## Contents

**Preface** xvi

**Acknowledgments** xvii

**Acronyms** xix

**Contributors** xxv

1 **Antenna Basics**

*Luigi Boccia and Olav Breinbjerg*

1.1 Introduction 1

1.2 Antenna Performance Parameters 2

1.2.1 Reflection Coefficient and Voltage Standing Wave Ratio 2

1.2.2 Antenna Impedance 3

1.2.3 Radiation Pattern and Coverage 4

1.2.4 Polarization 6

1.2.5 Directivity 7

1.2.6 Gain and Realized Gain 8

1.2.7 Equivalent Isotropically Radiated Power 8

1.2.8 Effective Area 9

1.2.9 Phase Center 9

1.2.10 Bandwidth 9

1.2.11 Antenna Noise Temperature 9

1.3 Basic Antenna Elements 10

1.3.1 Wire Antennas 10

1.3.2 Horn Antennas 10

1.3.3 Reflectors 15

1.3.4 Helical Antennas 17

1.3.5 Printed Antennas 19

1.4 Arrays 26

1.4.1 Array Configurations 28

1.5 Basic Effects of Antennas in the Space Environment 30

1.5.1 Multipaction 30

1.5.2 Passive Inter-modulation 31

1.5.3 Outgassing 31

References 32
2 Space Antenna Modeling
Jian Feng Zhang, Xue Wei Ping, Wen Ming Yu, Xiao Yang Zhou, and Tie Jun Cui

2.1 Introduction
2.1.1 Maxwell’s Equations 37
2.1.2 CEM 37

2.2 Methods of Antenna Modeling
2.2.1 Basic Theory 39
2.2.2 Method of Moments 40
2.2.3 FEM 45
2.2.4 FDTD Method 49

2.3 Fast Algorithms for Large Space Antenna Modeling
2.3.1 Introduction 54
2.3.2 MLFMA 54
2.3.3 Hierarchical Basis for the FEM 62

2.4 Case Studies: Effects of the Satellite Body on the Radiation Patterns of Antennas 68

2.5 Summary 73

Acknowledgments 73
References 73

Michael A. Thorburn

3.1 Introduction 76
3.2 Elements of Satellite System Architecture 76
3.3 Satellite Missions 77
3.4 Communications Satellites 77
3.4.1 Fixed Satellite Services 77
3.4.2 Broadcast Satellite Services (Direct Broadcast Services) 78
3.4.3 Digital Audio Radio Services 78
3.4.4 Direct to Home Broadband Services 78
3.4.5 Mobile Communications Services 78

3.5 Radar Satellites 79
3.6 Navigational Satellites 79
3.7 Remote Sensing Satellites 80
3.8 Architecture of Satellite Command and Control 80

3.9 The Communications Payload Transponder 80
3.9.1 Bent-Pipe Transponders 81
3.9.2 Digital Transponders 81
3.9.3 Regenerative Repeater 81

3.10 Satellite Functional Requirements 81
3.10.1 Key Performance Concepts: Coverage, Frequency Allocations 82
3.10.2 Architecture of the Communications Payload 82
3.10.3 Satellite Communications System Performance Requirements 83

3.11 The Satellite Link Equation 83

3.12 The Microwave Transmitter Block 84
3.12.1 Intercept Point 85
3.12.2 Output Backoff 86
3.12.3 The Transmit Antenna and EIRP 87
3.13 Rx Front-End Block
  3.13.1 Noise Figure and Noise Temperature 88
3.14 Received Power in the Communications System’s RF Link 90
  3.14.1 The Angular Dependencies of the Uplink and Downlink 91
3.15 Additional Losses in the Satellite and Antenna 91
  3.15.1 Additional Losses due to Propagation Effects and the Atmosphere 91
  3.15.2 Ionospheric Effects – Scintillation and Polarization Rotation 93
3.16 Thermal Noise and the Antenna Noise Temperature 93
  3.16.1 The Interface between the Antenna and the Communications System 93
  3.16.2 The Uplink Signal to Noise 94
3.17 The SNR Equation and Minimum Detectable Signal 94
3.18 Power Flux Density, Saturation Flux Density and Dynamic Range 95
  3.18.1 Important Relationship between PFD and Gain State of the Satellite Transponder 95
3.19 Full-Duplex Operation and Passive Intermodulation 96
3.20 Gain and Gain Variation 96
3.21 Pointing Error 97
3.22 Remaining Elements of Satellite System Architecture 98
3.23 Orbits and Orbital Considerations 98
3.24 Spacecraft Introduction 100
3.25 Spacecraft Budgets (Mass, Power, Thermal) 101
  3.25.1 Satellite Mass 101
  3.25.2 Satellite Power 101
  3.25.3 Satellite Thermal Dissipation 101
3.26 Orbital Mission Life and Launch Vehicle Considerations 102
3.27 Environment Management (Thermal, Radiation) 102
3.28 Spacecraft Structure (Acoustic/Dynamic) 103
3.29 Satellite Positioning (Station Keeping) 103
3.30 Satellite Positioning (Attitude Control) 104
3.31 Power Subsystem 104
3.32 Tracking, Telemetry, Command and Monitoring 105
3.33 References 105

4 Space Environment and Materials 106
   J. Santiago-Prowald and L. Salghetti Drioli
   4.1 Introduction 106
   4.2 The Space Environment of Antennas 106
     4.2.1 The Radiation Environment 107
     4.2.2 The Plasma Environment 109
     4.2.3 The Neutral Environment 110
     4.2.4 Space Environment for Typical Spacecraft Orbits 111
     4.2.5 Thermal Environment 111
     4.2.6 Launch Environment 113
   4.3 Selection of Materials in Relation to Their Electromagnetic Properties 117
     4.3.1 RF Transparent Materials and Their Use 117
     4.3.2 RF Conducting Materials and Their Use 117
     4.3.3 Material Selection Golden Rules for PIM Control 118
4.4 Space Materials and Manufacturing Processes
4.4.1 Metals and Their Alloys
4.4.2 Polymer Matrix Composites
4.4.3 Ceramics and Ceramic Matrix Composites
4.5 Characterization of Mechanical and Thermal Behaviour
4.5.1 Thermal Vacuum Environment and Outgassing Screening
4.5.2 Fundamental Characterization Tests of Polymers and Composites
4.5.3 Characterization of Mechanical Properties
4.5.4 Thermal and Thermoelastic Characterization
Acknowledgements
References

5 Mechanical and Thermal Design of Space Antennas
J. Santiago-Prowald and Heiko Ritter

5.1 Introduction: The Mechanical–Thermal–Electrical Triangle
5.1.1 Antenna Product
5.1.2 Configuration, Materials and Processes
5.1.3 Review of Requirements and Their Verification
5.2 Design of Antenna Structures
5.2.1 Typical Design Solutions for Reflectors
5.2.2 Structural Description of the Sandwich Plate Architecture
5.2.3 Thermal Description of the Sandwich Plate Architecture
5.2.4 Electrical Description of the Sandwich Plate Architecture in Relation to Thermo-mechanical Design
5.3 Structural Modelling and Analysis
5.3.1 First-Order Plate Theory
5.3.2 Higher Order Plate Theories
5.3.3 Classical Laminated Plate Theory
5.3.4 Homogeneous Isotropic Plate Versus Symmetric Sandwich Plate
5.3.5 Skins Made of Composite Material
5.3.6 Honeycomb Core Characteristics
5.3.7 Failure Modes of Sandwich Plates
5.3.8 Mass Optimization of Sandwich Plate Architecture for Antennas
5.3.9 Finite Element Analysis
5.3.10 Acoustic Loads on Antennas
5.4 Thermal and Thermoelastic Analysis
5.4.1 The Thermal Environment of Space Antennas
5.4.2 Transverse Thermal Conductance Model of the Sandwich Plate
5.4.3 Thermal Balance of the Flat Sandwich Plate
5.4.4 Thermal Distortions of a Flat Plate in Space
5.4.5 Thermoelastic Stability of an Offset Parabolic Reflector
5.4.6 Thermal Analysis Tools
5.4.7 Thermal Analysis Cases
5.4.8 Thermal Model Uncertainty and Margins
5.5 Thermal Control Strategies
5.5.1 Requirements and Principal Design Choices

References
13.2 Challenges of Antenna Design for SAR 518
  13.2.1 Reflector Antennas 518
  13.2.2 Active Antennas and Subsystems 519

13.3 A Review of the Development of Antennas for Spaceborne SAR 534
  13.3.1 TecSAR 534
  13.3.2 SAR-Lupe 535
  13.3.3 ASAR (EnviSat) 535
  13.3.4 Radarsat 1 535
  13.3.5 Radarsat 2 535
  13.3.6 Palsar (ALOS) 535
  13.3.7 TerraSAR-X 536
  13.3.8 COSMO (SkyMed) 536

13.4 Case Studies of Antennas for Spaceborne SAR 539
  13.4.1 Instrument Design 539
  13.4.2 SAR Antenna 540

13.5 Ongoing Developments in SAR Antennas 544
  13.5.1 Sentinel 1 544
  13.5.2 Saocom Mission 544
  13.5.3 ALOS 2 545
  13.5.4 COSMO Second Generation 545

13.6 Acknowledgments 546
References 546

14 Antennas for Global Navigation Satellite System Receivers 548
  Chi-Chih Chen, Steven (Shichang) Gao, and Moazam Maqsood 548

14.1 Introduction 548

14.2 RF Requirements of GNSS Receiving Antenna 551
  14.2.1 General RF Requirements 551
  14.2.2 Advanced Requirements for Enhanced Position Accuracy and Multipath Signal Suppression 556

14.3 Design Challenges and Solutions for GNSS Antennas 561
  14.3.1 Wide Frequency Coverage 562
  14.3.2 Antenna Delay Variation with Frequency and Angle 562
  14.3.3 Antenna Size Reduction 567
  14.3.4 Antenna Platform Scattering Effect 568

14.4 Common and Novel GNSS Antennas 572
  14.4.1 Single-Element Antenna 572
  14.4.2 Multi-element Antenna Array 580

14.5 Spaceborne GNSS Antennas 582
  14.5.1 Requirements for Antennas On Board Spaceborne GNSS Receivers 582
  14.5.2 A Review of Antennas Developed for Spaceborne GNSS Receivers 584

14.6 Case Study: Dual-Band Microstrip Patch Antenna for Spacecraft Precise Orbit Determination Applications 586
  14.6.1 Antenna Development 586
  14.6.2 Results and Discussions 588

14.7 Summary 591
References 592
15 Antennas for Small Satellites
Steven (Shichang) Gao, Keith Clark, Jan Zackrisson, Kevin Maynard, Luigi Boccia, and Jiadong Xu

15.1 Introduction to Small Satellites 596
15.1.1 Small Satellites and Their Classification 596
15.1.2 Microsatellites and Constellations of Small Satellites 597
15.1.3 Cube Satellites 598
15.1.4 Formation Flying of Multiple Small Satellites 599

15.2 The Challenges of Designing Antennas for Small Satellites 600
15.2.1 Choice of Operating Frequencies 600
15.2.2 Small Ground Planes Compared with the Operational Wavelength 601
15.2.3 Coupling between Antennas and Structural Elements 601
15.2.4 Antenna Pattern 602
15.2.5 Orbital Height 602
15.2.6 Development Cost 602
15.2.7 Production Costs 602
15.2.8 Testing Costs 602
15.2.9 Deployment Systems 603
15.2.10 Volume 603
15.2.11 Mass 603
15.2.12 Shock and Vibration Loads 603
15.2.13 Material Degradation 603
15.2.14 Atomic Oxygen 603
15.2.15 Material Outgassing 604
15.2.16 Creep 604
15.2.17 Material Charging 604
15.2.18 The Interaction between Satellite Antennas and Structure 604

15.3 Review of Antenna Development for Small Satellites 606
15.3.1 Antennas for Telemetry, Tracking and Command (TT&C) 606
15.3.2 Antennas for High-Rate Data Downlink 609
15.3.3 Antennas for Global Navigation Satellite System (GNSS) Receivers and Reflectometry 615
15.3.4 Antennas for Intersatellite Links 618
15.3.5 Other Antennas 619

15.4 Case Studies 621
15.4.1 Case Study 1: Antenna Pointing Mechanism and Horn Antenna 621
15.4.2 Case Study 2: X-band Downlink Helix Antenna 623

15.5 Conclusions 627

References 628

16 Space Antennas for Radio Astronomy
Paul F. Goldsmith

16.1 Introduction 629
16.2 Overview of Radio Astronomy and the Role of Space Antennas 629
16.3 Space Antennas for Cosmic Microwave Background Studies 631
16.3.1 The Microwave Background 631
18.4.3 Promising Antenna Concepts and Technologies 702
18.5 Increase Telecommunication Satellite Throughput 707
  18.5.1 Problem Area and Challenges 707
  18.5.2 Present and Expected Future Space Missions 707
  18.5.3 Promising Antenna Concepts and Technologies 708
18.6 Enable Sharing the Same Aperture for Multiband and Multipurpose Antennas 709
  18.6.1 Problem Area and Challenges 709
  18.6.2 Present and Expected Future Space Missions 710
  18.6.3 Promising Antenna Concepts and Technologies 710
18.7 Increase the Competitiveness of Well-Established Antenna Products 710
  18.7.1 Problem Area and Challenges 710
  18.7.2 Present and Expected Future Space Missions 711
  18.7.3 Promising Antenna Concepts and Technologies 712
18.8 Enable Single-Beam In-Flight Coverage/Polarization Reconfiguration 713
  18.8.1 Problem Area and Challenges 713
  18.8.2 Present and Expected Future Space Missions 714
  18.8.3 Promising Antenna Concepts and Technologies 714
18.9 Enable Active Antennas at Affordable Cost 715
  18.9.1 Problem Area and Challenges 715
  18.9.2 Present and Expected Future Space Missions 717
  18.9.3 Promising Antenna Concepts and Technologies 718
18.10 Develop Innovative Antennas for Future Earth Observation and Science Instruments 724
  18.10.1 Problem Area and Challenges 724
  18.10.2 Present and Expected Future Space Missions 725
  18.10.3 Promising Antenna Concepts and Technologies 729
18.11 Evolve Towards Mass Production of Satellite and User Terminal Antennas 732
  18.11.1 Problem Area and Challenges 732
  18.11.2 Present and Expected Future Space Missions 732
  18.11.3 Promising Antenna Concepts and Technologies 732
18.12 Technology Push for Enabling New Missions 734
  18.12.1 Problem Area and Challenges 734
  18.12.2 Promising Antenna Concepts and Technologies 734
18.13 Develop New Approaches for Satellite/Antenna Modelling and Testing 735
  18.13.1 Problem Area and Challenges 735
  18.13.2 Promising Antenna Concepts and Technologies 736
18.14 Conclusions 737
Acronyms 738
Acknowledgements 740
References 740
Index 741