UAV-based method for the sensitivity measurement on low-frequency receiving systems

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Abstract – **One of the most important requirements for the astronomical Low-Frequency Aperture Arrays (LFAAs) is the high sensitivity, defined as the ratio between the effective area and the system noise temperature. This figure of merit is strictly related to the single element sensitivity, which is difficult to measure using astronomical sources. On the other hand, the characterization of a low-frequency antenna inside an anechoic chamber is not straightforward down to 50 MHz. In this contribution a novel method to measure the sensitivity of a single LFAA receiving chain is presented. The proposed technique utilizes a micro Unmanned Aerial Vehicle equipped with a RF test source. A preliminary error budget analysis demonstrated that this technique is able to measure the sensitivity of a LFAA chain with high accuracy.**

1 INTRODUCTION

Recently, several Low Frequency Aperture Arrays (LFAAs) have been installed around the world and an innovative radio telescope of unprecedented performance, the Square Kilometre Array (SKA), is envisaged to be built in Western Australia [1]. One of the main requirements of these facilities, in particular of the SKA, is the high sensitivity. The overall sensitivity of a radio interferometer is strictly related to that of its individual elements. Unfortunately, the characterization of a low frequency antenna, as well as of the whole receiving chain, is difficult to obtain for many reasons. The antenna pattern measurement of a single element in an anechoic chamber neglects both the mutual coupling between the array elements and other important effects of the surrounding environment (soil, sky noise, etc.) in which the antenna is operating. On the other hand, the in-situ characterization of low frequency antennas and arrays through radio astronomical sources is possible but it is challenging because the bright compact radio sources, suitable for this kind of measurement, are not numerous. This is especially true in the southern hemisphere, where the SKA will be installed. Moreover, the measurement with astronomical sources is limited to the specific source apparent path in the sky (θ, ϕ) due to the Earth rotation [2].

In this paper, we propose a novel method for the measurement of the system sensitivity, using a test source installed on a micro Unmanned Aerial Vehicle (UAV) able, in principle, to overcome these issues. In section 2 the UAV system is described. The basics on sensitivity measurements are given in section 3. Section 4, after the description of the on/off measurement procedure, gives the results of the error budget analysis. Finally, in section 5 the concluding remarks are given.

2 THE UAV SYSTEM

The test source is a micro-UAV equipped with a continuous-wave RF transmitter and a dipole antenna (Fig.1). The drone is a hexacopter capable to perform automated flights along scheduled trajectories with programmed source orientation, as well as to make autonomous take-off and landing. A Differential Global Navigation Satellite System (DGNSS) yields the UAV position with centimeter-level accuracy [3].

Figure 1: The micro-UAV equipped with RF transmitter, dipole antenna and GNSS system.

The UAV-system, developed in Italy, has been successfully utilized for the characterization of isolated and embedded element radiation patterns [4] and for the array instrumental calibration [5]. The application of the UAV system has been proposed also in the calibration of the array element position [6].

3 FORMULATION

The sensitivity of a radio telescope is a figure of merit that can be expressed in many ways. Following the SKA-low Level 1 requirements document [7], here we adopt the sensitivity metric $\mathrm{A_{eff}/T_{sys}}$ in which $\mathrm{A_{eff}}$ is the effective area [$\mathrm{m^2}$] and $\mathrm{T_{sys}}$ is the system equivalent noise temperature [K]. According

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to this definition, the sensitivity in a given direction (θ, ϕ) is described by the following equation [8]:

$$\left(\frac{A_{eff}}{T_{sys}}\right)_{\theta,\phi} = \frac{\lambda^2}{4\pi} \frac{G(\theta,\phi)}{\eta T_A + (1-\eta)T_0 + T_{rec}} \quad \left[\frac{m^2}{K}\right] \quad (1)$$

in which λ is the wavelength, $G(\theta, \phi)$ is the antenna gain in the θ, ϕ direction according to the Std. 145-1993 IEEE definition, η is the radiation efficiency, T_A is the antenna temperature (including the sky contribution), T_0 is the physical antenna temperature (300 K) and T_{rec} is the noise temperature of the receiving chain under test.

The proposed method is based on both the linearity of the receiving chain and the capability to produce a known Power Flux Density (PFD) on the antenna under test (AUT). Assuming the far-field approximation and the perfect polarization matching between the source and the AUT, the PFD impinging on the AUT from the UAV is defined as:

$$PFD_{UAV} = \frac{P_T\, G_T(\theta',\phi')}{L_T\, 4\pi R^2} \quad \left[\frac{W}{m^2}\right] \quad (2)$$

where P_T represents the transmitter power, $G_T(\theta', \phi')$ is the gain pattern of the test source in the direction of the AUT, L_T is the loss in the transmitting chain (due to insertion loss, mismatch loss, etc.) and R is the distance between the UAV and the AUT. Since the UAV position, orientation, source gain and transmitted power are known, the PFD_{UAV} can be estimated. The PFD_{UAV} and the measured power P_{meas} are linearly related according to the following equation:

$$P_{meas} = m\, PFD_{UAV} + P_{sys} \quad [\mathrm{W}] \quad (3)$$

The measured power is the sum of two terms: the first one is due to the UAV transmission and the second one, P_{sys}, is the contribution associated to the system temperature:

$$P_{sys} = k\, T_{sys} B\, G_R \quad [\mathrm{W}] \quad (4)$$

in which k is the Boltzmann constant, B is the bandwidth and G_R is the overall gain of the receiving system (LNA, cables, receiver, etc.).

The slope, m, in equation (3) is given by the product of two factors:

$$m = A_{eff}\, G_R \quad [\mathrm{m}^2] \quad (5)$$

The straight line (Fig. 2) intersects the x-axis in the negative half-plane.

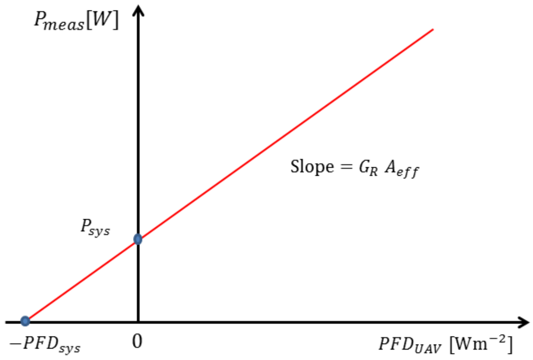

Figure 2: Relationship between the PFD from the UAV and the measured power at the receiver.

The absolute value of the abscissa of this intersection is the system equivalent power flux density (PFD_{sys}) associated to the system temperature. In other words, PFD_{sys} is the PFD that would produce a doubling of the system temperature.
The sensitivity is then obtained from the PFD_{sys} as:

$$\frac{A_{eff}}{T_{sys}} = \frac{kB}{PFD_{sys}} \quad \left[\frac{m^2}{K}\right] \quad (6)$$

4 MEASUREMENT PROCEDURE AND ITS ACCURACY

On the basis of the general formulation discussed above, the A_{eff}/T_{sys} can be in principle calculated by means of different measurement procedures [9]. In the following we present a two points (on/off) procedure that is divided in two steps:

- Step-1 (ON): measurement of the power P_{meas} corresponding to a known PFD_{UAV} level;
- Step-2 (OFF): measurement of the P_{sys} obtained without the UAV transmission.

The sensitivity is then given by:

$$\frac{A_{eff}}{T_{sys}} = \frac{k\, B\, (P_{meas} - P_{sys})}{PFD_{UAV}\;\; P_{sys}} \quad \left[\frac{\mathrm{m}^2}{\mathrm{K}}\right] \quad (7)$$

For this procedure we performed a preliminary error budget calculation at 50, 175 and 350 MHz, exploiting the error propagation approach. In our

analysis, a relative error of ± 0.1 dB has been assumed for each power level contribution measured with a spectrum analyzer and for the simulated gain of the transmitting antenna [10]. The absolute errors in the UAV position coordinates x, y, z have been set to 0.02 m, 0.02 m and 0.06 m, respectively. Moreover, since the SKA sensitivity requirements are given for the zenith direction [7], here we have supposed the UAV hovering above the zenith of the AUT at a quote of 200 m. Furthermore, to be sure to remain within the dynamic range of the power measurement system during the whole procedure, UAV transmitter power has been set to about -25 dBm.
Table 1 shows the UAV transmitting system specifications at 50, 175 and 350 MHz.

	50 MHz	**175MHz**	350 MHz
P_{TX} (dBm)	-25	-25	-25
$\varepsilon_{P_{TX}}$ (dB)	0.1	0.1	0.1
G_{TX} (dBi)	2.6	5.0	5.7
$\varepsilon_{G_{TX}}$ (dB)	0.1	0.1	0.1
InsLoss (dB)	0.28	0.53	0.81
$\varepsilon_{\text{InsLoss}}$ (dB)	0.1	0.1	0.1
MisLoss (dB)	9.53	1.26	1.07
$\varepsilon_{\text{MisLoss}}$ (dB)	0.73	0.03	0.01

Table 1: The main UAV transmitting system specifications at 50, 175 and 350 MHz.

The mismatch loss is significantly high at 50 MHz because, for UAV flight stability reasons, an unmatched 2-m long thin dipole is used. This in turns provides a higher associated uncertainty level with respect to the higher frequencies.
Concerning the sky noise contribution, we assumed the same uniform temperature model of the SKA Level 1 requirements document [7]:

$$T_{sky} = 60\, \lambda^{2.55} \quad [K] \tag{8}$$

The system temperature is the sum of the sky noise and the noise of the receiving chain: $T_{sys} = T_{sky} + T_{rec}$. The latter term is calculated from the noise temperature and the gain of each element within the receiving chain according to the cascade formulation of the Friis equation.

Remaining within the SKA context, for the receiving chain specifications we have considered the SKALA2 antenna design [11] and the SKA-Low requirements [7]. The bandwidth in which the power is measured has been set to 781.25 KHz, the same value of the SKA coarse channel bandwidth [12].

The results of the error analysis are summarized in Table 2, which shows the expected relative errors in the A_{eff}/T_{sys} measured at the three selected frequencies by means of the on/off technique.

	50 MHz	**175MHz**	**350 MHz**
Relative error (%)	23.3	6.8	6.7
Relative error (dB)	0.91	0.28	0.28

Table 2: Relative errors in the measurement of A_{eff}/T_{sys} using the on/off procedure.

It is important to notice that the larger error occurs at 50 MHz frequency. It is mainly due to significant uncertainty in the mismatch loss of the UAV dipole. At this frequency, the error in the sensitivity measurement can be significantly reduced either improving the accuracy of the source EM model or using another specific matched antenna.

In addition to the analytic approach, some Monte-Carlo simulations have been carried out considering a combination of different levels of Gaussian and systematic errors in the measurement procedure. The numerical simulations are essentially in agreement with the analytical results showed above.

5 CONCLUSIONS

In this paper we have presented a novel UAV-based method for the sensitivity measurement on a LFAA receiving chain. The proposed method is based on the linear response of the receiving system under test. It requires the capability to produce a known power flux density of the signal impinging on the AUT from the UAV-mounted source and the measurement of the corresponding received power.
A preliminary error analysis demonstrated that the proposed procedure is very promising in terms of accuracy when compared with other traditional measurement techniques in which the uncertainties mainly depends on those of the radio-source fluxes which typically range from $\pm 10\%$ to $\pm 15\%$ [13]. Moreover, it will allow for sensitivity validation across the overall sky coverage (varying the position of the UAV-mounted source) as well as the whole frequency band.
In order to validate the method, we are planning to perform a test campaign using a calibrated antenna.

Acknowledgments

This work has been supported by INAF through the TECNO-INAF project "Advanced calibration techniques for next generation low-frequency radio astronomical arrays" (PI P. Bolli) funded in 2014.

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