MODERN ANTENNA HANDBOOK

Edited by

Constantine A. Balanis

WILEY

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To my teachers, students, colleagues, relatives and friends

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PREFACE

Antennas and antenna systems are the eyes and ears of wireless communication systems, which have experienced an unprecedented rapid expansion. Part of this advancement has been attributed to contributions of antenna technology. These wireless systems, no matter how simple or complex, cannot operate efficiently unless they utilize transmitting and receiving elements/antennas to efficiently radiate and receive the waves that carry the information. This is analogous to humans whose daily schedule and contributions are largely controlled by the efficiency of their eyes and ears.

The future of the communication systems is even more challenging, and their efficacy will depend on what we, as antenna engineers and scientists, can invent and contribute. In fact, some of the future services and performances of wireless communication may be dependant on and limited by antenna designs which will require our imagination and vision to push the outer limits of the laws of physics. For example, handheld mobile units, which in 2008 numbered nearly 1 billion subscribers, are ubiquitous from the smallest rural village to the largest urban city and provide numerous services, such as voice, video, email, news, weather, stock quotes, GPS, TV, satellite, wireless LAN, Bluetooth, WiFi, WiMax, Radio Frequency ID (RFID), and so on. In the very near future, the number of services will expand and the number of units will increase at an almost exponential rate as everyone, from the youngest to the oldest around the world, will possess one. To integrate all these services into a single unit, and to provide them reliably and efficiently, we must develop broadband antenna designs to accommodate these demands, while at the same time provide esthetic visualization of the devices. Using single antenna elements for each of these services will not “cut the mustard.” Therefore we are faced with unique challenges, and we must respond.

To meet the demands of this rapidly evolving technology, the *Modern Antenna Handbook* provides leadership towards these challenges, as seen by some of our visionary contributors. The handbook covers a wide range of topics, from the fundamental parameters of antennas to antennas for mobile wireless communications and medical applications. The information is practical in nature and is intended to be useful to practicing engineers and scientists, researchers, educators, consultants and students. There are a plethora of antenna elements and all could not be covered with some depth in a book with space constraints. Also, many antenna elements and designs are seen to be static and have been covered in other publications. We opted to include some of the classic antenna topics, to make the handbook self contained, and to focus more on contemporary topics and modern technologies, including wireless communication, materials and structures, techniques and computational methods relating to antennas. The 33 included chapters are all new, contemporary, provide breadth and depth, and are detailed. The chapters have been authored by 68 leading international experts who have contributed to the unprecedented advancement of antenna technology, and include coverage of current and future antenna-related vision.

Computational methods, which have been instrumental in the rapid evolutionary advancement of the modeling, simulation, animation, and visualization of antenna design, are an integral part of this handbook. In the past few years, Computational Electromagnetic Methods (CEM) have basically served as the working “slide rule” of the 1950s and 1960s. There is hardly any modern and efficient antenna design whose operation has not been influenced, modeled, simulated, and optimized using one or more computational methods. We expect that CEM will play an even bigger role in the future.

In addition to antenna topics, the handbook also covers modern and contemporary technologies such as metamaterials, micro-electromechanical systems (MEMS), frequency selective surfaces (FSS), radar cross section (RCS) and their applications to antennas.

The handbook is basically subdivided into six main themes.

PART I : FUNDAMENTAL PARAMETERS AND DEFINITIONS OF ANTENNAS

This part introduces the fundamental parameters and definitions of antennas. It is probably one of the most important chapters because it prepares the reader for the understanding of the various topics and parameters that are used throughout the handbook.

PART II : ANTENNA ELEMENTS

Some of the most basic and classic antenna configurations, from the wire-type to low-profile and apertures, such as monopoles, dipoles, loops, microstrips, apertures, reflectors, frequency independent, leaky-wave, reconfigurable, wideband, traveling, small, and fractal elements are included in this second part.

PART III: ARRAYS AND SYNTHESIS METHODS

Arrays are probably the most versatile antenna designs with a wide range of applications from ground-based to space-borne. Three chapters have been devoted to this theme, including smart antennas and adaptive arrays which we expect to play a key role in the advancement of the wireless communication technology. Some unique and intriguing designs of arrays for wideband operation are part of this section. Synthesis methods, although classic, will always be part of any antenna technology advancement.

PART IV: STRUCTURES AND TECHNIQUES RELATED TO ANTENNAS

Advanced materials and structures, such as metamaterials and artificial magnetic conductors, are modern technologies which already have been contributing factors to the evolution of antennas. In addition, MEMS, FSS, and RCS are contemporary devices and designs which are now integral parts of antenna technology. Measurement techniques, both conventional and near-to-far field, are also included.

PART V: ANTENNA APPLICATIONS

The applications emphasized in this theme are more toward wireless communications, including mobile units, base stations, multiple-input multiple-output (MIMO) techniques, and medical and biomedical applications. These will play a pivotal role in the advancement of wireless communication system efficiency, in terms of increasing capacity and range.

PART VI: METHODS OF ANALYSIS, MODELING AND SIMULATION

Five chapters are devoted to advanced numerical/computational methods targeted primarily for the analysis, modeling, simulation, design, animation and visualization of antennas. These methods have been an integral part of modern antenna technology, and include Integral Equations/Method of Moments, Finite-Difference Time-Domain (FDTD), Finite Element Method (FEM), Genetic Algorithms (GA) and Neural Networks.

There are many people that have contributed to the completion of this publication, and I would like to extend my sincere appreciation for their interest, contributions, cooperation, and support. First of all, I would like to thank the 68 authors, all of national and international acclaim, who volunteered to contribute to this handbook. The contents reflect their present and future vision of antenna technology. The interest and support from Wiley-Interscience was very critical from the genesis to the final production of this handbook. I would like to acknowledge the vision, dedication for excellence, and support provided within Wiley-Interscience by George Telecki (Editor) and the assistance from Rachel Witmer, Melissa Valentine, and the expert production led by Lisa Morano Van Horn.

Last, but not list, I would like to thank my family, Helen, Renie and Stephanie, for their patience, support, and encouragement over the years for all my challenging undertakings, including this one.

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Tempe, Arizona,
May 2008

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PART I

INTRODUCTION

CHAPTER 1

Fundamental Parameters and Definitions for Antennas

CONSTANTINE A. BALANIS

1.1 INTRODUCTION

To describe the performance of an antenna, definitions of various parameters are necessary. Some of the parameters are interrelated and not all of them need be specified for complete description of the antenna performance. Parameter definitions are given in this chapter. Many of those in quotation marks are from the *IEEE Standard Definitions of Terms for Antennas* (IEEE Std 145-1983).[†] This is a revision of the IEEE Std 145-1973. A more detailed discussion can be found in Ref. 1.

1.2 RADIATION PATTERN

An antenna *radiation pattern* or *antenna pattern* is defined as "a mathematical function or a graphical representation of the radiation properties of the antenna as a function of space coordinates. In most cases, the radiation pattern is determined in the far-field region and is represented as a function of the directional coordinates. Radiation properties include power flux density, radiation intensity, field strength, directivity, phase, or polarization." The radiation property of most concern is the two- or three-dimensional spatial distribution of radiated energy as a function of the observer's position along a path or surface of constant radius. A convenient set of coordinates is shown in Figure 1.1. A trace of the received electric (magnetic) field at a constant radius is called the amplitude *field pattern*. On the other hand, a graph of the spatial variation of the power density along a constant radius is called an amplitude *power pattern*.

Often the *field* and *power* patterns are normalized with respect to their maximum value, yielding *normalized field* and *power patterns*. Also, the power pattern is usually plotted on a logarithmic scale or more commonly in decibels (dB). This scale is usually desirable because a logarithmic scale can accentuate in more detail those parts of the

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[†] *IEEE Transactions on Antennas and Propagation*, Vol. AP-17, No. 3, May 1969; Vol. AP-22, No. 1, January 1974; and Vol. AP-31, No. 6, Part II, November 1983.

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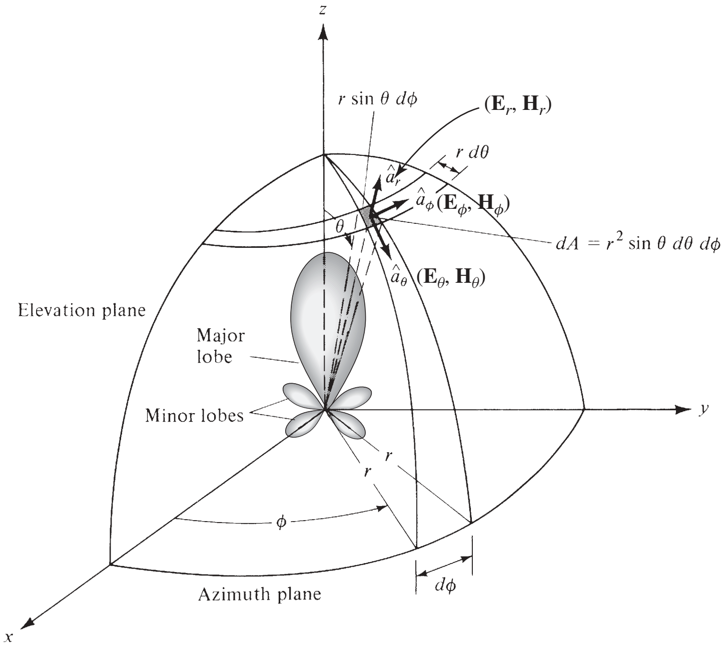
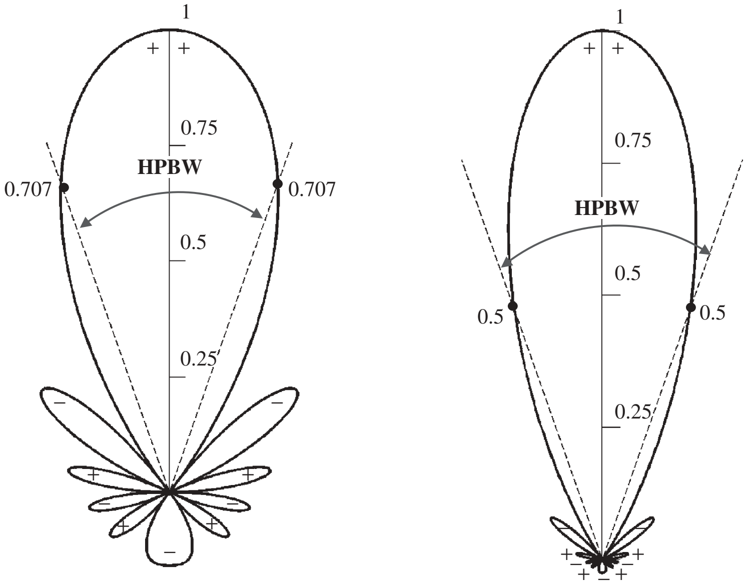


Figure 1.1 Coordinate system for antenna analysis.

pattern that have very low values, which later we refer to as minor lobes. For an antenna, (1) the *field* pattern in (*linear scale*) typically represents a plot of the magnitude of the electric or magnetic field as a function of the angular space; (2) the *power* pattern in (*linear scale*) typically represents a plot of the square of the magnitude of the electric or magnetic field as a function of the angular space; and (3) the *power* pattern in (*dB*) represents the magnitude of the electric or magnetic field, in decibels, as a function of the angular space.

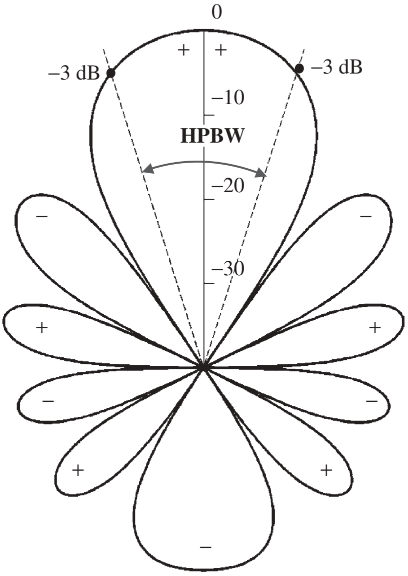
To demonstrate this, the two-dimensional normalized field pattern (*plotted in linear scale*), power pattern (*plotted in linear scale*), and power pattern (*plotted on a logarithmic dB scale*) of a 10-element linear antenna array of isotropic sources, with a spacing of $d = 0.25\lambda$ between the elements, are shown in Figure 1.2. *In this and subsequent patterns, the plus* (+) *and minus* (−) *signs in the lobes indicate the relative polarization of the amplitude between the various lobes, which changes (alternates) as the nulls are crossed*. To find the points where the pattern achieves its half-power (−3 dB points), relative to the maximum value of the pattern, you set the value of (1) *the field pattern at 0.707 value of its maximum, as shown in Figure 1.2a;* (2) *the power pattern (in a linear scale) at its 0.5 value of its maximum, as shown in Figure 1.2b; and* (3) *the power pattern (in dB) at −3 dB value of its maximum, as shown in Figure 1.2c*. All three patterns yield the same angular separation between the two half-power points, 38.64°, on their respective patterns, *referred to as HPBW* and illustrated in Figure 1.2. This is discussed in detail in Section 1.5.

In practice, the three-dimensional pattern is measured and recorded in a series of two-dimensional patterns. However, for most practical applications, a few plots of the pattern as a function of θ for some particular values of ϕ, plus a few plots as a function of ϕ for some particular values of θ, give most of the useful and needed information.



(a) Field pattern (*in linear scale*)

(b) Power pattern (*in linear scale*)



(c) Power pattern (*in dB*)

Figure 1.2 Two-dimensional normalized *field* pattern (*linear scale*), *power* pattern (*linear scale*), and *power* pattern (in *dB*) of a 10-element linear array with a spacing of $d = 0.25\lambda$.

1.2.1 Radiation Pattern Lobes

Various parts of a radiation pattern are referred to as *lobes*, which may be subclassified into *major* or *main, minor, side*, and *back* lobes.

A *radiation lobe* is a "portion of the radiation pattern bounded by regions of relatively weak radiation intensity." Figure 1.3a demonstrates a symmetrical three-dimensional polar pattern with a number of radiation lobes. Some are of greater radiation intensity than others, but all are classified as lobes. Figure 1.3b illustrates a linear two-dimensional pattern (one plane of Figure 1.3a) where the same pattern characteristics are indicated.

MATLAB-based computer programs, designated as *polar* and *spherical*, have been developed and are included in the CD of [1]. These programs can be used to plot the two-dimensional patterns, both polar and semipolar (in *linear* and *dB scales*), in polar form and spherical three-dimensional patterns (in *linear* and *dB scales*). A description

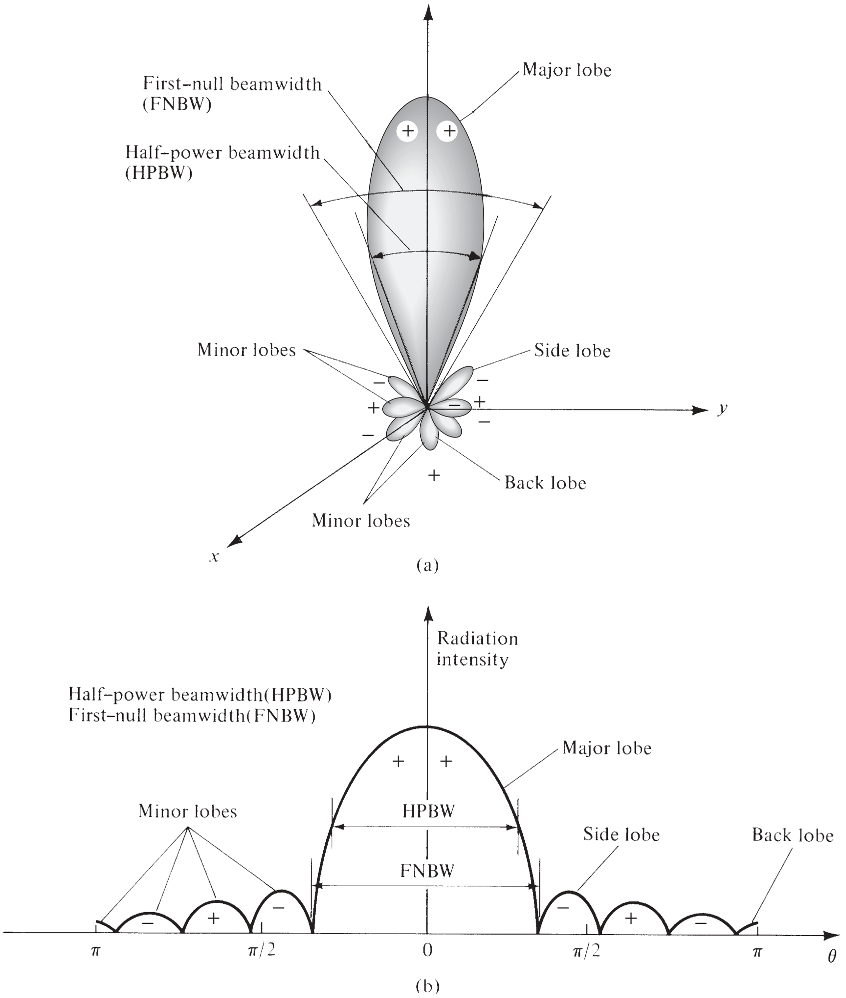


Figure 1.3 (a) Radiation lobes and beamwidths of an antenna pattern. (b) Linear plot of power pattern and its associated lobes and beamwidths.

of these programs is found in the CD attached to Ref. 1. Other programs that have been developed for plotting rectangular and polar plots are those of Refs. 1–5.

A *major lobe* (also called main beam) is defined as "the radiation lobe containing the direction of maximum radiation." In Figure 1.3 the major lobe is pointing in the $\theta = 0$ direction. In some antennas, such as split-beam antennas, there may exist more than one major lobe. A *minor lobe* is any lobe except a major lobe. In Figures 1.3a and 1.3b all the lobes with the exception of the major can be classified as minor lobes. A *side lobe* is "a radiation lobe in any direction other than the intended lobe." (Usually a side lobe is adjacent to the main lobe and occupies the hemisphere in the direction of the main beam.) A *back lobe* is "a radiation lobe whose axis makes an angle of approximately 180° with respect to the beam of an antenna." Usually it refers to a minor lobe that occupies the hemisphere in a direction opposite to that of the major (main) lobe.

Minor lobes usually represent radiation in undesired directions, and they should be minimized. Side lobes are normally the largest of the minor lobes. The level of minor lobes is usually expressed as a ratio of the power density in the lobe in question to that of the major lobe. This ratio is often termed the side lobe ratio or side lobe level. Side lobe levels of −20 dB or smaller are usually not desirable in many applications. Attainment of a side lobe level smaller than −30 dB usually requires very careful design and construction. In most radar systems, low side lobe ratios are very important to minimize false target indications through the side lobes.

A normalized three-dimensional far-field amplitude pattern, plotted on a linear scale, of a 10-element linear antenna array of isotropic sources with a spacing of $d = 0.25\lambda$ and progressive phase shift $\beta = -0.6\pi$ between the elements is shown in Figure 1.4. It

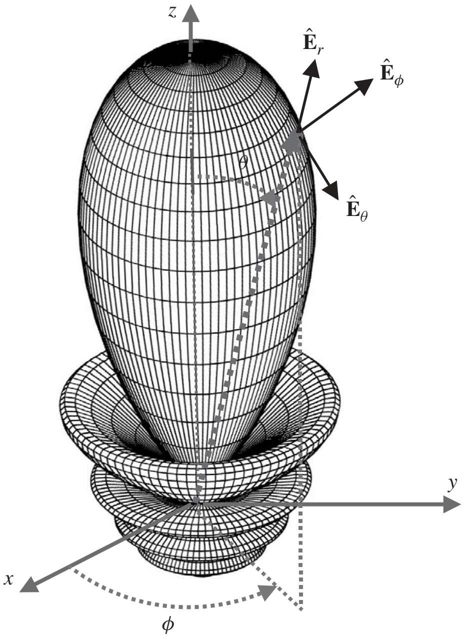


Figure 1.4 Normalized three-dimensional amplitude *field* pattern (in *linear scale*) of a 10-element linear array antenna with a uniform spacing of $d = 0.25\lambda$ and progressive phase shift $\beta = -0.6\pi$ between the elements.

is evident that this pattern has one major lobe, five minor lobes, and one back lobe. The level of the side lobe is about −9 dB relative to the maximum. A detailed presentation of arrays is found in Chapter 6 of Ref. 1. For an amplitude pattern of an antenna, there would be, in general, three electric-field components (E_r, E_θ, E_ϕ) at each observation point on the surface of a sphere of constant radius $r = r_c$, as shown in Figure 1.1. In the far field, the radial E_r component for all antennas is zero or, vanishingly small compared to either one, or both, of the other two components (see Section 3.6 of Chapter 3 of Ref. 1). Some antennas, depending on their geometry and also observation distance, may have only one, two, or all three components. In general, the magnitude of the total electric field would be $|\mathbf{E}| = \sqrt{|E_r|^2 + |E_\theta|^2 + |E_\phi|^2}$. The radial distance in Figure 1.4, and similar ones, represents the magnitude of $|\mathbf{E}|$.

1.2.2 Isotropic, Directional, and Omnidirectional Patterns

An *isotropic* radiator is defined as “a hypothetical lossless antenna having equal radiation in all directions.” Although it is ideal and not physically realizable, it is often taken as a reference for expressing the directive properties of actual antennas. A *directional* antenna is one “having the property of radiating or receiving electromagnetic waves more effectively in some directions than in others. This term is usually applied to an antenna whose maximum directivity is significantly greater than that of a half-wave dipole.” Examples of antennas with directional radiation patterns are shown in Figures 1.5 and 1.6. It is seen that the pattern in Figure 1.6 is nondirectional in the azimuth plane ($f(\phi)$, $\theta = \pi/2$) and directional in the elevation plane ($g(\theta)$, $\phi = \text{constant}$). This type of a pattern is designated as *omnidirectional*, and it is defined as one “having an essentially nondirectional pattern in a given plane (in this case in azimuth) and a directional pattern in any orthogonal plane (in this case in elevation).” An *omnidirectional* pattern is then a special type of a *directional* pattern.

1.2.3 Principal Patterns

For a linearly polarized antenna, performance is often described in terms of its principal E- and H-plane patterns. The *E-plane* is defined as “the plane containing the electric-field vector and the direction of maximum radiation,” and the *H-plane* as “the plane containing the magnetic-field vector and the direction of maximum radiation.” Although it is very difficult to illustrate the principal patterns without considering a specific example, it is the usual practice to orient most antennas so that at least one of the principal plane patterns coincides with one of the geometrical principal planes. An illustration is shown in Figure 1.5. For this example, the *x-z* plane (elevation plane; $\phi = 0$) is the principal E-plane and the *x-y* plane (azimuthal plane; $\theta = \pi/2$) is the principal H-plane. Other coordinate orientations can be selected.

The omnidirectional pattern of Figure 1.6 has an infinite number of principal E-planes (elevation planes; $\phi = \phi_c$) and one principal H-plane (azimuthal plane; $\theta = 90^\circ$).

1.2.4 Field Regions

The space surrounding an antenna is usually subdivided into three regions: (1) *reactive near-field*, (2) *radiating near-field* (*Fresnel*), and (3) *far-field* (*Fraunhofer*) regions as shown in Figure 1.7. These regions are so designated to identify the field structure in

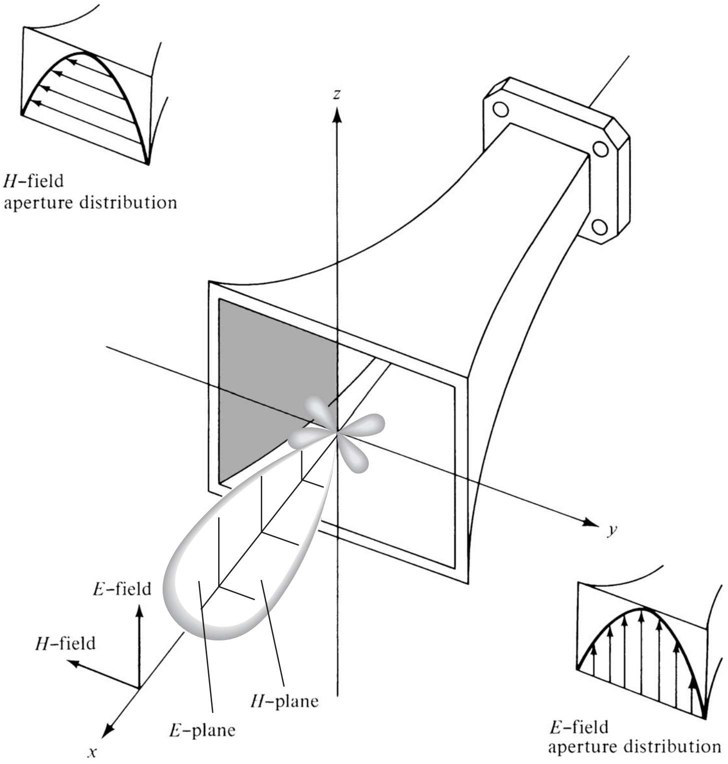


Figure 1.5 Principal *E*- and *H*-plane patterns for a pyramidal horn antenna.

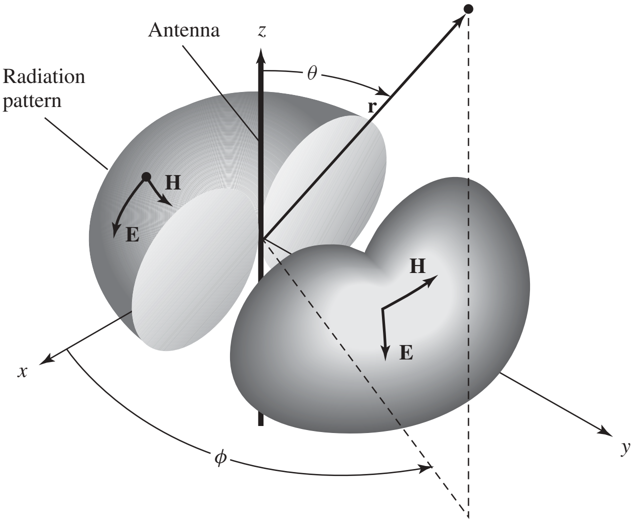


Figure 1.6 Omnidirectional antenna pattern.

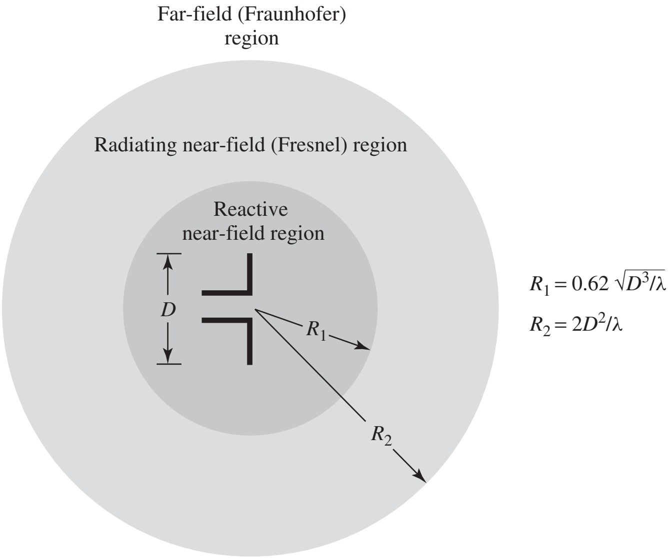


Figure 1.7 Field regions of an antenna.

each. Although no abrupt changes in the field configurations are noted as the boundaries are crossed, there are distinct differences among them. The boundaries separating these regions are not unique, although various criteria have been established and are commonly used to identify the regions.

Reactive near-field region is defined as "that portion of the near-field region immediately surrounding the antenna wherein the reactive field predominates." For most antennas, the outer boundary of this region is commonly taken to exist at a distance $R < 0.62\sqrt{D^3/\lambda}$ from the antenna surface, where λ is the wavelength and D is the largest dimension of the antenna. "For a very short dipole, or equivalent radiator, the outer boundary is commonly taken to exist at a distance $\lambda/2\pi$ from the antenna surface."

Radiating near-field (Fresnel) region is defined as "that region of the field of an antenna between the reactive near-field region and the far-field region wherein radiation fields predominate and wherein the angular field distribution is dependent upon the distance from the antenna. If the antenna has a maximum dimension that is not large compared to the wavelength, this region may not exist. For an antenna focused at infinity, the radiating near-field region is sometimes referred to as the Fresnel region on the basis of analogy to optical terminology. If the antenna has a maximum overall dimension which is very small compared to the wavelength, this field region may not exist." The inner boundary is taken to be the distance $R \geq 0.62\sqrt{D^3/\lambda}$ and the outer boundary the distance $R < 2D^2/\lambda$, where D is the largest[†] dimension of the antenna. This criterion is based on a maximum phase error of $\pi/8$. In this region the field pattern is, in general, a function of the radial distance and the radial field component may be appreciable.

Far-field (Fraunhofer) region is defined as "that region of the field of an antenna where the angular field distribution is essentially independent of the distance from the

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[†] To be valid, D must also be large compared to the wavelength ($D > \lambda$).