

ANTENNA

THEORY

ANALYSIS AND DESIGN

SECOND EDITION

CONSTANTINE A. BALANIS

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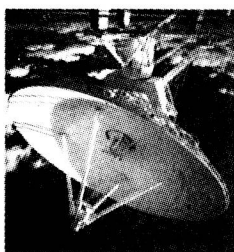


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FRONT COVER PHOTO: Parabolic reflector (25-m diameter) of 27-element Very Large Array (VLA) radio telescope. National Radio Astronomy Observatory (NRAO), Socorro, New Mexico.

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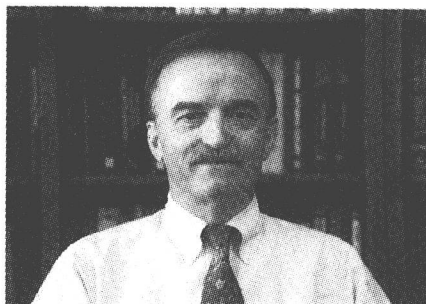
To my mother, and to the memory of
my father, uncle, and aunt

About The Author

Constantine A. Balanis received his BSEE degree from Virginia Polytechnic Institute, Blacksburg, in 1964, his MEE degree from University of Virginia, Charlottesville, in 1966, and his PhD degree in electrical engineering from Ohio State University, Columbus, in 1969.

From 1964 to 1970 he was with the NASA Langley Research Center in Hampton, Virginia, and from 1970 to 1983 he was with the Department of Electrical Engineering, West Virginia University, Morgantown. In 1983 he joined Arizona State University, Tempe, and he is now Regents' Professor of Electrical Engineering and Director of ASU's Telecommunications Research Center. He teaches graduate and undergraduate courses in electromagnetic theory, antennas, and microwave circuits. His research interests are in low- and high-frequency numerical and computational techniques for antennas and scattering, electromagnetic wave propagation in microwave-integrated circuit transmission lines, and multipath wave propagation. He received the Graduate Teaching Excellence Award, School of Engineering, Arizona State University for 1987–1988, the 1989 IEEE Region 6 Individual Achievement Award, and the 1992 Special Professionalism Award of the IEEE Phoenix Section.

Dr. Balanis is a Fellow of IEEE, and a member of ASEE, Electromagnetics Academy, Sigma Xi, Tau Beta Pi, Eta Kappa Nu, and Phi Kappa Phi. He has served as the Associate Editor of the *IEEE Transactions on Antennas and Propagation* (1974–1977) and *IEEE Transactions on Geoscience and Remote Sensing* (1982–1984), Editor of the *Newsletter* for the IEEE Geoscience and Remote Sensing Society (1982–1983), Second Vice-President of the IEEE Geoscience and Remote Sensing Society (1984), and as Chairman of the Distinguished Lecturer Program (1988–91) and member of the Administrative Committee (1992–95) of the IEEE Antennas and Propagation Society. He is also the author of *Advanced Engineering Electromagnetics* (John Wiley & Sons, New York, 1989), and “Horn Antennas,” Chapter 8 in *Antenna Handbook: Theory, Applications, and Design* (Y. T. Lo and S. W. Lee, Editors), Van Nostrand Reinhold Co., New York, 1988.



Preface

This second edition of *Antenna Theory* is designed to meet the needs of electrical engineering and physics students at the senior undergraduate and beginning graduate levels, and those of practicing engineers as well. The text presumes that the students have a knowledge of basic undergraduate electromagnetic theory, including Maxwell's equations and the wave equation, introductory physics, and differential and integral calculus. Mathematical techniques required for understanding some advanced topics in the later chapters are incorporated in the individual chapters or are included as appendices.

The second edition of the book has maintained all of the attractive features of the first edition. However there have been many new features added to this edition. In particular, an entire new chapter is devoted to the analysis and design of microstrip antennas; introductory material has been added for the Fourier transform (spectral domain) method, coupling, radar cross section for antennas, aperture-matched and multimode horns, near-field to far-field measurements, and compact range chamber designs and instrumentation for antenna and RCS measurements. There is an increase in design procedures and equations; FORTRAN computer programs at the end of most of the chapters that can be used for design and analysis; additional examples, end-of-chapter problems, and two- and three-dimensional illustrations; and updated material on Moment Method and mutual impedances. In addition, a computer program has been developed, based on the Finite Difference Time-Domain method to animate and visualize radiation. All the computer programs are contained in a 3.5-inch disc, which is included with the book.

The book's main objective is to introduce, in a unified manner, the fundamental principles of antenna theory and to apply them to the analysis, design, and measurements of antennas. Because there are so many methods of analysis and design and a plethora of antenna structures, applications are made to some of the most basic and practical configurations, such as linear dipoles, loops, arrays, broadband and frequency-independent antennas, aperture antennas, horn antennas, microstrip antennas, and reflector antennas.

Introductory material on analytical methods, such as the Moment method and Fourier transform (spectral) technique, is also included. These techniques, with the fundamental principles of antenna theory, can be used to analyze and design almost any antenna configuration. A chapter on antenna measurements introduces state-of-the-art methods used in the measurements of the most basic antenna characteristics (pattern, gain, directivity, radiation efficiency, impedance, current, and polarization) and updates progress made in antenna instrumentation, antenna range design, and scale modeling. Techniques and systems used in near- to far-field measurements and transformations are also discussed.

A sufficient number of topics have been covered, some for the first time in an undergraduate text, so that the book will serve not only as a text, but also as a reference for the practicing and design engineer and even the amateur radio buff. These include design procedures for Yagi-Uda and log-periodic arrays, horns, and microstrip patches; synthesis techniques using the Schelkunoff, Fourier transform, Woodward-Lawson, Tschebyscheff, and Taylor methods; radiation characteristics of corrugated, aperture-matched, and multimode horns; analysis and design of rectangular and circular microstrip patches; and matching techniques such as the binomial, Tschebyscheff, T-, gamma, and omega matches.

The text contains sufficient mathematical detail to enable the average undergraduate electrical engineering and physics students to follow, without too much difficulty, the flow of analysis and design. A certain amount of analytical detail, rigor, and thoroughness allows many of the topics to be traced to their origin. My experiences as a student, engineer, and teacher have shown that a text for this course must not be a book of unrelated formulas, and it must not resemble a "cookbook." This book begins with the most elementary material, develops underlying concepts needed for sequential topics, and progresses to more advanced methods and systems configurations. Each chapter is subdivided into sections or subsections whose individual headings clearly identify the antenna characteristic(s) discussed, examined, or illustrated.

A distinguished feature of this book is its three-dimensional graphical illustrations from the first edition, which have been expanded and supplemented in the second edition. In the past, antenna texts have displayed the three-dimensional energy radiated by an antenna by a number of separate two-dimensional patterns. With the advent and revolutionary advances in digital computations and graphical displays, an additional dimension has been introduced for the first time in an undergraduate antenna text by displaying the radiated energy of a given radiator by a single, three-dimensional graphical illustration. Such an image, formed by the graphical capabilities of the computer and available at most computational facilities, gives a clear view of the energy radiated in all space surrounding the antenna. It is hoped that this will lead to a better understanding of the underlying principles of radiation and that it will provide a clearer visualization of the pattern formation in all space.

In addition, there is an abundance of general graphical illustrations, design data, references, and additional problems. Many of the principles are illustrated with examples, graphical illustrations, and physical arguments. Although students are often convinced that they understand the principles, difficulties arise when they attempt to use them. An example, especially a graphical illustration, can often better illuminate those principles. As they say, "a picture is worth a thousand words."

Numerical techniques and computer solutions are illustrated and encouraged. A number of FORTRAN computer programs and subroutines are included at the end of Chapters 1, 2, 4, 5, 6, 8, 10, 11, 13, and 14. The program at the end of Chapter 1 can be used to animate and then visualize radiation by an infinite line source driven by a Gaussian pulse and an E-plane sectoral horn energized by a continuous cosinusoidal source. To accomplish this, the user needs the professional edition of MATLAB. All of the computer programs, especially those at the end of Chapters 6, 11, 13, and 14, have been developed to design, respectively, uniform and nonuniform arrays, log-periodic dipole arrays, horns, and microstrip patch antennas. In some cases, the computer programs also perform analysis on the designs. The programs at the end of Chapters 2, 4, 5, 8, and 10 are primarily developed for analysis. A computer disc with the source codes is included with the book. These can be used to perform routine calculations of complex functions and/or formulations, to carry out numerical integrations that cannot be performed in closed form, and to display solutions in graphical

form. The problems at the end of each chapter can be used to apply the underlying principles of antenna theory to the analysis and design of many practical radiators.

For course use, the text is intended primarily for a two-semester (or two- or three-quarter) sequence in antenna theory. The first course should be given at the senior undergraduate level and should cover most of the material in Chapters 1 through 7 and Chapter 16. The material in Chapters 8 through 15 should be covered in a beginning graduate-level course. Selected chapters and sections from the book can be covered in a single semester, without loss of continuity. However, it is almost essential that most of the material in Chapters 2 through 6 be covered in the first course and before proceeding to any more advanced topics. To cover all the material of the text in the proposed time frame would be, in some cases, a very ambitious task. Sufficient topics have been included, however, to make the text complete and to give the teacher the flexibility to emphasize, de-emphasize, or omit sections or chapters. Some of the chapters and sections can be omitted without loss of continuity.

In the entire book an $e^{j\omega t}$ time variation is assumed, and it is suppressed. The International System of Units, which is an expanded form of the rationalized MKS system, is used in the text. In some cases, the units of length are in meters (or centimeters) and in feet (or inches). Numbers in parentheses () refer to equations, whereas those in brackets [] refer to references. For emphasis, the most important equations, once they are derived, are boxed. A Solutions Manual for all end of chapter problems is available for the instructor.

I would like to acknowledge the invaluable suggestions and constructive criticisms of the reviewers for the second edition of this book: Dr. Edward B. Joy of Georgia Tech, Dr. Stuart A. Long of University of Houston, Dr. David M. Pozar of University of Massachusetts and Dr. Paul E. Mayes of University of Illinois, Urbana, and those of the first edition from my colleague Dr. Thomas E. Tice of Arizona State University and Dr. Charlton H. Walter of TRW (formerly of Ohio State University). Also I would like to acknowledge the suggestions, end of the chapter problems, and figures provided by my colleague Dr. James T. Aberle and Dr. Roger D. Radcliff of Ohio University.

The book, especially the graphical illustrations, computer programs, solutions to many of the problems, solutions manual, and proofreading of the galleys and page proofs would not have been possible without the contributions from many of my and other graduate students at Arizona State University. It is a pleasure to acknowledge those of Anastasis C. Polycarpou for the development of many of the computer programs for Chapters 6, 8, 13, and 14, and preparation of the computer disc; Seong-Ook and Jeong-Suk Park for completion of the solutions manual and proofreading the galleys and page proofs; Dr. Panayiotis A. Tirkas for the development of the computer programs for Yagi-Uda arrays and analysis of horns, and many of the new three-dimensional computer generated illustrations; William V. Andrew for the development of the animation-visualization computer program; Craig R. Birtcher for antenna pattern measurements, and material on near- to far-field measurements and compact ranges; Chris B. Bishop for the development of the computer program for the design and analysis of log-periodic dipole arrays; David M. Kokotoff for revising the Hallén's-Moment Method computer program; and Tamara Spreckic, Konstantinos D. Katsibas, and Jian Peng for proofreading the galleys and preparation of graphical illustrations.

Since many of the unique features of this book carry over from the first edition, I still acknowledge the contributions of my graduate students at West Virginia University, especially those of John L. Jeffrey. Many thanks go to all those professors, practicing engineers, and students, who over the years of the first edition provided invaluable suggestions and corrections. I also want to acknowledge the expert typing

by Linda S. Arneson of the additional material included in the revised manuscript and to Kathy Muckenhirn for handling many of the logistics during publication. Many thanks to Dr. Atef Z. Elsherbeni and Clayborne D. Taylor, Jr., of University of Mississippi for permitting and providing the use of the *2-D Antenna Pattern Plotter: Rectangular-Polar* computer program.

To the companies and individuals that provided illustrations and copyright permissions, I am most appreciative. I am also grateful to the staff of John Wiley & Sons, Inc., especially Steven Elliot, Wiley editor of electrical engineering, for the interest in the publication of the second edition. Special thanks also to Suzanne Ingrao of Ingrao Associates, production editor of this book, for her professional help. Finally, I must express my gratitude to Helen, Renie and Stephanie for proofreading the galleys and for their encouragement, patience, sacrifice and understanding for the many hours of neglect during the completion of the first and second editions of this book.

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