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北京航空航天大学“空间技术应用”系列丛书

Global Navigation Satellite System —Principle and Applications

全球卫星导航系统——原理与应用

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Abstract

This book provides an overview of the principles of operation of Global Navigation Satellite Systems (GNSS, i. e., GPS, GLONASS, BeiDou and Galileo) with primary emphasis on the GPS. It covers the fundamentals of both hardware and algorithms/software aspects of GNSS.

This book is intended to serve as a textbook for both undergraduates and postgraduates interested in pursuing study in GNSS. It is also intended as a source of information for engineers, geodesists, surveyors, navigators, teachers, etc., who have an interest in radio navigation principles and systems.

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Preface

Global Navigation Satellite System (GNSS) is a standard generic term for satellite navigation systems that provide autonomous geospatial positioning information with global coverage. A GNSS allows small electronic receiver to determine their location (latitude, longitude, and altitude) and precise time information using radio signals transmitted from navigation satellites along a line of sight. The need to determine precise locations for use in a variety of innovative and emerging applications such as surveying, navigation, tracking, mapping, earth observation, mobile-phone technology, and rescue applications is inevitable. Satellite navigation and positioning systems are robust and evolving technology that uses a global network of navigation satellites to achieve this in a variety of ways perhaps as many ways of its applications. GNSS technology is accurate enough to pinpoint locations anywhere in the world, in any weather condition, and at any time of the day.

There are currently several layers of satellite navigation systems. The United States' GPS is a fully operational GNSS, and Russian GLONASS is rejuvenating. Two other such systems are also being developed—European Union's Galileo and Chinese BeiDou. All of these four are for or intended towards global coverage. Several regional systems are also available or initiated for regional coverage by several countries: Japan's Quasi-Zenith Satellite Systems (QZSS) and the India Regional Navigation Satellite System (IRNSS). In addition, augmentation systems on these core systems are also offered by several government and private agencies. All of humanity will benefit if these systems can operate as one super system, with users able to navigate using any four satellites.

The benefits of Satellite Navigation are enormous. For example, the International Civil Aviation Organization and the International Maritime Organization have accepted GNSS as essential in their navigation. GNSS is revolutionizing and revitalizing the way nations operate in space, from guidance systems for the International Space Station's return vehicle, to the management of tracking and control for satellite constellations. Military applications of GNSS are extremely widespread from mobilizing troop to supply of arms and amenities, aid in rescue operations to missile guidance.

Vehicle manufacturers now provide navigation units that combine vehicle location and road data to avoid traffic jams, and reduce travel time, fuel consumption, and therefore pollution. Road and rail transport operators are now capable to monitor the goods' movements more efficiently, and combat theft and fraud more effectively by means of GNSS. Taxi companies now use these systems to offer a faster and more reliable service to customers. Delivery service providers are increasingly being dependent on GNSS.

Surveying systems incorporating GNSS signals are being used as tools for many applications such as urban development. GNSS can be incorporated into geographical information systems for the efficient management of agricultural land and for aiding environmental protection; this is a critical role of the paramount importance to assist developing nations in preserving natural resources and expanding their international trade. Another key application is the integration of third-generation mobile phones with Internet-linked applications. It will facilitate the interconnection of telecommunications, electronics, and banking networks and systems via the extreme precision of its atomic clocks.

Incorporating the GNSS signal into emergency-services applications creates a valuable tool for the emergency services (fire brigade, police, paramedics, sea and mountain rescue), allowing them to respond more rapidly to those in danger. There is also potential for the signal to be used to guide the blind; monitor Alzheimer's sufferers with memory loss; and guide explorers, hikers, and sailing enthusiasts.

This book is intended to serve as a text for final-year undergraduates and for postgraduates. It is also intended as a source of information for engineers, geodesists, surveyors, navigators, teachers, etc., who have an interest in radionavigation principles and systems. The background required to use this book is an undergraduate level of mathematics and mathematical statistics and a basic knowledge of electronics components and systems, especially communication systems. Although the book contains a special chapter concerning relevant aspects of electromagnetic wave propagation, fundamental knowledge of waves, antennae and propagation would prove useful.

Falin Wu, Yan Zhao

5 December, 2016

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Chapter 1
Introduction

1.1 Overview

Navigation is defined as the science of getting a craft or person from one place to another safely and efficiently. Each of us conducts some form of navigation in our daily lives. Driving to work or walking to a store requires that we employ fundamental navigation skills. For most of us, these skills require utilizing our eyes, common sense, and landmarks. However, in some cases where a more accurate knowledge of our position, intended course, or transit time to a desired destination is required, 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. Some other navigation aids transmit electronic signals and therefore are more complex. These are referred to as **radionavigation aids.**

Signals from one or more radionavigation aids enable a person (herein referred to as the **user**) to compute their position. (Some radionavigation aids provide the capability for velocity determination and time dissemination as well.) It is important to note that it is the user's radionavigation 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 radionavigation 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 radionavigation 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 (LOS), whereas systems broadcasting at lower frequencies (longer wavelengths) are not limited to LOS but are less accurate. Early spaced-based systems (namely, the U. S. Navy Navigation Satellite System, referred to as Transit, and the Russian Tsikada system) provided a two-dimensional high-accuracy positioning service. However, the frequency of obtaining a position fix is dependent on the user's latitude. Theoretically, a Transit user at the equator could obtain a position fix on the average of once every 110 minutes, whereas at 80° latitude the fix rate would improve to an average of once every 30 minutes. Limitations applicable to both systems are that each position fix requires approximately 10 to 15 minutes of receiver processing and an estimate of the user's position. These attributes were suitable for shipboard navigation because of the low velocities, but not for aircraft and high-dynamic users[1]. It was these shortcomings that led to the development of the U. S. Global Positioning System (GPS).

1.2 U.S. Global Positioning System

In the early 1960s, several U. S. government organizations, including the Department Of Defense (DOD), the National Aeronautics and Space Administration (NASA), and the Department Of Transportation (DOT), were interested in developing satellite systems for three-dimensional position determination. The optimum system was viewed as having the following attributes: global coverage, continuous, all weather operation, ability to serve high-dynamic platforms, and high accuracy. When Transit became operational in 1964, it was widely accepted for use on low-dynamic platforms. However, due to its inherent limitations, the Navy sought to enhance Transit or develop another satellite navigation system with the desired capabilities mentioned earlier. Several variants of the original Transit system were proposed by its developers at the Johns Hopkins University Applied Physics Laboratory. Concurrently, the Naval Research Laboratory (NRL) was conducting experiments with highly stable space-based clocks to achieve precise time transfer. This program was denoted as Timation. Modifications were made to Timation satellites to provide a ranging capability for two-dimensional position determination. Timation employed a sidetone modulation for satellite-to-user ranging[2-4].

At the same time as the Transit enhancements were being considered and the Timation efforts were underway, the Air Force conceptualized a satellite positioning system denoted as System 621B. It was envisioned that System 621B satellites would be in elliptical orbits at inclination angles of 0°, 30°, and 60°. Numerous variations of the number of satellites

(15—20) and their orbital configurations were examined. The use of Pseudo Random Noise (PRN) modulation for ranging with digital signals was proposed. System 621B was to provide three-dimensional coverage and continuous worldwide service. The concept and operational techniques were verified at the Yuma Proving Grounds using an inverted range in which pseudosatellites or pseudolites (i. e., ground-based satellites) transmitted satellite signals for aircraft positioning[2-4]. Furthermore, the Army at Ft. Monmouth, New Jersey, was investigating many candidate techniques, including ranging, angle determination, and the use of Doppler measurements. From the results of the Army investigations, it was recommended that ranging using PRN modulation be implemented[4].

In 1969, the Office of the Secretary of Defense (OSD) established the Defense Navigation Satellite System (DNSS) program to consolidate the independent development efforts of each military service to form a single joint-use system. The OSD also established the Navigation Satellite Executive Steering Group, which was charged with determining the viability of the DNSS and planning its development. From this effort, the system concept for NAVSTAR GPS was formed. The NAVSTAR GPS program was developed by the GPS Joint Program Office (JPO) in El Segundo, California[4]. The system is now most commonly referred to as simply GPS.

Presently, GPS is fully operational and meets the criteria established in the 1960s for an optimum positioning system. The system provides accurate, continuous, worldwide, three-dimensional position and velocity information to users with the appropriate receiving equipment. GPS also disseminates a form of Coordinated Universal Time (UTC). The satellite constellation nominally consists of 24 satellites arranged in six orbital planes with four satellites per plane. A worldwide ground control/monitoring network monitors the health and status of the satellites. This network also uploads navigation and other data to the satellites. GPS can provide service to an unlimited number of users since the user receivers operate passively (i. e., receive only). The system utilizes 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 a GPS time base. The satellites broadcast ranging codes and navigation data on two frequencies using a technique called Code Division Multiple Access (CDMA); that is, there are only two frequencies in use by the system, called L1 (1 575.42 MHz) and L2 (1 227.6 MHz). Each satellite transmits on these frequencies, but with different ranging codes than those employed by other satellites. These codes were selected because they have low cross-correlation properties with respect to one another. Each satellite generates a short code referred to as the coarse/acquisition or C/A code and a long code denoted as the precision or P(Y) code. (Additional signals are forthcoming. Satellite signal characteristics are discussed in Chapter 5.) 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 were 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 height is accurately known, less than four satellites are required. Chapter 2 and Chapter 4 provide elaboration on TOA ranging as well as user Position, Velocity, and Time (PVT) determination.

1.2.1 GPS Services

GPS is a dual-use system. That is, it provides separate services for civil and military users. These are called the Standard Positioning Service (SPS) and the Precise Positioning Service (PPS). The SPS is designated for the civil community, whereas the PPS is intended for U.S. authorized military and selected government agency users. Access to the GPS PPS is controlled through cryptography. Initial Operating Capability (IOC) for GPS was attained in December 1993, when a combination of 24 prototype and production satellites was available and position determination/timing services complied with the associated specified predictable accuracies. GPS reached Full Operational Capability (FOC) in early 1995, when the entire 24 production satellite constellation was in place and extensive testing of the ground control segment and its interactions with the constellation was completed.

The SPS is available to all users worldwide free of direct charges. There are no restrictions on SPS usage. This service is specified to provide accuracies of better than 13 m (2DRMS, 95%) in the horizontal plane and 22 m (95%) in the vertical plane (global average; signal-in-space errors only). UTC(USNO) time dissemination accuracy is specified to be better than 40 ns (95%)[3]. The Distance Root Mean Square (DRMS) is a common measure used in navigation. Twice the DRMS value, or 2DRMS, is the radius of a circle that contains at least 95% of all possible fixes that can be obtained with a system (in this case, the SPS) at any one place. SPS measured performance is typically much better than specification. The SPS is the predominant satellite navigation service in use by millions throughout the world.

The PPS is specified to provide a predictable accuracy of at least 22 m (2DRMS, 95%) in the horizontal plane and 27.7 m (95%) in the vertical plane. The PPS provides a UTC time transfer accuracy within 200 ns (95%) referenced to the time kept at the U.S. Naval Observatory (USNO) and is denoted as UTC (USNO)[4]. Velocity measurement accuracy is specified as 0.2 m/s (95%)[5,6].

As stated earlier, the PPS is primarily intended for military and selected government agency users. Civilian use is permitted, but only with special U.S. DOD approval. Access to the aforementioned PPS position accuracies is controlled through two cryptographic features denoted as Anti-Spoofing (AS) and Selective Availability (SA). AS is a mechanism intended to defeat deception jamming through encryption of the military signals. Deception jamming is a technique in which an adversary would replicate one or more of the satellite ranging codes, navigation data signal(s), and carrier frequency Doppler effects with the intent of deceiving a victim receiver. SA had intentionally degraded SPS user accuracy by dithering the satellite's clock, thereby corrupting TOA measurement accuracy. Furthermore, SA could have introduced errors into the broadcast navigation data parameters[3]. SA was discontinued on 1 May, 2000, and per current U.S. government policy is to remain off. When it was activated, PPS users removed SA effects through cryptography[1].

1.2.2 GPS Modernization Program

In January 1999, the U.S. government announced a new GPS modernization initiative that called for the addition of two civil signals to be added to new GPS satellites[7]. These signals are denoted as L2C and L5. The L2C signal will be available for nonsafety of life applications at the L2 frequency; the L5 signal resides in an Aeronautical RadioNavigation Service (ARNS) band at 1 176.45 MHz. L5 is intended for safety-of-life use applications. These additional signals will provide SPS users the ability to correct for ionospheric delays by making dual frequency measurements, thereby significantly increasing civil user accuracy. By using the carrier phase of all three signals (L1 C/A, L2C, and L5) and differential processing techniques, very high user accuracy (on the order of millimeters) can be rapidly obtained. (Ionospheric delay and associated compensation techniques are described in

Chapter 4, while differential processing is discussed in Chapter 7.) The additional signals also increase the receiver's robustness to interference. If one signal experiences high interference, then the receiver can switch to another signal. It is the intent of the U. S. government that these new signals will aid civil, commercial, and scientific users worldwide. One example is that the combined use of L1 (which also resides in an ARNS band) and L5 will greatly enhance civil aviation.

During the mid to late 1990s, a new military signal called M code was developed for the PPS. This signal will be transmitted on both L1 and L2 and is spectrally separated from the GPS civil signals in those bands. The spectral separation permits the use of noninterfering higher power M code modes that increase resistance to interference. Furthermore, M code will provide robust acquisition, increased accuracy, and increased security over the legacy P(Y) code. Chapter 5 contains descriptions of the legacy (C/A code and P(Y) code) and modernized signals mentioned earlier.

Both M code and L2C were on orbit when the first Block IIR-M ("R" for replenishment, "M" for modernized) satellite was launched. (The Block IIR-M also broadcasts all legacy signals.) The Block IIF ("F" for follow on) satellites have been launched from 2010 and generated all signals, including L5. Figure 1.1 provides an overview of GPS signal evolution. Figure 1.2 and Figure 1.3 depict the Block IIR-M and Block IIF satellites, respectively. The GPS Ⅲ program was underway. This program was conceived in 2000 to reassess the entire GPS architecture and determine the necessary architecture to meet civil and military user needs through 2030. It is envisioned that GPS Ⅲ will provide sub-meter position accuracy, greater timing accuracy, a system integrity solution, a high data capacity inter-satellite crosslink capability, and higher signal power to meet military anti-jam requirements.

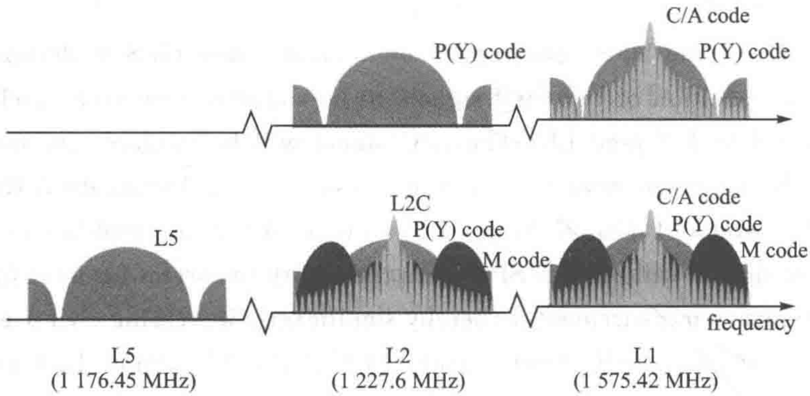

Figure 1.1 GPS signal evolution.