# Chapter 2
# Celestial-Based Navigation: An Overview

## 2.1 Introduction

In this chapter, we present an overview of spacecraft navigation using X-ray pulsars. In Sect. 2.2, we present a concise treatment of current navigation methods being utilized for space missions. Section 2.3.1 describes why employing celestial-based navigation techniques is desirable for space missions. We introduce different types of pulsars in Sect. 2.3.2. Section 2.3.3 explains why X-ray pulsars are interesting candidates to be used for navigation purposes. A short history of pulsar-based navigation is given in Sect. 2.3.4.

## 2.2 Current Spacecraft Navigation Systems

Most of space vehicle operations, thus far, have relied widely on Earth-based navigation methods for absolute position determination [1, 2]. Methods such as radar range and optical tracking are widely used for this purpose [3]. Although a ground-based tracking system has the advantage of not requiring an active hardware on the spacecraft itself, it does need extensive ground operations and careful analysis of the measured data in an electromagnetically noisy background environment. Also, as a spacecraft moves further away from Earth, its position estimation error increases if a radar-based navigation system is used. To achieve the necessary range determination, the radar system needs to know the observation station's position on Earth accurately. Another limitation is that such a system requires the knowledge of positional information of the solar system objects [1]. However, even if precise information of the radar station and solar system objects is available, the vehicle position estimation can only be accurate to a finite angular accuracy. The transmitted radar beam, along with the reflected signal, travels in a cone of uncertainty. This uncertainty degrades the position knowledge of the vehicle as a linear function of distance. Alternatively, many space vehicles, traveling into deep space or on interplanetary missions, employ active transmitters for orbit determination purposes [1]. The spacecraft receives a ping from an observation station on Earth

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and retransmits the signal back to Earth. Then, the radial velocity is measured at the receiving station by measuring the Doppler frequency of the transmitted signal. Although some improvements are achieved in spacecraft navigation utilizing such systems, this method still has errors that increase with distance. Early experiments using these tracking systems on the Viking spacecraft showed accuracies to about 50 km in position estimation error for missions to Mars and positional accuracies on the order of hundreds of kilometers at the outer planets [2].

Another navigation approach is optical tracking. Spacecraft navigation based on optical tracking measurements is performed in a similar way as radar tracking [4]. This technique is based on the use of the visible light reflected from a vehicle to determine its location. For some optical measurements, a photograph needs to be taken and the vehicle's position is calculated after analysis of the photograph and comparison to a fixed star background. Therefore, real-time measurements using such systems typically are not achieved easily. Furthermore, optical measurements are limited by environmental conditions.

As many missions have concentrated on planetary observations, spacecraft navigation can be done by taking video images of the planet and comparing them to the known planetary parameters such as diameter and position relative to the other celestial objects. Throughout this procedure, the position of the spacecraft relative to the planet can be determined [5]. This requires the vehicle to be within the vicinity of the investigated planet.

To obtain accurate absolute navigation solutions for deep space missions, a combination of Earth-based radar ranging and on-vehicle planet imaging is typically required. This approach still requires human interaction and interpretation of data. Furthermore, as radar-ranging errors increase as the vehicle's distance from Earth increases, accurate navigation becomes more complex because of the required finer pointing accuracy of ground antennas. Additionally, the vehicles that process video images for navigation purposes need to have complicated onboard systems, which increase their cost. The imaging process also requires the vehicles to be sufficiently close to the planets. Therefore, it is necessary to investigate alternative methods that could provide a complete, accurate absolute navigation solution throughout the solar system, and perhaps eventually the intergalactic regimes.

For vehicles operating in space close to the Earth, the current Global Positioning System (GPS) can provide a complete autonomous navigation solution [6]. The GPS uses a constellation of between 24 and 32 medium Earth orbit satellites that transmit precise microwave signals, enable GPS receivers to determine their location, speed, direction, and time. However, these satellite systems have limited scope for the operation of vehicles relatively far from Earth.

For deep space missions, many spacecraft utilize the Deep Space Network (DSN). This system is an international network of antennas that supports interplanetary spacecraft missions, and radio and radar astronomy observations for the exploration of the solar system and the universe [7]. The network also supports selected Earth-orbiting missions. The DSN currently consists of three deep space communications facilities placed $\sim 120^\circ$ apart around the world: at Goldstone, in California's Mojave desert; near Madrid, Spain; and near Canberra, Australia.

This strategic placement permits constant observation of spacecraft as the Earth rotates and helps to make the DSN the largest and most sensitive scientific telecommunications system in the world.

Although accurate radial position can be determined using DSN, it requires extensive ground operations and scheduling to coordinate the observations. Even utilizing interferometry, the angular uncertainty still can increase significantly with distance. Position accuracies in the order of 1–10 km per astronomical unit (AU) of distance from Earth are achievable using interferometric measurements of the Very Long Baseline Interferometer (VLBI) through the DSN [1]. The VLBI is a type of astronomical interferometry used in radio astronomy. It allows observations of an object that are made simultaneously by many telescopes to be combined, emulating a telescope with a size equal to the maximum separation between the telescopes. Data received at each antenna in the array is paired with timing information, usually from a local atomic clock, and then stored for later analysis on magnetic tape or hard disk. At a later time, the data is correlated with data from other antennas similarly recorded to produce the resulting image. The resolution achievable using interferometry is proportional to the observing frequency and the distance between the antennas farthest apart in the array. The VLBI technique enables this distance to be much greater than that possible with conventional interferometry, which requires antennas to be physically connected by coaxial cable, waveguide, optical fiber, or other types of transmission line.

## 2.3 Pulsar-Based Navigation

### *2.3.1 Why Celestial-Based Systems?*

Autonomous formation flying of multiple spacecraft is an important technology for both deep-space and near-Earth applications [8, 9]. One of the main requirements of a formation flight is accurate knowledge of the relative position and velocities between the vehicles. The spacecraft absolute navigation solution is also needed for any space mission. Several researchers have shown that the navigation solution for aerial and low-Earth-orbit applications can be obtained by utilizing differential GPS (DGPS). DGPS is an enhancement to Global Positioning System that uses a network of fixed, ground-based reference stations to broadcast the difference between the positions indicated by the satellite systems and known fixed positions. These stations broadcast the difference between measured satellite pseudoranges and actual (internally computed) pseudoranges, with receiver stations correcting their pseudoranges by the same amount. However, for deep space missions or situations where GPS is not available, an alternative approach is needed. Employing Earth-based navigation systems, such as DSN, is a possibility. But, as mentioned in Sect. 2.2, such systems suffer from low performance in situations where long range navigation is required. Furthermore, they are highly based on communicating with Earth to analyze their data.

Because of the aforementioned problems, the need for higher accuracy, and the continuing increase in cost of vehicle operations, spacecraft navigation is evolving from Earth-based solutions toward more autonomous methods [10, 11]. Autonomous operation means determination of a complete navigation solution by the spacecraft to guide itself toward its destination without human interaction or assistance. An autonomous navigation system internally computes its own navigation and guidance information by using onboard sensors. Any deviation from its planned path is detected, reported, and corrected without input from the ground mission control. These autonomous operations reduce the dependence of space missions on human interaction and communication with Earth. To reduce dependence of navigation systems on ground-based operations and achieve more autonomy, utilizing celestial-based navigation systems is desirable. Another reason for developing such novel navigation methods is to augment current systems by employing additional measurements to improve their performance. Celestial-based systems use signals emitted from celestial sources located at great distances from Earth. Of various celestial sources, X-ray pulsars are interesting candidates for use in both absolute and relative navigation systems because of their special characteristics. These characteristics are explained in detail in the following.

### *2.3.2 Pulsars*

Celestial sources have played significant roles in navigation throughout history, although the majority of sources used have been fixed, persistent stars with visible radiation. Sources that produce signals with variable intensity are referred to as variable celestial sources. There are several classes of variable celestial objects emitting signals whose intensities vary from radio signals to gamma-ray over the electromagnetic spectrum. Of the different variable source types, ones producing a uniquely identifiable signal that is periodic and predictable can be utilized in a specific manner for navigation purposes. One particular class of variable celestial sources having this property is pulsars. Pulsars are rapidly rotating, highly magnetized neutron stars [12]. As the neutron star spins, charged particles are accelerated out along magnetic field lines in the magnetosphere. This acceleration causes the particle to emit electromagnetic radiation as a sequence of pulses produced and as the magnetic axis (and hence, the radiation beam) crosses the observer's line of sight in each rotation (see Fig. 2.1). The repetition period of the pulses is simply the rotation period of the neutron star. Pulsars are observed in the radio, visible, X-ray, and gamma-ray bands of the electromagnetic spectrum [13].

Radio pulsars are broadband, stellar pulsating radio sources powered by the rotation of a neutron star, resulting in a great stability in the pulsar period [14]. Over 1,300 pulsars are known [13], and more are being discovered through new research. In some pulsars, irregularities (glitches) in their rotational frequency are observed every few years, ranging from the order of $10^{-6}$ s for the Vela pulsar to only $10^{-8}$ s for the Crab pulsar. Although individually emitted pulses from the pulsars vary over

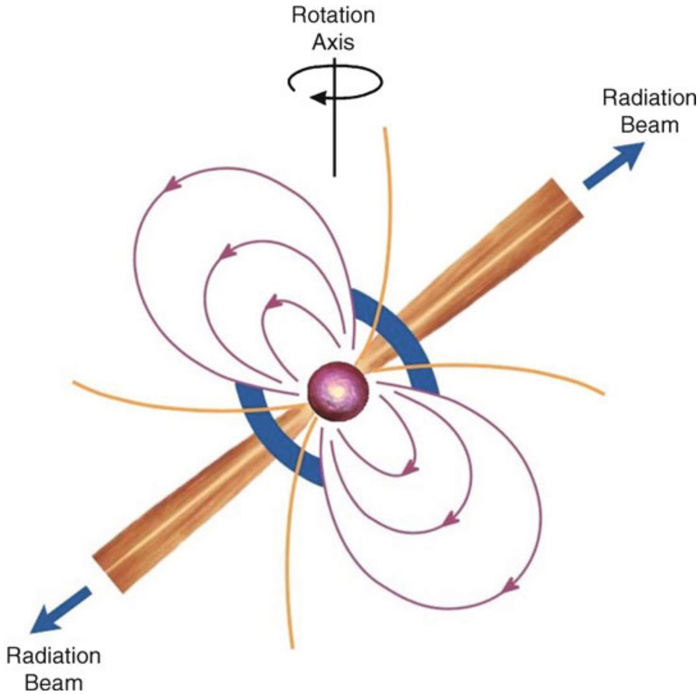


**Fig. 2.1** Diagram of a pulsar. Photo courtesy of National Radio Astronomy Observatory (NRAO)

time, the average pulse shape is stable and characterizes the pulsar. Very precise models are established for the mean arrival time of pulsars, whose stability outperforms even the most precise artificial time bases. Of all pulsars, the most stable ones are the millisecond pulsars. Joseph Taylor and collaborators have demonstrated that the timing stability of millisecond pulsars is comparable with terrestrial atomic clocks [15]. Millisecond pulsars have been detected in the radio, X-ray, and gamma-ray portions of the electromagnetic spectrum. Currently, there are 130 millisecond pulsars known in globular clusters. Unfortunately, their signal to noise ratio (SNR) is considerably lower than that of longer period pulsars.

X-ray pulsars are grouped in two different categories according to the source of energy that powers the radiation: accretion-powered and rotation-powered pulsars [17].

1. Accretion-powered pulsars are a class of astronomical objects that are X-ray sources displaying strict periodic variations in X-ray intensity. The X-ray periods range from as little as a fraction of a second to as much as several minutes. An X-ray pulsar consists of a magnetized neutron star in orbit with a normal stellar companion and is a type of binary star system. The magnetic field strength at the surface of the neutron star is typically about $10^{12}$ Gauss, over a trillion times stronger than the strength of the magnetic field measured at the surface of the

Earth (0.6 Gauss). If the magnetic field and rotation axes of the neutron star are misaligned then X-ray pulsations are observed. Accretion pulsars are not stable timing sources because their period changes over time. More than 30 accretion-powered X-ray pulsars have been discovered with periods from 0.069 to 1,413 s.

2. Rotation-powered pulsars are rapidly rotating neutron stars whose electromagnetic radiation is observed in regularly spaced intervals, or pulses. They differ from other types of pulsars in that the source of power for the production of radiation is the loss of rotational energy. For a long time, the Crab pulsar, the most luminous rotation-powered pulsar, had been the only pulsar detected at X-ray energies. More than 20 rotation-powered X-ray pulsars have since been detected [18, 19]. Figure 2.2 depicts a Chandra X-ray image of the Vela rotation-powered pulsar (PSR B083345) [20].

Pulsars are the original gamma-ray celestial sources. A few years after the discovery of radio pulsars by astronomers, the Crab and Vela pulsars were detected at the gamma-ray band of the electromagnetic spectrum. Pulsars accelerate particles with tremendous energies in their magnetospheres. These particles are ultimately responsible for the gamma-ray emission seen from pulsars. The Vela pulsar, which spins 11 times a second, is the brightest persistent source of gamma rays in the sky. Yet gamma rays, the most energetic form of light, are few and far between. Even Fermi's Large Area Telescope sees only about one gamma-ray photon from Vela every 2 min. As opposed to a pulsar's radio beams which only content a few parts per million of its total power, gamma-rays represent 10% or more.

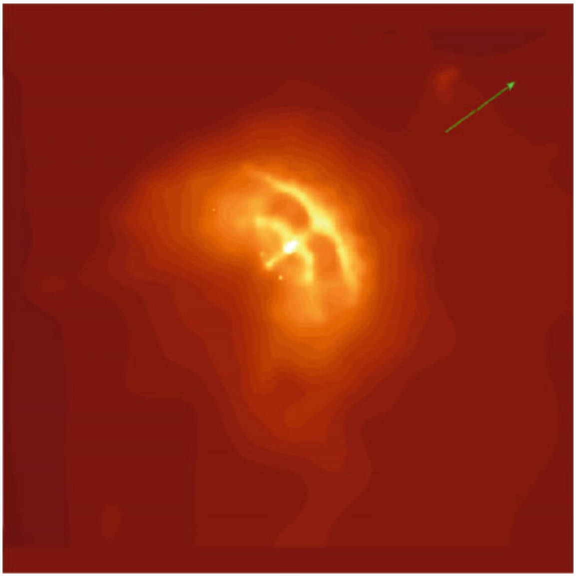

**Fig. 2.2** Vela Pulsar (PSR B083345) X-ray image taken by Chandra X-ray observatory (Credit: The National Aeronautics and Space Administration (NASA)/PSU/G. Pavlov et al.)

By the end of 2004 there were about 1,500 radio pulsars known, but only seven had been detected in the gamma-ray band. Pulsars tend to have large magnetic fields and to be spinning rapidly. The loss of the pulsar's spin energy eventually appears as radiation across the electromagnetic spectrum, including gamma-rays. Both observations and models indicate that pulsars eventually lose the ability to emit gamma-rays as the pulsar's rotational speed slows down.

With NASA's Fermi gamma-ray space telescope, astronomers can now have a better look at pulsars. In two studies published in the July 2, 2009 edition of Science Express, international scientists have analyzed gamma-rays from two dozen pulsars, including 16 discovered by Fermi (see Fig. 2.3). Fermi is the first spacecraft able to identify pulsars by their gamma-ray emission alone [21]. The new pulsars were discovered as part of a comprehensive search for periodic gamma-ray fluctuations using 5 months of Fermi Large Area Telescope data and new computational techniques. In another part of the study, Fermi team examined gamma-rays from eight pulsars, all of which were previously discovered at radio wavelengths. Before Fermi launched, it was not clear that pulsars with millisecond periods could emit gamma rays. Now it is cleared that they do. It has also become clear that, despite their differences, both normal and millisecond pulsars share similar mechanisms for emitting gamma-rays.

NASA's Fermi Gamma-ray Space Telescope is an astrophysics and particle physics partnership, developed in collaboration with the U.S. Department of Energy, along with important contributions from academic institutions and partners in France, Germany, Italy, Japan, Sweden, and the U.S. [21].

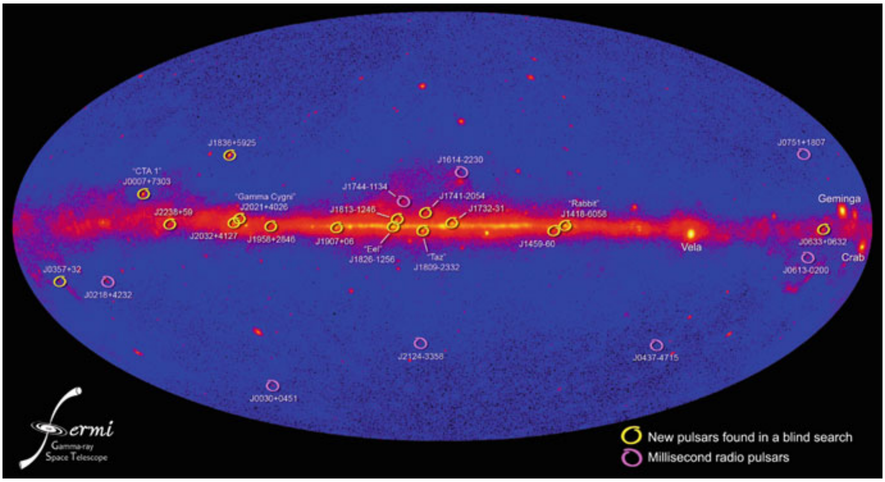


**Fig. 2.3** This gamma-ray all-sky map, which is aligned with the plane of the Milky Way Galaxy, shows the pulsar positions, with the 16 new pulsars, detected by Fermi Gamma-ray Space Telescope, *circled* in *yellow* (eight previously known radio pulsars are in magenta) (Credit: NASA/DOE/Fermi LAT Collaboration)

### 2.3.3 Why Use X-ray Pulsars for Navigation?

Variable sources emitting signals in the radio band are certainly one potential candidate that can be used in a navigation system. However, at the radio frequencies that these sources emit, i.e., from 100 MHz to a few GHz, antennas with 20 m in diameter or larger are required to detect their signals [22, 23]. At these wavelengths, "dish" style radio telescopes predominate. The angular resolution of a dish style antenna is a function of the diameter of the dish in proportion to the wavelength of the electromagnetic radiation being observed. This dictates the size of the dish that a radio telescope needs to have a useful resolution.

For most space missions, large antennas highly impact the design and cost of the operation [24]. Furthermore, because of neighboring sources that emit in radio bands and also low signal intensity of radio pulsars, long integration times are needed to obtain a signal with acceptable SNR, suitable for use in a navigation system. Similar limitations exist for the visible variable sources. Additionally, there are only five isolated pulsars known to emit in the visible band, and all are faint. There are also a only few pulsars discovered which emit in the gamma-ray wavelengths. This is another limitation for utilizing the visible and gamma-ray pulsars in a navigation system.

The disadvantages of the radio and visible sources diminish for sources that emit in X-ray band. The main advantage of spacecraft navigation using X-ray sources is that small sized detectors can be employed [25]. This provides savings in power and mass for spacecraft operations. Another advantage of using X-ray sources is that they are widely distributed. The geometric dispersion of pulsars in the sky is important to enhance accuracy of three-dimensional position estimation since the observability of the source is an important issue. An important complication that must be addressed in utilizing an X-ray source in a navigation system is the timing glitches in its rotation rates. Of X-ray pulsars, ones that are bright and have extremely stable and predictable rotation rates are suitable candidates for the purpose of navigation. These sources are usually older pulsars that have rotation periods on the order of several milliseconds. Figure 2.4 provides an image of the Crab Nebula and its pulsar (PSR B0531+21), which is the brightest rotation-powered pulsar within the X-ray band. The Crab pulsar shows high-flux X-ray emissions with known stable period. Hence, it can be considered a suitable candidate for use in navigation.

### 2.3.4 History of Pulsar-Based Navigation

The first pulsar was observed in July 1967 by Bell and Hewish. In 1971, Reichley, Downs, and Morris proposed using pulsar signals as a clock for Earth-based systems [26]. In 1980, details of methods to determine pulse time of arrivals from pulsar signals were provided by Downs and Reichley [27]. In the 1980s and 1990s, it was demonstrated that several pulsars matched the quality of atomic clocks [12, 15, 16, 28]. Because of their stability, pulsars were considered as accurate celestial clocks, suitable for navigation.

**Fig. 2.4** Composite optical/X-ray image of the Crab Nebula pulsar showing surrounding nebular gasses stirred by the pulsar's magnetic field and radiation. Photo courtesy of NASA

In 1974, Downs, a member of the telecommunication division of the Jet Propulsion Laboratory (JPL), proposed a spacecraft navigation method based upon employing radio signals from a pulsar [29]. Using 27 radio pulsars for navigation over an integration time of 24 h, in [29], he showed that an absolute position accuracy on the order of 150 km was attainable. This introductory paper on pulsar navigation serves as the original basis for the work of other researchers in the field.

During the 1970s, pulsars with X-ray signature were discovered that emit signals within the X-ray band of 1–20 keV ($2.5e17 - 4.8e18$ Hz). In 1981, Chester and Butman proposed using X-ray pulsars as an option to enhance Earth satellite navigation [30]. Their research showed that by comparing the arrival times of pulses at a spacecraft and at the Earth (via an Earth orbiting satellite), a three-dimensional position of the spacecraft can be determined. They reported that a day's worth of data from a small onboard X-ray detector yielded a three-dimensional absolute position accurate to $\sim 150$ km.

In 1988, Wallace studied the issues related to using celestial sources that emit radio emission, including pulsars, for navigation applications on Earth [31]. He stated that the existence of other celestial radio sources obscured weak pulsar signals. As expected, radio-based systems require large antennas to detect sources, which make them impractical tools for spacecraft. Furthermore, the low signal intensity of radio sources requires long integration time to achieve an acceptable SNR. Also, the small population of radio pulsars in the optical band of the spectrum severely limits an optical pulsar-based navigation system.

In 1993, as a part of the NRL-801 experiment for the Advanced Research and Global Observation Satellite (ARGOS), Wood proposed a comprehensive approach to X-ray navigation covering attitude, position, and time. This study employed X-ray sources other than pulsars. As a part of the Naval Research Laboratory (NRL) development of this study, Hanson produced a Ph.D. thesis in the field of X-ray navigation in 1996 [32]. In his work, he studied attitude determination of spacecraft using X-ray pulsars. He used practical data from the HEAO-A1 spacecraft. His approach was based on counting the number of received photons, fitting the data to preknown curves and minimizing the Chi-squared error. He obtained roll estimates with error bias equal to 0.32 deg and standard deviation of $0.030°$ using a single detector and an error bias value equal to $0.012°$ with $0.0075°$ of standard deviation. He also suggested autonomous timekeeping using X-ray sources by employing a phase-locked-loop (PLL).

In 2004, a research group in Spain revealed a study on the feasibility of an absolute navigation system based on radio and X-ray pulsars [33]. The group developed some models of radio and X-ray pulsar signals, it proposed different algorithms for timing estimation of these two categories of celestial sources, studied their performance, and reported the possibility of obtaining absolute position accuracies on the order of $10^6$ meters [33].

In 2005, Sheikh, a member of NRL, produced his Ph.D. thesis in the field of X-ray navigation [19, 34, 35]. His work was a part of a research called the X-ray Navigation (XNAV), which was directed by the Defense Advanced Research Projects Agency (DARPA). He proposed a navigation system based on X-ray measurements used by an extended Kalman filter (EKF) for three-dimensional position estimation [36, 37].

Woodfork suggested the use of X-ray pulsars for aiding GPS satellite orbit determination in his M.Sc. thesis in 2005 [38].

In 2009, Emadzadeh proposed a relative navigation algorithm based on use of X-ray pulsar measurements in his Ph.D. thesis [39]. He has studied different aspects of the signal processing techniques needed to obtain the X-ray pulsar measurements. His dissertation is the main reference of the current book.

## 2.4 Summary

This chapter presents a concise overview of current space navigation methods. It provides an introduction on different types of pulsars and their characteristics. It suggest using X-ray pulsars to navigate in space for situations where current systems are not available or it is desirable to augment the current navigation solutions. There are two main reasons that make X-ray pulsars interesting candidates for space navigation. One is their stable periodic profile, and the other is that relatively small size detectors are needed to detect the X-ray pulsar photons. The latter provides a huge advantage for the spacecraft design procedure. A brief history of pulsar-based navigation and previous research on this field is also discussed.

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