

Contents

Preface	vii
Abbreviations	xvii
1 Introduction	1
1.1 Subject of Satellite Geodesy	1
1.2 Classification and Basic Concepts of Satellite Geodesy	3
1.3 Historical Development of Satellite Geodesy	5
1.4 Applications of Satellite Geodesy	7
1.5 Structure and Objective of the Book	9
2 Fundamentals	10
2.1 Reference Coordinate Systems	10
2.1.1 Cartesian Coordinate Systems and Coordinate Transformations	10
2.1.2 Reference Coordinate Systems and Frames in Satellite Geodesy	12
2.1.2.1 Conventional Inertial Systems and Frames	13
2.1.2.2 Conventional Terrestrial Systems and Frames	15
2.1.2.3 Relationship between CIS and CTS	17
2.1.3 Reference Coordinate Systems in the Gravity Field of Earth .	21
2.1.4 Ellipsoidal Reference Coordinate Systems	23
2.1.5 Ellipsoid, Geoid and Geodetic Datum	25
2.1.6 World Geodetic System 1984 (WGS 84)	28
2.1.7 Three-dimensional Eccentricity Computation	30
2.2 Time	31
2.2.1 Basic Considerations	31
2.2.2 Sidereal Time and Universal Time	32
2.2.3 Atomic Time	35
2.2.4 Ephemeris Time, Dynamical Time, Terrestrial Time	37
2.2.5 Clocks and Frequency Standards	39
2.3 Signal Propagation	42
2.3.1 Some Fundamentals of Wave Propagation	43
2.3.1.1 Basic Relations and Definitions	43
2.3.1.2 Dispersion, Phase Velocity and Group Velocity	45
2.3.1.3 Frequency Domains	46
2.3.2 Structure and Subdivision of the Atmosphere	48
2.3.3 Signal Propagation through the Ionosphere and the Troposphere	52
2.3.3.1 Ionospheric Refraction	54
2.3.3.2 Tropospheric Refraction	56

3	Satellite Orbital Motion	62
3.1	Fundamentals of Celestial Mechanics, Two-Body Problem	62
3.1.1	Keplerian Motion	63
3.1.2	Newtonian Mechanics, Two-Body Problem	66
3.1.2.1	Equation of Motion	66
3.1.2.2	Elementary Integration	69
3.1.2.3	Vectorial Integration	74
3.1.3	Orbit Geometry and Orbital Motion	77
3.2	Perturbed Satellite Motion	82
3.2.1	Representation of the Perturbed Orbital Motion	84
3.2.1.1	Osculating and Mean Orbital Elements	84
3.2.1.2	Lagrange's Perturbation Equations	85
3.2.1.3	Gaussian Form of Perturbation Equation	87
3.2.2	Disturbed Motion due to Earth's Anomalous Gravity Field	88
3.2.2.1	Perturbation Equation and Geopotential	89
3.2.2.2	Perturbations of the Elements	94
3.2.2.3	Perturbations Caused by the Zonal Coefficients J_n	96
3.2.3	Other Perturbations	98
3.2.3.1	Perturbing Forces Caused by the Sun and Moon	98
3.2.3.2	Solid Earth Tides and Ocean Tides	101
3.2.3.3	Atmospheric Drag	102
3.2.3.4	Direct and Indirect Solar Radiation Pressure	104
3.2.3.5	Further Perturbations	105
3.2.3.6	Resonances	107
3.2.4	Implications of Perturbations on Selected Satellite Orbits	108
3.3	Orbit Determination	109
3.3.1	Integration of the Undisturbed Orbit	110
3.3.2	Integration of the Perturbed Orbit	114
3.3.2.1	Analytical Methods of Orbit Integration	114
3.3.2.2	Numerical Methods of Orbit Integration	116
3.3.2.3	Precise Orbit Determination with Spaceborne GPS	119
3.3.3	Orbit Representation	120
3.3.3.1	Ephemeris Representation for Navigation Satellites	121
3.3.3.2	Polynomial Approximation	122
3.3.3.3	Simplified Short Arc Representation	124
3.4	Satellite Orbits and Constellations	126
3.4.1	Basic Aspects	126
3.4.2	Orbits and Constellations	128
3.4.3	Sun-synchronous, Geostationary, and Transfer Orbits	131

4	Basic Observation Concepts and Satellites Used in Geodesy	135
4.1	Satellite Geodesy as a Parameter Estimation Problem	135
4.2	Observables and Basic Concepts	139
4.2.1	Determination of Directions	139
4.2.2	Determination of Ranges	141
4.2.3	Determination of Range Differences (Doppler method)	143
4.2.4	Satellite Altimetry	144
4.2.5	Determination of Ranges and Range-Rates (Satellite-to-Satellite Tracking)	144
4.2.6	Interferometric Measurements	145
4.2.7	Further Observation Techniques	147
4.3	Satellites Used in Geodesy	147
4.3.1	Basic Considerations	147
4.3.2	Some Selected Satellites	149
4.3.3	Satellite Subsystems	152
4.3.3.1	Drag Free Systems	152
4.3.3.2	Attitude Control	153
4.3.3.3	Navigation Payload, PRARE	154
4.3.4	Planned Satellites and Missions	156
4.4	Some Early Observation Techniques (Classical Methods)	158
4.4.1	Electronic Ranging SECOR	159
4.4.2	Other Early Observation Techniques	160
5	Optical Methods for the Determination of Directions	161
5.1	Photographic Determination of Directions	161
5.1.1	Satellites used for Camera Observations	162
5.1.2	Satellite Cameras	163
5.1.3	Observation and Plate Reduction	164
5.1.4	Spatial Triangulation	169
5.1.5	Results	170
5.2	Directions with CCD Technology	172
5.2.1	Image Coordinates from CCD Observations	172
5.2.2	Star Catalogs, Star Identification and Plate Reduction	174
5.2.3	Applications, Results and Prospects	176
5.3	Directions from Space Platforms	176
5.3.1	Star Tracker	177
5.3.2	Astrometric Satellites, HIPPARCOS	177
5.3.3	Planned Missions	178
6	Doppler Techniques	181
6.1	Doppler Effect and Basic Positioning Concept	183
6.2	One Successful Example: The Navy Navigation Satellite System	186
6.2.1	System Architecture	187
6.2.2	Broadcast and Precise Ephemerides	188

6.3	Doppler Receivers	190
6.3.1	Basic concept	190
6.3.2	Examples of Doppler Survey Sets	192
6.4	Error Budget and Corrections	193
6.4.1	Satellite Orbits	194
6.4.2	Ionospheric and Tropospheric Refraction	195
6.4.3	Receiver System	196
6.4.4	Earth Rotation and Relativistic Effects	197
6.4.5	Motion of the Receiver Antenna	198
6.5	Observation Strategies and Adjustment Models	199
6.5.1	Extended Observation Equation	199
6.5.2	Single Station Positioning	201
6.5.3	Multi-Station Positioning	202
6.6	Applications	203
6.6.1	Applications for Geodetic Control	204
6.6.2	Further Applications	205
6.7	DORIS	207
7	The Global Positioning System (GPS)	211
7.1	Fundamentals	211
7.1.1	Introduction	211
7.1.2	Space Segment	213
7.1.3	Control Segment	217
7.1.4	Observation Principle and Signal Structure	218
7.1.5	Orbit Determination and Orbit Representation	222
7.1.5.1	Determination of the Broadcast Ephemerides	222
7.1.5.2	Orbit Representation	223
7.1.5.3	Computation of Satellite Time and Satellite Coordinates	225
7.1.5.4	Structure of the GPS Navigation Data	227
7.1.6	Intentional Limitation of the System Accuracy	229
7.1.7	System Development	230
7.2	GPS Receivers (User Segment)	234
7.2.1	Receiver Concepts and Main Receiver Components	234
7.2.2	Code Dependent Signal Processing	239
7.2.3	Codeless and Semicodeless Signal Processing	240
7.2.4	Examples of GPS receivers	243
7.2.4.1	Classical Receivers	243
7.2.4.2	Examples of Currently Available Geodetic Receivers	245
7.2.4.3	Navigation and Handheld Receivers	248
7.2.5	Future Developments and Trends	250
7.3	GPS Observables and Data Processing	252
7.3.1	Observables	252

7.3.1.1	Classical View	252
7.3.1.2	Code and Carrier Phases	255
7.3.2	Parameter Estimation	258
7.3.2.1	Linear Combinations and Derived Observables	258
7.3.2.2	Concepts of Parametrization	265
7.3.2.3	Resolution of Ambiguities	269
7.3.3	Data Handling	277
7.3.3.1	Cycle Slips	277
7.3.3.2	The Receiver Independent Data Format RINEX	281
7.3.4	Adjustment Strategies and Software Concepts	283
7.3.5	Concepts of Rapid Methods with GPS	289
7.3.5.1	Basic Considerations	289
7.3.5.2	Rapid Static Methods	290
7.3.5.3	Semi Kinematic Methods	292
7.3.5.4	Pure Kinematic Method	294
7.3.6	Navigation with GPS	295
7.4	Error Budget and Corrections	297
7.4.1	Basic Considerations	297
7.4.2	Satellite Geometry and Accuracy Measures	300
7.4.3	Orbits and Clocks	304
7.4.3.1	Broadcast Ephemerides and Clocks	304
7.4.3.2	Precise Ephemerides and Clocks, IGS	307
7.4.4	Signal Propagation	309
7.4.4.1	Ionospheric Effects on GPS Signals	309
7.4.4.2	Tropospheric Propagation Effects	314
7.4.4.3	Multipath	316
7.4.4.4	Further Propagation Effects, Diffraction and Signal Interference	319
7.4.5	Receiving System	320
7.4.5.1	Antenna Phase Center Variation	320
7.4.5.2	Other Error Sources Related to the Receiving System	323
7.4.6	Further Influences, Summary, the Issue of Integrity	323
7.5	Differential GPS and Permanent Reference Networks	325
7.5.1	Differential GPS (DGPS)	326
7.5.1.1	DGPS Concepts	326
7.5.1.2	Data Formats and Data Transmission	329
7.5.1.3	Examples of Services	332
7.5.2	Real Time Kinematic GPS	336
7.5.3	Multiple Reference Stations	338
7.5.3.1	Wide Area Differential GPS	339
7.5.3.2	High Precision Networked Reference Stations	341
7.6	Applications	345
7.6.1	Planning and Realization of GPS Observation	345

7.6.1.1	Setting Up an Observation Plan	346
7.6.1.2	Practical Aspects in Field Observations	348
7.6.1.3	Observation Strategies and Network Design	350
7.6.2	Possible Applications and Examples of GPS Observations	356
7.6.2.1	Geodetic Control Surveys	357
7.6.2.2	Geodynamics	362
7.6.2.3	Height Determination	366
7.6.2.4	Cadastral Surveying, Geographic Information Systems	368
7.6.2.5	Fleet Management, Telematics, Location Based Services	371
7.6.2.6	Engineering and Monitoring	372
7.6.2.7	Precise Marine Navigation, Marine Geodesy, and Hydrography	375
7.6.2.8	Photogrammetry, Remote Sensing, Airborne GPS	378
7.6.2.9	Special Applications of GPS	380
7.7	GNSS – Global Navigation Satellite System	383
7.7.1	GLONASS	384
7.7.2	GPS/GLONASS Augmentations	392
7.7.3	GALILEO	393
7.8	Services and Organizations Related to GPS	397
7.8.1	The International GPS Service (IGS)	397
7.8.2	Other Services	401
8	Laser Ranging	404
8.1	Introduction	404
8.2	Satellites Equipped with Laser Reflectors	406
8.3	Laser Ranging Systems and Components	411
8.3.1	Laser Oscillators	411
8.3.2	Other System Components	412
8.3.3	Currently Available Fixed and Transportable Laser Systems	414
8.3.4	Trends in SLR System Developments	416
8.4	Corrections, Data Processing and Accuracy	418
8.4.1	Extended Ranging Equation	418
8.4.2	Data Control, Data Compression, and Normal Points	422
8.5	Applications of Satellite Laser Ranging	424
8.5.1	Realization of Observation Programs, International Laser Ranging Service (ILRS)	424
8.5.2	Parameter Estimation	427
8.5.3	Earth Gravity Field, Precise Orbit Determination (POD)	428
8.5.4	Positions and Position Changes	431
8.5.5	Earth Rotation, Polar Motion	432

8.5.6	Other applications	435
8.6	Lunar Laser Ranging	436
8.7	Spaceborne Laser	441
9	Satellite Altimetry	443
9.1	Basic Concept	443
9.2	Satellites and Missions	444
9.3	Measurements, Corrections, Accuracy	451
9.3.1	Geometry of Altimeter Observations	451
9.3.2	Data Generation	452
9.3.3	Corrections and Error Budget	454
9.4	Determination of the Mean Sea Surface	460
9.5	Applications of Satellite Altimetry	461
9.5.1	Geoid and Gravity Field Determination	462
9.5.2	Geophysical Interpretation	464
9.5.3	Oceanography and Glaciology	465
10	Gravity Field Missions	469
10.1	Basic Considerations	469
10.2	Satellite-to-Satellite Tracking (SST)	473
10.2.1	Concepts	473
10.2.2	High-Low Mode, CHAMP	476
10.2.3	Low-Low Mode, GRACE	477
10.3	Satellite Gravity Gradiometry	480
10.3.1	Concepts	480
10.3.2	GOCE mission	482
11	Related Space Techniques	485
11.1	Very Long Baseline Interferometry	485
11.1.1	Basic Concept, Observation Equations, and Error Budget	485
11.1.2	Applications	491
11.1.3	International Cooperation, International VLBI Service (IVS)	496
11.1.4	VLBI with Satellites	498
11.2	Interferometric Synthetic Aperture Radar (InSAR)	500
11.2.1	Basic Concepts, Synthetic Aperture Radar (SAR)	500
11.2.2	Interferometric SAR	502
11.2.3	Differential Radar Interferometry	505
12	Overview and Applications	506
12.1	Positioning	506
12.1.1	Concepts, Absolute and Relative Positioning	506
12.1.2	Global and Regional Networks	510
12.1.3	Operational Positioning	511
12.2	Gravity Field and Earth Models	514

12.2.1	Fundamentals	514
12.2.2	Earth Models	519
12.3	Navigation and Marine Geodesy	523
12.3.1	Possible Applications and Accuracy Requirements in Marine Positioning	523
12.3.2	Marine Positioning Techniques	524
12.4	Geodynamics	527
12.4.1	Recent Crustal Movements	527
12.4.2	Earth Rotation, Reference Frames, IERS	529
12.5	Combination of Geodetic Space Techniques	534
12.5.1	Basic Considerations	534
12.5.2	Fundamental Stations	535
12.5.3	Integrated Global Geodetic Observing System (IGGOS) . . .	537
	References	539
	Index	575