

Understanding GPS/GNSS

Principles and Applications

Third Edition

Contents

| | |
|---|------------|
| Preface to the Third Edition | <i>xix</i> |
| Third Edition Acknowledgments | <i>xxi</i> |
| CHAPTER 1 | |
| Introduction | 1 |
| 1.1 Introduction | 1 |
| 1.2 GNSS Overview | 2 |
| 1.3 Global Positioning System | 3 |
| 1.4 Russian GLONASS System | 4 |
| 1.5 Galileo Satellite System | 5 |
| 1.6 Chinese BeiDou System | 7 |
| 1.7 Regional Systems | 8 |
| 1.7.1 Quasi-Zenith Satellite System (QZSS) | 8 |
| 1.7.2 Navigation with Indian Constellation (NavIC) | 10 |
| 1.8 Augmentations | 10 |
| 1.9 Markets and Applications | 11 |
| 1.10 Organization of the Book | 12 |
| References | 18 |
| CHAPTER 2 | |
| Fundamentals of Satellite Navigation | 19 |
| 2.1 Concept of Ranging Using Time-of-Arrival Measurements | 19 |
| 2.1.1 Two-Dimensional Position Determination | 19 |
| 2.1.2 Principle of Position Determination via Satellite-Generated Ranging Codes | 22 |
| 2.2 Reference Coordinate Systems | 24 |
| 2.2.1 Earth-Centered Inertial (ECI) Coordinate System | 25 |
| 2.2.2 Earth-Centered Earth-Fixed (ECEF) Coordinate System | 26 |
| 2.2.3 Local Tangent Plane (Local Level) Coordinate Systems | 28 |
| 2.2.4 Local Body Frame Coordinate Systems | 30 |
| 2.2.5 Geodetic (Ellipsoidal) Coordinates | 31 |

| | | |
|-------|--|----|
| 2.2.6 | Height Coordinates and the Geoid | 34 |
| 2.2.7 | International Terrestrial Reference Frame (ITRF) | 36 |
| 2.3 | Fundamentals of Satellite Orbits | 37 |
| 2.3.1 | Orbital Mechanics | 37 |
| 2.3.2 | Constellation Design | 45 |
| 2.4 | GNSS Signals | 52 |
| 2.4.1 | Radio Frequency Carrier | 52 |
| 2.4.2 | Modulation | 53 |
| 2.4.3 | Secondary Codes | 57 |
| 2.4.4 | Multiplexing Techniques | 57 |
| 2.4.5 | Signal Models and Characteristics | 58 |
| 2.5 | Positioning Determination Using Ranging Codes | 65 |
| 2.5.1 | Determining Satellite-to-User Range | 65 |
| 2.5.2 | Calculation of User Position | 69 |
| 2.6 | Obtaining User Velocity | 73 |
| 2.7 | Frequency Sources, Time, and GNSS | 76 |
| 2.7.1 | Frequency Sources | 76 |
| 2.7.2 | Time and GNSS | 85 |
| | References | 86 |

CHAPTER 3

| | | |
|-------|--|-----|
| | Global Positioning System | 89 |
| 3.1 | Overview | 89 |
| 3.1.1 | Space Segment Overview | 89 |
| 3.1.2 | Control Segment Overview | 90 |
| 3.1.3 | User Segment Overview | 90 |
| 3.2 | Space Segment Description | 91 |
| 3.2.1 | GPS Satellite Constellation Description | 91 |
| 3.2.2 | Constellation Design Guidelines | 94 |
| 3.2.3 | Space Segment Phased Development | 96 |
| 3.3 | Control Segment Description | 117 |
| 3.3.1 | OCS Current Configuration | 118 |
| 3.3.2 | OCS Transition | 133 |
| 3.3.3 | OCS Planned Upgrades | 136 |
| 3.4 | User Segment | 137 |
| 3.4.1 | GNSS Receiver Characteristics | 137 |
| 3.5 | GPS Geodesy and Time Scale | 142 |
| 3.5.1 | Geodesy | 142 |
| 3.5.2 | Time Systems | 143 |
| 3.6 | Services | 145 |
| 3.6.1 | SPS Performance Standard | 145 |
| 3.6.2 | PPS Performance Standard | 148 |
| 3.7 | GPS Signals | 150 |
| 3.7.1 | Legacy Signals | 152 |
| 3.7.2 | Modernized Signals | 167 |
| 3.7.3 | Civil Navigation (CNAV) and CNAV-2 Navigation Data | 175 |

| | | |
|-------|---|-----|
| 3.8 | GPS Ephemeris Parameters and Satellite Position Computation | 180 |
| 3.8.1 | Legacy Ephemeris Parameters | 181 |
| 3.8.2 | CNAV and CNAV-2 Ephemeris Parameters | 183 |
| | References | 185 |

CHAPTER 4

| | | |
|-------|---|-----|
| | GLONASS | 191 |
| 4.1 | Introduction | 191 |
| 4.2 | Space Segment | 192 |
| 4.2.1 | Constellation | 192 |
| 4.2.2 | Spacecraft | 194 |
| 4.3 | Ground Segment | 198 |
| 4.3.1 | System Control Center (SCC) | 198 |
| 4.3.2 | Central Synchronizer (CS) | 199 |
| 4.3.3 | Telemetry, Tracking, and Command (TT&C) | 200 |
| 4.3.4 | Laser Ranging Stations (SLR) | 200 |
| 4.4 | GLONASS User Equipment | 200 |
| 4.5 | Geodesy and Time Systems | 201 |
| 4.5.1 | Geodetic Reference System | 201 |
| 4.5.2 | GLONASS Time | 202 |
| 4.6 | Navigation Services | 203 |
| 4.7 | Navigation Signals | 204 |
| 4.7.1 | FDMA Navigation Signals | 204 |
| 4.7.2 | Frequencies | 205 |
| 4.7.3 | Modulation | 206 |
| 4.7.4 | Code Properties | 206 |
| 4.7.5 | GLONASS P-Code | 207 |
| 4.7.6 | Navigation Message | 208 |
| 4.7.7 | C/A Navigation Message | 209 |
| 4.7.8 | P-Code Navigation Message | 209 |
| 4.7.9 | CDMA Navigation Signals | 210 |
| | Acknowledgments | 213 |
| | References | 214 |

CHAPTER 5

| | | |
|-------|---------------------------------|-----|
| | Galileo | 217 |
| 5.1 | Program Overview and Objectives | 217 |
| 5.2 | Galileo Implementation | 218 |
| 5.3 | Galileo Services | 219 |
| 5.3.1 | Galileo Open Service | 219 |
| 5.3.2 | Public Regulated Service | 220 |
| 5.3.3 | Commercial Service | 220 |
| 5.3.4 | Search and Rescue Service | 220 |
| 5.3.5 | Safety of Life | 221 |
| 5.4 | System Overview | 221 |

| | | |
|-------|--|-----|
| 5.4.1 | Ground Mission Segment | 224 |
| 5.4.2 | Ground Control Segment | 231 |
| 5.4.3 | Space Segment | 231 |
| 5.4.4 | Launchers | 240 |
| 5.5 | Galileo Signal Characteristics | 240 |
| 5.5.1 | Galileo Spreading Codes and Sequences | 245 |
| 5.5.2 | Navigation Message Structure | 245 |
| 5.5.3 | Forward Error Correction Coding and Block Interleaving | 248 |
| 5.6 | Interoperability | 248 |
| 5.6.1 | Galileo Terrestrial Reference Frame | 249 |
| 5.6.2 | Time Reference Frame | 249 |
| 5.7 | Galileo Search and Rescue Mission | 250 |
| 5.7.1 | SAR/Galileo Service Description | 251 |
| 5.7.2 | European SAR/Galileo Coverage and MEOSAR Context | 251 |
| 5.7.3 | Overall SAR/Galileo System Architecture | 252 |
| 5.7.4 | SAR Frequency Plan | 257 |
| 5.8 | Galileo System Performance | 259 |
| 5.8.1 | Timing Performance | 259 |
| 5.8.2 | Ranging Performance | 260 |
| 5.8.3 | Positioning Performance | 265 |
| 5.8.4 | Final Operation Capability Expected Performances | 266 |
| 5.9 | System Deployment Completion up to FOC | 267 |
| 5.10 | Galileo Evolution Beyond FOC | 269 |
| | References | 269 |

CHAPTER 6

| | | |
|-------|--|-----|
| | BeiDou Navigation Satellite System (BDS) | 273 |
| 6.1 | Overview | 273 |
| 6.1.1 | Introduction to BDS | 273 |
| 6.1.2 | BDS Evolution | 275 |
| 6.1.3 | BDS Characteristics | 280 |
| 6.2 | BDS Space Segment | 281 |
| 6.2.1 | BDS Constellation | 281 |
| 6.2.2 | BDS Satellites | 286 |
| 6.3 | BDS Control Segment | 287 |
| 6.3.1 | Configuration of the BDS Control Segment | 287 |
| 6.3.2 | Operation of the BDS Control Segment | 288 |
| 6.4 | Geodesy and Time Systems | 290 |
| 6.4.1 | BDS Coordinate System | 290 |
| 6.4.2 | BDS Time System | 291 |
| 6.5 | The BDS Services | 291 |
| 6.5.1 | BDS Service Types | 291 |
| 6.5.2 | BDS RDSS Service | 292 |
| 6.5.3 | BDS RNSS Service | 293 |
| 6.5.4 | BDS SBAS Service | 296 |

| | | |
|-------|---|-----|
| 6.6 | BDS Signals | 297 |
| 6.6.1 | RDSS Signals | 297 |
| 6.6.2 | RNSS Signals of the BDS Regional System | 298 |
| 6.6.3 | RNSS Signals of the BDS Global System | 306 |
| | References | 310 |

CHAPTER 7

| | | |
|-------|--|-----|
| | Regional SATNAV Systems | 313 |
| 7.1 | Quasi-Zenith Satellite System | 313 |
| 7.1.1 | Overview | 313 |
| 7.1.2 | Space Segment | 313 |
| 7.1.3 | Control Segment | 317 |
| 7.1.4 | Geodesy and Time Systems | 319 |
| 7.1.5 | Services | 319 |
| 7.1.6 | Signals | 321 |
| 7.2 | Navigation with Indian Constellation (NavIC) | 325 |
| 7.2.1 | Overview | 325 |
| 7.2.2 | Space Segment | 326 |
| 7.2.3 | NavIC Control Segment | 328 |
| 7.2.4 | Geodesy and Time Systems | 330 |
| 7.2.5 | Navigation Services | 332 |
| 7.2.6 | Signals | 333 |
| 7.2.7 | Applications and NavIC User Equipment | 334 |
| | References | 336 |

CHAPTER 8

| | | |
|-------|---|-----|
| | GNSS Receivers | 339 |
| 8.1 | Overview | 339 |
| 8.1.1 | Antenna Elements and Electronics | 341 |
| 8.1.2 | Front End | 342 |
| 8.1.3 | Digital Memory (Buffer and Multiplexer) and Digital Receiver Channels | 342 |
| 8.1.4 | Receiver Control and Processing and Navigation Control and Processing | 343 |
| 8.1.5 | Reference Oscillator and Frequency Synthesizer | 343 |
| 8.1.6 | User and/or External Interfaces | 343 |
| 8.1.7 | Alternate Receiver Control Interface | 344 |
| 8.1.8 | Power Supply | 344 |
| 8.1.9 | Summary | 344 |
| 8.2 | Antennas | 344 |
| 8.2.1 | Desired Attributes | 345 |
| 8.2.2 | Antenna Designs | 346 |
| 8.2.3 | Axial Ratio | 347 |
| 8.2.4 | VSWR | 351 |
| 8.2.5 | Antenna Noise | 352 |

| | | |
|--------|---|-----|
| 8.2.6 | Passive Antenna | 354 |
| 8.2.7 | Active Antenna | 354 |
| 8.2.8 | Smart Antenna | 355 |
| 8.2.9 | Military Antennas | 355 |
| 8.3 | Front End | 356 |
| 8.3.1 | Functional Description | 357 |
| 8.3.2 | Gain | 358 |
| 8.3.3 | Downconversion Scheme | 359 |
| 8.3.4 | Output to ADC | 360 |
| 8.3.5 | ADC, Digital Gain Control, and Analog Frequency Synthesizer Functions | 361 |
| 8.3.6 | ADC Implementation Loss and a Design Example | 362 |
| 8.3.7 | ADC Sampling Rate and Antialiasing | 367 |
| 8.3.8 | ADC Undersampling | 370 |
| 8.3.9 | Noise Figure | 372 |
| 8.3.10 | Dynamic Range, Situational Awareness, and Effects on Noise Figure | 373 |
| 8.3.11 | Compatibility with GLONASS FDMA Signals | 375 |
| 8.4 | Digital Channels | 377 |
| 8.4.1 | Fast Functions | 378 |
| 8.4.2 | Slow Functions | 396 |
| 8.4.3 | Search Functions | 402 |
| 8.5 | Acquisition | 424 |
| 8.5.1 | Single Trial Detector | 424 |
| 8.5.2 | Tong Search Detector | 429 |
| 8.5.3 | M of N Search Detector | 431 |
| 8.5.4 | Combined Tong and M of N Search Detectors | 434 |
| 8.5.5 | FFT-Based Techniques | 435 |
| 8.5.6 | Direct Acquisition of GPS Military Signals | 437 |
| 8.5.7 | Vernier Doppler and Peak Code Search | 443 |
| 8.6 | Carrier Tracking | 445 |
| 8.6.1 | Carrier Loop Discriminator | 446 |
| 8.7 | Code Tracking | 452 |
| 8.7.1 | Code Loop Discriminators | 452 |
| 8.7.2 | BPSK-R Signals | 454 |
| 8.7.3 | BOC Signals | 458 |
| 8.7.4 | GPS P(Y)-Code Codeless/Semicodeless Processing | 458 |
| 8.8 | Loop Filters | 459 |
| 8.8.1 | PLL Filter Design | 462 |
| 8.8.2 | FLL Filter Design | 463 |
| 8.8.3 | FLL-Assisted PLL Filter Design | 463 |
| 8.8.4 | DLL Filter Design | 464 |
| 8.8.5 | Stability | 465 |
| 8.9 | Measurement Errors and Tracking Thresholds | 474 |
| 8.9.1 | PLL Tracking Loop Measurement Errors | 474 |
| 8.9.2 | PLL Thermal Noise | 475 |

| | | |
|------------------|---|------------|
| 8.9.3 | Vibration-Induced Oscillator Phase Noise | 478 |
| 8.9.4 | Allan Deviation Oscillator Phase Noise | 479 |
| 8.9.5 | Dynamic Stress Error | 480 |
| 8.9.6 | Reference Oscillator Acceleration Stress Error | 481 |
| 8.9.7 | Total PLL Tracking Loop Measurement Errors and Thresholds | 482 |
| 8.9.8 | FLL Tracking Loop Measurement Errors | 484 |
| 8.9.9 | Code-Tracking Loop Measurement Errors | 486 |
| 8.9.10 | BOC Code Tracking Loop Measurement Errors | 493 |
| 8.10 | Formation of Pseudorange, Delta Pseudorange, and Integrated Doppler | 495 |
| 8.10.1 | Pseudorange | 497 |
| 8.10.2 | Delta Pseudorange | 509 |
| 8.10.3 | Integrated Doppler | 511 |
| 8.10.4 | Carrier Smoothing of Pseudorange | 512 |
| 8.11 | Sequence of Initial Receiver Operations | 514 |
| 8.12 | Data Demodulation | 517 |
| 8.12.1 | Legacy GPS Signal Data Demodulation | 518 |
| 8.12.2 | Other GNSS Signal Data Demodulation | 523 |
| 8.12.3 | Data Bit Error Rate Comparison | 525 |
| 8.13 | Special Baseband Functions | 526 |
| 8.13.1 | Signal-to-Noise Power Ratio Estimation | 526 |
| 8.13.2 | Lock Detectors | 529 |
| 8.13.3 | Cycle Slip Editing | 536 |
| | References | 543 |
| CHAPTER 9 | | |
| | GNSS Disruptions | 549 |
| 9.1 | Overview | 549 |
| 9.2 | Interference | 550 |
| 9.2.1 | Types and Sources | 550 |
| 9.2.2 | Effects | 554 |
| 9.2.3 | Interference Mitigation | 583 |
| 9.3 | Ionospheric Scintillation | 588 |
| 9.3.1 | Underlying Physics | 588 |
| 9.3.2 | Amplitude Fading and Phase Perturbations | 589 |
| 9.3.3 | Receiver Impacts | 590 |
| 9.3.4 | Mitigation | 591 |
| 9.4 | Signal Blockage | 591 |
| 9.4.1 | Vegetation | 592 |
| 9.4.2 | Terrain | 594 |
| 9.4.3 | Man-Made Structures | 598 |
| 9.5 | Multipath | 599 |
| 9.5.1 | Multipath Characteristics and Models | 600 |
| 9.5.2 | Effects of Multipath on Receiver Performance | 605 |
| 9.5.3 | Multipath Mitigation | 612 |
| | References | 614 |

CHAPTER 10

| | |
|--|-----|
| GNSS Errors | 619 |
| 10.1 Introduction | 619 |
| 10.2 Measurement Errors | 620 |
| 10.2.1 Satellite Clock Error | 621 |
| 10.2.2 Ephemeris Error | 625 |
| 10.2.3 Relativistic Effects | 630 |
| 10.2.4 Atmospheric Effects | 633 |
| 10.2.5 Receiver Noise and Resolution | 651 |
| 10.2.6 Multipath and Shadowing Effects | 652 |
| 10.2.7 Hardware Bias Errors | 652 |
| 10.3 Pseudorange Error Budgets | 656 |
| References | 658 |

CHAPTER 11

| | |
|---|-----|
| Performance of Stand-Alone GNSS | 661 |
| 11.1 Introduction | 661 |
| 11.2 Position, Velocity, and Time Estimation Concepts | 662 |
| 11.2.1 Satellite Geometry and Dilution of Precision in GNSS | 662 |
| 11.2.2 DOP Characteristics of GNSS Constellations | 668 |
| 11.2.3 Accuracy Metrics | 672 |
| 11.2.4 Weighted Least Squares | 676 |
| 11.2.5 Additional State Variables | 677 |
| 11.2.6 Kalman Filtering | 679 |
| 11.3 GNSS Availability | 679 |
| 11.3.1 Predicted GPS Availability Using the Nominal 24-Satellite GPS Constellation | 680 |
| 11.3.2 Effects of Satellite Outages on GPS Availability | 682 |
| 11.4 GNSS Integrity | 688 |
| 11.4.1 Discussion of Criticality | 688 |
| 11.4.2 Sources of Integrity Anomalies | 690 |
| 11.4.3 Integrity Enhancement Techniques | 693 |
| 11.5 Continuity | 704 |
| 11.5.1 GPS | 705 |
| 11.5.2 GLONASS | 705 |
| 11.5.3 Galileo | 705 |
| 11.5.4 BeiDou | 706 |
| References | 706 |

CHAPTER 12

| | |
|---|-----|
| Differential GNSS and Precise Point Positioning | 709 |
| 12.1 Introduction | 709 |
| 12.2 Code-Based DGNS | 711 |
| 12.2.1 Local-Area DGNS | 711 |

| | | |
|--------|---|-----|
| 12.2.2 | Regional-Area DGNSS | 715 |
| 12.2.3 | Wide-Area DGNSS | 716 |
| 12.3 | Carrier-Based DGNSS | 718 |
| 12.3.1 | Precise Baseline Determination in Real Time | 719 |
| 12.3.2 | Static Application | 740 |
| 12.3.3 | Airborne Application | 741 |
| 12.3.4 | Attitude Determination | 744 |
| 12.4 | Precise Point Positioning | 746 |
| 12.4.1 | Conventional PPP | 747 |
| 12.4.2 | PPP with Ambiguity Resolution | 749 |
| 12.5 | RTCM SC-104 Message Formats | 753 |
| 12.5.1 | Version 2.3 | 753 |
| 12.5.2 | Version 3.3 | 756 |
| 12.6 | DGNSS and PPP Examples | 757 |
| 12.6.1 | Code-Based DGNSS | 757 |
| 12.6.2 | Carrier-Based | 778 |
| 12.6.3 | PPP | 782 |
| | References | 784 |

CHAPTER 13

| | | |
|--------|---|-----|
| | Integration of GNSS with Other Sensors and Network Assistance | 789 |
| 13.1 | Overview | 789 |
| 13.2 | GNSS/Inertial Integration | 790 |
| 13.2.1 | GNSS Receiver Performance Issues | 791 |
| 13.2.2 | Review of Inertial Navigation Systems | 794 |
| 13.2.3 | The Kalman Filter as System Integrator | 802 |
| 13.2.4 | GNSSI Integration Methods | 807 |
| 13.2.5 | Typical GPS/INS Kalman Filter Design | 809 |
| 13.2.6 | Kalman Filter Implementation Considerations | 816 |
| 13.2.7 | Integration with Controlled Reception Pattern Antenna | 817 |
| 13.2.8 | Inertial Aiding of the Tracking Loops | 819 |
| 13.3 | Sensor Integration in Land Vehicle Systems | 826 |
| 13.3.1 | Introduction | 827 |
| 13.3.2 | Land Vehicle Augmentation Sensors | 831 |
| 13.3.3 | Land Vehicle Sensor Integration | 851 |
| 13.4 | A-GNSS: Network Based Acquisition and Location Assistance | 859 |
| 13.4.1 | History of Assisted GNSS | 863 |
| 13.4.2 | Emergency Response System Requirements and Guidelines | 864 |
| 13.4.3 | The Impact of Assistance Data on Acquisition Time | 871 |
| 13.4.4 | GNSS Receiver Integration in Wireless Devices | 877 |
| 13.4.5 | Sources of Network Assistance | 880 |
| 13.5 | Hybrid Positioning in Mobile Devices | 895 |
| 13.5.1 | Introduction | 895 |
| 13.5.2 | Mobile Device Augmentation Sensors | 898 |
| 13.5.3 | Mobile Device Sensor Integration | 906 |

| | |
|--|-----|
| References | 908 |
| CHAPTER 14 | |
| GNSS Markets and Applications | 915 |
| 14.1 GNSS: A Complex Market Based on Enabling Technologies | 915 |
| 14.1.1 Introduction | 915 |
| 14.1.2 Defining the Market Challenges | 916 |
| 14.1.3 Predicting the GNSS Market | 919 |
| 14.1.4 Changes in the Market over Time | 921 |
| 14.1.5 Market Scope and Segmentation | 921 |
| 14.1.6 Dependence on Policies | 921 |
| 14.1.7 Unique Aspects of GNSS Market | 922 |
| 14.1.8 Sales Forecasting | 922 |
| 14.1.9 Market Limitations, Competitive Systems and Policy | 923 |
| 14.2 Civil Applications of GNSS | 924 |
| 14.2.1 Location-Based Services | 925 |
| 14.2.2 Road | 926 |
| 14.2.3 GNSS in Surveying, Mapping, and Geographical Information Systems | 927 |
| 14.2.4 Agriculture | 928 |
| 14.2.5 Maritime | 929 |
| 14.2.6 Aviation | 930 |
| 14.2.7 Unmanned Aerial Vehicles (UAV) and Drones | 933 |
| 14.2.8 Rail | 933 |
| 14.2.9 Timing and Synchronization | 934 |
| 14.2.10 Space Applications | 935 |
| 14.2.11 GNSS Indoor Challenges | 935 |
| 14.3 Government and Military Applications | 935 |
| 14.3.1 Military User Equipment: Aviation, Shipboard, and Land | 936 |
| 14.3.2 Autonomous Receivers: Smart Weapons | 938 |
| 14.4 Conclusions | 938 |
| References | 939 |
| APPENDIX A | |
| Least Squares and Weighted Least Squares Estimates | 941 |
| Reference | 942 |
| APPENDIX B | |
| Stability Measures for Frequency Sources | 943 |
| B.1 Introduction | 943 |
| B.2 Frequency Standard Stability | 943 |
| B.3 Measures of Stability | 944 |
| B.3.1 Allan Variance | 944 |
| B.3.2 Hadamard Variance | 945 |
| References | 946 |

APPENDIX C

| | |
|---|-----|
| Free-Space Propagation Loss | 947 |
| C.1 Introduction | 947 |
| C.2 Free-Space Propagation Loss | 947 |
| C.3 Conversion Between Power Spectral Densities and Power Flux Densities | 951 |
| References | 951 |
| About the Authors | 953 |
| Index | 961 |