

**ANTENNAS**  
**L.V. Blake**

# ANTENNAS

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## *Preface to the second edition*

The original edition of this book was published in 1966 (by John Wiley & Sons, Inc., New York), and remained in print until 1982, without revision. It is now republished, with an additional chapter on antenna developments that have occurred since 1966, because it is believed that this book fills a need that is not filled elsewhere. It is understandable to engineers who are not antenna specialists, but who need a text that presents both theory and practical design information on antennas of all types. Although it is not an "advanced" text, it treats antennas at a fully professional level, and it is therefore also suitable as an introductory textbook, even for students who may later specialize in antenna design and development.

Because the scientific principles that are the basis of antenna theory do not change with time, the original text remains as valid (and essentially as up-to-date) today as it was in 1966. There have, of course, been many significant developments in antenna technology since that time, and the chapter that has been added (Chapter 9) presents the essentials of those developments that the author has judged to be most significant. All of these developments are understandable in terms of the basic principles presented in the original eight chapters. Therefore, those chapters remain unchanged, except for correction of some typographical errors and a few minor technical errors.

The field of antenna design and development expanded tremendously during World War II (1941-1945), and that expansion has continued up to the present time. Consequently, it has not been possible to treat all of the new developments in complete detail, and no doubt the topics selected for the fullest treatment reflect to some extent the author's personal interests, although that was not the intent. In particular, the greatest emphasis in Chapter 9 is on developments in microwave antennas. That is undoubtedly the area in which development has been most intense, particularly because that is used for both radar and for satellite communications. However, the types of antennas used at lower frequencies are by no means slighted in the preceding

chapters. Included in Chapter 9 is a brief discussion (necessarily somewhat superficial, but with reference to sources of fuller treatment) of the improved analytical and mathematical techniques that are the basis of many of the advances that have taken place in antenna design technology.

The author is grateful to many persons who provided information on particular topics, but most especially to Dr. William F. Gabriel of the Naval Research Laboratory (adaptive arrays), David K. Barton of Raytheon Company, Bedford, MA (data on modern phased arrays, and for other assistance), Kenneth R. Grimm of Technology Service Corporation (near-field measurements), Helmut E. Schrank of Westinghouse Corporation, Baltimore (low-sidelobe antennas), and Dr. Robert M. Sorbello of the Comsat Corporation, Clarksville, MD (satellite antennas). Thanks are also extended to Dr. Joe Frank, Gerald Rose, and Charles Shipley of Technology Service Corporation for reviewing portions of Chapter 9 and providing helpful criticisms. The writing of this chapter, like those that precede it, has been a purely private undertaking of the author, who assumes full responsibility for the accuracy of the material.

## *Preface*

Some excellent books on advanced antenna theory and practice, which require a fairly high level of mathematical sophistication on the part of the reader, have been written for the graduate or advanced undergraduate engineer. Such books serve an essential purpose, but there is also a need for a book on antennas on the professional level, yet comprehensible to the technician and to the engineer who is not a specialist in the field of antennas. I have attempted to meet that need in this book.

I have assumed that the reader has a basic knowledge of electronics, radio, and a-c circuit theory and also some background in engineering mathematics. At a very few points elementary calculus has been used, but in such a way that the essential information will be conveyed to readers who have not studied it. A knowledge of algebra, geometry, and trigonometry will suffice. Complex-variable algebra has been applied when appropriate, and a brief review of the basics of that subject is provided in an appendix.

The first chapter reviews the radio-wave aspects of electromagnetic theory at the level and in the degree of detail required as a basis for the subsequent chapters. It will serve as a review and as a reference source for those who have already studied the subject. The second chapter serves the same need with respect to transmission lines, of which a basic knowledge is required in the study of antennas. Both chapters, although not advanced in their treatment, are quite condensed, and a reader who has had no previous experience in these subjects may find it advisable to consult an elementary textbook that treats them in a more tutorial fashion.

The remaining six chapters cover specific topics in antenna theory



and practice, in a development suitable for teaching at the technical institute level, for introductory-level engineering courses, or for independent study. Where information from other chapters is needed for understanding the topic under discussion reference has been made to relevant section numbers. References to books and papers containing more detailed information are provided in footnotes. A brief bibliography of books suitable for further study is given at the end of the book. Problems and exercises designed to assist in the acquisition of a working knowledge of the chapter subject appear at the end of each chapter.

Stimulated by the demands of expanding radio applications, such as television, radar, radio astronomy, space communication, and weapon guidance, the science and technology of antennas have progressed rapidly in the last few decades. The categories of antenna types now cover a vast span, ranging from the simple wires, towers, and loops of the low frequencies to the horns, slots, and lenses of the microwave region. Recent developments include new forms of reflectors, lenses, arrays, frequency-independent antennas, and surface-wave antennas. In the face of such wide-ranging progress, I have attempted to be as up-to-date and comprehensive as possible within the limitations of space. But the emphasis of the book is on the basic antenna concepts and principles that are essential to an understanding of whatever new antenna developments may be introduced in the future.

I gratefully acknowledge helpful discussions with many of my co-workers at the Naval Research Laboratory. The writing of the book has been a private undertaking, however, and I assume sole responsibility for the validity of the contents.

LAMONT V. BLAKE

*Alexandria, Virginia*

*April 1966*

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# 1.

## *Electromagnetic waves*

This book begins with an elementary discussion of electromagnetic wave theory, which is basic to an understanding of antennas. Readers who are quite familiar with the principles of electromagnetic waves may prefer to begin with the second (or third) chapter, but even they should find this introductory chapter a review of the subject and a useful reference source.

Electromagnetic waves in space are the basis of radio transmission over great distances without direct wire connection between the sending\* and receiving points. At the transmitting and receiving stations radio signals exist in the form of high (radio) frequency alternating currents in conductors and in such amplifying devices as electron tubes and transistors. Between the transmitter and receiver they exist as electromagnetic waves in space. Antennas, the subject of this book, are the devices that act as go-betweens.

At the transmitting station the antenna is energized by the electrical currents generated in the transmitter, and it converts the energy into the form of an electromagnetic field. It "launches" the waves into space. At the receiving station the antenna captures energy from the arriving field, and by a reversal of the transmitting antenna process it converts the field variations into current and voltage replicas of those at the transmitter (though of much smaller amplitude).

\* As is modern usage, the word *transmitting* will henceforth be used in the sense of "sending," although originally *transmission* referred to the entire process of sending, propagation, and reception of radio waves.

Current and voltage in conductors are always accompanied by electric and magnetic fields in the adjoining region of space, and in a sense it is incorrect to speak of "converting" electrical energy from the form of current and voltage into the form of an electromagnetic field, and vice versa. In a practical sense, however, the distinction is made. In the one case the fields are bound to the conductors in which the current flows; in the other they are "free."

The picture of electromagnetic waves presented here is considerably simplified and necessarily leaves unanswered some questions that may be disturbing to the reader with an inquiring mind. Often these questions can be answered, but only through the use of rather sophisticated mathematical and physical concepts, based on James Maxwell's equations, which he published in 1873. Bear in mind that most of the ideas and principles to be discussed have this background, even though it will not be necessary to look very deeply into it for the purposes of this book.

## 1-1. Characteristics of Electromagnetic Waves

A wave is an oscillatory motion of any kind, the most familiar being waves on the surface of water. Sound waves, another common example, are vibrations of the air or of various material substances. Both wave types involve mechanical motion. Electromagnetic waves are electric and magnetic field variations that can occur in empty space as well as in material substances.

All waves are characterized by the property called *propagation*. The vibrations at a particular point in space excite similar vibrations at neighboring points, and thus the wave travels or *propagates* itself. This concept is given more specific form as Huygens' principle, to be discussed later in this chapter. The particular substance or space in which a wave exists is the *propagation medium*.

**Wave Velocity.** Waves travel at characteristic speeds, depending on the type of wave and the nature of the propagation medium. For example, sound travels about 1100 feet per second in the normal atmosphere, but in water the speed is in the neighborhood of 5000 feet per second. In both media the figure varies with the temperature and other factors.

Electromagnetic waves travel much faster—in free space\* at approximately 186,000 statute miles per second. In other propagation media their speed may be less, but ordinarily it is very high compared with the speeds of things observable without special instruments. In the gases of the earth's normal atmosphere, in fact, the speed is only slightly less than in empty space (vacuum), and for practical purposes the difference is negligible except over very long paths. Even then it is ordinarily permissible to use the free-space velocity figure for calculating how long it will take a radio wave to travel from one point to another in the atmosphere.

An important exception to this statement occurs when waves at certain radio frequencies travel in the ionosphere, a layer of charged particles (ions) lying above the earth between the heights of about 40 and 200 miles. At very low radio frequencies radio waves cannot penetrate the ionosphere; they are reflected from it. At very high frequencies waves pass through the ionosphere unimpeded at the same speed they would have in empty space. But in a critical intermediate frequency region, depending on ionospheric conditions (which vary considerably from day to night and with the season and other factors), the wave velocity in the ionosphere may be different than it is in vacuum.

The speed of electromagnetic propagation in a vacuum is of fundamental importance. This value, commonly called the "speed of light" in vacuum, is designated by the symbol  $c$ . (Light waves are actually electromagnetic waves of very high frequency.) The value of  $c$  is 186,283 statute miles per second, or 299,793 kilometers per second, rounded off for most purposes to 186,000 miles per second or  $3 \times 10^8$  meters per second.

**Frequency and Wavelength.** The oscillations of waves are *periodic*; or *repetitious*. They are characterized by a *frequency*, the rate at which the periodic motion repeats itself, as observed at a particular point in the propagation medium. Complex waves may contain more than one frequency. The frequency is expressed in *cycles per second*, a cycle being one full period of the wave. A single-frequency wave motion has the form of a sinusoid.

\* *Free space* is a term much used in discussion of electromagnetic waves. It implies not only *empty space* (a vacuum) but also remoteness from any material substances from which waves may be reflected.



The *wavelength* of an electromagnetic wave is the spatial separation of two successive "oscillations," which is equal to the distance that the wave travels during one sinusoidal cycle of oscillation. Therefore, if the wave velocity is  $v$  meters per second and the frequency is  $f$  cycles per second, the wavelength in meters is

$$\lambda = \frac{v}{f} \quad (1-1)$$

As has been noted,  $v$  may have different values in different propagation media. When the value in free space (vacuum),  $c$ , is used in Eq. 1-1, the resulting value of  $\lambda$  is the *free-space wavelength*, sometimes denoted by  $\lambda_0$ .

Radio waves, the particular form of electromagnetic waves with which antennas are concerned, are defined as those that lie in a certain range of frequency, although the exact limits are difficult to define. It is of interest to look at the frequencies associated with the various categories of electromagnetic waves. Because the radio spectrum is of primary interest here, it is subdivided in the table into

<i>Type of Electromagnetic Wave</i>	<i>Frequency Range</i>	<i>Free-Space-Wavelength Range</i>
Extremely low frequency (ELF)	< 3 kc	> $10^5$ m
Very low frequency radio (VLF)	(3–30 kc)	$10^4$ – $10^5$ m
Low frequency (LF)	(30–300 kc)	$10^3$ – $10^4$ m
Medium frequency (MF)	(300 kc–3 Mc)	$10^2$ – $10^3$ m
High frequency (HF)	(3–30 Mc)	10–100 m
Very high frequency (VHF)	(30–300 Mc)	1–10 m
Ultrahigh frequency (UHF)	(300 Mc–3 Gc)	10 cm–1 m
Superhigh frequency (SHF)	(3–30 Gc)	1–10 cm
Extremely high frequency (EHF)	(30–300 Gc)	0.1–1 cm
Infrared waves	$8 \times 10^{11}$ – $4 \times 10^{14}$ cps	0.04 cm–8000 Å
Visible light	$4 \times 10^{14}$ – $7.5 \times 10^{14}$ cps	4000–8000 Å
Ultraviolet light	$7.5 \times 10^{14}$ – $10^{16}$ cps	120–4000 Å
X-rays, gamma ( $\gamma$ ) rays	$10^{16}$ – $10^{20}$ cps	0.06–120 Å
Cosmic-ray radiation	> $10^{20}$ cps	< 0.06 Å

*Key to abbreviations.* cps—cycles per second; kc—kilocycles per second ( $\text{cps} \times 10^3$ ); Mc—megacycles per second ( $\text{cps} \times 10^6$ ); Gc—gigacycles per second ( $\text{cps} \times 10^9$ ); m—meters; cm—centimeters; Å—angstrom unit ( $10^{-8}$  cm).

*Note:* In Europe the designation hertz (abbreviation, Hz) has been substituted for cycles per second, and it has been adopted by some groups in the United States. Other units affected are MHz—megahertz; kHz—kilohertz; GHz—gigahertz.