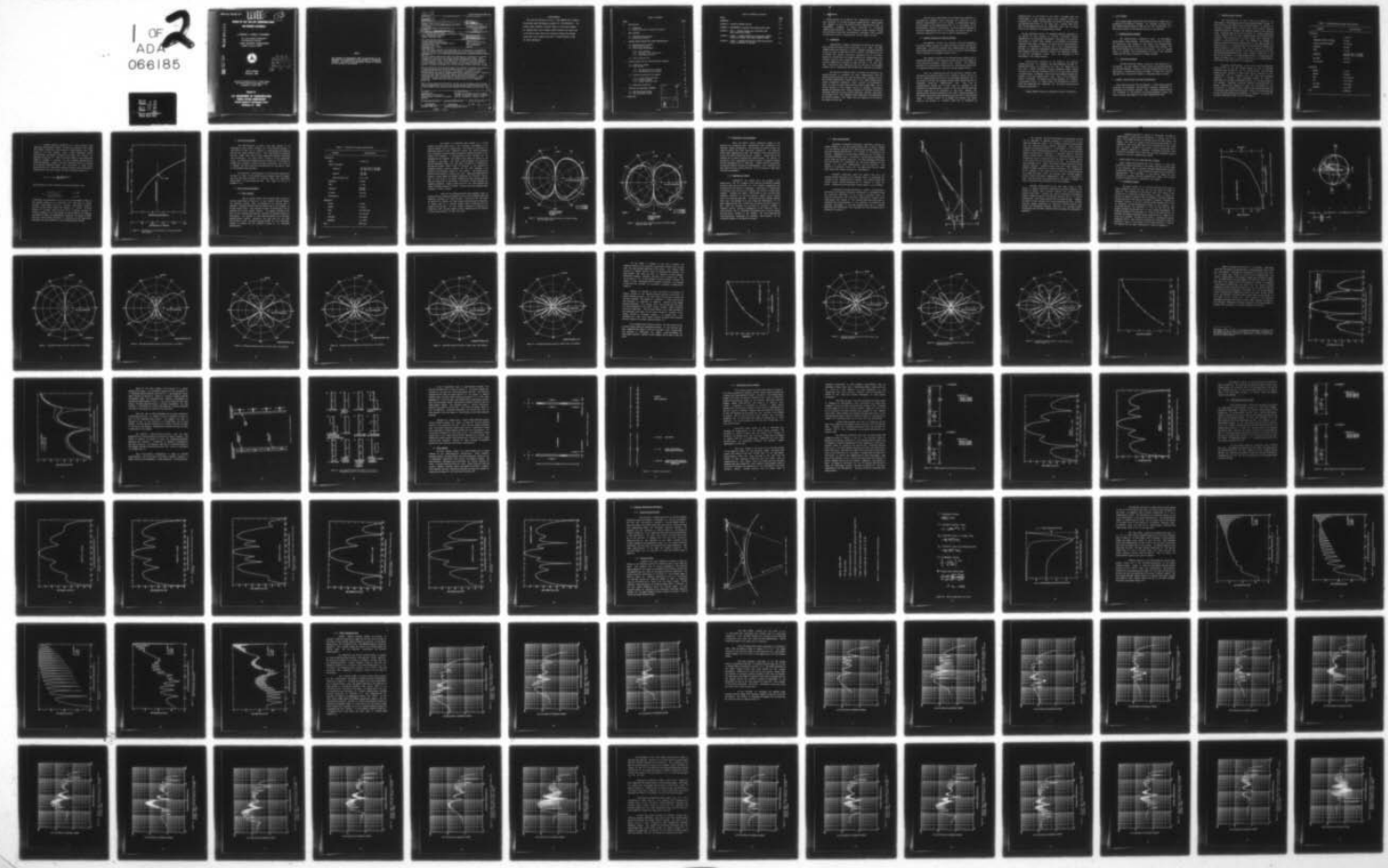
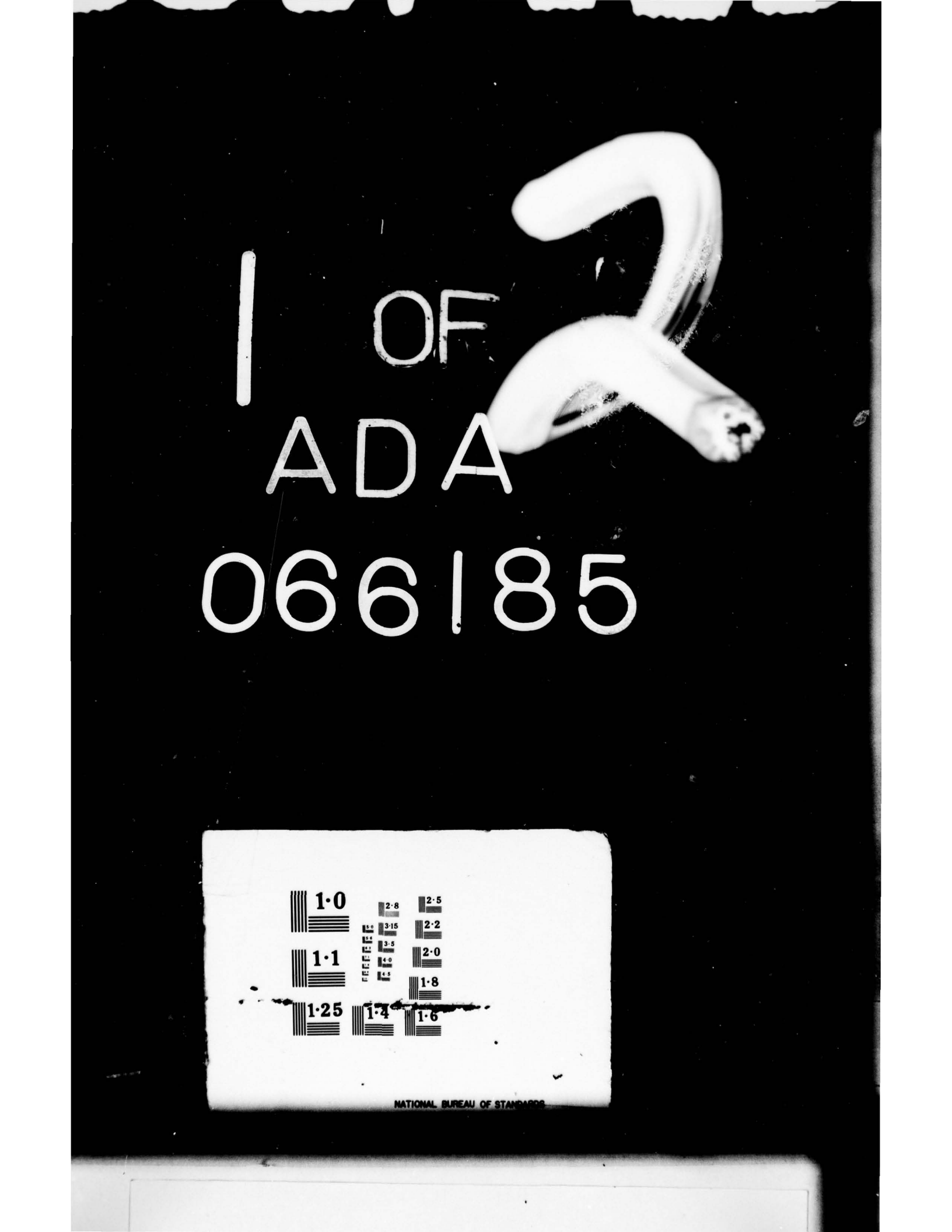
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Report No. FAA-RD-79-7

LEVEL II

12 B.S

DESIGN OF VHF AND UHF COMMUNICATIONS AIR/GROUND ANTENNAS

A. SINDORIS, F. FARRAR, D. SCHAUBERT

U.S. Army Materiel Development
and Readiness Command

HARRY DIAMOND LABORATORIES
Adelphi, Maryland 20783

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15. Supplementary Notes

This study report completes the design phase for new antennas to be subsequently built and evaluated in the follow-up phases, and to have ultimate application in improving the R.F. voice communications coverage used in air/ground traffic control.

16. Abstract

The Harry Diamond Laboratories (HDL) has undertaken the investigation of improved communication antennas for the Federal Aviation Administration (FAA). These antennas are used in VHF (118-136 MHz) and UHF (225-400 MHz) frequency spectrums in air/ground air traffic control operations. The FAA is looking for improved antenna standards in terms of space coverage and environmental durability, in the process of planning replacements for several thousand current operational antennas.

HDL has devoted an intensive design search into available technology, and conducted a concurrent analysis of the key variables affecting the performance of FAA antennas during the first six months of this effort. In doing so, it has concentrated on six types of antennas specifically designated for primary consideration by the FAA, namely VHF and UHF dipoles, VHF and UHF medium gain omnidirectional types, and high-gain VHF and UHF directional antennas. Certain constraints were also specified such as limiting sizes and weights, and power capacities. Analysis was also required in related areas such as lightning protection.

The two dipole designs were deleted by the FAA, but the remaining results include design recommendations for four of the FAA applications and should prove very useful in establishing future antenna design standards and performance specifications.

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TABLE OF CONTENTS

Title		Page
1.	INTRODUCTION	1
	1.1 Background	1
	1.2 General Criteria for Improved Antennas	2
2.	BASIC DESIGNS	4
	2.1 Omnidirectional Antennas	4
	2.2 Directional Antennas	4
3.	ANTENNA SPECIFICATIONS AND OTHER CONSIDERATIONS	4
	3.1 Omnidirectional Antennas	5
	3.2 Directional Antennas	9
	3.3 Other Design Requirements	9
	3.3.1 Mast Coupling	9
	3.3.2 Reliability and Maintenance	14
	3.3.3 Lightning and Static	14
	3.4 Other Considerations	15
4.	DESIGN CONCEPT FOR GAIN OMNIDIRECTIONAL ANTENNAS	18
	4.1 Prelminiary Designs	18
	4.2 Final Designs	39
	4.2.1 VHF Omnidirectional Designs	42
	4.2.2 UHF Omnidirectional Designs	47
	4.3 Simulated Operational Performance	55
	4.3.1 Ground Reflection Model	55
	4.3.2 Vertical Lobing	55
	4.3.3 Flight Simulation Data	66
	4.4 Mechanical Properties	94
5.	DESIGNS FOR DIRECTIONAL ANTENNAS	101
	5.1 VHF Directional Design	101
	5.2 UHF Directional Design	101
6.	CONCLUSION	101

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TABLE OF CONTENTS (Continued)

Title		Page
REFERENCES		104
APPENDIX A	ISOLATION BETWEEN DIPOLES	A-1
APPENDIX B	MEASUREMENT OF ANTENNA VSWR THROUGH LOSSY CABLE	B-1
APPENDIX C	ARY4 -- FORTRAN PROGRAM FOR CALCULATING FREE SPACE RADIATION PATTERNS	C-1
APPENDIX D	FIXEDR -- FORTRAN PROGRAM FOR CALCULATING ANTENNA RADIATION PATTERNS OVER SMOOTH SPHERICAL EARTH	D-1
APPENDIX E	FLTSIM -- FORTRAN PROGRAM FOR CALCULATING RECEIVED SIGNAL AS FUNCTION OF DISTANCE	E-1

1. INTRODUCTION

Design concepts for new VHF and UHF communications antennas have been developed to provide air/ground communications. These antennas are intended for use by the Federal Aviation Administration (FAA) as standardized equipment at ground facilities of air/ground communications operations. These improved antenna designs provide state-of-the-art electrical and mechanical performance while meeting the important practical considerations of size, weight, and cost.

1.1 Background

Communication 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 channel allocations separated by 25, 50 or 100 kHz. Channels in the VHF band are intended primarily for communications with civilian aircraft--both 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) over a certain portion of the airspace sector is required, 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.

With the recent improvements in performance and reliability of the radios and telephone lines connecting the controllers to the remotely located radios, it is now possible to significantly improve the performance of the communications link by an improvement in the ground antenna portion of the system. The heavy work load imposed on the radio communications link by increasing air-traffic density is partially responsible for this need to improve communications.

1.2 General Criteria for Improved Antennas

The important criteria for improved electrical performance from these antenna concepts are complete radiation pattern coverage and antenna gain. 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 antenna so as 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 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 is acceptable over angular portions where the aircraft is high over head 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 most important criteria 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 all weather conditions and in many situations at radio sites far from maintenance personnel, environmental durability and a 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, are also considered since it is in some cases possible to adjust antenna performance factors that will maximize overall performance of the radio communications link. These are the peripheral effects considered: (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.

Antenna design criteria are discussed in detail in section 3.

2. BASIC DESIGNS

Four antenna design concepts have been developed to satisfy the requirements of the improved antennas. The antennas are these: (1) a gain omnidirectional antenna for VHF and one for the UHF band, (2) a directional antenna for the VHF band and one for the UHF band.

2.1 Omnidirectional Antennas

The omnidirectional antennas are three- or four-element, linear phased array antennas. Each element in the array is a dipole. The array has a gain maximum on the horizon and omnidirectional azimuthal coverage with no holes in the vertical plane coverage. The VHF and UHF designs are electrically very similar. The two designs differ in physical size by approximately the ratio of the operating frequencies with small differences in element spacing.

2.2 Directional Antennas

The VHF directional antenna concept is a yagi antenna of 6 to 10 elements. The exact number is chosen to give the required high gain over the VHF bandwidth. Because of the large bandwidth required of the UHF antenna, a log-periodic antenna is needed. To obtain the required high gain from a log-periodic antenna, a pyramidal design is chosen.

3. ANTENNA SPECIFICATIONS AND OTHER CONSIDERATIONS

These antenna concepts that are designed to meet certain specific electrical and mechanical specifications represent improvements in performance over existing antennas. Also, peripheral design criteria are considered in the design of the improved antennas to insure that there is overall improvement of the radio communications link.

3.1 Omnidirectional Antennas

The specifications in table 1 have been applied in the development of the design concepts for the omnidirectional antenna. A gain of 5 dBi at the maximum in the radiation pattern is obtained by vertically arraying dipole antennas. This large vertical aperture produces the gain by narrowing the radiation pattern in the elevation plane. Sufficient gain in the vertical plane is, however, maintained to give adequate ERP for good communications with aircraft located overhead. (The calculations of received signal level discussed in section 4.3 show this to be true.) The antennas are designed to produce 5-dBi 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 the gain omnidirectional antennas in some cases 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 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.)

Table 1. 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 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

A maximum aperture height of 6 m is the practical limit imposed on the mechanical design. At VHF, this aperture size limits the maximum theoretical gain available to approximately 7 dBi. When losses in the feed network, cable losses, nonuniform current distributions, and radiator efficiencies are taken into account, the specified actual gain of 5 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 radiation pattern of

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

The directivity is then calculated by pattern integration from

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

At UHF where the wavelength is 1/2 to 1/3 of the wavelength at VHF, the 6-m maximum height is not restrictive and 5-dBi gain is easily achieved. Light weight (9 kg) 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 with 1.25 cm of ice at a maximum altitude of 3.8 km in humidity of 5 to 100 percent are the extremes of the physical environment to which the communications antennas are exposed. A $1000 unit cost, which affects the choice of materials and the construction technique, has been considered in the following design concepts.

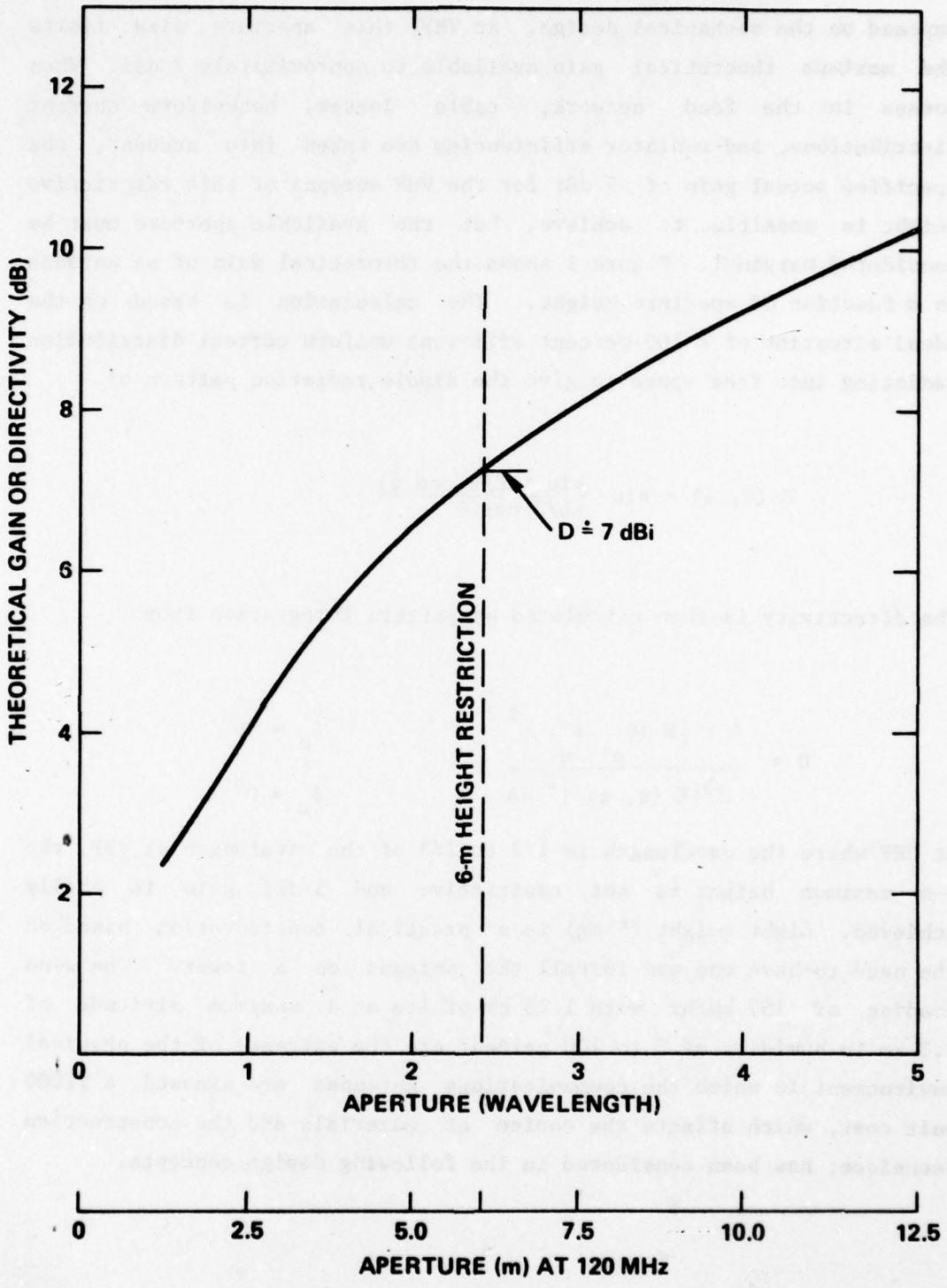


Figure 1. Directivity of wire antenna with uniform current distribution.

3.2 Directional Antennas

The specifications in table 2 have been applied in the development of the design concepts for the directional antennas. A gain value of 10 dBi can be achieved by concentrating the radiation pattern over a small airspace sector. The beam widths are consistent with the 10-dBi gain value but will change with frequency especially over the UHF band. The beam widths in table 2 are only approximate values. By limiting the backward directed radiation to 18 dB below the forward peak, coupling to towers and support structures can be held to a minimum. The other electrical specifications are the same as those of the omnidirectional antennas.

The mechanical specifications of the directional antennas are the same as those of the omnidirectional antennas except for height. Since the directional antennas are end-fire types, the appropriate specification is length along the boom. This length is set at a maximum of 6 m.

3.3 Other Design Requirements

3.3.1 Mast Coupling

When an antenna couples radio frequency (RF) currents to the mast supporting the antenna or to any metallic structure nearby, the radiation pattern, gain, and impedance of the antenna may be degraded. Although isolation from the support mast is not normally an antenna specification, such coupling and means of minimizing it are an important part of the design concepts. For example, coupling to the mast, as the following data indicate, distorts the radiation pattern of the antenna. The problem of mast coupling applies only to the gain omnidirectional antenna. Because of the high gain and the high front-to-back ratio, the mast coupling problem for the directional antenna is minimal and the radiation pattern is not perturbed significantly.

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 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

One method of measuring mast coupling is to first operate the antenna under test in the free-space environment of an anechoic chamber with no support mast. The antenna is supported by a Styrofoam dielectric tower. Radiation pattern and gain are measured with a miniature, battery-powered transmitter connected directly to the antenna RF terminals. A simulated mast is then attached and the measurements are repeated. Any change of the pattern is caused by RF coupling to the mast. The solid curve in figure 2 is a mast-free pattern measurement made on an FAA model FA-8955 (R. A. Miller,Inc), UHF discone antenna. When a mast is attached to the antenna, the radiation pattern distorts slightly and the gain decreases a few decibels at the $\pm$90-deg points on the pattern. The portion of the pattern around 90-deg is critical for good, long-range communications because at these angles the antenna illuminates the horizon. A loss in gain at the horizon can affect communications with distant aircraft that are located low to the horizon. The effects of mast coupling are frequency sensitive. Figure 3 shows data from the mast-coupling test taken at 400 MHz instead of 225 MHz. Pattern distortion caused by mast coupling is clearly evident.

Coyle [1] has performed similar mast-coupling tests on numerous FAA and commercial antennas and has reported similar distorted radiation patterns and losses in gain. The test of the FAA model FA-79571A (R. A. Miller, Inc.) VHF coaxial dipole antenna is important. It showed that for a specific length of mast a 20-dB deep null was formed at the horizon. If this antenna happened to be mounted on a tower with that specific length of mast, communications with aircraft at the horizon would be, at best, very poor.

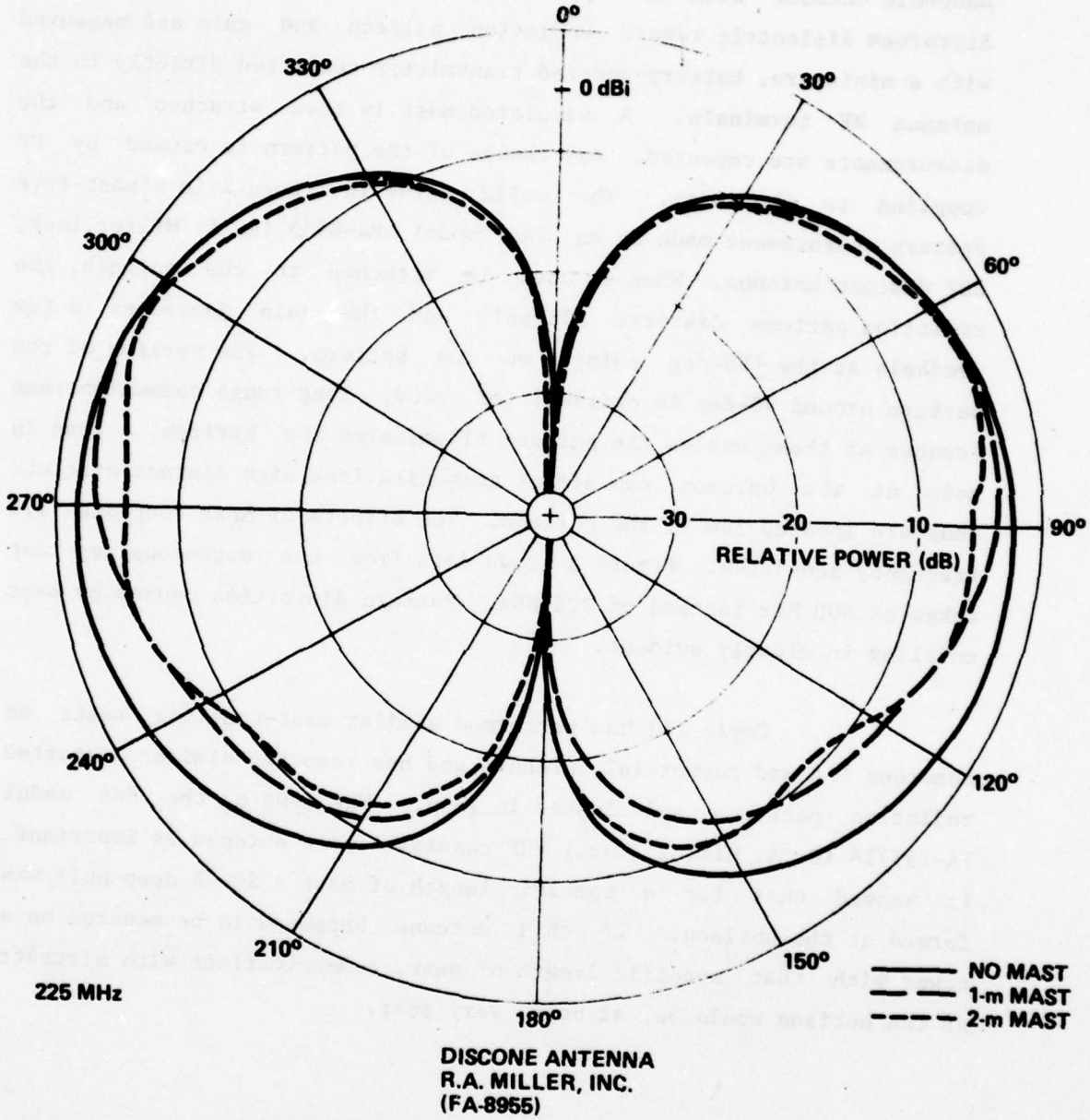


Figure 2. Elevation plane radiation patterns of discone antenna with and without mast.

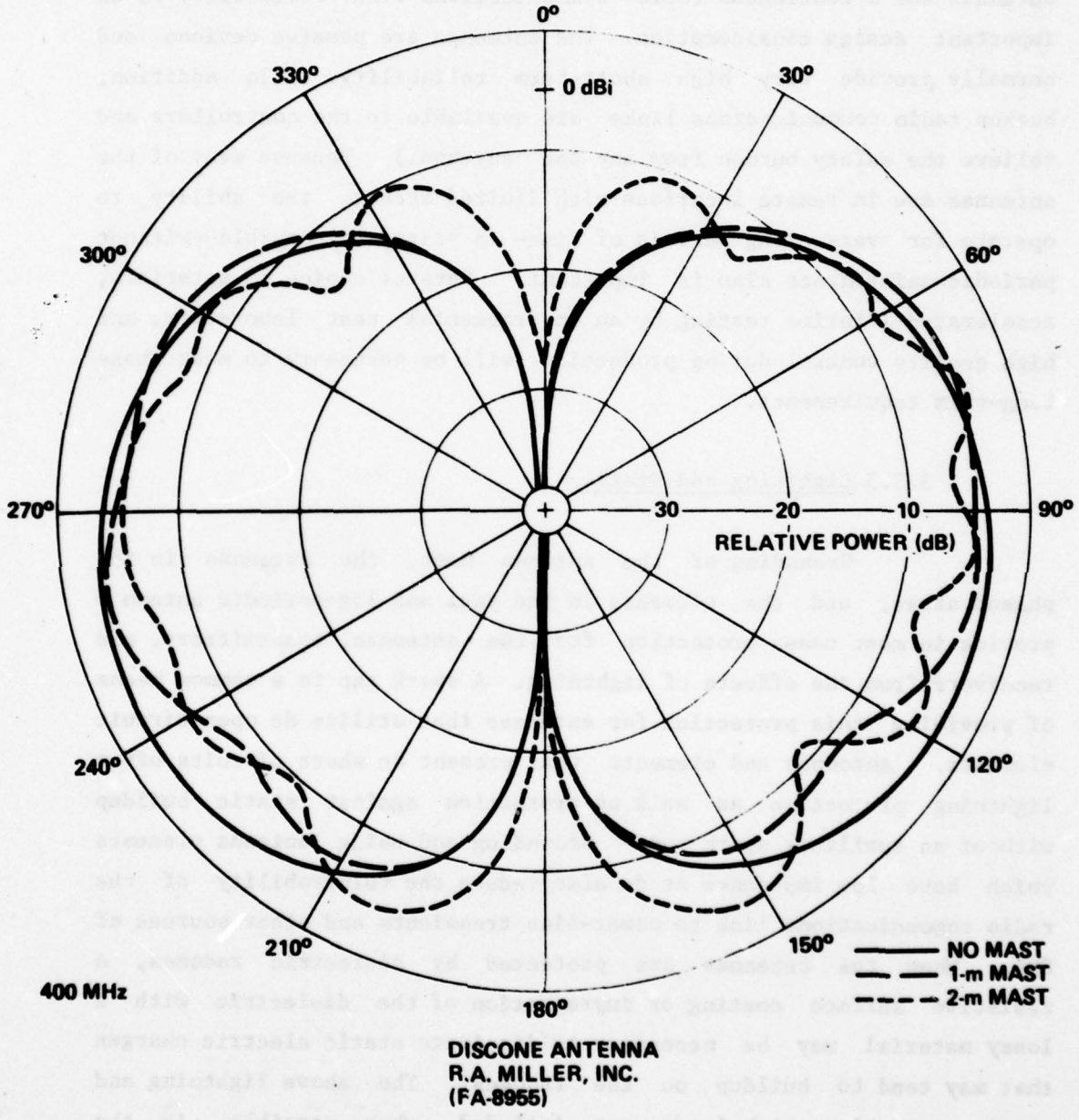


Figure 3. Elevation plane radiation patterns of discone antenna with and without mast.

3.3.2 Reliability and Maintenance

Since air-traffic control operations depend on the antennas for a continuous radio communications link, reliability is an important design consideration. The antennas are passive devices and normally provide very high short-term reliability. (In addition, backup radio communications links are available to the controllers and relieve the safety burden from any one antenna.) Because many of the antennas are in remote locations with limited access, the ability to operate for very long periods of time--15 years, if possible--without periodic maintenance also is important. Careful choice of materials, accelerated lifetime testing by an environmental test laboratory, and high quality control during production will be necessary to meet these long-term requirements.

3.3.3 Lightning and Static

Grounding of the antenna mast, the antennas in the phased array, and the elements in the yagi and log-periodic antennas provide in most cases protection for the antennas, transmitters, and receivers from the effects of lightning. A spark gap is a common means of providing this protection for antennas that utilize dc open-circuit elements. Antennas and elements that present dc short circuits offer lightning protection as well as protection against static buildup without an auxiliary spark gap. Grounding and using antenna elements which have low impedance at dc also reduce the vulnerability of the radio communications link to power-line transients and other sources of EMI. When the antennas are protected by dielectric radomes, a resistive surface coating or impregnation of the dielectric with a lossy material may be necessary to dissipate static electric charges that may tend to buildup on the radomes. The above lightning and static-protection techniques are included, where possible, in the conceptual designs of the improved antennas.

3.4 Other Considerations

Multipath interference from ground reflections affects the signal strength in the radio communications link. As shown in figure 4, as the aircraft approaches the communications antenna, both a direct wave and a ground reflected wave are received by the antenna on the aircraft. Depending on the path length differences and the phase of the ground reflected wave, constructive and destructive interference occurs along the aircraft flight path. The same phenomenon takes place when the aircraft is transmitting and the receive antenna is on the ground, i.e., the radio communications link is reciprocal. (The theorem of reciprocity states that the signal level does not change when receive and transmit antennas are interchanged.)

Multipath interference makes the antenna look as if the radiation pattern has lobes in the elevation plane. In developing the concepts for the omnidirectional antennas, this lobing is taken into account because antenna parameters can be adjusted to lessen its effect. Eliminating elevation-plane lobing, however, is not possible.

To minimize multipath interference, vertical polarization is preferred over horizontal. Multipath interference is minimized because the reflection coefficient of the ground is typically lower for vertical polarization. The reflection coefficient is, however, still large enough that lobing of the vertical radiation pattern must be considered when the performance of the antennas is evaluated in the multipath environment of the radio communications link. (A computer modelling code--FLTSIM--has been developed for this evaluation and is discussed in section 4.)

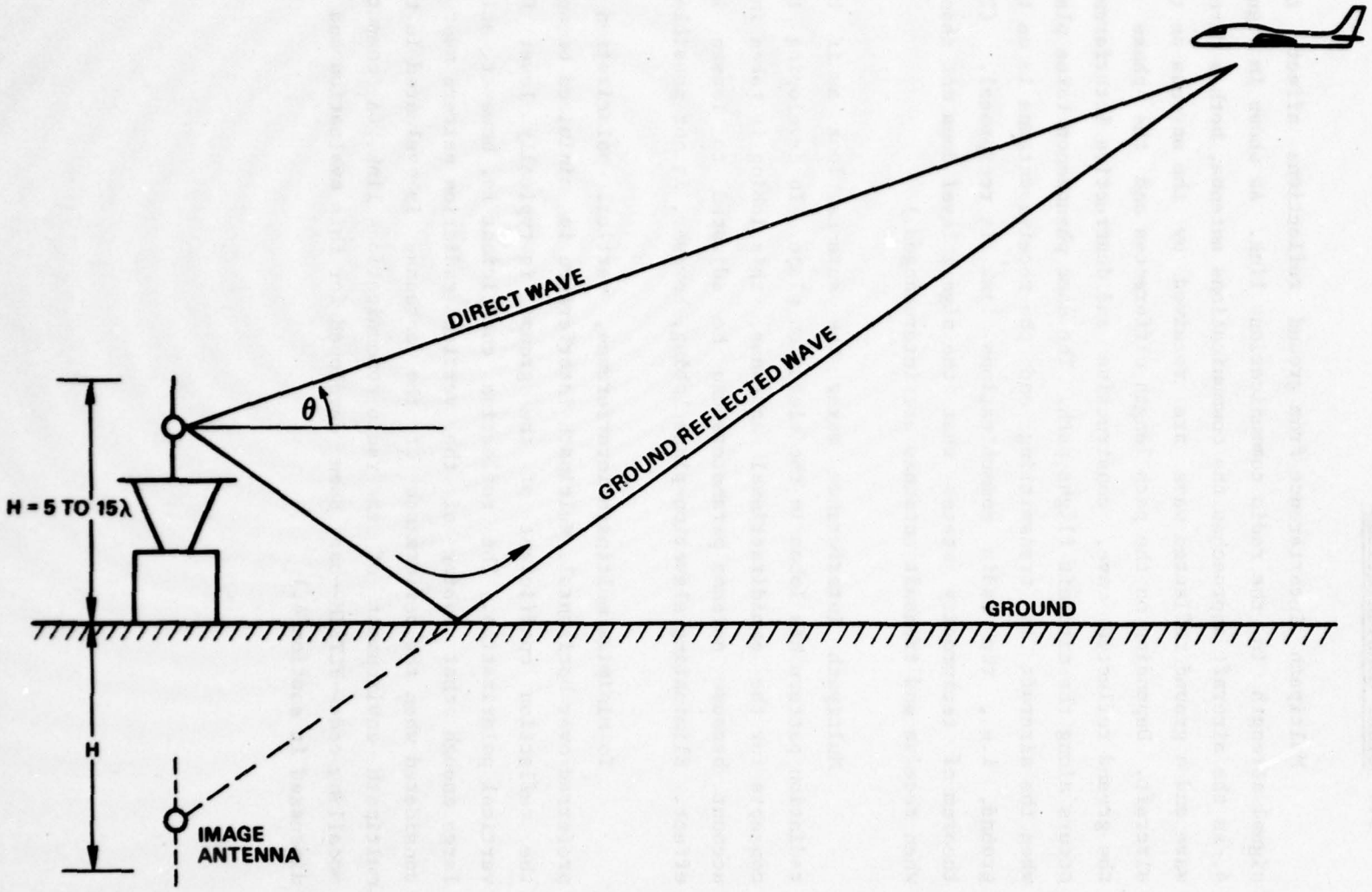


Figure 4. Ground reflections and multipath interference

The improved electrical performance of these design concepts can be destroyed by improper mounting on FAA towers or by poor tower-top design and layout. The antennas should be mounted higher than all railings and other ancillary structures. Where possible, railings and structures within 1 or 2 wavelengths (λ) of the antenna should be made of nonconducting material. The mast and its associated support structure may be composed of conducting material since the metallic coaxial cable to the antenna is always present and since the illumination level of structures below the antenna is minimal because of the pattern null in the direction of the mast. The installation of other antennas, beacon lights, and weather equipment should be avoided whenever possible. Complete plastic tower tops could minimize the effects of nearby conductors on antenna performance. The illumination of the hardware on the tower tops can distort the radiation pattern [2], change the antenna VSWR, and decrease gain severely enough to produce a hole in the radio communications link. It is important to take precautions before the installation of the improved antennas in order to guarantee high performance from these antennas.

Coupling among antennas on the same tower causes a small amount of pattern distortion depending on separation distance, but because of limited space available normally four antennas must be placed on each tower. Besides the pattern distortion, interference between channels because of interantenna coupling may be a special consideration that dictates another type of antenna design. Campbell and Arnold [3] have studied this coupling phenomenon and have provided practical design information on vertically stacked antennas that provide low interantenna coupling. Their data for coupling between horizontally and vertically separated dipole antennas are reproduced in Appendix A.

Appendix B describes a method for monitoring the VSWR of a communications antenna from the transmitter or receiver end of the cable. This method includes a correction factor for cable losses. For example, the curve in figure 5 shows how the measured VSWR at the transmitter end of the cable needs to be corrected for the 3-dB cable loss to obtain the VSWR at the antenna. Loss in antenna gain due to the impedance mismatch is indicated. Performing the perodic tests described in Appendix B helps insure the specified performance from the antennas in the radio communications system.

4. DESIGN CONCEPT FOR GAIN OMNIDIRECTIONAL ANTENNAS

Linear phased array antennas have been designed to give omnidirectional radiation patterns in the azimuth plane and sufficient gain in the elevation plane to provide continuous communications coverage. A preliminary design of a mast-supported antenna has been rejected as unsatisfactory. The performance of each antenna design has been evaluated by a computer code that simulated the flight of an aircraft through an airspace sector illuminated by the antenna.

4.1 Preliminary Designs

The basic antenna is a vertically oriented linear array of dipole elements for both the VHF and the UHF bands as shown in figure 6a. The orientation of this linear array with respect to the horizon and in a spherical coordinate system is shown in figure 6b. The data in figures 7 though 12 show the changes in elevation radiation pattern and gain of the array as the number of elements, or dipoles, is increased from one to six for a constant element spacing of 0.6 λ and an excitation of equal amplitude and phase on the elements. The calculated patterns are applicable to both the VHF and the UHF designs although the physical size of each antenna is different. By substituting meters for wavelength (λ is 2.36 m at 127 MHz and 1.0 m at 300 MHz), the physical distance between elements and the length of the array can be obtained. The gain of the array is calculated by pattern integration and is more correctly interpreted as directivity, which is equivalent to gain if the antenna is 100 percent efficient. A copy of the computer code for these calculations is listed in Appendix C.

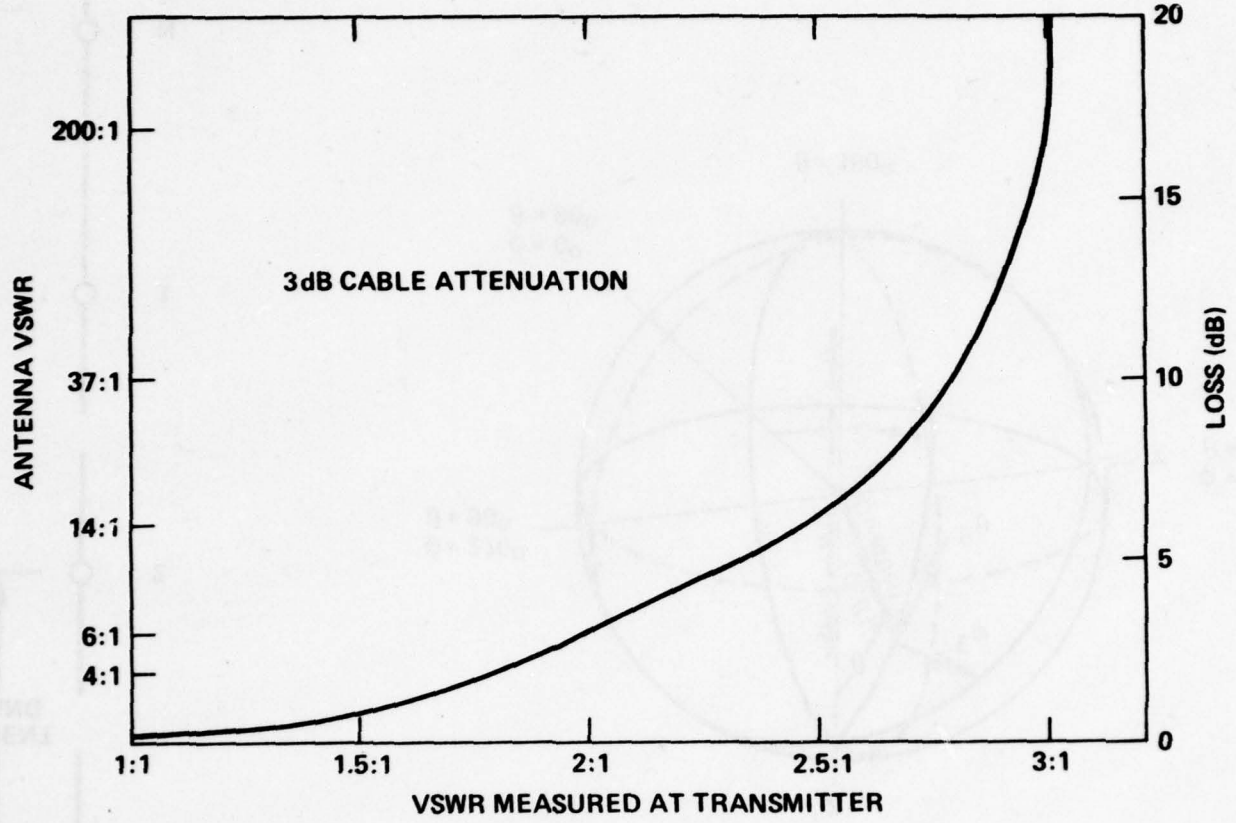


Figure 5. Effect of 3-dB cable attenuation on VSWR measurements

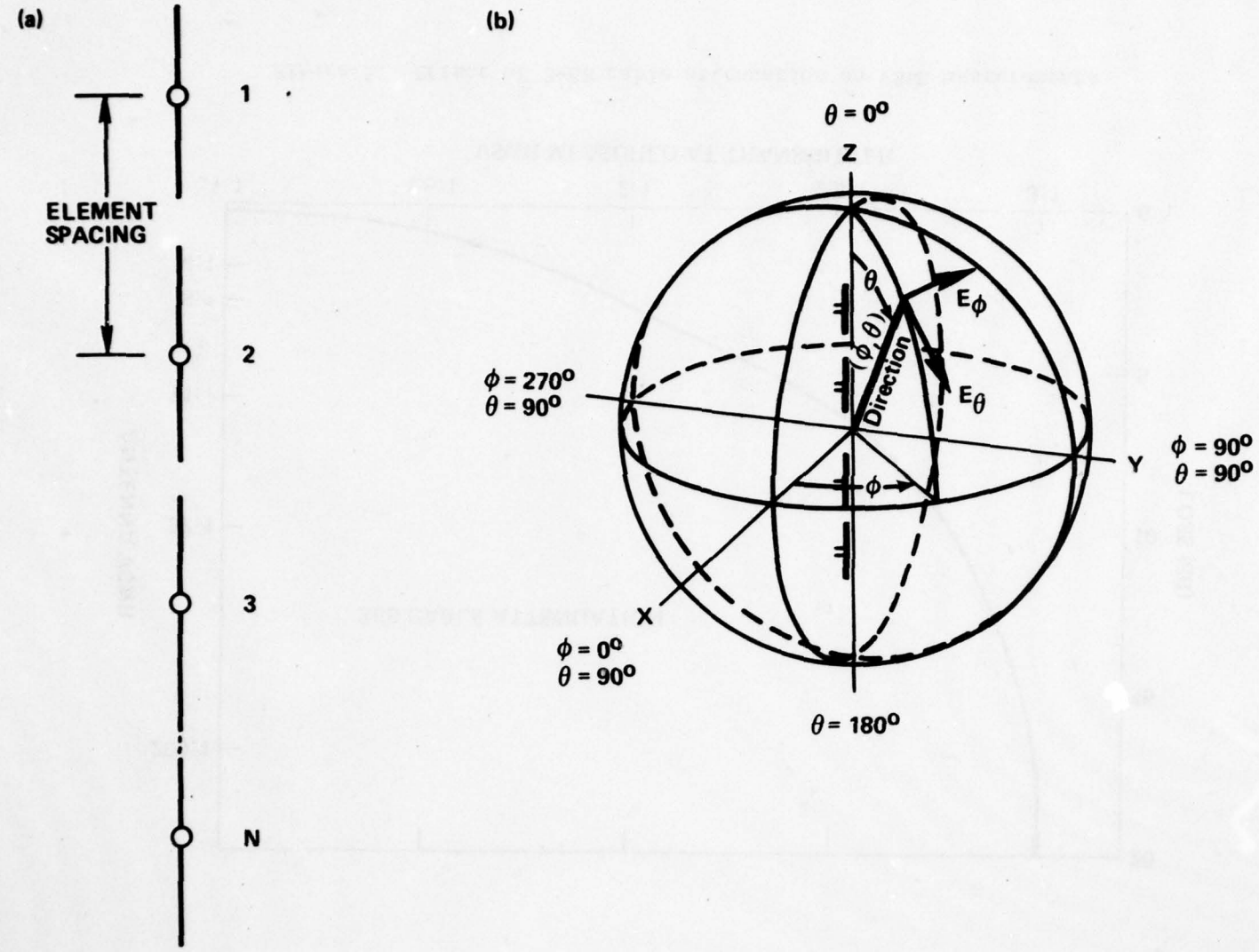


Figure 6. Linear array (a) of half-wavelength dipoles and (b) in spherical coordinate system

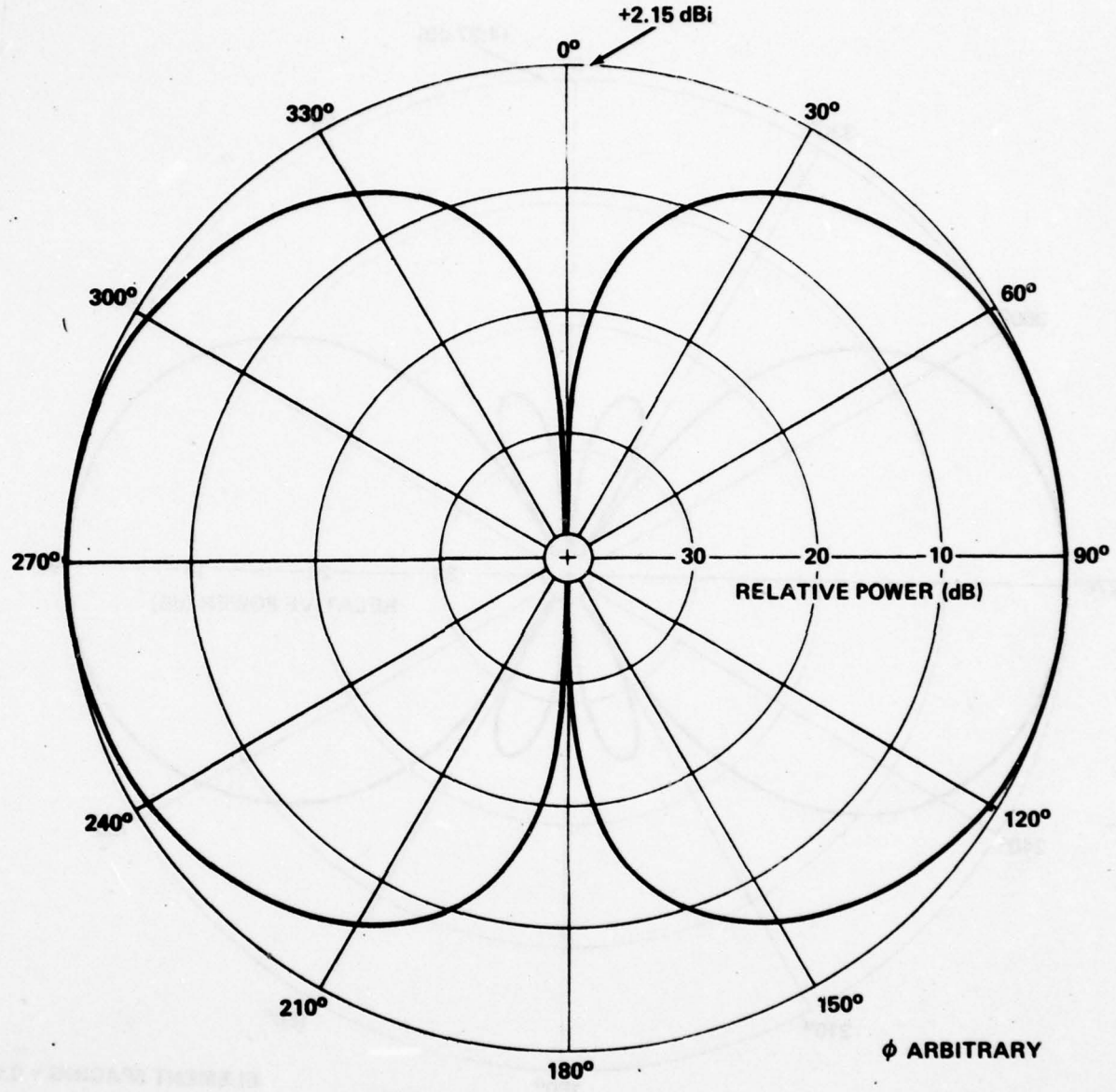


Figure 7. Calculated radiation pattern of dipole array, one element

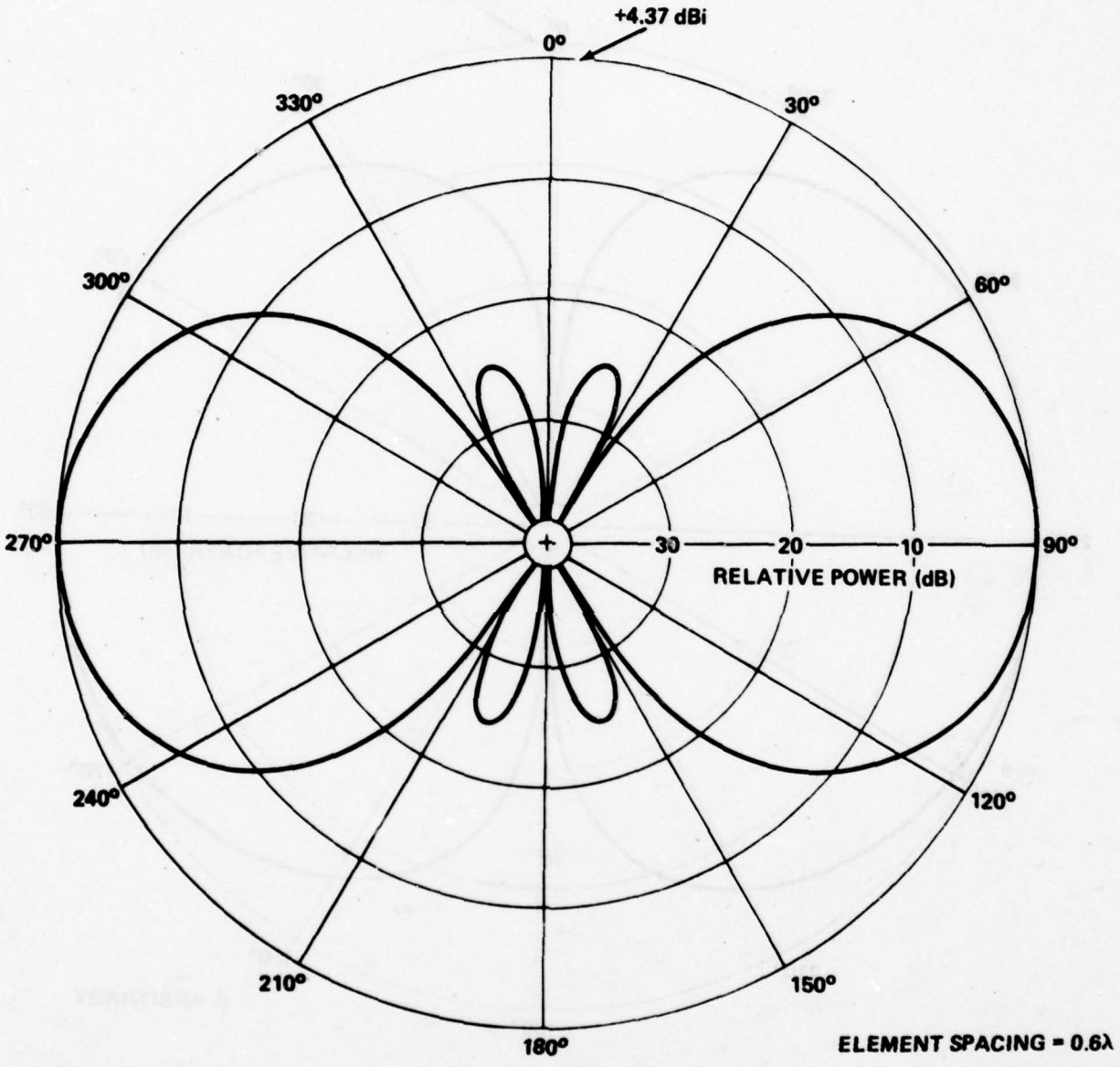


Figure 8. Calculated radiation pattern of dipole array, two elements

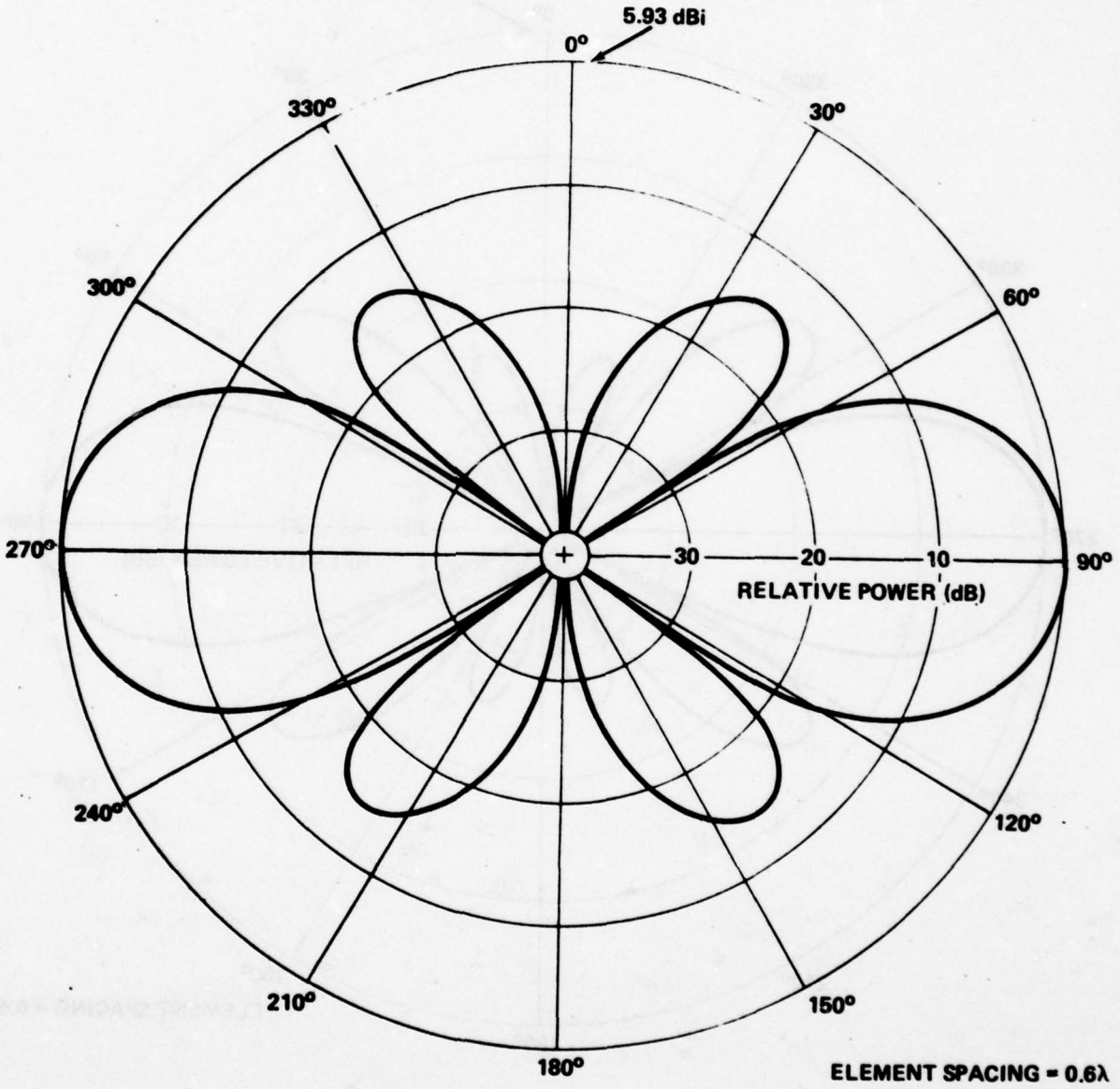


Figure 9. Calculated radiation pattern of dipole array, three elements

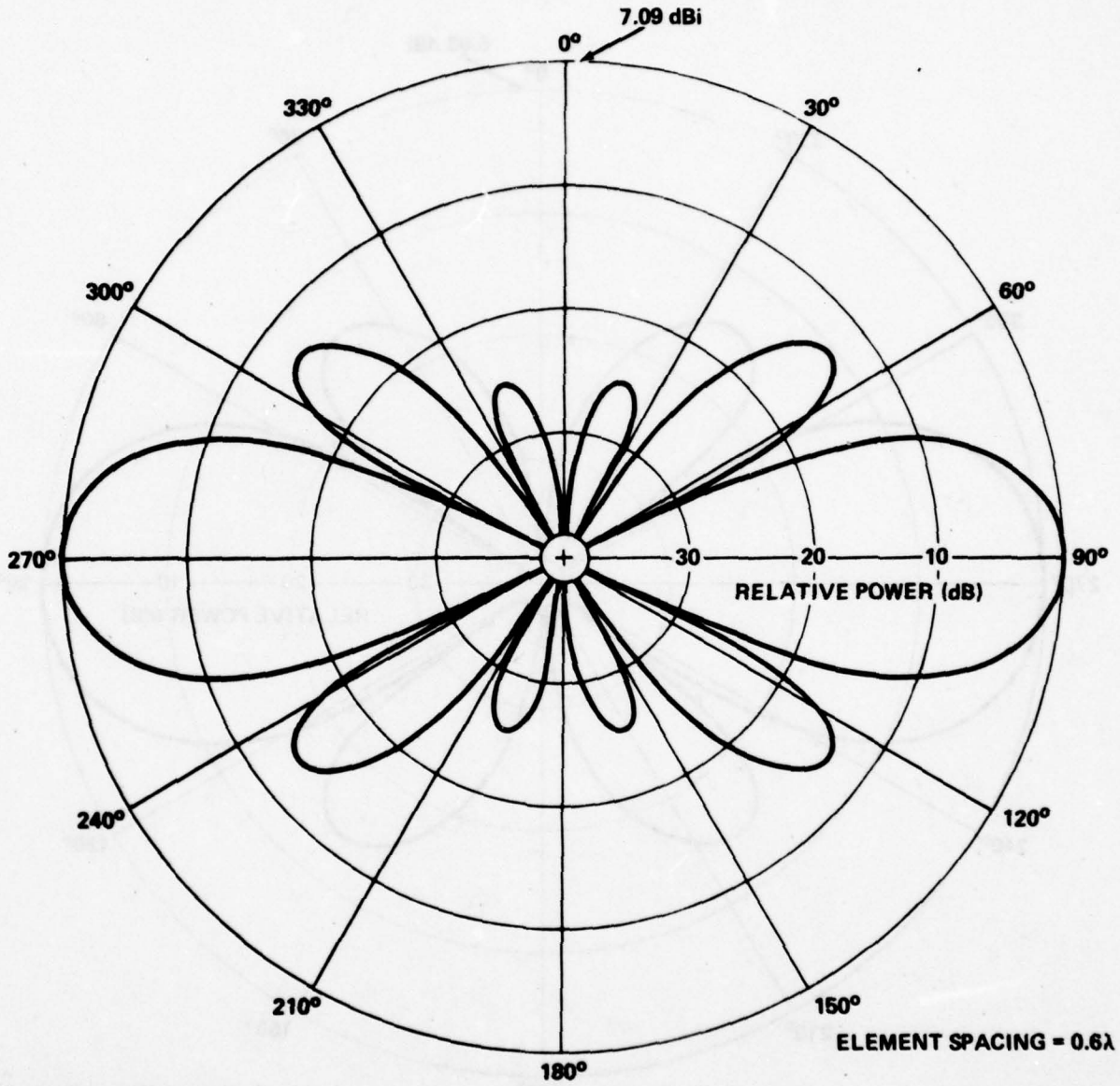


Figure 10. Calculated radiation pattern of dipole array, four elements

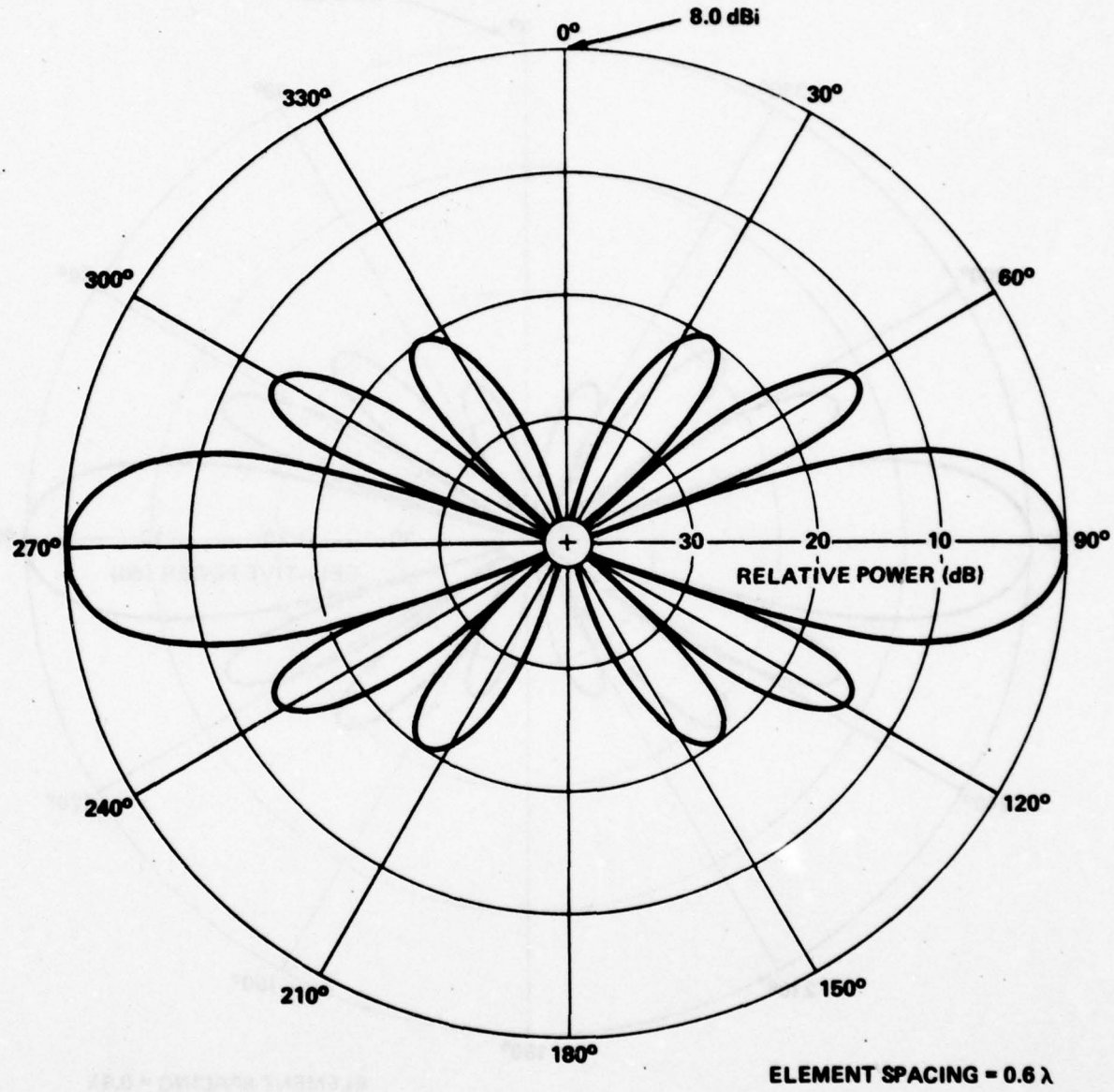


Figure 11. Calculated radiation pattern of dipole array, five elements

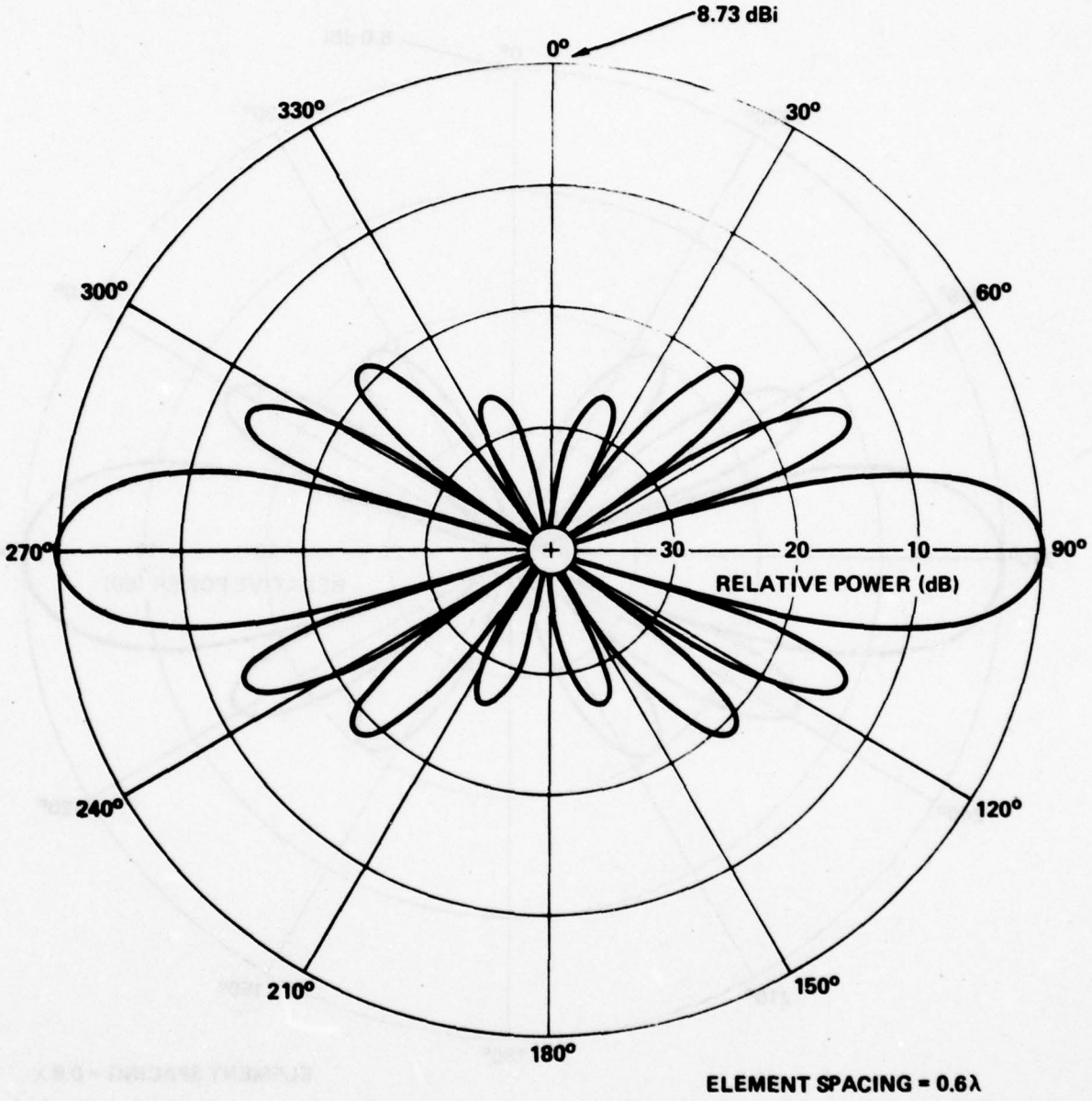


Figure 12. Calculated radiation pattern of dipole array, six elements

As the number of elements in the array increases, the radiation pattern in the elevation plane becomes narrower with the main beam and gain maximum remaining on the horizon. The azimuth plane pattern is uniform because this is an omnidirectional antenna. The gain exceeds 5 dBi when the array is composed of three elements. Adding more elements increases the gain, but at a slower rate. Also, for an array of two or more elements, vertical lobing is present, the number of lobes increasing with the number of elements. The increase in gain with the increase in the number of elements is summarized in figure 13.

Figures 14 through 16 show the effects of an increase in element spacing on the radiation pattern and gain of the array. As element spacing increases, the main beam of the pattern narrows and the gain increases. The antenna is presenting a larger aperture and gain increases in proportion to aperture. However, as the element spacing approaches λ, the grating lobes near ± 20 and ± 160 deg, which have been suppressed by the dipole element pattern, begin to greatly increase in amplitude. This increase causes a less rapid increase in main beam gain (see figure 17) and causes the gain to decrease as the element spacing is increased beyond λ. (A grating lobe , the equivalent of a main lobe, begins to appear in phased array radiation patterns whenever the element spacing exceeds $\lambda/2$.)

In the phased array radiation pattern, the nulls caused by the elevation plane lobing are undesirable because, if the nulls are very deep, communications might be lost as an aircraft flies through them. The technique of defocusing the phased array--perturbing the equal-phase condition applied to each element--can be used to fill the nulls.

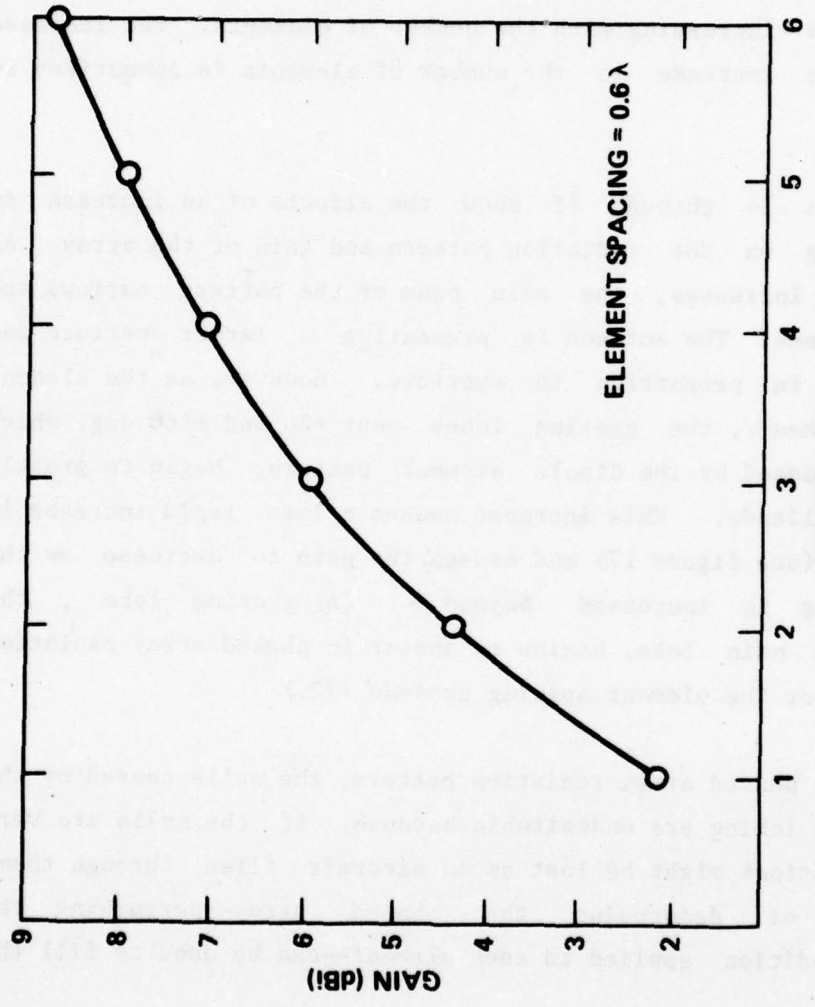


Figure 13. Dipole array gain versus number of elements

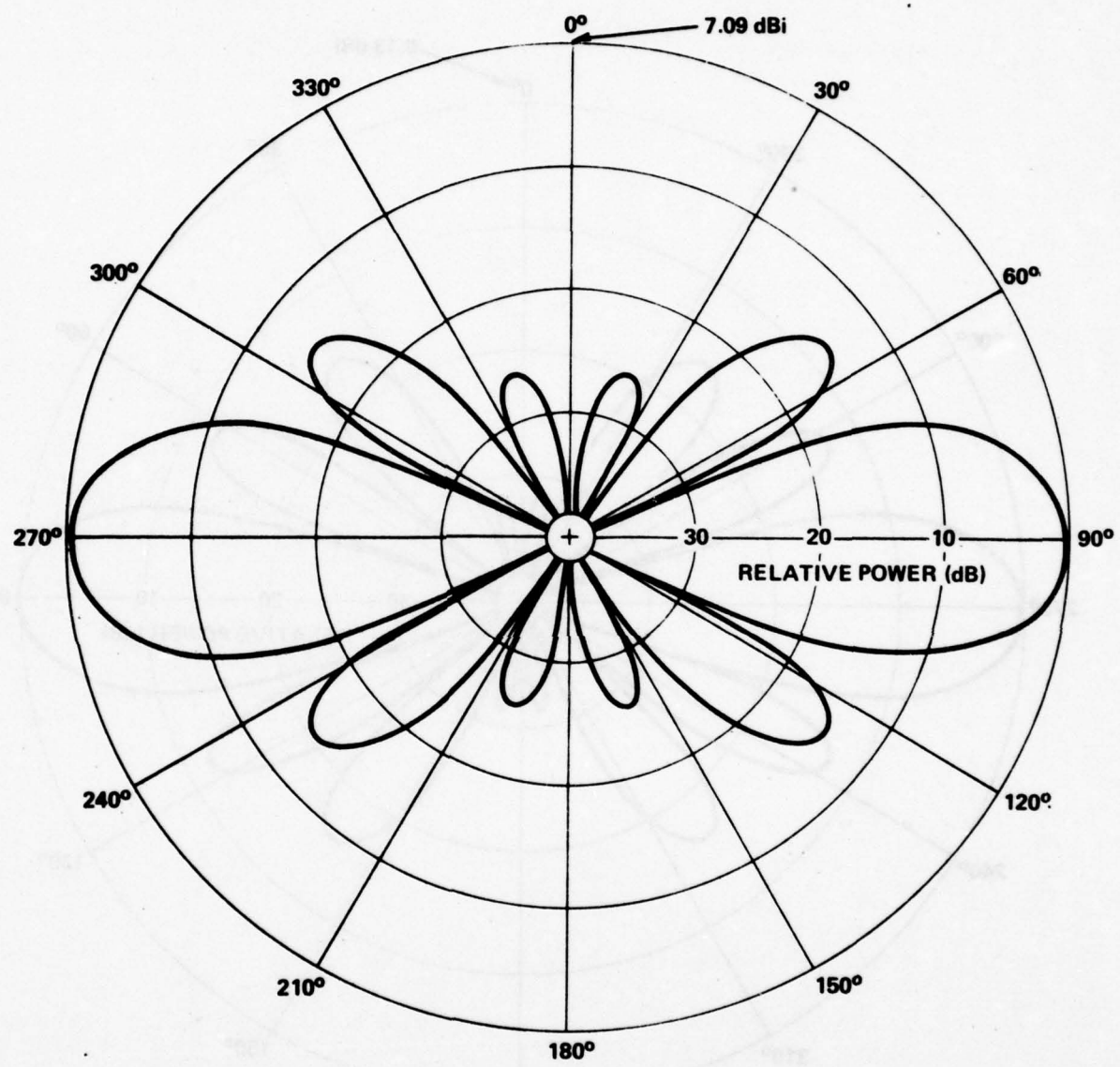


Figure 14. Calculated radiation pattern of dipole array, four elements spaced 0.6λ

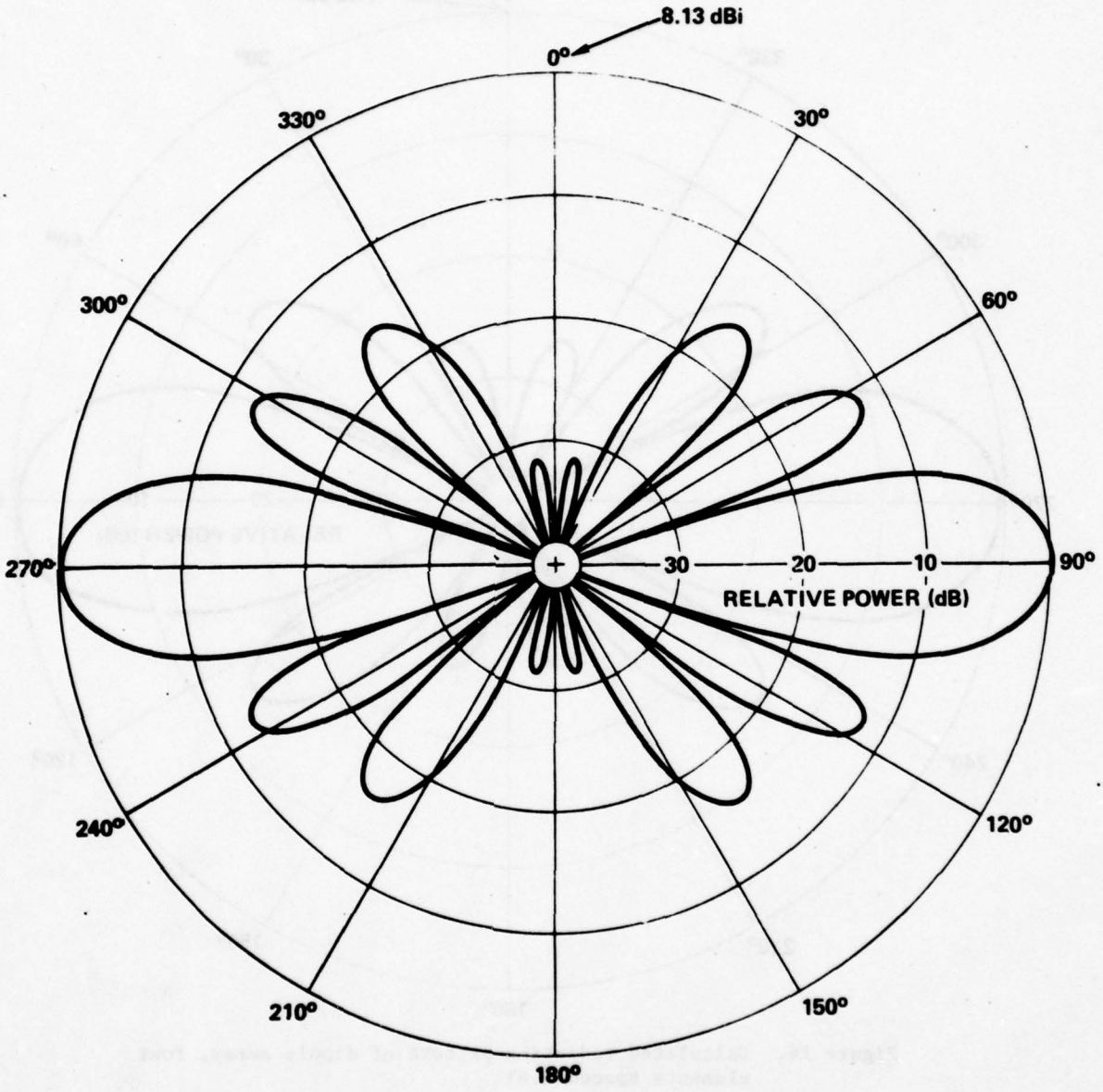


Figure 15. Calculated radiation pattern of dipole array, four elements spaced 0.8λ

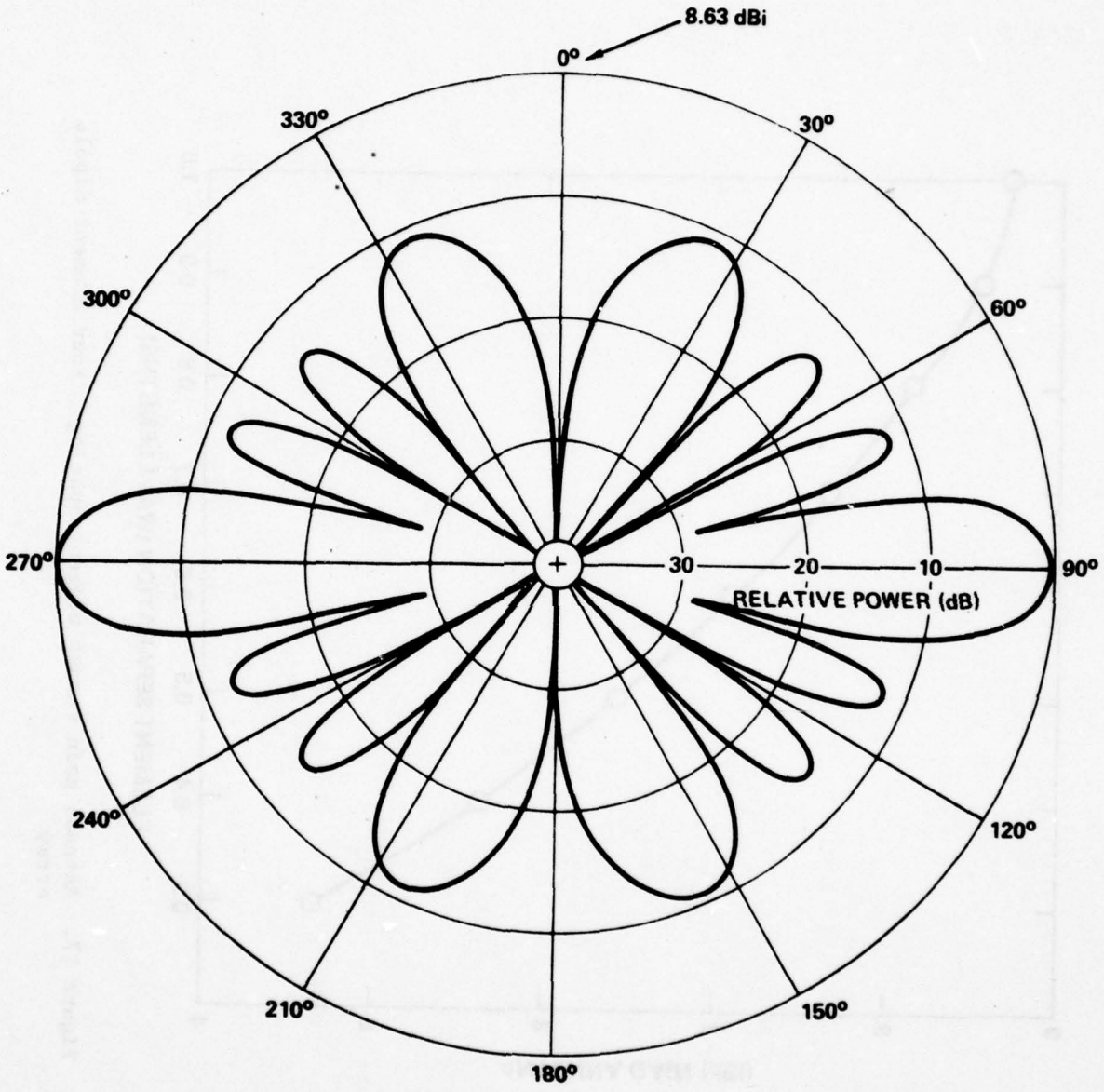


Figure 16. Calculated radiation pattern of dipole array, four elements spaced 1.0λ

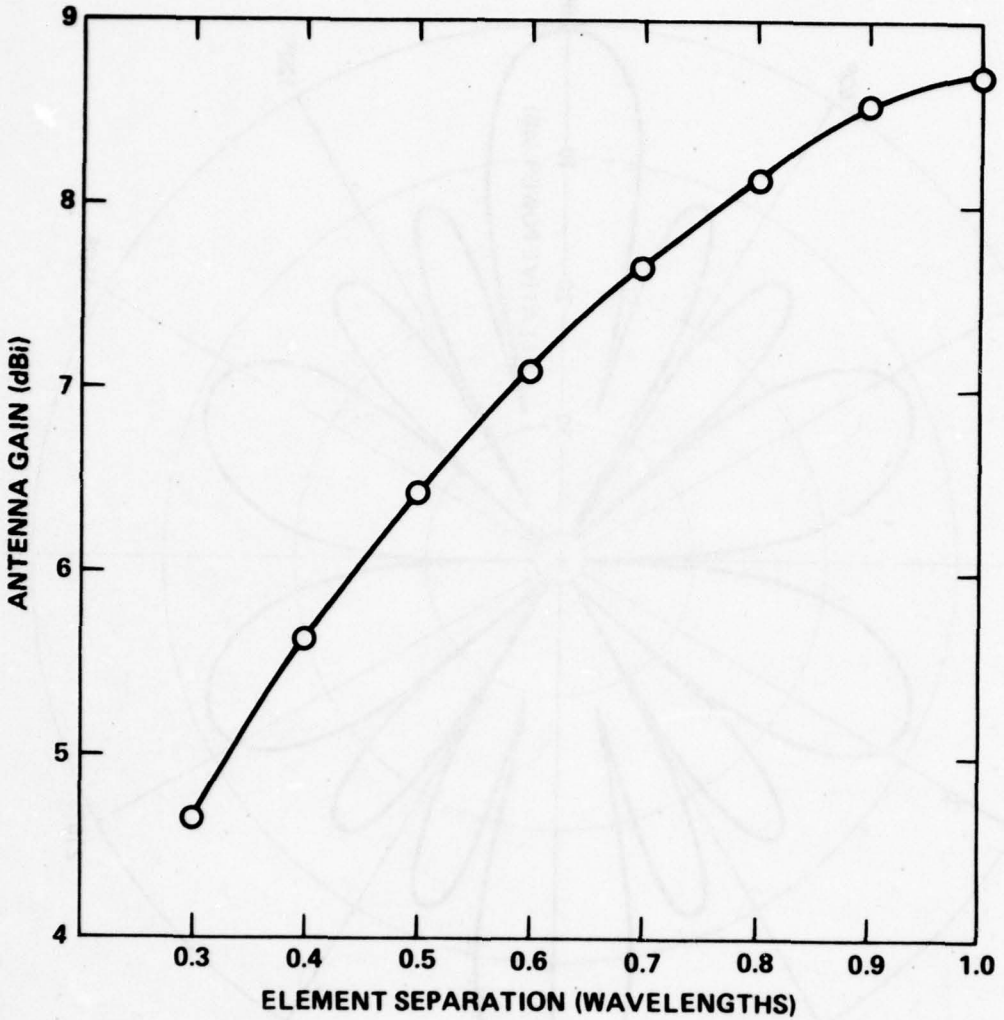


Figure 17. Antenna gain versus element spacing. Four element dipole array

Figure 18 compares the pattern of a six-element, equal-phase array with the pattern calculated after a defocusing phase taper of βX^2 has been applied.* Peak gain has decreased by 0.3 dB, but the nulls are no longer deep enough to cause a loss in communications. The results of defocusing a four-element phased array are shown in figure 19. For βX^2=25 deg at the end elements, the first null fills in with a main beam loss in gain of only a few tenths of a decibel. By applying a perturbation of βX^2=50 deg, the first null can be made to almost disappear, but main beam gain decreases by 1 dB. The null is filled by the sacrifice of main beam gain. The second null in the four-element array is affected only slightly but is not of as much concern as the first null because an aircraft would be much closer to the antenna at the angle of the second null. (The results of the simulated performance discussed in section 4.3 more fully explain the need for null filling.) Defocusing is applied carefully in the final designs to optimize the performance of the radio communications system.

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*The phase taper of $\beta X^2 = \phi$ is applied by advancing the phase of the end elements ϕ deg relative to the center of the array. The phases of the other elements are adjusted to approximate a parabalic phase front across the array aperture.

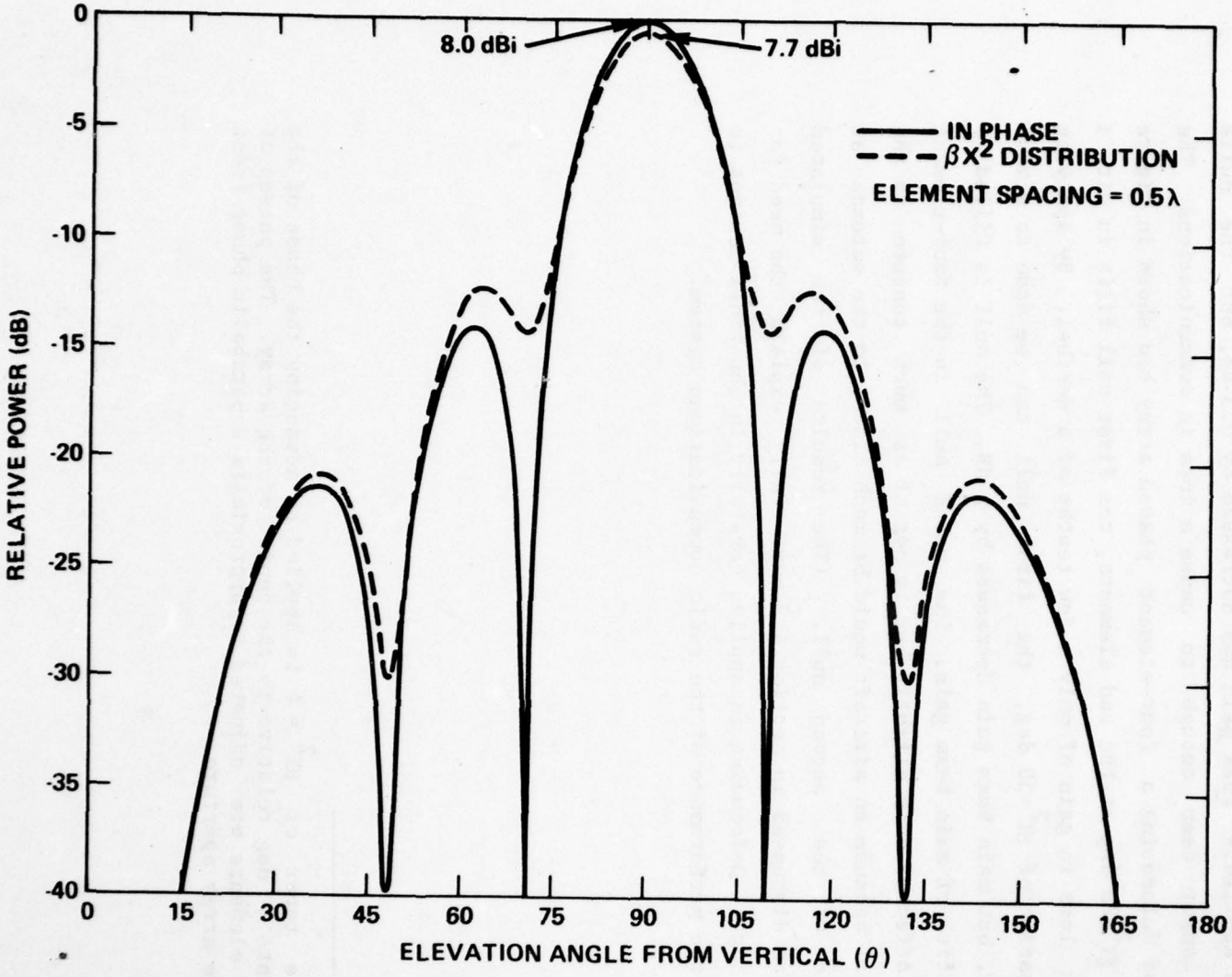


Figure 18. Calculated radiation pattern of six-element array showing effect of non-linear phase distribution

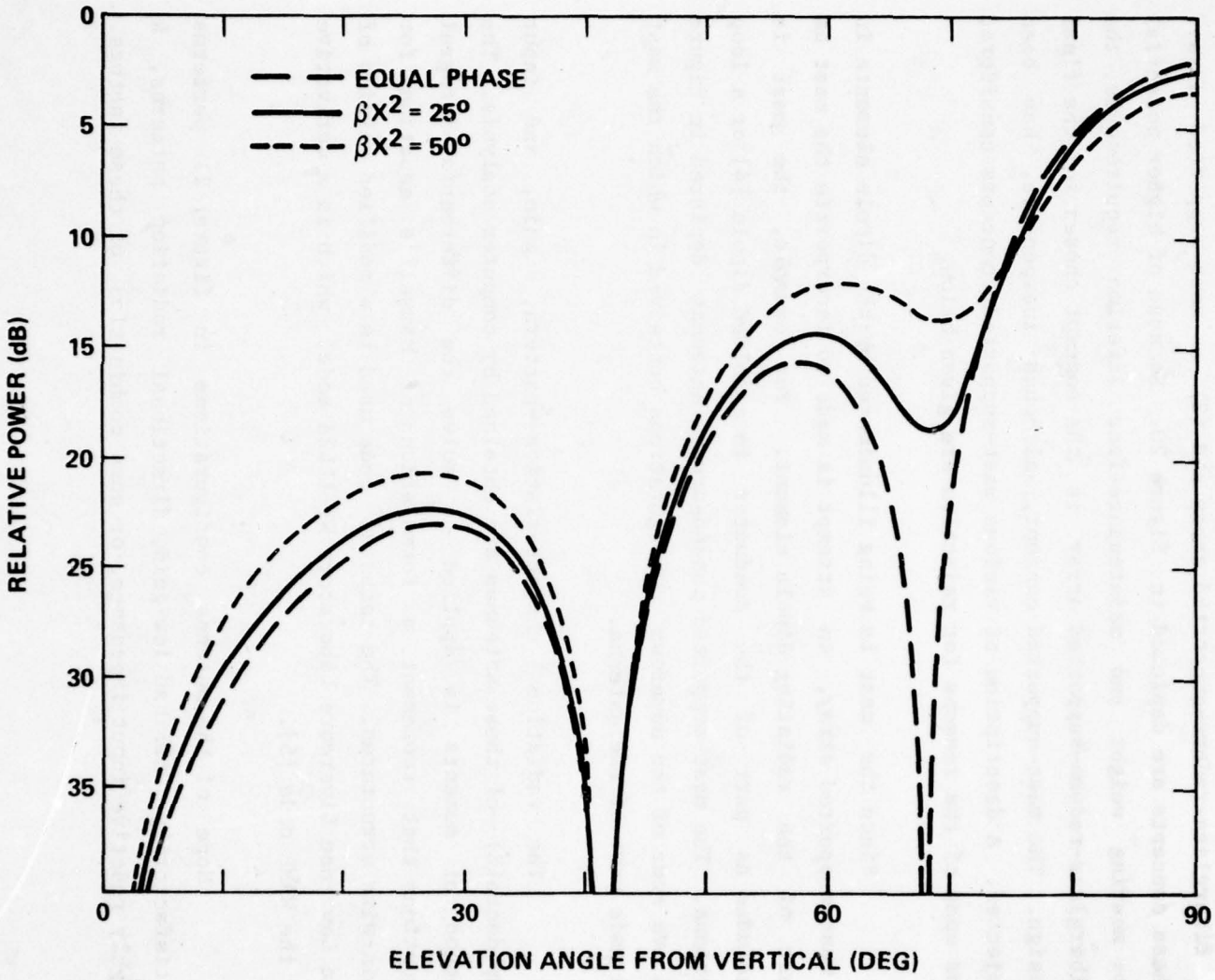


Figure 19. Beam defocusing for various phase distributions

Based on the above analysis of the concept of a linear, phased-array antenna, two preliminary designs have been developed: (]) a fiberglass-radome-supported array and (2) a mast-supported array. These concepts are depicted in figure 20. Because of higher potential for meeting weight and maintenance-free lifetime requirements, the fiberglass-radome-supported array is the concept chosen for the final design. The mast-supported concept, although inexpensive, has been rejected. A description of various mast-supported concepts considered and some of the reasons for rejection are given below.

Since the mast is being illuminated by the dipole elements in a mast-supported array, an attempt is made to incorporate the mast as part of the radiating dipole element. For example, the mast is included as part of the conductor in a folded dipole [4] or a loop antenna. The mast-supported phased-array antennas depicted in figure 21 are some of the numerous configurations conceived in which the mast is made part of the antenna.

The radiation characteristics--pattern, gain, and input impedance(Z)--of these antennas are obtained by computer analysis. The method of moments is applied to solve the differential-integral equations that represent a formulation of Maxwell's equations for thin-wire structures. The computer code used is a modified version of the Lawrence Livermore Laboratory WF-LLL2A code, which is a derivative of the WAMP code [5].

None of the antenna configurations in figure 21 performs satisfactorily. All had low gain, directional radiation patterns, a highly reactive input impedance, or some combination of these factors.

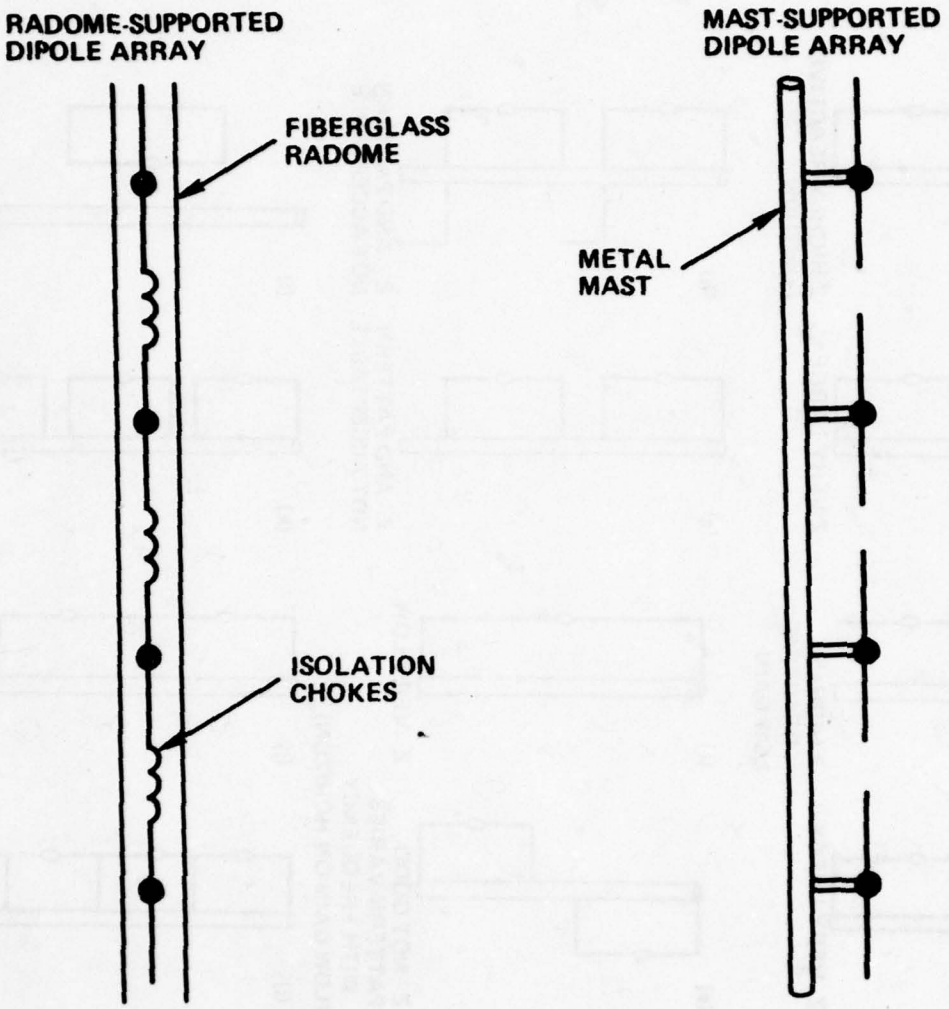


Figure 20. Two design approaches

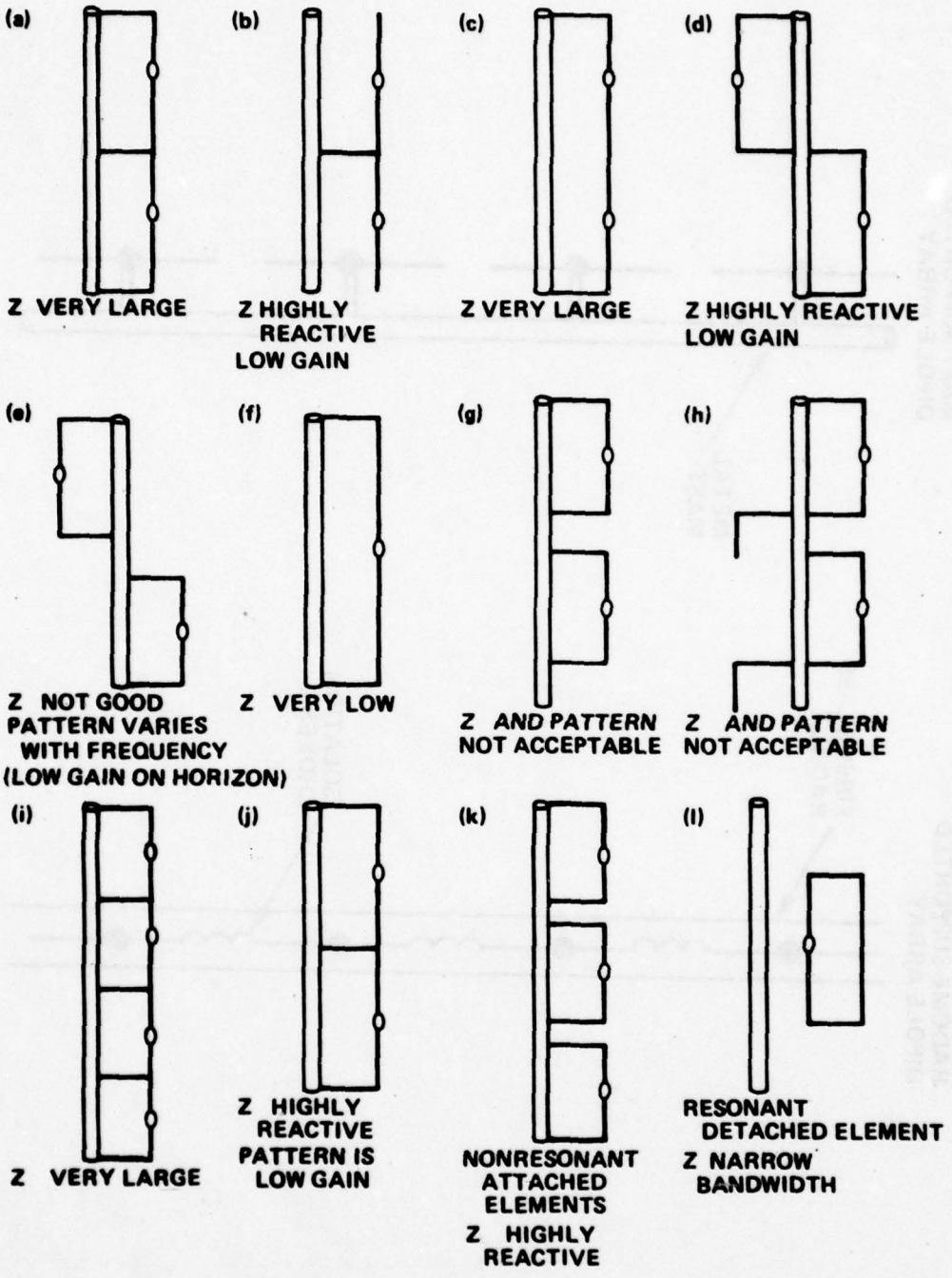


Figure 21. Mast-supported antenna structures: (a) to (f) 1λ structures and (g) to (l) folded dipole structures

A more conventional type of mast-supported antenna that performs satisfactorily is shown in figure 22. The dipole elements are attached to the mast by an insulating support material. The radiation characteristics, which are again analyzed by the method of moments computer code, are good. These antennas have gains of 5 to 7 dBi, input impedances of 50 to 100 ohms, and omnidirectional radiational patterns with the four-element design showing more azimuthal variation than the eight-element design. The analysis shows a serious deficiency, however--the antenna is narrow band. This limits the design concept to only the VHF band. Acceptable performance over the UHF band has not been obtained from this design or from designs of other mast-supported antennas.

Although not a phased array, a simple radome-supported antenna called a Franklin antenna [6] (shown in figure 23) has been analyzed because of its potentially low cost. Since the wire antenna modelling code can analyze reactively loaded wires, both an inductively loaded and a capacitively loaded Franklin antenna have been investigated. The calculated performance in both cases is poor. The capacitively loaded version has a very highly reactive input impedance and low gain. The inductively loaded version shows moderate gain levels but has a highly reactive input impedance. Because of these problems, the Franklin antenna has been discarded from further consideration.

4.2 Final Designs

The final design concept is a linear phased array of dipole elements in the radome-supported configuration. Dipole elements, isolation chokes, the feed network, and interconnecting cables are all of lightweight construction and provide no mechanical support. The small-diameter, fiberglass tube surrounding the dipoles supports the array. A potting material fixes the parts firmly inside the tube and protects against vibration, shock, and weather. The dipole elements, their spacing, and their excitation amplitude and phase are adjusted to optimize each design for each operating frequency band.

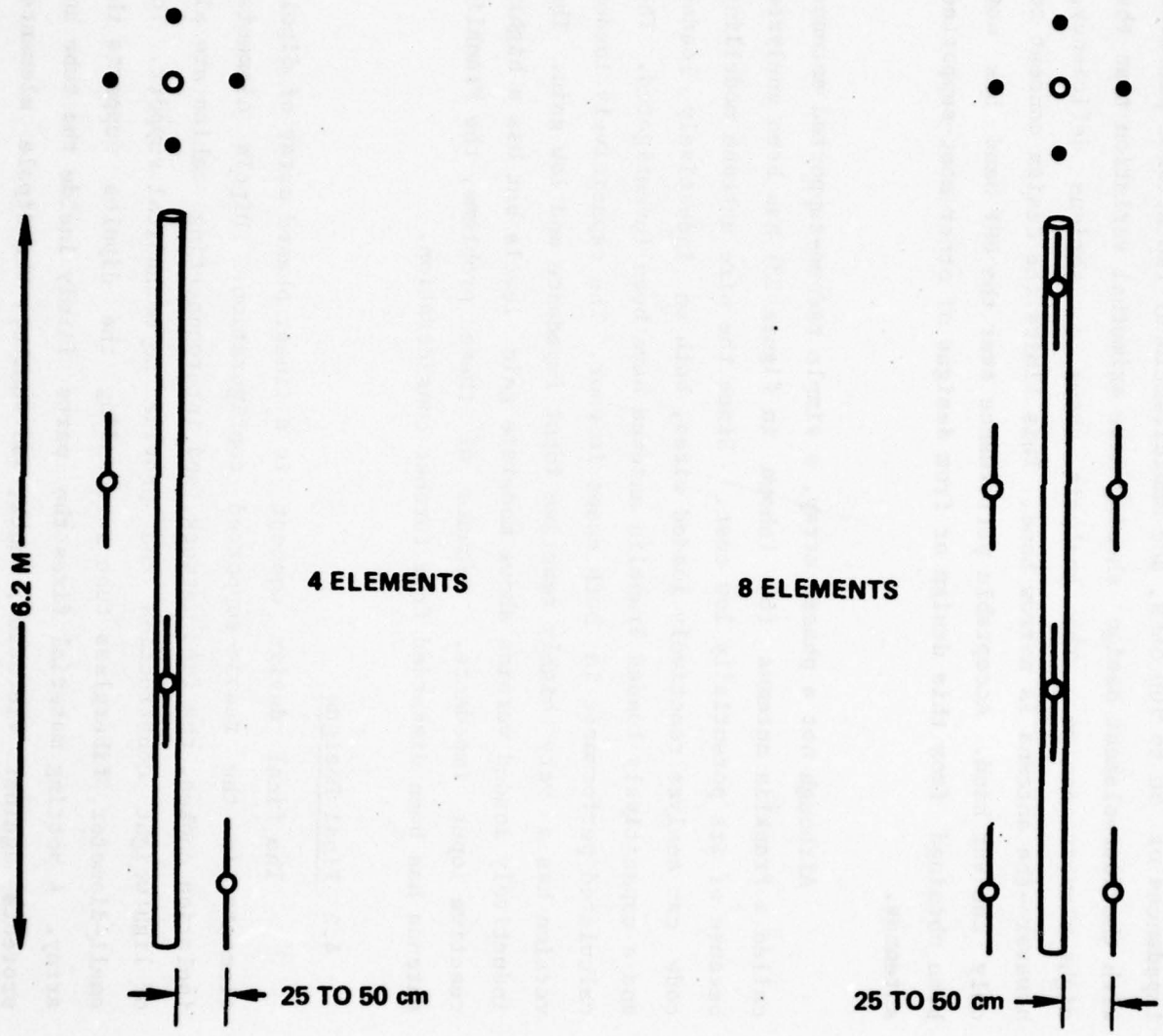
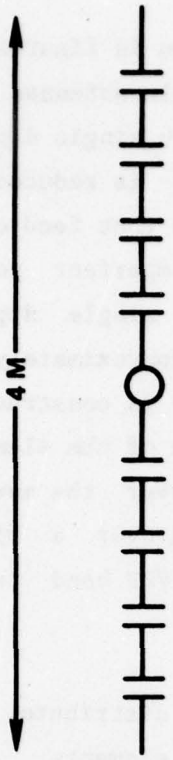
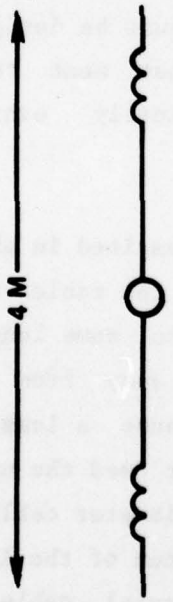


Figure 22. Possible VHF antenna designs



LARGE Z
VERY LOW GAIN



L = 0.01 μH NO EFFECT

L = 1 μH HIGHLY REACTIVE Z
GAIN LOSS AT HORIZON

L = 100 μH INDUCTOR STOPS CURRENT
GAIN LOSS DUE TO REDUCED
APERTURE

Figure 23. Franklin-type antenna

4.2.1 VHF Omnidirectional Designs

The antenna patterns and gain values shown in figures 14 to 16 were calculated by assuming perfect lossless dipole antennas fed in phase with equal-amplitude signals. The gain of each single dipole element is 2.15 dBi. In practice, the gain of any array is reduced by element inefficiencies, losses in the coaxial cables that feed each element, radome inefficiencies, and losses in an imperfect power divider. In general, it is possible to construct a single dipole element that is very nearly lossless and has a gain of approximately +2 dBi over a narrow bandwidth. However, when the element is constructed so that the bandwidth specifications are met, the gain of the element is reduced. That is, the efficiency of the radiator over the narrow bandwidth must be reduced when the element is operated over a wider bandwidth. An actual element gain of +1 dBi over the VHF band is a more realistic goal.

An isolated power divider is used to distribute the incoming RF energy equally to the various dipole elements. The isolation is needed to insure that the antenna will continue to function if an element fails. Also, the power divider must be designed to operate with 50 W of input power. Components that meet these specifications are commerically available and typically exhibit approximately 0.5-dB loss.

Since each element in the array is to be excited in phase or very nearly in phase for the defocused design, the cables that connect each element to the power divider must be the same length. Unequal-length cables will cause the beam to tilt away from the horizon at some operating frequencies and thus cause a loss of communications at long ranges. Since the cables that feed the upper elements must pass through the lower elements, small-diameter cable is desirable to minimize the degradation of the performance of the lower elements. However, because insertion loss of coaxial cable is

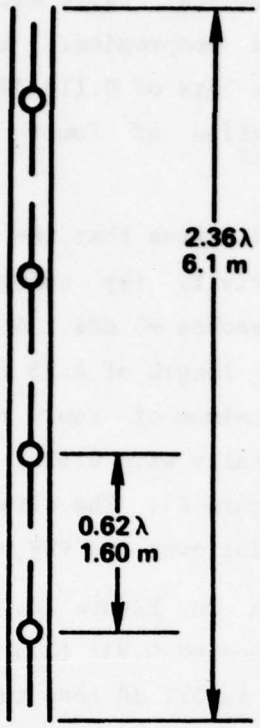
inversely proportional to cable diameter, large-diameter cable is desirable to reduce cable loss. A semi-rigid coaxial cable with 0.141 in. (0.36 cm.) outer diameter is a good compromise. At VHF frequencies, this cable typically exhibits a loss of 0.118 dB/m (3.6 dB/100 ft) and causes only minimal degradation of lower element performance.

The total of these loss factors dictates that the antenna be designed for approximately 7-dBi directivity (by using ideal elements) so that the actual realizable gain reaches +5 dBi. A maximum antenna height of 20 ft (6.1 m) and an element length of 4.25 ft (1.29 m) (a $\lambda/2$ dipole at 116 MHz) indicate that a maximum of four elements can be used. These elements are stacked vertically with 0.62 λ (1.6 m) spacing between element centers as shown in figure 24. The directivity ("gain" for a lossless antenna) is at least 7 dBi over the VHF band.

A three element design, also shown in Figure 24, has the same total height but the element centers are spaced 0.93λ (2.4 meters) apart. Although the calculated directivity is 0.1 dB less than the desired 7 dBi at some frequencies, the realizable gain should still exceed +5 dBi.

The radiation patterns for the four- and three-element VHF designs are shown in figures 25 and 26. The elevation angle (θ) measured from vertical is plotted on the horizontal axis so that 0 deg corresponds to directly overhead and 90 deg corresponds to the horizon. Relative power is plotted on the vertical axis. (Radiation patterns show E_θ (θ).) If ideal lossless radiators 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. Maximum power is directed at the horizon to insure good communication at these long ranges. High gain is not required at the low elevation angles since the aircraft is nearly overhead, and the distance between transmitter and receiver is small. In figure 25, the nulls at 68 and 112 deg have been filled by using the defocusing technique discussed in section 4.1. The nulls appearing at 42 and 138 deg will be partially filled by scattering from rough terrain.

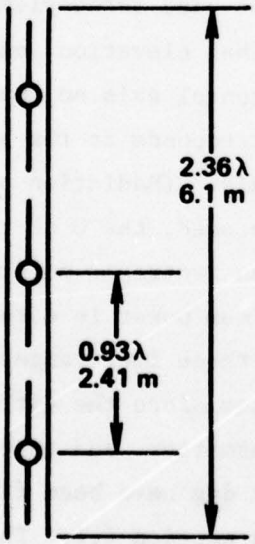
4 ELEMENTS



DIRECTIVITY:

7.05 dB at 116 MHz
7.30 dB at 125 MHz
7.59 dB at 136 MHz

3 ELEMENTS



DIRECTIVITY:

6.98 dB at 116 MHz
7.00 dB at 125 MHz
6.91 dB at 136 MHz

Figure 24. Radome-supported VHF omnidirectional gain antenna

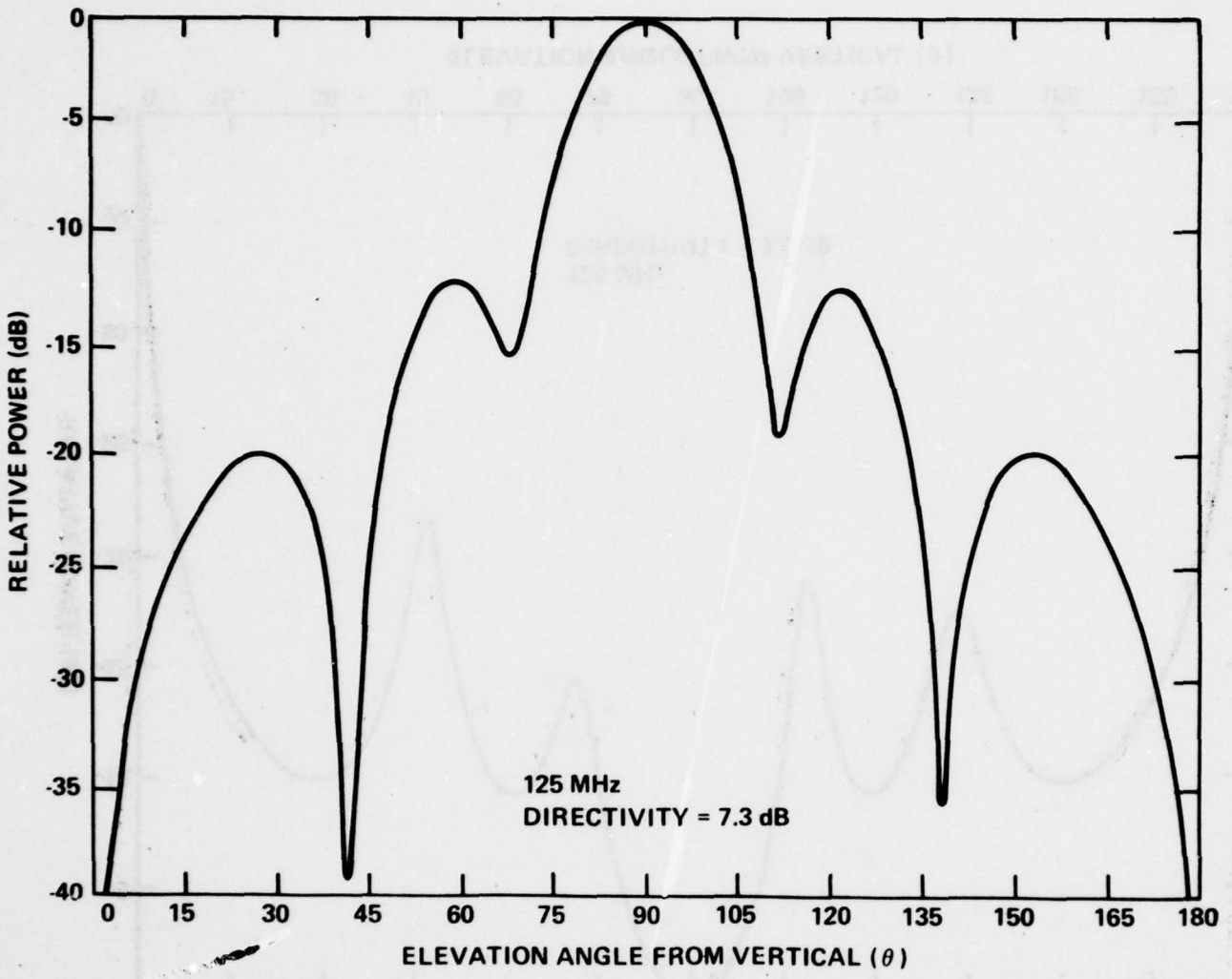


Figure 25. Radiation pattern of four-element VHF omnidirectional antenna

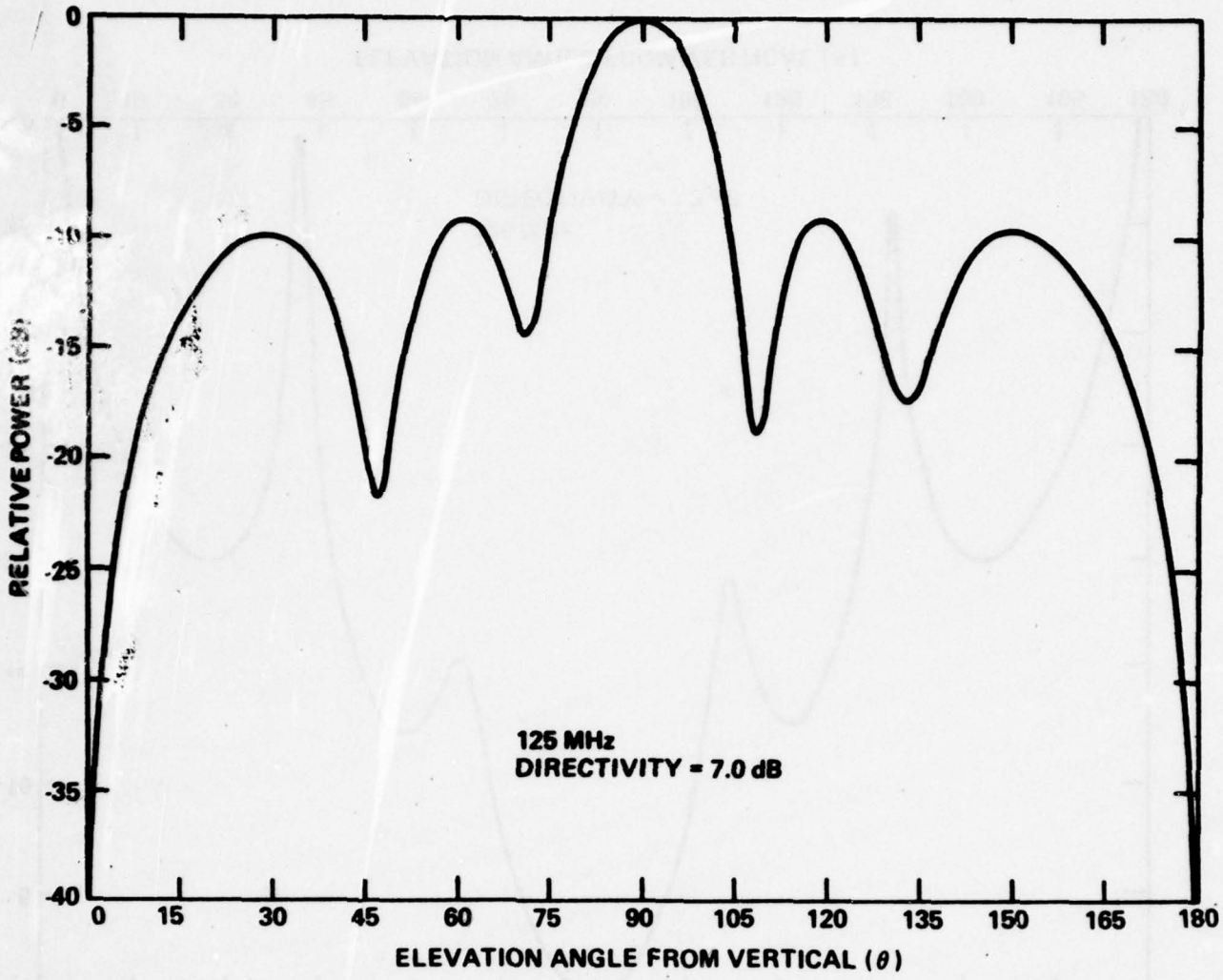


Figure 26. Radiation pattern three-element VHF omnidirectional antenna

The radiation pattern of the three-element VHF design is shown in figure 26. The larger spacing between element centers in this design causes the increased size of the grating lobes at 30 and 150 deg. Although the gain of the three-element design is not as high as that of the four-element design, its inherent lower cost warrants further consideration.

4.2.2 UHF Omnidirectional Designs

Basic antenna theory states that the gain of an antenna is proportional to the physical aperture (in this case, height), measured in wavelengths. Therefore, to achieve a specified gain, a UHF antenna will be proportionally smaller than a similar VHF antenna. Figure 27 indicates the relative sizes and the element spacings for the three- and four-element designs. The large UHF bandwidth (225 to 400 MHz) dictates that certain compromises be made. For example, in the three-element design, if the interelement spacing 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 decreases the size of the grating lobes and thereby increases the directivity at 400 MHz, but the overall array is smaller and no longer has sufficient gain at 225 MHz. The radiation patterns at a compromise spacing of 1.07 m are plotted in figures 28 to 30.

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 31 to 33). 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 deg.

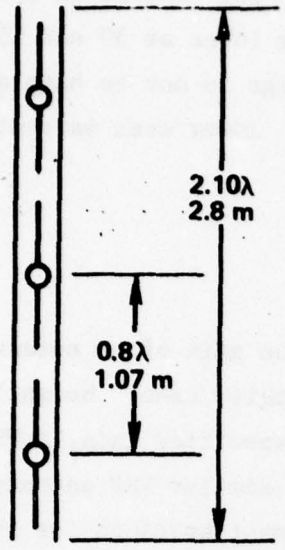


Figure 27. Radome-supported UHF omnidirectional gain antenna

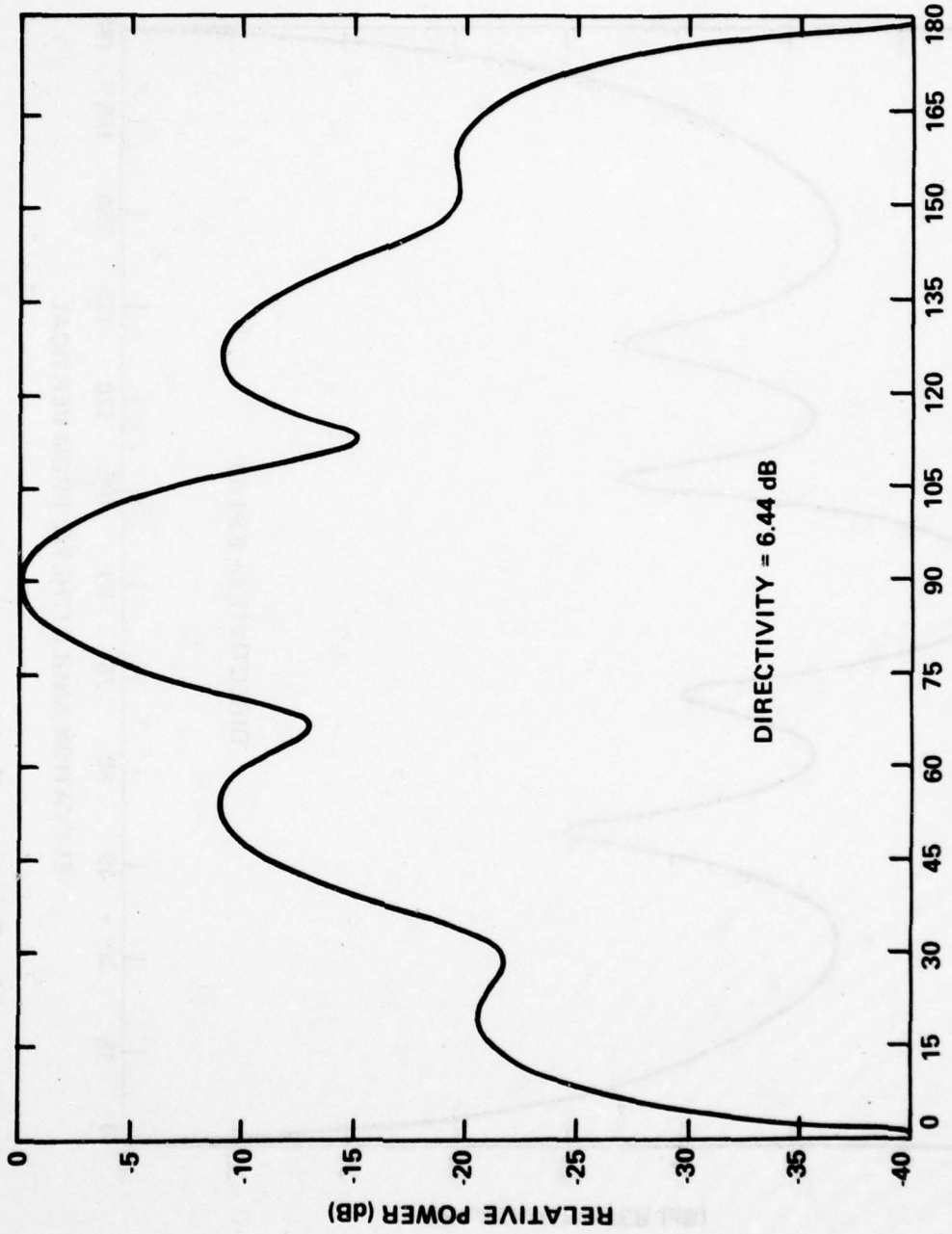


Figure 28. Radiation pattern of three-element UHF omnidirectional antenna at 225 MHz

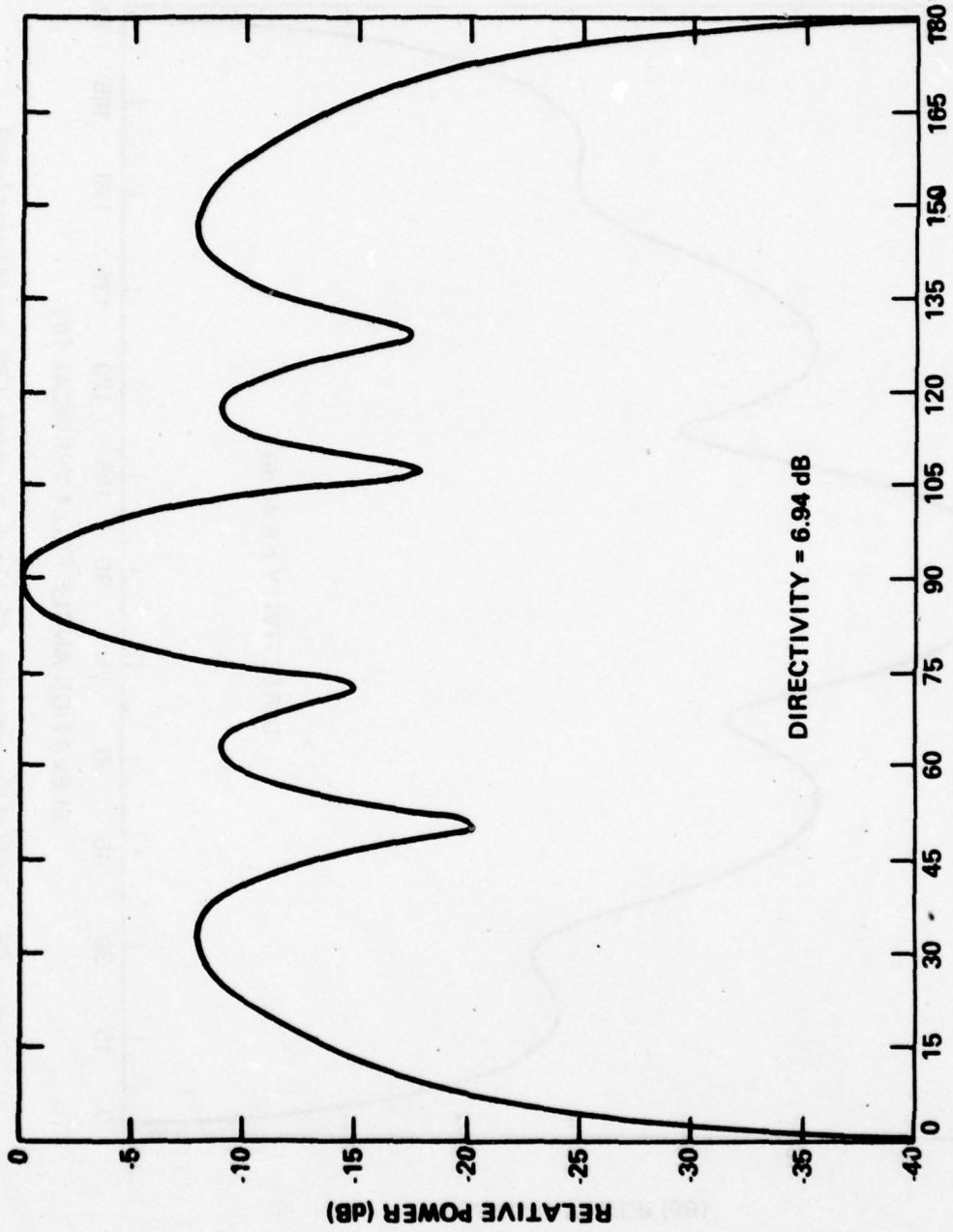


Figure 29. Radiation of three-element UHF omnidirectional antenna at 300 MHz

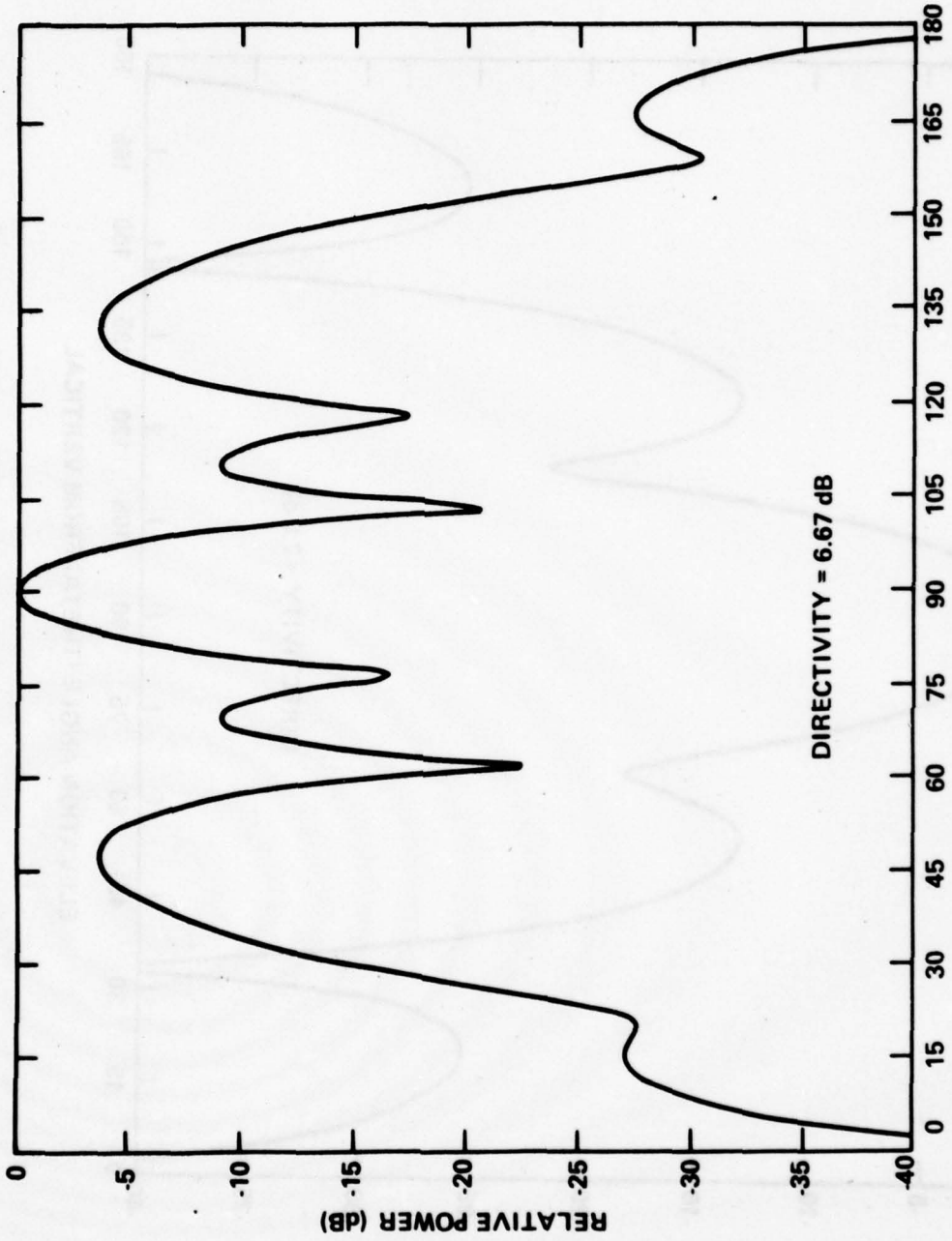


Figure 30. Radiation pattern of three-element UHF omnidirectional antenna at 400 MHz

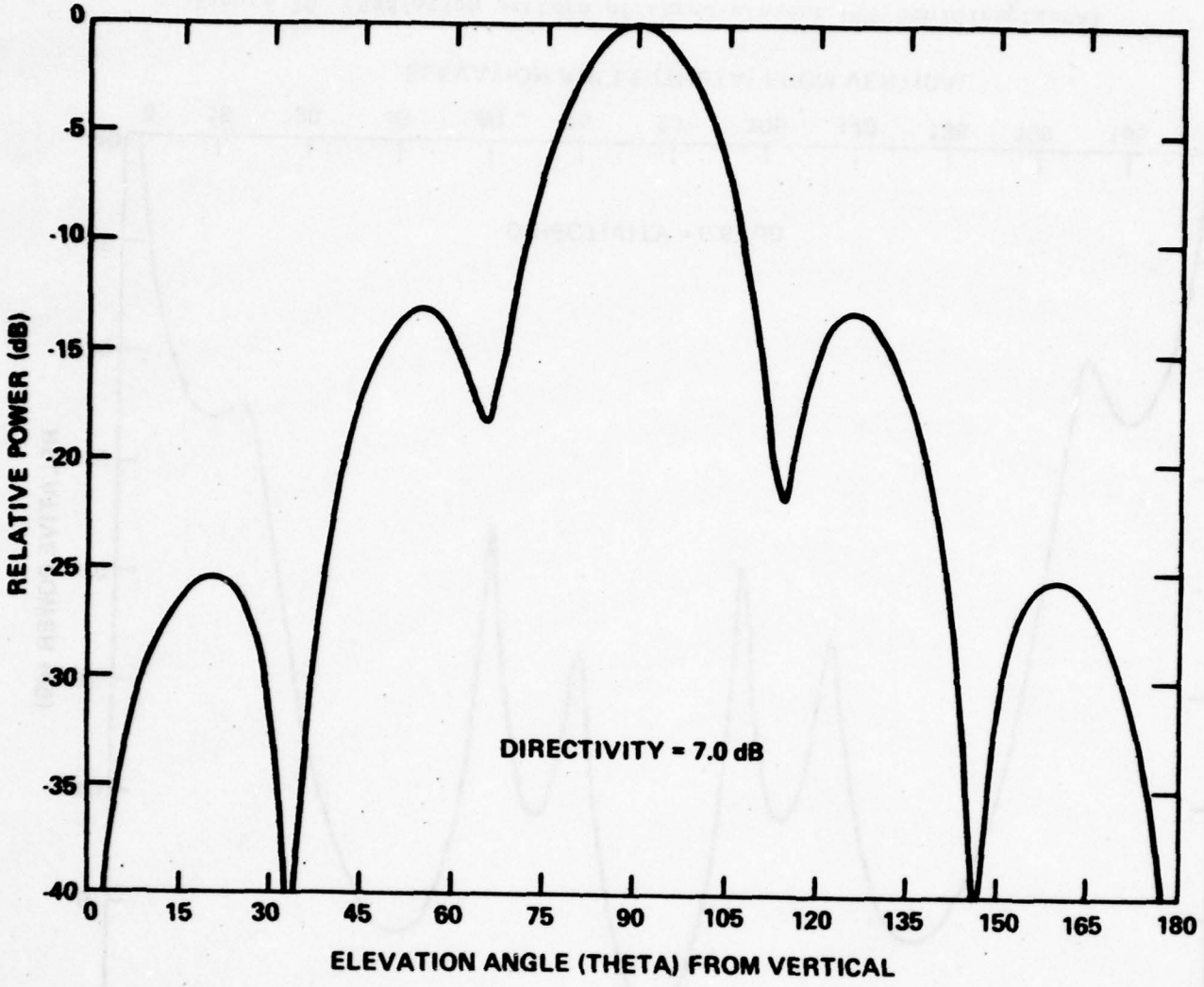


Figure 31. Radiation pattern of four-element UHF omnidirectional antenna at 225 MHz

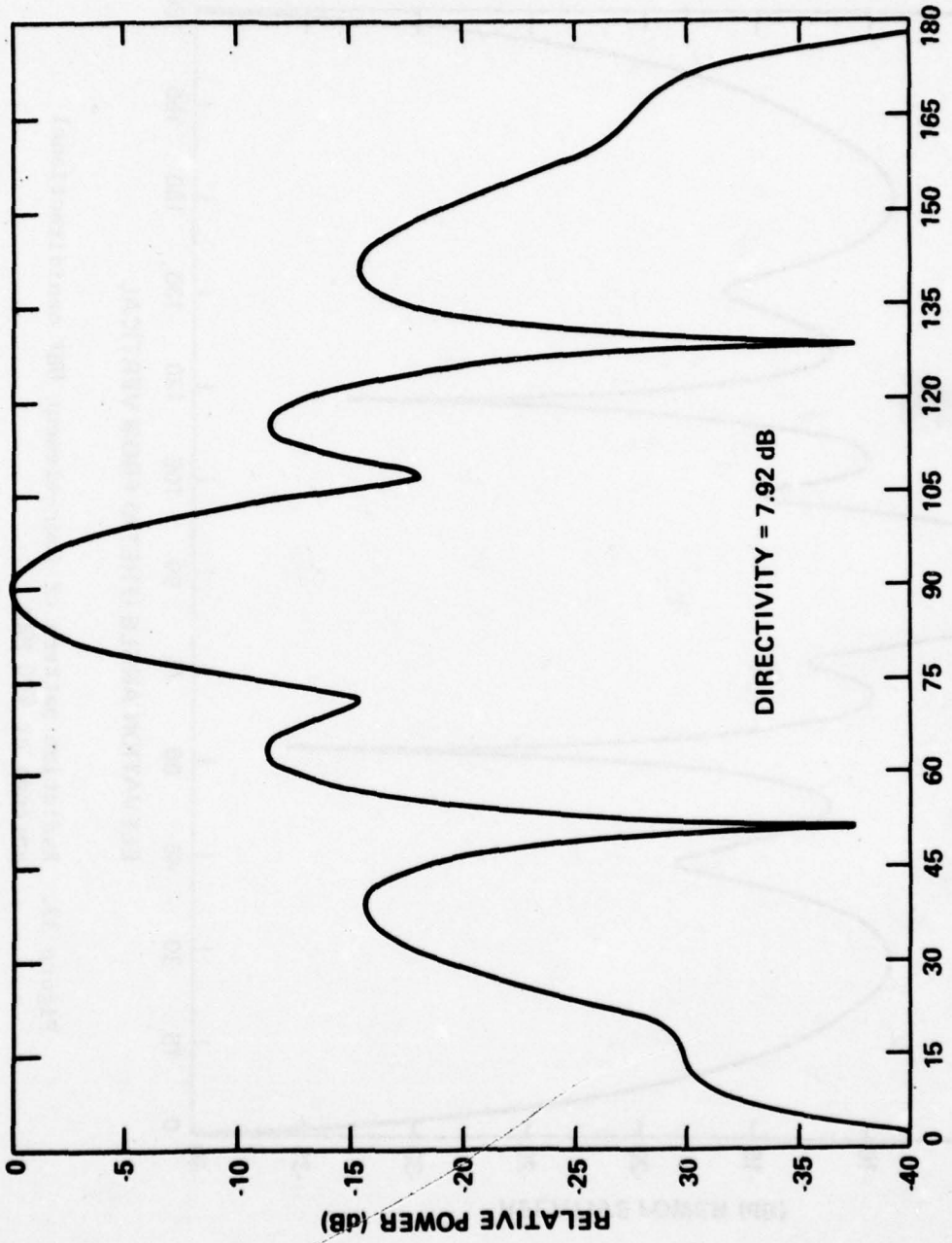


Figure 32. Radiation of four-element UHF omnidirectional antenna at 300 MHz

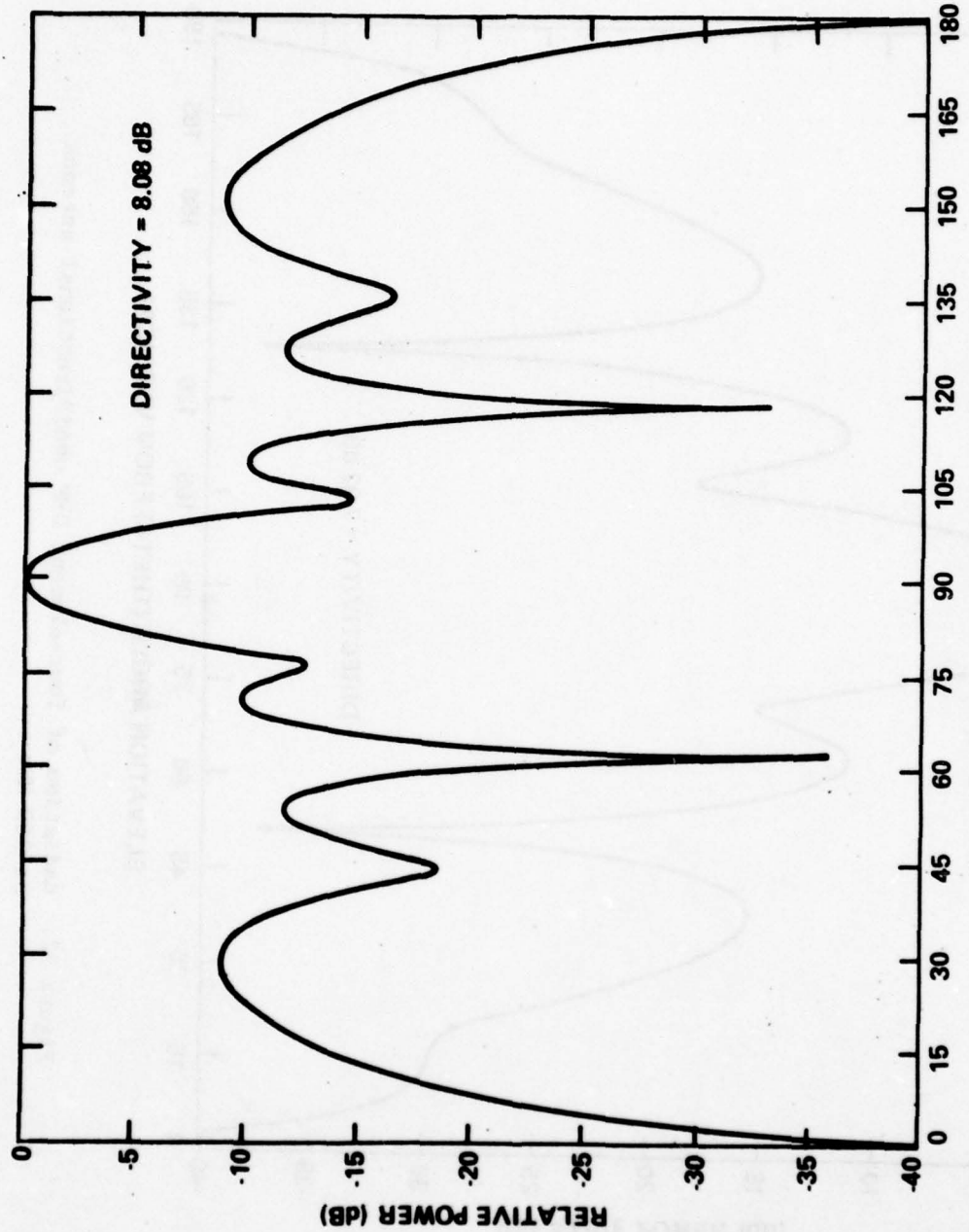


Figure 33. Radiation pattern of four-element UHF omnidirectional antenna at 400 MHz

4.3 Simulated Operational Performance

4.3.1 Ground Reflection Model

The free-space antenna patterns do not provide complete information about the antenna's performance in the real environment. The fact that the antenna is operated a certain height above a dielectric sphere (the earth) means that there will be reflections that will significantly modify the free-space radiation patterns. The geometry for this situation is shown in figure 34. The antenna is located a height h_1, above a spherical earth with relative permittivity ϵ_r and conductivity σ. The wave that travels along the direct path, R_d, to the aircraft is combined with the wave that follows the reflection path, R_r. The amplitude of the signal received at the aircraft depends on the separation distance d, the ground reflection coefficient, and the direct and reflected path length difference. Some other characteristics of the model are listed in figure 35. The received voltage can be calculated by using the equations shown in figure 36.

4.3.2 Vertical Lobing

A computer code called FIXEDR was developed to model the effects on the radiation patterns of reflections from a lossy spherical earth. This computer code is listed in Appendix D. The reflected signal magnitude and phase are dependent on the distance traveled and the magnitude and the phase of the ground reflection coefficient. The ground reflection coefficient is a function of the incidence angle as shown in figure 37. Complete cancellation occurs at the horizon (θ = +90 deg) because the reflected signal is equal in magnitude ($|R_v|$=1) and 180 deg out of phase with the direct signal. As the elevation angle decreases, the reflected signal adds or subtracts as the path length difference varies the relative phase. At some elevation angle, the magnitude of the reflection coefficient reaches a minimum and the angle changes from out of phase to in phase. This is called the pseudo-Brewster angle.

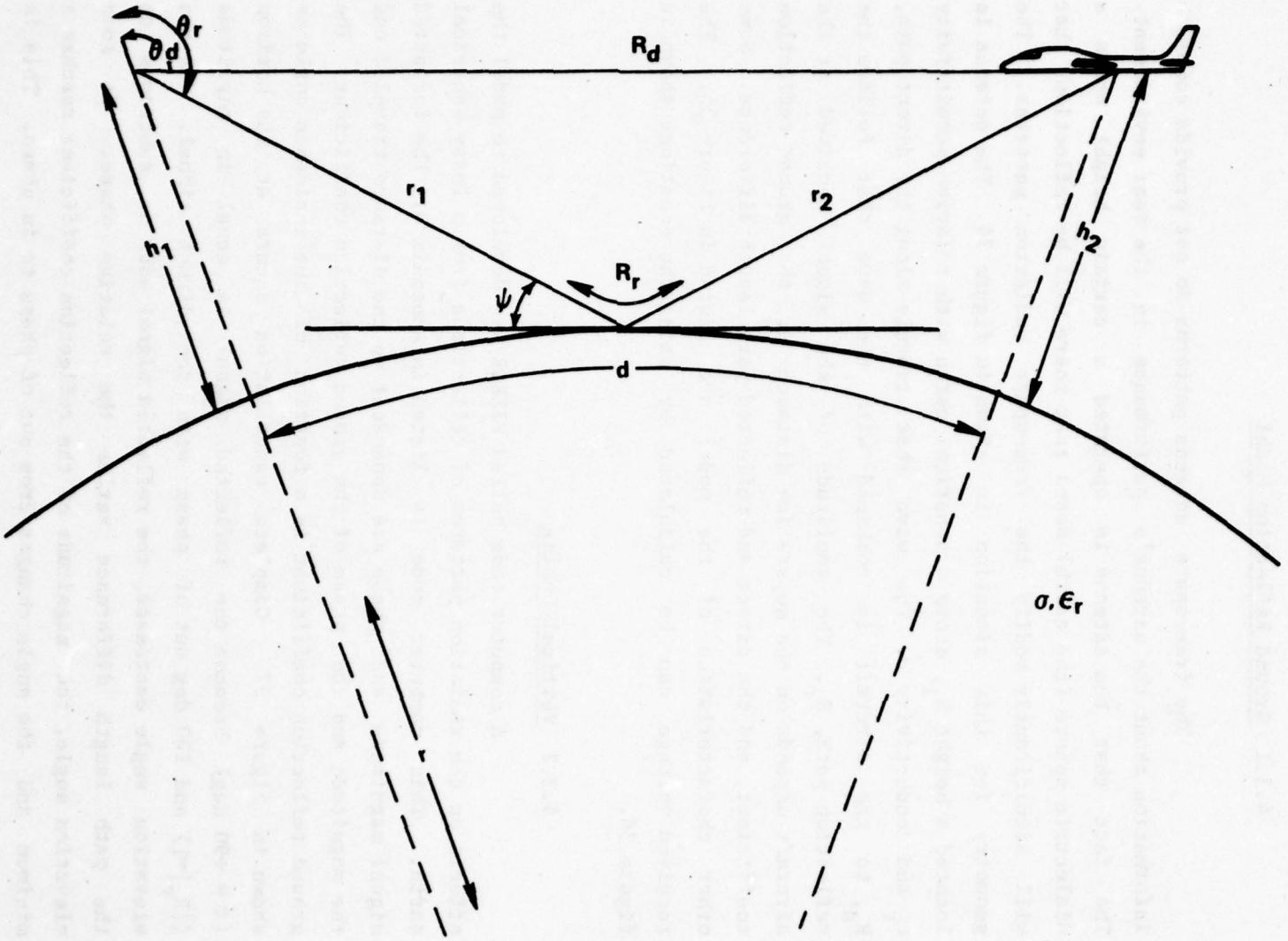


Figure 34. Earth reflection of radio signals

' SMOOTH, CURVED EARTH

' 4/3 RADIUS EARTH

' HALF-SPACE REFLECTION COEFFICIENT

' DIVERGENCE FACTOR INCLUDED FOR SPHERICAL EARTH REFLECTION

' DIRECT AND REFLECTED PATH ANGLES AND LENGTHS

' ANTENNA PATTERN NULLS LIMITED TO -25 dB

Figure 35. Characteristics of earth reflection model

V = RECEIVED VOLTAGE

$$= \lambda \sqrt{Z_0 G_R}\, E/4\pi$$

E = INCIDENT ELECTRIC FIELD

$$= E_D + E_R D \mathbf{R} e^{-JK(R_R - R_D)}$$

E_D = ELECTRIC FIELD VIA DIRECT PATH

$$= F(\theta_D) \sqrt{G_T P_T}/4\pi R_D$$

E_R = ELECTRIC FIELD VIA REFLECTED PATH

$$= F(\theta_R) \sqrt{G_T P_T}/4\pi R_R$$

D = DIVERGENCE FACTOR

$$= \left[1 + \frac{2 R_1 R_2}{RD \text{ TAN } \psi}\right]^{-1/2}$$

$\mathbf{R}$ = REFLECTION COEFFICIENT

$$= \frac{N^2 \text{ SIN}\psi - \sqrt{N^2 - \cos^2\psi}}{N^2 \text{ SIN}\psi + \sqrt{N^2 - \cos^2\psi}}$$

$$N^2 = \varepsilon_R - J\, 60\sigma\lambda$$

Figure 36. Radio transmission over earth

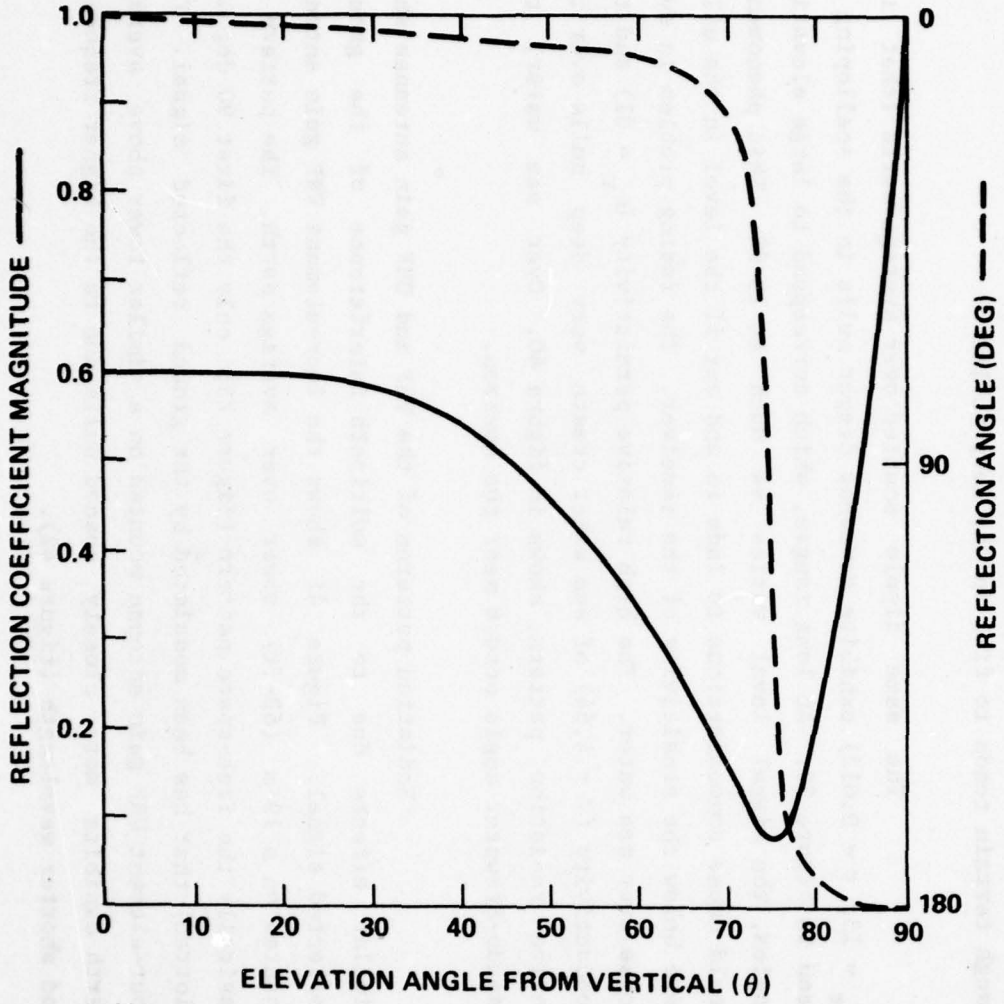


Figure 37. Ground reflection coefficient for average earth

The radiation pattern of a single dipole antenna mounted on top of a 13-m (40-feet) tower above dry earth is shown in Figure 38. Dry earth is assumed to have a relative permittivity of 2 and a conductivity of 0.001. The scalloping of the radiation pattern is due to the interference of the ground reflected wave. The pseudo-Brewster angle is clearly seen at 55 deg. The low signal level on the horizon (θ = 90 deg) is due to the destructive interference described above. In practice, since the earth is not a smooth sphere, scattering from rough terrain tends to fill in the deep nulls.

The same dipole mounted over average earth (that is, ε_r = 15, σ = 0.012) exhibits somewhat deeper nulls in the scalloping as seen in figure 39. At long ranges, which correspond to large elevation angles, the signal level varies as much as 15 dB. This phenomenon could cause communications to fade in and out if the level in the nulls were below the sensitivity of the receiver. The fading problem is even worse over sea water. The high relative permittivity (ε_r = 81) and the conductivity (σ = 4.64) of sea water create very deep nulls over the entire radiation pattern, shown in figure 40. Over sea water, the pseudo-Brewster angle occurs near the horizon.

Radiation patterns of the VHF and UHF gain antennas show similar effects due to the multipath interference of the ground reflected signal. Figure 41 shows the four-element VHF gain antenna mounted on a 19-m (62-ft) tower over average earth. The pattern is basically the free-space pattern (figure 25; only the first 90 deg are plotted) that has been modulated by the ground reflected signal. The four-element UHF gain antenna mounted on a similar tower above average earth exhibits more closely spaced nulls due to the higher frequency and shorter wavelength (figure 42).

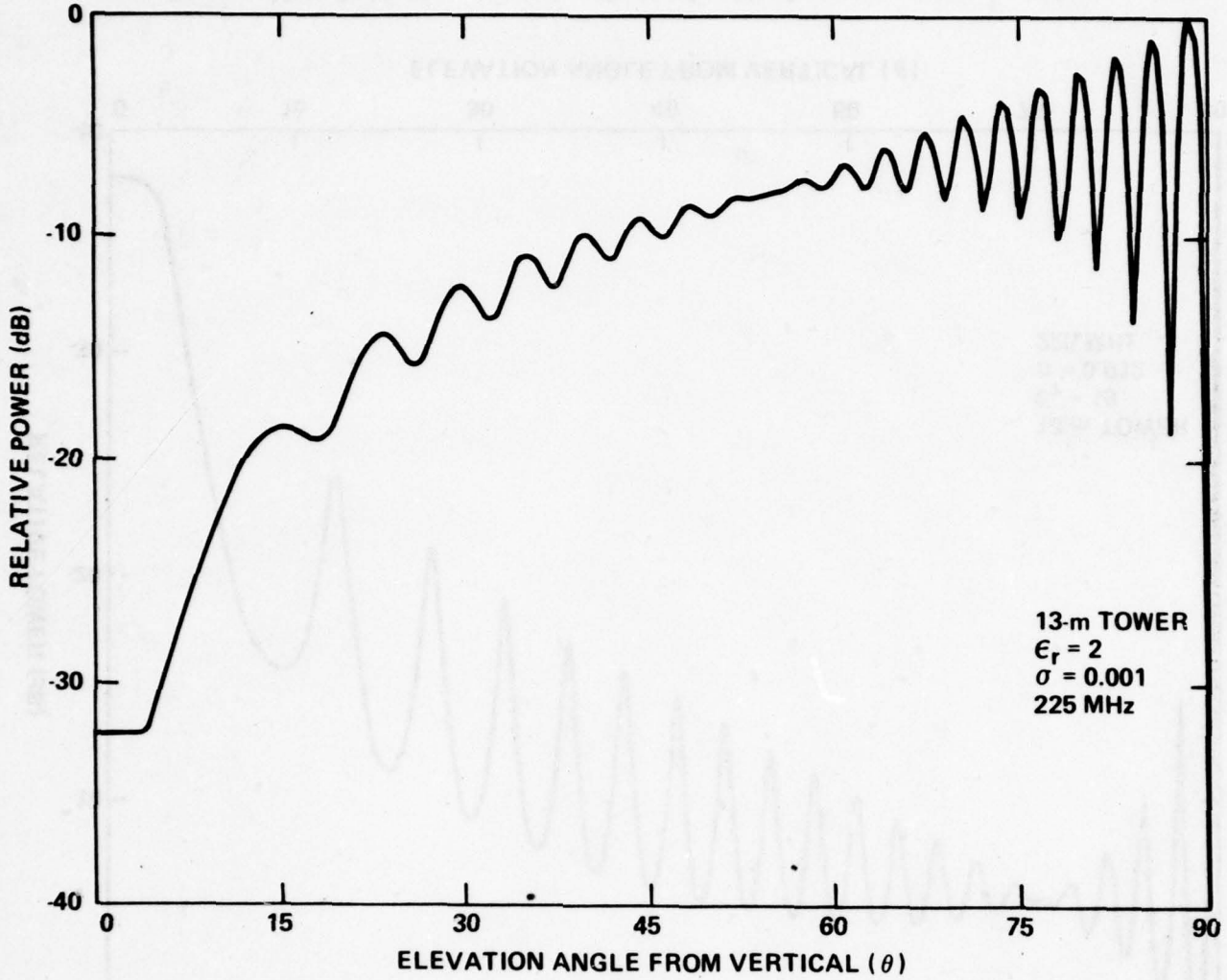


Figure 38. Radiation pattern of single dipole antenna over dry earth with ground reflections

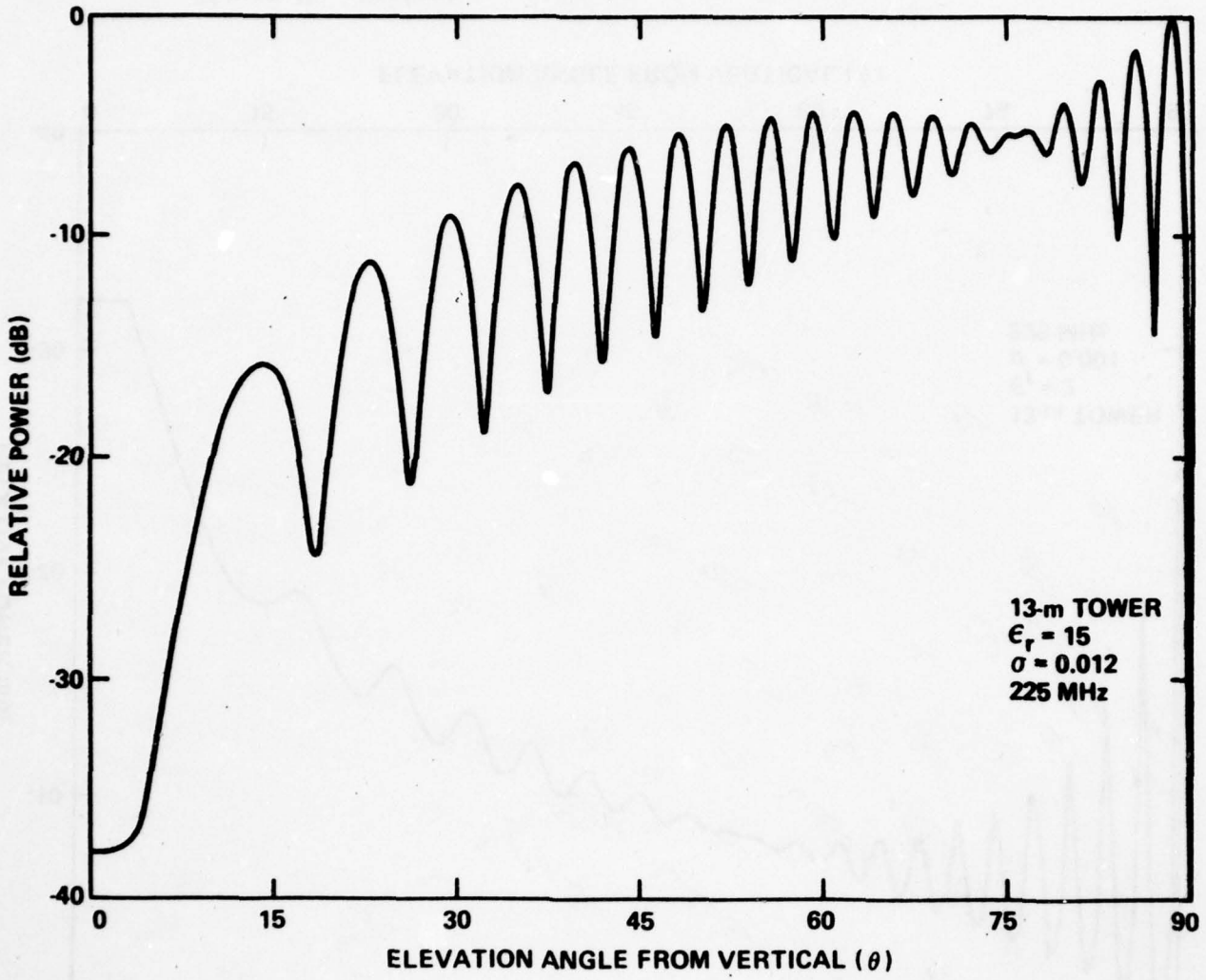


Figure 39. Radiation pattern of single dipole over average earth with ground reflection

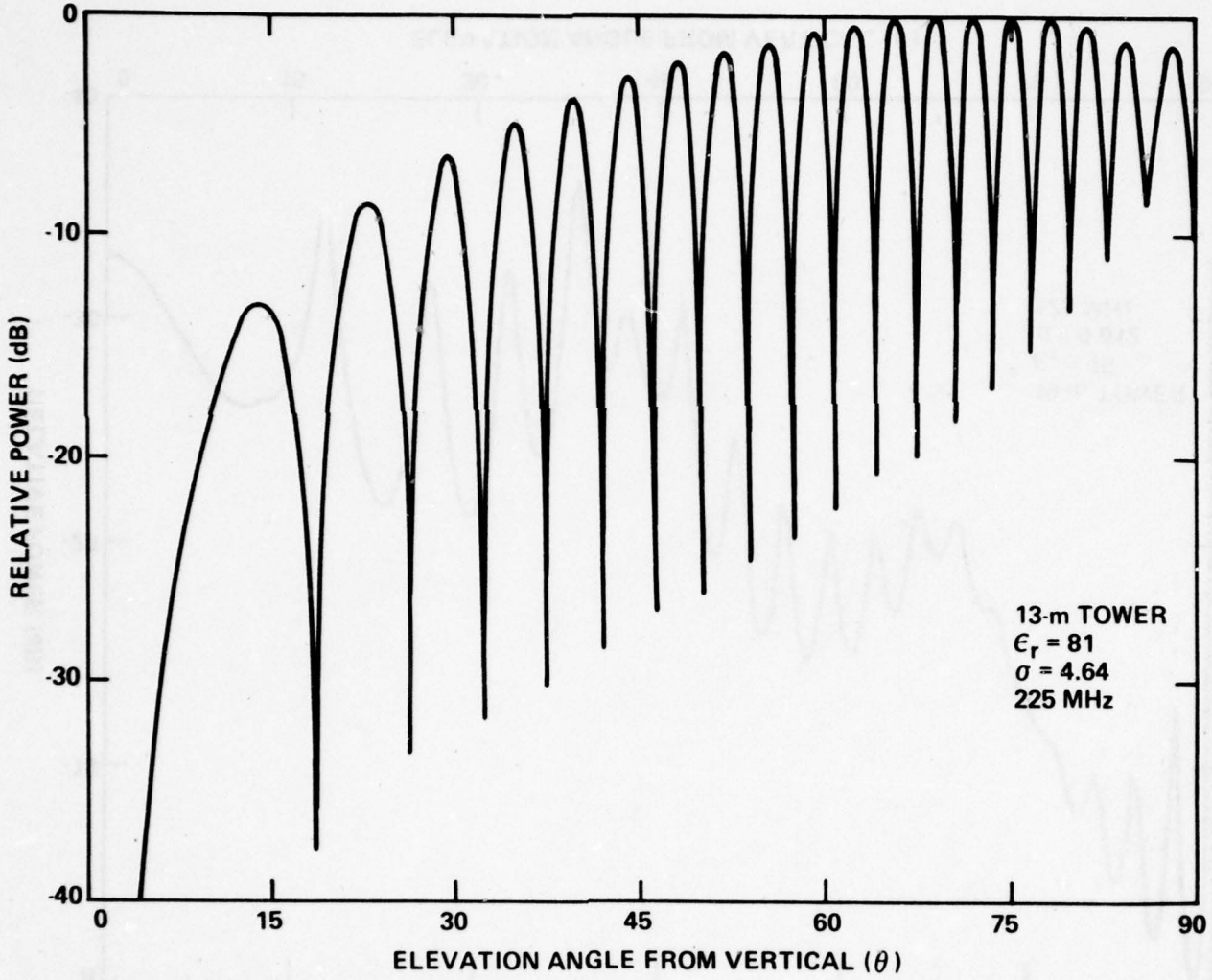


Figure 40. Radiation Pattern of single dipole over sea water with reflections

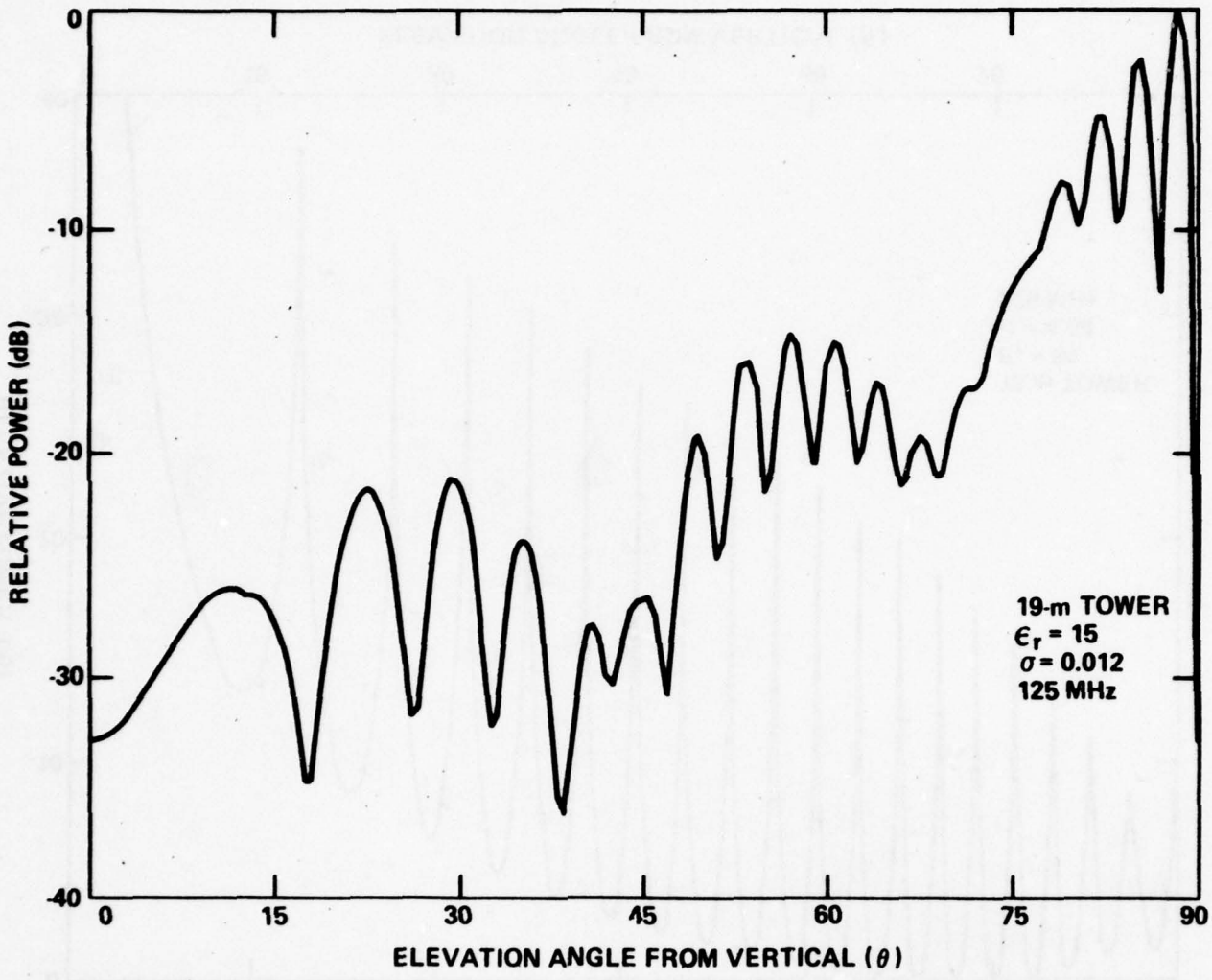


Figure 41. Radiation pattern of four-element VHF antenna over average earth with ground reflections

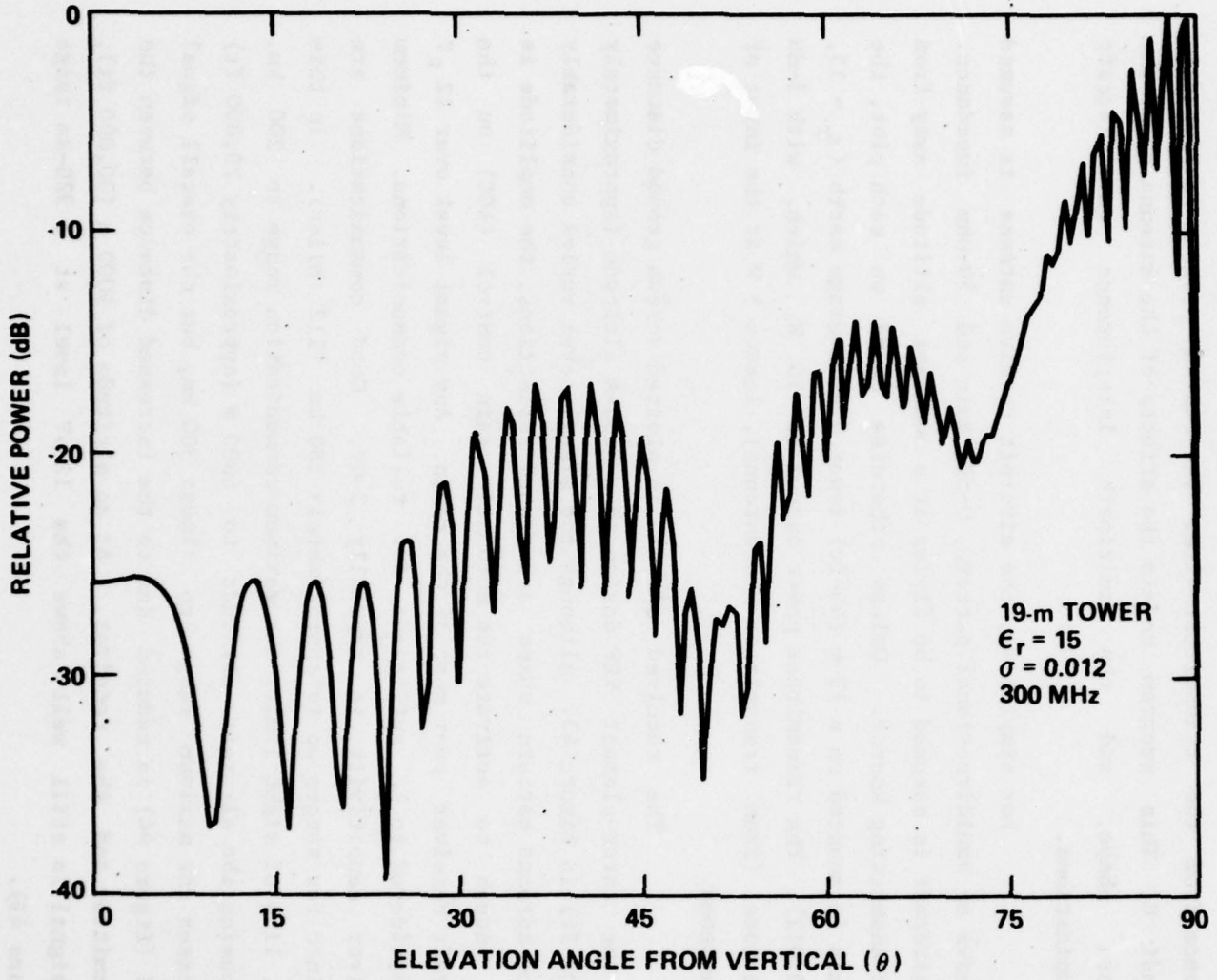


Figure 42. Radiation pattern of four-element UHF antenna over average earth with ground reflections

4.3.3 Flight Simulation Data

Another computer program, FLTSIM, was written to calculate (using the equations in figure 36) and plot the RF voltage at the output of the aircraft receive antenna as a function of the ground distance from the transmitter site. The FORTRAN program is listed in Appendix E. This program models the effects of the antenna gain, the pattern shape, and the multipath interference on aircraft communications.

For simplicity, the aircraft receive antenna is assumed to have an omnidirectional 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 (40-ft) tower over average earth (ϵ_r = 15, σ = 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 three-element VHF design at a 3000-m altitude (approximately 10,000 ft) in figure 43. 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. Any signal level over 12 μV is considered to be sufficient for reliable communications. Minimum receiver sensitivity is typically 3 μV. Good communications are obtained for ranges up to approximately 180 km (112 miles). In this case, line of sight limits the maximum communication range to 200 km. Increasing the aircraft altitude to 6000 m (approximately 20,000 ft) increases the maximum range to almost 300 km, but the overall signal level (figure 44) 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 45).

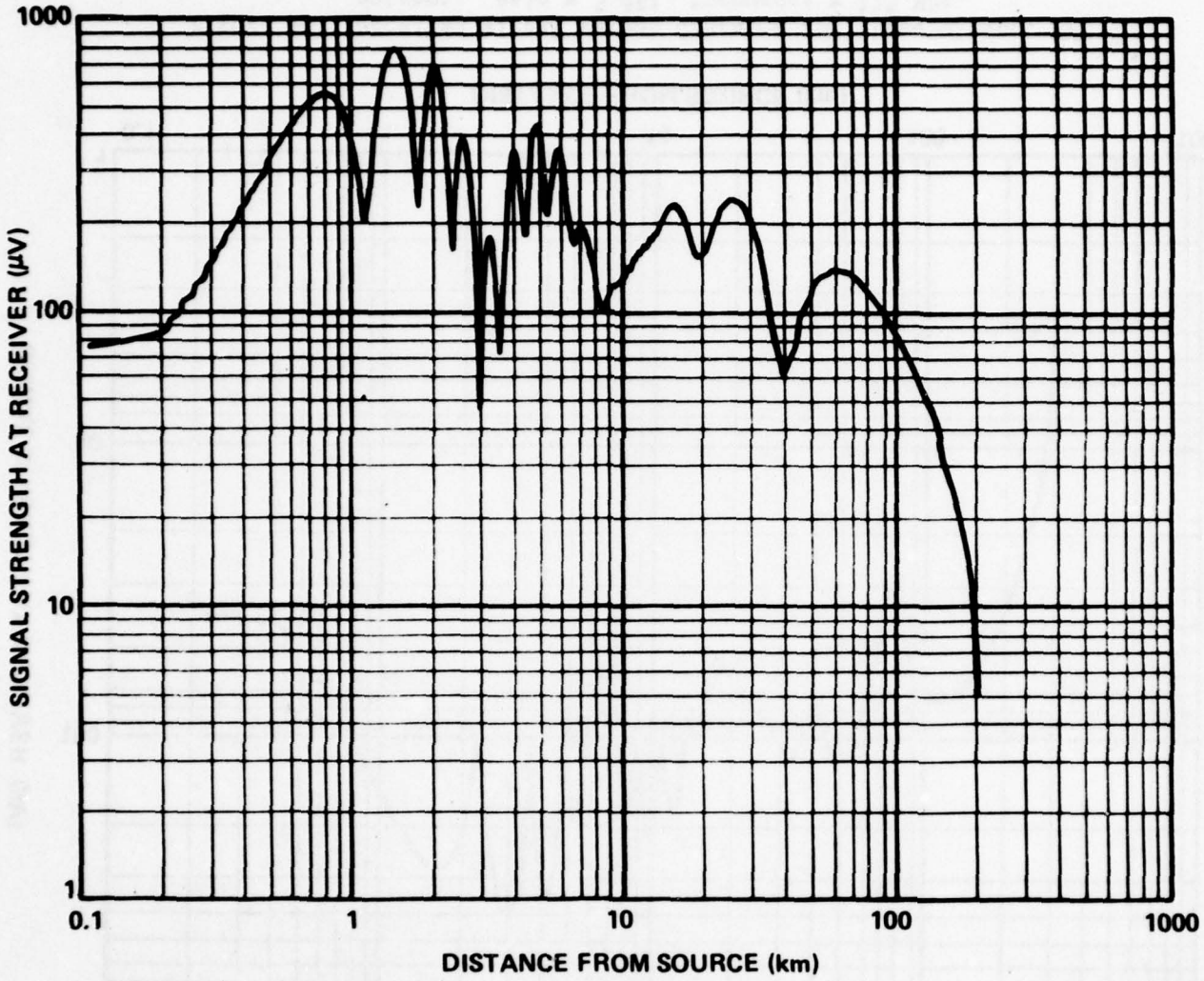


Figure 43. Received signal versus distance for three-element VHF antenna: gain = 5 dBi, frequency = 125 MHz, altitude = 3000m

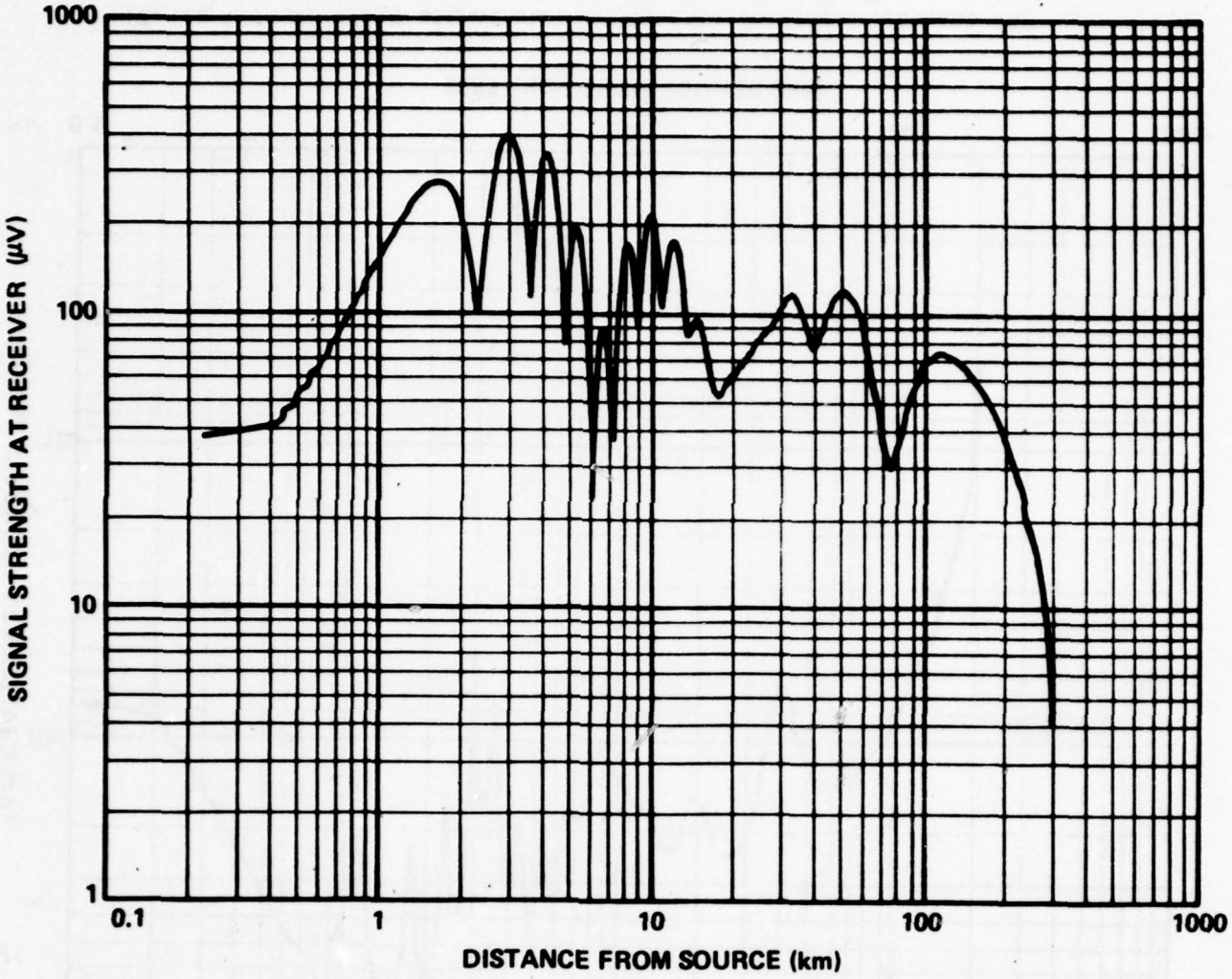


Figure 44. Received signal versus distance for three-element VHF antenna: gain = 5 dBi, frequency = 125 MHz, altitude = 6000m

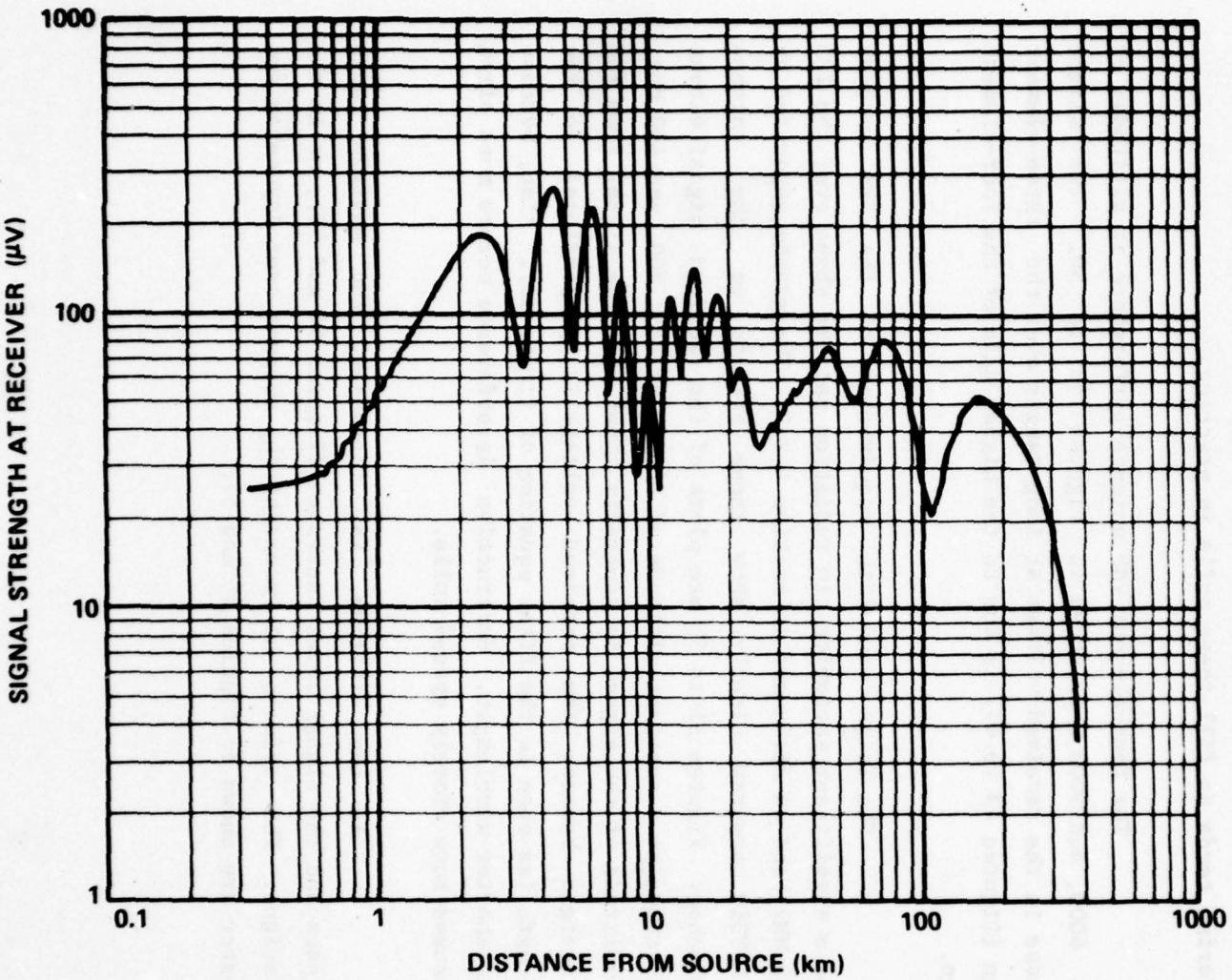


Figure 45. Received signal versus distance for three-element VHF antenna: gain 5 dBi, frequency = 125 MHz, altitude = 9000m

The same antenna mounted over dry earth ($\varepsilon_r = 2$, $\sigma = .001$) shows less scalloping with reduced nulls at close range (figure 46). Over sea water (figure 47), the nulls are very deep and occasionally drop below the level for good communications. Random scattering tends to fill these nulls in practice.

The four-element VHF antenna performance at altitudes of 3000, 6000, and 9000 m is shown in figures 48 to 50. The slight increase in the received voltage at long ranges over the three-element design (figures 43 to 45) is due to the higher gain of the four-element design.

The large bandwidth requirement of the UHF antenna causes a significant variation in radiation pattern shape over the 225 to 400 MHz band as discussed in section 4.2.2. The graphs generated by the FLTSIM program clearly show these effects on the antenna performance. Figures 51 to 53 are plots of the received signal versus the distance at a constant altitude of 6000 m at 225, 300, and 400 MHz. The amplitude of the signal is generally lower than the signal from the VHF designs because the received voltage is proportional to the wavelength (as seen in the first equation of figure 36). Also, because of the shorter wavelength, destructive interference occurs more often and causes more closely spaced nulls.

As the altitude is increased, the maximum range increases and the signal level decreases (figures 54 and 55), as in the VHF designs. The effects of mounting the antenna over dry earth and sea water are shown in figures 56 and 57.

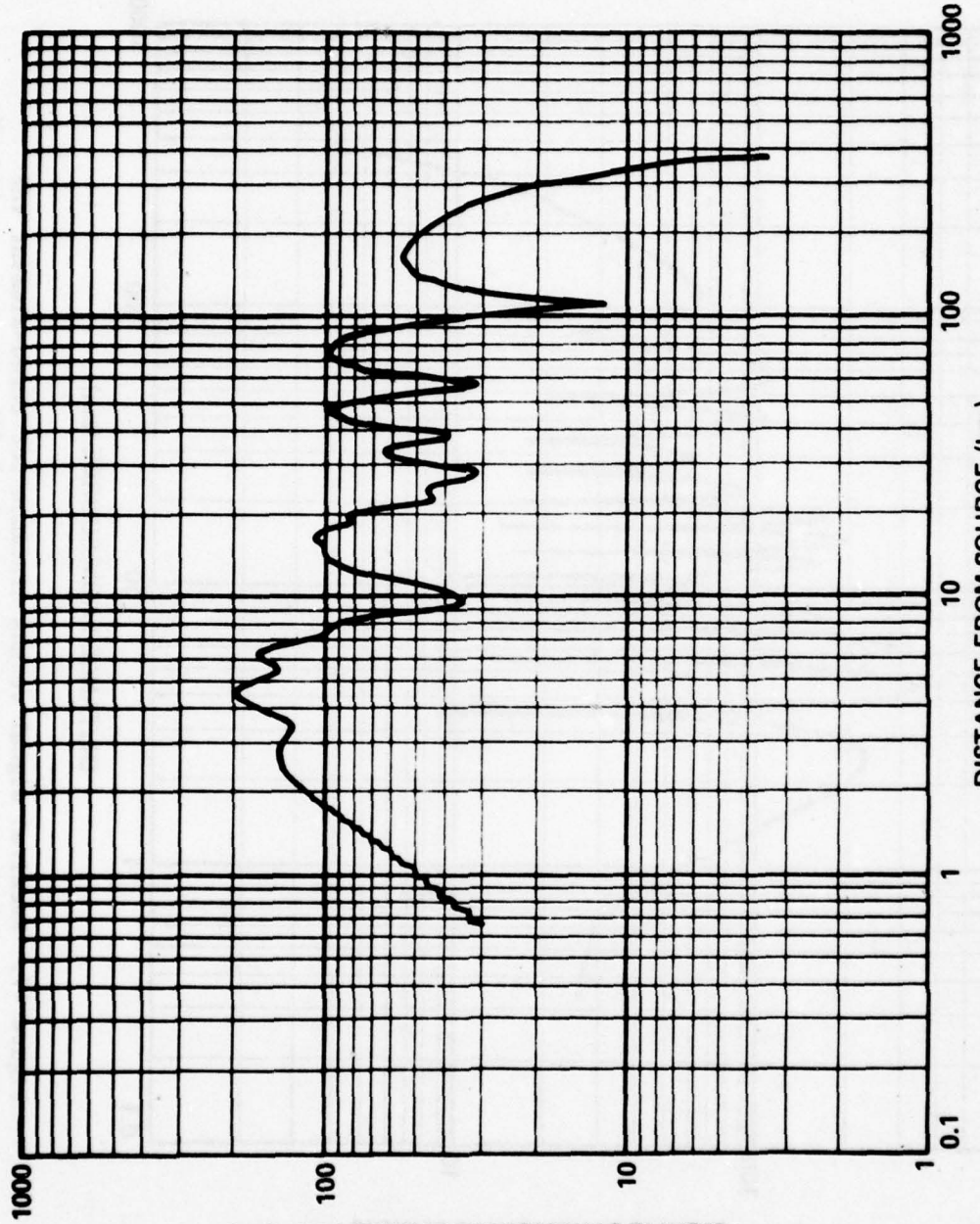


Figure 46. Received signal versus distance for three-element VHF antenna over dry earth: gain = 5 dBi, frequency = 125 MHz, altitude = 9000m

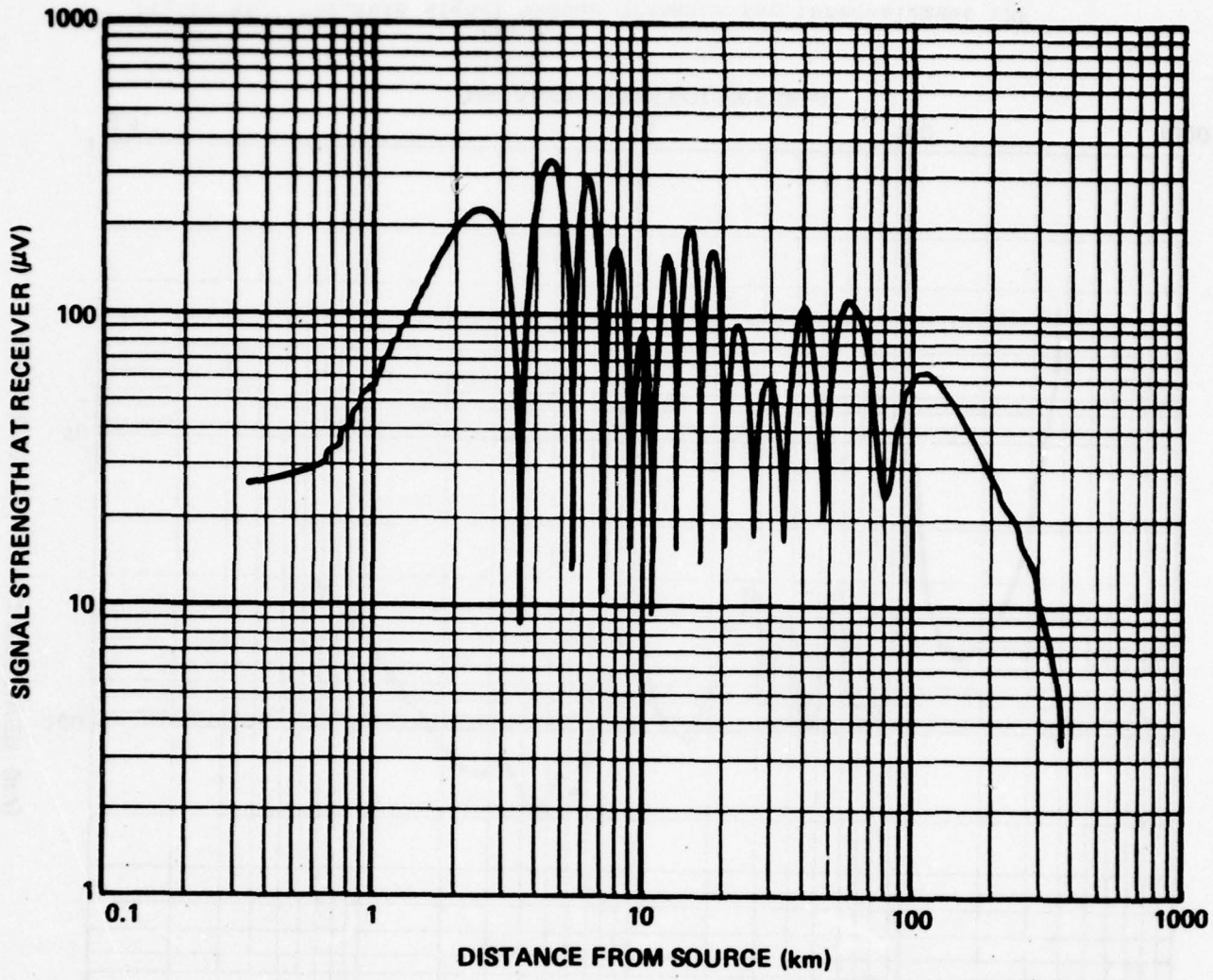


Figure 47. Received signal versus distance for three-element VHF antenna over sea water: gain = 5 dBi, frequency = 125 MHz, altitude = 9000m

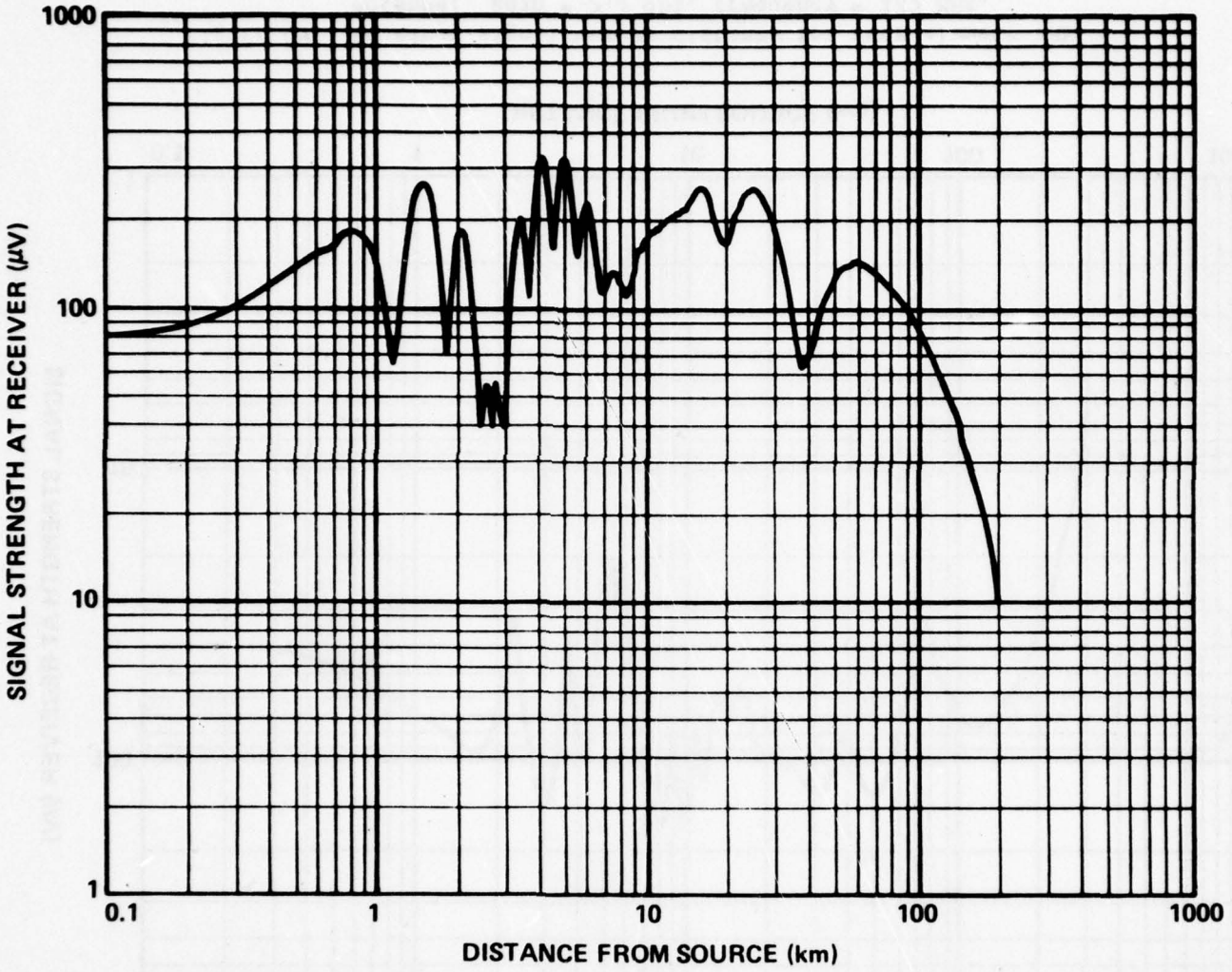


Figure 48. Received signal versus distance for four-element VHF antenna: gain = 5.3 dBi, frequency = 125 MHz, altitude = 3000m

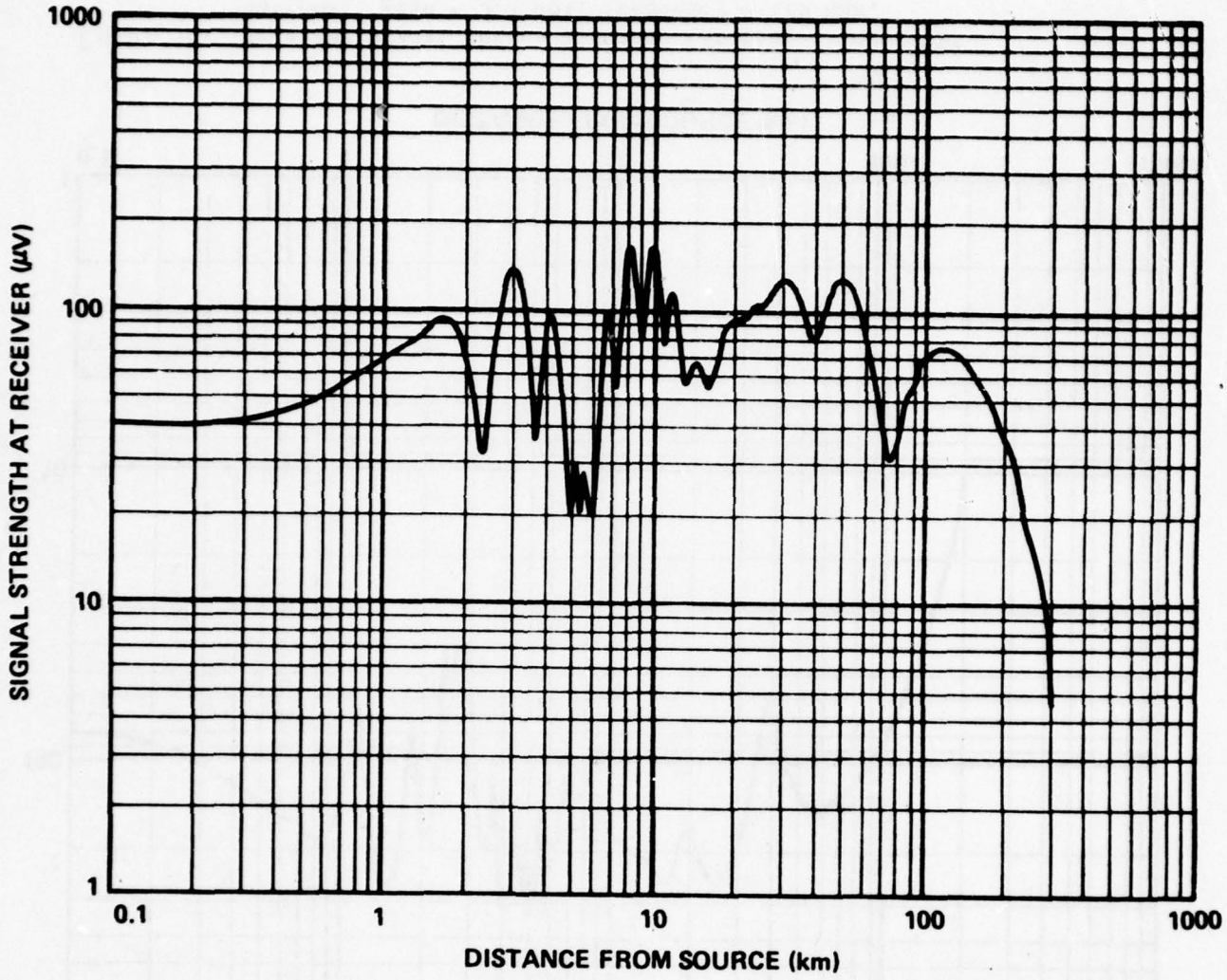


Figure 49. Received signal versus distance for four-element VHF antenna: gain = 5.3 dBi, frequency = 125 MHz, altitude = 6000m

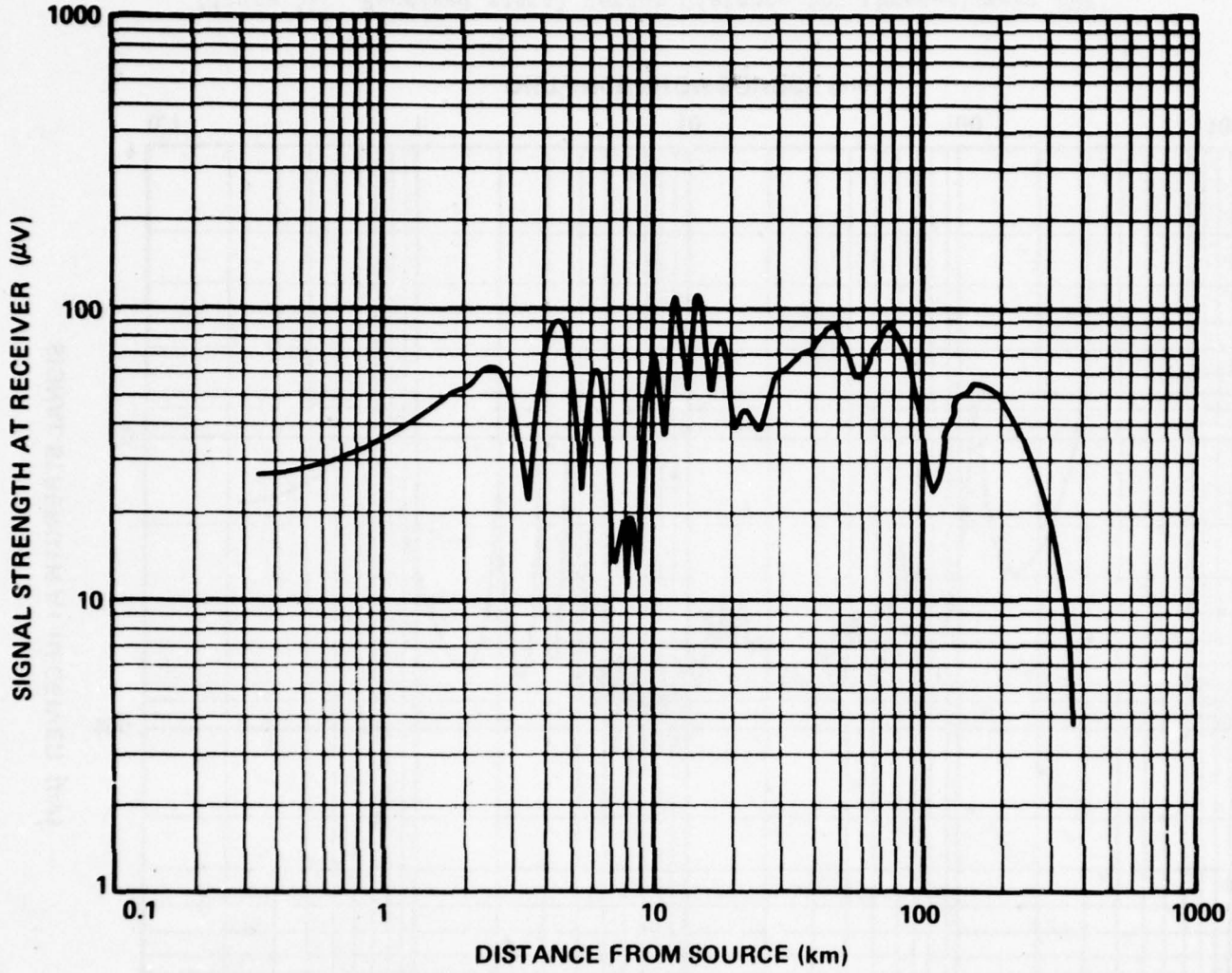


Figure 50. Received signal versus distance for four-element VHF antenna: gain = 5.3 dBi, frequency = 125 MHz, altitude = 9000m

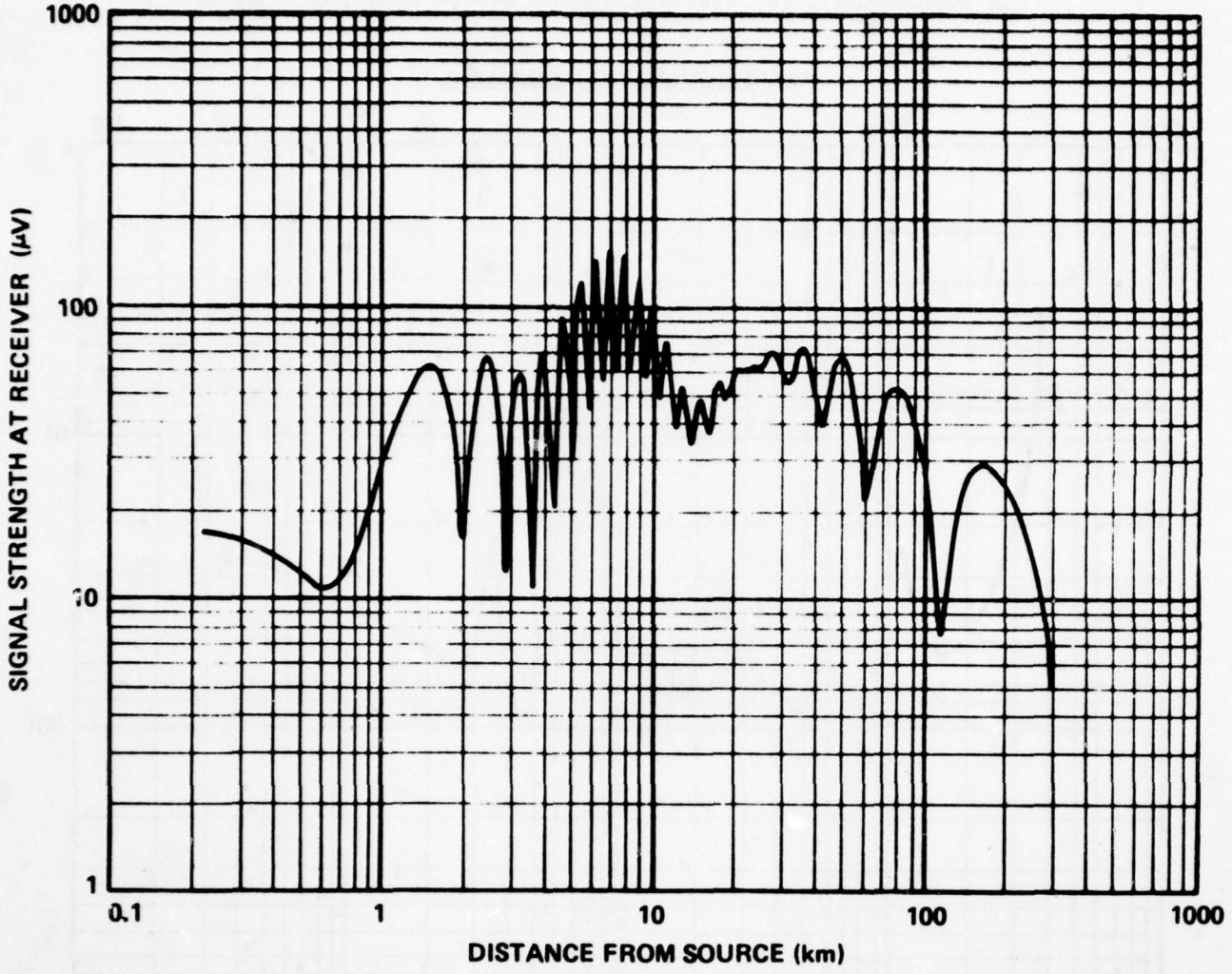


Figure 51. Received signal versus distance for three-element UHF antenna: gain = 4.44 dBi, frequency = 225 MHz, altitude = 6000m

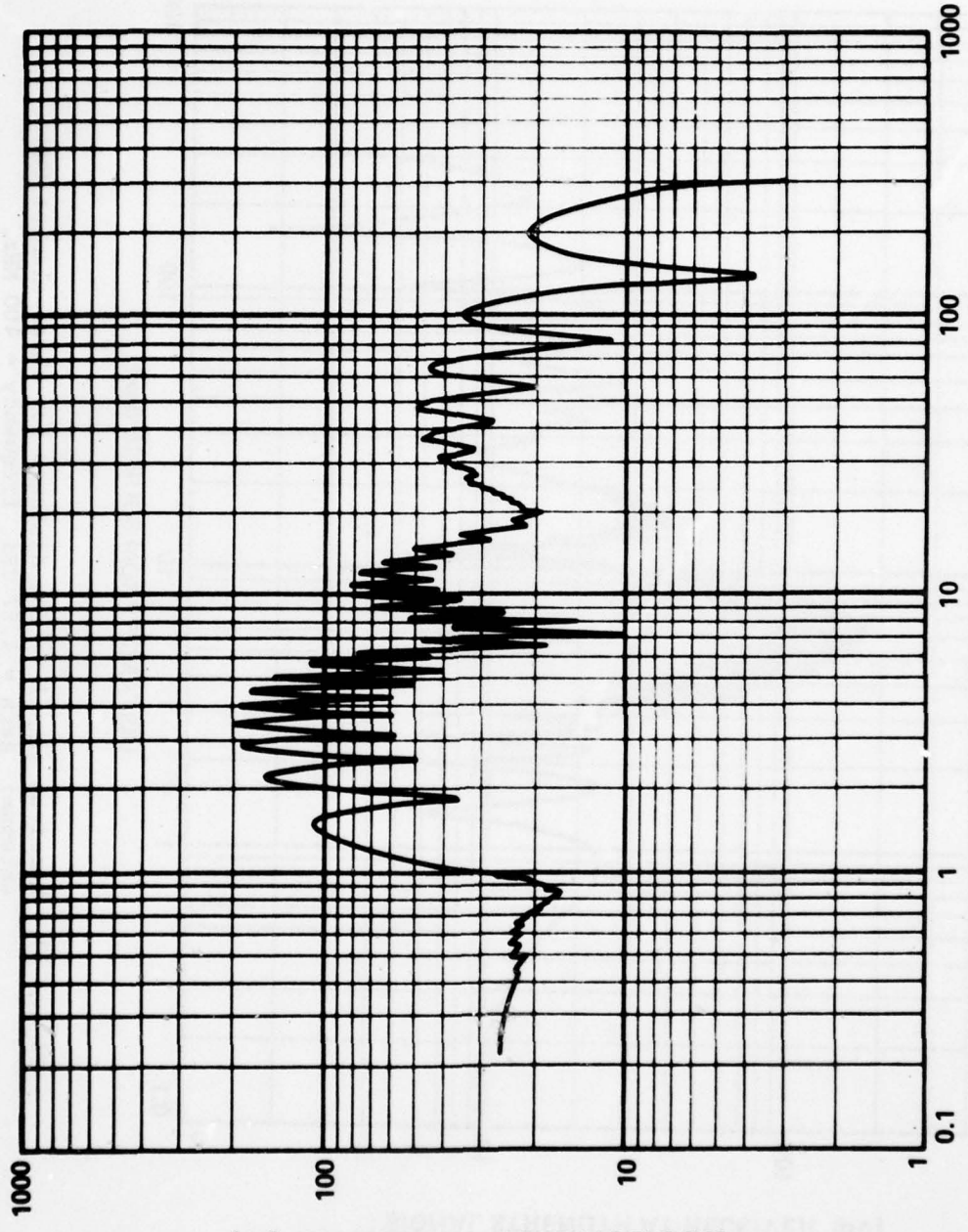


Figure 52. Received signal versus distance for three-element UHF antenna: gain = 4.94 dBi, frequency = 300 MHz, altitude = 6000m

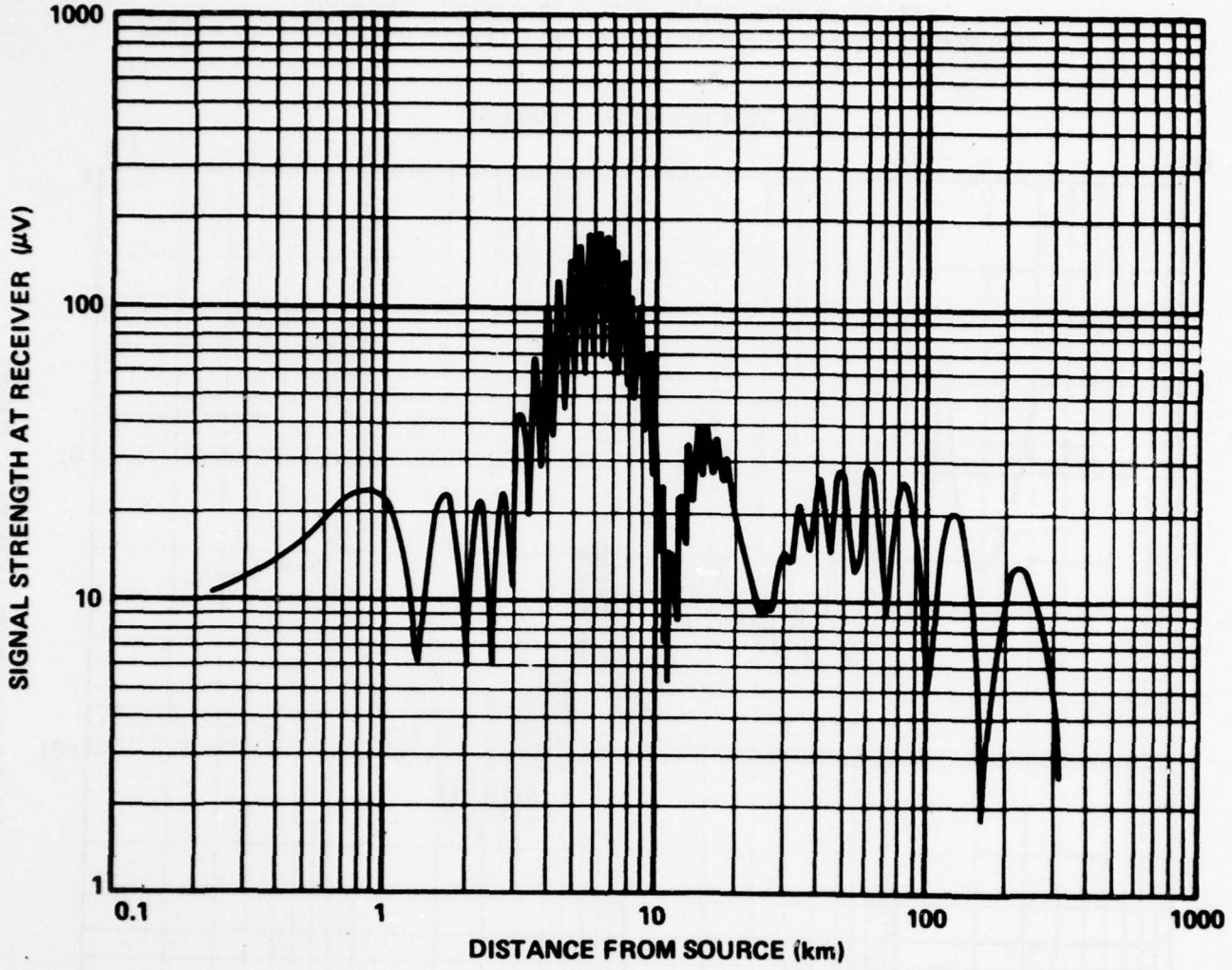


Figure 53. Received signal versus distance for three-element UHF antenna: gain = 4.67 dBi, frequency = 400 MHz, altitude = 6000m

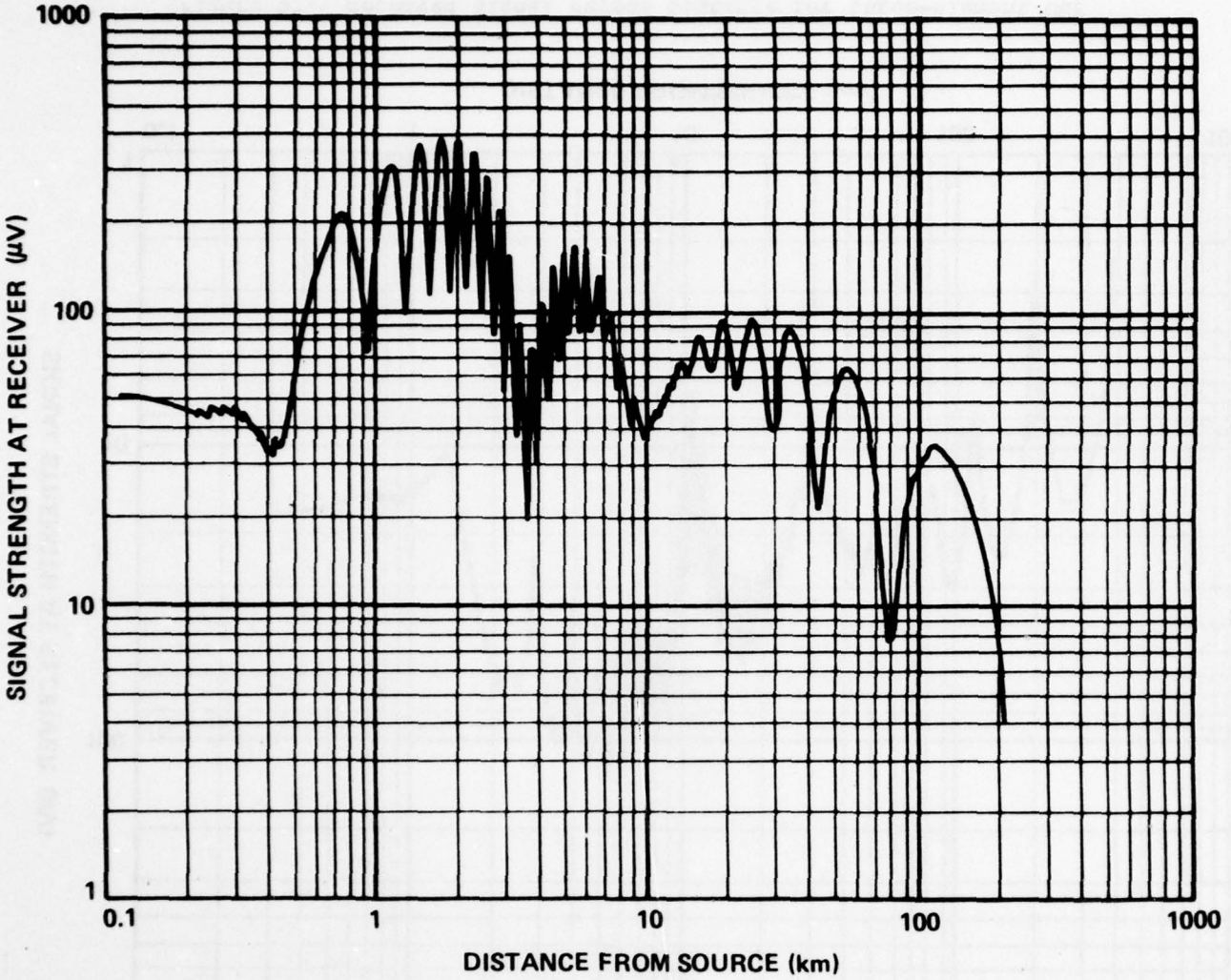


Figure 54. Received signal versus distance for three-element UHF antenna: gain = 4.94 dBi, frequency = 300 MHz, altitude = 3000m

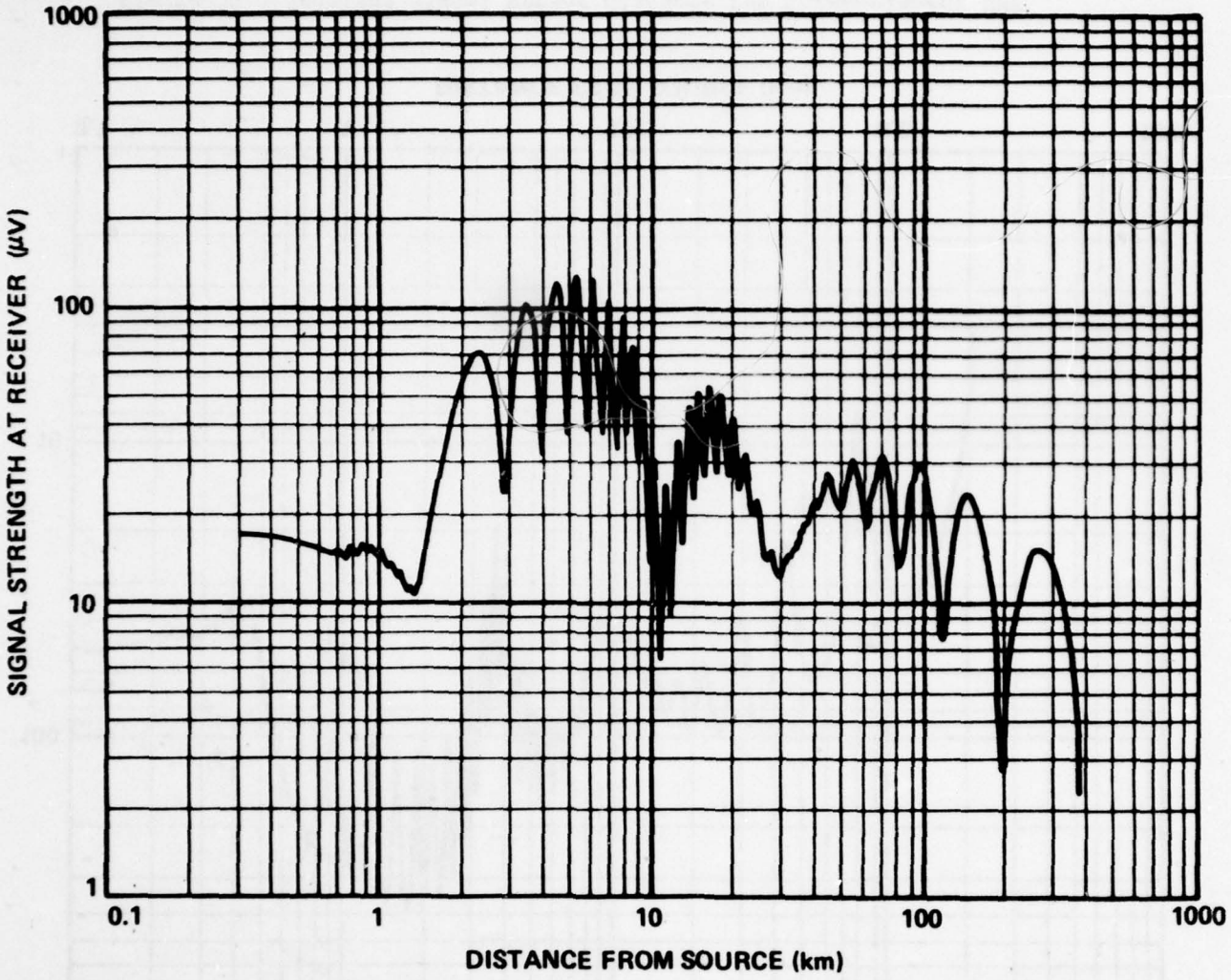


Figure 55. Received signal versus distance for three-element UHF antenna: gain = 4.94 dBi, frequency = 300 MHz, altitude = 9000m

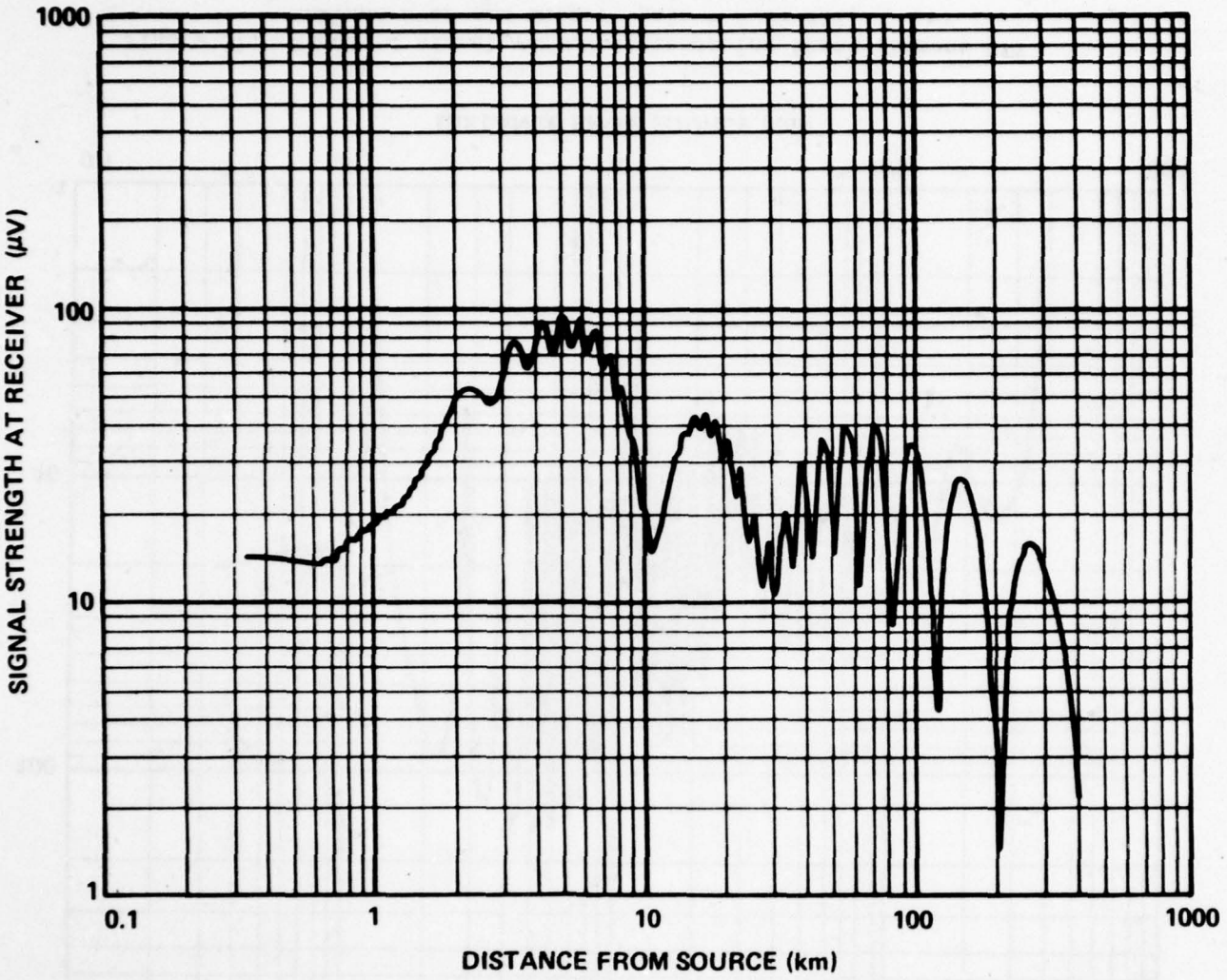


Figure 56. Received signal versus distance for three-element VHF antenna over dry earth: gain = 4.94 dBi, frequency = 300 MHz, altitude = 9000m

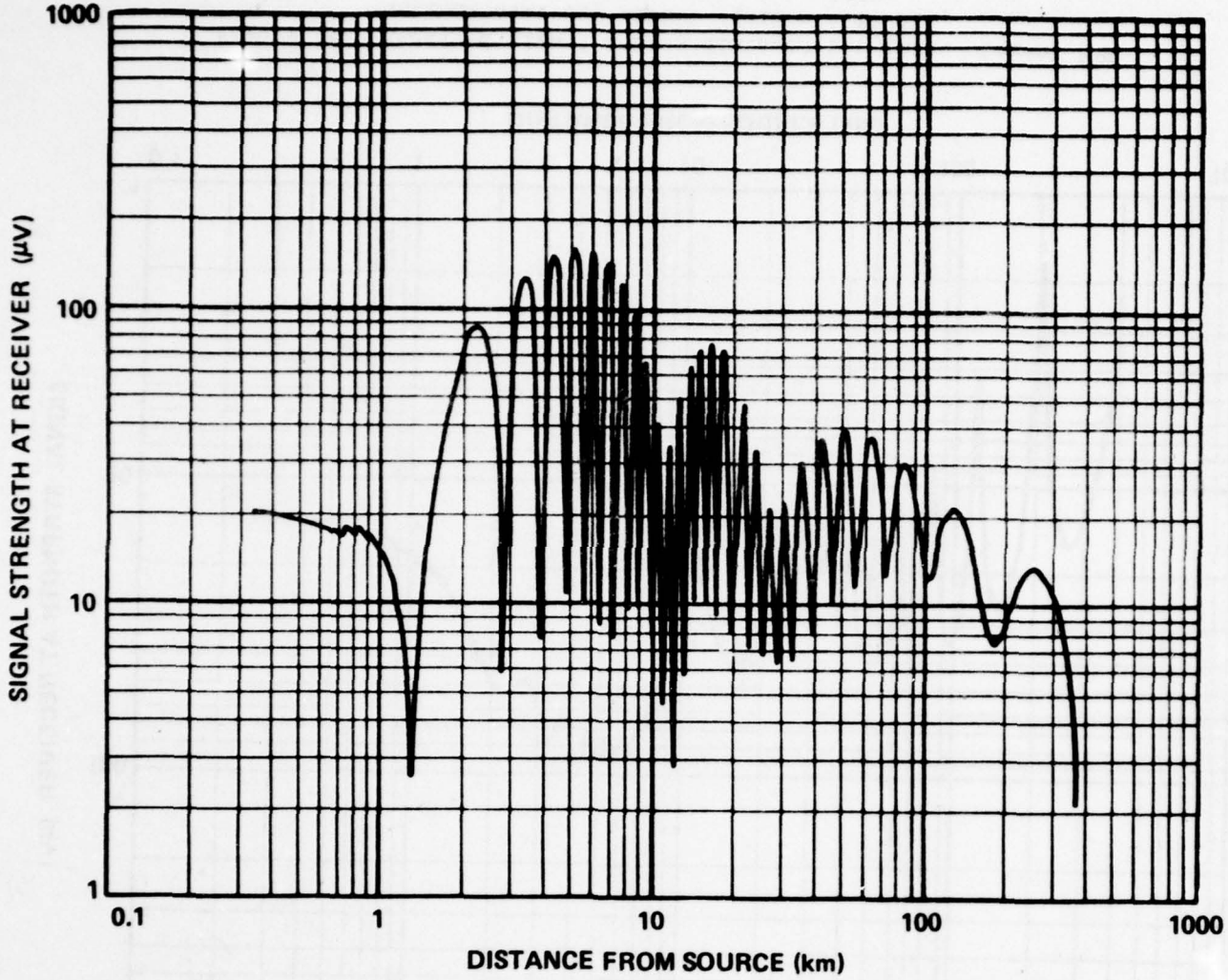


Figure 57. Received signal versus distance for three-element UHF antenna over sea water: gain = 4.94 dBi, frequency = 300 MHz, altitude = 9000m

The performance of the four-element design shown in figure 27 also has been analyzed. Figures 58 to 60 show typical received signal levels at constant altitude over the UHF band. For a frequency of 300 MHz, the received signal is plotted at altitudes of 3000 and 9000 m in figures 61 and 62. The effects of the relative permittivity and the conductivity of the smooth earth model are shown in figures 63 and 64, in which the antenna is over dry earth ($\varepsilon_r = 2$, $\sigma = .001$) and sea water ($\varepsilon_r = 81$, $\sigma = 4.64$).

Mounting the antenna on a higher tower merely changes the path length and the incident angle of the reflected signal. The result of placing the four-element VHF antenna on a 29-m (95-ft) tower is shown in figure 65. Comparing this to figure 50 (the same antenna on a 13-m tower) shows that elevating the antenna height above the ground increases the number of interference nulls in the received signal.

Increasing the transmitter output power from 10 to 50 W corresponds to a power ratio of 7 dB. However, 7 dB corresponds to a voltage ratio of 2.24. Therefore, a 50-W transmitter increases the received signal voltage level by a factor of 2.24. Comparing the received signal level for a 50-W transmitter (figure 66) with that of a 10-W transmitter (figure 50) shows this to be true.

To show the actual increase in received voltage for a 5-dBi-gain antenna, FLTSIM has been used to plot the received signal versus the distance for a single dipole antenna. The gain of the dipole, set at 0 dBi, is typical of many commercially available broadband dipoles. The results for the dipole (0-dBi gain) and the three-element VHF (5-dBi gain) design are shown in figure 67. To simplify the comparison, the effects of the ground reflected signal have been ignored. That is, the antenna is located in free space.

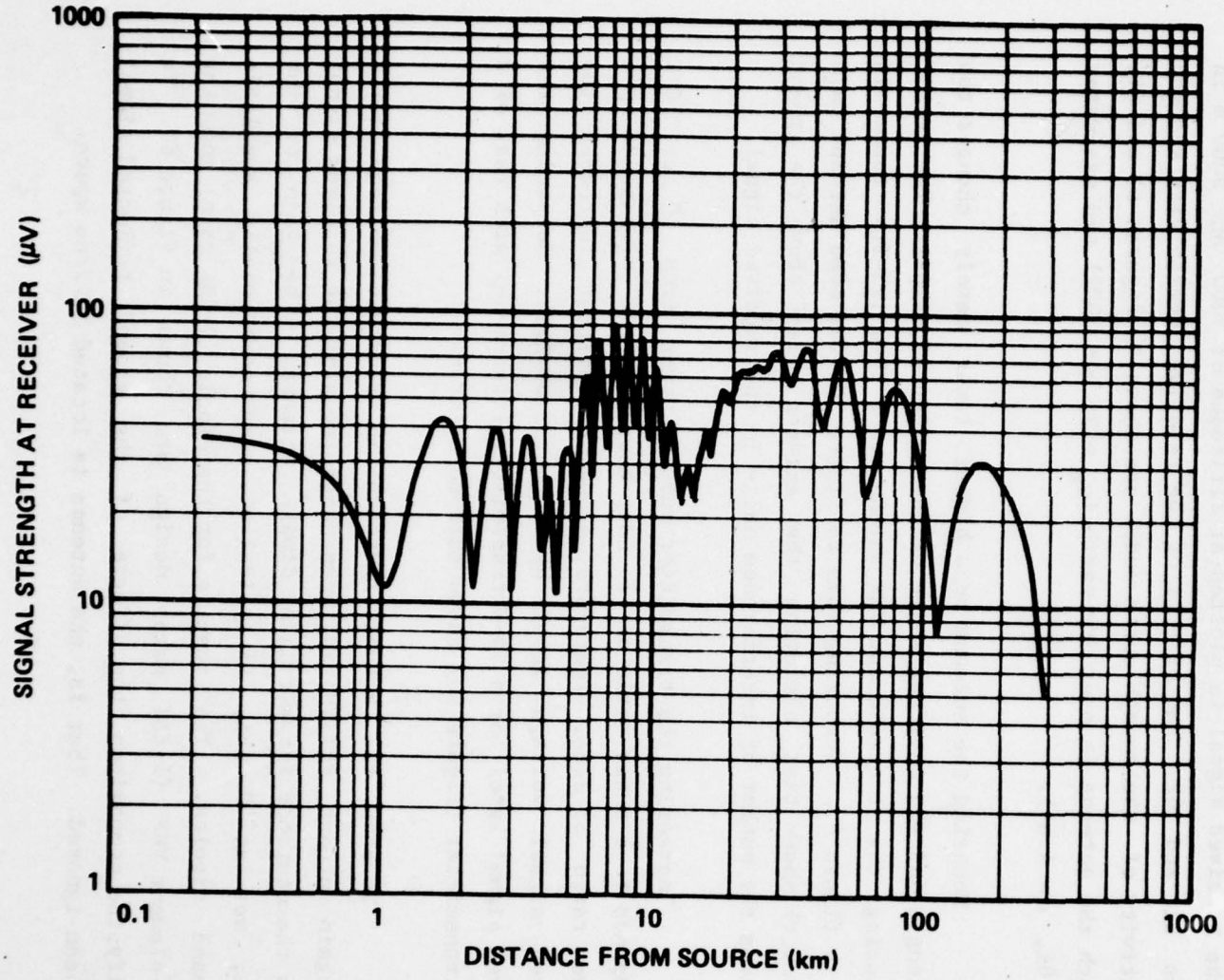


Figure 58. Received signal versus distance for four-element UHF antenna: gain = 5 dBi, frequency = 225 MHz, altitude = 6000m

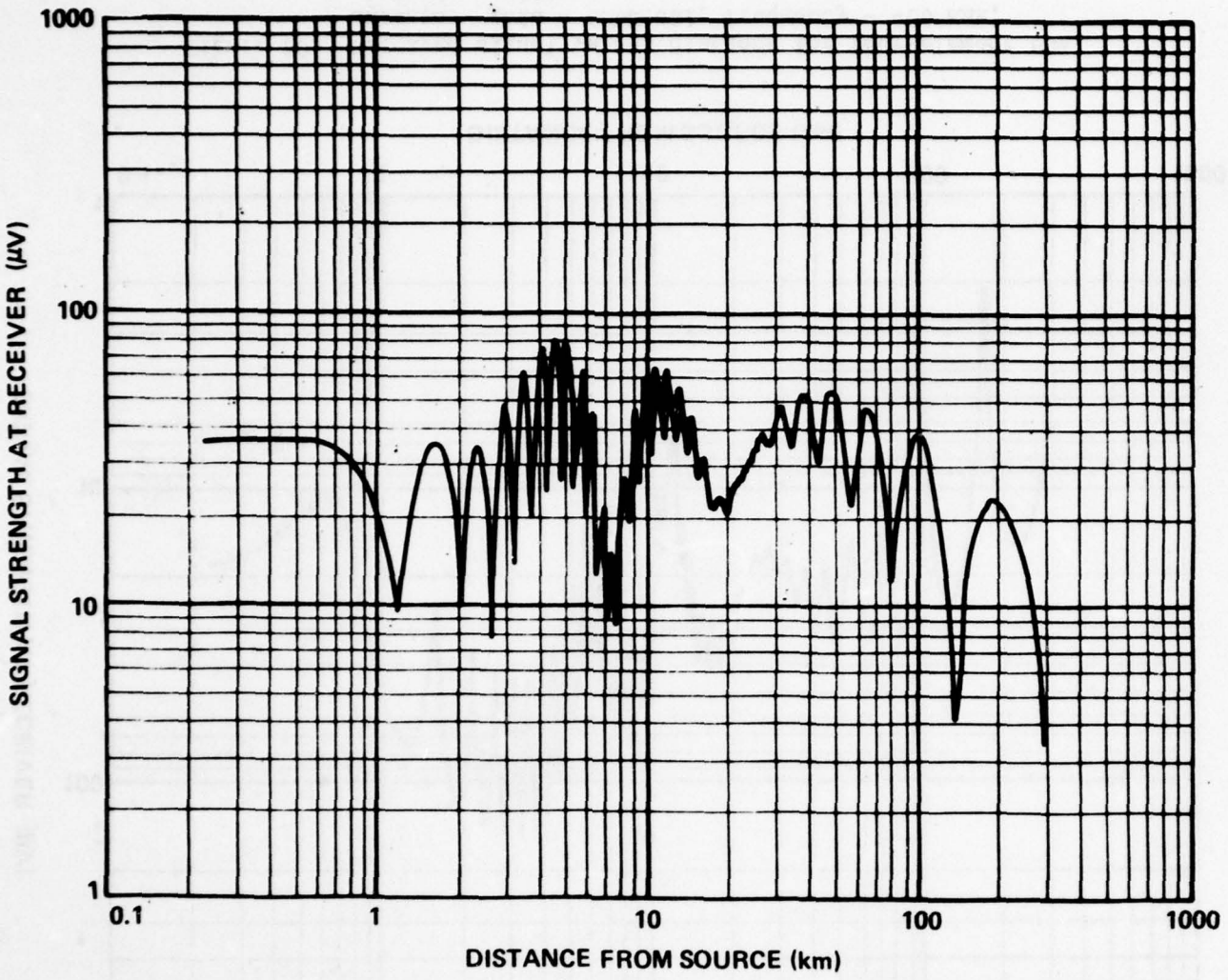


Figure 59. Received signal versus distance for four-element UHF antenna: gain = 5.95 dBi, frequency = 300 MHz, altitude = 6000m

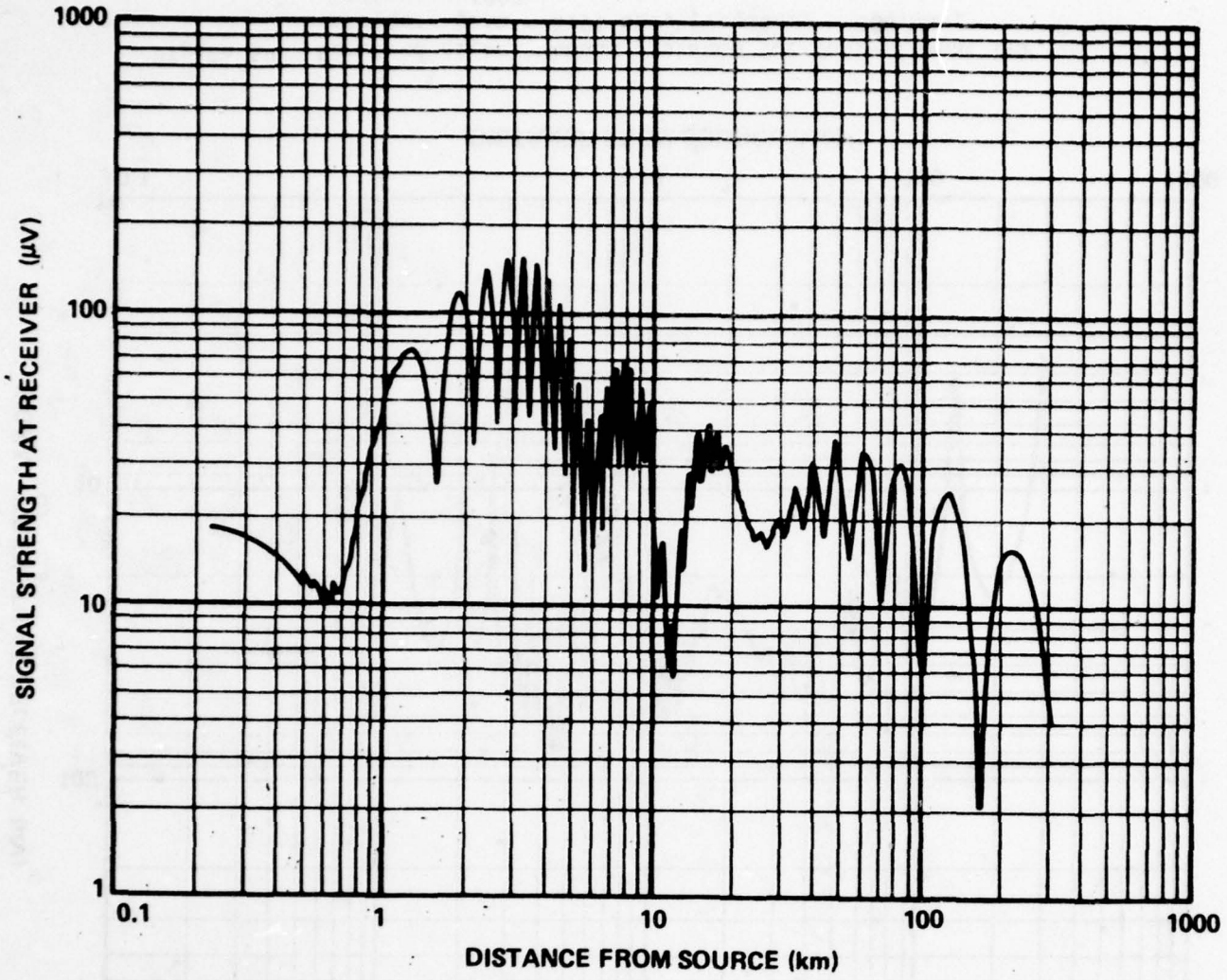


Figure 60. Received signal versus distance for four-element UHF antenna: gain = 6.08 dBi, frequency = 400 MHz, altitude = 6000m

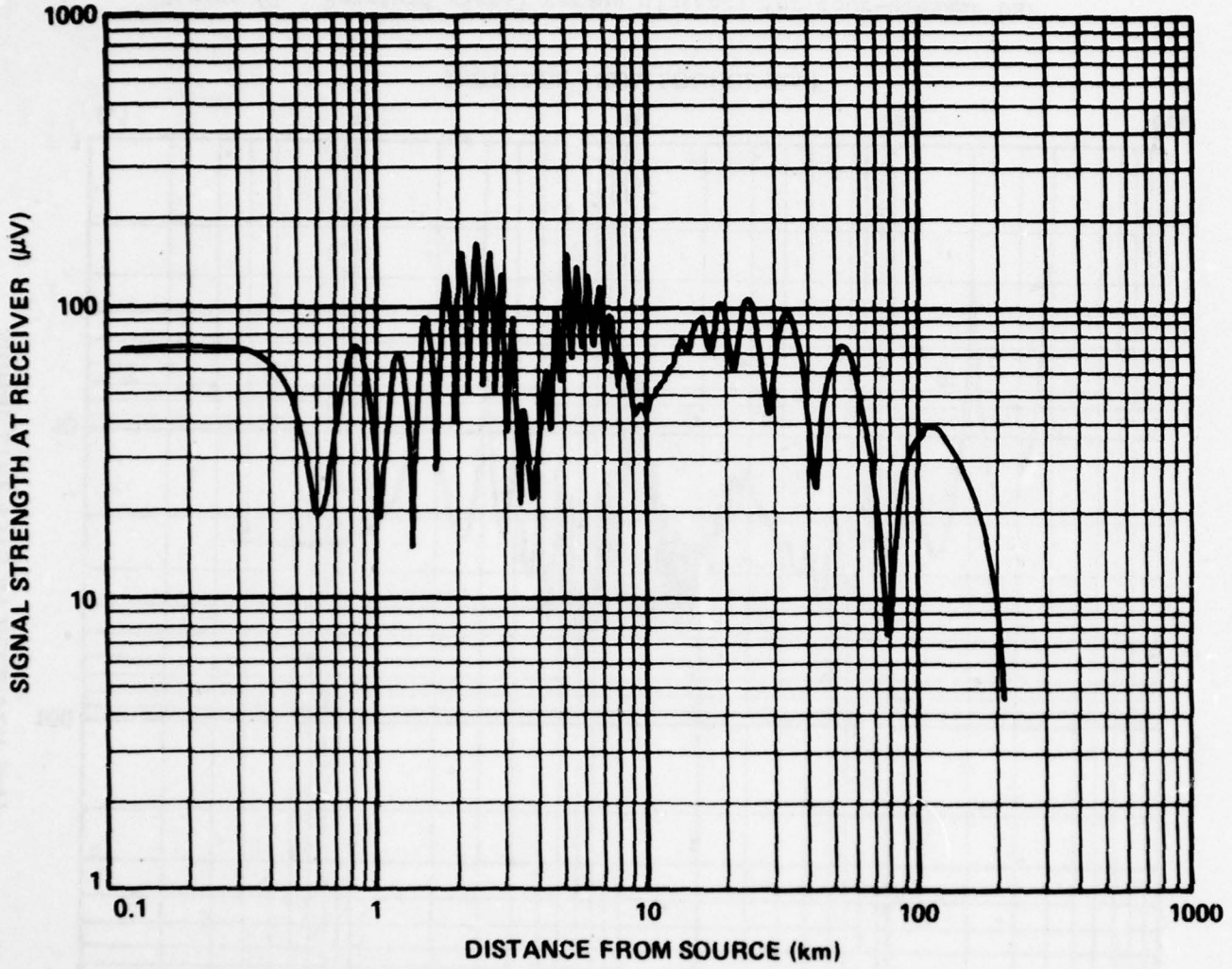


Figure 61. Received signal versus distance for four-element UHF antenna: gain = 5.92 dBi, frequency = 300 MHz, altitude = 3000m

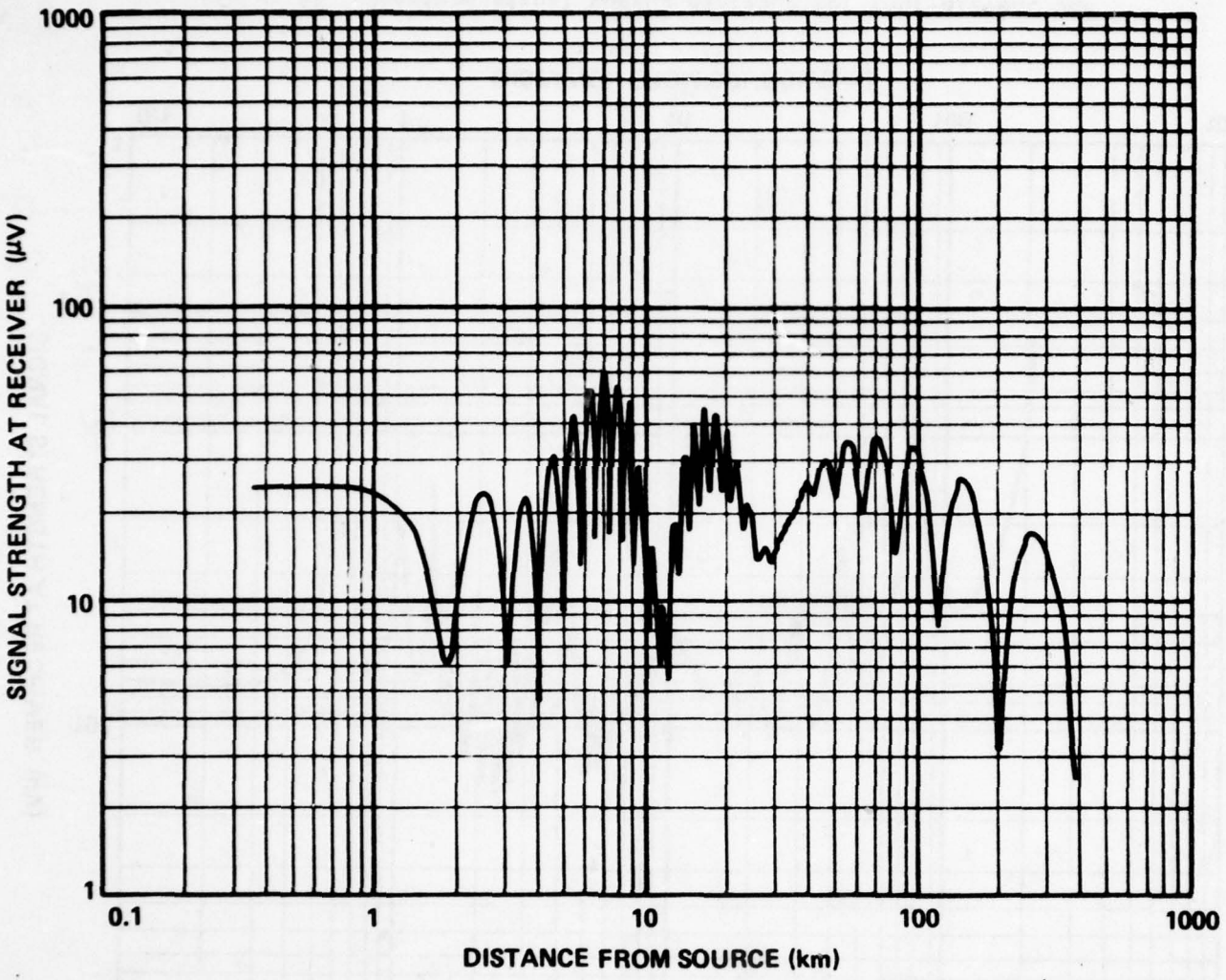


Figure 62. Received signal versus distance for four-element UHF antenna: gain = 5.92 dBi, frequency = 300 MHz, altitude = 9000m

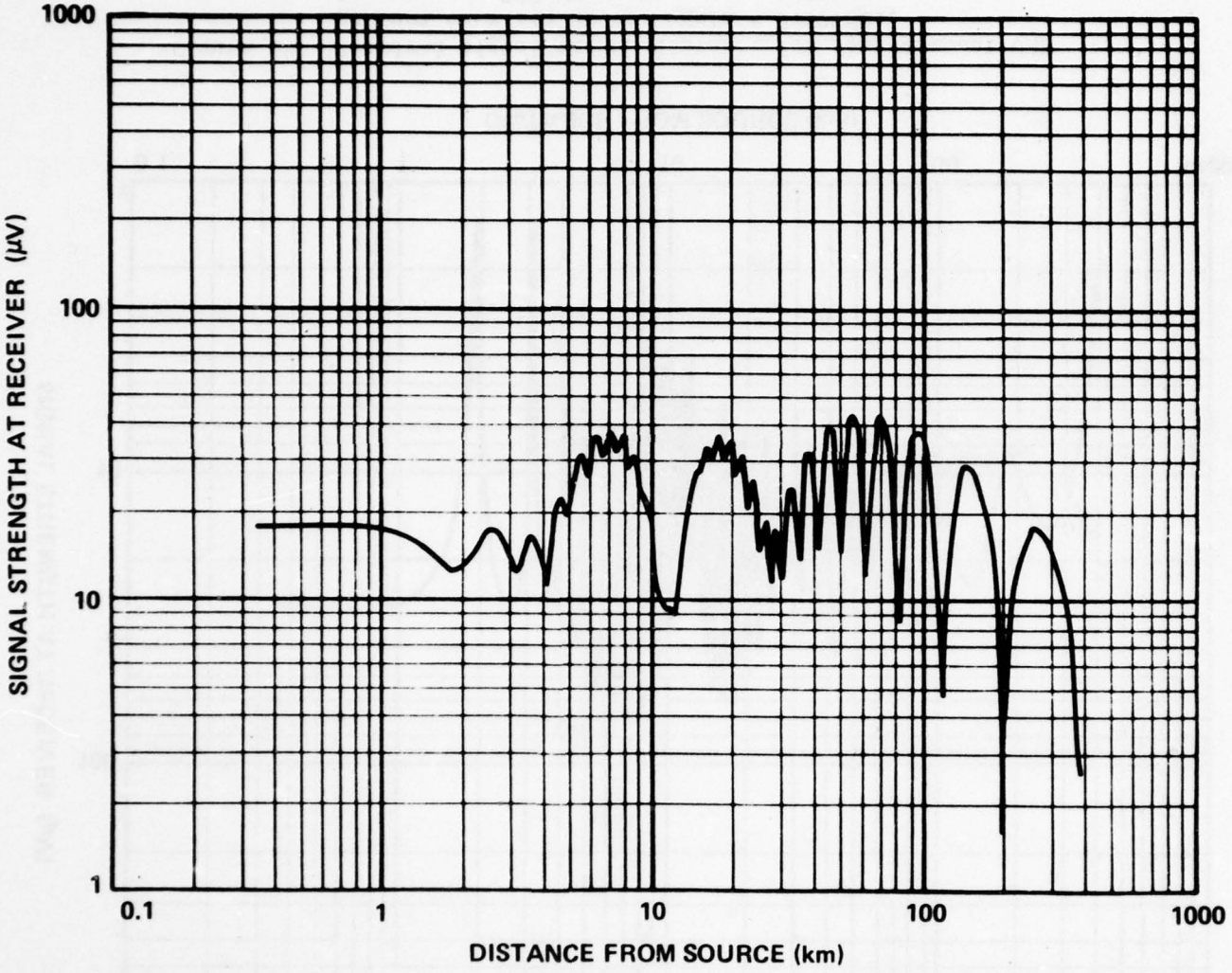


Figure 63. Received signal versus distance for four-element UHF antenna over dry earth: gain = 5.92 dBi, frequency = 300 MHz, altitude = 9000m

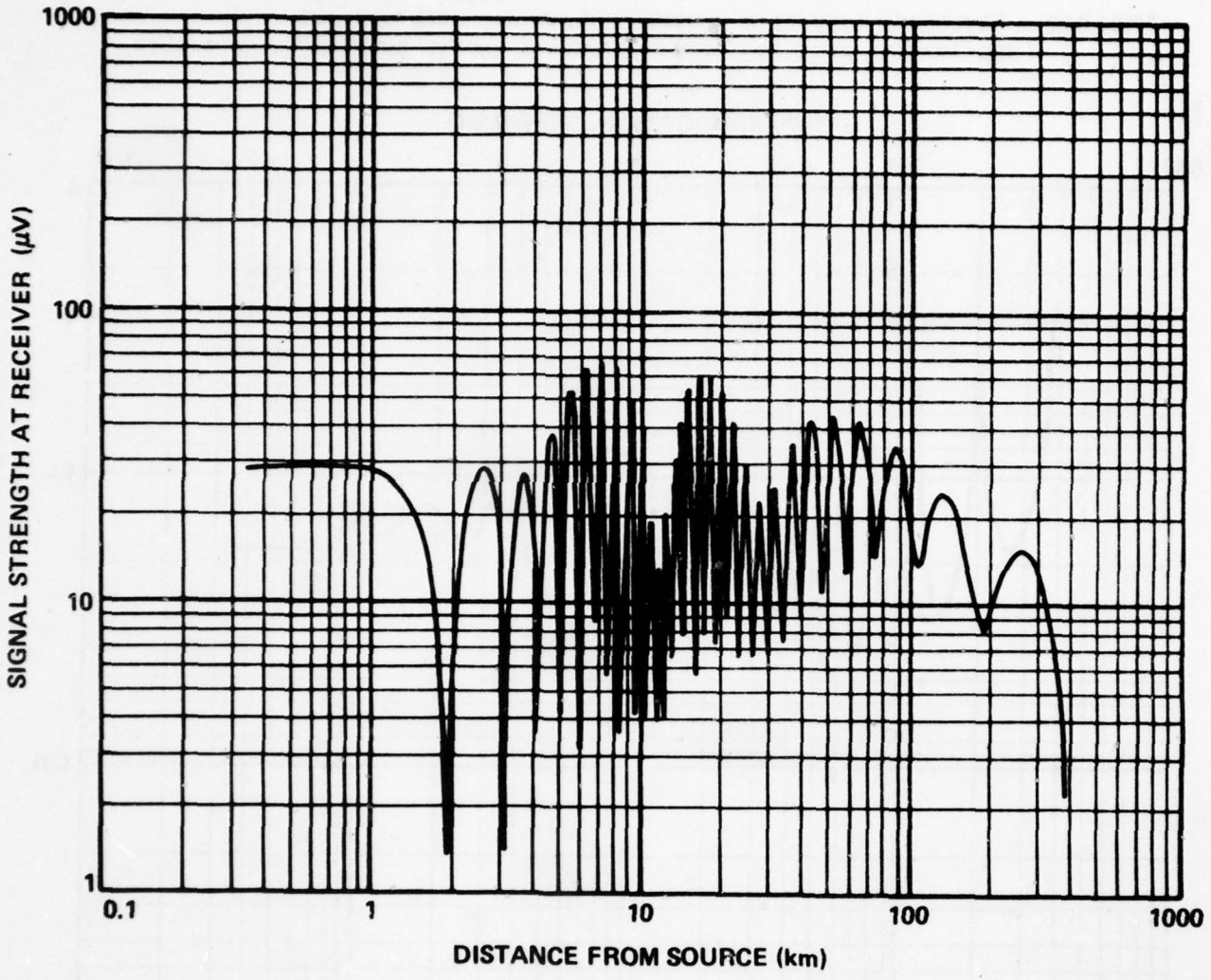
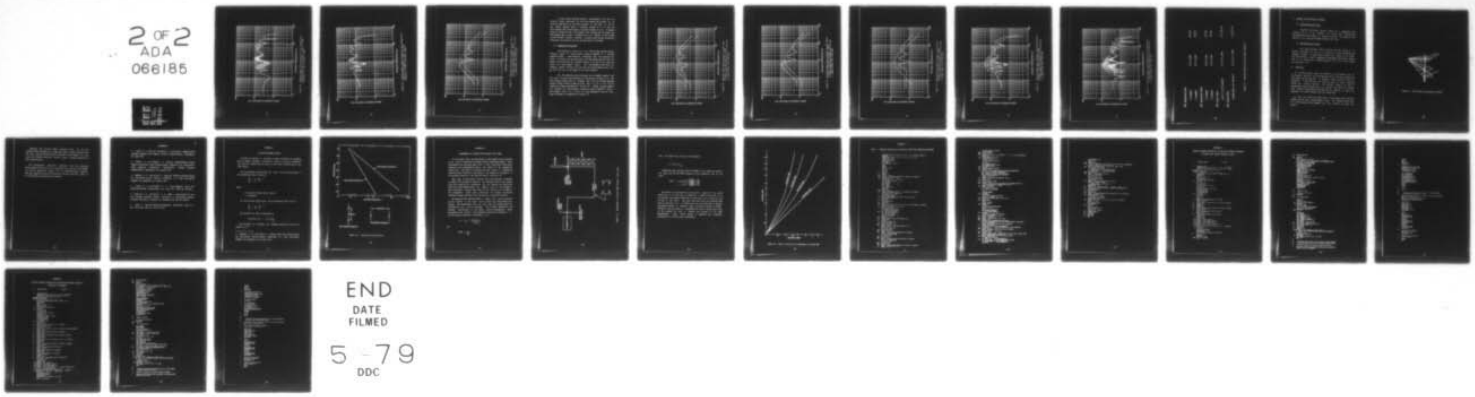


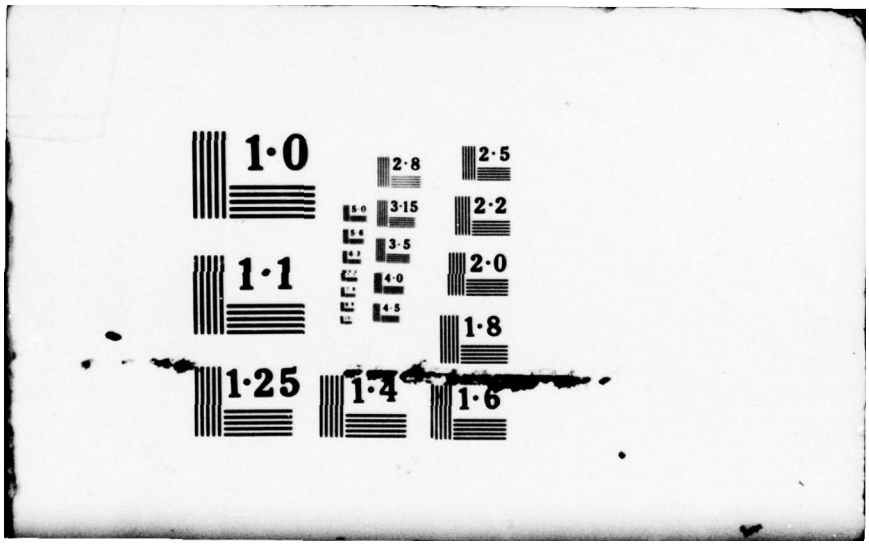
Figure 64. Received signal versus distance for four-element UHF antenna over sea water: gain = 5.92 dBi, frequency = 300 MHz, altitude = 9000m

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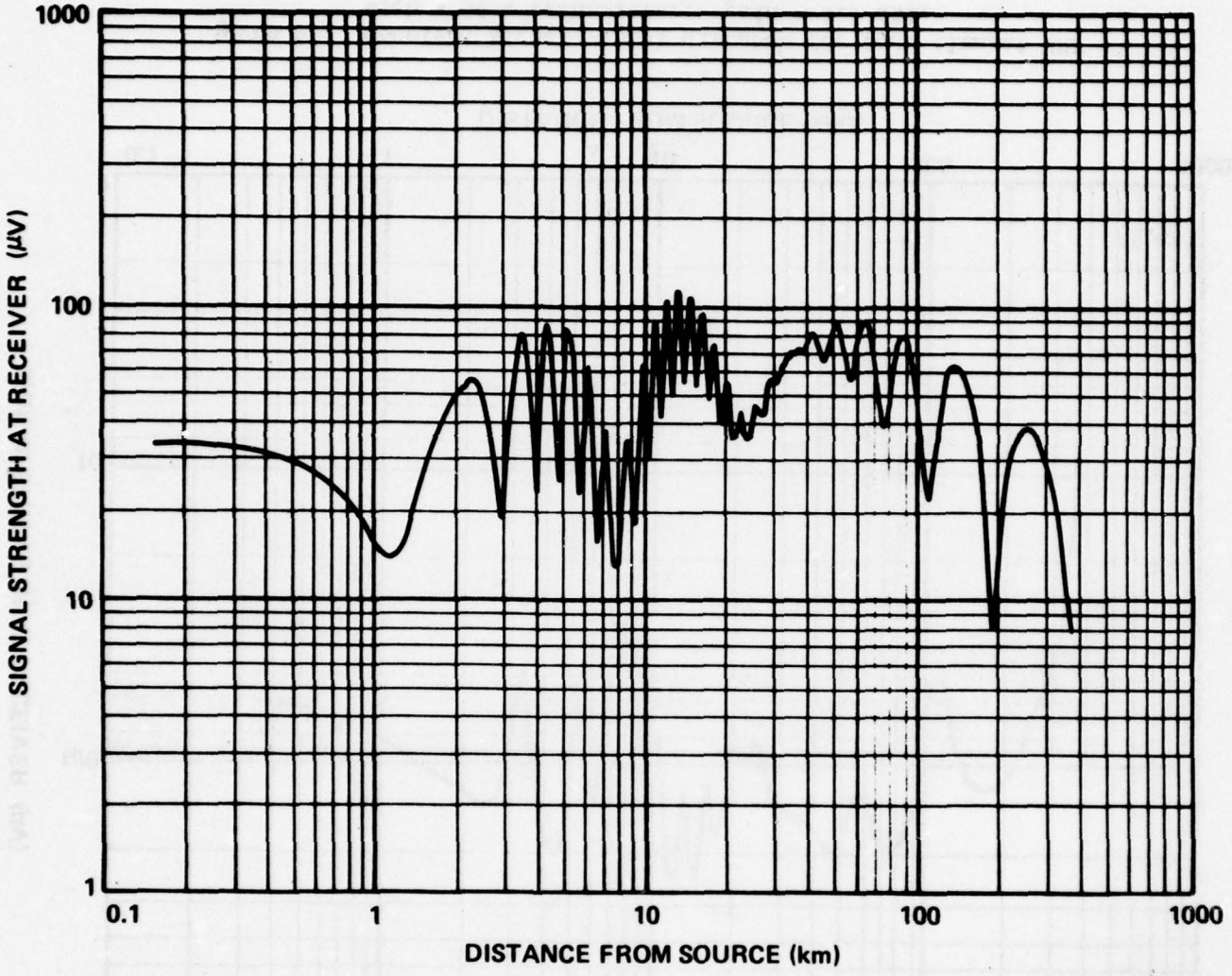


Figure 65. Received signal versus distance for four-element VHF antenna mounted on a 29-m tower : gain = 5.3 dBi, frequency = 125 MHz, altitude = 9000m

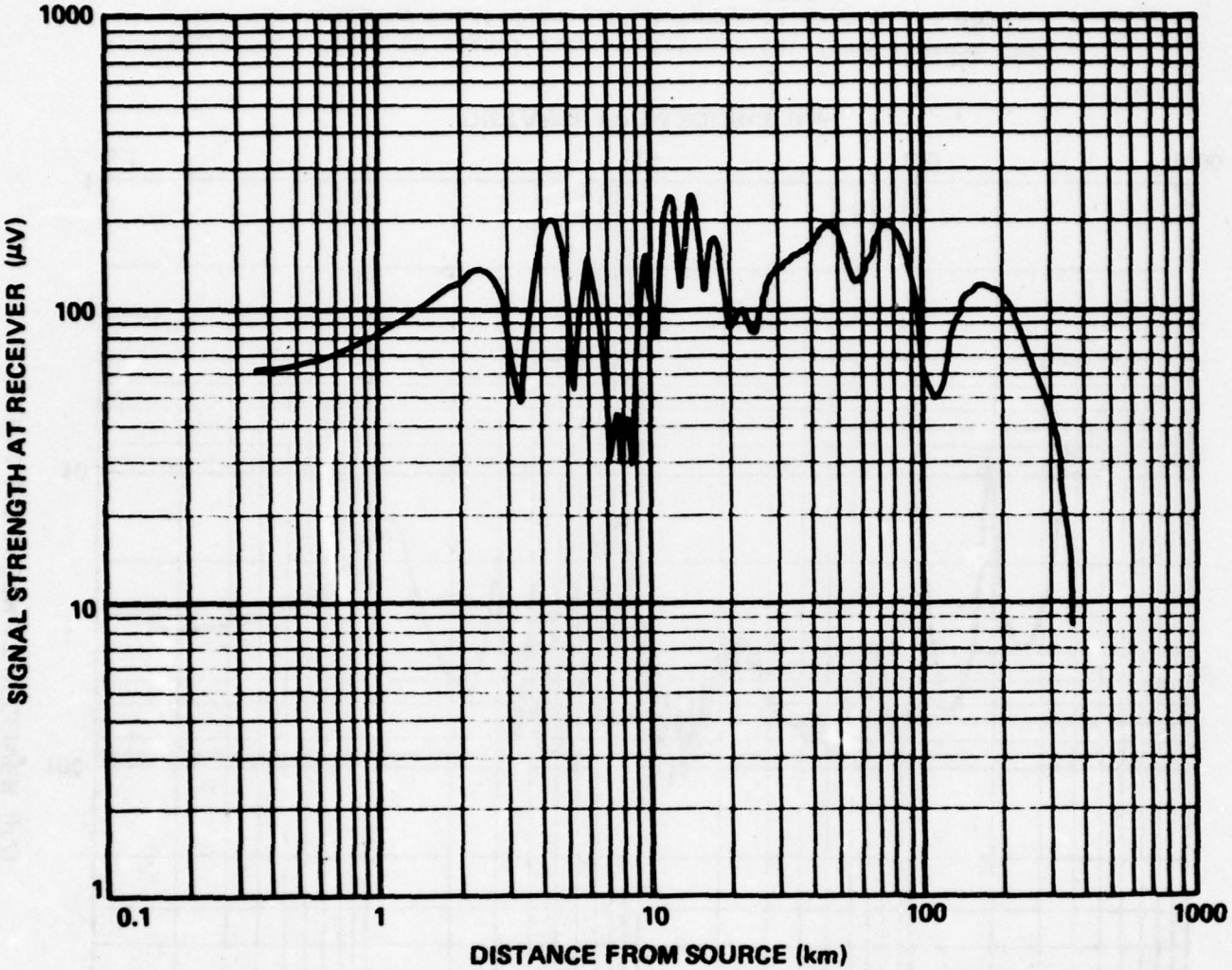


Figure 66. Received signal versus distance for four-element VHF with a 50 w transmitter: gain = 5.3 dBi, frequency = 125 MHz, altitude = 9000m

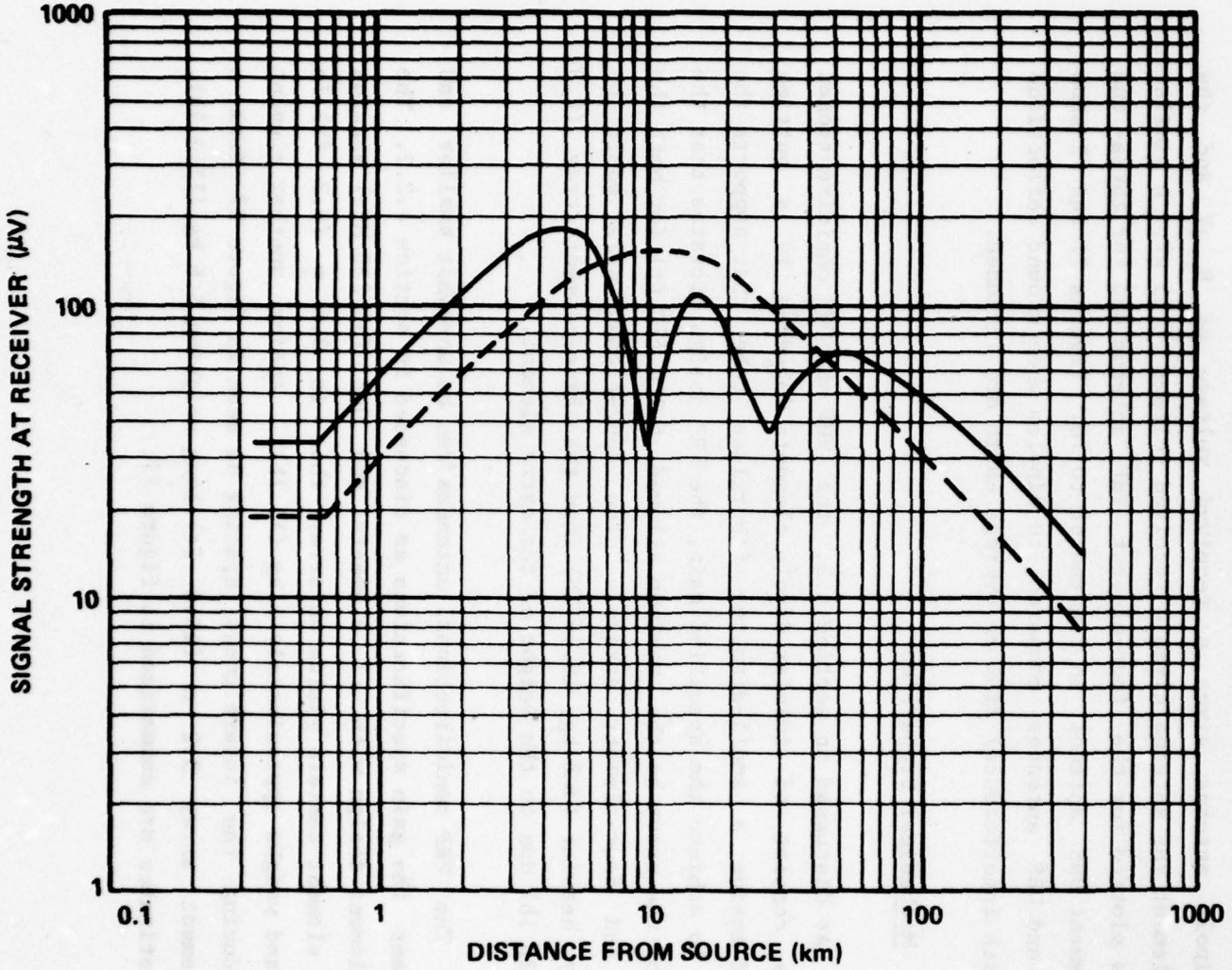


Figure 67. Received signal versus distance in free space: frequency = 125 MHz, altitude = 9000m
—— three-element VHF antenna with 5 dBi gain,
--- single dipole with 0 dBi gain

At the horizon (maximum range of approximately 350 km), the received signal amplitude for the three-element VHF antenna is 1.8 times the amplitude for the dipole antenna. In this case, at 350 km the dipole antenna gives a received voltage of 8 μV and the three-element VHF antenna gives a received voltage of 15 μV. A similar graph is plotted for the four-element VHF antenna and for three- and four-element UHF antenna in figures 68 to 70. Figures 71 and 72 show the VHF and UHF antennas compared to dipoles when ground reflections (multipath interference) from an average earth are included.

4.4 Mechanical Properties

As discussed in section 4.2, the VHF and UHF omnidirectional antennas consist of tubular dipole elements imbedded in a potting compound inside a small-diameter fiberglass tube that supports the array. To achieve the specified gain, the VHF design dictates that the length of the array be the maximum allowed, 6.1 m (20 ft) for both the three- and four-element arrays. The four-element array would be slightly heavier (8.8 kg, 19.36 lb) than the three-element array (8.3 kg, 18.26 lb) due to the weight of the extra element.

The UHF omnidirectional antennas can be somewhat smaller and still meet the gain specifications as discussed in section 4.2.2. The three-element design with $\lambda/2$ elements and 0.8λ (at 225 MHz) spacing between element centers yields an array that is 2.8 m (9.2 ft) in length and weighs approximately 5 kg (11 lb). Adding another element and reducing the interelement spacing as seen in figure 27 form a four-element array 3.2 m (10.5 ft) long weighing 5.6 kg (12.3 lb). These estimates are summarized in figure 73.

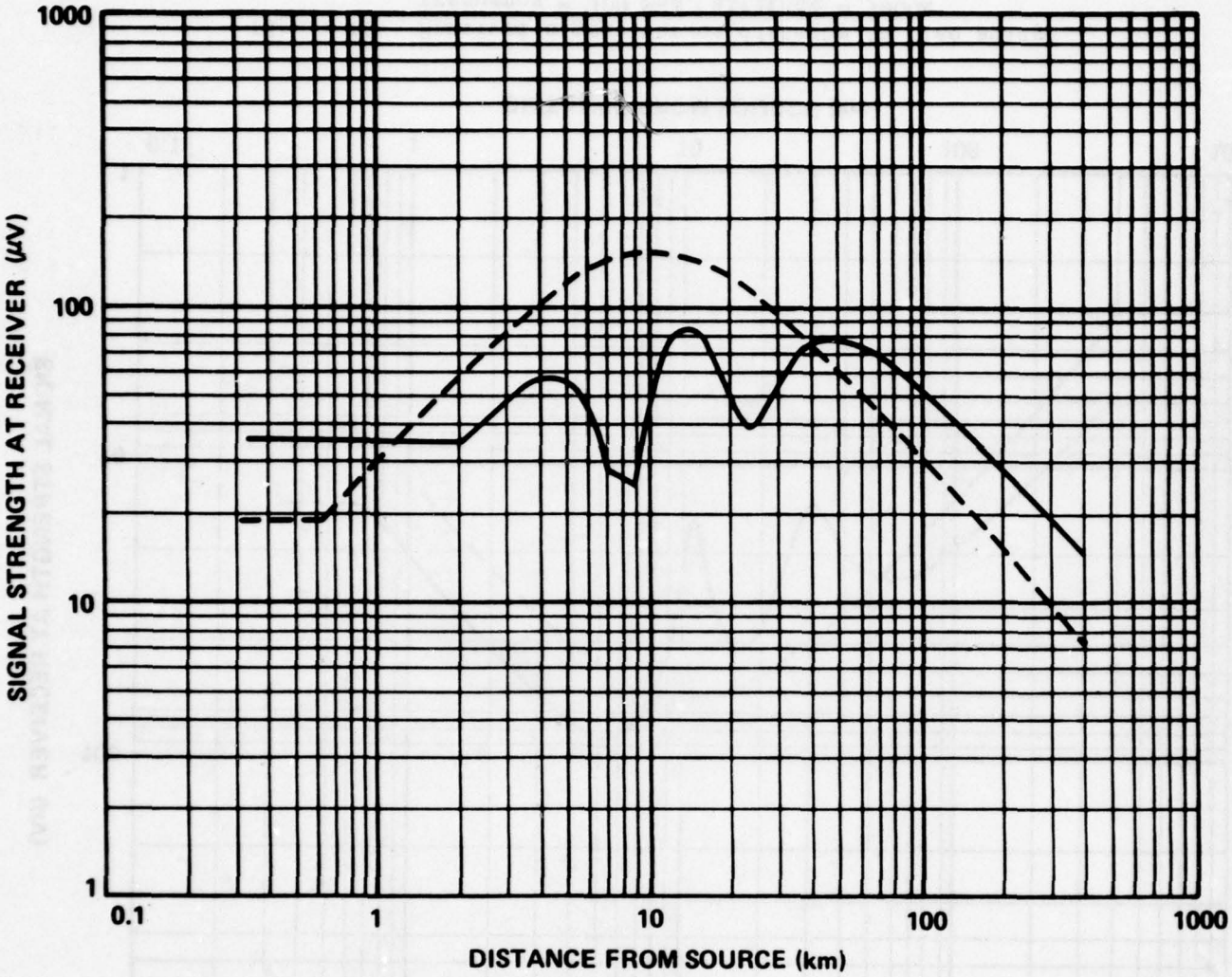


Figure 68. Received signal versus distance in free space:
frequency = 125 MHz, altitude = 9000m
—— four-element VHF antenna with 5.3 dBi gain,
--- single dipole with 0 dBi gain

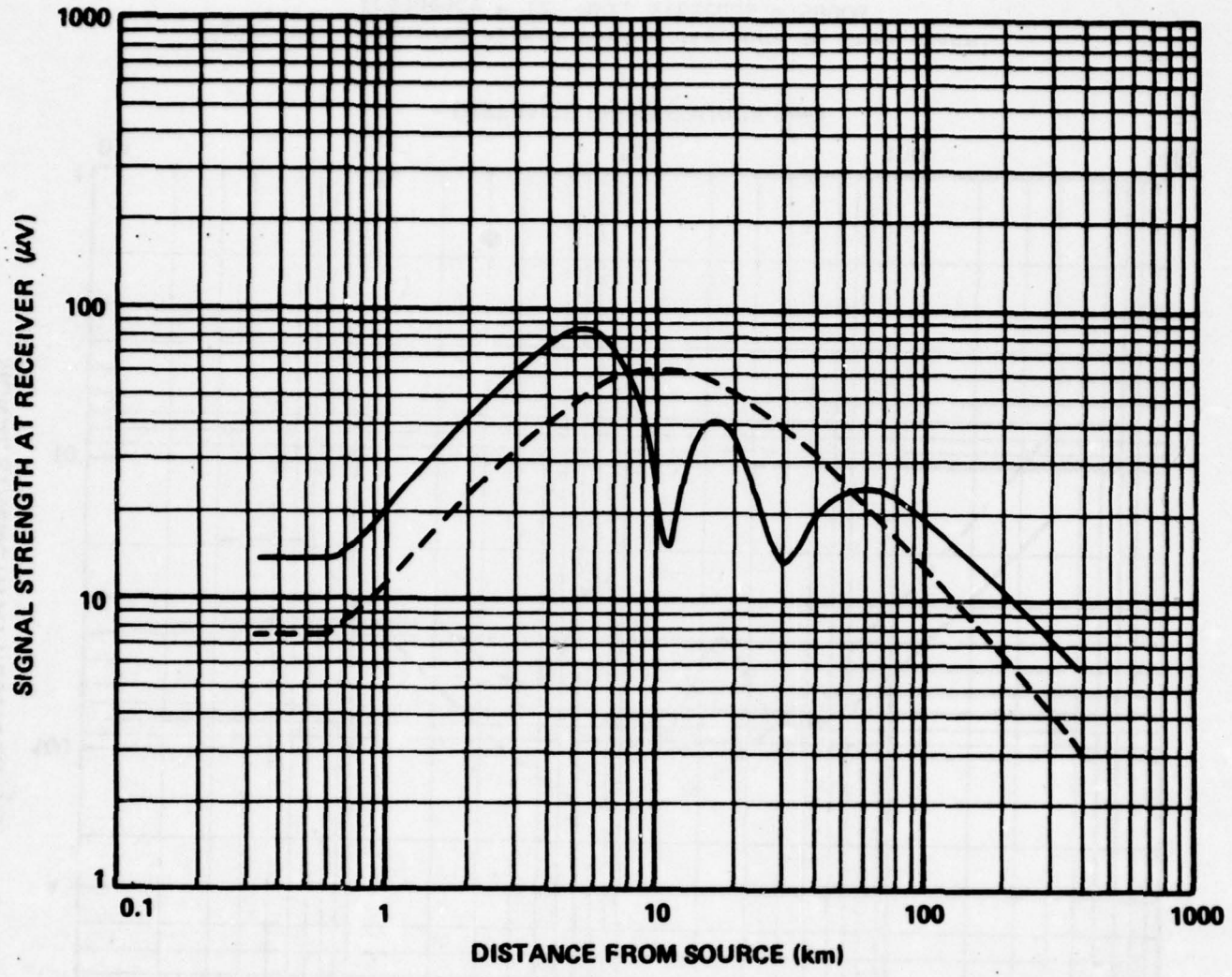


Figure 69. Received signal versus distance in free space:
frequency = 300 MHz, altitude = 9000m
—— three-element *UHF* antenna with 4.94 dBi
--- single dipole with 0 dBi gain

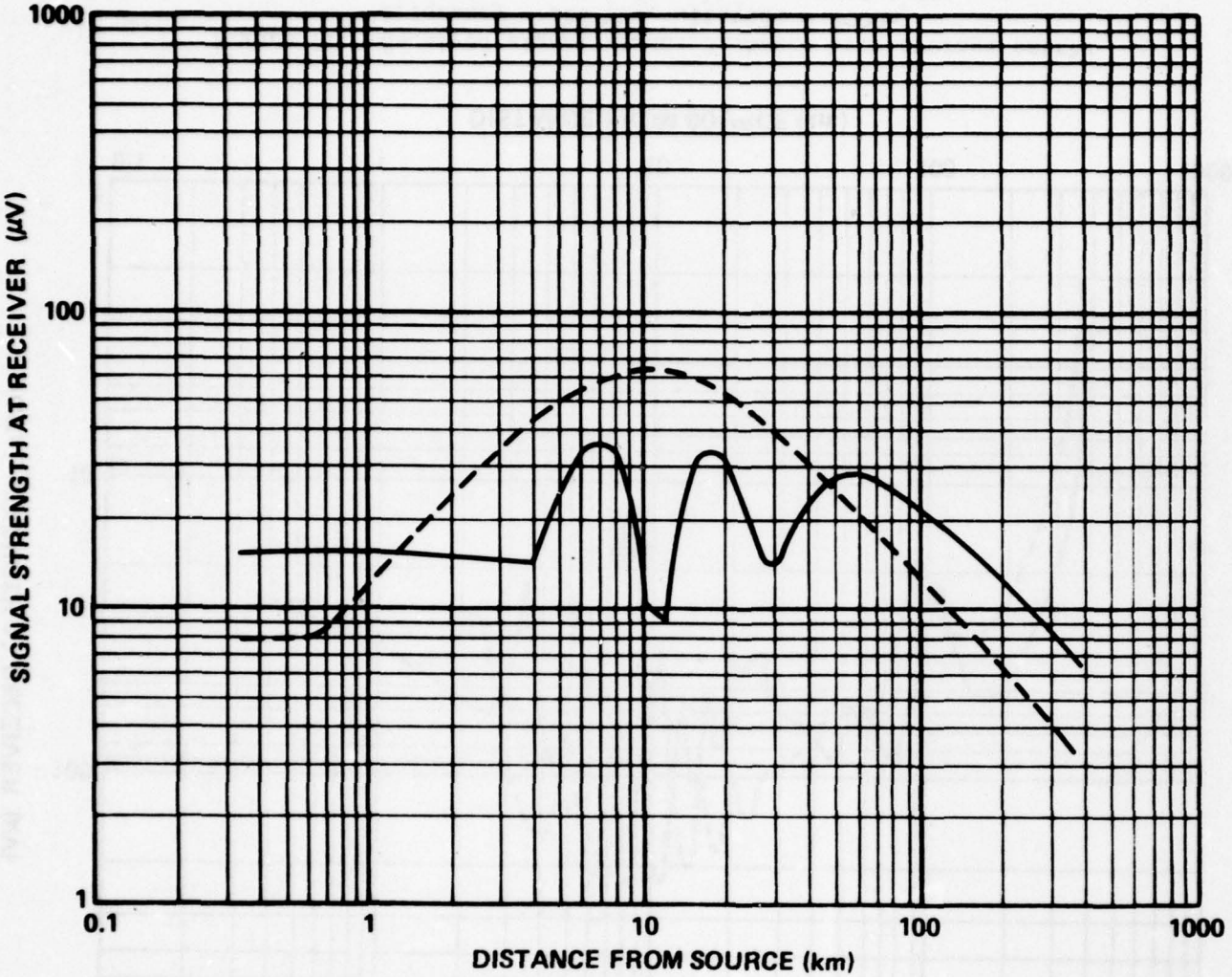


Figure 70. Received signal versus distance in free space:
frequency = 300 MHz, altitude = 9000m
—— three-element VHF antenna with 5 dBi gain,
--- single dipole with 0 dBi gain

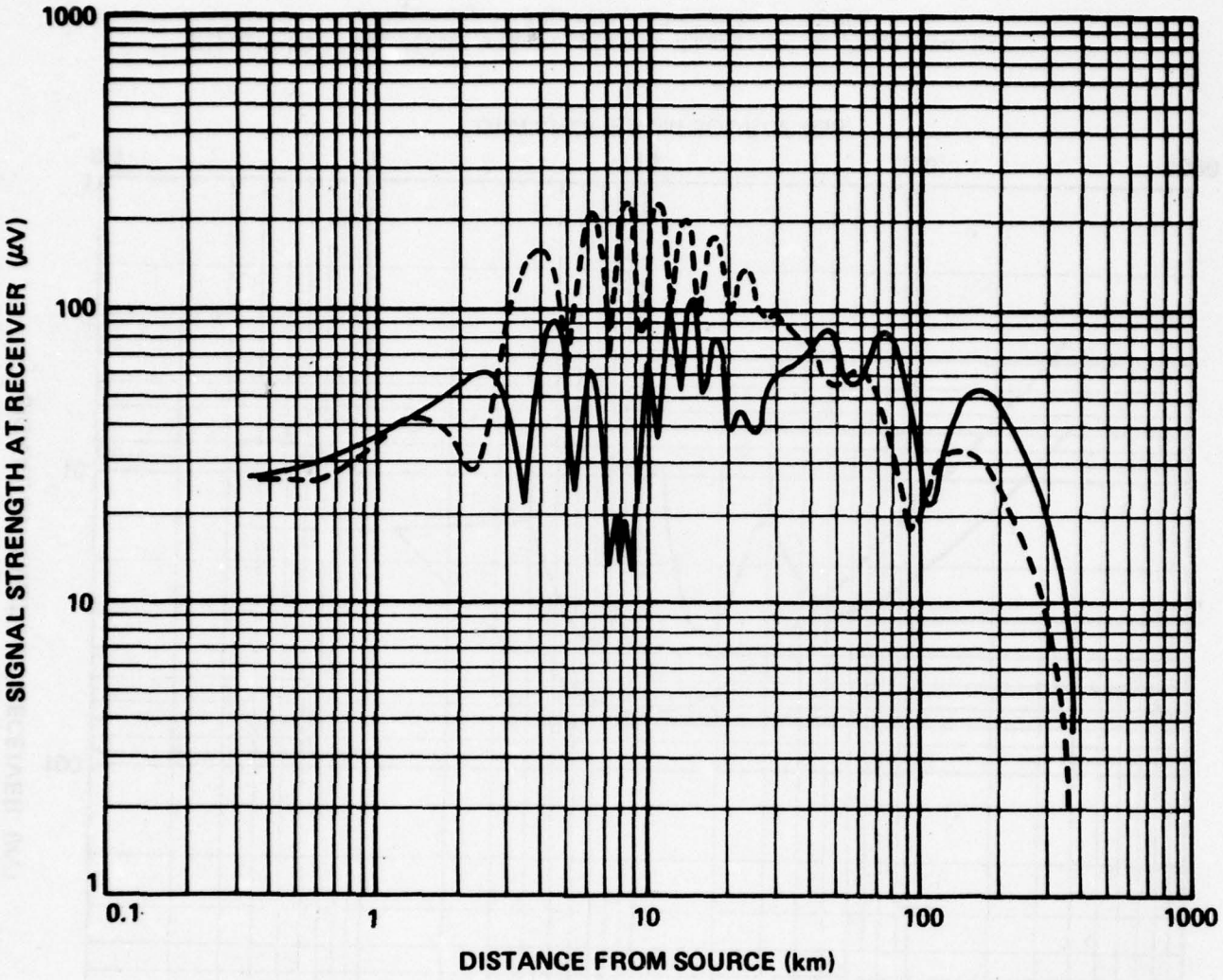


Figure 71. Received signal versus distance over average earth:
frequency = 125 MHz, altitude = 9000m
—— four-element VHF antenna with 5.3 dBi gain,
--- single dipole with 0 dBi gain

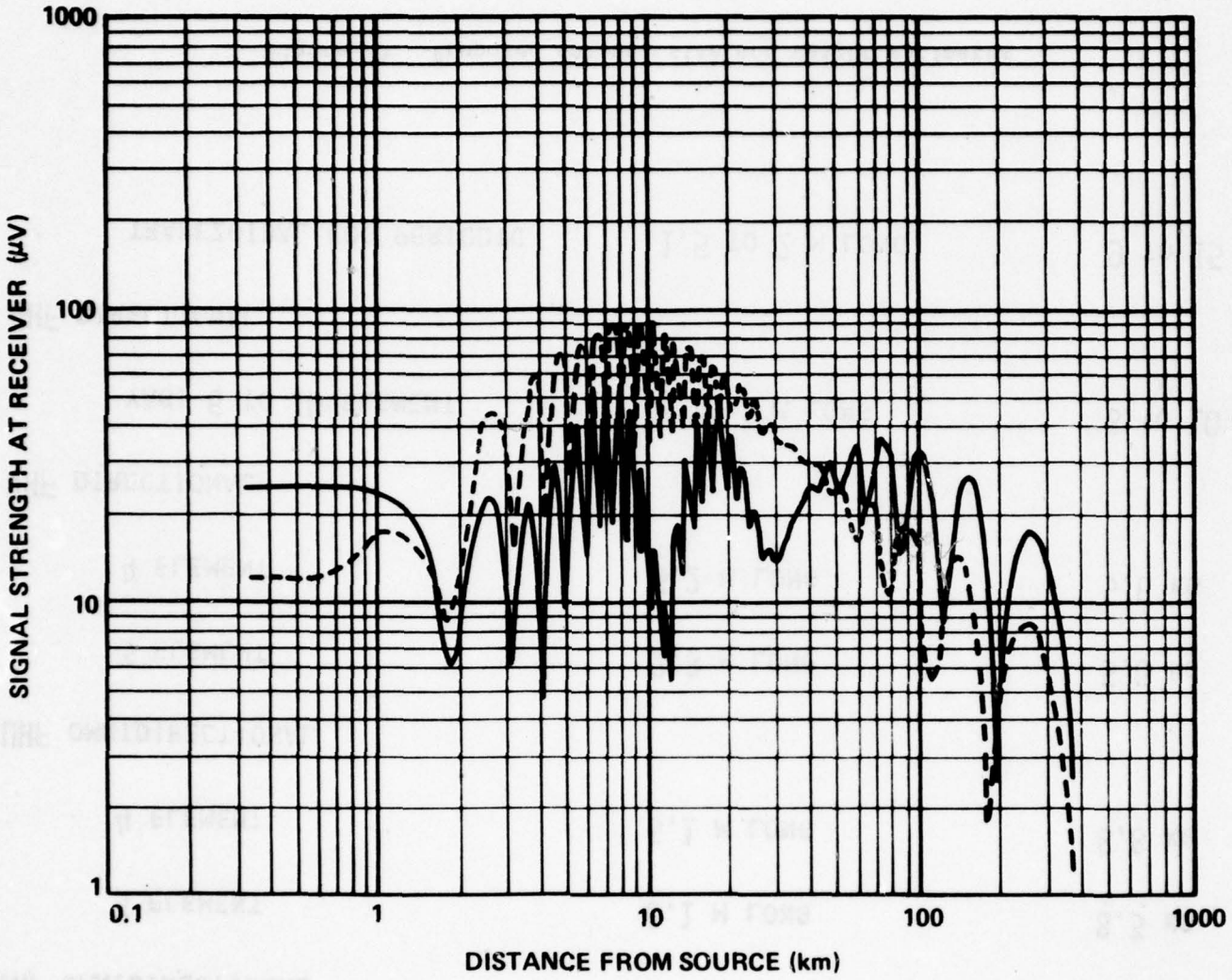


Figure 72. Received signal versus distance over average earth:
—— four-element VHF antenna with 5.92 dBi gain,
--- single dipole with 0 dBi gain

VHF OMNIDIRECTIONAL		
3 ELEMENT	6.1 M LONG	8.3 KG
4 ELEMENT	6.1 M LONG	8.8 KG
UHF OMNIDIRECTIONAL		
3 ELEMENT	2.8 M LONG	5.0 KG
4 ELEMENT	3.2 M LONG	5.6 KG
VHF DIRECTIONAL		
YAGI 6 TO 10 ELEMENT	2 TO 3 M LONG	6 TO 10 KG
UHF DIRECTIONAL		
TRAPEZOIDAL LOG PERIODIC	1.5 TO 2 M LONG	9 TO 15 KG

Figure 73. Proposed antenna size and weight estimates

5. DESIGNS FOR DIRECTIONAL ANTENNAS

5.1 VHF Directional Design

The VHF directional antenna design is a ruggedized yagi antenna with 6 to 10 elements. The 10-dBi gain specification determines the exact number of elements required. An antenna of this type is 2 to 3 m long and weighs between 6 and 9 kg.

5.2 UHF Directional Design

The large frequency range over which the UHF antenna is to operate precludes the use of an inherently narrow bandwidth yagi antenna. Instead, a log-periodic design (e.g., figure 74) is chosen. For the UHF band, a typical ruggedized trapezoidal log-periodic antenna has 8- to 10-dBi gain, a maximum length of 1.5 to 2.0 m and a weight not exceeding 15 kg.

6. CONCLUSION

At the VHF frequency band, the limitation on the maximum size of the antenna restricts the radiating aperture so that the antenna gain just meets the specification. A slightly larger aperture would be desirable. In the UHF band, the required gain is easily obtained within the allowed aperture. The problem, however, is that a conventional dipole antenna does not operate over the 225 to 400 MHz band. Special broadbanding techniques must be employed to match the impedance of a dipole antenna over this large band.

In both the VHF and the UHF bands, a four-element array performs slightly better than a three-element array. The inherent lower cost of a three-element array suggests that both versions be built and tested.

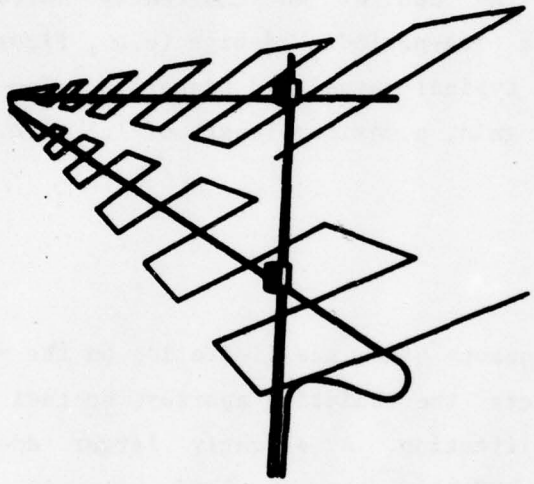


Figure 74. UHF trapezoid log-periodic antenna

Comparing the received signal strength levels for the gain omnidirectional antennas and a 0-dBi gain dipole antenna indicates that the gain antenna increases signal strength at long ranges. At close range, both antennas generally provide signal strengths adequate for good communications.

FAA environmental experience indicates that the fiberglass radome-supported structure is an excellent way to protect the elements and provide mechanical support for the omnidirectional antennas. Existing ruggedized yagi and log-periodic antennas have been shown to be electrically and mechanically adequate.

REFERENCES

1. Coyle, J. J., Test and Evaluation of Air/Ground Communications Antennas, FAA-NA-77-39, Federal Aviation Administration, Washington, DC, June 1978.

2. Hansen, J., and Webster, A., Advanced Communications System Support--Air/Ground Radio Antenna System (Analysis and Evaluation), Verve Research Corporation, FAA-RD-78-11, Federal Aviation Administration, Washington, DC, January 1978.

3. Campbell, D. V., and Arnold, J., Improved UHF Multi-Antenna System for Air-Traffic Control Centers, ECOM-4269, U.S. Army Electronics Command, Fort Monmouth, NJ, October 1974.

4. Jordan, E. C., and Balmain, K. G., Electromagnetic Waves and Radiating Systems, Prentice-Hall, Inc., New York, 1968, pp. 401-406.

5. Deadrick, F. J., and Miller, E. K., WAMP: A Users Manual for the Wire Antenna Modeling Program, University of California, Lawrence Livermore Laboratory, Berkeley, CA, December 1973 (DDC AD 773769).

6. Jasik, H., Antenna Engineering Handbook, McGraw-Hill Book Co., Inc., New York, 1961, pp. 22-6 to 22-9.

APPENDIX A

ISOLATION BETWEEN DIPOLES

The mutual coupling, or isolation, between collinear and broadside pairs of dipole antennas is defined in terms of the power transmitted (P_T) from one dipole and the amount of that power received (P_R) by the other dipole.

For the collinear dipole pair, the ratio of the received power to the transmitted power is given by

$$\frac{P_R}{P_T} = \frac{9}{4} \left(\frac{2\pi r}{\lambda} \right)^{-4}$$

where

r = distance between dipole centers,

λ = wavelength.

For the broadside dipole pair, the corresponding power ratio is

$$\frac{P_R}{R_T} = \frac{9}{16} \left(\frac{2\pi r}{\lambda} \right)^{-2}$$

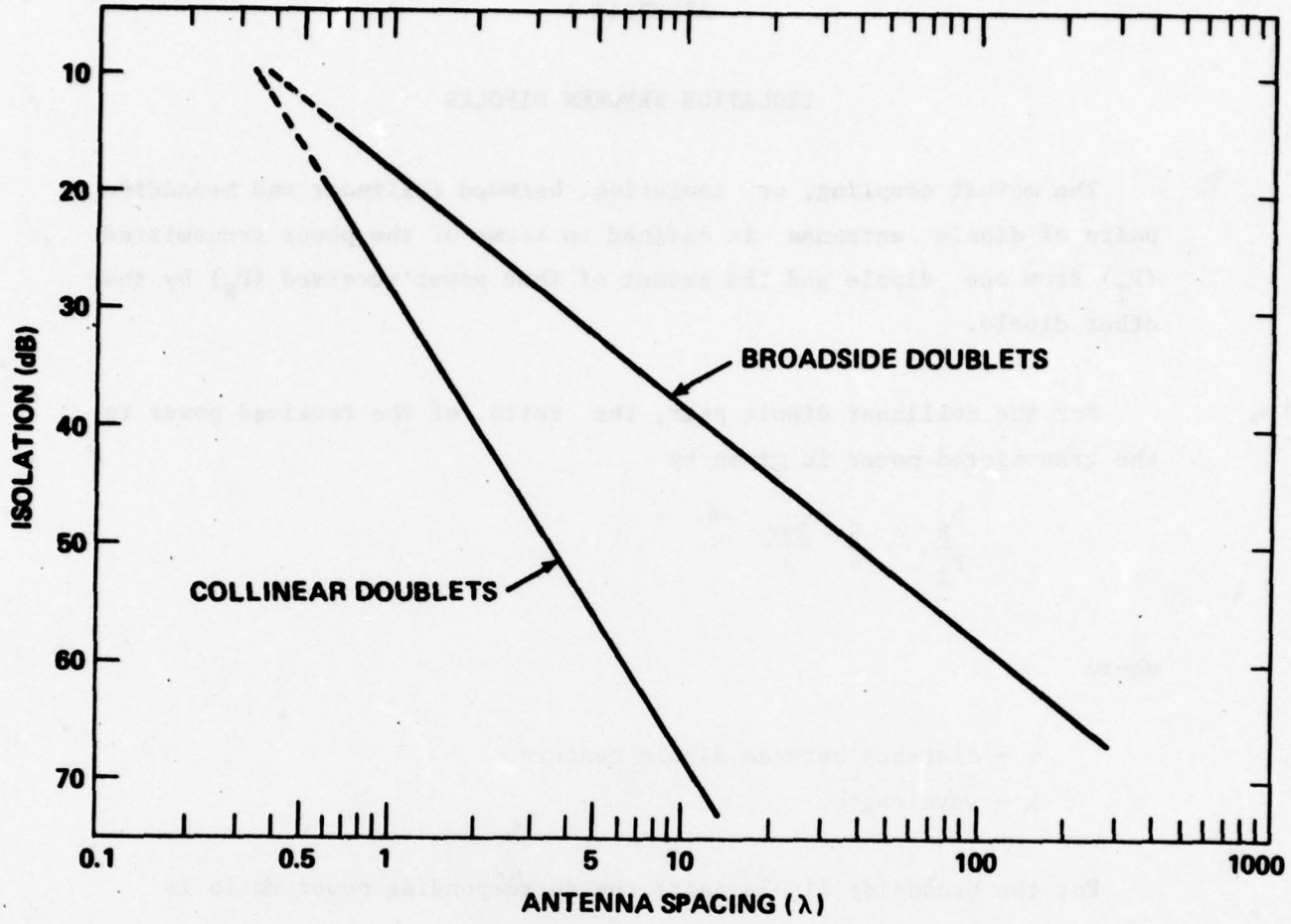
The isolation can then be expressed by

$$\text{Isolation (dB)} = -10 \log \frac{P_R}{P_T} .$$

The isolation of collinear and broadside doublets is plotted in figure A-1 [1].

---

1. Campbell, D. V., and Arnold, J., Improved UHF Multi-Antenna System for Air-Traffic Control Centers, ECOM-4269, U.S. Army Electronics Command, Fort Monmouth, NJ, October 1974.



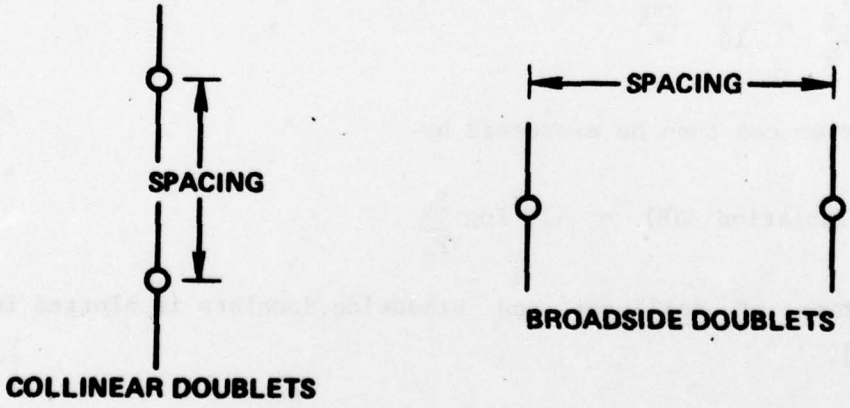


Figure A-1. Isolation between dipoles

APPENDIX B

MEASUREMENT OF ANTENNA VSWR THROUGH LOSSY CABLE

At the present time, the performance of FAA communications antennas in the field is monitored by making periodic VSWR measurements. These measurements are typically made with a Bird directional power meter inserted in the transmission line at the output of the transmitter (figure B-1). The VSWR is calculated from the values of forward and reflected power obtained in this manner. The antenna is considered to be operating properly if the measured VSWR is less than 4:1.

This type of measurement, however, does not accurately determine the VSWR of the antenna in question. The insertion loss of the coaxial cable that connects the transmitter and the antenna can effectively mask any antenna VSWR problem. For example, even if the antenna is short-circuited, a typical cable loss of 3 dB results in a 3:1 VSWR at the transmitter. Under these conditions, the present monitoring technique wrongly indicates that the antenna is operating properly.

The measured VSWR (labeled VSWR' in figure B-1) can be corrected for the effects of the cable loss to obtain the actual VSWR of the antenna. The transmission line (in this case, the coaxial cable) is characterized by a set of constants: the voltage reflection and transfer coefficients of the cable, called S-parameters. These S-parameters are related to the measured reflection coefficient, ρ', and the antenna reflection coefficient, ρ, by

$$\rho' = S_{11} + \frac{S_{21}\, S_{12}\, \rho}{1 - S_{22}\, \rho}.$$

But

$$\text{VSWR} = \frac{1+\rho}{1-\rho},$$

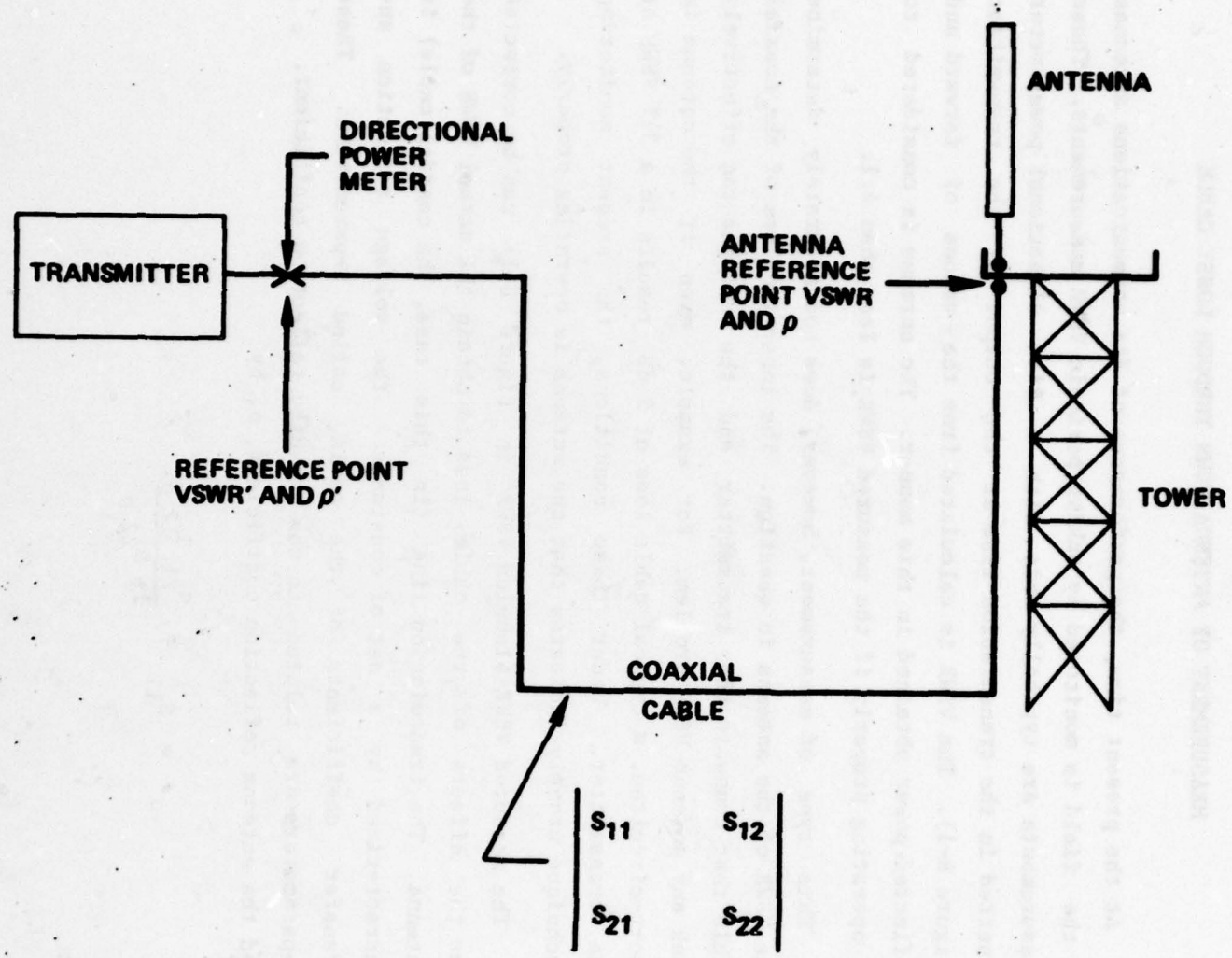


Figure B-1. Measurement of antenna VSWR through a lossy cable

and α, the cable loss in dB, can be expressed,

$$\alpha = -20 \log S_{12}.$$

Combining these equations gives the VSWR of the antenna in terms of the cable loss and the VSWR' measured at the transmitter end of the cable:

$$VSWR = \frac{1 + 10^{\alpha/10}\left(\frac{VSWR' - 1}{VSWR' + 1}\right)}{1 - 10^{\alpha/10}\left(\frac{VSWR' - 1}{VSWR' + 1}\right)}.$$

The results of this equation are plotted in figure B-2 for cable losses of 0, 1, 2, and 3 dB. To guarantee a VSWR of less than 4:1 at the antenna, the measured VSWR must be less than 1.9:1 if there is 3 dB of loss in the cable. With only 1-dB cable loss, the measured VSWR must be less than 2.6:1. Low VSWR values are very difficult to measure accurately because an extremely high directivity coupler is needed. Therefore, low-loss cable is recommended not only to reduce power loss to the antenna but also to improve the accuracy of the VSWR measurements. These cables should be inspected and calibrated periodically to insure proper performance.

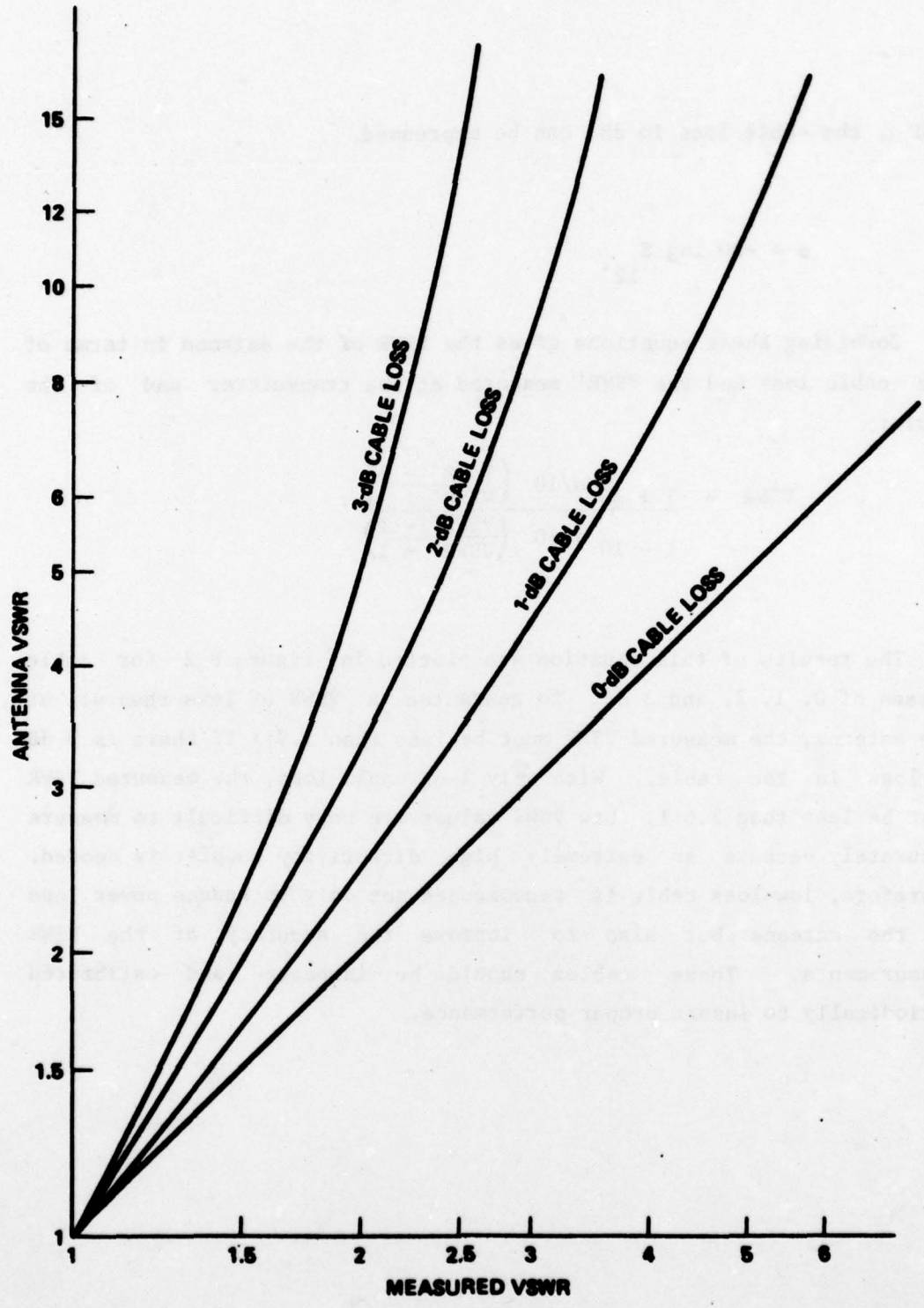


Figure B-2. Effect of cable loss on measurement of antenna VSWR

APPENDIX C

ARY4 -- FORTRAN PROGRAM FOR CALCULATING FREE SPACE RADIATION PATTERNS

```
      DIMENSION AMP(1050),PHA(1050),R(1050),TH(1050),PH(1050),IDATA(3),
     1PWR(1050)
      COMMON NMAX, K, AMP, PHA, R, TH, PH, E2, RD, TO, PO
      COMMON/CN2/IDATA
      COMMON/CN3/ISDFN(3)
      COMMON/CN4/IDFN(3)
      DATA IDFN/'      '/
      DATA IREST/0/
      IF (IREST.EQ.1) GO TO 51
      TO=0.
      PO=0.
      NMAX=0
      DO 50 I=1,1050
      AMP(I)=1.
      PHA(I)=0.
      R(I)=0.
      TH(I)=0.
   50 PH(I)=0.
      IREST =1
   51 WRITE (1,400)
  400 FORMAT (' ENTER DATA FILE NAME, IF DESIRED (LIST FORMAT)')
      READ (1,410,ERR=51) IDATA
  410 FORMAT (3A2)
      IF (IDATA(1).EQ.'  ') GO TO 735
      CALL SEARCH (1,IDATA,1)
      CALL INP(AMP,'          ')
      CALL INP(PHA,'          ')
      CALL INP(R,'          ')
      CALL INP(TH,'          ')
      CALL INP(PH,'          ')
      CALL SEARCH (4,0,1)
      IDATA(1)='  '
      GO TO 105
  735 WRITE(1,740)
  740 FORMAT('ENTER DATA FILE NAME, IF DESIRED (TABLE FORMAT)')
      READ(1,410,ERR=735)IDATA
      IF(IDATA(1).EQ.'  ')GO TO 100
      CALL SEARCH(1,IDATA,1)
      READ(5,410,END=760)I
  750 READ(5,662,END=760)I,AMP(I),PHA(I),R(I),TH(I),PH(I)
      IF(I.GT.NMAX)NMAX=I
      GO TO 750
  760 IDATA(1)='  '
      CALL SEARCH(4,0,1)
      GO TO 105
  100 WRITE(1,610)
  610 FORMAT(' FOR TCHEB TAPER, GIVE FIRST AND LAST ELEMENT NO. AND SIDE
     1LOBE LEVEL (DB)')
      READ (1,615,ERR=100) IEF,IEL,ISLL
  615 FORMAT (2I4,F10.0)
      IF (IEF.EQ.0) GO TO 620
      CALL ECHB(IEF,IEL,ISLL,AMP)
      IF (IEL.GT.NMAX) NMAX=IEL
  620 CALL INP(AMP,'AMPLITUDE ')
      CALL INP (PHA,'PHASE     ')
      CALL INP (R,'DISTANCE  ')
      CALL INP (TH,'THETA     ')
      CALL INP (PH,'PHI       ')
  900 WRITE(1,901)
  901 FORMAT(' CONVERT AMPLITUDE FROM DB, Y/N')
      READ(1,903)I
  903 FORMAT(A1)
      IF(I.NE.'Y')GO TO 910
      DO 902 I=1,NMAX
  902 AMP(I)=10**(AMP(I)/20.)
  910 WRITE(1,911)
  911 FORMAT(' CONVERT PHASE FROM DEGREES, Y,N')
      READ(1,903)I
      IF(I.NE.'Y')GO TO 500
      DO 912 I=1,NMAX
  912 PHA(I)=PHA(I)/360.
  500 WRITE (1,160)
  160 FORMAT (' ENTER UNIFORM SEPARATION IF DESIRED')
      READ (1,140,ERR=500) DOL
      IF (DOL.EQ.0) GO TO 300
      DO 170 I=1,NMAX
  170 R(I)=DOL*(I-1)
  300 WRITE (1,310)
  310 FORMAT (' ENTER DISTANCE SCALE FACTOR IF DESIRED')
      READ (1,140,ERR=300) SF
      IF (SF.EQ.0) GO TO 125
      DO 320 I=1,NMAX
  320 R(I)=SF*R(I)
  125 WRITE (1,130)
  130 FORMAT (' ENTER LAMBDA/LAMBDA(G)*COS(THETA) IF DESIRED')
      READ (1,140,ERR=125) ELOLG
  140 FORMAT (F10.5)
```

```
      IF (ELOLG.EQ.0) GO TO 625
      DO 150 I=1,NMAX
  150 PHA(I)=ELOLG*R(I)
  625 WRITE(1,630)
  630 FORMAT(' TO SHIFT Z AXIS ELEMENTS (THETA=0),GIVE DISTANCE AND PHI
     1DIRECTION')
      READ(1,635,ERR=625) R1,P1
  635 FORMAT (2F10.6)
      IF(R1.EQ.0.) GO TO 165
      DO 640 I=1,NMAX
      IF (TH(I).NE.0.) GO TO 640
      PH(I)=P1
      TH(I)=ATAN2(R1,R(I))
      R(I)=SQRT(R(I)*R(I)+R1*R1)
      TH(I)=57.2958*TH(I)
  640 CONTINUE
  165 CALL PRT(AMP,PHA,R,TH,PH)
      WRITE (1,166)
  166 FORMAT (' INPUT ELEMENT OPTION:'/5X,'0 OMNIDIRECTIONAL'/
     15X,'1 SPIRAL WITH MAX AT THETA=PHI=90'/
     25X,'2 HALF-WAVE SLOT ON CYLINDER'/
     35X,'3 HALF-WAVE DIPOLE, MAX AT THETA=90'/
     45X,'4 HALF-WAVE DIPOLE, MAX AT PHI=90')
      READ (1,222,ERR=166) K
      WRITE (1,110)
  110 FORMAT (' TO CHANGE DISTRIBUTION, TYPE 1')
      READ (1,120) I
  120 FORMAT (I1)
      IF (I.EQ.1) GO TO 100
  535 WRITE (1,540)
  540 FORMAT (' FOR CALCULATION OF DIRECTIVITY AND DBMAX, TYPE D'/
     1' TO INPUT DBMAX, TYPE X FOLLOWED BY VALUE')
      READ (1,550,ERR=535) I, DBMAX
  550 FORMAT (A1,F20.0)
      RD=R(1)*SIND(TH(1))
      IF (I.EQ.'X') GO TO 700
      IF (I.EQ.'D') GO TO 502
      A=0.
      DO 650 I=1,NMAX
      A=A+ABS(AMP(I))
  650 CONTINUE
      DBMAX=-1000.
      IF (A.NE.0.) DBMAX=20.*ALOG10(A)
      WRITE(1,655) DBMAX
  655 FORMAT (' ESTIMATED DBMAX=',F10.5,' DB')
      GO TO 700
  502 DBMAX=-10000.
      POW=0.
      DO 200 I=2,178,4
      WRITE (1,222) I
  222 FORMAT (I8)
      THETA=I
      IF (K.EQ.2) CALL SCMP(THETA)
      DO 200 J=2,358,4
      PHI=J
      CALL DBCMP(DB,THETA,PHI)
      POW=POW+E2*SIND(THETA)
      IF (DB.GT.DBMAX) DBMAX=DB
  200 CONTINUE
      DIR=DBMAX-10.*ALOG10(POW/2578.668)
      WRITE (1,560) DBMAX
  560 FORMAT (' DBMAX=',F10.5,' DB')
      WRITE (1,202) DIR
  202 FORMAT (' DIRECTIVITY=',F7.2,' DB')
  700 WRITE(1,710)
  710 FORMAT(/'TO FILE DEFERRED 2D PLOT DATA,'/
     *'GIVE FILE NAME,TYPE,CUT,ANGLE AND RANGES(DB,DEG) (A6,2A1,8I8)'/
     *'FFFFFFTCAAAYYYXXX')
      READ(1,715,ERR=700) ISDFN,ITP,IAN,IAV,IDBR,IAR
  715 FORMAT(3A2,2A1,3I8)
      WRITE(1,715) ISDFN,ITP,IAN,IAV,IDBR,IAR
      IF(ISDFN(1).NE.'  ')CALL DBRSD(DBMAX,ITP,IAN,IAV,IDBR,IAR)
  720 WRITE(1,725)
  725 FORMAT('TO OUTPUT DEFERRED PLOT GIVE FILE NAME')
      READ(1,410)IDATA
      IF(IDATA(1).NE.'  ')GO TO 730
  505 WRITE (1,510)
  510 FORMAT (' FOR 2D PLOT, INDICATE TYPE (P,R OR XD, CUT (T OR P), ABS
     1ILE, AND RANGES (DB,DEG) (2A1,8I8)')
      READ (1,520,ERR=505) ITP,IAN,IAV,IDBR,IAR,IDFN
  520 FORMAT (2A1,8I8,8A2)
      IF (IDBR.EQ.0) GO TO 205
      IF(IDFN(1).NE.'  ')CALL OPENWP(IDFN,2)
  730 IF (IDATA(1).NE.'  ') CALL SEARCH(1,IDATA,1,0730)
      CALL PLT2D(DBMAX,ITP,IAN,IAV,IDBR,IAR)
      IF (IDATA(1).NE.'  ') CALL SEARCH(4,0,1)
      IDATA(1)='  '
```

```
      CALL SEARCH(4,0,2)
      IDFN(1)='   '
      GO TO 700
  205 WRITE (1,210)
  210 FORMAT (' FOR 3D PLOT, GIVE TYPE (RDP,GRF),INITIAL PLOT COORDINATE
     1S, RANGE, AND MIN. DB (A3,3I3,F3.0)')
      READ (1,220,ERR=205) ITP, ICT,ICP,IDEL, DBMIN, I3DFN
  220 FORMAT (A3,3I3,F3.0,3A2)
      IF (IDEL.EQ.0) GO TO 530
      IF (I3DFN(1).NE.'   ') CALL OPENWF(I3DFN,1)
      CALL PLT3D(DBMAX,ITP,ICT,ICP,IDEL,DBMIN)
      IF (I3DFN(1).NE.'   ') CALL SEARCH(4,0,1)
  530 WRITE (1,230)
  230 FORMAT (' FOR NEW PLOT, TYPE 1')
      READ (1,120,ERR=530) I
      IF (I.EQ.1) GO TO 700
      WRITE (1,110)
      READ (1,120,ERR=530) I
      IF (I.EQ.1) GO TO 100
      WRITE(1,660)
  660 FORMAT(' TO FILE DISTRIBUTION, GIVE NAME')
      READ(1,410,ERR=530) IDATA
      IF (IDATA(1).EQ.'   ') GO TO 670
      CALL OPENWF(IDATA,1)
      WRITE(5,661)
  661 FORMAT('   NO. AMPLITUDE  PHASE     DISTANCE    THETA      PHI')
      WRITE(5,662)(I,AMP(I),PHA(I),R(I),TH(I),PH(I),I=1,NMAX)
  662 FORMAT(I5,5F10.5)
      CALL SEARCH(4,0,1)
      IDATA(1)='   '
  670 WRITE(1,675)
  675 FORMAT(' FOR SERIES ARRAY POWER DISTRIBUTION, GIVE EFFICIENCY')
      READ(1,677,ERR=670) EFF
  677 FORMAT (F10.0)
      IF (EFF.EQ.0.) GO TO 695
      IF (EFF.GT.1.) EFF=EFF/100.
      WRITE(1,680) EFF
  680 FORMAT('EFFICIENCY= ',F6.3//'NO. PR/INPUT  PR/INCIDENT')
      SUM=0.
      DO 685 I=1,NMAX
      PWR(I)=AMP(I)*AMP(I)
      SUM=SUM+PWR(I)
  685 CONTINUE
      POW=1.
      DO 690 I=1,NMAX
      PWR(I)=EFF*PWR(I)/SUM
      P=PWR(I)/POW
      WRITE(1,688) I,PWR(I),P
  688 FORMAT(I2,2F10.5)
      POW=POW-PWR(I)
  690 CONTINUE
      GO TO 670
  695 CALL EXIT
      END
```

APPENDIX D

FIXEDR--FORTRAN PROGRAM FOR CALCULATING ANTENNA RADIATION PATTERNS OVER SMOOTH SPHERICAL EARTH.

```
C       PROGRAM FIXEDR                          PAGE 0001


C       PROGRAM FIXEDR
        COMPLEX VD,VR,VT,N2,CARG,CEX,F(362),CFAC,CREF,CTEMP
        DIMENSION V(362),D(362),A(362),B(362),NAME(3),VDB(362)
        REAL*8 X1,X2,Y1,Y2,R,R1,R2,R12,DTEMP
$INSERT SYSCOM$ASKEYS
$INSERT SYSCOM$KEYS.F
        CALL OPEN3A(ASWRIT+ASSAMF,'FIXOUT',6,2)
        CALL OPNP3A('FILE NAME',9,ASREAD+ASSAMF,NAME,6,1)
        FMIN=0.05623
        FMAX=0.0
        DO 30 I=1,361
        READ(5)A(I),B(I),F(I)
        FMAG=CABS(F(I))
        IF(FMAG.GT.FMAX) FMAX=FMAG
 30     CONTINUE
        DO 50 I=1,361
        F(I)=F(I)/FMAX
        FMAG=CABS(F(I))
        IF(FMAG.GE.FMIN) GO TO 50
        RF=REAL(F(I))
        XF=AIMAG(F(I))
        IF(FMAG.LT.0.000001) RF=0.001
        FANG=ATAN2(XF,RF)
        RF=FMIN*COS(FANG)
        XF=FMIN*SIN(FANG)
        F(I)=CMPLX(RF,XF)
 50     CONTINUE
        CALL CLOSSA(1)
        GAIN=1.0
        PT=1.0
        WRITE(1,41)
 41     FORMAT('WRITE AIRCRAFT RANGE IN METERS')
        READ(1,49) RANGE
        WRITE(1,45)
 45     FORMAT('WRITE TRANSMITTING ANTENNA HEIGHT IN METERS')
        READ(1,49)H1
 49     FORMAT(F12.7)
 52     FORMAT(I3)
        WRITE(1,60)
 60     FORMAT('WRITE RELATIVE DIELECTRIC CONSTANT OF GROUND')
        READ(1,49)EPSIL
        WRITE(1,61)
 61     FORMAT('WRITE CONDUCTIVITY OF GROUND')
        READ(1,49)SIGMA
        WRITE(1,46)
 46     FORMAT('WRITE FREQUENCY IN MEGAHERTZ')
        READ(1,49)FR
  1     CONTINUE
        WRITE(6,1000)
        WRITE(1,1000)
 1000 FORMAT('    *** FIXEDR ***  ')
        WRITE(6,1200) (NAME(I),I=1,3)
 1200 FORMAT('    INPUT FILE NAME:'3A2)
        WRITE(6,2000) H1,RANGE
 2000 FORMAT('  H1='F9.3,'    RANGE='E12.4)
        WRITE(6,3000) EPSIL,SIGMA,FR
 3000 FORMAT('  EPSILON='F9.3'    SIGMA='F9.3'    FREQUENCY='
     &F7.3' MHZ')
        WL=300./FR
        AIN2=-60.0*SIGMA*WL
        N2=CMPLX(EPSIL,AIN2)
        R=8497440.0
        SCAL=WL*SQRT(50.*GAIN*PT)/(4.*3.14159)
C
        DTHETA=0.5
        DO 200 I=1,181
        V(I)=0.0
200     D(I)=(I-1)*DTHETA
        N=1
```

```
C     BEGIN RANGE LOOP
C
400   CONTINUE
      N=N+1
      PSI=1.570796-D(N)/57.2939
      CALL AIRPOS(X1,Y1,X2,Y2,R,H1,RANGE,PSI,FR,ISTOP)
      CALL GEOM(X1,Y1,X2,Y2,R,H1,RANGE,PSI,THETA1,THETA2,THETA,
     &D0,R1,R2,R12,THETT1,THETT2)
      IF (ISTOP .GT. 0) GO TO 600
      THET1D=THETT1*57.29578
      THET2D=THETT2*57.29578
      IDX1=(THET1D*2.0+1.5)
      IDX2=THET2D*2.0+1.5
      DTEMP=(R-Y1)/X1
      DTEMP=2.0*R1*R2/(R*D0*DTEMP)
      DTEMP=1.0+DTEMP
      DTEMP=DSQRT(DTEMP)
      DTEMP=1.0/DTEMP
      DIV=DTEMP
      CTEMP=N2-(COS(PSI))**2
      CFAC=CSQRT(CTEMP)
      CREF=(N2*SIN(PSI)-CFAC)/(N2*SIN(PSI)+CFAC)
      R12S=R12
      VD=F(IDX1)*SCAL/R12S
      DEM=R1+R2
      VR=F(IDX2)*SCAL*DIV*CREF/DEM
      ALG=6.283185*(R1+R2-R12)/WL
      CARG=CMPLX(0.0,ARG)
      CEX=CEXP(-CARG)
      VT=VD+VR*CEX
      V(N)=CABS(VT)
      N1=N
C
C      CHECK IF N1>181
C
      IF(N1.GT.181) GO TO 99
      GO TO 400
600   CONTINUE
C
C      END OF RANGE LOOP
C
      V(1)=V(2)
      VMAX=0.0
      DO 700 I=1,181
      IF(V(I).GT.VMAX) VMAX=V(I)
700   CONTINUE
      DO 800 I=1,181
      V(I)=V(I)/VMAX
      IF(V(I).LT.0.01) VDB(I)=-40.00
      IF(V(I).LT.0.01) GO TO 800
      VDB(I)=20.0*ALOG10(V(I))
800   CONTINUE
C
      N1=181
      CALL SETPDG
      CALL SCREEN
      CALL INIT(1.40,0.60)
      CALL AXPREC(0)
      CALL YOURSC(15.,0.,0)
      CALL YOURSC(10.,-40.,1)
      CALL FACTOR(1.33333333,1.5)
      CALL ENTGRA
      CALL GRID(6.,4.,1.,1.0,1,0)
56    CALL XAXIS('  THETA  ',9,6.)
57    CALL YAXIS(' REL SIGNAL  DB',15,4.)
      CALL DATAG(D,VDB,N1,1,1)
59    CALL EXITGR
      GO TO 100
 99   CONTINUE
      WRITE(1,9999)
9999  FORMAT('  ***** ERROR  N1.GT.181  *****  '/
     &'  DO YOU WANT TO RETURN TO INPUT NEW ALPHA AND RESTART'/
     &'  YES=1 ')
      READ(1,52) ICONT
      IF(ICONT.GT.0) GO TO 1
100   CONTINUE
      CALL SRCH90(KSCLOS,'FIXOUT',6,2,0,IER)
      CALL EXIT
      END
C
C
C      SUBROUTINE AIRPOS CALCULATES THE LOCATION OF THE AIRCRAFT
C      AND THE TRANSMIT ANTENNA FROM THE GIVEN R,RANGE,H1, AND PSI
C
      SUBROUTINE AIRPOS(X1,Y1,X2,Y2,R,H1,RANGE,PSI,FR,ISTOP)
C
      REAL*8 DX1,DX2,DY1,DY2,DR,DR1,DR2,DTANPS,DA,DB,DC,DARG,DPSI
      REAL*8 X1,X2,Y1,Y2,R,DRANGE
```

```
      ISTOP=0
      DX1=X1
      DR=R
      DR1=DR+H1
      DRANGE=RANGE
C
      DPSI=PSI
      DTANPS=DSIN(DPSI)/DCOS(DPSI)
      TANMIN=0.01777/(FR**0.33333)
      CHECK=DTANPS-TANMIN
      IF(CHECK.LT.0.0) ISTOP=1
      IF(ISTOP.GT.0) RETURN
C
      DA=1.0+DTANPS**2
      DB=-2.0*DR*DTANPS
      DC=DR*DR-DR1*DR1
      DARG=DB*DB-4.0*DA*DC
      DARG=DSQRT(DARG)
      DX1=(-DB-DARG)/(2.0*DA)
      DY1=-DTANPS*DX1+DR
      DX2=DRANGE*DCOS(DPSI)
      DY2=DRANGE*DSIN(DPSI)+DR
      X1=DX1
      Y1=DY1
      X2=DX2
      Y2=DY2
C
      RETURN
      END
C
C
C       SUBROUTINE GEOM CALCULATES GEOMETRICAL PARAMETERS NEEDED
C       FOR EVALUATING THE RECEIVED VOLTAGE
C
      SUBROUTINE GEOM(X1,Y1,X2,Y2,R,H1,RANGE,PSI,THETA1,THETA2,THETA,
     &D0,R1,R2,R12,THETT1,THETT2)
      REAL*8 DARG,DANG,DTEMP,DY,DYN,DR,DX
      REAL*8 X1,X2,Y1,Y2,R,R1,R2,R12
C
      PI=3.14159
      DARG=-X1/Y1
      DANG=DATAN(DARG)
      THETA1=DANG
      DARG=X2/Y2
      DANG=DATAN(DARG)
      THETA2=DANG
      THETA=THETA1+THETA2
      D0=R*THETA
C
      DYN=Y1
      DR=R
      DY=DYN-DR
      DARG=X1*X1+DY*DY
      DTEMP=DSQRT(DARG)
      R1=DTEMP
      DYN=Y2
      DY=DYN-DR
      DARG=X2*X2+DY*DY
      DTEMP=DSQRT(DARG)
      R2=DTEMP
      DX=X2-X1
      DY=Y2-Y1
      DARG=DX*DX+DY*DY
      DTEMP=DSQRT(DARG)
      R12=DTEMP
C
      BETA1=PI/2.0-PSI-THETA1
      DARG=(Y2-Y1)/(X2-X1)
      DANG=DATAN(DARG)
      PHI1=DANG
C
      THETT1=PI/2.0+THETA1-PHI1
      THETT2=PI-BETA1
C
      RETURN
      END
```

APPENDIX E

FLTSIM--FORTRAN PROGRAM FOR CALCULATING RECEIVED SIGNAL AS FUNCTION OF DISTANCE

```
C       PROGRAM FLTSIM                          PAGE 0001


C       PROGRAM FLTSIM
        COMPLEX VD,VR,VT,N2,CARG,CEX,F(362),CFAC,CREF,CTEMP
        DIMENSION V(1000),D(1000),A(362),B(362),NAME(3)
        REAL*8 X1,X2,Y1,Y2,R,R1,R2,R12,DTEMP
$INSERT SYSCOM$KEYS
$INSERT SYSCOM$KEYS.F
        CALL OPENSA(A$WRIT+A$SAMF,'OUTPUT',6,2)
        CALL OPNPSA('FILE NAME',9,A$READ+A$SAMF,NAME,6,I)
        FMIN=0.03623
        FMAX=0.0
        DO 30 I=1,361
        READ(5)A(I),B(I),F(I)
        FMAG=CABS(F(I))
        IF(FMAG.GT.FMAX) FMAX=FMAG
   30   CONTINUE
        DO 50 I=1,361
        F(I)=F(I)/FMAX
        FMAG=CABS(F(I))
        IF(FMAG.GE.FMIN) GO TO 50
        RF=REAL(F(I))
        XF=AIMAG(F(I))
        IF(FMAG.LT.0.000001) RF=0.001
        FANG=ATAN2(XF,RF)
        RF=FMIN*COS(FANG)
        XF=FMIN*SIN(FANG)
        F(I)=CMPLX(RF,XF)
   50   CONTINUE
        CALL CLOS$A(1)
        WRITE(1,62)
   62   FORMAT('WRITE POWER GAIN(IN DB) OF ANTENNA')
        READ(1,49)PGDB
        GAIN=10.0**(0.1*PGDB)
        WRITE(1,63)
   63   FORMAT('WRITE POWER (IN WATTS) DELIVERED TO TRANSMIT ANTENNA')
        READ(1,49)PT
        WRITE(1,41)
   41   FORMAT('WRITE AIRCRAFT ELEVATION IN METERS')
        READ(1,49)H2
        WRITE(1,45)
   45   FORMAT('WRITE TRANSMITTING ANTENNA HEIGHT IN METERS')
        READ(1,49)H1
   49   FORMAT(F12.7)
        WRITE(1,51)
   51   FORMAT('DO YOU WANT A LOGARITHMIC X AXIS. IF YES TYPE 1')
        READ(1,52)J
   52   FORMAT(I3)
        WRITE(1,60)
   60   FORMAT('WRITE RELATIVE DIELECTRIC CONSTANT OF GROUND')
        READ(1,49)EPSIL
        WRITE(1,61)
   61   FORMAT('WRITE CONDUCTIVITY OF GROUND')
        READ(1,49)SIGMA
        WRITE(1,46)
   46   FORMAT('WRITE FREQUENCY IN MEGAHERTZ')
        READ(1,49)FR
        WRITE(1,47)
   47   FORMAT('WRITE MINIMUM X1 IN METERS')
        READ(1,49)X1HOLD
    1   CONTINUE
        WRITE(1,48)
   48   FORMAT('WRITE LOGARITHMIC SCALE FACTOR ALPHA')
        READ(1,49) ALPHA
        X1=X1HOLD
        WRITE(6,1000)
        WRITE(1,1000)
 1000   FORMAT('    *** FLTSIM ***  ')
        WRITE(6,1200) (NAME(I),I=1,3)
 1200   FORMAT('    INPUT FILE NAME:'3A2)
        WRITE(6,2000) H1,H2,PGDB,PT
 2000   FORMAT('  H1='F9.3,'   H2='F9.3'   TRANSMIT ANTENNA GAIN='
       8F6.3'   TRANSMIT POWER='F6.3)
        WRITE(6,3000) EPSIL,SIGMA,FR,X1,ALPHA
 3000   FORMAT('  EPSILON='F9.3'   SIGMA='F9.3'   FREQUENCY='
       8F7.3' MHZ'/'  X1='E12.4'   ALPHA='F6.3)
        WL=300./FR
        AIN2=-60.0*SIGMA*WL
        N2=CMPLX(EPSIL,AIN2)
        R=8497440.0
        SCAL=WL*SQRT(30.*GAIN*PT)/(4.*3.14159)
        N=0
        X1=-X1/(1.0+ALPHA)
```

```
C     BEGIN RANGE LOOP
C
400   CONTINUE
      N=N+1
      X1=X1*(1+ALPHA)
      CALL AIRPOS(X1,Y1,X2,Y2,R,H1,H2,PSI,FR,ISTOP)
      CALL GEOM(X1,Y1,X2,Y2,R,H1,H2,PSI,THETA1,THETA2,THETA,
     &D0,R1,R2,R12,THETT1,THETT2)
      IF (ISTOP .GT. 0) GO TO 600
      THET1D=THETT1*57.29578
      THET2D=THETT2*57.29578
      IDX1=(THET1D*2.0+1.5)
      IDX2=THET2D*2.0+1.5
      DTEMP=(R-Y1)/X1
      DTEMP=2.0*R1*R2/(R*D0*DTEMP)
      DTEMP=1.0+DTEMP

      DTEMP=DSQRT(DTEMP)
      DTEMP=1.0/DTEMP
      DIV=DTEMP
      CTEMP=N2-(COS(PSI))**2
      CFAC=CSQRT(CTEMP)
      CREF=(N2*SIN(PSI)-CFAC)/(N2*SIN(PSI)+CFAC)
      R12S=R12
      VD=F(IDX1)*SCAL/R12S
      DEM=R1+R2
      VR=F(IDX2)*SCAL*DIV*CREF/DEM
      ARG=6.283185*(R1+R2-R12)/WL
      CARG=CMPLX(0.0,ARG)
      CEX=CEXP(-CARG)
      VT=VD+VR*CEX
      V(N)=CABS(VT)*1.0E+06
      D(N)=D0/1000.0
      N1=N
C
C      CHECK IF N1>1000
C
      IF(N1.GT.1000) GO TO 99
      GO TO 400
600   CONTINUE
C
C      END OF RANGE LOOP
C
      CALL SETPDQ
      CALL SCREEN
      CALL INIT(2.,1.)
      IF(J.EQ.1)GO TO 55
      CALL SCALE(D,N1,6.,1,0)
      GO TO 54
53    CALL LOGSCA(0.2,1000.0,6.,SF1,VLO,0)
54    CALL LOGSCA(1.,1000.,6.,SF2,VLO,1)
      CALL ENTGRA
      IF(J.EQ.1)GO TO 55
      CALL GRID(6.,6.,2.,-3,1,0)
      GO TO 56
55    CALL GETSCA(SF1,VLO,1)
      CALL GETSCA(SF2,VLO,0)
      X3=6.*SF1+0.001
      X4=6.*SF2+0.001
      CALL GRID(6.,6.,-X4,-X3,1,0)
      CALL XLOGAX('DISTANCE FROM SOURCE IN KM',26,6.)
      GO TO 57
56    CALL XAXIS('DISTANCE FROM SOURCE IN KM',26,6.)
57    CALL YLOGAX('MICROVOLTS AT RECEIVER',22,6.)
      IF(J.EQ.1)GO TO 58
      CALL DATLOG(D,V,N1,1,1,2)
      GO TO 59
58    CALL DATLOG(D,V,N1,1,1,3)
59    CALL EXITGR
      GO TO 100
 99   CONTINUE
      WRITE(1,9999)
9999  FORMAT('  ***** ERROR  N1.GT.1000  *****  '/
     &'  DO YOU WANT TO RETURN TO INPUT NEW ALPHA AND RESTART'/
     &'  YES=1 ')
      READ(1,52)  ICONT
      IF(ICONT.GT.0) GO TO 1
 100  CONTINUE
      CALL SRCHSC(KECLOS,'OUTPUT',6,2,0,IER)
      CALL EXIT
      END
C
C
C      SUBROUTINE AIRPOS CALCULATES THE LOCATION OF THE AIRCRAFT
C      FROM THE GIVEN H1,H2,R, AND X1
C
      SUBROUTINE AIRPOS(X1,Y1,X2,Y2,R,H1,H2,PSI,FR,ISTOP)
C
      REAL*8 DX1,DX2,DY1,DY2,DR,DR1,DR2,DTANPS,DA,DB,DC,DARG,DPSI
      REAL*8 X1,X2,Y1,Y2,R
```

```
      ISTOP=0
      DX1=X1
      DR=R
      DR1=DR+H1
      DR2=DR+H2
C
      DY1=DSQRT(DR1*DR1-DX1*DX1)
      DTANPS=(DR-DY1)/DX1
      TANMIN=0.01777/(FR**0.33333)
      CHECK=DTANPS-TANMIN
      IF(CHECK.LT.0.0) ISTOP=1
      IF(ISTOP.GT.0) RETURN
C
      DPSI=DATAN(DTANPS)
      PSI=DPSI
C
      DA=1.0+DTANPS**2
      DB=2.0*DR*DTANPS
      DC=DR*DR-DR2*DR2
      DARG=DB*DB-4.0*DA*DC
      DARG=DSQRT(DARG)
      DX2=(-DB+DARG)/(2.0*DA)
      DY2=DSQRT(DR2*DR2-DX2*DX2)
      Y1=DY1
      X2=DX2
      Y2=DY2
C
      RETURN
      END
C
C
C       SUBROUTINE GEOM CALCULATES GEOMETRICAL PARAMETERS NEEDED
C       FOR EVALUATING THE RECEIVED VOLTAGE
C
      SUBROUTINE GEOM(X1,Y1,X2,Y2,R,H1,H2,PSI,THETA1,THETA2,THETA,
     &D0,R1,R2,R12,THETT1,THETT2)
C
      REAL*8 DARG,DANG,DTEMP,DY,DYN,DR,DX
      REAL*8 X1,X2,Y1,Y2,R,R1,R2,R12
C
      PI=3.14159
      DARG=-X1/Y1
      DANG=DATAN(DARG)
      THETA1=DANG
      DARG=X2/Y2
      DANG=DATAN(DARG)
      THETA2=DANG
      THETA=THETA1+THETA2
      D0=R*THETA
C
      DYN=Y1
      DR=R
      DY=DYN-DR
      DARG=X1*X1+DY*DY
      DTEMP=DSQRT(DARG)
      R1=DTEMP
      DYN=Y2
      DY=DYN-DR
      DARG=X2*X2+DY*DY
      DTEMP=DSQRT(DARG)
      R2=DTEMP
      DX=X2-X1
      DY=Y2-Y1
      DARG=DX*DX+DY*DY
      DTEMP=DSQRT(DARG)
      R12=DTEMP
C
      BETA1=PI/2.0-PSI-THETA1
      DARG=(Y2-Y1)/(X2-X1)
      DANG=DATAN(DARG)
      PHI1=DANG
C
      THETT1=PI/2.0+THETA1-PHI1
      THETT2=PI-BETA1
C
      RETURN
      END
```