Navigation: Science and Technology 5

Wei Zheng
Yidi Wang

X-ray Pulsar-based Navigation

Theory and Applications

Science Press
Beijing

Springer

Navigation: Science and Technology

Volume 5

This series *Navigation: Science and Technology (NST)* presents new developments and advances in various aspects of navigation - from land navigation, marine navigation, aeronautic navigation to space navigation; and from basic theories, mechanisms, to modern techniques. It publishes monographs, edited volumes, lecture notes and professional books on topics relevant to navigation - quickly, up to date and with a high quality. A special focus of the series is the technologies of the Global Navigation Satellite Systems (GNSSs), as well as the latest progress made in the existing systems (GPS, BDS, Galileo, GLONASS, etc.). To help readers keep abreast of the latest advances in the field, the key topics in NST include but are not limited to:

- Satellite Navigation Signal Systems
- GNSS Navigation Applications
- Position Determination
- Navigational instrument
- Atomic Clock Technique and Time-Frequency System
- X-ray pulsar-based navigation and timing
- Test and Evaluation
- User Terminal Technology
- Navigation in Space
- New theories and technologies of navigation
- Policies and Standards

This book series is indexed in **SCOPUS** database.

More information about this series at http://www.springer.com/series/15704

Wei Zheng · Yidi Wang

X-ray Pulsar-based Navigation

Theory and Applications

Science Press
Beijing

Springer

Wei Zheng
College of Aerospace Science
and Engineering
National University of Defense Technology
Changsha, Hunan, China

Yidi Wang
College of Aerospace Science
and Engineering
National University of Defense Technology
Changsha, Hunan, China

The Funder information: National Natural Science Foundation of China (Grant No. 61703413).

ISSN 2522-0454 ISSN 2522-0462 (electronic)
Navigation: Science and Technology
ISBN 978-981-15-3292-4 ISBN 978-981-15-3293-1 (eBook)
https://doi.org/10.1007/978-981-15-3293-1

Jointly published with Science Press
The print edition is not for sale in China (Mainland). Customers from China (Mainland) please order the print book from: Science Press.
ISBN of the Co-Publisher's edition: 978-7-03-064771-9

© Science Press and Springer Nature Singapore Pte Ltd. 2020
This work is subject to copyright. All rights are reserved by the Publishers, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
The publishers, the authors, and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publishers nor the authors or the editors give a warranty, express or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publishers remain neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

Foreword

Spacecraft increase in number with the development of space science and technology. If the position and velocity of those spacecraft are still provided by the ground-based tracking system, there are numerous human efforts and investment should be involved. In addition, the ground tracking is not capable of providing a timely response to some emergencies because of the distance between spacecraft and the Earth. Therefore, the autonomous navigation technique is important for future spacecraft. X-ray pulsar-based navigation is a promising spacecraft autonomous navigation method, which can make the spacecraft get rid of the support of the ground-based tracking system and the other artificial beacons. The NICER performed on the International Space Station, the Insight-Hard X-ray Modulation Telescope, and the X-ray pulsar-based navigation-01 satellite all has a common aim that is to verify the X-ray pulsar-based navigation. It might indicate a new surge of X-ray pulsar-based navigation.

The authors' research group has been working on X-ray pulsar-based navigation since 2004. They have proposed many methods to enhance the navigation performance of such navigation system. Now, the authors published their achievements, aiming to provide theoretical guidance and technical support for researchers working on the spacecraft autonomous navigation, especially X-ray pulsar-based navigation.

This book aims to investigate the X-ray pulsar-based navigation and to expand its application field. This book starts with introducing the X-ray pulsar-based spacecraft positioning/time-keeping/attitude determination methods, analyzes the error propagation mechanism and corresponding error compensation methods, proposes integrated navigation methods based on the information from X-ray pulsar and that from the other measurement sources, introduces the idea that autonomous navigation for spacecraft group with X-ray pulsar time difference of arrival, and finally designs a ground-based verification system. In addition, the methods in this book also provide a useful reference for solving related technical problems on spacecraft autonomous navigation.

I am glad to see this book get published and sincerely hope it will help upgrade the study on X-ray pulsar-based navigation.

Bao Weimin

May 2019

Bao Weimin
Academician of Chinese
Academy of Sciences
Beijing, China

Preface

Spacecraft navigation information nowadays is generally provided by the ground-based tracking and control system. However, the on-orbit spacecraft increase in number as space technologies develop, thus significantly burdening the ground-based tracking and control system and reducing the survivability of spacecraft in special cases. Therefore, greatly developing autonomous navigation technologies is in urgent demand in coping with increasingly complicated space missions and a key to enhance the survivability of spacecraft and to reduce operation costs.

X-ray pulsar-based navigation is a new spacecraft autonomous navigation method whereby the pulsar is performed as a celestial beacon to provide the reference information for spacecraft to estimate its state including position, attitude, and time. Compared with satellite navigation, X-ray pulsar-based navigation is not just applicable to near-earth space but also insensitive to manual inference. Compared with the traditional celestial navigation method, X-ray pulsar-based navigation can simultaneously provide complete navigation information such as the position, attitude, and time. X-ray pulsar-based navigation shows obvious characteristics in the X band and can avoid jamming from various signals in space. Compared with radio pulsars, X-ray pulsar with high energy at the X band can guarantee the minimization of detectors that have sufficient flux sensitivity and temporal-spatial resolution.

The X-ray pulsar-based autonomous navigation method was proposed initially in 1980s. From the end of the twentieth century to the beginning of the twenty-first century, a relatively complete navigation framework has been gradually developed. The Flight Dynamics and Control Team in the National University of Defense Technology has been studying the theory and methodology of X-ray pulsar-based navigation since 2004 and is one of the first teams in China that researches X-ray pulsar-based navigation. This book introduces our research achievements over the past 13 years, combining with the latest global development in the field.

This book is divided into seven chapters. Chapter 1 first provides a schematic picture on the autonomous navigation for spacecraft and reviews the development of X-ray pulsar-based navigation. Chapter 2 provides the basic knowledge supporting X-ray pulsar-based navigation; Chap. 3 analyzes how to process X-ray pulsar signals when the spacecraft is stationary and when the spacecraft is orbiting; Chap. 4 investigates the error within X-ray pulsar-based navigation and proposes methods to overcome them; Chap. 5 introduces the integrated navigation by fusing the X-ray pulsar signal and other information sources; Chap. 6 employs the X-ray pulsar time difference of arrival to fulfill the spacecraft autonomous navigation; Chap. 7 designs and constructs an X-ray pulsar-based navigation ground simulation and verification system.

We hereby would like to sincerely thank the National Natural Science Foundation of China, National Science and Technology Major Project, National High Technology Research and Development Program of China (863 Program), and relevant experts in China for their supporting research presented in this book.

We referred much literature of scholars home and abroad and cited such literature to the best of our knowledge when writing this book. We hereby want to express our sincere appreciation to them.

We would also like to thank the academicians Bao Weimin and Wei Ziqing for their consistent care and support. We would especially thank Academician Bao Weimin for contributing Foreword of this book. We thank researchers Zhang Shuangnan, Shuai Ping, Liu Siwei and Lu Fangjun, Prof. Li Xiaoping and Prof. Fei Baojun, and Associate Professor Yao Guozheng for their help in specific research work and their precious suggestions on this book. We thank Mr. Qian Jun, the editor, for his great efforts in getting this book published.

X-ray pulsar-based navigation is an interdisciplinary research field involving navigation theories, orbital dynamics, X-ray astronomy, high-energy physics, microelectronics, etc. It is developing continuously in its theories and applications. Authors welcome any corrections from peers and readers for mistakes in this book.

Changsha, China
October 2017

Wei Zheng
Yidi Wang

Contents

Chapter 1
Introduction

1.1 Basic Concept of Spacecraft Autonomous Navigation System

1.1.1 Definition of Spacecraft Autonomous Navigation System

A navigation system for spacecraft can be viewed as an autonomous one if it is self-contained, could provide real-time operation, does not radiate, and is independent of the ground support. In practice, the definition of autonomous navigation system for spacecraft can be loosen to be that a navigation system which gets rid of the support from the ground-based system is the autonomous navigation system.

1.1.2 Necessity of Autonomous Navigation Systems

The current spacecraft are commonly tracked by the ground-based systems. However, as aerospace missions become increasingly elaborate, the future spacecraft will be encouraged to experience unknown environment. In this case, spacecraft are expected to autonomously cope with emergencies, since the ground-based systems might not provide timely emergence responses due to the huge distance between spacecraft and the Earth. The autonomous navigation technique is a key technique to fulfill the autonomous operation [1].

1.1.2.1 Necessity for Earth-Orbiting Spacecraft

Earth-orbiting spacecrafts, which include various satellites, spaceships, space maneuvering spacecraft, and orbit transfer vehicles, perform important roles in the modern

W. Zheng and Y. Wang, *X-ray Pulsar-based Navigation*, Navigation: Science and Technology 5, https://doi.org/10.1007/978-981-15-3293-1_1

society. With the development of aerospace science and techniques, the Earth-orbiting spacecraft launched in recent years increase sharply in type and number, burdening ground systems.

In order to reduce the manual effort involved in the ground-based support and to enhance the survivability when a spacecraft facing hostile environment, the spacecraft is suggested to have the autonomous navigation capability. For the spacecraft in the near-Earth space with orbital altitude of lower than 3000 km, the autonomous navigation can be well implemented by the global navigation satellite system (GNSS). However, for those spacecraft orbiting on the high Earth orbit, the received signal of GNSS is instable, and is difficult to be employed to fulfill the function of autonomous navigation. Nevertheless, high-Earth-orbit spacecraft, with an advantage in the orbit altitude, play a role in daily life more important than low-Earth-orbit spacecraft. How high-Earth-orbit spacecraft could have autonomously positioning performance is a hot issue for the study on spacecraft autonomous navigation.

1.1.2.2 Necessity for Deep Space Explorers

Since the beginning of the 21st century, the countries in the world all attached importance to the deep space exploration, which help human beings probe the secrets of the universe. As the flight distance and duration of mission are huge, deep space explorers put new demands on each key techniques supporting the missions, especially on the navigation technique [2].

At present, most of the international deep space exploration missions are supported by the ground-based radio tracking systems, among which the Deep Space Network (DSN) of the United States (US) is the most famous one. The radio tracking systems determine the position of deep space explorers by measuring the distance and radial velocity of the deep space explorer relative to the ground-based system [3].

However, this method has inevitable shortcomings as follows:

(1) It involves frequent communications between the ground-based system and the deep space explorer. There would be a huge time delay within the communication caused by the huge distance between the ground-based system and the deep space explorer. The time delay within the communication from the Mars to the Earth can be up to 45 min and that of communication concerning exploration for the Jupiter, Saturn and other celestial bodies would be larger. In addition, communication signals might be blocked or be disturbed by celestial bodies providing radio radiation. In this case, the ground-based system cannot provide a timely response to the request of deep space explorers facing emergence.

(2) It involves numerous manual efforts. An increasing number of deep space explorers would aggravate the burden of ground-based systems. A deep space exploration mission usually continues for several years or even several decades, during which numerous manual efforts and investment are needed by the ground-based systems to ensure the success of the mission.

(3) It cannot provide an accurate and real-time navigation result. For deep space missions such as approaching, flying over and impacting target celestial bodies, the position, velocity, and attitude of deep space explorers should be accurately known. However, those target celestial bodies are far away from the Earth, and the measurement accuracy of ground-based tracking technique would reduce by 4 km if the distance between the spacecraft and the Earth grows an astronomical unit (AU). Thus, the above missions are difficult to be accomplished if only the support of ground-based systems is available.

In order to extend the field of deep space exploration and to ensure the survivability of deep space explorers which might lose the contact with the ground-based systems, it is benefit to develop the autonomous navigation technique.

1.1.2.3 Necessity for Navigation Satellite Constellations

For objects on the ground or in the air, the navigation satellites are the most common approach to provide them with a high-precision position and a reference time. The ephemeris errors and clock errors of navigation satellites are the important factor that affects the positioning results based on observing navigation satellites. The current ephemeris and parameters of clock error of navigation satellites are corrected and uploaded by the ground-based systems. If there is any problems occurred in the ground-based systems, the performance of navigation satellite constellations would degrade. Hence, it is promising to allocate the function of autonomous navigation to the navigation satellite constellations.

For navigation satellite constellations, the autonomous orbit determination can be well approached by measuring the distance between satellites provided by inter-satellite links [4]. However, the measurement of relative distance can only accurately determine the relative positions of satellites but cannot resist the constellation as a whole to rotate in the inertial system [5].

Thus, it is significant to develop an autonomous navigation system for navigation satellite constellations to resist the whole rotation in the inertial system.

1.2 Three Main Types of Spacecraft Autonomous Navigation Systems

1.2.1 Inertial Navigation System

The inertial navigation system (INS) could provide the position and attitude information of spacecraft by measuring the apparent acceleration and the rotation speed of body system with respect to the inertial system and by propagating the dynamics model [6]. Featured by being independent of external information, free from interference, and elusive, INS has been widely utilized in aerospace, marine and military fields.

INS can be classified into gimbaled inertial navigation systems (GINS) and strapdown inertial navigation systems (SINS), according to the way how to gain the inertial measurements. An INS usually consists of a gyro and an accelerometer. There are two types of gyro that are widely applied, including mechanical gyro and optic gyro. The mechanical gyro senses the angular speed or angular displacement via the directing property and procession of mechanical rotors [7]. In 1852, Foucault, a French physicist, preliminarily proposed the concept of gyros. Since the 20th century started, mechanical gyro technique was stimulated by the growing requests of military and industrial applications and developed rapidly, bringing out the buoyancy gyros and electrostatical gyros [8], among which buoyancy gyros included liquid floated gyros, gas-floated gyros, magnetically suspended gyros, etc. [9]. To reduce the manufacture cost, vibration gyros were invented [10]. Vibration gyros include hemispherical resonator gyro, quartz tuning fork vibrating gyro, micro electro-mechanical system (MEMS) gyro, and etc. [11]. Optic gyro are classified into three categories: laser gyro, fiber-optic gyro and integrated optic gyro [12], among which laser gyro and fiber-optic gyro have been widely used while integrated optic gyro is still in the phase of development, but is promising in application. Besides mechanical gyro and optic gyro, the cold atom interferometry gyro benefited from the rapid development of optics technique is developing rapidly and is of great prospect [13].

The impact of error within the gyro on the positioning performance of INS is a cubic function of time. In order to improve the navigation performance of INS, it is necessary to understand profoundly the INS error model and to compensate the impact of errors besides improving the hardware manufacture quality [14]. Inertial navigation error models will change in parameters as the service environment, which will reduce the reliability of parameters calibrated in laboratories. In this case, some methods such as missile-borne tests, rocket sled tests and vehicle tests can be utilized to systematically verify the inertial navigation error model [15, 16].

1.2.2 Celestial Navigation System

Celestial navigation system (CNS) could determines the position and attitude of a spacecraft by measuring the position or direction information related to celestial bodies. This system is featured by strong autonomy, immunity from interference, high reliability, and shows an advantage because its navigation error does not accumulate over time [17].

CNS was first applied to the navigation for ships, and was introduced into the field of spacecraft navigation in 1950s, being benefited by the rapid development of electronic, computer and space techniques. Both the Apollo program and the space station of the Soviet Union utilized CNS.

The sole utilization of directional information of stars could only determine the attitude of a spacecraft. In order to determine the position of the spacecraft, the directional information of the spacecraft with respect to a nearby celestial body has to be obtained. For Earth-orbiting satellites, the nearby celestial body is commonly selected as the Earth or the moon. There are two ways to gain the directional information of the satellite with respect to the selected nearby celestial body, i.e., direct horizon sensing and indirect horizon sensing [17].

The direct horizon-sensing navigation method provides the position and attitude of spacecraft by employing horizon sensors and star sensors. In 1960s, the United States Air Force developed the first satellite autonomous navigation program (283 program) [18], which comprised three strapdown gyros, a star sensor, and a horizon sensor. The positioning performance of this system was mainly limited by the undesirable accuracy of the horizon sensor, and could only achieve an accuracy of 2 km. In 1973, the United States Air Force launched the Space Sextant-autonomous Navigation and Attitude Reference System (SS/ANARS) [19] consisting of two optical telescopes installed on a 3 degree of freedom rotation platform, between which one telescope was for tracking the bright edge of the moon and the other one was for tracking a known star. This system was designed to have an attitude-determination accuracy of $0.6''$ and a positioning accuracy of 224 m.

The indirect horizon-sensing navigation method, which is based the stellar refraction, could provide the position of a spacecraft by employing high-precision star sensors. In 1979, the US developed the Multi-mission Attitude Determination and Autonomous Navigation (MADAN) [20] which could provide real-time and continuous inertial attitude and orbit information through three star sensors and was featured by full autonomy. The target positioning accuracy of the system was 0.9 km for low Earth orbit satellites and 9 km for high Earth orbit satellites.

Besides the direct and indirect horizon-sensing methods, the Microcosm, Inc., in 1989, developed a system which determined the real-time orbit and attitude of a spacecraft by measuring the Earth, Moon and Sun with satellite-borne special autonomous navigation sensors—Microcosm Autonomous Navigation System (MANS) [21]. MANS could provide an autonomous navigation service for medium-low Earth orbit satellites. Its navigation sensor was an improved version of a conical scanning infrared earth sensor, featured by light weight, low power consumption, low cost, and etc. In March, 1994, this system was loaded by the Space Test Platform-0 spacecraft to verify its feasibility and key techniques involved. Unfortunately, the data of MANS had to be transmitted to the ground-based system for further analysis due to the failure in the satellite-borne computer. The positioning accuracy of MANS was estimated to be about 200–500 m.

When the 21st century began, the US, France and Japan initialed a new upsurge in deep space exploration. The CNS for deep space explorers is gradually becoming a critical backup navigation system supporting the ground-based system in deep space exploration missions. Both the "Deep Impact" mission and "Hayabusa (MUSES-C)" detector utilized CNS to enhance the autonomous survivability of deep space explorers [22, 23].

1.2.3 Navigation Satellite System

Navigation satellite system can be viewed as a combination of CNS and radio tracking technique. It determines the position and velocity of a spacecraft by measuring the distance and Doppler frequency from the spacecraft to navigation satellites, the position and velocity information of which can be previously gained by the public ephemerides of navigation satellites. As being featured by low cost and high-accuracy, navigation satellite systems have been widely applied to the current aerospace missions.

In 1958, the US developed a navigation satellite system named Transit, also known as Navy Navigation Satellite System (NNSS), which used navigation satellites instead of ground-based stations as the navigation reference beacons. This system came into service in 1964, was used for public use in 1967 [24], but was phased out since 1990, which was caused by the successful applications of the Global Positioning System (GPS).

GPS is a second-generation global navigation satellite system that was first proposed in 1973 and was put into the full operation in 1994 [25]. This system overcomes the shortcomings of the first-generation global satellite navigation system, such as the failure to perform continuously positioning, low accuracy and long interval for positioning, and can provide the high-precision position, velocity, reference time, and attitude of clients. GPS comprises 24 operational satellites and 3 backup satellites, at orbits with inclination of 55° and average height of 20,200 km and period of 11 h 58 min. Navigation satellites are distributed on 6 equally-spaced orbits, with 4 satellites on each orbit. The right ascensions of ascending nodes between two orbits differ by 60° and the arguments of perigee of the satellites on the adjacent orbits differ by 30° (Fig. 1.1).

Besides GPS, the Soviet Union declared to construct GLONASS (Global Navigation Satellite System) and launched the first satellite on October 12th 1982 (Fig. 1.2) [26]. After the Soviet Union collapsed, Russia took this system over and continued to develop it. In 1995, Russia declared the initial operation of GLONASS. The whole GLONASS constellation is also comprised of 24 operational satellites and 3 backup satellites, but unlike GPS, these satellites, spaced with each other by 120°, are distributed on 3 orbits with inclination of 64.8°, height of 19,100 km and period of 11 h 15 min. 8 satellites are on each orbit and distributed with interval of 45°.

The European Unit (EU) announced to develop GALILEO satellite navigation system in 1999 (Fig. 1.3) [27]. The GALILEO satellite constellation comprises 30 navigation satellites (including 3 backup satellites) which are evenly distributed on 3 orbits with inclination of 56° and height of 23,616 km. 9 operational satellites and 1 backup satellite are on each orbit with period of 14 h 4 min.

In China, Beidou-1 navigation satellite system project was officially approved in 1994, two satellites were successfully launched respectively on Oct. 31st and Dec. 21st, 2000 and a backup satellite was also successfully launched on May 25th, 2003 (Fig. 1.4). Beidou-1 consists of 3 geosynchronous satellites, among which two operational navigation satellites are respectively positioned at 80° E and 140° E

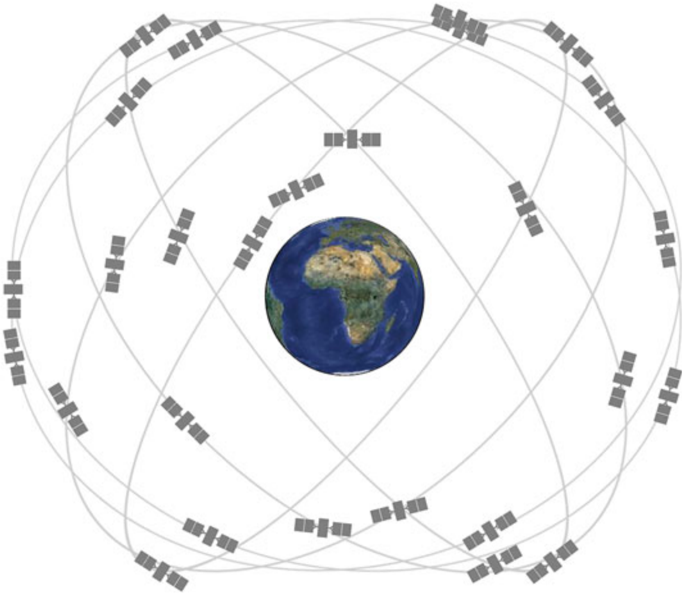


Fig. 1.1 GPS Constellation (from www.gps.gov)

Fig. 1.2 GLONASS constellation (from http://gssc.esa.int)

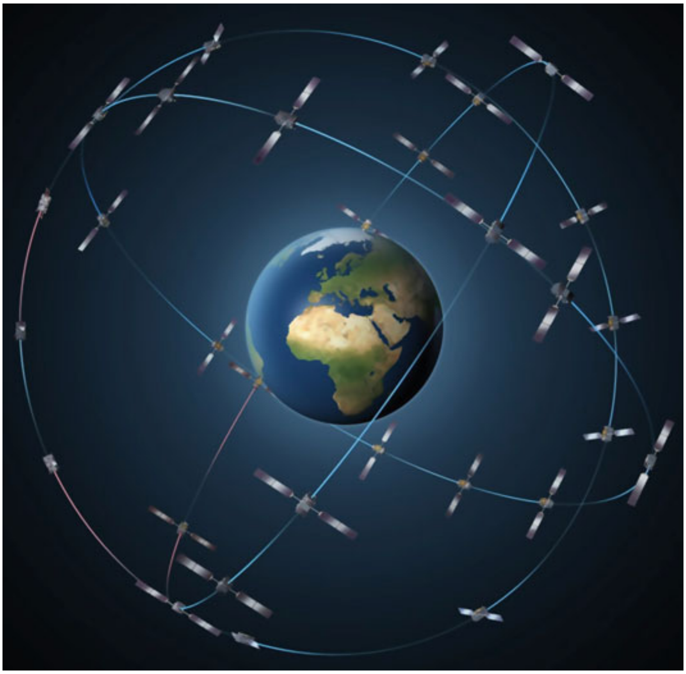


Fig. 1.3 GALILEO navigation constellation

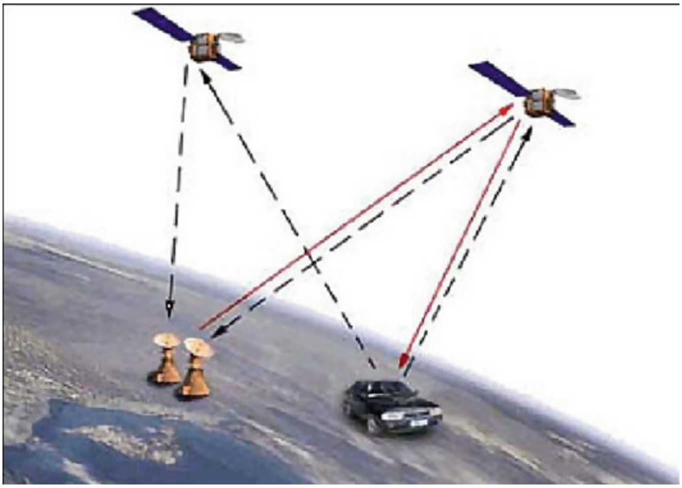


Fig. 1.4 Schematic diagram of navigation performed by “Beidou-1” navigation satellite system (*Image credit* sinodefence)

while the backup satellite is positioned at 110.5° E. The Beidou-1 Navigation Satellite System is an active system. For positioning, a client should first send a request to the ground station which will compute the position of client and then it to the client. It causes the client has to carry a receiver including the function of transmitter, which would increase the weight, cost and power consumption.

Hence, Beidou-2 Navigation Satellite System started to be constructed in 2004 and the construction was planned to be performed in two steps: first, establishing the local Beidou Navigation Satellite System in 2012 to form a local covering ability and offer function of passive positioning, navigation and timing services to China and the Asian-Pacific region; second, expanding the local Beidou Navigation Satellite System from 2013 and completely establishing the Beidou Navigation Satellite System around 2020 which can offer passive positioning, navigation and timing services to the whole world [28]. On December 27th, 2012, the first step of the Beidou-2 Navigation Satellite System was completed and the system has the functions as designed.

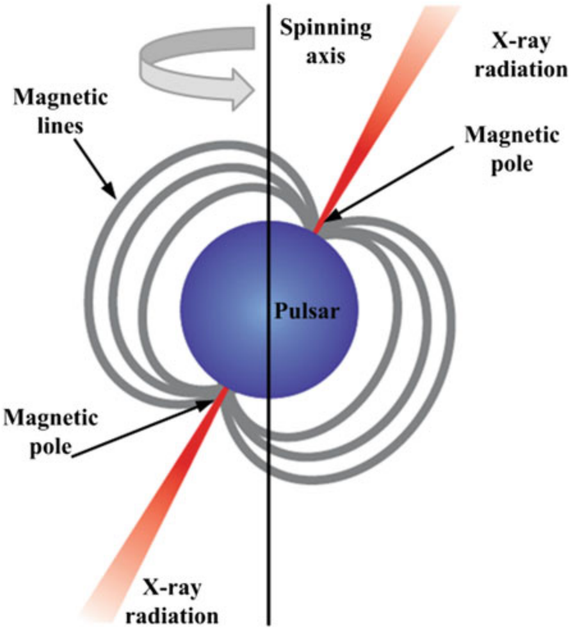
The final version of Beidou Navigation Satellite System will consist of 5 geostationary satellites and 30 non-geostationary satellites, with main functions of passive positioning, velocity measurement, single/double way timing service and short-message communications. This system offers positioning, velocity-measuring and timing services with the accuracy higher than 10 m, 0.2 m/s and 20 ns respectively, and performs short message communication with a capacity of more than 120 Chinese characters per time.

1.3 Review of X-Ray Pulsar-Based Navigation

1.3.1 Brief Introduction of Pulsar

As a branch of neutron star, pulsars are the products of supernova explosions caused by massive stars at the end of their lifetime. For a pulsar, the spinning axis and the magnetic axis do not coincide and its two magnetic poles simultaneously emit electromagnetic radiation beams as shown in Fig. 1.5. When a spacecraft is swept over by the beams, it could receive a pulsed signal like a ship receives signals from a lighthouse. Pulsars are spinning at periodicities with excellent long-term stabilities, and some millisecond pulsars could even match the current atomic clocks. Most of time, a pulsar could simultaneously radiate at different wavebands, such as optical, radio, X-ray, and γ-ray. The X-ray radiation is recommended to facilitate navigation, as it needs sensors quite smaller than devices that function in radio and optical wavelengths [29]. In pulsar astronomy, pulsars that could provide X-ray and radio radiation are usually called X-ray and radio pulsars, respectively.

Fig. 1.5 Lighthouse model of pulsar



1.3.2 Brief Introduction of X-Ray Pulsar-Based Navigation

X-ray pulsar-based navigation (XPNAV) is a developing and promising autonomous navigation technique. XPNAV works by utilizing the X-ray radiation of pulsars. Compared with the current celestial navigation systems, which work mainly by measuring the position or direction information of celestial bodies, XPNAV utilizes the timing information of pulsars and thus its navigation performance is little affected by the distance between the pulsar and the spacecraft. Compared with navigation satellite system, XPNAV is applicable to the near-Earth and deep space, and resists the artificial inference.

By employing the timing information of pulsars, XPNAV could accomplish three types of applications distinct from the other autonomous navigation systems:

- Autonomous maintenance of time reference
  The onboard atomic clock is expected to provide the accurate timing information for the whole spacecraft. However, the unavoidable frequency drift of onboard atomic clock might degrade all the operations of spacecraft. In this case, pulsars could be employed as natural time references to reduce the impact of onboard clock error by means of pulsar timescale and pulsar-aided time-keeping. Pulsar timescale is a timescale utilizing the high periodicity of pulsar. If pulsars are observed for 10 years, the stability of ensemble pulsar timescale could achieve the order of 10^{-14} which was comparable to the estimated long-term stabilities of the

best atomic clocks. Pulsar-aided time-keeping is realized by steering the onboard atomic clock to the observed pulsar.

- Autonomous navigation for navigation satellite constellation
  As illustrated in Sect. 1.1.2.3, the autonomous navigation for satellite constellation is currently implemented by using inter-satellite link. However, inter-satellite links could only well determine the relative positions of satellites within a constellation but cannot resist the rotation of the whole constellation. In this case, pulsars can be viewed as natural “anchors” which could provide absolute direction reference for the whole satellite constellation in the inertial coordinate system. Compared with the previous ground-based “anchor” method, pulsar-based method could completely get rid of human interference.
- Accurate autonomous interplanetary navigation
  The current autonomous navigation method available for deep space explorers (DSEs) in the Sun-centered cruise is accomplished by measuring the stellar angular distance with an accuracy of on the order of arc-minute which corresponds to a positioning accuracy of above a thousand kilometer. In contrast, XPNAV works by handling the timing information of pulsar. If the timing information has an accuracy of higher than 0.1 ms, which is easy to be achieved, the positioning accuracy of XPNAV is higher than 30 km. Thus, XPNAV could achieve an accurate autonomous navigation for DSEs performing the Sun-centered cruise.

In order to realize XPNAV, three key techniques, i.e., navigation pulsar database, the technique of pulsar signal detection and processing, and the technique of navigation theory, are needed.

1.3.3 Famous Programs on XPNAV

These are some famous programs have been performed to study and verify XPNAV.

1.3.3.1 Programs of the US

(1) **Unconventional stellar aspect (USA) experiment**

The US experiment, also called NRL-801 [30], aimed at verifying the feasibility of determining the orbit and attitude of a spacecraft via space X-ray sources and the feasibility of keeping the time reference via X-ray pulsars. It was jointly developed by the Stanford Linear Accelerator Center (SLAC) and the United States Naval Research Laboratory (NRL), and was launched as a payload of the Advanced Research and Global Observation Satellite (ARGOS) in 1999. Although the experiment was designed to last for 3 years, it had to be aborted in the November 2000, as the onboard X-ray sensor broke down.