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DESIGN, FABRICATION AND EVALUATION OF AN L-BAND CYLINDRICAL ARR--ETC(U)

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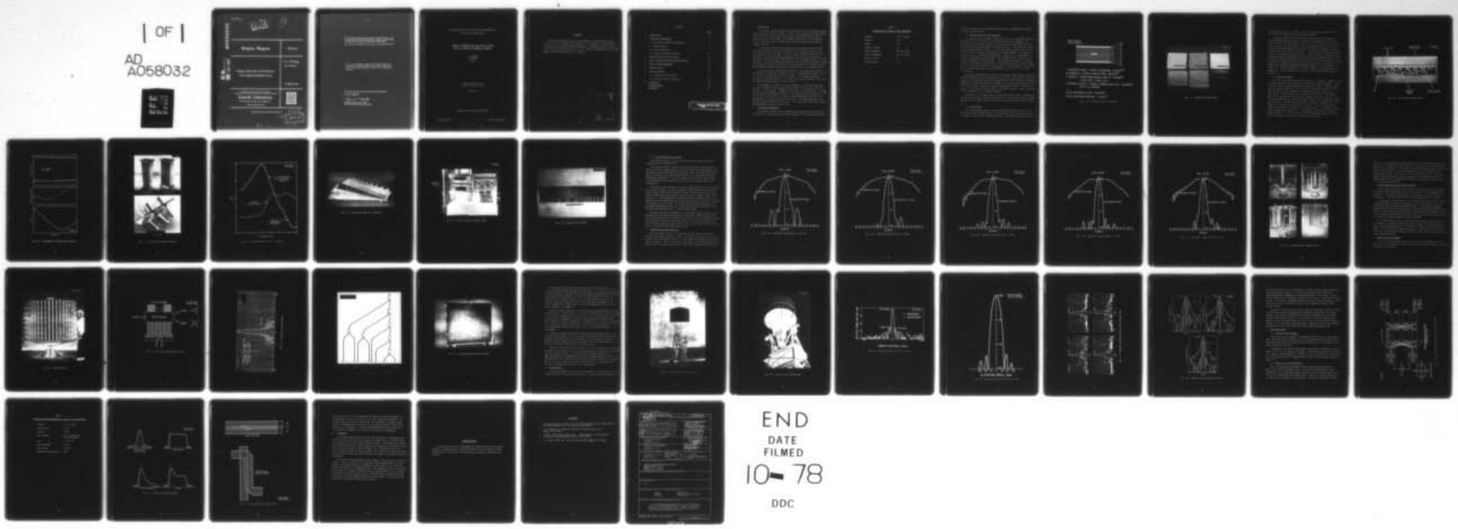

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Project Report

TST-21

K. J. Keeping
J-C. Sureau

Design, Fabrication and Evaluation of an L-Band Cylindrical Array

10 May 1978

Prepared for the Department of the Air Force
under Electronic Systems Division Contract F19628-78-C-0002 by

Lincoln Laboratory

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LEXINGTON, MASSACHUSETTS

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This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

Raymond L. Loiselle

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Chief, ESD Lincoln Laboratory Project Office

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LINCOLN LABORATORY

DESIGN, FABRICATION AND EVALUATION OF AN L-BAND CYLINDRICAL ARRAY

K. J. KEEPING

J-C. SUREAU

Group 43

PROJECT REPORT TST-21

(Tactical Systems and Technology)

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LEXINGTON MASSACHUSETTS

ABSTRACT

An L-band cylindrical array has been assembled for demonstration purposes. The array is 6 ft in diameter and contains 48 4-ft columns. It was fabricated using novel, low-cost and lightweight techniques. Measurements indicate that this array is usable at least from 1.0 to 1.4 GHz. Plans for implementing the scanning matrix and other design options are indicated.

CONTENTS

1. INTRODUCTION

For some time Lincoln Laboratory has advocated the use of cylindrical arrays in fulfilling the needs of a number of radar or even communications applications. While the specific reasons have tended to vary with each application and are beyond the scope of this report, the fundamental attribute of the cylindrical array is that it is unique in combining inertialess scanning and constant performance over 360°.

Its traditional competitors have been the electronically scanned, planar array and the mechanically rotating antenna, both of which feature one of the above attributes, but not both. In spite of this, cylindrical arrays have not been widely utilized principally because they were not found cost-effective. In the tactical applications the added problem of size and weight has been a further deterrent. The Lincoln Laboratory cylindrical array technology development program was formulated to specifically address both problem areas as its primary concern. The design decisions made throughout the program reflect this fundamental goal.

As the first step of what appeared likely to be an evolutionary process, it was decided to assemble an L-band array capable of supporting both radar (1.2 to 1.4 GHz) and ATC beacon/IFF (1.03 and 1.09 GHz). The essential parameters of this array are shown in Table 1.1. The size of the array was chosen on the basis of handling convenience and the level of effort.

This document is intended to provide a summary of the overall development. Section 2 is devoted to the design and fabrication of the vertical columns and Section 3 to the structure. Together they describe the array aperture. The beam forming design is discussed in Section 4. The range measured performance of the array is described in Section 5. While a beam-scanning unit has not yet been implemented, its design is discussed in Section 6. Possible variations on the current design are described in Section 7. This report ends with several comments providing some perspective on this effort.

2. COLUMN ARRAY DEVELOPMENT

A monolithic assembly using stripline dipoles and integral power dividers was selected as best suited for our stated purposes. This section describes the

TABLE 1.1

DEMONSTRATION CYLINDRICAL ARRAY PARAMETERS

Frequency	1.0 to 1.4 GHz
Diameter	6 ft
Height	4 ft
Number of Columns	48
Azimuth Beamwidth	9^{o} (@ 1.3 GHz)
Elevation Beamwidth	12^{o} (@ 1.3 GHz)
Number of Beams	48
Beam Separation	7.5^{o}

entire development process from materials selection to experimental evaluation of a modest production run.

2.1 Materials Selection and Properties

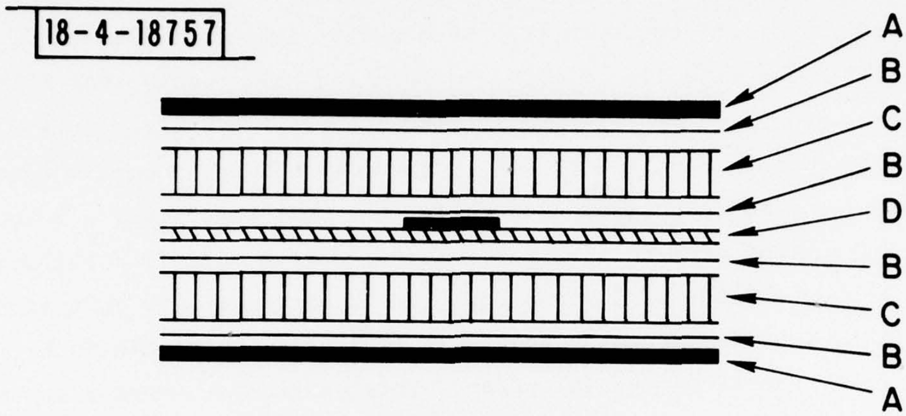
At L-band and even the higher frequencies, the use of conventional microwave materials is out of the question from both weight and cost viewpoints. The materials which were finally selected to form the basic strip transmission line ("tri-plate") are shown in Figure 2.1 (also see ref. 1). The center skin carries the photo-etched printed circuit. It is the only element commonly used in electronics and also, maybe not coincidentally, the most expensive. The others are used in a variety of commercial applications. Surlyn 1652 is a thermoplastic which has the appearance of Saran Wrap. The honeycomb spacer is typically used to make lightweight structural panels. It is readily available in 8-ft sheets, and up to 12-ft sheets on special order. This particular overall laminate weighs 1/3 lb/ft^2 and costs $3.50/ft^2$ for raw materials. Bulk properties of this medium used as a 50Ω transmission line were measured at 1.3 GHz to be $\varepsilon = 1.17$ and $\alpha = 0.08$ db/λ.

Extensive environmental tests were also performed. Under thermal cycling from $-40^{\circ}F$ to $+130^{\circ}F$ we found that the laminated test pieces retained their mechanical integrity, but some moisture absorption was detected. This effect was intentionally magnified by leaving test pieces in a chamber at 95 percent relative humidity and $150^{\circ}F$ from 24 hours. Results of electrical measurements indicate a 50 percent increase in loss factor but little change in dielectric constant. Given the severity of the environment this was judged acceptable.

Recently, for other applications, we have worked with different laminates involving several types of honeycombs (see Figure 2.2) including the lower loss HRH-310 material and thinner center skin (3 mil. G10) and outer ground planes (2 mil. Al.).

2.2 Column Design

For demonstration purposes the array columns were selected to be 4 ft tall and contain eight radiating elements. These elements were to be excited so as to provide a 25-dB sidelobe Tchebycheff pattern. The complete RF printed circuit



A. GROUND PLANES – 0.006 in. ALUMINUM – $\$0.10/\mathrm{ft}^2$

B. ADHESIVE – 0.002 in. SURLYN 1652 – $\$0.01/\mathrm{ft}^2$

C. SPACER – HONEYCOMB HEXCEL HRH 10 – $\$0.65/\mathrm{ft}^2$
(1/8 in. thick × 3/8 in. cell)

D. PRINTED CIRCUIT – 0.007 in. FIBERGLASS (G10) – $\$2.00/\mathrm{ft}^2$
WITH 1 ox COPPER

TOTAL MATERIALS COST: $\$3.54/\mathrm{ft}^2$

TOTAL MATERIALS WEIGHT: $1/3\ \mathrm{lb}/\mathrm{ft}^2$

Fig. 2.1. Stripline materials breakdown.

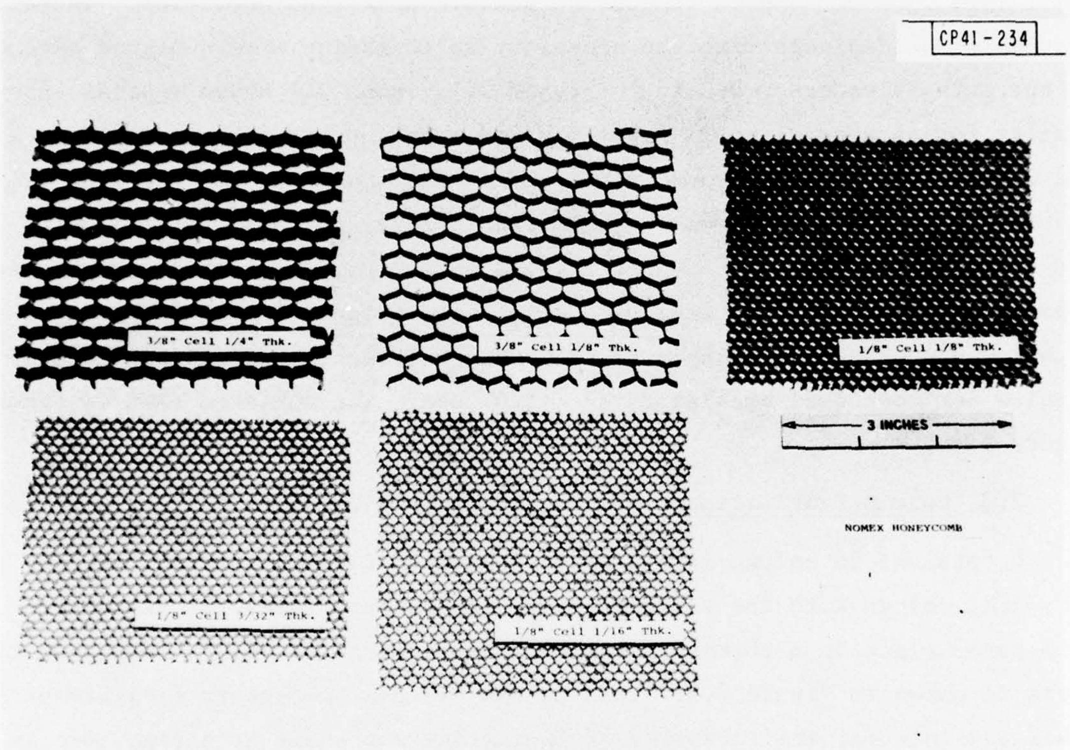


Fig. 2.2. Available honeycomb sizes.

is shown in Figure 2.3. A column is itself a linear array consisting of an input connector, a power divider, and radiating dipoles.

A standard type-N tri-plate end launcher was modified to be compatible with the measured medium dielectric constant and the parameters of a 50Ω line. An input VSWR of 1.07 was achieved. The selected power divider was of the binary split type with equal path lengths to achieve broadband operation. Therefore, matched power dividers with the necessary split ratios were designed according to the principles described in reference 2. Figure 2.4 shows typical experimental results for an unequal ratio power divider. This represents a "first-cut" design and could probably be improved with more iterations. The dipoles were excited by a deformed ring hybrid balun which is particularly suitable for tri-plate construction since the combination can be printed on the same side of the center skin. The dipoles were matched in a waveguide simulator designed for 30° scan angle (see Figure 2.5). This corresponds to the average effective active environment of the dipoles for co-phasal excitation of a 120° arc. The achieved VSWR is shown in Figure 2.6.

2.3 Column Fabrication

A total of 56 column arrays were fabricated (48 + 8 spares). Figure 2.7 shows a typical column with the various layers fanned out, ready for assembly. Lamination takes place in a thermal press at a temperature of 280°F. One such typical press is shown in Figure 2.8. This is the Lincoln Laboratory facility used for small test pieces; it is capable of laminating two units at a time, one in each opening. The 4-ft columns were laminated at Polyply Corp., New Bedford, Mass., in a larger press. All units were laminated in one day, eight at a time. The total fabrication cost was under $300 per column, this included all materials, outside services, tooling and in-house labor assessed at a burdened rate. The weight of each column is a little over one pound. This type of construction results in a structural panel which is unusually stiff for its weight, and which can be handled with relative ease. A photograph of a laminated 4-ft column is shown in Figure 2.9. Note that no special mode-suppression devices were found necessary, except for the use of a symmetrical end launcher.

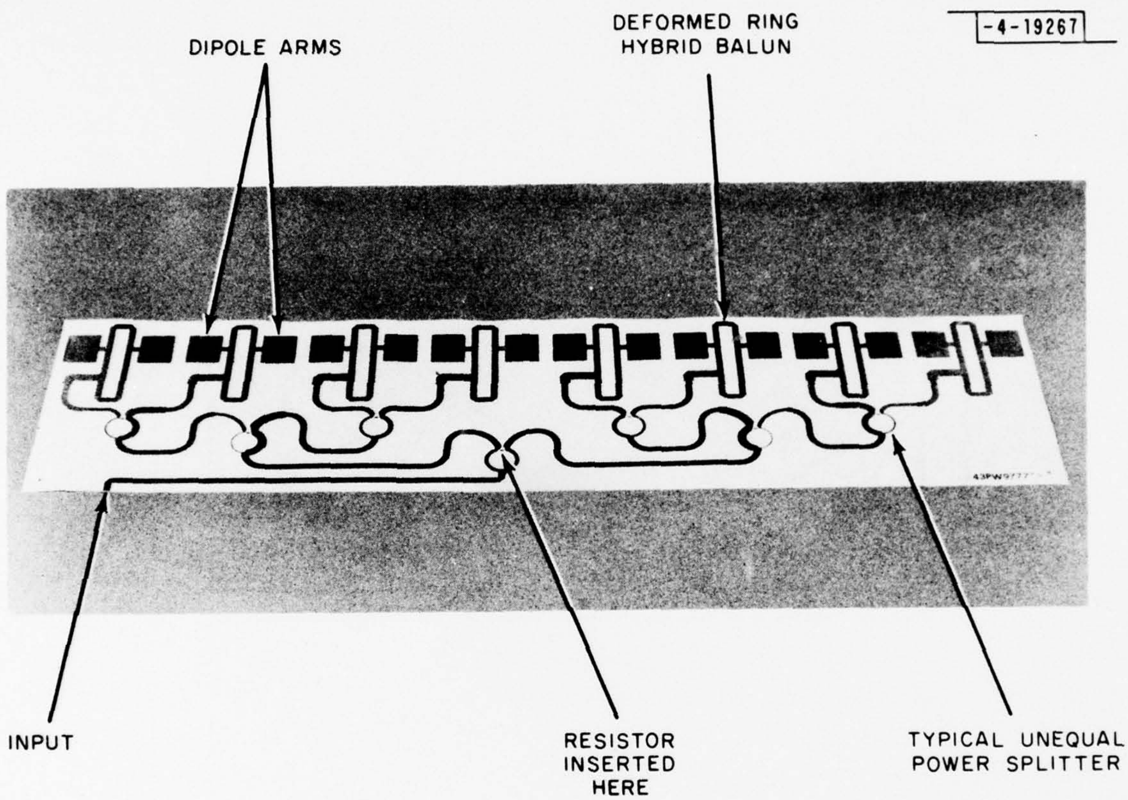


Fig. 2.3. Array column printed circuit

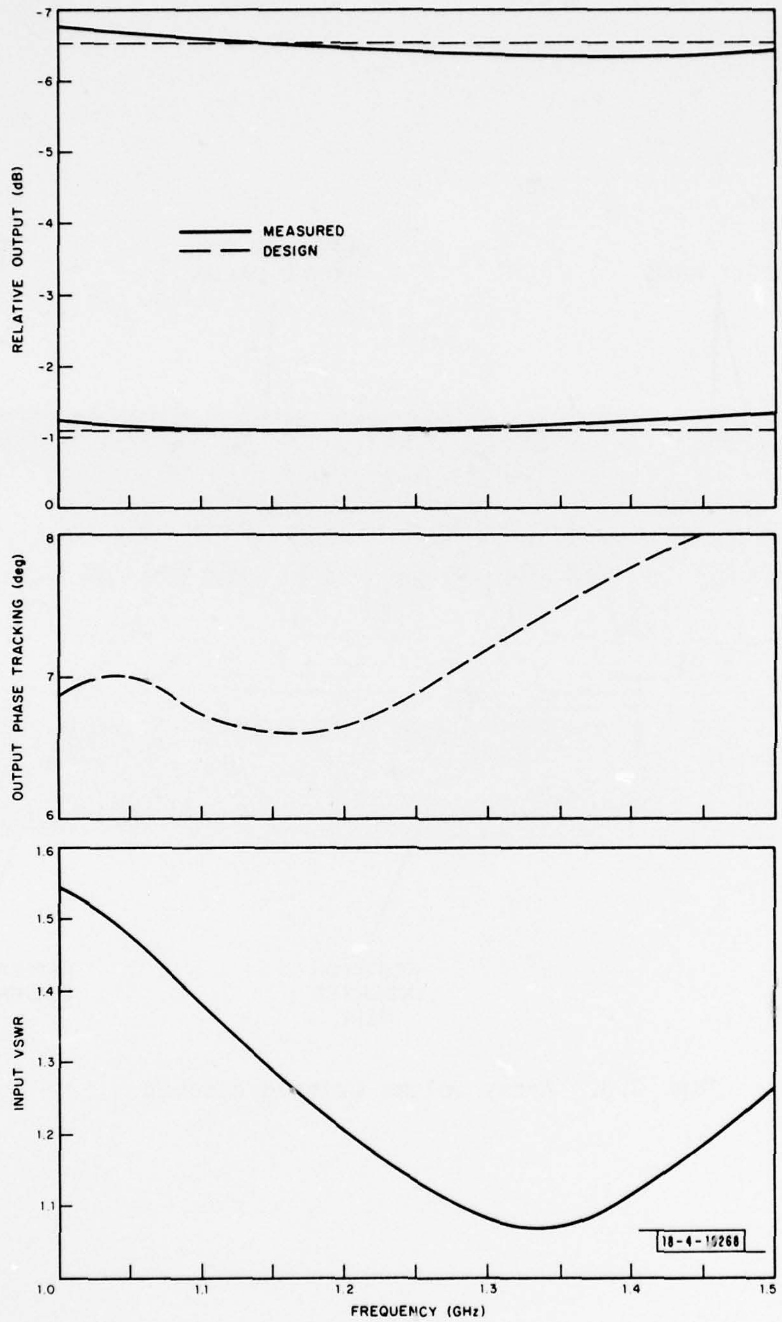
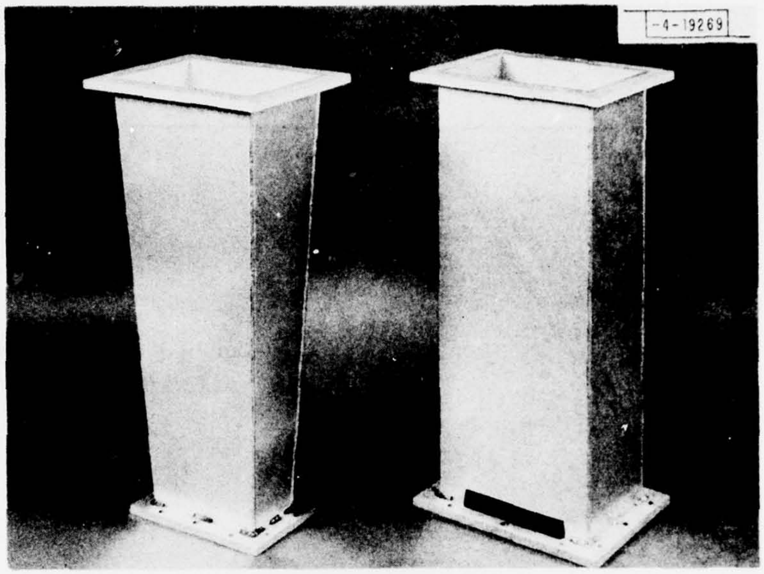
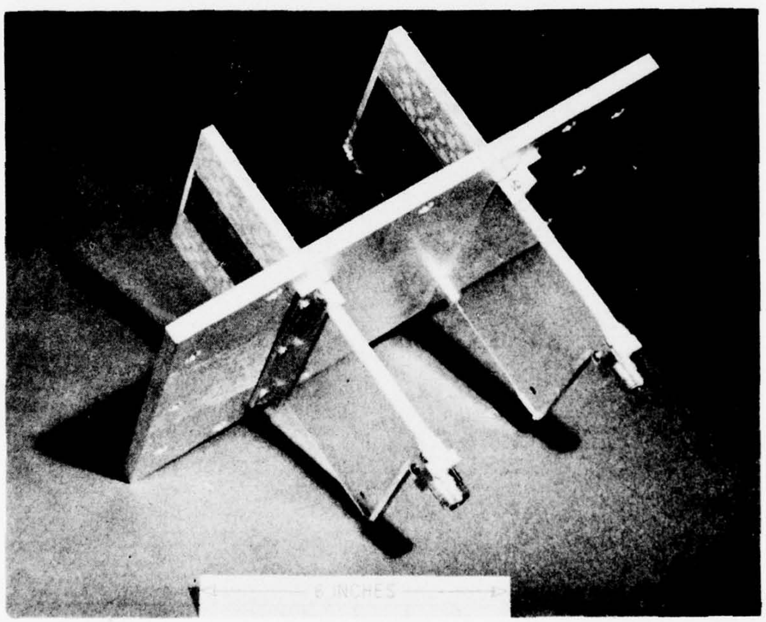


Fig. 2.4. Performance of typical power splitter.



TRANSITION FROM
WR-650 WAVEGUIDE

ARRAY SIMULATOR
WAVEGUIDE



DIPOLES INSERT

Fig. 2.5. Dipoles and waveguide simulator.

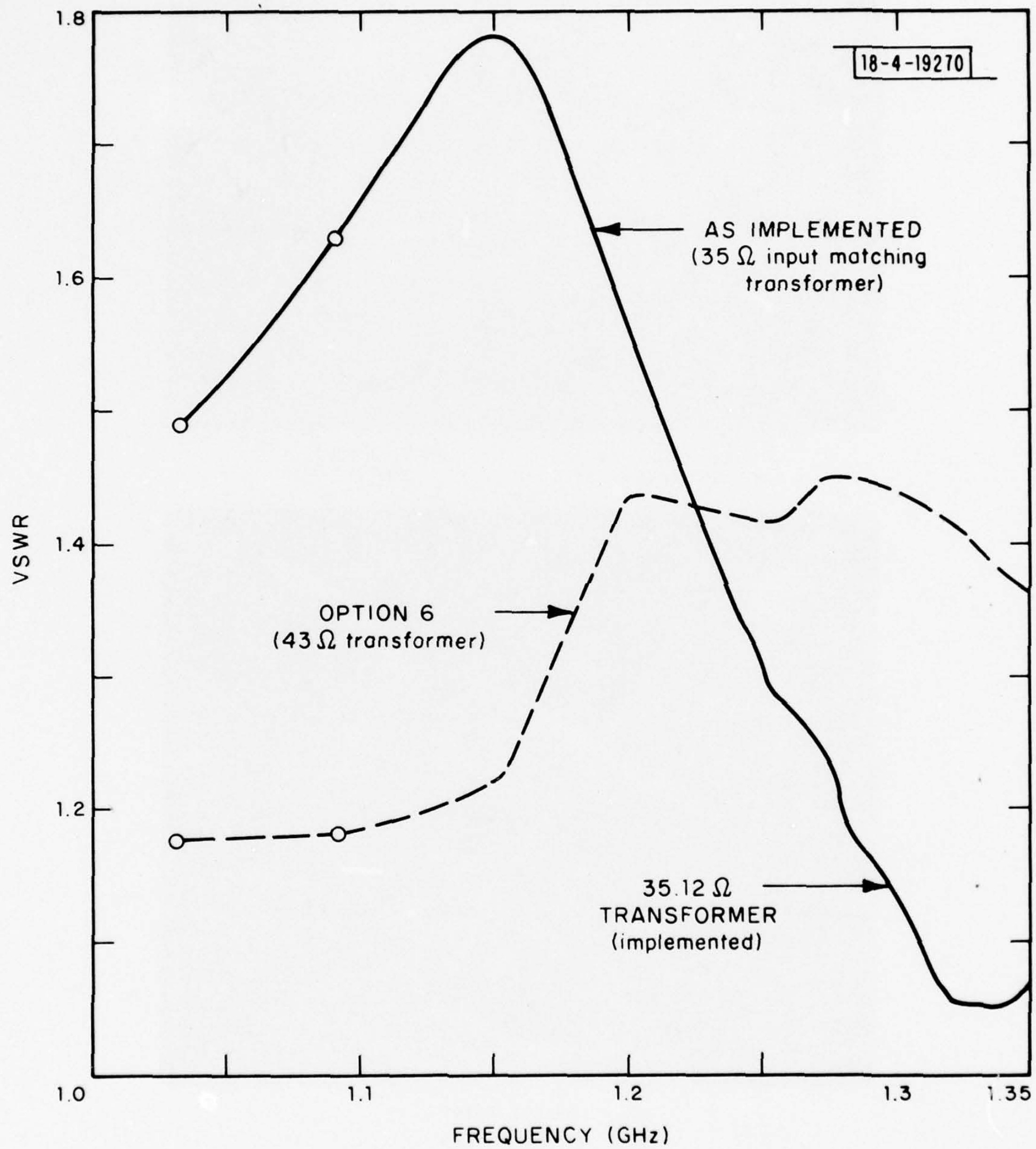


Fig. 2.6. Measured VSWR of dipole in simulator.

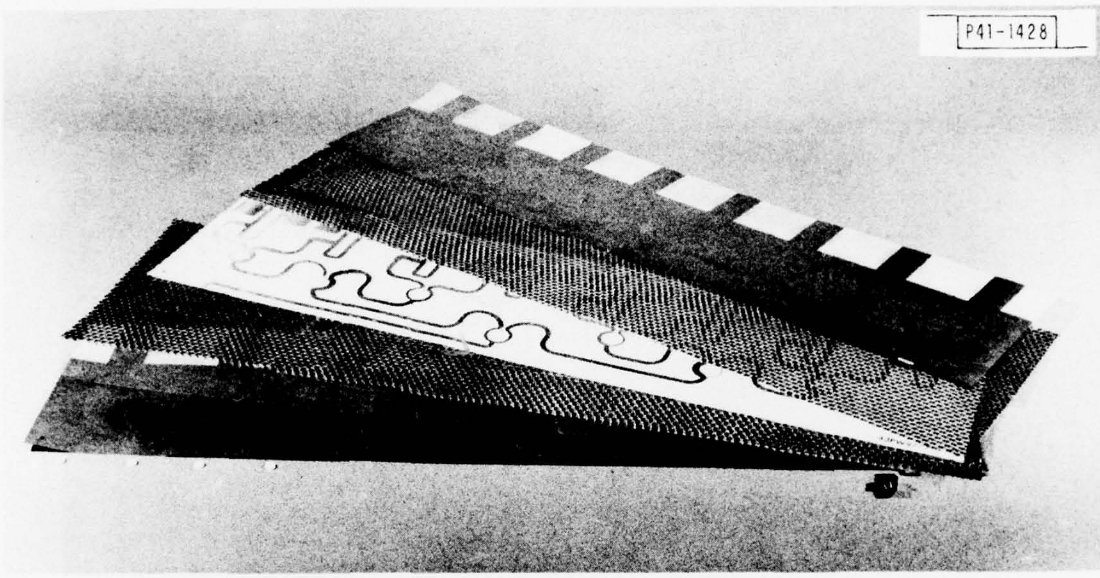


Fig. 2.7. Array column ready for lamination.

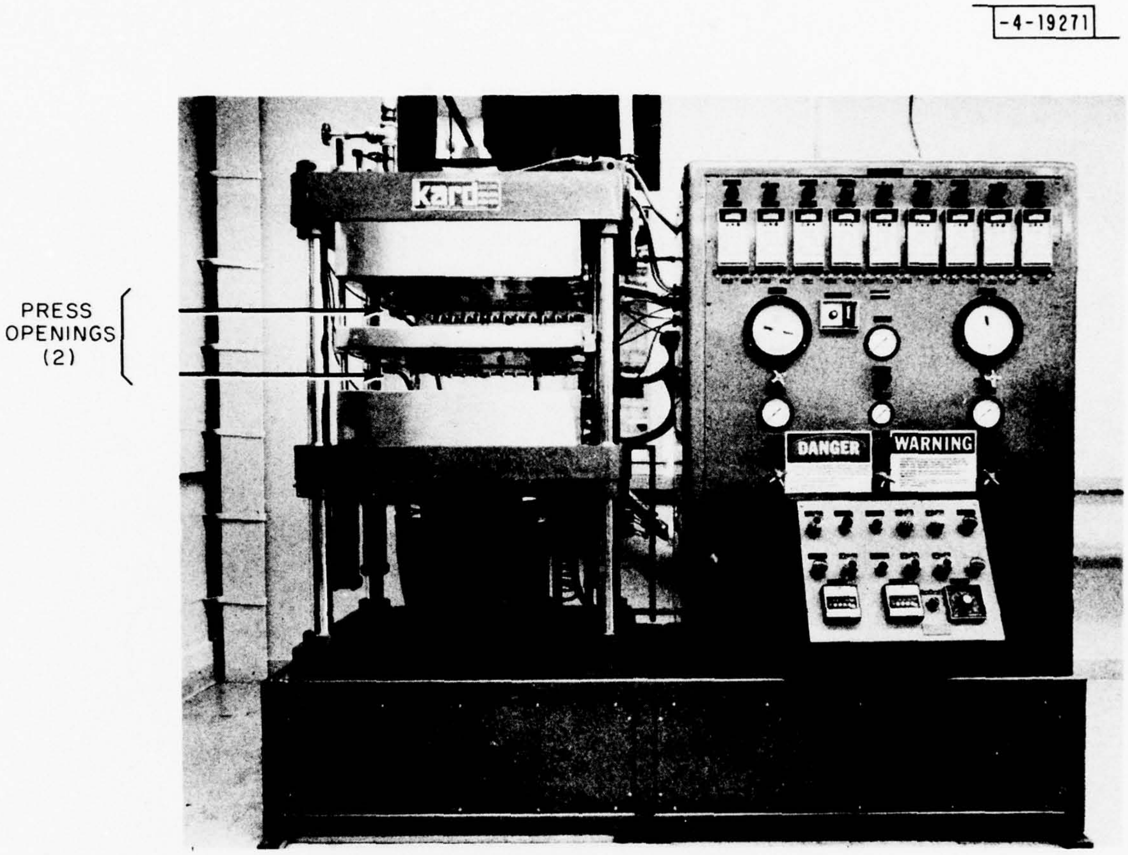


Fig. 2.8. Lincoln Laboratory thermal press.

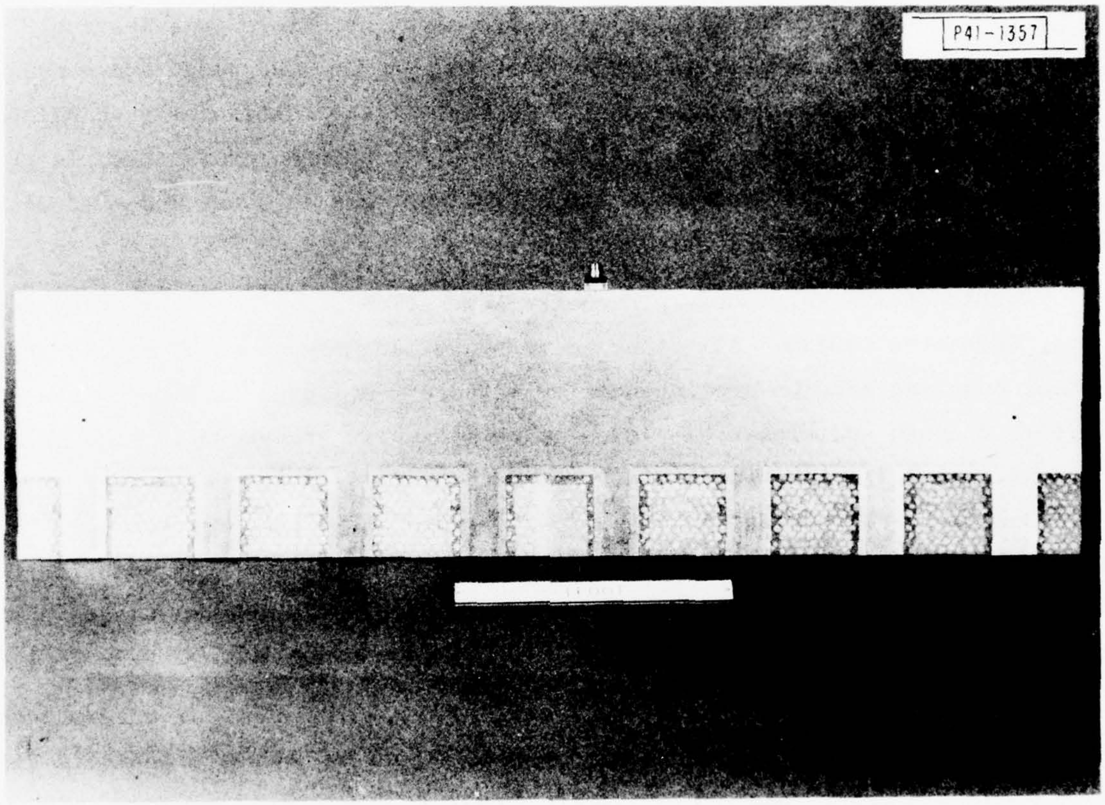


Fig. 2.9. Laminated array column.

2.4 Column Performance Evaluation

Two different types of tests were performed on the fabricated columns: similarity tests and pattern tests.

The similarity tests consisted of measuring the relative amplitude and phase of each array column installed in the array structure (see Section 3 for description) at the same frequency and the same angle. We found these measurements to be difficult to make reliably because of the continuously changing environmental conditions. The best assessment at this point is that, in the array environment, the variations are at the most $\pm 5^{\circ}$ in phase and ± 0.2 dB in amplitude.

Pattern tests were performed on a single column, again in the array environment, chosen at random. All other columns are match-terminated, hence normal mutual coupling effects are inherently included. Measured amplitude patterns in both azimuth and elevation planes as well as gain are shown in Figures 2.10 through 2.14. The sharpening of the azimuth pattern as frequency goes up is as expected since the element spacing to wavelength ratio also increases. By design this spacing is $\lambda/2$ at 1.3 GHz. The elevation pattern is nearly identical to the 25-dB Tchebycheff design at the 1.3-GHz center frequency, sidelobes are below 20 dB over the entire 1.0 to 1.4-GHz frequency band.

The phase pattern of the element was also measured since it enters into the specification of the phase correction for collimation. Results indicate that over $\pm 60^{\circ}$ this phase pattern was nearly identical to that of an isotropic element located slightly in front of the actual dipoles. The difference between the actual measured values and those predicted on the basis of this effective phase center is within $\pm 4^{\circ}$ across the frequency band.

3. STRUCTURE DESIGN AND FABRICATION

The array support structure was designed with the same cost and weight considerations given to the array column. An overview of the basic concept is provided by the photograph in Figure 3.1 which shows the structure in progressive states of assembly. Except for the four rings which were rolled and welded, all other pieces are riveted to one another. The vertical members are 0.020" sheets

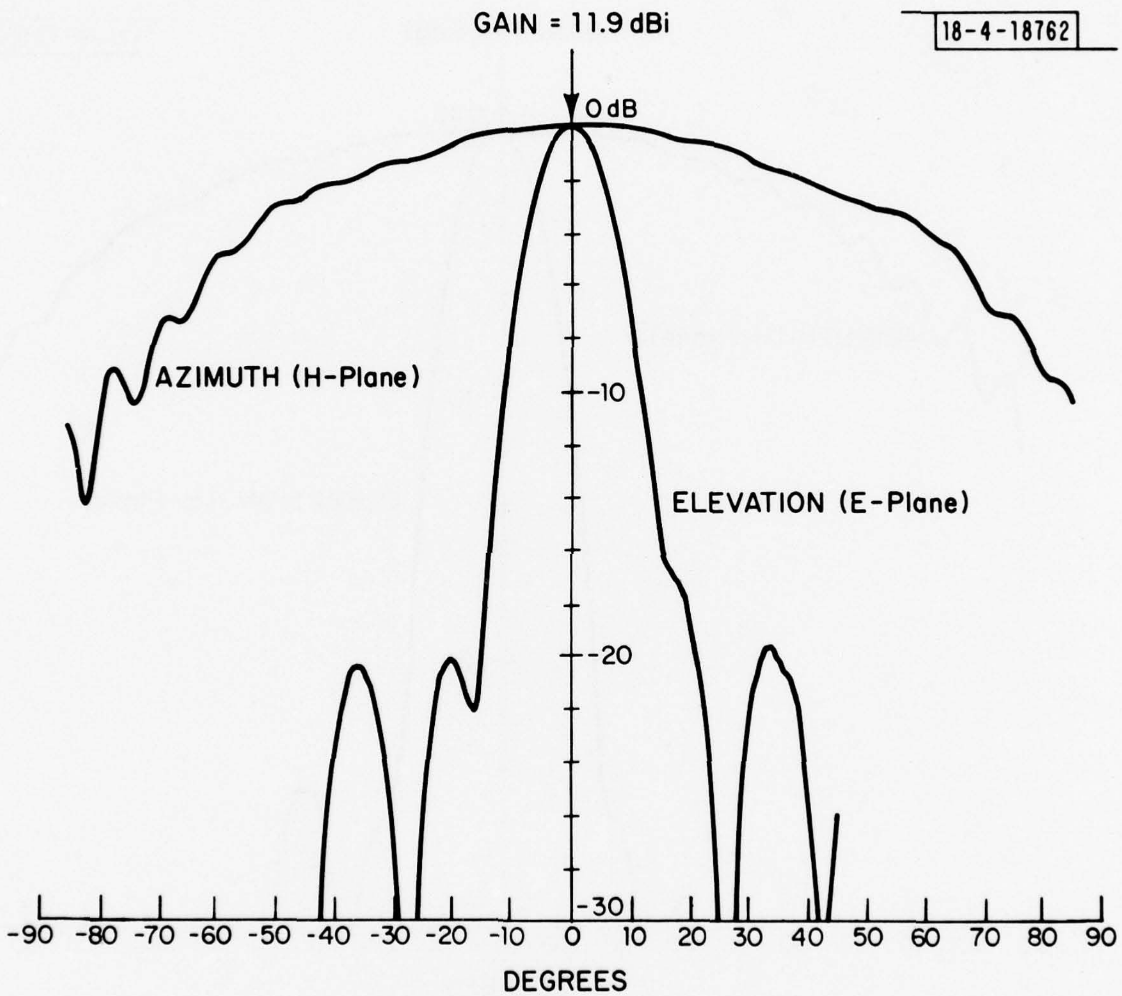


Fig. 2.10. Individual column patterns, 1.03 GHz.

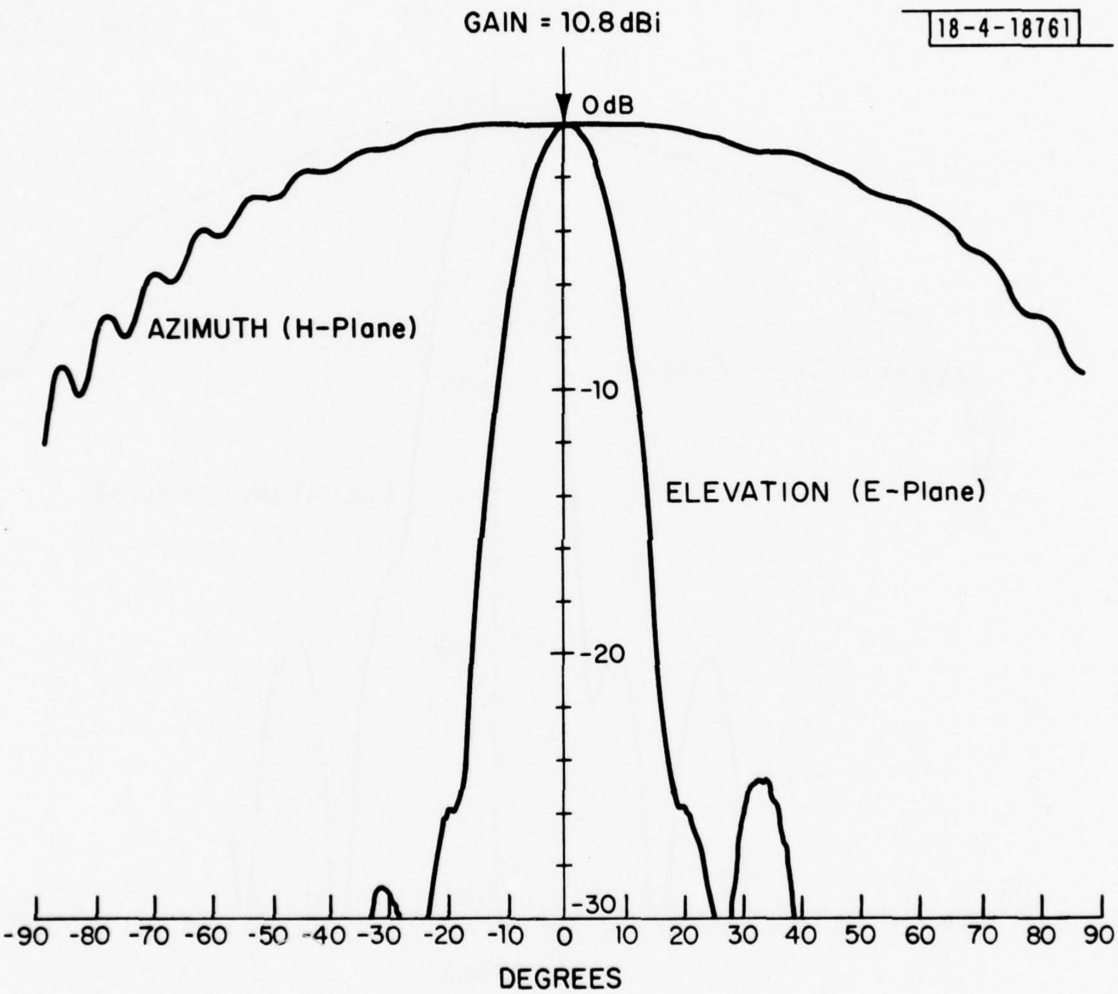


Fig. 2.11. Individual column patterns, 1.09 GHz.

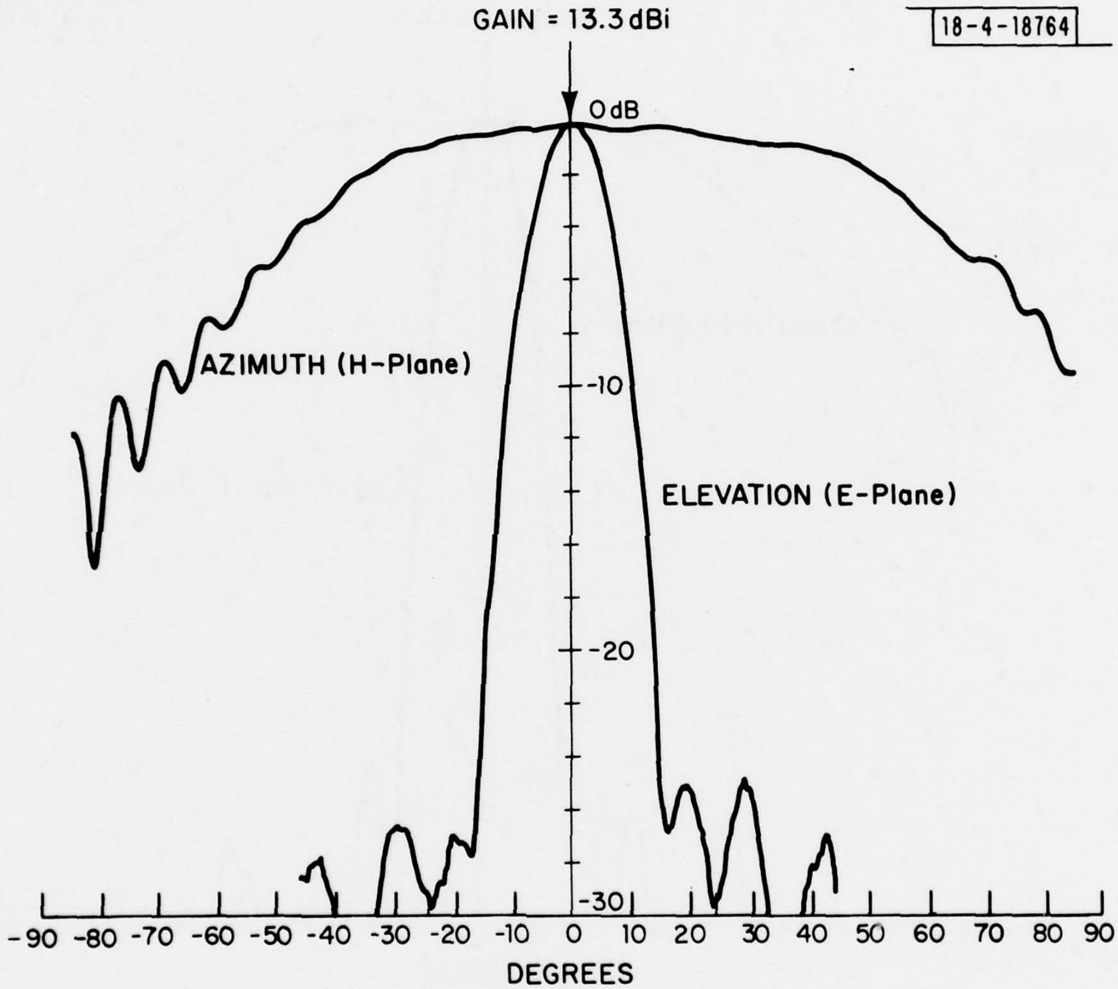


Fig. 2.12. Individual column patterns, 1.2 GHz.

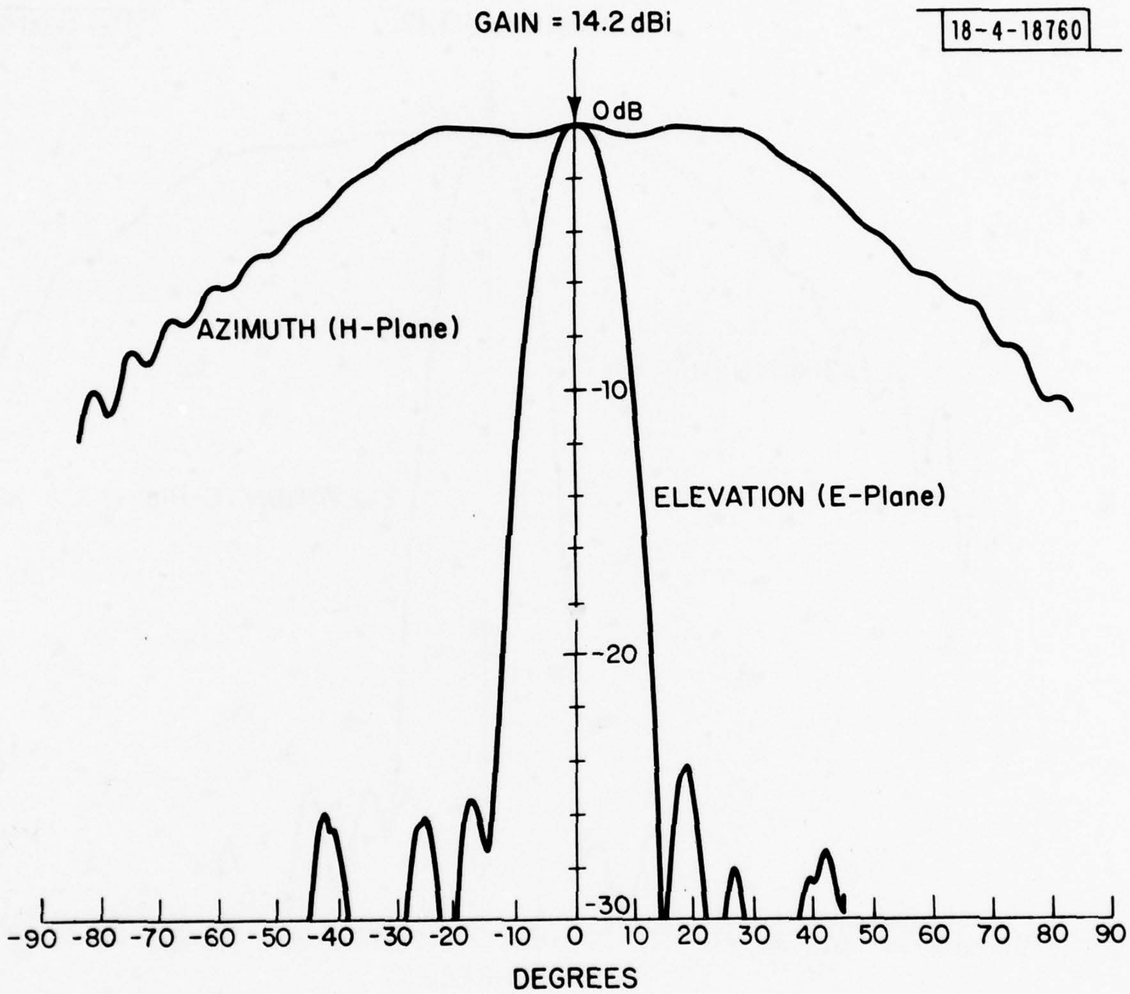


Fig. 2.13. Individual column patterns, 1.3 GHz.

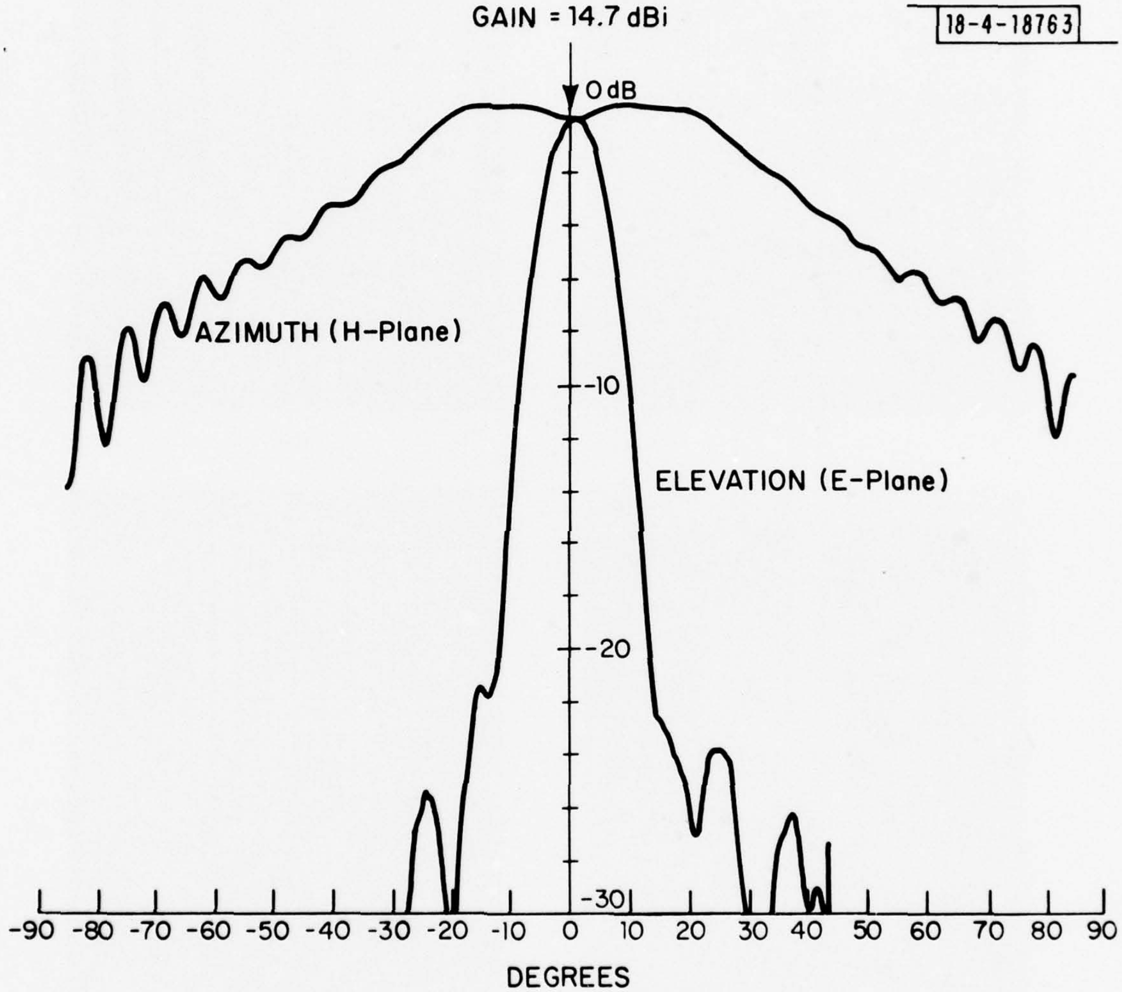


Fig. 2.14. Individual column patterns, 1.4 GHz.

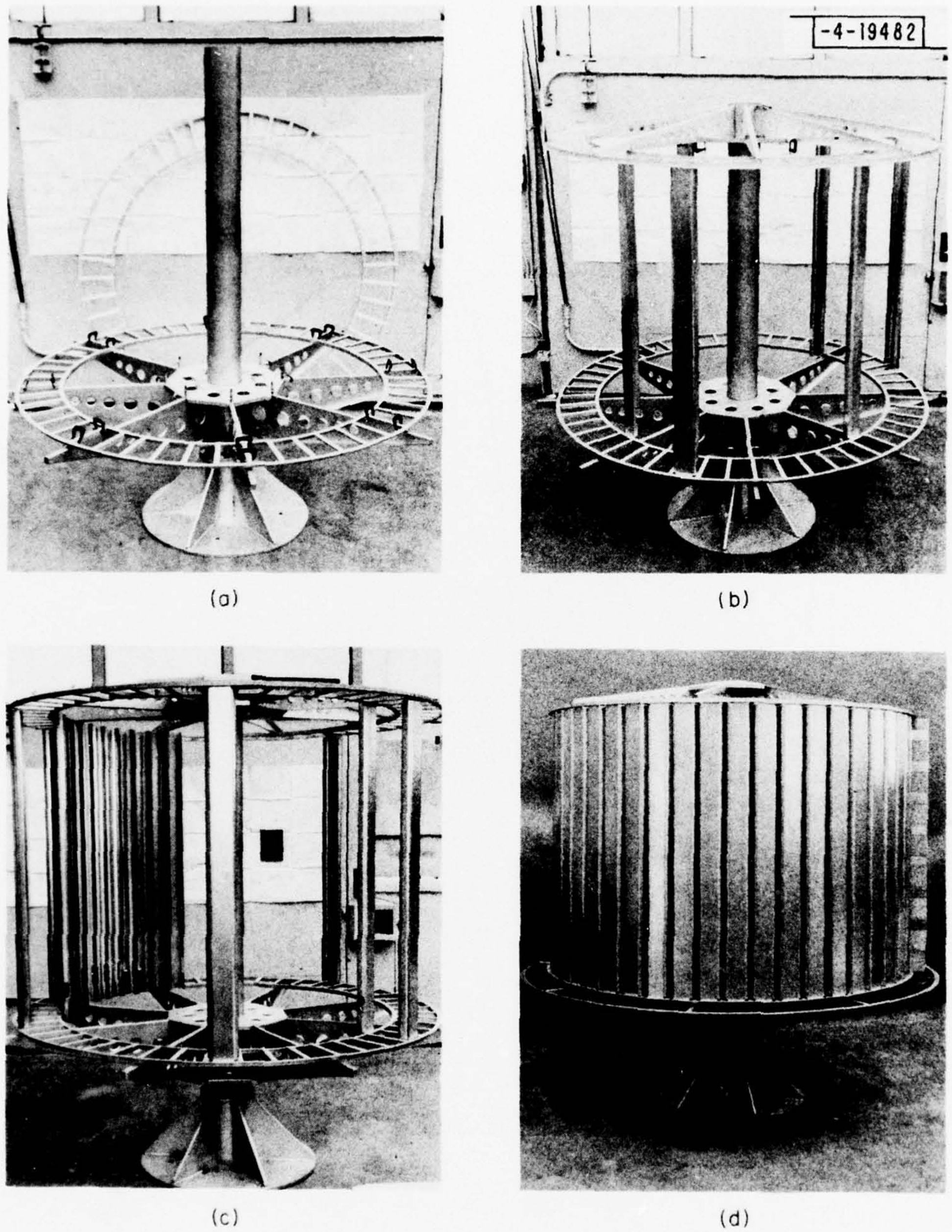


Fig. 3.1. Array structure assembly process.

bent on edge to form guiding, flexible grooves into which the array columns are inserted. The columns are further locked into position by nylon locating screws going through the laminate. The completely assembled structure weighs slightly less than 110 lbs, exclusive of the stand designed to interface with a pedestal for measurements purposes. Fabrication cost of the structure was $5K. This figure agains consists of materials, tooling, manfacturing and assembly assessed at burdened labor rate. The completely assembled array aperture is shown in Figure 3.2. It weighs about 160 lbs.

4. AZIMUTH POWER DIVIDER AND PATTERN SYNTHESIS

In the complete cylindrical array system, the azimuth pattern is determined by a power divider which controls the relative amplitude of each element in the excited arc. This power divider appears at the input to the system as depicted in Figure 4.1. The switch matrix merely controls which beam/arc is excited.

In principle, the specification of a cylindrical array excitation to produce a particular pattern requires the knowledge of the element pattern. The power divider which was actually implemented was based on an assumed cosine-shaped element pattern which differs significantly from the subsequently measured pattern. Figure 4.2 shows the two predicted patterns corresponding to each element pattern. It may be possible, by optimizing the power divider for the actual element pattern, to synthesize an azimuth pattern with lower sidelobes.

The monopulse power divider was implemented in the same stripline medium as the columns by two identical tapered 8:1 power dividers (see printed circuit on Figure 4.3) connected together by a 3-dB hybrid to produce a sum and difference output. The final product is shown in Figure 4.4. The difference thus obtained is clearly not optimized for monopulse direction finding, but could have been with a more complicated design.

5. ARRAY PATTERN MEASUREMENTS

By directly connecting the azimuth power divider and collimating cables to various arcs of 16 consecutive elements, beams can be formed even though a scanning matrix was not available.

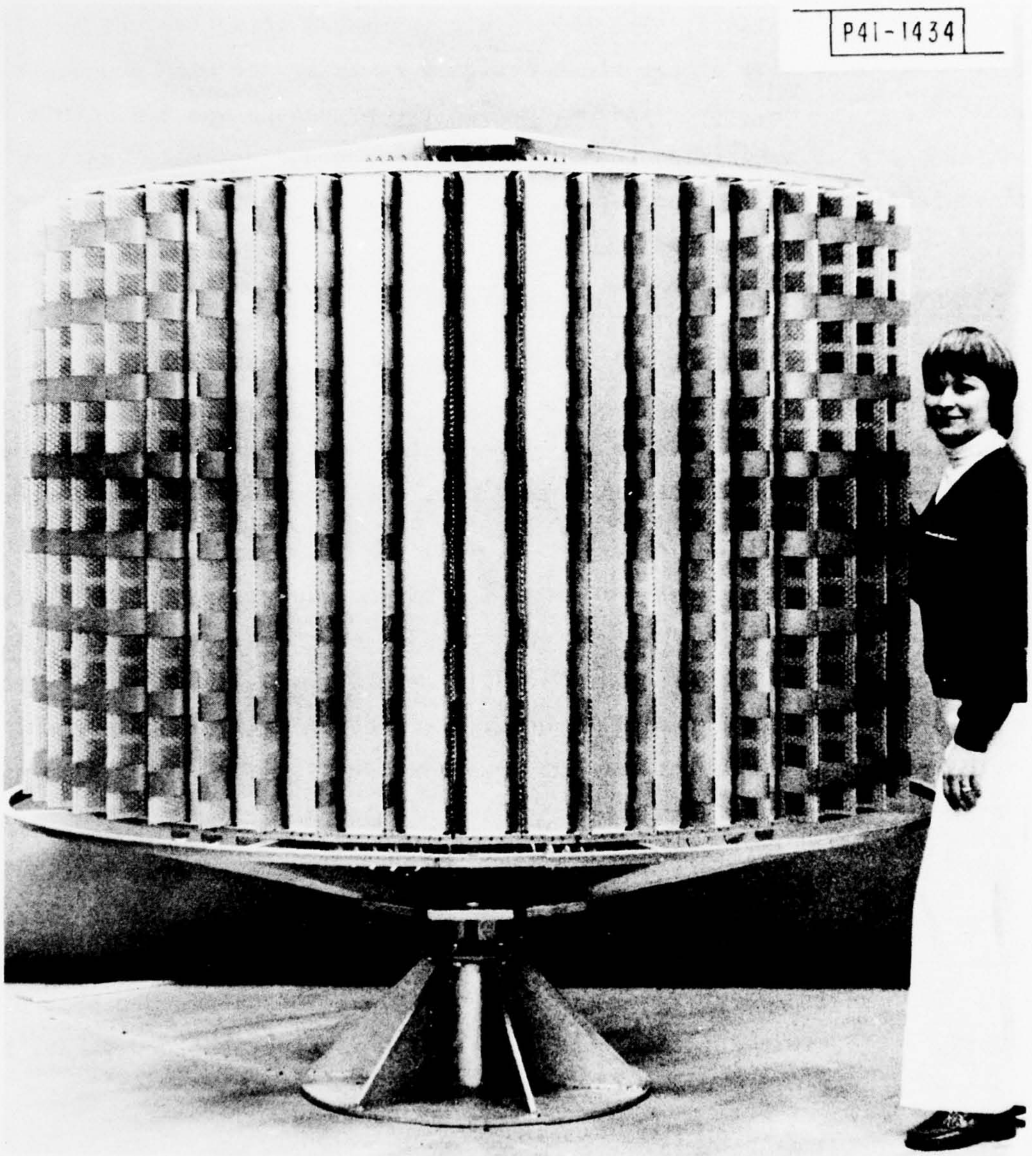


Fig. 3.2. Assembled array.

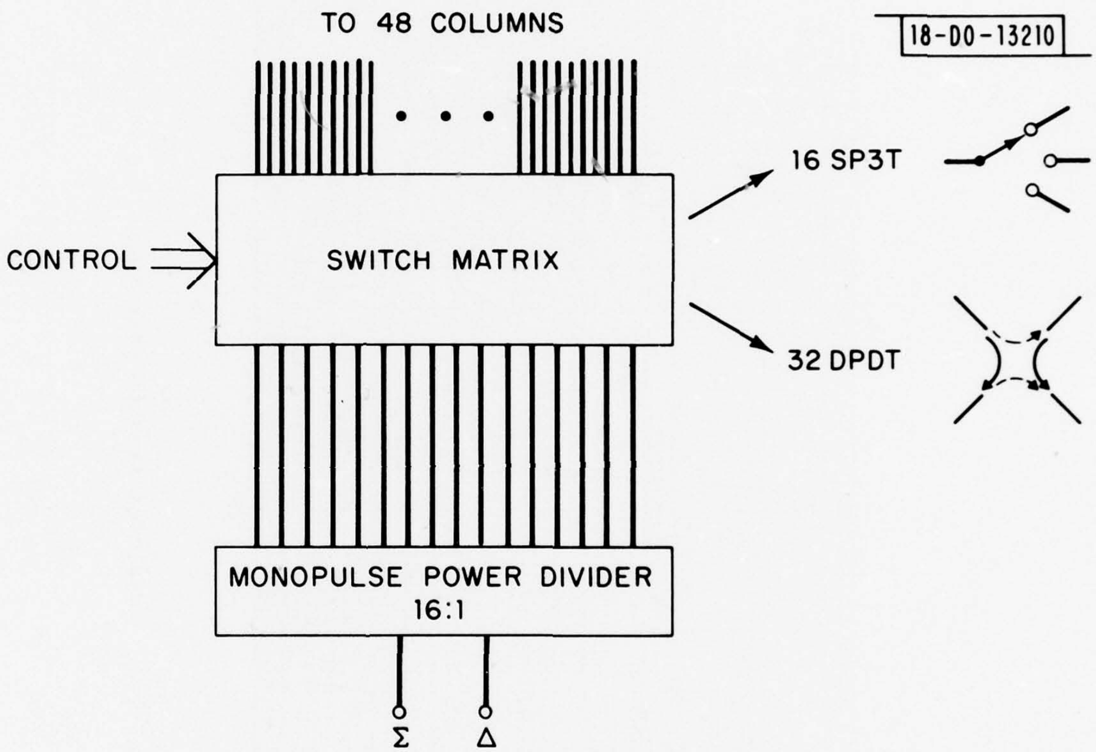


Fig. 4.1. Array beam forming and scanning.

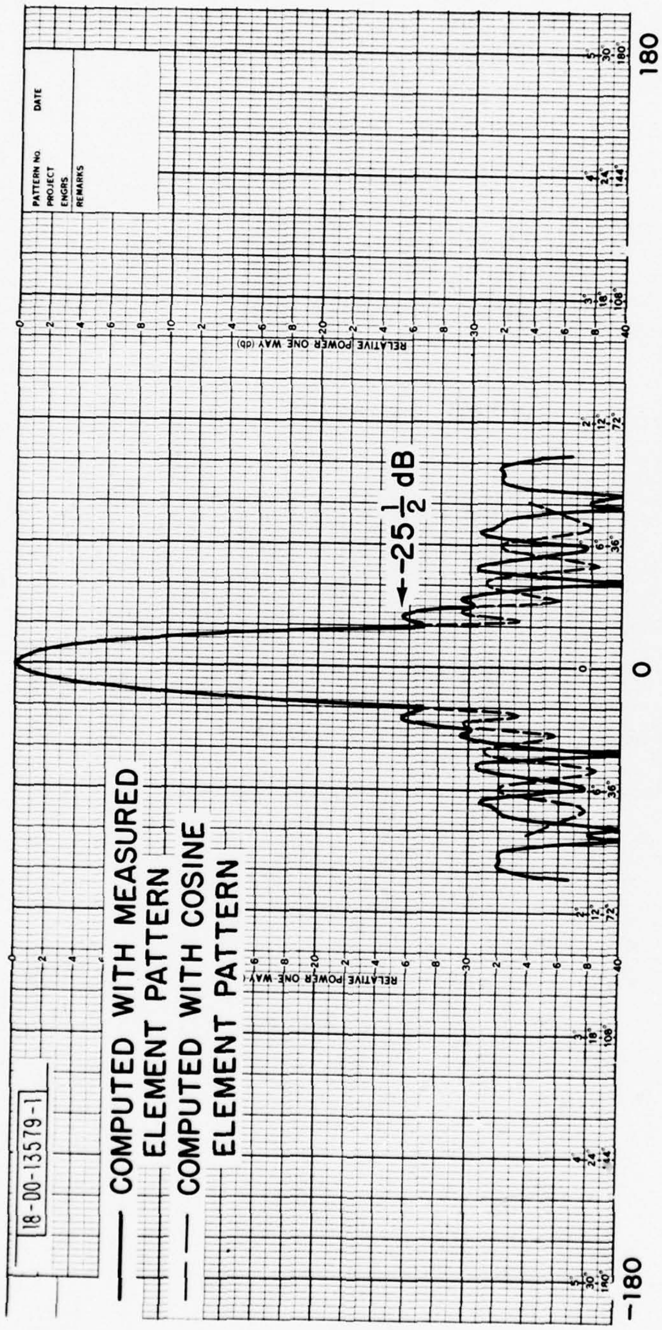


Fig. 4.2. Predicted azimuth patterns.

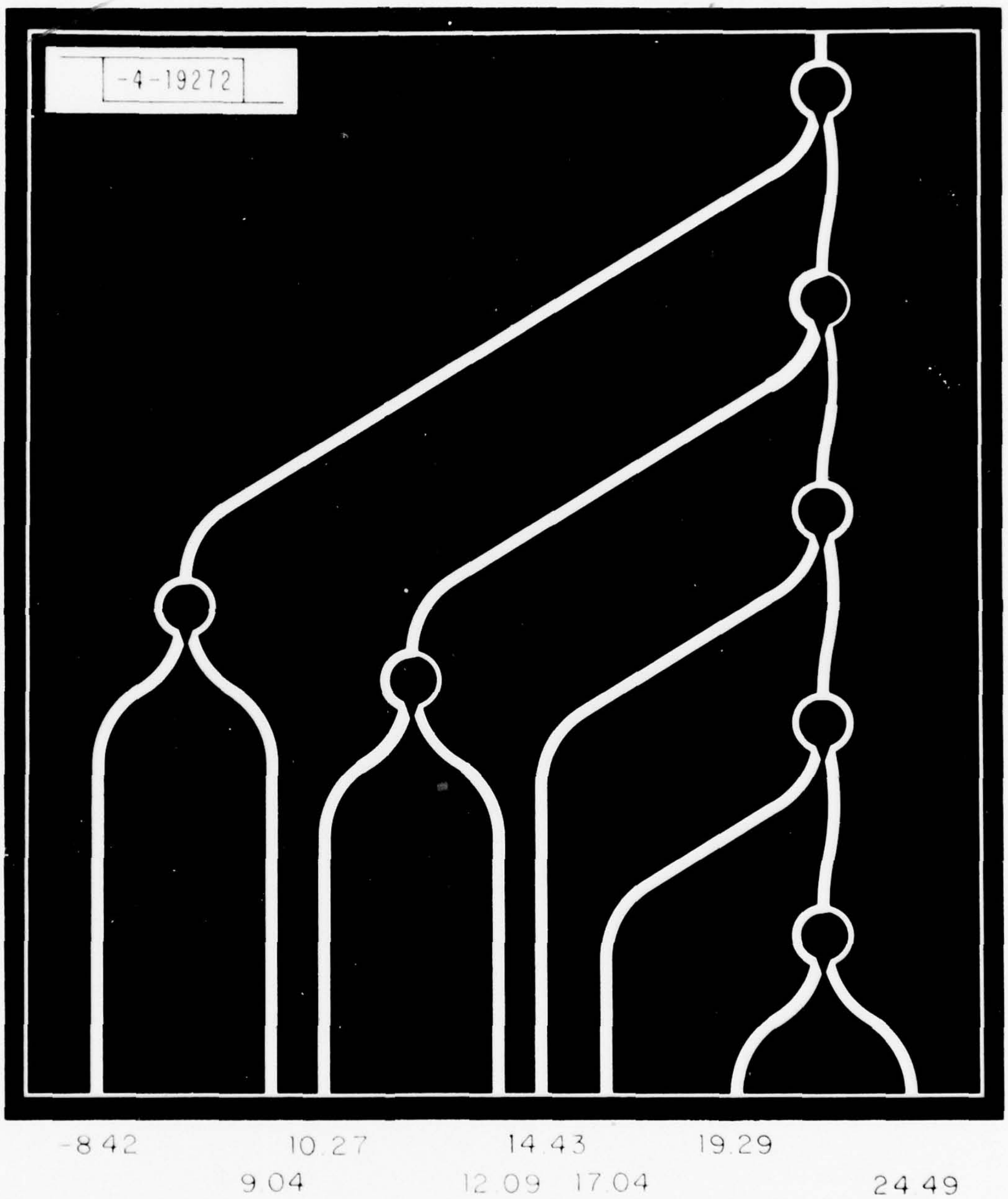


Fig. 4.3. Printed circuit for azimuth power divider.

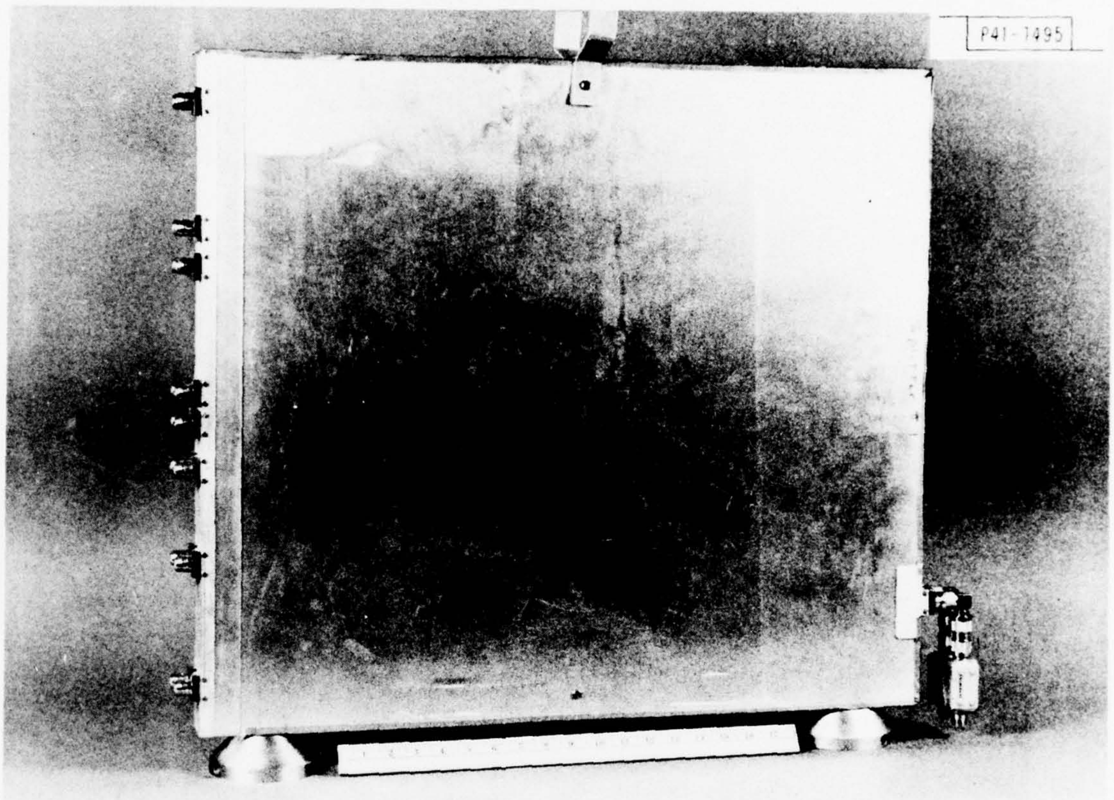


Fig. 4.4. Assembled monopulse power divider.

The patterns of the array were measured at two different sites at the Lincoln Laboratory Antenna Test Range (Bedford, Mass.). At the first location, as shown in Figure 5.1, difficulties were experienced in reliably measuring sidelobes because of the proximity of trees at the same height as the array. The second location, as shown in Figure 5.2, was a high tower on top of the ATR building. This location proved to be considerably better, although not completely satisfactory. Sample results of pattern measurements at that site are shown in Figures 5.3 through 5.6.

Figure 5.3 shows a comparison of the predicted and measured patterns at the design frequency. The discrepancy in the first sidelobe level is still unresolved. It could not be accounted for by measured errors in the azimuth feeding network. It may be due to re-radiation of mutually coupled energy not absorbed in the power divider as a result of mismatches. The asymmetry in the far angle sidelobes still leads one to suspect range effects. Note that these levels are less than -10 dBi and would be expected to require a very clean range for reliable measurements.

Figure 5.4 shows the associated elevation pattern through the peak of the beam at the same frequency. Note that the -25 dB sidelobe level is very nearly achieved. This should not be too surprising since the individual columns were measured to have a similar behavior (see Figure 2.12) and since azimuth errors do not, in principle, affect the array elevation pattern.

Figure 5.5 shows azimuth patterns taken across the frequency band. The shape and gain of these patterns vary only slightly beyond what is expected on the basis of normal frequency effects. Sum and difference monopulse pattern pairs are shown in Figure 5.6. As mentioned earlier, the difference pattern exhibits high sidelobes which may be undesirable when monopulse azimuth estimation is attempted but are necessary if used in a sidelobe suppression mode. As the antenna is presently configured, both functions can be accommodated.

6. SCANNING MATRIX

As mentioned earlier the array, whose performance is being reported in this document, did not include a beam-scanning unit. A block diagram of the beam

Fig. 5.1. Array on ground level tower.

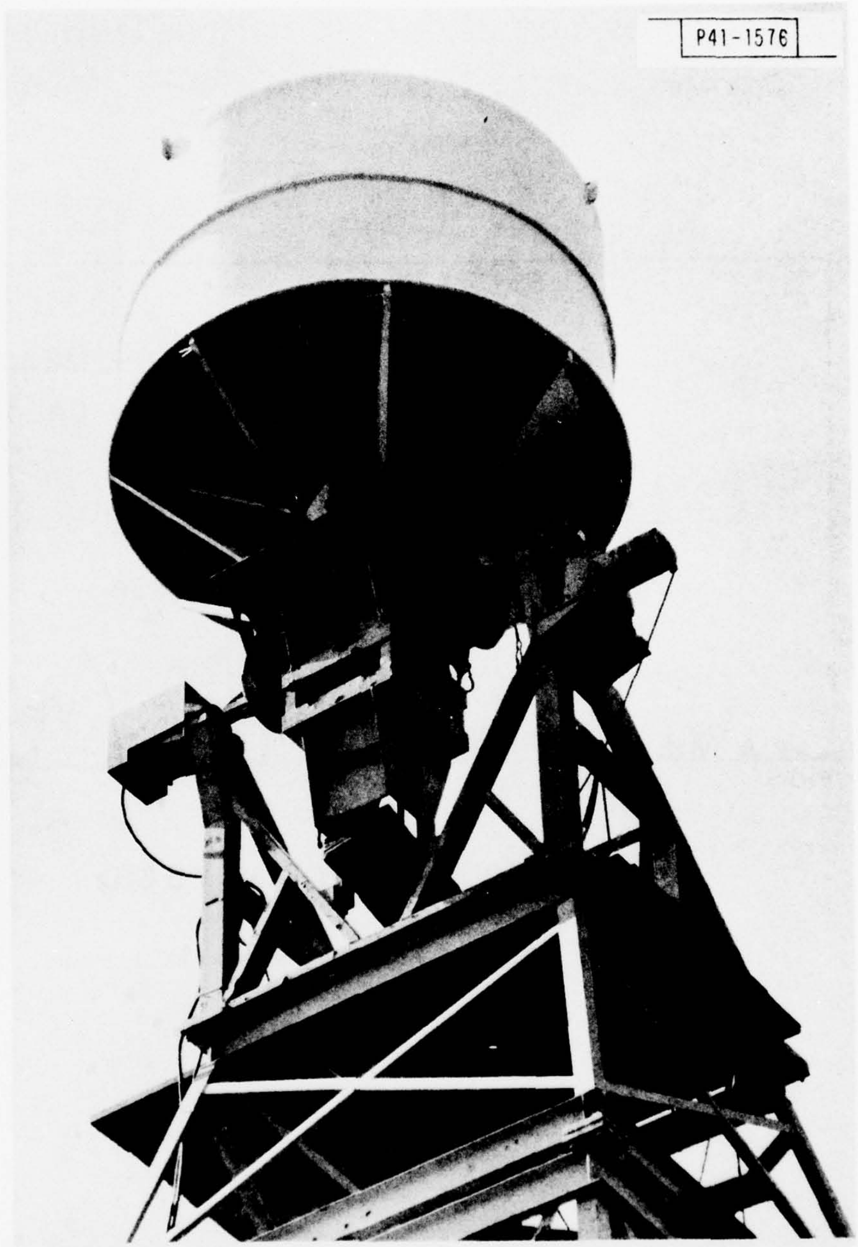
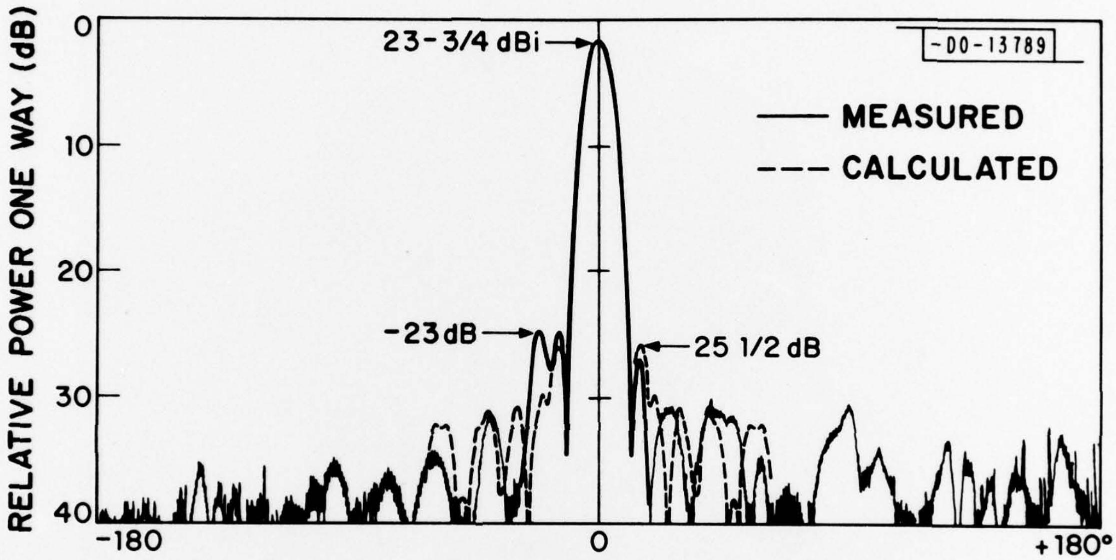


Fig. 5.2. Array on top of ATR building.



AZIMUTH PATTERN; 1.3 GHz

Fig. 5.3. Measured azimuth pattern at 1.3 GHz.

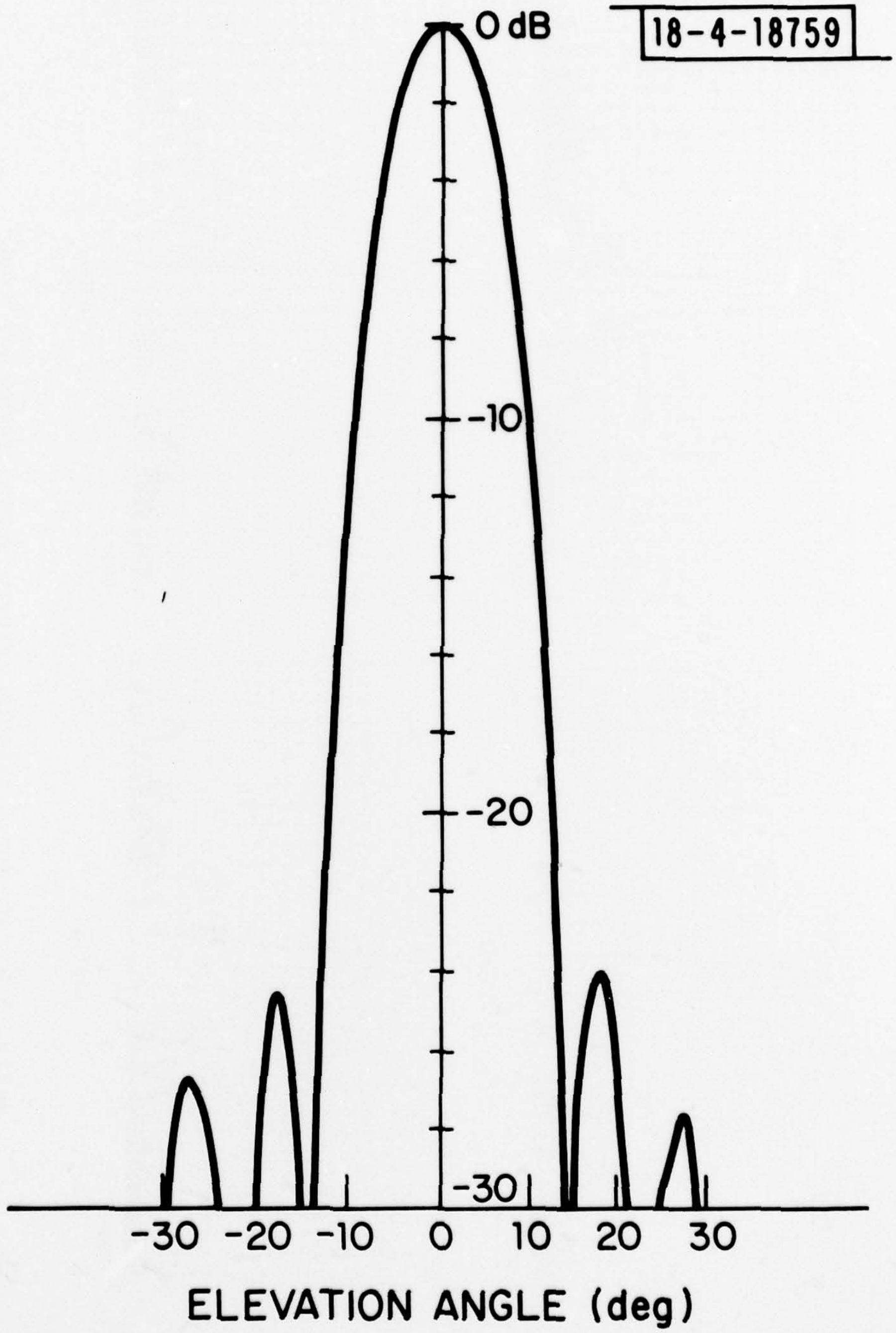


Fig. 5.4. Measured elevation pattern at 1.3 GHz.

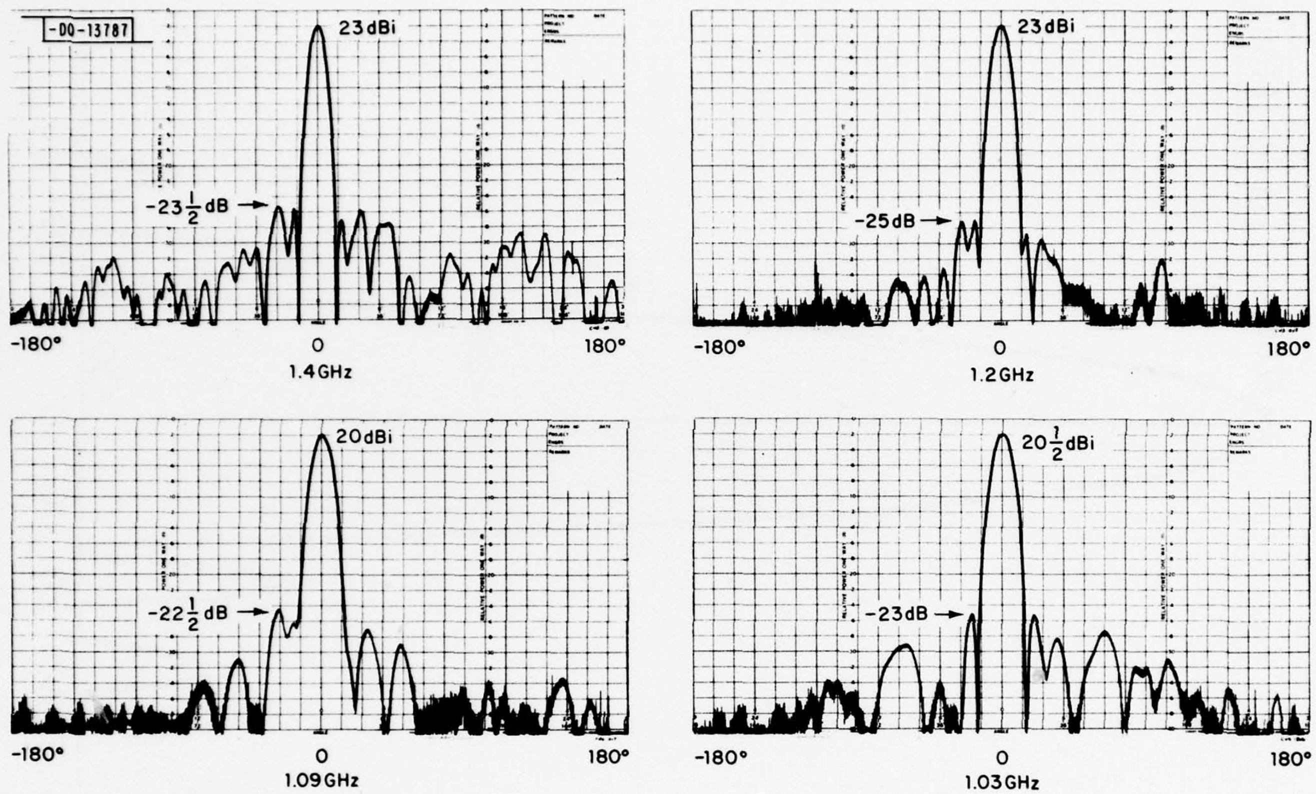


Fig. 5.5. Measured azimuth pattern across frequency band.

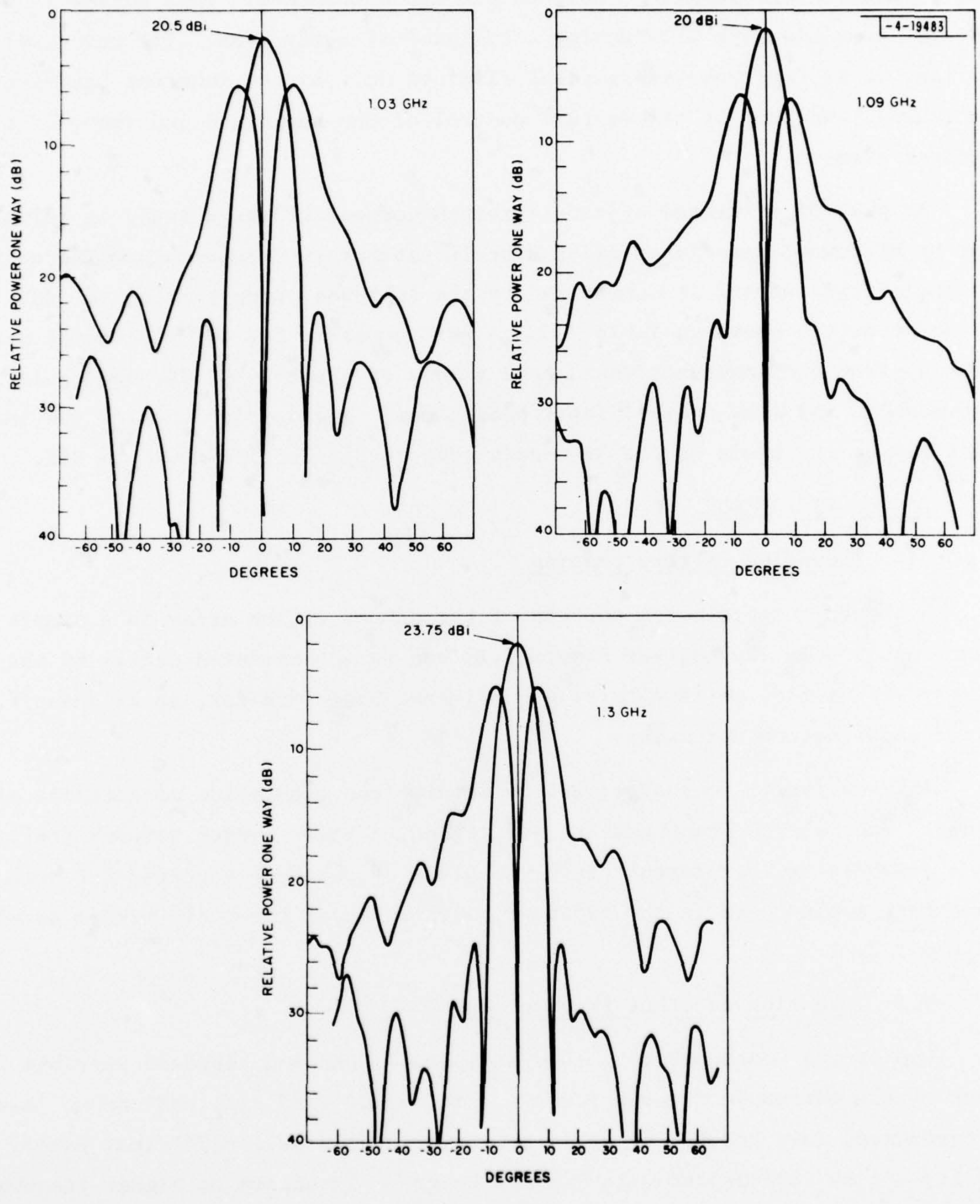


Fig. 5.6. Measured azimuth monopulse patterns.

forming and scanning unit to be completed at a further date is shown in Figure 6.1. The scanning matrix consists of 32 transfer switches grouped in eight four-switch modules and 16 single-pole triple-throw switches. This scheme is one of several possible ways of scanning a cylindrical array beam. Its principal advantage is that it is frequency independent (limited only by the inherent bandwidth of the switches), and that it allows full control of the amplitude and phase of each excited element.

As part of a related effort, a switch component design study is being carried out by Microwave Associates under Lincoln Laboratory sponsorship. The current status of this effort is summarized by the achieved parameters of an individual transfer switch shown in Table 6.1. A switch matrix for the 48-element array made up from such switches would have a loss of about 2-1/2 dB, and could handle between 1/2 and 1 kW overall input peak power. Acquisition cost of the individual switches on the basis of the $100 unit cost for production would be $5K.

7. DESIGN VARIATIONS

7.1 Elevation Pattern Shaping

Although the elevation pattern of the demonstration array is a simple narrow beam, other beam shapes (see Figure 7.1) can be accommodated easily by the binary type power divider while retaining sufficient bandwidth for, as an example, combined radar/beacon operation.

Alternatively, some applications require the generation of multiple elevation beams. When only a few beams are sufficient, a Blass ladder network (reference 3) is a commonly used implementation. Couplers of the type required for such networks have been implemented in the expanded multiple layer honeycomb medium as shown in Figure 7.2.

7.2 Extension to Other Frequencies

Use of the honeycomb supported stripline technology appears possible for much of the microwave frequency range. It should find applications at lower frequencies, down to UHF, since large, structurally self-sufficient panels (up to 12 ft) can be implemented with minimal weight. Extension to higher frequencies is limited by the thickness of the honeycomb. Currently, the thinnest available

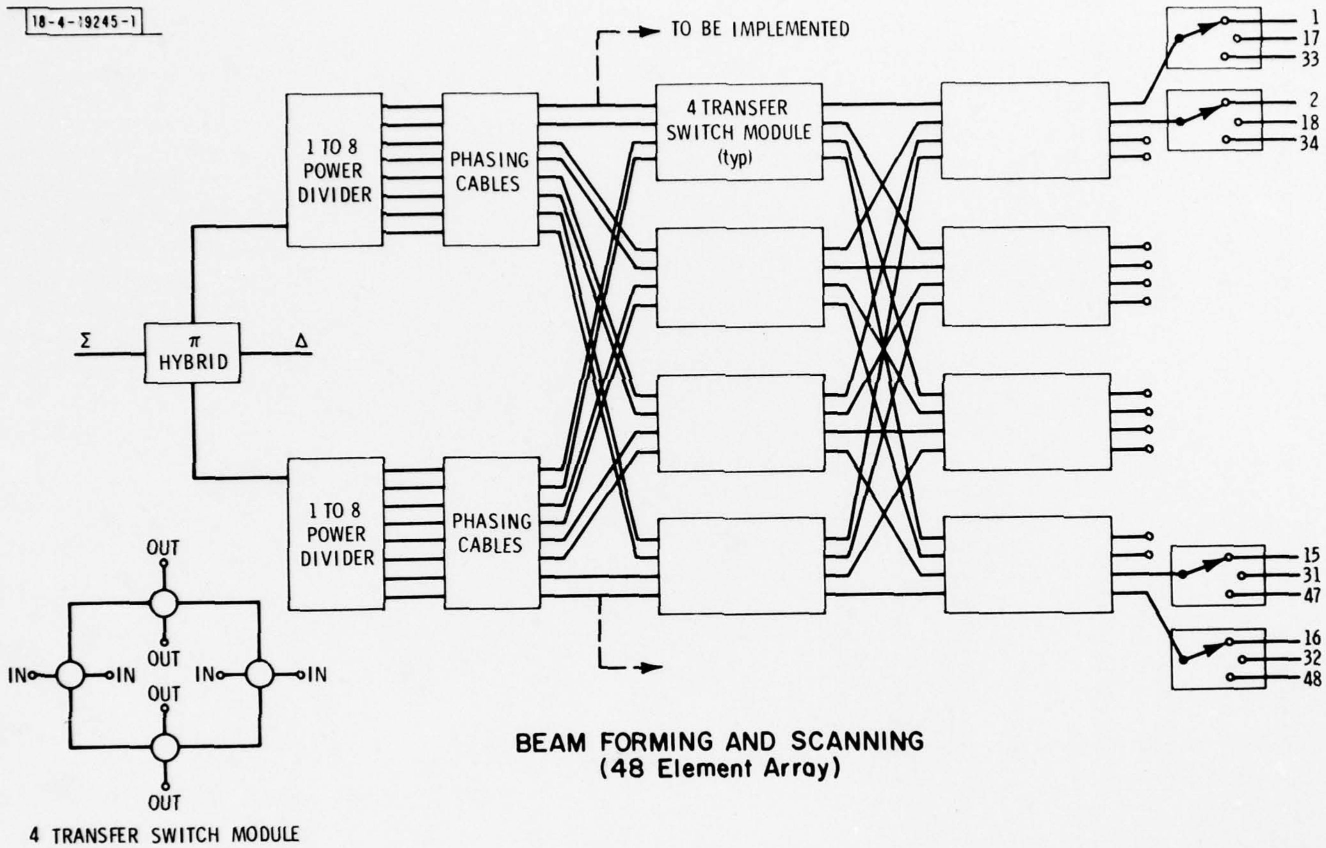


Fig. 6.1. Beam scanning matrix for 48 element arrays.

TABLE 6.1

TRANSFER SWITCH CHARACTERISTICS (from Microwave Associates)

Frequency	1.0 - 1.4 GHz
Insertion Loss	0.5 dB
Isolation	>40 dB
Power Handling	30 to 50 watts peak (100-μsec pulse)
Size	8 cm x 8 cm
Switching Speed	5 μsec
Driver Power	1/2 watt
Estimated Production Cost	$100

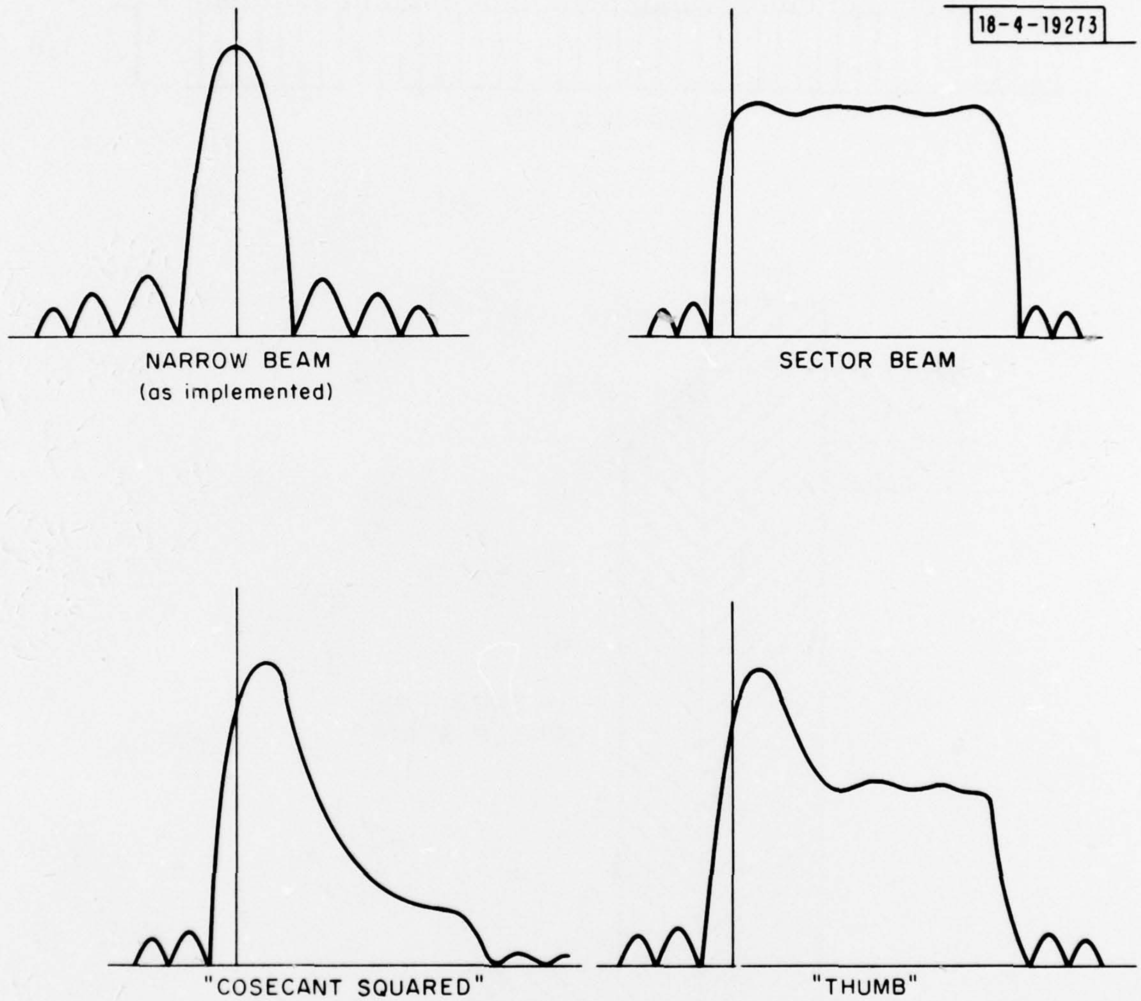


Fig. 7.1. Alternate elevation patterns.

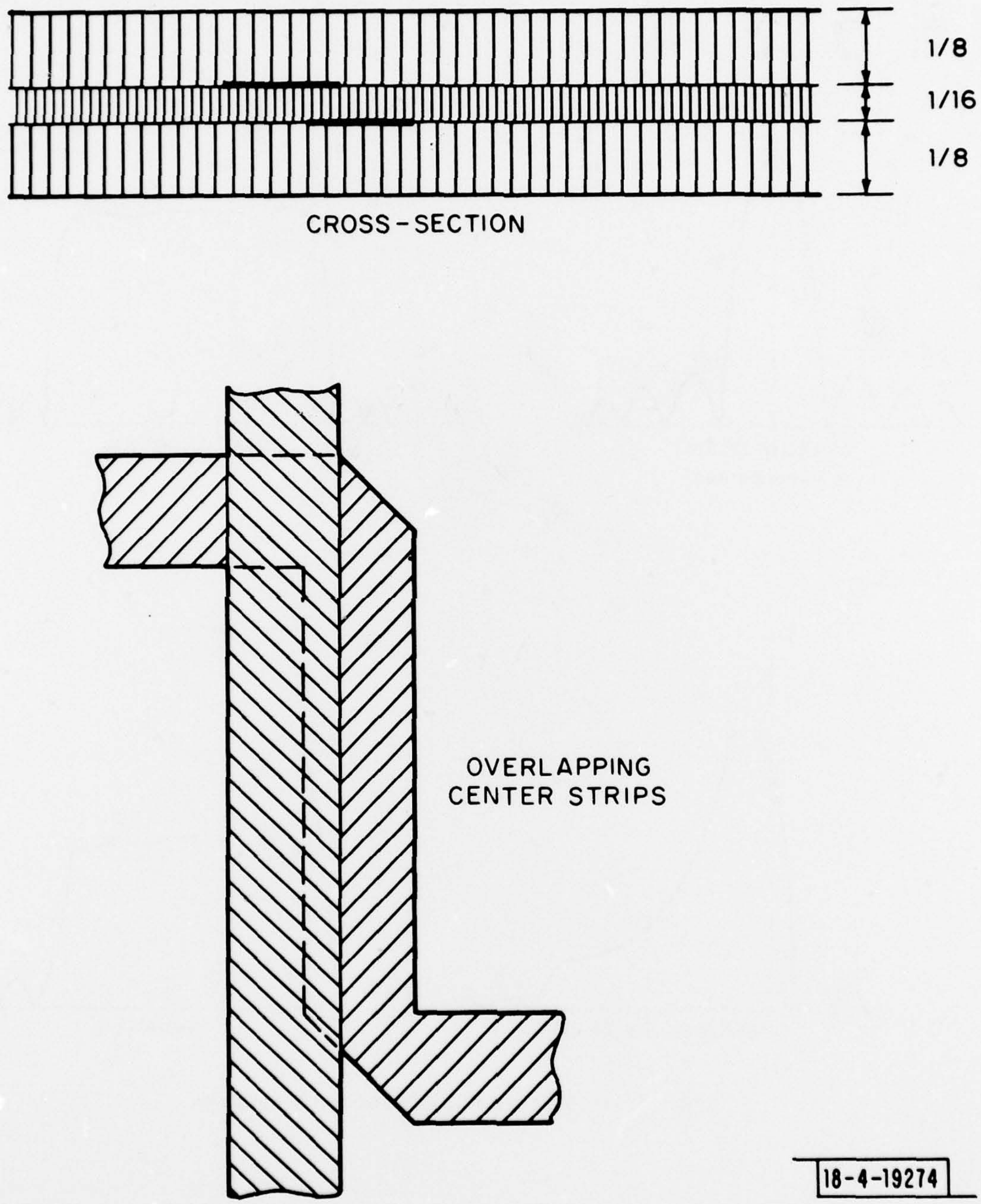


Fig. 7.2. Off-set parallel coupled lines.

material is 1/16". A 50Ω transmission line, with a 1/8" total thickness, has been measured to have a loss of 0.5 to 0.75 dB/ft depending on materials. At higher frequencies the loss increases but, more importantly, component design becomes intolerably difficult because the line width represents a significant fraction of a wavelength. If and when honeycomb materials become available in 1/32" thickness, extension to X- and even K_u-band may be contemplated.

8. DISCUSSION

It is hoped that the results of this effort will serve to demonstrate that cylindrical arrays can be built to perform as designed and at a cost which makes them competitive with other types of antenna systems. A few observations warrant special attention because of their impact on the perspective of the overall results. This effort was carried out with no definite set of requirements other than a loosely expressed desire for low cost/weight. As a result, the design was allowed to evolve along its most natural path and was not biased or distorted by artificial constraints.

The selection of the materials shown in Figure 2.1 set the tone for the entire system. It was, in effect, a cost and weight reference against which all other aspects of the design (structure, assembly processes, switches, etc.) were compared to and driven to be commensurate with. The suggested low cost of the system is not based on a potential, postulated large volume production as is often done to amortize high initial start-up costs. The materials and processes which have been used are readily available and tooling is very modest. As such, this technology should be easily transferrable to industry.

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20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

An L-band cylindrical array has been assembled for demonstration purposes. The array is 6 ft in diameter and contains 48 4-ft columns. It was fabricated using novel, low-cost and lightweight techniques. Measurements indicate that this array is usable at least from 1.0 to 1.4 GHz. Plans for implementing the scanning matrix and other design options are indicated.

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