CR- 171845
c.1

INTERLEAVED ARRAY ANTENNA TECHNOLOGY DEVELOPMENT

NASA CONTRACT NAS5-16430

GERA-2702

30 JANUARY 1985

GOODYEAR AEROSPACE
ARIZONA DIVISION

GOODYEAR
AEROSPACE

GOODYEAR AEROSPACE CORPORATION
Litchfield Park, Arizona 85340-0085

INTERLEAVED ARRAY ANTENNA TECHNOLOGY DEVELOPMENT

NASA Contract NAS9-16430

GERA-2702
Code 99696

30 January 1985

54003

ABSTRACT

This report covers work performed by Goodyear Aerospace Corporation for NASA-Johnson Space Center on contract NAS9-16430, during the period of 1 July 1983 through 30 September 1984.

This is the third phase of a program to establish an antenna concept for shuttle and free-flying spacecraft earth resources experiments using Synthetic Aperture Radar. Phases one and two are covered by GERA-2644, 30 June 1983.

The objective of this phase was to establish the feasibility of plated graphite epoxy waveguide for a space antenna. To achieve this objective, a quantity of flat panels and waveguides were developed, procured, and tested for electrical and mechanical properties. In addition, processes for the assembly of a unique waveguide array were investigated. Finally, trades between various configurations that would allow elevation (range) electronic scanning and that would minimize feed complexity for various RF bandwidths were made.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

SECTION I – INTRODUCTION AND SUMMARY

This report covers work performed by Goodyear Aerospace Corporation for NASA-Johnson Space Center on contract NAS9-16430, during the period of 1 July 1983 through 30 September 1984.

This is the third phase of a program to establish an antenna concept for shuttle and free-flying spacecraft earth resources experiments using Synthetic Aperture Radar (SAR). Phases one and two are covered by GERA-2644, 30 June 1983.

The objective of this phase was to establish the feasibility of plated graphite epoxy waveguide for a space antenna. To achieve this objective, a quantity of flat panels and waveguides were developed, procured, and tested for electrical and mechanical properties. In addition, processes for the assembly of a unique waveguide array were investigated. Finally, trades between various configurations that would allow elevation (range) electronic scanning and that would minimize feed complexity for various radio-frequency (RF) bandwidths were made.

Most of the emphasis on this phase was placed on the development of a plating technique for graphite epoxy assemblies. Fabrication of tubes, plates, and other assemblies from a variety of available prepreg cloths is considered to be a well-understood and controllable process, but the best choice for plating has not been established. Likewise, the specific steps required in the plating process that will produce acceptable RF and mechanical properties needed to be established.

Results achieved during this phase are:

1. A quantity of waveguide tubes has been successfully fabricated, plated, and RF and mechanically tested. As part of this, a number of plating procedures were investigated and an acceptable procedure was developed
2. Acceptable waveguide RF attenuation values can be achieved. Values of 0.10 dB and lower were measured. Additional process development will be required to improve yield and more fully establish the plating thickness needed

3. Satisfactory adhesion of metal-to-graphite can be obtained. Thermal cycling of tubes showed that blistering and flaking of metal can be controlled to acceptable levels. Tape peel tests performed on prototype tubes did indicate some unevenness of plating which should be corrected in production tubes, but tests on these were not completed in time to be included in this report.

In addition to the above, electrical trades were made to reconfigure the antenna to allow electronic scanning of the beam in the range direction. Also, simplifications in feed networks can be realized by reduction in the C- and X-band frequency bandwidths to 50 MHz.

SECTION II – WAVEGUIDE DEVELOPMENT

1. PARTS PROCUREMENT

a. Selection of Parts

The objective of this phase of the program was to demonstrate that acceptable metal plated waveguide tubes could be fabricated and assembled into representative sections of the interleaved arrays. Because of funding limitations, a decision was made to fabricate only X-band parts, which, because of size and tolerances, were judged to be most critical and would represent the most difficult challenge.

Dimensions and specifications for the parts had been established on Phase 2 of the contract. The specifications are listed in Table I, the parts drawings are shown in Figures 1 through 4, and the parts to be procured are listed in Table II. These parts will allow:

1. Verification of dimensional control and coefficient of thermal expansion (CTE)
2. Establishment of electrical and mechanical properties
3. Demonstration of plating and adhesion of the silver to the graphite epoxy
4. An initial assessment of assembly techniques.

b. Subcontractor Selection

(1) General

A number of subcontractors were contracted during Phase 2. Of these, the six listed in Table III were judged to be technically capable of fabricating the tubes, and were issued a statement of work (SOW) covering development, fabrication, and documentation requirements and a request for price.

Summaries of the proposed approaches of all subcontractors are in the following paragraphs.

TABLE I – WAVEGUIDE SPECIFICATIONS

1. Components must withstand space environment, including shuttle launch and re-entry.

2. Isotropic thermal coefficient of expansion less than 0.7×10^{-6}/F deg over -100 F to 170 F.

3 Components to meet drawing SK-682813:

a.	Interior wall dimensions	0.730 ±0.002 in.; 0.350 ±0.010 in.
b.	Interior corner radi	0.030 ± .005 in.
c.	Wall thickness	0.020 +0.004 in. - 0.000
d.	Wall taper	0.002 Max

4. Interior and partial exterior surface metalized with silver:

a.	Silver thickness	0.2×10^{-3} in. min
b.	Metalized surface roughness	32×10^{-6} in. max

c. Interior surface and edges to be metalized

d. Exterior surface to be partially metalized (see SK-682813)

e. Adherence to graphite composite through vacuum thermal cycling between ±250 deg F.

f. Metalized surfaces must pass tape test ASTM-D-3359-74

g. Silver coating must not peel, blister, or crack under space conditions.

h. Internal surface resistivity equal to or less than 2×10^{-6} ohm cm.

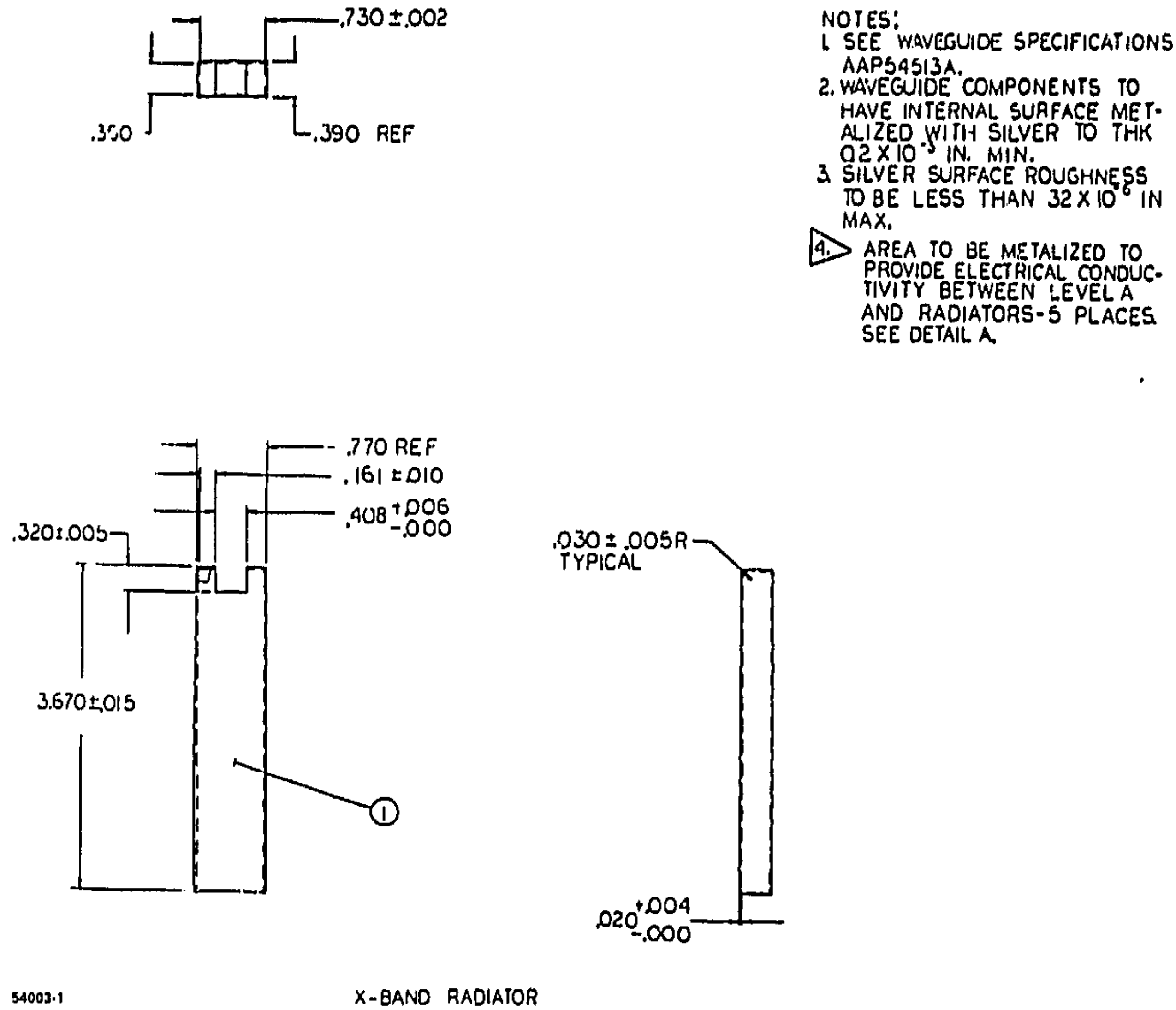
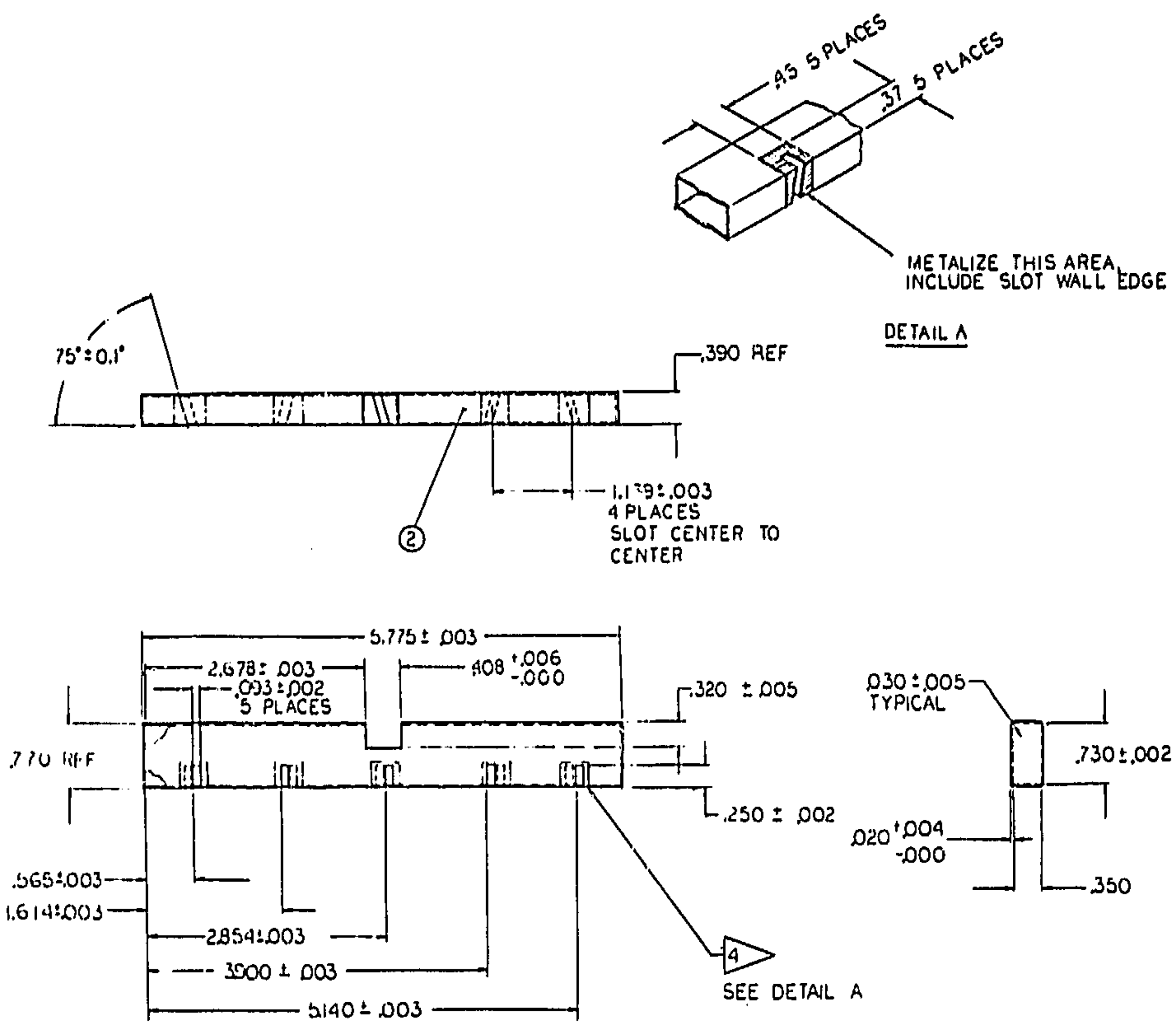


Figure 1 — X-Band Waveguide Radiator

(2) Composite Optics, Inc.

The approach of Composite Optics Inc., was as follows:

1. Composite Optics proposed using a P55S/930 graphite/epoxy unidirectional prepreg tape system. The advantages of this material were availability, low cost, good producibility and meeting the performance requirements



54003-2 X-BAND LEVEL A

Figure 2 – X-Band Waveguide Feed

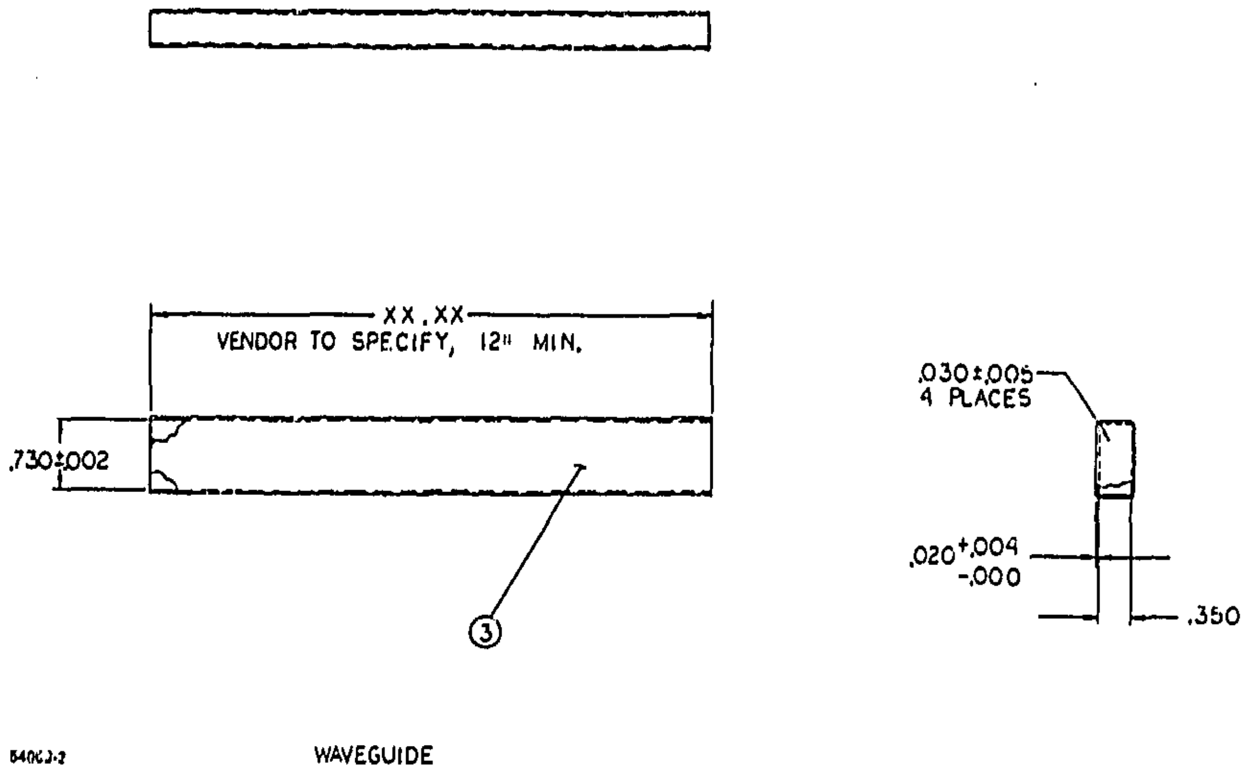
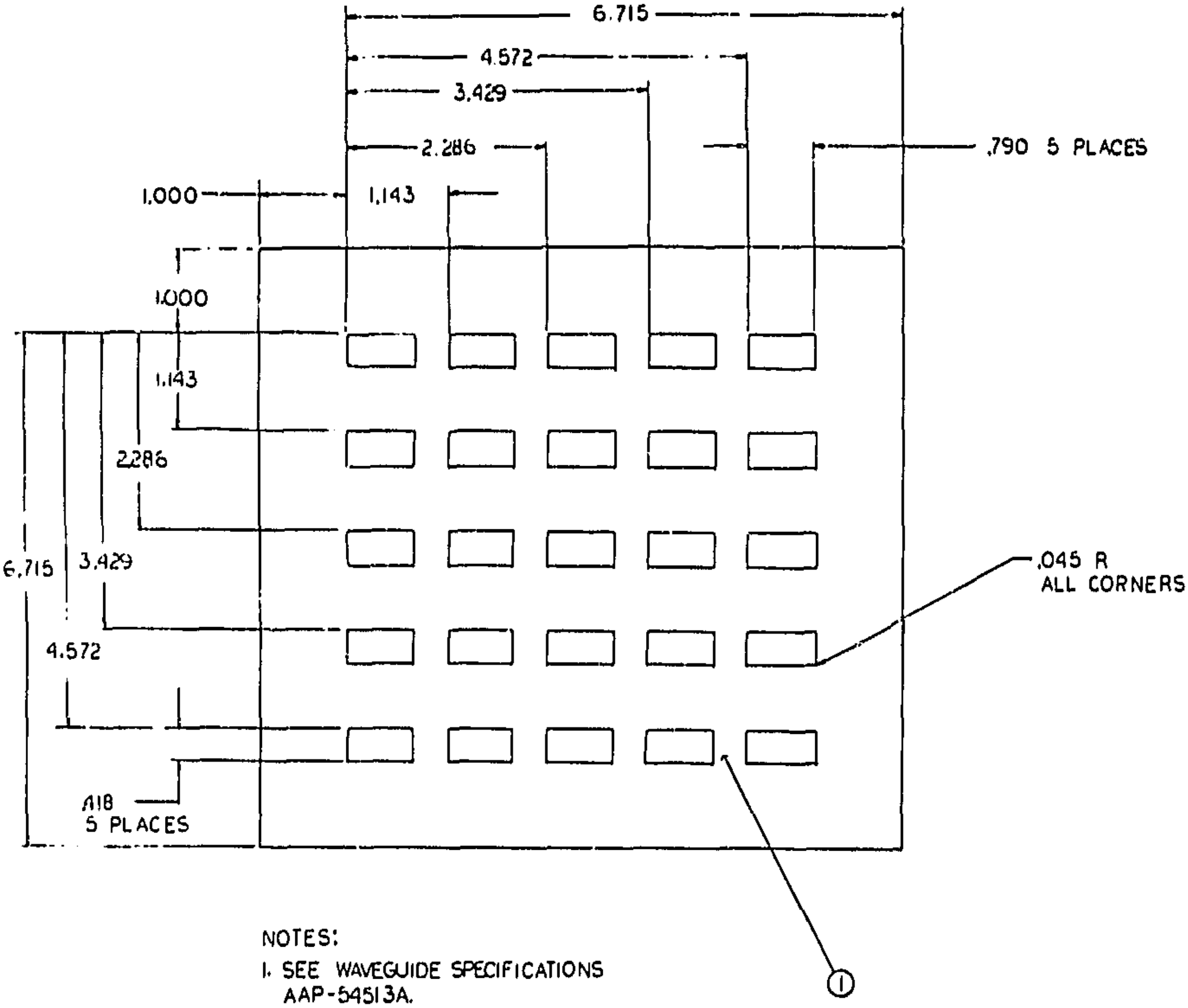


Figure 3 – X-Band Waveguide Tube

2. The method of fabrication for the rectangular waveguide components would be hand lay-up. Two methods were proposed for the waveguide end caps; the first was to fabricate, coat, and trim the cap from a single large hand laid-up panel and the second alternative was to utilize compression molding

3. Two metalization techniques were proposed. These were direct electro-deposition of the composite surfaces or a transfer plating method. The electro-deposition method is used after fabrication of the component. The transfer plating method is done concurrently with fabrication by vapor depositing a strike coat of silver on the mandrel, then fabricating the part.



NOTES:
1. SEE WAVEGUIDE SPECIFICATIONS AAP-54513A.
2. FACEPLATE TO BE METALIZED WITH SILVER .025 MIL THICK, FRONT AND BACK.
3. SILVER SURFACE ROUGHNESS TO BE LESS THAN 32 X 10^{-6} IN.

54003-4

Figure 4 – Faceplate/Ground Plane

TABLE II – PARTS LISTING

Quantity	Part	Usage
6	6 in. x 6 in. flat metalized plate	Adhesion testing
12	20 in. X-band waveguide tubes	CTE and electrical testing
25	X-band radiators	Assembly and fabrication testing
2	X-band level A feeds	Assembly and fabrication testing
2	Faceplates	Assembly and fabrication testing

TABLE III – SUBCONTRACTOR CANDIDATES

Contractor	Location
Composite Optics, Inc.	San Diego, CA
Dittmer & Dacy, Inc.	San Diego, CA
Exxon Enterprises	Fountain Inn, SC
Fiber Science	Salt Lake City, UT
Goldsworthy Engineering	Torrance, CA
Russell Plastics Technology, Inc.	Lindenhurst, L.I., NY

(3) Dittmer & Dacy, Inc.

The approach of Dittmer & Dacy, Inc., was as follows:

1. The material proposed was Fiberite 2030D unidirectional graphite epoxy prepreg tape. The advantages of this tape are that it is space qualified, and readily available in a 0.0025-in. thick tape necessary to meet the wall thickness requirements

2. The fabrication of rectangular waveguide components will be done by tape winding eight plies at the necessary fiber orientations onto a resin-coated mandrel. The tape-wrapped mandrel is then placed in a female mold cavity, heated, and press closed to cure. The plates will be fabricated using a hand lay-up procedure, then press molded. It is proposed that the end caps be fabricated out of 0.006 in. to 0.010 in. thick stainless steel

3. The metalization technique proposed is an electroless nickel and copper coating method over a resin rich surface. Silver electroless plating will then be deposited over the nickel.

(4) EXXON Enterprises

EXXON Exterprises approach was as follows:

1. No particular graphite composite material was specified

2. Open mold fabrication of the waveguide components is the proposed method of fabrication. The method of fabricating end plates and closures was not addressed

3. Metalization would be completed by coating the mandrel before fabrication or by using a plating process afterwards.

(5) Fiber Science

The Fiber Science approach was as follows:

1. Thornel 300/(DEN 431/XU205) is the material system proposed by Fiber Science. This material is specially suited to rigorous space environments

2. The fabrication process proposed is to filament wind the tubes on steel mandrels. The end caps would be molded graphite composite, machined to size, and bonded in place

3. Two methods of metalization were listed as possibilities. The first method is overwrapping foil bonded to the tube. The second method is to electroplate silver onto a base layer of electroless nickel plate.

(6) Goldsworthy Engineering

The Goldsworthy Engineering approach was as follows:

1. The materials to be used by Goldsworthy Engineering would be graphite tow and nonwoven cloth. The epoxy resin will be a fast-cure, protrudable epoxy resin such as Epon 9302 resin/9350 hardner

2. The fabrication process would be pultrusion for the rectangular waveguide components. The faceplates and end caps would be compression molded

3. Three methods of metalization were proposed. The first method is to plate the waveguides with a conductive primer, then follow with normal plating and processing techniques. The second method would be vacuum metalization. Metalized film is the third method. This method copultrudes the film with the waveguide.

(7) Russell Plastics Technology

The Russell Plastics Technology approach was as follows:

1. The quote from Russell Plastics did not specify a particular graphite composite

2. Fabrication would be done by building the components on a mandrel. The graphite lay-up will be made over an adhesive layer. The waveguide will be made of cross plied sheet using two wraps. The components will then be cured by placing caul plates over the tubes wrapping with heat shrinkable tape and autoclaving. The closed ends will be made of plated graphite sheet bonded in place with silver epoxy

3. Metalization will be accomplished by using a thin-wall aluminum mandrel. The plating will be deposited on the mandrel and then, after the waveguide is wrapped and cured, the aluminum will be etched away. There are three steps to this operation. First there must be nickel plating over the aluminum mandrel. Second, copper must be plated over the nickel and finally, a film adhesive is laid over the etched copper before the graphite is laid up. After the aluminum has been etched out, the interior surfaces will be brush plated with silver using special anodes.

c. Selection of Subcontractor

Dittmer & Dacy, Inc was selected to fabricate the waveguide components and flat-plates for this contract. Comparison of all returned quotes showed that Dittmer & Dacy, Inc had the highest level of technical knowledge and the most cost-efficient method of manufacture for the quantities needed at this time. The process proposed can be easily automated for future large production runs. They also showed their expertise and interest by manufacturing and plating a sample piece of X-band rectangular tubing during the subcontractor selection phase.

2. PARTS FABRICATION AND DEVELOPMENT

a. Prepreg Selection

There are several graphite fibers which are capable of meeting the less than 0.7 x 10^{-6} in./in./deg F isotropic CTE requirement. Union Carbide's P75 fiber (75 x 10 pounds per square inch (psi) modulus) in Fiberite's 930 epoxy resin was selected for fabrication of the 5 x 5 array. This fiber-resin combination becomes Fiberite's HYE2030D unidirectional graphite epoxy prepreg tape, which is space qualified and readily available in an 0.0025-in. thick prepreg so as to allow a symmetric isotropic orientation in the 0.020 in. wall thickness. This fiber, under close process control, will allow a less than 0.10 x 10^{-6} in./in./deg F isotropic CTE. The prepreg tape is priced at approximately $400 per pound.

b. Fabrication

The graphite epoxy waveguide tubes are made by tape winding 8 plies (at 0.0025 in.) of prepreg in 0, 45, 135, 90, 90, 135, 45, and 0 degree fiber orientations onto a surface-hardened, resin-coated rectangular mandrel, in the manner shown in Figure 5. A 0.001-in. thick resin coat on the mandrel assures a fiber-free inside surface layer for the subsequent metalization process. The tape-wrapped mandrel is covered with a 0.0015-in. thick random fiber protective mat and placed into a female mold cavity. The mold is heated to 350 deg F and press closed to cure the graphite composite. This process is commonly known as compression molding. The mandrel is then extracted leaving the graphite rectangular tube ready for machining and metalization into radiators, feeds, or waveguide lengths. Although for this project the tape winding was done by "hand" in a laboratory setup, this method can be easily automated for high-volume production. Under the contract the vendor supplied 25 radiators, 6 feeds, and twelve 17-in. waveguide lengths. Six 17-in. waveguide parts were delivered to Goodyear Aerospace for evaluation prior to final production.

The compression molding process is ideally suited for production of CTE critical parts with several precision surfaces. All surfaces of the parts are defined by hard steel tooling rather than compressible elastomeric fixtures used in some processes. Thus the close tolerances at several points on the part that are required for efficient assembly of the interleaved arrays antenna are achievable in production. Secondly, the volume, and therefore fiber-to-resin ratio, of each part is precisely controllable as is necessary to hold close tolerances on CTE and other thermal and mass properties.

The graphite epoxy faceplates and metalization samples are laminated in the same symmetric isotropic orientations as the waveguide tubes. As with waveguide, a 0.001-in. thick resin surface coating is applied to the molding plates to provide a fiber-free, resin-rich surface for subsequent metalization. The plates are press molded to the 0.020-in. thickness and heated to cure. All machining, such as the milling of the faceplate holes for radiator insertion, is done by the vendor prior to metalization.

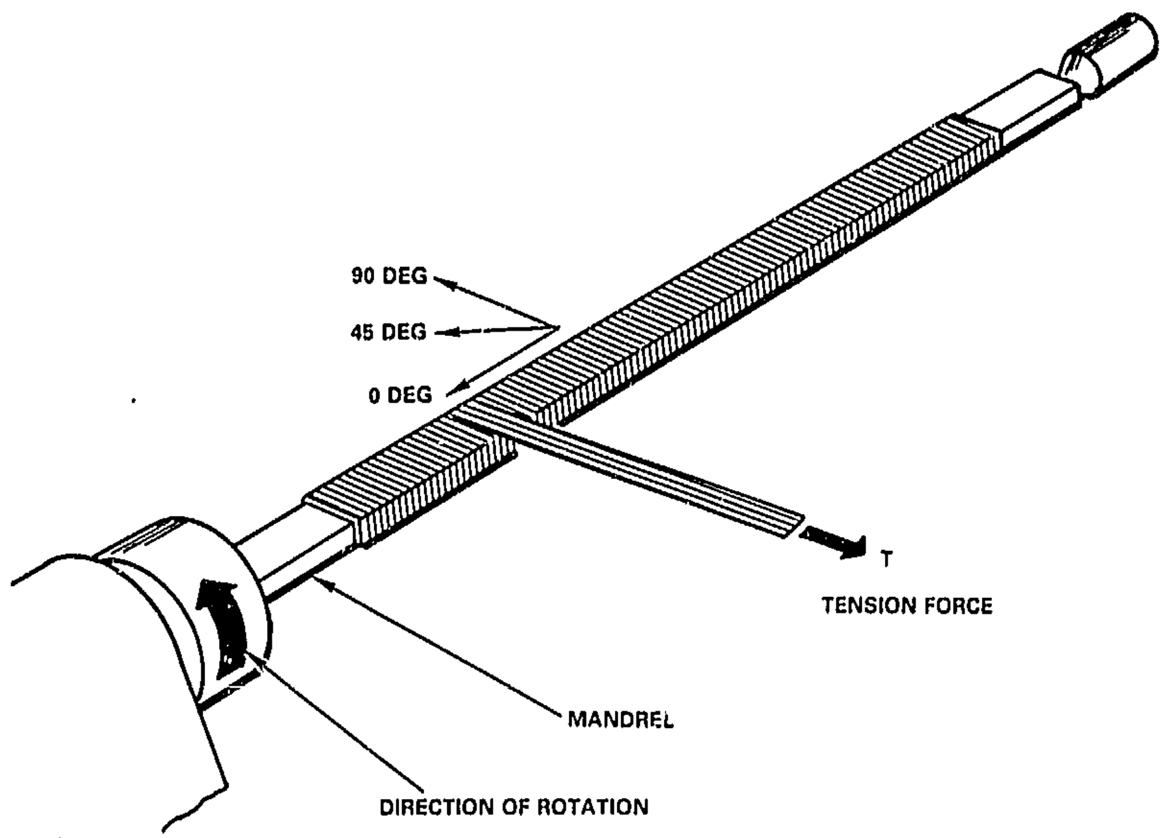


Figure 5 – Winding of Rectangular Tube

Closure caps and feed-to-radiator assembly brackets were fabricated from 0.006-in. thick, 1/4 hard stainless steel sheet stock. These parts, shown in Figure 6, are designed to maximize surface area of conductive adhesive bonds for low-resistance conduction and strength.

c. Metalization

Various methods and sources for the metalization of graphite fiber reinforced materials have been evaluated. Metalized mandrel techniques have been successfully used to produce relatively small quantities of waveguide parts. However, limitations in part length and production problems of mandrel-to-part metal transfer

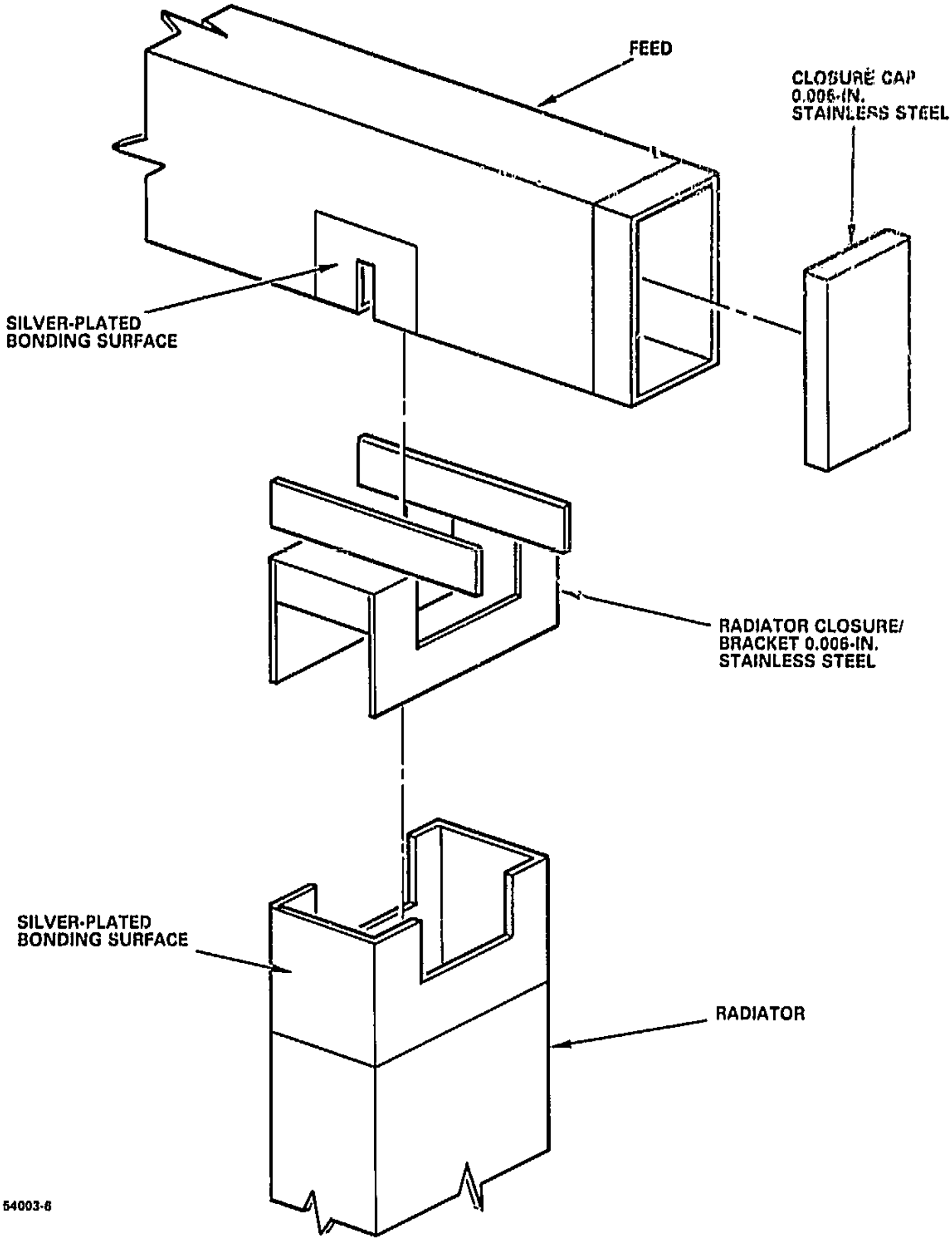


Figure 6 — Feed-to-Radiator Assembly and Closure

make direct metalization of the waveguide attractive. Paint and metal spraying techniques produce coatings that are too thick, rough, nonuniform, and not suitable for complicated shapes. Development of a vacuum deposition process for narrow tubing would be risky and expensive. Production costs for similar methods, such as sputtering, are high for the metal thickness required. This program has focused on electroless nickel and copper coating methods because they: (1) allow very thin (1-2 micron), uniform, smooth, replicate coatings for irregular shapes, holes, and cavities; (2) are proven production methods, and; (3) allow secondary electrodeposition. Excellent coatings with respect to coverage adhesion and smoothings have been produced with electroless nickel. It was learned that it is necessary to provide a fiber-free, resin-only surface layer for the electroless coating. Hence, in the tubular elements, the rectangular mandrel is resin coated prior to applying the grapite epoxy prepreg; and likewise, the plates will have resin-rich surfaces.

The electroless nickel plating process uses Shipley Company products in the order described in Table IV. Nickel plate quality is a function of the exposure, dilution, temperature, and agitation of each of these baths. There were difficulties in producing an adequately abraded surface for good adhesion while not destroying the resin-rich surface layer and exposing graphite fibers. Surfaces were selectively plated by applying an elastic spray-on mask to those areas not to be plated.

The electroless nickel coating provides the conduction required for electrodeposition of the primary silver coating. The waveguide part is connected at each end to the cathode of the electro-plating apparatus. The anode is a 0.25 in. x 0.25 in. bar of 99.99 weight percent silver that is inserted in the tube and is supported at each end. The anode-to-cathode surface area ratio is not critical because of the proximity of the two. A twisted wire bundle was used as an anode with unsatisfactory results.

Upon completion of the electro-plating, the part is rinsed and the plating mask removed.

TABLE IV – ELECTROLESS NICKEL PLATING PROCESS

	Time (min)	Temperature (deg F)
Concentrated H_2SO_4(clean)	2	Room temperature
Rinse	2	
Etch PM-930	5	150
Rinse		
Neutralizer PM-950	5	120
Rinse	1	
Cataprep 404	1	110
Cataposit 44 1-1/2 percent	3	110
Rinse	1	
Accelerator PM-960 10 percent by volume	2	Room temperature
Electroless Nickel PM-980 14.5 percent by volume	10	95

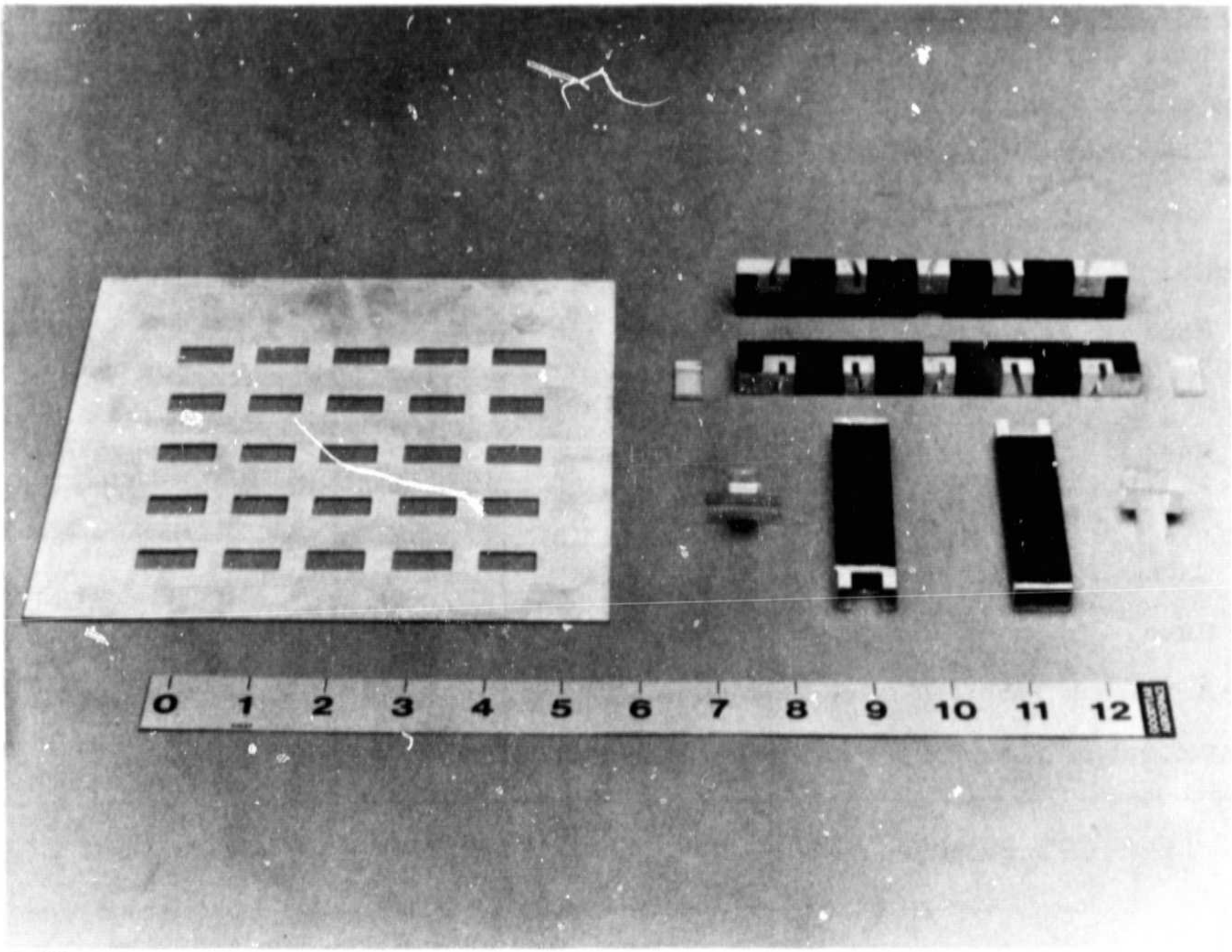
d. Parts Delivery

Initially, six prototype waveguide tubes, each 17 in. long, were delivered and tested. Detailed results are presented in Paragraph 3 for these.

The data was used to modify the fabrication and plating process for the deliverable, or production tubes.

The first 12 production tubes delivered exhibited dents and cracks caused by a holding fixture used during plating. The tubes are being replaced, but were not received in time to include in this report.

Radiators, feeds, faceplates (ground planes), brackets, and end caps considered representative of array hardware is shown in Figure 7. The parts exhibit uniform



54003-7

Figure 7 – Silver-Plated Graphite Epoxy Waveguide Parts

plating and have improved smoothness over any of the prototype tubes. They are also free of dents and cracks.

These parts will be used to establish assembly techniques. The assembly concept, without brackets or positioning hardware, is shown in Figures 8 and 9.

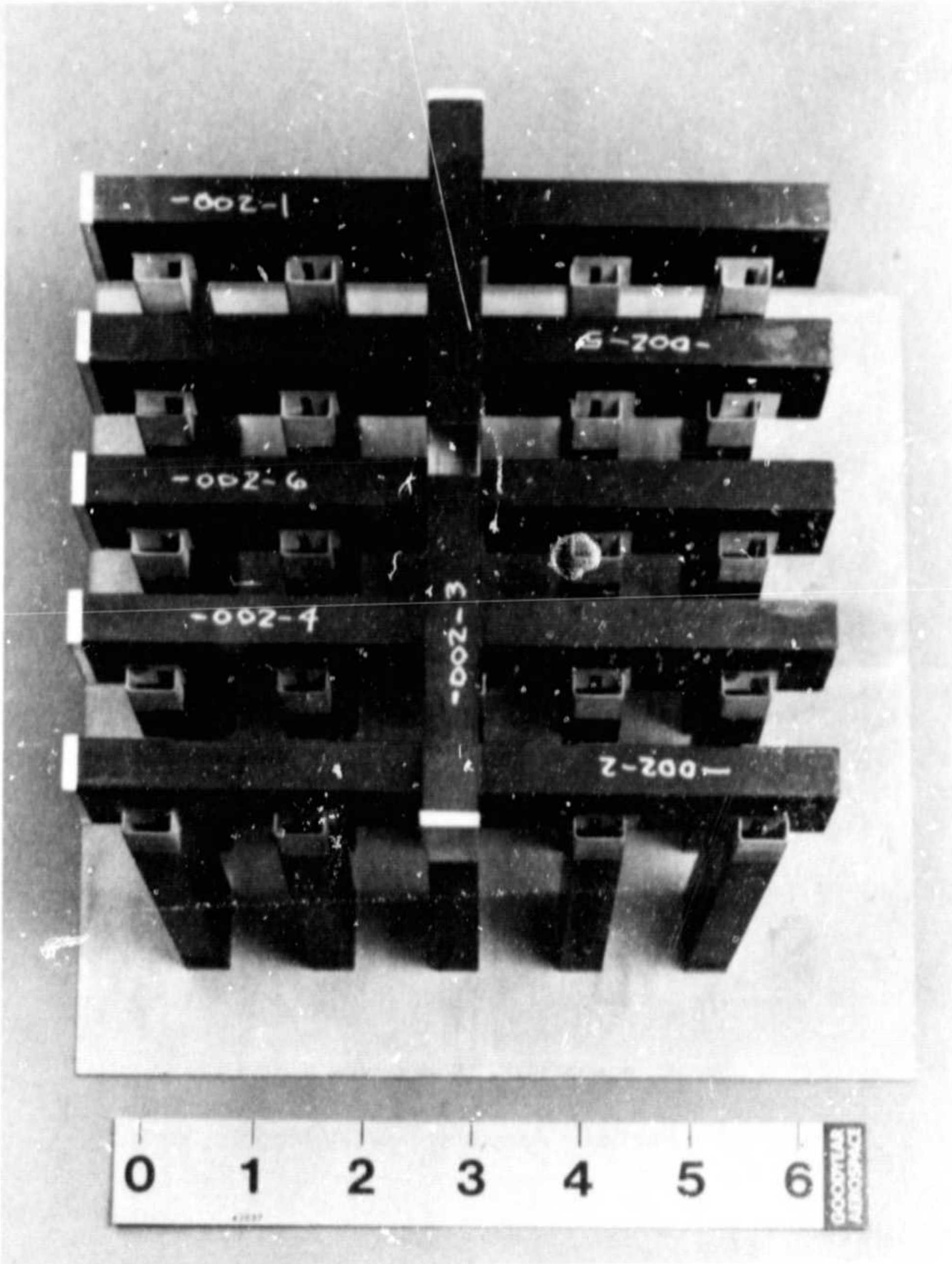
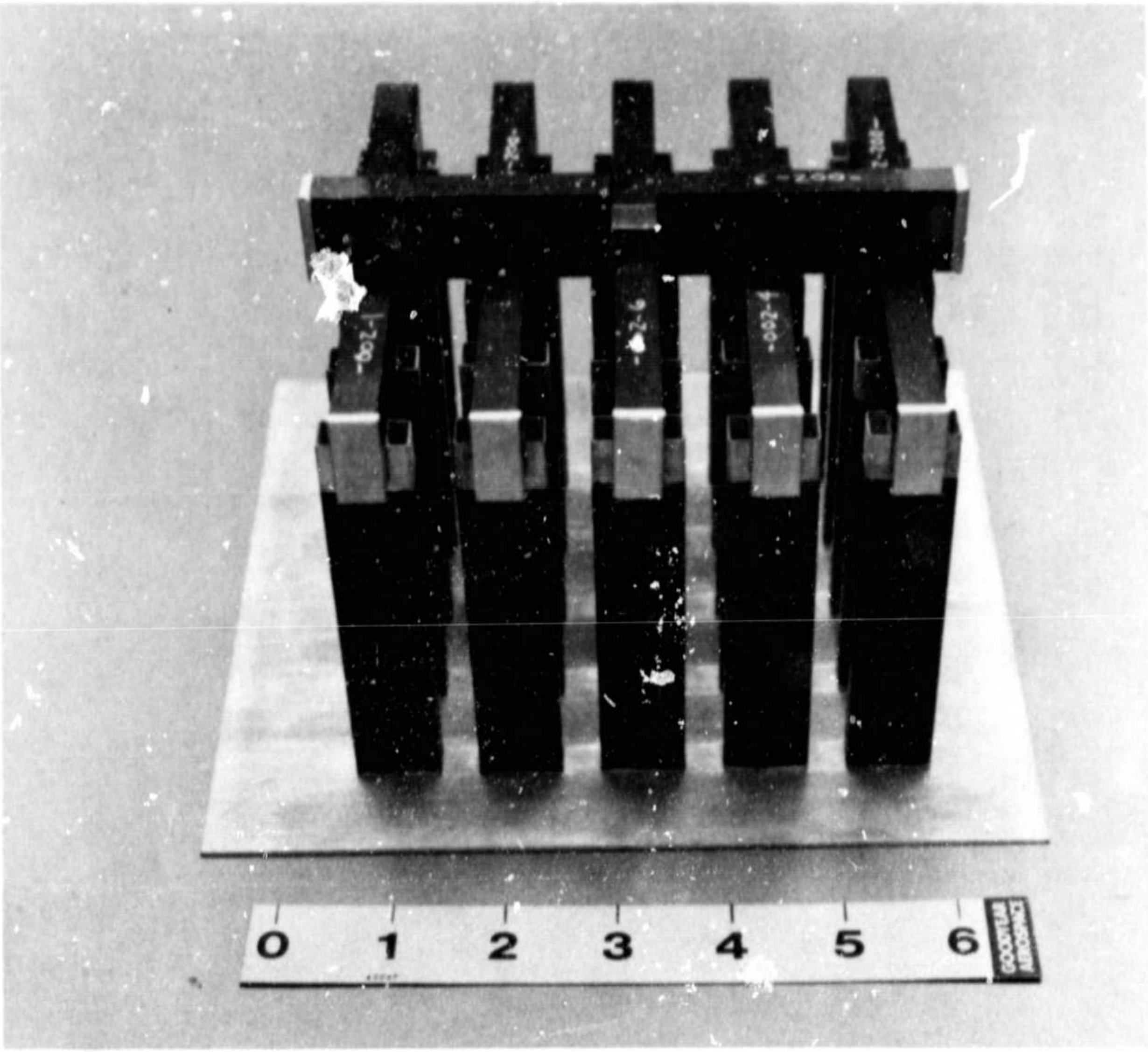


Figure 8 – Partially Assembled Array Module, View 1



54003-9

Figure 9 – Partially Assembled Array Module, View 2

3. TEST RESULTS

a. Electrical

Waveguide losses will be a major factor in system design. Antenna losses can only be overcome by improved receiver performance or increased transmitter power, both of which are expensive and difficult to achieve in space.

At C- and X-bands, waveguide losses can be about 10 times lower than stripline, but careful design is necessary to fully realize this advantage.

The attenuation of a rectangular copper air-filled waveguide operating in the TE_{10} mode is

$$\alpha_c = \frac{0.01107}{a^{3/2}} \left[\frac{\frac{1}{2}\left(\frac{a}{b}\right)\left(\frac{f}{f_c}\right)^{3/2} + \left(\frac{f}{f_c}\right)^{-1/2}}{\left[\left(\frac{f}{f_c}\right)^2 - 1\right]^{1/2}} \right] \text{dB/ft} \tag{1}$$

where f is operating frequency and f_c is the cutoff frequency. The inner dimensions of the guide, a and b, are in inches. The larger dimension is a. If some metal other than copper is used as a conductor, the attenuation given by this formula should be multiplied by the square root of the ratio of the resistivities.

The resistivities of metals, relative to copper, and the computed attenuation, in dB/ft, are given in Table V, for the X-band waveguide fabricated on this project.

Initially, the five of the six prototype waveguide tubes were measured for insertion loss. These tubes, numbered 1-5 in Figure 10, represent experience gained in the plating process, with numbers 3 and 5 the latest manufactured.

The test set up employed is shown in Figure 11. The phase-locked signal source, a dial indicator on the slotted line with 0.0001 in. resolution, and a receiver provided the control necessary for repeatable, accurate data.

The measurement technique was:

1. For a given short position, determine the position of a null on the slotted line, and the positions at which the power coupled out the probe is 3 dB greater than at the null (minimum power)

2. Compute the voltage standing wave ratio (VSWR) from

$$\text{VSWR} = \frac{\lambda gSL}{\pi\ (3\ \text{dBW})} \tag{2}$$

where λ gSL is the guide wavelength in the slotted line, and 3dBW is the distance between the 3 dB points

TABLE V – THEORETICAL WAVEGUIDE ATTENUATION

Material	Relative Resistivity	Attenuation (dB/ft)
Copper (OF-DLP)	1.00	0.068
Aluminum (1100)	1.63	0.087
Copper alloy (UNS-C22000)	2.19	0.101
Silver (Grade C)	1.14	0.073

Notes: Frequency of operation is 9.6 GHz
Internal dimensions of waveguides are 0.730 in. x 0.350 in.

3. Compute the loss

$$\alpha_t = 8.686 \tanh\left(\frac{1}{VSWR}\right) \qquad (3)$$

where α_t is the total loss

4. Move the short about one-half wavelength, and repeat

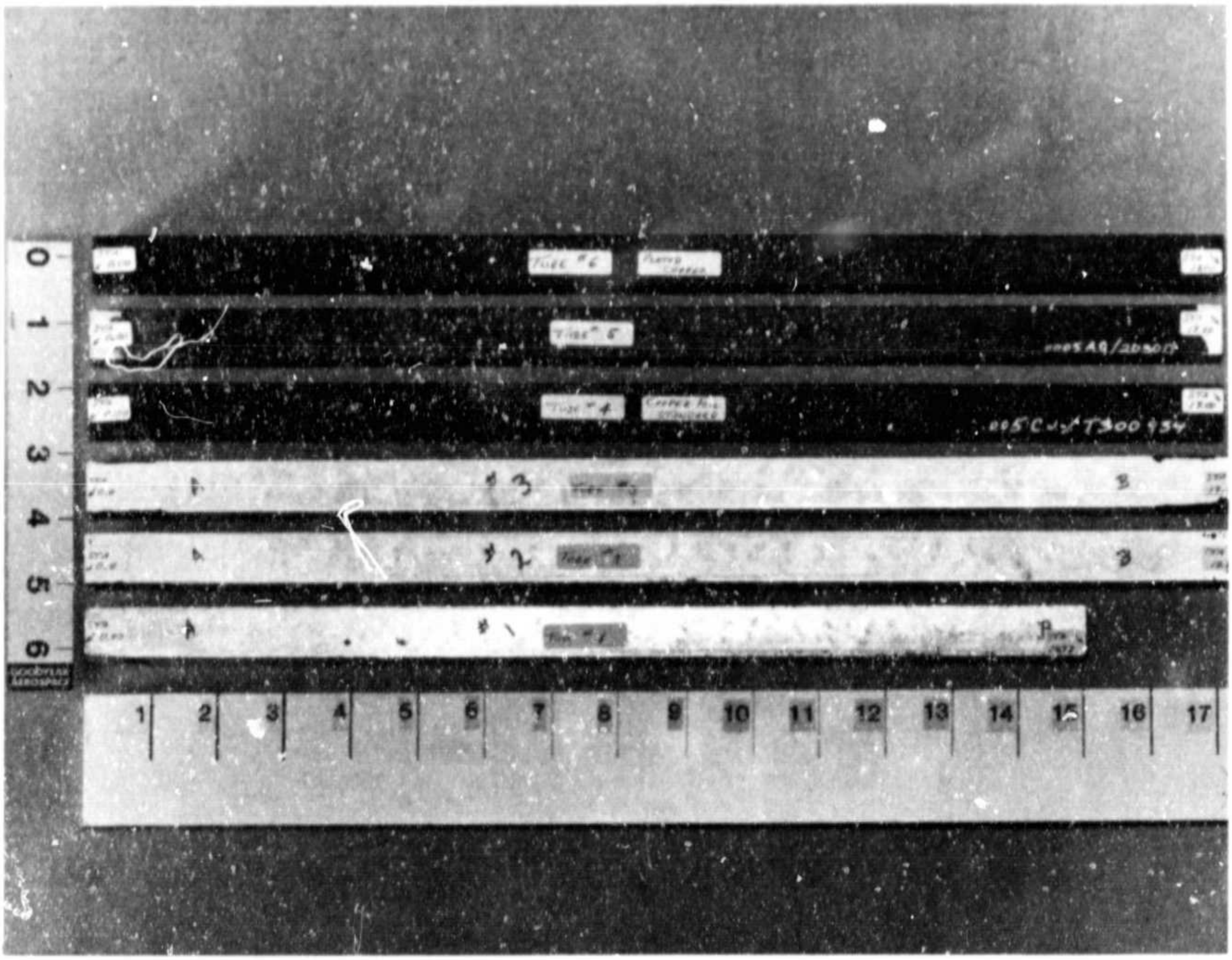
5. Plot α_t as a function of short position. The slope of the plot is the attenuation per unit length.

Measured data for tubes 1 through 5 are summarized in Table VI.

Tubes 1 and 2 represent early plating efforts and are clearly unacceptable. Tube 2, in particular, exhibited an attenuation which was a function of position.

Tubes 3 and 5 are considered to have acceptable losses, but, based upon the mechanical data described in Paragraph 3b., could be improved upon.

Tube 4 is not plated, but rather was constructed by first wrapping a 0.005-in. thick copper sheet around a mandrel and then forming the graphite epoxy outer material. This tube represents a "standard" and was used to verify the calculated data and the test setup.



54005-10

Figure 10 – Prototype Waveguide Tube

In addition to the above, an 18-in. aluminum tube of WR-90 waveguide was tested. The measured value of 0.051 dB/ft agreed with the calculated value.

A number of factors will cause degradation from calculated values. For the tubes fabricated on this project, these are surface roughness, thickness of plating, pits and voids, and nonadhesion of the plating. These are further discussed in Paragraph 3b.

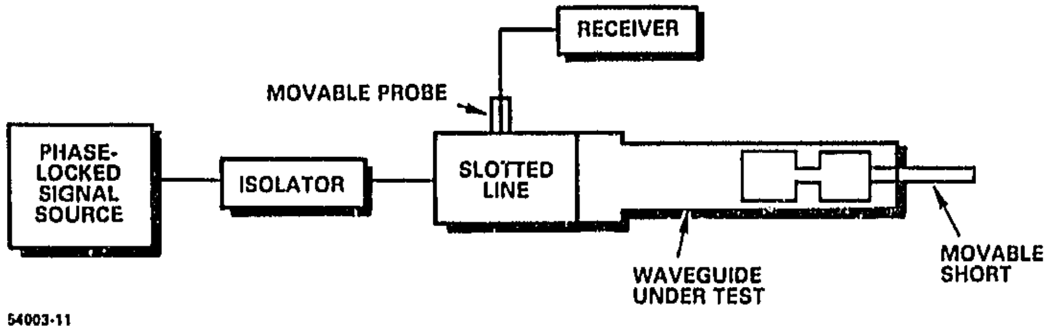


Figure 11 – Attenuation Measurement Test Setup

TABLE VI – MEASURED WAVEGUIDE ATTENUATION

Tube	Attenuation (dB/ft)
1	0.41
2	0.37/0.75
3	0.090
4	0.080
5	0.109
6	0.087
7	0.095
8	0.110
9	0.140

Additional data was measured on the 12 production waveguide tubes. Of these, only four provided acceptable attenuation values and are identified in Table VI as tubes 6 through 9. All tubes had been damaged by the holding fixture used in the plating process and contained cracks and dents which made measurement of most of the tubes meaningless. New tubes are being fabricated using new tooling in order to provide acceptable quality.

b. Mechanical

(1) Plating

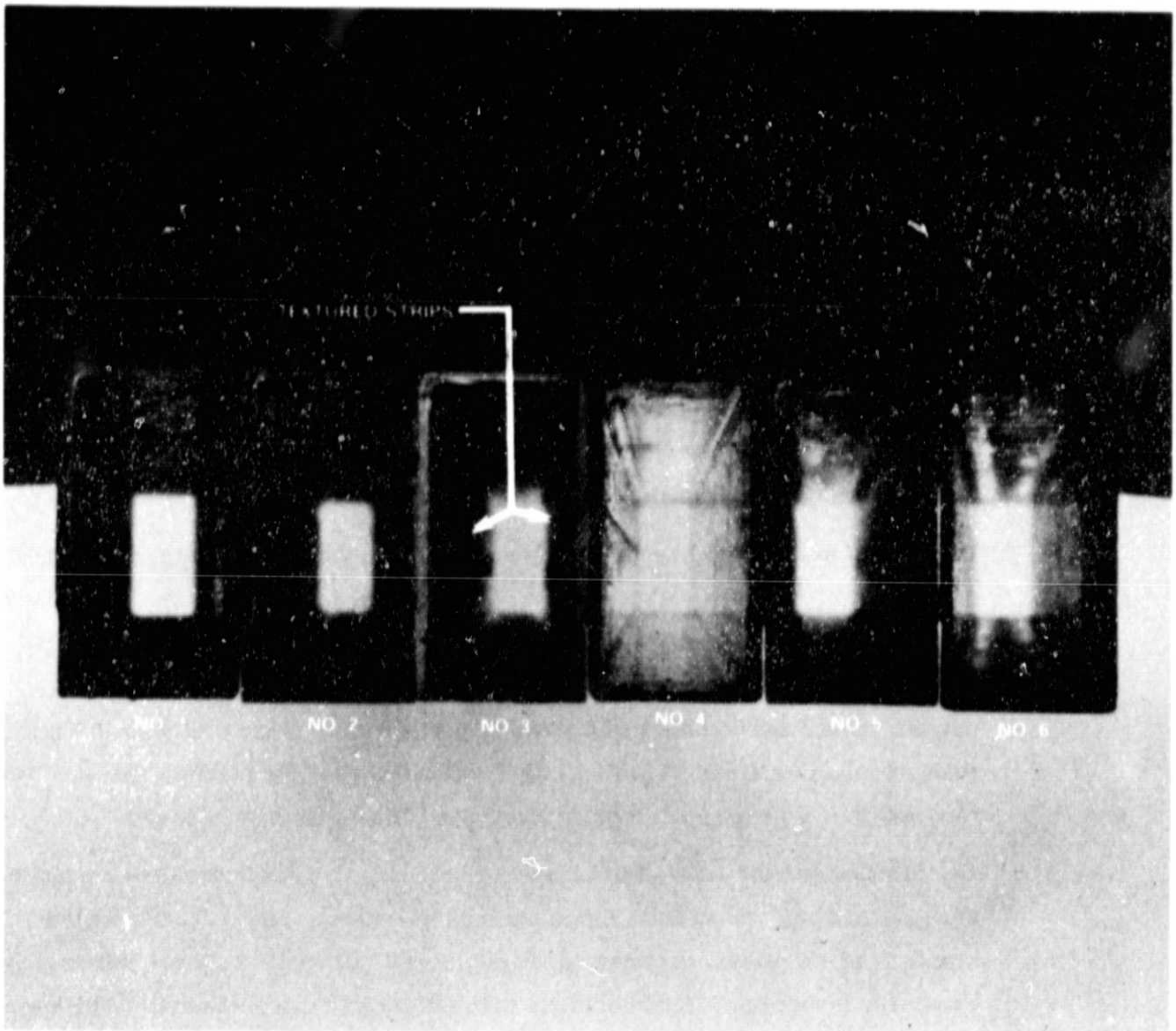
As part of a preproduction development phase, Goodyear Aerospace received six waveguide tubes for electrical and mechanical inspection. They have been shown in Figure 10.

Tubes 1, 2, 3, and 5 were metalized with electrodeposited silver on a electroless nickle conductive layer. Only tube 5 was masked on the exterior. Tube No. 6 was electroplated with gold (incorrectly labeled copper in the photographs) on electroless nickle. Tube No. 4 is a copper foil wrapped electrical test standard. The unidirectional prepreg tape construction was used for all tubes except tube 4, the copper foil standard, which was laid up with bidirectional wooven fabric.

Tubes 1, 2, and 3 were the first delivered to Goodyear Aerospace. The tubes differ in that the etch and plating times were increased from tube 1 to tube 2 and from tube 2 to tube 3. The increased plating time and therefore plating thickness was evident by the mass of the specimens. Tube 3, and to some degree, tube 2 showed blistered spots of metal where the metal was thicker than surrounding areas. These blisters indicated that the plating rate was too fast and that voltage should be reduced and plating time increaased.

The interiors of the tubes were inspected for relative roughness by comparison of reflected brightness and clarity through the tubes. Figure 12 shows the interiors of the tubes, with the tubes numbered 1 through 6 shown left to right. From this inspection, it was obvious that the copper foil surface of tube 4 was the most reflective and therefore the most smooth. Tubes 3 and 6 were somewhat smoother than 1, 2, and 5. Textured strips along the length of tubes 1 and 3 were visible and indicate discontinuities in the interior laminate.

Thorough inspection of tube interiors required destructive techniques, i.e., sawing the tubes into sections. This made available specimens for microscopic inspection of the waveguide cross-section, as well as roughness inspection and adhesion testing of the interior. Two of the silver metalized tubes



54003-12

Figure 12 – Plated Tube Interiors

were chosen for this intensive mechanical inspection. Tube 3 was chosen for its excellent electrical performance and tube 1 was chosen because it performed poorly. Figure 13 describes the kinds of waveguide pieces that were obtained. The first three sections illustrated were for microsection

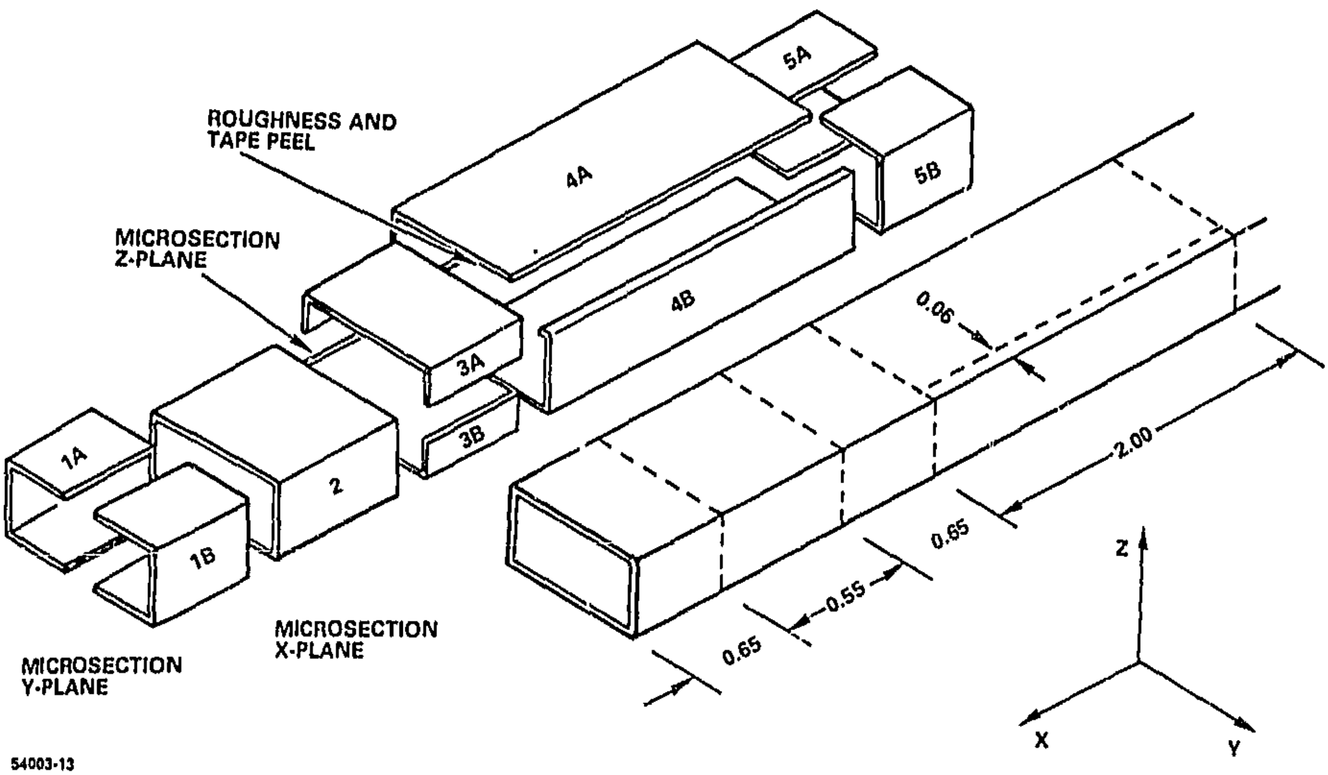


Figure 13 – Waveguide Mechanical Inspection Scheme

inspection in each plane. Specimens 1-A, 2, 3-A, and subsequent similar specimens were then potted, polished, and inspected by standard printed circuit board inspection techniques. There were five of each of these sample orientations in a 17-in. tube for a total of 15 potted specimens. The fourth section illustrated in Figure 13 is a two-in. piece which is split for roughness testing and tape peel adhesion tests. There are four such sections in a 17-in. tube. The sectioning scheme which was followed across the length of a tube is illustrated in Figure 14. Figure 15 is a photograph of tube 1 after section and potting.

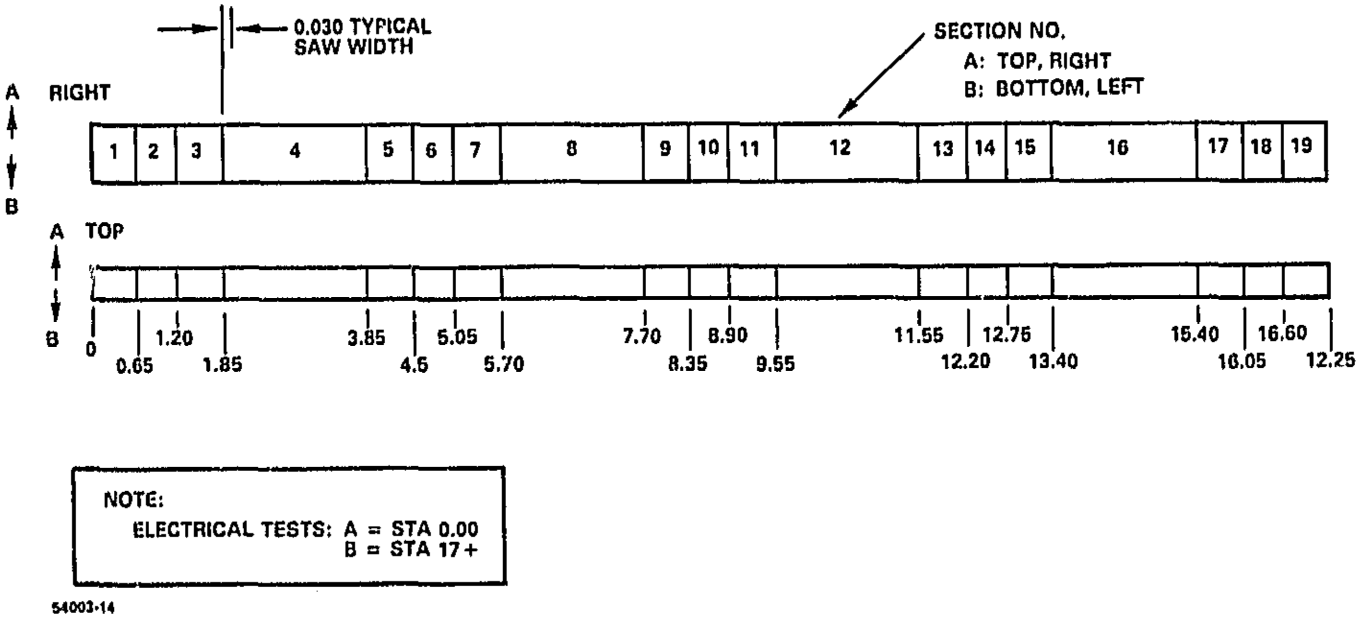


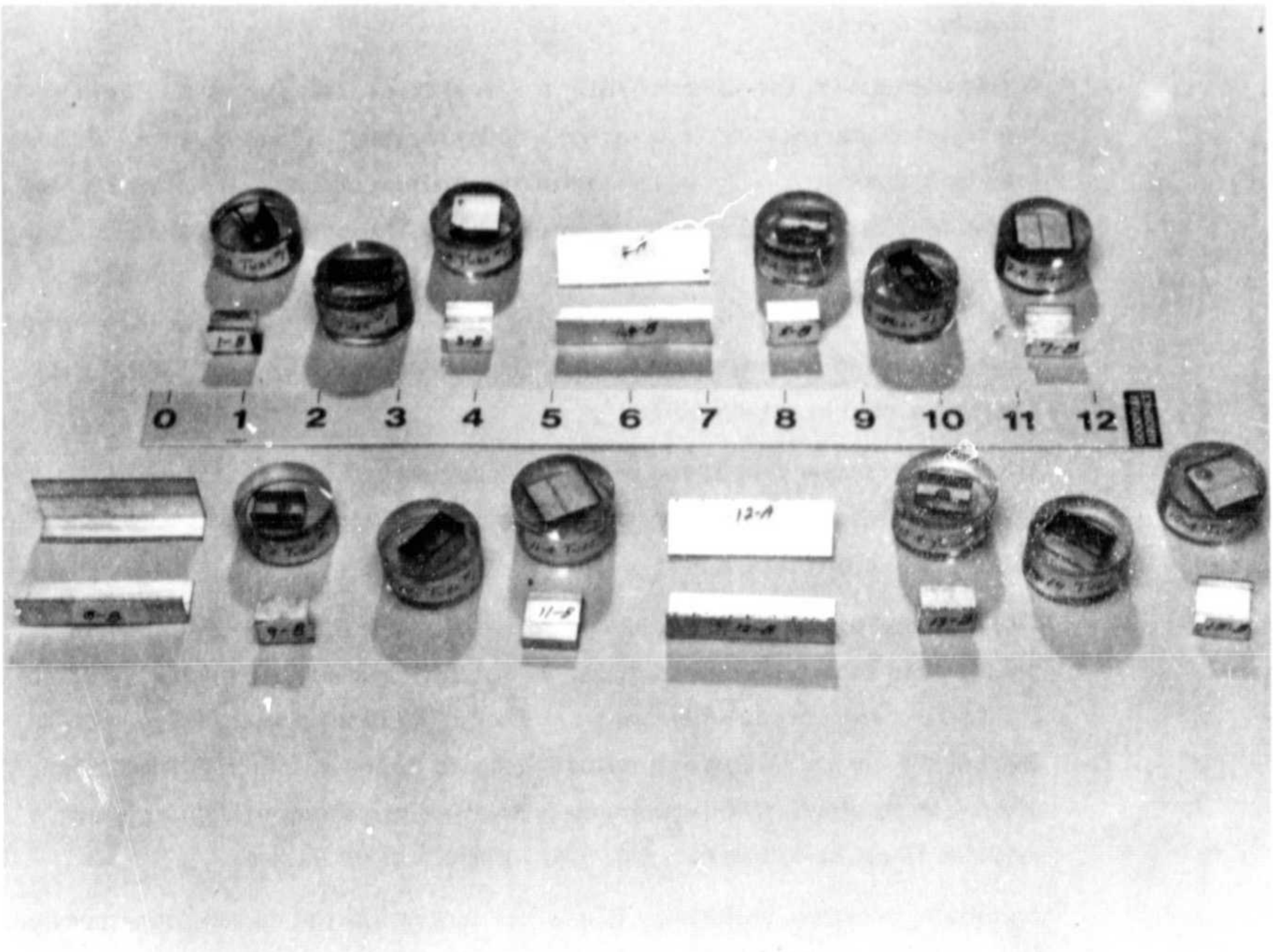
Figure 14 – Waveguide Sectioning and Identification Scheme

(2) Microsection

Microscopic inspection of the polished cross-section specimens revealed information including metalization coverage and thickness, surface condition, fiber condition, and laminate thickness. Study of these parameters may be referenced to cross-section position and station along the tube. Some of the findings are described in the following paragraphs.

Metalization on the interior of tube 3 was approximately one-half a fiber diameter or 0.0002 in. thick. In tube 1, silver was less than 0.0001 in. thick. Metal thickness was uniform around the perimeter of the tube and along its length. Edge coatings around the ends of tubes were uniform, strong, and void free.

The resin-rich surface, which was implemented by coating the mandrel, was etched away on both tubes. Plating was directly on fibers and epoxy matrix, resulting in an unsatisfactorily rough surface. Subsequent tubes have had



54003-15

Figure 15 – Waveguide Tube Mechanical Test Sections

thicker resin coatings and a less severe etch. The etch left cavities in the interior ply and completely exposed fibers near the surface. However, the silver adhered well to all surfaces. Smaller cavities, less than two metal thicknesses wide, were completely filled with silver. Exposed fibers were encased with silver. The silver coating tended to smooth the rough graphite surface. For instance, although the excessively etched graphite of tube 3 was rougher than tube 1 prior to plating, the thick metal surface of tube 3 was smoother overall.

If left untouched, the silver coating was void free. The only voids found were the result of damage to the relatively delicate, rough fiberous areas. A fiber may be broken or torn from the metalized surface creating a void at its root. It was rare that such damage was so extreme. The silver coating was surprisingly durable and resilient to abrasion and tearing, especially in the case of tube 3. The coating, under repeated abrasion would first scratch, then stretch, loosen from the graphite/epoxy substrate to form a blister, and finally tear, creating a void in the coating.

Microscopic inspection of the graphite/epoxy substrate revealed some flaws. These are presently being investigated and design improvements will be implemented in future tubes.

The most obvious flaw in the lay-up design is the fracture of graphite fibers bent around the waveguide corners. It was anticipated that the high modulus P-75 fiber might break when bent around the 0.030 in. corner radius. As feared, the entire 90-deg laminates fractured at some corners. The design alteration to alleviate this problem is to either use a more flexible, lower modulus fiber, or to increase the tube interior corner radius.

Laminate thickness uniformity is another concern in the current construction. Nominally the laminates are 0.0025 in. thick. However, the laminate thicknesses were found to vary as much as 50 percent. The interior 0 deg laminate suggests that there are systematic reasons for thickness variations. In specimens of both tubes the 0-deg laminate was as thin as 0.0016 in. on the short E-plane walls and as thick as 0.0036 in. (9-fiber diameters) on the long, H-plane walls. These irregularities do not noticeably effect substrate CTE, flatness or overall thickness; that is, the 0.020 in. 8-ply overall wall thickness is consistent. The fabrication process will be reviewed until laminate thickness variations are understood.

(3) Roughness Test

A standard surface roughness measurement was conducted on the interior of each of the two-inch specimens. Results for tube 1 and tube 3 are in Table VII and Table VIII, respectively.

Roughness in tube 1 was found to vary widely according to station increments smaller than the specimen size. That is, roughness would vary on the specimen depending on where along the length the measurement was being taken. Transverse roughness was very station dependent.

Tube 3 had an obviously rough strip down both of the wide H-plane walls. Axial roughness both on and off these strips was recorded. Most of the high roughness spots were small bumps. Mean roughness would be somewhat less than the average of the highs and lows indicated in the Tables. The cause of the rough strips along the H-plane walls in tube 3 is being investigated. Microscopic inspection of these strips indicates that the strips may be a result of abrasion, possibly during mandrel removal. Surface fibers are broken, short, and randomly oriented.

In general, the measured roughness of both tubes was unacceptable. The specified roughness for delivered waveguide parts is less than 62 micro-inches root mean square (rms). The microsection inspection showed that surface roughness was driven by the condition of the substrate surface. The substrates for both tubes were overetched to the point that fibers were exposed and cavities created in the matrix. The tubes delivered for assembly of the 5 x 5 array will see a milder etch and should meet the roughness specification.

(4) Adhesion

Qualitative adhesion testing was performed on preproduction parts to monitor the trends and improvements of the processes under development. Standardized reproducible tests should be established to quantitatively measure adhesion strengths when processes are mature and strict process

TABLE VII – SURFACE ROUGHNESS – WAVEGUIDE NO. 1

Specimen	Station	Roughness (μ in. rms)		
		Short Wall (E-Plane)	Long Wall (H-Plane)	
		Axial (0 deg)	Axial (0 deg)	Transverse (90 deg)
4A	1.85 - 3.85	20 to 110	50 to 180	70 to 220
4B	1.85 - 3.85	70 to 180	30 to 200	50 to 160
8A	5.70 - 7.70	40 to 140	50 to 150	80 to 160
8B	5.70 - 7.70	50 to 140	50 to 200	100 to 170
12A	9.55 - 11.55	40 to 130	50 to 180	80 to 180
12B	9.55 - 11.55	40 to 140	50 to 200	70 to 180

TABLE VIII – SURFACE ROUGHNESS – WAVEGUIDE NO. 3

Specimen	Station	Roughness (μ in. rms)		
		Short Wall (E-Plane)	Long Wall (H-Plane)	
		Axial	Typical Axial	Rough Strip Axial
4A	1.85 - 3.85	70 - 120	20 - 60	60 - 120
4B	1.85 - 3.85	30 - 110	20 - 60	100 - 230
8A	5.70 - 5.70	70 - 170	50 - 120	60 - 130
8B	5.70 - 5.70	70 - 130	70 - 130	50 - 150
12A	9.55 - 11.55	40 - 70	50 - 150	100 - 200
12B	9.55 - 11.55	30 - 60	60 - 90	100 - 170
16A	13.40 - 15.40	40 - 120	30 - 60	70 - 130
16B	13.40 - 15.40	50 - 120	20 - 40	100 - 220

control is required. During this development phase, tape peel testing was used for a quick economical appraisal of adhesion quality. Most of this testing was done at the vendor's facility where test results could quickly affect process changes. Goodyear Aerospace performed tape peel tests on sectioned portions of tubes 1 and 3 to observe adhesion quality with respect to metalization thickness, surface condition, and tube station.

In the tape peel test, an adhesive backed tape is pressed to the plated surface of interest, in this case the waveguide interior, and removed by peeling it from one end. Acceptable adhesion exists if no metal is removed or blistered as the tape is removed. The three adhesive tapes listed in Table IX were used for these tests. Adhesion performance of tubes 1 and 3 are described in Table X and Table XI, respectively. Not all specimens were tested to provide for later test and inspection.

Metal specimens suffered partial loss of metal coating or coating blistering. The tape that bonded best with the silver coating and therefore caused the most severe coating delamination was the no. 850 transparent tape. No. 232, a common masking tape was the least severe. Several specimens passed the tape peel test with no. 232, but failed against the other two tapes.

There was no apparent relationship between adhesion strength and station point along the tube. Inconsistencies in results seemed random. The test was performed by hand and not closely controlled so that quantitative results, such as percent of surface area peeled was influenced by many factors. Some of these could be tape adhesive consistency, pull speed, pull direction, surface cleanliness, and application pressure. However, even considering these uncontrolled factors, it was concluded that adhesion strength did vary randomly through the tube. It should be stated again, that in production, standardized tests will be used to enforce strict fabrication process control.

Tube 1 showed significantly greater loss of metal than tube 3. This apparent adhesion strength difference between the two waveguide tubes was, in part, a

TABLE IX – ADHESION TESTS

Tape	Adhesion to Steel (oz/in. width)	Adhesive	Backing
3M No. 850	25	Acrylic	Polyester Film
3M No. 232	40	Rubber-resin	Crepe Paper
3M No. Y427	65	Acrylic	Aluminum, 1145-D

TABLE X – TUBE NO. 1 ADHESION TEST RESULTS

Specimen	Tape	Peel (percent)
4A	232	Speckled 2
4B	850	Speckled 5
	Y427	Speckled 3
8A		
8B	850	Speckled 30
	Y427	Speckled 10
12A	232	Speckled 3
12B	850	Speckled 20
	Y427	Speckled 10

result of the difference in coating thickness. The greater tensile strength of the thick coating contributed to the propagation of metal to substrate failure in tube 3. This was evident in the mode of coating failure. On tube 1, the coating was removed in small speks, that is, small portions of metal where adhesion was weak. The tensile strength of the coating was not strong enough to pull up neighboring metal where adhesion was stronger. The result was a speckled pattern of small metal flakes on the tape. In contrast, the coating on

TABLE XI – TUBE NO. 3 ADHESION TEST RESULTS

Specimen	Tape	Blister (percent)	Peel (percent)	Comment
4A	232			1st Pass
	232	10	5	2nd Pass
	850	30	20	3rd Pass
	Y 427		80	4th Pass
4B	Before Tape	10		
	850		90	on smooth strip
	850		5	on rough strip
8A	850	5	50	
	Y 427		50	
8B	232			
12A	232			
	850	15	10	
	Y 427		10	
12B				
16A	850	50		better on rough strip
16B	Before Tape	Some Blisters		

tube 3 failed in large patches where both weak and strong bonded portions of metal held together by virtue of their greater thickness and strength. The result was a tearing mode of adhesion failure. In some spots, the metal coating may be torn from the tube even without the support of adhesive tape.

Blisters occurred where metal-to-graphite bond had broken, but the metal coating itself had not. Blisters were formed on tube 3, but not on the thin coating of tube 1.

It was observed that substrate surface roughness was important to metal adhesion. The rough graphite surfaces produced more tenacious bonds with the silver coatings. This property was best demonstrated on specimen 4A of tube 3. On this test, a single piece of tape was placed across distinct smooth and rough surfaces of the part. The smooth surface lost 90 percent of its metal coating whereas only 5 percent peeled from the rough strip surface.

The metal-to-graphite bond could be stressed repeatedly, weakened, and finally broken. This phenomena was observed in two tests; repeated peel test and burnishing. In a repeated peel test, the same coated surface was subjected to multiple tape peels. As in the case of specimen 4A of tube 3, the surface may pass one peel test but under subsequent tests more and more of the coating will fail.

Burnishing is the repetitious rubbing of the coating surface with a blunt instrument. Pressure on the surface is sufficient to cold work on the metal, but not dig into it. The specimens of tube 3 all formed blisters after substantial burnishing. The coating of tube 1 flaked. Blisters, lifting or peeling, should not develop if acceptable adhesion exists.

The peel test described above is an extreme test of adhesion. A more representative test of operation is a thermal cycle test.

Thermal tests were run by the vendor to evaluate various metalization processes, but were not closely controlled or documented. Data did indicate that blistering or flaking of metal due to thermal cycling should be minimal or nonexistant.

Controlled thermal cycle tests will be done on the production tubes.

(5) Thermal Expansion

The isotropic CTE was found to be 0.28×10^{-6}in./in./deg F over a temperature range of -270 to +300F, well within the 0.7×10^{-6}/F specified. The test was performed on a graphite/epoxy tube of identical construction to that of the delivered waveguide.

(6) Production Tubes

Mechanical tests on the 12 production tubes were not completed for this report, but they were expected to exhibit improved characteristics based upon improvements implemented in the fabrication process.

In addition to the mechanical tests described, thermal tests will also be conducted.

4. ASSEMBLY PROCESS DEVELOPMENT

Under the next phase of the multifunction synthetic aperture radar technology (MSART) program the 5 x 5 array will be assembled and will undergo vibration tests. Work has been done to data to develop assembly processes in anticipation of assembly and test is reported below.

Parts were acquired that are necessary to build a test fixture structurally similar to the L-Band lattice in which the X-Band array is interleaved and supported. Two identical faceplates were produced, one of which will be used only as an assembly tool.

A variety of joint designs, adhesives, and secondary bonding procedures are being evaluated for use on the 5 x 5 array and for application to subsequent larger arrays. Joint designs must emphasize structural resiliency to vibration of the mating graphite parts, low electrical resistance across a broad temperature range, and adaptability to high-volume application. All the electrically conductive joints are geometrically similar in that they are all right angle butt joints of two thin, graphite epoxy, silver-plated walls. Two approaches to the joining of these two walls are being investigated: The application of an external, lap bonded bracket and direct bonding with one or a combination of adhesives and coatings.

The external bracket approach is described in Figure 5 and Figure 16. Mechanical adhesion and electrical conduction between the silver plated graphite and the bracket are optimized by the large surface area lap joint with a conductive adhesive. Loads and current are carried solely by the bracket. The external bracket designed for feed-to-radiator assembly (Figure 16) is 0.006-in. thick stainless steel. Such a bracket may be fabricated

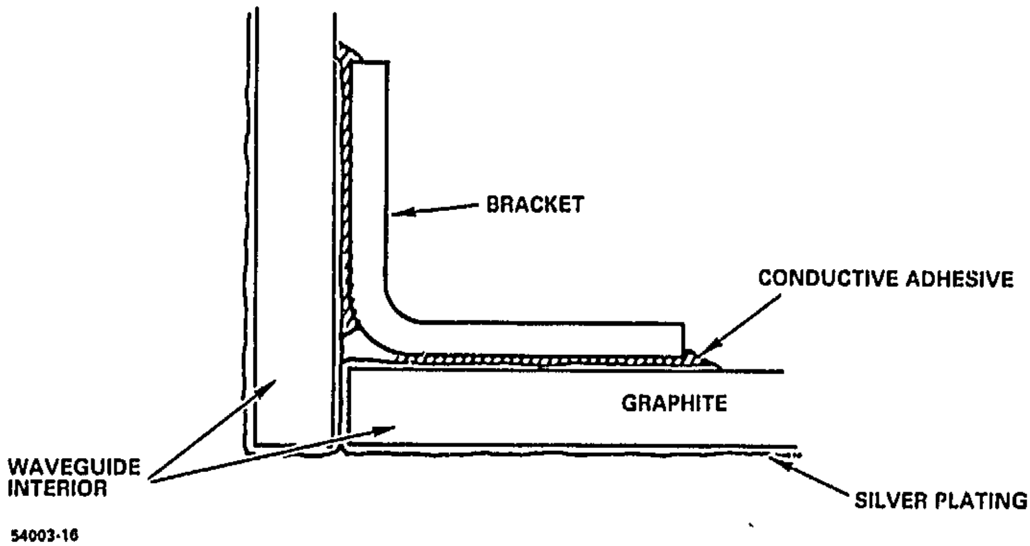


Figure 16 – External Bracket Joint

in graphite epoxy and silver plated. The advantage of the external bracket is that it provides a strong continuous member across the joint that couple loads by shear into the large contact area lap joints on the mating parts. Several conductive adhesives capable of the required shear strength across the lap joint are available. Disadvantages include the added cost and weight of the many brackets required for assembly. It is anticipated that thermal expansion of metal brackets will have negligible impact on the dimensional stability of the entire array. However, should the CTE of the brackets become a concern, the graphite epoxy construction could be used.

The potential cost and weight advantages of direct bonding of waveguide parts make it worthy of thorough study. Three direct bond designs have been investigated so far.

The most simple direct bonding configuration is shown in Figure 17 where a single conductive adhesive is used as both the structural adhesive and electrical conductor. The fillet must adhere to the silver plated coating on each part because it is both the electrical and mechanical conductor. Two adhesives are used in the second configuration shown in Figure 18. Here, a relatively small fillet of a conductive/nonstructural agent is first applied and cured. Then, a structurally dedicated adhesive is applied over the

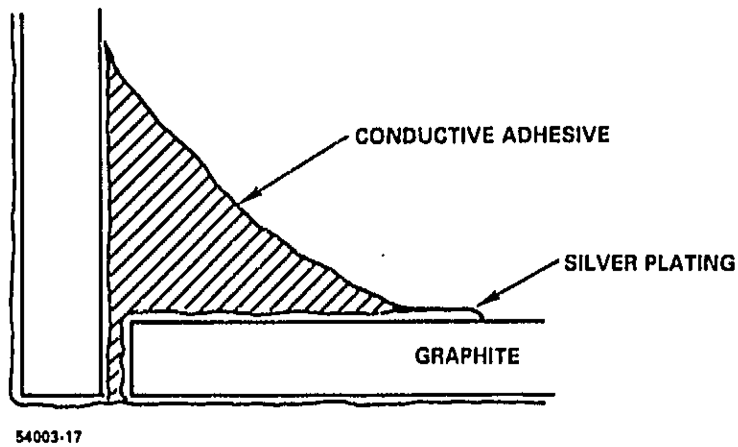


Figure 17 – Conductive Adhesive Joint

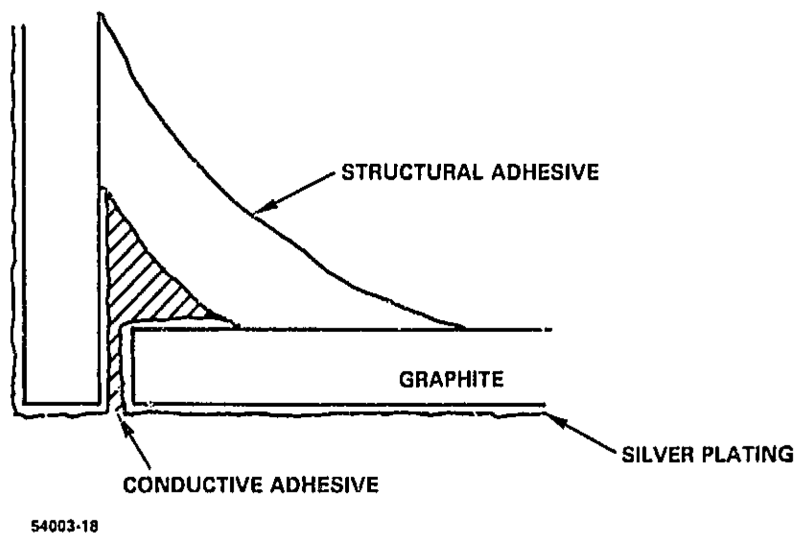


Figure 18 – Dual Fillet Joint

conductor to form a wide-based, mechanical fillet. The advantage of this approach is the freedom to maximize the conductive or structural properties of each fillet without concern for the other. Also, the silver-plated coating may be masked or removed in the area of the structural fillet so that the adhesive may bond directly to the graphite epoxy and adhesion of the silver coating to the graphite epoxy is not a factor in the strength of the joint. There is a disadvantage in the added application and curing cycles required for assembly. A third configuration under study shown, in Figure 19, utilizes a coat of conductive paint over the interior of the joint. A single structural adhesive fillet on the exterior requires no silver-plated coating as with the conductive adhesive configuration. Disadvantages of this approach are induced surface roughness by the paint and the risk of cracking of the paint near the relatively soft and flexible joint. An option under consideration for bonding radiators to the faceplate is the use of high temperature polyimide foam as a structural fillet over a small conductive fillet or paint (Figure 20). The foam would be applied to the faceplate in a continuous sheet after machining for radiator insertion. The 1/4-in. thick foam would act as a superb structural fillet and would attenuate vibration of the faceplate. Disadvantages of the foam are cost and thermal expansion mismatch with the graphite epoxy.

The structural design of the 5 x 5 array and future X-band structures is simple and sound. Acceleration loads generated within the array are coupled through the faceplate and level-A feeds into the L-band lattice. Every radiator has two load paths to the lattice which are only two joints and one member in length. Given the low mass and high modulus of the graphite epoxy parts, low frequency loading of the assembly should not be a problem. The threat to be addressed in selection of joint design and adhesives is high-frequency and noise-induced cracking. In other words, joint strength is not as critical as toughness. Brittle adhesives may pose problems over multiple launches and handling operations. For this reason, a wide variety of adhesives listed in Table XII are being evaluated for use in the 5 x 5 array. Inclusion of silicones is directed at the flexible low strength, vibration dampening requirements of the small X-band cell. Larger structures such as the L-band lattice may warrant the use of stronger, stiffer epoxies.

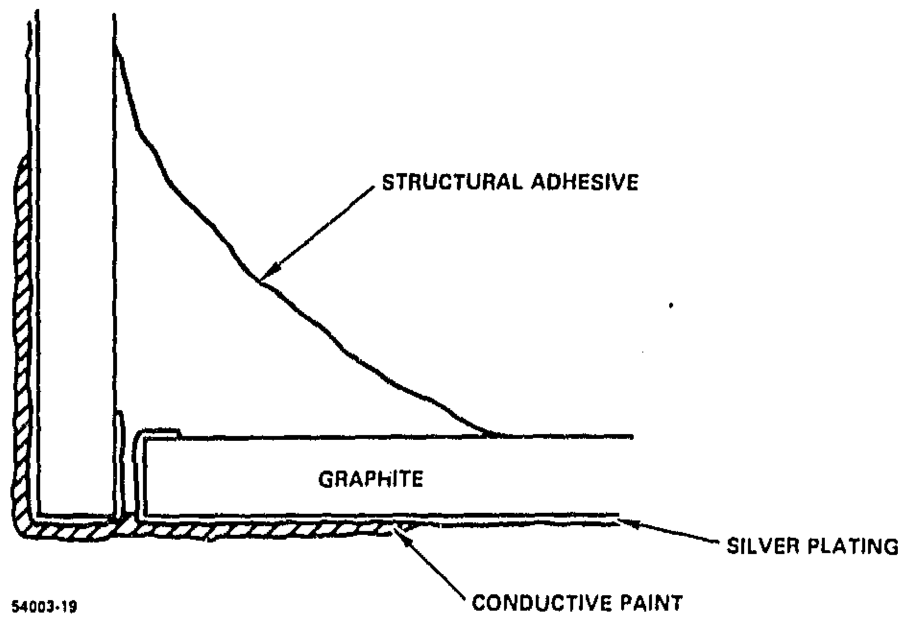


Figure 19 – Conductive Paint Joint

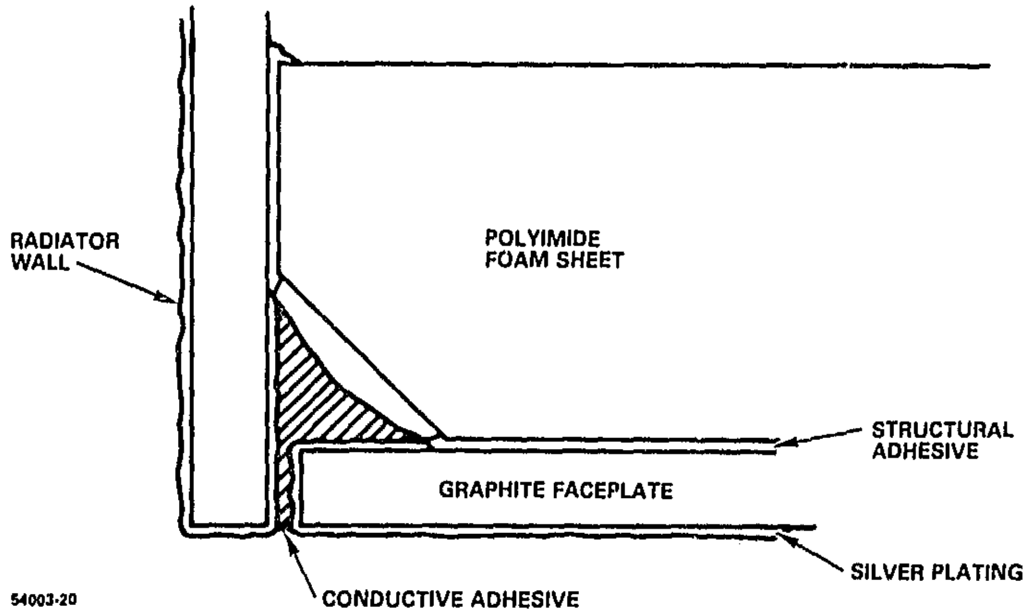


Figure 20 – Reinforced Conductive Adhesive Joint

TABLE XII – ADHESIVE CANDIDATES

	Maximum Service Temp F (C)	Minimum Service Temp F (C)	Volume Resistivity (Ohm-cm)	Coefficient of Thermal Expansion ppm/deg F (deg C)	Components	Core Temp (F)	Lap Shear Strength (psi)	
Emerson and Cuming Ecco Bond 59C	500 (260)	-80 (-62)	1×10^{-3}	35 (63)	1	RT-300	300	Silicone
Emerson and Cuming Ecco Bond 83C	275 (135)	-65 (-54)	4×10^{-4}	25 (45)	2	RT-220	1000	with Catalyst 9 or 11
Ablestik 84-1 LMIT	300 (150)	-67 (-55)	2×10^{-4}	30 (55)	1	250-320	1600	
Amicon C-770			1×10^{-3}		1	250-480	1500	
Goodyear Aerospace GR60-8-2-1			1×10^{-4}		2	RT-180	1800	
Transcene Silver Bond Type-40	390 (200)	-85 (-65)	1×10^{4}		2	120-300	1500	Silver-Epoxy
Transcene Microcircuit Type-N	390 (200)	-76 (-60)	2×10^{-3}	50 (90)	1	275-350	3500	Silver-Epoxy
Transcene PDA S-500	700	-49	1×10^{-4}		1	518	2000	Polyimide

SECTION III – ALTERNATE ELECTRICAL DESIGNS

In the original interleaved array design, the beam positions were fixed, and the entire array was to be positioned to direct the beam at a desired location on the earth. Such a method of deployment is probably unworkable or at least extremely awkward; consequently, electronic beamsteering in the elevation plane is considered to be essential.

The antenna is required to operate at L (1.275 GHz), C (5.3 GHz), and X (9.6 GHz) band. Horizontally and vertically polarized radiating elements are needed for each band and polarization isolation should be greater than 25 dB. Single axis electronic scanning of ±25 deg is required in the elevation plane. The antenna should have the integrated sidelobe levels of at least -15 dB and an input VSWR of 1.5 to 1 or less over the bandwidth. The power handling requirements are 1.5 kW, 10 kW, and 10 kW at L, C, and X-bands, respectively.

Additional parameters were provided in the form of baseline antenna specification[1a] at the program kickoff meeting on 28 October 1981. The specification gave antenna heights of 2.1 m, 0.51 m and 0.28 m at L, C, and X-bands, respectively. These heights result in a 3-dB elevation beamwidths of slightly less than 6 deg in all bands. The antenna length is specified from 12 m to 18 m for all bands. Presently, the 12 m appears to be the preferred length for the proposed shuttle missions in the planning stages.

The only major changes in the requirement from previous studies is elevation beam scanning and the reduced bandwidth requirements at C and X-bands. These requirements do not alter the basic interleaving concept for the various frequency band and polarization, as presented in Figure III-1 of GERA-2644[2]. However, there will be more radiating elements required to accommodate the elevation plane beam scanning. The number of element rows is increased from 10 to 15 for both polarizations of C and X-band, and for horizontally polarized L-band. The number of L-band vertically polarized element rows increases from 11 to 16. The number of rows, number of elements per row per panel and the number of elements for a 12-m and 16-m antenna are presented in Table XIII.

---

[a]Superior numbers in the text refer to items in the List of References.

TABLE XIII – NUMBER OF RADIATING ELEMENTS

Band	Polarization	No. of Rows	No. Element No./Row/Panel	Total No. of Elements	
				12 m	16 m
L	Horizontal	15	20	900	1200
	Vertical	16	20	960	1280
C	Horizontal	15	80	3600	4800
	Vertical	15	80	3600	4800
X	Horizontal	15	140	6300	8400
	Vertical	15	140	6300	8400

When the elements are insufficiently close, electronic beamsteering causes grating lobes to occur. At the onset of a grating lobe into real space, the input mismatch increases dramatically. At some scan angles, the grating lobe phenomenon causes array blindness. Therefore, the occurrence of grating lobes should be avoided at all costs within the desired scan limits. The maximum permissible element spacing in wavelengths, d/λ, for a grating lobe null at 90 deg is given by[3]

$$\frac{d}{\lambda} = \frac{\left[(N-1)^2 + \beta^2\right]^{1/2}}{N\,(1 + \sin\theta)} \tag{4}$$

where N is the number of elements, θ is the maximum scan angle and β is a factor which adjusts for the sidelobe level. For a sidelobe level of 20 dB, $\beta = 0.7386$. For N = 15 rows and maximum scan angle of 25 degrees in the elevation plane, maximum permissible spacing is 0.657 λ.

In the azimuth plane the beam is unscanned, so the maximum permissible spacing in wavelength for a 12-m antenna is 0.983 λ, 0.996 λ, and 0.998 λ for L, C, and X-bands, respectively. In addition to the avoidance of the grating lobe phenomenon, elements of each band must be spaced so they can be duplicated periodically without interference. The selected element spacing is given in the Table XIV.

The radiating elements are open ended waveguides. The design of these elements is influenced by the need to satisfy the element spacing requirements for grating lobe avoidance. For the vertical polarized elements where the electric, E, field lies in the elevation plane, there is no spacing problems because the narrow wall waveguide dimensions are less than the elevation plane spacing, and ordinary waveguide elements can be used. For the horizontally polarized element, the E field is in the azimuth plane and the broadwalls of the waveguide elements lie in the elevation plane. To satisfy the elevation plane element spacing requirements, the waveguide element needs to be dielectrically loaded with material ranging from 1.7 to 2.5 in dielectric constant or ridge loaded to permit propagation at the operating frequencies. The interior element dimensions are tabulated in Table XV. A layout of an array cell of these elements is shown in Figure III-10 to III-13 of the GERA-2644.[2]

To provide elevation plane electronic scanning, the phase of each element row must be controlled independently. This need plus bandwidth considerations influence the design of the feed network. Each row of elements is fed by a elevation plane corporate feed as shown in Figure III-21 of the GERA-2644[2]. In the azimuth plane, a coaxial corporate feed network extends to each radiating element at L-band, whereas at C and X bands a waveguide corporate feed extends to traveling waveguide feeds which feed each element.

For feeding the horizontally polarized C and X-band elements, a narrow wall slotted waveguide section will be used. The waveguide radiating elements will be end fed. To feed the vertical polarized C and X-band elements, the traveling-wave feed and the elements will be coupled through the broadwalls of both the element and the feed. Two kinds of broadwall feeding are possible. One approach uses rotated series slots. However, a shorted waveguide section must extend beyond the last slot by one-half guide wavelength which increases the mechanical design problem. A second approach uses longitudinal shunt slots displaced at alternating positions along the centerline of the broadwall of the feeding waveguide. The terminating section of the feed extends only a quarter wavelength beyond the last slot, but slight element phase errors are introduced by the slot locations from the centerline. These errors are believed to be acceptably small. This latter feed concept is the preferred approach. Both the horizontal and vertical polarized waveguide feeds are shown in Figure 21.

TABLE XIV – ELEMENT SPACINGS

Frequency Band	Frequency (GHz)	Plane	Element Spacings		
			in.	cm	λ
L	1.275	Elevation	5.4	13.72	0.584
		Azimuth	8	20.32	0.864
C	5.3	Elevation	1.35	3.43	0.606
		Azimuth	2	5.08	0.898
X	9.6	Elevation	0.771	1.96	0.627
		Azimuth	1.143	2.903	0.930

TABLE XV – ELEMENT DIMENSIONS FOR SCANNING ARRAY

Frequency Band	Polarization	Dimensions (in.)	
		Broadwall	Narrow Wall
L	Vertical	6.4	0.25
	Horizontal	4.6	0.2
C	Vertical	1.35	0.65
	Horizontal	0.9	0.4
X	Vertical	0.729	0.35
	Horizontal	0.48	0.21

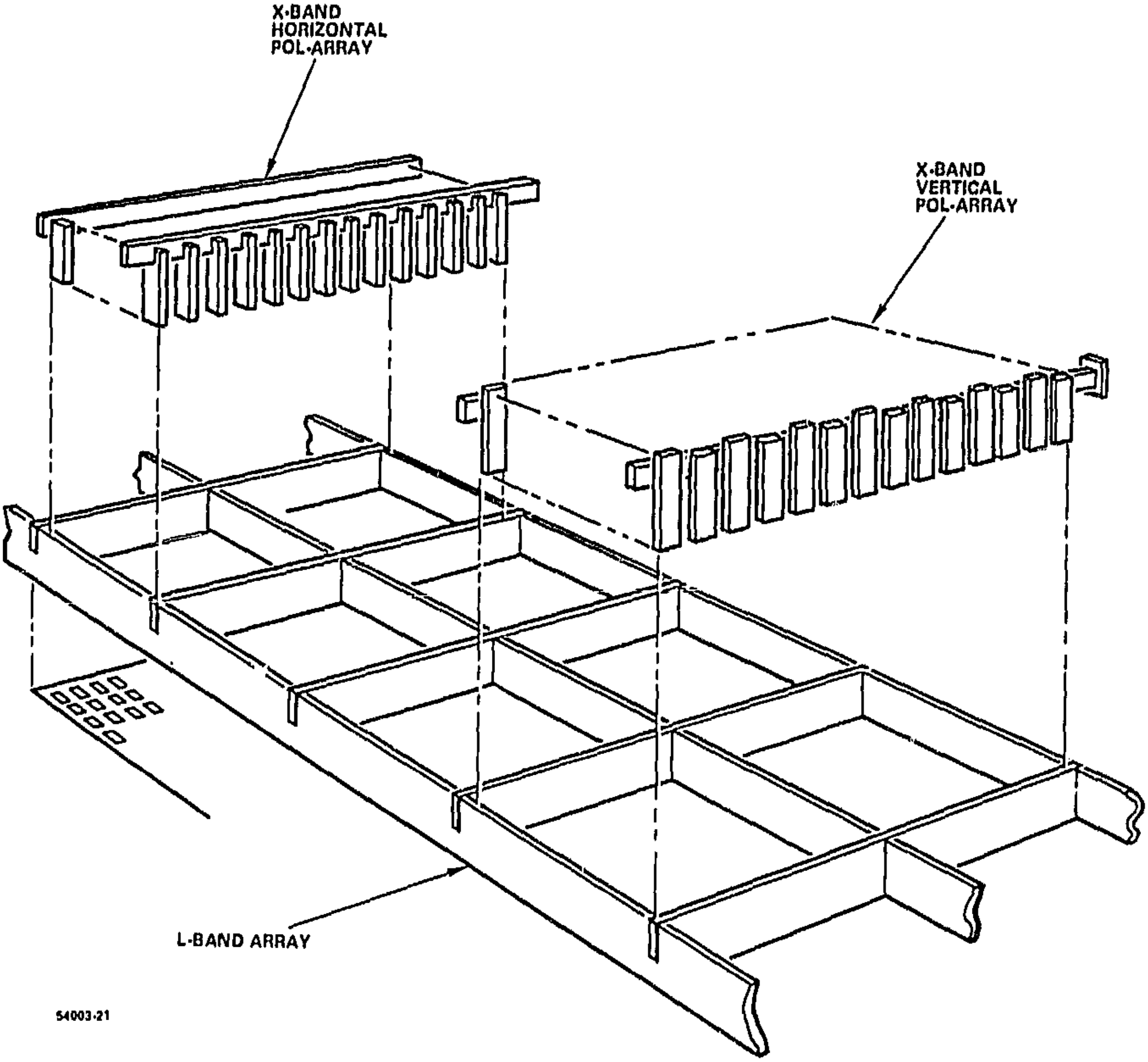


Figure 21 – Partial View of Elevation Plane Scannable Interleaved Array

Simplicity in the azimuth plane feed network is obtained by feeding as many waveguide elements as possible through a resonant waveguide feed. On the basis of analysis, it is estimated that 8 elements per arm can be fed at C-band, and 14 elements per arm at X-band, for 50 MHz bandwidths. This gives rise to maximum phase errors of 10 deg for C-band and 11 deg for X-band. According to Woody[4], these phase errors cause peak sidelobes of -25.4 dB and -24.5 dB for the C-band and X-band, respectively. These sidelobes are well below the sidelobe specifications for the antenna.

However, impedance mismatch rather than sidelobe levels is the limiting factor which sets an upper limit on the number of elements which can be fed from a single arm.

The calculated maximum VSWR for an 8 element per arm C-band guide is 1.30, and 1.29 for a 14-element, X-band guide. To achieve comparable levels for 150 or 300 MHz bandwidths respectively, only 5 elements can be fed per arm, as was discussed in GERA-2644.

LIST OF REFERENCES

1. Carver, K.R.: Briefing Notes, Kickoff Meeting, NASA-JSC, October 28, 1981, Contract NAS9-16430.

2. GERA-2644: "Shaped Reflector/Multiple Horn/Interleaved Array Technology Development," Contract NAS9-16430, Goodyear Aerospace, Litchfield Park, Arizona, 30 June 1983.

3. Hansen, R. and Phelen, R.: "Array Element Spacing for Grating Lobe Null at 90 deg", Microwave Journal, January 1975, p. 102.

4. Woody, W.C.: "Determination of Corporate Feed Errors from Pattern Measurements," 21st U.S. Air Force Antenna Symposium, University of Illinois, August 1977.