, it is important to identify eventual limits or restrictions, in order to study some “innovative” solution.

3.1 Analyses of the Positioning System and Electromagnetic Interferences

The UAV is equipped with an internal GPS receiver and an internal IMU, which allows to define the attitude during the flight. The first question that has been considered is related to the simultaneous use of the RF transmitter and the navigation sensors. Using the dedicated tool called “MikroKopter tools”, it is possible to analyze the tracked satellites and the corresponding signal-to-noise ratio expressed in dB. Three tests (Fig. 3) were performed to verify if the use of the transmitter interferes with the internal sensors observing the signal power and the satellites number under these conditions:

- only the GPS receiver switched on;
- both GPS receiver and RF transmitter switched on (frequency: 300 MHz);
- both GPS receiver and RF transmitter switched on (frequency: 300 MHz) and introduction of a low-pass filter connected to the transmitter to reduce the spurious higher-order harmonics.

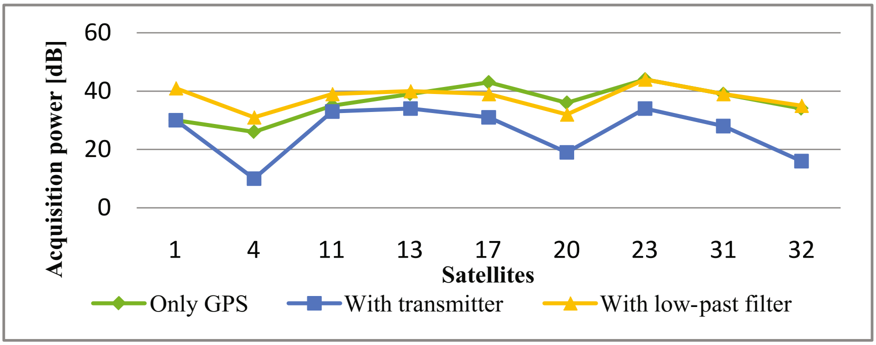

Fig. 3. Received signal power: tests with the transmitter and the low-pass filter

The tests show that there is actually a reduction of the signal power received by the internal GPS if the transmitter is turned on (since L_1 frequency is close to GPS one). This effect is particularly significant if the transmitter is turned on before the GPS receiver. For this reason, a low-pass filter has been installed (cutoff frequency of 650 MHz) and the influence of the transmitter is now negligible.

As a second test, the accuracy of the external DGNSS (Novatel OEM 615) has been experimentally estimated. In order to obtain a set of reference data, the position of the UAV has been automatically tracked along a flying path with a motorized total station (TS) (Fig. 4), using a dedicated retro-reflector installed under the transmitter.

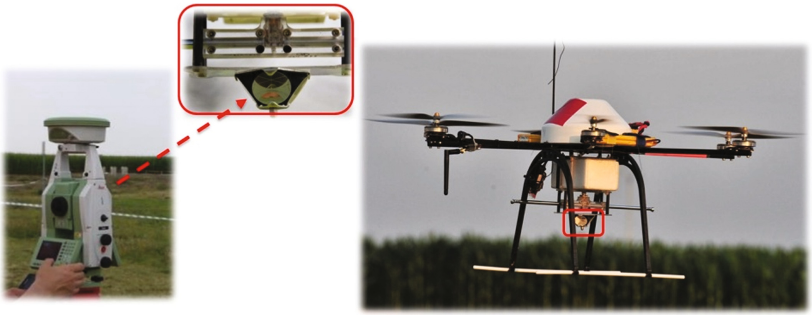

Fig. 4. The retro-reflector on-board and the track with the total station

The two available solutions (TS and DGNSS) have been compared to estimate the differences. The results (Table 2) demonstrate that the estimated DGNSS positions follow the TS trajectory with an accuracy of few cm. This is acceptable according to the nominal precision of the PPK (Post Processing Kinematic) solution [3–9].

Table 2. Evaluation of the positioning results of the external GNSS receiver

Direction	Min [m]	Max [m]	Mean [m]	Std [m]
Horizontal	−0.124	0.130	0.010	0.040
Vertical considering level arm	−0.182	0.213	0.032	0.092

Tests demonstrate good performance in positioning using the external DGNSS receiver where maximum discrepancies are in the initial part of the test (especially for the vertical component). For this reason, some strategies for the GNSS initialization (time to fix the phase ambiguity) have been adopted to avoid positioning errors. The recommendations to have an accuracy of few cm for the entire flight are as follows:

- the GNSS OEM card should be turned on about 2–3 min before starting the flight and it has to stay on the flight initial point;
- after take-off, UAV must stay on air on the first waypoint for a few seconds;
- then the flight can be performed with a maximum speed of about 5–7 m/s;

- finally it is important to wait 2–3 min on the ground after landing before turning off the receiver.

Another aspect that has been investigated is the obtainable precision of the external receiver using different GNSS constellations [8], in particular, only GPS or GPS+ GLONASS. The estimated 3D precisions for the GPS-only solution and the performances obtained with the two constellations are summarized in Table 3.

Table 3. Average precision of different GNSS solutions related to satellite constellations

GPS sat.	GLO. sat.	Std x [m]			Std y [m]			Std z [m]		
		Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
8	0	0.006	0.520	0.180	0.005	0.430	0.130	0.015	1.420	0.420
10	11	0.014	0.036	0.016	0.015	0.025	0.017	0.016	0.041	0.031

It became apparent that, for the correct use of dual-frequency GNSS receiver on-board the UAVs, the usage of the GLONASS constellation have a strong influence in the final solution. For this reason, in precise positioning surveys, the use of multi-constellation antennas is recommended.

3.2 Practical Procedures and Problems

With reference to the scheme reported in Fig. 5, the operative procedure for the characterization of the AUT pattern can be divided in three main steps:

- the survey planning and ground measurements;
- the data acquisition;
- the processing of the acquired (UAV and RF) data.

Different practices need to be adopted before the flight to correctly use the system and obtain the expected accurate result. Procedures include the following practices:

1. It is important to orient the antenna on the ground along the correct direction to avoid any offset between it and the transmitting antenna on the UAV. Additionally, the verticality of the antenna needs to be adjusted. These operations can be performed positioning the antenna on the ground, measuring its position with the total station and iteratively adjusting it according to the taken measurements;
2. To have an absolute reference system for the measurements, a reference network needs to be set. The position of the vertices can be acquired by a GNSS receiver in static mode and process to obtain a position accuracy of few millimeters;
3. Before the first flight, the calibration of the UAV navigation sensor needs to be performed, which included accelerometers, magnetometers and gyroscopes. These operations have to be performed before the flights in an area free from magnetic field and far from the ground GNSS station to avoid interferences;
4. To set the flight direction with very high precision (some centimeters) [7], it is necessary to characterize the systematic error of the compass. The UAV should be

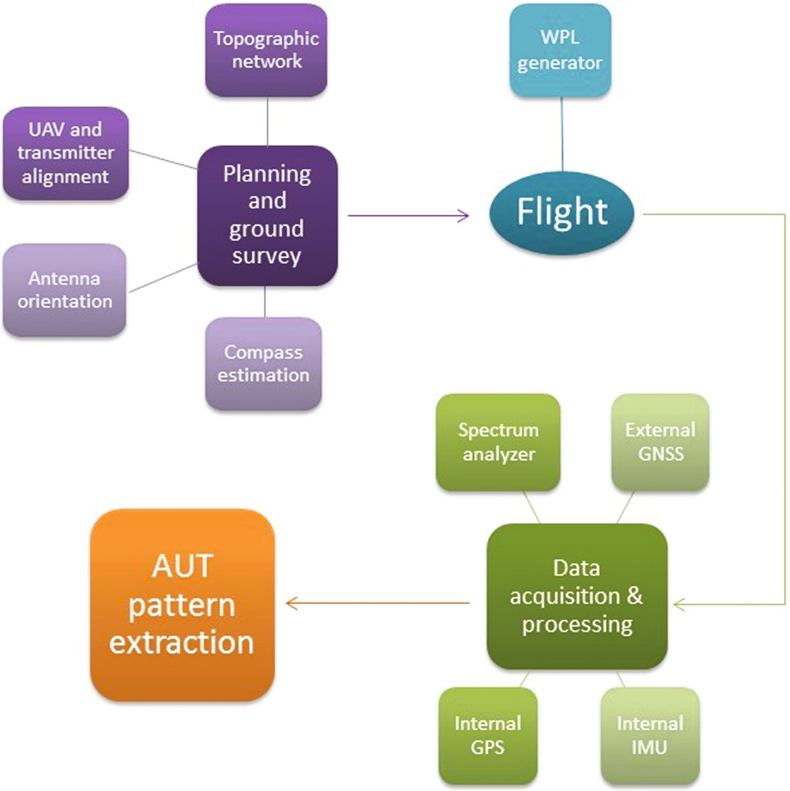

Fig. 5. General workflow for the pattern characterization of antennas

properly oriented along the mapping axes using a total station in tracking mode. Afterwards, thanks to the telemetry, the values of the compass are recorded under different conditions with the engines off and then on and an average value in azimuth is estimated for all the tested solutions. This value is added in the flight planning direction consider the systematic behavior of the compass. Moreover, the magnetic declination and the meridian convergence need to be estimated and taken into account for each new survey place;

5. Finally, the mechanical alignment between the UAV direction and the on-board transmitter antenna needs to be estimated. To perform this measurement, two markers (left in Fig. 6) are placed on the UAV and two additional targets are used on the RF antenna (right in Fig. 6). Four measurements may be sufficient to determine the relative position between the two elements.

Since complex flights may be adopted to analyze the pattern, they are scheduled through a script developed in Matlab that defines the trajectories establishing the way-points position (Fig. 7). This custom tool is very useful because it gives the possibility to set the antenna position as central reference for the flight and to define the type of flight with specific compass angle value (either 0 or 90° for co-polar or cross-polar pattern).

Fig. 6. Points used to estimate the relative orientation between the UAV direction and the transmitter antenna

Moreover, the tool is fundamental to estimate also the flight duration since batteries have a lifetime of about 15 min. For the majority of flights this time is sufficient, but, in some cases, it is necessary to split it.

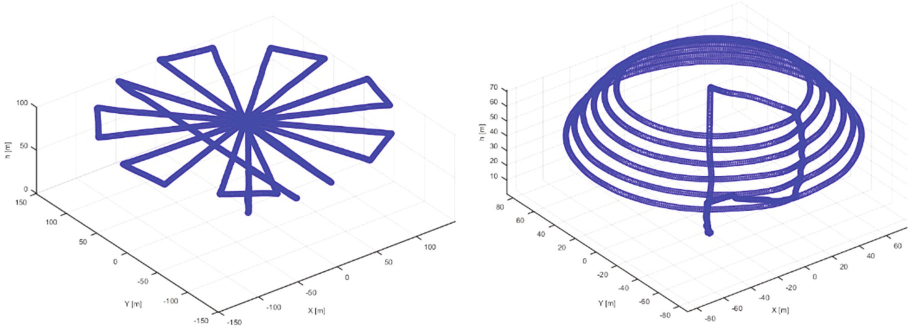

Fig. 7. Example of trajectories through waypoints generated with the WPL generator tool

4 Case Study

The presented case study is finally used to evaluate if the developed system and methodology can be applied for the characterization of the antenna pattern.

The relevant information of the antenna pattern is generally contained in two orthogonal principal planes. The AUT is therefore oriented so that the principal planes coincide with North-South and East-West. So, two orthogonal rectilinear flights of the UAV along the NS and EW direction are sufficient to characterize the AUT.

For this measurement we used a PMM LP-02 log-periodic antenna at the frequency of 250 MHz (picture of the AUT on the measurement field in Fig. 8).

Fig. 8. The log-periodic antenna PMM LP-02

According to the Friis formula [11], the AUT pattern is extracted from the measured RF power (given by the spectrum analyzer) by removing the contributions of the path loss, the constant gains and attenuations (e.g. cables and amplifiers), and the simulated contribution of the test source gain. In addition, both the real UAV path and its orientation may be slightly different from the programmed ones [10], i.e. the UAV does not follow the required rectilinear path. However, this fact is kept into account in the pattern extraction procedure, since the above mentioned contributions are computed according to both the real UAV position (DGNSS data) and orientation (IMU data).

The error of the position measured with the internal GPS receiver is considerably higher than the error produced by the DGNSS. Figure 9 shows the trajectories in the two cases (GPS and DGNSS) for this particular experiment: mean discrepancy is around 1 m for the horizontal component (Fig. 9a) and 3 m for the vertical one, with 5 m peak.

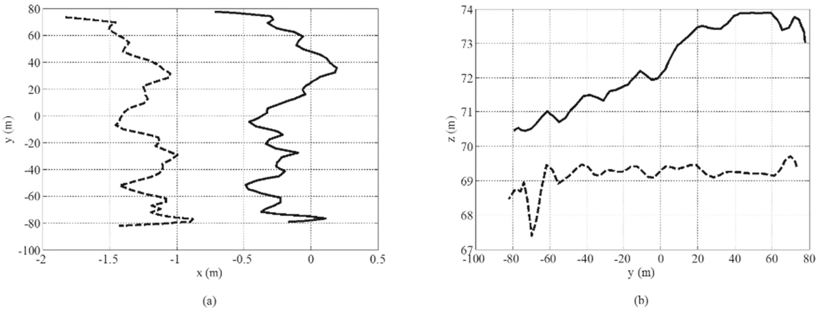

Fig. 9. Trajectories of the UAV measured with on-board GPS (solid lines) and DGNSS (dashed lines). (a) Top view (horizontal plane); (b) UAV height as a function of the y coordinate (North-South position)

There are two main consequences. Firstly, the two trajectories lead to different values of distance between AUT and UAV. Thus, the spatial attenuation of the radiated signal (path loss) is different in the two cases. Also the test-source gain has different values. In fact, its value depends on the relative position of the AUT with respect to the UAV. Owing these errors, the resulting AUT patterns are much different.

Figure 10a shows the AUT pattern extracted using the position data provided by the UAV navigation board (consisting of a GPS), whereas Fig. 10b shows the AUT pattern computed using the position data of the DGNSS receiver considering all the described operative practices for the flight and the developed system. Both the curves are compared to the simulated AUT pattern. Figure 10a (GPS) shows a significant discrepancy between measurement and simulation, generally 1.5 dB, which also produces an evident distortion of the pattern. Such a discrepancy is consistent with the combined effect of the two errors introduced on the path loss and the test-source gain. In contrast, Fig. 10b (DGNSS) shows a better agreement. The discrepancy is generally within 0.3 dB, which demonstrates the higher position accuracy of the differential GNSS. The same accuracy levels were obtained tracking the UAV with the total station [8]. This residual discrepancy can be mainly explained by uncertainties in: (a) the electromagnetic model of both AUT and test-source, (b) the measured UAV orientation during the flight (IMU), and (c) the AUT positioning on the measurement field.

For more sensible pattern measurements, as for the cross-polar components, whose amplitude levels are up to −30 dB lower than the co-polar component, the lower accuracy of the native UAV navigation board would be definitively unacceptable.

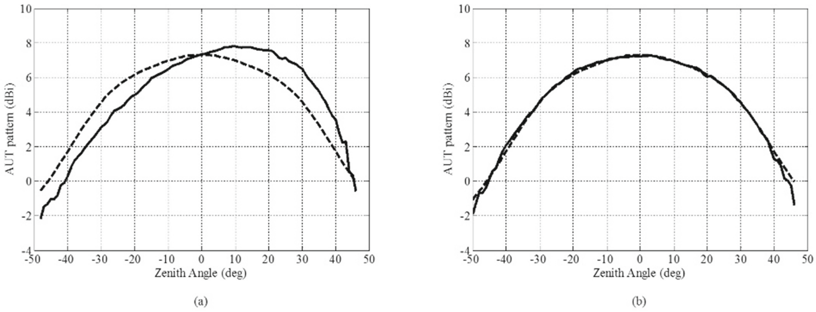

Fig. 10. AUT pattern at 250 MHz extracted using the position data of (a) the UAV navigation board (GPS), (b) the DGNSS unit. In both sub-plots: measurement (solid line), simulation (dashed line).

5 Conclusions

A low-cost technique for the characterization of installed low-frequency antenna has been presented in this paper. The implemented system demonstrated good performances for characterizing antennas and arrays [11] and the cost effectiveness and the transportability are the main advantages of this system.

Moreover, in order to measure the UAV position with an accuracy of few cm, a DGNSS unit and its multi-constellation antenna have been mounted on the vehicle as part of the payload. The orientation data provided by the IMU (included in Mikrokopter FC) has been also exploited to increase the accuracy of the electromagnetic measurements. However, the reliability of the angles data derived from the internal IMU sensor needs to be more investigated to analyze its behavior and investigate if it is necessary to introduce an external sensor also in this case.

To obtain a reliable result and perform correct flight, the calibration of the system is also a fundamental step; specific procedures needs to be properly performed.

The presence of interferences has been investigated and this problem solved with additional hardware items (attenuators, filters), but it is important to take into account the interferences possibility at each new test and when the transmitter and antennas sources change.

Another topic that is closely related to this system is the range of application of the technology itself. This aspect must be investigated in terms of type of antenna to characterize, the sensors installed on board and the UAV limits of use. In fact, this last aspect could be very significant if we consider the location of the installed antennas where national and international rules may establish significant flights limits that can influence the use of this technique and also the duration of the batteries that needs to be improved in the case of arrays of millions of antennas.

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