Improving the accuracy of a model-based approach for the near-field measurement of antenna arrays with UAVs

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***Abstract*—We improve the accuracy of a technique developed in [1] for the evaluation of the embedded element patterns from near-field measurements taken with a source mounted on an unmanned areal vehicle. The method relies on a reduced model of the current distributions induced on the array using a collection of current modes. This approach potentially allows for a smaller number of measurement samples than classical transformation techniques. We present here a new set of measurement equations obtained by substituting a multipole decomposition into the Lorentz reciprocity theorem. A numerical experiment including an array of 16 log-periodic antennas and a quadcopter shows that, with this formulation, the numerical accuracy of the near-field link between the drone and these modal currents is improved and that the values of the embedded element patterns are reproduced to almost 2 digits at intermediate-field distances.**

***Index Terms*—antenna arrays, measurements, plane-wave spectrum, multipoles, calibration, Unmanned Areal Vehicle**

I. Introduction

In [1], a model-based approach has been proposed for the calibration of non-regular arrays. The goal consists of reproducing the embedded element patterns (EEPs) as patterns radiated by a limited set of modal currents on the excited elements, as well as on all neighboring elements (the neighborhood can include the whole array). From a numerical perspective, the modal currents are described as Macro Basis Functions (MBFs) [2]. The problem is looked at from the perspective of transmitting array antennas; reciprocity trivially provides the patterns of the receiving elements. For excitation at any port of the array, the near-fields produced by all MBFs on all elements contribute to the voltage observed at the receiving antenna on the drone. Considering at least as many positions for the drone as there are MBFs defined on the whole array, this leads to a linear system of equations that provides the amplitude factor associated to each MBF. A more accurate representation of the near-field link between array antennas and drone contributes to a better estimation of the embedded element patterns. Another point of attention is the conditioning of the system of equation. To avoid conditioning issues, the number of MBFs defined on each antenna should be kept to a minimum, which scales with the size of the antenna in wavelengths. This point has been tackled in [1] but is not handled here. In this paper, we will derive a new set of measurement equations which estimate the near-field interactions more accurately and we will show through a numerical expirement that the EEP is then reconstructed more precisely when the Unmanned Areal Vehicle (UAV) is flying in the close vincinity of the array.

II. Mathematical formulation of the measurement problem

The measurement scenario, sketched in Fig. 1, consists of two sources of polarization $p = \{X, Y\}$ mounted on a UAV located above an array of N_a passive antennas. The objective is to evaluate the EEP $\mathbf{f}_{e,n}$ of antenna n from the measured voltages v_{np} appearing at the input of its amplifier when source p is transmitting in the near/intermediate-field region of the array. We assume that the orientation and position of the UAV are known and that the isolated radiation patterns $\mathbf{f}_{s,p}(\hat{\mathbf{u}})$ of the sources have been measured beforehand.

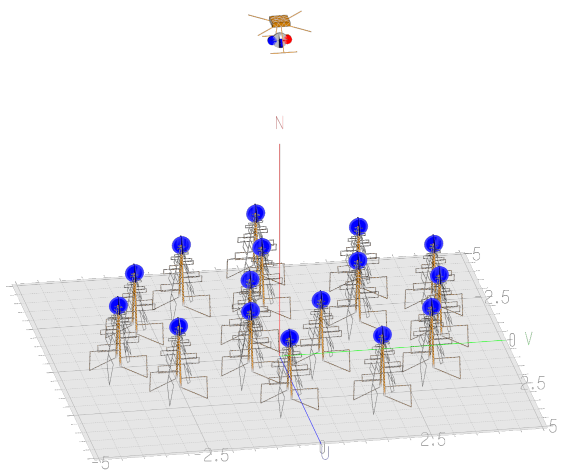


Fig. 1. A dual-polarized source mounted on a UAV flying over an irregular array of 16 SKALA2 antennas.

Using Lorentz's reciprocity theorem, the voltage v_{np} can be expressed [4] as

$$v_{np} = -r_n \iint_{S_a} \frac{\mathbf{J}_n}{i_n} \cdot \mathbf{E}_{s,p} \, \mathrm{d}S_a \tag{1}$$

where the surface S_a envelops the N_a PEC antennas of the array, $r_n = Z_{L,n}/(Z_{a,n} + Z_{L,n})$ with $Z_{a,n}$ the input impedance of antenna n and $Z_{L,n}$ the input impedance of the amplifier, the electric field $\mathbf{E}_{s,p}$ is scattered by currents on the UAV when source p is active and the current distribution $\mathbf{J}_n$ is induced when a current source i_n is connected to antenna n. If we now neglect the coupling between the drone and the array then the radiation pattern of the current distribution $\mathbf{J}_n$ corresponds to the EEP $\mathbf{f}_{e,n}$ when $i_n = 1/(Z_{a,n} + Z_{L,n})$ [5].

The model-based approach [1] decomposes $\mathbf{J}_n$ into a superposition of known modal currents defined on the excited element n and neighboring antennas. In this paper, we consider only one mode $\mathbf{J}_n^m$ per antenna m s.t. we have $\mathbf{J}_n = \sum_{m=1}^{N_a} c_n^m \, \mathbf{J}_n^m$. The unknown coefficient c_n^m must be solved for and account for a deviation of $\mathbf{J}_n^m$ from the real current existing in the field on antenna m when antenna n is active. Substituting this expansion of $\mathbf{J}_n$ into (1) allows us to write

$$v_{np} = \sum_{m=1}^{N_a} c_n^m v_{np}^m \tag{2}$$

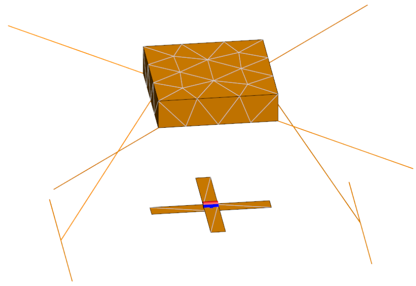
where the partial voltages v_{np}^m are obtained by replacing $\mathbf{J}_n$ with $\mathbf{J}_n^m$ in (1). By analogy with a method-of-moments equation, the right-hand side of (1) can be viewed as an integral reaction testing the field $\mathbf{E}_{s,p}$ against the current $\mathbf{J}_n$. This type of integral can be formulated in the angular domain using the multipoles decomposition of the Green's function [8] s.t. we re-express the partial voltage [6] as

$$v_{np}^m = \frac{Z_{L,n}}{\eta} \iint_{\Omega} \mathbf{f}_{e,n}^m(\hat{\mathbf{k}}) \cdot \mathbf{f}_{s,p}(-\hat{\mathbf{k}}) T(kr_{sn}, \hat{\mathbf{k}} \cdot \hat{\mathbf{r}}_{sn}) \, d\Omega \tag{3}$$

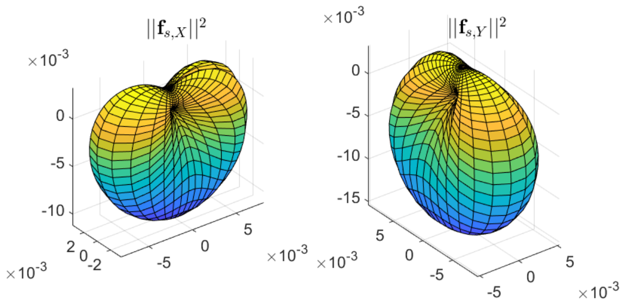
where k is the wavenumber, η is the free-space impedance, $\hat{\mathbf{k}}$ is unit direction over the sphere Ω, $\mathbf{r}_{sn} = r_{sn}\hat{\mathbf{r}}_{sn} = \mathbf{r}_s - \mathbf{r}_n$ is the vector distance between the center $\mathbf{r}_n$ of antenna n and the center $\mathbf{r}_s$ of the drone and T is the translation operator [8]. The center of the antenna m is taken as phase reference to compute the unitless partial pattern $\mathbf{f}_n^m$. Note that, since we assumed no coupling with the drone, the isolated pattern $\mathbf{f}_{s,p}$ can be inserted directly into (3).

III. Numerical Results

We consider a numerical example with a quadcopter flying over a pseudo-random array of 16 log-periodic antennas (SKALA2, [7]) placed on top of an infinite PEC ground plane. The 1m-wide frame of the UAV is entirely modeled with a PEC material and carries two small orthogonal plate dipoles. The geometrical model of the UAV and the isolated patterns $\mathbf{f}_{s,p}$ of the sources are shown in Fig. 2. We look at a particular element located on the bottom right edge of the antenna array. The frequency is set to 175 MHz and the wavelength is $\lambda = 1.7$m. The current modes $\mathbf{J}_n^m$ as well as their associated patterns $\mathbf{f}_n^m$ are computed using the FEKO commercial software [9]. The order of the translation function is set to 10 and thus the number of integration points for the computation of the angular integrals (3) is 11×21. In the following figures, the voltages v_{np} are expressed in dBV and are obtained when the UAV antennas are fed with a unit voltage. The radiation patterns have been normalized w.r.t. their maximum value.



(a)



(b)

Fig. 2. Geometrical model of the UAV (a) and normalized power patterns of the source (b).

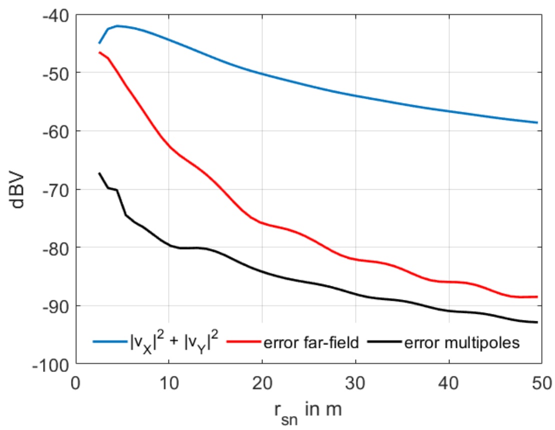


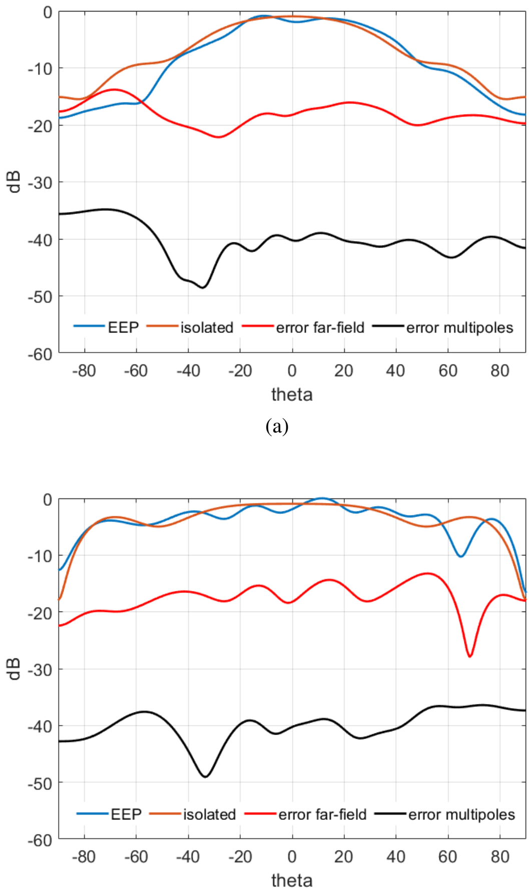
Fig. 3. Received voltages (blue) and absolute errors when using the mulipoles formulation (black) and the far-field formulation in [3] (red) assuming a radial path centred on the array.

In the first case, we test the accuracy of formula (3) as function of the distance from the array. The coefficients c_n^m are assumed known s.t. the voltage v_{np} can be assembled from (2) without errors. The reference solution for v_{np} is simulated with FEKO and accounts for the drone-array coupling. Fig. 3 illustrates the voltage sum $|v_X|^2+|v_Y|^2$ as function of relative distance r_{sn} when the UAV is following a path pointing straight up above the array center and starting at 0.4λ from the antenna tops. One can see that, for instance at $r_{sn} = 10$m, the absolute error when using equation (9) in [3] based on a far-field approximation is -18 dB while it is reduced to -36 dB when the multipoles-based formulation (3) is implemented. This corresponds to a gain of 1 digits of accuracy on the voltage v_{np}. The difference between the two approaches then seems to attenuate as r_{sn} increases.

In the second case, the coefficients are unknown and must be found by building a system of measurement equations using (2) and then inverting it [1]. The drone is now hovering in a plane of side length 8m parallel to the array at 8m above the ground. The voltages v_{np} are measured when the UAV is positioned on the nodes of a 10×10 grid. The EEP and the isolated pattern are shown in Fig. 3. The amplitude of the ripples caused by the mutual coupling is around 2dB. Again, one can observe that the absolute errors are about -15 and -40 dB near zenith for the two computation methods. Hence, in this example, we are able to estimate the EEP with one more digit using the formulation (3).

IV. Conclusion

We have proposed a multipole-based method to compute the near-field interactions between the drone and the current modes appearing in the model-based approach [1]. The accuracy of the EEP reconstruction can be improved by one digit at close intermediate-field distances from the array. In this method, the amplitude and the phase of the drone patterns must be precisely measured in an isolated environement beforehand and the position and the orientation of the drone must be known accurately during the flight.



(a) (b)

Fig. 4. E-plane (a) and H-plane (b) cuts of the reconstructed EEP (blue), the isolated pattern (orange), the absolute errors using the far-field approximation (red) and the multipole expansion (black).

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