CONFORMAL ARRAY DESIGN SOFTWARE

H.K. Schuman

CSC Professional Services Group
P.O. Box 4308
Rome, New York 13442-4308

ABSTRACT

A powerful conformal array design computer program can be developed by modification of a physical optics based array fed reflector analysis computer program.

1. INTRODUCTION

The antenna requirements of RF sensor systems such as radars are becoming increasingly demanding. Electronically beam steered (phased array) antennas, for example, are sought that are conformal to the system enclosure surface because of limited enclosure volume and the need to minimize antenna blockage. It is difficult to design conformal arrays to meet stringent pattern requirements, especially for a field of view (FOV) (steerable range) beyond several beamwidths. The difficulty is largely a result of nonidentically oriented element patterns. Stringent pattern performance of planar arrays, on the other hand, is considerably easier to maintain over a wide FOV because the elements are identically oriented.

A procedure for determining the complex weights of a conformal array that will yield radiation patterns meeting sidelobe, beamwidth, pointing, and, for monopulse difference patterns, null depths, is likely to be as much art as science. This is because the "synthesis" problem of determining excitations that yield a specified pattern is ill conditioned [1], and often there is no "best" solution. Some form of "realizability" constraint on the excitations typically is required in such a procedure [1]. Also, it is particularly difficult to realize low sidelobes over a wide pattern range with conventional synthesis procedures. Conventional synthesis procedures are applicable to meeting main beam shaping criteria [1] and achieving maximum gain [2 (Section 10-3)].

A synthesis method that (1) greatly facilitates the design of conformal arrays to meet a wide range of performance and surface constraints, including that of low sidelobes, (2) is not sensitive to the aforementioned inverse problem difficulties, and (3) is readily programmable is described here. The underlying theory is based upon a "synthesis" procedure that is similar, but not identical, to the projective synthesis method described in Chapter 2 of the Conformal Antenna Array Design Handbook [3]. A "synthesizing" planar array is located within the enclosure surface. Complex excitations are determined for the synthesizing array on the basis that it radiate a desired pattern in the absence of the enclosure. Such excitations may be, for example, Taylor (for low sidelobe sum patterns) or Bayliss (for low sidelobe difference patterns). The enclosure surface, then, is "illuminated" by the array and the current excited on the inside of the surface by the array is determined. This current is (within a trivial minus sign) precisely that which, in free space, radiates the same pattern as that of the planar synthesizing array. (Both current distributions, one conformal and the other planar, radiate the same patterns when radiating in free space, e.g., no ground plane backing on the conformal array.) The conformal current thus identifies the ideal excitations to apply to radiating elements located on the enclosure surface. This "equivalence" formulation is different from that described in the Handbook [3] but just as valid. (A proof of this equivalence is given in [4] where application to a related aperture coupling problem is described. It is recast for the synthesis problem in Section 2.1.) This equivalence formulation is particularly attractive since it identifies how a well developed array feed reflector analysis computer program such as ARCREF2 [5], would form a natural basis for construction of a conformal array synthesis/analysis program, as was done in creating ARCSYN from ARCREF2 [6]. In ARCREF2, the physical optics current on a reflector surface excited by an array feed is computed, and this current is often an excellent approximation to the equivalent current referred to above.

In principle, the equivalent current on the enclosure surface radiates in free space the exact same field that the synthesizing planar array radiates in the absence of the enclosure. In practice, however, a conformal array would at best only sample the ideal current over only a portion of the enclosing surface. The conformal array elements would be associated with nonideal element patterns, including the shadowing resulting from a curved conducting ground plane, and nonideal polarizations as dictated by orientation constraints and radiator type constraints. As had been demonstrated in the creation of ARCSYN from ARCREF2, a reflector code can be easily modified to include these effects in computing the gain patterns resulting from a synthesis. Validation of ARCSYN proved to be a very modest task because it was implemented basically as an extension of the thoroughly validated computer program ARCREF2 [5]. In addition, a large flat plate "enclosure surface" option was included in the conformal surface modeling so as to ascertain that the physical optics current sampled on the surface and the corresponding radiation pattern were in close agreement with the radiation pattern of the synthesizing array.

Section 2 contains a discussion of the theory underlying ARCSYN. Section 3 identifies typical surface types available from reflector codes. Section 4 describes alternative applications of the synthesizing array. Section 5 contains an example.

2. THEORETICAL BASIS

The physical optics analysis underlying much of the synthesis function of ARCSYN is identical to that described in numerous documents pertaining to reflector analysis [7]. The discussions here are limited to (1) the fundamental equivalence theorem by which the reflector analysis program can form the basis of a conformal array synthesis program and (2) to element pattern modeling.

2.1 An Equivalence Theorem

The theorem discussed here is an adaptation of that attributed to Schelkunoff [8]. Consider the "original problem" consisting of a planar array radiating in free space (Figure 1, top). The radiated field intensity is denoted $\vec{E}_o$. If the array were to be completely enclosed by a conducting sheet, the exterior region field would be nulled and a surface current $\vec{J}$ would be induced on the interior wall of the enclosure (Figure 1, middle). This current is precisely that which radiates an external field, $\vec{E}(\vec{J})$, that cancels $\vec{E}_o$. Thus, $\vec{E}_o = -\vec{E}(\vec{J})$ and, since the fields are linear functions of the current, $-\vec{E}(\vec{J}) = \vec{E}(-\vec{J})$. Thus $-\vec{J}$, radiating in free space, i.e., in the absence of the conducting enclosure, would give rise to $\vec{E}_o$ (Figure 1, bottom). This latter problem then is equivalent to the original problem and forms the basis for converting a physical optics reflector analysis program into a conformal array synthesis program. The physical optics analysis is used to approximate $\vec{J}$. The conformal array excitations of amplitudes a_i and phases ψ_i then are determined by sampling a suitable component of $\vec{J}$ at the surface locations of the conformal array radiating elements. Only an approximation to the equivalent source would be realized with the conformal array for the following reasons:

1. The Physical Optics approximation is employed in computing $\vec{J}$,
2. The array is not likely to completely cover the enclosure surface,
3. The array only samples $\vec{J}$, and
4. The pattern of any practical conformal array radiating element will not be identical to that radiated by the corresponding sampled current $\vec{J}$. In particular, the conformal array element is likely to be constrained in polarization and would be backed by a conducting surface.

The agreement between the planar array pattern ("original problem") and the conformal array pattern is likely to be greatest when the planar array is located close to the conformal array. Also, an accurate assessment of the performance of the conformal array requires suitable modeling of the antenna gain pattern and especially the complex element pattern.

2.2 Conformal Array Antenna Gain Pattern

The antenna gain (sometimes referred to as power gain) is defined in terms of available average power supplied by the transmitter (or receiver by invoking reciprocity and replacing the receiver with a "reciprocal source"). In the element pattern approach to computing antenna gain, the conformal array element excitations, $a_i \exp(j\psi_i)$, are treated as incident voltages. The i^{th} element source with all other elements terminated in their source impedance (feedline impedance) gives rise to the i^{th} element pattern. The element pattern approach assumes that"cross talk" between feedlines is negligible, i.e., energy reflected at one antenna radiating element will not appear at another via the feed network. An expression for the antenna gain pattern $G = G(\theta, \phi, v')$ in terms of the complex element patterns $\vec{e}_i$ is determined from superposition by noting that

$$G = |\vec{E} \cdot \hat{v}'|^2 \qquad (1)$$

where $\hat{v}'$ is the far field polarization unit vector, and the x,y,z components of the far radiated field $\vec{E}$ in the θ, ϕ direction are given by

$$\begin{bmatrix} E_x \\ E_y \\ E_z \end{bmatrix} = \sum_{i=1}^{N} c\, a_i\, e^{j\psi_i}\, e^{jk\hat{r}\cdot\vec{r}_{oi}}\, [\tilde{T}_i] \begin{bmatrix} e_{xi} \\ e_{yi} \\ e_{zi} \end{bmatrix} \qquad (2)$$

where

N = number of elements,
k = wavenumber,
$\hat{r} = \hat{r}(\theta, \phi)$ = far field direction unit vector,
$\vec{r}_{oi}$ = antenna coordinate system position vector of the i^{th} radiating radiating element,
e_{xi}, e_{yi}, e_{zi} = element local coordinate system components of i^{th} element complex element pattern,
$[\tilde{T}_i]$ = transformation (rotation) matrix between conformal surface system x,y,z coordinates and i^{th} element local coordinates, and c = a convenient normalization.

An important distinction between conformal arrays and planar arrays is that, for conformal arrays, the antenna pattern cannot be factored into an element pattern and an array factor. In general, therefore, the element phase pattern, ψ_i, must be considered in determining the array pattern.

The element patterns have a substantial effect on the conformal array pattern, due principally to shadowing by the curved surface. The element patterns are key modeling elements, therefore, and are discussed further in Section 2.3.

2.3 Element Pattern

Generally the complex element patterns may differ between elements in an array. If the patterns are nearly identical in shape but only "point" in different directions (Figure 2), only one pattern shape need be specified. Coordinate system transformations then will account for the differing pattern orientations in computing the overall antenna gain.

Element patterns generally are broad beam. For planar arrays, therefore, they do not significantly affect the antenna gain patterns in the vicinity of broadside. A curved array surface, however, is another matter since far out element pattern angles may contribute to near in antenna gain pattern angles. Also depolarization effects then may be more significant for conformal arrays than for planar arrays.

An approximate but general element pattern model that is representative of those associated with a wide variety of radiating elements including open ended waveguides, slots, microstrip patches, and dipoles is constructed as having uniform phase variation and amplitude θ variation that is cosinusoidal and ϕ variation that is appropriate for preserving the polarization of the elements. Both linear polarization and circular polarization elements can be so modeled. This element pattern, in vector notation, takes the following forms.

1. Linear polarization - excited orthogonal to the element reference orientation:

$$\vec{e} = \vec{e}\,' = \begin{cases} \cos\theta_i \,(\cos\phi_i \,\hat{\theta}_i - \sin\phi_i \,\hat{\phi}_i) & \theta_i < \pi/2 \\ 0 & \theta_i \geq \pi/2 \end{cases} \tag{3}$$

2. Linear polarization - excited parallel to the element reference orientation:

$$\vec{e} = \vec{e}\,'' = \begin{cases} \cos\theta_i \,(\sin\phi_i \,\hat{\theta}_i + \cos\phi_i \,\hat{\phi}_i) & \theta_i < \pi/2 \\ 0 & \theta_i \geq \pi/2 \end{cases} \tag{4}$$

3. Circular polarization - right hand:

$$\vec{e} = (\vec{e}\,' - j\,\vec{e}\,'')\,\frac{1}{\sqrt{2}} \tag{5}$$

4. Circular polarization - left hand:

$$\vec{e} = (\vec{e}\,' + j\,\vec{e}\,'')\,\frac{1}{\sqrt{2}} \tag{6}$$

where subscript "i" denotes i^{th} element local coordinate or component. The local coordinate system is oriented such that the local y axis (y_i) is parallel to the element reference orientation and x_i is orthogonal to it and the surface normal (z_i).

There is no dissipated or reflected power loss in this model, and the constant c in (2) is determined such that $|\vec{E}\cdot\vec{v}'|^2$ of (1) is in units of gain in dBi. Thus

$$c^2 \sum_{i=1}^{N} a_i^2 \int_0^{2\pi} \int_0^{\pi/2} |\vec{e}\cdot\vec{e}^*|^2 \sin\theta \, d\theta \, d\phi = 4\pi \quad (7)$$

where, with $\vec{e}$ given by either of the forms in (3) through (6), it follows that

$$c^2 = \frac{6}{\sum_{i=1}^{N} a_i^2} \quad (8)$$

3. GEOMETRY

Four conic surface types, typically modeled in reflector codes, were modeled in ARCSYN as a result of their availability in ARCREF2. The surface types are parabolic, spheric, elliptic, and hyperbolic. (Flat planes were modeled in ARCSYN as well. These proved useful during the debugging and validation stages of ARCSYN.) Cones of any vertex angle can be approximated to any accuracy by a hyperboloid. Relations that would yield a suitable hyperboloid focus, f, and vertex, v, for approximating a cone of any half angle, θ, and base diameter, d, are

$$v = \alpha d$$
$$f = v \sqrt{1 + \tan^2 \theta} \quad (9)$$

The smaller the ratio $\alpha = v/d$, the better the approximation. A ratio of $\alpha = .001$ has been found adequate for all foreseeable applications.

4. SYNTHESIZING ARRAY

If the synthesizing array plane is oriented normal to the desired beam direction, the desired element phasing of the synthesizing array then would be uniform. Alternatively, the array can be phased so that the beam is launched in another direction other than normal to the synthesizing plane. This flexibility has proven particularly useful in situations where it is advantageous to orient the synthesizing array so that it is as close as possible to the conformal array and yet where this orientation is not consistent with the beam direction. An example is given in Section 5.

The synthesizing array can be amplitude weighted in accordance with user specifications. For example, weighting options in ARCSYN are uniform, circular Taylor or Bayliss, and linear Taylor or Bayliss.

5. EXAMPLE

An example illustrating the applicability of ARCSYN to conformal array synthesis is given here. The excitations of a 95 element array on a 15° half angle cone are determined for realizing monopulse sum and difference patterns.

The cone array pertains to one of two such experimental arrays under construction at the Naval Air Warfare Center, China Lake, CA. The geometry for the 95 element cone surface array is shown in Figure 3. The orientation of the synthesizing array to achieve a $\theta = 0^{\circ}$ beam in the yz plane ($\phi = 90^{\circ}$) is shown in Figure 4. The uniformly weighted synthesizing array and corresponding conformal array gain patterns are shown in Figures 5 and 6. The synthesizing array was rotated 15° to yield the 15° scanned beam of Figure 7. The poor quality of the conformal array patterns for these severe beam directions could be attributed to an undesirable positioning of the planar synthesizing array. The 15° beam was resynthesized with the synthesizing array located close to, and nearly parallel to, the conformal array (Figure 8) and phased to yield the desired beam direction. As is apparent from Figure 9, the resulting synthesized conformal array pattern is much improved. This exercise demonstrates the considerable flexibility available to the designer for optimizing the conformal array weights. Here use was made of the option to scan the synthesizing array to achieve the desired beam direction thus allowing the synthesizing array to be located close to the conformal array (a desirable condition to minimize de-collimation effects in transmission between synthesizing and conformal array).

Figures 10, 11, and 12 pertain to a $\theta = 75^{\circ}$ beam that is near broadside to the surface, a less demanding goal. 25 dB sidelobe Taylor (sum) and Bayliss (difference) pattern synthesizing array distributions were applied in obtaining these results.

6. ACKNOWLEDGMENT

This work was supported by the Naval Air Warfare Center (NAWC), China Lake, CA under Contract N60530-92-C-0149. Appreciation is due Ms. Donna Owens of the NAWC for helpful discussions and guidance throughout the development of ARCSYN. Appreciation is due also to Mr. R.S. Mandry of CSC Professional Services Group for assistance in computer programming and implementation. Finally, appreciation is due Ms. Kelly Durant for expert preparation of several versions of the manuscript.

7. REFERENCES

1. J.R. Mautz and R.F. Harrington, "Computational Methods for Antenna Pattern Synthesis," IEEE Trans. Ants. Propg., Vol. AP-23, No. 4, pp. 507-512, July 1975.

2. R.F. Harrington, Field Computation by Moment Methods, McGraw-Hill, 1968.

3. R.C. Hansen, Ed., Conformal Antenna Array Design Handbook, DTIC AD A110091, September 1981.

4. H.K. Schuman and D.E. Warren, "Aperture Coupling in Bodies of Revolution," IEEE Trans. Ants. Propg., Vol. AP-26, No. 6, pp. 778-783, November 1978.

5. H.K. Schuman, et. al., "Simulation Support for Radar Analysis," Final Report, USAF Rome Laboratory Contract No. F30602-89-D-0028, Task 28, May 1992.

6. H.K. Schuman and R.S. Mandry, "Conformal Array Synthesis/Analysis," Final Report-Phase I, NAWC Contract N60530-92-C-0149, March 1993.

7. P.T. Lam, S.W. Lee, et al., "Strategy for Reflector Pattern Calculation: Let the Computer do the Work," IEEE Trans. Ants. Propg., Vol AP-34, pp. 592-595, April 1986.

8. R.E. Collin, Field Theory of Guided Waves, McGraw-Hill, 1960.

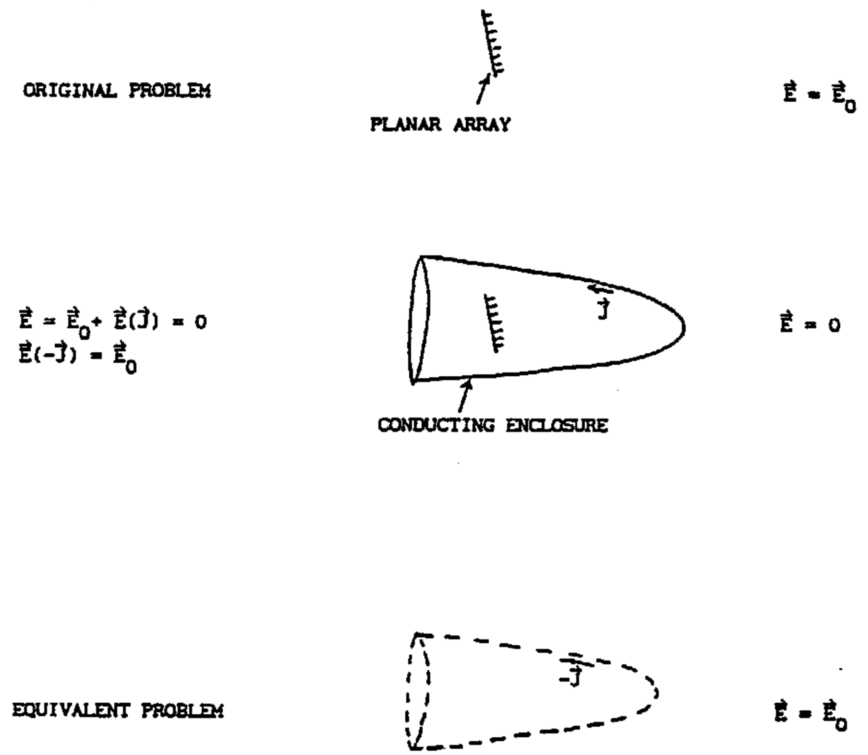

Figure 1. An Equivalence Theorem

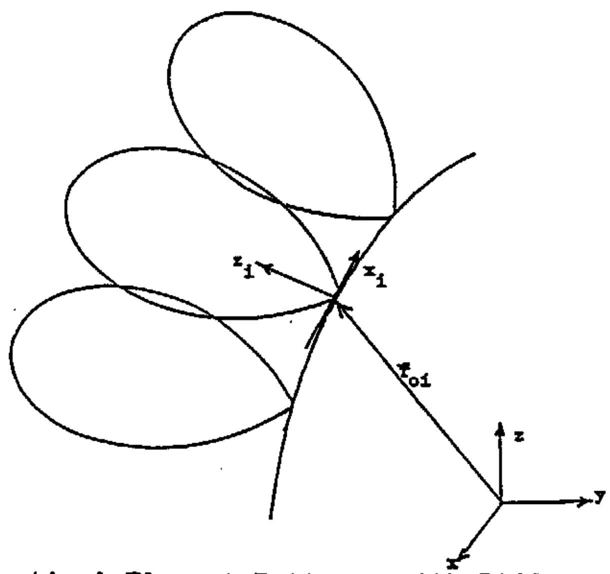

Figure 2. Identical Element Patterns with Differing Orientations Due to the Array Surface Curvature

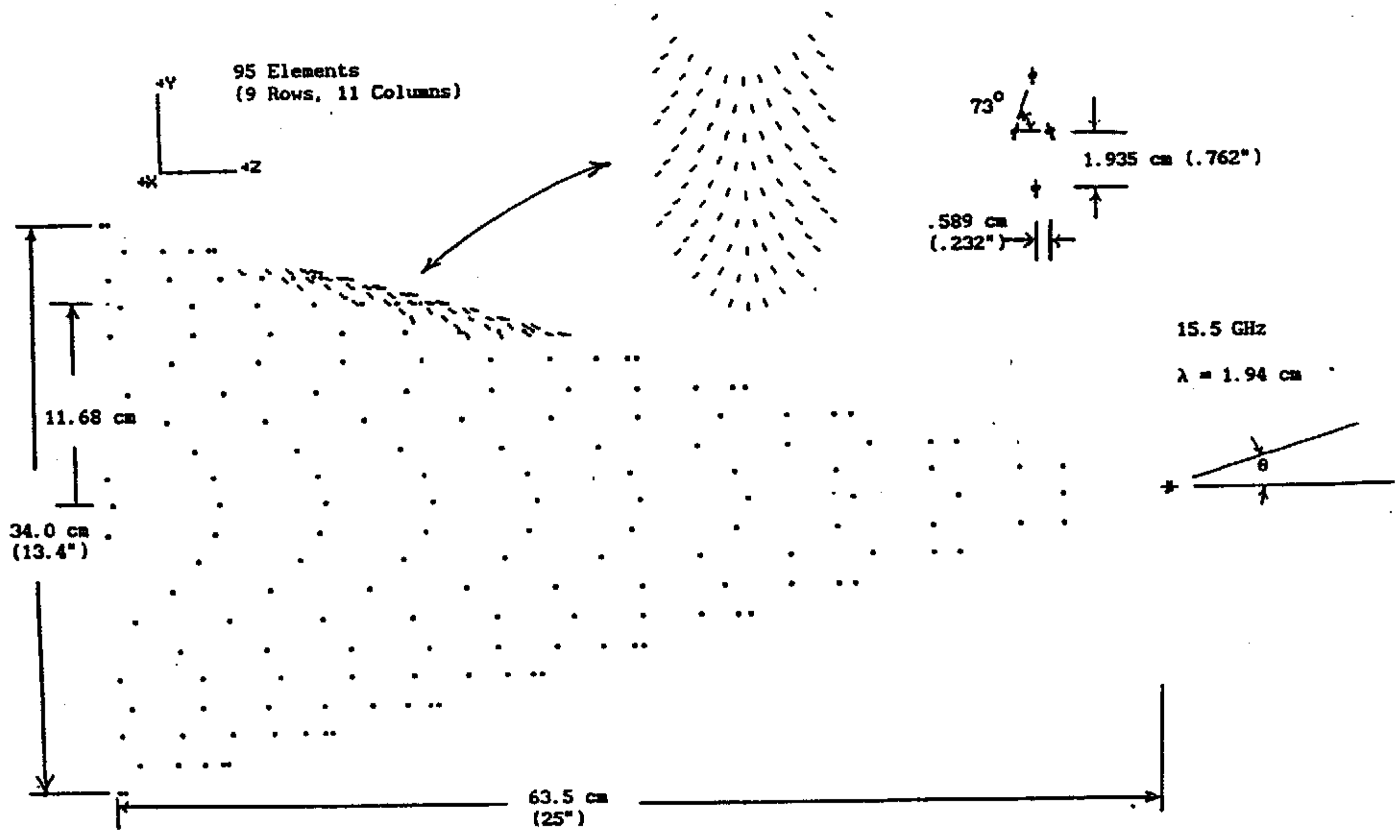

Figure 3. Cone Array

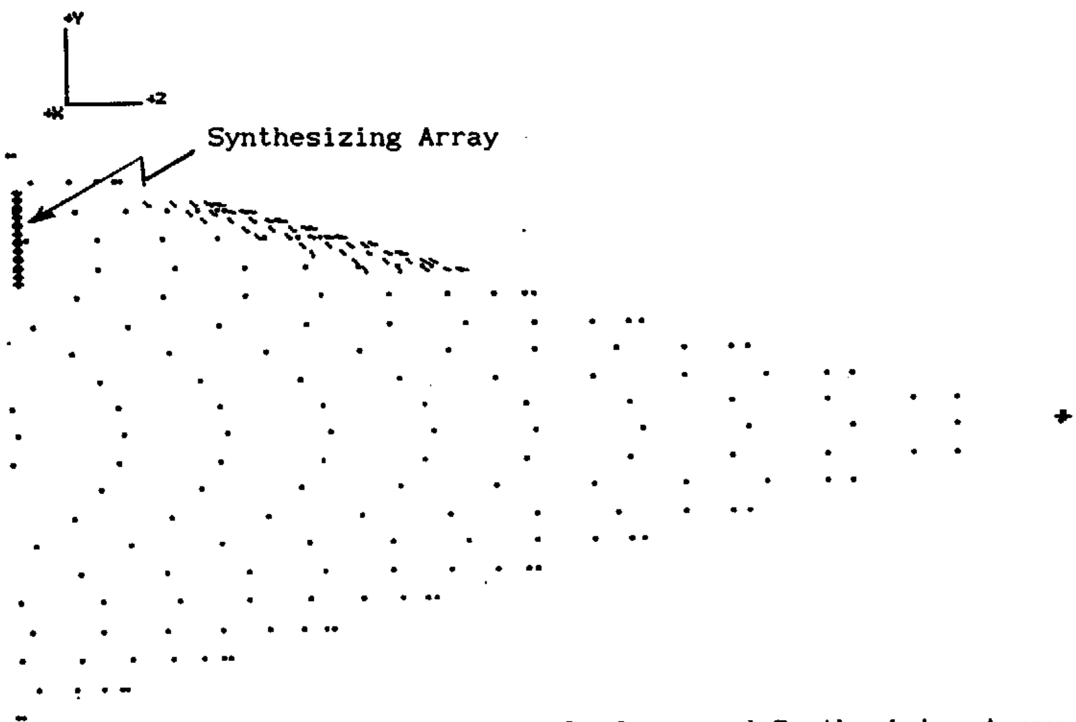

Figure 4. Conformal Array, Surface, and Synthesizing Array

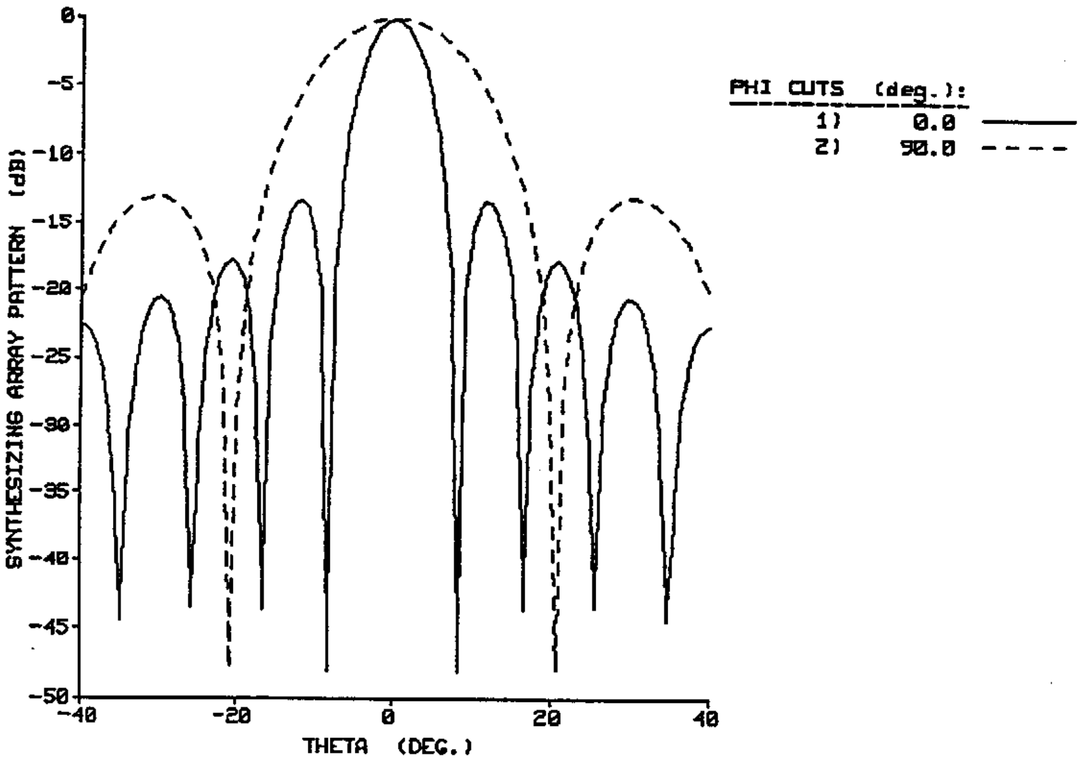

Figure 5. Uniformly Excited Synthesizing Array Patterns

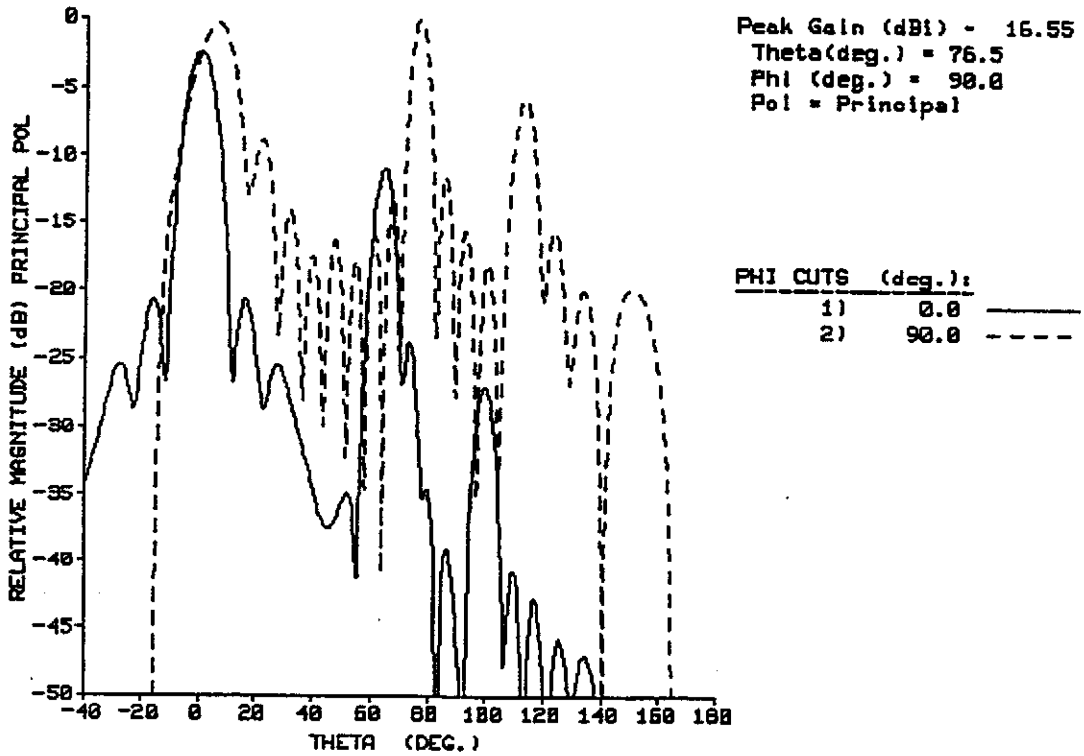

Figure 6. Conformal Array Patterns (Axial Beam)

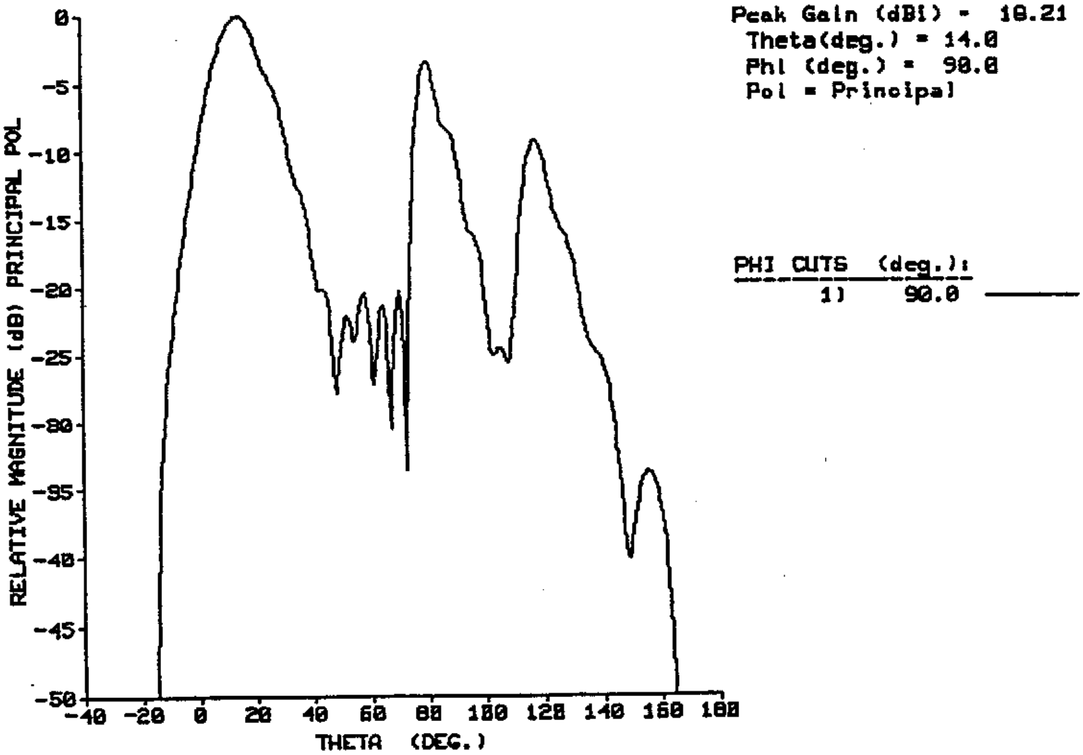

Figure 7. Conformal Array Pattern for a 15° Beam

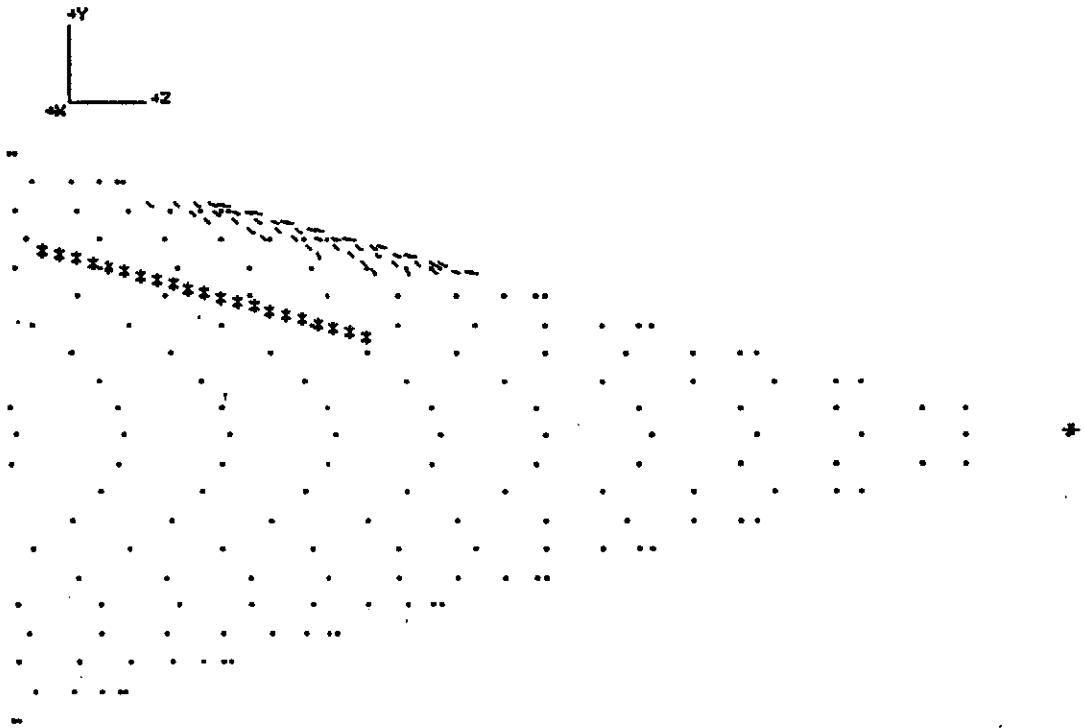

Figure 8. Tilted Synthesizing Array (15° Off Axis Beam Achieved by Phasing Synthesizing Array to Launch Beam 60° from Local Normal)

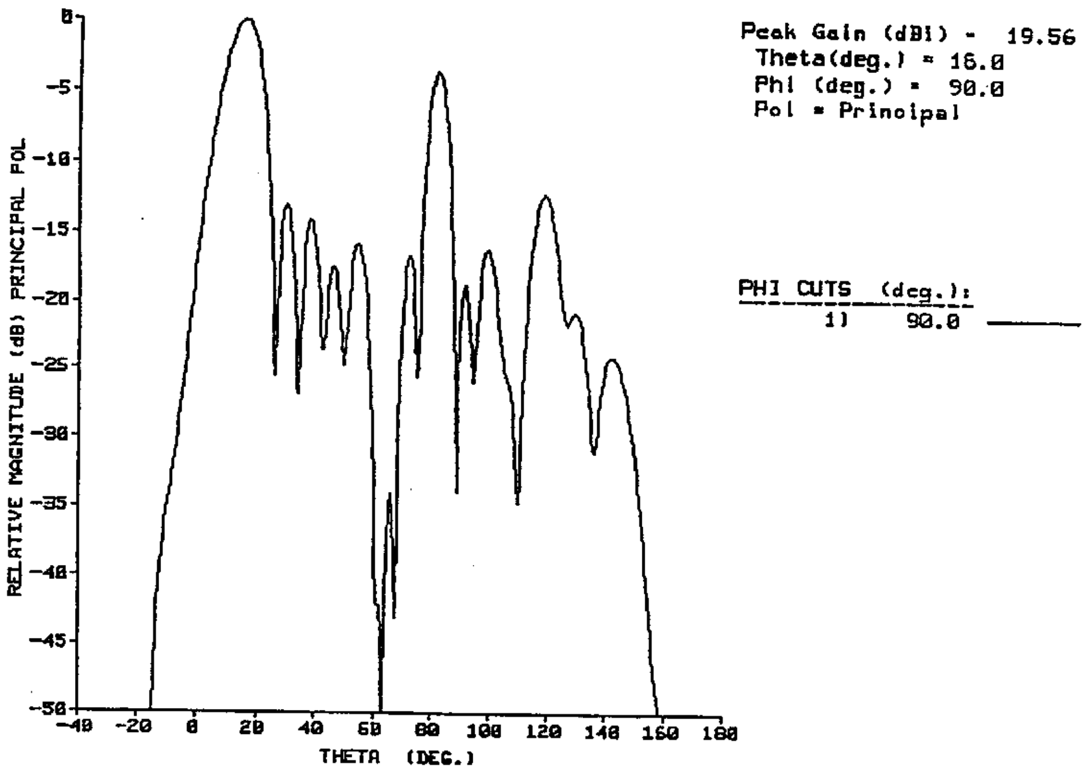

Figure 9. Conformal Array Pattern - Excitations Determined From Tilted, Phased Synthesizing Array

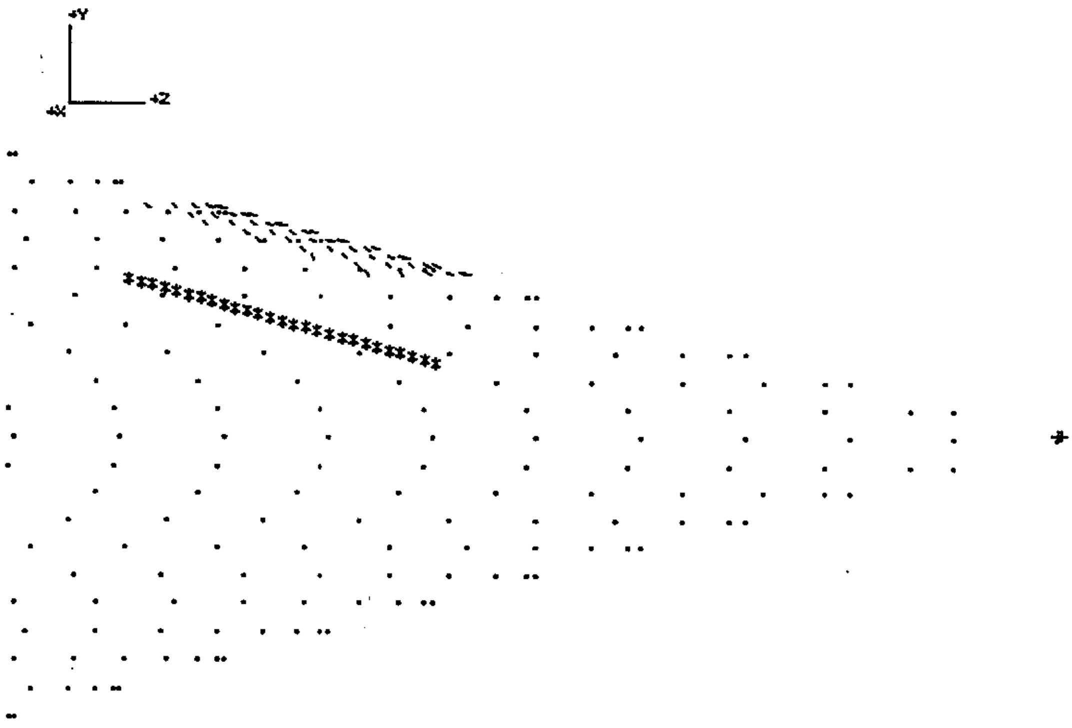

Figure 10. Synthesizing Array Tilted and Shifted to Achieve 75° Off Axis Beam

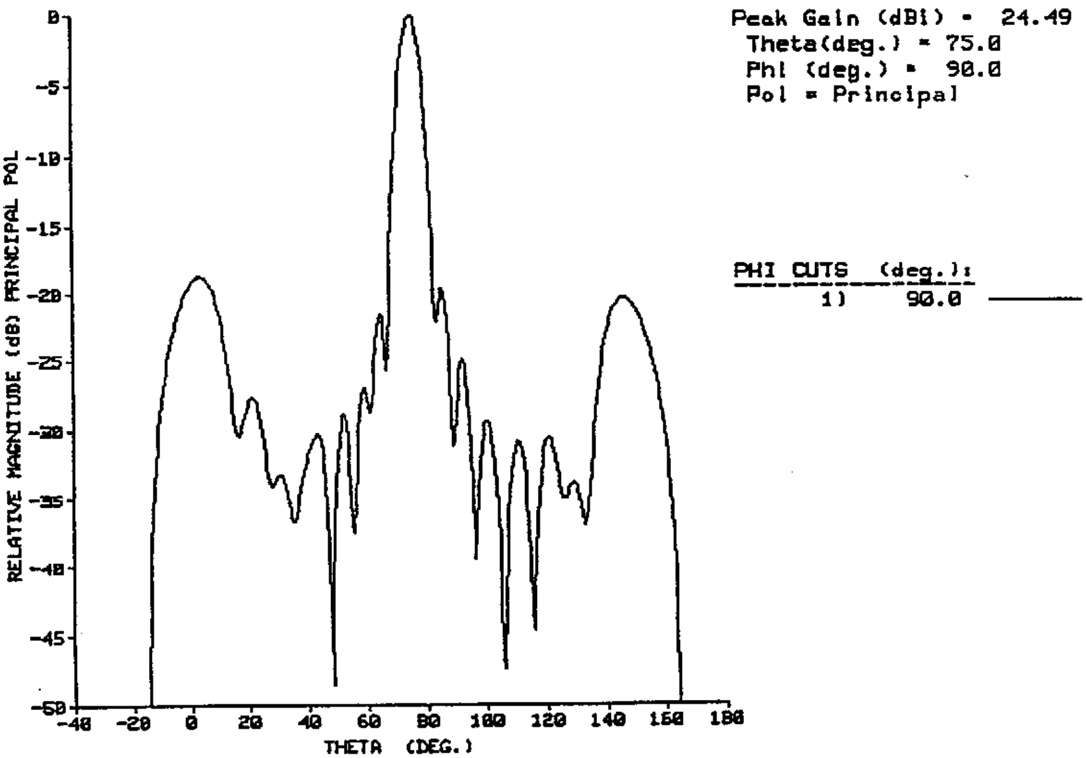

Figure 11. Conformal Array Sum Pattern - 75° Off Axis Beam

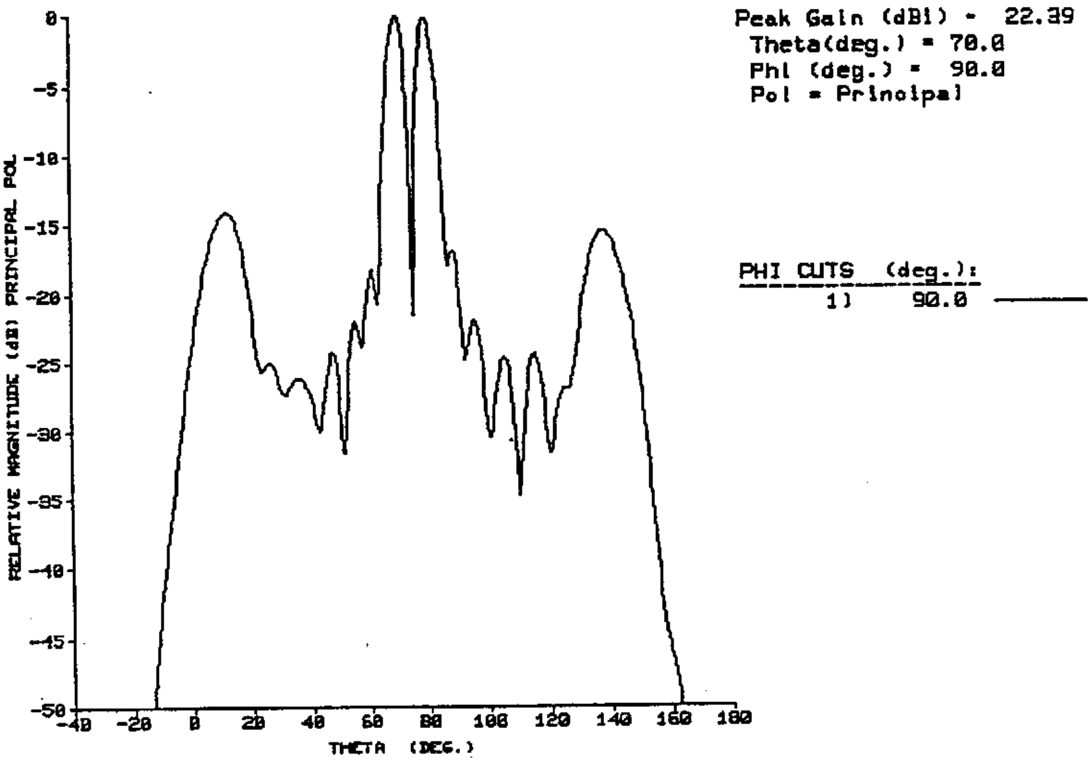

Figure 12. Conformal Array Difference Pattern - 75° Off Axis Beam