An overview of Beam Modeling Techniques for Future Radio Telescopes

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An Overview of Beam Modeling Techniques for Future Radio Telescopes

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I. INTRODUCTION

The quality of the images produced by future radio telescopes will be limited by how accurately direction-dependent effects can be calibrated for [1]. This includes calibrating for the full polarization antenna pattern over a wide angular region, as polarization leakage and radio sources in the sidelobe region may become significant due to the high dynamic range specifications of these instruments. Temporal variation of the system properties dictates that the instruments are characterized at the time of an observation. In order to prevent substantial parameter drift during such a characterization and the subsequent observation, measurement of the radiation pattern on a direction-by-direction basis is not feasible, and the pattern has to be determined through a small number of measurements. This requires a compact parametrized representation of the beam pattern in which only a few unknown parameters need to be solved [2].

Recently a number of methods to address this requirement have been reported and shown to be able to model antenna beam patterns with a high degree of accuracy [3]–[5]. This contribution presents an overview of the latest developments of the various approaches.

II. PATTERN MODELS

The desired form of the beam pattern model can be expressed as [2]

$$\tilde{M}_{pq}(\theta,\phi) = \sum_{i=1}^{N} \alpha_{ipq} f_{ipq}(\theta,\phi) \tag{1}$$

in which $\tilde{M}_{pq}$ is an element in the estimated 2×2 direction-dependent gain Jones-matrix $\tilde{\mathbf{M}}$ for the antenna that measures the reception of a q-polarized signal by a nominally p-polarized receiver, $\{f_{ipq}\}$ is a set of basis functions used to model the corresponding gain function, and $\{\alpha_{ipq}\}$ are the unknown coefficients that need to be estimated. The objective is to minimize the error between the actual gain $\mathbf{M}$ and the estimated gain $\tilde{\mathbf{M}}$ using the least number of terms N in (1) through an appropriate choice of basis functions.

A. Jacobi-Bessel series

The JB-series solution for reflector antenna patterns [6] presents a set of analytic basis functions suitable for compact representation as in (1)

$$\left\{ \begin{array}{c} g^{c}_{n,m}(\theta,\phi) \\ g^{s}_{n,m}(\theta,\phi) \end{array} \right\} = \frac{J_{n+2m+1}(ka\sin\theta)}{ka\sin\theta} \cdot \left\{ \begin{array}{c} \cos n\phi \\ \sin n\phi \end{array} \right\}$$
$$n,m = 0,1,2,\ldots \tag{2}$$

where J_x is the xth order Bessel function of the first kind, k is the free-space wavenumber, and a is the antenna aperture radius. Ensuring efficient summation in (1) requires selecting the dominant basis functions from (2) for a particular antenna pattern, as shown in Fig. 1.

B. Characteristic Basis Function Patterns

Using this approach a number of basis functions f_{ipq} are created through numerical simulation or measurement under various operating conditions which are chosen such that the obtained basis functions span the space of expected patterns [4]. This procedure ensures that fine features in the beam patterns that are unique to the specific antenna design are accurately modeled with a single primary basis function. Deviations of the beam pattern from this ideally expected pattern are then accurately modeled through only a few higher-order basis functions, as shown in Fig. 2.

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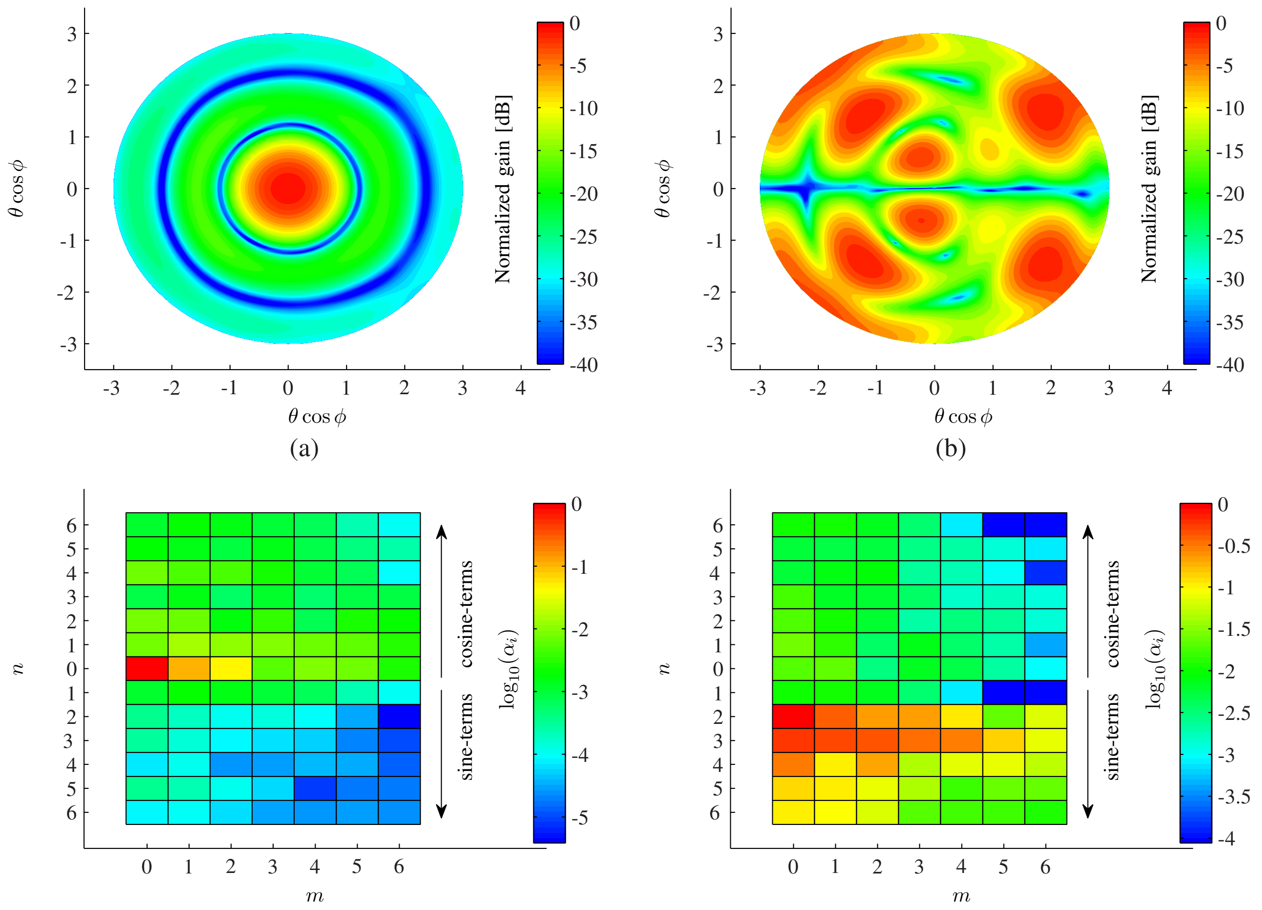
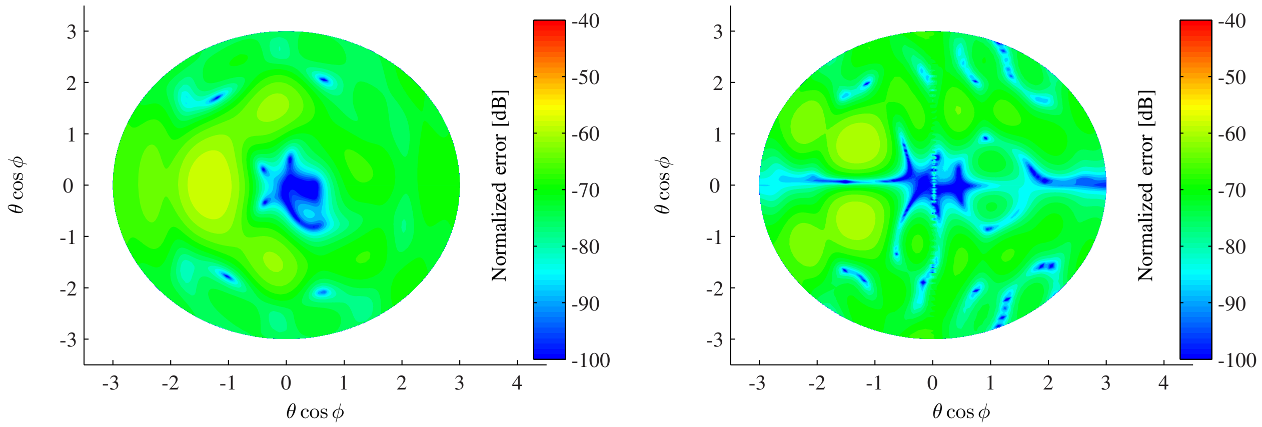


(a) (b) (c) (d)

Fig. 1. Co- and cross-pol patterns of a PAF-based offset Gregorian reflector antenna are shown in (a) and (b), respectively. The patterns are expanded using the JB-series basis functions of (2) and the magnitudes of the coefficients are shown for the (c) co-pol, and (d) cross-pol patterns. The cosine-term with $m, n = 0$ is seen to be the dominant component of the co-pol pattern, whereas higher-order sine-terms are dominant in the expansion of the cross-pol pattern.



(a) (b)

Fig. 2. Normalized error in the (a) co- and (b) cross-polarized component of a pattern model employing 9 CBFPs to approximate the beam pattern of an offset Gregorian reflector antenna which is subject to feed and subreflector positioning errors.