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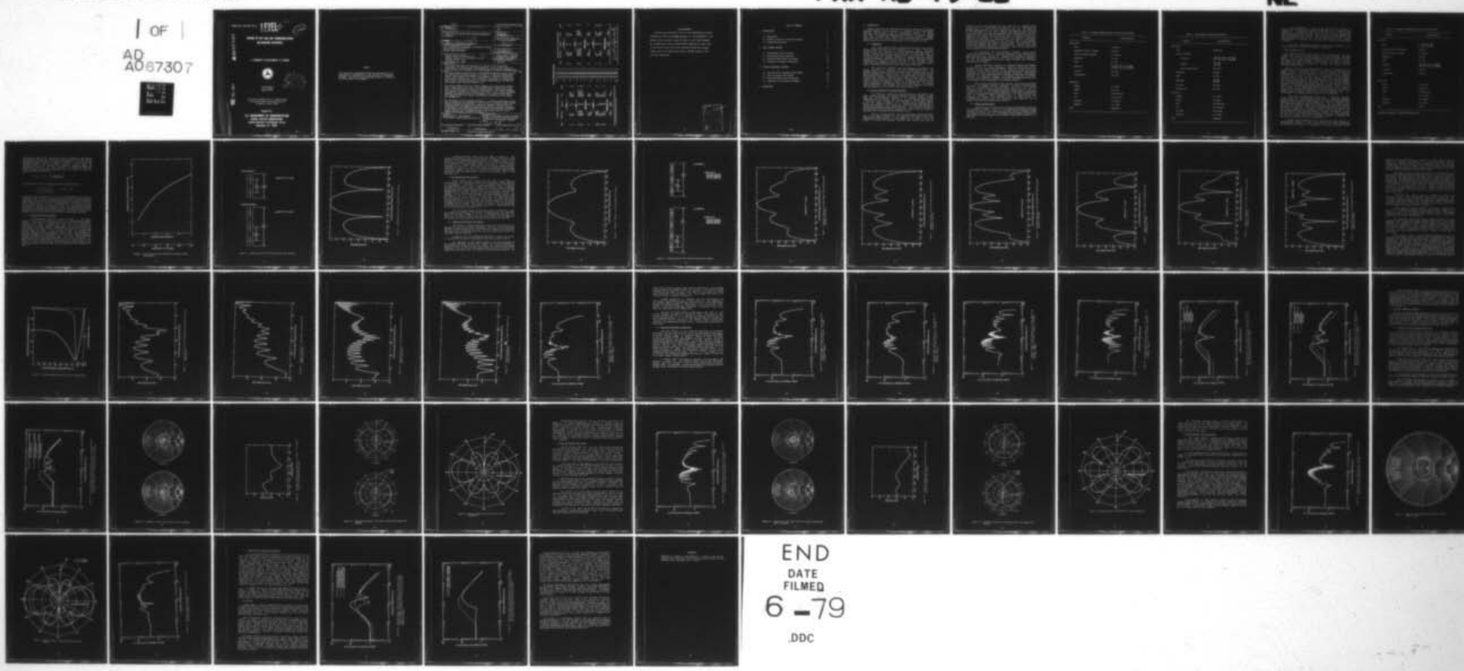

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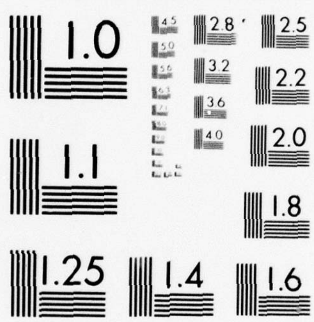
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Report No. FAA-RD-79-22

LEVEL II

DESIGN OF VHF AND UHF COMMUNICATIONS AIR/GROUND ANTENNAS

F. FARRAR, D. SCHAUBERT, H. JONES

Final Report
March 1979

Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161.

Prepared for

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FEDERAL AVIATION ADMINISTRATION
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15. Supplementary Notes

This study requirement was generated in response to FAA operational requirements for updating and standardizing the design and performance of field antennas used throughout the United States in air/ground communications.

16. Abstract

The Harry Diamond Laboratories has investigated contemporary design concepts are investigated for improved ground-based antennas to be used in air/ground communication links. These concepts are based on requirements to maintain satisfactory and reliable communications - with coincident constraints of reduced transmitter power, handling tolerances, and design standardization for VHF and UHF antenna types, mounting brackets, etc.

The study determined that four antenna designs will satisfy these requirements. Each design will cover a full communications frequency band, and will also provide improved radiation characteristics. The design findings and candidate antennas are reviewed in this report. Much of the preliminary detailed investigation work is incorporated in the interim design report, also prepared under this effort, and published in February 1979 as Report No. FAA-RD-79-7.

The performance of the candidate antennas in a simulated operational environment is calculated and presented for several sets of conditions which closely resemble operational applications. While the analyses indicate that the predominant FAA requirements are satisfied by antennas presently available to the Agency, very significant gain deficiencies were detected in multiple-element antennas and are apparently due to the ferrite material used to achieve inter-element electrical isolation.

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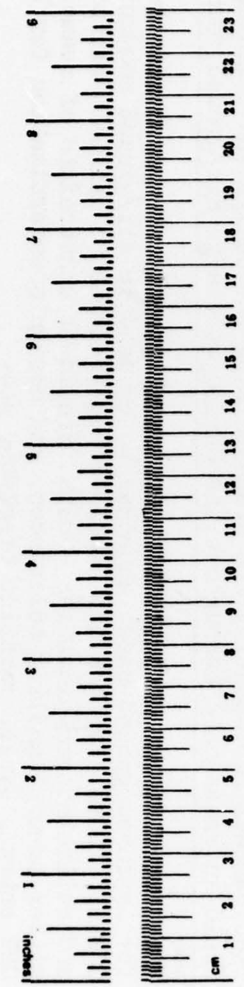
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

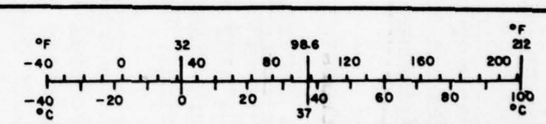
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



Acknowledgement

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TABLE OF CONTENTS

1. INTRODUCTION

Design concepts for new VHF and UHF air/ground communications antennas have been studied. The new antennas are intended for use by the Federal Aviation Administration (FAA) as standardized equipment at ground facilities of air/ground communications operations. The antenna designs have been evaluated and compared with existing antennas. Primary importance has been placed upon electrical and mechanical performance, while meeting the practical considerations of size, weight, and cost.

1.1 Background

Voice communications between ground-based controllers and aircraft pilots during air traffic control operations is by radio. The radio communications link operates on a double sideband, amplitude modulated carrier in either the VHF band of 118 to 136 MHz or the UHF band of 225 to 400 MHz with allocated channels separated by 25, 50, or 100 kHz. Channels in the VHF band are intended primarily for communications with civilian aircraft--government, commercial, and general aviation. Military aircraft communicate on channels in either the VHF or the UHF band. Since controllers must communicate with all aircraft in each assigned airspace sector, simultaneous VHF and UHF radio links must be provided.

Two distinctly different types of antennas are required at the ground facilities to establish the radio communications link. The omnidirectional antenna is the most prevalent type of antenna since it can provide communications coverage over a very large airspace sector without directional preference. Where aircraft are constrained to fixed air routes or where high effective radiated power (ERP) is required over a certain portion of the airspace sector, directional antennas are employed. Both types of antennas are typically located on 19-m-high towers for en route control operations, although some towers are as high as 28 m. For terminal control operations, the antennas may be located on smaller, 13-m towers near the runways or on the roof of the airport control cab.

1.2 General Criteria for Improved Antennas

The important criteria for improved electrical performance from these antenna concepts are complete radiation pattern coverage, antenna gain, and full-bandwidth operation. To provide continuous radio communications, the antennas must provide adequate radiated power density or electric field strength at all locations in the assigned airspace sector. The radiation patterns of the omnidirectional antennas must be sufficiently uniform in all directions around and above the antennas to provide the necessary radiated power density. The radiation patterns of the directional antennas must be sufficiently uniform only in a specific direction over a much more limited airspace sector.

Both the omnidirectional and the directional antennas must have gain in the angular portion of the radiation pattern that is in use for communications with aircraft at long ranges and at angles low to the horizon to provide the necessary radiated power density and thus an acceptable, noise-free communications link. Gain from an omnidirectional antenna may at first seem in violation of the definition--an omnidirectional antenna is one that radiates uniformly over all space and is by definition of zero gain. However, the omnidirectional antennas discussed in this report radiate uniformly in the azimuth plane only, with substantial gain roll-off in the elevation plane. A vertical dipole is an example of an antenna that gives gain--2.1 dB relative to isotropic (dBi)--yet is classified as omnidirectional in the context of this study. Decreased gain and nonuniformity in the vertical plane of the radiation pattern are acceptable over angular portions where the aircraft is high overhead and therefore much closer to the radio site. However, deep, broad nulls in the radiation pattern are undesirable since they can cause holes in the coverage of the communications system.

The requirement for full-bandwidth operation places severe restrictions on the choice of radiating elements, but this requirement is important for the FAA. The use of a single antenna design for the entire VHF or UHF band greatly reduces the inventory and logistical problems of the FAA, and it eliminates the need to change antennas when operating frequencies are changed.

The most important criterion for improved mechanical performance is the ability of these antennas to perform electrically without degradation in the operational environment. Since most of the antennas are located on towers fully exposed to the extremes of weather and in many situations at radio sites far from maintenance personnel, environmental durability and long maintenance-free lifetime are important requirements affecting the mechanical designs. Wind loading during icing, vibration, moisture, and temperature extremes are specific environmental factors that are considered in the development of the design concepts.

Other criteria considered in the design of the improved antennas are these: (1) impedance and gain bandwidth, (2) VSWR, (3) maximum input power, (4) polarization, (5) size, (6) weight, and (7) unit cost. Certain peripheral criteria, though not antenna design criteria per se, also are considered since it is sometimes possible to adjust antenna performance factors that will maximize overall performance of the radio communications link. The peripheral effects considered are (1) isolation from other antennas, (2) influence and shadowing effects of nearby towers, (3) vulnerability to static, power line transients, and lightning, and (4) ground reflections and multipath interference.

1.3 Design Specifications

Omnidirectional and directional antennas were designed to meet the specifications in tables 1 and 2. The omnidirectional antenna designs consisted of three or four dipole-type elements inside a fiberglass radome and support structure [1]. The directional antenna designs consisted of a yagi antenna for the VHF band and a pyramidal log-periodic antenna for the UHF band.

Table 1. Original omnidirectional antenna specifications

Property	Specifications
Electrical	
Gain	5 dBi min
Azimuthal pattern coverage	Uniform
Vertical pattern maximum	At horizon
Impedance	50 ohms
VSWR	2:1 max
Bandwidth	14% VHF (118 to 136 MHz) 56% UHF (225 to 400 MHz)
CW power	50 W max
Polarization	Vertical
Mechanical	
Height	6.1 m max
Weight	9 kg max
Wind	157 km/hr max
Ice	1.25 cm max
Altitude	3.8 km max
Humidity	5 to 100%
Cost	$1000 max

Table 2. Directional antenna specifications

Property	Specifications
Electrical	
Gain	10 dBi min
Pattern Coverage	
Elevation	~50° VHF (118 to 136 MHz) ~45° UHF (225 to 400 MHz)
Azimuth	~65° VHF ~58° UHF
Front-to-back ratio	18 dB min
Impedance	50 ohms
VSWR	2:1 max
Bandwidth	14% VHF 56% UHF
CW power	50 W max
Polarization	Vertical
Mechanical	
Length	6.1 m max
Weight	9 kg max
Wind	157 km/hr max
Ice	1.25 cm max
Altitude	3.8 km max
Humidity	5 to 100%
Cost	$1000 max

The performances of these antenna designs were analyzed by computer and the results were presented to the FAA in the interim design report [1]. Subsequently, HDL was instructed not to continue the development of directional antenna designs. Also, the design requirements for the omnidirectional antennas were changed as shown in table 3. The gain requirement was reduced to a value consistant with the reduced aperture size. The reduced height and weight will make the antennas easier to install.

The new, reduced-size antenna designs are described in the following section, and their performances are analyzed.

2. FINAL ANTENNA DESIGNS

The radome-supported linear phased array design concept has been retained for the reduced-size antennas. The dipole elements, isolation chokes, feed network, and interconnecting cables are fixed in potting material inside a small-diameter fiberglass tube that supports the array. The number of dipole elements, their spacing, and their excitation amplitudes and phases are adjusted to optimize the designs for each operating frequency band.

Gains of 4.3 dBi over the VHF band and 4.5 dBi over the UHF band at the maximum level in the radiation pattern are obtained by vertically arraying dipole antennas. The large vertical aperture produces the gain by narrowing the radiation pattern in the elevation plane. However, sufficient gain in the vertical plane is maintained to give adequate effective radiated power for good communications with aircraft overhead. The antennas are designed to produce the required gain at the low frequency end of the band; because the electrical size of the antenna aperture increases with frequency--the physical aperture is fixed--the gain can be expected to increase slightly with increasing frequency. This effect is more evident in the UHF antenna design because of the large frequency range--225 to 400 MHz--of the UHF band. A 2:1-VSWR impedance match to a 50-ohm system is needed to minimize loss in gain (0.5-dB loss for a 2:1 VSWR mismatch) and minimize power reflected to the transmitter.

The above specifications are met over a 14-percent bandwidth around 127 MHz for the VHF antenna design and over a 56-percent bandwidth around 313 MHz for the UHF antenna design. Since some gain omnidirectional antennas may be connected to 50-W transmitters, 50-W of continuous wave (CW) input power handling capability is provided. This requirement impacts the choice of components such as power dissipating resistors in the feed network of the antennas. Vertically polarized radiation is required from all ground communications antennas to match the polarization of the aircraft antennas and to mitigate vertical lobing of the radiation pattern due to multipath reflections from the ground. (There is a slight advantage in that the ground reflection coefficient in general is smaller for vertical polarization than it is for horizontal.)

A maximum aperture height of 4.3 m is the practical limit imposed on the mechanical design. At VHF, this aperture size limits the maximum theoretical gain available to approximately 5.8 dBi. When losses in the

Table 3. Revised omnidirectional antenna specifications

Property	Specifications
Electrical	
Gain	4.3 dBi min VHF* 4.5 dBi min UHF*
Azimuthal pattern coverage	Uniform
Vertical pattern maximum	At horizon
Impedance	50 ohms
VSWR	2:1 max
Bandwidth	14% VHF (118 to 136 MHz) 56% UHF (225 to 400 MHz)
CW power	50 W max
Polarization	Vertical
Mechanical	
Height	4.3 m max*
Weight	6 kg max*
Wind	157 km/hr max
Ice	1.25 cm max
Altitude	3.8 km max
Humidity	5 to 100%
Cost	$1000

*Indicates changes to original specifications feed network, cable losses, nonuniform current distributions, and radiator efficiencies are taken into account, the specified gain of 4.3 dBi for the VHF antenna of this restrictive height is possible to achieve, but the available aperture must be considered marginal. Figure 1 shows the theoretical gain of an antenna as a function of aperture height. The calculation is based on the ideal situation of a 100-percent efficient uniform current distribution radiating into free space to give the dipole-type radiation pattern of

$$E(\theta, \phi) = \sin\theta \, \frac{\sin(\frac{1}{2} kl \cos\theta)}{\frac{1}{2} kl \cos\theta} \, .$$

The directivity is then calculated by pattern integration from

$$D = \frac{4\pi \, |E(\theta_o, \phi_o)|^2}{\iint |E(\theta, \phi)|^2 \, dS}, \qquad \theta_o = 90^\circ, \ \phi = 0^\circ .$$

At UHF where the wavelength is 1/2 to 1/3 of the wavelength at VHF, the 4.3 m maximum height is not restrictive, and 4.5-dBi gain is easily achieved. Light weight is a practical consideration based on the need to have one man install the antenna on a tower. The wind loading of 157 km/hr, 1.25 cm of ice, a maximum altitude of 3.8 km, and humidity of 5 to 100 percent are the extremes of the physical environment to which the communication antennas are exposed. A maximum cost of $1000 per unit in quantities influences the choice of materials and construction technique. This stated unit cost is a reasonable goal and has been factored into the chosen design concepts.

2.1 VHF Omnidirectional Antennas

A two-element VHF design is shown in figure 2. Each dipole element is 1.3 m (4.26 ft) long with 2.2-m (7.2-ft) spacing between element centers. This yields an array that is only 3.5 m (11.8 ft) long with a directivity of 5.4 dB. Increasing the array size to 4.3 m (14 ft) by increasing the element spacing significantly increases the grating lobe level without increasing the gain. The radiation pattern of the 3.5-m-long array is shown in figure 3. The elevation angle, (θ), measured from vertical is plotted on the horizontal axis so that 0° corresponds to directly overhead and 90° corresponds to the horizon. Relative power (in decibels) is plotted on the vertical axis. If ideal lossless radiating elements were used, the 0-dB relative power level would correspond to a gain above an isotropic point source equal to the directivity of the antenna. Element inefficiencies and feed network, radome, mismatch, and cable losses reduce the actual gain to the required gain level specified in table 3.

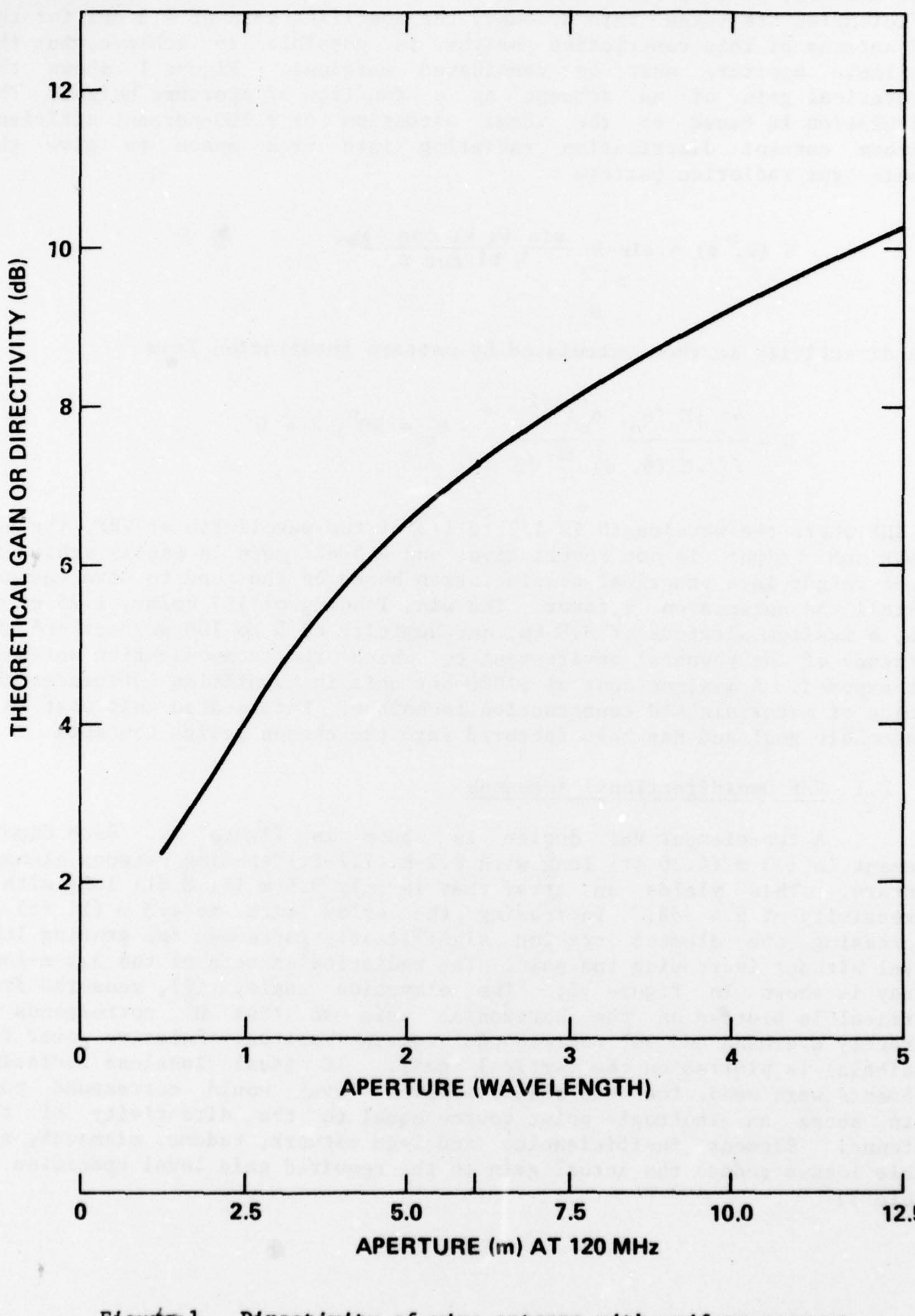


Figure 1. Directivity of wire antenna with uniform current distribution.

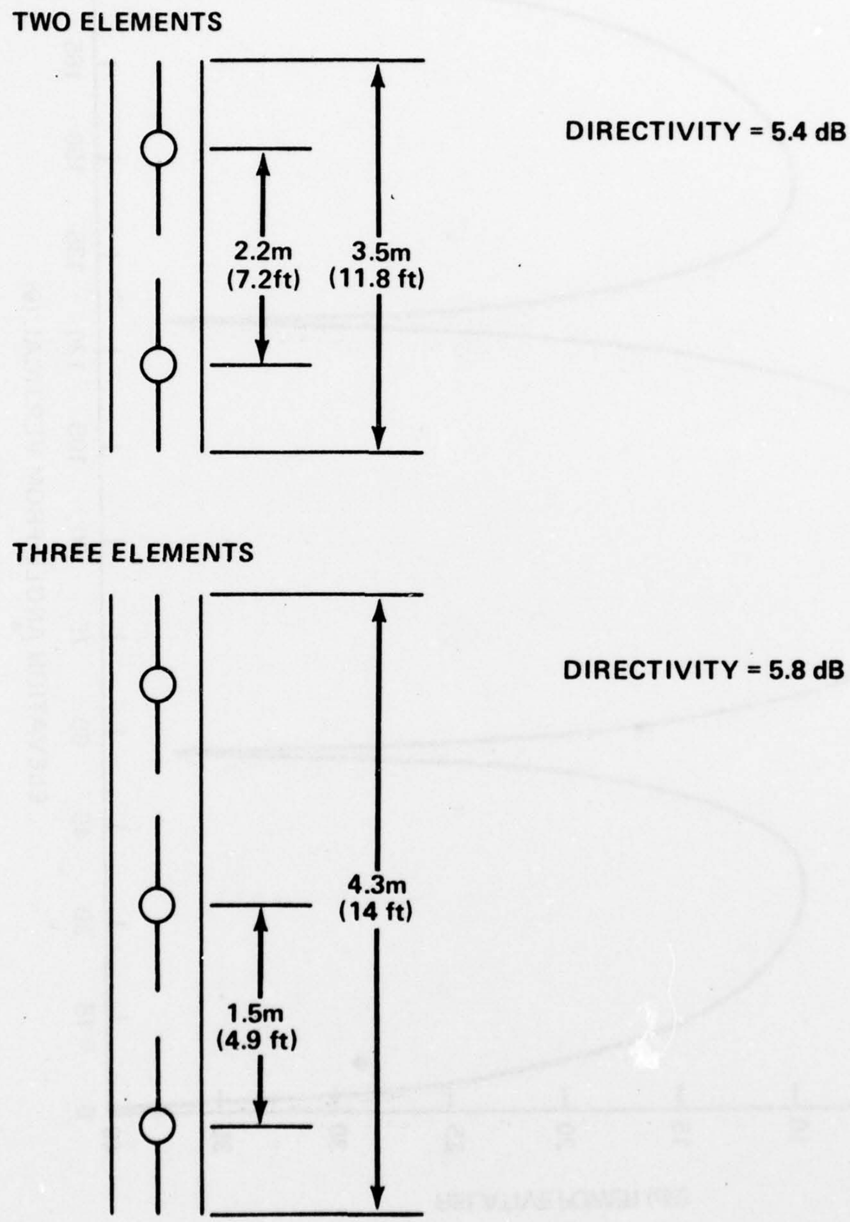


Figure 2. Radome-supported VHF omnidirectional gain antenna.

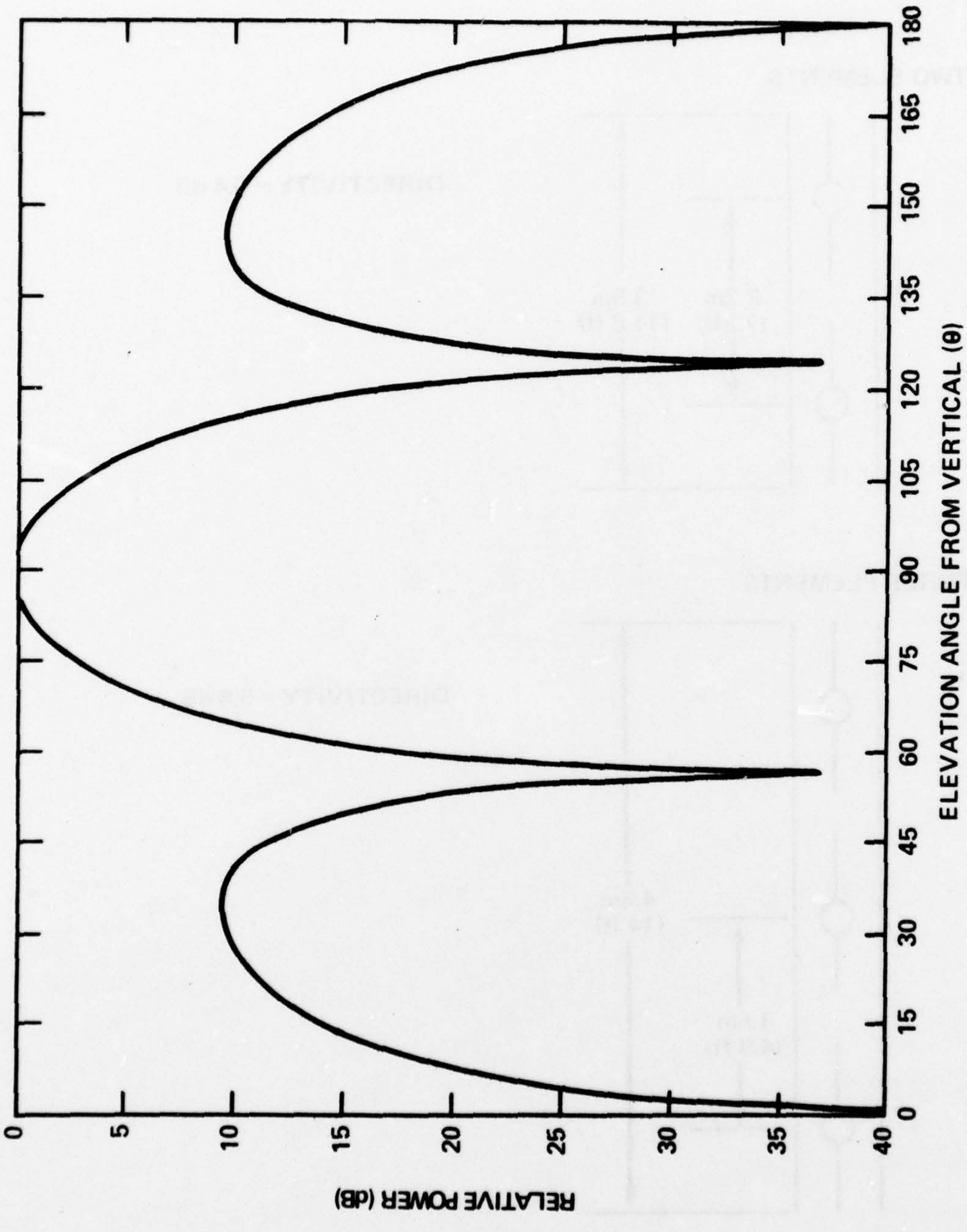


Figure 3. Radiation pattern of two-element VHF antenna.

A three-element VHF design also is shown in figure 2. The interelement spacing is small so that the three elements fit in the allowed aperture. The corresponding radiation pattern is shown in figure 4. The nulls in the pattern at elevation angles of 50° and 130° have been filled in by applying a defocusing phase taper to the array [1]. In this design, the phase of the signal applied to the top and bottom elements has been retarded 25° relative to the center element. Although the three-element antenna has a higher directivity, the extra cable and feed network losses associated with the third element reduce the achievable gain to the specified level.

2.2 UHF Omnidirectional Antennas

Basic antenna theory states that the gain of an antenna is proportional to the physical aperture (in this antenna, height), measured in wavelengths (λ). Therefore, to achieve a specified gain, a UHF antenna is proportionally smaller than a similar VHF antenna. Figure 5 indicates the relative sizes and element spacings for the three- and four-element designs where each dipole element is 0.67 m (2.2 ft) long. The large UHF bandwidth (225 to 400 MHz) dictates that certain compromises be made. For example, if the interelement spacing on the three-element antenna were increased to 1.33 m to achieve 7-dB directivity at 225 MHz, then at 400 MHz, the grating lobes would be so large that the directivity would decrease well below 6 dB. Reducing the element spacing to 0.8 m would decrease the size of the grating lobes and thereby increase the directivity at 400 MHz, but the overall array would be smaller and no longer have sufficient gain at 225 MHz. The radiation patterns at a compromise spacing of 1.07 m are plotted in figures 6 to 8.

The four-element design has sufficient gain at 225 MHz and, since the elements are spaced only 0.8 m apart, the grating lobes are relatively small at 400 MHz (figures 9 to 11). Between 225 and 300 MHz, the directivity increases 0.92 dB, but from 300 to 400 MHz, it increases only 0.16 dB due to the increased size of the grating lobes at 30° and 150°.

2.3 Simulated Operational Performance

The free-space antenna radiation patterns do not indicate how the antenna will perform in the real environment. The fact that the antenna is operated a certain height above a lossy dielectric sphere (the earth) means that there will be multipath reflections that will significantly modify the free-space radiation patterns.

A computer code called FIXEDR was developed to model the effects on the radiation patterns of reflections from a lossy spherical earth.

The amplitude of the signal received at the aircraft depends on the separation distance between the transmit and receive antennas, the ground reflection coefficient, and the direct and reflected path length difference. The wave that travels along the direct path to the aircraft is combined with the wave that is reflected from the earth's surface. The

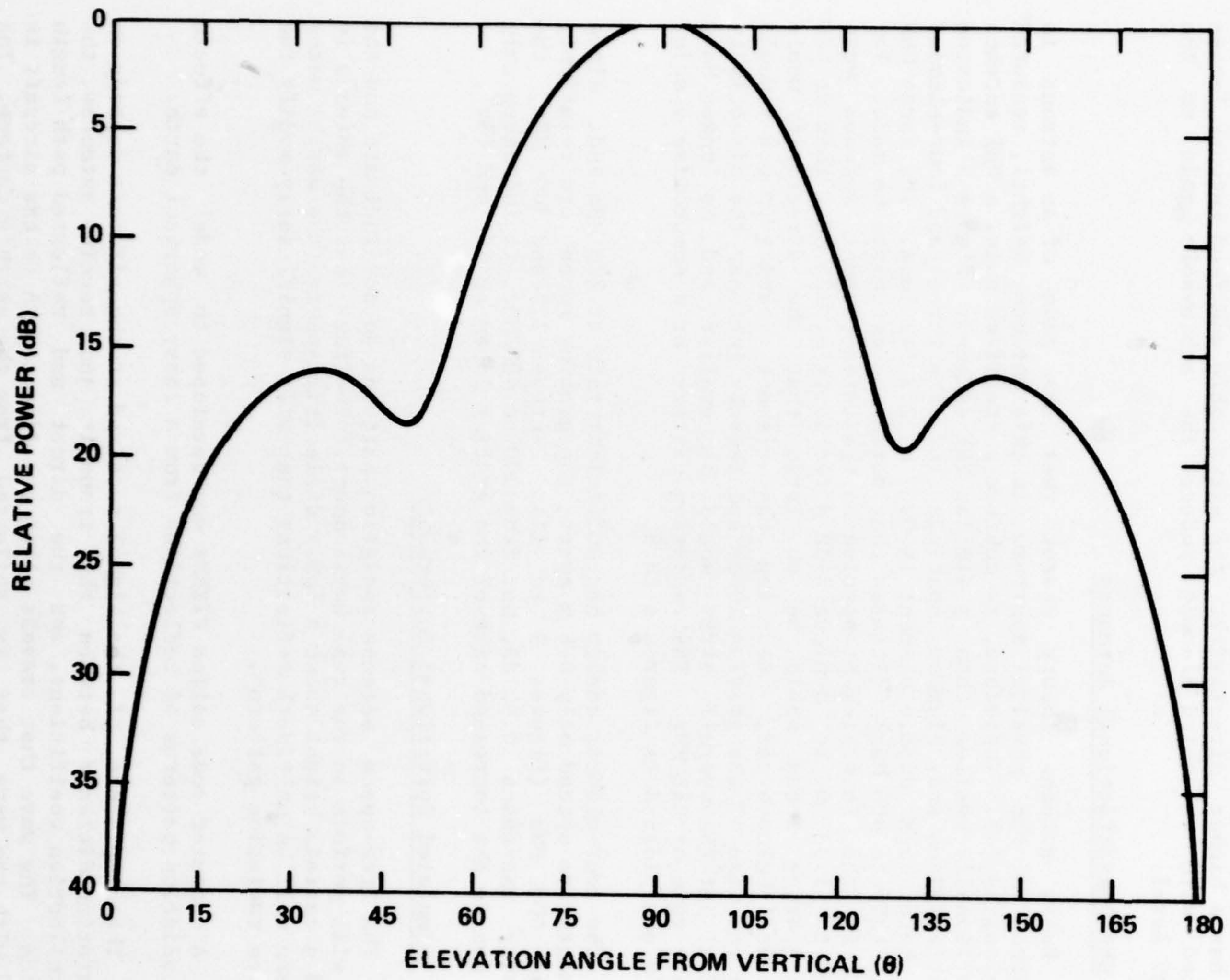


Figure 4. Radiation pattern of three-element VHF antenna.

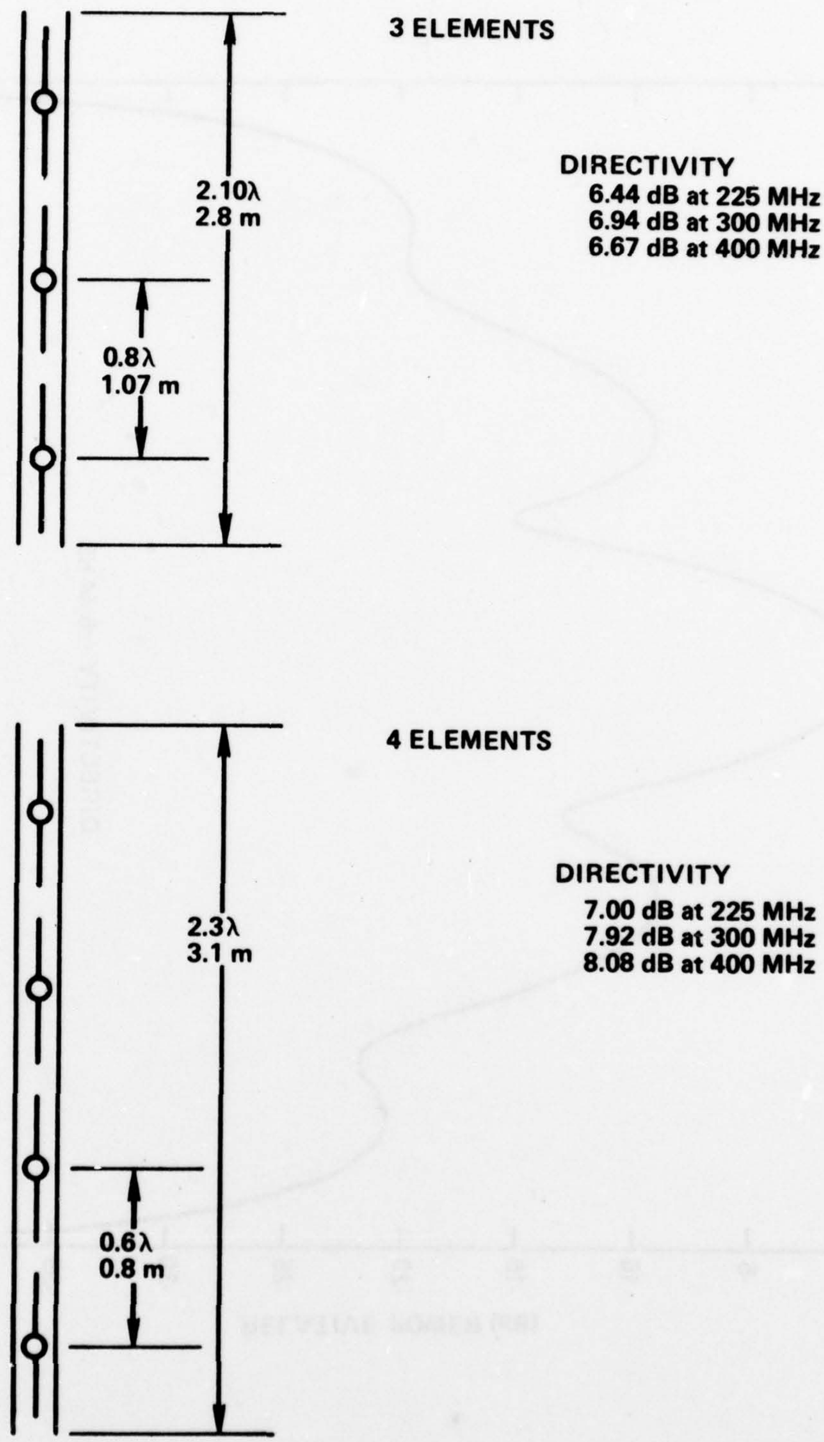


Figure 5. Radome-supported UHF omnidirectional gain antenna.

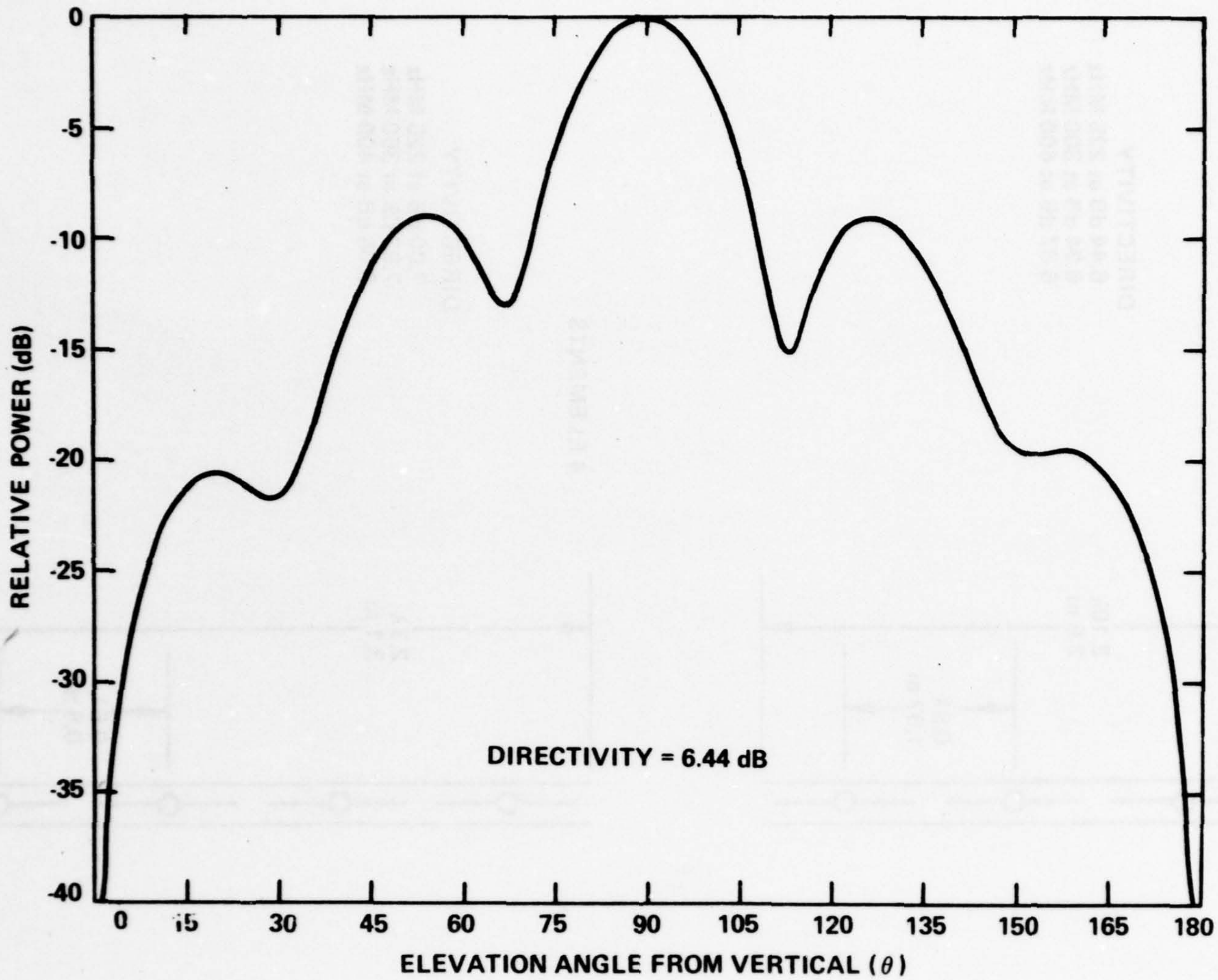


Figure 6. Radiation pattern of three-element UHF omnidirectional antenna at 225 MHz

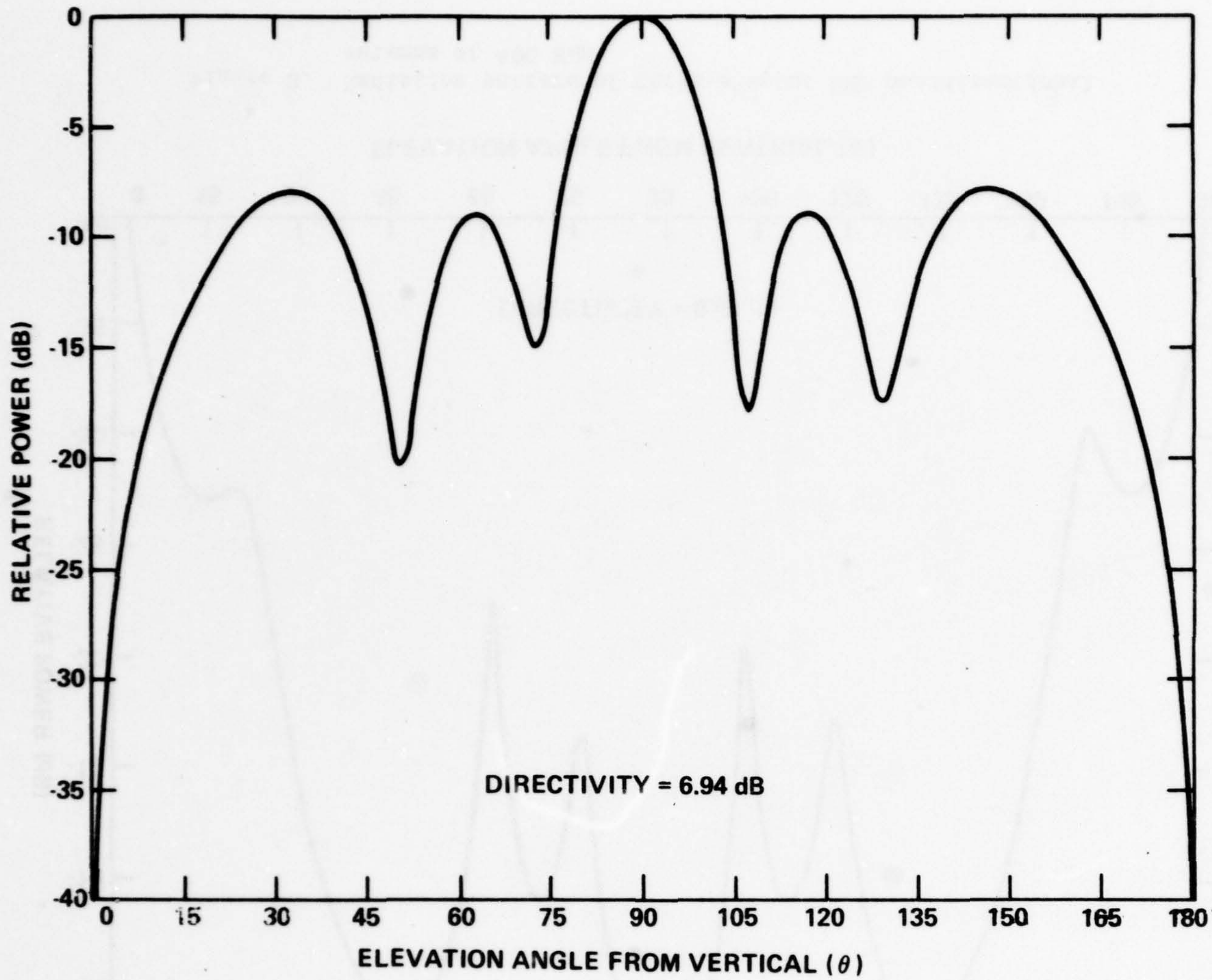


Figure 7. Radiation pattern of three-element UHF omnidirectional antenna at 300 MHz.

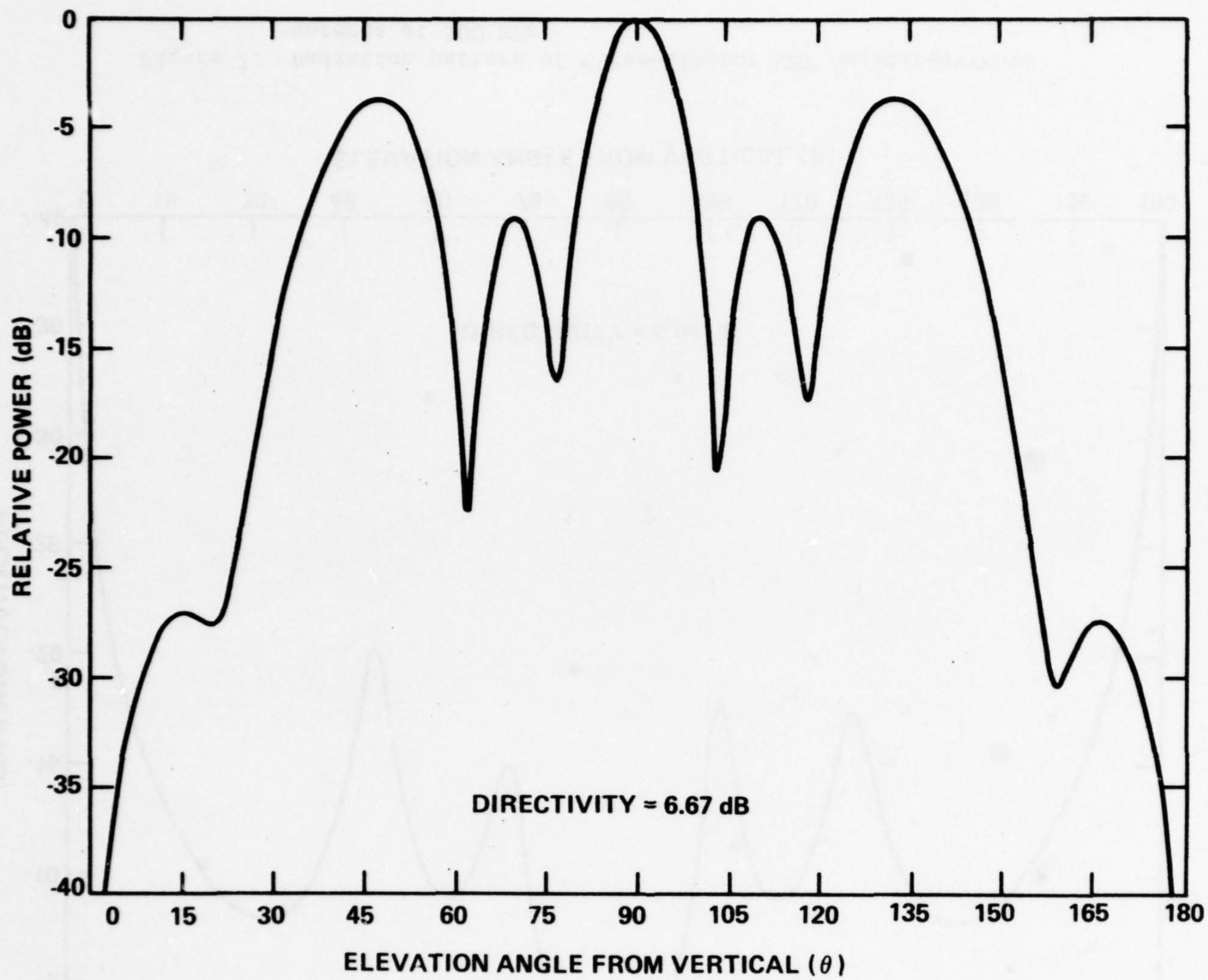


Figure 8. Radiation pattern of three-element UHF omnidirectional antenna at 400 MHz

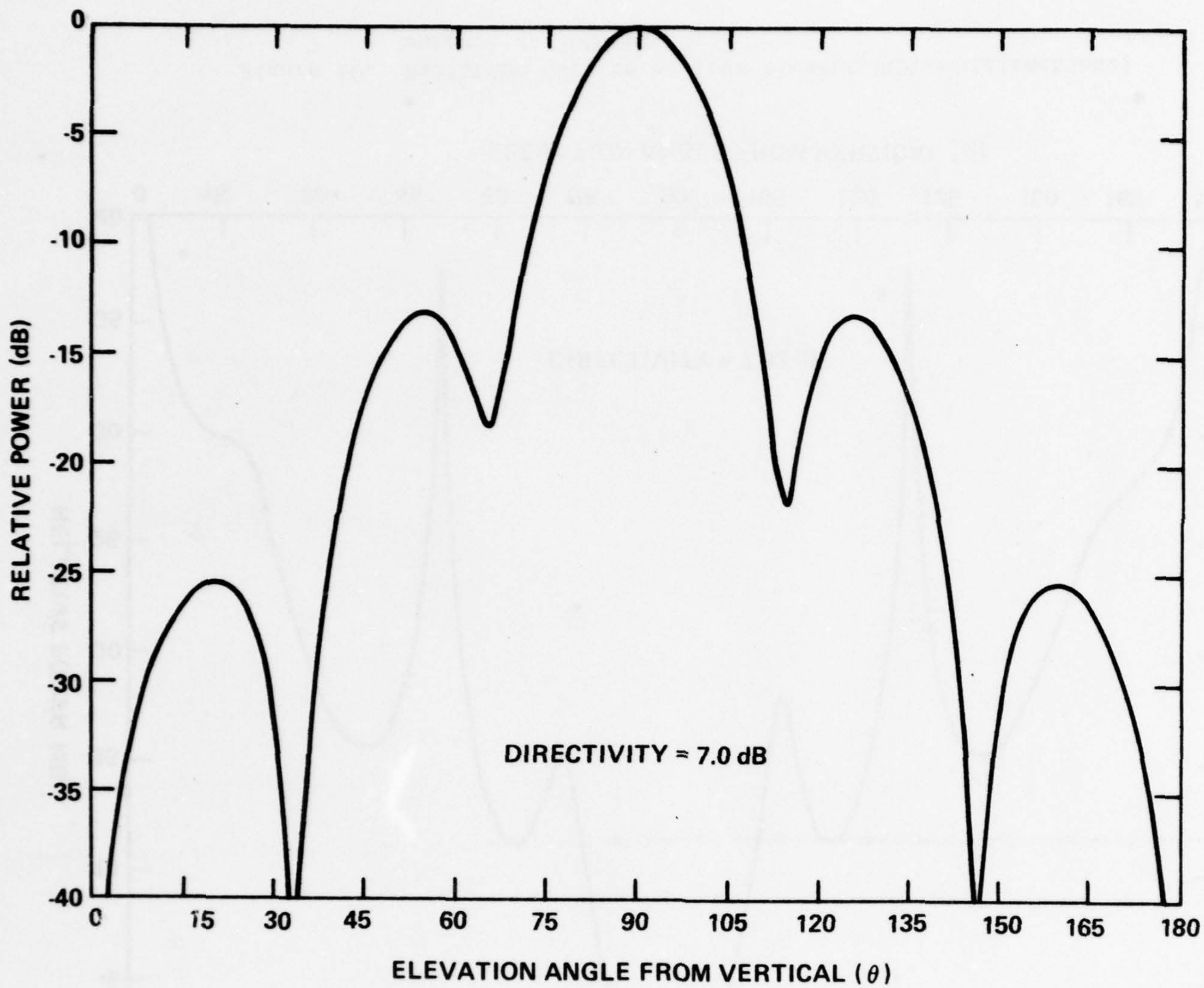


Figure 9. Radiation pattern of four-element UHF omnidirectional antenna at 225 MHz

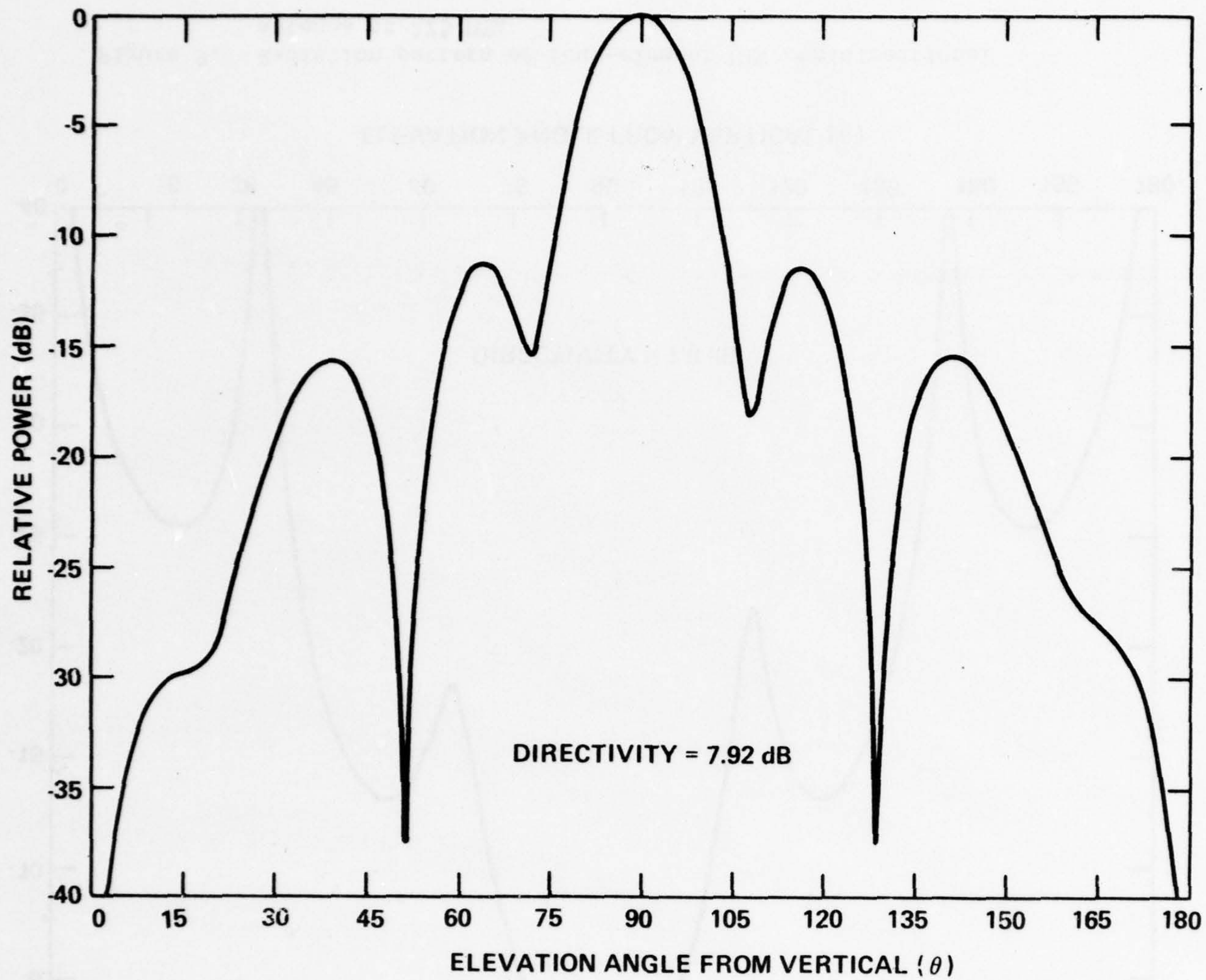


Figure 10. Radiation pattern of four-element UHF omnidirectional antenna at 300 MHz.

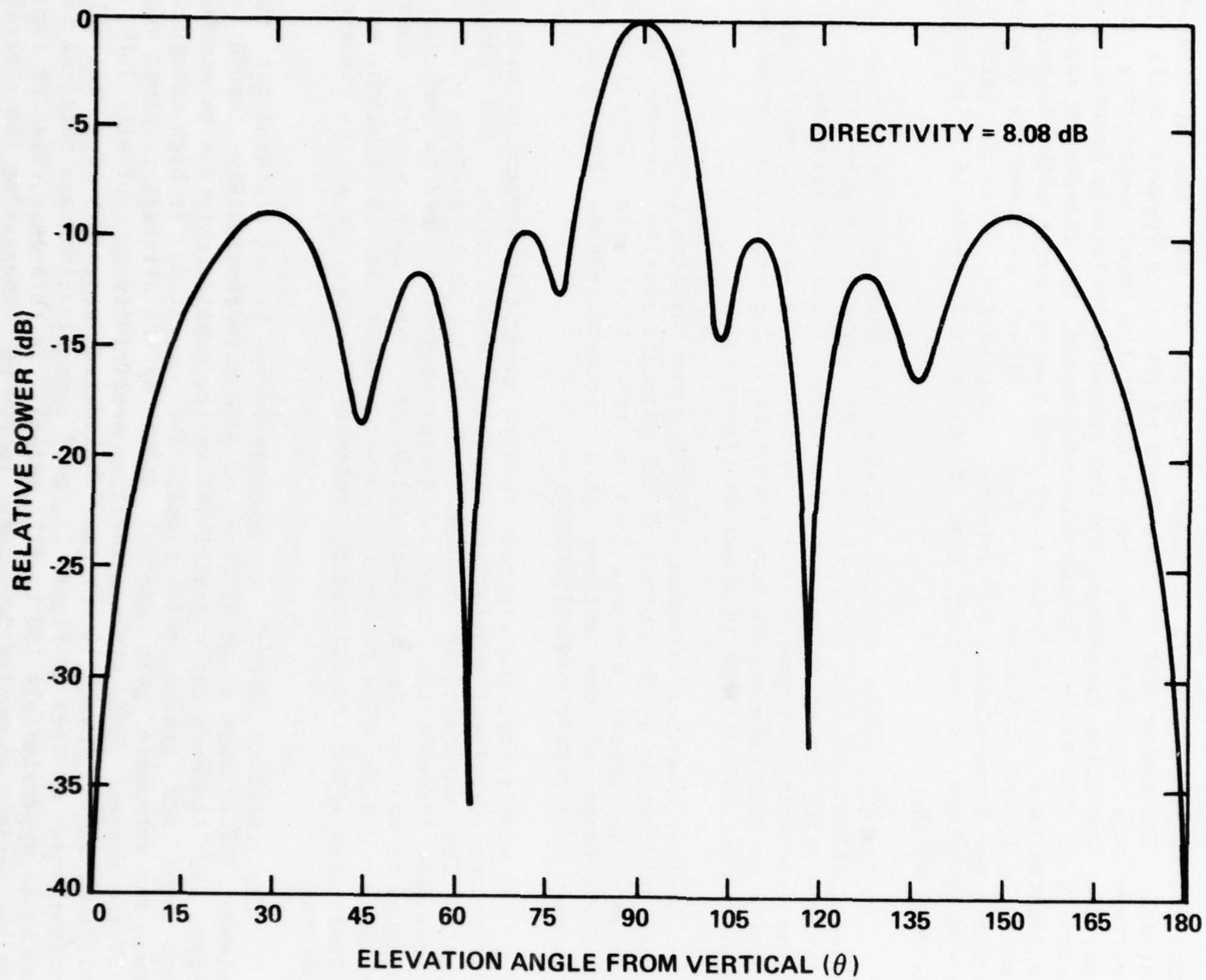


Figure 11. Radiation pattern of four-element UHF omnidirectional antenna at 400 MHz

ground reflection coefficient is a function of incidence angle as shown in figure 12. Complete cancellation will occur at the horizon ($\theta = 90^o$) because the reflected signal is equal in magnitude ($|R_v| = 1$) and 180^o out of phase with the direct signal. As the elevation angle and path length vary, the magnitude and phase of the ground-reflected signal will also vary and will add to or subtract from the direct signal.

The result of this multipath interference is a lobing structure in the vertical radiation pattern as shown in figure 13 for the two-element VHF antenna. The number and relative depth of the interference nulls in the pattern are dependent on the height of the tower supporting the antenna, the operating frequency, and the relative dielectric constant and conductivity of the earth. Unless otherwise noted, the antenna is assumed to be mounted on a 13-m (42.6-ft) tower over average earth with dielectric constant $\varepsilon_r = 15$ and conductivity $\sigma = 0.012$. Figure 14 shows the antenna pattern for the three-element VHF antenna. In practice, since the earth is not a smooth sphere, scattering from rough terrain tends to fill in the sharp, deep nulls.

In the UHF band, similar effects are observed. As seen in the radiation pattern of the three-element UHF antenna (figure 15), the interference nulls are spaced closer than those of the VHF antennas. With a higher operating frequency and correspondingly shorter wavelength, destructive interference occurs more frequently. The radiation pattern for the four-element UHF antenna is shown in figure 16.

Another computer program, FLTSIM, was written to calculate and plot the rf voltage at the output of the aircraft receive antenna as a function of the ground distance from the transmitter site. This program models the effects of the antenna gain, pattern shape, and multipath interference on aircraft communications.

For simplicity, the aircraft receive antenna is assumed to have an omnidirectional vertically-polarized pattern, 0-dBi gain, and 50-ohm impedance. The aircraft is assumed to be flying at a constant altitude away from the transmitting source. Unless otherwise noted on each plot, the antenna is mounted on a 13-m (42.6-ft) tower over average earth ($\varepsilon_r = 15$, $\sigma = 0.012$). The transmitter power output is 10 W which, with 3-dB cable loss (from transmitter to antenna), leaves 5 W at the input of the antenna.

The received signal is plotted versus ground distance for the two-element VHF antenna at an altitude of 3000 m (approximately 10,000 ft) in figure 17. Although the signal level varies considerably due to antenna pattern shape and ground reflections, the amplitude is high enough to activate the automatic gain control (AGC) on the aircraft receiver over most of the range. While minimum receiver sensitivity is typically 3 μV, a signal level of at least 12 μV is considered necessary for reliable communications. As seen in figure 17, good communications are obtained for ranges up to approximately 180 km (112 miles). In this case, line of sight limits the maximum communications range to 200 km. Increasing the aircraft altitude to 6000 m (approximately 20,000 ft) increases the maximum range to

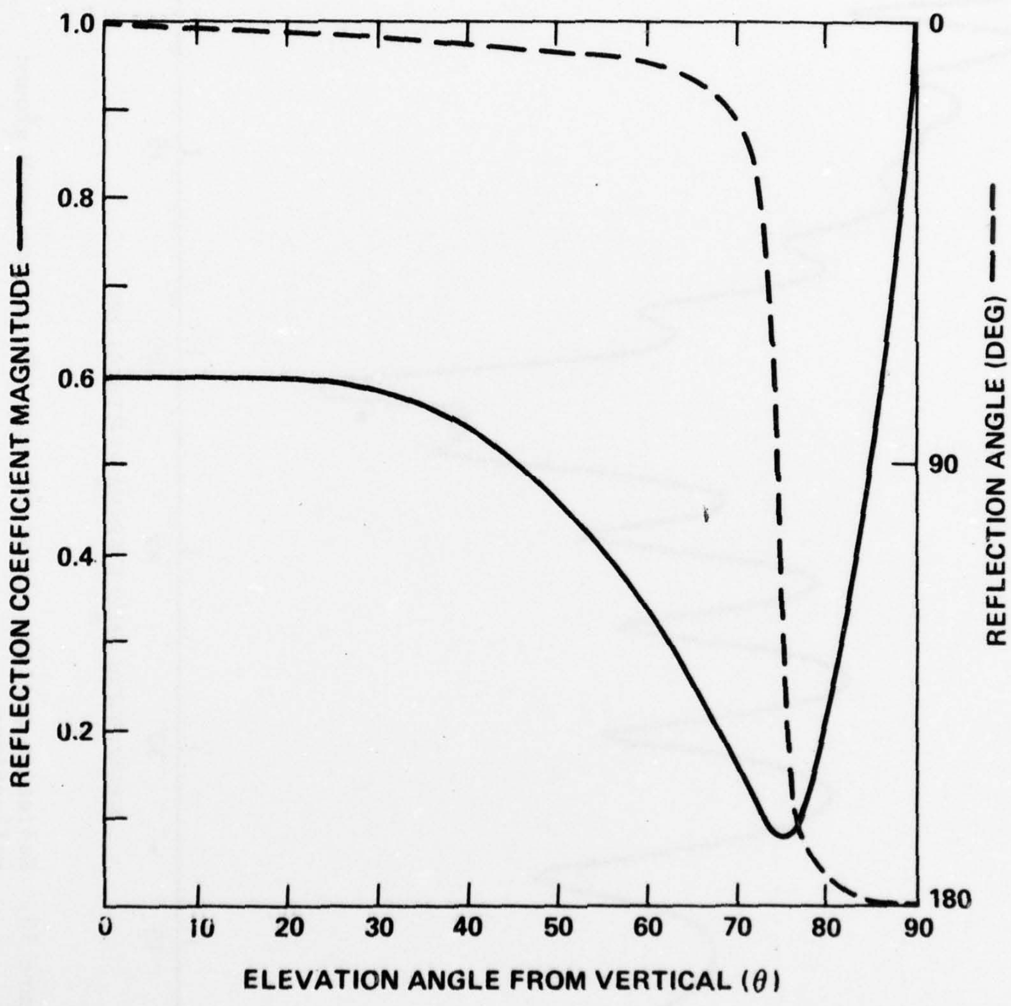


Figure 12. Ground reflection coefficient for average earth

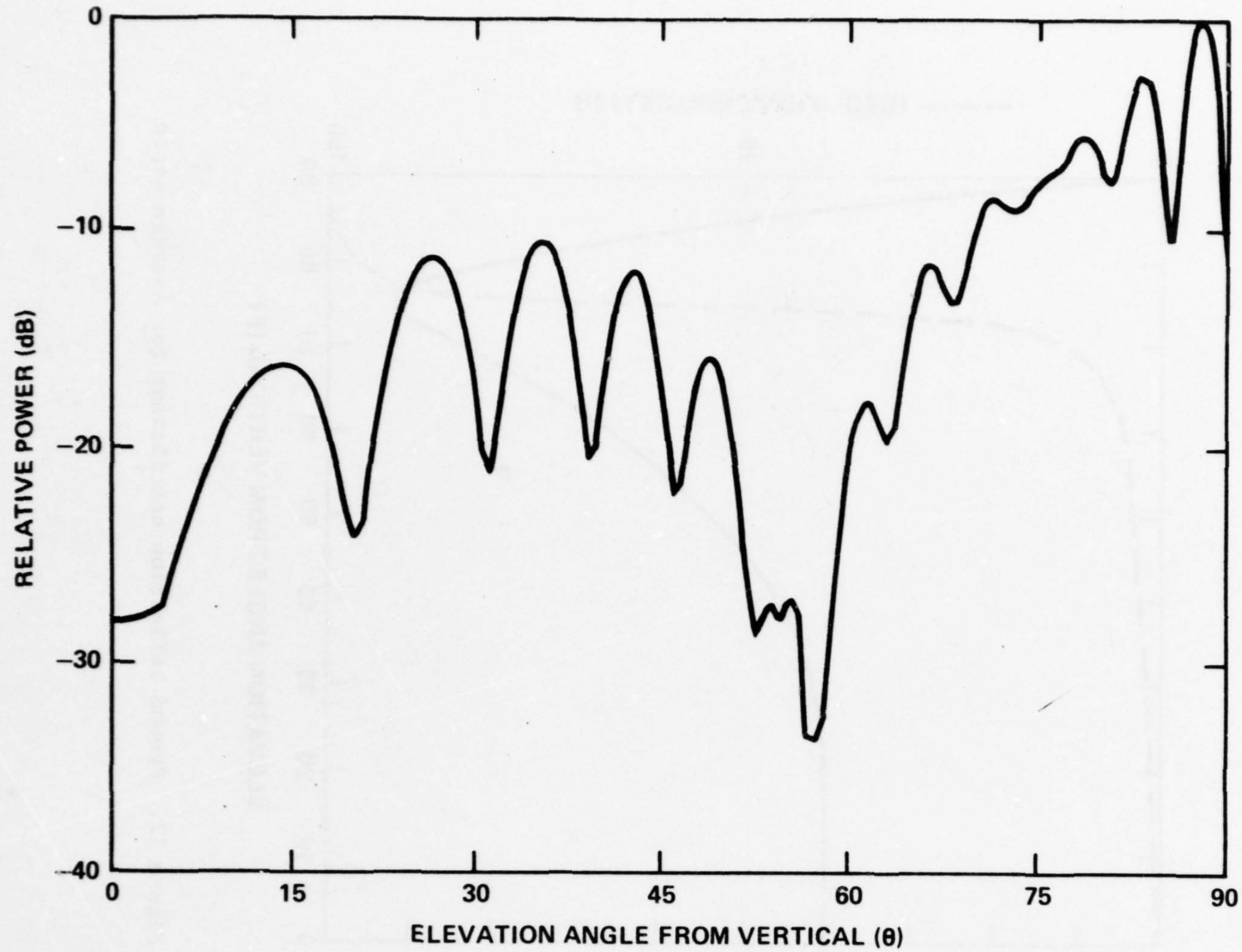


Figure 13. Radiation pattern of two-element VHF antenna with ground reflections.

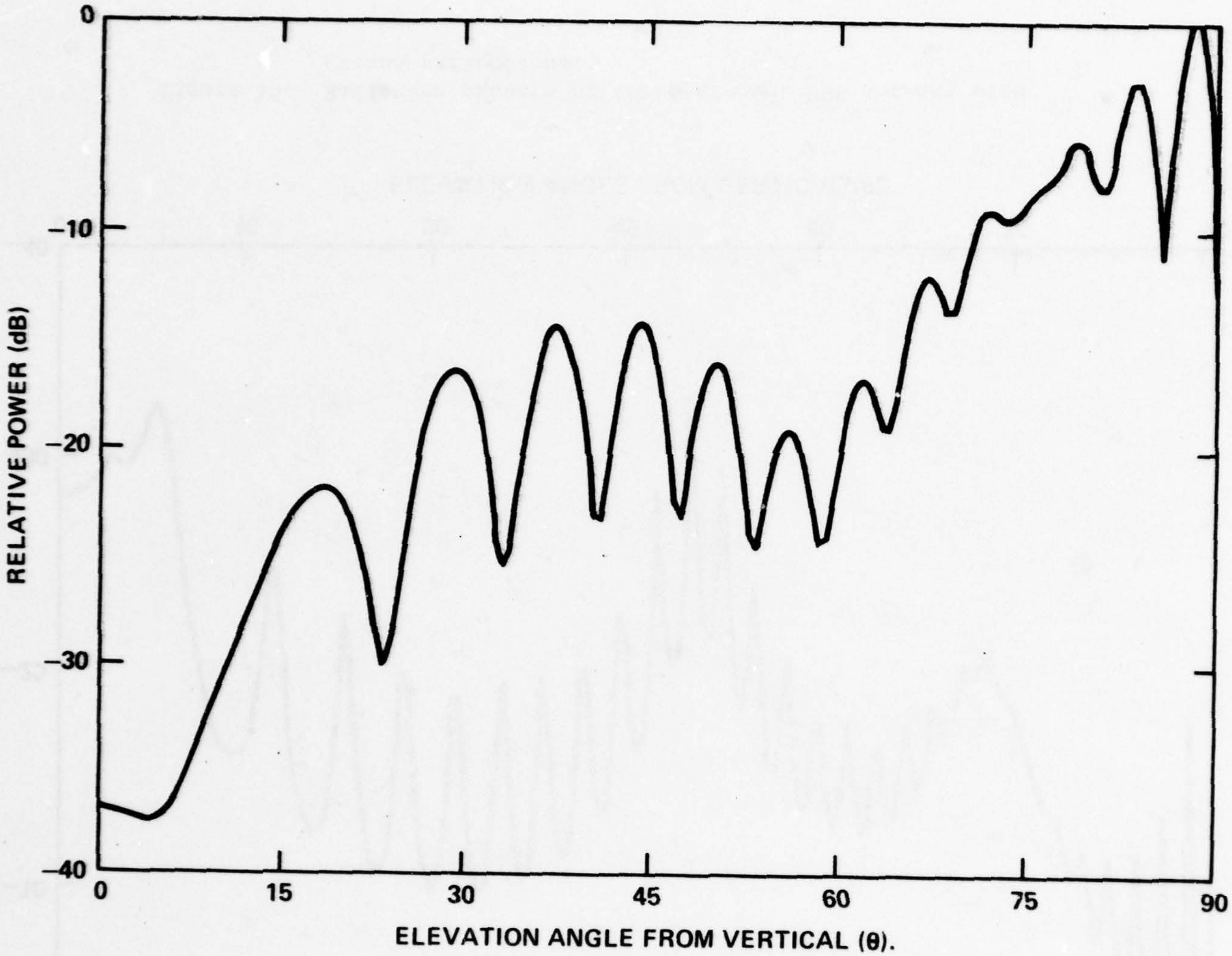


Figure 14. Radiation pattern of three-element VHF antenna with ground reflections.

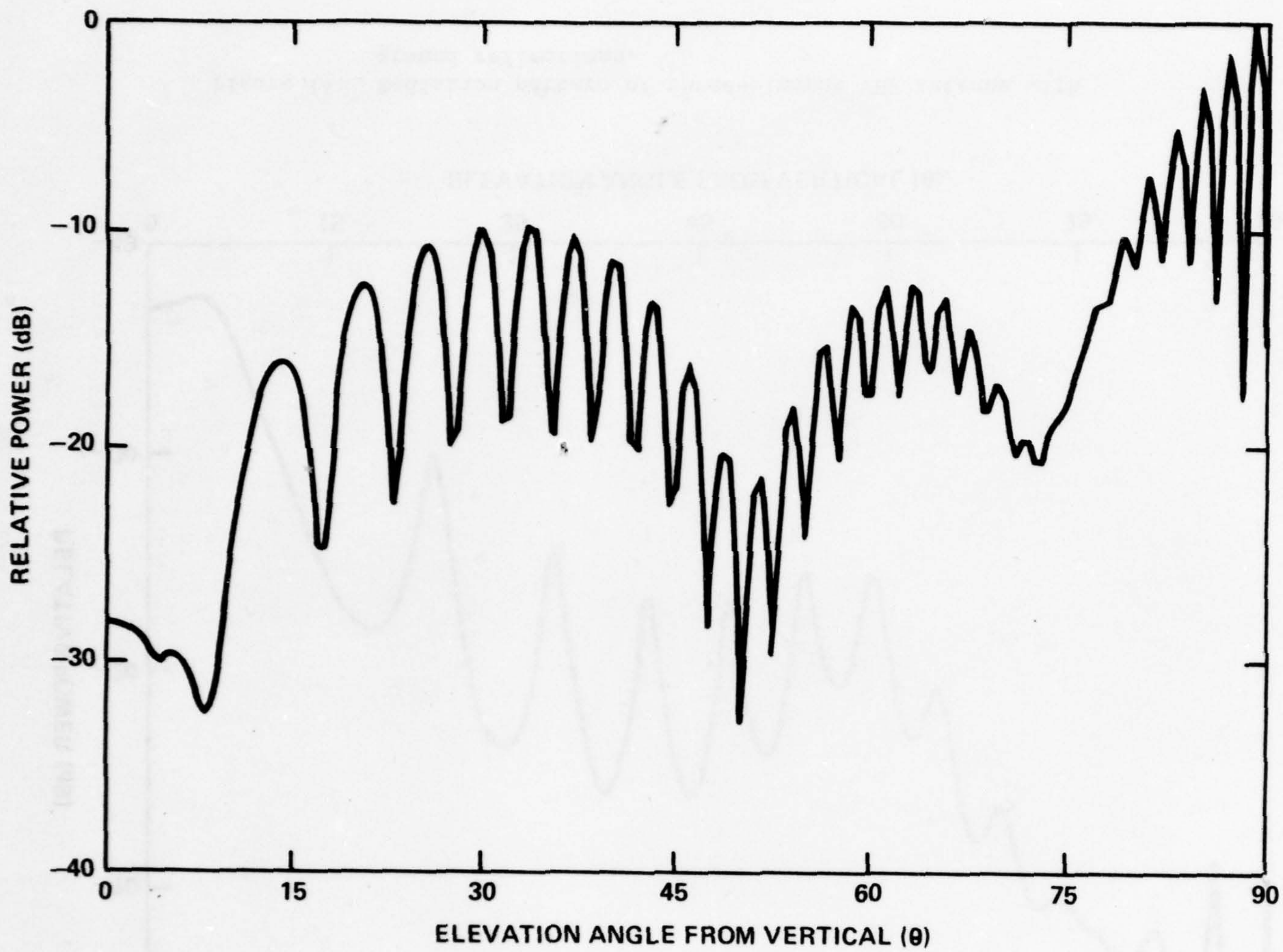


Figure 15. Radiation pattern of three-element UHF antenna with ground reflections.

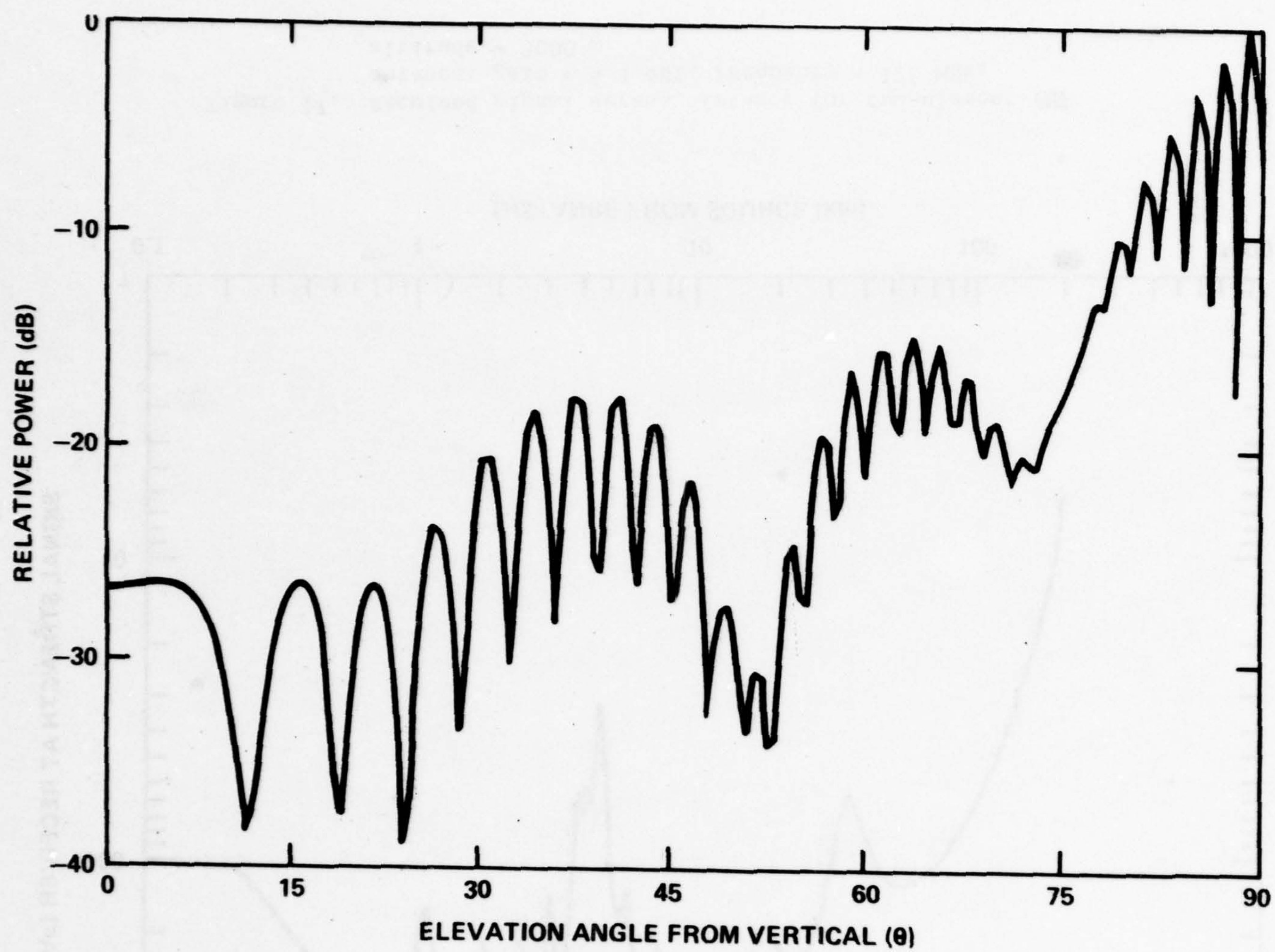


Figure 16. Radiation pattern of four-element UHF antenna with ground reflections.

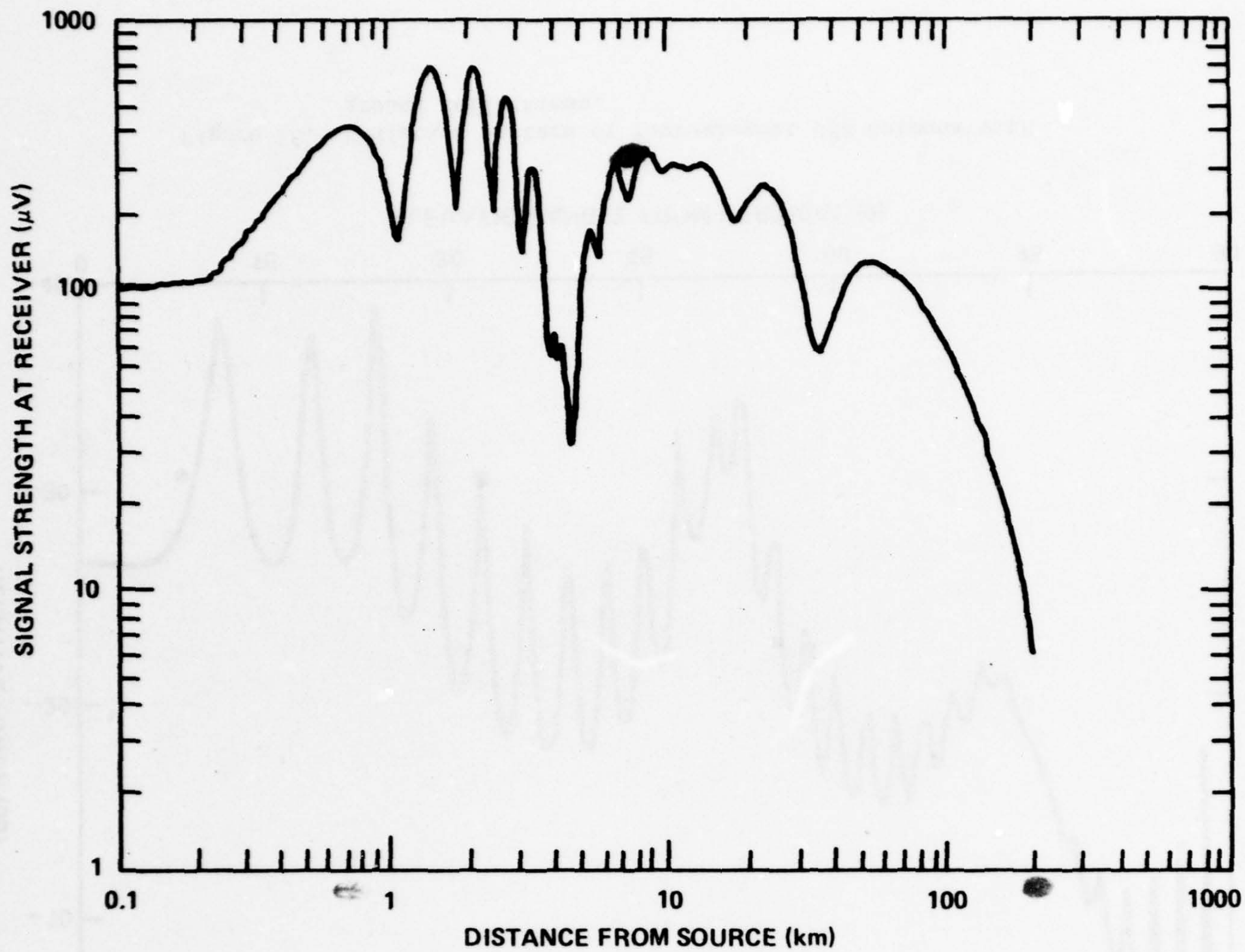


Figure 17. Received signal versus distance for two-element VHF antenna: gain = 4.3 dBi, frequency = 125 MHz, altitude = 3000 m.

almost 300 km, but the overall signal level is reduced due to the increased distance between the transmitter and the receiver. At an altitude of 9000 m (30,000 ft) the signal is still well above the 12-μV level at a 320-km range (figure 18). The performance of the three-element VHF antenna at an altitude of 9000 m is shown in figure 19.

Similar performance is observed with the three-element and four-element UHF antennas as shown in figures 20 and 21. The amplitude of the received signal is generally lower than the signal from the VHF designs because the received voltage is proportional to the wavelength. Also, because of the shorter wavelength, destructive interference occurs more often and causes more closely spaced nulls.

The plots of received signal voltage assume 0-dBi gain for the aircraft antenna, including its associated cables and apparatus. Many aircraft antennas will not be this good, and some may have deep nulls in their radiation patterns. If an aircraft antenna system has -20 dBi gain in the direction of the transmitter, the received signal voltage (and, therefore, the communications range) will be one-tenth the values given on these plots.

2.4 Simulated Performance Comparisons

Since the effects of the multipath interference on the antenna performance are about the same for the two- and three-element VHF designs, the ground reflected signal can be ignored when the simulated performance of the two antenna designs is compared. Figure 22 shows the signal received from the two- and three-element VHF gain antennas and from a single dipole antenna with 0-dBi gain. The dipole curve is included so that these designs can be compared with typical state-of-the-art broadband dipoles. Both the two- and three-element antennas have equal gain and produce a received signal of 13 μV at maximum range. This level is 4.3 dB higher than the 7.9-μV signal received from the 0-dBi gain dipole. Since it is not possible to defocus the two-element antenna, the null in the radiation pattern causes a low signal level of 17 μV at a range of 12 km (7.2 miles). The defocussing technique has partially filled in this null in the three-element antenna pattern.

A similar graph is plotted for the three- and four-element UHF antennas in figure 23. The slightly higher gain of the four-element antenna causes an increase of 0.8 μV over the three-element antenna at maximum range. Both antennas provide approximately twice as much received voltage as that provided by the single dipole antenna.

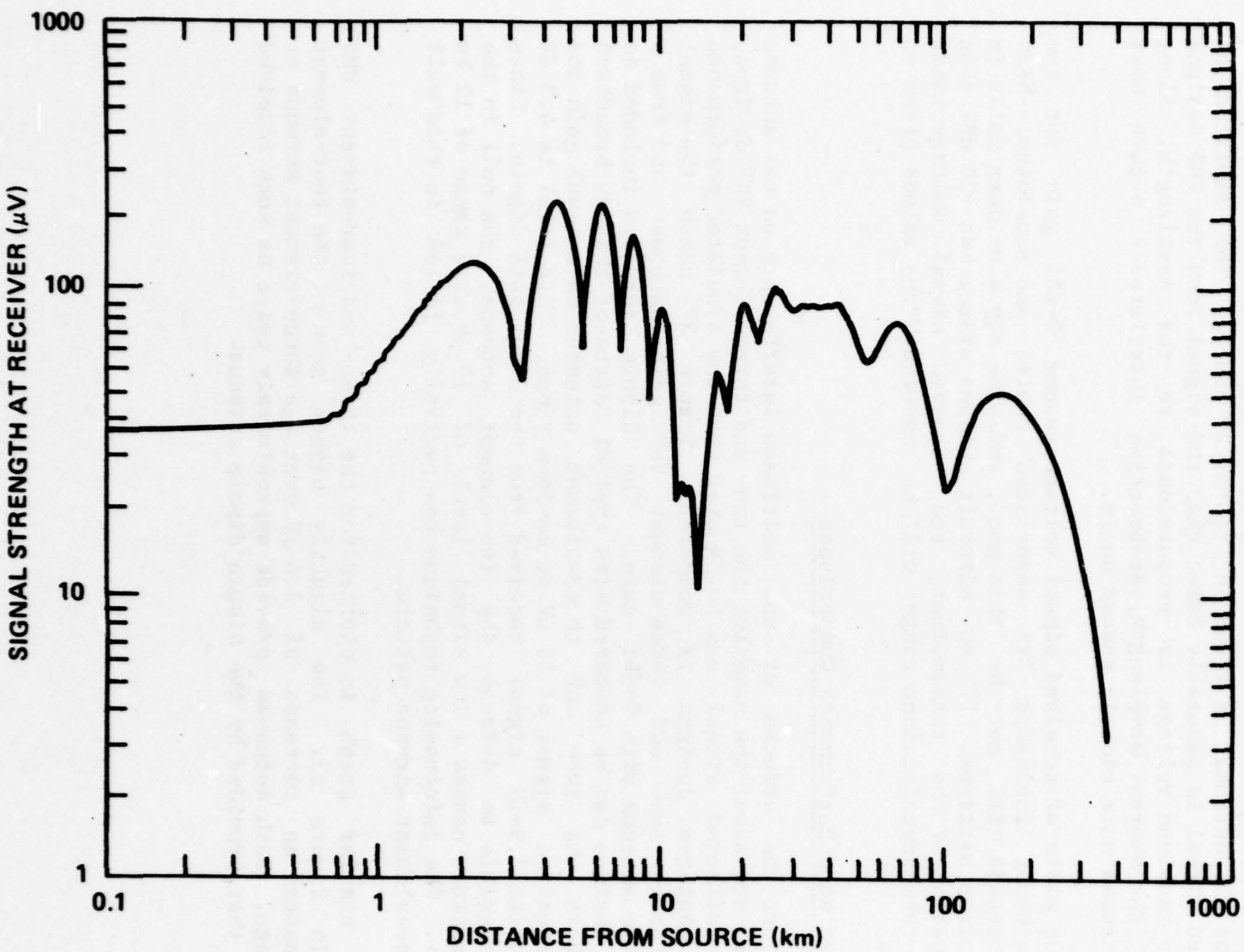


Figure 18. Received signal versus distance for two-element VHF antenna: gain = 4.3 dBi, frequency = 125 MHz, altitude = 9000 m.

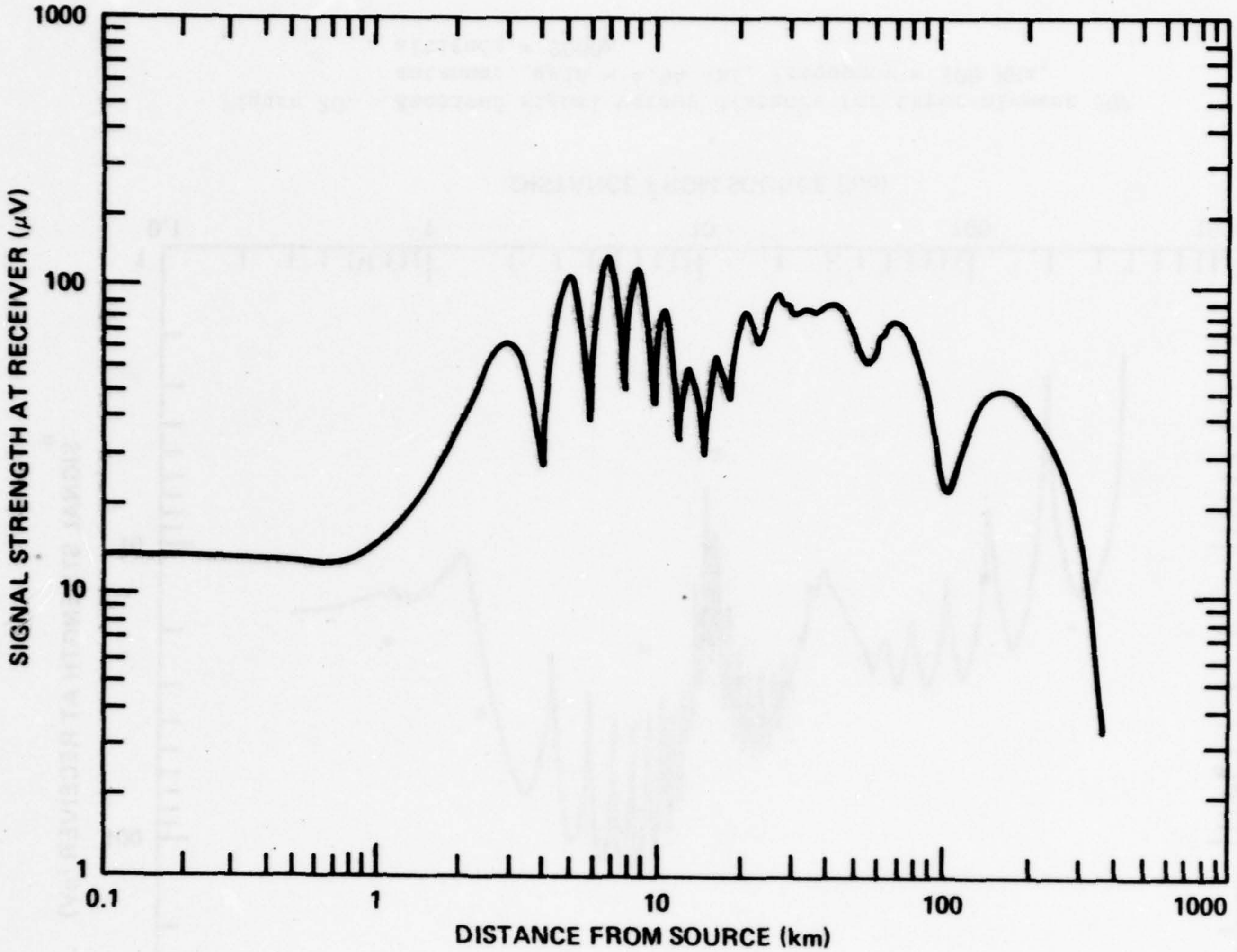


Figure 19. Received signal versus distance for three-element VHF antenna: gain = 4.3 dBi, frequency = 125 MHz, altitude = 9000 m.

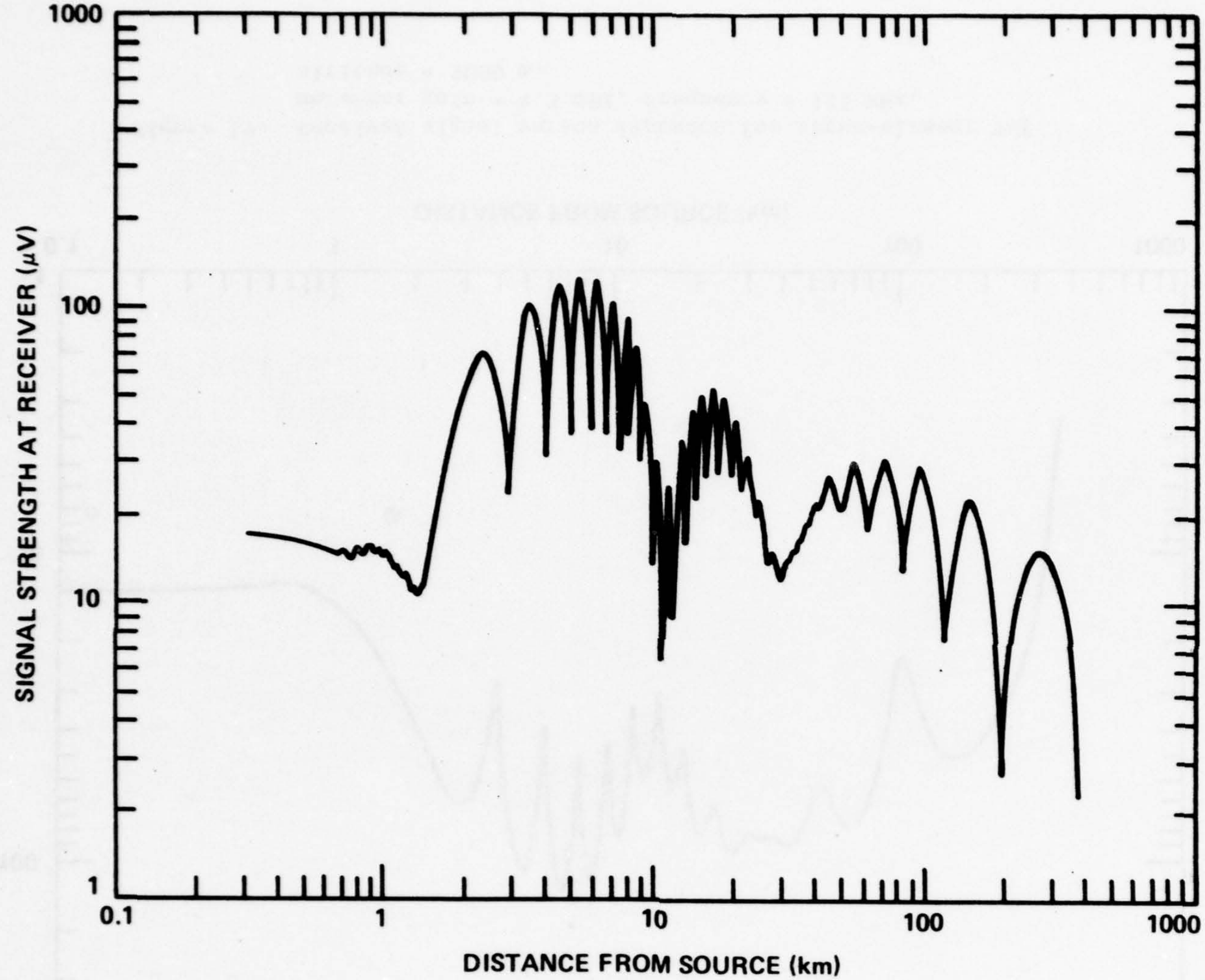


Figure 20. Received signal versus distance for three-element UHF antenna: gain = 4.94 dBi, frequency = 300 MHz, altitude = 9000m

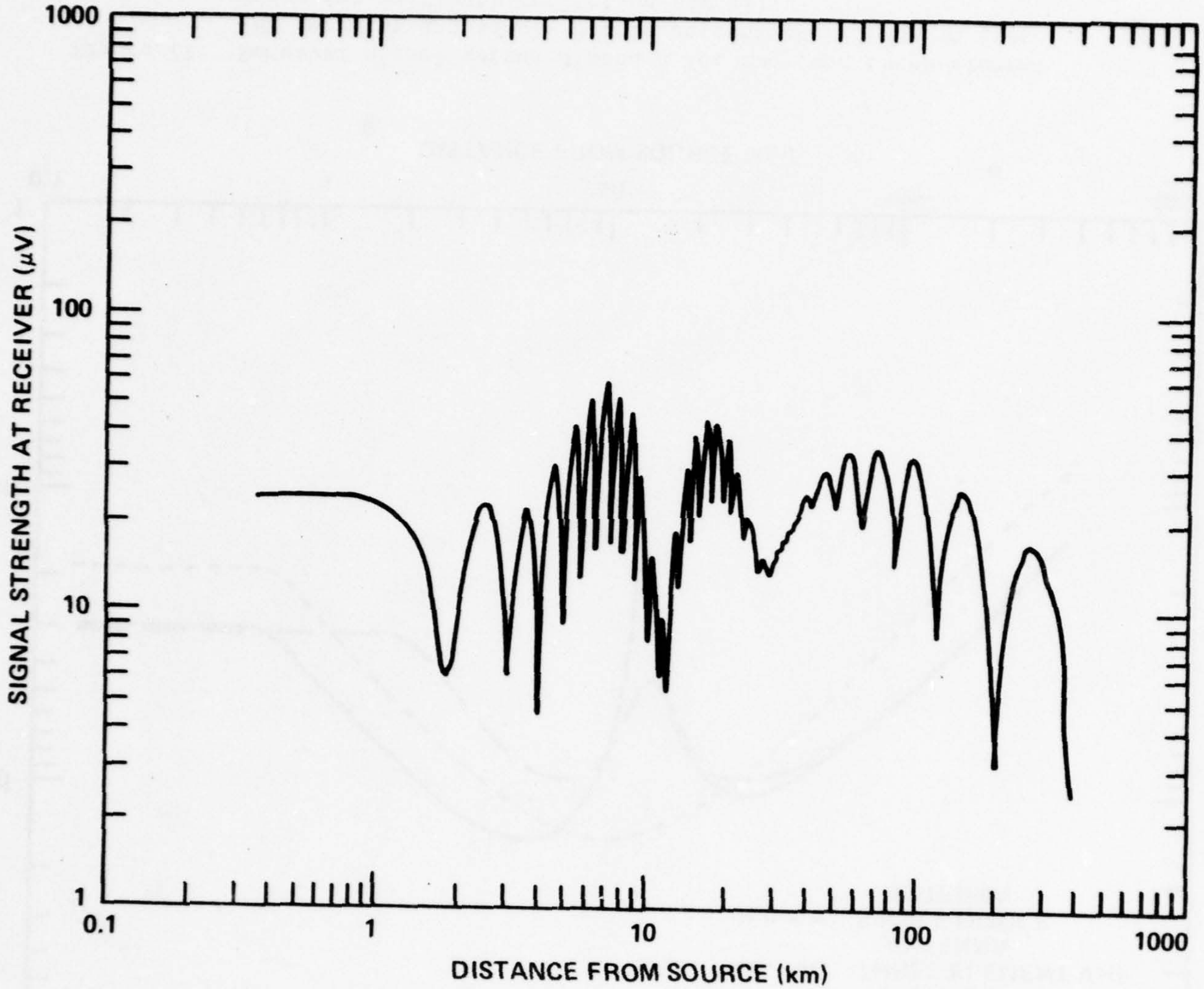


Figure 21. Received signal versus distance for four-element UHF antenna: gain = 5.92 dBi, frequency = 300 MHz, altitude = 9000 m.

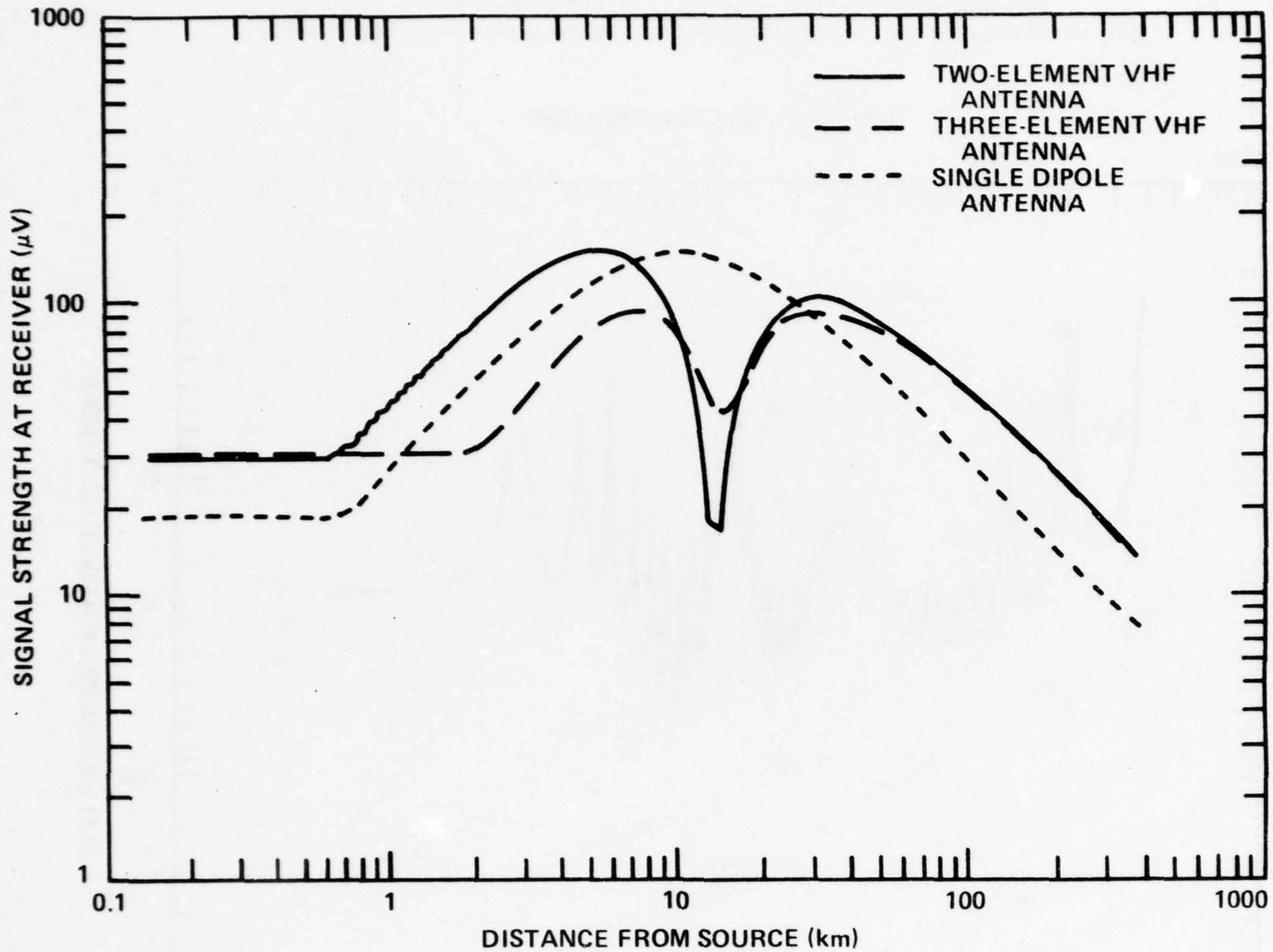


Figure 22. Received signal versus distance for two- and three-element VHF antennas and single dipole antenna at 125 MHz in free space (no multipath reflection signal).

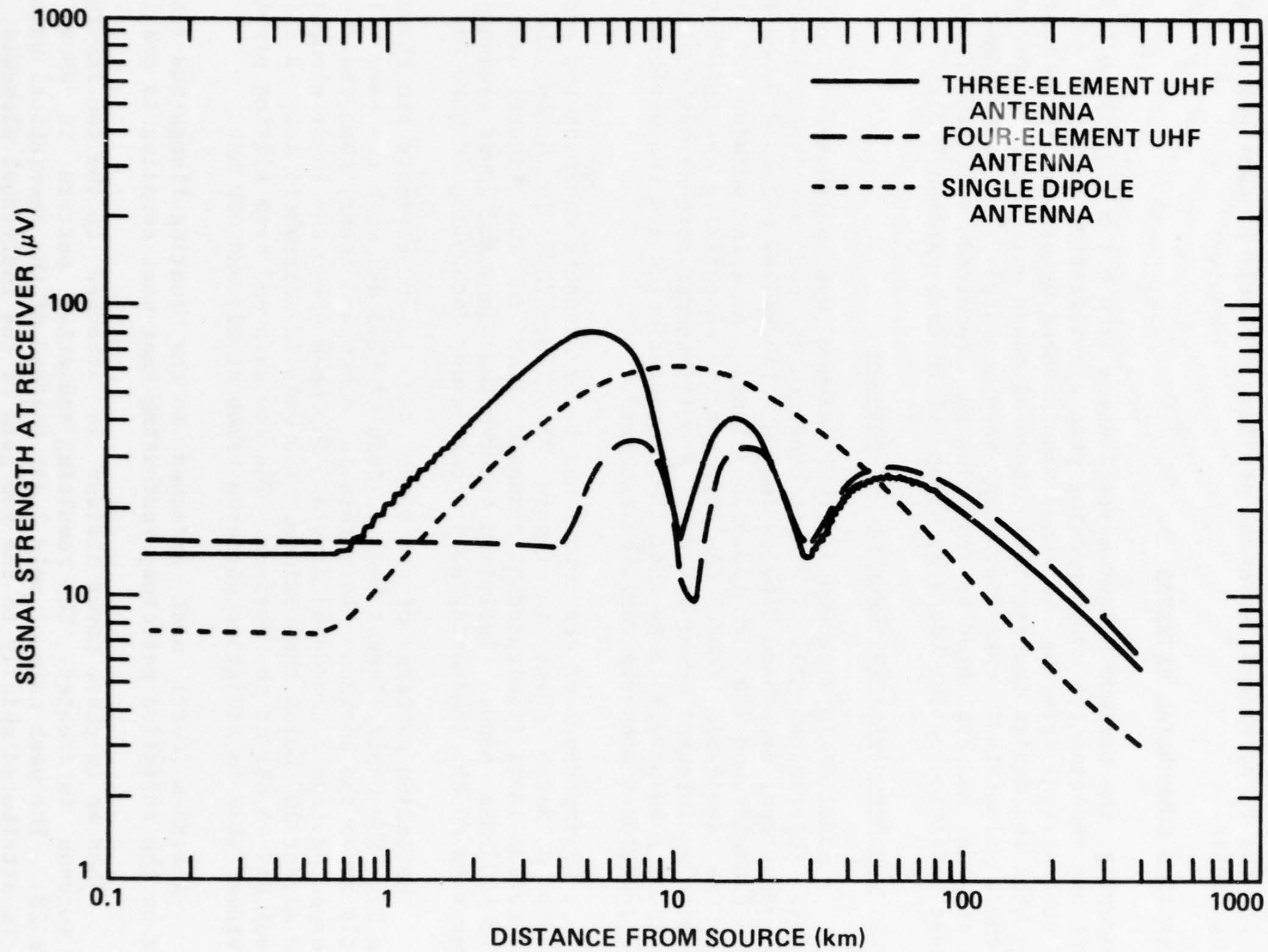


Figure 23. Received signal versus distance for three- and four-element UHF antennas and for single dipole antenna at 300 MHz in free space (no multipath reflection signal).

When the maximum height of the VHF antenna was reduced from 6.1 m (20 ft) to 4.3 m (14 ft), the corresponding gain specification was reduced from 5 to 4.3 dBi. The change in performance is plotted in figure 24. The received voltage from the three- and four-element 6.1-m antennas has been compared with the signal from a three-element 4.3 m antenna. While all three antennas provide adequate coverage out to the maximum range, the higher gain of the 6.1-m antennas (5.3 dBi for the four-element antenna and 5 dBi for the three-element antenna) provides slightly greater signal level at long ranges.

3. EXISTING COMMERCIAL ANTENNAS

Reducing the maximum height specification from 6.1 m (20 ft) to 4.3 m (14 ft) and reducing the corresponding gain specification from 5 to 4.3 dBi means that several existing antennas manufactured by private firms meet or nearly meet the design requirements. Some of these antennas were obtained, and their electrical characteristics were measured. The performance of each antenna was evaluated by computing the received voltage from the measured radiation pattern data by using FLTSIM (see section 2.3).

3.1 Chu Associates Two-Channel UHF Antenna

A model CA-1079 two-channel UHF antenna was purchased from Chu Associates (Littleton, MA). The unit consists of two vertically stacked, radome-supported, broadband dipoles inside a fiberglass radome 8.9 cm (3.5 in.) in diameter and 148.6 cm (58.5 in.) long. A gain version of this antenna is available (Model CA-1402) that is essentially the two-channel model with an integral power divider. A multichannel antenna was purchased instead of a gain version so that the characteristics and the performances of the individual elements could be examined.

The impedance of the upper and lower elements was measured and is plotted on a Smith chart in figure 25. The VSWR is below the 2:1 specification level (indicated by a dashed line in the figure) over the 225- to 400-MHz band. Isolation between the upper and lower elements is greater than 20 dB, indicating good interelement decoupling (figure 26).

Radiation patterns of the upper and lower elements are shown in figure 27. The upper element has a gain of -0.5 dBi with the beam tilted slightly above the horizon. This gain is somewhat lower than the 0 dBi gain expected from a broadband dipole. The beam from the lower element is tilted almost 20° below the horizon. The gain is extremely low, -2 dBi at the peak and -3 dBi at the horizon. The low gain and beam tilting problems are evident also in radiation patterns taken at 225 and 400 MHz.

A 1.83-m (6-ft) mast attached to the mounting flange had little effect on the radiation patterns, indicating that mast coupling is small.

When an in-phase power divider is attached to the two inputs, a gain antenna is created. The resulting radiation pattern is shown in figure 28. The peak gain of only 2 dBi instead of the theoretical gain of 5 dBi is attributed chiefly to the low gain of the individual elements.

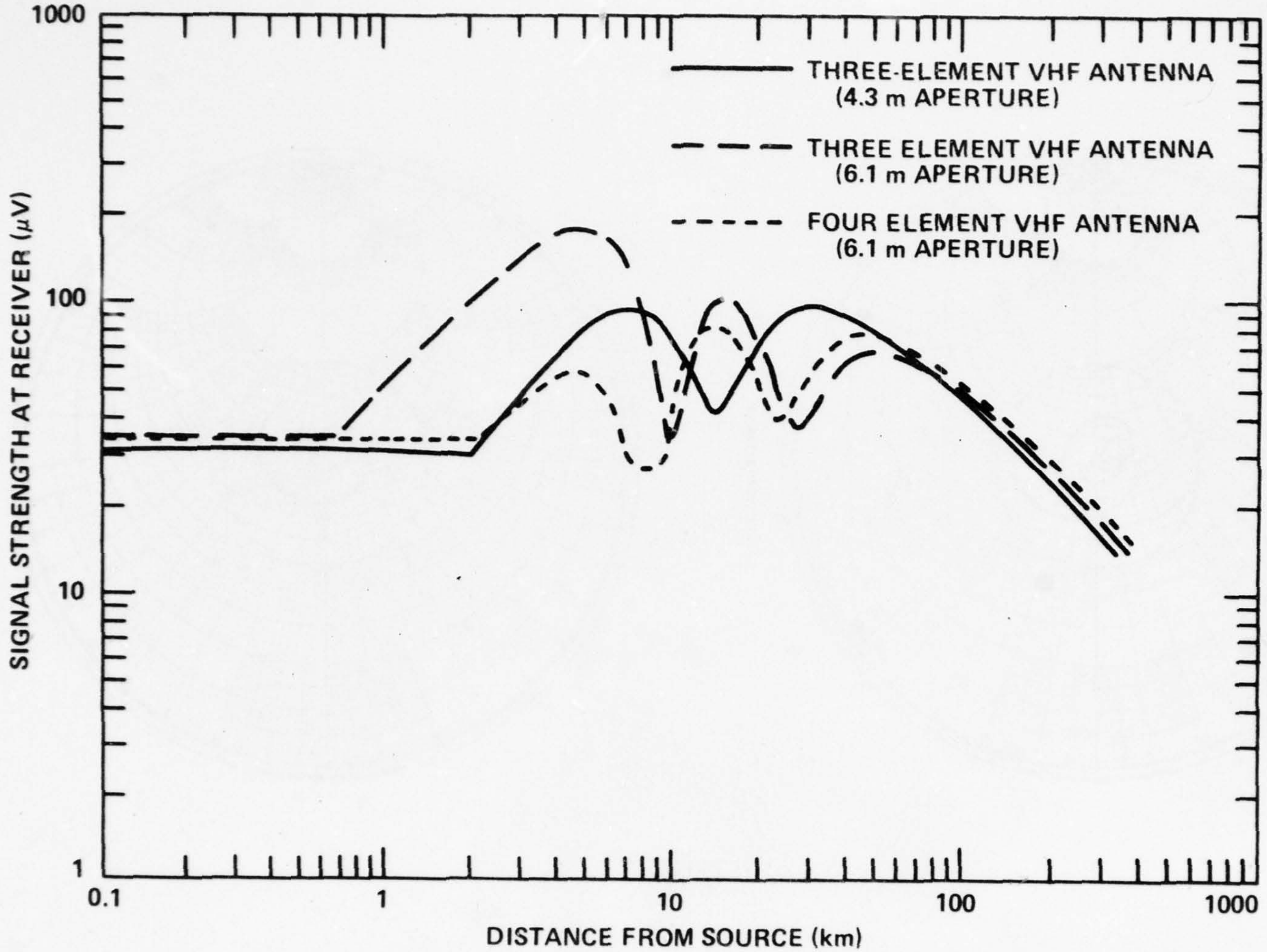
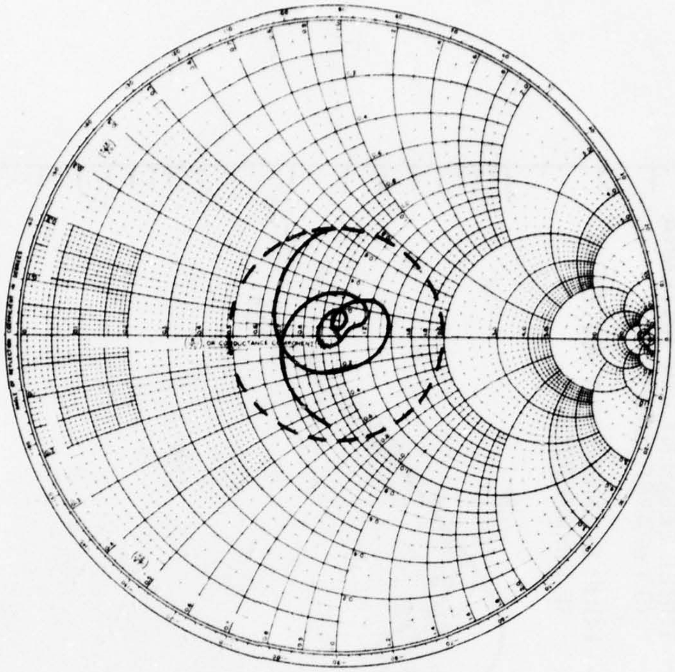
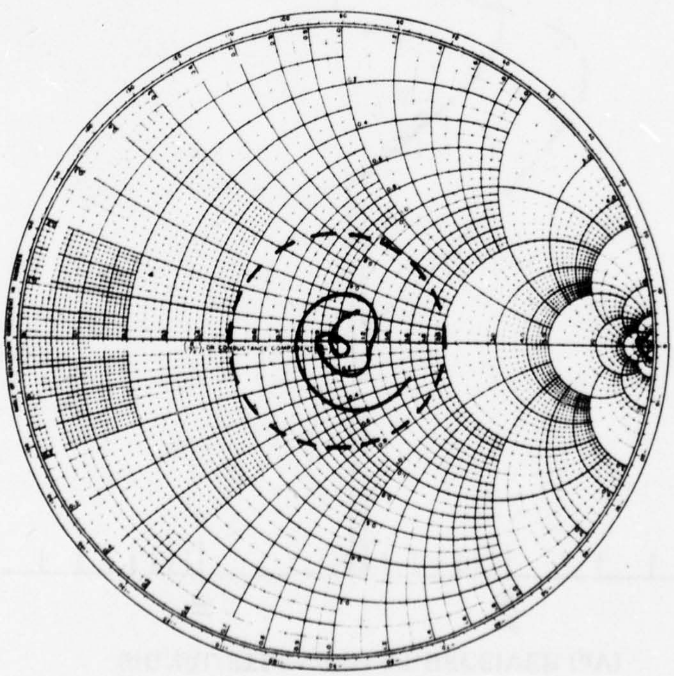


Figure 24. Received signal versus distance for three- and four-element 6.1-m VHF antennas and for three-element 4.3-m VHF antenna in free space (no multipath reflection signal).



(a) UPPER ELEMENT



(b) LOWER ELEMENT

Figure 25. Impedance of Chu model CA-1079 (225 to 400 MHz).

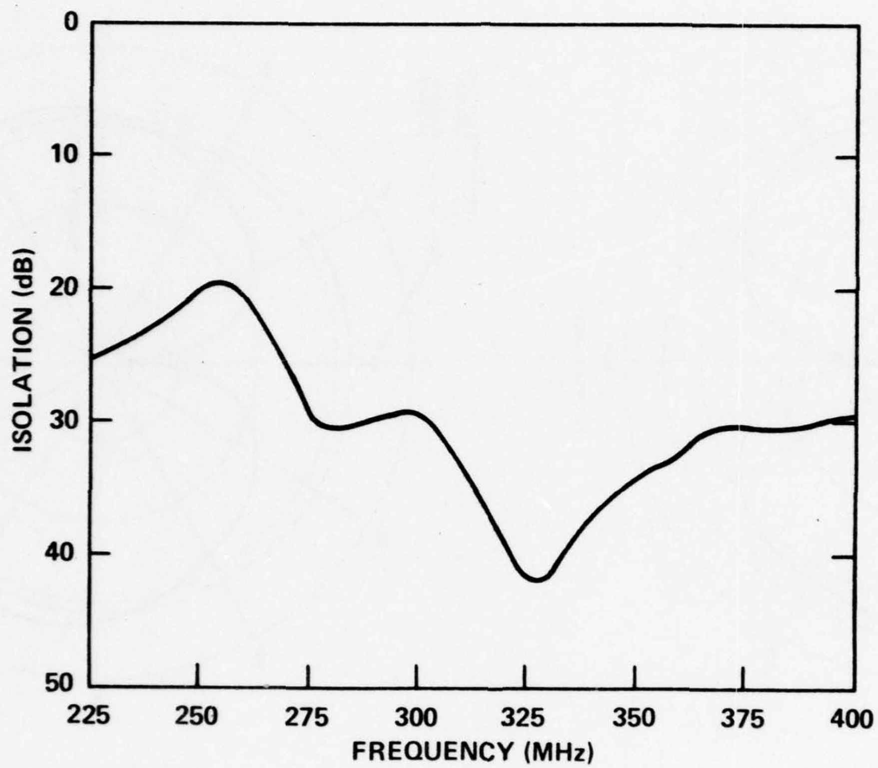


Figure 26. Isolation between upper and lower elements of Chu model CA-1079 two-channel UHF antenna.

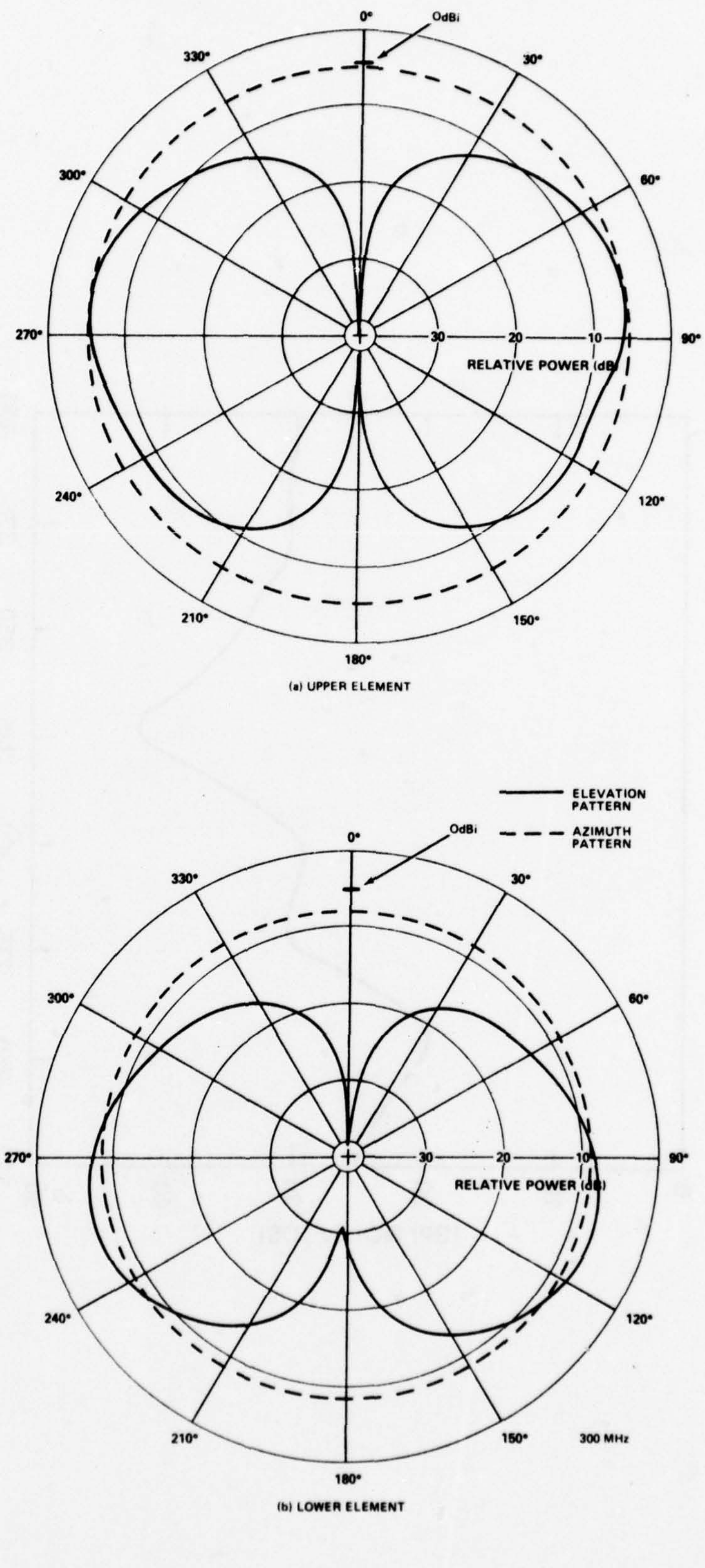


Figure 27. Radiation patterns of Chu model CA-1079 two-channel UHF antenna.

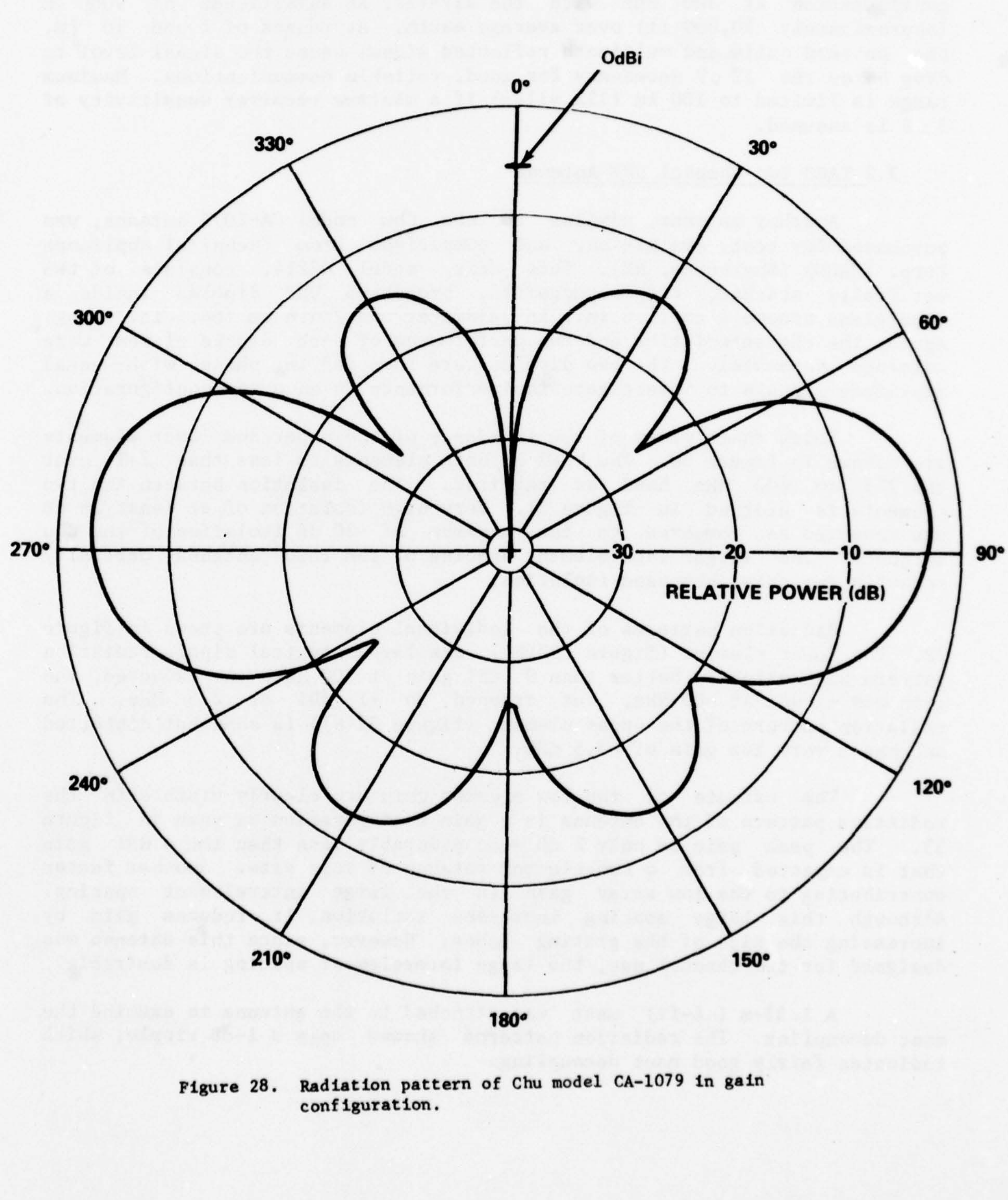


Figure 28. Radiation pattern of Chu model CA-1079 in gain configuration.

This measured data has been used to calculate the level of the signal at the aircraft receiver as a function of distance from the transmitter. As before, FLTSIM computes and plots the received voltage for aircraft flying at a constant altitude over a lossy-dielectric spherical earth. Figure 29 is a plot for the Chu model CA-1079 antenna in the gain configuration at 300 MHz with the aircraft at an altitude of 9000 m (approximately 30,000 ft) over average earth. At ranges of 2 and 10 km, the pattern nulls and multipath reflected signal cause the signal level to drop below the 12 μV necessary for good, reliable communications. Maximum range is limited to 180 km (112 miles) if a minimum receiver sensitivity of 3 μV is assumed.

3.2 TACO Two-Channel UHF Antenna

Another antenna, similar to the Chu model CA-1079 antenna, was purchased for test, evaluation, and comparison from Technical Appliance Corp. (TACO) (Sherburne, NY). This unit, model D2214, consists of two vertically stacked, radome-supported, broadband UHF dipoles inside a fiberglass radome 4 cm (1.6 in.) in diameter and 214.6 cm (84.5 in.) long. Again, the characteristics and the performance of each dipole element were examined separately. The two dipoles were then fed in phase with equal amplitude signals to investigate the performance in an array configuration.

Smith chart plots of the impedance of the upper and lower elements are shown in figure 30. The VSWR of both elements is less than 2:1 over the 225 to 400 MHz band as required. The isolation between the two elements is plotted in figure 31. Very high isolation of at least 28 dB was measured as compared to the minimum of 20 dB isolation of the Chu antenna. The larger interelement spacing of the TACO antenna partially accounts for this increased isolation.

Radiation patterns of the individual elements are shown in figure 32. The lower element (figure 32(b)) displays a typical dipole radiation pattern with slightly better than 0 dBi gain at 300 MHz. As expected, the gain was +1 dBi at 400 MHz, but dropped to -1 dBi at 225 MHz. The radiation pattern of the upper element (figure 32(a)) is somewhat distorted and has a very low gain of -3.5 dBi.

The effects of the low element gain are clearly visible in the radiation pattern of the antenna in a gain configuration as seen in figure 33. The peak gain is only 2 dBi--considerably less than the 4 dBi gain that is expected from a two-element antenna of this size. Another factor contributing to the low array gain is the large interelement spacing. Although this large spacing increases isolation, it reduces gain by increasing the size of the grating lobes. However, since this antenna was designed for two-channel use, the large interelement spacing is desirable.

A 1.83-m (6-ft) mast was attached to the antenna to examine the mast decoupling. The radiation patterns showed only a 1-dB ripple, which indicates fairly good mast decoupling.

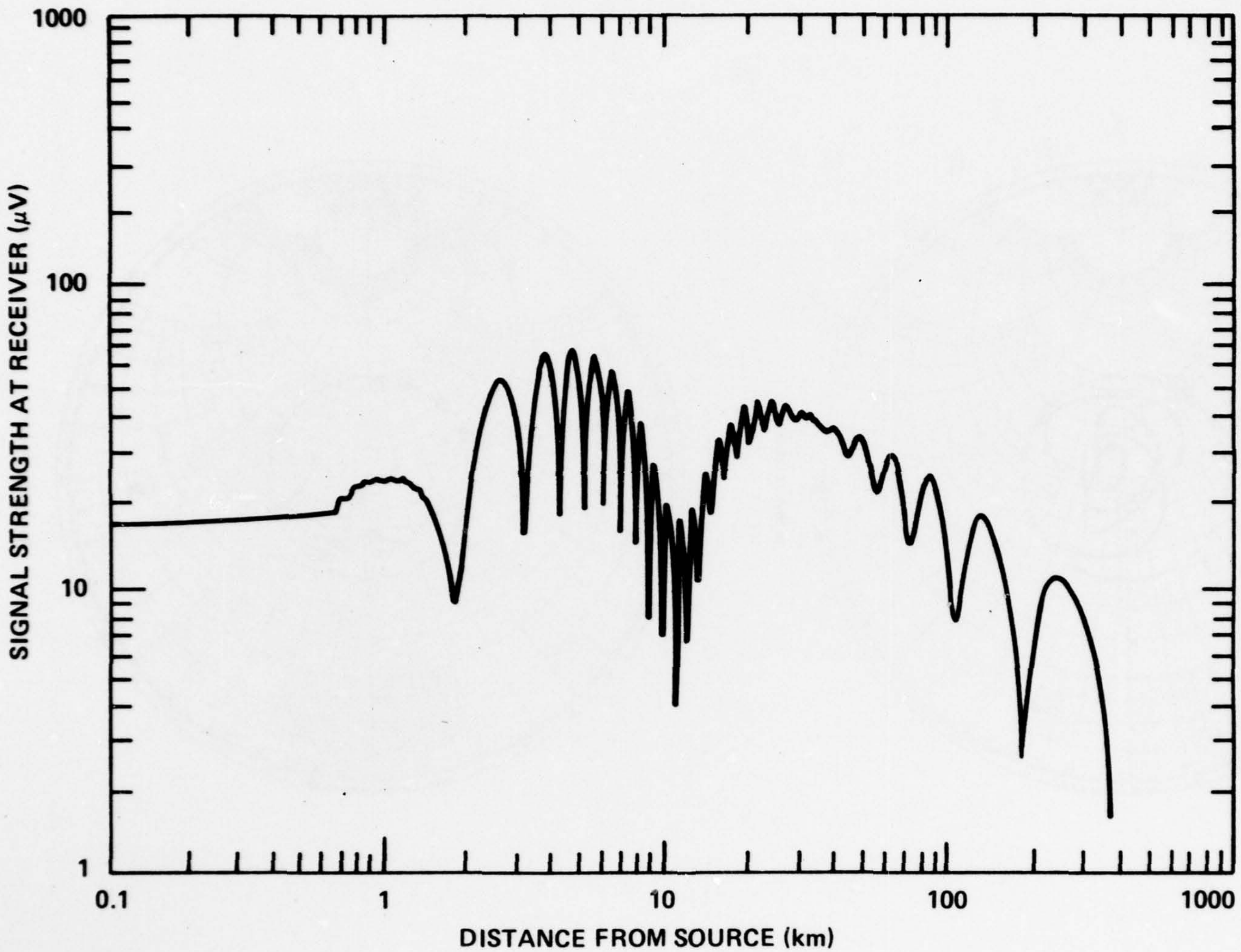
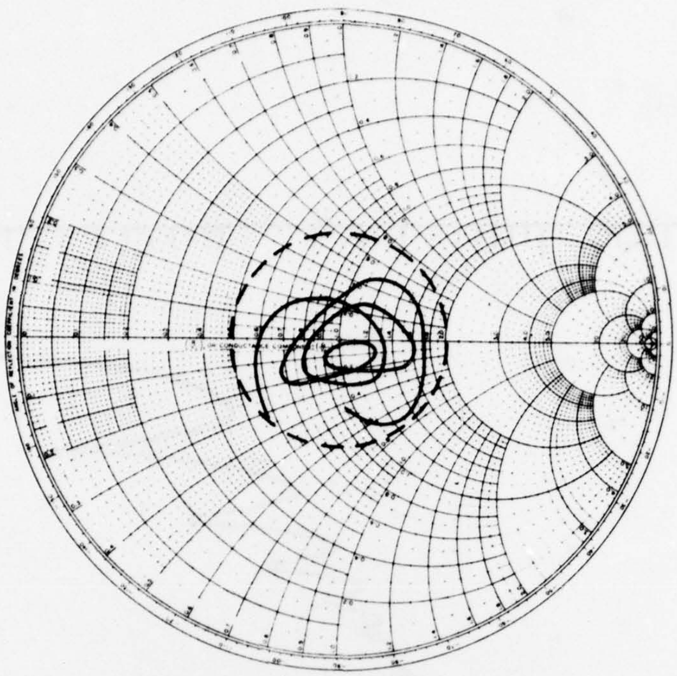
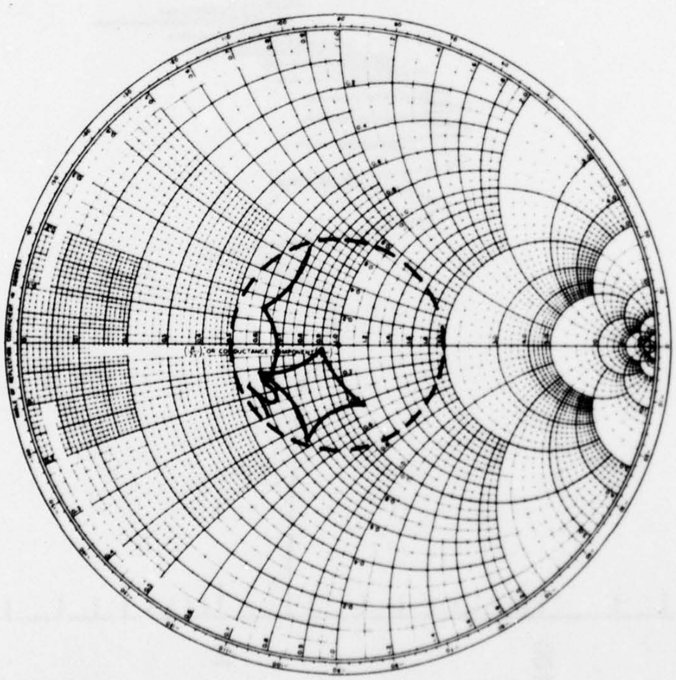


Figure 29. Received-voltage versus distance for Chu model CA-1079 UHF antenna in gain configuration at 300 MHz.



(a) UPPER ELEMENT



(b) LOWER ELEMENT

Figure 30. Impedance of TACO model D2214 two-channel UHF antenna (225 to 400 MHz).

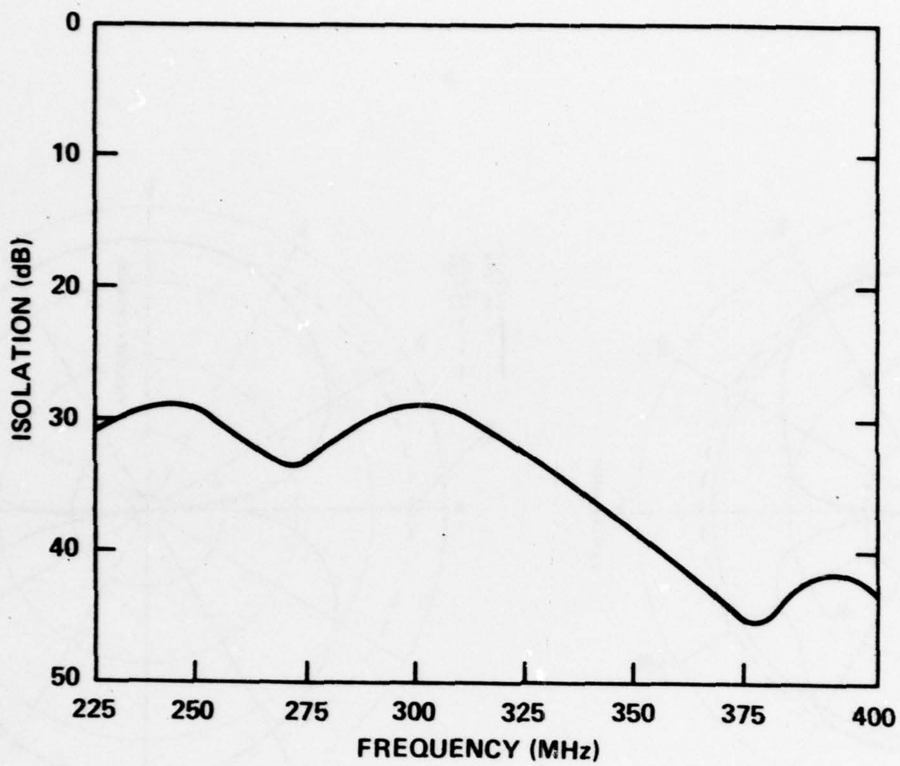


Figure 31. Isolation between upper and lower elements of TACO model D2214 two-channel UHF antenna.

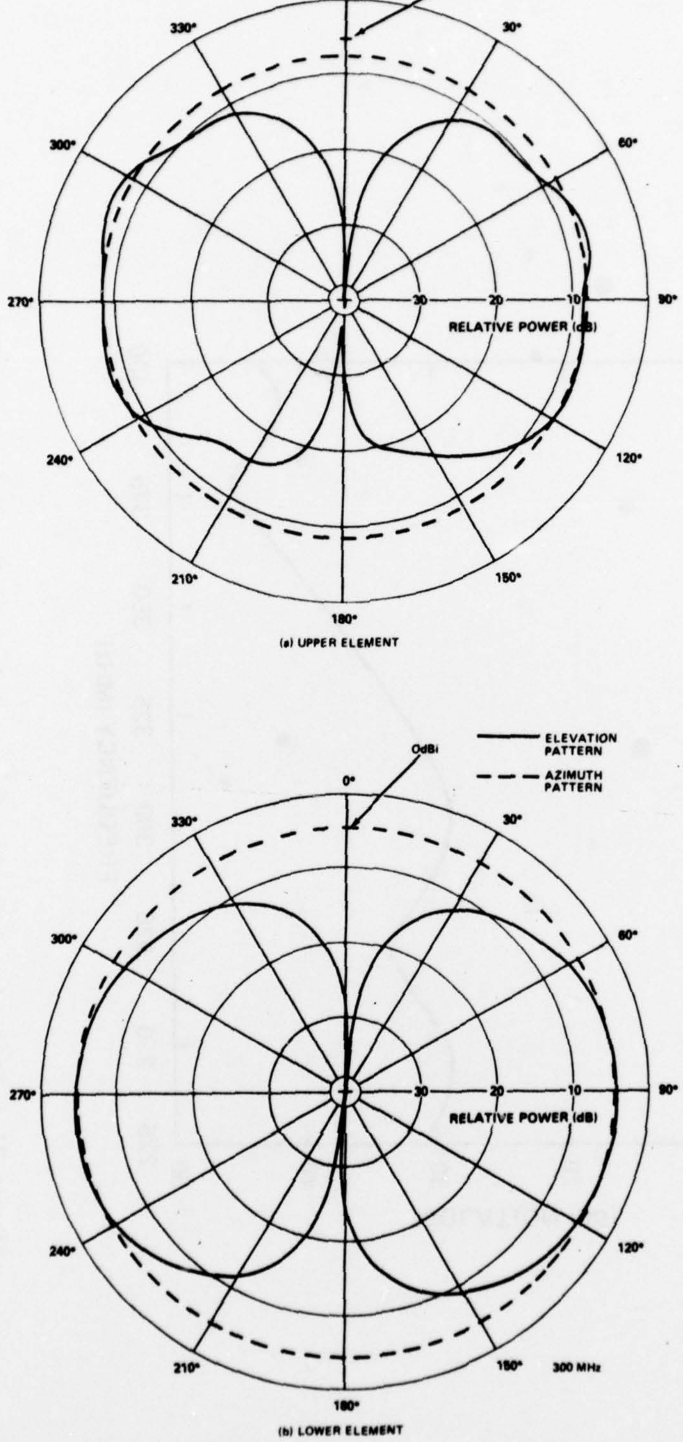


Figure 32. Radiation patterns of TACO model D2214 two-channel UHF antenna.

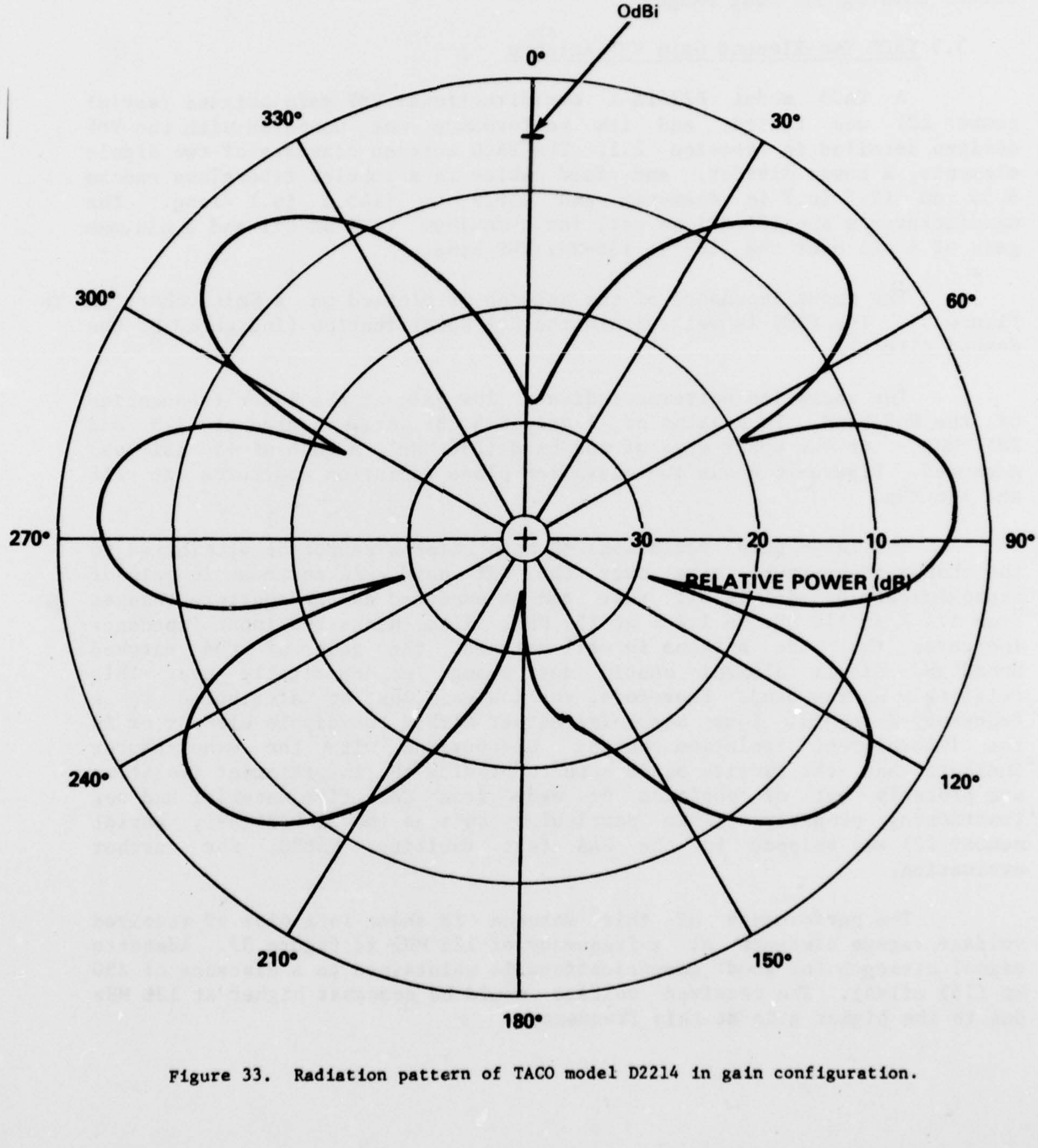


Figure 33. Radiation pattern of TACO model D2214 in gain configuration.

The calculated received voltage is plotted versus distance in figure 34 for an aircraft at a 9000-m altitude over average earth. The large grating lobe at 45° in the radiation pattern corresponds to the maximum in received voltage at an 8-km range. The power radiated at these close ranges would be better radiated closer to the horizon to provide better coverage at long range.

3.3 TACO Two-Element Gain VHF Antenna

A TACO model D2261A-1 omnidirectional VHF gain antenna (serial number 22) was tested, and its performance was compared with the VHF designs detailed in section 2.1. The TACO antenna consists of two dipole elements, a power divider, and feed cables in a tubular fiberglass radome 6.35 cm (2.5 in.) in diameter and 356.9 cm (140.5 in.) long. The manufacturer's specifications call for a maximum VSWR of 2:1 and a minimum gain of 4 dBi over the 118- to 136-MHz VHF band.

The input impedance of the antenna is plotted on a Smith chart in figure 35. The VSWR is well within the 2:1 specification (indicated by the dashed circle).

The radiation patterns indicate low gain at the lower frequencies of the VHF band. Peak gains of -1 and -0.5 dBi were measured at 118 and 125 MHz. At the upper edge of the band (136 MHz), a gain of +5 dBi was measured. Figure 36 shows the elevation-plane radiation patterns at 118 and 136 MHz.

The large gain variations of this antenna cannot be attributed to the change in aperture size over the VHF band. An increase in gain of approximately 0.5 dBi is all that can be expected as the aperture changes from 1.4 λ at 118 MHz to 1.6 λ at 136 MHz. Also, since the input impedance indicates that the antenna is well matched, the gain of the matched broadband dipole element should not change so drastically over this relatively narrow band. Therefore, the low gain must be attributed to a frequency-dependent loss mechanism either within the dipole element or in the interelement isolation chokes. Discussions with the manufacturer indicate that the ferrite beads used to provide the interelement isolation are probably out of position or made from defective material and not functioning properly. This particular antenna (model D2261A-1, serial number 22) was shipped to the FAA test facility, NAFEC, for further evaluation.

The performance of this antenna is shown in a plot of received voltage versus distance at a frequency of 125 MHz in figure 37. Adequate signal strength for good communications is maintained to a distance of 250 km (155 miles). The received voltage would be somewhat higher at 136 MHz due to the higher gain at this frequency.

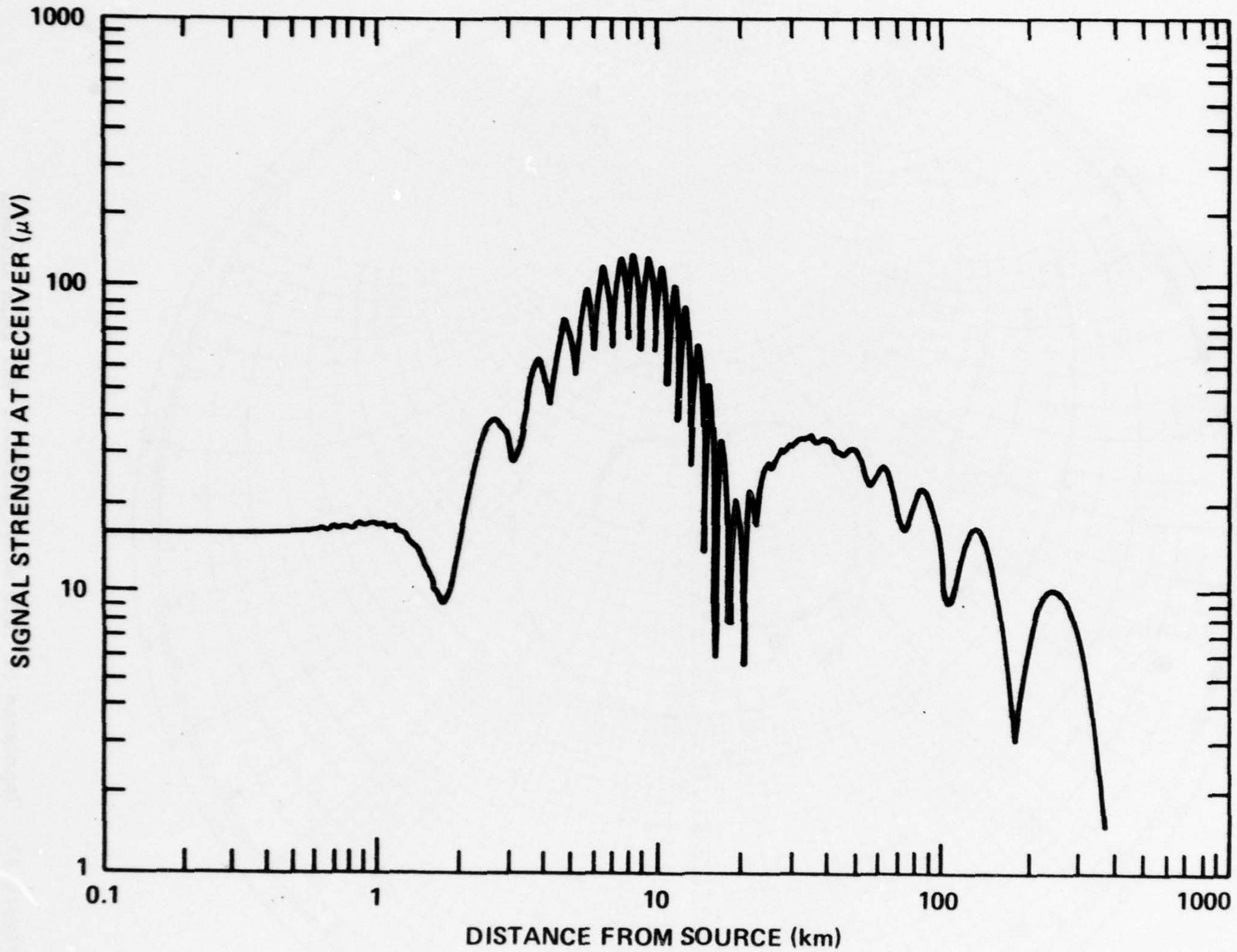


Figure 34. Received voltage versus distance for TACO model D2214 UHF antenna in gain configuration at 300 MHz.

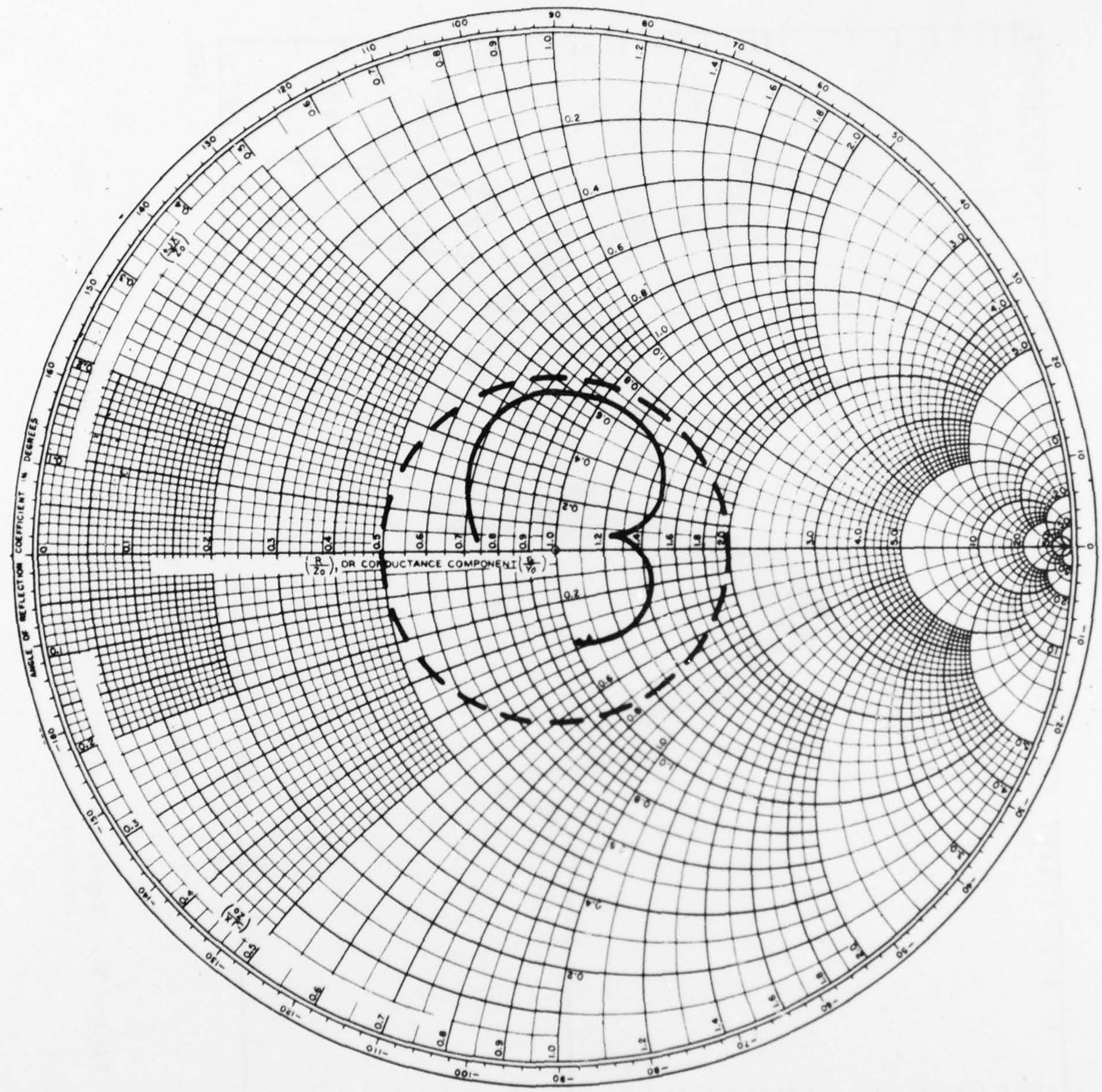


Figure 35. Impedance of TACO model D2261A-1 VHF gain antenna (118 to 136 MHz).

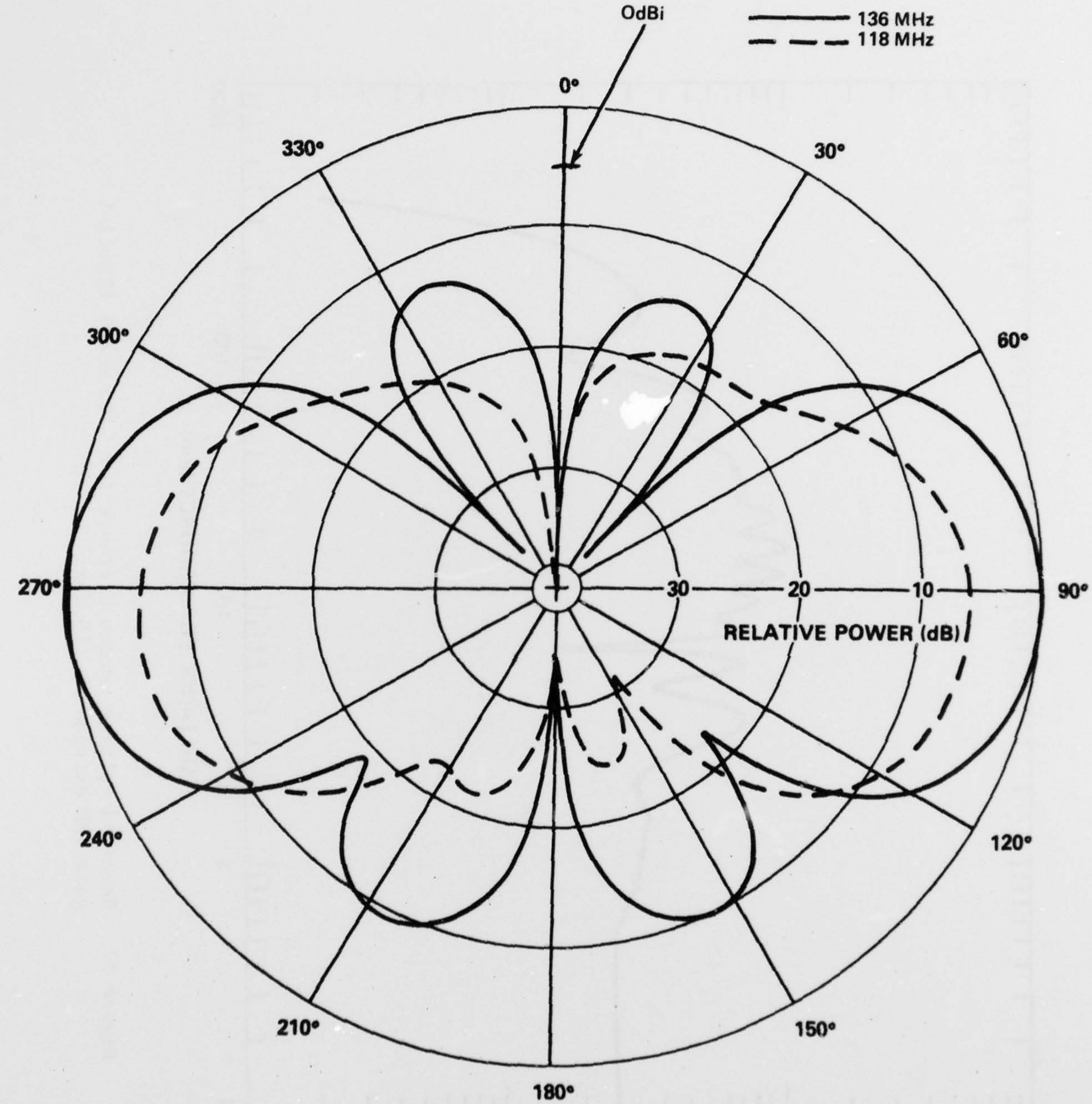


Figure 36. Radiation patterns of TACO model D2261A-1 VHF gain antenna.

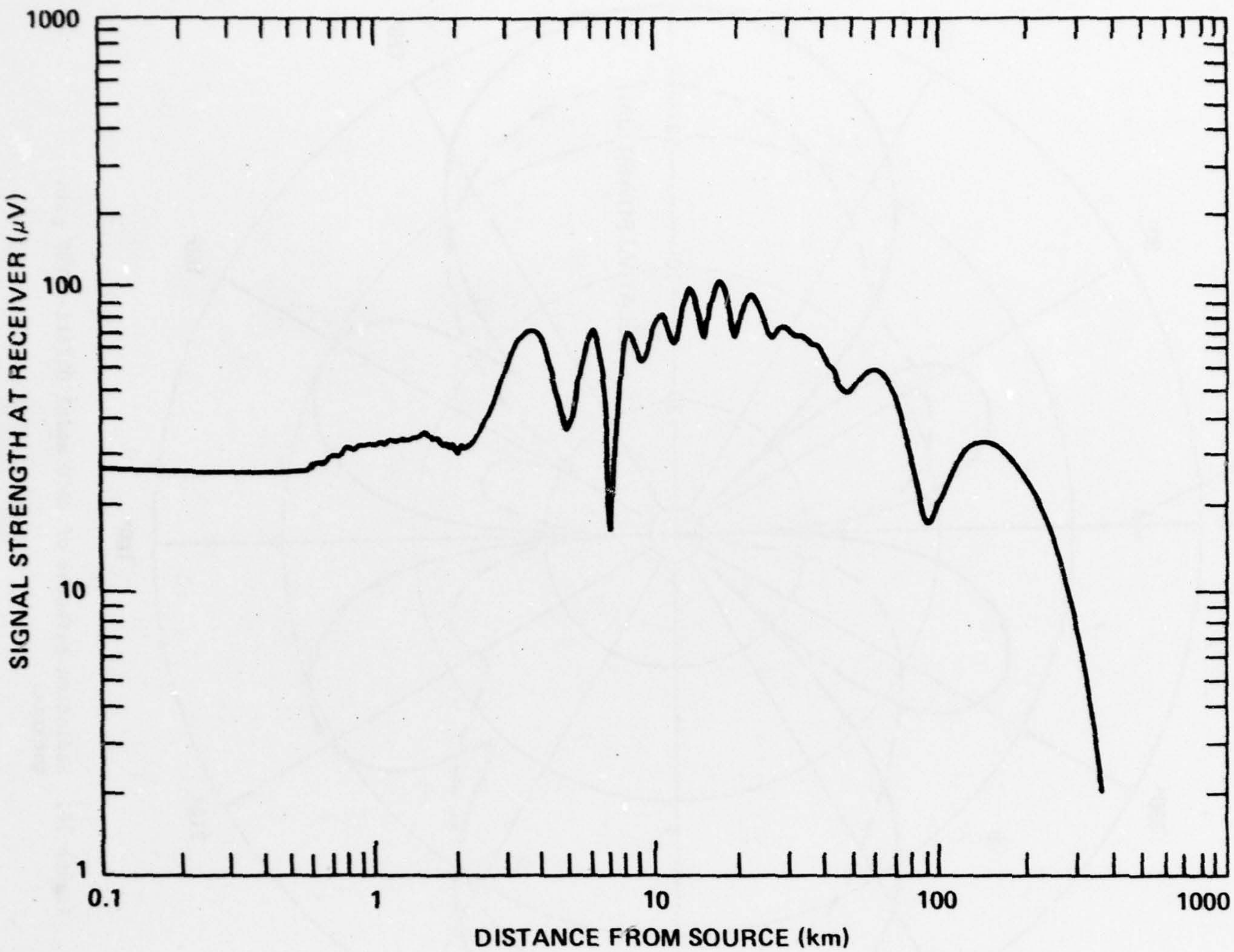


Figure 37. Received voltage versus distance for TACO model D2261A-1 gain VHF antenna at 125 MHz.

3.4 Comparison of Predicted Performance

The calculated received voltages for both the Chu CA-1079 and the TACO D2214 UHF antennas in gain confugurations is shown in figures 29 and 34. The modulation effect of the ground reflected signal makes it very difficult to compare the performance of these antennas. Therefore, to simplify the comparison, the multipath reflected signal is ignored and the signal strengths are plotted in figure 38. The signal strength corresponding to a single broadband dipole antenna having 0-dBi gain also is plotted on this figure. Both the TACO and the Chu antennas have nulls in the radiation patterns that cause low received signal levels at relatively close ranges of 10 to 20 km (6 to 12 miles). At a range of 40 km (24 miles) both commercial antennas provide higher signal levels than the single dipole antenna. At the maximum range, where the curvature of the earth just blocks the direct signal, the gain antennas provide approximately 3.8 μV to the receiver, while the single dipole antenna curve indicates that a 3-μV signal would be received. Both gain antennas have 2-dBi gain at the horizon. The ratio of the 3.8-μV signal to the 3-μV signal corresponds exactly to a gain difference of 2 dB.

A similar graph for the TACO model D2261A-1 VHF gain antenna is shown in figure 39. Again, a single 0-dBi gain dipole antenna curve is plotted for comparison. Since both antennas have 0-dBi gain at the horizon, the signal levels at long range are the same. At close range, the single dipole actually provides a high received voltage level since the dipole pattern is significantly broader than the TACO antenna pattern.

4. CONCLUSIONS

A large number of antenna designs have been evaluated for possible use at ground facilities of the FAA's air/ground communications system. These antennas were intended to be replacements for existing VHF and UHF antennas and were expected to offer improved radiation patterns, higher gains, and full-bandwidth operation. The required antennas were of two types: omnidirectional and directional.

Initial requirements permitted an antenna height (or length) of 6.1 m (20 ft). By using a vertical array of broadband, dipole-type elements, omnidirectional VHF antennas having 5-dBi gain can be built within this height limit. Because of the shorter wavelength at UHF, 5-dBi gain omnidirectional antennas can be built within a much smaller aperture. By using a yagi antenna, a 10-dBi gain directional antenna can be built for the VHF band. However, to build directional antennas for the UHF band, log-periodic designs are required. A pyramidal, log-periodic antenna will have 9- to 10-dBi gain.

At the FAA's request, the Harry Diamond Laboratories (HDL) evaluated omnidirectional antenna designs subject to a reduced height limit of 4.3 m (14 ft). By using two- and three-element arrays, VHF antennas having approximately 4.3 dBi gain can be built. These antennas would be constructed of lightweight materials and would be potted by foaming material inside a tubular, fiberglass radome that supports the entire structure. Antennas of this type are being manufactured and used by the FAA and the military.

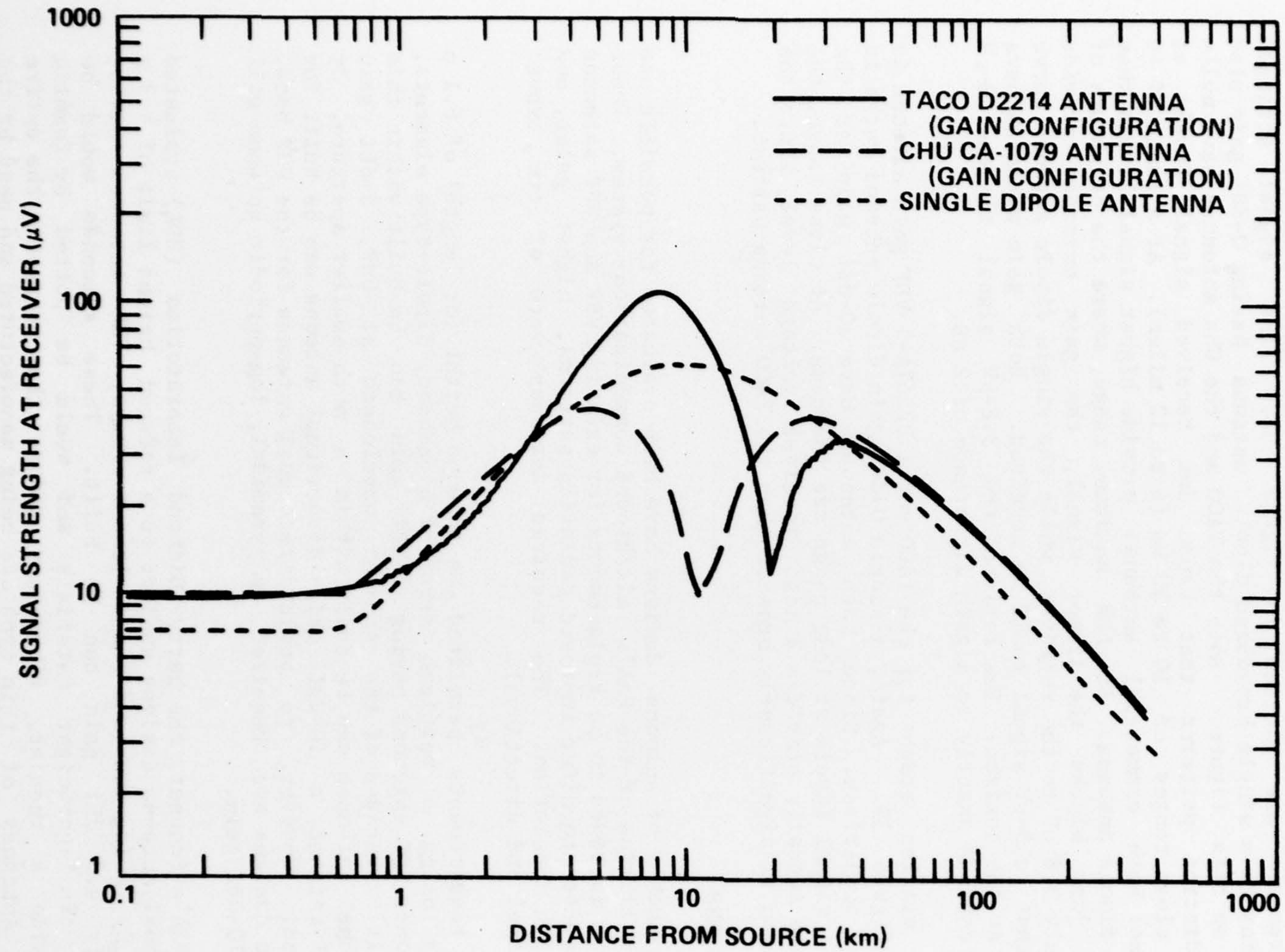


Figure 38. Received signal versus distance for TACO D2214 and Chu CA-1079 antennas in gain configurations and for single dipole antenna at 300 MHz in free space (no multipath reflection signal).

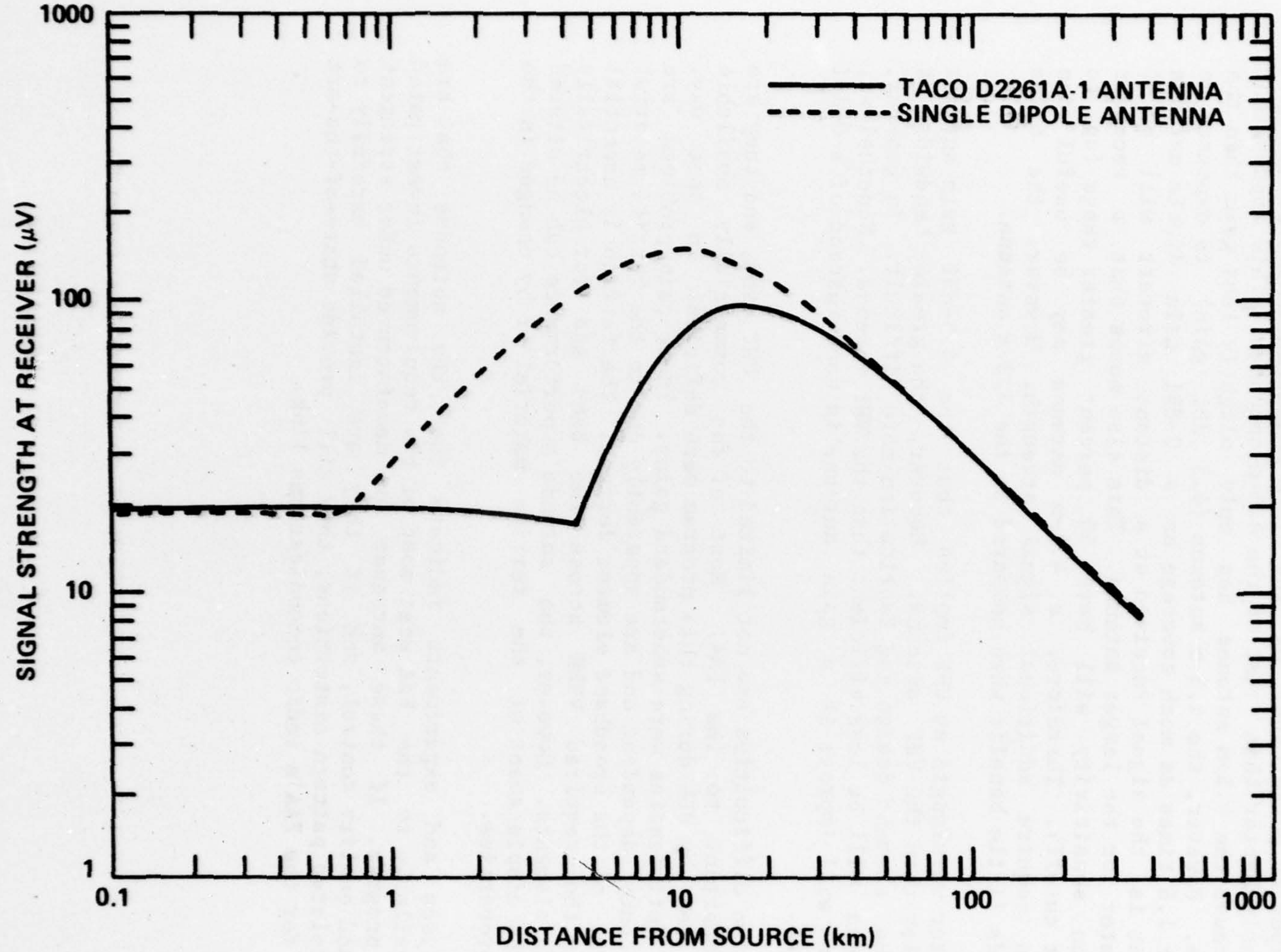


Figure 39. Received signal versus distance for TACO model D2261A-1 VHF gain antenna and single dipole antenna at 125 MHz in free space (no multipath reflection signal).

The performances of the new 6.1- and 4.3-m designs have been analyzed and compared to each other and to existing commercial antennas. By using a flight simulation program, a computer analysis of the signal received by an aircraft has been calculated. This calculation permits a comparison of the antennas with respect to their performance in the radio communications link. The expected performance of the 6.1-m omnidirectional VHF antennas is only slightly better than that of the 4.3-m antennas. This improvement is slight because the 4.3-m antenna has only slightly less gain than the 6.1-m antenna. However, the 4.3-m antenna (4.3 dBi gain) is expected to provide about 1.6 times as much coverage as a 0-dBi gain dipole antenna (2.5 m). That is, the signal received at a distant aircraft will be 60 percent greater for the larger antenna. This also means that a receiver with a given sensitivity will have 60 percent greater range (up to line-of-sight cutoff). Therefore, a 4.3-m antenna may be useful when circumstances require additional signal strength. However, the 6.1-m antenna yields little benefit when compared to the 4.3-m antenna.

The shorter wavelength at UHF implies that the 4.5-dBi gain antenna will be smaller than the VHF antenna. However, the greater bandwidth at UHF makes the element design and fabrication more difficult. In general, the UHF antenna will be less efficient than the VHF antenna. Nonetheless, communications will improve if a gain antenna is used instead of a 0-dBi dipole antenna.

Fabrication difficulties are not limited to the UHF band, and they are extremely important to the FAA. Most of the commercially available antennas tested by HDL during this program were deficient in some way. Most of the deficiencies were substandard gains. These gain problems are usually frequency dependent and are apparently due to the ferrite material used in most of the broadband element designs. The ferrite is essential for obtaining the required VSWR across the band and for electrically isolating the elements. However, the antenna's performance can be altered drastically by misplacement of the ferrite material or by changes in the material's properties.

The analyses and experiments indicate that the antennas that are presently available to the FAA meet most of the requirements investigated during this program. If these antennas are manufactured under stringent tolerances and quality control, and if they are installed carefully to avoid site-related pattern distortions, they will provide state-of-the-art performance for the FAA's radio communications link.

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1. Sindoris, A., Farrar, F., and Schaubert, D., Design of VHF and UHF Communications Air/Ground Antennas--Interim Report, Federal Aviation Administration, Washington, D.C., (1978).