

# *Global Positioning Systems, Inertial Navigation, and Integration*

**MOHINDER S. GREWAL**

California State University at Fullerton

**LAWRENCE R. WEILL**

California State University at Fullerton

**ANGUS P. ANDREWS**

Rockwell Science Center



*A John Wiley & Sons, Inc. Publication*

NEW YORK / CHICHESTER / WEINHEIM / BRISBANE / SINGAPORE / TORONTO

# *Contents*

<b>PREFACE</b>	<b>ix</b>
<b>ACKNOWLEDGMENTS</b>	<b>xiii</b>
<b>ACRONYMS</b>	<b>xv</b>
<b>1 Introduction</b>	<b>1</b>
1.1 GPS and GLONASS Overview	2
1.2 Differential and Augmented GPS	5
1.3 Applications	7
<b>2 Fundamentals of Satellite and Inertial Navigation</b>	<b>9</b>
2.1 Navigation Systems Considered	9
2.2 Fundamentals of Inertial Navigation	10
2.3 Satellite Navigation	14
2.4 Time and GPS	24
2.5 User Position Calculations with No Errors	26
2.6 User Velocity Calculation with No Errors	28
Problems	29
<b>3 Signal Characteristics and Information Extraction</b>	<b>30</b>
3.1 Mathematical Signal Waveform Models	30
3.2 GPS Signal Components, Purposes and Properties	32
3.3 Signal Power Levels	45
3.4 Signal Acquisition and Tracking	46

3.5 Extraction of Information for Navigation Solution	61
3.6 Theoretical Considerations in Pseudorange and Frequency Estimation	67
3.7 Modernization of GPS	71
3.8 GPS Satellite Position Calculations Problems	76
	78
<b>4 Receiver and Antenna Design</b>	<b>80</b>
4.1 Receiver Architecture	80
4.2 Receiver Design Choices	85
4.3 Antenna Design Problems	98
	100
<b>5 GPS Data Errors</b>	<b>103</b>
5.1 Selective Availability Errors	103
5.2 Ionospheric Propagation Errors	110
5.3 Tropospheric Propagation Errors	114
5.4 The Multipath Problem	115
5.5 How Multipath Causes Ranging Errors	116
5.6 Methods of Multipath Mitigation	118
5.7 Theoretical Limits for Multipath Mitigation	124
5.8 Ephemeris Data Errors	126
5.9 Onboard Clock Errors	126
5.10 Receiver Clock Errors	127
5.11 Error Budgets Problems	128
	130
<b>6 Inertial Navigation</b>	<b>131</b>
6.1 Background	131
6.2 Inertial Sensors	135
6.3 Navigation Coordinates	152
6.4 System Implementations	153
6.5 System-Level Error Models Problems	170
	178
<b>7 Kalman Filter Basics</b>	<b>179</b>
7.1 Introduction	179
7.2 State and Covariance Correction	181
7.3 State and Covariance Prediction	190
7.4 Summary of Kalman Filter Equations	198
7.5 Accommodating Correlated Noise	201
7.6 Nonlinear and Adaptive Implementations	207
7.7 Kalman–Bucy Filter	213

7.8 GPS Receiver Examples	215
Problems	224
<b>8 Kalman Filter Engineering</b>	<b>229</b>
8.1 More Stable Implementation Methods	229
8.2 Implementation Requirements	239
8.3 Kalman Filter Monitoring	245
8.4 Schmidt–Kalman Suboptimal Filtering	250
8.5 Covariance Analysis	251
8.6 GPS/INS Integration Architectures	252
Problems	264
<b>9 Differential GPS</b>	<b>265</b>
9.1 Introduction	265
9.2 LADGPS, WADGPS, and WAAS	266
9.3 GEO Uplink Subsystem (GUS)	269
9.4 GEO Uplink Subsystem (GUS) Clock Steering Algorithms	276
9.5 GEO Orbit Determination	282
Problems	290
<b>Appendix A Software</b>	<b>291</b>
A.1 Chapter 3 Software	291
A.2 Chapter 5 Software	291
A.3 Chapter 6 Software	291
A.4 Chapter 7 Software	292
A.5 Chapter 8 Software	294
<b>Appendix B Vectors and Matrices</b>	<b>296</b>
B.1 Scalars	296
B.2 Vectors	297
B.3 Matrices	300
<b>Appendix C Coordinate Transformations</b>	<b>324</b>
C.1 Notation	324
C.2 Inertial Reference Directions	326
C.3 Coordinate Systems	328
C.4 Coordinate Transformation Models	346
<b>GLOSSARY</b>	<b>370</b>
<b>REFERENCES</b>	<b>374</b>
<b>INDEX</b>	<b>383</b>