



ANTENNA THEORY

**ANALYSIS
AND DESIGN**

FOURTH EDITION

CONSTANTINE A. BALANIS



WILEY

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About the Companion Websites

There is a student companion website contains:

- PowerPoint Viewgraphs
- MATLAB Programs
- JAVA Applets
- Animations
- End-of-Chapter Interactive Questionnaires

To access the material on the companion site simply find your unique website redemption code printed on the inside front endpaper of this book. Peel off the sticker and then visit www.wiley.com/go/antennatheory4e to follow the instructions for how to register your pin.

If the original access code has expired or already been used, go to <http://support.wiley.com> to purchase a new code.

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by the original purchaser.**

Peel
Here

Peel
Here

ANTENNA THEORY



To the memory of my parents, uncle and aunt

Στη μνήμη των γονέων, του θείου και της θείας μου



Preface

The fourth 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. The text presumes that the students have 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 book, since its first edition in 1982 and subsequent two editions in 1997 and 2005, has been a pacesetter and trail blazer in updating the contents to keep abreast with advancements in antenna technology. This has been accomplished by:

- Introducing new topics
- Originating innovative features and multimedia to animate, visualize, illustrate and display radiation characteristics
- Providing design equations, procedures and associate software

This edition is no exception, as many new topics and features have been added. In particular:

- New sections have been introduced on:
 1. Flexible and conformal bowtie
 2. Vivaldi antenna
 3. Antenna miniaturization
 4. Antennas for mobile communications
 5. Dielectric resonator antennas
 6. Scale modeling
- Additional MATLAB and JAVA programs have been developed.
- Color and gray scale figures and illustrations have been developed to clearly display and visualize antenna radiation characteristics.
- A companion website has been structured by the publisher which houses the MATLAB programs, JAVA-based applets and animations, Power Point notes, and JAVA-based interactive questionnaires. A solutions manual is available only for the instructors that adopt the book as a classroom text.
- Over 100 additional end-of-chapter problems have been included.

While incorporating the above new topics and features in the current edition, the book maintained all of the attractive features of the first three additions, especially the:

- Three-dimensional graphs to display the radiation characteristics of antennas. This feature was hailed, at the time of its introduction, as innovative and first of its kind addition in a textbook on antennas.

- Advanced topics, such as a chapter on *Smart Antennas* and a section on *Fractal Antennas*.
- Multimedia:
 1. Power Point notes
 2. MATLAB programs
 3. FORTRAN programs
 4. JAVA-based animations
 5. JAVA-based applets
 6. JAVA-based end-of-the-chapter questionnaires

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.

A tutorial chapter on Smart Antennas is included to introduce the student in a technology that will advance antenna theory and design, and revolutionize wireless communications. It is based on antenna theory, digital signal processing, networks and communications. MATLAB simulation software has also been included, as well as a plethora of references for additional reading.

Introductory material on analytical methods, such as the Moment Method and Fourier transform (spectral) technique, is also included. These techniques, together 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, and associated computer programs, 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 and Tschebyscheff. Also new sections have been introduced on flexible & conformal bowtie and Vivaldi antennas in Chapter 9, antenna miniaturization in Chapter 11 and expanded scale modeling in Chapter 17.

Chapter 14 has been expanded to include antennas for Mobile Communications. In particular, this new section includes basic concepts and design equations for the Planar Inverted-F Antenna (PIFA), Slot Antenna, Inverted-F Antenna (IFA), Multiband U-type Slot Antenna, and Dielectric Resonator Antennas (DRAs). These are popular internal antennas for mobile devices (smart phones, laptops, pads, tablets, etc.). A MATLAB computer program, referred to as **DRA_Analysis_Design**, has been developed to analyze the resonant frequencies of Rectangular, Cylindrical, Hemicylindrical, and Hemispherical DRAs using TE and TM modal cavity techniques by modeling the walls as PMCs. Hybrid modes are used to analyze and determine the resonant frequencies and quality factor (Q) of the Cylindrical DRA. The MATLAB program **DRA_Analysis_Design** has the capability, using a nonlinear solver, to design (i.e., find the Q , range of values for the dielectric constant, and finally the dimensions of the Cylindrical DRA) once the hybrid mode ($TE_{01\delta}$, $TM_{01\delta}$ or $HE_{11\delta}$), fractional bandwidth (BW, in %), VSWR and resonant frequency (f_r , in GHz) are specified. A detailed procedure to follow the design is outlined in Section 14.10.4.

The text contains sufficient mathematical detail to enable the average undergraduate electrical engineering and physics students to follow, without 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 system 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, third and fourth editions. 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. In this fourth edition, almost all of the three-dimensional amplitude radiation patterns, along with many two-dimensional graphs, are depicted in color and gray-scale. This is a new and pacesetting feature adopted, on a large scale, in this edition. It is hoped that this will lead to a better understanding of the underlying principles of radiation and 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 an expanded list of end-of-the chapter 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 MATLAB computer programs are included in the publisher’s website for the book. Each program is interactive and prompts the user to enter the data in a sequential manner. Some of these programs are translations of the FORTRAN ones that were included in the first and second editions. However, many new ones have been developed. Every chapter, other than Chapters 3 and 17, has at least one MATLAB computer program; some have as many as four. The outputs of the MATLAB programs include graphical illustrations and tabulated results. For completeness, the FORTRAN computer programs are also included, although nowadays there is not as much interest in them. The computer programs can be used for analysis and design. Some of them are more of the design type while some of the others are of the analysis type. Associated with each program there is a READ ME file, which summarizes the respective program.

The purpose of the Power Point Lecture Notes is to provide the instructors a copy of the text figures and some of the most important equations of each chapter. They can be used by the instructors in their lectures but may be supplemented with additional narratives. The students can use them to listen to the instructors’ lectures, without having to take detailed notes, but can supplement them in the margins with annotations from the lectures. Each instructor will use the notes in a different way.

The Interactive Questionnaires are intended as reviews of the material in each chapter. The student can use them to review for tests, exams, and so on. For each question, there are three possible answers, but only one is correct. If the reader chooses one of them and it the correct answer, it will so indicate. However, if the chosen answer is the wrong one, the program will automatically indicate the correct answer. An explanation button is provided, which gives a short narrative on the correct answer or indicates where in the book the correct answer can be found.

The Animations can be used to illustrate some of the radiation characteristics, such as amplitude patterns, of some antenna types, like line sources, dipoles, loops, arrays, and horns. The Applets cover more chapters and can be used to examine some of the radiation characteristics (such as amplitude patterns, impedance, bandwidth, etc.) of some of the antennas. This can be accomplished very rapidly without having to resort to the MATLAB programs, which are more detailed.

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 some sections of Chapters 14, 16 and 17. The material in Chapters 8 through 16 should be covered in detail 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 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, an ambitious and challenging task. Sufficient topics have been included, however, to make the text complete and to give the teacher the flexibility to emphasize, deemphasize, 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. In some of the basic chapters, the most important equations are summarized in tables.

I will like to acknowledge the invaluable suggestions from all those that contributed to the first three additions of the book, too numerous to mention here. Their names and contributions are stated in the respective editions. It is my pleasure to acknowledge the suggestions of the reviewers for the fourth edition: Dr. Stuart A. Long of the University of Houston, Dr. Leo Kempel of Michigan State University, and Dr. Cynthia M. Furse of the University of Utah. There have been other contributors to this edition, and their contributions are valued and acknowledged. Many graduate and undergraduate students at Arizona State University have written and verified most of the MATLAB computer programs; some of these programs were translated from FORTRAN, which appeared in the first three editions and updated for the fourth edition. However some new MATLAB and JAVA programs have been created, which are included for the first time in the fourth edition. I am indebted to Dr. Alix Rivera-Albino who developed with special care all of the color and gray scale figures and illustrations for the fourth edition and contributed to the manuscript and figures for the Vivaldi and mobile antennas. The author also acknowledges Dr. Razib S. Shishir of Intel, formerly of Arizona State University, for the JAVA-based software for the third edition, including the Interactive Questionnaires, Applets and Animations. These have been supplemented with additional ones for the fourth edition. Many thanks to Dr. Stuart A. Long, from the University of Houston, for reviewing the section on DRAs and Dr. Christos Christodoulou, from the University of New Mexico, for reviewing the manuscript on antennas for mobile devices, Dr. Peter J. Bevelacqua of Google for material related to planar antennas for mobile units, Dr. Arnold Mckinley of University College London (formerly with the Australian National University) for information and computer program related to nonuniform loop antennas, Dr. Steven R. Best of Mitre Corporation for figures on the folded spherical helix, Dr. Edward J. Rothwell, from Michigan State University, for antenna miniaturization information, Dr. Seong-Ook Park of the Korea Advanced Institute of Science and Technology (KAIST), for the photo and permission of the U-slot antenna, and Dr. Yahia Antar and Dr. Jawad Y. Siddiqui, both from the Royal Military College of Canada, for information related to cylindrical DRAs. I would also like to thank Craig R. Birtcher, and my graduate students Dr. Ahmet C. Durgun (now with Intel), Dr. Nafati Aboserwal (now at the University of Oklahoma), Sivaseetharaman Pandi, Mikal Askarian Amiri, Wengang Chen, Saud Saeed and Anuj Modi, all of Arizona State University, for proofreading of the manuscript and many other contributions to the fourth edition.

Special thanks to the companies that contributed photos, illustrations and copyright permissions for the third edition. However, other companies, Samsung, Microsoft and HTC have provided updated photos of their respective smart phones for the fourth edition.

During my 50+ year professional career, I have made many friends and professional colleagues. The list is too long to be included here, as I fear that I may omit someone. Thank you for your friendship, collegiality and comradery. I will like to recognize George C. Barber, Dennis DeCarlo and the entire membership (members, government agencies and companies) of the Advanced Helicopter Electromagnetics (AHE) Program for the 25 years of interest and support. It has been an unprecedented professional partnership and collaboration. To all my teachers and mentors, thank you. You have been my role models and inspiration.

This journey got started in the middle to the late 1970s, at the early stages of my academic career. Many may speculate why I have chosen to remain as the sole author and steward for so many years, dating back to first edition in 1982 and then through the subsequent three editions of this book and two editions of the *Advanced Engineering Electromagnetics* book. I wanted, as long as I was able to accomplish the tasks, to have the books manifest my own fingerprint and reflect my personal philosophy, methodology and pedagogy. Also I wanted the manuscript to display continuity and consistency, and to control my own destiny, in terms of material to be included and excluded, revisions, deadlines and timelines. Finally, I wanted to be responsible for the contents of the book. In the words of Frank Sinatra, 'I did it my way.' Each edition presented its own challenges, but each time I cherished and looked forward to the mission and venture.

I am also grateful to the staff of John Wiley & Sons, Inc., especially Brett Kurzman, Editor, Alex Castro, Editorial Assistant, and Danielle LaCourciere, Production Editor for this edition. Special thanks to Shikha Sharma, from Aptara, Inc., for supervising the typesetting of the book. Finally I must pay tribute and homage to my family (Helen, Renie, Stephanie, Bill, Pete and Ellie) for their unconditional support, patience, sacrifice, and understanding for the many years of neglect during the completion of all four editions of this book and two editions of the *Advanced Engineering Electromagnetics*. Each edition has been a pleasant experience although a daunting task.

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About the Companion Website

There is a student companion website that contains:

- PowerPoint Viewgraphs
- MATLAB Programs
- JAVA Applets
- Animations
- End-of-Chapter Interactive Questionnaires

To access the material on the companion site simply find your unique website redemption code printed on the inside front endpaper of this book. Peel off the sticker and then visit www.wiley.com/go/antennatheory4e to follow the instructions for how to register your pin.

If you have purchased this title as an e-book, Wiley Customer Care will provide your access code for the companion website. Visit <http://support.wiley.com> to request via the “Live Chat” or “Ask A Question” tabs, within 90 days of purchase, and please have your receipt for verification.

This book is also accompanied by a password protected companion website for instructors only. This website contains:

- Power Point Viewgraphs
- MATLAB Programs
- JAVA Applets
- Animations
- End-of-Chapter Interactive Questionnaires
- Solutions Manual

To access the material on the instructor's website simply visit www.wiley.com/go/instructors_antennatheory4e and follow the instructions for how to register.



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