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) Ω_A 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

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 5 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

5–10 Example of Dolph-Tchebyscheff (D-T) Distribution for an Array of Eight Sources 137
5–11 Comparison of Amplitude Distributions for Eight-Source Arrays 139
5–12 Continuous Arrays 140
5–13 Huygens' Principle 144
5–14 Huygens' Principle Applied to the Diffraction of a Plane Wave Incident on a Flat Sheet. Physical Optics 147
5–15 Rectangular-Area Broadside Arrays 150
5–16 Arrays with Missing Sources and Random Arrays 152
5–17 Broadside versus End-Fire Arrays. Turns versus Dipoles and Three-Dimensional Arrays 154
5–18 Directions of Maxima for Arrays of n Isotropic Point Sources of Equal Amplitude and Spacing 159
References 162
Problems 162

Chapter 6 The Electric Dipole and Thin Linear Antennas 165

6–1 The Short Electric Dipole 165
6–2 The Fields of a Short Dipole 166
6–3 Radiation Resistance of Short Electric Dipole 175
6–4 The Thin Linear Antenna 177
6–5 Radiation Resistance of $\lambda/2$ Antenna 181
6–6 Radiation Resistance at a Point Which is not a Current Maximum 182
6–7 Two Half-Wave Dipoles: Broadside and End-Fire (The W8JK Array) 183
6–8 Fields of a Thin Linear Antenna with a Uniform Traveling Wave 187
References 193
Problems 193

Chapter 7 The Loop Antenna 197

7–1 The Small Loop 197
7–2 Comparison of Far Fields of Small Loop and Short Dipole 199
7–3 The Loop Antenna. General Case 200
7–4 Far-Field Patterns of Circular Loop Antennas with Uniform Current 202
7–5 The Small Loop as a Special Case 205
7–6 Radiation Resistance of Loops 206
7–7 Directivity of Circular Loop Antennas with Uniform Current 209
7–8 Table of Loop Formulas 212
7–9 Square Loops 212
7–10 Radiation Efficiency, Q, Bandwidth and Signal-to-Noise Ratio 214
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

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 $\lambda/2$ 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

References 499
Problems 500

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

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

21–26 Antennas for Ground Penetrating Radar (GPR): Pulse Bandwidth 781
21–27 Embedded Antennas 784
21–28 Ultra-Wide-Band (UWB) Antennas for Digital Applications 785
21–29 The Plasma Antenna 788
References 789
Problems 792

Chapter 22 Terahertz Antennas 796

22–1 Introduction 796
22–2a Pyramidal Horn Cavity with Dipole 797
22–2b Corner Reflector Array 798
22–2c Bow-Tie Dipole 798
22–3 A 600-THz Antenna? 798
22–4 Planar Antenna Structures on Dielectric Lenses 799
22–5 THz Waveguide Structures 800
References 802

Chapter 23 Baluns, etc. By Ben A. Munk 803

23–1 Introduction 803
23–2 Balun Types I, II and III and Choke Baluns 803
23–3 Bandwidth 806
23–4a Sleeve-Dipole Baluns 808
23–4b Modifications 808
23–5 Mast Balun 810
23–6 Printed Baluns 810
23–7 The $\lambda/2$ Bypass Balun 813
23–8 Balanced Transformer 815
23–9 Cutaway Baluns 818
23–10 Natural Baluns 821
23–11 Folded Dipole to J-Match 822
23–12 Matching Stubs 823
23–13 Traps 823
23–14 Conclusion 824
References 825
Additional References 825
Problems 825

Chapter 24 Antenna Measurements. By Arto Lehto and Pertti Vainikainen 827

24–1 Introduction 827
24–2 Basic Concepts 828
24–3 Typical Sources of Error in Antenna Measurements 835

24–4 Measurement Ranges 838
24–5 Measurement of Different Antenna Parameters 854
24–6 Miscellaneous Topics 873
References 883
Problems 885

Appendix A Tables for References 888

A–1 Table of Antena 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 (Codes) 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