Contents

Symbols, Prefixes and Abbreviations  (Inside front cover and facing inside front cover)
Constants and Conversions  (Facing inside back cover)
Gradient Divergence and Curl in Rectangular, Cylindrical and Spherical Coordinates
   (Inside back cover)
Preface, xv

Chapter 1  Introduction  1
1–1  Introduction  1
     A Short History of Antennas  1
1–2  Dimensions and Units  3
1–3  Fundamental and Secondary Units  3
1–4  How to Read the Symbols and Notation  4
1–5  Equation and Problem Numbering  6
1–6  Dimensional Analysis  6
1–7  The Electromagnetic Spectrum; Radio-Frequency Bands  9
References  10

Chapter 2  Antenna Basics  11
2–1  Introduction  11
2–2  Basic Antenna Parameters  12
2–3  Patterns  14
2–4  Beam Area (or Beam Solid Angle) ΩA  19
2–5  Radiation Intensity  22
2–6  Beam Efficiency  22
2–7  Directivity D and Gain G  23
2–8  Directivity and Resolution  26
2–9  Antenna Apertures  27
2–10  Effective Height  30
2–11  The Radio Communication Link  36
2–12  Fields from Oscillating Dipole  37
2–13  Antenna Field Zones  39
2–14  Shape- Impedance Considerations  40
2–15  Linear, Elliptical and Circular Polarization  44
2–16  Poynting Vector for Elliptically and Circularly Polarized Waves  47
2–17  The Polarization Ellipse and the Poincaré Sphere  47
References  52
Problems  52
Contents

**Chapter 3**

The Antenna Family 57

3-1 Introduction 57
3-2 Loops, Dipoles and Slots 57
3-3 Opened-Out Coaxial-Line Antennas 60
3-4 Opened-Out 2-Conductor (Twin-Line) Antennas 61
3-5 Opened-Out Waveguide Antennas (Aperture Types) 62
3-6 Flat-Sheet Reflector Antennas 63
3-7 Parabolic Dish and Dielectric Lens Antennas 64
3-8 End-Fire Antennas 66
3-9 Broad Bandwidth Antennas: The Conical Spiral and the Log-Periodic 67
3-10 The Patch Antenna, Patch Array, and the Grid Array 67

References 70
Problems 70

**Chapter 4**

Point Sources 72

4-1 Introduction. Point Source Defined 72
4-2 Power Patterns 73
4-3 A Power Theorem and Its Application to an Isotropic Source 75
4-4 Radiation Intensity 75
4-5 Examples of Power Patterns 76
4-6 Field Patterns 81
4-7 Phase Patterns 86

Problems 88

**Chapter 5**

Arrays of Point Sources, Part I 90

5-1 Introduction 90
5-2 Arrays of Two Isotropic Point Sources 90
5-3 Nonisotropic but Similar Point Sources and the Principle of Pattern Multiplication 98
5-4 Example of Pattern Synthesis by Pattern Multiplication 102
5-5 Nonisotropic and Dissimilar Point Sources 106
5-6 Linear Arrays of $n$ Isotropic Point Sources of Equal Amplitude and Spacing 109
5-7 Null Directions for Arrays of $n$ Isotropic Point Sources of Equal Amplitude and Spacing 116

Problems 120

**Chapter 6**

Arrays of Point Sources, Part II 126

5-8 Linear Broadside Arrays with Nonuniform Amplitude Distributions. General Considerations 126
5-9 Linear Arrays with Nonuniform Amplitude Distributions. The Dolph-Tchebyscheff Optimum Distribution 129
## Contents

<table>
<thead>
<tr>
<th>Page</th>
<th>Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-10</td>
<td>Example of Dolph-Tchebyscheff (D-T) Distribution for an Array of Eight Sources</td>
</tr>
<tr>
<td>5-11</td>
<td>Comparison of Amplitude Distributions for Eight-Source Arrays</td>
</tr>
<tr>
<td>5-12</td>
<td>Continuous Arrays</td>
</tr>
<tr>
<td>5-13</td>
<td>Huygens’ Principle</td>
</tr>
<tr>
<td>5-14</td>
<td>Huygens’ Principle Applied to the Diffraction of a Plane Wave Incident on a Flat Sheet. Physical Optics</td>
</tr>
<tr>
<td>5-15</td>
<td>Rectangular-Area Broadside Arrays</td>
</tr>
<tr>
<td>5-16</td>
<td>Arrays with Missing Sources and Random Arrays</td>
</tr>
<tr>
<td>5-17</td>
<td>Broadside versus End-Fire Arrays. Turns versus Dipoles and Three-Dimensional Arrays</td>
</tr>
<tr>
<td>5-18</td>
<td>Directions of Maxima for Arrays of n Isotropic Point Sources of Equal Amplitude and Spacing</td>
</tr>
</tbody>
</table>

References 162

Problems 162

---

### Chapter 6

**The Electric Dipole and Thin Linear Antennas** 165

<table>
<thead>
<tr>
<th>Page</th>
<th>Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-1</td>
<td>The Short Electric Dipole</td>
</tr>
<tr>
<td>6-2</td>
<td>The Fields of a Short Dipole</td>
</tr>
<tr>
<td>6-3</td>
<td>Radiation Resistance of Short Electric Dipole</td>
</tr>
<tr>
<td>6-4</td>
<td>The Thin Linear Antenna</td>
</tr>
<tr>
<td>6-5</td>
<td>Radiation Resistance of λ/2 Antenna</td>
</tr>
<tr>
<td>6-6</td>
<td>Radiation Resistance at a Point Which is not a Current Maximum</td>
</tr>
<tr>
<td>6-7</td>
<td>Two Half-Wave Dipoles: Broadside and End-Fire (The W8JK Array)</td>
</tr>
<tr>
<td>6-8</td>
<td>Fields of a Thin Linear Antenna with a Uniform Traveling Wave</td>
</tr>
</tbody>
</table>

References 193

Problems 193

---

### Chapter 7

**The Loop Antenna** 197

<table>
<thead>
<tr>
<th>Page</th>
<th>Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>7-1</td>
<td>The Small Loop</td>
</tr>
<tr>
<td>7-2</td>
<td>Comparison of Far Fields of Small Loop and Short Dipole</td>
</tr>
<tr>
<td>7-3</td>
<td>The Loop Antenna. General Case</td>
</tr>
<tr>
<td>7-4</td>
<td>Far-Field Patterns of Circular Loop Antennas with Uniform Current</td>
</tr>
<tr>
<td>7-5</td>
<td>The Small Loop as a Special Case</td>
</tr>
<tr>
<td>7-6</td>
<td>Radiation Resistance of Loops</td>
</tr>
<tr>
<td>7-7</td>
<td>Directivity of Circular Loop Antennas with Uniform Current</td>
</tr>
<tr>
<td>7-8</td>
<td>Table of Loop Formulas</td>
</tr>
<tr>
<td>7-9</td>
<td>Square Loops</td>
</tr>
<tr>
<td>7-10</td>
<td>Radiation Efficiency, Q, Bandwidth and Signal-to-Noise Ratio</td>
</tr>
</tbody>
</table>

References 220

Problems 220
Chapter 8

End-Fire Antennas: The Helical Beam Antenna and the Yagi-Uda Array, Part I  222

8–1 The Helical Beam Antenna Story by John Kraus  222
8–2 Helical Geometry  227
8–3 Practical Design Considerations for the Monofilar Axial-Mode Helical Antenna  231
8–4 Helical Beam Antenna with Loops Replacing the Ground Plane  242
8–5 Dipole Arrays with Parasitic Elements  242
8–6 The Yagi-Uda Array Story  246
Problems  249

Chapter 8

The Helical Antenna: Axial and Other Modes, Part II  250

8–7 Introduction  250
8–8 Axial-Mode Patterns and the Phase Velocity of Wave Propagation on Monofilar Helices (Kraus-4)  251
8–9 Monofilar Axial-Mode Single-Turn Patterns of Square Helix  258
8–10 Complete Axial-Mode Patterns of Monofilar Helices  261
8–11 Axial Ratio and Conditions for Circular Polarization of Monofilar Axial-Mode Helical Antennas  263
8–12 Wideband Characteristics of Monofilar Helical Antennas Radiating in the Axial Mode  268
8–13 Table of Pattern, Beamwidth, Gain, Impedance and Axial Ratio Formulas  270
8–14 Radiation from Linear Periodic Structures with Traveling Waves with Particular Reference to the Helix as a Periodic Structure Antenna  271
8–15 Arrays of Monofilar Axial-Mode Helical Antennas  280
8–16 The Monofilar Axial-Mode Helix as a Parasitic Element and Polarizer (see Fig. 8–57)  284
8–17 The Monofilar Axial-Mode Helical Antenna as a Phase and Frequency Shifter  285
8–18 Linear Polarization with Monofilar Axial-Mode Helical Antennas  286
8–19 Monofilar Axial-Mode Helical Antennas as Feeds  287
8–20 Tapered and Other Forms of Axial-Mode Helical Antennas  289
8–21 Multifilar Axial-Mode Helical Antennas  291
8–22 Monofilar and Multifilar Normal-Mode Helical Antennas  292
8–23 Axial-Mode Helix Terminations  297
8–24 Antenna Rotation Experiments  297
8–25 Bifilar and Quadrifilar Axial-Mode Helices  299
8–26 Genetic Algorithm Five-Segment Helix versus Circular Helix  299
References  300
Additional References on Helical Antennas  303
Problems  303
Chapter 9  Slot, Patch and Horn Antennas  304
9-1   Slot Antennas  304
9-2   Patterns of Slot Antennas in Flat Sheets. Edge Diffraction  307
9-3   Babinet’s Principle and Complementary Antennas  311
9-4   The Impedance of Complementary Screens  314
9-5   The Impedance of Slot Antennas  317
9-6   Slotted Cylinder Antennas  321
9-7   Patch or Microstrip Antennas  322
9-8   Horn Antennas  330
9-9   The Rectangular Horn Antenna  333
9-10  Beamwidth Comparison  338
9-11  Conical Horn Antennas  339
9-12  Ridge Horns  339
9-13  Septum Horns  340
9-14  Corrugated Horns  341
9-15  Aperture-Matched Horn  343
References  344
Problems  345

Chapter 10  Flat Sheet, Corner and Parabolic Reflector Antennas  347
10-1  Introduction  347
10-2  Flat Sheet Reflectors  349
10-3  Corner Reflectors  352
10-4  Passive (Retro) Corner Reflector  364
10-5  The Parabola. General Properties  365
10-6  A Comparison between Parabolic and Corner Reflectors  367
10-7  The Paraboloidal Reflector  368
10-8  Patterns of Large Circular Apertures with Uniform Illumination  372
References  375
Problems  375

Chapter 11  Broadband and Frequency-Independent Antennas  378
11-1  Broadband Basics  378
11-2  Infinite and Finite Biconical Antennas  380
11-3  Directional Biconicals, Conicals, Disk Cones and Bow Ties  382
11-4  The Frequency-Independent Concept: Rumsey’s Principle  386
11-5a  The Illinois Story  387
11-5b  The Frequency-Independent Planar Log-Spiral Antenna  387
11-6  The Frequency-Independent Conical-Spiral Antenna  391
11-7  The Log-Periodic Antenna  392
11-8  The Composite Yagi-Uda–Corner–Log-Periodic (YUCOLP) Array  399
Contents

References 399
Problems 400

Chapter 12 Antenna Temperature, Remote Sensing and Radar Cross Section 401
12–1 Antenna Temperature 401
12–2 System Temperature 409
12–3 SNR (Signal-to-Noise Ratio) 411
12–4 Passive Remote Sensing 414
12–5 Radar and Radar Cross Section 417
References 427
Problems 427

Chapter 13 Self and Mutual Impedances 438
13–1 Introduction 438
13–2 Reciprocity Theorem for Antennas 439
13–3 The 73-Ω Radiation Resistance of a λ/2 Antenna 441
13–4 Radiation Resistance at a Point Which is Not a Current Maximum 444
13–5 Self-Impedance of a Thin Linear Antenna 446
13–6 Mutual Impedance of Two Parallel Linear Antennas 448
13–7 Mutual Impedance of Parallel Antennas Side-by-Side 450
13–8 Mutual Impedance of Parallel Collinear Antennas 454
13–9 Mutual Impedance of Parallel Antennas in Echelon 454
13–10 Mutual Impedance of Other Configurations 455
13–11 Mutual Impedance in Terms of Directivity and Radiation Resistance 457
References 459
Problems 459

Chapter 14 The Cylindrical Antenna and the Moment Method (MM) 461
14–1 Introduction 461
14–2 Outline of the Integral-Equation Method 462
14–3 Current Distributions 463
14–4 Input Impedance 465
14–5 Patterns of Cylindrical Antennas 470
14–6 The Thin Cylindrical Antenna 471
14–7 Cylindrical Antennas with Conical Input Sections 472
14–8 Antennas of Other Shapes. The Spheroidal Antenna 472
14–9 Current Distributions on Long Cylindrical Antennas 473
14–10 Integral Equations and the Moment Method (MM) in Electrostatics 477
14–11 The Moment Method (MM) and Its Application to a Wire Antenna 482
14–12 Self-Impedance, Radar Cross Section and Mutual Impedance of Short Dipoles by the Method of Moments by Edward H. Newman 490
Chapter 15  The Fourier Transform Relation between Aperture Distribution and Far-Field Pattern  501

15-1  Continuous Aperture Distribution  501  
15-2  Fourier Transform Relations between the Far-Field Pattern and the Aperture Distribution  503  
15-3  Spatial Frequency Response and Pattern Smoothing  506  
15-4  The Simple (Adding) Interferometer  509  
15-5  Aperture Synthesis and Multiaperture Arrays  518  
15-6  Grating Lobes  520  
15-7  Two-Dimensional Aperture Synthesis  521  
15-8  Phase Closure or Self-Calibration for “Clean” Maps  523  
References 526  
Problems 526  

Chapter 16  Arrays of Dipoles and of Apertures  529  

16-1  Introduction  529  
16-2  Array of Two Driven $\lambda/2$ Elements. Broadside Case  530  
16-3  Array of 2 Driven $\lambda/2$ Elements. End-Fire Case  539  
16-4  Array of 2 Driven $\lambda/2$ Elements. General Case with Equal Currents of Any Phase Relation  544  
16-5  Closely Spaced Elements, Radiating Efficiency and Q. The W8JK Array  548  
16-6  Array of $n$ Driven Elements  553  
16-7  Horizontal Antennas above a Plane Ground  555  
16-8  Vertical Antennas above a Plane Ground  566  
16-9  Yagi-Uda Modifications  570  
16-10  Phased Arrays  572  
16-11  Frequency-Scanning Arrays  576  
16-12  Retroarrays. The Van Atta Array  581  
16-13  Adaptive Arrays and Smart Antennas  582  
16-14  Microstrip Arrays  584  
16-15  Low-Side-Lobe Arrays  585  
16-16  Long-Wire Antennas  585  
16-17  Curtain Arrays  591  
16-18  Location and Method of Feeding Antennas  592  
16-19  Folded Dipole Antennas  593  
16-20  Modifications of Folded Dipoles  596  
16-21  Argus Type All-Sky Surveillance Antennas  597  
References 599  
Additional References on Adaptive Arrays  601  
Problems 602  

References 499  
Problems 500
### Chapter 17  
**Lens Antennas**  607  
17-1 Introduction  607  
17-2 Nonmetallic Dielectric Lens Antennas. Fermat’s Principle  
   (Equality of Path Length)  609  
17-3 Artificial Dielectric Lens Antennas  616  
17-4 E-Plane Metal-Plate Lens Antennas  619  
17-5 Tolerances on Lens Antennas  625  
17-6 H-Plane Metal-Plate Lens Antennas  627  
17-7 Reflector-Lens Antenna  628  
17-8 Polyrods  629  
17-9 Multiple-Helix Lenses  631  
17-10 Luneburg and Einstein Lenses  632  
References  634  
Problems  635  

**Chapter 18**  
**Frequency-Selective Surfaces and Periodic Structures**  
By Ben A. Munk  636  
18-1 Introduction. Definition of FSS  636  
18-2 The Halfwave Dielectric Radome  638  
18-3 Slotted Metal Radome  639  
18-4 The Simple Hybrid Radome  641  
18-5 The Ideal Stealth Radome  642  
18-6 Transmission and Reflection Properties of Simple Periodic Surfaces of Wires  642  
18-7 Complementary Surfaces and Babinet’s Principle  646  
18-8 Oblique Angle of Incidence  646  
18-9 On the Shape and Development of Elements  647  
18-10 Controlling Bandwidth with Angle of Incidence and Polarization  651  
18-11 Other Applications  654  
References  658  
Problems  659  

**Chapter 19**  
**Practical Design Considerations of Large Aperture Antennas**  660  
19-1 Aperture Distributions and Efficiencies  660  
19-2 Surface Irregularities and Gain Loss  673  
19-3 Off-Axis Operation of Parabolic Reflectors  678  
19-4 Cassegrain Feed, Shaped Reflectors, Spherical Reflectors and Offset Feed  680  
19-5 Low-Side-Lobe Considerations  684  
References  687  
Additional References for Further Reading  688  
Problems  689
Chapter 20  Some Examples of Large or Unique Antennas  691
Bonn  691
Arecibo  691
Bell Telephone Laboratories  694
Nobeyama  695
Ohio  696
Gorki  698
Five College Observatory  699
Nancay  701
RATAN-600  701
Parkes  702
Manchester  702
VLA  702
Nauen  703
Green Bank  705
References  707

Chapter 21  Antennas for Special Applications  708
21-1  Introduction  708
21-2  Electrically Small Antennas  709
21-3  Physically Small Antennas  712
21-4  Antenna Siting and the Effect of Typical (Imperfect) Ground  713
21-5  Ground-Plane Antennas  719
21-6  Sleeve Antennas  721
21-7  Turnstile Antenna  722
21-8  Superturnstile Antenna  724
21-9  Other Omnidirectional Antennas  726
21-10  Circularly Polarized Antennas  727
21-11  The High-Gain Omni  729
21-12  Submerged Antennas  729
21-13  Surface-Wave and Leaky-Wave Antennas  734
21-14  Antenna Design Considerations for Satellite Communication  742
21-15  Receiving versus Transmitting Considerations  746
21-16  Bandwidth Considerations  748
21-17  Architecturally Acceptable Antennas  748
21-18  ILS (Instrument Landing System) Antennas  750
21-19  The “Sugar Scoop Antenna” and the 3K Cosmic Sky Background Story  755
21-20  LEO Satellite Link Antennas  760
21-21  Asteroid Detection Antenna  769
21-22  Leaky Transmission Lines as Antennas  771
21-23  Artistic Antennas (Fractals)  772
21-24  Cell-Tower trees  772
21-25  Antennas for Terrestrial Mobile Communications Systems by Pertti Vainikainen  775
Appendix A  Tables for References  888
A-1  Table of Antenna and Antenna System Relations  888
A-2  Formulas for Input Impedance of Terminated Transmission Lines  890
A-3  Reflection and Transmission Coefficients and VSWR  891
A-4  Characteristic Impedance of Coaxial, 2-Wire and MicroStrip Transmission Lines  891
A-5  Characteristic Impedance of Transmission Lines in Terms of Distributed Parameters  892
A-6  Material Constants (Permittivity, Conductivity and Dielectric Strength)  893
A-7  Permittivity Relations  894
A-8  Maxwell’s Equations  894

Appendix B  Books, Tapes and Articles  896
B-1  Books  896
B-2  Video Tapes  899
B-3  Selected Articles for Further Reading  900

Appendix C  Computer Programs (Code)  904
C-1  Introduction  904
C-2  Software Modeling Philosophy  905
C-3  Codes Illustrating Results in Antennas  906
C-4  Expert MININEC for Students  907
C-5  Other Useful Codes  907
References  907
References for Further Reading on Antenna Computer Simulation  908

Appendix D  Absorbing Materials  909
References  913

Appendix E  Measurement Error  914

Appendix F  Answers to Starred Problems  915

Index  921