GPS Navigation

Principles and Applications

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SCIENCE PRESS

Alpha Science

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Alpha Science International Ltd.

GPS Navigation
Principles and Applications
326 pgs. | 123 figs. | 16 tbls.

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Co-Published by:

Science Press
16 Donghuangchenggen North Street
Beijing 100717, China

and

Alpha Science International Ltd.
7200 The Quorum, Oxford Business Park North
Garsington Road, Oxford OX4 2JZ, U.K.

www.alphasci.com

ISBN 978-1-84265-563-4 (Alpha Science)

Printed in India

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Preface

NAVSTAR/GPS is the acronym composed of the first letters of Navigation Satellite Timing and Ranging or Global Positioning System. Its meaning is using navigation satellites for measurement of time and range. GPS is the most advanced precision satellite navigation and positioning system.

GPS is established by the U.S. Department of Defense to meet military department's requirements of precision navigation and positioning for the sea, air and land vehicles. The system cost a large research funding for more than 10 billion U.S. dollars. After more than 20 years of unremitting efforts from the program demonstration, research, development, testing and networking, when finally on March 10, 1994 all the 24 satellites entered into predetermined orbit, the system was put fully in normal operation.

GPS is a new space-based radio navigation system. GPS not only has the precise three-dimensional, global, all-weather and continuous positioning capabilities, but also can measure the speed and attitude for transport carriers with precise timing. GPS is the crystallization of the development of modern science and technology, and it is the third largest space project for the U. S. following the Apollo missions and the space shuttle. Therefore, GPS has become the most important modern milestone for the U. S. navigation technology.

According to reports, early in the Gulf War of 1990, despite the GPS system being not yet fully developed, it was the fundamental solution to the positioning and navigation problems of air, land and sea transport carriers. GPS played an unprecedented role in precision strike of enemy forces and guiding the forces correctly across the desert, to occupy the intended targets, to provide logistical assistance efficiently for the U.S. and the allied forces. Currently, a large number of GPS user equipments are being used in all the military fields such as navigation of ships, tanks and aircrafts, in tactical and strategic missile tests, measurements, controls and guidance, and in almost all kinds of satellite monitoring. Military experts believe that future wars will be a high tech "digital war," and the advanced navigation and positioning will be the necessary conditions for "digital war". Therefore, GPS technology and its military applications require full attention of all the governments and the defense departments in the world.

In addition its the applications in the military field, in the past decade, GPS precise positioning technology has made extensive infiltration into various fields of economic construction and scientific experiments. For example, it has been applied to geodesy and the city control network successfully. It has been applied to civil aircraft navigation, precision approach and landing. It has been applied to intelligent navigation and traffic management for land vehicles. It has applied to earth resources surveys, design measurement and deformation monitoring of major projects and it has been applied in aerial and satellite remote sensing. High-precision and automation of GPS technology profoundly impacted on earth dynamics science, geodesy, astronomy and related disciplines. It has achieved a rapid development and remarkable achievement in these basic disciplines of applied research and pioneering work, which demonstrated tremendous advantages and potential of GPS.

In recent years, GPS technology has entered into people's daily lives, such as in vehicle tracking, vehicle navigation, tourism, adventure, hunting, security, geographic information, orientation of agriculture and communication and other related aspects.

GPS technology is booming in all areas of applications. It is believed that the penetration and application of GPS in military and civilian fields will move rapidly at a broader and

more profound level.

To meet the developmental needs of GPS applications, the book introduces the basic working principles and the theoretical knowledge on the application of technology of GPS for general GPS users and other interested readers. Particularly, the book makes a more in-depth analysis in GPS/INS integrated navigation system. As the GPS/INS integrated navigation systems can fully exploit their respective advantages and overcome the shortcomings, they can achieve real-time and high precision navigation and positioning in high dynamic and strong electronic jamming environment, therefore, GPS/INS integrated navigation systems have very important roles and broad applications, especially in the navigation of aeronautics and astronautics, and precision guiding of weapons.

This book is divided into ten chapters. The first chapter is an introduction. To enable readers having a general understanding of GPS, a brief history and background of satellite navigation and positioning technology is introduced in the chapter. Chapter two briefly introduces the coordinate system and time system required for the GPS measurements. Leaving the time and space frame of reference for the measurement is meaningless, so to understand the definition of these systems and exchange method between different reference systems is essential for in-depth grasp of GPS measurement principles. Chapter three introduces the basics calculation method of satellite motion and satellite coordinates according to Kepler theorem, which is very important for understanding the basic rules of GPS satellites and the ephemeris calculation. Chapter four briefly describes the basic concepts of the GPS satellites broadcast signals, and outlines the produce principle of C/A code and P code, and finally introduces the GPS satellite navigation message. Chapter five has a more in-depth analysis for the observations of GPS navigation and positioning and a detailed discussion of the main error sources for the measurements. The pseudo-range measurement observation equations as well as their linear equation have been given, which is an important basis used for high accuracy GPS positioning and navigation. Chapter six and chapter seven discuss the GPS statics and dynamics theories respectively. The observation equations and their linear form of the positioning have been analyzed in detail, and important concepts of observation data processing and accuracy assessment have been discussed. Location parameter is the most important parameters of navigation parameters, so using GPS technology to determine the user's location coordinates is the focus of this book. Chapter eight introduces indispensable carrier speed measurement, vehicle attitude measurement, and GPS timing of the navigation parameters, which provide all the necessary parameters for GPS navigation.

In Chapter nine the GPS/INS integrated navigation systems are discussed in detail. The inertial navigation system (INS) has excellent autonomous navigation capabilities relying on inertial measurement, the independent vector position, velocity and attitude parameters can be given, which have strong anti-interference ability, but the error will accumulate over time which can have serious impact on navigation accuracy. The GPS navigation system has advantages of global, all-weather, high precision real-time location, but its dynamic performance and robustness are poor. Therefore integrated GPS/INS can achieve complementation of the two systems. This chapter firstly has a brief discussion of the Kalman filtering technique, then it introduces some methods and characteristics for using of the Kalman filtering, and finally analyses some application programs of the Kalman filtering used in GPS/INS integrated navigation system. It is generally considered that the GPS/INS integrated navigation system is a more satisfactory system for air, sea and land navigation and positioning systems at present and for the future. So this chapter is the most important one for the reader to the study and use the navigation system. Chapter ten uses the limited space to introduce the application knowledge of GPS technology in a few more important areas, and thus the broad application prospects of GPS positioning technology can be seen.

Since first printing published by the Science Press at the August 2003, the book has been

used as teaching materials of electronic information in institutions of higher learning. It has been carried out 6 times printing with good feedback, and was recommended as graduate students by the Ministry of Education in China. Thanks to many nationwide colleges and universities who selected it as a senior undergraduate and graduate textbooks or reference books, this book has been used and recognized by teachers and students widely.

In view of the good effects and further expand the use of the book, Science Press recommend this book to the international issue, and commissioned us the translation of the book. Translation of the book was organized by the associate professor Hai-ying Liu, he and Zhi-ming Chen shared the main work of translation and integration. The personnel involved in translation work also includes Cheng-tao Feng, Jing Li, Shi-yong Fu, Fei Teng, Ping Qian, Miao Zhu, and Xiao-song Cui, they participate some chapters of the translation. After nearly a year of efforts with translate group, the English version "GPS Navigation Principles and Applications" has been dedicated to the readers finally. Here I would like to thank my students Hai-ying Liu and other students who translated and published the book, and also sincerely thank Science Press and Alpha Science International Ltd. for their effort.

GPS navigation is a new interdisciplinary science. Its theories are still developing and its applications are continuously being deepened and widened. Due to author's limitations on the level of practical experience, and also owing to very pressing time deadlines, the book is likely to contain quite a few errors or inappropriate material etc, so we look forward to the criticism, feedback, and suggestions from the readers.

Hui-nan Wang

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Chapter 1

Introduction

1.1 Development of GPS positioning technology

In 1973, the U.S. Department of Defense organized armed forces to research the establishment of a new generation of satellite navigation system: "Navigation Satellite Timing and Ranging/ Global Positioning System", that is, "Timing and Ranging Navigation System", usually referred to as "Global Positioning System"(GPS). It is a new generation of precise satellite positioning system, which is an achievement based on rapid development of modern science and technology.

In October 1957, the former Soviet Union launched the world's first artificial Earth satellite successfully. From then on, humanity has entered a new era of rapid development of space science and technology. The research for positioning and navigation using satellite has attracted great importance of military departments in various countries. By the end of 1958, U.S. Naval Weapons Laboratory began developing a satellite navigation system for the navigation services of military ships, that is, "the Navy Navigation Satellite System" (NNSS). In this system, all satellite orbits pass through the earth's north and south poles, and the ground trace of satellites coincides with the Earth's meridian, hence it is also called the "meridian instrument (transit) satellite navigation system". In January 1964, the system was successfully developed. It is used for navigation and positioning of Polaris nuclear submarine, and is applied to navigation and positioning for other types of ships gradually. On July 29, 1967, the U.S. government declared decryption of the navigation message partly in "TRANSIT satellite navigation system" for civil commercial applications, such as ocean-going ship navigation and marine location-based services. With the further improvement of TRANSIT satellite navigation system technology, the accuracy of satellite orbit determination has been improved, as well as the user receiver's performance has been enhanced. This positioning technology for space satellite Doppler measurements by the user receiver, continuously improve its positioning accuracy. At the same time, the satellite Doppler positioning technology is not subject to the impact of meteorological conditions, and the high degree of automation makes it suitable for a broader range of applications. The system has been used in many areas, such as the offshore oil exploration, drilling location, survey and mapping coastal submarine cable laying, island alliance, as well as geodetic control network measurement. Countries around the world have carried out a great deal of applied research and practice, and made remarkable achievements. China also introduced a meridian instrument satellite navigation system receiver in the early 80s of 20th century, which was very effectively applied to navigation and geodesy.

Although the TRANSIT satellite navigation system has an epoch-making significance in the development of navigation and positioning technology, however, there are still significant deficiencies in it. The system makes up navigation network using six satellites, which are in circular polar orbit about 1080km from the ground. There is only one satellite in each orbit with the running cycle of 107min. As the number of satellites is small and the orbit is low,

the satellite has been followed-up only by ground observation station once every 1∼2h. In addition, because of using of Doppler positioning theory, a receiver needs 15 qualified satellite observations in order to obtain a single point positioning parameter with accuracy of ±10m. Due to the long periods of observation and solution for navigation parameters, it cannot meet the requirements of continuous real-time three-dimensional navigation, especially for high-precision navigation requirements of the high-dynamic targets (such as aircraft, missiles, etc.).

From the geodetic point of view, because its positioning velocity is slow (average observation time need 1 ∼ 2d for a station) and accuracy is also low (single point positioning accuracy is about 3 ∼ 5m, and the relative positioning accuracy is about 1m), the application of TRANSIT satellite navigation system has been greatly restricted in the research for geodesy and geodynamics.

In the 60 years of mid-20th century, considering the TRANSIT satellite navigation system's success and its shortcomings, U.S. Navy and Air Force were prompted to study more advanced satellite navigation system to improve the navigation performance. The proposed plan of Navy is known as the "Timation" (Time Navigation), and Air Force's plan is called 621B. Each of these two very different programs has advantages and disadvantages. "Timation" program buildup global positioning network using 12 to 18 satellites with altitude of about 10000km, has circular orbit with cycle of 8h. Two test satellites were launched in May 1967 and November 1969 respectively.

"Timation" program is basically a two-dimensional system, which does not meet the requirements for continuous real-time positional parameters of Air Force's aircraft or missiles in high dynamic environment. Air Force's "621B" program was designed to work in high dynamic environment. In order to provide global coverage, the 621B program intended to use 3 to 4 constellation and each one consisted of 4 to 5 satellites, in which the middle satellite used a fixed-point synchronous orbit and the other used inclined orbit with period of 24h. Each constellation needed a separate ground control station for its services. The system had two main problems: First, the coverage of polar region, and second, needing foreign stations. These make the system difficult to independently operate safely and reliably.

In 1973 based on these two programs the U.S. Defense Department decided to develop a global Positioning system for common use of various services. United States Department of Defense specified that this program was led by the Air Force research. In the Air Force Systems Command, Department of Space set up a joint program office, in charge of development, testing, procurement and deployment for GPS. The units participated included the Air Force, Army, Navy, Marines, Coast Guard, Department of Transportation, Defense Agency and defense mapping pre-research projects agency. In 1978 some members of the North Atlantic Treaty Organization, and Australia also participated in the GPS program through bilateral agreements. GPS is a space system for Timing and Ranging which can be designated rendezvous navigation. It can be put to the global customers for continuous, real-time, high-precision three-dimensional position, three-dimensional velocity and time information to meet the military and civilian sectors needs.

The whole development plan of GPS is divided into three stages.

The first phase of the program was the principle and feasibility validation phase. From 1978 to 1979, a total of four experimental satellites were launched, the ground tracking networks were established and ground GPS receivers were developed. The system's hardware and software were tested and test results were satisfactory.

The second phase was the system's development and testing phase, from 1979 to 1984. Seven test satellites were successively launched. In the first stage and second stages a total of 11 satellites were launched. These experimental satellites known as the first generation of satellites as shown in Tab. 1.1. At the same time, a variety of navigation-type receivers and