

How to Design GPS/GNSS Receivers

The Principles,
Applications & Markets

3rd Edition

By

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How to Design GPS/GNSS Receivers
The Principles, Applications & Markets
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Section I

Fundamentals of Satellite Navigation Systems

Section 2

GLONASS, Galileo, BeiDou Navigation System (BDS) & Regional SATNAV Systems

Section 3

How to Design GPS/GNSS Receivers

Section 4

GNSS Errors, Performance of Stand-alone GNSS, Differential GNSS & Precise Point Positioning

Section 5

GNSS Markets & Applications – Integration with Sensors & Network Assistance

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DEDICATION

This is for you, Mom & Dad. Thanks for always being there for me.

Table of Contents

Objective of This Book.....	15
Terms of Use.....	16
Preface.....	17
1. Introduction.....	19
1.1 Navigation.....	19
1.2 GNSS Overview.....	19
1.3 Global Positioning System.....	21
1.4 Russian GLONASS System.....	23
1.5 Galileo Satellite System.....	23
1.6 Chinese BeiDou System.....	25
1.7 Regional Systems.....	26
1.8 Augmentations.....	28
1.9 Markets and Applications.....	29
1.10 Organization of the Book.....	29
References.....	36

2. Fundamentals of Satellite Navigation.....	37
2.1 Concept of Ranging Using Time-of-Arrival Measurements.....	37
2.2 Reference Coordinate Systems.....	42
2.3 Fundamentals of Satellite Orbits.....	55
2.4 GNSS Signals.....	69
2.5 Positioning Determination Using Ranging Codes.....	81
2.6 Obtaining User Velocity.....	88
2.7 Frequency Sources, Time, and GNSS.....	92
References.....	102
3. Global Positioning System.....	105
3.1 Overview.....	105
3.2 Space Segment Description.....	107
3.3 Control Segment Description.....	133
3.4 User Segment.....	153
3.5 GPS Geodesy and Time Scale.....	158
3.6 Services.....	161
3.7 GPS Signals.....	166
3.8 GPS Ephemeris Parameters and Satellite Position Computation.....	196
References.....	201

4. GLONASS.....	206
4.1 Introduction.....	206
4.2 Space Segment.....	207
4.3 Ground Segment.....	213
4.4 GLONASS User Equipment.....	215
4.5 Geodesy and Time Systems.....	216
4.6 Navigation Services.....	218
4.7 Navigation Signals.....	219
Acknowledgments.....	228
References.....	229
5. Galileo.....	232
5.1 Program Overview and Objectives.....	232
5.2 Galileo Implementation.....	233
5.3 Galileo Services.....	234
5.4 System Overview.....	236
5.5 Galileo Signal Characteristics.....	255
5.6 Interoperability.....	263
5.7 Galileo Search and Rescue Mission.....	265
5.8 Galileo System Performance.....	274
5.9 System Deployment Completion up to FOC.....	282
5.10 Galileo Evolution Beyond FOC.....	284
References.....	284

6. BeiDou Navigation Satellite System (BDS).....	287
6.1 Overview.....	287
6.2 BDS Space Segment.....	295
6.3 BDS Control Segment.....	301
6.4 Geodesy and Time Systems.....	304
6.5 The BDS Services.....	305
6.6 BDS Signals.....	311
References.....	324
7. Regional SATNAV Systems.....	327
7.1 Quasi-Zenith Satellite System.....	327
7.2 Navigation with Indian Constellation (NavIC).....	339
References.....	350
8. GNSS Receivers.....	353
8.1 Overview.....	353
8.2 Antennas.....	358
8.3 Front End.....	370
8.4 Digital Channels.....	391
8.5 Acquisition.....	438
8.6 Carrier Tracking.....	459
8.7 Code Tracking.....	466
8.8 Loop Filters.....	473
8.9 Measurement Errors and Tracking Thresholds.....	488
8.10 Formation of Pseudorange, Delta Pseudorange, and Integrated Doppler.....	509

8.11 Sequence of Initial Receiver Operations.....	528
8.12 Data Demodulation.....	531
8.13 Special Baseband Functions.....	540
References.....	557
9. GNSS Disruptions.....	563
9.1 Overview.....	563
9.2 Interference.....	564
9.3 Ionospheric Scintillation.....	602
9.4 Signal Blockage.....	605
9.5 Multipath.....	613
References.....	628
10. GNSS Errors.....	632
10.1 Introduction.....	632
10.2 Measurement Errors.....	633
10.3 Pseudorange Error Budgets.....	669
References.....	671
11. Performance of Stand-Alone GNSS.....	673
11.1 Introduction.....	673
11.2 Position, Velocity, and Time Estimation Concepts.....	674
11.3 GNSS Availability.....	691
11.4 GNSS Integrity.....	700
11.5 Continuity.....	716
References.....	718

12. Differential GNSS and Precise Point Positioning.....	720
12.1 Introduction.....	720
12.2 Code-Based DGNSS.....	722
12.3 Carrier-Based DGNSS.....	729
12.4 Precise Point Positioning.....	757
12.5 RTCM SC-104 Message Formats.....	764
12.6 DGNSS and PPP Examples.....	768
References.....	795
13. Integration of GNSS with Other Sensors and Network Assistance.....	800
13.1 Overview.....	800
13.2 GNSS/Inertial Integration.....	801
13.3 Sensor Integration in Land Vehicle Systems.....	837
13.4 A-GNSS: Network Based Acquisition and Location Assistance.....	870
13.5 Hybrid Positioning in Mobile Devices.....	906
References.....	919
14. GNSS Markets and Applications.....	926
14.1 GNSS: A Complex Market Based on Enabling Technologies.....	926

14.2 Civil Applications of GNSS.....	935
14.3 Government and Military Applications.....	946
14.4 Conclusions.....	949
References.....	950

APPENDIX A.....	951
Least Squares and Weighted Least Squares Estimates.....	951
Reference.....	952

APPENDIX B.....	953
Stability Measures for Frequency Sources.....	953
B.1 Introduction.....	953
B.2 Frequency Standard Stability.....	953
B.3 Measures of Stability.....	954
B.3.1 Allan Variance.....	954
B.3.2 Hadamard Variance.....	955
References.....	956

APPENDIX C.....	957
Free-Space Propagation Loss.....	957
C.1 Introduction.....	957
C.2 Free-Space Propagation Loss.....	957
C.3 Conversion Between Power Spectral Densities and Power Flux Densities.....	961
References.....	961
Index.....	962

Objective of this Book

The objective of this book is to provide you the reader a complete systems engineering treatment of GNSS. I am an expert with practical experience in GPS/GNSS design and similar areas that are addressed within the book. I provide a thorough, in-depth treatment of each topic.

Within this book, updated information on GPS and GLONASS is presented. In particular, descriptions of new satellites, such as GPS III and GLONASS K2 and their respective signal sets (e.g., GPS III L1C and GLONASS L3OC), are included.

In this combined volume I provide in-depth technical descriptions of each emerging satellite navigation system: BeiDou, Galileo, QZSS, and NavIC. Dedicated chapters cover each system's constellation configuration, satellites, ground control system and user equipment. Detailed satellite signal characteristics are also provided. Recently, I've heard from many engineers that they learned how GPS receivers work from this title. In this title, the design is included, and treatment of receivers is updated and expanded in several important ways. New material has been added on important receiver components, such as antennas and front-end electronics.

The increased complexity of multiconstellation, multifrequency receivers, which are rapidly becoming the norm today, is addressed in detail. Other added features of this title are the clear step-by-step design process and associated trades required to develop a GNSS receiver, depending on the specific receiver application.

This subject will be of great value to those readers who need to understand these concepts, either for their own design tasks or to aid their satellite navigation system engineering knowledge. To round out the discussion of receivers, updated treatments of interference, ionospheric scintillation, and multipath are provided along with new material on blockage from foliage, terrain, and man-made structures.

Now there has been major developments in GNSS augmentations, including differential GNSS (DGNSS) systems, Precise Point Positioning (PPP) techniques, and the use of external sensors/networks. The numerous deployed or planned satellite-based augmentation system (SBAS) networks are detailed, including WAAS, EGNOS, MSAS, GAGAN, and SDCM, as are groundbased differential systems used for various applications.

The use of PPP techniques has greatly increased in recent years, and the treatment in this title has been expanded accordingly. Material addressing integration of GNSS with other sensors has been thoroughly revamped, as has the treatment of network assistance as needed to reflect the evolution from 2G/3G to 4G cellular systems that now rely on multiconstellation GNSS receiver engines.

While this title has generally been written for the engineering/scientific community, one of the series is devoted to GNSS markets and applications. Marketing projections (and the challenge thereof) are enumerated and discussion of the major applications is provided.

This book is structured such that a reader with a general science background can learn the basics of GNSS. The reader with a stronger engineering/scientific background will be able to delve deeper and benefit from the more in-depth technical material. It is this ramp-up of mathematical/technical complexity along with the treatment of key topics that enables this publication to serve as a student text as well as a reference source.

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Preface

The progress of the **Global Navigation Satellite System** (GNSS) has been staggering. GNSS usage is nearly ubiquitous, providing the position, velocity, and timing (PVT) information that enables applications and functions that permeate our daily lives.

In 1996, GNSS included two fully operational satellite navigation systems: the U.S. **Global Positioning System** (GPS) and the Russian **Global Navigation Satellite System** (GLONASS). By 2006, GNSS had regressed with respect to the total number of operational satellites due to a decline in size of the GLONASS constellation.

Today, not only is GLONASS back to full strength, but GPS and GLONASS are also being modernized and further GNSS users worldwide are benefitting from the deployment of two more global satellite navigation systems: the **Chinese BeiDou** and the **European Galileo**. One regional system—**Navigation with Indian Constellation** (NavIC)—has been fully deployed, and another is in development, the Japanese **Quasi-Zenith Satellite System** (QZSS). A myriad of GNSS augmentations are available and provide enhanced performance for those users who require more than the GNSS constellations alone can provide.

The objective of this first edition is to provide the reader with a complete systems engineering treatment of GNSS. The author is an expert with practical experience in the areas that are addressed within this text. He provides a thorough, in-depth treatment of each topic.

Within this and the rest of the series, updated information on GPS and GLONASS is presented. In particular, descriptions of new satellites, such as **GPS III** and **GLONASS K2** and their respective signal sets (e.g., **GPS III L1C** and **GLONASS L3OC**), are included.

In this edition are in-depth technical descriptions of each emerging satellite navigation system: BeiDou, Galileo, QZSS, and NavIC. Dedicated chapters cover each system's constellation configuration, satellites, ground control system and user equipment. Detailed satellite signal characteristics are also provided.

Over the past two decades, I've heard from many engineers that they learned how GPS receivers work from my previous titles. In this title, the design is included, and treatment of receivers is updated and expanded in several important ways. New material has been added on important receiver components, such as antennas and front-end electronics. The increased complexity of multiconstellation, multifrequency receivers, which are rapidly becoming the norm today, is addressed in detail.

Other added features of this title are the clear step-by-step design process and associated trades required to develop a GNSS receiver, depending on the specific receiver application. This subject will be of great value to those readers who need to understand these concepts, either for their own design tasks or to aid their satellite navigation system engineering knowledge. To round out the discussion of receivers, updated treatments of interference, ionospheric scintillation, and multipath are provided along with new material on blockage from foliage, terrain, and man-made structures.

Now there has been major developments in GNSS augmentations, including **differential GNSS** (DGNSS) systems, **Precise Point Positioning** (PPP) techniques, and the use of external sensors/networks. The numerous deployed or planned satellite-based augmentation system (SBAS) networks are detailed, including WAAS, EGNOS, MSAS, GAGAN, and SDCM, as are groundbased differential systems used for various applications.

The use of PPP techniques has greatly increased in recent years, and the treatment in this title has been expanded accordingly. Material addressing integration of GNSS with other sensors has been thoroughly revamped, as has the treatment of network assistance as needed to reflect the evolution from 2G/3G to 4G cellular systems that now rely on multiconstellation GNSS receiver engines.

While this title has generally been written for the engineering/scientific community, one of the series is devoted to GNSS markets and applications. Marketing projections (and the challenge thereof) are enumerated and discussion of the major applications is provided.

As in the other series, this book is structured such that a reader with a general science background can learn the basics of GNSS. The reader with a stronger engineering/scientific background will be able to delve deeper and benefit from the more in-depth technical material. It is this ramp-up of mathematical/technical complexity along with the treatment of key topics that enables this publication to serve as a student text as well as a reference source.

Over 10,000 copies of my previous title have been sold throughout the world. I hope that this new title will be far more successful, and that this text will prove to be of value to the rapidly increasing number of engineers and scientists working on systems and applications involving GNSS. I wish you, the reader, the very best in your GNSS endeavors!

1. Introduction

1.1 Navigation

Navigation is defined as the science of getting a craft or person from one place to another. Each one of us conducts some form of navigation in our daily lives. Driving to work or walking to a store requires that we employ fundamental navigational skills. For most of us, these skills necessitate utilizing our eyes, common sense, and landmarks. However, in some cases where a more accurate knowledge of our position, intended course, and/or transit time to a desired destination is needed, navigation aids other than landmarks are used. These may be in the form of a simple clock to determine the velocity over a known distance or the odometer in our car to keep track of the distance traveled. Other navigation aids transmit electronic signals and therefore, are more complex. These are referred to as *radio navigation aids*.

Signals from one or more radio navigation aids enable a person (herein referred to as the *user*) to compute their position. (Some radio navigation aids provide the capability for velocity determination and time dissemination as well.) It is important to note that it is the user's radio navigation receiver that processes these signals and computes the position fix. The receiver performs the necessary computations (e.g., range, bearing, and estimated time of arrival) for the user to navigate to a desired location. In some applications, the receiver may only partially process the received signals with the navigation computations performed at another location.

Various types of radio navigation aids exist, and for the purposes of this text, they are categorized as either ground-based or space-based. For the most part, the accuracy of ground-based radio navigation aids is proportional to their operating frequency.

Highly accurate systems generally transmit at relatively short wavelengths and the user must remain within line of sight, whereas systems broadcasting at lower frequencies (longer wavelengths) are not limited to line of sight but are less accurate. The satellite navigation (SATNAV) systems that exist at the time of this writing utilize relatively short wavelengths and are generally highly accurate and line-of-sight-limited. These systems can be augmented to provide enhanced performance as well as to overcome line-of-sight limitations.

1.2 GNSS Overview

Today, there are numerous SATNAV systems operating around the world. Some are global and others only provide service within a certain region. The term *Global Navigation Satellite System* (GNSS) is defined as the collection of all SATNAV systems and their augmentations. (Unfortunately, the term GNSS is also widely used today to refer to any individual global SATNAV system. This book utilizes the original definition, but the reader should be aware of the second definition.)

The SATNAV systems discussed within this book are the Chinese BeiDou Navigation Satellite System (BDS), the European Galileo system, the Russian Federation GLObal Navigation Satellite System (GLONASS), the U.S. Global Positioning System (GPS), India's Navigation with Indian Constellation (NavIC), and Japan's Quasi-Zenith Satellite System (QZSS).

The GNSS provides accurate, continuous, worldwide, three-dimensional position and velocity information to users with the appropriate receiving equipment; it also disseminates time within the Coordinated Universal Time (UTC) timescale. Global constellations within the GNSS, sometimes referred to as core constellations, nominally consist of 24 or more medium Earth orbit (MEO) satellites arranged in 3 or 6 orbital planes with four or more satellites per plane. A ground control/monitoring network monitors the health and status of the satellites. This network also uploads navigation and other data to the satellites.

With the exception of the radio determination service (RDSS) provided by a portion of the BDS, which relies on active ranging to geostationary satellites for positioning, the SATNAV systems discussed within this book provide service to an unlimited number of users since the user receivers operate passively (i.e., receive only).

These SATNAV systems utilize the concept of one-way time of arrival (TOA) ranging. Satellite transmissions are referenced to highly accurate atomic frequency standards onboard the satellites, which are in synchronism with an internal system time base. All of the SATNAV systems discussed within this book broadcast ranging codes and navigation data on two or more frequencies using a technique called direct-sequence spread spectrum. Each satellite transmits signals with the ranging code component precisely synchronized to a common timescale.

The navigation data provides the means for the receiver to determine the location of the satellite at the time of signal transmission, whereas the ranging code enables the user's receiver to determine the transit (i.e., propagation) time of the signal and thereby determine the satellite-to-user range. This technique requires that the user receiver also contain a clock. Utilizing this technique to measure the receiver's three-dimensional location requires that TOA ranging measurements be made to four satellites. If the receiver clock was synchronized with the satellite clocks, only three range measurements would be required. However, a crystal clock is usually employed in navigation receivers to minimize the cost, complexity, and size of the receiver. Thus, four measurements are required to determine user latitude, longitude, height, and receiver clock offset from internal system time. If either system time or altitude is accurately known, less than four satellites are required.

Chapter 2 provides elaboration on TOA ranging as well as user position, velocity, and time (PVT) determination. Present-day commercial user equipment utilizes measurements from multiple SATNAV constellations to form the PVT solution. This ensures signal availability if problems are experienced with one or more SATNAV systems.

Regional SATNAV systems are comprised of the same three segments as the global systems: space, control, and user. The key difference is that the space segment utilizes satellites in geostationary and/or inclined geostationary orbits that provide coverage over the region of interest. The Chinese BDS, NavIC [formerly called the Indian Regional Navigation Satellite System (IRNSS)], and QZSS utilize satellites in these orbital configurations.

While the BDS incorporates geostationary and inclined geostationary satellites, it will also have 27 MEO satellites when fully deployed so will provide both a global service and enhanced service within the region surrounding China. (Section 2.3.2 describes these various orbit types.)

1.3 Global Positioning System

Since its inception in the 1970s, the U.S. Global Positioning System (GPS) has continually evolved. System performance has improved in terms of accuracy, availability and integrity. This is attributed to not only major technological enhancements of the three segments: space, control and user but also to increased experience of the U.S. Air Force operational community. Chapter 3 provides details on GPS.

GPS provides two primary services: Precise Positioning Service (PPS) and Standard Positioning Service (SPS). The PPS is an encrypted service intended for military and other authorized Government users. The SPS is free of direct user fees and is in use by billions of civil and commercial users worldwide [1]. Both services provide navigation signals for a user receiver to determine position, velocity and UTC referenced to the U.S. Naval Observatory (USNO).

For the space segment, seven satellite blocks have been developed to date, with each block providing increased capability. At the time of this writing, the GPS constellation consisted of Block IIR, Block IIR-M, and Block IIF satellites. By February 2016, all Block IIF satellites had been launched. The first GPS III satellite was planned for launch in the 2018 timeframe [2]. Figures 1.1 and 1.2 are artist depictions of the GPS Block IIF and GPS III satellites on orbit.

The nominal GPS constellation consists of 24 satellites in 6 MEO orbital planes, known as the baseline 24-slot constellation. For many years, the U.S. Air Force (USAF) has been operating the constellation with more than the baseline number of satellites. In June 2011, the U.S. Air Force formally updated the GPS constellation design to be expandable to accommodate up to 27 satellites in defined slots. This formalized reconfiguration of up to 27 satellites has resulted in improved coverage and geometric properties in most parts of the world [3]. Additional satellites (beyond 27) are typically located next to satellites that are expected to need replacement in the near future.

Improvements have been made to the control and space segments such that the root mean square (rms) value of the space and control segment contribution to ranging error from all satellites in the constellation is approximately 0.5m. The control segment continues to evolve with the Next Generation Operational Control Segment known as OCX planned to become operational prior to 2025.

In terms of user equipment, civil SPS users have a choice of various types of receivers in multiple form factors (e.g., wristwatch, handheld, or mobile phone application). The majority of these utilize signals from GPS and other GNSS constellations.

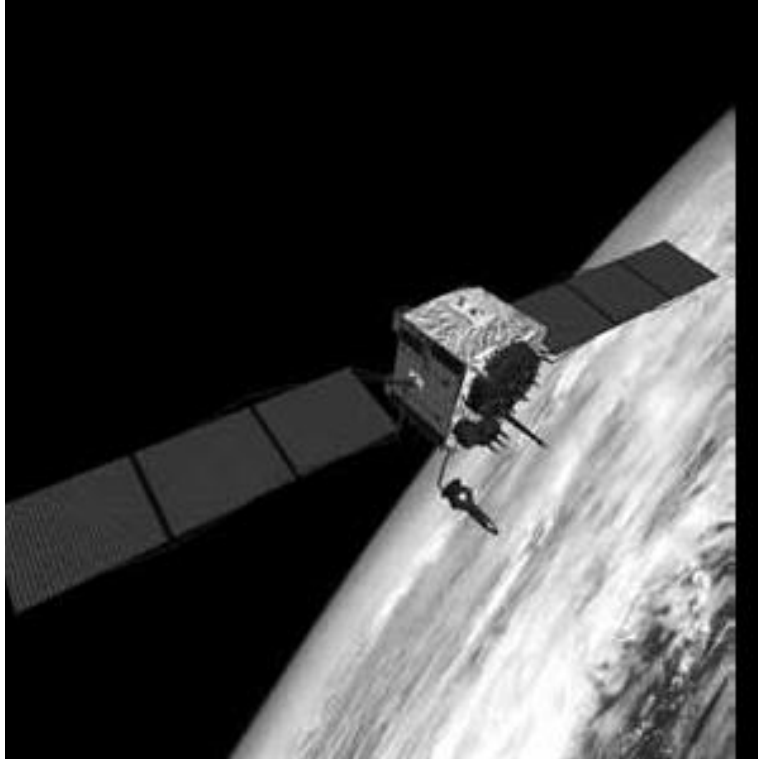


Figure 1.1: GPS Block IIF satellite. (Courtesy of The Boeing Company.)



Figure 1.2: GPS III satellite. (Courtesy of Lockheed-Martin.)

At the time of this writing, the GPS Directorate continued to oversee the development and production of new satellites, ground control equipment, and the majority of U.S. military user receivers.

1.4 Russian GLONASS System

The Global Navigation Satellite System (GLONASS) is the Russian counterpart to GPS. GLONASS provides military and civil multifrequency L-band navigation services for PVT solutions for maritime, air, land, and space applications both inside Russia and internationally. The form of time provided to users is UTC(SU). GLONASS consists of a constellation of satellites in MEO, a ground control segment, and user equipment. GLONASS is described in detail in Chapter 4. At the time of this writing, there were 24 active satellites and 2 spares.

The number of spare satellites is planned to increase to 6. Under the 24-satellite concept, the performance of all 30 satellites will be determined by GLONASS controllers and the best 24 will be activated.

The remaining six will be held for backup or in reserve. Periodically, the mix will be evaluated and, if necessary, a new best set of 24 will be defined. At the beginning of 2017, the GLONASS constellation was populated with two types of spacecraft: Glonass-M, which is a modernized version of the original legacy spacecraft launched from 1982 through 2005, and the newer Glonass-K1 spacecraft design, first launched in 2011. Russia planned to introduce the next generation of spacecraft, Glonass-K2, starting in 2018. Figures 1.3 and 1.4 depict the Glonass-M and Glonass-K1 satellites, respectively.

Both Glonass-M and Glonass-K1 satellites broadcast short- and long-ranging codes and navigation data using frequency division multiple access (FDMA). These satellites also broadcast a code division multiple access (CDMA) ranging code with navigation data, which, at the time of this writing, is serving as a test signal. GLONASS signal characteristics and frequency assignments are contained in Section 4.7 (Part II of this title). The Glonass-K satellites carry a search-and-rescue payload (SAR). The payload relays the 406-MHz SAR beacon transmissions that are designed to work with the currently deployed COSPAS-SARSAT system. GLONASS is supported by a network of ground sites mainly located within the borders of Russia and augmented by monitor sites outside its borders.

GLONASS provides an authorized (military) navigation and a civil navigation service similar to GPS. The Russian government has decreed that the GLONASS open service is available to all national and international users without any limitations. Thus, it is presently incorporated in multiconstellation GNSS single-chip receivers used by millions every day.

1.5 Galileo Satellite System

In 1998, the European Union (EU) decided to pursue a satellite navigation system independent of GPS designed specifically for civilian use worldwide. The development of the Galileo system has followed an incremental approach. Each of the subsequent phases had its own set of objectives.

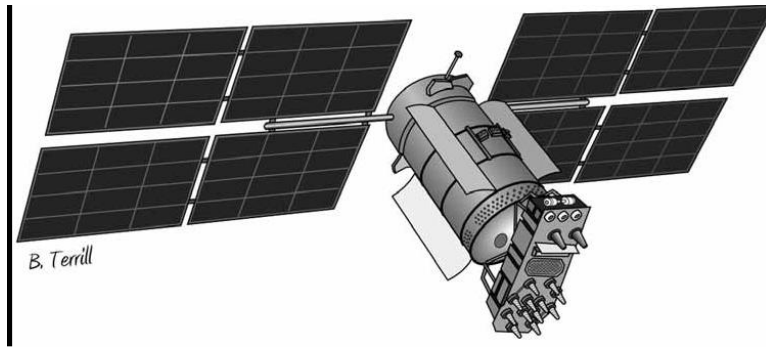


Figure 1.3: Glonass-M satellite. (Courtesy of Brian Terrill.)

The two major implementation phases are the in-orbit validation (IOV) phase and the full operational capability (FOC) phase. The IOV phase has been completed. IOV provided the end-to-end validation of the Galileo system concepts based on an initial constellation of four operational Galileo spacecraft and a first ground segment. Accomplishing a successful service validation campaign, performed throughout 2016, the European Commission (EC) declared the start of the Galileo Initial Services on December 15, 2016.

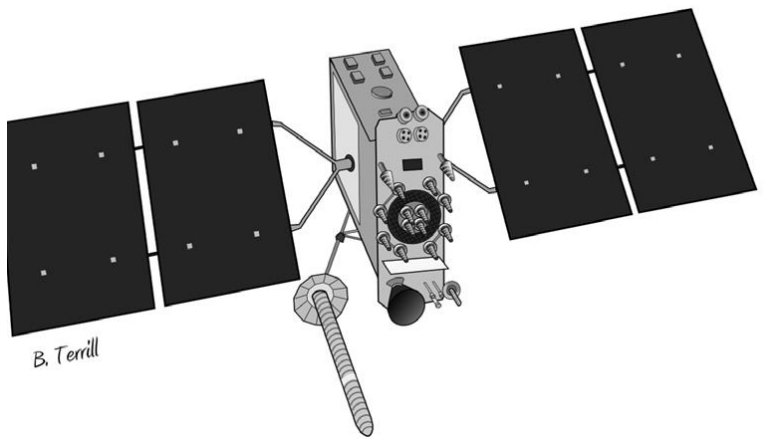


Figure 1.4: Glonass-K1 satellite. (Courtesy of Brian Terrill.)

The system is presently in the FOC phase. FOC will complete the deployment of the Galileo constellation and ground infrastructure and achieve full operational validation and system performance. During the deployment completion, the infrastructure will be integrated and tested in system builds that contain gradually enhanced segment versions, increasing number of remote elements and satellites. The ongoing FOC phase will lead to the fully deployed and validated Galileo system. During this phase, the Galileo system will be handed over in stages to the EC and the European GNSS Agency (GSA)¹ for service provision and exploitation.

1. The European GNSS Agency (GSA) is an agency of the European Union (EU). The GSA's mission is to support EU objectives and achieve the highest return on European GNSS investment, in terms of benefits to users, economic growth, and competitiveness. www.gsa.europa.eu.

When completed, GALILEO will provide multiple levels of service to users throughout the world. Four services are planned: an open service that will be free of direct user charges, a commercial service that will combine value-added data to a high-accuracy positioning service, a public regulated service strictly for

government-authorized users requiring a higher level of protection (e.g., increased robustness against interference or jamming), and support for search and rescue.

At the time of this writing, a 30-satellite MEO constellation and a full worldwide ground control segment were in development. Figure 1.5 depicts a Galileo satellite. One key goal is to be interoperable with GPS. Primary interoperability factors being addressed are signal structure, geodetic coordinate reference frame, and time reference system. Full operational capability has been planned for 2020. Chapter 5 (Part II of this title) describes the Galileo system including satellite signal characteristics.

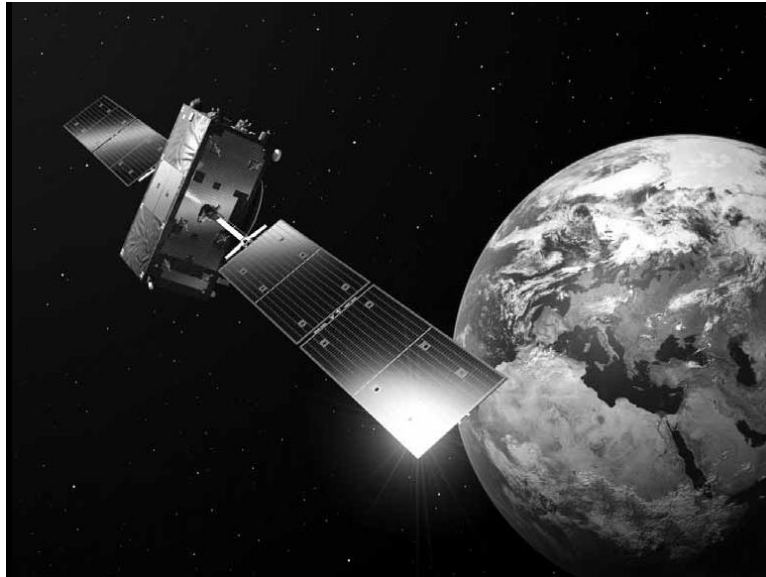


Figure 1.5: Galileo satellite. (©ESA-P. Carill.)

1.6 Chinese BeiDou System

The BDS is a multifunction SATNAV system that integrates many services. Upon its completion scheduled for 2020, BDS will provide global users with PVT services. It will provide a form of UTC traceable to the National Time Service Center (NTSC) of the Chinese Academy of Science denoted as UTC(NTSC). In addition, it will also provide users in China and surrounding areas with a wide-area differential service with positioning accuracy of better than 1m, as well as a short message service (SMS). Those services can be classified as the following three types [4, 5]:

1. Radio navigation satellite service (RNSS): The RNSS comprise the basic navigation services that all GNSS constellations offer, namely PVT. As with other GNSS constellations, using signals of multiple frequencies, BDS provides users with two kinds of services. The open services are available to global users free of charge. The authorized services are available only to authorized users.
2. RDSS: The RDSS is unique to BDS among the GNSS constellations. These services include rapid positioning, short messaging, and precision timing services via GEO satellites for users in China and surrounding areas. This was the only service type provided by Phase 1 of BDS deployment, BD-1. This functionality has been incorporated into BDS as the system continues to evolve to FOC. With more in-orbit GEO satellites, the RDSS service performance has been further improved with respect to the two GEO satellites in Phase 1.

Since the BDS RNSS offers better passive positioning and timing performance, the SMS is the most useful feature in the RDSS service family, and is widely used for user communications and position-reporting. From the viewpoint of RDSS services, BDS is actually a satellite communication system with SMS services. A user identification number is required for a user to use the RDSS services; hence, the RDSS services belong to the authorized service category.

3. Wide-area differential services: The augmentation systems of other GNSS systems (see Chapter 12) are built independently from their nominal systems. For example, after GPS was deployed, the United States developed an independent augmentation system, Wide Area Augmentation System (WAAS), to meet the demands of the civil aviation industry. The multiple GEO satellites in the BDS constellation make it possible to have an integrated design to combine the nominal services with the augmentation services. As one of the important BDS services, the space-based augmentation system has been designed and developed in parallel with the nominal system in the BDS development process.

The deployment of the BDS global system with 35 satellites (5 GEO, 3 inclined GEO and 27 MEO) is planned to be completed by around 2020 [6]. Figures 1.6 and 1.7 illustrate the BDS GEO and IGSO/MEO satellites, respectively.

1.7 Regional Systems

1.7.1 Quasi-Zenith Satellite System (QZSS)

QZSS is a regional civil SATNAV system operated by the Japan Aerospace Exploration Agency (JAXA) on behalf of the Japanese government. The QZSS constellation currently consists of one satellite in an inclined-elliptical geosynchronous orbit (denoted as a quasi-zenith (QZ) orbit), providing high-elevation coverage to complement and augment the U.S. GPS (and potentially other GNSS constellations) over Japan. This QZSS satellite is providing experimental navigation and messaging services.

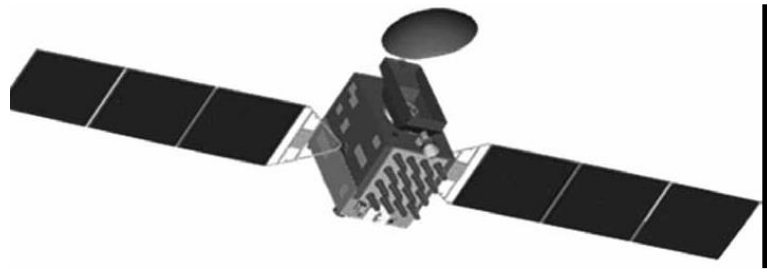


Figure 1.6: BDS GEO satellite [6].

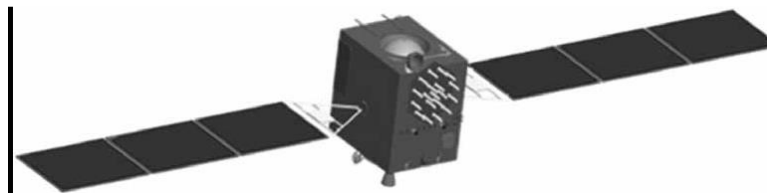


Figure 1.7: BDS IGSO/MEO satellite [6].

By 2018, plans call for the QZSS constellation to expand to four satellites (one satellite in geostationary orbit and three in QZ orbits), and by 2023 the constellation is planned to consist of seven satellites (one in geostationary orbit, the others in QZ orbits) that will provide independent regional capability in addition to complementing or augmenting other GNSS constellations [7–9]. Figure 1.8 is a depiction of a QZSS satellite. QZSS is designed to provide three types of services: navigation services to complement GPS, differential GPS augmentation services to improve GPS accuracy, and messaging services for public safety applications during crisis or disasters. As the constellation is completed, QZSS will provide an independent regional navigation capability independent of other GNSS constellations in addition to the current services. Currently, QZS-1 provides operational services that are being used for a variety of applications in Japan and experimental services which are being tested for future operational use. Planned QZS-2 through QZS-4 satellites will add new experimental augmentation services. Satellites in QZ orbits will provide satellite-based augmentation services (SBAS) corrections while the GEO space vehicle (SV) will provide S-band messaging services. The navigation and augmentation charges are offered free of any user fees. Section 7.1 provides details on QZSS.

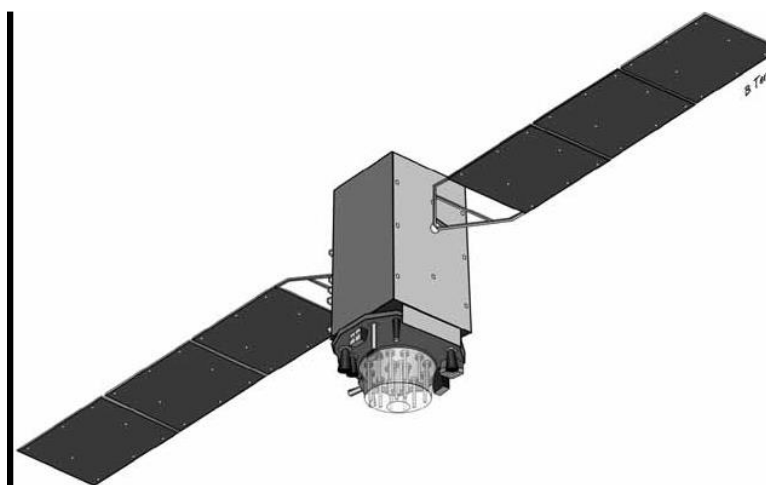


Figure 1.8: QZSS satellite. (Courtesy of Brian Terrill.)

1.7.2 Navigation with Indian Constellation (NavIC)

NavIC is a regional military and civil SATNAV system operated by the Indian Space Research Organization (ISRO) in cooperation with the Indian Defense Research and Development Organization (DRDO) [10, 11]. While other SATNAV systems work primarily in the L-band, NavIC transmits navigation signals in both the L5- band and S-band.

At the time of this writing, NavIC consisted of 3 geostationary and 4 inclined geosynchronous satellites, ground support segment, and user equipment. The system provides PVT for a region from 30° South Latitude to 50° North Latitude and from 30° East Longitude to 130° East Longitude, which is a region approximately extending about 1500 km around India. A NavIC satellite is depicted in Figure 1.9. NavIC provides two levels of service, a public Standard Positioning Service (SPS) and an encrypted Restricted Service (RS); both will be available on both L5-band (1176.45 MHz) and S-band (2492.028 MHz) [12–14]. NavIC SPS is designed to support both signal-frequency (L5-band) position fixes using a broadcast ionospheric-correction model and dual-frequency using L5-band and S-band together [15]. A common oscillator provides the timing of both the L5- and S-band signals, thus allowing the receiver to measure the ionospheric delay in real-time and allowing the user equipment to apply corrections. Details of NavIC are contained in Section 7.2.

1.8 Augmentations

Augmentations are available to enhance standalone GNSS performance. These can be space-based such as a geostationary satellite overlay service that provides satellite signals to enhance accuracy, availability, and integrity or ground-based as in a network that assists embedded GNSS receivers in cellular telephones to compute a rapid position fix. The need to provide continuous navigation between the update periods of the GNSS receiver, during periods of shading of the GNSS receiver's antenna, and through periods of interference, is the impetus for integrating GNSS with various additional sensors.

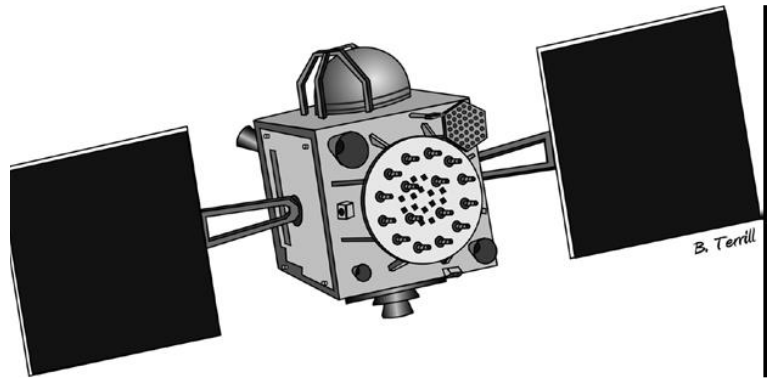


Figure 1.9: NavIC (IRNSS) satellite. (Courtesy of Brian Terrill.)

The most popular sensors to integrate with GNSS are inertial sensors, but the list also includes dopplerometers (Doppler velocity/ altimeters), altimeters, speedometers, and odometers, to name a few. The method most widely used for this integration is the Kalman filter.

In addition to integration with other sensors, it can also be extremely beneficial to integrate a GNSS sensor within a communications network. For example, many cellular handsets now include embedded GNSS engines to locate the user in the event of an emergency, or to support a wide variety of location-based services (LBS). These handsets are often used indoors or in other areas where the GNSS signals are so highly attenuated that demodulation of the GNSS navigation data by the handset takes a long time or is not possible. However, with network assistance, it is possible to track weak GNSS signals and quickly determine the location of the handset.

The network can obtain the requisite GNSS navigation data from other GNSS receivers with a clear-sky view or other sources. Further, the network can assist the handset in a number of other ways such as the provision of timing and a coarse position estimate. Such assistance can greatly increase the sensitivity of the GNSS sensor embedded in the handset enabling it to determine position further indoors or in other environments where the GNSS signal is highly attenuated. Chapter 13 covers both integration of GNSS with other sensors and network-assisted GNSS.

Some applications, such as precision farming, aircraft precision approach, and harbor navigation, require far more accuracy than that provided by standalone GNSS. They may also require integrity warning notifications and other data. These applications utilize a technique that dramatically improves standalone system performance, referred to as differential GNSS (DGNSS). DGNSS is a method of improving the positioning or timing performance of GNSS by using one or more reference stations at known locations, each equipped

with at least one GNSS receiver to provide accuracy enhancement, integrity or other data to user receivers via a data link.

There are several types of DGNSS techniques and depending on the application, the user can obtain accuracies ranging from millimeters to decimeters. Some DGNSS systems provide service over a local area (10–100 km) from a single reference station, while others service an entire continent. The European Geostationary Navigation Overlay Service (EGNOS) and Indian GAGAN system are examples of wide area DGNSS services. Chapter 12 describes the underlying concepts of DGNSS and details a number of operational and planned DGNSS systems.

1.9 Markets and Applications

Today's 4 billion GNSS deployed devices are projected to grow to over 9 billion by 2023. That is more than one unit for every person on Earth. It is anticipated that while the United States and Europe will grow at 8% per year, Asia and the Pacific Region will grow at 11% per year. The total world market is expected to grow about 8% over the next 5 years due primarily to GNSS use in smart phones and location-based services. Revenues can be broken into core elements like GNSS hardware/software sales and the enabled revenues created by the applications. With these definitions, annual core revenue is expected to be just over €100 billion (\$90 billion) by 2020. Enabled revenue stays fairly flat at €250 billion (\$225 billion) over the period, but is estimated to rise dramatically after 2020 as Galileo and Bei-Dou reach full operational capability [1].

Figure 1.10 shows the projected growth of the installed base of GNSS receivers and Figure 1.11 shows the growth of GNSS devices per capita. The projected global GNSS market size through 2023 is shown in Figure 1.12. GNSS revenue growth between now and 2023 was estimated to be dominated by both mobile users and location-based services as shown in Figure 1.13.

Applications of GNSS technology are diverse. These range from navigating a drone to providing a player's position on a golf course and distance to the hole. While most applications are land-based such as providing turn-by-turn directions using a smartphone, there are also aviation, maritime, and space-based usages. Further discussion on market projections and applications is contained in Chapter 14.

1.10 Organization of the Book

This book is structured to first familiarize the reader with the fundamentals of PVT determination using GNSS. Once this groundwork has been established, the SATNAV systems mentioned above that comprise the GNSS are described.

Each description provides details of the system architecture, geodetic and time references, services and broadcast navigation signals.

Next, the discussion focuses on how a GNSS receiver is actually designed. A step-by-step description of the design process and associated trades required to design a GNSS receiver depending on the specific receiver application is put forth. Each stage of a creating a GNSS receiver is described. Details of receiver signal acquisition and tracking as well as range and velocity measurement processes are provided.

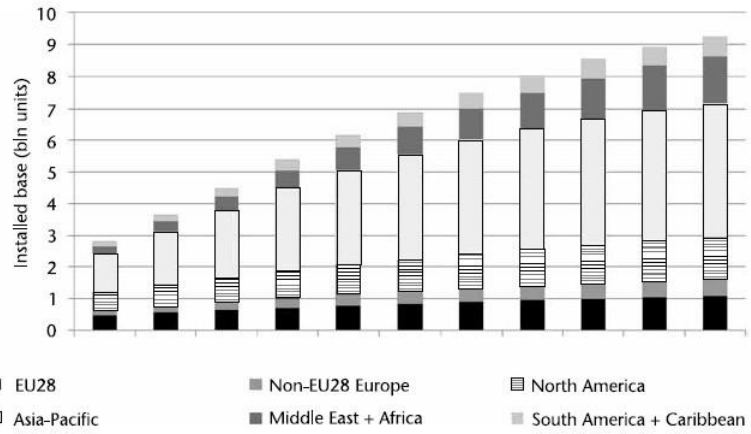


Figure 1.10: Installed base of GNSS devices by region. (Courtesy of GSA.)

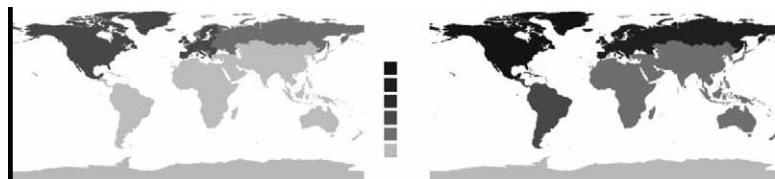


Figure 1.11: GNSS devices per capita: 2014 and 2023. (Courtesy of GSA.)

Global GNSS Market Size (€bln)

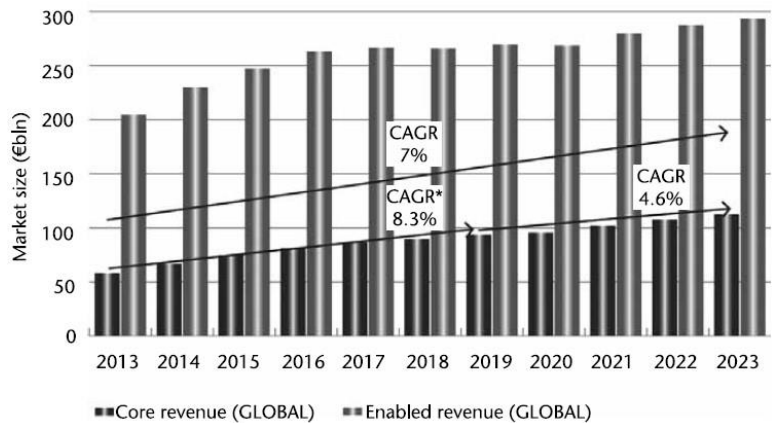


Figure 1.12: Global GNSS market size (billions of Euros). (Courtesy of GSA.)

*CAGR: Compound Annual Growth Rate

Signal acquisition and tracking is also analyzed in the presence of interference, multipath and ionospheric scintillation. GNSS error sources are examined followed by an assessment of GNSS performance (accuracy, availability, integrity, and continuity). GNSS differential techniques are then covered. Sensor-aiding techniques including automotive applications and network-assisted GNSS are presented. Finally, information on GNSS applications and their corresponding market projections is discussed. The highlights of each chapter are summarized next.

Chapter 2 provides the fundamentals of user PVT determination. Beginning with the concept of TOA ranging, the chapter develops the principles for obtaining three-dimensional user position and velocity as well as UTC from a SATNAV system. Included in this chapter are primers on GNSS reference coordinate systems, Earth models, satellite orbits, and constellation design. This chapter also provides an overview of GNSS signals including commonly used signal components. Background information on modulations that are useful for satellite radionavigation, multiplexing techniques, and general signal characteristics including autocorrelation functions and power spectra is covered.

In Chapter 3, details of GPS are presented. These include descriptions of the space, control (i.e., worldwide ground control/monitoring network), and user (equipment) segments.

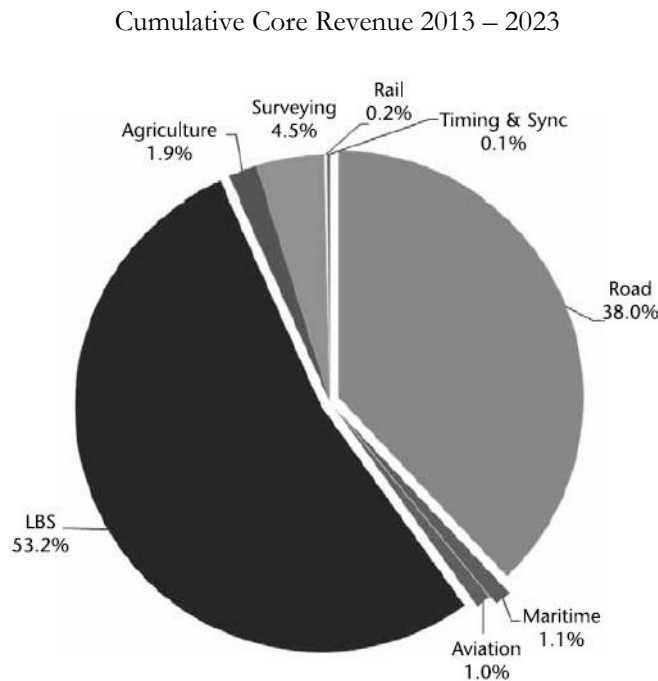


Figure 1.13: Cumulative core revenue 2013 to 2023 by market segment (billions of Euros). (Courtesy of GSA)

Particulars of the constellation are described. Satellite types and corresponding attributes are provided including the Block IIF and GPS III. One will note the increase in the number of transmitted civil and military navigation signals as the various satellite blocks progress. Of considerable interest are interactions

between the control segment (CS) and the satellites. This chapter provides a thorough understanding of the measurement processing and building of a navigation data message. A navigation data message provides the user receiver with satellite ephemerides, satellite clock corrections and other information that enable the receiver to compute PVT. An overview of user receiving equipment is presented as well as related selection criteria relevant to both civil and military users.

This chapter also describes the GPS legacy and modernized satellite signals and their generation including frequency assignments, modulation format, navigation data, received power levels, and ranging code generation.

Chapter 4 discusses the Russian GLONASS system. An overview of the system is first presented, accompanied with pertinent historical facts. The constellation and associated orbital plane characteristics are then detailed. This is followed by a description of the ground control/monitoring network and current and planned spacecraft designs. The GLONASS coordinate system, Earth model, time reference, and satellite signal characteristics are also discussed. System performance in terms of accuracy and availability is covered as well as an overview of differential services. (Chapter 12 provides details of differential services.)

Chapter 5 introduces Galileo. The overall program is first discussed followed by details of system services. Next, a detailed technical description of the system architecture is provided along with constellation particulars, satellite design, and launch vehicle descriptions. Extensive treatment of the downlink satellite signal structure is put forth. Interoperability factors are considered next. In addition to providing navigation services, Galileo will also contribute to the international search and rescue (SAR) architecture. Details of the SAR/Galileo service are contained in Section 5.7.

Chapter 6 is dedicated to BeiDou. The chapter begins with an overview of the Beidou program, which is denoted as the BeiDou Navigation Satellite System (BDS). Program history and its three-phased evolutionary approach are described. The BDS program began with a regional RDSS and is now expanding to worldwide coverage. The chapter details constellation and satellite design particulars as well as particulars of the ground control segment. Interoperability factors (e.g., geodetic coordinate reference system, time reference system) are covered. This is followed by BDS services and an extensive treatment of satellite signal characteristics. The regional RDSS provides both navigation and messaging services.

In Chapter 7, we describe regional SATNAV systems. There is a growing realization that total dependency on one or more global core constellations for PVT services will not address unique specific regional needs. Without being closely partnered with the core constellation providers, these unique needs may not be met. Among the requirements that a regional service can provide are: guaranteed quality of service within the coverage regions (positioning and timing services to users) and unique messaging requirements for users.

In Chapter 7, we discuss the NavIC, a regional service provided by India to support the region of the world centered on the continent of India and the QZSS, the regional service provided by Japan serving the western Pacific region. These constellations improve the coverage of global core constellations in mountainous territories where masking of the core constellation satellites can impact coverage in the mountain valleys and within urban canyons by assuring high-elevation angle satellite availability.

Section 7.1 describes the emerging QZSS. The QZSS program was initiated in 2002 as a government/industry effort. The first satellite was launched in 2010 and the decision to proceed for the initial operating capability came in 2012. In Section 7.1.2, the QZSS space segment is described. Although the

QZSS constellation consisted of a single satellite in an inclined geosynchronous orbit at the time of this writing, the remainder of the IOC constellation were planned to be in-orbit before 2023. QZSS will transmit timing signals in the L1, L2, and L5 navigation bands (similar to the U.S. GPS).

Section 7.1.3 focuses on the QZSS control segment (CS). To ensure that the PVT requirements are met, the CS consists of satellite tracking functions (radar and laser ranging), signal monitoring stations, and timing management for the constellation.

Section 7.1.4 discusses the geodesy and timing services. Of note is that QZSS plans to be closely synchronized (i.e., very small timing offset) with GPS time. In Section 7.1.5, the QZSS services to military and civil users are described and include specific augmentations for high-precision users as well as crisis and safety messaging services.

Given the extremely rugged and mountainous locations in Japan, these services are considered critical for emergency uses. Finally, the specific characteristics of the six QZSS signals are discussed in Section 7.1.6.

Section 7.2, describes the NavIC. In Section 7.2.2, the space segment is discussed. After the initial decision by India to proceed to develop and deploy NavIC in 2006, the first satellite was launched in 2013. At the time of this writing, the NavIC space segment had seven satellites in a combination of geosynchronous orbits and inclined geosynchronous orbit providing the current operational capability. The current satellites transmit positioning signals in L5 and S bands to provide both civil and military PVT services. The NavIC CS is discussed in Section 7.2.3.

The function of the CS is to assure high-accuracy position and timing information and to provide special messaging services to meet the unique civil and military needs. Section 7.2.4 concentrates on the geodesy and time systems while Section 7.2.5 covers the navigation services. Section 7.2.6 covers the NavIC signals and their characteristics and Section 7.2.7 describes the user equipment for military and civil users.

Chapter 8 provides a comprehensive overview at a high level of virtually every GNSS receiver and lays the foundation for how they are designed. This chapter describes in detail every function in a GNSS receiver required to search, acquire and track the SV signals, then extract the code and carrier measurements as well as the navigation message data from the GNSS SVs. The subject matter is so extensive that rigor is often replaced with first principles as a trade-off for conveying the most important objective of this chapter seldom presented elsewhere: how a GNSS receiver is actually designed. Once these extensive design concepts are understood as a whole, the reader will have the basis for understanding or developing new innovations. Numerous references are provided for the reader seeking additional details.

Chapter 9 discusses four general classes of GNSS radio frequency (RF) signal disruptions that can deteriorate GNSS receiver performance. The first class of signal disruptions is interference (the focus of Section 9.2), which may be either unintentional or intentional (commonly referred to as jamming). Section 9.3 discusses the second class of GNSS disruptions called ionospheric scintillation, which is a signal-fading phenomenon caused by irregularities that can arise at times in the ionospheric layer of the Earth's atmosphere.

The third class of disruptions is signal blockage, which is discussed in Section 9.4. Signal blockage is manifested when the line-of-sight paths of GNSS RF signals are attenuated excessively by heavy foliage, terrain, or man-made structures. The fourth and final class of GNSS disruptions, discussed in Section 9.5, is

multipath. Invariably, there are reflective surfaces between each GNSS spacecraft and the user receiver that result in RF echoes arriving at the receiver after the desired (line-of-sight) signal.

GNSS measurement errors are covered in Chapter 10. A detailed explanation of each pseudorange measurement error source and its contribution to overall error budgets is provided. Spatial and time correlations characteristics are also examined. This treatment lays the groundwork for the reader to better understand DGNSS. All DGNSS systems exploit these correlations to improve overall system performance. (DGNSS system details are discussed in Chapter 12.) The chapter closes with a presentation of representative error budgets for both the single- and dual-frequency GNSS user.

Performance of standalone GNSS is discussed in Chapter 11. This chapter first provides algorithms for estimating PVT using one or more GNSS constellations. A variety of geometry factors are defined that are used in the estimation of the various components (e.g., horizontal, vertical) of the GNSS navigation solution. In Section 11.2.5, usage of additional state variables is discussed including methods to address system time offsets when using measurements from multiple GNSS constellations. This is especially important if a receiver is tracking satellites from two or more GNSS constellations; then the difference in system times (e.g., GPS System Time, GLONASS System Time, Galileo System Time, BeiDou System Time) needs to be accounted for when blending the measurements to form the PVT solution.

Sections 11.3 through 11.5 discuss, respectively, the three other important performance metrics of availability, integrity, and continuity. Each of these metrics is covered within the context of multiconstellation GNSS. It should be noted that the comprehensive treatment of integrity includes a discussion of Advanced Receiver Autonomous Integrity Monitoring (ARAIM).

There are many applications that demand higher levels of accuracy, integrity, availability, and continuity than provided by standalone GNSS. For such applications, augmentation is required. There are several classes of augmentation, which can be used singly or in combination: DGNSS, Precise Point Positioning (PPP), and the use of external sensors. Chapter 12 introduces DGNSS and PPP. Chapter 13 will discuss various external sensors/systems and their integration with GNSS.

Both DGNSS and PPP are methods to improve the positioning or timing performance of GNSS by making use of measurements from one or more reference stations at known locations, each equipped with at least one GNSS receiver. The reference station(s) provides information that is useful to improve PNT performance (accuracy, integrity, continuity, and availability) for the end user.

This chapter describes the underlying concepts of DGNSS and details a number of operational and planned DGNSS systems. The underlying algorithms and performance of code- and carrier-based DGNSS systems are presented in Sections 12.2 and 12.3, respectively. PPP systems are addressed in Section 12.4. Some important DGNSS message standards are introduced in Section 12.5. The final section, Section 12.6, details a number of operational and planned DGNSS and PPP systems.

Chapter 13 focuses on the need to provide continuous navigation between the update periods of the GNSS receiver, during periods of shading of the GNSS receiver's antenna, and through periods of interference. This is the impetus for integrating GNSS with various additional sensors.

In Section 13.2, the motivations for GNSS/inertial integration are detailed. The Kalman filter is described, including an example of a typical Kalman filter implementation. Various classes of GNSS/ inertial

integrations are introduced and discussed. Section 13.3 addresses sensor integration for land vehicles. A description of the sensors, their integration with the Kalman filter, and test data taken during field testing of a practical multisensory system are presented. Section 13.4 discusses methods of enhancing GNSS performance using network assistance.

This section includes descriptions of network assistance techniques, performance, and emerging standards. Lastly, Section 13.5 introduces the topic of extending positioning systems into indoor and other areas with GNSS signal blockage using hybrid positioning systems incorporating GNSS, low-cost inertial sensors, and various other RF signals available on mobile devices.

Chapter 14 is dedicated to GNSS markets and applications. This chapter starts with reviews of numerous market projections and continues with the process in which a company would target a specific market segment. Differences between the civil and military markets are discussed. It is of prime importance to understand these differences when targeting a specific segment of either market. The influence of governmental policy on the GNSS market is examined. Numerous civil, government, and military applications are presented.

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