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Developed by the

Antennas and Propagation Standards Committee
of the
IEEE Antennas and Propagation Society

Approved 23 September 2021

IEEE SA Standards Board

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Abstract: The recommended practices for the measurement of antenna transmitting and receiving properties are presented. Throughout this standard it is assumed that the antenna to be measured can be treated as a passive, linear, and reciprocal device. A fundamental property of any antenna is its radiation pattern. The measurement of radiation patterns in an antenna test facility is discussed. The design of antenna test facilities is described along with instrumentation requirements for the proper operation of the antenna facility, directions for the evaluation of an (existing) range, and the operation of ranges is discussed. References are provided that are illustrative of measurement techniques and in which details may be found.

Keywords: absorbers, accuracy, alignment, anechoic, antenna, antenna gain, antenna measurements, calibration, chamber, compact range, EIRP, electromagnetic compatibility, electromagnetic testing, EMC, equivalent isotropically radiated power, errors, evaluation, facilities, far field, far-field range, gain/temperature, ground bounce, high power, IEEE 149, impedance, instrumentation, inter-range comparison, measurement, near-field, near zone, noise, outdoor range, passive, pattern, phase, polarization, probe, quiet zone, radar, radiation, radio frequency, radome, range, receiver, reflector, safety, scale model, scanner, software, standard gain horn, standard, tapered chamber, target support, techniques, test facility, test range, test zone, three-antenna measurement, tracking, uncertainties, uncertainty analysis, verification

The Institute of Electrical and Electronics Engineers, Inc.
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PDF: ISBN 978-1-5044-8017-8 STD24975
Print: ISBN 978-1-5044-8018-5 STDPD24975

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Introduction

This introduction is not part of IEEE Std 149™-2021, IEEE Recommended Practice for Antenna Measurements.

This document is a major revision of IEEE Std 149-1977 (reaffirmed 2008) which it supersedes. As with the rest of industry, much has changed in the area of antenna measurements over the more than four decades that have passed since the last update. While most practitioners are still interested in the fundamental properties of antennas, such as radiation patterns, gain, impedance, and radiation efficiency, the equipment and methods for measuring these quantities have evolved due to improved tools and significant innovation. Many of these advances are discussed herein, however due to the diversity of antenna measurement challenges it was not practical to retain the original mandate as a standard test procedure. Instead, this update has been reclassified as a recommended practices document, with the intent to serve as a guideline for obtaining the highest quality measurements without dictating a specific approach. Consequently, this document is devoid of "shall" directives but full of "should" recommendations, in accordance with the IEEE Standard Association Standards Board Operations Manual.

This revision emphasizes the industry trend away from the outdoor measurements that were common in the 1970s. While some outdoor range content is retained in this document, much of it has been supplanted with information on various indoor measurement techniques, to include far-field anechoic chamber topologies, the compact antenna test range (CATR), reverberation chambers, and some discussion on near-field antenna testing. This revision retains many of the familiar IEEE Std 149-1977 topics on antenna measurement and range evaluation but describes them using industry best-practice techniques and modern equipment. Several new special measurement techniques are included in this revision, along with an entire section devoted to uncertainty evaluation to emphasize the importance of this topic to any measurement of antenna properties. Finally, this revision has been re-formatted and restructured to conform to modern IEEE SA style and layout principles.

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IEEE Recommended Practice ~~Standard Test Procedures~~ for Antenna Measurements ~~Antennas~~

1. Overview

1.1 Scope

This document comprises recommended practices ~~test procedures~~ for the measurement of antenna transmitting and receiving properties. It is a comprehensive revision and extension of ~~the previous test procedure~~ ANSI/IEEE Std 149™-1979 (Revision of IEEE Std 149-1963) IEEE Standard Test Procedures for Antennas ~~1965 (Reaff 1971)~~.

Throughout this standard it may be ~~is~~ assumed that the antenna to be measured can be treated as a passive, linear, and reciprocal device. Therefore, its radiation properties can be measured in either the transmitting or the receiving mode. Many of the test practices described can, however, be adapted for use in the measurement of antenna systems containing circuit elements that may be active, nonlinear, or nonreciprocal. For these cases, there is no simple relationship between the antenna system~~'~~s transmitting and receiving properties. Therefore, measurements should ~~shall~~ be performed for the mode or modes in which the antenna system has been designed to be used.

A fundamental property of any antenna is its radiation pattern. The measurement of radiation patterns in ~~on~~ an antenna test facility ~~range~~ is discussed ~~in Section 3., with the emphasis placed on amplitude patterns~~. The design of antenna ~~ranges, or antenna~~ test facilities~~,~~ is described along with ~~in Section 4. The~~ instrumentation requirements ~~required~~ for the proper operation of the antenna facility ~~range~~, directions for the evaluation of an (existing) range, and the operation of ranges is ~~are~~ discussed ~~in Sections 5., 6., and 8., respectively. A variety of special measurement techniques are included in Section 7~~.

~~The working environment in which an antenna is installed may substantially modify the intrinsic pattern of an antenna. Consequently measurements *in situ* are frequently required. These are discussed in Section 9.~~

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For each direction of space, the radiation pattern is characterized by amplitude, phase, and polarization. From the measurement of these parameters, gain, directivity, and radiation efficiency can be determined ~~The latter characteristics are taken up in Sections 10. and 11., respectively~~.

~~The relative amplitude pattern information may be converted into absolute intensities through information derived from the measurement of antenna gain. The determination of gain and closely related directivity is described in Section 12.. Errors in conventional gain calibration measurements are discussed particularly in 12.5. Losses in the antenna itself can be of importance in some types of antennas. These losses can be accounted for by the radiation efficiency. Procedures for their determination are treated in Section 13.~~

~~Section 14. deals with boresight measurements, which are concerned with the precise determination of the direction of the beam or tracking axis of an antenna system. The sensitive components of the antenna frequently require protection from harsh influences of the environment. The electrically transmissive shield or radome which provides this protection shall frequently be evaluated so that its effect on the radiation pattern is understood. This topic is treated in Section 15.~~

Power transfer from generator to antenna is controlled by the input impedance to the antenna. This important parameter frequently limits the useful bandwidth of the antenna. Measurement procedures and network descriptions for antenna impedance are described ~~appropriate from low to microwave frequencies are presented in Section 16~~.

Measurement of the radiation pattern includes errors. A method of uncertainty analysis is presented and discussed for its applicability to the various test facilities described.

~~An important class of antennas relies on ground to enhance the received signal. In this case the ground shall be considered as an integral part of the antenna. The modification of antenna concepts and additional data on the ground-wave propagation are presented in Section 17.~~

~~The antenna and its associated circuits rather than the capacity of the transmitter generator may limit the amount of power, either average power or peak power, that can be effectively radiated. It is desirable therefore to determine these limitations as well as the environmental factors that may modify them independently of the system context. Procedures for testing power-handling capacity are outlined in Section 18.~~

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~~Another concern to the antenna engineer is that of radiation hazards. It is well known that radio-frequency (rf) fields of sufficient intensity can cause damage to biological tissue. Therefore it is usually necessary to determine the level of the radiation intensity in the vicinity of antennas radiating high radio frequency power so that appropriate safety precautions can be taken before personnel enter the area. This important aspect of antenna measurements is discussed in Section 19.~~

~~Mechanical or structural properties along with environmental factors are described in Section 20. Because these properties are so varied and specialized in nature, no attempt has been made to include descriptions of actual measurements in this test procedure. The environmental impact of an antenna is also an important consideration for the antenna engineer. One aspect of environmental impact is that of aesthetics. Large antenna structures are necessarily conspicuous, and their appearance is of concern to those who live in their vicinity. This is particularly true in an urban setting. Since the aesthetic quality of the antenna structure is highly subjective, it is beyond the scope of this document to suggest any evaluation procedure.~~

Throughout this standard, attempts are ~~test procedure an attempt has been~~ made to discuss measurement techniques as thoroughly as is practicable. However, in general, step-by-step procedural descriptions have been avoided. References are provided that ~~which~~ are illustrative of measurement techniques and in which details may be found. ~~Because measurement techniques undergo continuing refinement, the reader should be alert to references on the subject of antenna measurement that will have appeared after this test procedure was prepared.~~

~~Many commonly used terms used in this test procedure are defined in ANSI/IEEE Std 145-1973, Definitions of Terms for Antennas. Commonly used terms that do not appear in that standard are italicized in this test procedure.~~

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1.2 Purpose

Many individuals and organizations are involved in the design, manufacture, measurement, and use of antennas for many different applications. This standard is intended to provide a guideline into the typical methods and procedures used to characterize the performance of typical antennas. This recommended practice is not intended to be all-encompassing or to strictly define strict procedures. Its purpose is to provide someone practiced in the art of antennas the knowledge to perform quality measurements and to interpret the results of antenna measurements.

1.3 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall* equals is *required to*).[1, 2]

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should* equals is *recommended that*).

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may* equals is *permitted to*).

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can* equals is *able to*).

1.4 Background

This recommended practice discusses in much detail the measurement of antennas and discusses the most popular metrics for stating the performance of antennas. Throughout this document, terms are used describing properties of antennas and propagation. These terms are defined in IEEE Std 145™-2013 and IEEE Std 211™. Among the specific terms, references to the radiation pattern of an antenna are extensive enough to warrant a brief introduction.

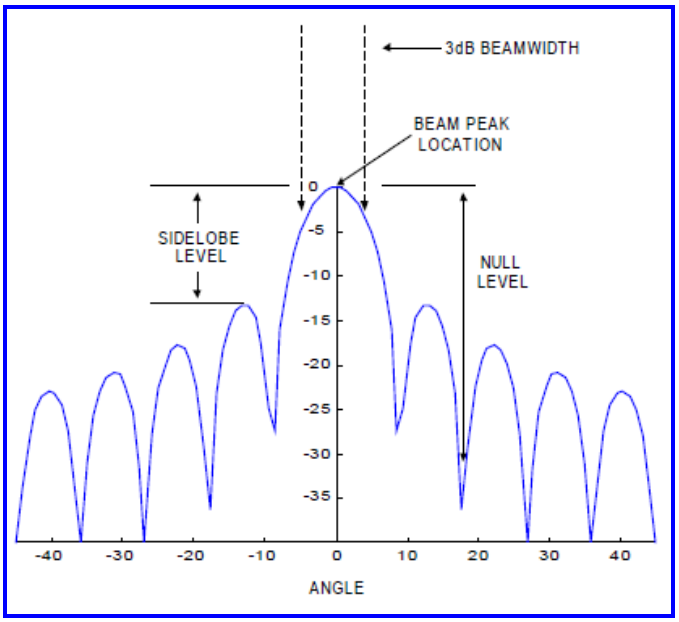
[1] The use of the word *must* is deprecated and cannot be used when stating mandatory requirements, *must* is used only to describe unavoidable situations.

[2] The use of *will* is deprecated and cannot be used when stating mandatory requirements, *will* is only used in statements of fact.

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The *radiation pattern* of an antenna is defined in IEEE Std 145-2013 to be: The spatial distribution of a quantity that characterizes the electromagnetic field generated by an antenna. While the radiation pattern exists over a full *radiation sphere* surrounding the antenna, a commonly used antenna radiation pattern representation is shown in Figure 1. This figure shows a *radiation pattern cut* on the radiation sphere of normalized *gain* or *directivity* on a decibel (dB) scale versus angle. Many other representations of radiation patterns are common such as *phase patterns*, *axial ratio patterns*, and *polarization patterns*.

Many metrics can be extracted from the antenna radiation pattern to summarize the performance of an antenna. These metrics provide quantitative results that can then be compared to specification limits or requirements. A few metrics are illustrated in Figure 1. The metrics shown include the half-power (3 dB) beamwidth, which is the angle between the two directions in which the radiation intensity is one-half of the maximum value; a first sidelobe level representing a local maximum in the radiation pattern cut; a null level or null depth representing a local minimum in the radiation pattern cut; and the beam peak location representing the global maximum of the radiation pattern. It should be noted in Figure 1 that many radiation pattern metrics are relative quantities referenced to the beam peak regardless of whether the pattern is normalized or not.



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Figure 1 —A typical antenna radiation pattern

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This document adheres to the IEEE convention for wave propagation and polarization to describe right-hand and left-hand sense. All propagating waves are described relative to the direction of propagation. Therefore, when determining polarization sense, the thumb points toward the destination and the fingers are curled to match the rotation of the electric field vector, i.e., from the phase-leading component toward the phase-lagging component along the shortest angular path between them, per IEEE Std 145-2013.

This document adheres to the IEEE standard time convention for time-harmonic electromagnetic fields with a time factor of $e^{+j\omega t}$, where j is the imaginary unit ($j^2 = -1$), ω the angular frequency, and t is time, per IEEE Std 145-2013. Using this convention, the corresponding propagation phase factor is e^{-jkr}, where k is the wavenumber and r is the propagation distance. Modern antenna measurement systems often record data in this $e^{+j\omega t}\ e^{-jkr}$ format, but to avoid mistakes in data analysis it is recommended to confirm the time convention in each unique radio frequency (RF) measurement system configuration.

In physics, the $e^{-j\omega t}\ e^{+jkr}$ phasor convention is mainly used, where i is the imaginary unit ($i^2 = -1$). Although this convention is avoided in the text of this document, several of the references in Annex A employ the physics time convention. This discrepancy can be problematic, e.g., a right-hand sense can be incorrectly identified as left-hand sense if the time convention of the measured data does not match the time convention assumed when deriving the selected sense equation. In cases where it is desirable to use equations derived with the $e^{-j\omega t}$ convention assumed there are two valid approaches:

1. Replace $-i$ with $+j$ in all equations.

2. Conjugate the input data, use the equations as provided, and then conjugate the results.

Note that it is common to suppress the time factor $e^{\pm j\omega t}$ in equations to achieve a more simplified form, but the propagation phase factor is not suppressed and therefore is used to confirm the chosen time convention.

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2. Normative ~~Standards~~ references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

~~When the following standard documents referenced in the text are superseded by an approved revision, the revision shall apply.~~

~~ANSI C95.1-1974, Safety Level of Electromagnetic Radiation with Respect to Personnel.~~

~~ANSI C95.3-1973, Techniques and Instrumentation for the Measurement of Potentially Hazardous Electromagnetic Radiation at Microwave Frequencies.~~

~~ANSI/IEEE Std 100-1977, Dictionary of Electrical and Electronics Terms. ANSI/IEEE Std 145-1973, Definitions of Terms for Antennas.~~

~~ANSI/IEEE Std 148-1959 (Reaff 1971), Measurement of Waveguides and Components.~~

IEEE Std 211, IEEE ~~1977,~~ Standard Definitions of Terms for Radio Wave Propagation.[3, 4]

IEEE Std 145-2013, IEEE Standard for Definitions of Terms for Antennas.

~~IEEE Std 291-1969, Standards Report on Measuring Field Strength in Radio Wave Propagation.~~

[3] The IEEE standards or products referred to in Clause 2 are trademarks owned by The Institute of Electrical and Electronics Engineers, Incorporated.

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3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.[5]

antenna: That part of a transmitting or receiving system designed to radiate or to receive electromagnetic waves.

antenna measurements: The process of characterizing the electromagnetic performance metrics of an antenna by experiment.

antenna range: Experimental setup enabling antenna measurements. *Syn:* **antenna test range**.

antenna under test (AUT): The antenna and all associated equipment or structure to be considered as part of the object being characterized. This means that the antenna under test can be considered physically larger than the antenna alone. In this recommended practice, the term *antenna under test* and *AUT* are used interchangeably. *Syn:* **test antenna**.

compact range: Measurement device consisting of one or more parabolic reflectors and range antenna for creating a quiet zone for antenna measurements.

compact antenna test range (CATR): A measurement system incorporating a compact range.

quiet zone: A limited region in which the radiation from the range antenna approximates a plane wave condition.

radiation pattern: The spatial distribution of a quantity that characterizes the electromagnetic field generated by an antenna. *Syn:* **antenna pattern**.

[5] *IEEE Standards Dictionary Online* is available at: http://dictionary.ieee.org. An IEEE Account is required for access to the dictionary, and one can be created at no charge on the dictionary sign-in page.

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NOTE 1— The electromagnetic field distribution can be expressed as a mathematical function or as a graphical representation.[6]

NOTE 2— The quantities that are most often used to characterize the radiation from an antenna are proportional to or equal to power flux density, radiation intensity, directivity, phase, polarization, and field strength. NOTE 3— The spatial distribution over any surface or path is also a radiation pattern.

NOTE 4— When the amplitude or relative amplitude of a specified component of the electric-field vector is plotted graphically, it is called an *amplitude pattern, field pattern,* or *voltage pattern.* When the square of the amplitude or relative amplitude is plotted, it is called a *power pattern.*

NOTE 5— Throughout this document an amplitude or power pattern is implied if not specifically defined otherwise.

range antenna: Part of the antenna range and used in the characterization of the antenna under test.

test zone: *Syn:* **quiet zone (QZ).**

3.2 Acronyms and abbreviations

AESA	active electronically steered array
AUT	antenna under test
CW	continuous wave
CR	compact range
CATR	compact antenna test range
DUT	device under test

6 Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

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dBm	decibels with respect to a milliwatt
dBi	decibels with respect to isotropic radiation
EM	electromagnetic
EMC	electromagnetic compatibility
EIRP	equivalent isotropically radiated power (far-field condition)
EIS	equivalent isotropic sensitivity (far-field condition)
FCC	Federal Communications Commission
FFT	fast Fourier transform
G/T	gain over temperature
GPIB	general purpose interface bus
GNSS	global navigation satellite system
ICNIRP	International Commission on Non-Ionizing Radiation Protection
LAN	local area network
LO	local oscillator
OTA	over the air
PWS	plane wave synthesizer
PWG	plane wave generator
RCS	radar cross section
REF	reference receive antenna
RF	radio frequency

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RFI	radio frequency interference
RSS	root sum squared
SNR	signal-to-noise ratio
TIS	total isotropic sensitivity
TRP	total radiated power
UHF	ultra high frequency
USB	universal serial bus
VNA	vector network analyzer
VHF	very high frequency
VSWR	voltage standing wave ratio
QZ	quiet zone

4. Antenna range design

4.1 General

Antenna ranges have been developed for the purpose of measuring the radiation patterns of antennas independent of their operational environment. The antenna range consists of the appropriate instrumentation and the physical space required for the measurements.

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In this clause, ~~section~~ the design of the antenna range is discussed. Evaluation and use of antenna ranges are described in Clause ~~Sections~~ 6~~.~~ and Clause 14, ~~8.. Emphasis is placed on the measurement of the relative amplitude patterns. The measurement of relative phase, polarization, and power gain is discussed in Sections 10., 11., and 12.,~~ respectively. It should be pointed out that the various criteria for antenna range design presented here, as well as the methods of evaluation, apply equally well to other types of ranges usually found at antenna testing facilities, such as radome ranges and radar cross section (RCS) ~~*scattering*~~ ranges. The ideal incident electromagnetic field wave front for measuring the far-field radiation characteristics of the antenna under test (AUT) is that of a uniform plane wave. In practice, it is only possible to approximate such a field. Attempts to do this have led to the development of three basic types of ranges: ~~Radome measurements are discussed in Section 15., and scattering ranges are beyond the scope of this standard.~~

~~The ideal incident field for measuring the radiation characteristics of the test antenna is that of a uniform plane wave. In practice it is only possible to approximate such a field. Attempts to do this have led to the development of two basic types of ranges:~~

— Free-space ranges. This type of range is designed in such a manner that all the effects of the surroundings are suppressed to acceptable levels.

— Ground reflection ranges. This type of range is designed to judiciously use reflections in order to produce an approximated plane wave or some other predictable combination of plane waves. – Near-field ranges. This type of range is designed to simulate the uniform plane wave through mathematical transforms of measurement samples (IEEE Std 1720™-2012~~.~~

Typical ranges that come under the free-space ~~-~~range classification are: the elevated range, the ~~slant range, the~~ compact range, and most anechoic chambers.

The elevated range (Cumming [B47]) ~~[3]~~ includes those ranges in which the AUT ~~test~~ and range ~~source~~ antennas are located on towers, on adjacent elevations on the surrounding topology, ~~or mountain peaks,~~ on the roofs of ~~adjacent~~ buildings ~~or on diagonally opposing sides of abandoned quarries~~. Generally, elevated ranges are ~~however, it is~~ designed over an approximately flat area, and the effects of the surroundings are suppressed:

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— By careful choice of the range ~~source~~ antenna regarding ~~with regard to~~ directivity and side-lobe level

— By clearance of the line of sight along the range surface

— By redirection or absorption of energy reaching the range surface or obstacles that cannot be removed

— By special signal-processing techniques such as time domain processing ~~modulation tagging of the desired signal~~

— By use of short pulses

The ground-reflection range (Cutler, King, and Kock [B48]) ~~[4]~~ is designed to make use of the energy that is specularly reflected from the range surface to create a constructive interference with the direct-path energy in the region of the AUT ~~test antenna~~. With proper design, the illuminating field will have a small, essentially symmetric amplitude taper. This is usually achieved by adjusting the height of the range ~~source~~ antenna above the range surface with the AUT ~~test antenna~~ at a fixed height. Since the elevated range over a flat surface and the ground-reflection range are so basic to antenna pattern measurements, their design will be discussed in detail in 4.3.2 and 4.3.6, respectively.

Typical ranges that come under the near-field range classification are: the planar near-field range, the spherical near-field range, and the cylindrical near-field range. Near-field range design is discussed in detail in IEEE Std 1720-2012 [B92] and Rodriguez, 2019 [B159].

~~Since the elevated range over a flat surface and the ground-reflection range are so basic to antenna pattern measurements, their design will be discussed in detail in 4.3 and 4.4, respectively. Other range types will be discussed in 4.5.~~

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4.2 Antenna range design criteria

4.2.1 General

To establish the design criteria for a ~~either~~ basic far-field range type, ~~one must consider~~ the following parameters should be considered:

— The coupling between range antenna ~~source~~ and AUT ~~test antennas~~

— The transverse and longitudinal amplitude taper of the illuminating wave front

— The phase curvature of the illuminating wave front

— Spatial variations in the illuminating wave front caused by reflections

— Interference from spurious radiating sources

Items associated with the fields radiated by the range antenna ~~(1) (3)~~ are discussed in this clause ~~section~~. The problems associated with reflections from the range surface and other obstacles are discussed in the different range design subclauses ~~4.3 and Section 6~~.

Outdoor ranges are often ~~usually~~ subjected to interference from signal sources outside the range area, such as. ~~These sources can be~~ mobile communications, radar, or telemetry systems. The use of filters can often suppress the effect of these interfering signals as long as they do not coincide with the test frequencies of interest. In indoor ranges the interference comes mainly from reflections off the lateral surfaces of the range.

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4.2.2 Effect of mutual coupling between range antenna ~~*Source*~~ and antenna under test ~~*Antennas*~~

The total field of any antenna consists of a radiating field ~~radiation part~~ and a reactive field ~~part~~. The radiating ~~radiation~~ field decays as the reciprocal of the distance from the antenna, whereas the reactive field decays at least as rapidly as the reciprocal of the square of the distance from the antenna. Usually the spacing between the range antenna ~~source~~ and AUT ~~test antennas~~ is large enough so that the level of the reactive field of the range ~~source~~ antenna is negligible. However, practical situations do arise for which this may not be the case. In these cases, the AUT ~~test antenna~~ will couple via ~~to~~ the reactive field, and for some types of measurements, this produces an error. Such effects are considered negligible when the spacing is greater than about 10 wavelengths. Based on ~~upon~~ calculations made for a very short dipole antenna at 10 wavelengths from the AUT ~~antenna~~, the level of the inductive field (which is the part of the reactive field that would couple) will be 36 dB below that of the radiation field (Hollis, Lyon, and Clayton [B84]).

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In addition to the reactive field coupling, the reradiated ~~reradiative~~ coupling or mutual coupling between the range antenna ~~source~~ and antenna under test ~~antennas~~ is also of concern (Pippard, Burrell, and Cromi [B149]) ~~[5]~~. For this case, part of the energy incident on ~~received by~~ the AUT ~~test antenna~~ is reradiated toward the range ~~source~~ antenna. In turn, part of this ~~the~~ energy incident on ~~received by~~ the range ~~source~~ antenna is again reradiated toward the AUT ~~test antenna~~. The reradiation levels are determined by the scattering cross section of each antenna, consisting of both a structural component and an impedance matching component. While this reradiation level is often quite low, it can cause a measurable error in the level of the signal observed near the peak of the AUT's ~~test antenna's~~ major lobe. The effect on the side-lobe levels is usually negligible. A careful analysis ~~[1, pp 14.3-14.5]~~ was performed~~; it was~~ based on an ~~upon~~ identical range antenna ~~source~~ and AUT ~~test antennas~~, each with a sinc function–shaped ~~(sin *x*)/*x*~~ antenna pattern, a 50% ~~percent~~ aperture efficiency, and an equivalent power reflection coefficient of 0.25 (Hollis, Lyon, and Clayton [B84]). The level of the reradiated signal reaching the AUT ~~test antenna~~ was at least 45 dB below that of the original received signal when the ~~ratio of the~~ plane angle subtended at the range ~~source~~ antenna by the diameter of the AUT was less than or equal to 0.3 times ~~test antenna, to~~ the 3 dB beamwidth of the range ~~source~~ antenna ~~was made equal to or less than 0.3~~. This ratio corresponds to a subtended angle that is approximately equal to the range ~~source~~ antenna's beamwidth~~beam width~~ at the 0.25 dB level. It is generally considered good practice to adhere to a 0.25~~2.5~~ dB criterion for the amplitude taper of the direct illuminating field in order to reduce mutual coupling (Cutler, King, and Kock [B48]; Hollis, Lyon, and Clayton [B84]); therefore, it is recommended to maintain both a minimum 10 wavelength separation and a maximum 0.25 dB amplitude taper in the quiet zone. ~~[1, pp 14.13-14.15], [4].~~

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4.2.3 Effect of a transverse amplitude taper over the test aperture

An amplitude taper of the illuminating field can produce an error in the measured antenna pattern of the AUT ~~test antenna~~. This effect depends on ~~is dependent upon~~ the aperture excitation function of the AUT ~~test antenna~~. For typical excitation functions, the effect of the amplitude taper of the incident field is a reduction in measured gain with a slight modification to the close-in sidelobes. This effect can be evaluated by recognizing that the variation of the amplitude of the incident field over the aperture of the AUT in receiving mode ~~test antenna on receive~~ is analogous to a modification of the aperture illumination from its feed in transmitting mode.~~on transmit.~~ Suppose that the AUT ~~test antenna~~ has an aperture illumination from its feed on transmit given by $f(x, y)$. If it is used in receiving mode ~~on receive~~ and is illuminated by an incident field with an amplitude variation given by $g(x, y)$, then the measured radiation pattern is essentially the same as that for the transmitting case, with the feed modified to produce a distribution over the AUT ~~test antenna~~ aperture given by the product $f(x, y) \times g(x, y)$. For example, consider an AUT ~~a test antenna~~ having a circular aperture with a 10 dB *cosine-on-pedestal* distribution, the far-field radiation pattern that ~~of which~~ is to be measured with the use of a range ~~source~~ antenna that produces a circularly symmetric amplitude taper over the aperture of the range ~~test~~ antenna. The taper is assumed to have a ~~$(\sin x)/x$~~ form of a sinc function. ~~One can now compute~~ The directivity of the equivalent distribution, which is the product of the cosine-on-pedestal and sinc ~~$(\sin x)/x$~~ functions for various tapers, can now be computed. If the amplitude taper is – ~~varies to~~ 0.5 dB at the periphery of the aperture, an apparent directivity reduction of approximately 0.15 dB will result as compared to the case without taper. If the amplitude taper is – ~~varies to~~ 0.25 dB at the periphery of the aperture, ~~one obtains~~ a reduction in directivity of about 0.10 dB is obtained (Hollis, Lyon, and Clayton [B84]).

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Generally, it is recommended ~~better~~ to choose a range ~~source~~ antenna that yields a 0.25 dB taper across the AUT aperture, rather than one with a broader beamwidth that ~~which~~ would produce a smaller amplitude taper. This is because the use of broader beamwidth range ~~source~~ antennas usually results in an increased error due to ~~the~~ reflections from the antenna range ~~(see Section 6.)~~. Conversely, there are situations that ~~in which~~ it may be necessary to use a range ~~source~~ antenna with a narrower beam ~~in order~~ to reduce the effect of reflections from the test environment. If a more directive range ~~source~~ antenna is used, the alignment of the range ~~source~~ antenna becomes more critical. The range antenna should ~~Care shall~~ be oriented ~~exercised in orienting the source antenna~~ so that the peak of its beam is centered on the AUT ~~test antenna~~ to prevent an excessive and asymmetrical illumination taper with a resultant increase in measurement error.

4.2.4 Effect of a longitudinal amplitude taper at the antenna under test ~~*Antenna*~~

To achieve a given accuracy in the measurement of the radiation pattern of an AUT ~~a test antenna~~, the illuminating field should ~~shall~~ be sufficiently constant in amplitude along the range axis, as well as in planes normal to the range axis. Consider an end-fire AUT ~~antenna under test~~ with an active region having a maximum dimension L along the range axis. If the separation between the range ~~source~~ antenna and the center of the active region is $R0$, then the ratio ρp~~,~~ of the power flux density at the forward extreme of the active region to that at the rear is given by Equation (1), which can be found in Chapter 14 of Hollis, Lyon, and Clayton [B84], as well as in Bachmann, King, and Hansen [B12]. ~~[7]~~

$$10 \log_{10} \rho_p = 20 \log_{10} \frac{R_0 + L/2}{R_0 - L/2} \quad \text{(in dB)} \qquad (1)$$

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~~$10 \log (\rho_p) = 20 \log \frac{R_0 + L/2}{R_0 - L/2}$ [dB]~~

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Severe axial variations of the illuminating field can cause a measurement error, particularly in the minor lobe structure of radiation patterns. For most antenna types that have a significant depth to their active regions, such an error is usually considered to be negligible when the power flux density over the region is constant to within 1 dB. Incorporating some additional margin, the recommended constraint for ~~This condition corresponds to an approximate restraint~~ on $R0$, given by Equation (2). ~~of~~

$$R_0 \geq 10L \tag{2}$$

The criterion for such structures as high-gain end-fire antennas often is more restrictive than the ~~greater of the previously discussed~~ range-length criteria ~~that were~~ based on either the suppression of reactive-field coupling (4.2.2) or ~~and~~ phase curvature (4.2.5).

4.2.5 Effect of phase variation over the test aperture

A criterion should ~~has to~~ be established for the phase variation of the illuminating field over the AUT ~~test antenna~~. For most practical situations, the phase variation is a function solely of the separation between the range ~~source~~ antenna and the AUT ~~antenna under test~~. If, in the absence of reflections, the 0.25 dB criterion for amplitude variation is adhered to, then the corresponding phase variation will be very close to that of a spherical wave emanating from the phase center of the range ~~source~~ antenna. This is true for spacings considerably less than $2d^2/\lambda$, where d is the diameter of the range ~~source~~ antenna. For example, calculations (Hollis, Lyon, and Clayton [B84]) ~~[1, pp 14.5-14.11]~~ made for a range ~~source~~ antenna with a 30 dB Taylor aperture current distribution revealed that its phase pattern differed from that of a spherical wave by at most 2° between the 1 dB points of its amplitude pattern at a spacing of D~~d~~$^2/\lambda$, where D is the maximum diameter of the AUT in the plane normal to the range axis. Thus, the expected phase variation can be determined by assuming that the phase front at the AUT ~~test antenna~~ is a sphere. ~~It can readily be shown [4] that for a test antenna diameter D and a separation R, a phase deviation $\Delta\phi$ will be given by~~

For a spherical wave front, it can readily be shown (Cutler, King, and Kock [B48]) that for an AUT diameter D and a separation R, where $D/R \ll 1$, the phase deviation $\Delta\varphi$ is given approximately by Equation (3).

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$$\Delta\phi = \frac{\pi D^2}{4\lambda R} \quad (3)$$

where

R is the separation distance between the range antenna and the AUT

A commonly employed criterion for determining the minimum allowable separation between the range antenna ~~source~~ and AUT ~~test antennas~~ is to restrict $\Delta\phi$ to $\pi/8$ radians, or 22.5° ~~rad~~. This results in the restriction shown in Equation (4), which defines the recommended distance R, or path length for a typical far-field antenna measurement. ~~that~~

$$R \geq 2D^2 / \lambda. \quad (4)$$

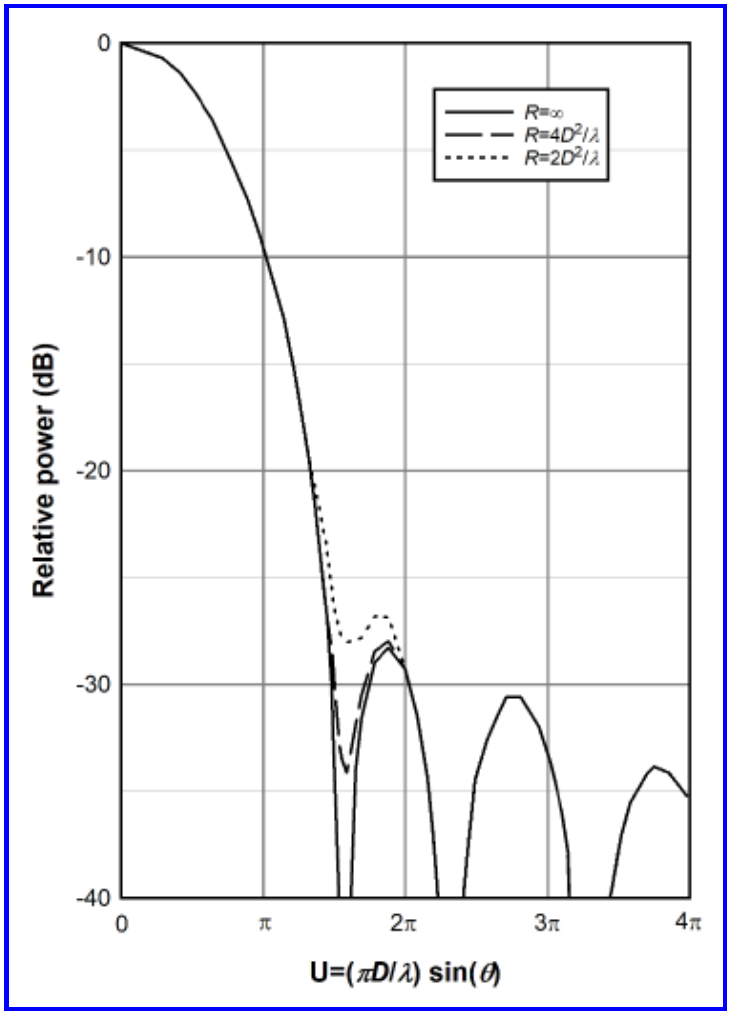
where

D is the aperture size of the AUT

λ is the wavelength at the frequency of interest

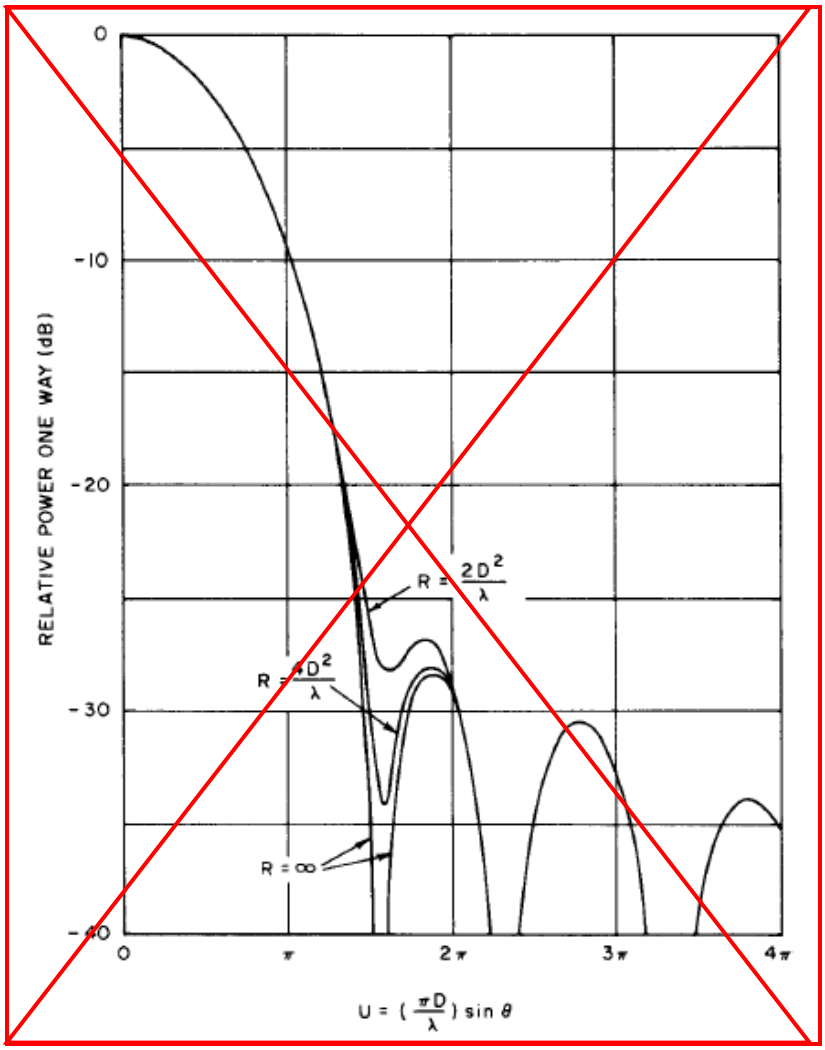
The effect of phase variation is that the nulls of the pattern are partially filled, and the amplitudes of the sidelobes are changed. An example is shown in Figure 2 that ~~Fig 3 which~~ depicts calculated patterns of a circular aperture antenna with a 30 dB Taylor aperture current distribution at separations of $2D^2 / \lambda$, $4D^2 / \lambda$, and approaching infinity. ~~It is possible to correct for phase deviations by changing the focus of the test antenna, a technique that is discussed in 7.2.~~

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Figure 2 —Calculated radiation patterns illustrating the effect of quadratic phase errors encountered in measuring patterns at the ranges indicated. A 30 dB Taylor aperture current distribution is assumed.

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4.3 Outdoor ranges

4.3.1 General

Outdoor ranges have an important role in the history of antenna testing; however, they are less common as compared to indoor antenna ranges where the cost of real estate, radio frequency interference (RFI), environmental variations, and radiation restrictions by governing bodies are less. Regardless of the practical challenges of operating and maintaining outdoor ranges, their design principles remain valuable, and are described here for some of the most successful outdoor range configurations.

4.3.2 Design of elevated ranges

~~4.3.1 *Elevated Ranges over Flat Surfaces*~~

In view of the interdependence between the diameter D of the AUT ~~test antenna~~ and the ~~range or~~ separation R between the range antenna ~~source~~ and the AUT ~~test antennas~~, it is convenient to specify the separation as $R = KD^2 / \lambda$, where K is a number to be chosen for a particular measurement as shown in Figure 2 with $K = 2$, $K = 4$, and $K = \infty$ ~~(see Fig 3)~~. It can be shown (Hollis, Lyon, and Clayton [B84]) ~~[1, pp 14.15–14.28]~~ that *for elevated ranges*, as shown in Figure 3, the 0.25 dB criterion for amplitude taper leads to a criterion for the diameter of the range ~~source~~ antenna. See Equation (5).~~, namely, that~~

$$d \leq 0.37KD \tag{5}$$

where

- K is a number to be chosen for a particular measurement as shown in Figure 2
- d is the diameter of the range antenna

This assumes that the main lobe of the range ~~source~~ antenna has a sinc function ~~$(\sin x)/x$~~ amplitude characteristic. The 0.25 dB beamwidth is shown by in Figure 3.

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If the elevated range is designed over a flat surface, as shown in Figure 3 ~~Fig 4~~, then steps should ~~shall~~ be taken to suppress the reflections from the range surface in the region near the range axis.

As a basic design goal, the range surface in front of the AUT ~~test antenna~~ should not intercept any energy contained in the main lobe of the range ~~source~~ antenna. It is suggested that the first null in the radiation pattern, located at the angle α_h as shown on Figure 3, of the range ~~source~~ antenna be directed toward the base of the AUT ~~test antenna~~ tower. This leads to the imposition of a minimum-size restriction on the range ~~source~~ antenna shown in Equation (6). ~~, namely,~~

$$d \geq 1.5KD^2 / h_{\mathrm{r}} \tag{6}$$

where

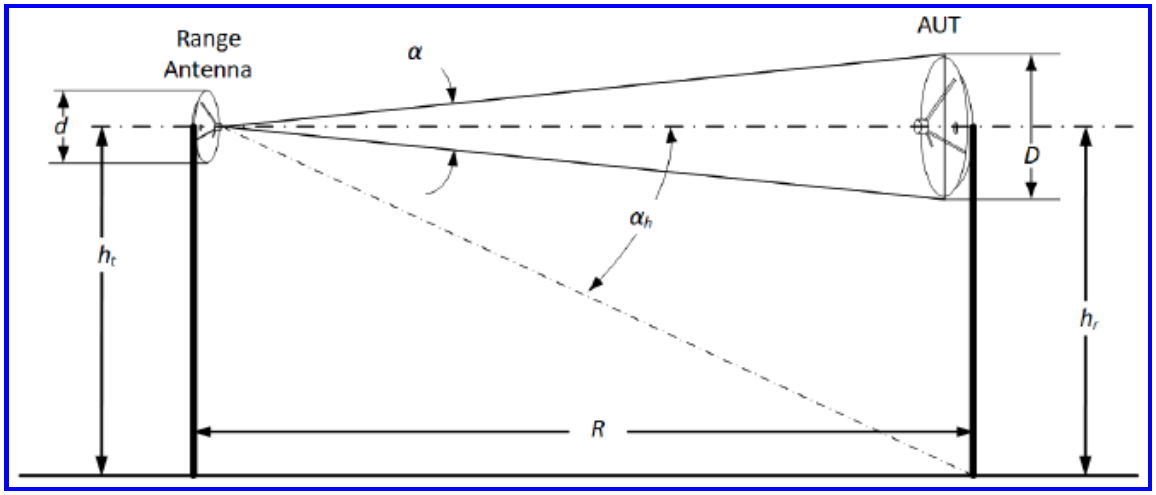
h_{r} is the height of the AUT ~~receiving antenna.~~

This result is based on ~~upon~~ the fact that typical range ~~source~~ antennas have a main-lobe width of approximately $3\ \lambda / d$ radians ~~rad~~. A comparison of the two criteria for the diameter of the range ~~source~~ antenna shows that the height of the AUT ~~test antenna~~ should satisfy the inequality shown in Equation (7).

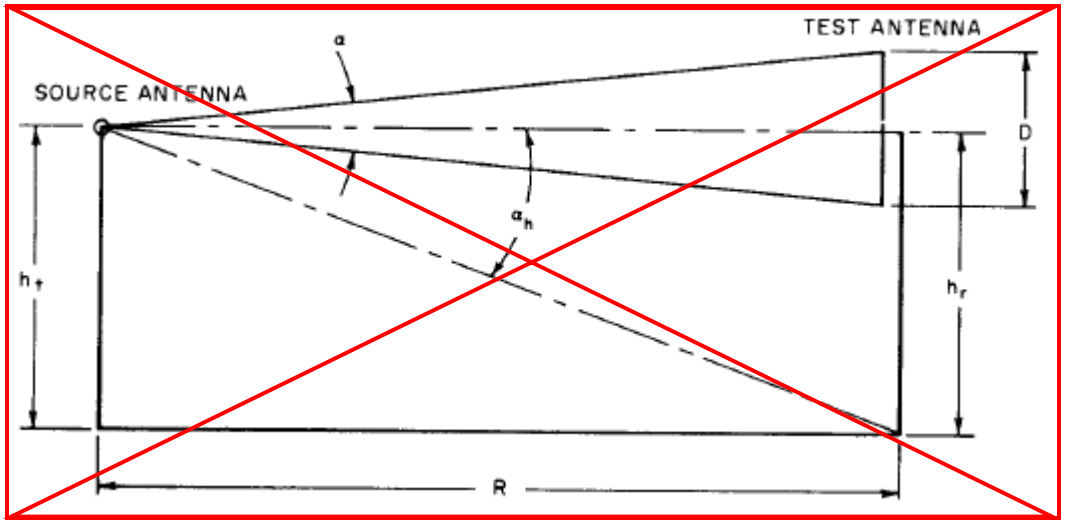
$$h_{\mathrm{r}} \geq 4D \tag{7}$$

~~where D is the diameter of the antenna under test.~~ The range ~~source~~ antenna should be elevated to the same height as the AUT, hence the range antenna height, h_r should be equal to the height of the AUT h_r ~~test antenna~~. For physically small antennas this requirement is easily met. However, as the AUT's ~~antenna's~~ size is increased, it becomes more difficult, and in some cases impractical, to satisfy.

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Figure 3 —Elevated range geometry

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4.3.3 Elevated ranges over irregular surfaces

Elevated ranges are often designed over irregular terrain, for example, between two adjacent mountain peaks or perhaps between two hilltops. Such ranges are useful for the testing of physically large antennas. For these ranges, the location of the points of specular reflection, which reflect energy toward the AUT ~~test antenna~~, may not be immediately obvious. When designing these ranges, it is usually necessary to construct a scaled drawing of the vertical profile of the range, showing the exact ground contour (Moeller [B133]) ~~[8]~~ from data obtained from the geological survey ~~U.S. Geological Survey~~ map of the area. These maps often give detailed information on the topography of the ground by means of regularly spaced contour lines ~~plotted every 20 ft~~ in elevation above sea level, which should be adequate for ranges operating as high in frequency as ultra-high frequency (UHF). For microwave frequencies it may be necessary to locate the points experimentally using directive antennas ~~(see Section 6.)~~. Once the points of specular reflection are determined, the level of the reflected energy at the AUT ~~test antenna~~ can be estimated (Moeller [B133]) ~~[8],~~ and corrective measures can be taken if the level of reflected energy is excessive. For these ranges, the restriction on the height of the AUT ~~test antenna~~ is removed, since the mountain itself is part of the test-antenna tower.

4.3.4 Estimation of errors due to reflections

A reflected signal will interfere with a direct-path signal and create an interference pattern with a certain peak-to-peak amplitude error bound. The ratio between the direct path and the reflected path signal is given by Equation (8), which is presented in Hollis, Lyon, and Clayton [B84].

$$\frac{E_R}{E_D} = 20\log_{10}\left(\frac{-1+10^{\sigma/20}}{1+10^{\sigma/20}}\right) \text{ (in dB)} \qquad (8)$$

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where

E_R is the amplitude of the reflected signal

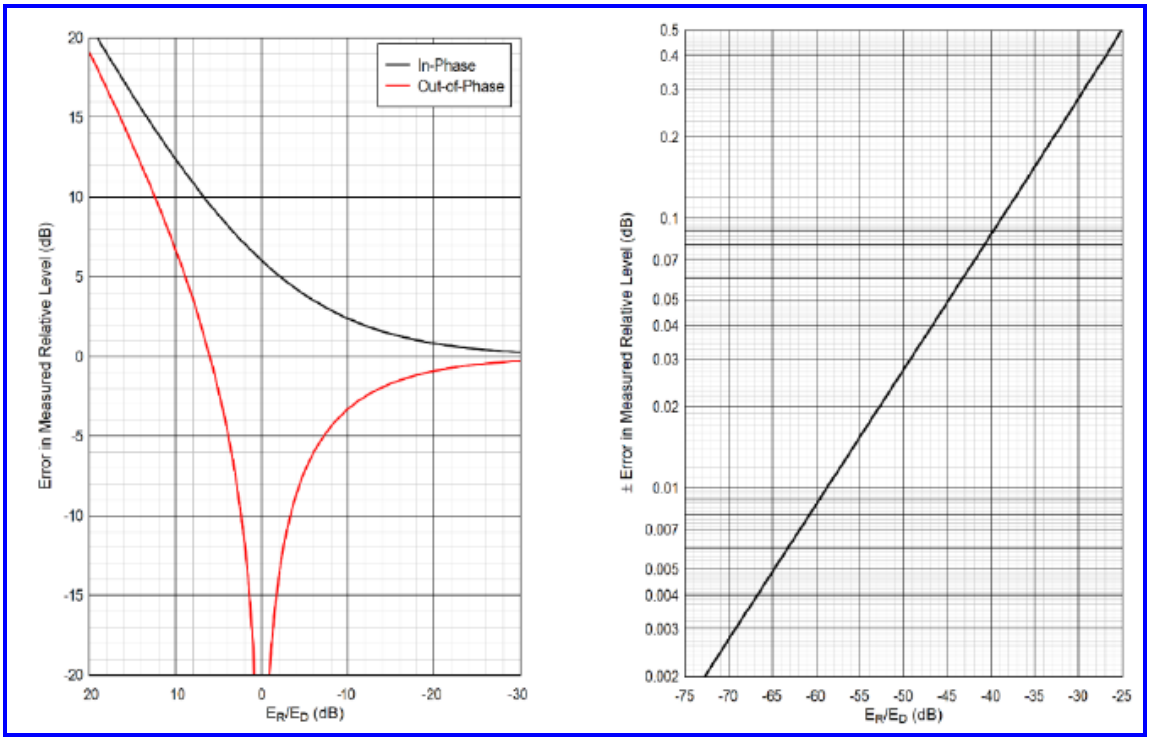
E_D is the amplitude of the direct signal

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σ is the difference in dB between the maxima and the minima of the interference pattern

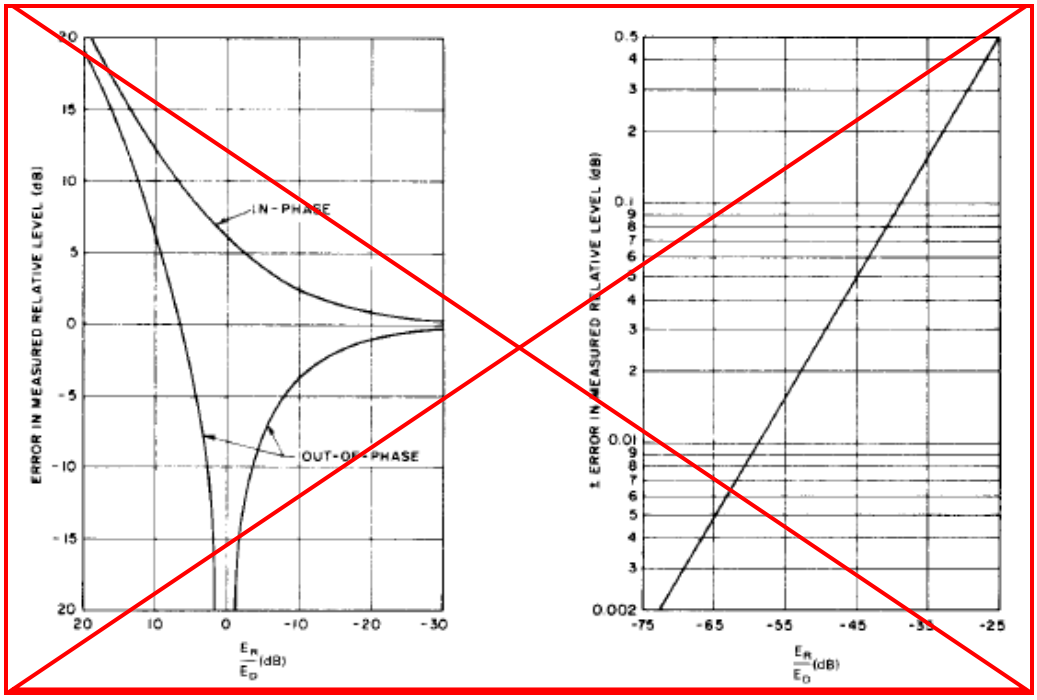
To illustrate the effect of reflections on the measured radiation patterns of an AUT ~~a test antenna~~, consider the following examples. Suppose that the nominal radiation pattern ~~side lobe~~ levels for the elevated range on Figure 3 are such that ~~of~~ both the range antenna ~~source~~ and AUT radiate ~~test antennas are~~ 25 dB below their respective maximum levels to a point on the range surface half-way between the two antennas. Assuming that ~~and~~ the range surface produces a 10 dB attenuation of the reflected wave, ~~,~~ then the extraneous signal level reaching the AUT from the reflection off the ground will be approximately 60 dB below the direct-path signal level for the case where the main lobe of the AUT ~~test antenna~~ is pointing toward the range ~~source~~ antenna. Figure 4 illustrates ~~The graph of Fig 5 can be used to determine~~ the possible error in the relative amplitude pattern of the AUT ~~test antenna~~ due to this reflected signal (Hollis, Lyon, and Clayton [B84]). Figure 4 ~~Fig 5~~ shows that the measured value of the peak of the beam will be in error by less than 0.01 dB. However, if the peak of the main lobe of the AUT ~~test antenna~~ is pointed toward the range surface and a −25 dB sidelobe is directed toward the range ~~source~~ antenna, the relative level of the extraneous signal will be only 10 dB below the level of the direct-path signal, and the measurement error is −3.3 dB to +2.4 dB. This example illustrates the fact that it is never advisable to direct the main beam of the AUT ~~test antenna~~ toward the ground when measuring sidelobes. The operational procedure for the range should be planned in such a way as to ensure that this does not happen. A means of rotating the AUT ~~test antenna~~ through at least 180° about the axis of the main lobe should be provided for this purpose, thereby allowing the same sidelobe measurement with the main beam pointed elsewhere along a horizontal plane.

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Figure 4 — ~~Possible~~ Error bounds in measured relative pattern level due to coherent extraneous signals. ~~Linear Scales Are Employed~~ For signal ratios from ~~of~~ +20 dB to −30 dB, ~~;~~ the graph on the left plots the error in dB on a linear scale. For signal ratios below ~~Plus-or-Minus *Errors Are Essentially Equal* for Ratios of~~ −25 dB ~~or Less~~, ~~as Indicated in~~ the in-phase and out-of-phase errors have essentially the same magnitude in dB and are plotted on a logarithmic scale to illustrate the errors ~~Plot~~ for ratios down to −75 dB.

More details are provided in Clause 6 about the measurement of the interference pattern as part of the range evaluation discussion.

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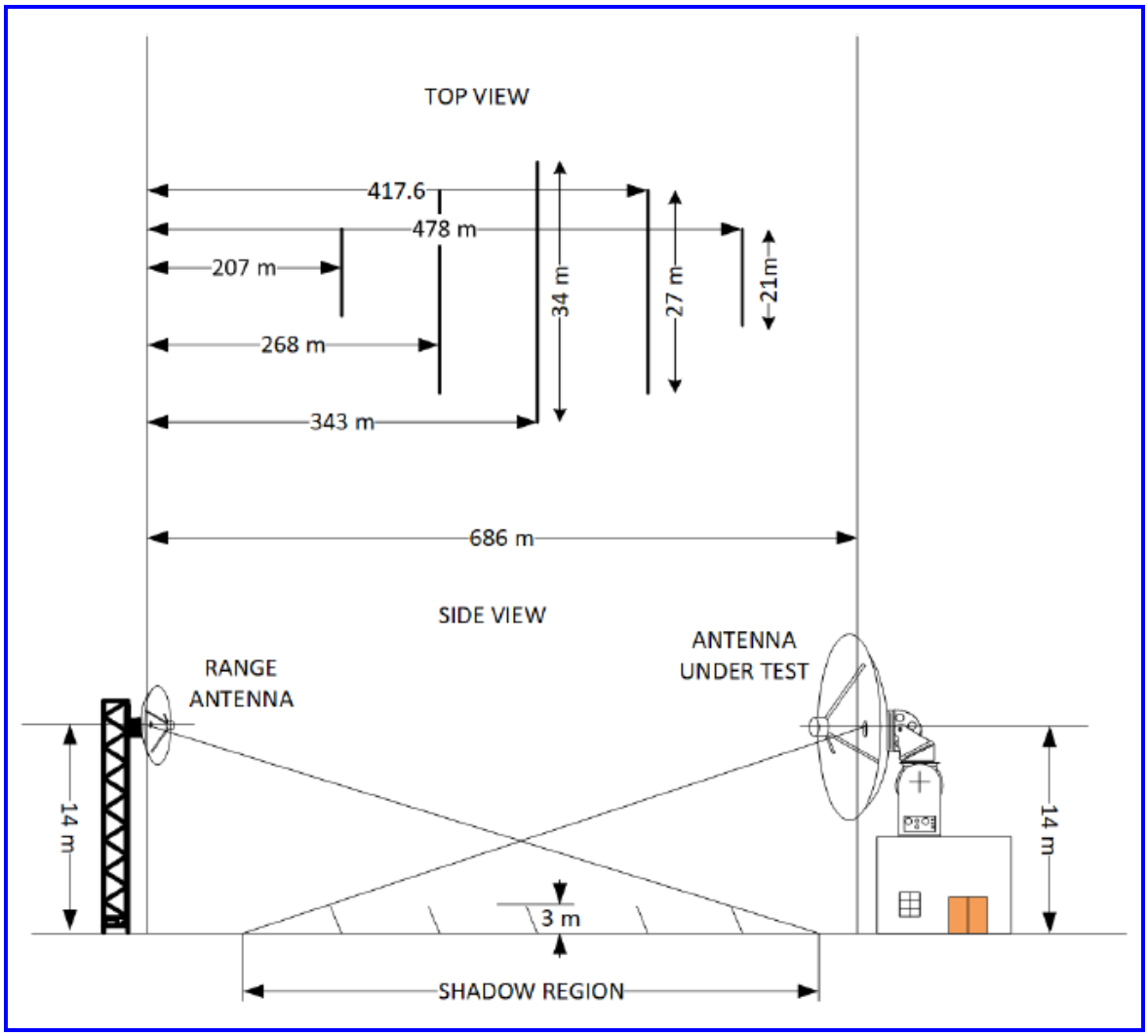
4.3.5 Use of diffraction fences and longitudinal ramps to redirect reflected energy

When the AUT ~~antenna under test~~ is essentially omnidirectional or when the required measurement calls for extremely small errors, then other means of suppressing the reflected signal could ~~will~~ be required. Two methods that ~~which~~ have found wide usage are diffraction fences and longitudinal ramps (Hollis, Lyon, and Clayton [B84]) ~~[1, pp 14.28–14.37]~~.

Diffraction fences are metallic screens that ~~which~~ are strategically located on the range in such a manner as to redirect, from the AUT ~~antenna under test~~, a portion of the energy that would, in the absence of the fence, be reflected from the range surface toward the AUT ~~test antenna~~. Diffraction fences may ~~can~~ be of simple wooden frame construction covered with an ordinary conducting screen that has a mesh size of approximately 0.1 wavelength or less. When designing diffraction fences, care should ~~shall~~ be exercised to reduce the diffraction by their top edges. The effect of this diffracted field can be estimated by means of the theory of Fresnel diffraction by a half-plane. This leads to a result given in terms of Fresnel integrals, which are usually presented in graphical form as Cornu's spiral (Hollis, Lyon, and Clayton [B84]). The fences should be designed and located in such a way that they will not be illuminated by the main lobe of the range ~~source~~ antenna. Thus, it might be desirable to use several fences, each with a lower height than if a single fence were used. Additional suppression of the diffracted field can be achieved by installing either tuned slots or serrations on the top edge of the fence. Tuned slots are more effective; however, they are frequency sensitive. The fences should also be tilted, especially if multiple fences are used, to suppress multiple reflections.

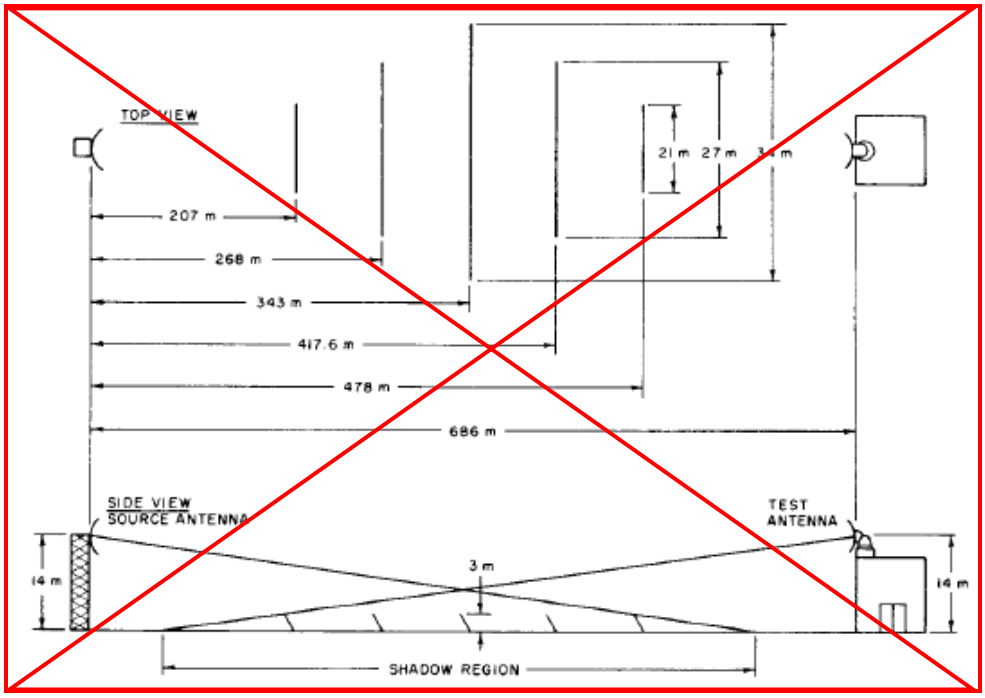
It is recommended that ~~The necessary width of~~ the fence widths ~~fences has been empirically determined to~~ span approximately 20 Fresnel ellipses ~~zones constructed~~ on the range surface. A possible diffraction-fence configuration for the 686 m ~~meter~~ elevated antenna range is shown in Figure 5 ~~Fig 6~~, and a sketch of a typical diffraction fence with serrations is shown in Figure 6 ~~Fig 7~~. ~~To save in cost, all fences are usually made identical in shape.~~ The actual number of fences required, and their positions and orientation, should be determined experimentally ~~(see 6.2)~~.

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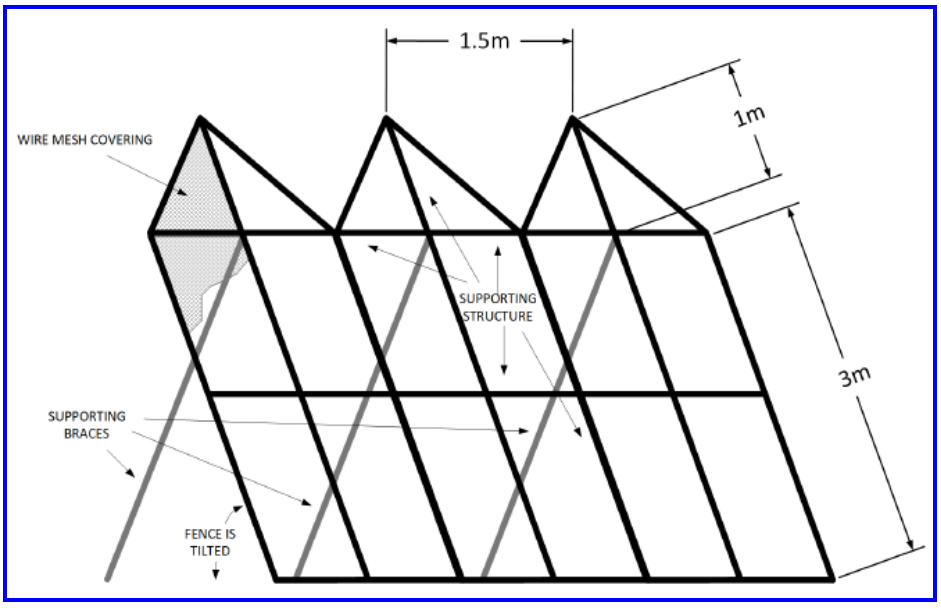
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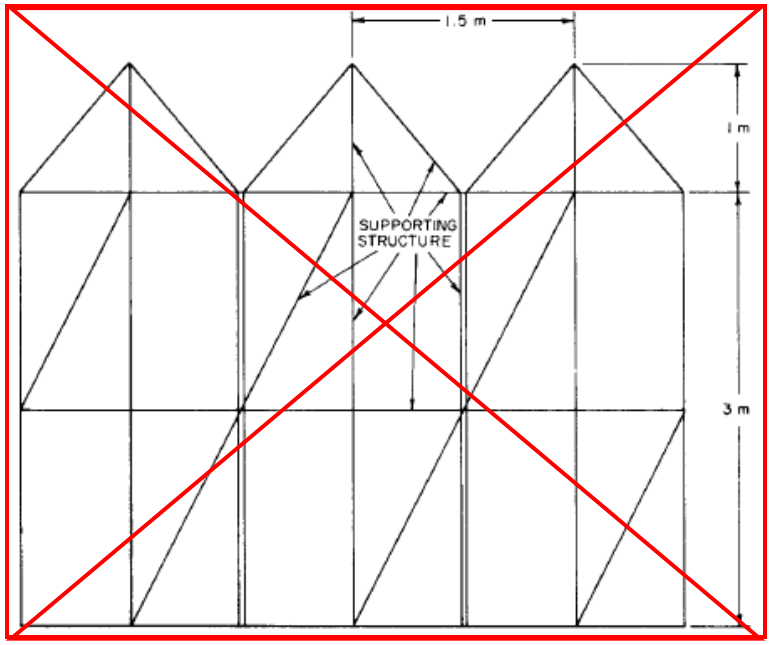
Figure 5 —Example [configuration](#) ~~Configurations~~ of a 686 [m](#) ~~Meter~~ elevated range with diffraction fences



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Figure 6 —Example configuration of a diffraction fence with serrations. All lines indicate supporting structure; partially ~~Not~~ shown is the wire-mesh covering.

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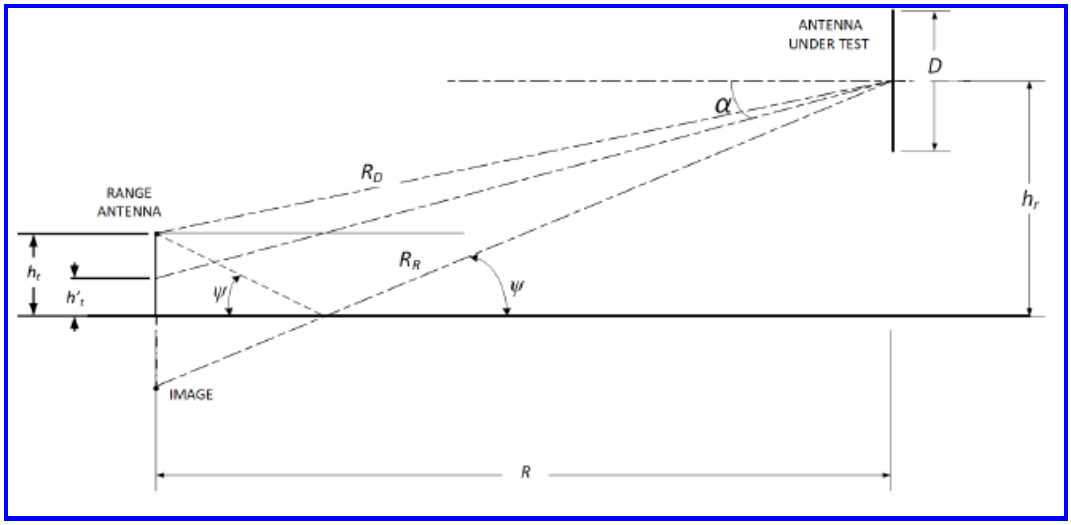
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A *longitudinal ramp* is a wedge-shaped reflecting surface symmetrically placed on the ground with its apex parallel to the range axis. Its purpose is to scatter the incident energy away from the AUT ~~test antenna~~. It can provide a moderate suppression of reflected energy at the AUT ~~test antenna~~; but generally, it is less effective than a diffraction fence. Ideally, the width of the base of the ramp should be such that it spans about 20 Fresnel ellipses ~~zones~~ as laid out on the ground surface between the range antenna ~~source~~ and AUT ~~test antennas~~. The apex angle is usually chosen to be about 120°. For many situations, these dimensions yield a prohibitively large structure, and a compromise is required, thus reducing the effectiveness of the ramp. For those ranges where the grazing angles of the incident energy are very small, more Fresnel ellipses ~~zones~~ are spanned by a ramp of a given size. Hence for these ranges ~~one would expect~~ the ramp would be expected to be more effective. Another design factor is the construction of the apex itself. Generally, it is necessary to round it off rather than having it as a sharp edge. This results in a degradation at the higher frequencies. An obvious disadvantage of the ramp is that it fixes the range axis. If either the range ~~source~~ antenna or the AUT ~~test antenna~~ is moved in the transverse direction, the symmetry of the range is destroyed, and the unwanted reflected energy level at the AUT ~~test antenna~~ increases. It is recommended to install ~~If~~ the antenna towers on a fixed rail system to control ~~range has permanent tracks installed for the~~ longitudinal motion and reduce the possibility of transverse motion ~~the antenna towers, then this is of little concern~~.

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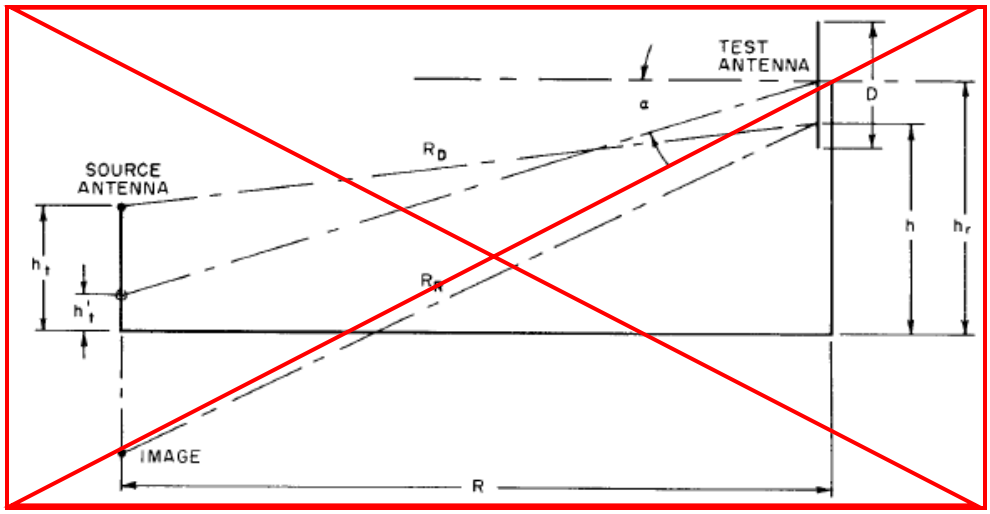
4.3.6 Design of ground-reflection ranges

In contrast with elevated ranges that attempt to move the specular reflection region out of the range antenna's main beam, ground-reflection ranges are constructed with the range antenna much closer to the range surface in order to intentionally achieve near-grazing geometry. The grazing angle ψ, shown in Figure 7 [an improved version of Figure 8 from IEEE Std 149-1977], is the angle an incident ray makes with the horizontal that should ~~The grazing angle ψ shall~~ be kept small in order to avoid operating at the Brewster angle, which occurs at approximately 14° ~~(measured from the horizontal)~~ over land (Jordan and Balmain [B103]) ~~[11]~~. As the Brewster angle is approached, the magnitude of the reflection coefficient of the flat range surface decreases to a low value for waves that are vertically polarized, whereas the reflection coefficient for horizontal polarization is unaffected. This is undesirable if the range is to be used for both polarizations ~~(see 6.4)~~. It should be noted that the Brewster angle depends on ~~is dependent upon~~ the electrical ~~electric~~ properties of the material used in the construction of the range surface (and subsurface). For example, if the range surface is ~~were~~ water~~,~~ then the Brewster angle can vary from 1° ~~would decrease~~ to 6° depending on the salinity and frequency of operation (Milligan [B132]; Reed and Russell [B156]) ~~approximately 4° [12]~~. In order for the polarization characteristics to be about the same as those for a range over land, the grazing angle would ~~shall~~ be correspondingly smaller. This usually means that the length of the range should ~~would have to~~ be increased.



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Figure 7 —Ground reflection range geometry

For the ground-reflection range, the amplitude taper of the illuminating field at the AUT ~~test antenna~~ in the horizontal direction will be the same as for the elevated range, and the criterion for the range ~~source~~ antenna size applies (see 4.3.2).

In the vertical direction, the reflected signal from the surface between the antennas combines with the direct signal to form an interference pattern (see Figure 7 ~~Fig 8~~). ~~By an adjustment of the height of the source antenna,~~ The first interference lobe should ~~can~~ be peaked at the center of the AUT (Cutler, King, and Kock [B48]), by an adjustment of the height of the range antenna ~~test antenna [4]~~. For a given frequency the height of the range ~~source~~ antenna h_t is given approximately by Equation (9).

$$h_t \approx \frac{\lambda R}{4h_r} \tag{9}$$

~~where h_t is the height of the test antenna.~~ The expected field at the AUT depends on ~~test antenna will be dependent upon~~ the complex reflection coefficient of the reflecting surface. In designing a ground reflection range, an attempt should be ~~Attempts are~~ made~~, in the design of these ranges,~~ to make the magnitude of the reflection coefficient approximately equal to 1.

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