

CONTENTS

Preface to the Second Edition	xvii
Acknowledgments	xix
Acronyms	xxi
1 Introduction	1
1.1 GNSS/INS Integration Overview,	1
1.2 GNSS Overview,	2
1.2.1 GPS,	2
1.2.2 GLONASS,	4
1.2.3 Galileo,	5
1.3 Differential and Augmented GPS,	7
1.3.1 Differential GPS (DGPS),	7
1.3.2 Local-Area Differential GPS,	7
1.3.3 Wide-Area Differential GPS,	8
1.3.4 Wide-Area Augmentation System,	8
1.4 Space-Based Augmentation Systems (SBASs),	8
1.4.1 Historical Background,	8
1.4.2 Wide-Area Augmentation System (WAAS),	9
1.4.3 European Geostationary Navigation Overlay System (EGNOS),	10

1.4.4	Japan's MTSAT Satellite-Based Augmentation System (MSAS), 11
1.4.5	Canadian Wide-Area Augmentation System (CWAAS), 12
1.4.6	China's Satellite Navigation Augmentation System (SNAS), 12
1.4.7	Indian GPS and GEO Augmented Navigation System (GAGAN), 12
1.4.8	Ground-Based Augmentation Systems (GBASSs), 12
1.4.9	Inmarsat Civil Navigation, 14
1.4.10	Satellite Overlay, 15
1.4.11	Future Satellite Systems, 15
1.5	Applications, 15
1.5.1	Aviation, 16
1.5.2	Spacecraft Guidance, 16
1.5.3	Maritime, 16
1.5.4	Land, 16
1.5.5	Geographic Information Systems (GISs), Mapping, and Agriculture, 16
	Problems, 17

2 Fundamentals of Satellite and Inertial Navigation 18

2.1	Navigation Systems Considered, 18
2.1.1	Systems Other than GNSS, 18
2.1.2	Comparison Criteria, 19
2.2	Fundamentals of Inertial Navigation, 19
2.2.1	Basic Concepts, 19
2.2.2	Inertial Navigation Systems, 21
2.2.3	Sensor Signal Processing, 28
2.2.4	Standalone INS Performance, 32
2.3	Satellite Navigation, 34
2.3.1	Satellite Orbits, 34
2.3.2	Navigation Solution (Two-Dimensional Example), 34
2.3.3	Satellite Selection and Dilution of Precision, 39
2.3.4	Example Calculation of DOPs, 42
2.4	Time and GPS, 44
2.4.1	Coordinated Universal Time Generation, 44
2.4.2	GPS System Time, 44
2.4.3	Receiver Computation of UTC, 45
2.5	Example GPS Calculations with no Errors, 46
2.5.1	User Position Calculations, 46
2.5.2	User Velocity Calculations, 48
	Problems, 49

3 Signal Characteristics and Information Extraction	53
3.1 Mathematical Signal Waveform Models,	53
3.2 GPS Signal Components, Purposes, and Properties,	54
3.2.1 50-bps (bits per second) Data Stream,	54
3.2.2 GPS Satellite Position Calculations,	59
3.2.3 C/A-Code and Its Properties,	65
3.2.4 P-Code and Its Properties,	70
3.2.5 L ₁ and L ₂ Carriers,	71
3.3 Signal Power Levels,	72
3.3.1 Transmitted Power Levels,	72
3.3.2 Free-Space Loss Factor,	72
3.3.3 Atmospheric Loss Factor,	72
3.3.4 Antenna Gain and Minimum Received Signal Power,	73
3.4 Signal Acquisition and Tracking,	73
3.4.1 Determination of Visible Satellites,	73
3.4.2 Signal Doppler Estimation,	74
3.4.3 Search for Signal in Frequency and C/A-Code Phase,	74
3.4.4 Signal Detection and Confirmation,	78
3.4.5 Code Tracking Loop,	81
3.4.6 Carrier Phase Tracking Loops,	84
3.4.7 Bit Synchronization,	87
3.4.8 Data Bit Demodulation,	88
3.5 Extraction of Information for Navigation Solution,	88
3.5.1 Signal Transmission Time Information,	89
3.5.2 Ephemeris Data,	89
3.5.3 Pseudorange Measurements Using C/A-Code,	89
3.5.4 Pseudorange Measurements Using Carrier Phase,	91
3.5.5 Carrier Doppler Measurement,	92
3.5.6 Integrated Doppler Measurements,	93
3.6 Theoretical Considerations in Pseudorange and Frequency Estimation,	95
3.6.1 Theoretical versus Realizable Code-Based Pseudoranging Performance,	95
3.6.2 Theoretical Error Bounds for Carrier-Based Pseudoranging,	97
3.6.3 Theoretical Error Bounds for Frequency Measurement,	98
3.7 Modernization of GPS,	98
3.7.1 Deficiencies of the Current System,	99
3.7.2 Elements of the Modernized GPS,	100
3.7.3 Families of GPS Satellites,	103
3.7.4 Accuracy Improvements from Modernization,	104
3.7.5 Structure of the Modernized Signals,	104
Problems,	107

4 Receiver and Antenna Design	111
4.1 Receiver Architecture, 111	
4.1.1 Radiofrequency Stages (Front End), 111	
4.1.2 Frequency Downconversion and IF Amplification, 112	
4.1.3 Digitization, 114	
4.1.4 Baseband Signal Processing, 114	
4.2 Receiver Design Choices, 116	
4.2.1 Number of Channels and Sequencing Rate, 116	
4.2.2 L ₂ Capability, 118	
4.2.3 Code Selections: C/A, P, or Codeless, 119	
4.2.4 Access to SA Signals, 120	
4.2.5 Differential Capability, 121	
4.2.6 Pseudosatellite Compatibility, 123	
4.2.7 Immunity to Pseudolite Signals, 128	
4.2.8 Aiding Inputs, 128	
4.3 High-Sensitivity-Assisted GPS Systems (Indoor Positioning), 129	
4.3.1 How Assisting Data Improves Receiver Performance, 130	
4.3.2 Factors Affecting High-Sensitivity Receivers, 134	
4.4 Antenna Design, 135	
4.4.1 Physical Form Factors, 136	
4.4.2 Circular Polarization of GPS Signals, 137	
4.4.3 Principles of Phased-Array Antennas, 139	
4.4.4 The Antenna Phase Center, 141	
Problems, 142	
5 Global Navigation Satellite System Data Errors	144
5.1 Selective Availability Errors, 144	
5.1.1 Time-Domain Description, 147	
5.1.2 Collection of SA Data, 150	
5.2 Ionospheric Propagation Errors, 151	
5.2.1 Ionospheric Delay Model, 153	
5.2.2 GNSS Ionospheric Algorithms, 155	
5.3 Tropospheric Propagation Errors, 163	
5.4 The Multipath Problem, 164	
5.5 How Multipath Causes Ranging Errors, 165	
5.6 Methods of Multipath Mitigation, 167	
5.6.1 Spatial Processing Techniques, 167	
5.6.2 Time-Domain Processing, 169	
5.6.3 MMT Technology, 172	
5.6.4 Performance of Time-Domain Methods, 182	
5.7 Theoretical Limits for Multipath Mitigation, 184	
5.7.1 Estimation-Theoretic Methods, 184	
5.7.2 MMSE Estimator, 184	
5.7.3 Multipath Modeling Errors, 184	

5.8	Ephemeris Data Errors,	185
5.9	Onboard Clock Errors,	185
5.10	Receiver Clock Errors,	186
5.11	Error Budgets,	188
5.12	Differential GNSS,	188
5.12.1	PN Code Differential Measurements,	190
5.12.2	Carrier Phase Differential Measurements,	191
5.12.3	Positioning Using Double-Difference Measurements,	193
5.13	GPS Precise Point Positioning Services and Products,	194
	Problems,	196
6	Differential GNSS	199
6.1	Introduction,	199
6.2	Descriptions of LADGPS, WADGPS, and SBAS,	199
6.2.1	Local-Area Differential GPS (LADGPS),	199
6.2.2	Wide-Area Differential GPS (WADGPS),	200
6.2.3	Space-Based Augmentation Systems (SBAS),	200
6.3	Ground-Based Augmentation System (GBAS),	205
6.3.1	Local-Area Augmentation System (LAAS),	205
6.3.2	Joint Precision Approach Landing System (JPALS),	205
6.3.3	LORAN-C,	206
6.4	GEO Uplink Subsystem (GUS),	206
6.4.1	Description of the GUS Algorithm,	207
6.4.2	In-Orbit Tests,	208
6.4.3	Ionospheric Delay Estimation,	209
6.4.4	Code–Carrier Frequency Coherence,	211
6.4.5	Carrier Frequency Stability,	212
6.5	GUS Clock Steering Algorithms,	213
6.5.1	Primary GUS Clock Steering Algorithm,	214
6.5.2	Backup GUS Clock Steering Algorithm,	215
6.5.3	Clock Steering Test Results Description,	216
6.6	GEO with L ₁ /L ₅ Signals,	217
6.6.1	GEO Uplink Subsystem Type 1 (GUST) Control Loop Overview,	220
6.7	New GUS Clock Steering Algorithm,	223
6.7.1	Receiver Clock Error Determination,	226
6.7.2	Clock Steering Control Law ,	227
6.8	GEO Orbit Determination,	228
6.8.1	Orbit Determination Covariance Analysis,	230
	Problems,	235
7	GNSS and GEO Signal Integrity	236
7.1	Receiver Autonomous Integrity Monitoring (RAIM),	236
7.1.1	Range Comparison Method of Lee [121],	237

7.1.2	Least-Squares Method [151],	237
7.1.3	Parity Method [182, 183],	238
7.2	SBAS and GBAS Integrity Design,	238
7.2.1	SBAS Error Sources and Integrity Threats,	240
7.2.2	GNSS-Associated Errors,	240
7.2.3	GEO-Associated Errors,	243
7.2.4	Receiver and Measurement Processing Errors,	243
7.2.5	Estimation Errors ,	245
7.2.6	Integrity-Bound Associated Errors,	245
7.2.7	GEO Uplink Errors,	246
7.2.8	Mitigation of Integrity Threats,	247
7.3	SBAS example,	253
7.4	Conclusions,	254
7.5	GPS Integrity Channel (GIC),	254

8	Kalman Filtering	255
8.1	Introduction,	255
8.1.1	What Is a Kalman Filter?,	255
8.1.2	How It Works,	256
8.2	Kalman Gain,	257
8.2.1	Approaches to Deriving the Kalman Gain,	258
8.2.2	Gaussian Probability Density Functions,	259
8.2.3	Properties of Likelihood Functions,	260
8.2.4	Solving for Combined Information Matrix,	262
8.2.5	Solving for Combined Argmax,	263
8.2.6	Noisy Measurement Likelihoods,	263
8.2.7	Gaussian Maximum-Likelihood Estimate,	265
8.2.8	Kalman Gain Matrix for Maximum-Likelihood Estimation,	267
8.2.9	Estimate Correction Using Kalman Gain,	267
8.2.10	Covariance Correction for Measurements,	267
8.3	Prediction,	268
8.3.1	Stochastic Systems in Continuous Time,	268
8.3.2	Stochastic Systems in Discrete Time,	273
8.3.3	State Space Models for Discrete Time,	274
8.3.4	Dynamic Disturbance Noise Distribution Matrices,	275
8.3.5	Predictor Equations,	276
8.4	Summary of Kalman Filter Equations,	277
8.4.1	Essential Equations,	277
8.4.2	Common Terminology,	277
8.4.3	Data Flow Diagrams,	278
8.5	Accommodating Time-Correlated Noise,	279
8.5.1	Correlated Noise Models,	279
8.5.2	Empirical Sensor Noise Modeling,	282
8.5.3	State Vector Augmentation,	283

8.6	Nonlinear and Adaptive Implementations,	285
8.6.1	Nonlinear Dynamics,	285
8.6.2	Nonlinear Sensors,	286
8.6.3	Linearized Kalman Filter,	286
8.6.4	Extended Kalman Filtering,	287
8.6.5	Adaptive Kalman Filtering,	288
8.7	Kalman–Bucy Filter,	290
8.7.1	Implementation Equations,	290
8.7.2	Kalman–Bucy Filter Parameters,	291
8.8	GPS Receiver Examples,	291
8.8.1	Satellite Models,	291
8.8.2	Measurement Model,	292
8.8.3	Coordinates,	293
8.8.4	Measurement Sensitivity Matrix,	293
8.8.5	Implementation Results,	294
8.9	Other Kalman Filter Improvements,	302
8.9.1	Schmidt–Kalman Suboptimal Filtering,	302
8.9.2	Serial Measurement Processing,	305
8.9.3	Improving Numerical Stability,	305
8.9.4	Kalman Filter Monitoring,	309
	Problems,	313

9 Inertial Navigation Systems 316

9.1	Inertial Sensor Technologies,	316
9.1.1	Early Gyroscopes,	316
9.1.2	Early Accelerometers,	320
9.1.3	Feedback Control Technology,	323
9.1.4	Rotating Coriolis Multisensors,	326
9.1.5	Laser Technology and Lightwave Gyroscopes,	328
9.1.6	Vibratory Coriolis Gyroscopes (VCGs),	329
9.1.7	MEMS Technology,	331
9.2	Inertial Systems Technologies,	332
9.2.1	Early Requirements,	332
9.2.2	Computer Technology,	332
9.2.3	Early Strapdown Systems,	333
9.2.4	INS and GNSS,	334
9.3	Inertial Sensor Models,	335
9.3.1	Zero-Mean Random Errors,	336
9.3.2	Systematic Errors,	337
9.3.3	Other Calibration Parameters,	340
9.3.4	Calibration Parameter Instability,	341
9.3.5	Auxilliary Sensors,	342
9.4	System Implementation Models,	343
9.4.1	One-Dimensional Example,	343
9.4.2	Initialization and Alignment,	344

9.4.3	Earth Models,	347
9.4.4	Gimbal Attitude Implementations,	355
9.4.5	Strapdown Attitude Implementations,	357
9.4.6	Navigation Computer and Software Requirements,	363
9.5	System-Level Error Models,	364
9.5.1	Error Sources,	365
9.5.2	Navigation Error Propagation,	367
9.5.3	Sensor Error Propagation,	373
9.5.4	Examples,	377
	Problems,	381
10	GNSS/INS Integration	382
10.1	Background,	382
10.1.1	Sensor Integration,	382
10.1.2	The Influence of Host Vehicle Trajectories on Performance,	383
10.1.3	Loosely and Tightly Coupled Integration,	384
10.1.4	Antenna/ISA Offset Correction,	385
10.2	Effects of Host Vehicle Dynamics,	387
10.2.1	Vehicle Tracking Filters,	388
10.2.2	Specialized Host Vehicle Tracking Filters,	390
10.2.3	Vehicle Tracking Filter Comparison,	402
10.3	Loosely Coupled Integration,	404
10.3.1	Overall Approach,	404
10.3.2	GNSS Error Models,	404
10.3.3	Receiver Position Error Model,	407
10.3.4	INS Error Models,	408
10.4	Tightly Coupled Integration,	413
10.4.1	Using GNSS for INS Vertical Channel Stabilization,	413
10.4.2	Using INS Accelerations to Aid GNSS Signal Tracking	,
10.4.3	Using GNSS Pseudoranges,	414
10.4.4	Real-Time INS Recalibration,	415
10.5	Future Developments,	423
Appendix A	Software	425
A.1	Software Sources,	425
A.2	Software for Chapter 3,	426
A.2.1	Satellite Position Determination Using Ephemeris Data•,	426
A.2.2	Satellite Position Determination Using Almanac Data for All Satellites,	426
A.3	Software for Chapter 5,	426
A.3.1	Ionospheric Delays,	426
A.4	Software for Chapter 8,	426

- A.5 Software for Chapter 9, 427
- A.6 Software for Chapter 10, 428

Appendix B Vectors and Matrices 429

- B.1 Scalars, 429
- B.2 Vectors, 430
 - B.2.1 Vector Notation, 430
 - B.2.2 Unit Vectors, 430
 - B.2.3 Subvectors, 430
 - B.2.4 Transpose of a Vector, 431
 - B.2.5 Vector Inner Product, 431
 - B.2.6 Orthogonal Vectors, 431
 - B.2.7 Magnitude of a Vector, 431
 - B.2.8 Unit Vectors and Orthonormal Vectors, 431
 - B.2.9 Vector Norms, 432
 - B.2.10 Vector Cross-Product, 432
 - B.2.11 Right-Handed Coordinate Systems, 433
 - B.2.12 Vector Outer Product, 433
- B.3 Matrices, 433
 - B.3.1 Matrix Notation, 433
 - B.3.2 Special Matrix Forms, 434
- B.4 Matrix Operations, 436
 - B.4.1 Matrix Transposition, 436
 - B.4.2 Subscripted Matrix Expressions, 437
 - B.4.3 Multiplication of Matrices by Scalars, 437
 - B.4.4 Addition and Multiplication of Matrices, 437
 - B.4.5 Powers of Square Matrices, 438
 - B.4.6 Matrix Inversion, 438
 - B.4.7 Generalized Matrix Inversion, 438
 - B.4.8 Orthogonal Matrices, 439
- B.5 Block Matrix Formulas, 439
 - B.5.1 Submatrices, Partitioned Matrices, and Blocks, 439
 - B.5.2 Rank and Linear Dependence, 440
 - B.5.3 Conformable Block Operations, 441
 - B.5.4 Block Matrix Inversion Formula, 441
 - B.5.5 Inversion Formulas for Matrix Expressions, 441
- B.6 Functions of Square Matrices, 442
 - B.6.1 Determinants and Characteristic Values, 442
 - B.6.2 The Matrix Trace, 444
 - B.6.3 Algebraic Functions of Matrices, 444
 - B.6.4 Analytic Functions of Matrices, 444
 - B.6.5 Similarity Transformations and Analytic Functions, 446
- B.7 Norms, 447
 - B.7.1 Normed Linear Spaces, 447
 - B.7.2 Matrix Norms, 447

B.8	Factorizations and Decompositions, 449
B.8.1	Cholesky Decomposition, 449
B.8.2	QR Decomposition (Triangularization), 451
B.8.3	Singular-Value Decomposition, 451
B.8.4	Eigenvalue–Eigenvector Decompositions of Symmetric Matrices, 452
B.9	Quadratic Forms, 452
B.9.1	Symmetric Decomposition of Quadratic Forms, 453
B.10	Derivatives of Matrices, 453
B.10.1	Derivatives of Matrix-Valued Functions, 453
B.10.2	Gradients of Quadratic Forms, 455

Appendix C Coordinate Transformations	456
--	------------

C.1	Notation, 456
C.2	Inertial Reference Directions, 458
C.2.1	Vernal Equinox, 458
C.2.2	Polar Axis of Earth, 459
C.3	Coordinate Systems, 460
C.3.1	Cartesian and Polar Coordinates, 460
C.3.2	Celestial Coordinates, 461
C.3.3	Satellite Orbit Coordinates, 461
C.3.4	ECI Coordinates, 463
C.3.5	ECEF Coordinates, 463
C.3.6	LTP Coordinates, 470
C.3.7	RPY Coordinates, 473
C.3.8	Vehicle Attitude Euler Angles, 473
C.3.9	GPS Coordinates, 475
C.4	Coordinate Transformation Models, 477
C.4.1	Euler Angles, 477
C.4.2	Rotation Vectors, 478
C.4.3	Direction Cosines Matrix, 493
C.4.4	Quaternions, 497

References	502
-------------------	------------

Index	517
--------------	------------