

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 DGNS	715
12.2.3	Wide-Area DGNS	716
12.3	Carrier-Based DGNS	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	DGNS and PPP Examples	757
12.6.1	Code-Based DGNS	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