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GENERAL AVIATION AIRCRAFT ANTENNAS FOR THE GLOBAL POSITIONING SYSTEM

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GENERAL AVIATION AIRCRAFT ANTENNAS FOR THE GLOBAL POSITIONING SYSTEM

by

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SUMMARY

The NAVSTAR Global Positioning System (GPS) is a sophisticated satellite navigation system which has the potential for meeting the needs of a wide range of users. With some sacrifice in accuracy, it is possible to reduce the cost of the equipment at the user end and make it attractive for general aviation aircraft applications. The purpose of this study was to evaluate several antenna designs that might be acceptable for use on general aviation aircraft in a low cost system. Experimental investigations were made of crossed-dipoles, various types of crossed-slots, and microstrip antennas with modifications to improve the coverage. Principal plane radiation patterns for several of these antennas measured on a one-seventh scale model of a Gates Lear jet are presented.

INTRODUCTION

The Global Positioning System (GPS) is a world-wide satellite based navigation system being developed under the USAF's Space and Missile System Organization (reference 1). GPS has the potential to become a single, universal navigation system meeting the needs of a broad variety of users (references 1, 2 and 3).

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The system is expected to replace VOR, LORAN, OMEGA, TACAN and Radar Altimeters and is evolutionarily implementable. The system enables the user to obtain position (x,y,z) and velocity with an accuracy of the order of 8 to 10 meters and 3 cm/sec., respectively. With some sacrifice in accuracy, it is possible to reduce the cost of the equipment at the user end considerably. GPS consists of three subsystems. These are the space, ground and user segments. The over-all GPS concept is shown in figure 1 (reference 1).

The space segment consists of 24 satellites rotating in circular orbits around the earth at a radius of 20,000 km with a period of 12 hours and an inclination of approximately 63°. An antenna on earth with an elevation angle in excess of 5° from the horizon will view at least six satellites. Each satellite transmits two L-band signals suitably modulated. The primary frequency of 1575.5 MHz is intended for general users with lower precision in navigation and the secondary frequency of 1227.6 MHz is for higher precision and also is used for compensation of propagation delays experienced in the ionosphere.

The ground segment consists of sophisticated equipment at suitably distributed points on earth. It has three functional elements. The monitoring station receives the signals from satellites and sends them after processing to the master control station which updates messages, recalibrates time-bases and clock signals, generates ephemeris data and formats this with clock data for uploading to the spacecraft. The uploading station transfers the navigational data to the satellite by an S-band link.

The navigational facilities of GPS can be utilized for defense purposes, general aviation, ships and boats, trucks, and forest rangers. The user community is divided into six classes depending on the type of service required. The basis of division of the user community is accuracy, user dynamics and immunity to electromagnetic warfare. The receiver sophisitcation is divided into three classes. The "X" receiver is "continuous" and tracks continually four satellites and provides approximately 10 solutions per second. For low dynamics the "Y" receiver is used which tracks sequentially four satellites and provides approximately 2 solutions per second.

If a reduction in achievable accuracy is allowed, the receiver can be designed to operate only on the "clear" code resulting in a much simpler version. This is the so called "Z" low cost GPS receiver and is the probable candidate for general aviation interest and slowly moving transport systems. This report will be mainly concerned with the design of antennas for general aviation for the "Z" receiver.

The proposed error budgets for both the "X" and "Z" receivers are indicated in Table 1 (reference 1). Table 2 shows an RF link calculation of user received power for Zenith and a worst case user elevation angle of 5° (reference 1).

ANTENNA DESIGN FOR GPS

The design of an antenna for GPS will depend on the category of the user (reference 4). For high dynamics and high accuracy some form of phased array (references 5 and 6) may be used. Thus

TABLE 1. GPS ERROR BUDGET (REFERENCE 1)

Source	Clear Code Only	Single Protected Code	Two Protected Code
Ephemeris	1.5	1.5	1.5
Satellite Clock and Electronics	1.0	1.0	1.0
Troposphere (model)	1.5	1.5	1.5
Ionosphere (model)	15.0	5.0	zero
Receiver Noise	3.0	1.5	2.5
Multipath	1.25	1.25	2.0
Total (meter-RMS)	15.5	6.0	4.0
	(Z Rcvr)		(X Rcvr)

(Assuming a geometric-dilution-of-precision of 1.5 to 3, the 15.5 meter RMS for clear only code translates to approximately 35 meters while the 4.0 meter RMS for the two protected codes translates to approximately 9 meters.

TABLE 2. RF LINK CALCULATION OF USER RECEIVED POWER (REFERENCE 1)

	ZENITH			USER ELEVATION ANGLE = 5°		
	L_1		L_2	L_1		L_2
	C/A	P	P	C/A	P	P
Satellite Transmitter Power (dBw)	14.25	11.25	6.35	14.25	11.25	6.40
RF Losses (dB)	1.0	1.0	1.0	1.0	1.0	1.0
Antenna Polarization Loss (dB)	0.25	0.25	0.25	0.25	0.25	0.25
Antenna Gain (dB)	15	15	15	12	12	12
Satellite EIRP (dBw)	28	25	20.1	25	22	17.15
Path Loss (dB)	182.5	182.5	180.6	184.2	184.2	182.3
Atmospheric Absorption (dB)	-	-	-	0.85	0.85	0.85
Total Power at User Antenna (dBw)	-154.5	-157.5	-160.5	-160	-163	-166

C/A - clear code

P - protected code

both gain and hemispherical coverage are obtained. These antennas may or may not be of low profile and are usually expensive. Antennas providing relatively broad coverage have been designed for aircraft (reference 7) and small spacecraft (references 8 and 9).

In this report, the studies are confined to the design of simple, inexpensive antennas for general aviation and applications where accuracies of a few meters are adequate. The antenna must operate at 1575.5 MHz (L_1) and must provide adequate coverage when mounted on aircraft. Since the radiation patterns of antennas on aircraft may differ considerably from those in free-space, it is necessary to make measurements utilizing scale models of the aircraft of interest. Several of the antenna designs were evaluated at X-band using the one-seventh scale Lear jet model shown in figure 2. The following considerations were taken into account for the antenna designs:

1. Upper hemispherical coverage
2. Low cost
3. Low profile (height $\approx$ a few centimeters at L-band)
4. Circular polarization

Several antenna designs were evaluated to determine their potential for satisfying the above requirements (reference 10). The salient features of the various designs will be discussed and principal plane (i.e., elevation and roll) radiation patterns measured on a scale model Lear jet are presented. Detailed descriptions of the various antennas will be presented in later reports.

Experimental investigations were made of the following antennas at X-band,

1. Crossed-dipoles (turnstile)
2. Crossed-slots
    a. Half-wavelength
    b. One-wavelength
    c. Modified one-wavelength
    d. Edge
3. Microstrip

Photographs of the antennas are given in figure 3 and principal plane radiation patterns are presented in figure 4.

In addition to the microstrip antenna measured on the scale model at X-band, the following microstrip antennas were measured at S-band on a large ground plane.

1. Microstrip antennas
    a. Modified resonator
    b. Coupled resonator

Photographs of these antennas are shown in figure 5 and principal plane radiation patterns are presented in figure 6.

ANTENNA DESCRIPTION AND PERFORMANCE

Most of the antenna designs consist of basic antenna types (i.e., crossed-dipoles, crossed-slots, microstrip) some of which have been modified to improve the pattern coverage near the horizon. The crossed-dipoles consist of two orthogonal one-wavelength dipoles. Each dipole arm is a half-wavelength long with horizontal and vertical portions being equal. The height of the dipole above the ground plane is slightly greater than one-quarter wavelength to provide clearance between the ground plane and the vertical portions of the dipole arms. The initial design shown in figure 3(a) utilized wires, bent in the desired shape, for the four arms. The feed network was constructed from printed circuit board material. The elevation and roll plane patterns measured for this antenna, mounted on the Lear jet model at the location shown in figure 2, are presented in figure 4(a). Both E_θ and E_ϕ patterns are given. The final crossed-dipole design shown in figure 3(b) utilizes elements constructed from printed circuit board material. The elements have been reduced in size to compensate for the dielectric constant ($\varepsilon_r \approx 2.5$) of the material. The length of each dipole is now approximately one wavelength measured in the dielectric medium. The measured radiation patterns for this antenna design are given in figure 4(b).

The crossed-slot antenna designs, shown in figure 3(c), are cavity backed with the dielectric filled cavity depth being one-eighth wavelength instead of the usual one-quarter wavelength depth. The slots and feed network were constructed from printed circuit board materials. The slot designs included both one-half wavelength and one wavelength slots. A modified one wavelength design (figure 3(c)), in which the slots were curved in an attempt to improve the low angle H-plane (E_ϕ) coverage, was also investigated. The radiation patterns measured for the various cavity backed crossed-slot antennas on the Lear jet scale model are presented in figures 4(c)-4(e).

The crossed edge-slot design shown in figure 3(d), which is the complimentary slot version of the crossed-dipoles, was developed and measured on the Lear jet model. The radiation patterns obtained for this antenna are given in figure 4(f). The antenna elements and feed network were constructed from printed circuit board materials. The total length of each slot is approximately one-half wavelength measured in the dielectric medium. The feed lines are run through the dielectric and connected at the top of each slot.

The microstrip antenna (figure 3(e)) is a circular disk element operating in the TM_{11} mode. Other possible microstrip antenna designs are discussed in reference 11. The design evaluated here utilizes a disk with a diameter of approximately one-half wavelength measured in the dielectric. The disk is fed from the back with two probes located at one-third of the radius from the center for matching to 50 ohms and spaced 90 degrees apart to provide circular polarization. The two probes are excited from a printed circuit feed network mounted directly behind the antenna and designed to provide circular polarization. The measured radiation patterns for this antenna are shown in figure 4(g).

Normal microstrip antennas (e.g., figure 5(a)) have poor pattern coverage at wide angles (i.e., near horizon) as shown in figure 6(a). Some modified designs for improving this wide angle coverage were investigated at S-band. The first of these designs was modified by elevating it above the ground plane (figure 5(b)) on a dielectric spacer and reducing the diameter of the bottom conductor of the microstrip resonator as shown in figure 5(c). This should tilt the electric field at the edge toward the ground plane. The E-plane (E_θ) patterns obtained for this design mounted on a flat ground plane approximately 4.5 wavelengths square with curved absorber covered edges in the E-plane are presented in figure 6(b). The results obtained for several different bottom conductor diameters are presented. The different dimensions evaluated are shown on the figure. The second modified microstrip antenna design, the coupled resonator, is shown in figure 5(d). This design consists of three microstrip resonators, having slightly different resonant frequencies, that are stacked and fed through a common feed line. The electric field at the edge is distorted; however, the wide angle coverage is improved as indicted by the radiation patterns presented in figure 6(c). In addition to the improved wide angle coverage, some improvement in bandwidth was also observed.

PHYSICAL CHARACTERISTICS OF ANTENNAS

Two different types of printed circuit board materials were considered for the construction of the various full scale antennas. These materials were OAK Materials Group Inc!s, Atlantic Laminates Divisions FLUORGLAS copper clad laminate type E601/2 with a dielectric constant of 2.50 and the 3M Company's EPSILAM-10 ceramic filled Teflon compound having a dielectric constant of approximately 10. The approximate costs for two different thicknesses of each of these materials are presented in Table 3.

TABLE 3

PRINTED CIRCUIT BOARD MATERIALS COST

Material	Dielectric Constant, ε_r	Thickness, cm	Cost, dollars/cm^2
EPSILAM 10	10	0.254	0.67
EPSILAM 10	10	0.063	0.19
FLUORGLAS Copper Clad Laminate	2.5	0.254	0.06
FLUORGLAS Copper Clad Laminate	2.5	0.078	0.02

Typical dimensions of antennas designed for 1575.5 MHz are given in Tables 4 and 5. Table 4 presents the values for a material with a dielectric constant of 2.5 and Table 5 contains the values obtained for a material having a dielectric constant of 10. The heights given in Tables 4 and 5 include 0.76 cm (0.3 in) for the thickness of the feed network and radome. This thickness will probably be less for the antennas constructed from the material having a dielectric constant of 10; therefore, the overall antenna heights will be reduced accordingly. The tables provide approximate quantities of materials required to construct the various antenna types so a relative comparison can be made between them. An approximate materials cost can be obtained with this information and the data provided in Table 3. To obtain a total antenna cost, the cost of the feed network, radome and fabrication must be added to the materials cost. The crossed-dipole and crossed-slot designs are the most expensive and the microstrip is the least expensive.

TABLE 4

DIMENSIONS OF ANTENNAS FOR MATERIAL WITH DIELECTRIC CONSTANT OF 2.5

Antenna	Dimension, cm	Material Required, cm^2
Crossed-Dipole in Dielectric Medium	Height = 3.84 Length = 6.10 Width = 6.10 Material Thickness = 0.254	74.20
Crossed-Slot	Height = 2.32 Diameter = 10.16 Material Thickness = 0.254	243.22
Edge-Slot	Height = 3.56 Diameter = 7.56 Material Thickness = 0.078	42.00
Microstrip	Height = 1.01 Diameter = 6.40 Material Thickness = 0.254	31.50
Modified Microstrip	Height = 1.07 Diameter = 6.40 Material Thickness = 0.254	31.50
Coupled Microstrip	Height = 0.95 Diameter = 6.40 Material Thickness = 0.078	94.50

Frequency = 1575.5 MHz

Height - includes 0.76 cm for thickness of feed network and radome

TABLE 5

DIMENSIONS OF ANTENNAS FOR MATERIAL WITH DIELECTRIC CONSTANT OF 10

Antenna	Dimension, cm	Material Required, cm^2
Crossed-Dipole in Dielectric Medium	Height = 2.32 Length = 3.05 Width = 3.05 Material Thickness=0.254	18.53
Crossed-Slot	Height = 1.56 Diameter = 5.08 Material Thickness=0.254	63.67
Edge-Slot	Height = 2.18 Length = 3.78 Width = 3.78 Material Thickness=0.063	10.50
Microstrip	Height = 0.89 Diameter = 3.20 Material Thickness=0.127	7.90
Modified Microstrip	Height = 0.89 Diameter = 3.20 Material Thickness=0.127	7.90
Coupled Microstrip	Height = 0.95 Diameter = 3.20 Material Thickness=0.063	23.60

Frequency = 1575.5 MHz

Height - includes 0.76 cm for thickness of feed network and radome.

CONCLUDING REMARKS

All the antennas described in this report meet the GPS technical requirements to a large extent. They differ mainly in the wide angle or near the horizon coverage provided. The cross-dipole and edge-slot antennas provide good pattern coverage; however, they are not of the conformal type. The height may be kept to within a few centimeters by the use of a high dielectric constant material. The crossed-slots are of conformal type but may require that a hole be made in the aircraft fuselage for mounting. The slot assembly may also be mounted directly to the fuselage surface; however, then it may not have any advantages over some of the other antenna tupes. The modified and coupled microstrip antenna designs show promise and further investigation is needed to determine their full potential for GPS applications.

The choice of the antenna for general aviation aircraft will probably be made based on cost. The microstrip designs and the edge-slot appear to be the cheapest and the crossed-slot designs the most expensive. Recent microstrip antenna designs that provide circular polarization with a single input, without the use of the normal phase shifter and power divider, look very promising. If these designs can satisfy the bandwidth and pattern coverage requirements, they can be constructed very inexpensively.

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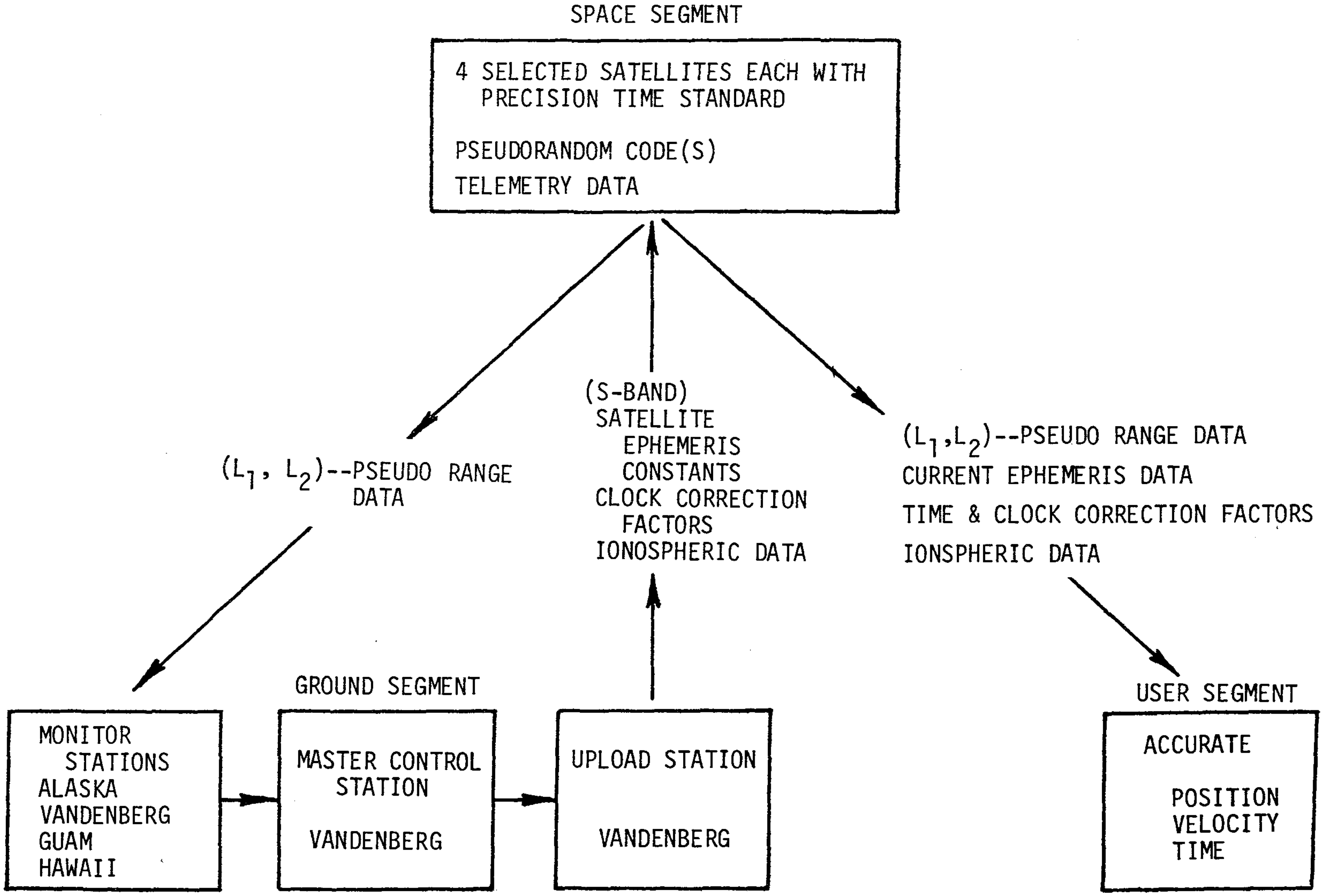


Figure 1. Overall GPS system concept (Ref. 1).

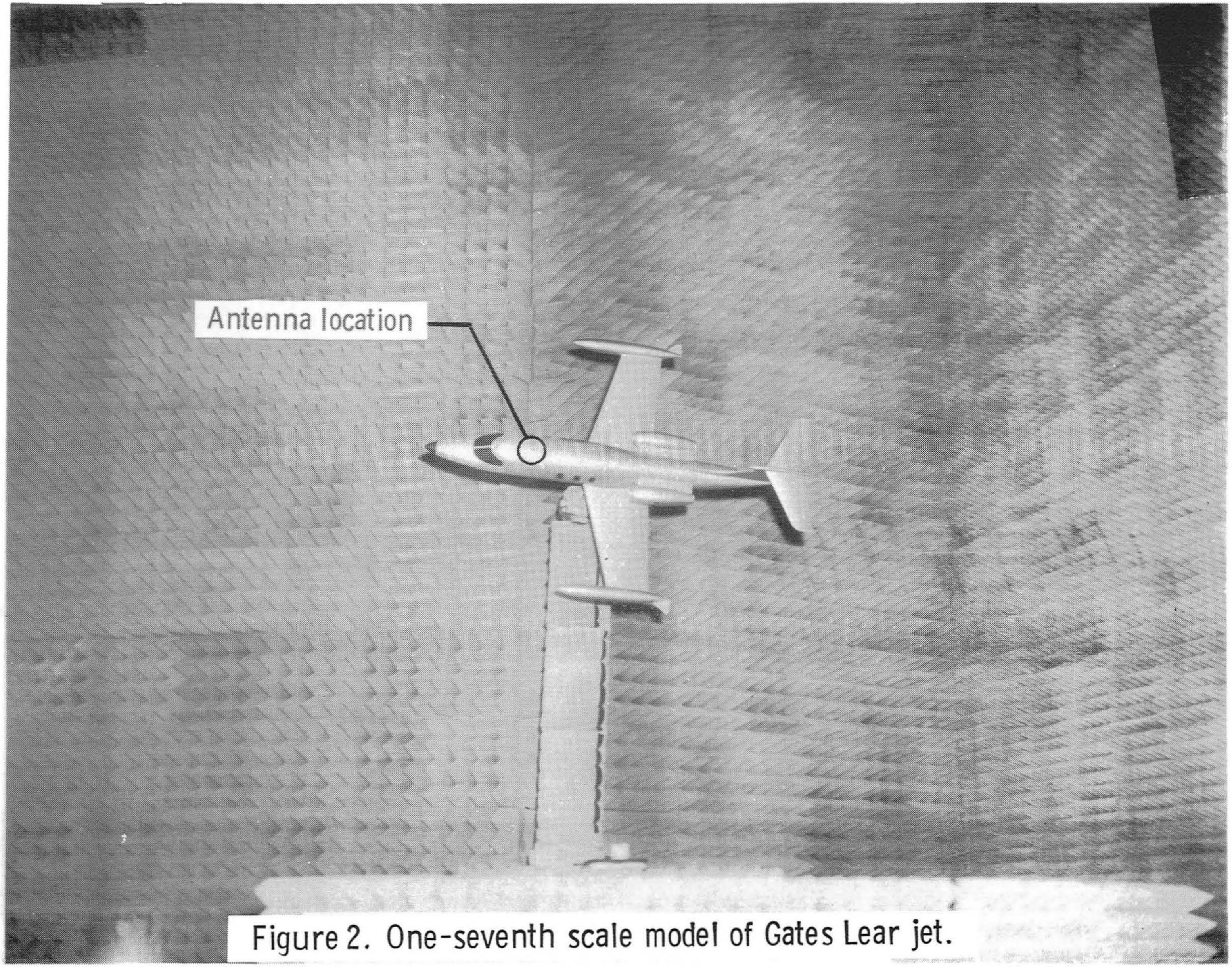
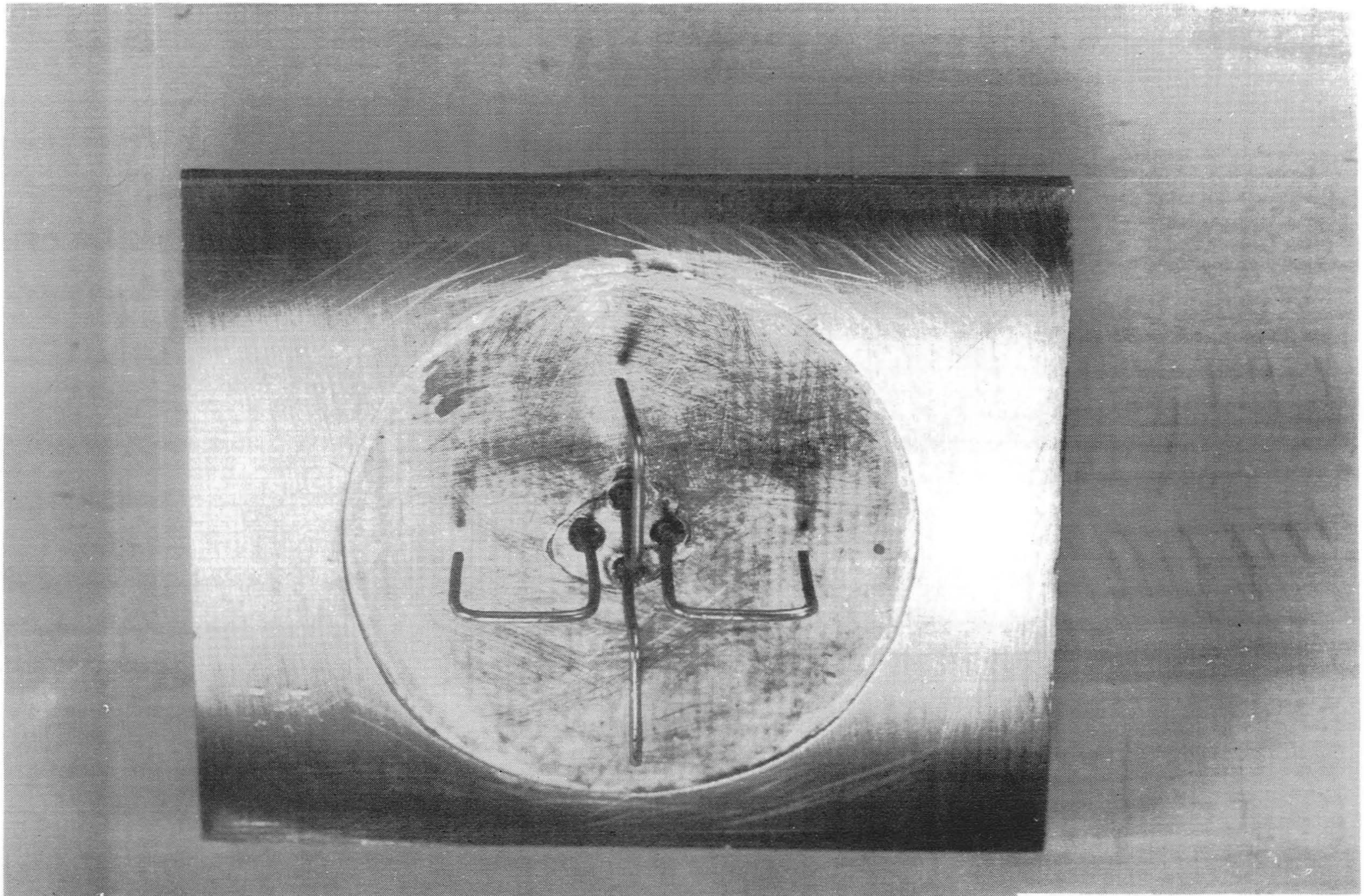


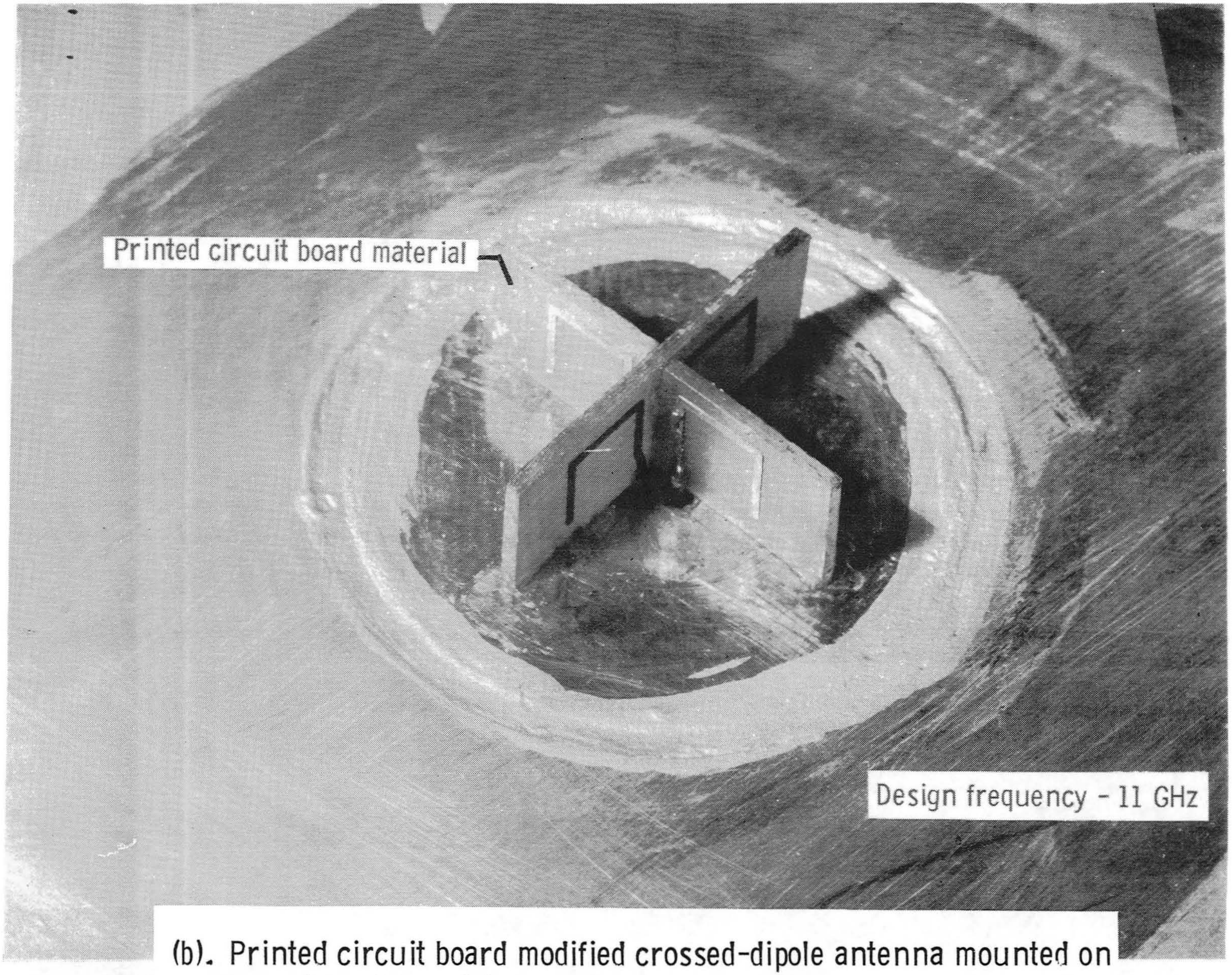
Figure 2. One-seventh scale model of Gates Lear jet.



Design frequency-11GHz

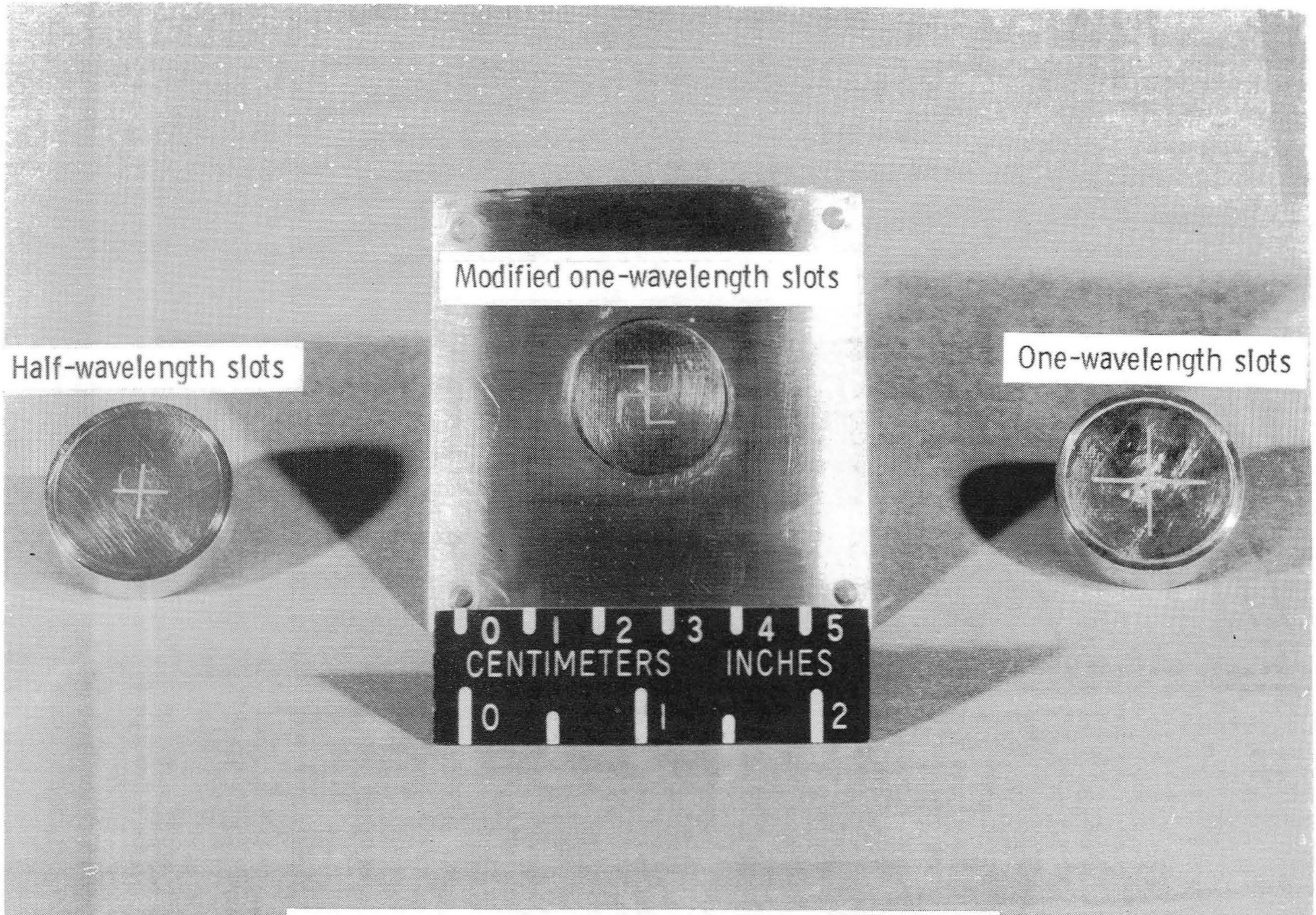
(a). Modified crossed-dipole design.

Figure 3. Photographs of GPS antenna designs.



(b). Printed circuit board modified crossed-dipole antenna mounted on Gates Lear jet model.

Figure 3. Continued.

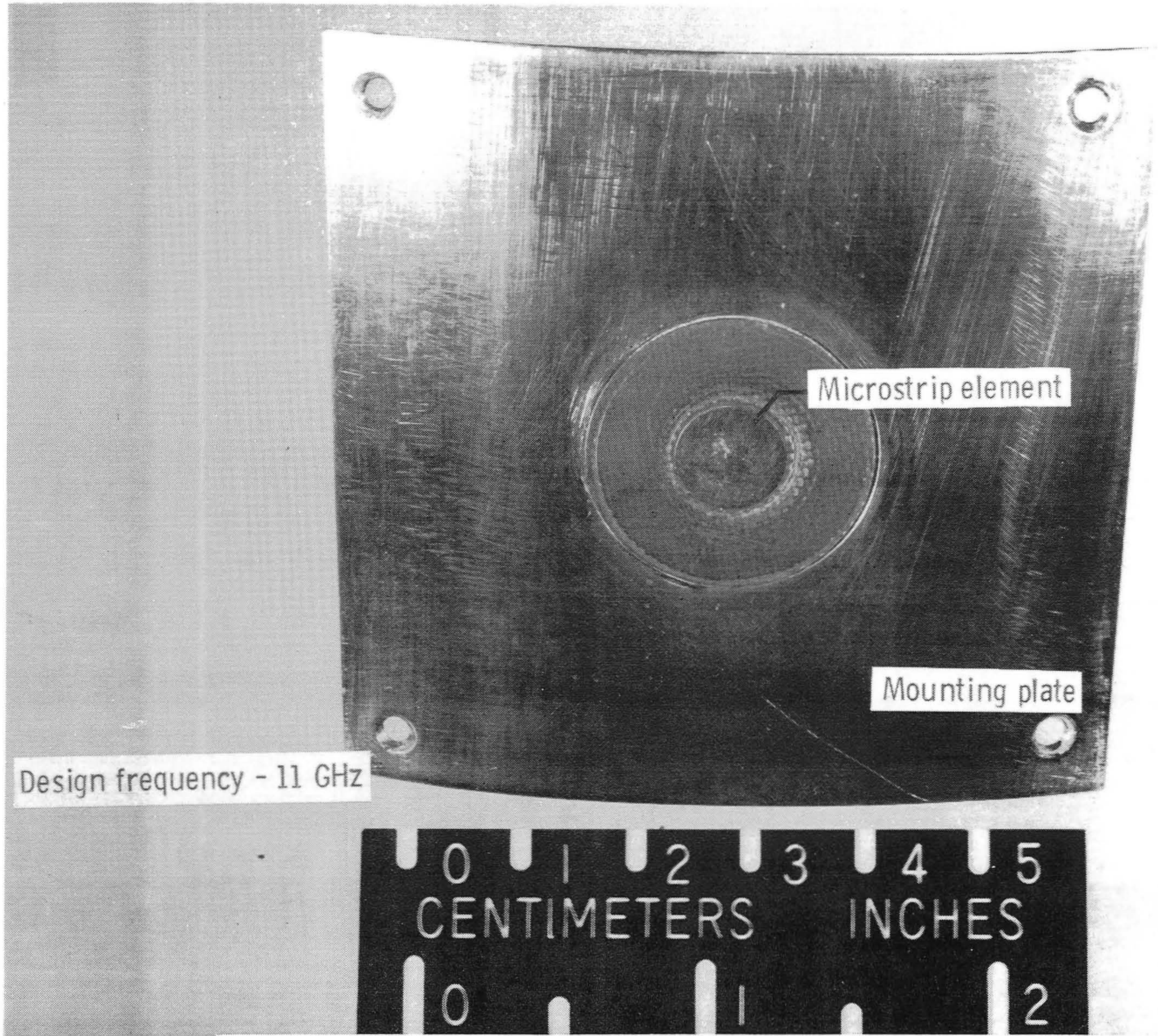


(c). Crossed-slot antenna designs.

Figure 3. Continued.

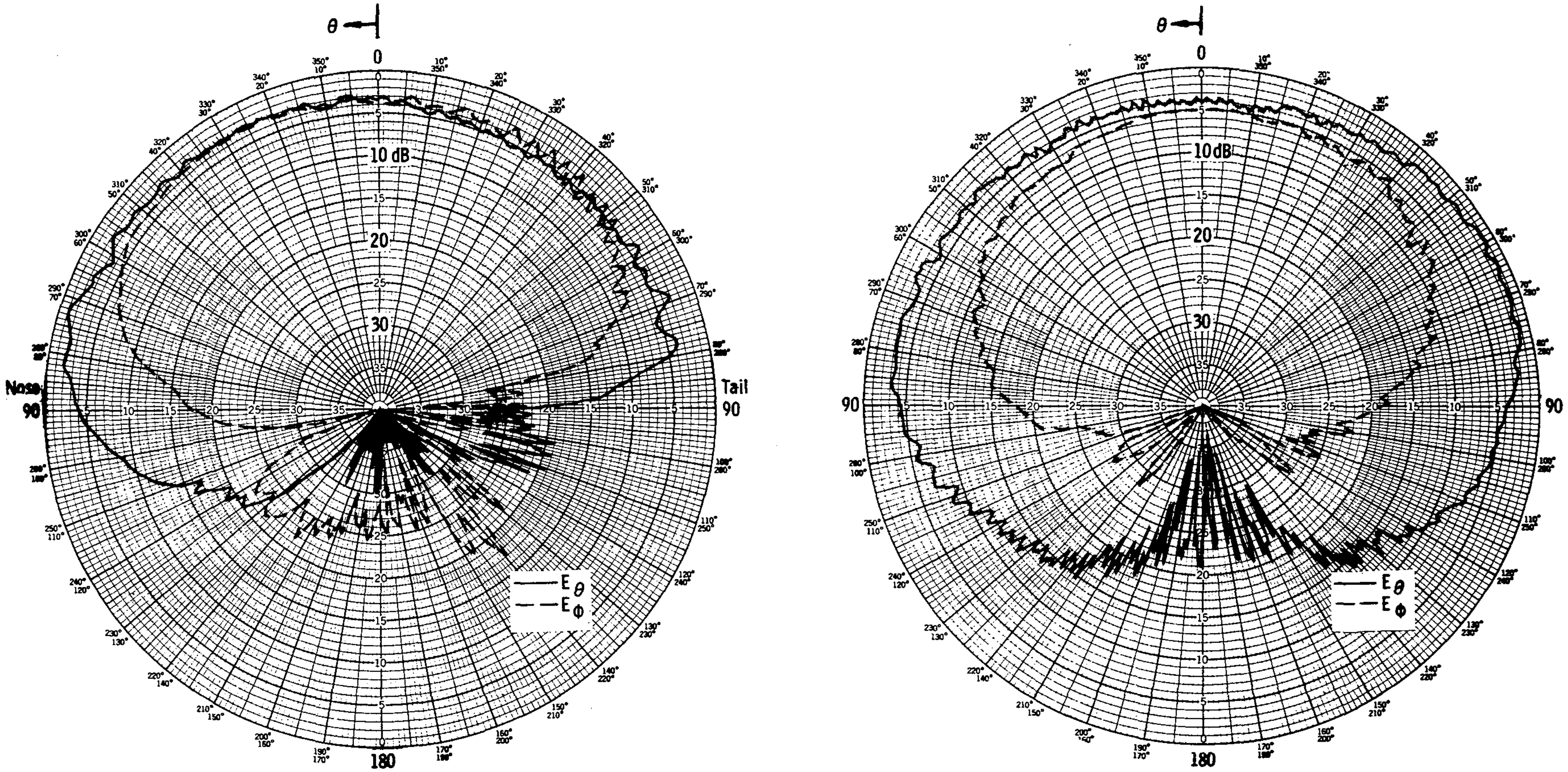
(d). Crossed-edge slot antenna mounted on Gates Lear jet model.

Figure 3. Continued.



(e). Microstrip disk antenna design.

Figure 3. Concluded.

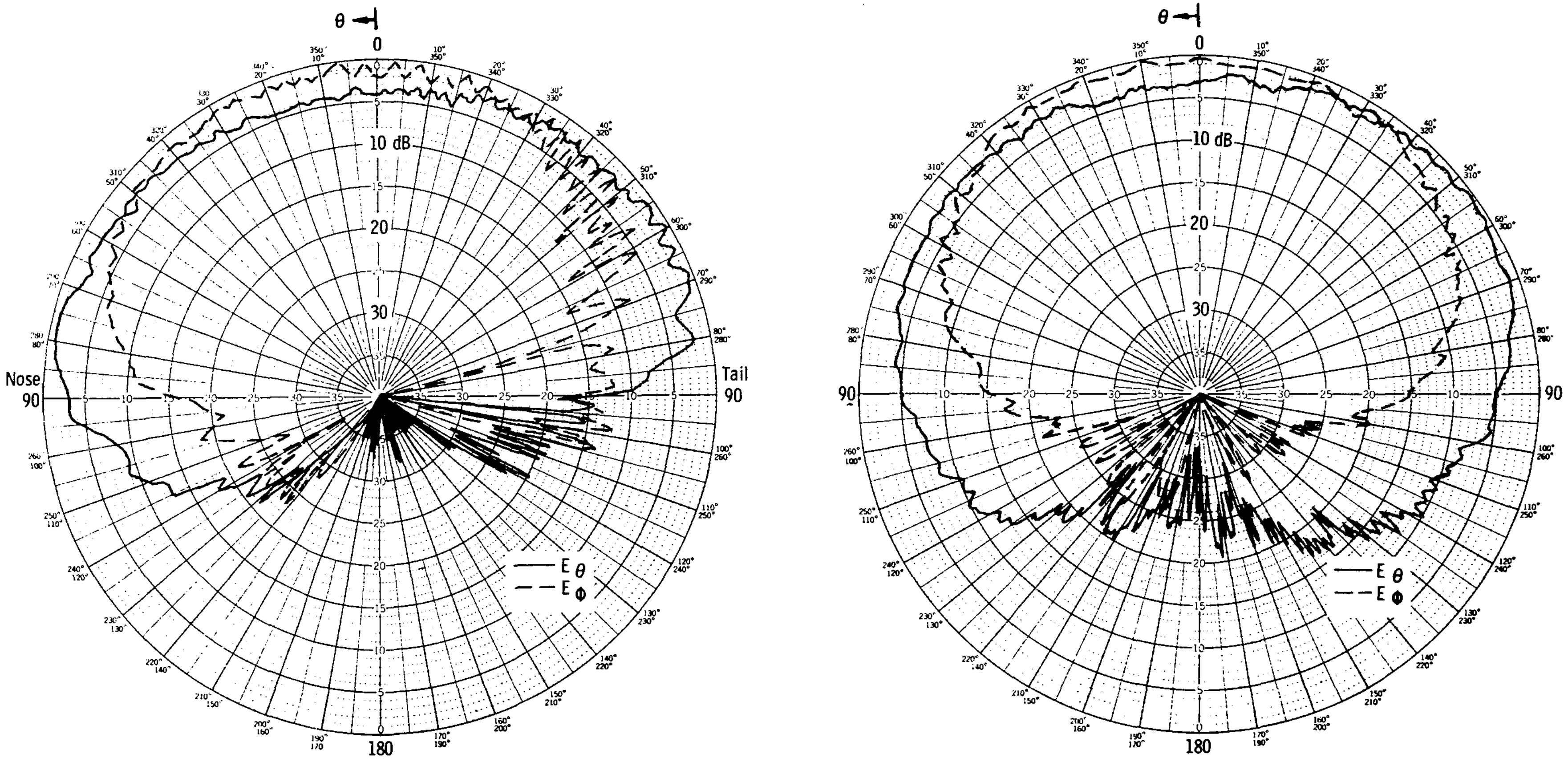


Elevation plane

Roll plane

(a). Modified crossed-dipole design.

Figure 4. Radiation patterns of GPS antenna designs measured on one-seventh scale model of Gates Lear jet.

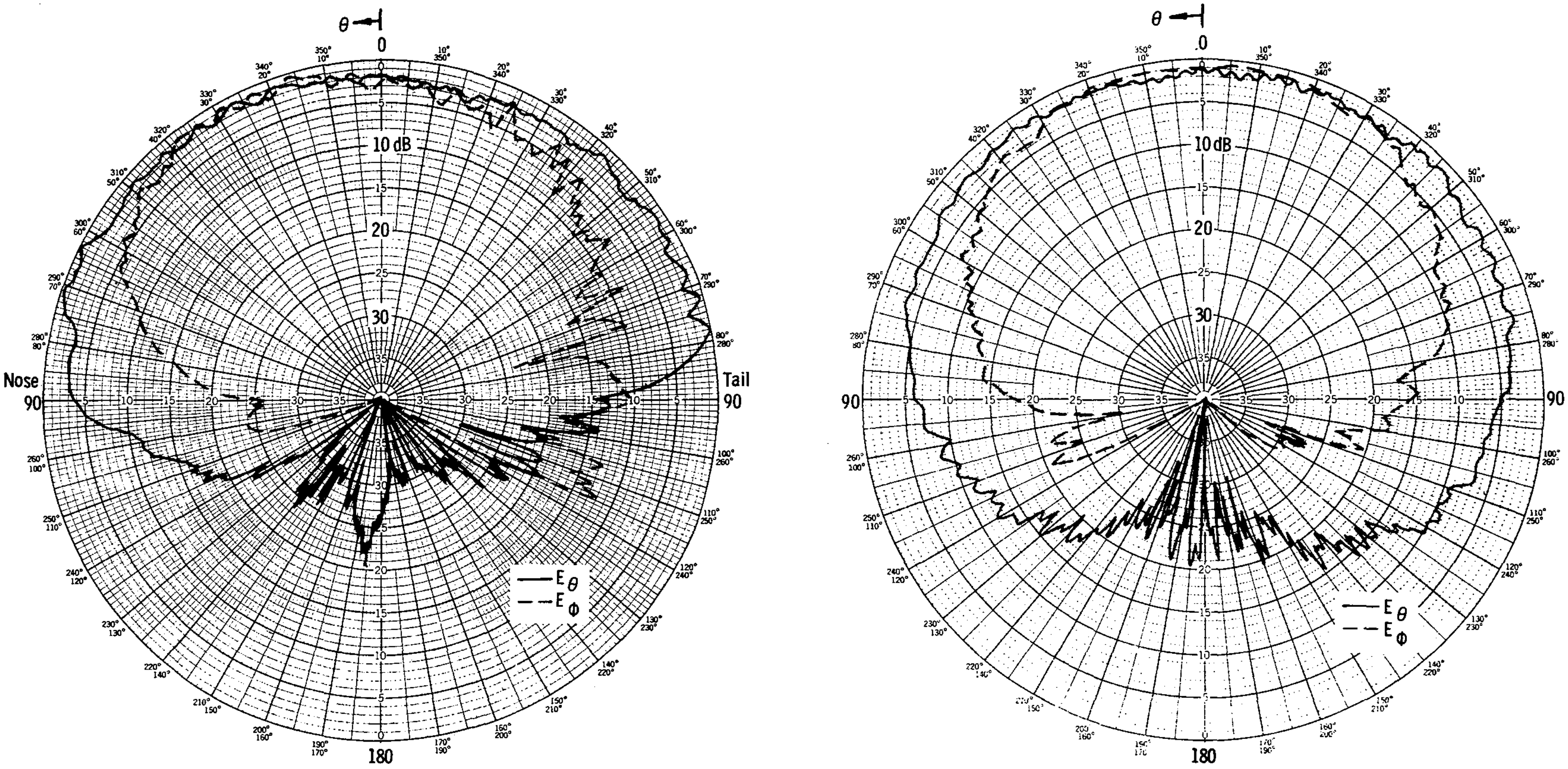


Elevation plane

Roll plane

(b). Printed circuit board modified crossed-dipole antenna.

Figure 4. Continued.

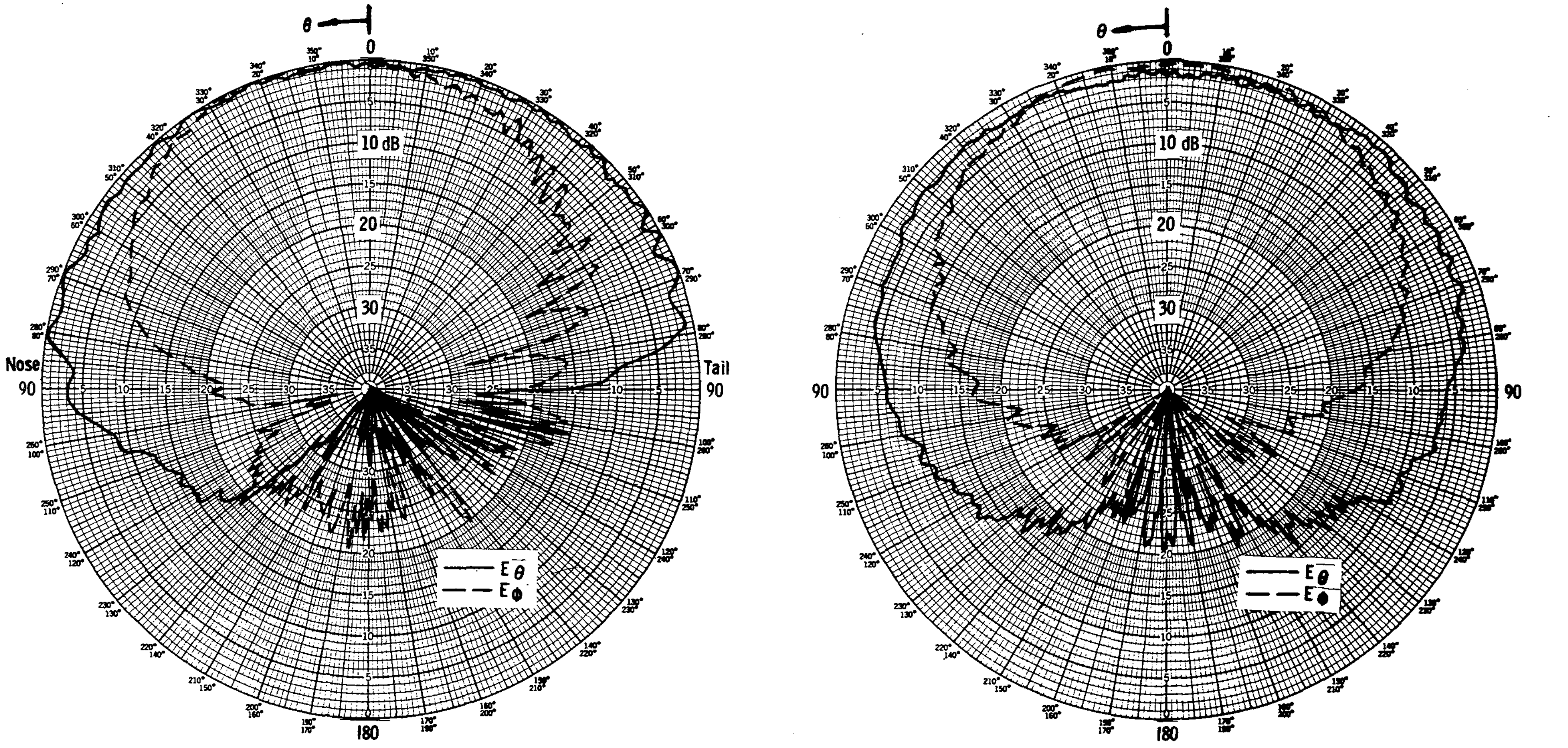


Elevation plane

Roll plane

(c). Half-wavelength crossed-slot antenna.

Figure 4. Continued.

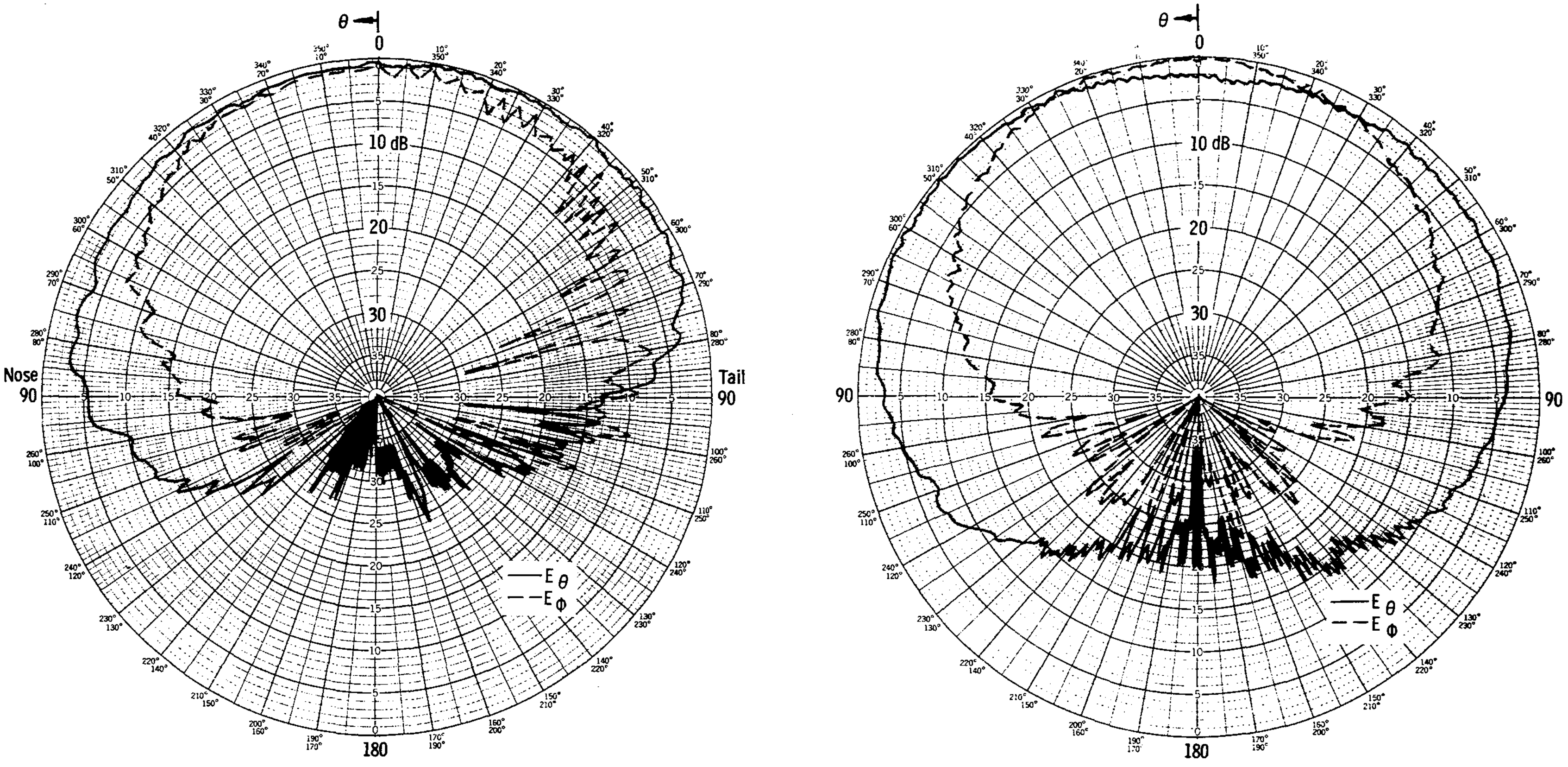


Elevation plane

Roll plane

(d). One-wavelength crossed-slot antenna.

Figure 4. Continued.

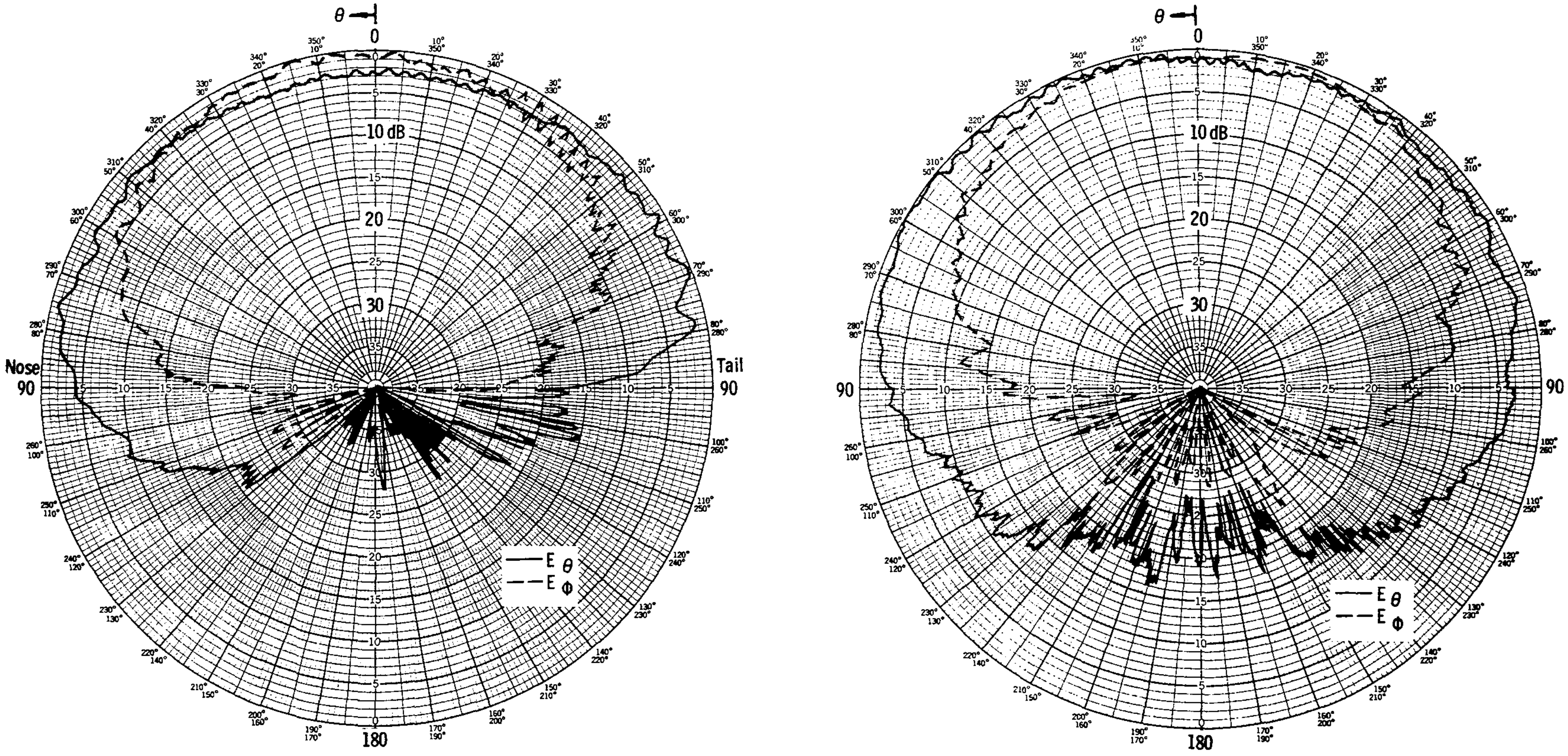


Elevation plane

Roll plane

(e). Modified one-wavelength crossed-slot antenna.

Figure 4. Continued.

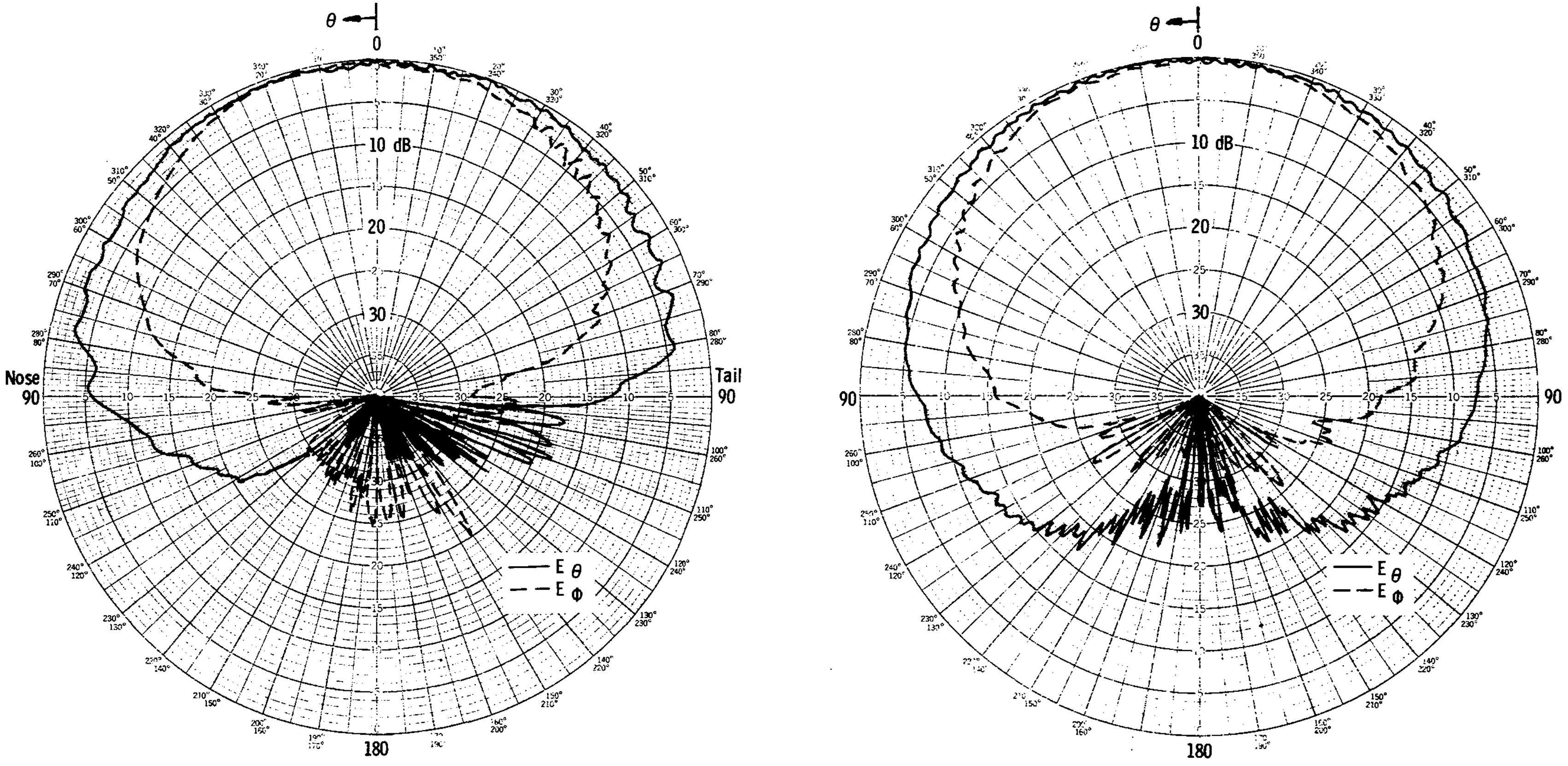


Elevation plane

Roll plane

(f). Crossed-edge slot antenna.

Figure 4. Continued.

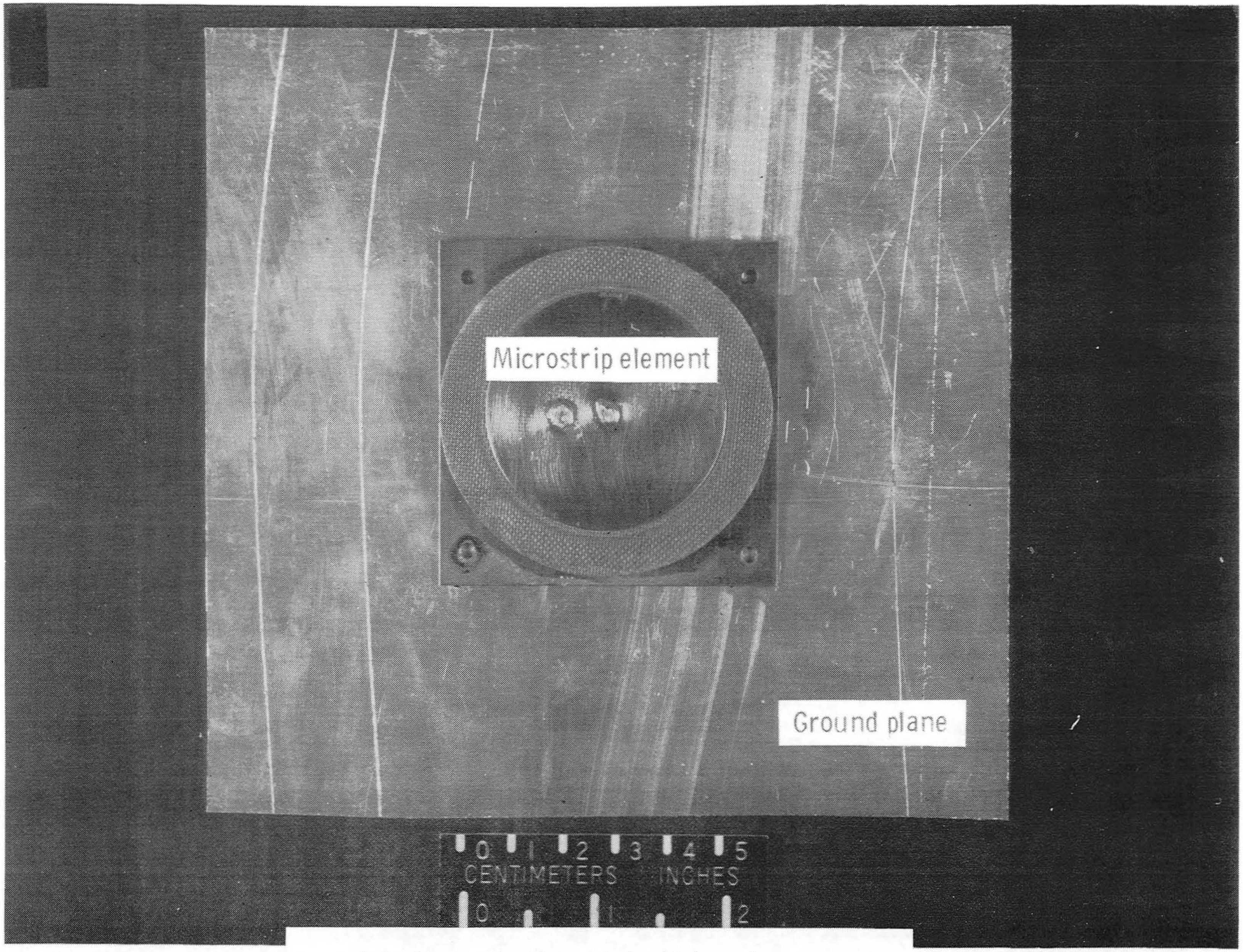


Elevation plane

Roll plane

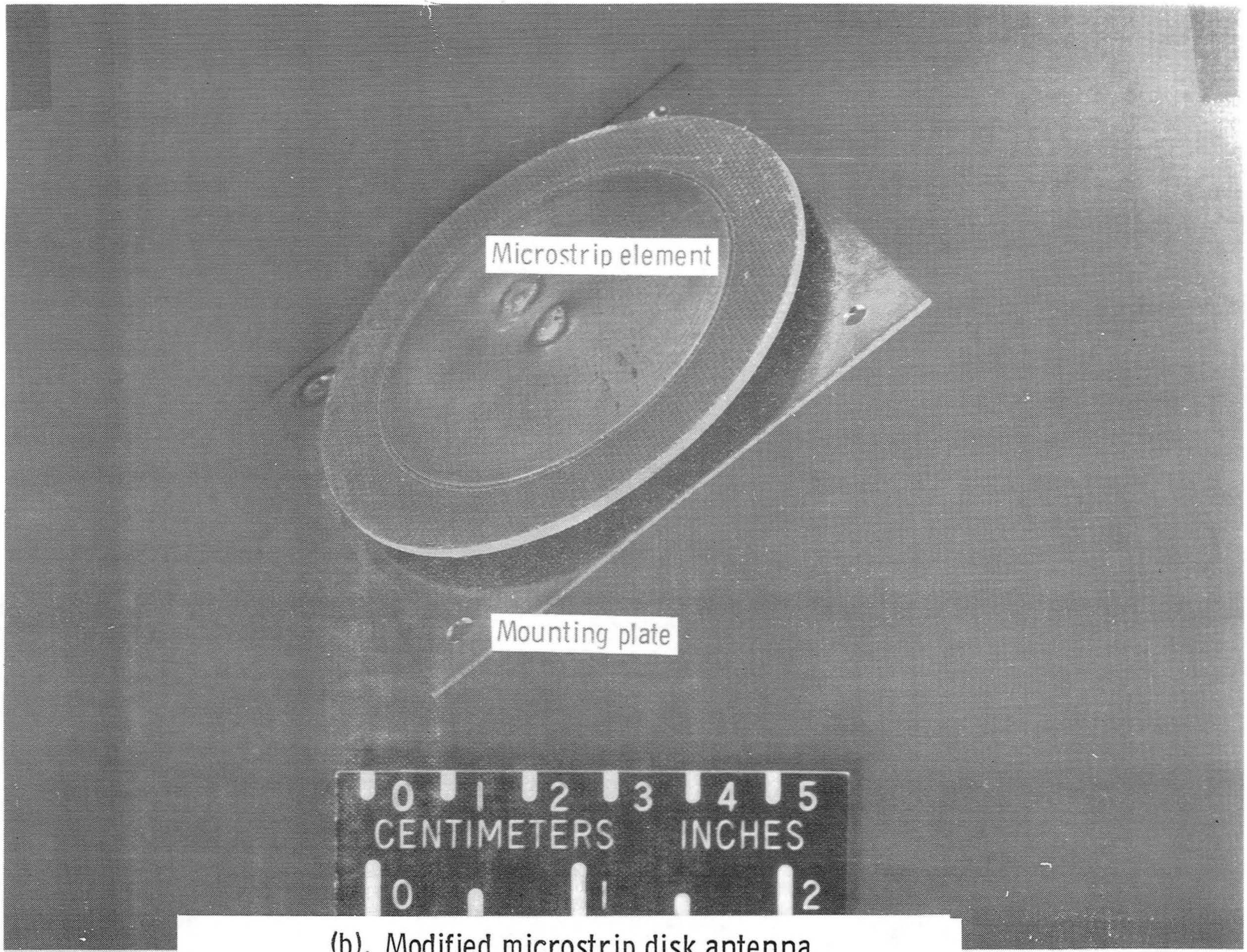
(g). Microstrip disk antenna.

Figure 4. Concluded.



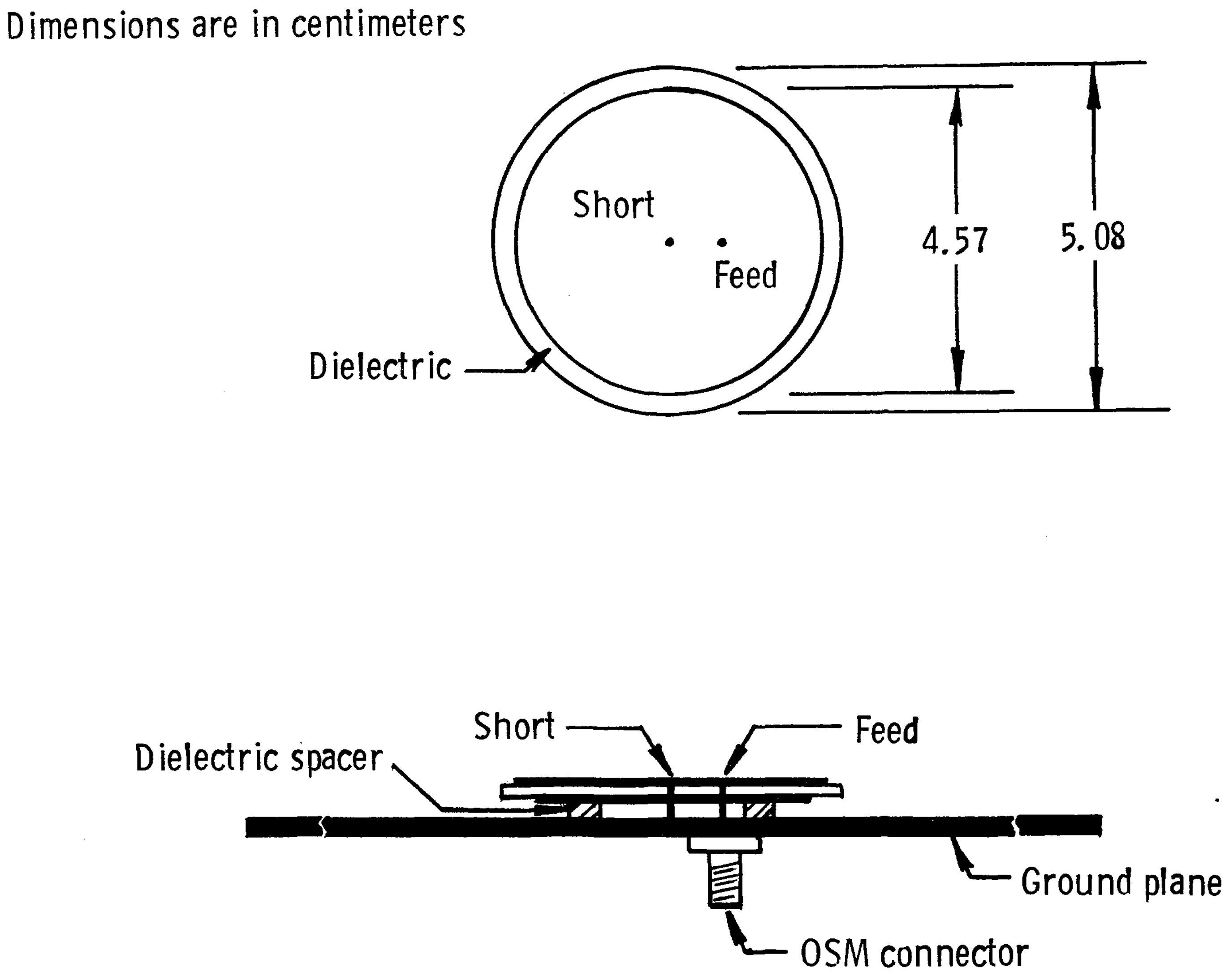
(a). Normal microstrip disk antenna.

Figure 5. S-band microstrip antennas.



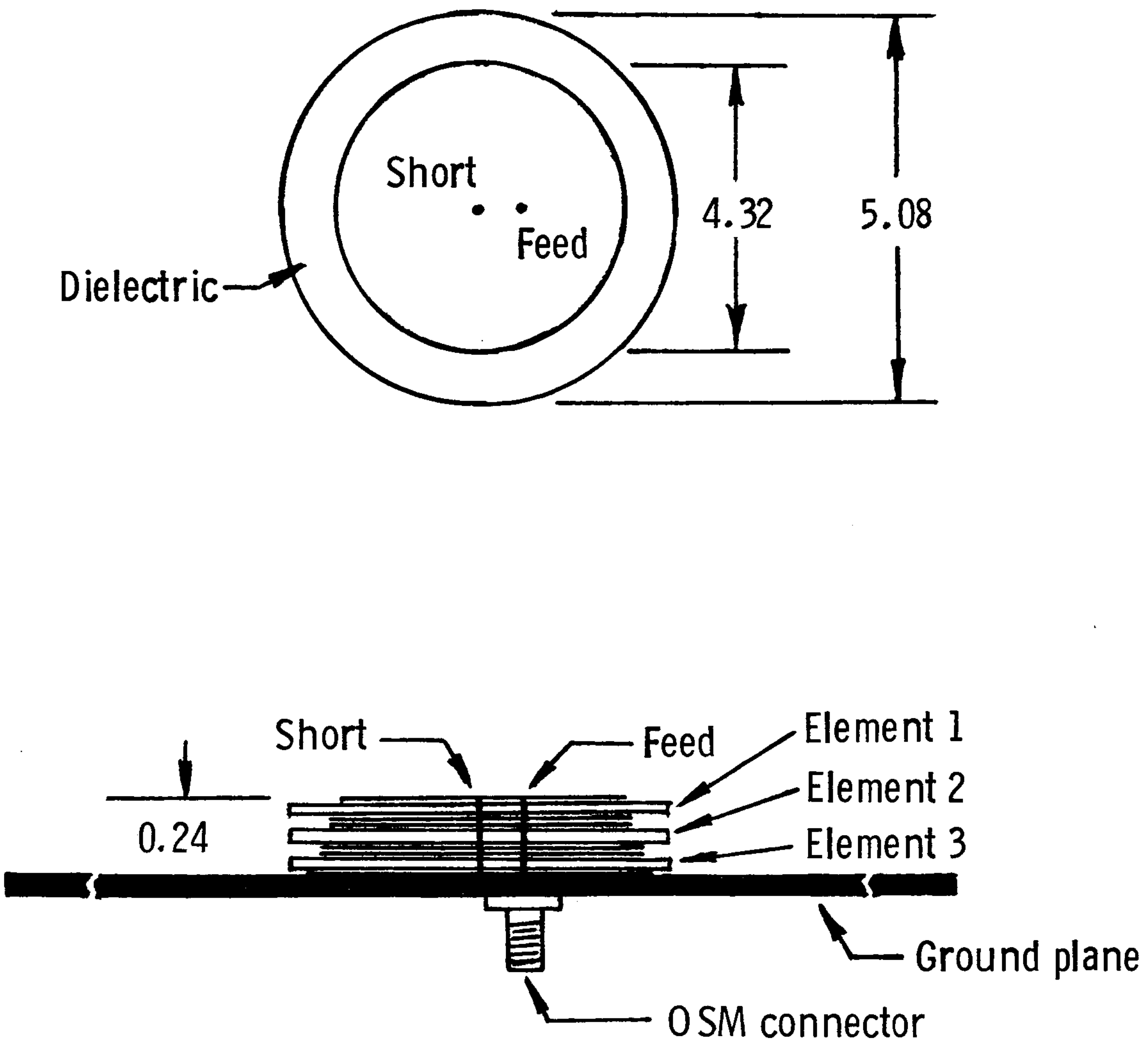
(b). Modified microstrip disk antenna.

Figure 5. Continued.



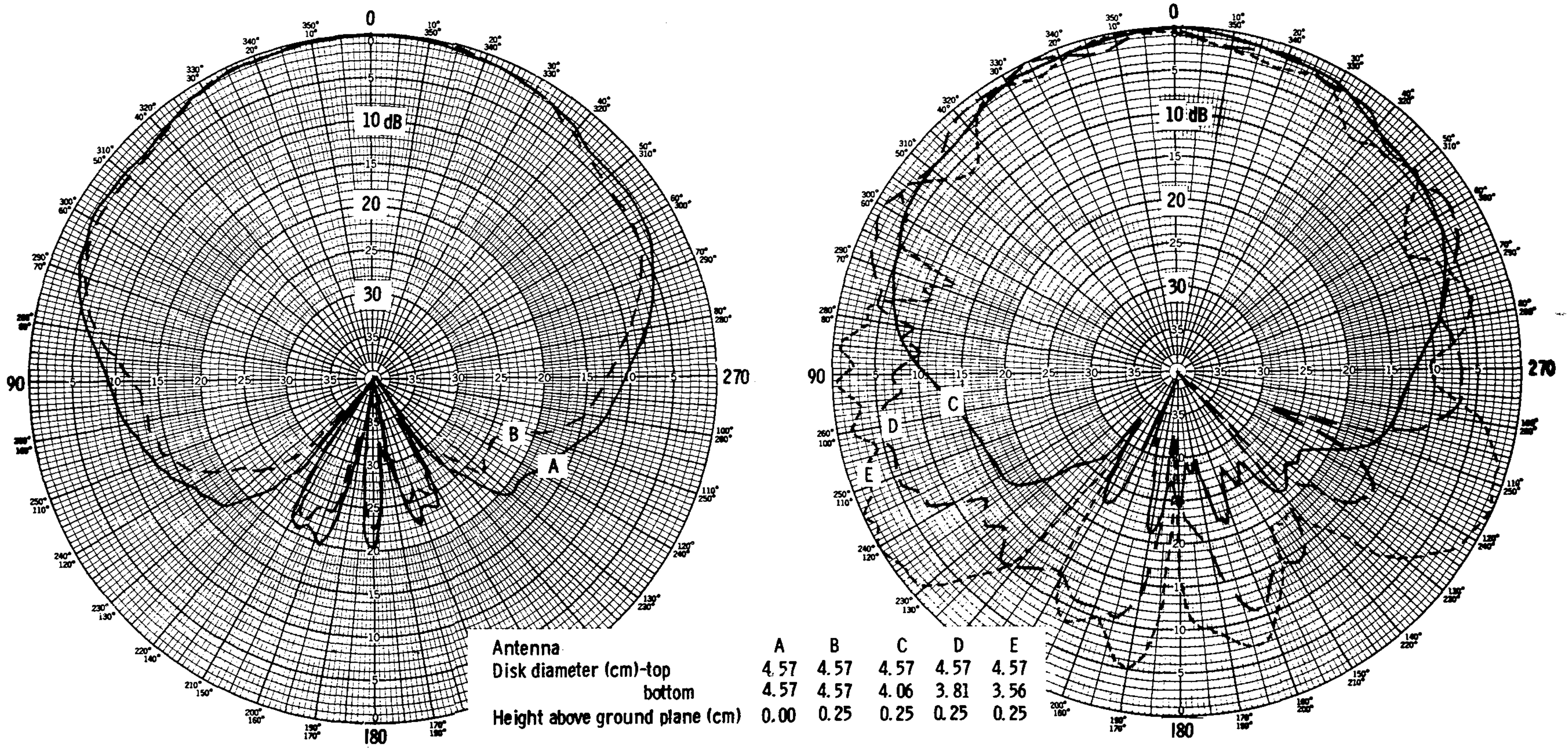
(c). Sketch of modified microstrip disk antenna.

Figure 5. Continued.


Dimensions are in centimeters

(d). Sketch of coupled circuit microstrip antenna.

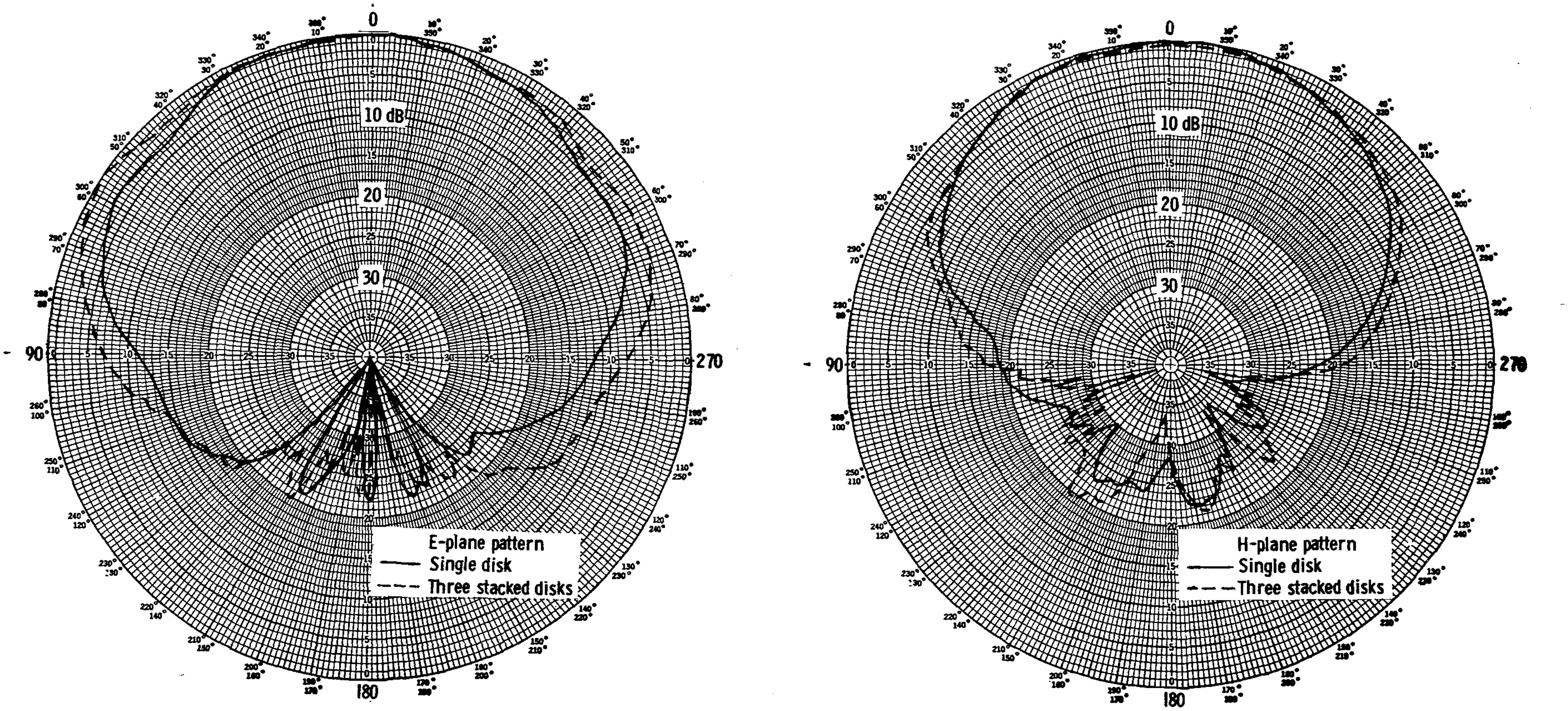
Figure 5. Concluded.



Antenna	A	B	C	D	E
Disk diameter (cm)-top	4.57	4.57	4.57	4.57	4.57
bottom	4.57	4.57	4.06	3.81	3.56
Height above ground plane (cm)	0.00	0.25	0.25	0.25	0.25

(a). E-plane patterns of modified microstrip antenna as a function of height above ground plane.

Figure 6. Radiation patterns of S-band microstrip antennas mounted on a curved ground plane.



(b). E- and H-plane patterns of coupled circuit antenna compared with normal microstrip antenna.

Figure 6. Concluded.

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16. Abstract
The NAVSTAR Global Positioning System (GPS) is a sophisticated satellite navigation system which has the potential for meeting the needs of a wide range of users. With some sacrifice in accuracy, it is possible to reduce the cost of the equipment at the user end and make it attractive for general aviation aircraft applications. The purpose of this study was to evaluate several antenna designs that might be acceptable for use on general aviation aircraft in a low cost system. Experimental investigations were made of crossed-dipoles, various types of crossed-slots, and microstrip antennas with modifications to improve the coverage. Principal plane radiation patterns for several of these antennas measured on a one-seventh scale model of a Gates Lear jet are presented.

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