Pattern Control for Reflector Antennas Using Electronically-Reconfigurable Rim Scattering

R.M. Buehrer and S.W. Ellingson
Virginia Tech, Blacksburg, VA 24061, USA (ellingson@vt.edu)

***Abstract*—In prior work, we demonstrated sidelobe nulling for a reflector antenna system by electronic modification of the phase of scattering from elements located near the rim of the reflector. Applications for such a system include radio astronomy, where deleterious levels of interference from satellites enter through sidelobes. However the prior work was limited to placing single nulls with no constraint on main lobe characteristics, leading to gain which varies as a function of null direction. In this work, we consider simulated annealing as a means of placing nulls simultaneously with enforcement of a gain constraint. Using this method, deep nulls are possible even when element control is limited to discrete binary (i.e., 1-bit) phase-only control.**

I. Introduction

Figure 1 shows the concept for dynamic control of the pattern of a reflector antenna system proposed in [1]. For simplicity, we limit scope to prime focus-fed circular axisymmetric paraboloidal reflectors; however the concept is applicable to other types of systems, including those employing subreflectors. In this concept, scattering from a fraction of the reflector surface around the rim is modified by manipulating the phase of scattering from elements comprising the surface. The elements are envisioned to be essentially contiguous elements having sub-wavelength dimension; for example as in a reflectarray with elements implemented as patch antennas whose scattering is controlled by manipulating the impedances presented to the antenna terminals (see e.g. [2]).

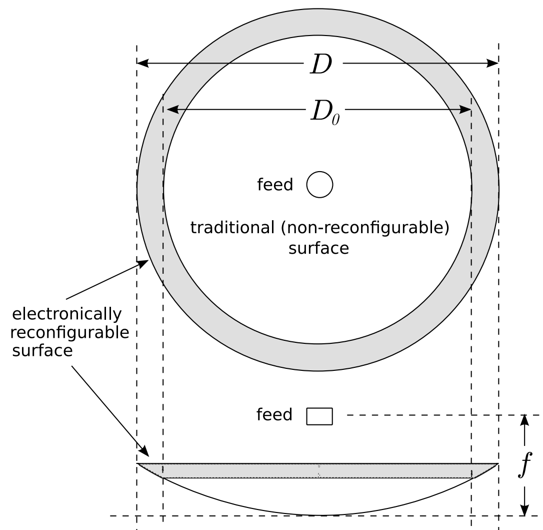

Fig. 1. On-axis (*top*) and side (*bottom*) views of an electronically-reconfigurable rim scattering system.

II. Theory

The gain, main lobe shape, and characteristics of the largest sidelobes of an electrically-large reflector antenna can be accurately determined using the theory of physical optics (PO; see e.g. [3]). As described in detail in [1], the receive gain and pattern is determined from the transmit gain and pattern, which in turn is calculated from the far field electric field intensity $\mathbf{E}^s$ scattered by the reflector. Using PO, $\mathbf{E}^s$ is calculated by integration over the reflector:

$$\mathbf{E}^s(\mathbf{r}) = -j\omega\mu_0 \frac{e^{-jkr}}{4\pi r} \int \mathbf{J}(\mathbf{s}^i)\ e^{jk\hat{\mathbf{r}}\cdot\mathbf{s}^i} ds \tag{1}$$

where $\mathbf{r} = \hat{\mathbf{r}}r$ points from the origin of the global coordinate system toward the field point, $\mathbf{J}$ is the PO surface current, $j = \sqrt{-1}$, ω is 2π times frequency, μ_0 is the permeability of free space, k is wavenumber, $\mathbf{s}^i$ points from the feed to the reflector, and ds is the differential element of surface area.

Here, $\mathbf{E}^s = \mathbf{E}^s_f + \mathbf{E}^s_r$ where $\mathbf{E}^s_f$ is the field scattered by the fixed (non-reconfigurable) center portion of the reflector and $\mathbf{E}^s_r$ is the field scattered by the reconfigurable surface. The former is given by Equation 1 where the integration is instead over the center (non-reconfigurable) surface, and the latter is given by Equation 1 where the integration is instead over the reconfigurable surface and $\mathbf{J}$ is the PO current modified by a scalar value representing the control of phase and possibly magnitude as a function of position on the reflector.

For the purposes of this paper, it suffices to model the reconfigurable surface as a contiguous surface of approximately square flat plates having side length 0.5λ (area $\Delta s = 0.25\lambda^2$), representing the elements. Scattering from the reconfigurable surface is in this case calculated by quantizing the integrand to the dimensions of the plates; i.e.,

$$\mathbf{E}^s_r(\mathbf{r}) = -j\omega\mu_0 \frac{e^{-jkr}}{4\pi r} \sum_n c_n \mathbf{J}(\mathbf{s}^i_n)\ e^{jk\hat{\mathbf{r}}\cdot\mathbf{s}^i_n} \Delta s \tag{2}$$

where $\mathbf{s}^i_n$ corresponds to the center of element n, n indexes the elements, and the complex-valued coefficient c_n accounts for reconfigurability. The motivation for 0.5λ quantization of the surface is simply that technologies that might be used to implement reconfigurability would normally consist of elements having approximately this periodicity in order to satisfy the Nyquist condition for full sampling of the available aperture.

Pattern control is achieved by appropriate selection of the c_n's. For example, setting a null in direction $\hat{\mathbf{r}}_1$ entails finding c_n's for which $\mathbf{E}^s_r(\hat{\mathbf{r}}_1 r) = -\mathbf{E}^s_f(\hat{\mathbf{r}}_1 r)$ in the far field. To emphasize the efficacy of practical implementation, we restrict scope to phase-only control of the c_n's, and further we limit phase control to either 1 bit ("binary", $c_n = \pm 1$) or 2 bits ("quaternary", $c_n = +1, +j, -1$, or $-j$).

III. Serial Search Method

As a proof-of-concept, in [1] we considered the following "serial search" method for placing a single null in the pattern: The pattern is computed in the direction of the desired null by summing the contributions from elements one at a time, along the way selecting whichever discrete value of c_n minimizes the magnitude of the accumulated co-polarized field at that step in the integration.

We demonstrated this method using a reflector antenna system having diameter $D = 18$ m and focal ratio $f/D = 0.4$, with a feed modeled as an electrically-short electric dipole with field additionally modified by the factor $(\cos\theta_f)^q$, where q controls the gain of the feed, θ_f is the angle from the vertex of the dish, and feed-radiated field is set to zero for $\theta_f > \pi/2$. Setting $q = 1.14$ yields edge illumination (EI; i.e., ratio of field intensity in the direction of the rim to the field intensity in the direction of the vertex), to approximately -11 dB, yielding aperture efficiency of about 81.5%. The radius D_0 was set to 17 m, so roughly 11% of the projected area of the dish is reconfigurable.

Applied to this system at 1.5 GHz, it was found that a single pass of the serial search method resulted in a deep null in the specified direction, even for binary phase control. Similar results are obtained for $q = 1.85$, which decreases EI to -16 dB, indicating that the proposed method does not require any particular level of edge illumination for effective operation. The consequence of higher frequency operation is that the elements (assumed to be half-wavelength in size and contiguously covering the surface) are smaller and so there are more of them.

The principal contraindication for the serial search method is that the main lobe is unconstrained, and so the system gain changes in an uncontrolled way as a function of null direction(s). This change in system gain and the dynamic variation in the main lobe generally are potentially problematic for radio astronomy.

IV. Simulated Annealing Method

In a forthcoming paper [4] we address the control problem in detail; specifically, schemes for selecting c_n's to achieve multiple pattern constraints; in particular, multiple nulls simultaneously with a main lobe (gain) constraint. Here, we report a particularly promising approach using simulated annealing [5].

We have evaluated this method in the same example and conditions reported in Section III. In this case, we place one null while constraining system gain to be constant, and then evaluate performance as the null direction is moved across the location of the first three sidelobes, in this case approximately 1° to 3° from the center of the main lobe. The system gain constraint is set at 47.7 dBi, equivalent to that of a non-reconfigurable $D_0 = D = 17$ m reflector, in order to ensure that the gain constraint does not require the full contribution of the reconfigurable portion of the surface. Here, 10^5 iterations of simulated annealing are used; see [4] for additional details. The result is shown in Figure 2. As expected, we find the method yields effectively perfect (to machine precision) enforcement of the main lobe constraint, with null depth which varies but is at least 50 dB below the system gain. Perfect nulls are not observed nor expected due to the quantization of phase and the lack of magnitude control. Note that the selected gain constraint is very conservative, since the degrees of freedom provided by reconfigurable surface are far in excess of what is needed to enforce two constraints, and so the remaining degrees of freedom are available to boost gain; perhaps to a value very close to that of a non-reconfigurable ($D_0 = D$) 18 m system. Therefore we anticipate that it is possible to significantly increase the system gain constraint (perhaps with correspondingly shallower nulls) and this is one of several follow-on studies currently underway.

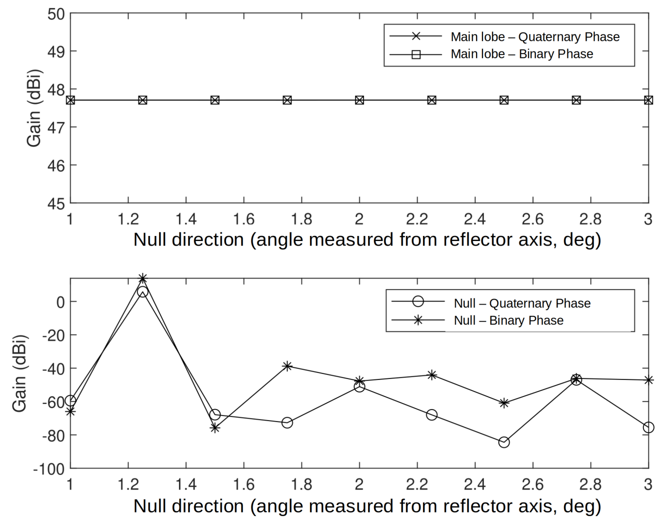

Fig. 2. System (main lobe) gain (*top*) and gain in the direction being nulled (*bottom*) as a function of direction being nulled. H-plane, co-pol. For reference, the first sidelobe level of the non-reconfigurable 18 m system is about $+22$ dBi.

Acknowledgement

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