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Analysis of RATAN-600 Radio Telescope Antenna Using the MLPO Algorithm

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Abstract—A fast and adaptive near-field physical optics algorithm is developed for the analysis of general multi-reflector antenna systems. The algorithm is applied to the radiation pattern computation of an extremely large antenna of RATAN-600 radio telescope operating at mm-wave frequencies.

I. INTRODUCTION

The RATAN-600 antenna is a multi-reflector system characterized by very large electrical dimensions. The optical scheme of the “South sector primary reflector + Flat reflector” antenna system as well as the enlarged geometry of the secondary and tertiary (auxiliary) reflectors of RATAN-600 radio telescope are shown in Fig. 1.

Analysis of such systems at mm-wave frequencies presents a substantial computational challenge since various reflectors measure thousands of wavelengths in size. This is especially true when repeated evaluation of the radiation patterns is required for antenna geometry optimization with multiple primary sources, for example, when employing a 10×10 focal array feed. Until recently, this quasi-optical system has been mainly analyzed using Geometrical Optics (GO)/ray-tracing techniques combined with the aperture integration method [1]. For this system, even the use of GO requires substantial computational resources. On the other hand, GO analysis does not provide sufficient information on near-field diffraction effects and other wave related phenomena. Also, the aperture integration method may only be used for calculating the main beam and the nearest sidelobes. At this stage, the use of numerically rigorous integral or differential equation-based techniques that could address these concerns for problems of such large dimensions is still out of reach of existing computers.

In this context, the Physical Optics (PO) approximation appears to strike the balance between the computational feasibility and accuracy requirements while still requiring excessively long computation times in its straightforward implementation. To that end, we adapt the Multilevel Physical Optics (MLPO) algorithm [2] for the computation of the radiation characteristics of the RATAN-600 antenna as will be described below.

II. MLPO ALGORITHMIC DEVELOPMENTS

The MLPO algorithm originally presented in [2] is based on the observation that small radiating apertures produce smooth radiation patterns, which can be sampled on very coarse grids and fully reconstructed by interpolation. Thus, the MLPO algorithm starts with a hierarchical decomposition of radiating surfaces into small patches, whose radiation patterns can be described on a coarse grid. Each of these patterns is interpolated in a patch-centered coordinate system allowing for slow phase variation of the fields. After translation to a common coordinate system, the field patterns of neighboring patches can be aggregated resulting in the radiation pattern of a larger patch. This sequence of operations is repeated until the pattern of the whole radiating surface is obtained.

This algorithm provides orders of magnitude acceleration of the PO integral evaluation, because it reduces the computational complexity from $O(N^4)$ to $O(N^2 \log N)$ ($N = kR$, with R the radius of the smallest circumscribing sphere and k the wavenumber). The MLPO algorithm achieves a computational efficiency similar to that of the FFT-based algorithms, while not being subject to their limitations (uniform sampling on planar apertures). The algorithm has been further developed in [3] by introducing a near-field (NF) version of the MLPO algorithm to analyze dual reflector antennas.

The following extensions of the original MLPO scheme are being developed to facilitate the analysis of the RATAN-600 antenna:

- a) Generic multi-reflector computational scheme is developed for sequential propagation between the reflectors and aggregation of the radiation patterns produced by all system components.
- b) The multilevel decomposition scheme is modified to allow for adaptive decomposition along dimensions that are substantially different in their sizes.
- c) The computational sequence is parallelized in two ways: (1) under MPI for distributed memory clusters and (2) for graphic Processing Units (GPUs).
- d) Large electrical dimensions lead to a large number of interpolation and aggregation levels incurring gradual error

accumulation. To that end, error levels are verified in the computational sequence.

These extensions make the MLPO algorithm adaptive to arbitrary shaped multi-reflector antennas of very large dimensions.

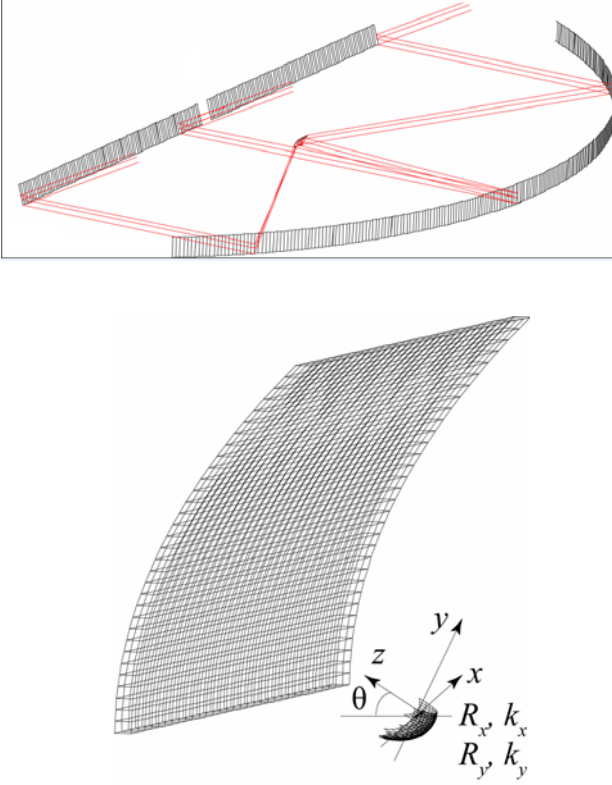


Fig. 1 RATAN-600 radio telescope antenna: (a) Optical scheme of the “South sector primary reflector + Flat reflector” antenna system and (b) geometry of the secondary and tertiary reflectors.

III. NEAR-FIELD MLPO APPROACH

The analysis of multi-reflector antenna system is conventionally performed by a successive propagation of the fields between the reflectors followed by the evaluation of the total radiation pattern. While the latter step can be performed via the conventional MLPO algorithm [2], here we focus on the field propagation between the reflectors. As a representative step in such computation, consider the field propagation from a reflector surface S' to the surface of the following reflector surface S . We assume that the reflector surfaces are sufficiently smooth and perfectly conducting. Harmonic time dependence $e^{j\omega t}$ is assumed and suppressed (with the corresponding wavenumber $k = \omega/c$). We assume that the antenna can be circumscribed by a sphere of radius R . In the following complexity analysis, we use $N = kR$ as a large parameter implying that linear dimensions of all antenna elements, viz. the reflectors, are proportional to R . We also assume that the magnetic field incident on S' , denoted $\mathbf{H}'(\mathbf{r}')$, $\mathbf{r}' \in S'$, is known. Then, the magnetic field reflected

by S' and incident upon S can be approximately computed via the PO integral

$$\mathbf{H}(\mathbf{r}) = \int_{S'} \mathbf{h}(\mathbf{r}, \mathbf{r}') \frac{e^{-jk|\mathbf{r}-\mathbf{r}'|}}{|\mathbf{r}-\mathbf{r}'|} ds' , \quad \mathbf{r} \in S \quad (1)$$

where

$$\mathbf{h}(\mathbf{r}, \mathbf{r}') = -\frac{jk}{2\pi} \hat{\mathbf{r}} \times (\hat{\mathbf{n}}(\mathbf{r}') \times \mathbf{H}'(\mathbf{r}')) \left(1 + \frac{1}{jk|\mathbf{r}-\mathbf{r}'|} \right) \quad (2)$$

Here, $\hat{\mathbf{n}}(\mathbf{r}')$ denotes the unit normal vector at point \mathbf{r}' , and $\hat{\mathbf{r}} = (\mathbf{r} - \mathbf{r}')/|\mathbf{r} - \mathbf{r}'|$ is a unit vector pointing from the source to observation point.

The number of quadrature points needed for a numerical evaluation of integral (1) over S' is proportional to its area normalized to the wavelength squared. Thus, the number of integrand evaluations in (1) is of $O(N^2)$. In order to facilitate subsequent propagation of the field reflected by S and evaluation of the radiation pattern, the number of observation points \mathbf{r} on S should also be of $O(N^2)$. Consequently, the complexity of direct computation of the field over S via (1) is of $O(N^4)$.

The complexity of evaluating the PO integral over S' for a set of quadrature points on S can be reduced from $O(N^4)$ to $O(N^2 \log N)$ by the use of the NF-MLPO algorithm. This algorithm is based on a hierarchical decomposition of the source domain S' into small patches (subdomains), whose radiated fields can be described on coarse grids of observation points on S . To obtain the total field, we aggregate the subdomain partial fields through a multilevel interpolation process to obtain the desired total field. The interpolation is based on the smoothness properties of the phase and amplitude compensated fields produced by sources that are confined to bounded subdomains.

Let \bar{S} denote a generic subdomain of S' . We now consider the magnetic field $\bar{\mathbf{H}}(\mathbf{r})$ produced by \bar{S} , i.e. defined by (1) with the integration domain restricted to \bar{S} . When observed over S , $\bar{\mathbf{H}}(\mathbf{r})$ comprises rapid oscillations, which are mainly caused by the phase factor in the integrand in (1). Towards approximate removal of the rapid variations of the field, we define a phase and amplitude compensated field

$$\tilde{\mathbf{H}}(\mathbf{r}, \bar{\mathbf{r}}) = \tilde{r}(\mathbf{r}, \bar{\mathbf{r}}) e^{jk\tilde{r}(\mathbf{r}, \bar{\mathbf{r}})} \bar{\mathbf{H}}(\mathbf{r}) \quad (3)$$

where $\tilde{r}(\mathbf{r}, \bar{\mathbf{r}}) = \sqrt{|\mathbf{r} - \bar{\mathbf{r}}|^2 + \bar{R}^2}/2$ as described in [4]. Here, $\bar{\mathbf{r}}$ and \bar{R} denote the center and the radius of the smallest sphere circumscribing \bar{S} . Thanks to the smoothness of $\tilde{\mathbf{H}}(\mathbf{r}, \bar{\mathbf{r}})$ versus observation point \mathbf{r} , this phase and amplitude compensated field can be computed over a coarse grid of points on S . Note that the required density of the grid is

roughly proportional to the subdomain size [4]. In the process of multilevel field computation the fields of smaller "children" subdomains are aggregated into fields of larger "parent" subdomains. To that end, the field can be computed on a denser grid of points corresponding to the parent subdomain of \bar{S} using a local interpolation. Following the interpolation, the phase and amplitude can be restored to obtain the partial field of subdomain \bar{S} :

$$\bar{H}(\mathbf{r}) = \frac{e^{-jk\bar{r}(\mathbf{r},\bar{\mathbf{r}})}}{\bar{r}(\mathbf{r},\bar{\mathbf{r}})} \tilde{H}(\mathbf{r},\bar{\mathbf{r}}) \quad (4)$$

Now the partial fields of children subdomains can be combined to obtain the field of their parent. This process comprising phase compensation, interpolation, aggregation, and phase restoration is repeated until the total field $H(\mathbf{r})$ produced by the whole of S' is obtained. The computational sequence involves $O(\log N)$ each requiring $O(N^2)$ floating point operations, thus, leading to the desired $O(N^2 \log N)$ complexity.

IV. NUMERICAL RESULTS

Radiation patterns of the multi-beam RATAN-600 antenna obtained using the adaptive NF-MLPO algorithm will be presented at the conference in comparison with the ones calculated by the combined GO-aperture integration method.

Partial results are shown below for a simplified antenna scheme. A parabolic cylindrical sub-reflector, equivalent to the secondary and tertiary reflectors shown in Fig. 1, is illuminated by a Gaussian feed modelled as a complex point source. The equivalent current distribution obtained on the sub-reflector surface is presented in Fig. 2. The near field MLPO algorithm is used to compute the magnetic fields radiated by those currents on the "main" reflector surface, namely the South sector primary reflector shown in Fig.1. The sub-reflector horizontal (along the x -axis) and vertical (along the y -axis) dimensions are 8.2 m and 5.5 m, respectively. The computations were performed for an operating wavelength $\lambda = 8$ mm. The radius R of the smallest sphere circumscribing the reflector is more than 600λ . The number of decomposition levels in the multilevel procedure was taken equal to 10, leading to circumscribing sphere radii \bar{R} for the sub-domains obtained after 10 subdivisions ranging between 0.6λ and 0.75λ . A Gaussian quadrature involving 6 points along each variable was used for integration on these sub-domains.

The angular dimensions of the main reflector surface, viewed from the sub-reflector, are roughly of 1.5° in elevation and 60° in azimuth. The number of points on the main reflector surface used to sufficiently describe the field radiated by the small sub-domains was taken equal to 21 along the horizontal axis, x , and to 6 along the vertical axis, y (including extra points used for interpolation). Fig. 3 shows the magnetic field magnitudes obtained on the main reflector surface after multilevel aggregation. On a single Intel X5472 @ 3.0GHz processor, this computation took about one hour.

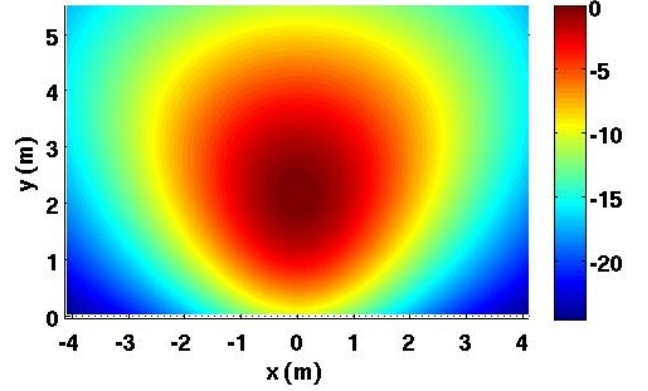


Fig. 2 Equivalent current norm on the subreflector surface.

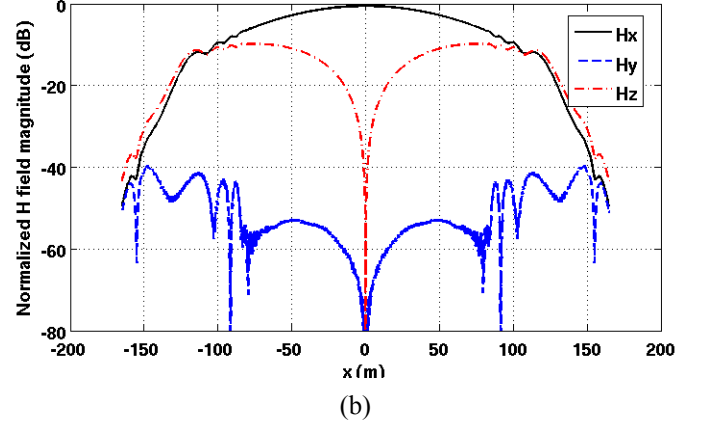
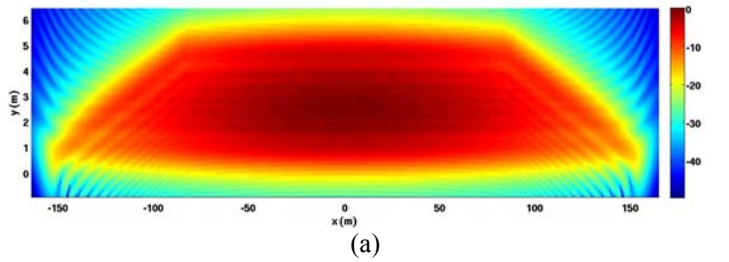


Fig. 3 Magnitude of the magnetic field on the main reflector surface: (a) projection on the local xy -plane and (b) Cartesian components along a horizontal line at $y = 2.75$ m (mid-height).

V. CONCLUSION

The near-field MLPO algorithm has been developed and applied to a multi-reflector antenna. The algorithm accuracy and computational efficiency have been tested on the case of 3D pattern computations for the very large RATAN-600 antenna.

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