Toward Electronically Reconfigurable Rims for Reflectors in Radio Astronomy

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Abstract

This paper presents full-wave simulation results of a reflector-reflectarray hybrid antenna used as a spatial beamformer for mitigating interference in radio astronomy applications. Such antennas employ fixed reflectors with electronically tunable reflectarray along their rim to dynamically form nulls in the direction(s) of interferer(s). Results from realistic models of such antenas demonstrate their potential in producing nulls and potentially effectiveness in mitigating interference from satellites with the field of view of the instrument.

1 Introduction

Reflector antennas are workhorses in radio astronomy, playing an important role in measurements of various radio sources in the universe. Terrestrial telescopes are subject to significant amounts of radio frequency interference (RFI), including potential interference from satellites within or close to the field of view of the instrument. GNSS satellites have been shown to be significant sources of RFI in astronomical measurements in the L-band [1], and the recent expansion of LEO constellations poses a significant RFI mitigation challenge.

RFI in astronomical measurements can be mitigated using a number of strategies, such as blanking, adaptive cancellation and spatial filtering [2]. In particular, spatial filtering uses beamforming techniques at the antenna to form null(s) in the direction of interferer(s) to prevent reception of interference before it enters the receiver chain, which is the approach adopted in this paper.

2 Reconfigurable Rim Concept and Implementation

The proposed concept revolves around treating the rim at the edge of a reflector antenna (such as a paraboloidal reflector) with an electronically reconfigurable reflectarray comprising unit cells placed along the periphery of the reflector. Using only a small fraction of the reflector's overall area, the reflectarray can be phased such that the scattering from the rim interferes with that from the main reflector to produce nulls in pre-selected directions in the vicinity of the main beam [3]. The pace of development in reconfigurable reflectarrays, especially experimental demonstrations [4], indicate strong potential in exploiting electronically reconfigurable reflectarrays for this purpose.

Initial demonstration of this concept was demonstrated using physical optics approximations of the reflector and corresponding rim, whereby induced surface currents on the rim were modified in terms of their phase, in order to simulate the effect of electronically manipulating the same in an actual reflectarray configuration. In this paper, we demonstrate the first step towards realizing an actual treated reflector, by demonstrating full-wave simulation results of a parboloidal reflector integrated with an actual reflectarray, albeit a passive one at this stage. In addition to demonstrating the feasibility of a more realistic implementation, this study can be used to anticipate the needs of reflectors realized in this way in the future.

The reflector under study is a paraboloidal reflector similar to the previous study [3], except the f/D ratio is set to 1 instead of 0.4. The reflector is axisymmetric and fed from the prime focus position. The system is designed to work at 1.5 GHz near the protected radio astronomy bands. The reflectarray occupies a flat, annular region of width w extending outward from the reflector edge and normal to its axis, as shown in Figure 1. In this study, the overall reflector diameter is 18 m, with the inner reflector having a diameter D_r such that the total diameter of the composite reflector is $D = D_r + 2w = 18$ m. With the reflector's vertex at the origin, the reflectarray lies in the plane $z = (D_r/2)^2/(4f)$, where the focal length is $f = D$.

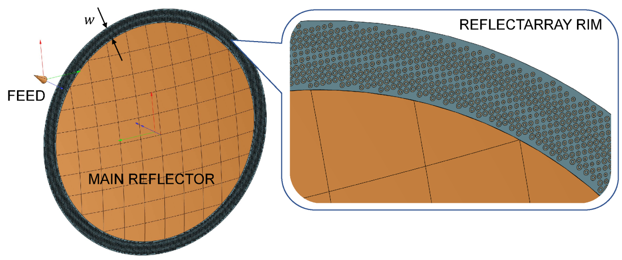

Figure 1. Reflector with Reflectarray Rim

The reflectarray unit cell is based on circular loop-shaped elements shown in Figure 2. Rings were selected due to their isotropic response and low sensitivity to angle of incidence. The cell period is $a = b = 0.1$ m. The elements themselves are printed on a 3 mm thick Rogers 5880 substrate ($\varepsilon_r = 2.2$), where dielectric and conductor losses are ignored for the initial analysis. The loop width is fixed at $t = 0.02$ m. The loops in this study are surrogates for reconfigurable cells in which the phase of the scattered field from each loop can be varied using varactor diodes or switches. For example, varactors can be integrated with loop-based cells to provide good phase characteristics, even over multiple bands [5].

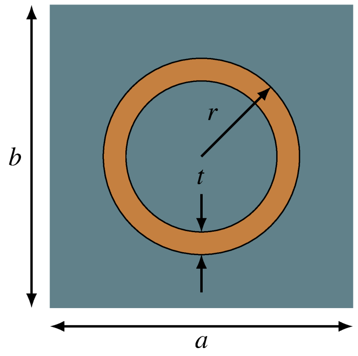

Figure 2. Reflectarray unit cell

To provide a range of phase shifts for null-forming, the outer radius r of the loop is swept from $0.025 - 0.045$ m in order to provide the phase curve. This configuration provides approximately 350° of phase range with a usable phase slope about resonance that can be used for selecting cells for the specific phase requirements in null-forming process. The cell radii comprising the rim are used as the degrees of freedom in the null-forming process.

3 Full-Wave Simulation Results

To validate the configuration, full-wave simulations are carried out in TICRA Tools 22.0 for analyzing the reflector (using GRASP) and quasi-periodic reflectarray surface (using the QUPES tool in TICRA) portions of the system. As a reference point, a standard 18 m paraboloidal reflector with the same characteristics described in Section 2 is simulated to establish baseline charateristics. The reflector is fed using a Gaussian feed establishing a -11 dB edge taper at the periphery of the reflector. The gain curve of this reflector is included in Figure 3. The reference reflector exhibits a gain of 48.1 dBi with 80.6% aperture efficiency. Next, the hybrid reflectarray-reflector combination in Figure 1 is analyzed.

The reflectarray rim width w plays an important role in the ability of the reflectarray to synthesize nulls in the radiation pattern of the entire system. If the rim is too narrow, there are insufficient reflectarray elements to produce a scattered field with sufficient strength to cancel fields produced by the main reflector in the vicinity of the main beam. From Figure 3, the peak gain outside the main lobe is 21.8 dBi. It is found that a minimum rim width of $w = 1$ m is required to provide sufficient scattered field to cancel the maximum fields seen outside the main lobe in Figure 3. This produces a reflectarray rim comprising 4,660 elements.

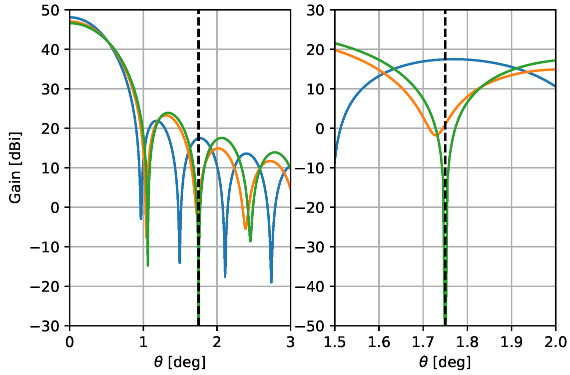

Figure 3. Simulated gain in the $\phi = 0°$ plane of various reflector configurations (left) with a zoomed-in region around the null (right). Legend: Reference 18 m reflector (blue); reflector with $w = 1$ m (orange) and $w = 1.25$ m (green)

Next, the reflectarray portion is optimized with a single-point goal to minimize the composite field from the reflector system at specific angles, with the radii of the 4,660 elements as direct optimization variables. Initially, the point $(\theta, \phi) = (1.75°, 0°)$ was targeted, since it resides at the location of the peak of the second sidelobe and as such, the most challenging test case. The minimax algorithm is used to carry out the optimization, with a target gain of -10 dBi or lower at the specified angle. With control over the element radii and negligible losses in the element, the optimizer essentially performs phase-only optimization of the reflectarray over a discrete number of possible loop radii. A curve illustrating the optimized result is included in Figure 3 for $w = 1$ m. The peak gain of the entire system is 46.5 dBi (a 1.0 dB drop from the reference reflector), and a null is formed at the desired angle, with a strength of 0 dBi. This does not quite achieve the desired goal, so an additional experiment with the rim increased in width to $w = 1.25$ m is optimized and the result also included in Figure 3. The increased rim encompasses 5,952 reflectarray elements. We see that a much deeper null is achieved ($G = -30$ dBi). Defining the angular width of the nulling region as that lying 20 dB below the peak of the sidelobe (i.e., $G = 1.8$ dBi, the angular widths of the two cases are similar, though more agressive nulling can be achieved with the large rim at the expense of reduced gain ($G = 46.5$ dBi, a 1.5 dB drop from the reference case).

The reflector solution is also capable of nulling at other angles. A case is analyzed in Figure 4, which illustrates the case for nulling at $(\theta, \phi) = (2.4°, 0°)$, the location of the peak of the third sidelobe, for the $w = 1.25$ m case. The reflector has no difficult nulling at this angle, and achieves a peak on-axis gain of 46.6 dBi, which is only 0.1 dB lower than the case where the null was at 1.75°.

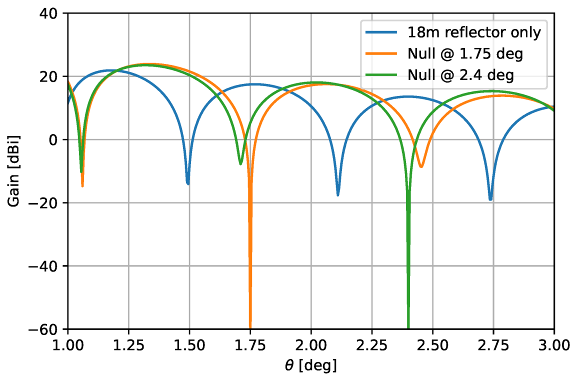

Figure 4. Simulated gain in the $\phi = 0°$ plane for two different null angles

4 Conclusion

This paper has demonstrated a hybrid reflector-reflectarray solution for potential adaptive null-forming capability in the vicinity of the main beam, which can be used for significant reduce interference from extraterrestrial sources that may lie in this region in an astronomical situation. Overall, while the null-forming ability is achieved at the expense of slightly reduced gain seems worth the tradeoff. While the required rim size is slightly larger than theoretically expected [3], this could be due to differences in the feeding scheme, or underlying sensitivities in the unit cell design that can be improved. Ongoing work is aims to further optimize the cells to reduce the rim width, while also investigate the bandwidth of the solution and fully electronically controlled implementations.

References

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