



IEEE Recommended Practice for Radar Cross-Section Test Procedures

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IEEE Antennas and Propagation Society

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Antennas and Propagation Standards Committee

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IEEE Recommended Practice for Radar Cross-Section Test Procedures

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

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Abstract: The process of the measurement of the radar cross section of objects using a test range is described in this recommended practice. The term *radar cross section* (RCS) is defined, and the characteristics of different types of test ranges are given. The responsibilities of the test range operators are shown to involve test and calibration of the measurement range systems and to take the measurements accurately. Techniques are described for each stage of this process.

Keywords: compact range, dynamic test range, elevated range, error, ground-plane range, IEEE 1502™, inverted-V range, near-field non-anechoic range, radar cross section (RCS), radar test range, RCS measurement, spherical-wave anechoic chamber, tapered chamber, uncertainty

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Introduction

This introduction is not part of IEEE Std 1502-2020, IEEE Recommended Practice for Radar Cross-Section Test Procedures.

The measurement of radar cross section began to be a very important science in the 1960s and 1970s. Many test ranges were designed and built during that time. In the 1980s and 1990s, radar cross-section test ranges and the procedures to test, calibrate, and use them remained individualized. The operators of each test range used practices developed by the scientists and engineers that designed the test ranges. This recommended practice for radar cross-section test procedures is an attempt to provide a standard of practice across this community. It is developed for the test-range operator, the test-range manager, and users of test-range data.

The IEEE Standards Board first approved this recommended practice as a new project on 20 March 1997. The original standard was first updated in 2007, and the current revision is the second update.

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IEEE Recommended Practice for Radar Cross-Section Test Procedures

1. Overview

1.1 Scope

This recommended practice establishes processes for the measurement of the electromagnetic scattering from objects. It is written for the personnel responsible for the operation of test ranges and not for the design of such ranges. It recommends procedures for testing and documenting the quality of the measurement system, for calibrating the measurement system, for carrying out the radar scattering measurements, and for delivering the measurement data in a useful format to the end user.

The document defines radar cross section (RCS), describes different types of test ranges, and reviews methods of characterizing and operating radar scattering measurement ranges. Issues related to test-object support systems, types of test ranges, instrumentation, signal polarization, calibration, data analysis, and range uncertainty are also discussed.

1.2 Purpose

Although many RCS measurement ranges are built for specific localized purposes (for example, airplane measurements) and methods of characterizing the ranges and performing the measurements are developed for the specific needs of each particular test range, many other objects are measured nowadays, and the corresponding ranges are probably not dedicated to a specific class of objects. Consequently, this recommended practice is intended to establish guidelines so that operators and users of RCS ranges can provide results that are useful across a larger community of users

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}

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.

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).

2. Normative 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.

IEEE Std 145™-2013, IEEE Standard for Definitions of Terms for Antennas. ^{3, 4}

IEEE Std 149™, IEEE Standard Test Procedures for Antennas.

IEEE Std 211™-2018, IEEE Standard Definitions of Terms for Radio Wave Propagation.

3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. IEEE Std 145-2013, IEEE Std 211-2018, and the *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause. ^{5, 6}

radar cross section (RCS): A measure of the reflective strength of a radar target, usually represented by the symbol σ and measured in square meters. RCS is defined as 4π times the ratio of the power per unit solid angle scattered in a specified direction to the power per unit area in a plane wave incident on the scatterer from a specified direction. More precisely, it is the limit of that ratio as the distance from the scatterer to the point where the scattered power is measured approaches infinity. Three cases are distinguished as follows:

- a) Monostatic or backscatter RCS: The incident and reflected scattering directions are coincident but opposite in sense.
- b) Forward-scatter RCS: Energy is reflected or scattered in the same direction as the incident wave.
- c) Bistatic RCS: Energy is reflected or scattered in any direction other than the incident direction or the opposite of the incident direction.

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⁵ Information on references can be found in Clause 2.

⁶ *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.

The radar scattering cross-section σ is given by the relationship:

$$\sigma = 4\pi \lim_{R \rightarrow \infty} R^2 \left[\frac{|E^s|^2}{|E^i|^2} \right]$$

where R is the distance between the target and the receiver, E^s is the scattered electric field from the target, and E^i is the incident electric field on the target. (IEEE Std 686TM-2017)

NOTE 1—See IEEE Std 686-2017 [B31].⁷ If not identified, RCS is usually understood to refer to case a). In all three cases, the RCS of a specified target is a function of frequency, transmitting and receiving polarizations, and target aspect angle (except for a sphere). For some applications, (e.g., statistical detection analyses), it is described by its average value (or sometimes its median value) and statistical characteristics over an appropriate range of one or more of those parameters.⁸

NOTE 2—For radar scattering cross-section σ , see (Maffett [B53], Ruck et al. [B64]).

target: Specifically, an object of a radar search or track function. More broadly, any discrete object that scatters energy back to a radar.

3.2 Acronyms and abbreviations

CDF	cumulative distribution function
CPS	complex polarimetric scattering
CW	continuous wave
dBsm	decibels with respect to a square meter
DR	dynamic range
EM	electromagnetic
EMI	electromagnetic interference
EPS	expanded polystyrene
FFT	fast Fourier transform
FM	frequency modulated
GTD	geometrical theory of diffraction
IF	intermediate frequency
ISAR	inverse synthetic aperture radar
MOM	method of moments

⁷ The numbers in brackets correspond to those of the bibliography in Annex A.

⁸ Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

PDF	probability density function
PO	physical optics
PSF	point-spread function
PTD	physical theory of diffraction
RAS	radar absorbing structure
RCS	radar cross section
RF	radio-frequency
RMS	root mean square
RSS	root sum square
SNR	signal-to-noise ratio
SSE	sum of squared estimate of errors
SSR	sum squared of residuals
UHF	ultra-high frequency
VHF	very high frequency

4. Radar cross-section measurement process

4.1 Introduction

Radar scattering is typically represented as the RCS of the test object. The term RCS evolved from the basic metric for radar scattering: the ratio of the power scattered from an object in units of power per solid angle (steradians) normalized to the plane-wave illumination in units of power per unit area. The RCS is thus given in units of area (or effective cross-sectional area of the target, hence the name). Note that the RCS of the test object is a property of the test object alone; it is neither a function of the radar system nor the distance between the radar and the test object, as long as the object is in the far field. Because the RCS of a target can have large amplitude variation in frequency and angle, it is expressed in units of decibels with respect to a square meter and is abbreviated as dBsm (sometimes DBSM or dBm²). In terms of this definition, the RCS of a radar target is a scalar ratio of powers. If the effects of polarization and phase are included, the RCS can be characterized by the complex polarimetric scattering (CPS) matrix, which is based on one-half the real part of the complex Poynting vector. The CPS is proportional to a Hadamard product of a 2×2 matrix of the real-valued RCSs corresponding to each of the four combinations of transmit-receive polarizations and a 2×2 matrix of the complex exponentials associated with the phases of the scattered fields for the same combinations of both polarizations (Bhattacharyya, Sengupta [B6], Ruck [B64]).

The measurement of the RCS of a test object requires the test object to be illuminated by an electromagnetic (EM) plane wave and the resultant scattered signal to be observed in the far field. After calibration, this process yields the RCS of the test object in units of area or the full scattering matrix (Ruck [B64]) as a set of complex scattering coefficients.

The responsibilities of the range operators from the perspective of this document are listed as follows:

- Understand electromagnetic safety requirements (IEEE Std C95.1™-2019 [B33]);
- Establish and document procedures for performing test measurements and follow those procedures;
- Conduct radar scattering measurements;
- Process the raw measurement data for quality assurance and measurement reporting;
- Calibrate the system to obtain data in standard units of RCS;
- Establish the overall accuracy of the measurement range (the error bars on the RCS measurements);
- Determine the accuracy of the measurement instrumentation;
- Determine the quality of the illuminating plane wave;
- Determine the accuracy of the calibration reference standards;
- Deliver the data and documentation to the end user in a usable format.

4.2 Radar cross-section measurement background

4.2.1 Measurement history

Radar reflectivity measurements go back to the earliest days of radar. What are now known as RCS measurements began to be more openly discussed in the literature in the late 1950s and early 1960s (Bachman [B3], Cummings [B13], Currie, Curie [B15], Johnson et al. [B38], Kennedy [B40], *Proceedings of the IEEE* [B60]), although much of that work was under the auspices of the military and thus not readily available. This situation began to change with the 1965 publication of a Special Issue of the *Proceedings of the IEEE* [B61], which concentrated on topics associated with radar reflectivity. Several of the 1965 papers in this issue specifically focused on the requirements of RCS measurements, including an overview of the state of the art in RCS measurements (Blacksmith et al. [B7], [B8]). In addition, this issue included papers on range requirements (Kouyoumjian, Peters [B50]), target support issues (Freeny [B26]), measurement techniques (Bachman [B3], Huynen [B29]), and discussions of typical facilities, both static (Marlow et al. [B54]) and dynamic (Olin, Queen [B59]). With the publication of this issue, a growing open-source literature base on RCS measurements became available to practitioners in the field.

The ensuing period marked the beginnings of two measurement trends: the rapid development of new approaches to making measurements, and measuring targets with low RCS. There was a major push to reduce significantly the radar scattering from military vehicles. Along with the objective to produce vehicles with reduced RCS came the requirement to measure these smaller signal levels accurately. In addition, many applications required the full complex polarimetric scattering matrix. Thus, significant efforts were made to improve the technology of RCS measurements, including increasing the dynamic range of the measurement system and adding complex phasor measurements.

During this same time period, significant research was being conducted on the theory of electromagnetic scattering. Universities such as Syracuse University, the University of Michigan, The Ohio State University, and the Georgia Institute of Technology were engaged in understanding the foundations of scattering, with the objectives of taking better measurements and being able to predict analytically and numerically the scattering from increasingly complex objects. During this period, increased computational power allowed tools like the method of moments (MOM) (Harrington [B28]), the geometrical theory of diffraction (GTD) (Keller [B39]), physical optics (PO) (Ufimtsev, Senior [B69]), and the physical theory of diffraction (PTD) (Ufimtsev [B68]) to be used for realistic scenarios. These developments were

significant for the measurement process, because calibration methods of that time period required the ability to predict the scattering from calibration targets to a high degree of accuracy. Furthermore, significant progress in RCS reduction required improvements in theory, prediction, and measurement. Despite the fact that the technical community had made great strides in its ability to perform RCS measurements, some areas still required improvement. Among these areas were the needs for community-wide recognized reference standards that could be used for calibration of RCS measurements and for a readily available standardized process for measuring RCS. Although no internationally accepted set of RCS procedures for characterizing the performance of an RCS measurement range existed, Clause 7 of this revision provides guidance to organize the documentation for the operation and characterization of a range in accordance with ANSI/NCSL Z540.3-2006 [B2] and ISO/IEC 17025:2017 [B34]. These developments led to IEEE Std 1502™-2007 [B32], which is updated herein. Alternately, some modern users of RCS ranges are not using the ANSI and ISO standards exclusively; instead, they are providing a good uncertainty evaluation for each RCS measurement, because they have assessed that it should be more important than characterizing range performance.

Sustained research on theoretical and computational electromagnetics over the last 30 years has led to advancements of earlier methods and the significant development of sophisticated commercial software packages. This document updates the 2007 standard to reflect improvements in numerical tools and measurement technology. Discussion topics include measurement standards, procedures, and practices. Before measurement standards, procedures, and practices are discussed, it is important to understand the origin of the requirements, which is addressed in 4.2.2.

4.2.2 RCS measurement requirements

The facility used to verify RCS values should have the capability to measure RCS values that are 10 dB to 20 dB below the lowest scattering level to be encountered while illuminating an area that is the full size of the test object under test. These figures—while not a hard requirement—are used in practice to establish an adequate signal-to-noise ratio (SNR) for typical measurements. For measurements requiring more precision, higher SNR values will be required.

Although these capabilities should be achievable with the current state of the art, care should be taken to achieve accurate and repeatable results. Obvious questions include:

- How is the RCS test-range accuracy defined?
- How close to the exact value does the measured value have to be?
- How is the exact value defined?
- When is a measurement considered repeatable?

These questions and others should be addressed to develop standards and standardized practices.

4.2.3 Need for a standardized RCS measurement process

Making RCS measurements will likely always be as much an art as it is a science. Each measurement facility is unique in terms of layout, equipment, capabilities, etc. Training at each facility varies, based upon the perceived needs of the facility. The targets being measured can vary from test to test. Without a recognized standard for RCS measurements, each range should independently determine how it might help ensure that measured results are accurate, repeatable, and verifiable, especially for dynamic measurement scenarios that require careful planning of flight programs to a target, the range geometry, and the tracking capability of the instrumentation system. Recognized standard procedures for RCS measurements, measurements of reference targets, and inter-comparisons of the measurements of the same targets in different ranges help ensure that test measurements are accurate within stated uncertainties.

4.2.4 Developing a standardized RCS measurement process

The remainder of this clause is devoted to laying out procedures and practices that make up a standardized RCS measurement system. The first requirement is to define the RCS measurement process. Key issues are the proper characterization of the range and its environment, the development of a range uncertainty budget, and an examination of the issues associated with calibrating the RCS measurements. Finally, an approach to implementing these standards is provided.

4.3 Standardized test procedures

4.3.1 Purpose

The development of standardized test procedures provides a framework for many components of the measurement process. Important components of the measurement process that are to be standardized include the following:

- Data collection
- Range calibration
- Post-processing
- Range characterization
- Range error budget

By developing standardized procedures for these and other components of the measurement process, several advantages can be realized. One important advantage is that the technical approach will be consistent from range to range, which means that users of the data know what to expect during the testing process. Preparation for additional measurements or follow-on tests is easier, and it becomes significantly easier to make comparisons between ranges. This last point should not be minimized. This type of comparison is often desired, but usually it is not carried out because the procedural differences between ranges (even of the same type) are sometimes considered too great to overcome.

Another advantage that will result from standardization is a minimization of error, especially human error. By developing and following standardized procedures, there is less chance of incorrect procedures being used. It also helps in the verification process if standard procedures are followed at different ranges. By using the same basic procedures in multiple ranges, the experience base for that type of procedure is increased, which leads to greater confidence that the procedure is robust and will produce the correct results under a variety of circumstances. Finally, by using standardized procedures, there is less chance that the application of a particular process will be called into question if there is a problem (or legal challenge) with the results at a later date.

4.3.2 Approach

Since there are several types of ranges and many examples of each type, it is important to organize the test procedures to cover the unique features of each possible range type while maintaining as much commonality in procedures between the different range types as possible.

One way of accomplishing this goal is to identify the essential features of each range type and to decide which features are common to other range types and to what degree. Arranging the different range types in a hierarchical structure has several advantages. For instance, any procedures that apply to ranges at the “top” of the structure (the most common range features) should also apply to those “lower” in the structure (ranges with more specific features). This approach implies that test plans developed for higher levels can

be specialized for lower levels, which keeps the procedures used common to many different range types. This approach also minimizes the work required to develop test plans and facilitates comparisons among different ranges.

5. Measurement techniques

5.1 General

IEEE Std 149 should be consulted for antenna measurement procedures. The purpose of the test range is to provide an environment that simulates free-space, far-field conditions. Measurements of objects placed in these environments and obtained by precision instrumentation radars can yield accurate measures of their RCSs.

5.2 Outdoor ranges

5.2.1 Introduction

To approximate the desired free-space, far-field conditions in an outdoor environment, it is common to separate the source radar physically from the targets with “sufficient separation” in a measurement environment that is free of unnecessary monostatic and bistatic radar clutter. The approximation to a plane wave is obtained by the range length and the approximation to free space by the absence of spurious signals originating from clutter multipath that eventually propagates to the desired test zone as an undesired interference term. The amplitude field taper in the test zone is determined by the radiation pattern of the instrumentation radar; the phase taper is determined by the distance between the radar and the test zone; and the amplitude ripple is determined by interference with the direct signal caused by spurious reflections. In the special case of the ground plane range, which is described in 5.2.2, the amplitude taper in the vertical direction is also determined by the ground-bounce geometry. Given surrounding areas that are free of obstacles, the principal source of contamination to the incident field is the reflection from the ground surface. Consequently, the control of signal reflections from the ground surface constitutes the principal design objective of the range.

Several techniques are used for the control or mitigation of ground reflections. These techniques include utilizing reflecting or absorbing fences to shield the signal path directed to the ground bounce region, elevating the receiving and transmitting antennas sufficiently so that the ground bounce is outside the main lobe of the antenna, using shaped berms running the length of the range to deflect the ground reflection away from the test zone, and exploiting the ground bounce by combining with the direct signal in a constructive manner. Each technique is reviewed in 5.2.3 through 5.2.5. In addition to controlling the detrimental effects of ground reflections, significant range-geometry parameters that drive the performance of outdoor ground-plane ranges are phase and amplitude tapers in the test zone and range clutter, both of which are summarized in the following paragraphs.

For an outdoor range, the rule of thumb that the far field starts at a distance R of $2D^2/\lambda$ from the transmitting antenna, where D is the maximum dimension of the antenna and λ is the corresponding wavelength of the radiated signal, is not universally valid. Abdallah et al. [B1] and Hansen, Bailin [B27] show that this rule of thumb is only valid for antennas in free space where $D \gg \lambda$ and consequently is not applicable for antennas if D is comparable to λ . For this condition ($D \gg \lambda$), the antenna pattern in free space closely resembles that of an omni-directional antenna if $R < 0.62 (D^3/\lambda)^{1/2}$ (reactive near field) and begins to take shape if $0.62 (D^3/\lambda)^{1/2} \leq R \leq 2D^2/\lambda$ (radiative near field). Then, when $R > 2D^2/\lambda$, one is in the far field, and the antenna radiation pattern is generated. However, $D \geq 5\lambda$ is a less restrictive condition

for ensuring that the far-field criteria for free space are satisfied at distances that exceed $2D^2/\lambda$. Furthermore, when an antenna operates over the Earth, one must account for the height of the antenna over the ground and its image into the ground, which is related to the effective aperture size and not merely to the dimension of the antenna. Consequently, D must be interpreted correctly as the twice the height of the antenna above the Earth. Finally, the far-field distance also depends on the azimuthal angle at which this radial distance is considered. To generate a plane wave, the radial component of the field should be negligible compared to the transverse component. However at off-broadside angles, the radial component of the field tends to increase with distance and does not diminish until the observation point is quite far from the antenna, at a distance that can be tens of times larger than $2D^2/\lambda$.

The outdoor range should be long enough so that the spherical wave radiated by the antenna can be approximated by a plane wave in the test zone within acceptable phase-taper limitations across the target volume. A common upper bound on the acceptable phase taper is 22.5° ($\pi/8$) at the edge of the target zone. A spherical wavefront incident on a normal plane located a distance R from the source has an off-axis phase taper that varies with the lateral distance x from the incidence axis [Figure 1(a)]. The deviation $\Delta\theta$ from the incident phase θ for a lateral offset x is $(2\pi/\lambda)\Delta R = (2\pi/\lambda)[(x^2 + R^2)^{1/2} - R]$.

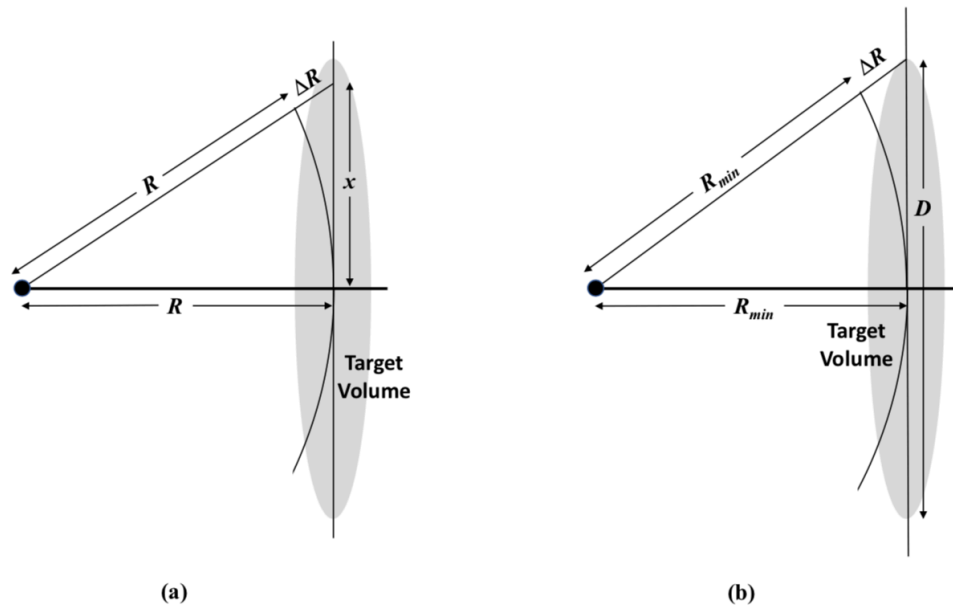


Figure 1—Geometry for plane-wave approximation of outdoor range

To determine the lower limit of the far field, consider the geometry in Figure 1(b). Since $R^2 + (D/2)^2 = (R + \Delta R)^2$, $D^2/4 = \Delta R(2R + \Delta R) \approx 2R\Delta R$ since $\Delta R \ll 2R$. Consequently, $\Delta R \approx D^2/(8R)$. To constrain the phase taper $\Delta\theta$ at the edge to a maximum of $\pi/8$ (22.5°), enforce the inequality $\Delta\theta = (2\pi/\lambda)\Delta R \leq \pi/8$, which implies that $2D^2/\lambda \leq R$. Consequently, the lower limit of the far field R_{min} with a desired maximum phase taper of $\pi/8$ over the extent D is shown in Equation (1):

$$R_{min} = 2D^2 / \lambda \quad (1)$$

When applied to RCS measurements, this relationship allows a maximum two-way phase taper of 45° . Although this criterion has been historically used as a general guideline for antenna and RCS measurements, some applications should require or tolerate different tapers. When the guideline is applied for measurements of large objects at high frequencies, the required range length should exceed the available real estate of the range, thus requiring a compromise. Consequences of larger phase tapers are

reductions in the magnitudes of specular peaks and increases in the sidelobe responses for near-specular angles. Because even moderate phase tapers strongly influence sidelobe levels, measurements of radiation patterns of low-sidelobe antennas should require that $R_{min} = KD^2/\lambda$ with $K > 2$. For RCS measurements, however, the levels of sidelobes surrounding specular peaks are of lesser interest, and greater phase tapers should be tolerated. In summary, although Equation (1) with $K = 2$ provides a general guideline, the allowable phase taper for a measurement should be determined for specific targets and test objectives.

The amplitude taper over the test zone is primarily a function of the antenna pattern of the measurement radar. The pattern of the illuminating antenna is selected such that the amplitude taper over the target zone is typically less than 0.5 dB at the highest operating frequency. As the frequency is reduced, the beamwidth of the antenna increases, and the amplitude taper is improved at the expense of illuminating additional clutter sources. In addition to the influence of the antenna pattern, the amplitude taper in the vertical extent of the test zone is influenced by reflections from the ground surface that interfere with the direct signal.

Several outdoor ground plane ranges are currently in use by the RCS measurement community. Typically, these ranges are located in remote and sparsely populated areas as a consequence of security and electromagnetic interference (EMI) considerations and economic factors like the cost of real estate. Subclauses 5.2.2 through 5.2.5 outline the significant parameters that govern the performance of various types of ranges.

5.2.2 Ground-plane ranges

In the presence of a ground plane, a target is illuminated by two distinct fields: one arriving directly from the transmitting antenna and the other via a reflection from the ground, constituting a multipath condition. Energy scattered by the target reaches the receiver by the same two paths, depicted in Figure 2 for a flat Earth. Rather than mitigating the effects of ground reflections, the design of the ground plane range uses the ground-reflected signal by arranging the target and antenna heights so that the signal reflected from the ground is approximately in phase with the direct-path signal. With this technique, the ground-reflected signal contributes to the target illumination in a controlled manner. In general, the ground-plane range produces an acceptable illumination field over the target that is large in the horizontal plane but limited in the vertical plane. The ground-plane geometry is an attractive choice for aircraft measurements where the target has large horizontal and small vertical dimensions.

The vertical amplitude taper in the test zone is primarily a function of the ground plane. The received signal power P_r of the illuminating monostatic radar for free space is given by the *radar transmission equation* (Skolnik [B65]) as shown in Equation (2):

$$P_r = (P_t G^2 \lambda^2 \sigma) / ((4\pi)^3 R^4) \quad (2)$$

where

- P_t is the transmitted power
- R is the distance from radar to target
- G is the radar antenna gain
- λ is the wavelength
- σ is the RCS of the radar target

When Equation (2) is rewritten to give an expression for R , it is called the *classical free-space radar range equation*.

If a smooth ground surface is illuminated by an antenna located at point A at height H_A , the incident field reflected from the specular point P on the ground, where α is the specular angle, joins the direct signal at the target located at point T at height H_T (Figure 2). The received scattered signal at A consists of the sum

of four distinct components traveling along paths *ATA*, *ATPA*, *APTA*, and *APTPA*. The first component (*ATA*) is the direct signal, the second (*ATPA*) and third (*APTA*) components undergo a single ground reflection from *P*, and the fourth component (*APTPA*) undergoes a double reflection from the ground. If the antenna gains in the direction of points *T* and *P* are identical and the target is an isotropic scatterer, the four components have equal magnitudes. Because the components add as field quantities, the effective RCS $\sigma_0^{1/2}$ is approximated by Equation(3):

$$\sigma_0^{1/2} = \sigma_0^{1/2} \left| e^{j2kD} + 2\rho e^{jk(I+D)} + \rho^2 e^{j2kl} \right| \quad (3)$$

where *D* is the distance between points *A* and *T* (direct path), *I* is the sum of the distances between *A* and *P* and between *P* and *T* (indirect path), ρ is the ground reflection coefficient, and *k* is the wavenumber $2\pi/\lambda$ (Maffett [B53]). Since the target scatterer is assumed isotropic, the intrinsic RCS $\sigma_0^{1/2}$ of the target is assumed to be the same for the direct and indirect paths. Readers may wish to consider carefully the ramifications of the idealized assumptions of identical antenna gains and target isotropy. For example, identical antenna gains may be questionable for broadband antennas. Moreover, the bistatic (*ATPA*, *APTA*) and monostatic (*ATA*, *APTPA*) scattering may differ significantly, even for small angles for many shapes.

Equation (3) can be rewritten as shown in Equation (4):

$$\sigma_0^{1/2} = \sigma_0^{1/2} \left| 1 + 2\rho e^{jk(I-D)} + \rho^2 e^{j2kl(I-D)} \right| \quad (4)$$

For a reflection coefficient of -1 , Equation (4) reduces to Equation (5):

$$\sigma_0^{1/2} = 4\sigma_0^{1/2} \sin^2 \left[\frac{k}{2}(I-D) \right] \quad (5)$$

The magnitude of the bracketed term, representing the enhancement factor or gain over the free-space field, has a maximum value of 4 for $(I-D) = m(\lambda/2)$, where *m* is a positive odd integer. From geometric considerations following the treatment by Knott [B48], Equation (5) for *m* = 1 leads to the relation shown in Equation (6):

$$H_A H_T = R\lambda / 4 \quad (6)$$

where *R* is the ground range between the radar and the target, shown in Figure 2.

The criterion of Equation (6) places the target at the center of the first of several vertically displaced multipath lobes, with the field falling to zero at ground level and at a height $2H_T$. Because the multipath lobe extends over twice the target height, the taper across a given target decreases with target height. The best amplitude taper in the vertical plane is therefore achieved when the target is mounted as high as possible and the instrumentation antenna is as low as practical while satisfying Equation (6). Since mounting large targets high in the air can be a difficult problem, practical trade-offs generally have to be made. It is common in outdoor ground-plane ranges to use truncated antennas for the higher frequencies. The top and bottom sections of a parabolic reflector are cut off to allow the antenna to be lowered closer to the ground to minimize the H_A term.

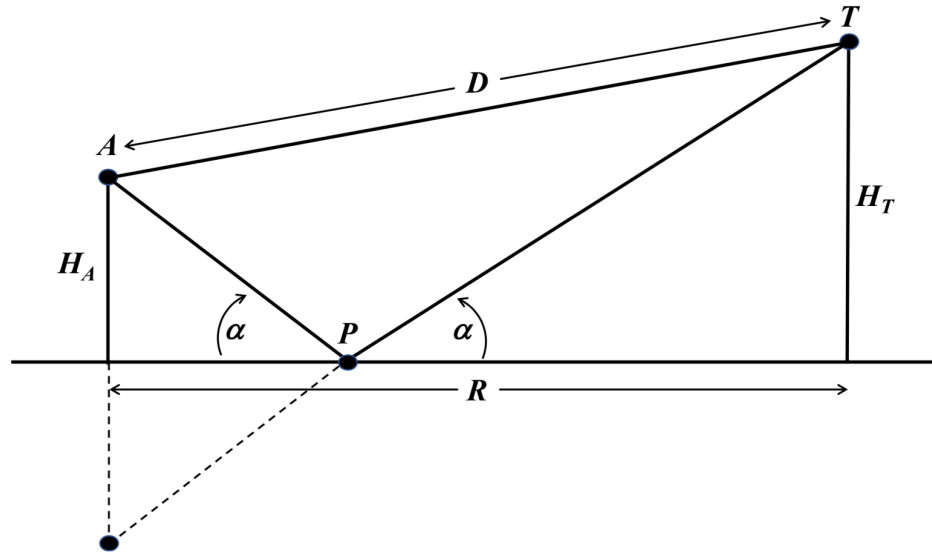


Figure 2—Geometry of signal paths for ground-plane range

The ground-plane geometry, arranged to maximize the received signal at the operating frequency as given in Equation (6), theoretically produces a 12 dB increase (two-way path) in the received signal over a free-space condition. This feature is an attractive advantage because it increases the achievable sensitivity for a given transmitted power. The advantage is somewhat offset by the center of the vertical lobe being frequency-dependent; achieving the limiting performance requires the antenna height to be adjusted with frequency, which is a condition of significance for wide-band measurements.

Modern RCS ranges generally require an imaging capability that represents inverse synthetic aperture radar (ISAR). Imaging requires a wide frequency band, which produces a wide variation in vertical taper. In this case, some trade-off in the taper of the vertical field should be made. A technique to minimize this effect is to use two or more antennas located at different heights and to switch the antennas electronically as the frequency is varied.

Because the ground-plane range inherently includes the strong illumination of the ground surface, irregularities of the surface in the vicinity of the specular point can scatter signals into the test zone and thus adversely influence the illuminating field by adding amplitude and phase uncertainties. To minimize the effects of this bi-statically scattered clutter, the surface is made as smooth as possible in the vicinity of the specular point. The elliptical region of the ground surface for which the phase of scattered signals is within 180° is termed a *Fresnel zone*; successive Fresnel zones form concentric elliptical footprints on the surface. The requirement for smoothness is most stringent for the central Fresnel zones and is less stringent for the outlying ones. A controlled surface spanning 15 to 20 Fresnel zones should be required with more stringent tolerances for the central zones and less stringent tolerances for the outer zones.

An additional consequence of the ground-plane range is the requirement to use separate test ranges for the different radar bands. This requirement is a consequence of practical antennas, the target, and antenna mounting heights. For example, if a given geometry has a range length of 914 m and a target height of 18 m, the antenna height for 12 GHz would be approximately 30 cm, but for 150 MHz, the antenna height would be 25 m.

5.2.3 Inverted-V range

The inverted-V outdoor range derives its name from a berm that runs along the center axis of the range and is shaped as an inverted-V. The antenna is centered over the apex of the berm at one end, and the target is centered over the berm at the other end.

The purpose of the inverted-V shaped berm is to scatter most of the ground reflected energy away from the target zone and thus substantially reduce the level of reflected energy. The sensitivity performance is predicted by the free-space radar range equation, which does not benefit from the ground-plane gain. The other sensitivity and performance parameters are essentially the same as the ground-plane range.

The field taper at the target zone is determined essentially by the antenna pattern, which allows the system to be operated over a wide frequency range while maintaining a uniform field over the target. The inverted-V berm adds significant cost to the range. To obtain satisfactory performance, the berm apex should be straight, and the sloping sides should be smooth. For best performance, the antenna needs to be centered over the V, and the operational bandwidth of the system should be obtained using only one antenna.

5.2.4 Elevated range

The elevated range concept requires that the antenna and target be mounted high enough to reduce the ground illumination to an acceptable level. The elevated range concept is used extensively for antenna measurement ranges but is rarely used for RCS measurements. Directive antennas should be mounted high above the ground on steel tower structures, and the main lobe should be measured with good accuracy. RCS measurements usually require the target to be mounted on a low cross-section support structure. It is difficult to design a tall support structure with low RCS.

5.2.5 Dynamic test range

Dynamic RCS measurements are made while the target is in motion. Although more complex and consequently more costly, this method is often the only practical measurement technique for some classes of targets. For example, it is difficult to mount a large operational aircraft on a low-RCS support without making major structural modifications to the aircraft. Large-dielectric foam column supports are often used, but changing the pitch and roll angles of such objects is then a difficult undertaking. Alternatively, some large anechoic chambers use slings for measuring large targets. Dynamic measurements have several significant benefits over static measurements because they include all contributors to the RCS such as engine plumes, rotating engine, and propulsion components. Far-field conditions are usually more achievable in dynamic systems, and scattering from support structures, typically the limiting factor in static measurements, is not present. The operational costs of performing dynamic measurements usually justify making the system multiband so that all measurements can be made with a minimum number of flights in the case of aircraft.

Dynamic measurement systems should rely on a system to track the target accurately and to provide the necessary angle and range information. The angle information (with appropriate parallax correction) is used to synchronize the instrumentation antenna pedestal(s) to the tracking radar to maintain the antenna beam patterns over the target, and the range information is used to position the range gate of the instrumentation system on the target echo.

Although measuring RCS as a function of aspect angle is readily accomplished on a static range, this task is considerably more difficult in dynamic measurements. For example, dynamic measurement scenarios of aircraft require careful planning of flight programs to ensure that all the desired aspects angles of the target are presented to the radar, which requires detailed knowledge of the flight characteristics of the target, the range geometry, and the tracking capability of the instrumentation system. The measurement radar will perform over a wide variation of ranges during a typical flight sequence; this broadband performance imposes a compromise for the selection of antennas to provide an acceptable taper at close ranges and system sensitivity at long ranges.

During the course of an RCS measurement, the dynamic system should also measure amplitude and phase, elevation and azimuth angles, and range as a function of time. To obtain the target aspect angle, these parameters should be merged with the target roll, pitch, and yaw data, obtained from the cooperative