RADIATION CHARARCTERISTICS OF REFLECTARRAY ANTENNAS: METHODOLOGY AND APPLICATIOS TO DUAL CONFIGURATIONS

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ABSTRACT

Reflectarrays combines key features of large reflectors and phased array elements to generate a collimated beam as required in high gain antennas. In reflectarrays, a large flat reflecting surface with many resonant patch elements is illuminated by a feed (or by a feed/subreflector in dual reflector configuration). In many space applications, reflectarrays applications can be advantageous because their large surface can be folded or rolled as a part of spacecraft payload before being deployed. Consequently, a reflectarray can significantly reduce both volume and mass requirements in space deployment.

To optimize reflectarray antenna performance, a phase correction mechanism must be applied to its individual array elements some of which are well documented in the literatures. In this study, we attempt to extend analytical techniques in reflector analysis to reflectarrays by introducing a number of approaches to estimate the reflectarray antenna performance independent of its phase compensation mechanism.

In one approach, a Physical Optics (PO) current will be assigned to the surface of individual reflectarray elements upon which a phase correction will be applied. In the second approach, a transmit/receive (TX/RX) radiation characteristics will be assigned to individual reflectarray elements from which coupling coefficients will be calculated and assigned as the excitation coefficient of individual elements. PO approach is modeled in the UCLA reflector code while coupling (TX/RX) method is implemented in both UCLA code as well as TICRA (GRASP) software. Results are presented for single and dual configurations with the main reflector as a reflectarray. The approach described is used to design a 3-m Cassegrain offset-fed configuration for dual X/Ka-bands application.

1. INTRODUCTION AND APPLIED METHODLOGY

Generalized reflectarray geometry to be addressed in this paper is depicted in Figure 1, a generalized feed network composed of an array of elements is illuminating a subreflector from which the main reflectarray elements are illuminated.

Large reflectarray geometries as will be presented in this paper demand significant computational time if one want to use existing full-wave approaches such as the one presented in [1]. In this paper, we demonstrate capability of a proposed technique in designing dual reflectarray antennas having nearly 300,000 elements in a given band.

In many existing multi-reflector codes, a great deal of machinery is often incorporated to accurately model and analyze the performance of multi-reflector geometries [2, 3]. Consequently, our goal in this paper is to demonstrate how one can employ the existing machineries in conjunction with reflectarrays to analyze a more generalized reflectarray topologies.

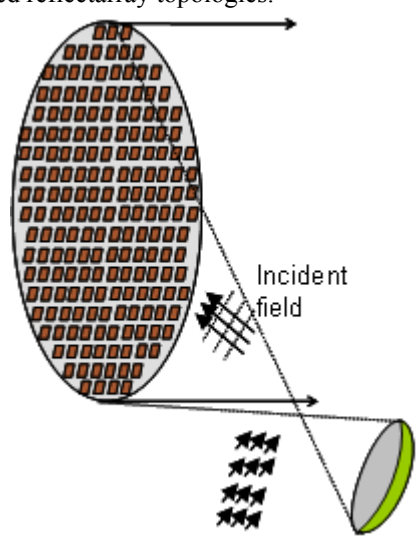

Figure 1: A geometrical description of a generalized reflectarray where arrays of feed elements are illuminating a subreflector from which the elements of reflectarray are excited.

A variety of reflector geometries such as Cassegrain or Gregorian can be modeled having a reflectarray serving as their main reflector. A feed can illuminate the reflectarray either directly or indirectly through a subreflector. Accordingly, one can assign a set of excitation coefficient

at the center of each reflectarray element which are evaluated based on the magnitude and phase of the incident field. Field excitation from the feed/subreflector system can be evaluated using various techniques including Physical Optics (PO/PTD) or the Geometrical Optics (GO/GTD) commonly available in reflector codes [2,3]. A transformation matrix modifies the field excitation on each

element and applies a phase correcting scheme on each element. Consequently, radiation from each array element will be modeled using representative element patterns from which a composite antenna pattern will be obtained.

2. OVERVIEW OF PROPOSED APPROACHES

Two approaches are considered in our analytical formulation of the problem. In one approach, a Physical Optics (PO) current will be assigned to the surface of individual reflectarray unit cells upon which a phase correction will be applied (losses may be included, too). In the second approach, a transmit/receive radiation characteristics will be assigned to individual reflectarray unit cells from which a coefficient of incident field will be modified to correct for the phases of each reflectarray elements. Each method will be described in more detail and the results will be compared and subsequently presented.

2.1 Approach I: Physical Optics (PO) Based:

PO is one of the more widely used scattering techniques in characterizing radiation of large reflector antennas. PO current is described by $\overline{J}_{po} = 2\hat{n} \times \overline{H}^{i}$, where $\overline{J}_{po}$ is PO current, $\hat{\boldsymbol{n}}$ is the unit normal to the surface, and $\overline{H}^{i}$ describes the incident field. It is suggested in [1] that the scattering from reflectarrays can be considered as a "PO-like numerical integration". Consequently, one may take advantage of the general availability of the PO current in many reflector codes to hereby estimate the re-radiated field of reflectarrays. However, PO current must be modified to incorporate the phase compensation on the surface of the reflectarray elements by associating a voltage excitation coefficient to each element. Assuming a locally plane wave incident field on x-polarized patch elements (other polarizations can be treated similarly), the complex-valued voltage excitation coefficient of $\widetilde{\boldsymbol{V}}_{\boldsymbol{o}}^{\boldsymbol{PO}}$ can be defined as follows:

$$\widetilde{V}_{o}^{PO} = \frac{\overline{J}_{po}}{2/\eta} \bullet \hat{x} = E_{\theta}^{i}\cos\varphi - E_{\varphi}^{i}\cos\theta\sin\varphi \qquad (1)$$

where E^{i}_{θ} , and E^{i}_{φ} are (θ,φ) components of the incident field, η is the free-space impedance. Reflectarray phase compensation is applied to $\widetilde{\boldsymbol{V}}_{\boldsymbol{o}}^{\boldsymbol{PO}}$ resulting in a modified coefficient of $\widetilde{V}_{o(m)}^{PO}$ which in turns can be associated with a cosine-q model describing the radiation of each reflectarray element:

$$\overline{E}^{Q}(\theta,\varphi) = \widetilde{V}_{0(m)}^{PO}\frac{e^{-jkr}}{r}\left[\hat{\theta}\cos^{q_x}\theta\cos\varphi - \hat{\varphi}\cos^{q_y}\theta\sin\varphi\right]$$

; x-polarized element (2)

where q_x and q_y are the associated q-factors in the x and y planes, k is the free space wave number and r is the distance from reflectarray elements to the observation point. The contribution from each reflectarray element will be summed up to give the aggregate reflectarray antenna radiation.

2.2 Approach II: Coupling Based:

On a somewhat more physical approach, one may model each of the reflectarray elements as a small broad-beam antenna having its own TX/RX characteristic. Each element is assumed to be attached to a voltage source whose strength is depended on the Electromagnetic coupling of the incident field. Moreover, each element is assumed to be characterized by a radiation model such as a cosine-q model as described before. An inner product of the incident field with the radiation characteristics of individual reflectarray elements can result in predicting the coupled incident field onto each array elements. Consequently, a similar complex-valued voltage excitation coefficient can be associated with each element in the RX mode, and is formulated by:

$$\widetilde{\boldsymbol{V}}_{\boldsymbol{o}}^{\boldsymbol{TX/RX}} = \boldsymbol{E}_{\boldsymbol{\theta}}^{\boldsymbol{i}}\cos^{\boldsymbol{q'}_{\boldsymbol{x}}}\boldsymbol{\theta}\cos\boldsymbol{\varphi} - \boldsymbol{E}_{\boldsymbol{\varphi}}^{\boldsymbol{i}}\cos^{\boldsymbol{q'}_{\boldsymbol{y}}}\boldsymbol{\theta}\sin\boldsymbol{\varphi}$$

(3)

Note that by properly selecting q'_x and q'_y (q'_x =0, q'_y =1), we can recover the PO based solution in Eq. (1), that is: $\widetilde{\boldsymbol{V}}_{\boldsymbol{o}}^{\boldsymbol{TX/RX}}(\boldsymbol{q'}_{\boldsymbol{x}} = \boldsymbol{0}, \boldsymbol{q'}_{\boldsymbol{y}} = \boldsymbol{1}) = \widetilde{\boldsymbol{V}}_{\boldsymbol{o}}^{\boldsymbol{PO}}$. Similarly, reflectarray phase compensation is applied to $\widetilde{V}_{o}^{TX/RX}$ resulting in a modified coefficient called $\widetilde{V}_{o(m)}^{TX/RX}$. Consequently, the excitation coefficient can be used in conjunction with Eq. (2) to find the radiation of individual reflectarray elements. Similarly, the contribution from each reflectarray element will be summed up to give the

aggregate reflectarray antenna radiation. The above formulation was originally implemented in the UCLA reflector code.

Inspired by the above coupling approach, and based on the Coupling module in GRASP software [3], a similar induced voltage concept was implemented by modifying GRASP8 generated data on the coupling coefficients. In doing so, an array of elements was assigned to the surface of a flat main surface in the GRASP software. Complex coupling voltages between the incident feed (feed plus subreflector radiation) was computed for each element in the GRASP software. Subsequently, each one of complex coupling voltages were modified later to generate an adequate uniform phase across the reflectarray. For comparison, phase of the coupled incident field on individual reflectarray elements were compared using PO/PTD, GO and the coupling method and found to be in good agreement with each other. In an integrated approach, GRASP executable files were called from MATLAB to generate the coupling coefficients while an algorithm in MATLAB were used to phase-compensate the individual reflectarray elements. Results based on comparing the method implemented in the UCLA code were compared very well with that of GRASP/MATLAB environment for single reflectarray geometry as will be discussed.

3. NUMERICAL RESULTS

Techniques presented in this paper will be applied to single reflectarray for verifications. It will then be applied to Dual reflectarray configurations.

3.1 Single Reflectarray

The first study is a 0.5-meter circular single reflectarray geometry (focal length to Diameter ratio of F/D=0.75) being illuminated by a 9-dB feed taper, (same as the geometry in [4]). A q-factor of q_x =1.25 and q_y =0.73 is selected to describe the radiation characteristics of the individual patch elements enclosed in a unit cell having a square dimension of 0.58λ x 0.58λ. Figure 2 shows a reflectarray antenna with its radiation shown in Figure 3 based on the PO and Coupling techniques described above. We have previously compared these results with that of [4]. An antenna beamwidth is computed as 1.23^o compare to the measured value of 1.2^o in [4]. The computed antenna gain is 43.22 dB which compares to the max gain measured in [4] to be 42.75 dB. This difference can easily be attributed to lack of modeling any losses into reflectarray elements (i.e. conductor, dielectric, ... losses) as well as ignoring feed and strut blockages in our model. For a similar geometry, results based on Physical Optics and coupling (TX/RX) approaches are compared in shows that both approaches have similar results for moderately larger F/D ratio of 0.75. It is argued in [5] that reflectarray antennas with large F/D have a wider operational bandwidth due to minimizing the

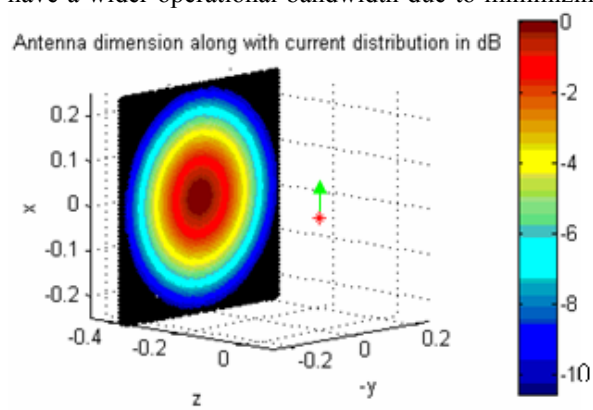

Figure 2: A single reflectarray circular antenna of diameter 0.5 meter. A feed taper of 9 dB is used for the computations presented for this study. In one study (shown Figure 3), feed is moved along the direction shown to compare coupling based technique implemented in the UCLA and modified GRASP data.

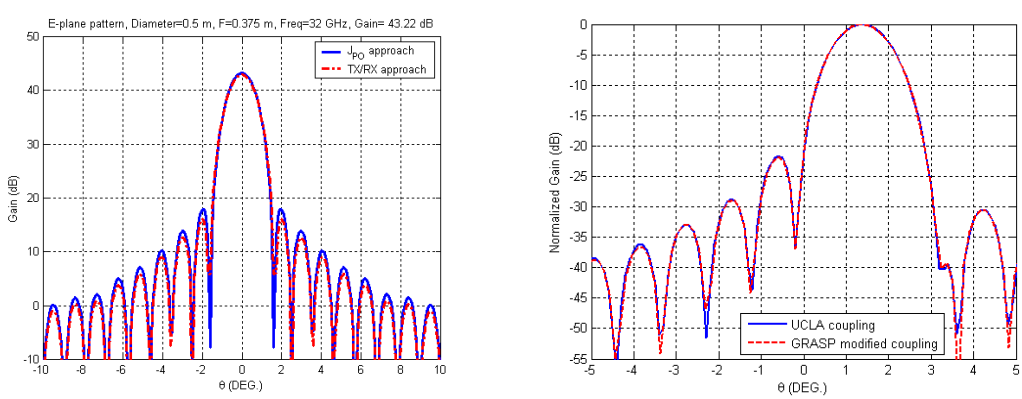

Figure 3: Left figure compares radiation pattern of the antenna using PO and Coupling based techniques implemented in the UCLA reflector code as described. Right figure shows a comparison between the coupling technique implemented in the UCLA code vs. that of the one implemented by appropriately modifying GRASP coupling coefficients for each reflectarray element. Right figure corresponds to the feed in the scan mode of Figure 2.

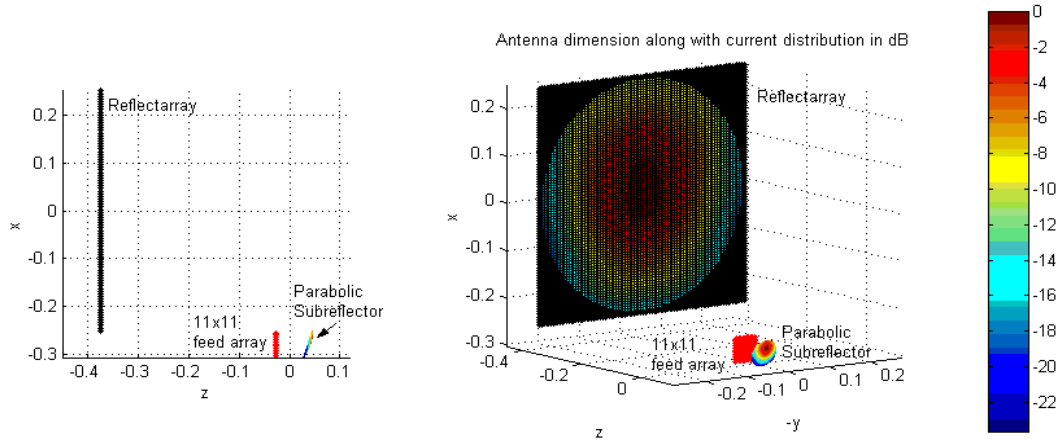

Figure 4: Side view (left) and front view (right) of a dual near-field reflectarray with an array of feed elements generating a plane wave near a parabolic subreflector. The reflectarray is a 0.5 m circular reflector. There is a 10 dB taper across the array of feed elements.

variation of differential spatial phase delay over a wider frequency band. In a separate study (no shown here), it was shown that once F/D is reduced, the PO based approach predicts higher antenna gain compare to the coupling based approach. This is due to a greater tapering of the field which is the influence of the cosine-q element pattern at the wider angular ranges as formulated in (3).

To further verify our coupling based technique, results of the UCLA code are compared to that of a similar technique based on the modifications we implemented when using GRASP software. In particular, we tried to examine scan capabilities of reflectarray antennas by moving the feed in its focal plane by 1 cm away from it focal point in the direction shown in Figure 2. In doing so, the following steps are taken to compute the scanned beam pattern:

(i) Phases of coupling coefficients are computed by either UCLA or GRASP software while the feed is placed exactly at the reflectarray focal point (this is assumed to be a nominal design for the reflectarray).

(ii) A conjugate-based phase correction is stored for each reflectarray element in the nominal feed position.

(iii) We then proceed to compute the phase of coupling coefficients when the feed is moved to its scan position. This is because it is assumed that a reflectarray is nominally designed when the feed is placed at its focal point. Obviously, reflectarray elements experience a difference magnitude and phase of the incident field when the feed is placed in the scan mode compare to the nominal non-scan mode as described in (i).

(iv) The conjugated-based phase corrections computed in step (ii) will be used to modify the phase of individual elements while the reflectarray elements are being illuminated by the feed in the scanning position.

The resultant modified voltages are reapplied to individual reflectarray elements from which reflectarray radiation is computed.

Having computed the above steps, reflectarray antenna pattern is computed by modifying the coefficient of the coupled field obtained from the UCLA and GRASP software. Agreement between two methods is nearly identical and both show the scanned behavior. The reason

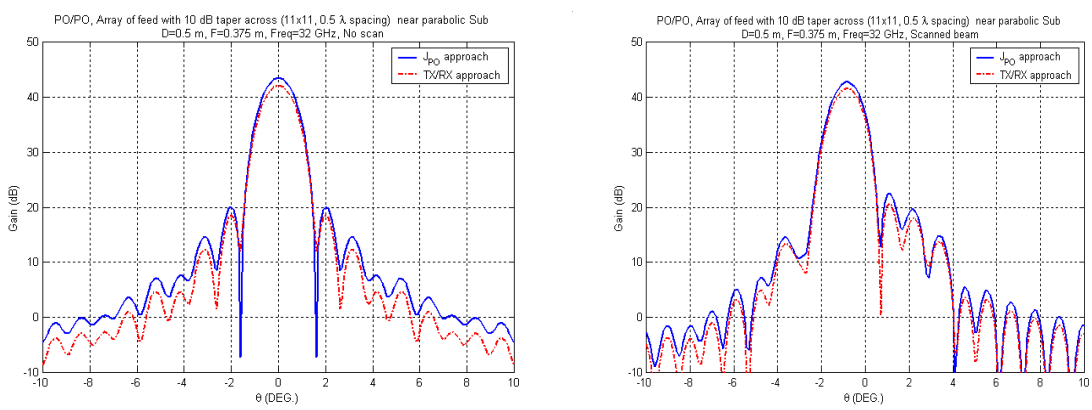

Figure 5: Left figure displays E-plane far-field pattern of near-field Gregorian reflectarray with no scan, while the right figure shows the scanned beam by appropriately phasing 11x11 feed array elements.

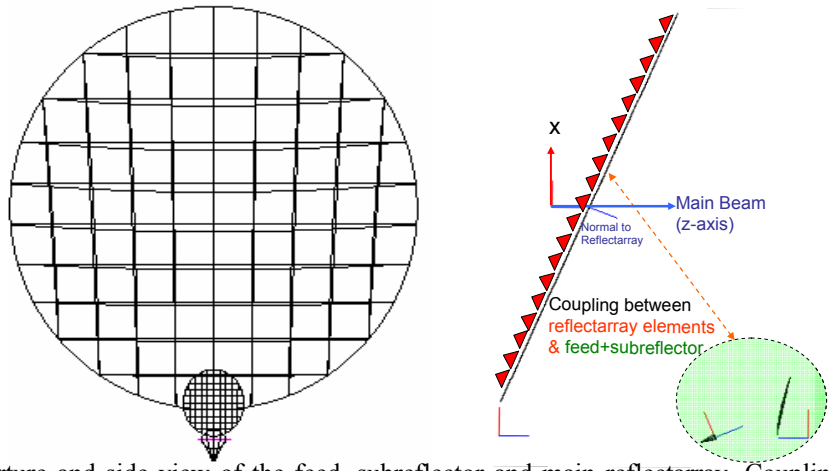

Figure 6: Projected aperture and side view of the feed, subreflector and main reflectarray. Coupling from combined feed and subreflector radiation is computed for each reflectarray elements. Consequently, coupling coefficients and phase compensation for each reflectarray element is assigned as the source terms for each reflectarray re-radiating element.

to plot the normalized pattern was that it was hard to assign the exact number of elements in the UCLA and GRASP code (due to circular boundary definition), resulting in defining slightly more number of elements in GRASP compare to that of UCLA code. Nevertheless, all antenna pattern features are preserved in both patterns.

3.2 Reflectarrays in Dual Configurations

3.2.1 Near-Field Gergorian Reflectarray

A dual configuration consisting of a near-field Gregorian reflectarray with a parabolic subreflector and a main reflectarray is shown in Figure 4. The feed is configured by an array of 11x11 elements which is placed near a parabolic subreflector generating a plane wave in the vicinity of the subreflector. The plane wave will converge toward the focal point of the subreflector upon reflection, which, in turns, illuminates the main reflectarray antenna elements. Consequently, this geometry allows a limited scan capability of the reflectarray antenna by steering the beam of the feed array elements. Figure 5 displays the antenna pattern with no scanning in addition to the case where the feed array elements are scanned by 10°. This would result in a main beam scanning of 0.8^o (somewhat less than the ratio of diameter of subreflector to that of main reflector). Again both PO based and coupling based approaches are compared for this geometry. Due to the highly offset antenna configuration, the PO based method predicts a higher antenna gain compare to that of TX/RX based approach. This is due to the fact that the coefficient of the incident field ($\tilde{V}_o^{PO}$) has more biased in the PO based approach by lowering the q of each reflectarray element in the receive mode when compared to that of its transmit mode. Note prediction of a lower gain translates into lower sidelobe prediction using coupling (TX/RX) based approach.

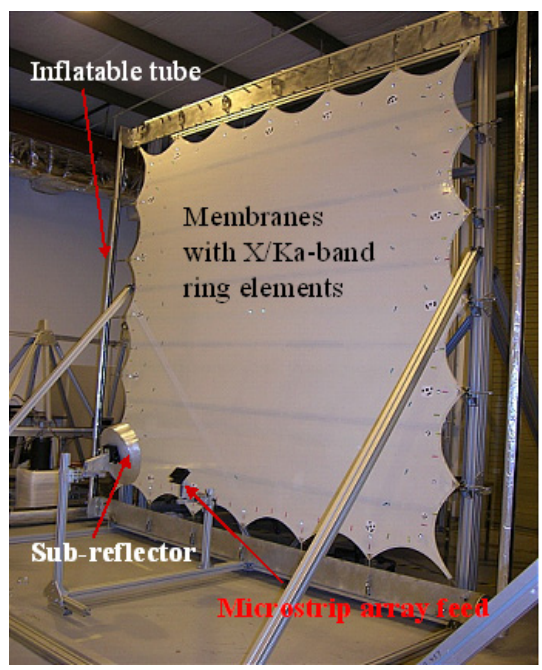

Figure 7: 3m X/Ka-band Inflatable Reflectarray Antenna

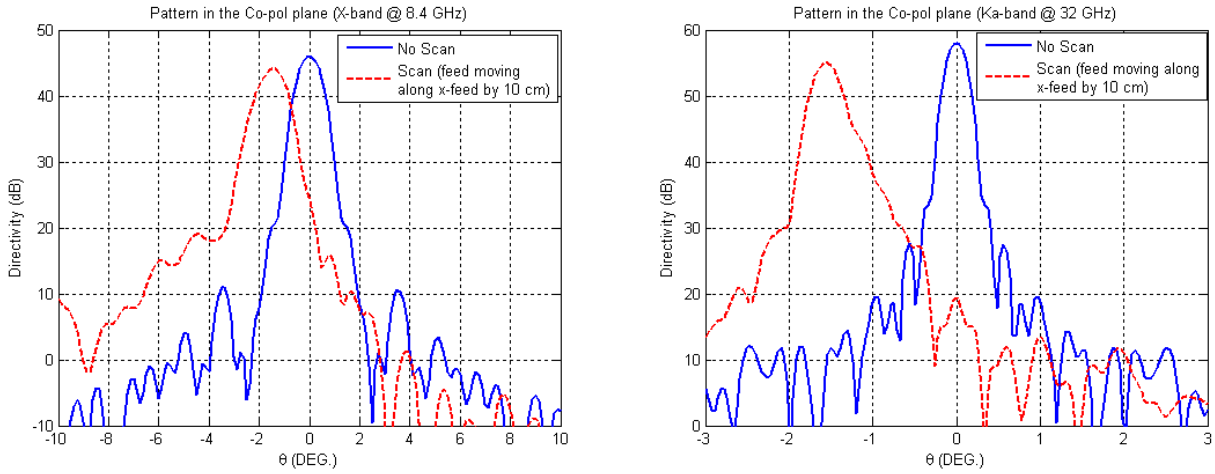

Figure 8: Reflectarray far-field pattern in the non-scan and scan mode for 8.4 and 32 GHz. In each case, the feed is moved along x-feed axis by 10 cm. Consequently, main beam will move by nearly 1.5^o for both 8.4 and 32 GHz.

3.2.2 A Dual Cassegrain Reflectarray (X/Ka-bands)

A 3-m dual Cassegrain reflectarray configuration is shown in Figure 7 whose model is built using GRASP software. The main reflector is a flat 3x2.77 m reflectarray. It is designed to operate at X-band (8.4 GHz) and Ka-band (32 GHz). To avoid substantial feed/subreflector blockages, reflectarray main beam is adjusted to an off angle direction away from the normal to the reflectarray surface. This is done by placing a progressive phase on the reflectarray elements to steer the beam as if the main reflector was a parabolic one.

Close to 19,000 elements are use for X-band and nearly 275,000 elements are used for the Ka-band. Reflectarray structure is a layered structure where Ka-band layer is placed closer to the ground plane.

For this study, it was attempted to see how much beam scanning can be achieve if one could mechanically move the feed along feed transverse plane. We considered a 10-cm feed movement along x-feed axis. Using the technique described before, it was found that nearly 1.5^o scan can be achieved by moving the feed while maintaining nearly 3-dB loss in the antenna gain (see Figure 8). Scan losses for feed movement along its y-axis was greater due to small subreflector size and spillover caused by that.

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