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ELECTRONICALLY STEERABLE ARRAY

T. R. Schiller
W. S. Heath

TECHNICAL REPORT NO. RADC-TR-65-361

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Techniques Branch
Rome Air Development Center
Research and Technology Division
Air Force Systems Command
Griffiss Air Force Base, New York

ELECTRONICALLY STEERABLE ARRAY

**T. R. Schiller
W. S. Heath**

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FOREWORD

This Interim Report was prepared by Sylvania Electronic Systems, Williamsville, N. Y., under Contract AF30(602)-3041, Project 4506, Task 450604. The RADC Project Monitor was Edward J. Christopher (EMATA).

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ABSTRACT

This report describes the effort expended during the third quarter on the Engineering Change "A" portion of the Electronically Steerable Array Program to design and build a high gain, electronically steerable, millimeter antenna system. During this period the block of ferrite used in the scanner was tapered so that the output end was larger than the input. This resulted in greater scan capability and lower sidelobes. In addition, the design of the final antenna model was finalized and construction of the antenna started.

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SECTION 1

INTRODUCTION

This document describes the effort expended by Sylvania Electronic Systems-Central between 31 May 1965 and 27 August 1965 under Engineering Change "A" to Rome Air Development Center Contract AF30(602)-3041, entitled "Electronically Steerable Array". Previous effort on this contract has been reported on in Technical Documentary Report No. RADC-TDR-64-222 (Ref. 1) and in the first and second quarterly reports on this change (Ref. 2 and 3).

The main objective of the Engineering Change "A" program is to design, build and test a breadboard model antenna incorporating a ferrite scanner which will use cubic lattice ferrite material. In addition, the model will include a magnetic control circuit, matching and feed system.

The major design goals for the breadboard model antenna are as follows:

Gain	- 35 to 38 db (relative to isotropic radiator)
Scan Angle	- 60 degrees or greater in two dimensions
Maximum Sidelobes	- 20 db below peak
Power Handling	- 5 kw (peak)
3 db Beamwidth	- 2 x 2 to 4 x 4 degrees

In addition to these specific objectives, the model will be designed to have minimum insertion loss and magnetic control power while still maximizing the scan speed.

The program has been divided into three phases. The first phase, which has been completed, consisted of material evaluation and preliminary

magnetic circuit design tasks. The second phase, which has started, consists of the final design and build stages. The final phase will be the breadboard model testing phase. The first phase extended through the first nine months of the program. The last two phases will cover the remaining portion of the program.

The major task during the first phase was to evaluate and select the ferrite material to be used. A secondary task was to consider various magnetic circuit configurations for the materials under evaluation.

The major task of the design and build phase is to use the material information obtained during the first phase to finalize the design of the components of the scanner consistent with design goals. A secondary task of this stage is the consideration of all practical antenna configurations, also by using the results obtained during the first phase. The results of this effort will be to define the parameters of practical configurations.

The third phase, as stated, will be the testing portion of the program. The tests during this phase will partially consist of obtaining radiation patterns of the model as a function of scan angle and applied magnetic field. Tests will also be run to obtain gain and insertion loss measurements for the model as a function of scan angle. Maximum scan speeds and control power will also be determined.

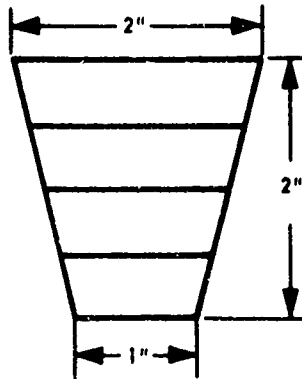
SECTION 2

FLARED SLAB FERRITE SCANNER

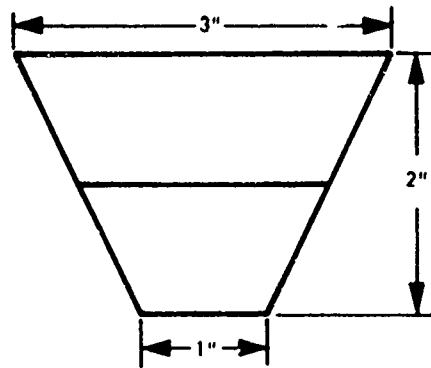
In the last quarterly report (Ref. 3), a change in the shape of the ferrite used in the scanner was proposed in order to lower the sidelobes and improve the scanning capability. This change consisted of flaring the ferrite such that the output end of the ferrite was larger than the input. Two proposed shapes for this flaring are shown in Figure 1.

Both of these ferrite slabs were tested during the last quarter. The first one had the dimensions shown in Figure 1a. It was constructed from four, one-half by one-half inch ferrite bars placed side by side and perpendicular to the direction of propagation. Figure 2a through 2f are the radiation patterns for this scanner. These patterns, taken as a function of applied current, show a considerable improvement in sidelobe level over the parallel side ferrite slabs tested earlier. The maximum sidelobe level occurs in Figure 2b, and it is -8.5 db below the main lobe. This represents a decrease of 5 db from the sidelobe level of the previously tested non-tapered slabs.

The second scanner tested had a three-inch output aperture and consisted of two, one-half by one inch slabs placed as shown in Figure 1b. Radiation patterns for this device are given in Figure 3a through 3j. Figure 3j indicates that as much as 35 degrees of scan are possible with this device. In addition, the maximum sidelobe level occurs in Figure 3b and is -6 db below the main lobe. It should also be noted that the beamwidth increases with scan angle from 10.5 degrees in Figure 3a to 14.5 degrees in Figure 3i. In Figure 3j, the beam has started to split into a narrow main beam and two rather high sidelobes. As the current is increased from this level, the sidelobes increase relative to the main lobe.

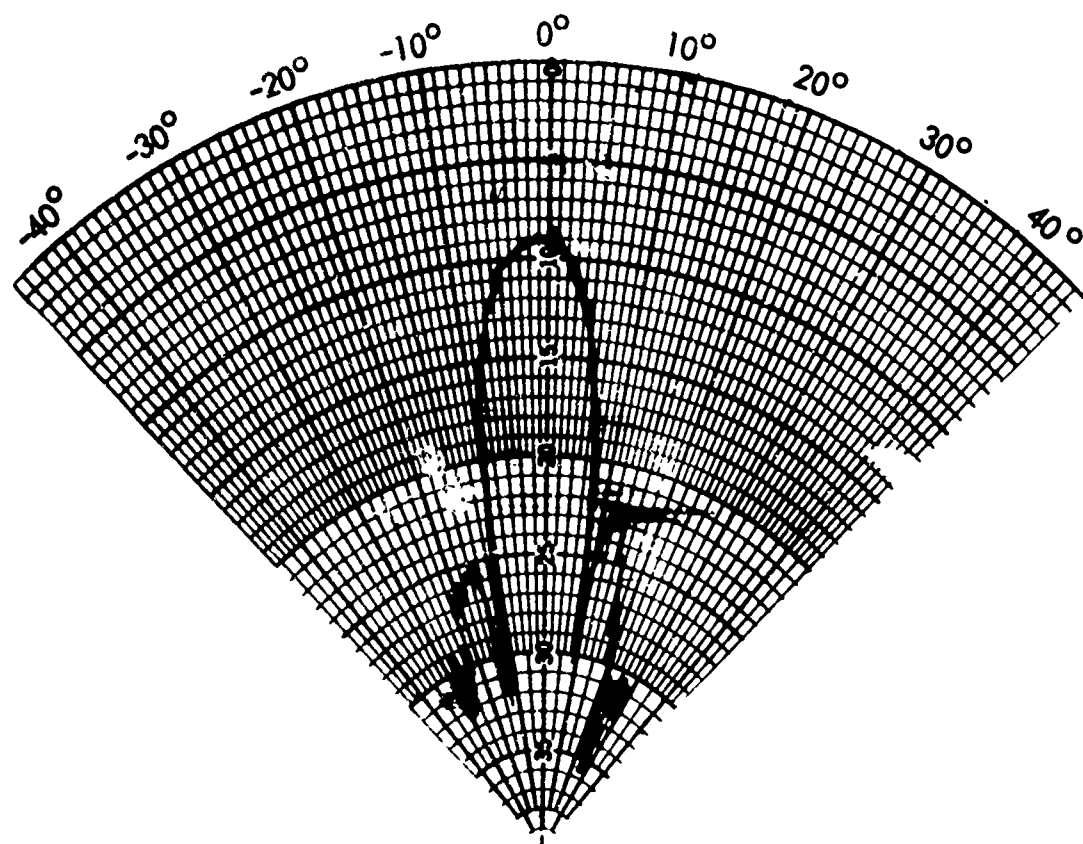


(a)

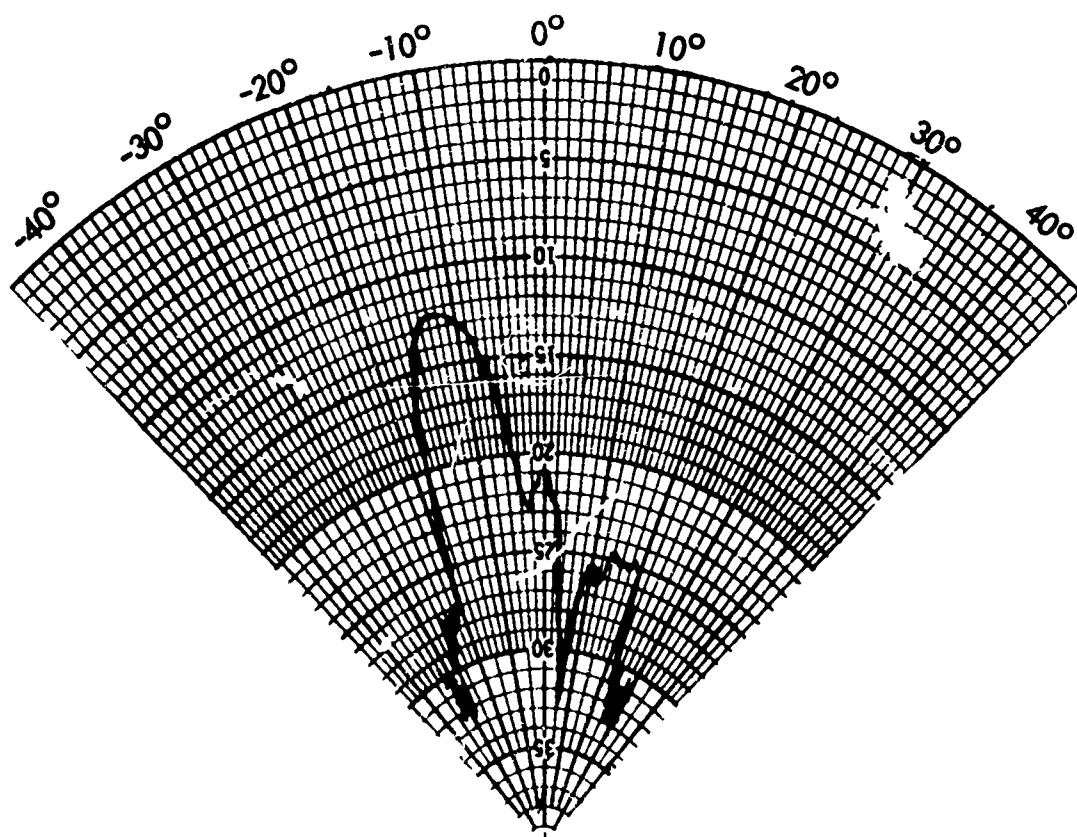


(b)

Figure 1. Geometry of Tapered Ferrite Slabs

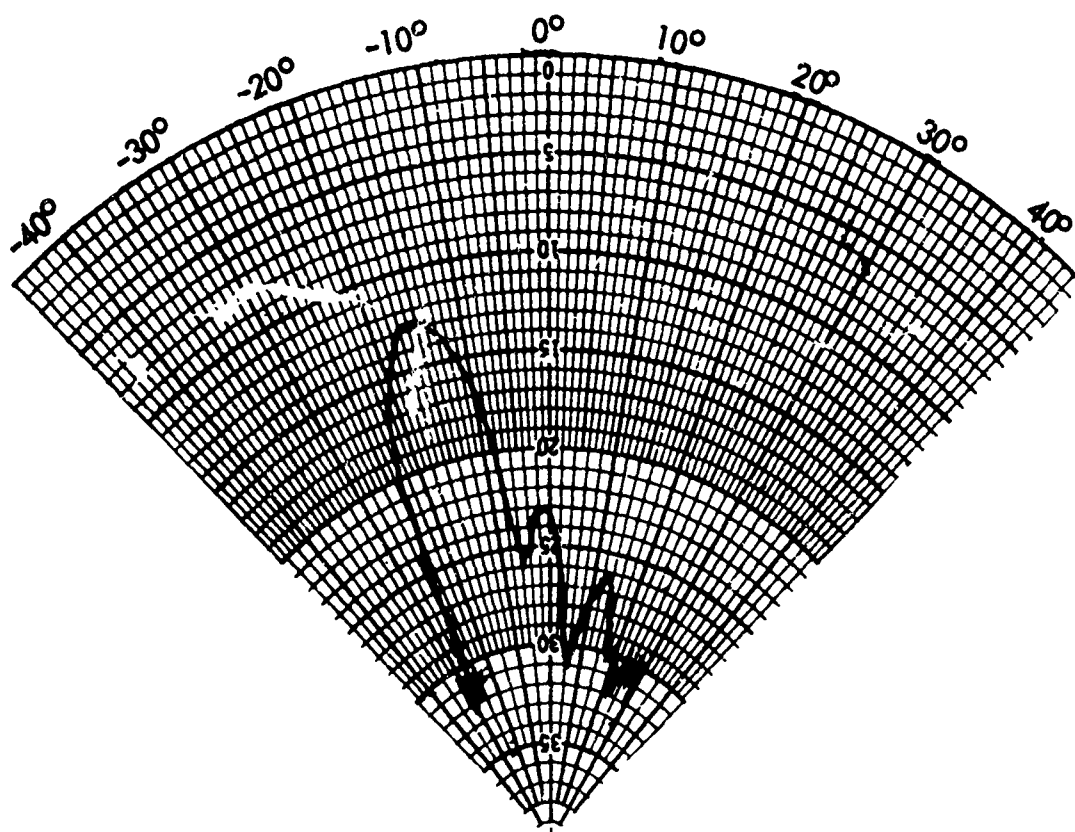


(a) $I = 0$ ma

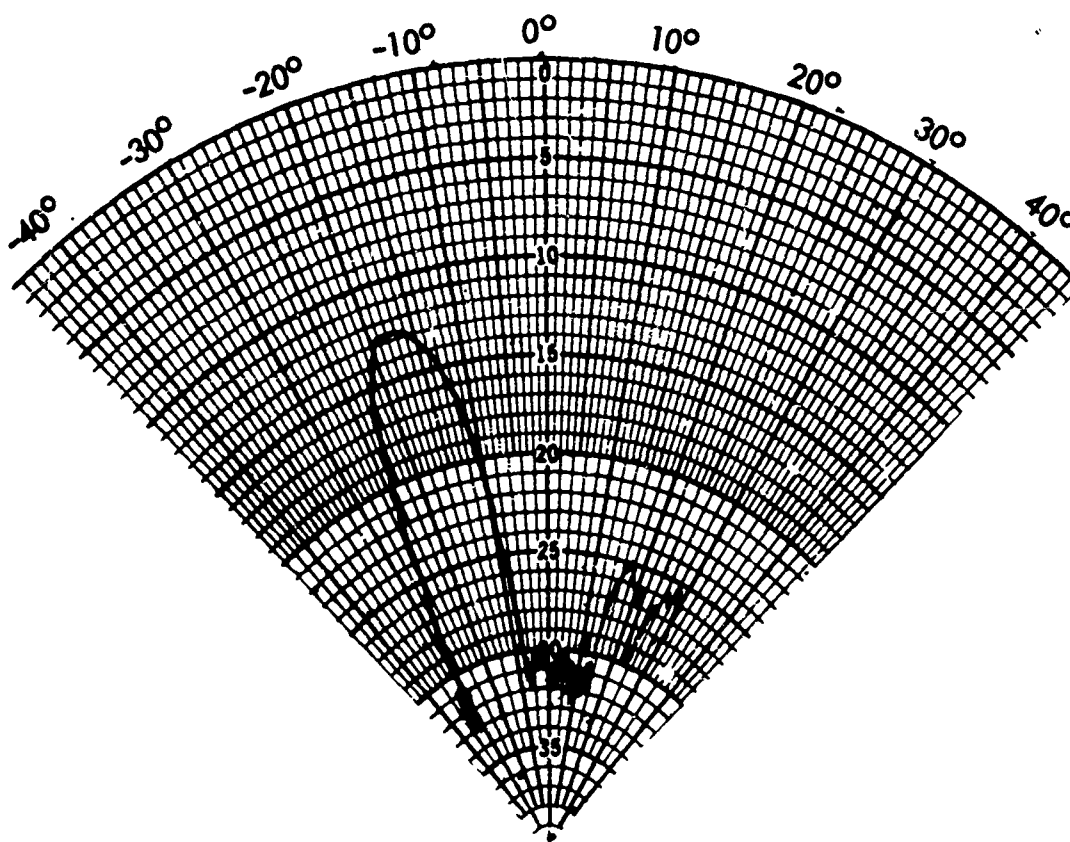


(b) $I = 100$ ma

Figure 2. Radiation Patterns Using Scanner 1a (Sheet 1 of 3)

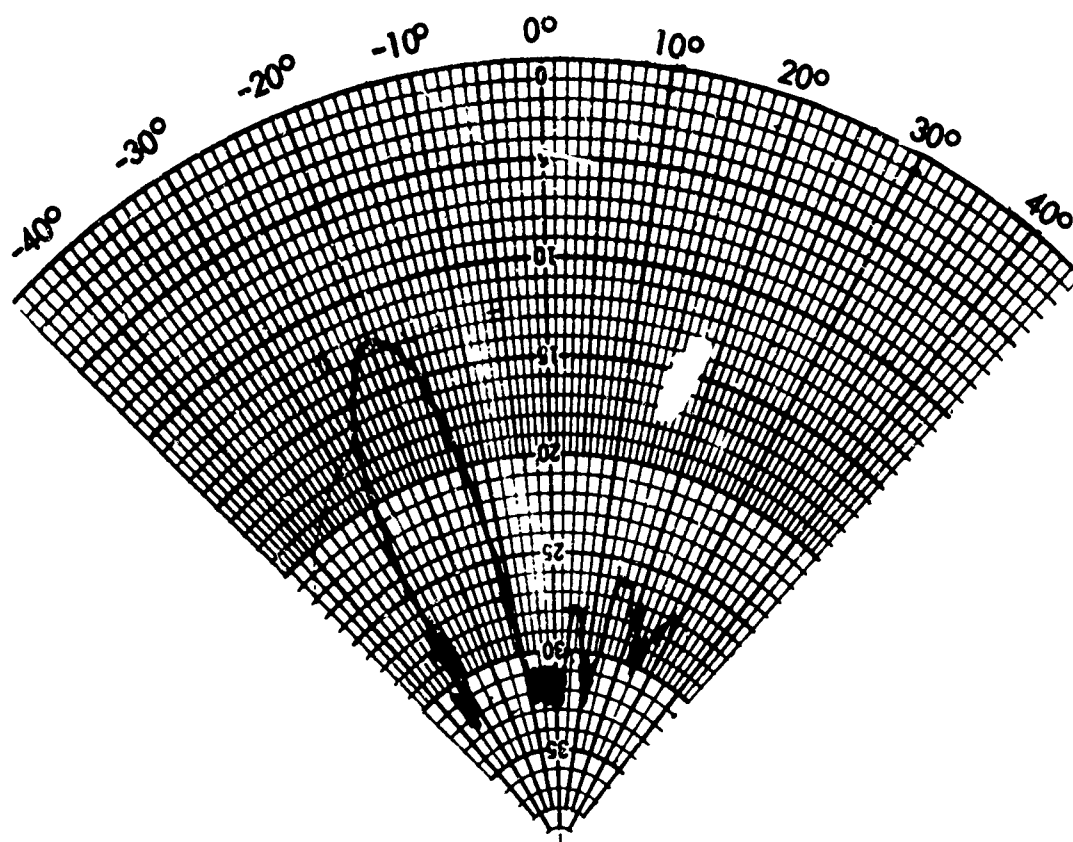


(c) $I = 150$ ma

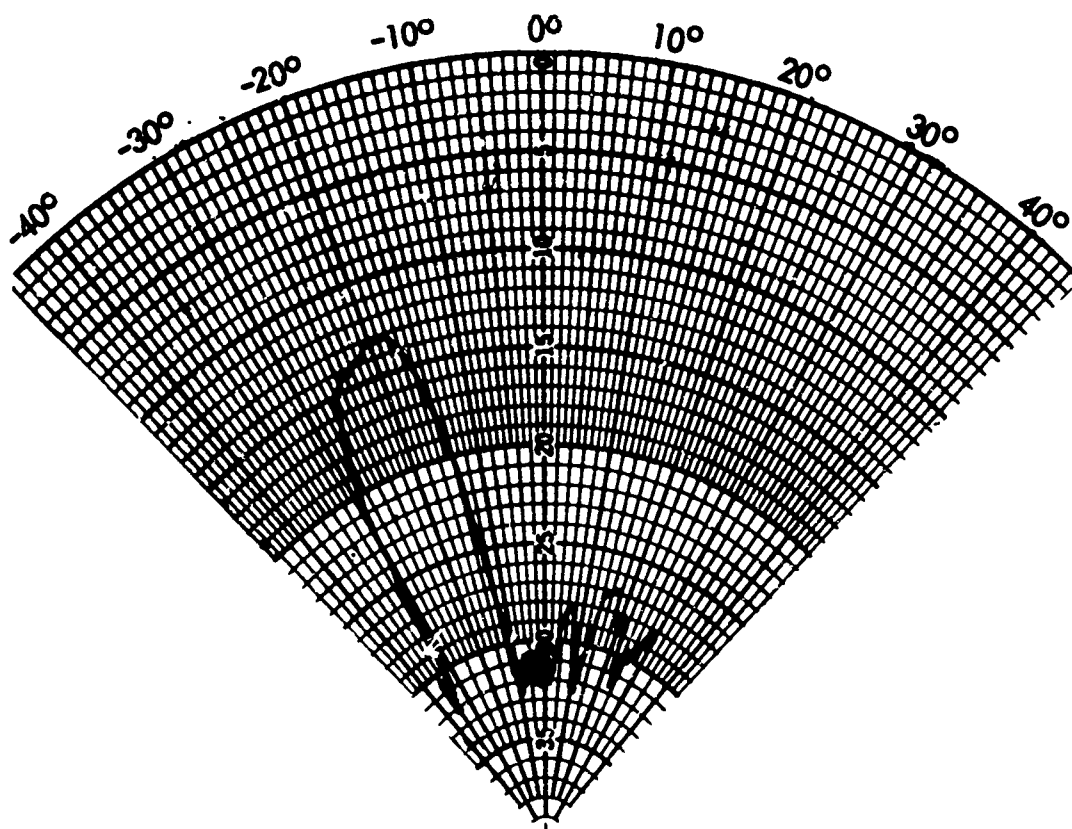


(d) $I = 200$ ma

Figure 2. Radiation Patterns Using Scanner 1a (Sheet 2 of 3)

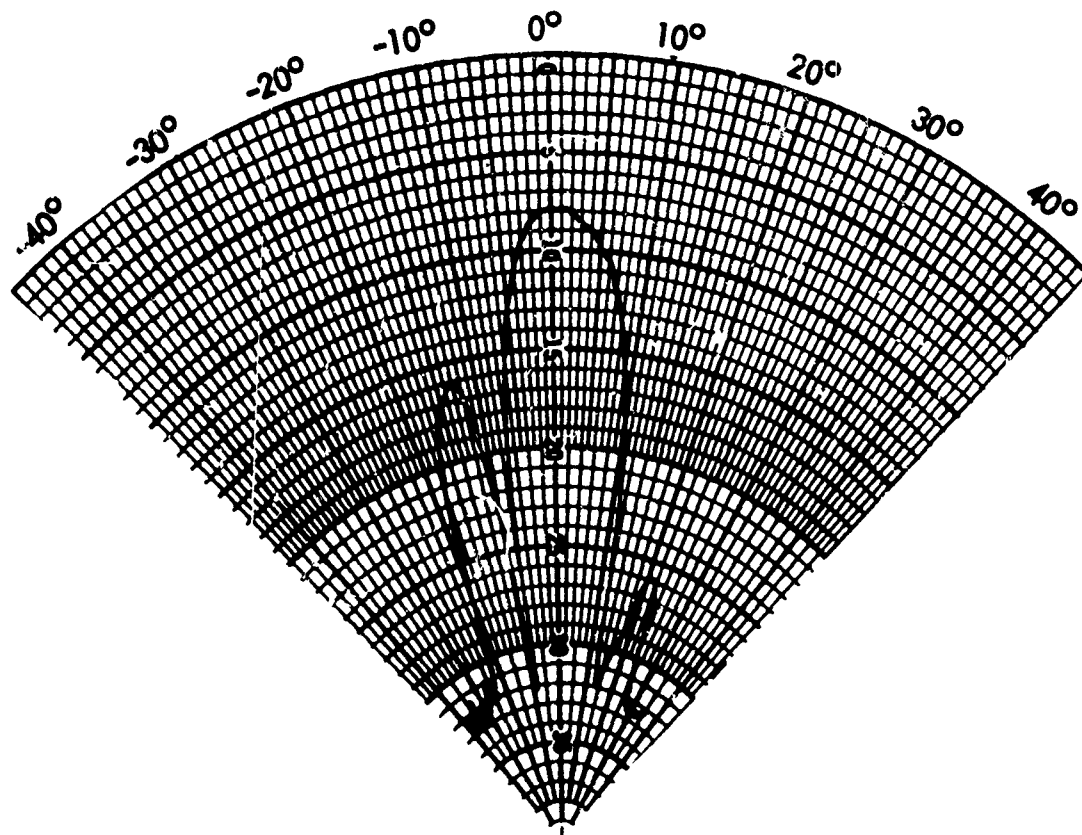


(e) $I = 250$ ma

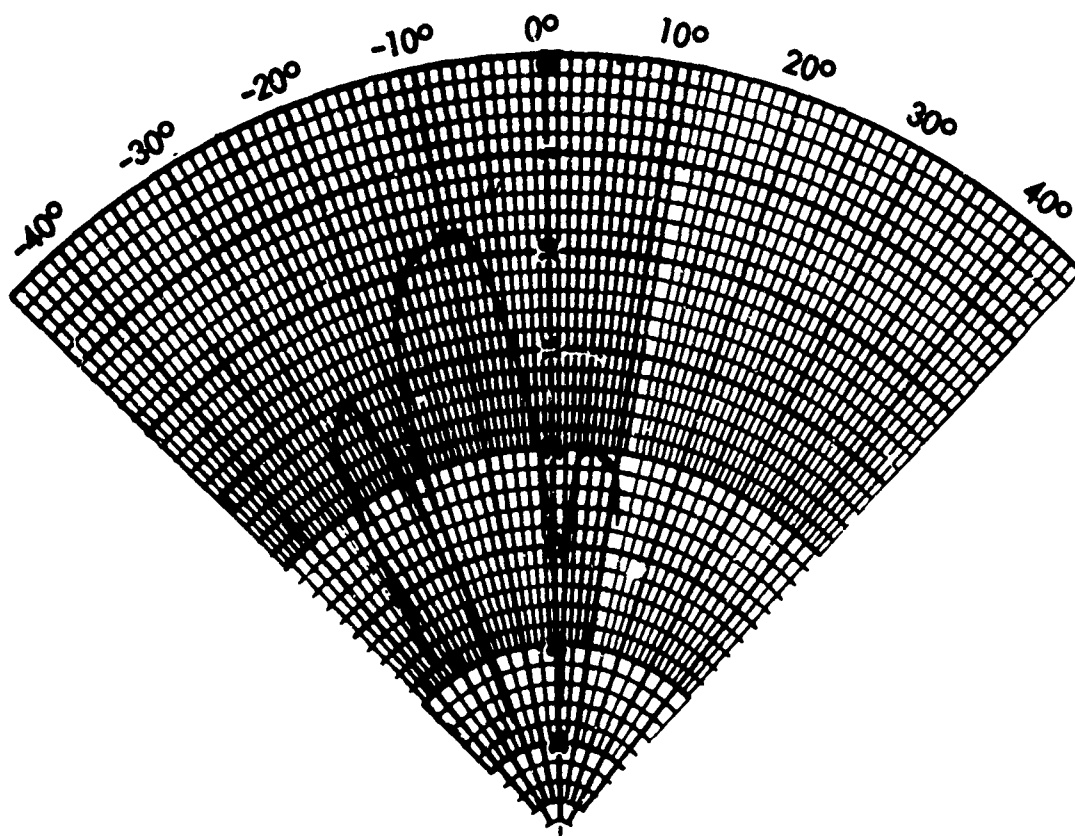


(f) $I = 275$ ma

Figure 2. Radiation Patterns Using Scanner 1a (Sheet 3 of 3)

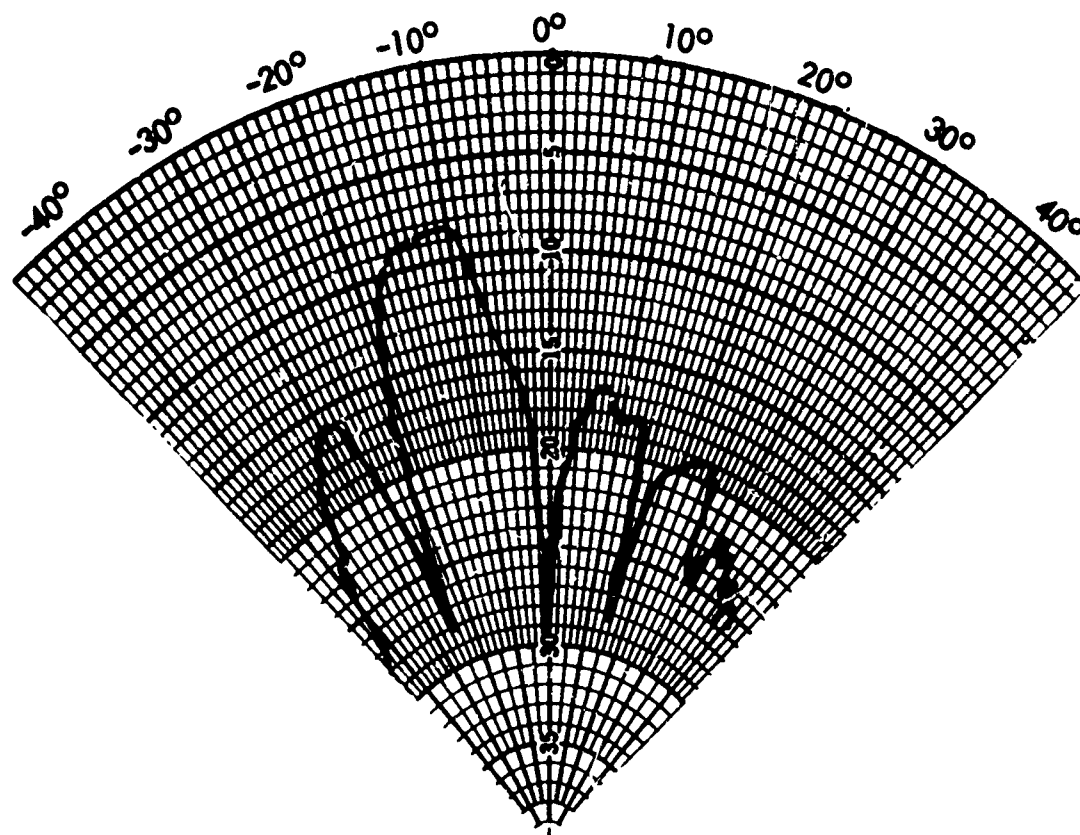


(a) $I = 0$ ma

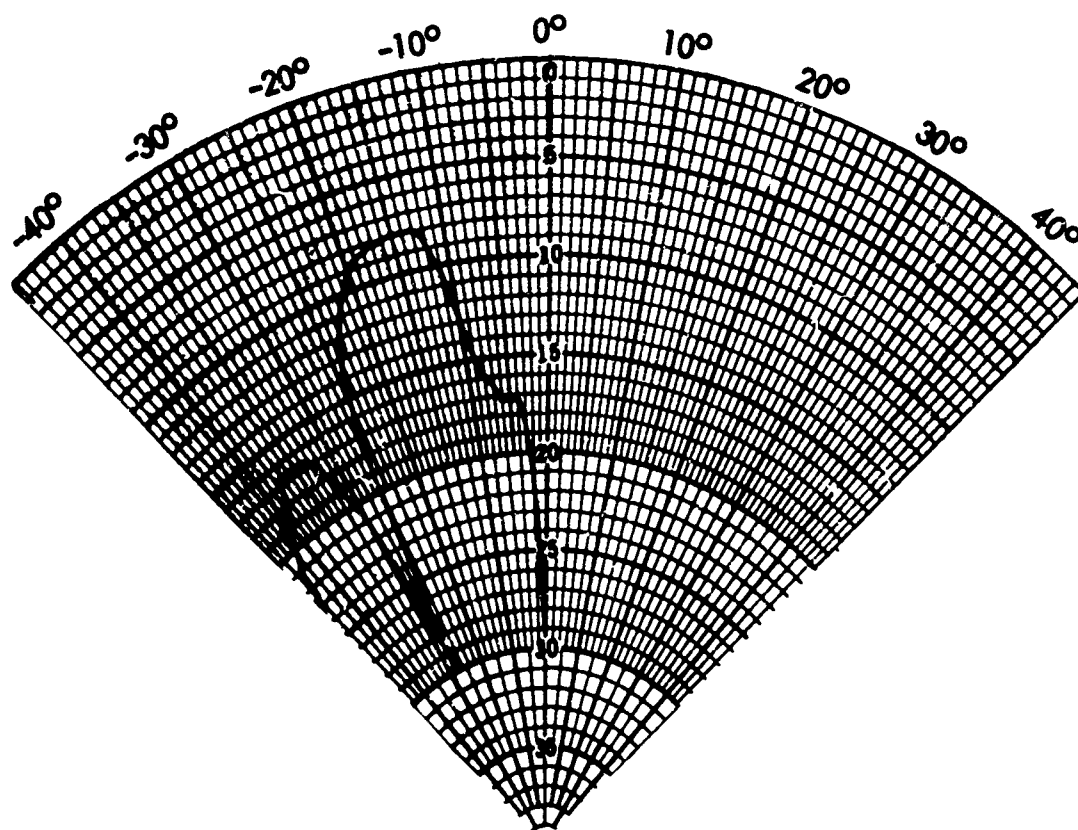


(b) $I = 100$ ma

Figure 3. Radiation Patterns Using Scanner 1b (Sheet 1 of 5)

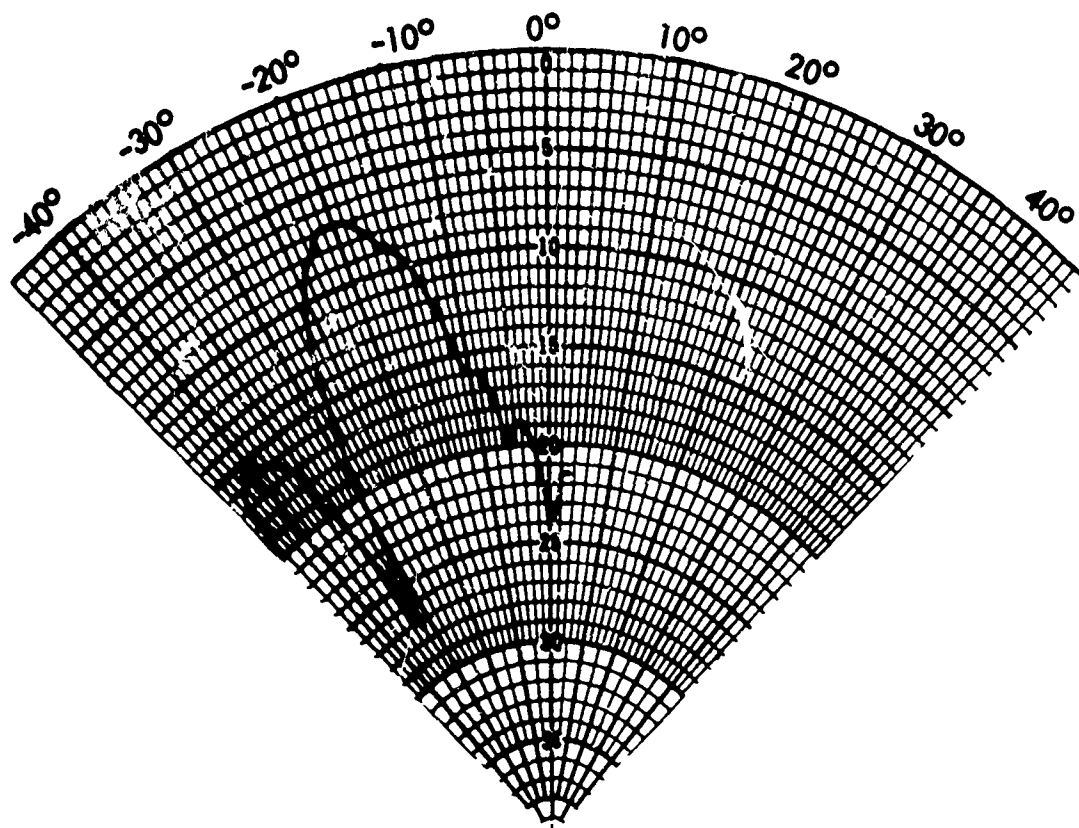


(c) $I = 200$ ma

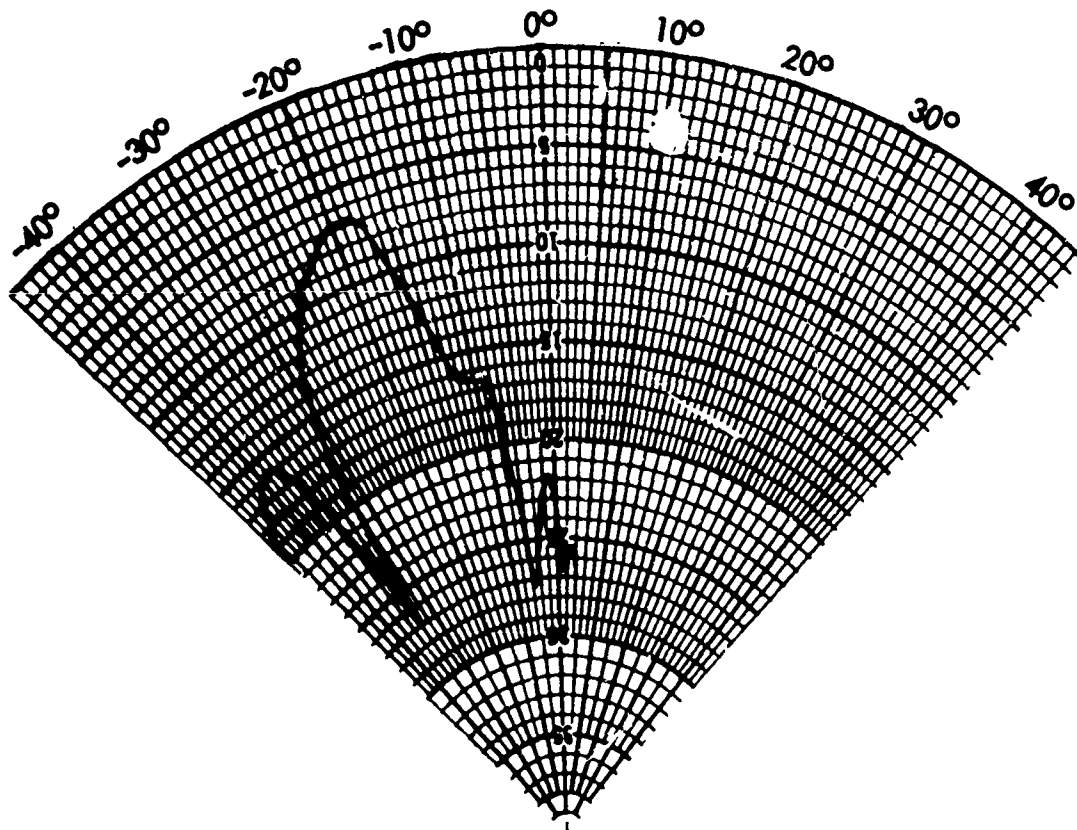


(d) $I = 400$ ma

Figure 3. Radiation Patterns Using Scanner 1b (Sheet 2 of 5)

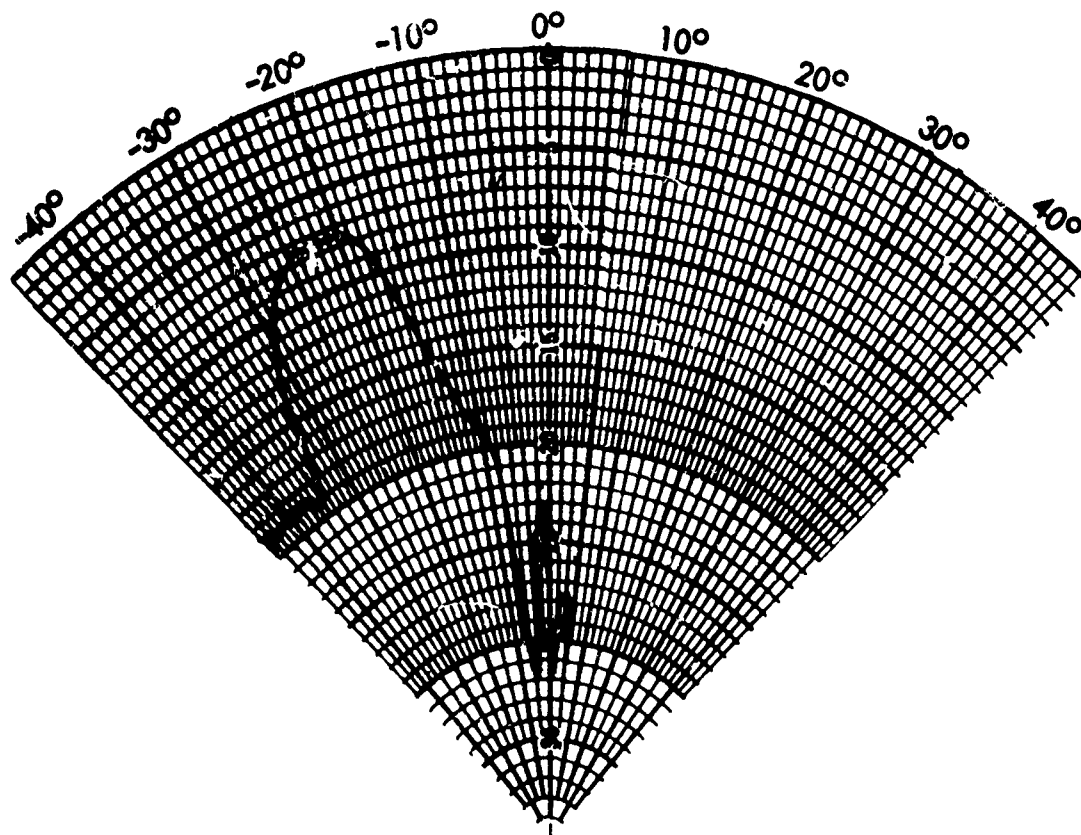


(e) $I = 600 \text{ ma}$

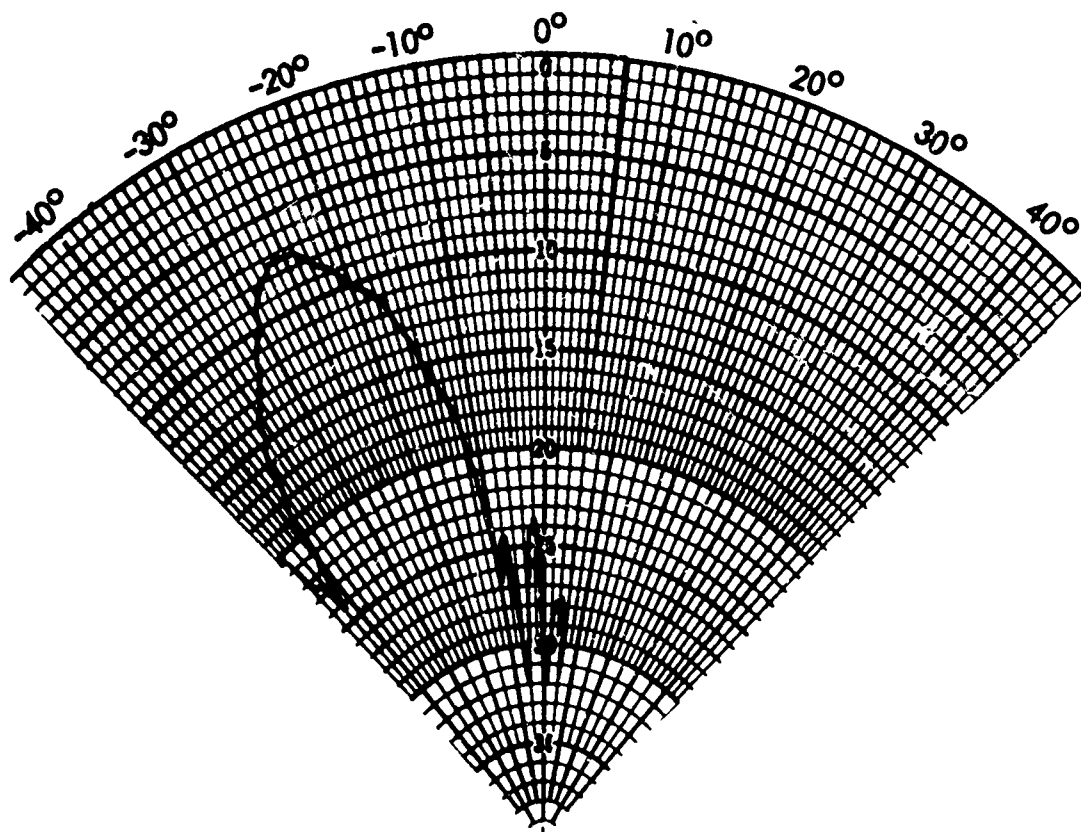


(f) $I = 800 \text{ ma}$

Figure 3. Radiation Patterns Using Scanner 1b (Sheet 3 of 5)

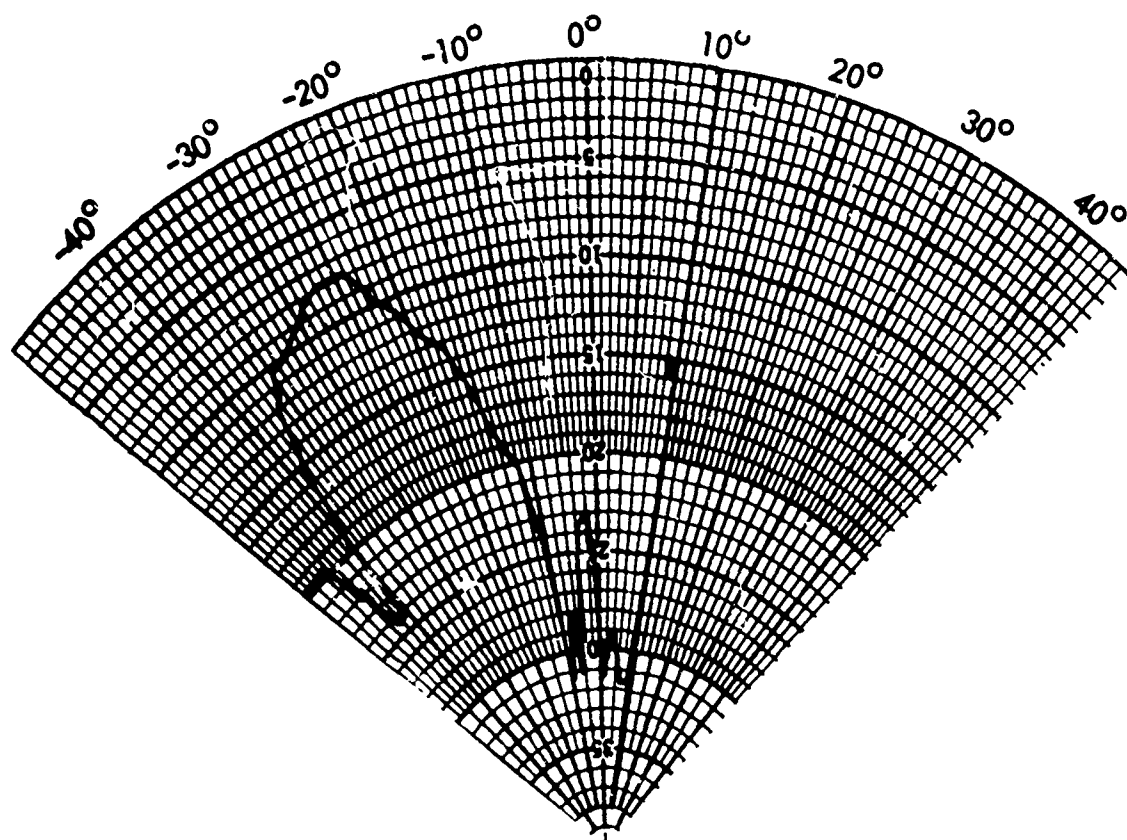


(g) $I = 1.0$

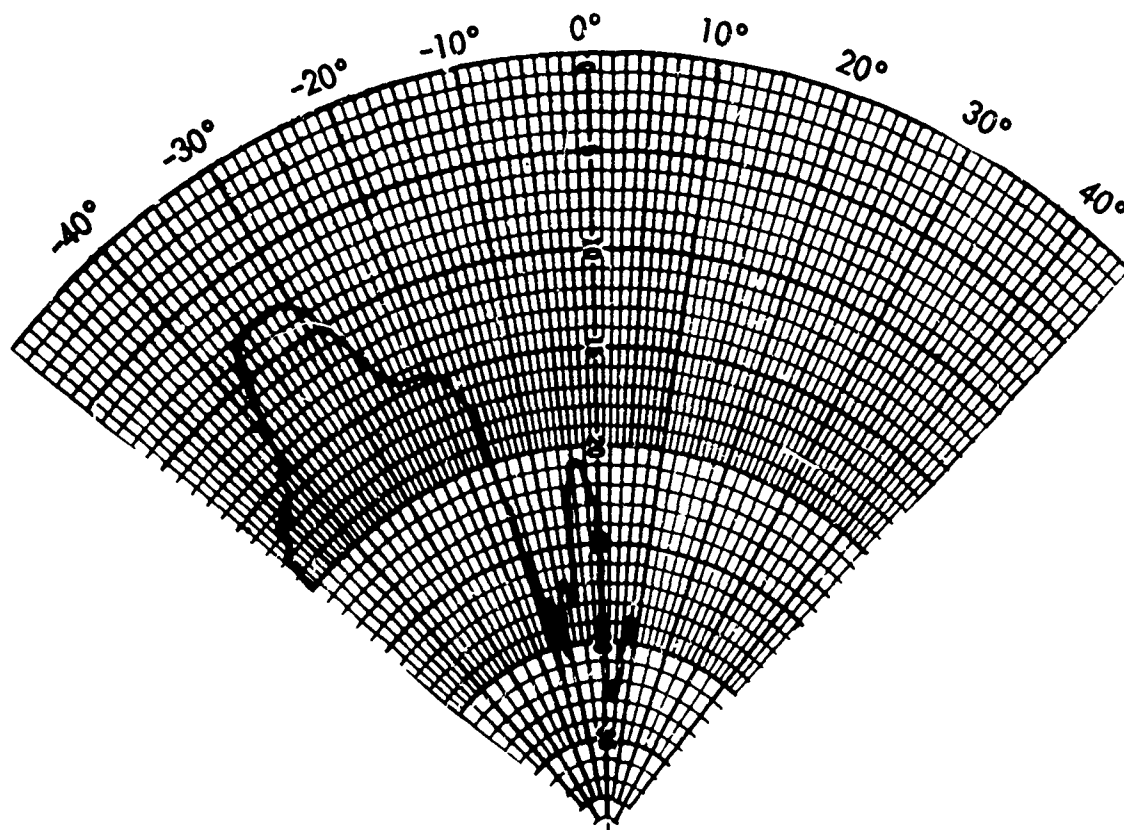


(h) $I = 1.2$

Figure 3. Radiation Patterns Using Scanner 1b (Sheet 4 of 5)



(i) $I = 1.4 a$



(i) $I = 1.8 a$

Figure 3. Radiation Patterns Using Scanner 1b (Sheet 5 of 5)

All tests performed on the tapered ferrite slab scanners indicate that these devices produce considerably lower sidelobes than the non-tapered devices tested earlier. This improvement in scanner shape will be incorporated in all future antenna designs.

It should also be noted that the principle of tapering the ferrite may be extended to the two dimensional scanner. Here the ferrite may be tapered in two directions such that a truncated pyramid shaped ferrite block is formed. Electromagnetic cores and coils may then be placed on the four tapered sides of the block.

Two dimensional scan was demonstrated earlier in the program using a parallel side ferrite block. The results of this work were included in Reference 3. Tapering the ferrite in two planes is expected to considerably improve the radiation patterns for two-dimensional scan.

SECTION 3

FINAL ANTENNA DESIGN

In the last quarterly report (Ref. 3), the various methods for employing the ferrite scanner technique in a narrow beam, steerable antenna were discussed. Both the single large scanner approach and the array of smaller scanners appear to be feasible. The multiple aperture approach has been chosen for further consideration in this program. A device of this type will be built, tested, and delivered as part of the program requirements.

3.1 Aperture Analysis

Considerable analysis of multiple aperture antennas was presented in Section 4 of Reference 3. The beam forming properties of such an array were analyzed using optical diffraction theory. Figure 4 shows the geometry of the aperture that was analyzed. One result of the analysis is that for ratios of S to D greater than one, the radiation pattern in the yz-plane has grating lobes, and the relative amplitude of these lobes increases as the S to D ratio increases. Therefore, in order to decrease sidelobes, the apertures should be placed as close together as possible. In particular, if $\frac{S}{D} = 1$, the grating lobes are eliminated altogether.

When ferrite scanners are used for the array elements, the problem of reducing the S to D ratio is complicated by the scanner geometry. The advantages of flaring the ferrite scanning element were discussed in Section 2 of this report. However, when flared elements are placed side by side to form an array, the S to D ratio is greater than one since the effective aperture of a scanner is the area of its input surface. This is shown in Figure 5 where the S to D ratio is two. For this value, and for a three-element array as shown, the first grating lobe would be only -5.0 db below the main beam. In addition,

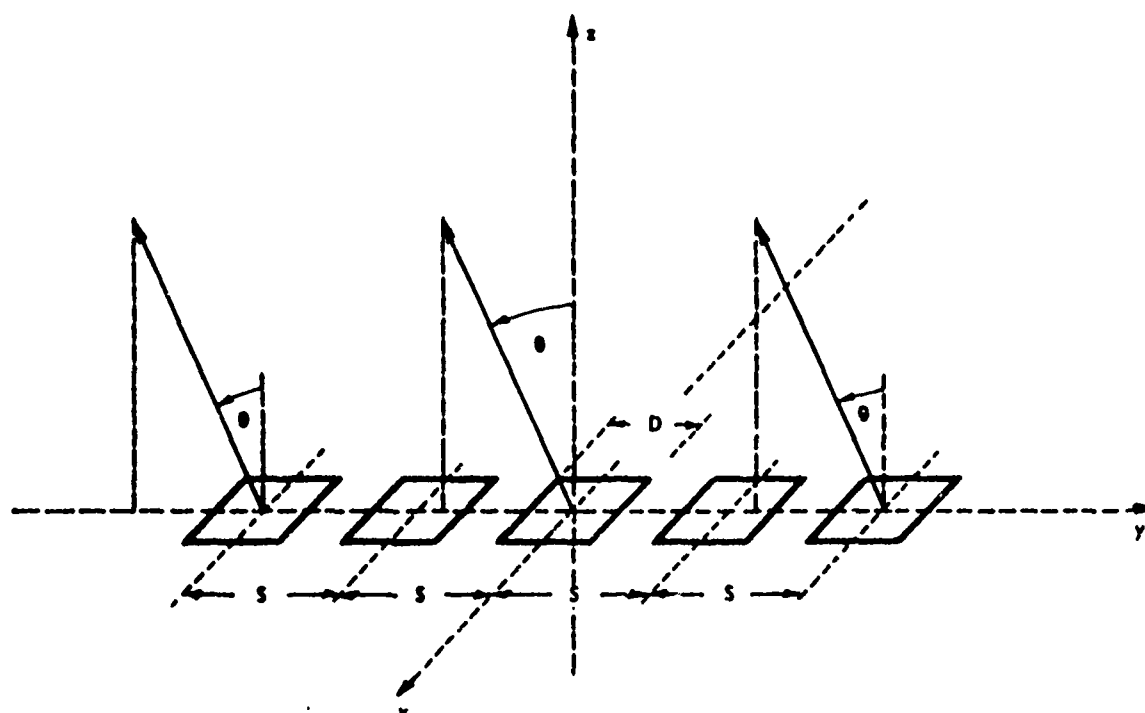


Figure 4. One-Dimensional Array of Rectangular Elements

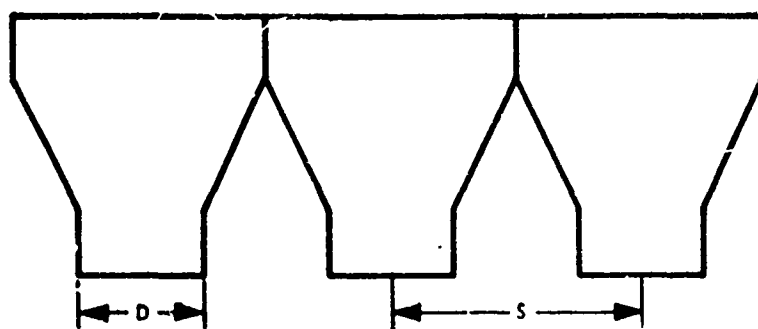


Figure 5. Tapered Scanners Placed as Close Together as Possible

if any phase errors are present between the elements, the grating lobe level will increase. This sidelobe level is unacceptable for many applications.

The sidelobe level may be substantially reduced by staggering the scanning elements as shown in Figure 6. Here the effective S to D ratio is one and the grating lobes have been eliminated. The final antenna design will employ staggered elements in order to take advantage of this sidelobe reduction.

An analysis of the radiation patterns for this aperture configuration has been performed and is included in Appendix I. The scanners are assumed to be fed by diagonal horns (Ref. 4) excited with circularly polarized waves. The radiation from this array will therefore be circularly polarized and, at each point in space, the electric field will have two components in time and space quadrature.

Calculated radiation patterns for the antenna shown in Figure 6 are given in Figures 7a and 7b. These patterns indicate that the antenna beamwidth is about 2.2 degrees and the largest sidelobe is 13.5 db below the main lobe.

3.2 Array Feed System

Ferrite scanners were chosen as antenna elements to provide a method for scanning the individual element patterns. However, in order to scan the overall array pattern, the relative phase between array elements must be adjusted. Phase shifters are therefore needed in the individual element feed lines.

Figures 8a and 8b show the proposed feed system for a five-element array. The figures show the elements on opposite sides of a common mounting plate. Note in Figure 8a that the center feed line does not contain a phase

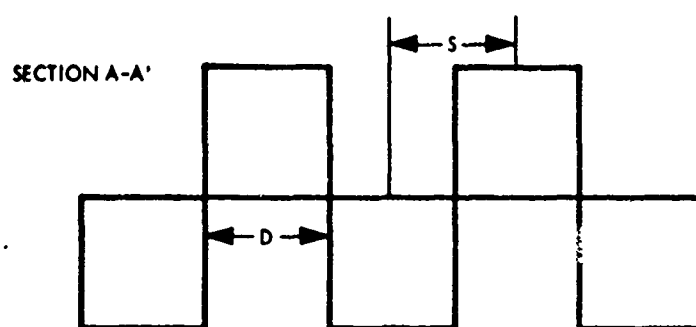
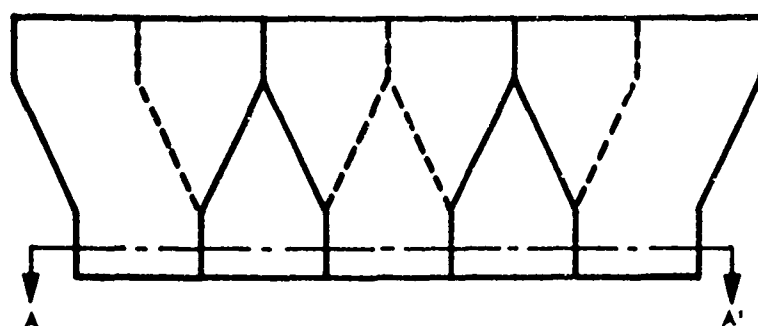


Figure 6. Tapered Scanners Staggered to Reduce the Effective S to D Ratio to One

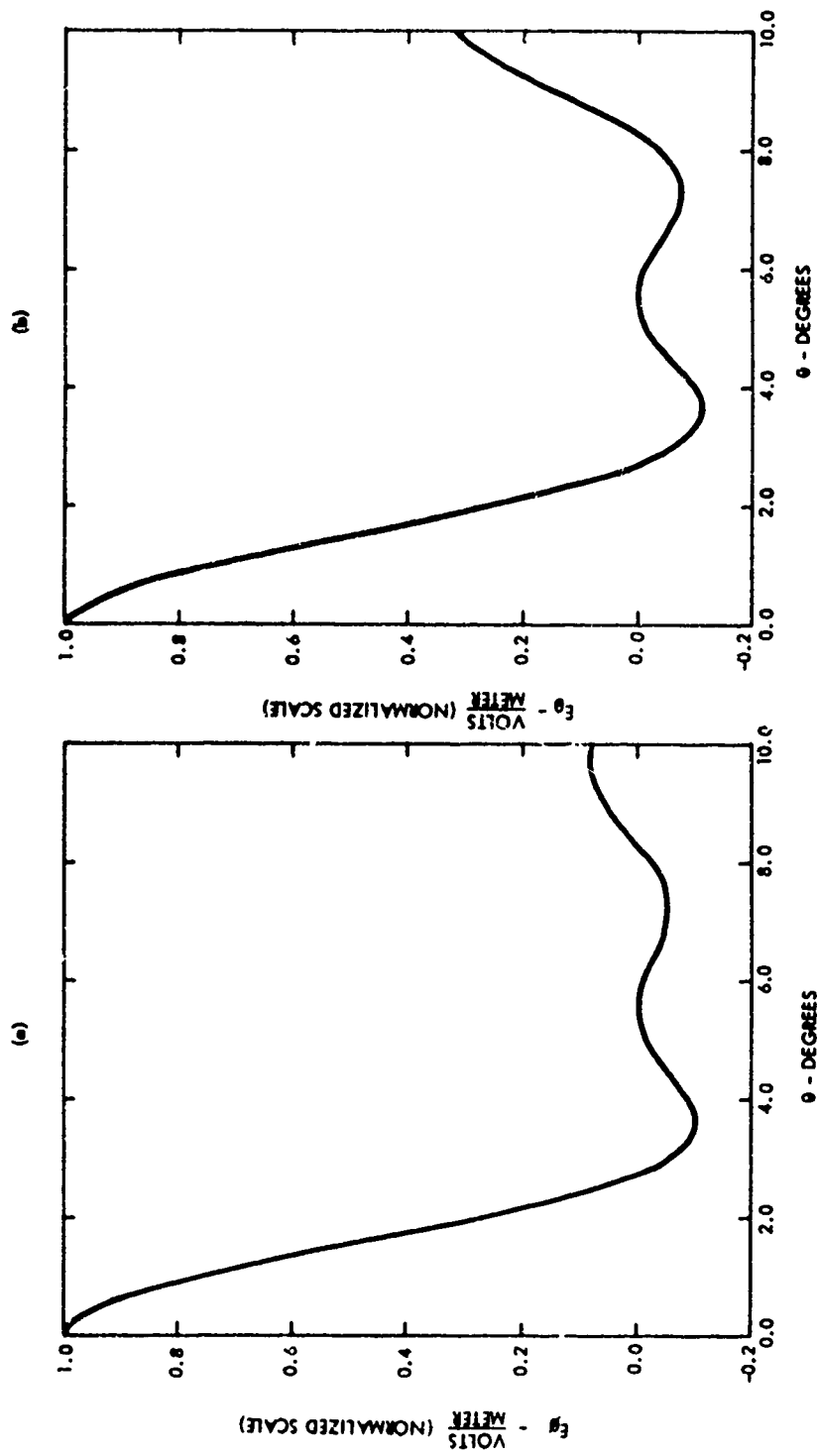
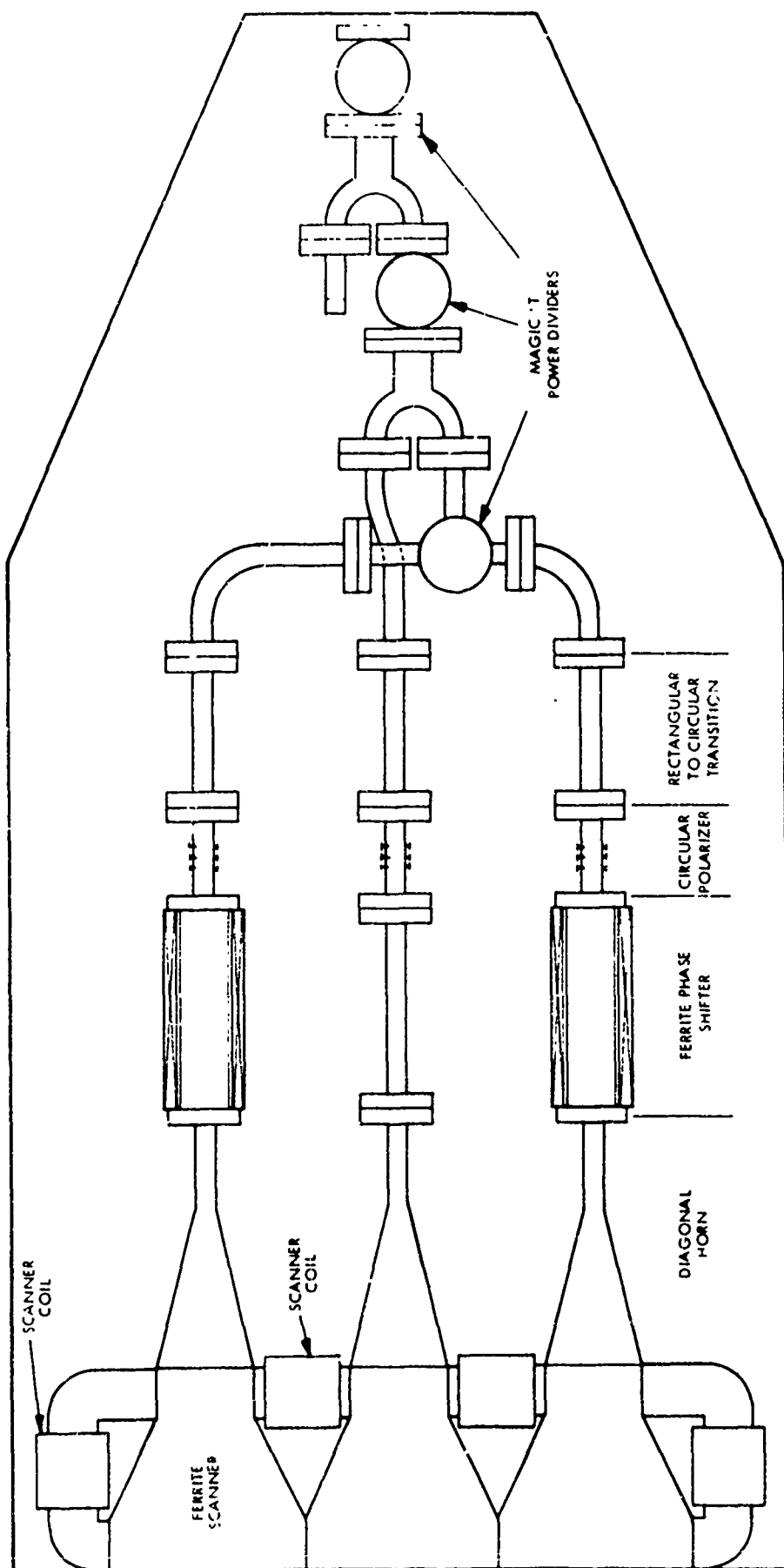
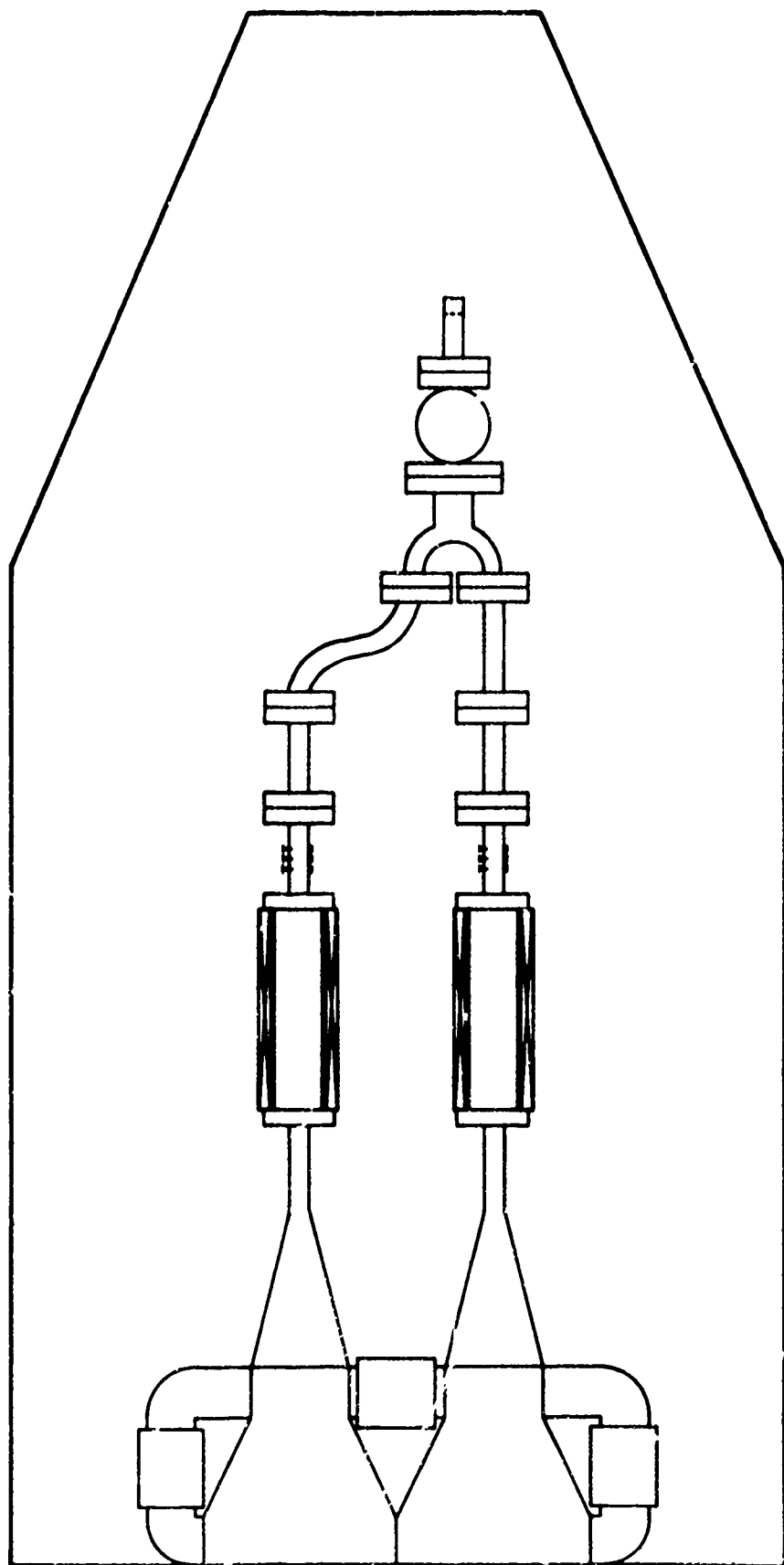


Figure 7. Components of Radiation Field



a) Side 1

Figure 8. Full Scale Drawing of Feasibility Antenna (Sheet 1 of 2)



b) Side 2

Figure 8. Full Scale Drawing of Feasibility Antenna (Sheet 2 of 2)

shifter. Thus, the phase shifts in the other four lines will be made relative to this line. Note also that each phase shifter is preceded by a circular polarizer. The input wave to each shifter is therefore circularly polarized.

The type of phase shifter being constructed is the Faraday rotator type as illustrated in Figure 9. This device consists of a ridged circular waveguide containing a rod of ferrite at its center. A DC magnetic field is applied along the guide axis. As this field is varied in magnitude, the phase of a circular polarized wave traveling down the guide will be shifted.

Other components of the feed system include diagonal horns and rectangular-to-circular waveguide transitions. These components are being constructed using electroforming techniques. The remaining feed components consist of sections of rectangular waveguide and magic "T" junctions which are used as power dividers.

Analysis of the feed system indicates that the center three array elements will each transmit one-fourth of the input power, and the outer two elements will transmit one-eighth. It is noted that this amplitude taper was assumed in calculating the radiation patterns shown in Figures 7a and 7b. Therefore, these figures represent the patterns of the antenna in Figures 8a and 8b.

3.3 Ferrite Scanner Magnetic Circuits

Figures 8a and 8b also show the ferrite scanners and the proposed arrangement of coils and magnetic core material. The DC magnetic fields for two scanners are shown in Figure 10. This figure illustrates how one coil is used to provide part of the field for each of two adjacent scanners. This method increases the efficiency of the magnetic circuit and reduces the required control power.

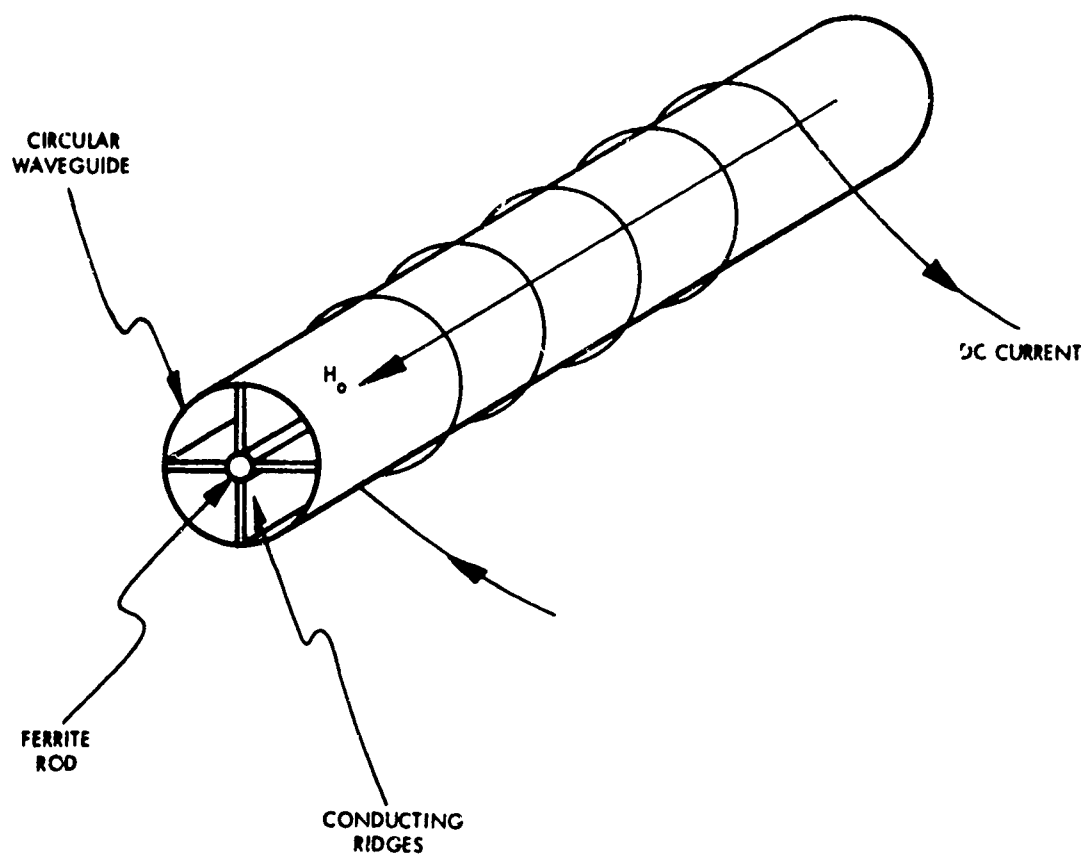


Figure 9. Geometry of Ferrite Phase Shifter

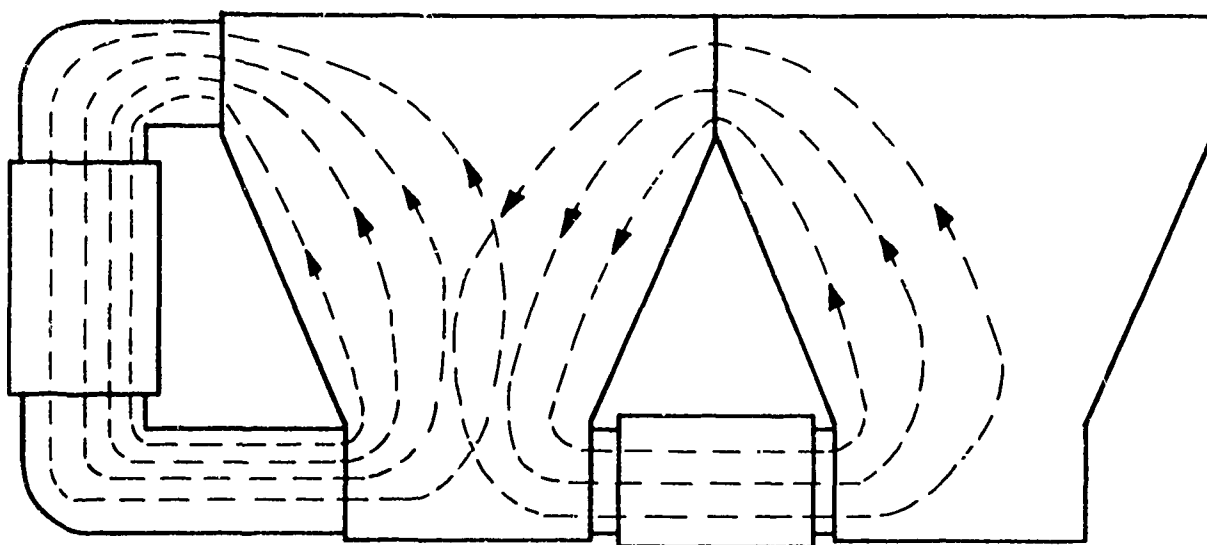


Figure 10. DC Magnetic Field Configuration in Scanners

3.4 Matching Layers

Dielectric matching layers will be provided at both the input and output ends of the ferrite scanners. A complete analysis of the thickness and dielectric constant required for this application was performed during the study phase of this contract, and the results are presented in Reference 1. The material used has a relative dielectric constant of 3.5, and the layer thickness needed to match plane waves into (or out of) the ferrite is .021 inches. This is the correct value for normal incidence. However, at the output end of the scanner, the wave is incident at oblique angles when the beam is scanned. Therefore, the layer will provide only an approximate match for these waves. The slight reduction in antenna gain at large scan angles will be partially due to this mismatch.

SECTION 4

OPERATION OF FINAL ANTENNA MODEL

The array antenna described in the previous sections, and as shown in Figures 8a and 8b, is capable of forming a 2.2° by 4.8° fan beam at broadside. In addition, the beam may be scanned through $\pm 35^\circ$ in the 2.2° beamwidth plane. This array has the capability to scan the individual element patterns as the overall array pattern is scanned. As a result, the antenna may be scanned over large angles with little decrease in pattern amplitude and beamwidth.

This antenna is currently being constructed and will be tested in the final quarter of this program. Measurements will include efficiency, pattern shape, polarization, maximum scan, control circuit power requirements and hysteresis effects.

SECTION 5

PROGRAM FOR NEXT QUARTER

During the next quarter, a ferrite phase shifter, similar to the one illustrated in Figure 9, will be tested. Construction of the final antenna model will be completed, and the antenna will be tested. Complete sets of data concerning radiation patterns, power requirements, etc., will be obtained. This data will be presented in the final report.

LIST OF REFERENCES

1. Schiller, T.R., "Electronically Steerable Array for Space Vehicle Application," RADC-TDR-64-222, Contract AF30(602)-3041, August 1964.
2. Schiller, T.R., and Heath, W.S., "Electronically Steerable Array - Change A," RADC-TDR-65-90, Contract AF30(602)-3041, May 1965.
3. Schiller, T.R., Weiss, P.F. and Heath, W.S., Electronically Steerable Array - Change A, " RADC-TDR-65-228, Contract AF30(602)-3041, November 1965.
4. Love, A.W., "The Diagonal Horn Antenna," Microwave Journal, March 1962, pp 117-122.
5. Silver, S., "Microwave Antenna Theory and Design," M.I.T. Rad. Lab. Series, McGraw-Hill, p 38.

APPENDIX I

ANTENNA RADIATION FIELD ANALYSIS

The effective aperture of the five-element array is equivalent to the lower drawing of Figure 6. In addition, for radiation patterns in the scan plane, the apertures may be considered to be in line, as in Figure 4.

The total radiation pattern of this antenna is the product of the array pattern E_a and the element pattern E_e :

$$E(\theta) = E_e(\theta)E_a(\theta) \quad (1)$$

From Figure I-1, it is seen that the array pattern is

$$E_a(\theta) = A_0 + A_1 e^{jkS \sin \theta} + A_1 e^{-jkS \sin \theta} \\ + A_2 e^{jk2S \sin \theta} + A_2 e^{-jk2S \sin \theta}$$

or,

$$E_a(\theta) = A_0 + 2A_1 \cos(kS \sin \theta) + 2A_2 \cos(2kS \sin \theta), \quad (2)$$

where A_0, A_1, A_2 are element amplitudes. Since the diagonal horn feeds are circularly polarized, the element pattern will have two components in time and space quadrature:

$$E_e(\theta) = E_\theta + jE_\phi \quad (3)$$

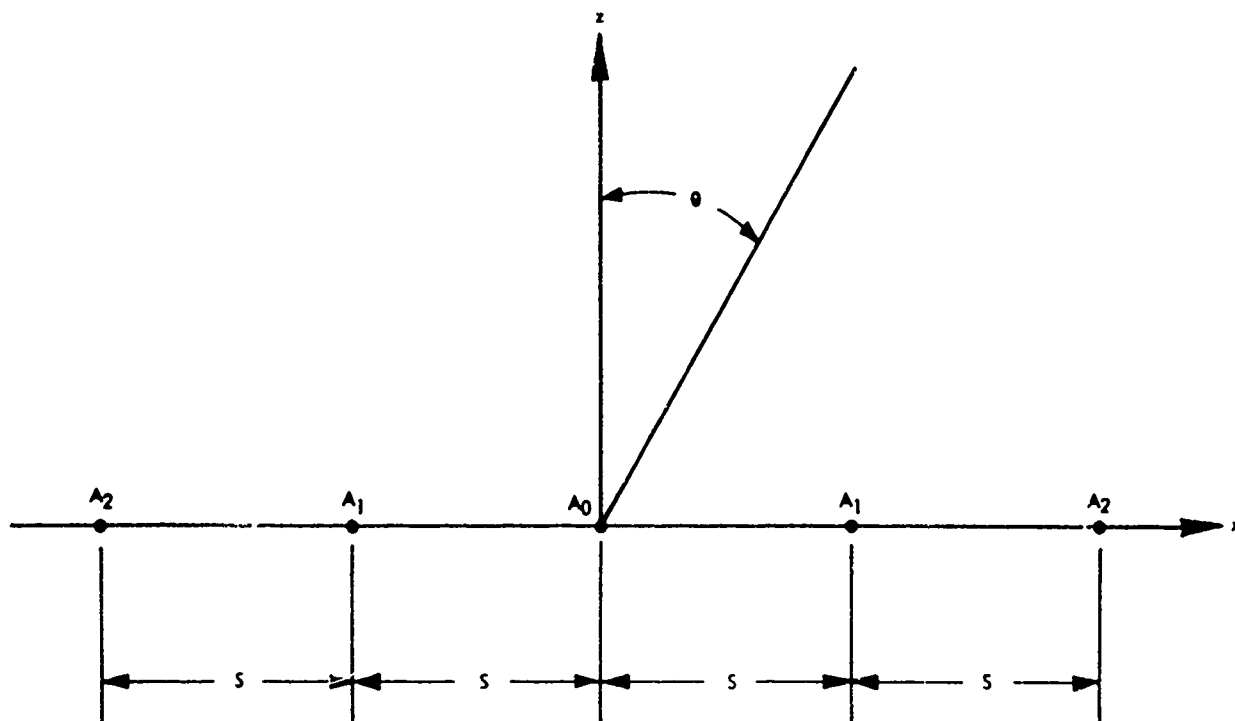


Figure I-1. Phase Centers of Array Elements

The expression for E_{θ} may be calculated using an equation given by Silver (Ref. 5):

$$E_{\theta}(u) = \frac{D}{2} \int_{-1}^1 f_{\theta}(x) e^{jux} dx,$$

where:

$$u = \frac{\pi D}{\lambda} \sin \theta; \text{ and}$$

$f_{\theta}(x)$ is the x dependence of the part of the aperture field which is parallel to E_{θ} (see Figure I-2).

Since the apertures are fed with diagonal horns. (Ref. 4),

$$f_{\theta}(x) = \cos \frac{\pi}{2} x,$$

as shown in Figure I-2.

Thus:

$$\begin{aligned} E_{\theta}(u) &= \frac{D}{2} \int_{-1}^1 \cos \frac{\pi}{2} x e^{jux} dx; \\ &= \frac{D}{2} \frac{4\pi \cos u}{\pi^2 - 4u^2}. \end{aligned}$$

After normalizing at $\theta = 0$ to unity,

$$E_{\theta}(u) = \frac{\pi^2 \cos u}{\pi^2 - 4u^2}. \quad (4)$$

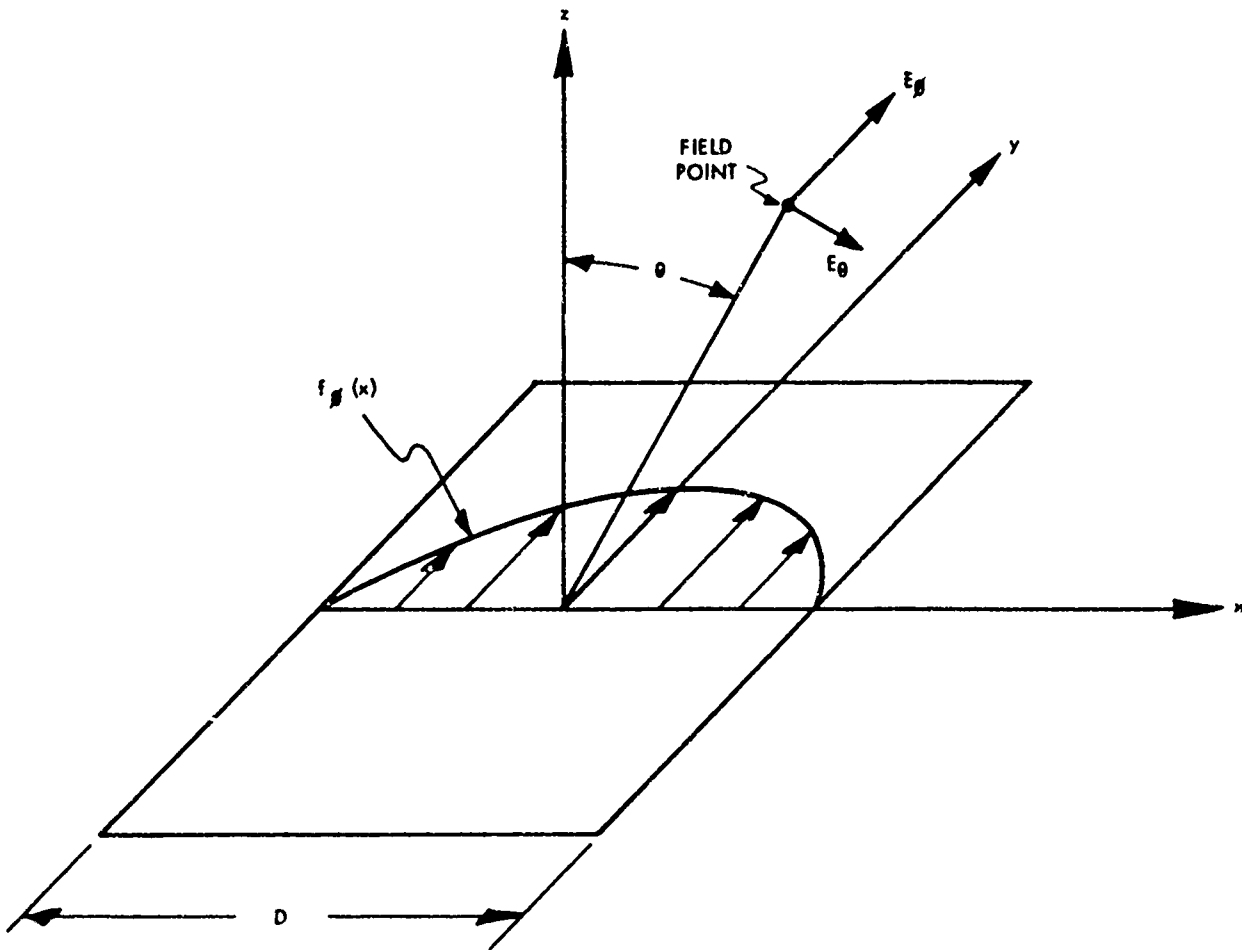


Figure I-2. Y-Component of Aperture Field

In a similar manner the θ component is

$$E_{\theta}(u) = \frac{D}{2} \int_{-1}^1 f_{\theta}(x) e^{jux} dx,$$

and from Figure I-3,

$$f_{\theta}(x) = 1.$$

Thus:

$$E_{\theta}(u) = \frac{\sin u}{u} . \quad (5)$$

Now from equations (1) and (3), the θ component of the total field is

$$E_{\theta}(\theta) = E_{\theta}(u) E_a(\theta). \quad (6)$$

If the following is substituted into equation (2):

$$\begin{aligned} kS \sin \theta &= \frac{2\pi S}{\lambda} \quad \sin \theta = \frac{2S}{D} \left(\frac{\pi D}{\lambda} \sin \theta \right); \\ &= \frac{2S}{D} u \end{aligned}$$

then equation (6) may be expressed completely in terms of u .

Thus:

$$E_{\theta}(u) = \frac{\pi^2 \cos u}{\pi^2 - 4u^2} \left[A_0 + A_1 \cos \left(\frac{2S}{D} u \right) + 2 A_2 \cos \left(\frac{4S}{D} u \right) \right], \quad (7)$$

where:

$$u = \frac{\pi D}{\lambda} \sin \theta .$$

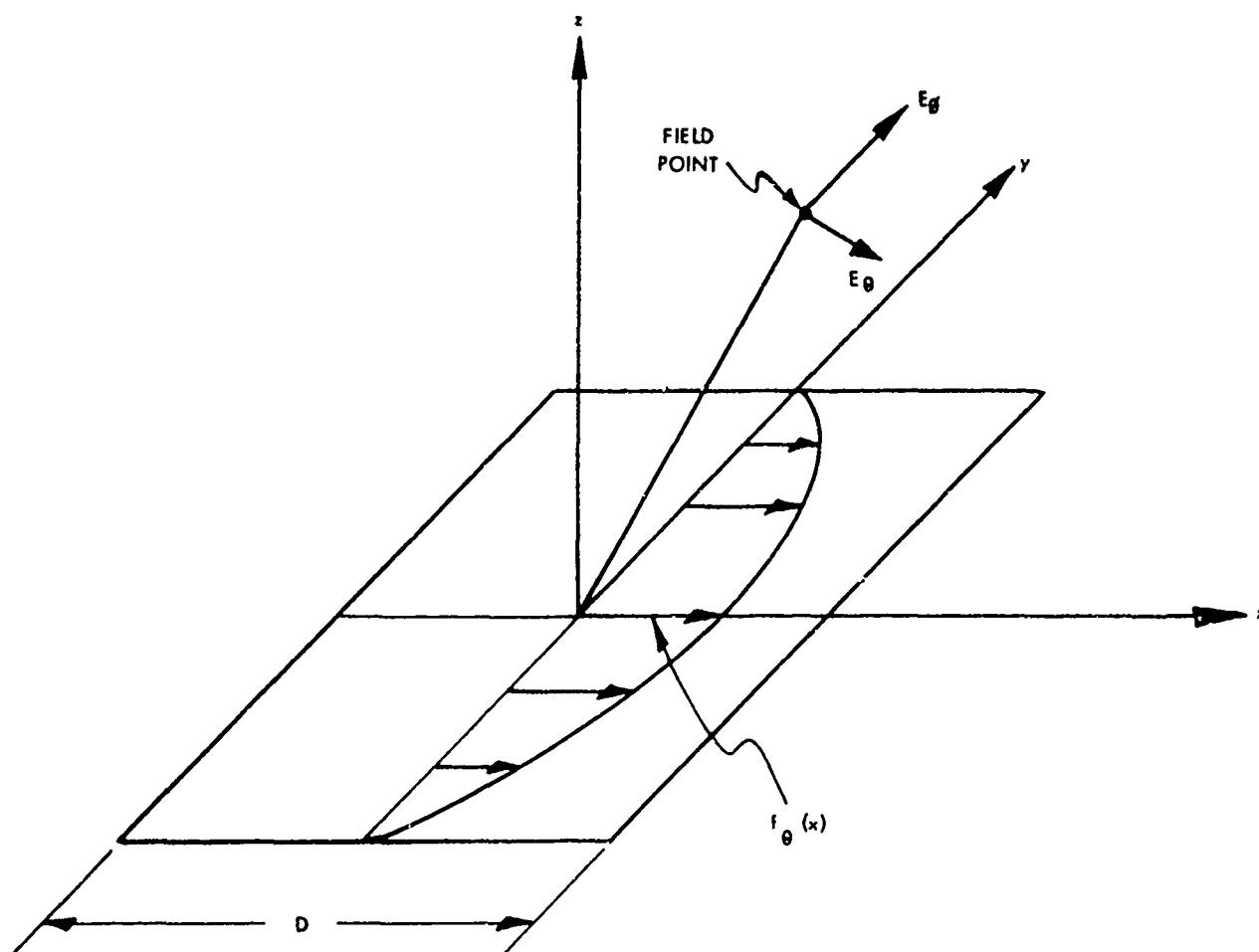


Figure I-3. X-Component of Aperture Field

For the particular feed network used, the power is divided between the elements such that $A_0 = A_1 = \frac{1}{4}$ and $A_2 = \frac{1}{8}$. Finally, equation (7) becomes

$$E_{\theta}(u) = \frac{\pi^2 \cos u}{\pi^2 - 4u^2} \left\{ \frac{1}{4} \left[1 + 2 \cos \left(\frac{2S}{D} u \right) + \cos \left(\frac{4S}{D} u \right) \right] \right\} \quad (8)$$

Similarly, the θ component is found to be

$$E_{\theta}(u) = \frac{\sin u}{u} \left\{ \frac{1}{4} \left[1 + 2 \cos \left(\frac{2S}{D} u \right) + \cos \left(\frac{4S}{D} u \right) \right] \right\}, \quad (9)$$

where:

$$u = \frac{\pi D}{\lambda} \sin \theta ;$$

S = spacing between element phase centers; and

D = width of each aperture.

For the aperture configuration shown in Figure 8, S equals D . Equations (8) and (9) were used to calculate radiation patterns for this aperture. The results are shown in Figures 7a and 7b.

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13 ABSTRACT This report describes the effort expended during the third quarter on the Engineering Change "A" portion of the Electronically Steerable Array Program to design and build a high gain, electronically steerable, millimeter antenna system. During this period the block of ferrite used in the scanner was tapered so that the output end was larger than the input. This resulted in greater scan capability and lower side lobes. In addition, the design of the final antenna model was finalized and construction of the antenna started.		

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