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AN EXTREMELY THIN, OMNIDIRECTIONAL, MICROWAVE ANTENNA ARRAY FOR SPACECRAFT APPLICATIONS

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SUMMARY

The design and development of an extremely thin, omnidirectional, microwave antenna array, which is bonded circumferentially to the outside surface of a spacecraft and then coated with a dielectric material for thermal protection, is presented. This antenna was designed for a specific payload application in the S-band (2200 to 2300 MHz) frequency range and provides an omnidirectional radiation pattern in the plane of the array and a near-omnidirectional pattern in the planes perpendicular to the array. A procedure is presented whereby this design technique can be applied to other frequencies.

INTRODUCTION

In the past, the standard telemetry frequencies for rocket-launched payloads have been in the range from 225 to 260 MHz. Presently, however, military and scientific requirements have caused these frequencies to become less available, and therefore most scientific telemetry applications must shift to the higher frequencies of 2200 to 2300 MHz (S-band). Because of the nature of the tracking problem at S-band frequencies and higher, omnidirectional radiation patterns are a stringent requirement for most spacecraft antenna systems. Therefore, a major problem expected in the shift to the S-band frequencies is the designing of antenna arrays mounted on surfaces large in terms of a wavelength that will (1) provide nearly omnidirectional patterns with a minimum fluctuation, (2) satisfy the structural requirements while arraying a large number of antennas, and (3) perform properly through expected spacecraft environments.

Although recent papers (refs. 1 and 2) discussed antenna designs of continuous arrays that provide omnidirectional characteristics, little emphasis was placed on design simplicity. Therefore, because of the problems encountered in flush-mounting spacecraft antennas, an array design was initiated whereby the problems of mounting and other considerations are greatly reduced. The design of an extremely thin antenna array is presented.

The array considered is composed of circumferential slots fed by a stripline circuit that is an integral part of the array. The array is formed by laminates of copper-clad dielectric material producing a total antenna thickness of 0.094 inch (2.39 mm). It is bonded circumferentially to the outside surface of the spacecraft and then coated with a suitable ablation material. All antennas are interconnected by way of the stripline circuit between the laminates, and the array is fed by providing a single hole through the spacecraft structure for a radio-frequency connector. This design is unlike a discrete source array in which mounting holes, brackets, and structural doublers would be required for each antenna as well as provision for power-distribution circuits. For the payload application discussed, this array reduced the antenna weight by at least 30 percent over that of a discrete source array, provided additional space inside the spacecraft for instrumentation, and provided excellent antenna characteristics.

It should be noted that Meredith W. Appleton of the Langley Research Center developed a working model that demonstrated a method of converting a standard coaxial feed to a stripline-fed slot design.

SYMBOLS

a	radius of conducting cylinder
b	width of rectangular transmission line
$F(\phi)$	element pattern
f	frequency, cycles/second
k	wave number, $2\pi/\lambda_V$
L	total length of slot
$(L/\lambda_V)_r$	length-to-wavelength ratio of resonant slot
l_1	distance between feed point and end of slot
t	thickness of center conductor of rectangular transmission line, inches (millimeters)
t_c	cavity depth or antenna thickness and stripline thickness
$t_{\epsilon r}$	dielectric-cover thickness, inches (millimeters)
w	width of center conductor of rectangular transmission line, inches (millimeters)
w_s	width of slot antenna, inches (millimeters)

Z_i input impedance, ohms

Z_L load impedance, ohms

Z_o stripline characteristic impedance, ohms

ϵ_r relative dielectric constant

θ angle in elevation plane, deg

λ_v wavelength in vacuum

$\lambda_{\epsilon r}$ wavelength in dielectric material

ϕ angle of far-field point, degrees

DESIGN APPROACH AND DISCUSSION

The extremely thin array is composed of eight cavity-backed slot antennas oriented circumferentially about a spacecraft surface. As discussed in references 3 and 4, the number of antennas required to produce an omnidirectional radiation pattern depends on the circumference of the spacecraft in wavelengths and on the acceptable amplitude fluctuation in the far-field pattern. Cavity-backed slot antennas have been used very extensively in the past and their design theory is well-known to the antenna engineer. Hence, from the initial conception of this design technique, cavity-backed slot antennas were believed to be the best possible elements for thin arrays from the following standpoints: (1) control of the input impedance and (2) simplicity of the feed circuit. Therefore, no other potential antennas were investigated.

After selecting the type of element that would be used in the array, the first major design step was to determine empirically the minimum dimensions for the cavity and slot that could be used efficiently. The next design step was to change from a typical coaxially fed cavity slot to a stripline-fed cavity slot. The stripline circuit would provide a later means of interconnecting several antennas and of eliminating many external coaxial transmission lines and the power-distribution circuit. Since the array design for this particular spacecraft configuration was bonded to the outside surface, the array had to be coated with a suitable heat-protective dielectric material. Therefore, the effect of a dielectric cover on the element design had to be determined because this effect would influence the final slot design. After this information was determined, a circuit was designed to feed or interconnect all elements of the array, and, finally, the array was fabricated. Photographs of the final version of the array, without and with the dielectric cover, and an outline drawing are shown in figure 1. The design of the subject antenna can be divided into five steps and will be discussed in that order: (1) design of a cavity-backed slot antenna, (2) design of a stripline-fed slot antenna, (3) dielectric-cover design, (4) array design, and (5) array fabrication.

Design of a Cavity-Backed Slot Antenna

As discussed in reference 5, a slot antenna may be conveniently energized by means of a coaxial transmission line if the outer conductor to the metal sheet is connected to the center conductor on the opposite side of the slot. The input impedance at the center of a resonant $\lambda_V/2$ slot in a large ground plane is 500 ohms. (See ref. 5.) However, a slot length of $0.485\lambda_V$ was actually needed to provide a terminal resistance of 500 ohms. Since the characteristic impedance of a coaxial transmission line is usually much less than 500 ohms, an off-center feed may be used to provide a better impedance match. If a cavity with a depth of approximately $\lambda_V/4$ is placed behind the thin rectangular slot, the input impedance of the slot is increased to approximately twice its value without the cavity. When attempts are made to reduce the cavity depth below $\lambda_V/4$, considerable changes occur in the slot impedance, resonant frequency (at minimum voltage standing wave ratio (VSWR)), and bandwidth. Therefore, a number of parametric tests were initiated to determine the optimum slot configuration.

The slot parametric tests were initiated by using a coaxially fed cavity slot (2.55 by 0.10 inches or 64.77 by 2.54 mm) and offsetting the feed point until an impedance match to 50 ohms was achieved. The cavity dimensions were chosen to be 3 by 4 by 0.125 inches (76.2 by 101.6 by 3.18 mm), based on the results of the experimental tests. The resonant frequency of the cavity-backed slot was then measured with and without a dielectric material $(\epsilon_r = 2.1)$ in the cavity. The slot $(L/\lambda_V)_r$ ratio decreased from 0.485 to 0.410 with the air-filled cavity behind the slot, and to 0.284 or $0.41/\sqrt{\epsilon_r}$ with the cavity filled with dielectric material. Hence, the direction was determined in which the slot resonant frequency would shift when a very shallow loaded cavity was placed behind the slot. Radiation patterns of this coaxially fed slot configuration revealed a peak gain of 2 decibels above an isotropic radiator; therefore, the radiation efficiency was acceptable.

The effect of cavity depth on the impedance characteristics of the slot was determined by modifying the existing 3- by 4- by 0.125-inch cavity (76.2 by 101.6 by 3.18 mm) so that the depth could be changed. Cavity depths of 0.090, 0.125, 0.219, and 0.266 inch (2.29, 3.18, 5.56, and 6.76 mm) were investigated, and for each depth the cavity was filled with layers of the same dielectric material as before. For each depth, or antenna thickness, the slot length and feed-point locations were adjusted to provide a good impedance match to 50 ohms at 2240 MHz. The results of the cavity depth on slot VSWR and impedance are shown in figure 2. One attempt was made to reduce the cavity depth below 0.090 inch (2.29 mm), but the bandwidth was such that the antenna would be too sensitive to mechanical and electrical tolerances. Hence, 0.090 inch (2.29 mm) was selected as the design goal for antenna thickness.

Design of a Stripline-Fed Slot Antenna

The design feature that resulted essentially in a very thin microwave antenna was the use of a rectangular transmission line. The rectangular transmission line was formed by placing bolts on both sides of a strip transmission line. The bolts, making contact with both conducting plates of the stripline, prevented edge excitation and the generation of higher order modes. The bolt spacing was found to be critical in that a sufficient number of bolts was required to insure a continuous short circuit around radio-frequency connectors, antenna apertures, and so forth. Typical design curves for determining the characteristic impedance of the strip and rectangular transmission lines are presented in references 6 and 7. These design curves were used in selecting the parametric values for b (width of rectangular line), w (width of center conductor), and t (thickness of center conductor) that would provide a 50-ohm characteristic impedance for $t_c = 0.090$ inch (2.29 mm). The characteristic impedance was measured by using a time-domain reflectometer.

After the proper dimensions of the stripline were determined for a characteristic impedance of 50 ohms $\left(w = 0.084 \text{ in. } (2.13 \text{ mm});\ t/t_c = 0.031;\ w/b = 0.15\right)$, a stripline-fed slot was then designed. Since the parametric tests indicated that a cavity depth of approximately 0.090 inch (2.29 mm) could be used, commercial stripline laminates were reviewed in order to select a suitable material close to that thickness. The material selected was a copper-clad, dielectric cloth that was 0.047 inch (1.19 mm) in thickness, and two layers were bonded together to form a 0.094-inch (2.39-mm) thickness. The slot antenna was formed by etching away the copper surface on one side of the laminate. A small hole (0.10 inch in diameter (2.54 mm)) was drilled in the center of the slot to accommodate the stripline feed on the dielectric side of the laminate. Before the stripline circuit could be provided, a radio-frequency connector had to be placed on the bottom laminate. The stripline circuit could then be soldered to the connector center conductor and then the stripline was fed through the hole in the slot and soldered to one side of the slot. The laminates were then bonded together. After bonding, the cavity backing the slot was formed by drilling through both layers and placing bolts or flush-mounted eyelets about the slot. This configuration was found to be very easy to work with; and in order to reduce the dimensions further, additional changes were made to the slot cavity with very little difficulty. The dimensions of the final stripline-fed cavity-backed slot configuration are given in table I. The impedance and radiation characteristics of the single-element design are presented in figure 3. The next step was to determine the effect of the dielectric cover on this extremely thin slot design.

Dielectric-Cover Design

The effects of dielectric-coated shunt slots in a waveguide have been investigated previously in references 8 and 9, and the experimental results from using the stripline-fed slot were found to corroborate the results found by Croswell and others. The heat-protective dielectric material that was to be used on a specific payload application was the noncharring type, radio-frequency transparent, and had a dielectric constant of $\epsilon_r = 2.54$ at 2240 MHz. The thermal analysis for this particular payload indicated that a dielectric-cover thickness of 0.150 inch (3.81 mm) would be required. The analysis also indicated that 0.050 inch (1.27 mm) of the cover would be lost during flight because of ablation. Therefore, the dielectric-cover design was made by using various thicknesses of the proposed material.

By using the cavity slot discussed in the previous section, the change in ratio of length to wavelength $(L/\lambda_v)_r$ of the resonant slot was determined by measuring the resonant frequency as various thicknesses of the dielectric-cover material were placed on the slot. The results of the resonant-frequency shift (see fig. 4) agree with the results found by Croswell and Higgins (ref. 8) in that for cover thicknesses greater than 0.60 inch (15.24 mm), the resonant frequency reaches a mean value. However, for thin layers (less than 0.30 inch (7.62 mm)) at S-band frequencies, severe resonant-frequency changes occur.

With these results, the ratio of length to wavelength of the resonant slot for a 0.150-inch (3.81-mm) cover thickness was found to be 0.428. Therefore, the slot length needed to provide a 50-ohm match at the design frequency of 2240 MHz was 2.26 inches (57.4 mm). Slot-impedance measurements, as a function of dielectric-cover thickness, indicated that as $t_{\epsilon r}$ is decreased, for the thickness range of interest, the slot impedance increases. (See fig. 5.) Therefore, the slot length was readjusted to $0.435\lambda_v$ ($L = 2.29$ inches (58.17 mm)) so that a 50-ohm impedance would occur at $t_{\epsilon r} = 0.100$ inch (2.54 mm). This adjustment would also improve the radiation efficiency as ablation began. The resulting element patterns for the two cover thicknesses are shown in figure 6(a). The element patterns as a function of frequency are presented in figure 6(b) for the 0.150-inch cover thickness.

Array Design

After completing the single-element design, the next step was to design an array of single elements. First, the number of slots for the specific payload application had to be determined. The proposed antenna location for this particular payload was a cylinder 8.610 inches (218.69 mm) in diameter (ka = 5.2 uncoated; ka = 5.4 coated). References 3 and 4 indicated that if the element pattern is expressed as a Fourier series, the required number of sources to provide a given fluctuation in the far-field pattern can be determined. The element pattern of figure 3(c) was then synthesized and the Fourier series that best approximated the element pattern was found to be $F(\phi) = 1 + \cos \phi$. By applying this series to the results in reference 3 it was determined that eight slots arrayed circumferentially should produce a pattern fluctuation of ±3 dB. Since this fluctuation would be acceptable, a method of arraying eight stripline-fed cavity-backed slots from a single feed point had to be determined.

The previous work using the single cavity-backed-slot elements indicated that the design could be expedited if a 50-ohm terminal impedance were provided instead of a higher impedance that could be made parallel with other elements. It was then decided that the terminal impedance for all eight slots of the array would be 50 ohms and a circuit would be required to interconnect eight 50-ohm loads. A series feedline was chosen instead of a parallel-type feedline in order to reduce the number of branch lines. With a series feedline the distance between branch points for this payload diameter is $0.94\lambda_{\epsilon r}$. Ideally, however, the distance between branch points should be $1.0\lambda_{\epsilon r}$, but the payload diameter and other antenna dimensions already chosen precluded this exact distance. Providing a 50-ohm slot impedance necessitated the characteristic impedance of the stripline to be adjusted to match the parallel impedance of the slots. This adjustment was achieved by selecting the dimensions for a rectangular transmission line so that the required characteristic impedances could be provided. A diagram of the desired circuit and characteristic impedances is shown in figure 7. Again, by using the design curves of reference 6, the stripline dimensions for the required characteristic impedances were determined and circuits were assembled. The actual impedances were determined by using a time-domain reflectometer. The results are shown in figure 8. The fabrication of an array using the stripline circuit design was then initiated.

Array Fabrication

The fabrication of the extremely thin array composed of eight circumferential slots will now be discussed. Two-ounce (0.057 kg) copper-clad dielectric cloth is commercially available in sheet sizes 15 by 35 by 0.047 inches (381 by 889 by 1.19 mm). The dielectric constant of the material is 2.10. The allowable space on the payload for such an array was a cylindrical section 6 inches (152.4 mm) in length with a diameter of 8.610 inches (218.69 mm). The 6-inch (152.4-mm) cylinder length was more than adequate to accommodate the array in that dimension.

The dielectric layers were cut to the proper size and each layer was rolled into a 9-inch-diameter cylinder. This diameter allowed a sufficient amount of overlap prior to cutting each layer to the exact circumferential length. The "inside" layer was rolled or formed with the dielectric side on the outside and the copper surface inside, as shown in figure 9. A butt joint was formed with the inside layer by soldering a copper strip across the joint on the copper side of the layer. The joint was later filled with an epoxy adhesive. Prior to rolling the "outside" layer, the layer with the copper surface on the outside and the dielectric surface inside, the slots were formed by cutting away the copper surface.

The slots were made 2.4 by 0.10 inches (60.96 by 2.54 mm) which is slightly longer than the 2.26-inch (57.4-mm) length specified by the test results using a single-coated slot. It was believed that this additional length would compensate slightly for tolerance effects, and the length could be easily shortened later after preliminary array measurements were concluded. The dimensions of each cavity were also outlined prior to rolling the outside layer. The outline would be the rivet line and the rivets would be placed in after the two layers were bonded together. In order to obtain a smooth surface on both sides of the flight antenna, copper counter-sunk rivets were used instead of bolts. The outside layer was then rolled into a 9-inch-diameter (228.6 mm) cylinder.

The stripline circuit according to figure 7 was bonded to the dielectric side of the outside layer, and the feed loops were then placed through holes 0.60 inch (15.24 mm) from the end of the slot. A hole 0.50 inch (12.7 mm) in diameter through the outside layer was provided at the feed-point location. This hole would facilitate soldering the stripline to the radio-frequency connector later.

Since the inside layer was in the form of a cylinder but was not close to 8.610 inches (218.69 mm) in diameter, a 0.125-inch-diameter hole (3.18 mm) for the feed connector was drilled 1.5 inches (38.1 mm) from one edge of the layer. The connector would be placed there later. The outside layer, also being in the form of a cylinder, was positioned so that the stripline feed would aline properly with the connector hole on the inside layer. The layers were then bonded together and a copper strap was soldered across the joint on the outside surface. Both dielectric surfaces were chemically treated to facilitate bonding. After the bond was sufficiently cured, pilot holes were drilled along the rivet line on the outside surface, and copper-countersunk rivets were then placed in the holes approximately 0.30 inch (7.62 mm) apart. These rivets thereby formed the individual cavities for the slots as well as for the rectangular transmission line. The countersunk rivets were placed through the two layers and peened over on the inside to form a fairly smooth surface inside and outside. The antenna was then ready to be bonded to the payload cylindrical section.

Since the antenna had been rolled to a slightly larger diameter, it could slide over one end of the cylinder. A hole large enough to accommodate the feed connector had already been drilled in the payload cylinder. The antenna was then bonded to the payload cylinder under a vacuum to eliminate air bubbles in the epoxy adhesive. After bonding, the feed connector was soldered in place on the inside antenna surface, and the hole in the outside surface provided a means of soldering the stripline circuit to the center conductor of the feed connector. A patch of copper-clad dielectric material was placed in the outside hole and soldered securely in place. The feed connector is shown in figures 1(c) and 7. The feedlines for the individual slots were then soldered in place and the array was ready for testing. Preliminary tests using the array indicated that the slot length had to be reduced to approximately 2.20 inches (55.88 mm). This adjustment was probably due to the mutual coupling of the slots after they were interconnected with the stripline circuit. After these adjustments were made to the slots, the array was ready for coating with the heat-protective material.

The heat-protective material was applied over the antenna and cured in a vacuum mold to eliminate air bubbles. After curing, the outside surface was machined down to the 0.150-inch (3.81-mm) total cover thickness. A photograph of the coated array is shown in figure 1(b). Impedance and pattern measurements were performed and the results are given in figure 10. The antenna provides a very good impedance bandwidth. The pattern bandwidth is considerably less but is still acceptable. The pattern ripple at the center frequency was better than expected, especially for the expected shift in antenna resonant frequency for the 0.100-inch (2.54-mm) cover thickness. The elevation plane pattern of figure 10 is presented with additional cylinders on both ends of the antenna to simulate the remaining portion of the booster. It should be stated that control of the elevation plane pattern may be required on bodies of different cylindrical shapes and sizes. A method of controlling the elevation plane pattern is discussed in reference 1. Control of the elevation plane pattern was not required for this payload application.

CONCLUDING REMARKS

The design and development of an extremely thin (0.094 inch or 2.39 mm) microwave antenna array has been discussed that presents a new technique in arraying discrete sources about cylindrical shapes that are large in terms of operating wavelengths. The antenna array was designed to give an omnidirectional radiation pattern in the equatorial plane at a frequency of 2240 MHz for a payload diameter of 8.610 inches (218.69 mm). The array was composed of eight stripline-fed cavity-backed slot antennas. The control of the array and slot impedances was obtained by varying the slot lengths as well as the feed-point location on the slot.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., September 15, 1969.

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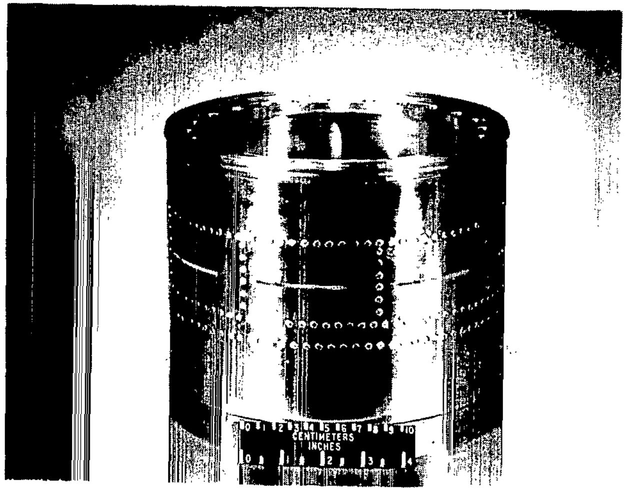
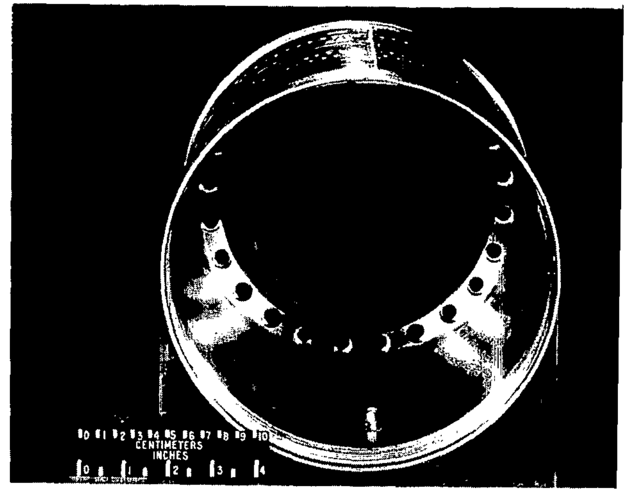
TABLE I.- DIMENSIONS OF FINAL STRIPLINE-FED CAVITY-BACKED SLOT CONFIGURATION

Description	Dimensions in –	
	Inches	Millimeters
Single element		
Slot size when uncoated	2.55 × 0.10	64.77 × 2.54
Minimum cavity dimensions	2 × 3.3 × 0.094	50.8 × 83.82 × 2.39
Feed-point location from end of slot for Z_0 = 50 ohms	0.60	15.24
Slot length L for $t_{\epsilon r}$ = 0.150	2.26	57.40
Slot length L for $t_{\epsilon r}$ = 0.100	2.29	58.17
Array		
Slot length L for $t_{\epsilon r}$ = 0.100	2.20	55.88
Cavity dimensions	2 × 3.3 × 0.094	50.8 × 83.82 × 2.39
Feed-point location from end of slot	0.60	15.24

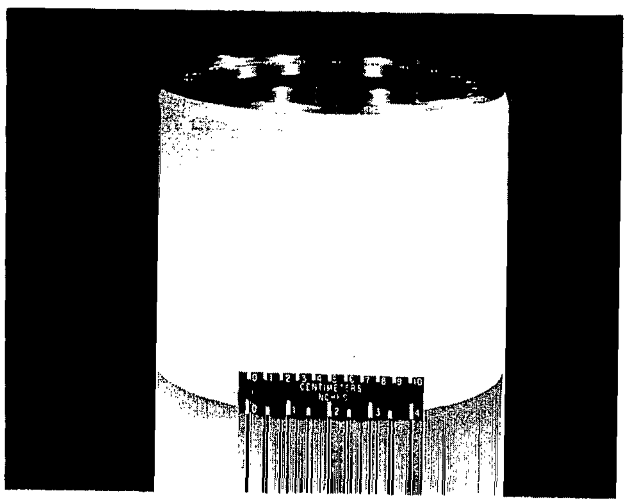


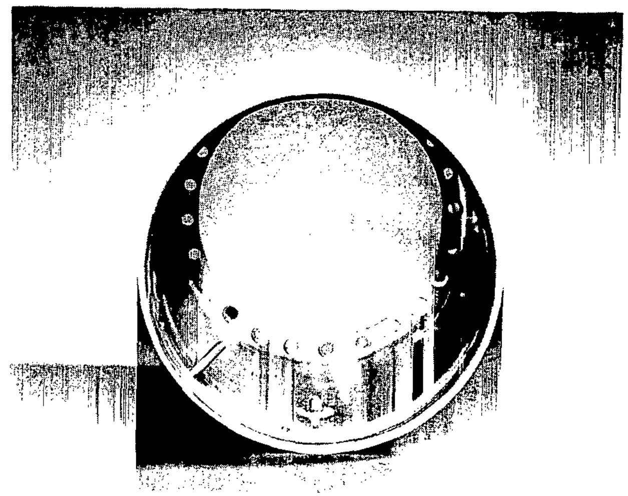


L-69-907

(a) Without dielectric cover.

L-69-905



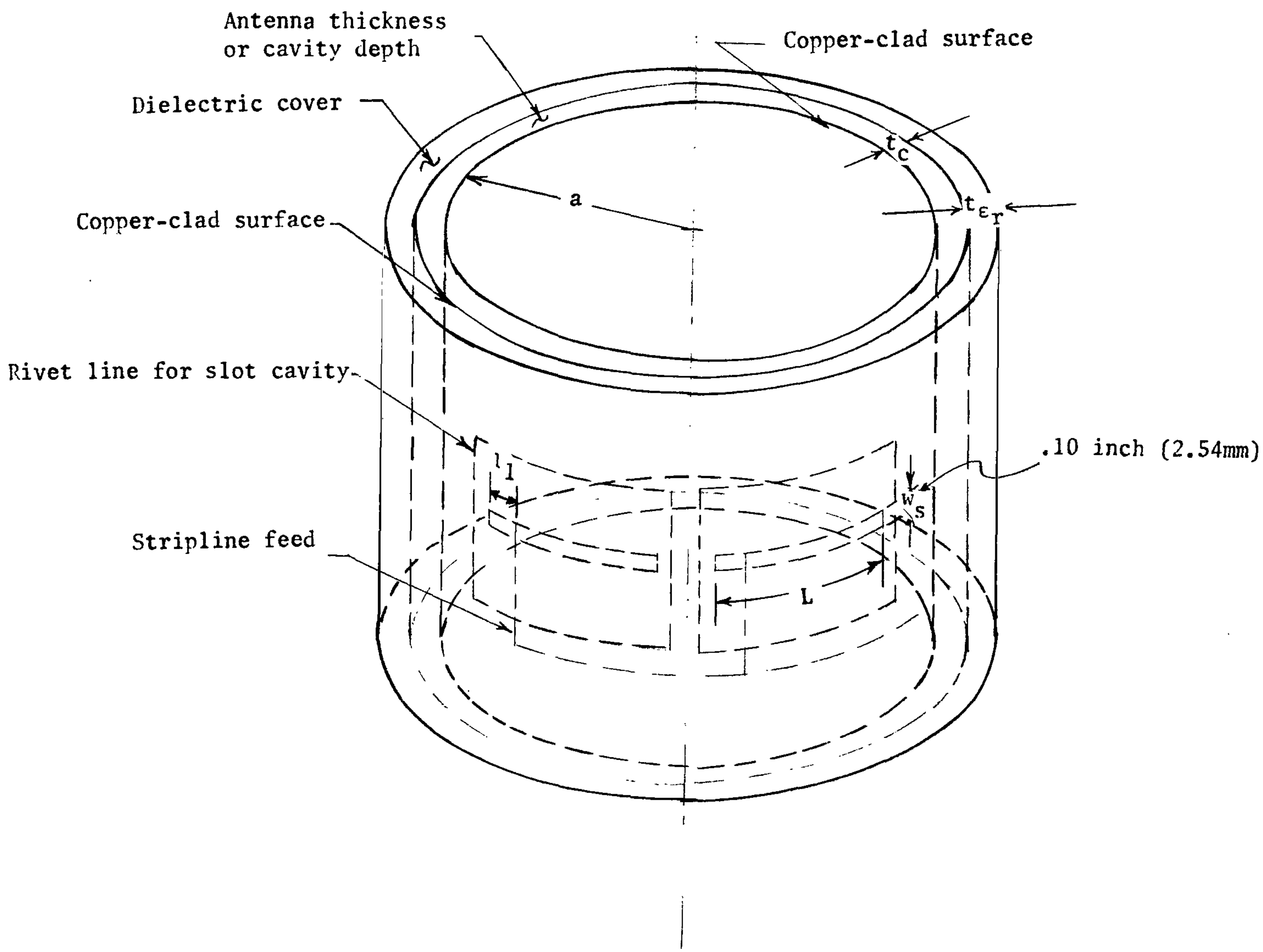


L-69-985

(b) With dielectric cover.

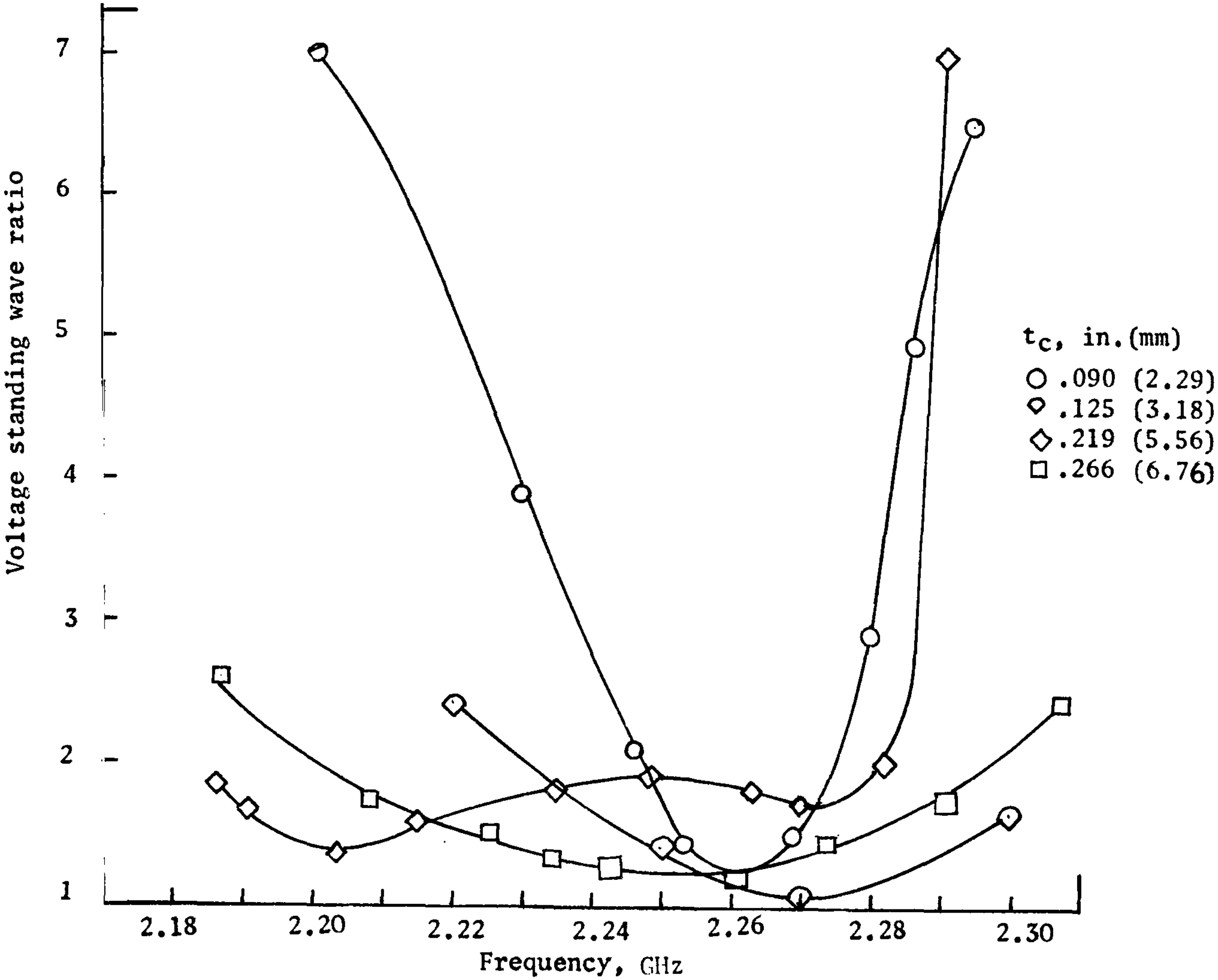
L-69-986

Figure 1.- Completed S-band array.



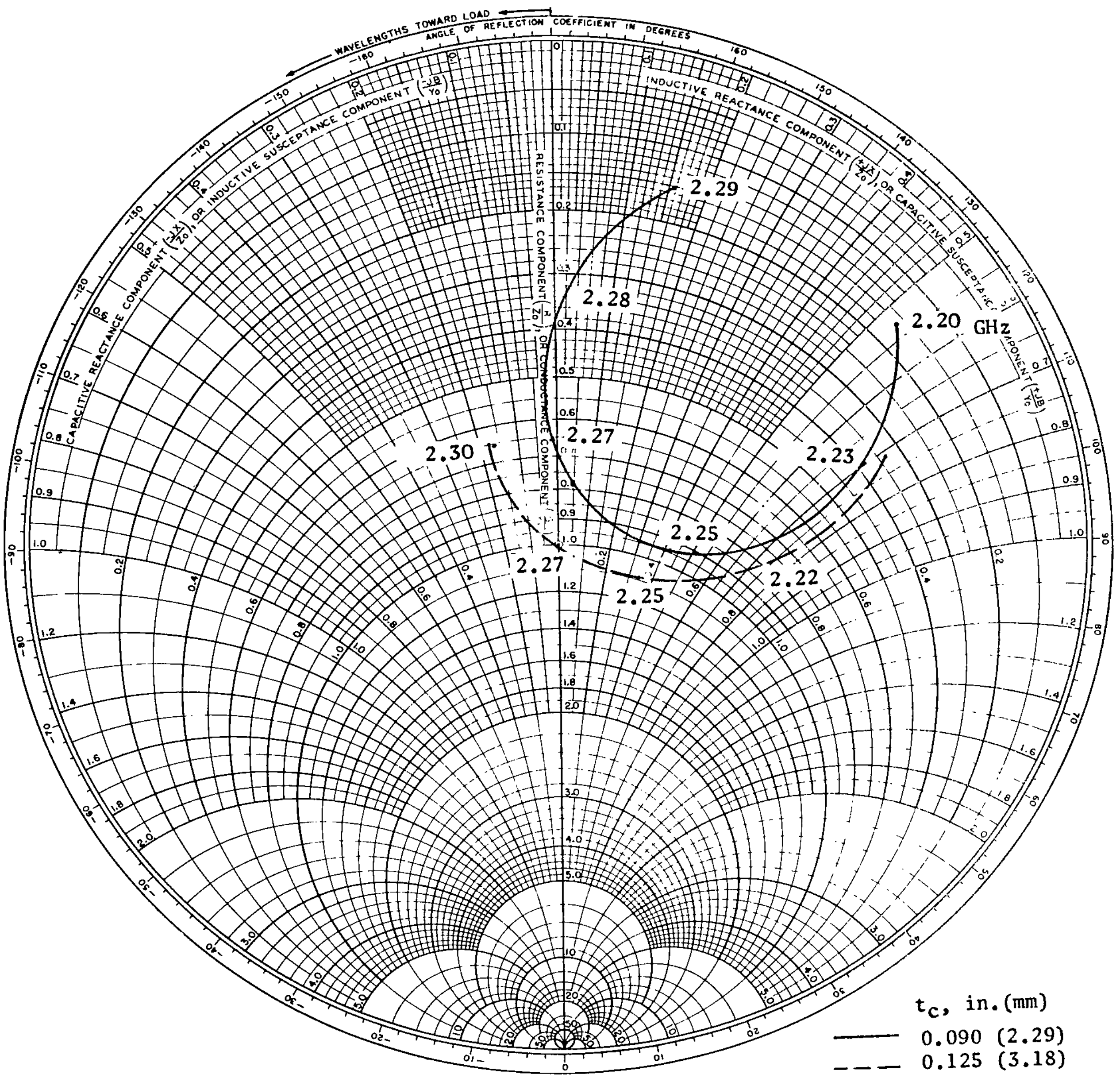
(c) Outline drawing.

Figure 1.- Concluded.



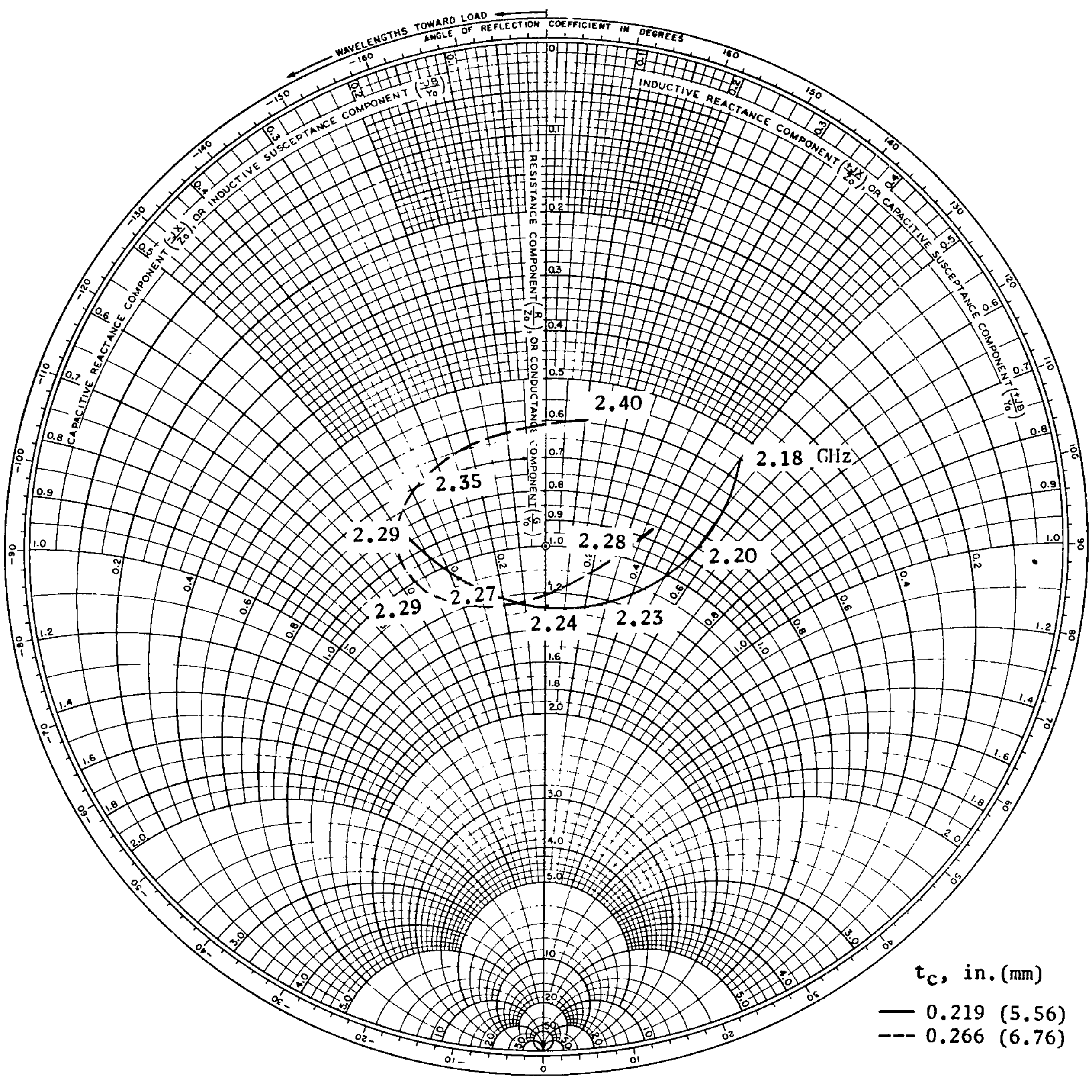
(a) Effect of cavity depth on VSWR of end-fed slot antenna.

Figure 2.- Effects of cavity depth on slot VSWR and impedance.



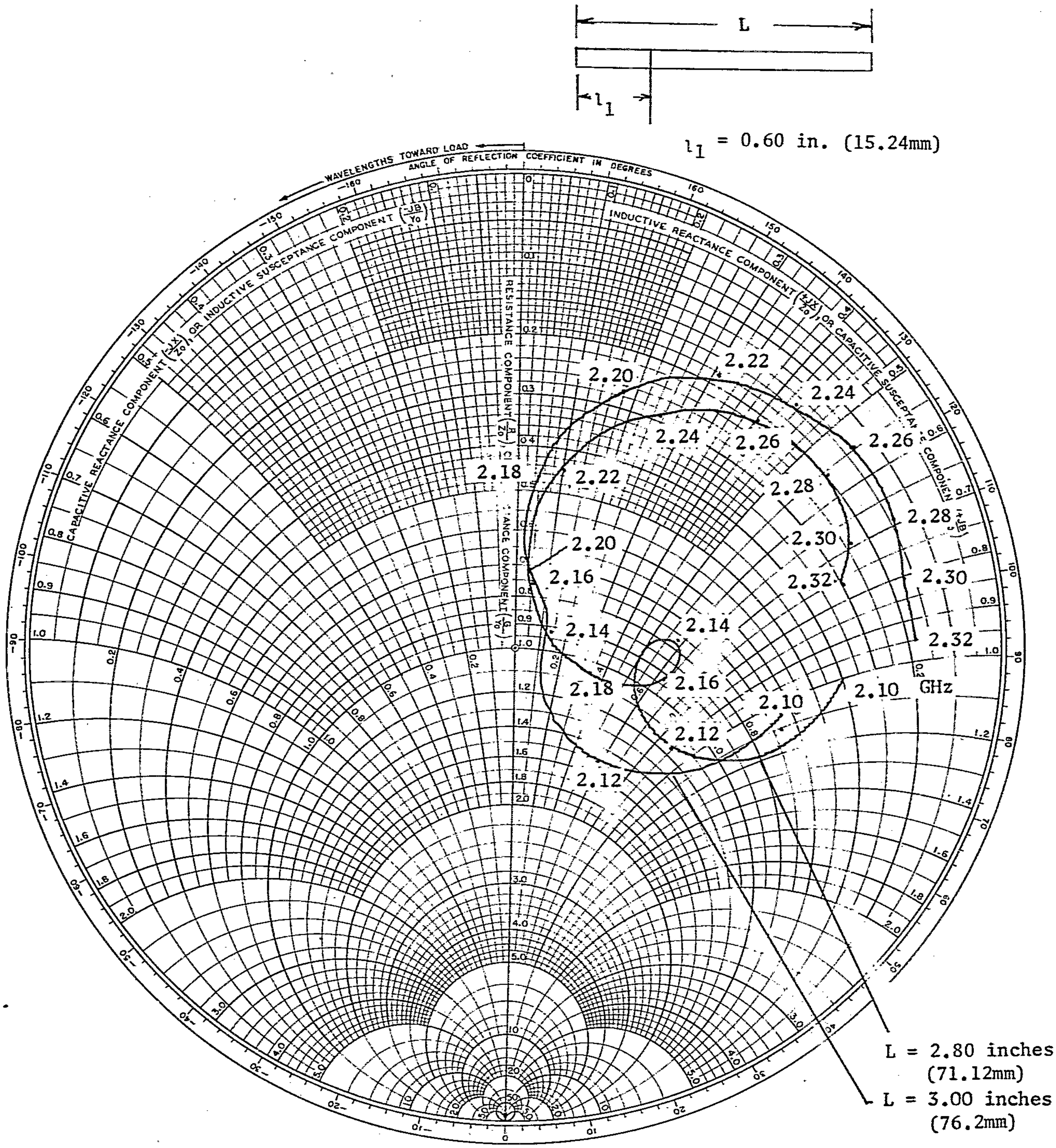
(b) Effect of cavity depth on slot impedance for t_c = 0.090 in. and 0.125 in. (2.29 mm and 3.18 mm).

Figure 2.- Continued.



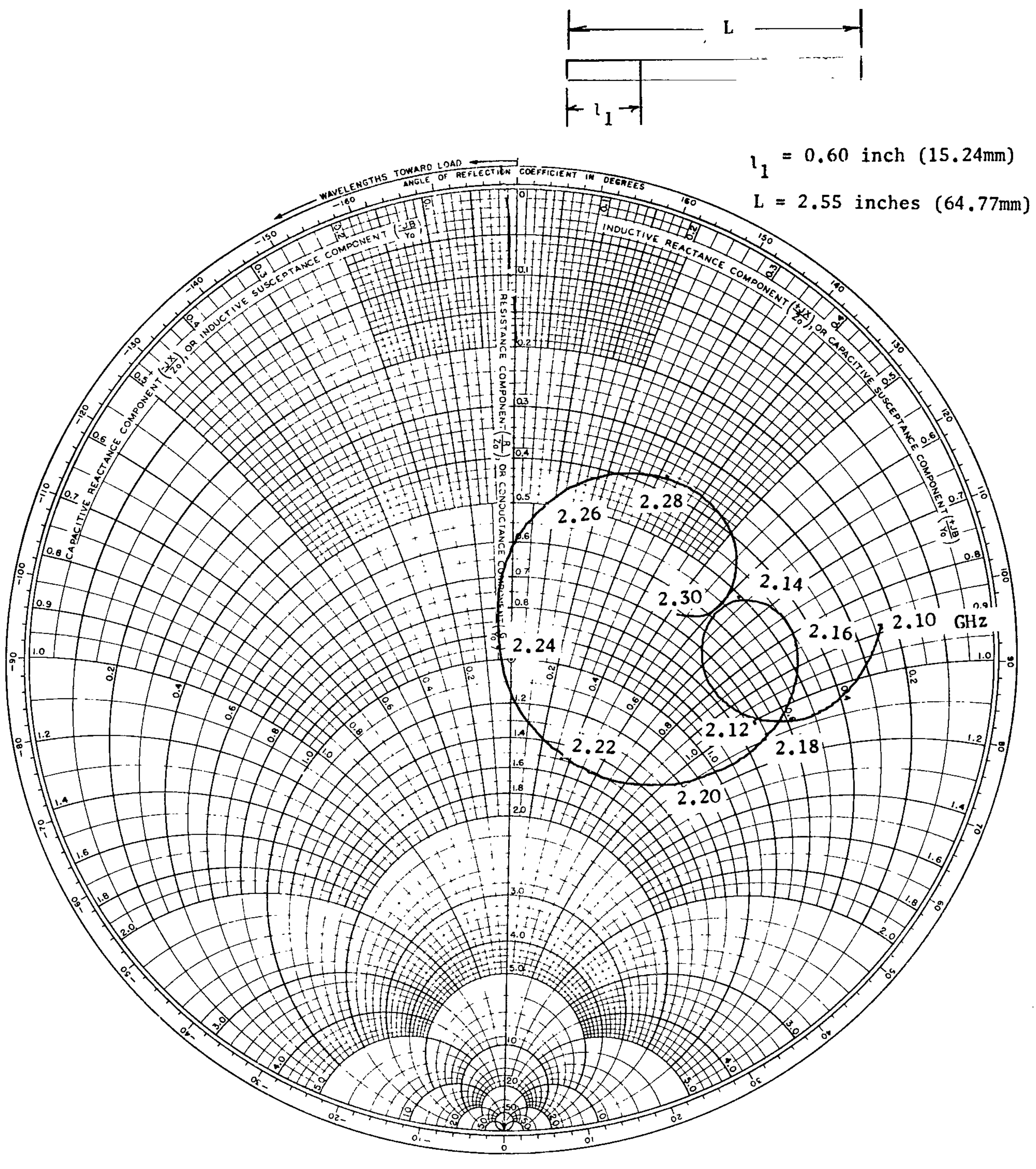
(c) Effect of cavity depth on slot impedance for t_c = 0.219 in. and 0.266 in. (5.56 mm and 6.76 mm).

Figure 2.- Concluded.



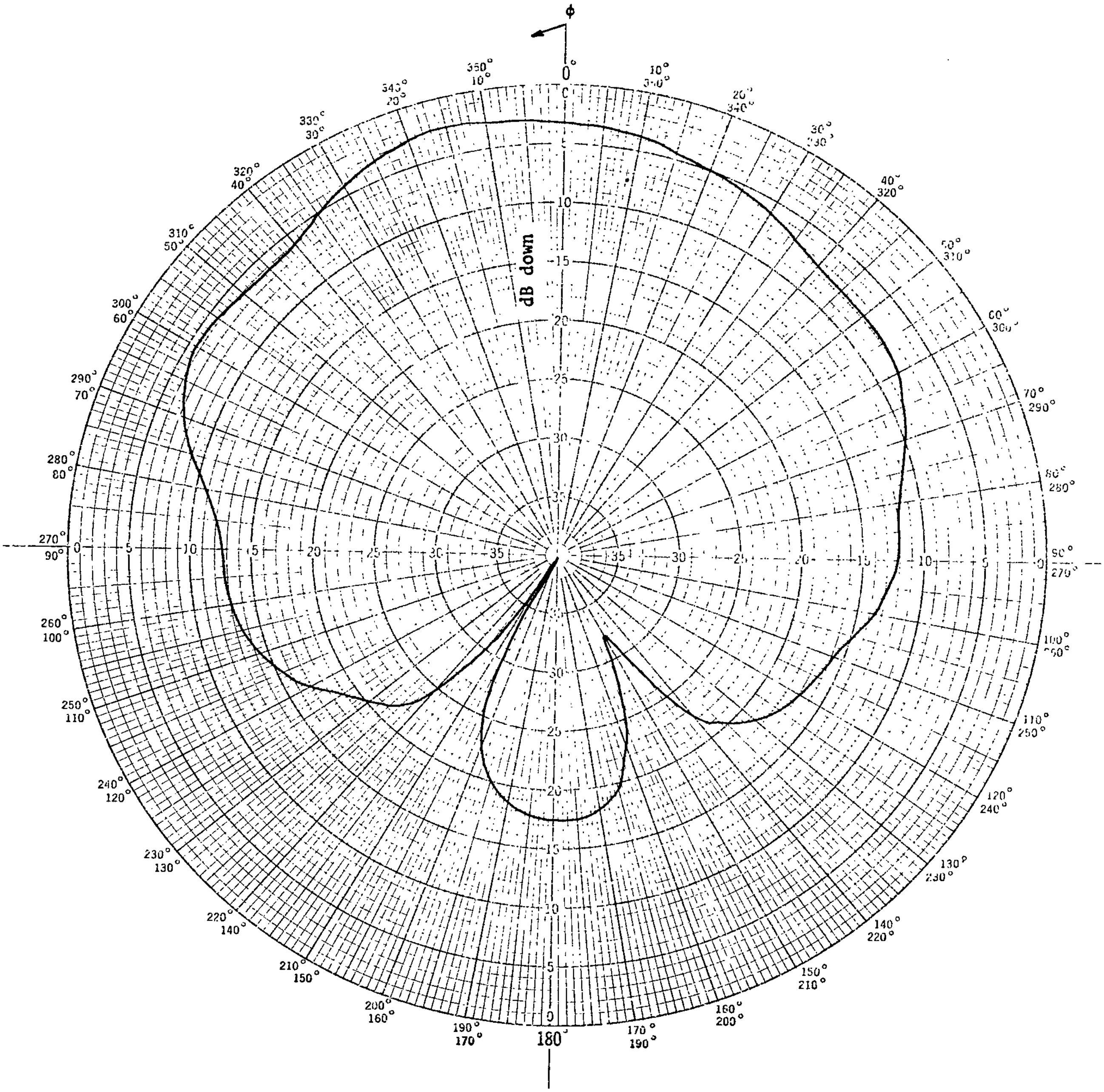
(a) Impedance of stripline-fed slot as a function of slot length and frequency.

Figure 3.- Impedance and radiation characteristics of the single-element design.



(b) Impedance of stripline-fed slot antenna as a function of frequency.

Figure 3.- Continued.



(c) Equatorial-plane radiation pattern of single stripline-fed circumferential slot with no coating. $(L/\lambda_v)_r = 0.51$.

Figure 3.- Concluded.

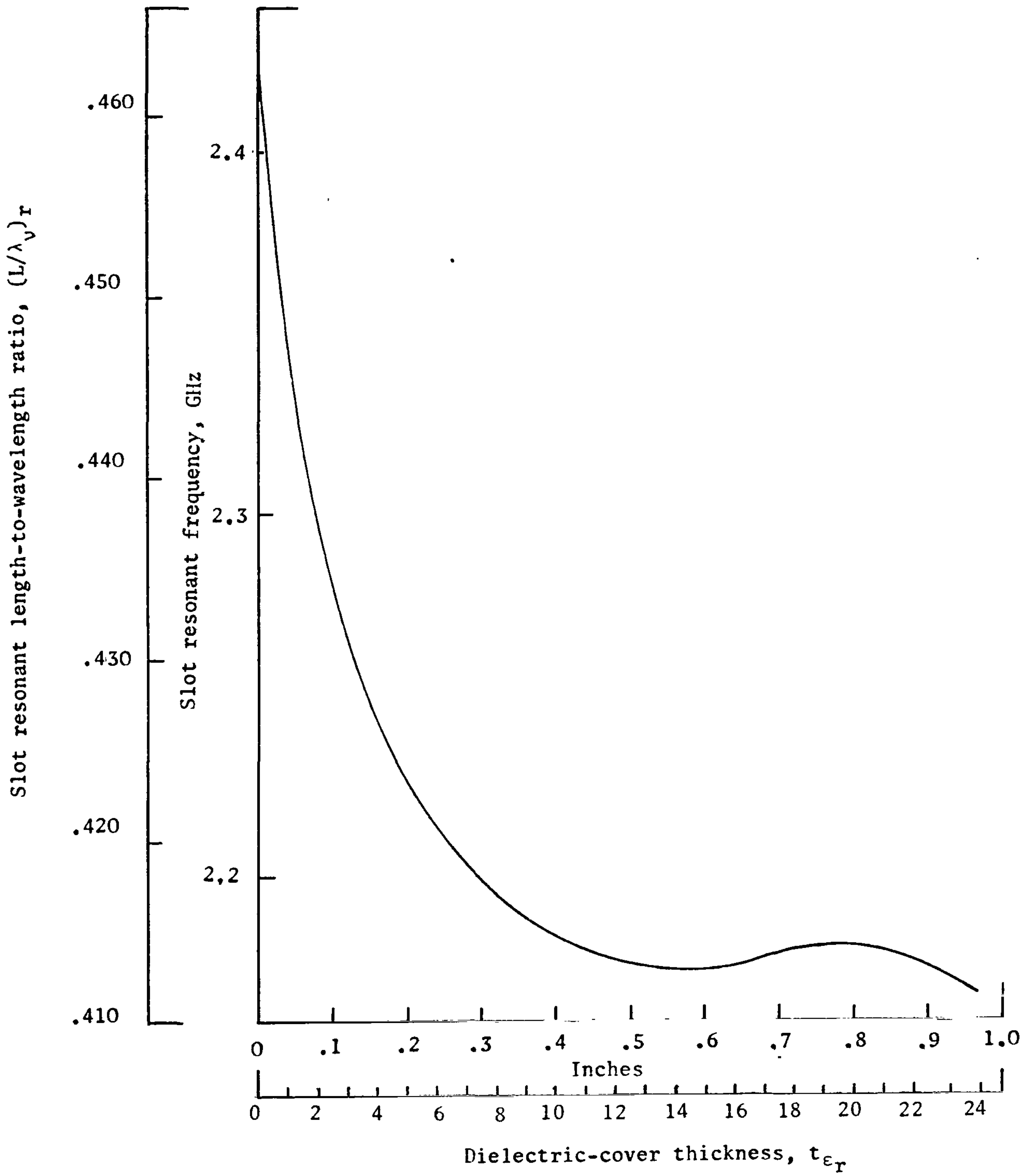
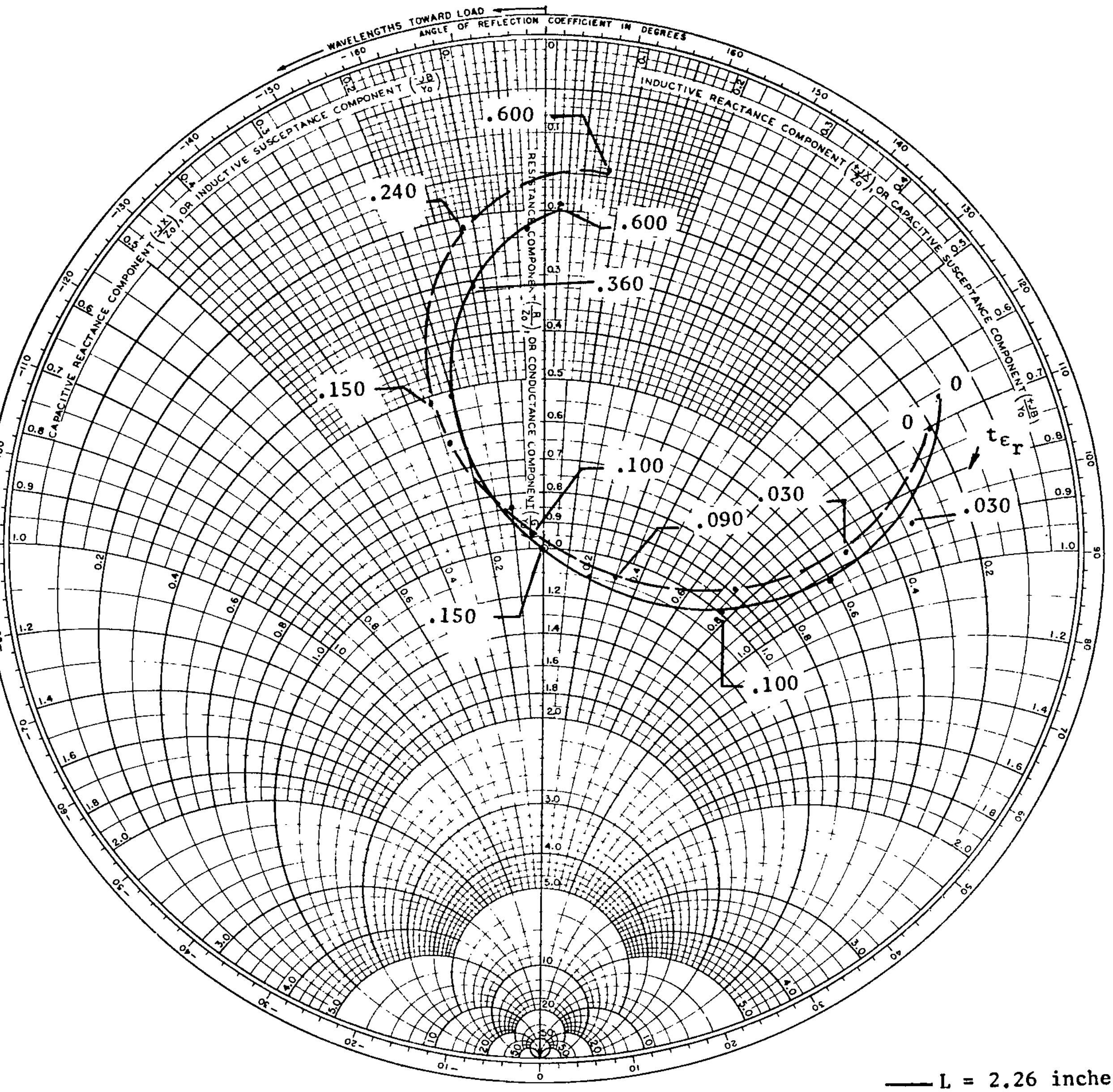
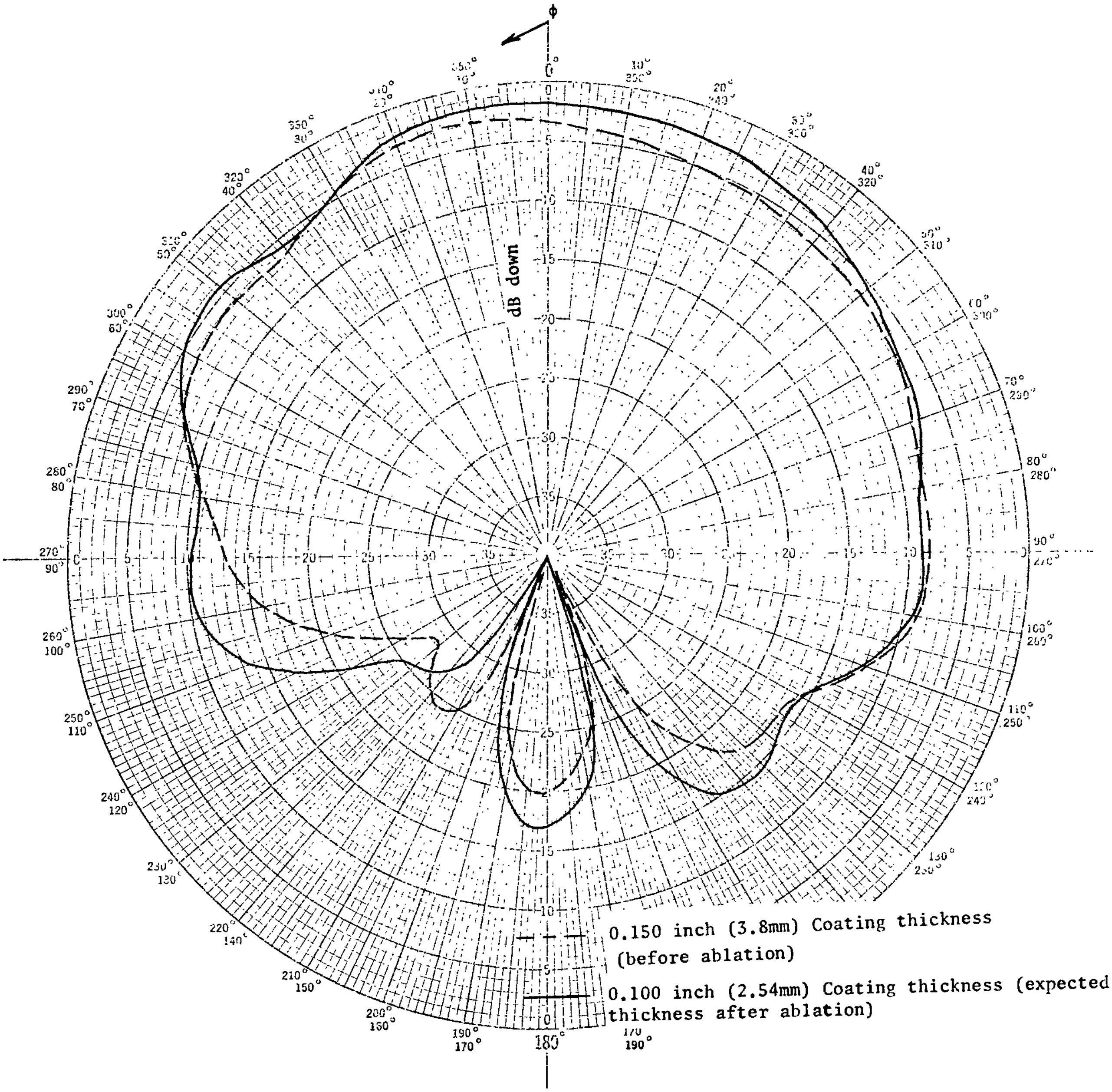


Figure 4.- Effect of dielectric-cover (ε_r = 2.54) thickness on stripline-fed slot resonant frequency.



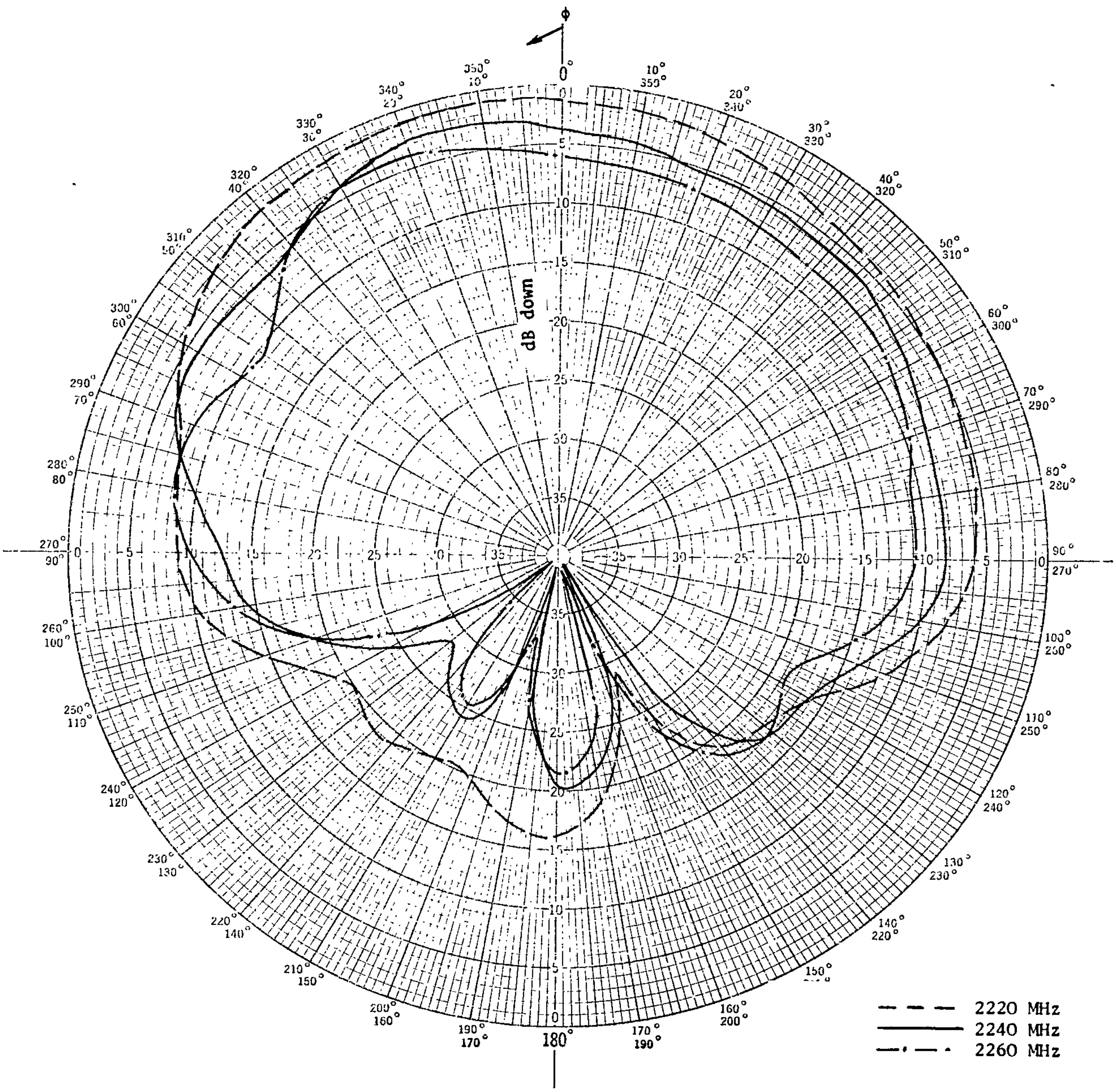
—— L = 2.26 inches (57.4mm)
--- L = 2.29 inches (58.17mm)

Figure 5.- Impedance of stripline-fed slot for various dielectric-cover (ε_r = 2.54) thicknesses $t_{\varepsilon r}$ at f = 2240 MHz.



(a) Slot coated with dielectric material; f = 2240 MHz; $(L/\lambda_v)_r$ = 0.435.

Figure 6.- Equatorial-plane radiation pattern of a circumferential stripline-fed slot.



(b) Patterns as a function of frequency for $t_{\epsilon r}$ = 0.150 in. (3.81 mm) and L = 2.26 in. (57.4 mm).

Figure 6.- Concluded.

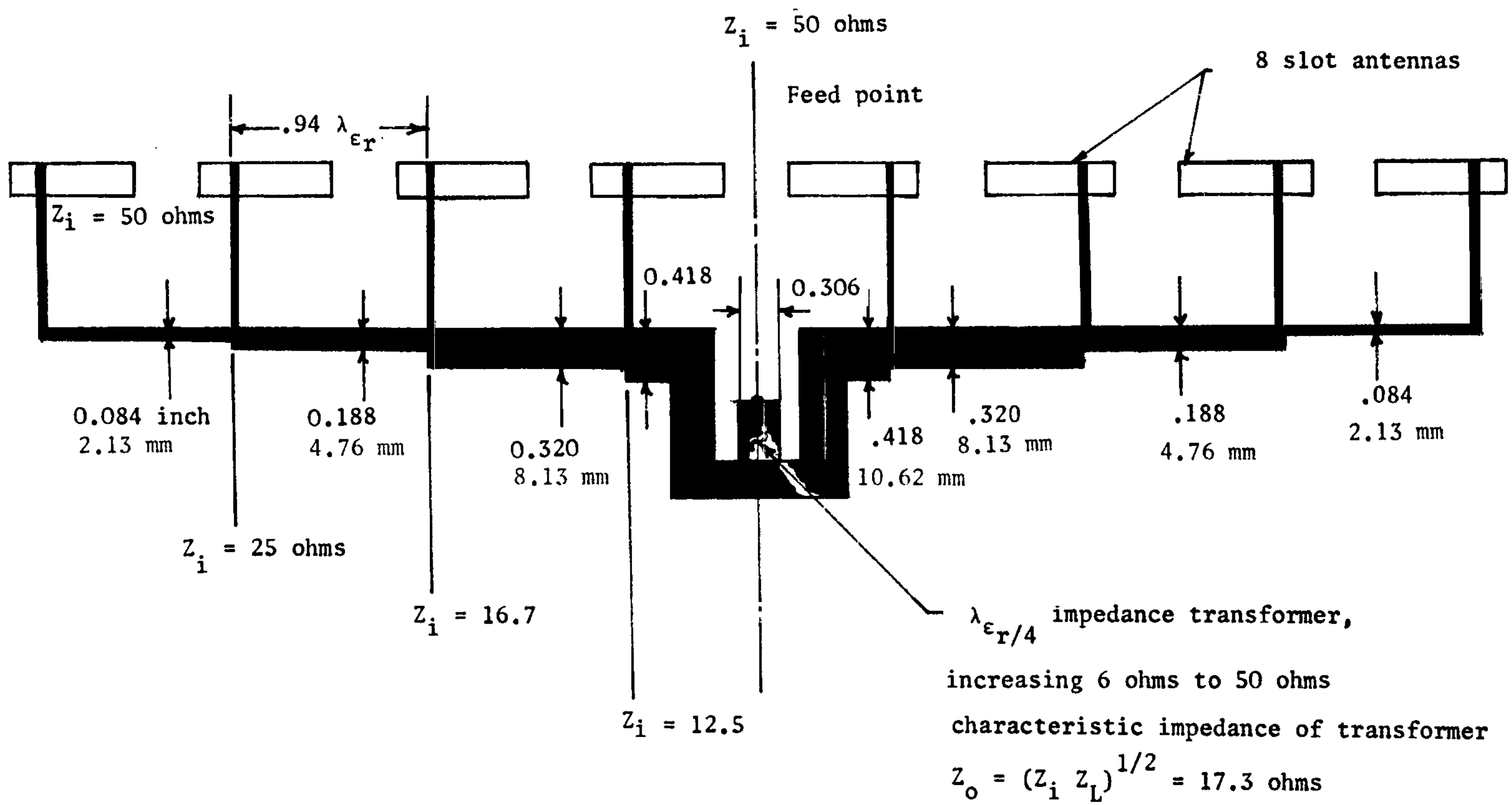


Figure 7.- Stripline circuit for the eight-slot array.

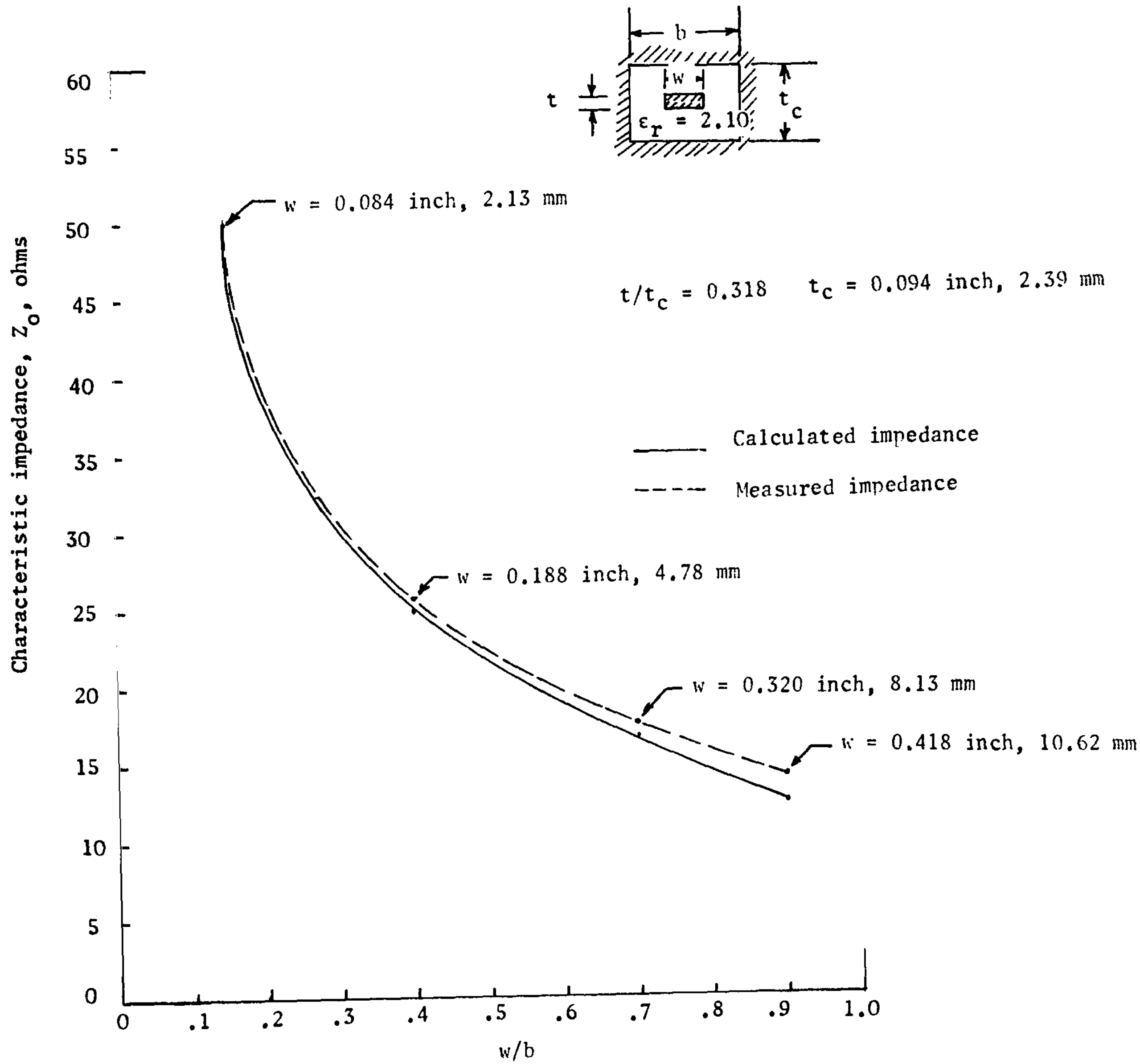
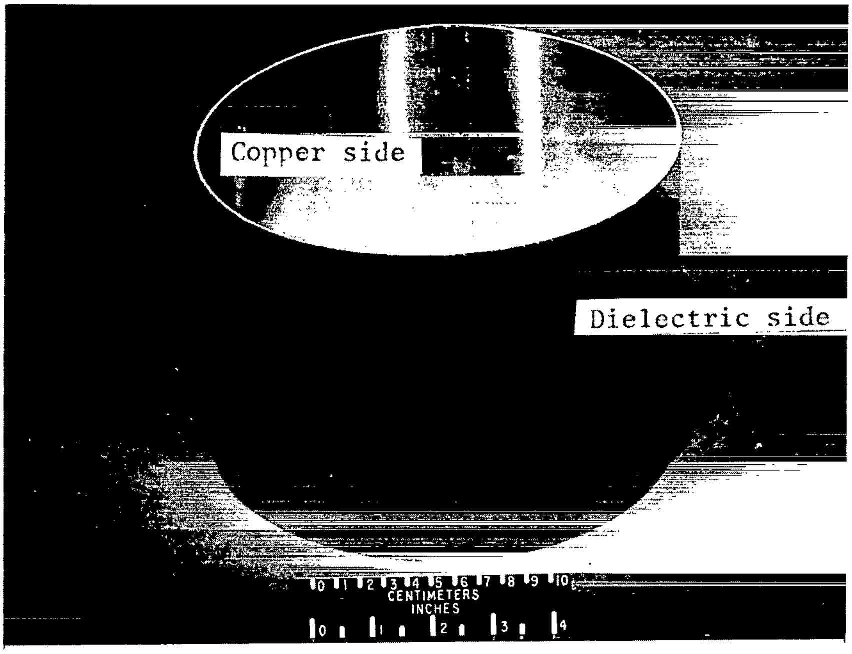
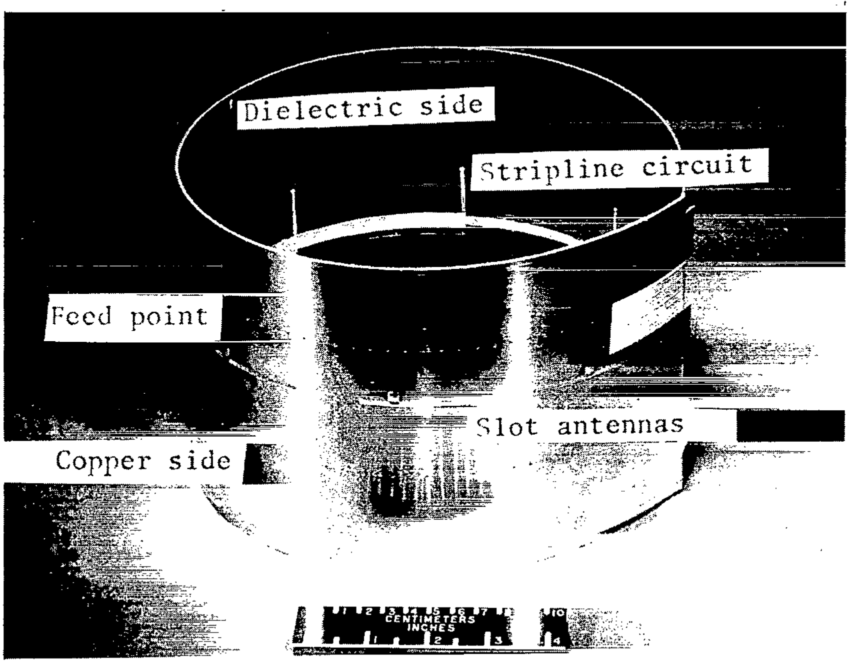


Figure 8.- Measured and calculated characteristic impedances of rectangular transmission line for array circuit.

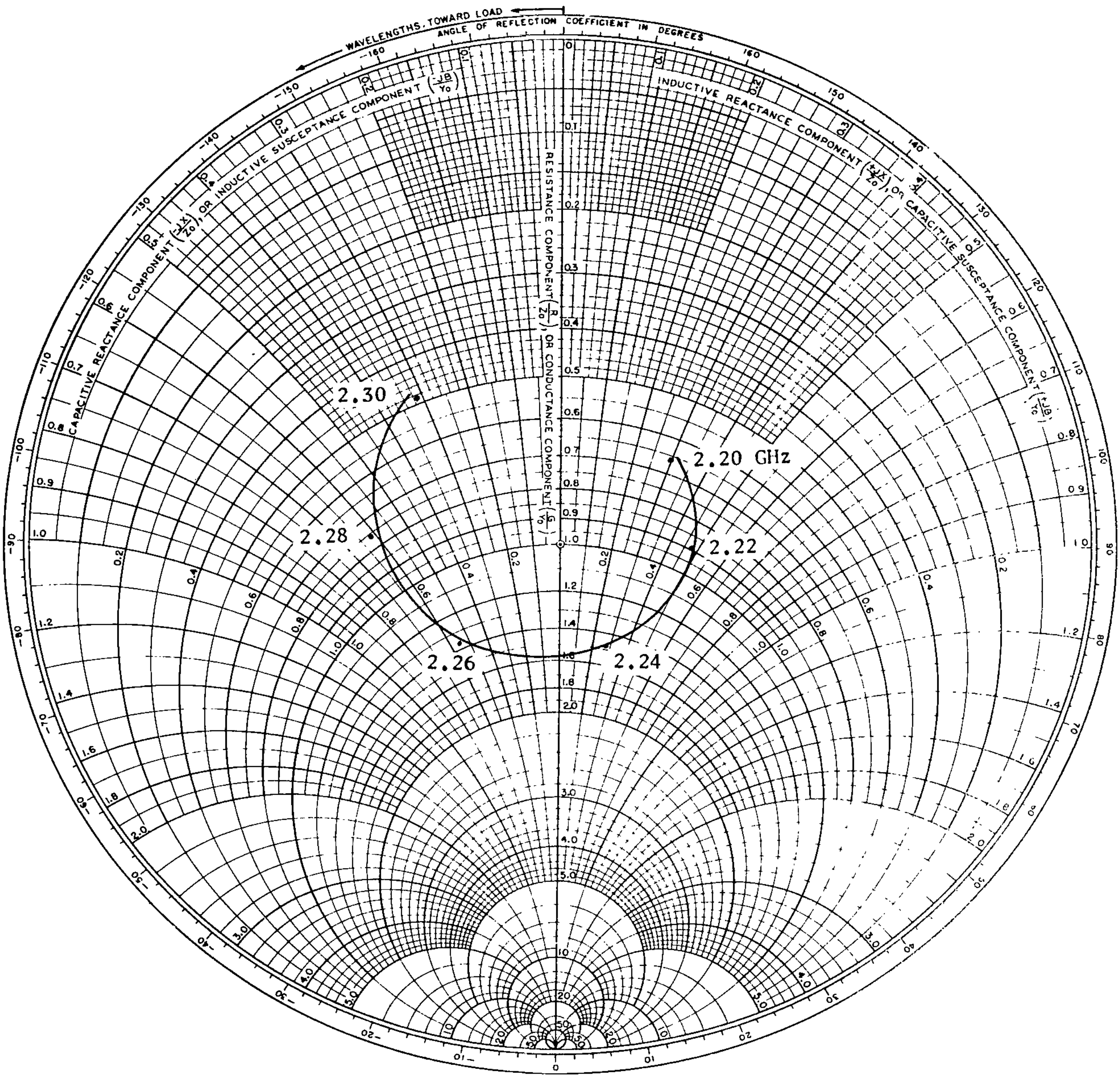


(a) Inside layer. L-69-895.1



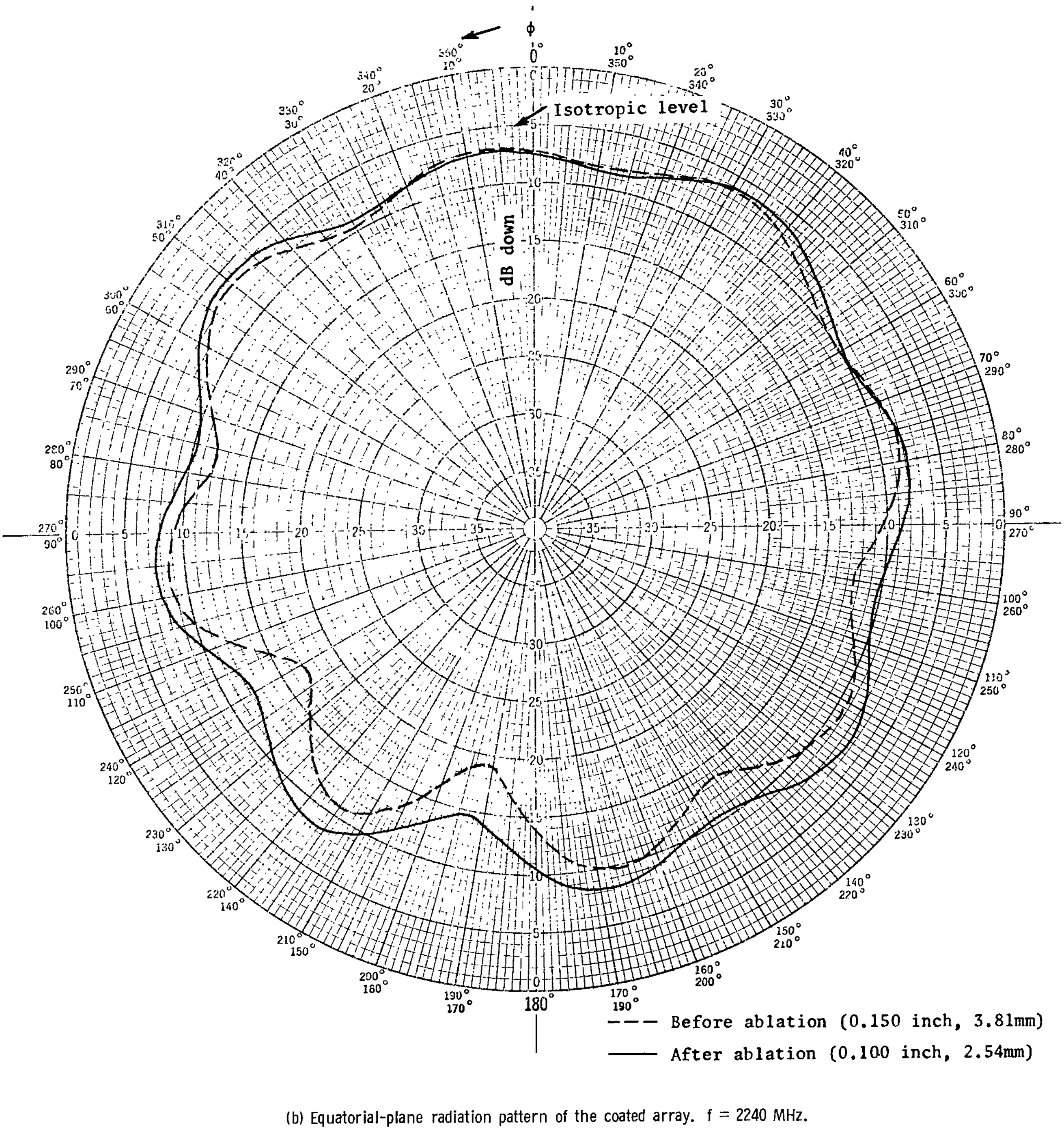
(b) Outside layer. L-69-896.1

Figure 9.- Inside and outside layers of the array antenna.



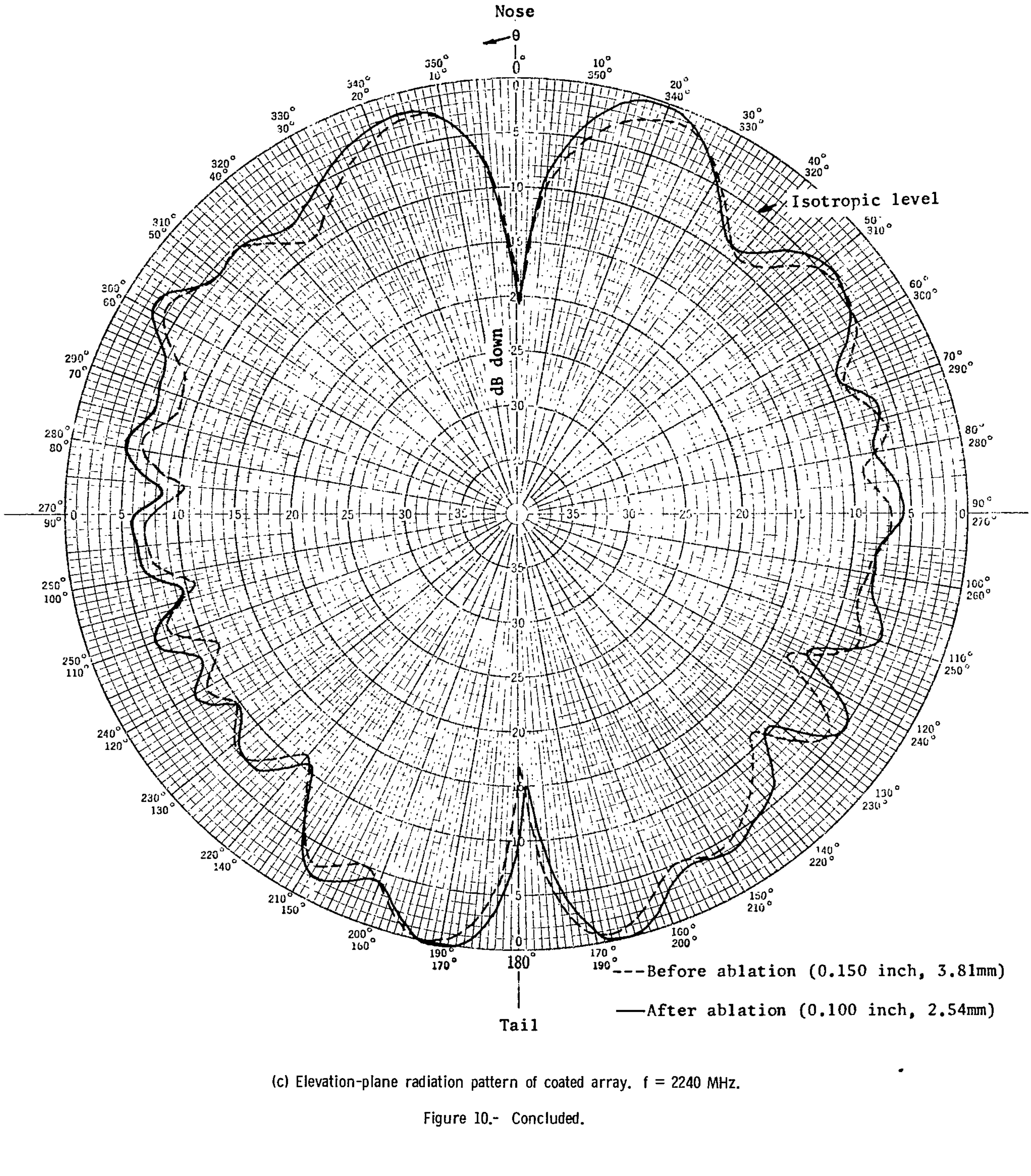
(a) Final impedance characteristics of the stripline-fed slot array. $t_{\epsilon r}$ = 0.150 inch (3.81 mm) as a function of frequency.

Figure 10.- Impedance and pattern measurements.



(b) Equatorial-plane radiation pattern of the coated array. f = 2240 MHz.

Figure 10.- Continued.



(c) Elevation-plane radiation pattern of coated array. f = 2240 MHz.

Figure 10.- Concluded.