

Near-field calibration of SKA-Low stations using unmanned aerial vehicles

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Abstract—The low frequency part of the Square Kilometre Array (SKA-Low), currently in development, will need accurate calibration [1]. A self-calibration is widely used in the radio astronomy literature and allows the calibration of several SKA pathfinders. However the increased sensitivity and the very large number of antennas of the SKA-Low reduce the hope for relying only on self-calibration. Research involving artificial sources carried by an unmanned aerial vehicle (UAV) has already led to successful far-field calibrations of radio telescopes [2], [3]. In this work, we show a characterization of the embedded element patterns (EEPs) carried out in the near field on a SKA-Low station composed of 256 log-periodic antennas. Two antennas mounted on a UAV act as calibration sources. Several flight strategies are studied with uncertainties on the UAV position and attitude. Using simulations, we show that near-field calibration enables to correctly model the array pattern. An advantage of near-field calibration is the lower required altitude which reduces the covering area of the UAV flight.

Index Terms—Irregular antenna arrays, HARMONIC Polynomial (HARP) Representation, Method of Moments, Square Kilometre Array (SKA), Unmanned Aerial Vehicle (UAV).

I. INTRODUCTION

With its 130 000 low frequency antennas spread between 500 stations, the Square Kilometer Array low frequency instrument (SKA-Low) will be after completion the largest low frequency antenna array ever constructed. Yet, these high sensitivity and dynamic ranges require a calibration at a similar level: high-resolution synthesis imaging would not be possible without accurate calibration [4].

Several pathfinders of the SKA-Low are calibrated using a self-calibration procedure, i.e. without the need of an external source, but concerns with respect to a sole self-calibration of the SKA-Low have been raised early in this project [5]. This paper focuses on the characterization of the embedded element patterns (EEPs) of a single SKA-Low station using an unmanned aerial vehicle (UAV). Indeed, in order to calibrate the whole array, the EEPs of each station have to be known by the radioastronomers with the highest possible degree of accuracy. To this day, a UAV has already been used to calibrate large antenna arrays. More specifically, a micro-UAV platform has been used in [6] to characterize the Intrinsic

Cross-Polarization Ratio (IXR), to obtain Antenna Pattern of Biconical and Log-Periodic Antennas in [7] and to perform calibration and pattern characterization in [3] for the Medicina Array Demonstrator (MAD). Such a platform has also been used in [2] to characterize the AAVS0 (Aperture Array Verification System 0). These measurement campaigns have been realized in the far field (FF) with respect to the antenna array and have shown very satisfying results. However, the MAD is a 3×3 regular array and the AAVS0 is a 16-antennas non-regular array. This limited number of antennas allows the UAV to fly at a relatively low altitude (100 m), while satisfying the far-field condition. Therefore in the case of a full SKA-Low station, with 256 elements, a near-field calibration should be contemplated. Such a procedure could give satisfying results without the need of covering a vast area with the UAV, nor of flying very high. Indeed for the frequency range of the SKA-Low (50 – 350 MHz), the required height to satisfy the FF condition at the lowest frequency is 3 km.

Here, we investigate the effect on the calibrated radiation pattern due to the *a posteriori* error on the position and attitude of the UAV acting as artificial sources. Using a commercial UAV with a real-time kinematic (RTK) and inertial measurement unit (IMU), centimeter-level accuracy for the position [8] and degree-level accuracy for the attitude [9] can be reached. This study is carried out considering low altitude, i.e. in the near field (NF) with respect to the station. We also studied the impact of the UAV flight path in the calibration outcomes. For the sake of computational efficiency, we used the software HARP [10], allowing a fast computation of the EEPs of the antenna array.

The remainder of this paper is organized as follows. In Section II the fields computation using HARP is explained and the calibration coefficients are introduced. The different studied flight paths are presented in Section III. Results regarding the different flight paths are described in Section IV. Finally, conclusions are drawn in Section V.

II. MATHEMATICAL DEFINITIONS

Instead of considering the radio telescope to receive, let us study the transmitting case with the following experiment: a UAV hovers above the station and receives a pulse from a single antenna under test (AUT) with the other antennas passively terminated. Here, we consider a frequency of 140 MHz. The obtained pattern, namely the embedded element pattern of the AUT, differs from the pattern of the single isolated antenna due to coupling. We assume noisy position $\mathbf{O}_D$ and noisy attitude $\mathbf{\Omega}_D$ of the UAV, but no other transmission or measurement perturbations are included at this point in the model. Considering the UAV as a pulse receiver (instead of a pulse sender) leads to a straightforward derivation of the fields. Note that the reciprocity theorem ensures a perfect equivalence between both formulations. Assuming that the UAV is in the far field with respect to the AUT, we compute the electric field $\mathbf{E}^i$ due to the ON-antenna i at distance R_i via its EEP $\mathbf{F}^i$ as

$$\mathbf{E}^i = \mathbf{F}^i \frac{e^{-jkR_i}}{R_i} V_i^t, \quad (1)$$

where V_i^t is the voltage applied on the antenna with a Z_T series impedance. Assuming a unitary voltage source with appropriate series impedance Z_L (from the Thevenin equivalent circuit), the received voltage on the UAV dipole antenna $k \in \{1, 2\}$ at observation point $\mathbf{P} := \overline{\mathbf{O}_A \mathbf{O}_D}$ and distance R_i of the AUT i is

$$V_{i,k}^r = \frac{2\lambda Z_L}{j\eta} \mathbf{F}_k^d \cdot \mathbf{F}^i \frac{e^{-jkR_i}}{R_i} V_i^t, \quad (2)$$

where $\mathbf{F}_k^d$ stands for the radiation pattern of the UAV antenna k . The scalar product appearing in (2) is hence a projection of a vector $\mathbf{F}^i$ expressed in terms of $(\mathbf{e}_\rho, \mathbf{e}_\theta, \mathbf{e}_\varphi)$ on a vector $\mathbf{F}_k^d$ expressed in terms of $(-\mathbf{e}_\rho, \mathbf{e}_{\theta'}, \mathbf{e}_{\varphi'})$ which is easily computed in the inertial frame of reference. Summing up the contributions of all antennas in the array, we obtain the total voltage across the port of the UAV antenna k ,

$$V_k^r = \sum_{i=1}^{N_a} V_{i,k}^r, \quad (3)$$

with N_a the number of antennas. Inspecting this setup, we observe that N_a measurements are collected for every position of the UAV. This is well appreciated because we consider a calibration coefficient for the contribution of each antenna to every EEP (Section II-C). Hence in the following, the terminology *experiment* is used for the pulse transmission associated with a single UAV position, leading to N_a measurements.

A. Macro Basis Functions (MBF)

In order to obtain the antenna patterns $\mathbf{F}^i$, the method of moments (MoM) is applied to the SKALA antenna with 1218 basis functions. Using Gaussian elimination to solve the system of linear equations induced by the impedance matrix, this yields a complexity of $\mathcal{O}(N_a^3 N_b^3)$ where N_b is the number of elementary basis functions. The MBF approach enables to

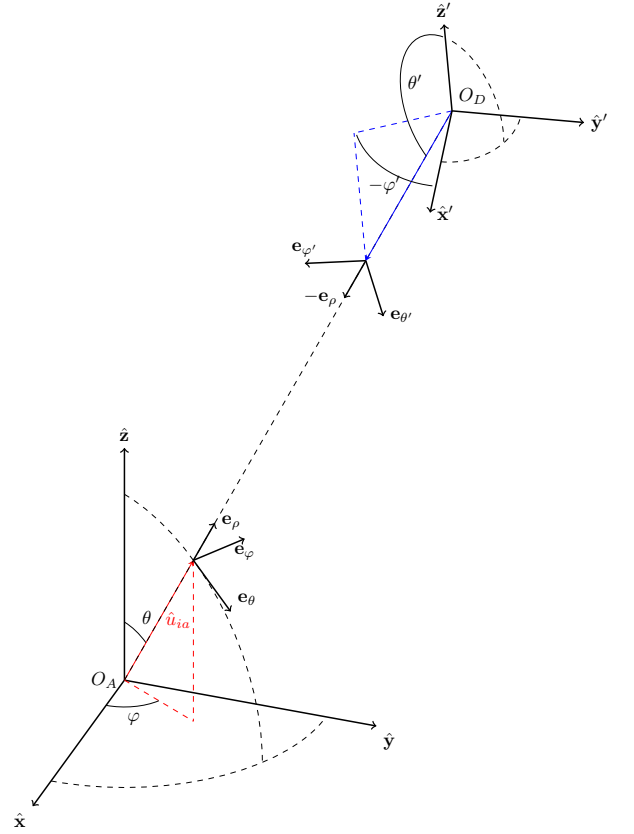


Fig. 1. Sketch of the geometry.

reduce this computational time by replacing the original set of elementary basis functions by a new set of functions, the macro basis functions, obtained through the solution of smaller problems [10], [11]. The resulting compressed problem has now a complexity of $\mathcal{O}(N_a^3 N_m^3)$ with N_m the number of MBFs. Given that $N_m \ll N_b$, this highly accelerates the method. This procedure is implemented in the HARP software [10]. In this work, $N_m = 20$ MBFs are used.

B. Pattern calculation

Using the MBF framework, the vertical-polarization component of the EEP of antenna i can be expressed as follows [10]

$$F_v^i(\theta, \varphi) = \sum_{i_m=1}^{N_m} \sum_{i_a=1}^{N_a} c f_{i_m, i_a}^i p_{v, i_m}(\theta, \varphi) e^{jk(x_{i_a} u_x + y_{i_a} u_y)}, \quad (4)$$

where (x_{i_a}, y_{i_a}) is the position of antenna i_a , (u_x, u_y, u_z) is a unit vector in the direction (θ, φ) of interest, p_{v, i_m} is the vertical-polarization component of the pattern of MBF i_m and $c f_{i_m, i_a}^i$ the coefficient for MBF i_m on antenna i_a when only antenna i is ON. One should note that every MBF is expressed in terms of the 1218 elementary basis functions.

Finally, the whole array pattern (AP) is computed as the weighted sum of the EEPs. For instance the vertical polariza-

tion is given by

$$F_v(\theta, \varphi) = \sum_{i=1}^{N_a} w_i F_v^i(\theta, \varphi), \quad (5)$$

with w_i the weight of antenna i . The weights depend on the direction of scan.

C. Calibration coefficients

Let us now introduce a complex calibration coefficient $c_{i_a}^i$ for the contribution of each antenna i_a to the EEP of antenna i . This adds up to a total of N_a^2 coefficients. The vertical-polarization component of the calibrated EEP at each testing point (θ, φ) , denoted as $\overline{\mathbf{F}}_v^i$, becomes

$$\overline{\mathbf{F}}_v^i = \sum_{i_m=1}^{N_m} \sum_{i_a=1}^{N_a} c_{i_m, i_a}^i \mathbf{p}_{v, i_m} e^{jk(x_{i_a} u_x + y_{i_a} u_y)} c_{i_a}^i. \quad (6)$$

For each ON-antenna i we solve a different optimization problem,

$$\min_{\mathbf{c}^i \in \mathbb{C}^{N_a}} \|\mathbf{F}_v^i - \overline{\mathbf{F}}_v^i\|_2^2 + \|\mathbf{F}_h^i - \overline{\mathbf{F}}_h^i\|_2^2. \quad (7)$$

This is equivalent to the minimization of the errors in both polarization energies. Minimizing the latter quantity can be viewed as a least-squares problem, for which a closed form solution exists.

D. Error definition

We define the error between the exact and modeled pattern as follows,

$$e_{\theta, \varphi} := 10 \log_{10} \left(|\mathbf{F}_v - \overline{\mathbf{F}}_v|^2 + |\mathbf{F}_h - \overline{\mathbf{F}}_h|^2 \right) - 10 \log_{10} \max_{\theta, \varphi} \{ |\mathbf{F}_v|^2 + |\mathbf{F}_h|^2 \}. \quad (8)$$

The maximum error e_M and the mean μ_e are also studied.

III. FLIGHT PATH DEFINITION

The flight path of the UAV is a parameter whose study is important in any practical experimental setup. Indeed, the battery life-time is a scarce resource. We will also show in Section IV that pattern characterization can be improved by changing the flight path. This work studies five different flight paths: spiral (S), grid (G), cuts (C), random (R) and equi-spaced (E). Figure 2 depicts the aforementioned paths. Notice that spiral, grid and equi-spaced can be achieved in a single flight while the cuts may need several flights. The random flight allows to assess whether a structured path is better than an unstructured one. Until now, all calibration campaigns of an array using a UAV have been operated using cuts-like flights [2], [7].

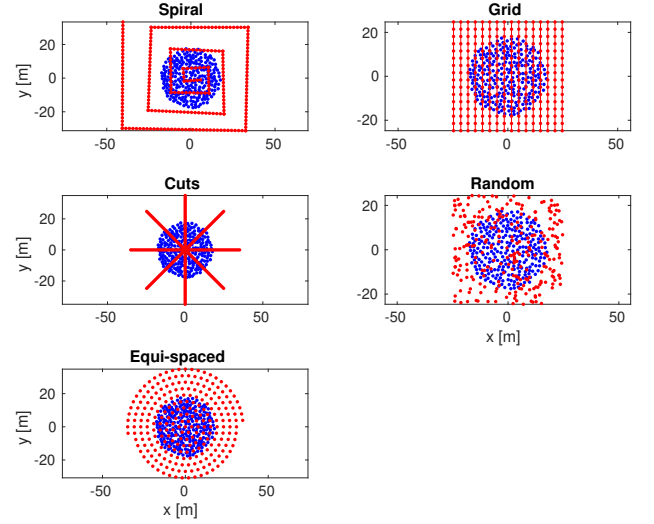


Fig. 2. Studied UAV flight strategies of a 256 antennas station (blue) with 512 experiment points (red).

IV. RESULTS AND DISCUSSION

The experimental setup is the following, let us assume a UAV flying in a plane above the station at 10 meter height following the paths defined before. Voltages are collected on both dipole antenna ports mounted on the UAV. The radiation patterns of the dipoles in the presence of the UAV platform have been obtained by solving a MoM problem in which the UAV is strongly simplified as a little square. Since real measurements are not available, a Gaussian noise on the spacial directions is firstly assumed. The standard deviation is $\sigma_e = 0.05$ m. Then a noise on the three Tait-Bryan angles (yaw, pitch and roll) with $\sigma_a = 1^\circ$ is studied.

A. Paths comparison

Figure 3 shows two cuts of the AP for a spiral flight with 2048 experiments. We observe a good agreement between the reference and computed patterns. One can observe the outcomes for several numbers of experiments in Figure 4. We see that flight types S, G, R, E follow the same pattern while type C, the cuts strategy, is less sensitive to the number of experiments. We observe that the maximum error decreases more slowly than the mean error. Besides, the cuts strategy appears to be quickly limited: an increase in the number of experiments will not improve the outcomes. This suggests either to increase the number of cuts or to select another strategy. Among the other strategies, the equi-spaced gives the best error but the difference with the three others is less than 2dB. Please notice that in (8) the dB reference is the main lobe and therefore error results should also be taken into account with the AP.

B. Noise analysis

a) *Attitude noise analysis:* The following table gathers the simulation results obtained with random unbiased Gaussian noise with standard deviations σ_y , σ_p and σ_r for yaw, pitch

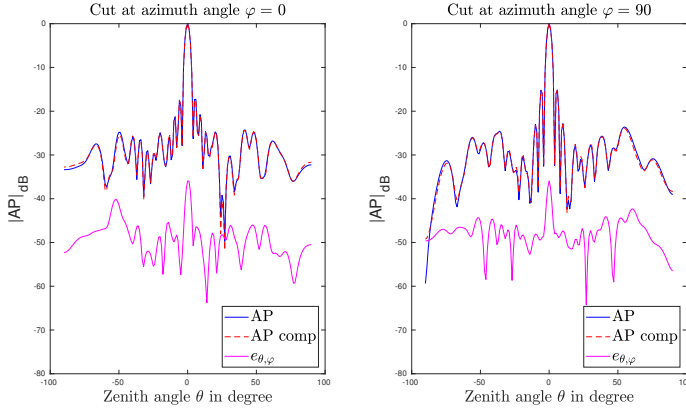


Fig. 3. Reference and computed, i.e. calibrated, array pattern.

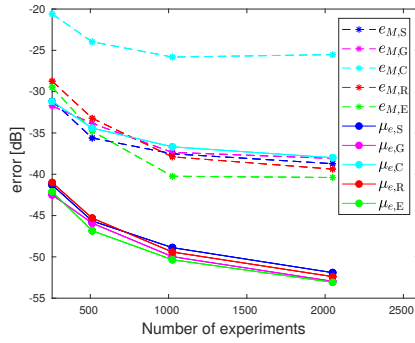


Fig. 4. Evolution of the errors for different flight strategies.

and roll angles, respectively. We observe that the error due to an inaccurate knowledge of the UAV attitude is smaller than the absolute position error. Moreover, the error is mostly carried by the yaw angle. It comes from the fact that rotating around the X-axis (pitch) only perturbs the signal received on the Y-axis, and vice-versa for the Y-axis (roll).

Max error (dB)	Mean error (dB)	σ_y	σ_p	σ_r	(degree)
-48.14	-57.38	2	2	2	
-48.46	-59.62	2	0	0	
-54.32	-65.46	0	2	0	
-54.32	-65.14	0	0	2	

Figure 5 illustrates the error rising when the knowledge on the attitude decreases. If the position is assumed to be exact, the output error and the input noise are characterized by a linear relationship in logarithmic scale. On the other hand, if the position is assumed to be inexact with fixed noise level $\sigma_e = 1$ cm, then we add a new regime: when the attitude noise ($\sigma_a \ll 1^\circ$) is dominated by the noise on position.

b) *Position noise analysis:* Careful investigation of Figure 6 shows that two regimes appear in the case without noise: a small position noise ($\sigma_e \ll 0.5$ m) gives a linear relationship in logarithmic scale but if $\sigma_e \geq 0.5$ m, there is too much noise in the system and the error soars. Besides, adding a fixed noise level on the attitude also adds a third regime.

c) *Full noise analysis:* Finally, we observe that the noise affecting mostly the system is the noise on position. Indeed,

even if the attitude noise has the worst behaviour – it rises with ~ 30 [dB/dec] compared with ~ 20 [dB/dec] in the other case – the fact that it begins far below implies that it barely catches up the position noise. Moreover, we can conclude that no undesired coupling effect emerges when both noises are considered together. They sum up and henceforth, only the largest is significant.

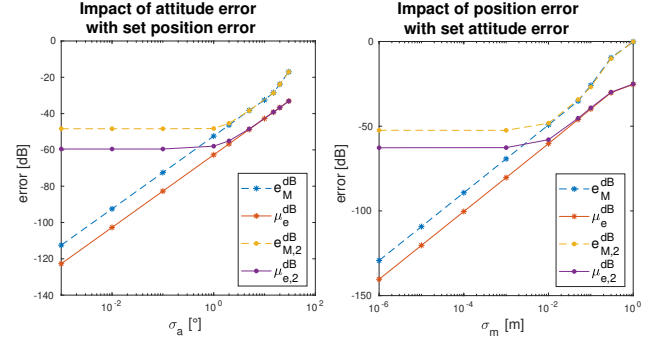


Fig. 5. Error versus noise level on attitude with fixed position noise level. Spiral flight with 512 points. Index "2" stands for inaccurate position knowledge: $\sigma_{e,2} = 1$ cm.

C. Computational time

Computational efficiency is also a target of this work since the very high number of antennas in the SKA slows down any computation. This justifies the use of HARP; this tool is faster than alternative commercial software, as it relies on pre-computation of interactions between MBFs [10]. These computations should be processed for each frequency, but this must be done once and for all. We therefore do not include this pre-computation time because it is negligible from a calibration point of view: if the array is calibrated once a month, this pre-computation investment is very quickly returned. In this work, two time-consuming parts emerge: first, creating the MBF patterns $\mathbf{p}_{i_m}$ and second, solving the N_a optimization problems. Both of these tasks have a great parallelization potential and, therefore, the utilization of a cluster with up to N_a processors is highly recommended. The initial computation time on a single processor is 86 minutes with 1048 experiment points and could be reduced to 6.8 minutes with 28 processors, hence leading to a speedup ratio of 12 and a parallel computing efficiency of 0.42.

V. CONCLUSION

We described a method to characterize the array pattern of a SKA-Low station using a UAV. In order to test the method, we simulated fields measurements at noisy positions and attempted to reconstruct the embedded element patterns. The patterns obtained from noisy fields are consistent with the reference patterns and we showed that the use of cuts flight strategies should be avoided. A near-field approach, in comparison with a far-field approach, is better in the sense that the lower altitude allows to cover smaller distance and yet

sample properly the patterns. On the other hand, the relative error on position is much weaker at high altitude. This is not true for the attitude error. Although this paper focuses on the SKA-Low, this procedure can be applied to any antenna array. Future works may involve the extension of the model, e.g. by taking into account the finite ground plane effect [12], as well as a validation of the method using real measurements.

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