Spacecraft Navigation and Timing Using X-ray Pulsars

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ABSTRACT: *Pulsars are unique celestial sources that produce distinctive, periodic signals. Since their discovery, they have been considered as potential navigation aids and timing beacons to form a reference coordinate system and universal time scale. Further study of these astronomical objects has shown that their pulse timing can achieve sub-microsecond level performance, and interest and research into these sources has grown to conceive a fully autonomous navigation and timing system for deep space vehicles. Sources that radiate within the X-ray band of the electromagnetic spectrum have high potential for creating a practical spacecraft navigation solution, which includes accurate time and position determination onboard a space vehicle using the precisely periodic sources, and precise attitude determination using both pulsating and steady sources. This paper provides an overview of spacecraft navigation methods and various research and results that have evolved since the concept of X-ray pulsar-based navigation was first proposed.*

INTRODUCTION

Recent analysis, scientific discoveries, and technological developments have moved the concept of using variable, celestial X-ray sources as navigation aids for spacecraft from an idea to a future reality. After being theorized for many decades, spinning neutron stars were discovered in the radio band in 1967 [1]. Due to their unique periodic pulses, these neutron stars are referred to as *pulsars*. Subsequent observations have discovered pulsars emitting radiation throughout the electromagnetic spectrum [2, 3]. However the X-radiation emitting sources are the most promising attitude, time, and position beacons for spacecraft operations, since smaller detectors can be employed when compared to optical or radio-band instruments. Over the past 40 years, the astronomy community has logged accurate time histories of these periodic signals, which have been crucial to the characterization of these sources. A particularly intriguing aspect of a subset of these catalogued sources is the measured inherent stability of the periodicity of their emissions, which has been shown to match the quality of today's atomic clocks [4–6]. As such, pulse-timing models have been developed for the stable, periodic signals from these sources, which can be employed as navigation aids.

The baseline X-ray pulsar-based navigation, or *XNAV*, approach uses observations of the X-ray emissions of millisecond period pulsars. With their wide geometric distribution in the sky and periodic radiation, pulsars appear to act as a kind of natural celestial beacon, or celestial lighthouse. However, as a group they conceivably act as a natural Global Positioning System (GPS), or, Universal Positioning System (UPS) on an intergalactic scale. Accurate pulse time-of-arrival estimates from multiple non-coplanar sources allow simultaneous determination of both position and velocity autonomously anywhere in the solar system. Accurate time can be maintained on a spacecraft by coupling onboard high-quality clocks with the long-term stability of several well-characterized pulsars, as an

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X-ray timing, or *XTIM* system. The generation of a reference timescale from an ensemble of pulsars as the pulsar timescale, or PT, is also conceivable due to their stability and regularity [7, 8]. In addition, brighter, but less stable X-ray sources may have utility as well, particularly in applications that require only relative navigation or to determine vehicle attitude.

This paper provides an overview of this novel navigation and timing technology. It provides a background on the types of sources and their characteristics that make them usable for navigation purposes, as well as the types of detectors that can be employed to observe them. It also provides a brief history of the research pursued to define a navigation system based upon these sources. A detailed review of proposed attitude, time, position, and velocity determination is provided, as well as a discussion on potential performance. Future mission applications are presented along with the known challenges for deploying this navigation system. This paper will concentrate on summarizing the work completed in the United States of America, although discussion of work completed in Europe and Asia is also provided.

VARIABLE CELESTIAL SOURCES

Celestial sources have proven to be significant aids for navigation throughout human history. Ancient mariners traveled vast distances across the globe with only the stars in the sky to guide them. A majority of these sources are fixed in their emissions and are considered optical point sources for navigation references. Instruments such as modern star trackers make use of the fact that in the visible band of the electromagnetic spectrum the stars in the sky are essentially constant in number and steady in brightness. As such, optical sources have contributed greatly to exploration. A fraction of celestial sources are objects that emit radiation with varying levels of intensity. Additionally, within the X-ray band (photon energies roughly within the 0.1–100 keV band), there are effectively *no* steady point sources.

Subsets of these variable celestial sources are spinning neutron stars [2, 3]. A neutron star (NS) is the result of a massive star that has exhausted its nuclear fuel and undergone a core-collapse resulting in a supernova explosion [9–11]. During their collapse, conservation of angular momentum spins these stars up to very high rotation rates. Newly born neutron stars typically rotate with periods on the order of tens of milliseconds, while older neutron stars through energy dissipation eventually slow down to periods on the order of several seconds. A unique aspect of this rotation is that it can be extremely stable and predictable [4–6].

Neutron stars harbor immense magnetic fields. Under the influence of these strong fields, charged particles are accelerated along the field lines to very high energies. Powerful beams of electromagnetic waves including X-rays are radiated out from the magnetic poles. If the neutron star's spin axis is not aligned with its magnetic field axis, then an observer will sense a pulse of electromagnetic radiation as the magnetic pole sweeps across the observer's line of sight to the star, hence these sources are referred to as pulsars. Since their discovery in 1967 [1], pulsars have been found to emit throughout the radio, infrared, visible (optical), ultraviolet, X-ray, and gamma-ray energies of the electromagnetic spectrum. Due to their specific evolution, variability mechanisms, and geometric orientation relative to Earth, each pulse frequency and shape provides a unique identifying signature for each star. A simple diagram of a pulsar showing its unique features is presented in Figure 1 [12].

Since radio band emissions from these pulsars are receivable on Earth's surface, much of the astronomical observation of these sources has been done in radio. X-ray emissions from these sources, however, are absorbed by Earth's atmosphere, and use of this wavelength is limited to space or planetary body applications. X-radiation observation requires much smaller detector sizes (order of a square meter) versus radio pulsars (requiring tens of square meters of detector area). Along with pulsars, the X-ray sky contains several other types of variable objects that can be used for different aspects of spacecraft navigation. Variable X-ray objects employ an array of energy sources for their X-ray emissions, and their variability is produced by either intrinsic or extrinsic mechanisms.

Many X-ray pulsars are rotation-powered pulsars (RPSRs). The energy source of this class of neutron stars is the stored rotational kinetic energy of the star itself. The X-ray pulsations occur due to two types of mechanisms, either magnetospheric or thermal emissions [13]. The better timing sources are the rotation-powered millisecond period pulsars (MSPs), and by far the brightest of these sources is the Crab Pulsar (PSR B0531+21) [14]. Unfortunately, young bright sources like the Crab tend to have relatively poor timing stability, whereas the best timing sources tend to be orders of magnitude dimmer. A subset of these rotation-powered pulsars is known as recycled MSPs, which are highly stable rotors with much lower dissipation rates than normal MSPs.

Accretion-powered pulsars (APSRs) are neutron stars in binary systems, where stellar material is being transferred from a companion star onto the

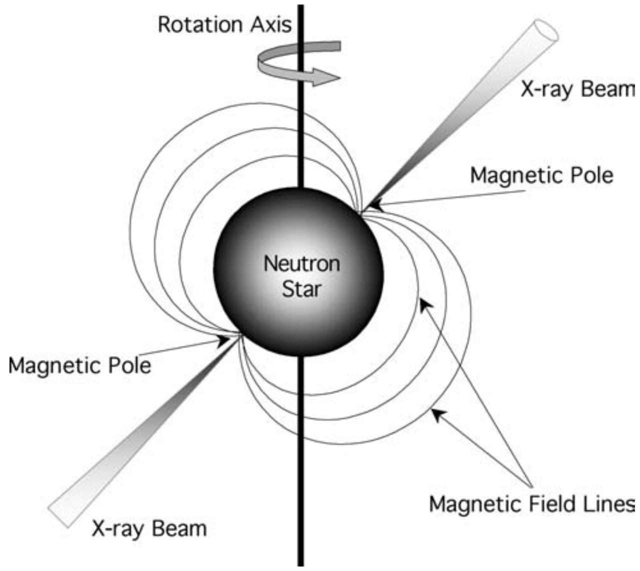

Fig. 1–Neutron star with rotation and magnetic axes [12]

neutron star. This flow of material is channeled by the magnetic field of the neutron star towards its poles, which creates hot spots on the star's surface. The pulsations are a result of the changing viewing angle of these hot spots as the neutron star rotates. Accretion powered pulsars generate X-rays due to the gravitational acceleration of the material from an accretion disk, which can reach relativistic velocities as the material approaches the surface of the star. They tend to be brighter but less stable due to the unsteadiness of the accretion process, sometimes fading in and out due to the eccentricity of the companion's orbit [15, 16]. Two types of APSRs are frequently catalogued based upon the mass of the orbiting companion of the neutron star, either a high-mass X-ray binary system (HMXB), where the companion object is typically 10–30 solar masses in size, or a low-mass X-ray binary system (LMXB), where the companion star is perhaps the size of less than one solar mass [13, 15]. Although they possess complicated pulse timing models due to their binary system dynamics, and many are transient sources with unpredictable durations of low signal intensity, these types of pulsars also have characteristics conducive to navigation.

Figure 2 provides an image of X-ray stars on the Galactic sphere in Galactic Longitude and Latitude coordinates [12, 17]. Many X-ray sources are found in binary systems and a majority of the detected sources are located in our Milky Way galaxy. This image shows the concentration of sources located along the Galactic plane and near the Galactic center, however, a sufficient number of sources for navigation are distributed off plane. The diffuse X-ray background is an appreciably strong signal that is observed when viewing the X-ray sky, and measures of this background radiation must be considered when observing a source [13].

Although pulsars have good visibility and detectability near Earth and throughout the solar system, they are extremely distant objects. Thus, unlike Earth satellite ranging systems, the absolute distances of these sources cannot be directly measured. Instead, once the initial location of the spacecraft is established, phase tracking of the pulsar signal must be used continuously to update estimated position. This is analogous to carrier phase tracking techniques that have become well established with Global Navigation Satellite System (GNSS) applications.

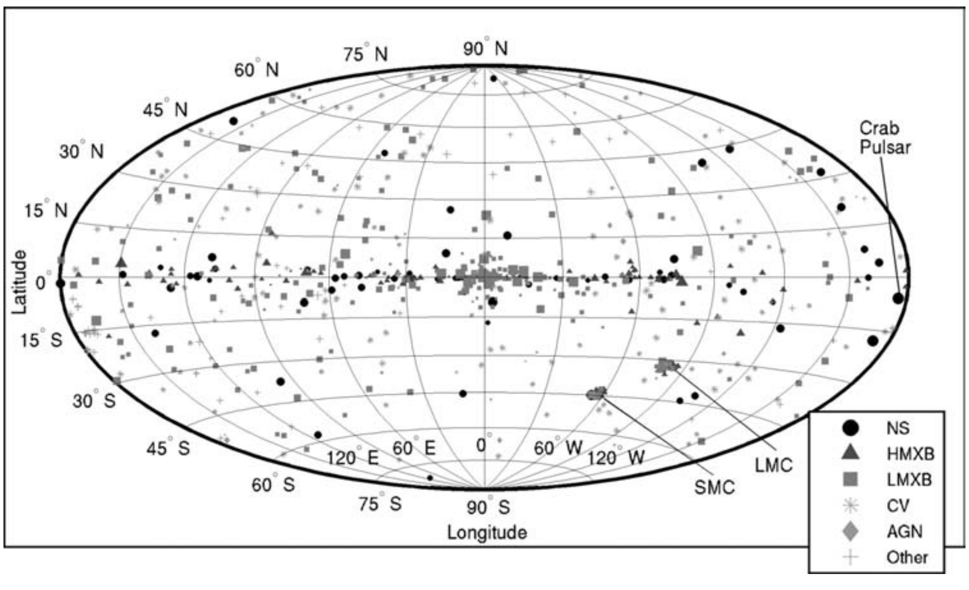

Fig. 2–Catalogued X-ray sources in Galactic longitude and latitude. The size of the marker indicates the relative magnitude of the source's flux in a logarithmic scale. [12]

Aperiodic Sources

In addition to the stable periodic sources, the use of unstable, but bright and highly variable X-ray sources can be utilized for cooperative observations between multiple spacecraft. The key source types are active galactic nuclei (AGN), cataclysmic variables (CV), supernova remnants, X-ray binaries, X-ray galaxy clusters, and stellar coronal. Nearly all of the bright X-ray point sources in the sky are X-ray binaries containing a compact object (neutron star or black hole) accreting material from a stellar companion. The accretion process is highly unstable and many of these sources exhibit pronounced variability over a broad range of frequency scales up to about 1000 Hz. This variability can take the form of red noise, broadband noise, shot noise, periodicities, and quasi-periodic oscillations (QPOs). A catalogue of bright X-ray sources is based on the continuous monitoring of the X-ray sky with the All-Sky Monitor (ASM) instrument aboard the Rossi Timing Explorer (*RXTE*) [18].

In addition to the short timescale variability, many of these sources exhibit transient behavior, when a source that normally is extremely faint brightens by a factor of 1000 or more [19]. The transient outbursts in these sources can last from hours to years, with most outbursts lasting one to several months. The recurrence times of these outbursts vary from a year to decades, or longer [19].

The Pulse Profile

At X-ray energy wavelengths, the primary measurable values of the received signal from a source are the individual high-energy photons emitted by the source. The rate of arrival of these photons can be measured in terms of flux of radiation, or number of photons per unit area per unit time. To observe a source, an X-ray detector is initially aligned along the line of sight to the chosen source. Once photon events from this source are positively identified, components within the detector system record the time of arrival of each individual X-ray photon to high precision with respect to the system's clock. During the total observation time of a specific source, a large number of photons will have each of their arrival times recorded. The measured individual photon arrival times must then be converted from the detector's system clock to their coordinate time in an inertial frame. This conversion provides an alignment of the photon's arrival time into a frame that is not moving with respect to the observed source [20, 21].

The profile of each pulse from an X-ray source is a representation of the characteristics of the pulse. Pulse profiles vary in terms of shape, size, cycle length, and intensities. Some sources produce sharp, impulsive, high intensity profiles, while others produce sinusoidal, elongated profiles. Although many sources produce a single, identifiable pulse, other pulse profiles contain sub-pulses, that are evident within the signal [2, 3].

This process of assembling all the measured photon events into a pulse profile is referred to as epoch folding, or averaging synchronously all the photon events with the expected pulse period of the source. An ensemble of these folded photons creates well-defined pulse shapes. For X-ray observations that record individual photon events, Poisson counting statistics typically dominate the random noise in pulse time-of-arrival (TOA) computation. Thus there will be a large amount of variability in the observed light curve simply due to counting statistics. The time shift necessary to align the peaks within the observed profile and a standard pulse template is added to the start time of the observation to produce the absolute TOA of the pulse for a particular observation. An estimate of the accuracy of the TOA measurement can be computed as an outcome of this comparison process. This estimate provides an assessment on the quality of the TOA measurement, and can be useful in the navigation algorithms [20]. Figure 3 shows a standard pulse template for the Crab pulsar in the X-ray band (1–15 keV) created using multiple observations with the Naval Research Laboratory's Unconventional Stellar Aspect (USA) experiment onboard the *ARGOS* vehicle [22].

Four of the fundamental classes of pulse TOA measurement processing techniques are summarized in Table 1. These approaches outline the various methods that can be used to process the individual pulsar photon data, either in a batch (large

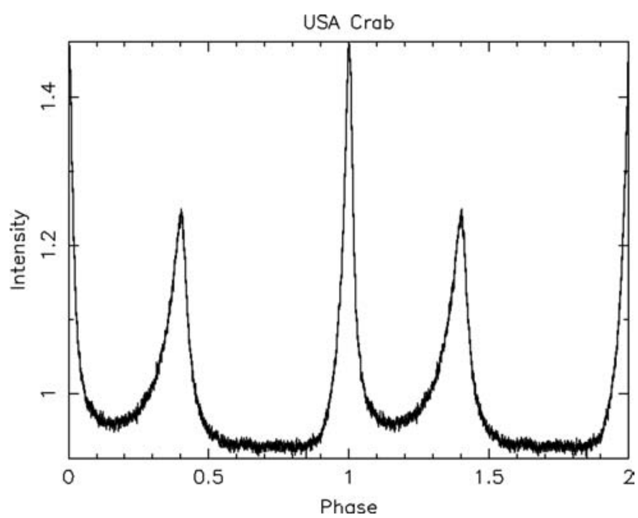

Fig. 3–Crab pulsar standard pulse template. The period is about 33.5 milliseconds. Two pulse cycles are shown for clarity, with each cycle containing one sharp main pulse and a smaller secondary inter-pulse with lower intensity amplitude

Table 1—Pulse TOA Measurement Techniques

	Batch Processing	Continuous Processing
Binned Photons	• Traditional astronomy approach • Photons collected into finite size bins • Many pulses folded together and known profile fit to data to estimate TOA • 10^4 sec or more between measurements • Good single TOA solution • Information lost in binning photons • No information available to update position between measurements • Reference: [23]	• Similar to communications approach • Photons collected into finite size bins • Pulsar signal extracted from noisy background with phase-locked loops (PLL) or digital PLL • Continuous measurements • PLL loop filter limits bandwidth of measurements to 10 μHz or less • Information lost in binning photons • Reference: [24]
Time-Tagged Photons	• E.g. Maximum Likelihood Estimation • Individual photons time-tagged • TOA estimated from entire photon history • 10^4 sec or more between measurements • Best possible single TOA solution • No information lost in time tagging photons • No information available to update position between measurements • Large processing burden • Reference: [25]	• Single photon processing • Individual photons time-tagged • Position/time estimate updated at each photon or small batch of photons based on individual photon times • Continuous measurements • Good single TOA solution • Maximum use of photon time information • Reference: [26]

single set) process, or a continuous mode where data is processed as soon as it is made available. A further distinction can be made between algorithms that use binned photon data, where the data are represented by the number of photons arriving in fixed duration time bins, versus single event processing algorithms that use a series of time-tagged photon events to provide pulse TOA updates, thereby using all available data to create the TOA estimate. This can be compared to the aforementioned binned approaches, which essentially truncate all photons' times-of-arrival in the binning process, thereby ignoring useful information.

Pulse timing is required to adequately characterize each source's unique characteristics such as spin period, companion orbit elements, and a star's evolutionary stage [2, 3]. A timing model is constructed by fitting data obtained over the entire observational history of a particular source, accounting for every pulse of the source. These models predict when specific pulses from the sources will arrive within the solar system. It is precisely this predictable behavior that allows pulsars to be considered as navigation beacons. Previous pulse timing methods have created binned pulse profiles through extended observations of a specific source and folding the full observed signal with the expected pulse period of the source [20]. These methods compute the observed pulse TOA by correlating an observed pulse profile with a high signal-to-noise ratio (SNR) profile template.

Pulse timing models are often represented as the total accumulated phase of the source's signal as a function of time. A starting cycle number, $\Phi_0 = \Phi(t_0)$, can be arbitrarily assigned to the pulse that arrives at a fiducial time, t_0, and a reference location, often selected as the solar system barycenter (SSB); all subsequent pulses can be numbered incrementally from this first pulse. The total phase, Φ, can be modeled as the sum of the fractional portion of the pulse period, ϕ, and the total number of integer cycles, N. Thus, total phase is expressed as a function of time as,

$$\Phi(t) = \phi(t) + N(t) \tag{1}$$

This model may also be expressed as a function of angular phase, $\Theta = 2\pi\Phi$. Using the determined pulse frequency, f, and its derivatives, the total phase can be specified using a pulsar phase model of,

$$\Phi(t) = \Phi(t_0) + f[t - t_0] + \frac{\dot{f}}{2}[t - t_0]^2 + \frac{\ddot{f}}{6}[t - t_0]^3 \tag{2}$$

Eq. (2) is known as the pulsar spin equation, or pulsar spin down law [2, 3]. In this equation, the observation time, t, is the coordinate time of arrival of the signal phase and t_0 is the chosen reference epoch for the model parameters [3, 21].

The model in Eq. (2) utilizes frequency and two of its derivatives; however, any number of derivatives may be required to accurately model a particular pulsar's timing behavior. Additional required parameters include the angular coordinates of the source (e.g., right ascension and declination and sometimes proper motion and parallax), orbital parameters for pulsars in binary systems, and dispersion measure (the column density of free electrons) for sources with timing measurements made in the radio band. Precise external information is also required to complete an accurate timing measurement, such as Earth and celestial reference frames, planetary ephemerides, and coordinate time scales. Each observation must accurately time the pulse signal with respect to an inertial coordinate system and time, effectively removing the dynamic motion of the observation station and the higher-order relativistic effects on the electromagnetic signal within the solar system [2, 3, 20, 27–29]. If the removal of motion and higher order contributions were done improperly, a smearing effect would be present within the observed pulse profile, and the uncertainty of the measured pulse TOA would increase. While the location and orientation of the coordinate system is not critical, it is important that the pulse timing models of all pulsars used as navigation beacons use the same reference frame.

To investigate pulsar source characteristics, accuracies on the order of 1 μs or better are often desired, and a number of sources are timed at this level or better [30, 31]. For spacecraft navigation, a desired accuracy of pulse arrival time on the order of 1 ns ($\approx$0.3 m) would allow significantly increased position and velocity solution accuracy. Thus, any errors within the analytical timing expressions or pulse timing models must be on the order of these uncertainties [21]. The data of the characteristics of several well-studied pulsars has been presented in past publications [12, 23, 32]. Nearly all of the useful X-ray pulsars are also bright radio pulsars and are routinely timed as part of long-term pulsar timing studies with large ground-based radio telescopes, which will contribute significantly to XNAV's future success.

As select sources have had extended observations over many years, long-term data analysis has verified that the spin rates are extremely stable for some of these sources and compare well to the stability of current day atomic clocks [5, 6]. Unfortunately, many of the pulsars that provide the most stable long-term timing models tend to be less bright, and conversely, the brightest sources tend to be less stable. Less stable sources can also be utilized, but they will require more frequent ephemeris and pulse model updates and could result in a lower performance system.

The key parameter for determining stability is the timing residuals, differences between the measured TOA and the best pulsar-timing model. These residuals can be used to create the square root of a third-order Allan variance, $\sigma_z(t)$, which is a measure of pulsar and atomic clock stability [6]. It has been shown that the stability of two pulsars, B1855+09 and B1937+21, detected in the radio band and measured over a range of data lengths up to decades is comparable to that of terrestrial atomic time standards [5]. In this work, these sources have been shown to reach values of $\sigma_z(t) = 10^{-13.2}$ and $10^{-14.1}$, respectively, for a data set length of one year. Figure 4 shows a comparison of PSRs B1937+21, B1855+09, and J0437-4715 with several atomic clocks.

X-ray Navigation and Timing Instruments

The instrument for X-ray navigation and timing will consist of three primary components: a collimator or imaging system to select the pulsar to be observed; a detector and time tagging system to measure the arrival times of the photons; and, processing electronics and algorithms to turn the photon time histories into position and/or time measurements. The design of the instrument will depend on the mission of the spacecraft. Some may require the instrument to be on a gimbal to allow the instrument to track pulsars serially, while other missions may require multiple detectors to track them simultaneously. Other missions may use a single fixed instrument and slew the spacecraft to track the pulsar during an observation. The instrument system design to optimize the detectability of these sources depends on the energy spectrum of the emitted X-rays. The magnetospheric emitting sources have very narrow pulse profiles and much harder X-ray emission and are best detected in the 2–10 keV medium-energy X-ray band, while the thermal emission sources tend to be intrinsically fainter and have broader pulse widths and are best detected in the 0.5–2 keV soft X-ray band.

Various types of detectors have been used in X-ray astronomy missions depending on the type of application of timing or imaging, such as gas proportional counters with collimators, microchannel plates, charge-coupled device semiconductors, scintillators, or focusing optics with small solid state detectors [34]. The instruments used on the previous 40 years of X-ray astronomy science missions, while extremely capable, were optimized for the needs of science and not for those of an operational XNAV system. In particular, gas proportional counters with their pressure regulation systems and lifetime limiting expendable gas are not suitable for a long-term XNAV system. The use of collimators to limit the instrument field-of-view has been demonstrated on several missions (*HEAO-1*, USA),

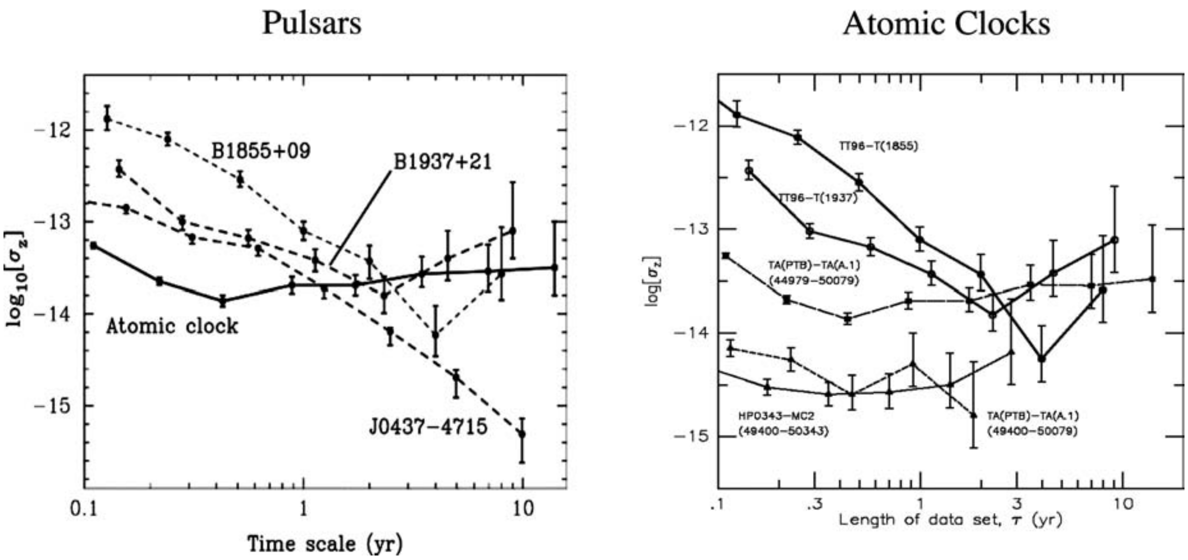

Fig. 4–Comparison of selected pulsars and atomic clocks [5, 6, 33]

as have coded aperture masks (*HETE-II*) and grazing incidence mirrors (*Chandra*, *RXTE*). Selection of the detector, optimized for the energy profiles of select pulsars, will be a key determinant in the overall performance of the system. Solid-state detectors with their sensitivity maximized in the medium (2-10 keV) energy band are likely candidates.

BRIEF HISTORY OF PAST RESEARCH

The principal scientific and technical advances that make the X-ray-based approach feasible have come about fairly recently. These include the characterization of sufficient numbers of highly stable X-ray pulsar sources using several recent scientific spacecraft (*RXTE*, USA, ASCA, *Chandra*, *ROSAT*, *XMM*, and others) to provide the basis for a timing system and the development of new X-ray detector technology with high time resolution of recorded events.

Technologies for exploiting celestial observations have improved tremendously over millennia, but it was not until the 1970s that terrestrial observations of radio pulsars suggested a fundamentally new type of measurement might be possible based on stable celestial timing signals from pulsars. A broad scope of navigation methods has been proposed to make use of variable sources that emit at radio or X-ray band wavelengths [12, 17, 22, 24, 32, 35, 36]. Much of this past navigation research has concentrated on using rotation-powered pulsars. Provided in Table 2 are some of the key events regarding navigational use of these sources. In addition to those listed, numerous conference and journal articles published by researchers in the United States, Europe, Russia, and China have elaborated further on various aspects on the concepts. Many of these engineering researchers, along with all the astronomical observations and astrophysical discoveries, have contributed greatly to the overall understanding of methods and techniques, and with these continued worldwide research efforts it is likely that this technology will yield useful capabilities.

X-RAY SOURCE NAVIGATION CONCEPTS

The navigation solutions proposed here are derived from X-radiation photon detection. An ensemble of many detected photons, formed either into images or average pulse profiles, can be used to compute directional (in the case of imaging) or timing (in the case of pulse profiles) information. Full three-dimensional (3-D) solutions are achievable from variable celestial sources, including vehicle attitude determination, position, and velocity determination, and clock corrections for maintaining accurate time. It is this potential of the full suite of onboard navigation solutions from these periodic sources that is currently driving the interest and research into their capabilities.

By measuring the pulse TOA from each source, this data can be related to a range measurement in order to update or compute 3-D position and velocity solutions. As most current X-ray telescope and detector designs can observe only a single source along one point on the celestial sphere, navigation concepts that utilize single axis ranging information have shown that accurate orbit solutions can be achieved [12, 32]. Extensions to this single measurement have also been pursued, including approaches similar to GNSS, where multiple variable sources are used to compute full 3-D position solutions [23, 42, 46]. These methods use lateration concepts to estimate the range from an inertial ori-

Table 2—Key Events Contributing Towards X-ray Navigation Advancement

- 1967: Bell J., Hewish A. et al., Successful discovery of radio pulsar [1]
- 1974: Downs, G.S. of NASA JPL, Outlines concepts of interplanetary navigation using pulsating radio sources [35]
- 1977: Manchester, & Taylor J., Initial detailed text describing pulsars [2]
- 1981: Chester & Butman of NASA JPL, Introduces navigation using X-ray pulsars [36]
- 1981–1983: Richter, G.W. & Matzner, R.A., Relativistic corrections for photon time of arrival [37–40]
- 1988: Wallace K., Presents use of radio stars for navigational systems [41]
- 1988: The NRL USA experiment proposed [22]
  - Operated onboard *ARGOS* from May 1999–Nov 2000
  - Investigated attitude, position, timekeeping
- 1996: Hanson, J.E., Stanford University Ph.D. dissertation "Principles of X-ray Navigation" [24]
- 1997: Matsakis, D., et al., Develops new statistic for pulsar and clock statistics [6]
- 2004: ESA Advanced Concepts Team ARIADNA, Pulsar navigation study [42]
- 2005: Sheikh, S.I., University of Maryland Ph.D. dissertation "The Use of Variable X-ray Sources for Spacecraft Navigation" [12]
- 2005: Woodfork, D. W., Air Force Institute of Technology Master's thesis "The Use of X-ray Pulsars for Aiding GPS Satellite Orbit Determination" [43]
- 2005–2006: Defense Advanced Research Projects Agency (DARPA) XNAV Phase I Program
  - Source characterizations, detector development, navigation algorithms
  - Demonstration system architecture (planned for ISS flight)
  - Did not proceed to Phase II flight demonstration development
- 2006–2011: Multiple NASA SBIR contracts on topic, including augmentation with Deep Space Network
  - Studying potential NASA applications of X-ray navigation
- 2006–2008: Rodin A., Concepts on developing ensemble of pulsars signals for new timescale [44]
- 2009: Emadzadeh, A.A., University of California Ph.D. dissertation "Relative Navigation Between Two Spacecraft Using X-ray Pulsars" [45]
- 2009–2010: DARPA XTIM Seedling program
  - Study use of pulsars for time transfer and investigate future demo scenarios

gin along multiple axes. As eventual detector systems may be produced that will monitor the whole sky, simultaneous observations of multiple source signals from different directions allow this concept to produce full 3-D solutions. Spacecraft that have accurate clocks onboard can track these signals over time to maintain full dynamic trajectory solutions. It has been considered to extend this concept and use the stable, periodic signals from these sources to produce accurate time as well as vehicle position, allowing complete navigation solutions with reduced needs for an on-board, ultra-stable clock.

It is important to time pulsar observations within an inertial reference frame that is stationary (at rest) with respect to the pulsar's frame. This is done in part so that all subsequent observations can be directly compared to the model, and any effects of an observer in a rotating frame are removed. Since an observer's frame will most likely be in motion with respect to the inertial frame, as an observer on Earth or on a spacecraft in orbit, and the observer will experience a different gravitational potential than a reference clock, the observer clock's measured proper-time must be converted to coordinate time in order to compare the result to other clocks. Standard methods provide conversions from the observer's proper time to coordinate time based upon the observer's clock motion and experienced gravitation potential [47–51].

For many pulsar observations, the common frame utilized as the SSB coordinate frame is the International Celestial Reference Frame (ICRF) whose axes are aligned with the equator and the equinox of epoch J2000 [52]. The reference time scale for these observations for variable t in Eqs. (1) and (2) is the *Temps Coordonnée Barycentrique* (TCB, Barycentric Coordinate Time), although the slightly different time scale of the *Temps Dynamique Barycentrique* (TDB, Barycentric Dynamic Time) has also been utilized [52]. These pulse-timing models are often described to be valid at the origin of the SSB frame. In order to compare a measured pulse arrival time at a remote observation station with the predicted time at the SSB origin, the station must project arrival times of photons by its detector onto the SSB origin. This comparison requires that time be transferred from the observation station, or spacecraft, to the SSB. The equations from this theory relate the emission time of photons that emanate from a source to their arrival time at a station, and define the path of the photons traveling through curved spacetime [27–29, 37–40].

Along with a well-defined pulsar pulse-timing model, providing pulse period and higher order derivatives, additional characteristics are required for use by the navigation algorithms. These include pulsar unit line of sight direction or apparent position, often represented as Right Ascension and

Declination of the source, distance, and proper-motion; X-ray photon flux rate from the source, often measured in photon counts per unit area per unit time; pulsed fraction, the ratio of pulsed photons to total source photons received; pulse profile, or flux variation as a function of time or phase cycle; and, any known transient, flaring, or bursting aspects of the source. Many techniques use the source direction information within their equations, thus any unknown errors in this term reduce the performance of the overall solutions. In order to have a negligible effect within the solar system, coordinate position accuracies on the order of 0.0005 μrad are required to approximately provide one km of spacecraft range accuracy. Fortunately, well-timed pulsars have sufficiently accurate position knowledge as part of their timing analysis. However, since their position accuracy is connected to their timing accuracy, or timing noise, other interesting potential pulsars do not have this quality of position accuracy. Other techniques, such as their closeness to optical partners, must be employed to help improve the positional accuracies of these lesser-studied sources.

Just as it is important to monitor and catalogue the defining characteristics of optical stars for on-Earth navigation and spacecraft attitude determination, in order for an eventual XNAV system to operate with high efficiency and accuracy, it will be necessary to continuously monitor, catalogue, and disseminate the information of existing and perhaps newly detected sources at regular intervals to spacecraft that rely on this information. In addition to ground-based radio source timing and characterization, it is envisioned that an orbiting X-ray observatory, serving as both an astrophysics science research instrument and a navigation base station would be required for long term X-ray navigation operations. Existing X-ray astrophysics missions can tentatively serve this function, such as *RXTE* [53] and *XMM*-Newton. However, a dedicated X-ray observatory that can communicate this critical pulsar almanac information would function more optimally for operational applications.

The XNAV navigation processing can be separated into the three general areas: attitude determination, time correction, and position and velocity determination. The following sections describe the further details of the techniques for solutions using X-ray celestial sources. Methods of evaluating the performance of these navigation solutions are presented as well as a review and summary of potential applications for this new technology.

Attitude Determination

X-ray emitting sources can be used as an attitude reference for resolving spacecraft orientation as well as navigation and timing beacons [22, 24]. Thus, the XNAV concept offers the potential for a single instrument to provide attitude, time, position, and velocity information to its host spacecraft. The operation and algorithms of an X-ray source-based attitude sensor is similar to that of a traditional optical star camera [54]. A camera comprised of a pixel array of detectors, when combined with a coded aperture mask or set of grazing incidence mirrors, that images sets of X-ray sources could determine the camera's orientation by matching multiple source patterns in the field of view or identifying a unique source. Alternatively, large single pixel cameras or trackers could use the source flux to determine spacecraft spin or orientation based upon a pattern of detected X-ray sources. However, an X-ray star camera offers several other advantages over traditional optical cameras:

- The diffraction limited angular resolution of an X-ray star camera is much finer than a traditional star camera of similar size due to the extremely short wavelengths of X-rays when compared to visible or UV wavelengths. This can lead to either a much higher performance star camera (sub-arcsecond accuracies), or a much smaller camera in a similar form-factor.
- The sensors used in an X-ray star camera are inherently radiation hardened due to their relatively large feature sizes, making them useful on missions in high radiation environments, including national security missions and missions to the outer planets.
- X-ray star cameras are robust against optical blinding by Sun, Moon and Earth crossings, eliminating the need for keep out zones and simplifying mission planning.

Three different classes of X-ray attitude sensor have been considered:

- The imaging star camera uses grazing incidence mirrors or a coded aperture mask and a pixilated detector to create an image of the X-ray sky. The stars in the image are identified and their positions are compared to a guide star catalogue using the same techniques used in traditional optical star cameras.
- The collimated star camera uses a collimator and a large, single pixel detector to measure the X-ray flux in a given direction. A mechanical gimbal is used to scan the instrument over a certain area of sky containing one or more guide stars. A map of guide stars is created by correlating the X-ray flux with gimbal angle. The known and measured locations of the guide stars determine the orientation of the spacecraft.

- The X-ray star scanner uses a fixed collimator on a spinning spacecraft to create a pattern of X-ray flux peaks. By having a narrow field-of-view in the direction of spin and a wide field-of-view normal to the spin direction, this pattern of guide stars can be matched against a catalogue to determine the orientation of the vehicle. Using flight data from the *HEAO-1* spacecraft, it has been shown that sub-arcminute level attitude determination is feasible using an instrument of this class [24].

The imaging X-ray star camera can be operated in a very similar manner to conventional optical star cameras, the primary advantage being the opportunity to achieve much more accurate solutions in a small form factor due to the short wavelength of X-ray light when compared with visible or ultra-violet light. While the majority of X-ray stars available to be used as guide stars are relatively continuous in their emission, the variability of some stars can be used to hasten the initial attitude acquisition – the lost-in-space scenario. While a traditional star camera has to sort through a large catalogue of guide stars to determine the initial attitude solution, an X-ray star camera can quickly identify the pulsars in its field of view and match their distinct pulse periods to the catalogue, rapidly arriving at an initial solution.

The key to the success of any X-ray star camera is the availability of a catalogue of X-ray guide stars, with the positions of the guide stars accurately defined. Several all-sky surveys have been made in X-rays over the past 40 years, including *Uhuru* (1973), *OSO-7* (1973), *HEAO-1* (1979), *ARIEL* (1980) and *ROSAT* (1991) that are useful in generating a guide star catalogue. The *ROSAT* Bright Star Survey is extensive, including a total of 18,806 stars covering three orders of magnitude in brightness [55]. The observations were made in the soft X-ray (0.1–2.4 keV) and extreme ultra-violet (0.025–0.2 keV) energy bands using imaging telescopes with proportional counters. While the response of the proportional counters is optimized for sensing softer X-rays than most likely will be detected by the solid-state detectors to be used in an X-ray star camera it still presents a complete catalogue that allows for reasonable proof of the concept. The spatial distribution of the brightest 200 stars in the *ROSAT* BSS is shown in Figure 5 indicating that the sources are sufficiently distributed in the sky to provide guide stars for missions in any orbit (about Earth or another planet) and in any orientation. A majority of the sources in the *ROSAT* BSS are not pulsars, so some of the brightest X-ray sources can be used as guide stars, making the X-ray star camera solution less susceptible to photon noise compared to a timing or position solution.

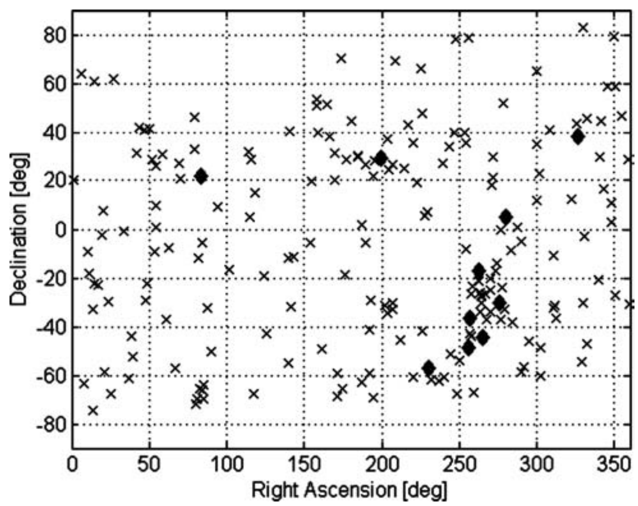

Fig. 5–Distribution of brightest 200 guide stars in the ROSAT catalogue. The top ten stars are shown with a diamond marker [55]

Time Determination

A unique capability that X-ray source detection can support to improve spacecraft mission operations is the ability to provide atomic clock quality time by monitoring these ultra-stable pulsars. This has been demonstrated with several highly stable sources [4–6]. Detection of these sources over long durations could reduce onboard clock errors, or at least stabilize any long-term clock drifts. Although absolute time cannot be recovered since no identifying code is attached to any pulsar signal, interestingly, once the position is determined, time relative to arriving pulsar wavefronts can be recovered uniquely from the time difference of arrival (TDOA) among the sources.

The frequency stability of the signals from X-ray and radio pulsars can be used to create a universal timescale, as Pulsar Time (PT) [7, 8]. The X-ray Timing system, or XTIM, is envisioned to create PT by combining long-term pulsar observations with an ultra-stable local clock for short-term stability. The concept of PT is not limited to X-ray pulsars, as work on creating a stable time reference based on pulsar observations has been done using radio pulsars [4–6] and comparisons of PT based on an ensemble of radio pulsar observations to UTC have been performed [8]. This new PT-based system has several unique and potentially mission-enabling characteristics:

- Stability – XTIM is based on observations of highly stable pulsars. While the accuracy of the pulsar observations are shot noise limited over short periods (seconds to hours), they are extremely stable over long periods (weeks to months) [4–6]. By slaving a local atomic clock to an ensemble of pulsars, a new clock with

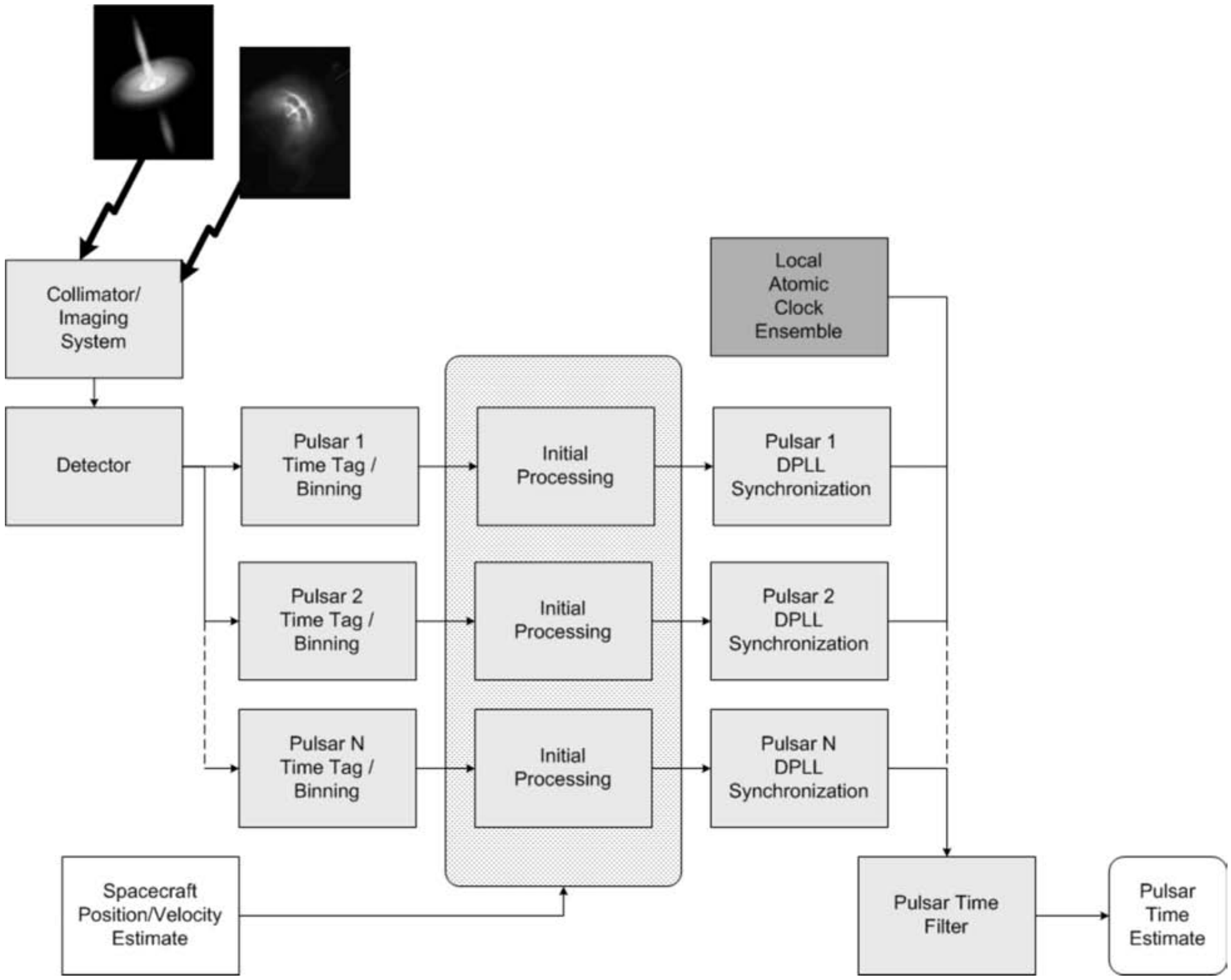

Fig. 6–Functional concept of an X-ray timing (XTIM) system

unprecedented stability over short to long time scales would be created.

- Autonomy – XTIM would provide users with an independent and precise measure of time. This measurement is not dependent on an external system, or on regular communication with other users. By tracking the same pulsars, multiple users can be guaranteed access to the same clock without communication between them.
- Universality – The pulsars used by XTIM are celestial sources, making them available to any user, anywhere in the solar system. Furthermore, any two users, no matter how widely separated, or without line-of-sight communications, can use XTIM to correlate events that occur on two or more spacecraft, enabling new missions for near-Earth observing spacecraft to spacecraft in the distant solar system. This also provides an opportunity to correlate measurements between platforms not originally designed for this task. If each spacecraft is using PT, comparison of observations after the fact becomes possible.

The XTIM concept diagram of Figure 6 uses a fine collimator or imaging system (grazing incidence mirrors or coded aperture mask) to select the pulsar signal and reject the signals from background radiation and other pulsars. The photons are detected, time-tagged, and passed to the processing algorithms. Knowledge of the spacecraft position and velocity over the observation is required to create PT. Position can be provided by a separate system, or more likely, by an XNAV system through the simultaneous observations of multiple pulsars. Concepts for XTIM algorithms are similar to those being developed for position and velocity determination, and include batch processing maximum likelihood estimators (MLEs) as well as new single photon processing concepts [23, 26].

While existing systems can provide accurate time through the broadcast of a common reference such as GNSS, or the transfer of precision time from one user to the next, such as two-way satellite time and frequency transfer (TWSTFT) [56], these systems will likely not offer the simultaneous stability, autonomy, and universality of XTIM. Furthermore, XTIM with XNAV is the only system that offers simultaneous attitude, time, and position determination from a single instrument anywhere in the solar system.

Position and Velocity Determination

Several methods and techniques of position and velocity determination using X-ray sources have been studied [12, 17, 22, 24, 32, 35, 36, 42, 43, 46]. These approaches can be categorized in an absolute sense, where methods are created to determine the absolute 3-D position and velocity in an inertial reference frame, and a correction, or delta-correction, sense, where updates to estimate range and range-rate values are generated from the pulsar measurements. Either of these methods contributes to maintaining a continuous, accurate navigation solution.

For deep space missions, where contact with Earth may be limited and where there may be no planetary bodies in the near vicinity, methods to uniquely determine the full 3-D absolute position solution are sought. Spacecraft that can generate autonomous absolute position solutions have increased functionality over vehicles that must rely upon transmitted solutions. Accurate position knowledge ensures the vehicle is following its intended path, allows the vehicle to safely control itself around potential obstacles, and most importantly assists the vehicle in pursuing its intended goals. Alternatively, techniques that produce spacecraft position solutions relative to other vehicles or planetary bodies that are typically in motion themselves allow the spacecraft to safely and reliably operate within the close proximity to these objects.

Methods to solve for the absolute position of a spacecraft include: orbit determination based upon measurements from Earth-based observation stations in either the optical or radio band; vehicle tracking using the NASA Deep Space Network (DSN) [57]; and, occultation of celestial objects [58, 59]. Increased use of GNSS has demonstrated significant utility for spacecraft navigation in orbit about Earth [50, 60]. However, limitations exist for GNSS systems used in orbit, including reduced signal visibility, availability, and low signal strength. GNSS systems are designed to operate only near-Earth, thus for applications far from Earth alternate methods must be utilized. The primary method of navigation for deep space missions is radiometric tracking using the DSN [57, 61]. The DSN provides range and range-rate measurements along the line-of-sight (LOS) from Earth via time-of-flight and Doppler measurements. The use of very long baseline interferometry (VLBI) with two of the three primary DSN tracking stations along with temporally close observations of nearby quasars to reduce some error contributions, called differential one-way ranging (Delta-DOR), angular measurements with accuracies near 1 nrad can be achieved [62]. Current and projected navigation performance for the DSN at long ranges have been established [63]. However, emerging accuracy and autonomy requirements for new missions cannot be satisfied by GNSS, DSN, or their current alternatives alone.

An XNAV position determination concept that borrows from optical source methods is the concept of occultation, where an X-ray source is viewed to be occulted by a planetary body passing in front of the source and becoming blocked from the field of view for some duration of the spacecraft's detector [22]. As with optical sources, given the known dimensions of the planetary body, the duration that the distant pulsar is occulted by the body provides an angular measure that helps determine how close the spacecraft is with respect to the body [12, 17]. Using accurate ephemeris information for the body and the unit direction to the source, estimated range to the body can be determined for the spacecraft. This method would require a body to be within the field of view and would be affected by any atmosphere of the body that may absorb the X-ray photons [64].

In order to utilize the variable celestial sources for absolute position determination, the specific pulse cycle received from a source must be identified. Analysis has demonstrated how the unknown, or *ambiguous*, number of pulse cycles can be resolved, such that the absolute position of a spacecraft can be produced with respect to a chosen reference frame origin [46]. An important attribute of these methods is they are applicable to all regions of space, throughout the solar system, as well as further into the Milky Way galaxy, and perhaps beyond. The determination of unknown cycles for variable celestial sources, or the pulse phase cycle ambiguity resolution process, is in some manner similar to the methods used in GNSS navigation systems. However, the ambiguity resolution process for variable celestial sources is also unique in many ways from its GNSS counterparts [46]. Instantaneous, full 3-D position solutions would require multiple X-ray detectors pointed towards all these individual sources, or a single X-ray detector system that has all-sky monitoring capabilities.

The primary analysis approach for determination of pulsar characteristics, or spacecraft navigation solutions, is to compare the pulse TOA measured at an observation site on Earth, or onboard an orbiting spacecraft, to the predicted arrival time based upon the model represented in Eq. (2).

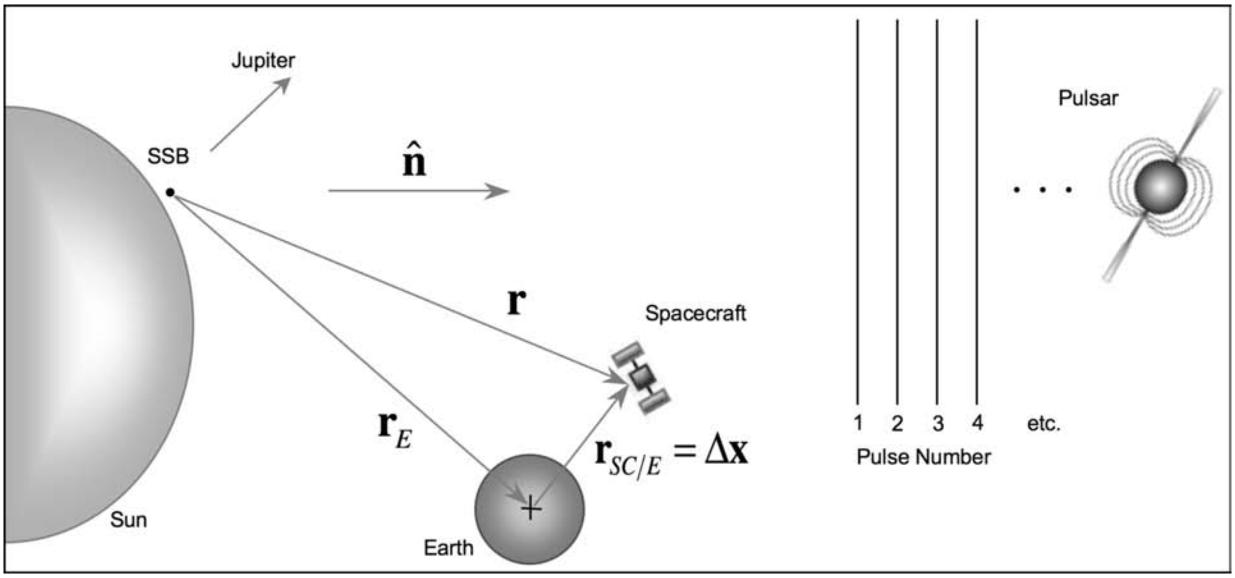

Fig. 7–Position of spacecraft as pulses arrive into solar system from distant pulsar [12]

The TOA timing residual is the calculated difference multiplied by the pulse period, P, as in [65],

$$\delta t_{TOA} = \{\Phi(t_{TOA}) - \mathrm{nint}[\Phi(t_{TOA})]\}P \qquad (3)$$

In Eq. (3), the function *nint* rounds the value to the nearest integer. In order to determine the timing residual with high performance, it is critical to compute t_{TOA} as accurately as possible, as well as to maintain well-defined pulse-timing models. Any errors in the pulsar-timing model will directly translate to errors in the navigation solution determined from them.

A common implemented approach is a single detector technique that provides corrections to estimated range using the TOA-difference described within Eq. (3). When viewing a single pulsar, with its known pulse-timing model as in Eq. (2), the computed TOA residual can be used to estimate the error in range along the line of sight to the source. Blending this information with estimated position from an orbit propagator produces corrections to the position and velocity solution which maintains accurate solutions over time.

Figure 7 shows the relationship of pulses from a pulsar as they arrive into the solar system relative to the SSB inertial frame and a spacecraft orbiting Earth. The positions of the spacecraft, $\mathbf{r}$, and the center of Earth, $\mathbf{r}_E$, with respect to the SSB are shown, as well as the unit direction to the pulsar, $\hat{\mathbf{n}}$. To produce accurate TOA measurements, long observation durations (many thousands of seconds) are required from sources based upon the error budget analysis or the Cramer-Rao lower bound achievable performance [23, 26].

An alternative delta-correction technique that can potentially provide continuous update information versus the infrequent TOA-difference technique is the method of continuous phase tracking of a source while it is being observed [26]. This method can estimate and lock onto the phase and frequency of a source based upon the known model of Eq. (2). By tracking these expected parameters of the source signal an estimate of the spacecraft vehicle motion within its orbit in an inertial frame is produced. Thus, over short time intervals (tens of seconds), continuous updates of vehicle motion are estimated and many measurements are possible [26]. Digital phase-locked loops (DPLL) can be implemented to insure proper tracking of these signals [12, 24]. An example of this tracking of pulsar frequency is shown in Figure 8 using an *RXTE* observation of the Crab pulsar while in orbit [26]. The measured DPLL frequency of the observation with short time blocks of several seconds shows good tracking of the true frequency variations due to spacecraft motion.

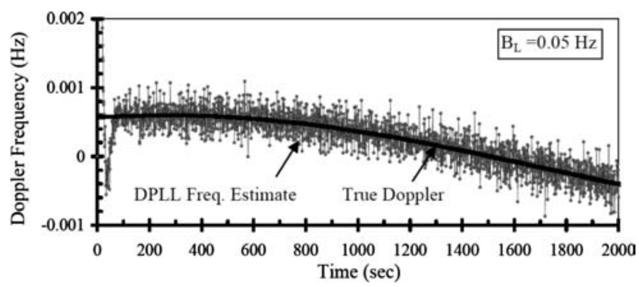

Fig. 8–Doppler frequency tracking of crab pulsar in RXTE orbit [26]

One method to determine a spacecraft's velocity is to compute the difference of successive position estimates divided by the time interval between estimates. However, this differentiation process will amplify noise in the system, which reduces the accuracy of the velocity calculation. Alternatively, for systems that evaluate pulse cycle ambiguities, the triple difference calculation can be utilized to produce an estimate of spacecraft velocity [46]. Although this method may also amplify measurement noise, once accurate pulse cycles are known, only the less noisy cycle phase measurements are processed.

A more straightforward method to determine vehicle speed is through the use of a pulsar's signal Doppler shift. Because pulsars transmit periodic signals, Doppler effects will be present in measured pulsar signals as a spacecraft moves toward or away from the source. Measuring the pulsar's pulse frequency and comparing this to its expected model can determine the Doppler shift. Second-order and higher order relativistic Doppler effects may be significant depending on the specific pulsar signal and vehicle motion and should be included to increase measurement accuracy [66]. Assembling measurements from several pulsars allows full three-dimensional velocity to be determined. Whereas some navigation processes attempt to minimize the Doppler effect by selecting sources that are perpendicular to the vehicle's plane of motion, this velocity determination method would pursue sources that produce the maximum Doppler effect.

Once measurements are produced from pulsar observations, effective techniques to incorporate this information must be designed within the spacecraft navigation system. The use of extended Kalman filters, which use the numerically integrated orbital dynamics of the spacecraft blended with pulsar observation measurements, has been proven very effective for this task [12, 32]. Errors within the position and velocity solutions have been correctly removed with these implementations, and filters such as these can be operated in real time onboard spacecraft for improved autonomous operations.

In addition to filter processing techniques, the augmentation of auxiliary navigation sensor measurements can lead to further improved solutions. Incorporating inertial sensors like gyros and accelerometers allows for attitude, position, and velocity processing [67]. Incorporating attitude sensors such as optical star trackers, sun sensors, horizon sensors, etc. improve not only the overall spacecraft navigation solution, but can aid in X-ray detector inertial pointing as well. To facilitate computing XNAV measurements, raw time-tagged photon events or pre-processed pulse TOAs or phases could be included as part of the downlink message from the spacecraft to the DSN tracking station antenna. The goal of this augmented navigation solution would be to improve the navigation solution of either DSN or XNAV alone. For those spacecraft already using DSN tracking, the additional range, range-rate, and angular position measurements from this Earth-based service would combine well with XNAV solutions to improve the overall navigation accuracy [63, 68, 69]. In addition, the three solutions of DSN-only, XNAV-only, and DSN+XNAV would provide a level of verification for each of these systems.

Relative Navigation

Various applications, such as coordinated communication or scientific observation, only require relative distance and speed information shared between similar instruments operating on cooperating multiple vehicles, rather than requiring an independent, complete 3-D absolute position and velocity solution for each vehicle. Absolute solutions may be difficult to obtain in some circumstances, particularly on missions where GNSS signals are not available, DSN tracking cannot be completed, or solutions may not have the accuracy desired for specific applications [50, 57]. In these cases, a method that directly determines relative position vectors between spacecraft may be beneficial. These vehicles may be following their own free paths, or be following prescribed trajectories such that multiple vehicles remain in a defined formation [70]. Thus, relative navigation between vehicles has been explored using variable X-ray sources [67, 71]. In these techniques, bright sources are desired so that high photon flux rates are provided, which help reduce the observation durations. Additionally, any type of signal variability is usable, thus many other sources other than the highly stable periodic sources can be utilized [71].

Given sufficient observation time, significantly greater than the light travel time between the two vehicles, the observed pattern of variability at one detector will appear as a delayed version of that seen by the other detector. The measurement of this delay provides a distance measurement between the two detectors, projected along the line of sight to the source, which is assumed to be at effectively infinite distance. There is no requirement that the variability pattern be predictable. In fact, a large number of bright X-ray sources exhibit some level of variability in their emitted radiation, which differentiates this from the MSP-based navigation techniques discussed above. Additionally, when utilizing aperiodic sources in this manner, one does not encounter the integer phase ambigu-

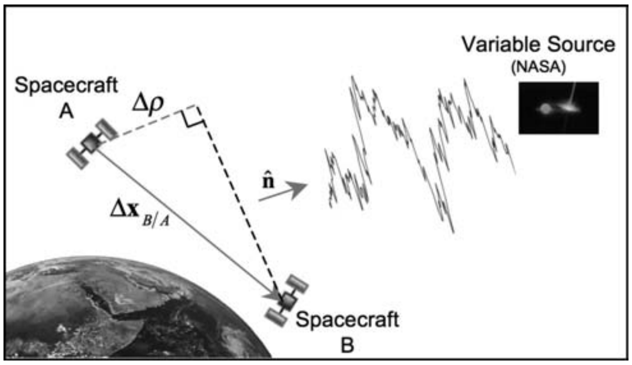

Fig. 9–Relative navigation between two spacecraft observing the same variable celestial source [46, 71]

ity problems that can occur with the periodic pulsar-based methods [46].

Figure 9 presents this concept, where two spacecraft are shown in orbit about Earth simultaneously measuring the arriving X-radiation from a variable source. This would be applicable to other applications, including those in orbit about any planetary body or operating in conjunction on deep space trajectories. This method requires that both spacecraft observe the celestial source simultaneously, but does not require an unobstructed line of sight between the two vehicles, as long as the data can be communicated between each other at some later time, or through some intermediary method. If there is significant delay between an observation and its data transmission between vehicles, it will be necessary to store vehicle navigation data over this interval to correctly compute a relative navigation solution.

To first order, by assuming that the difference in the relativistic effects is negligible, the range difference, $\Delta\rho$, along the direction to the source, $\hat{\mathbf{n}}$, is related to the measured time difference, Δt, and c, the speed of light, by

$$\Delta\rho = \hat{\mathbf{n}} \cdot (\mathbf{r}_B - \mathbf{r}_A) = \hat{\mathbf{n}} \cdot \Delta\mathbf{x} = c\Delta t \qquad (4)$$

In Eq. (4), $\Delta\mathbf{x}$ is the relative position vector between the two spacecraft. Relativistic effects are present in principle [28, 29], and should be included for greater precision.

The source photons detected by each spacecraft are distinct and independent, thus a measurement is not made through direct comparison of individual photon arrival times. Rather, a comparison of the time variability of the rate of detection of X-ray photons at each detector is computed. There will be a large amount of variability in the observed light curve simply due to counting statistics, and only the correlated portion of each signal contains useful information content for a relative range measurement.

The accuracy of a relative navigation offset measurement from a particular source will depend on the total photon count rate from the source, the total fractional variability, and the frequency distribution of the variability power. From Eq. (4), this accuracy is determined by the precision of the determination of Δt. Relative timing accuracies to within 1 ms produce range accuracies on the order of 300 km, whereas accuracies on the order of 1 μs yield 0.3 km range accuracies. The desired accuracy would depend on the specific application. With multiple sequential measurements, evaluating the rate of change of range provides an estimate of relative range-rate in the direction of the source. Also with multiple measurements, particularly from multiple sources, an estimate of a full 3-D relative navigation solution can be created.

The relative navigation scheme could be implemented in a variety of methods. For example, one spacecraft may have a large area detector array used for measuring the X-ray photon arrival, and all remaining spacecraft could have smaller sized detectors. This concept of a single base-station spacecraft and other remote spacecraft (or parent-child concept) may have all measured data transmitted to the base station. After processing onboard the base station, the relative navigation information between the base station and each remote vehicle would be transmitted to those vehicles that require this information. An alternative technique would be to utilize identical detectors on all spacecraft and maintain data communication between all vehicles such that each spacecraft can compute a relative navigation solution to other vehicles as needed. This symmetric scheme is useful when all spacecraft require constant communication between one another, and does not identify a hierarchy between vehicles. Depending on the type of communication, especially one that can encode time information with the data transmission for a preliminary range estimate, the methods discussed here can supplement this estimate as needed.

Noise Analysis and System Performance

The performance of any particular XNAV or XTIM implementation is a function of the characteristics of the X-ray pulsar and nature of its faint emission, the characteristics of the X-ray instrument, as well as the mission itself. A number of these potential noise sources have been addressed in the form of a noise table, as shown in Table 3. In general, a navigation measurement is made by first measuring the TOA of a pulse train from a given pulsar over some length of time. *A priori* knowledge of the pulse shape, pulse period, and pulse period derivatives is key to this fitting process and errors in the knowledge of these parame-

Table 3—Key X-ray Navigation Error Sources [23]

Source	Parameters
Source Shot Noise (Periodic)	s: Source strength A: Detector area Δt: Observation time η: Detector efficiency
Source Shot Noise (Steady)	b_s: Source background
Diffuse X-ray Background Noise	b_d: Diffuse X-ray background
Cosmic Background Noise	b_c: Cosmic X-ray background (after rejection)
Detector Noise	b_{det}: Detector noise
Local Clock Noise	$\nu(f)$: Noise power spectral density as a function of frequency
Clock Quantization	q_{clk}: Clock quantization bit
Photon Binning	t_{bin}: Bin size
Source Shape Uncertainty	Δb: Source parameter error
Pulse Period Uncertainty	ΔP: Source period error
Source Phase Jitter	$\Delta\phi(t)$: Source phase error
Source Position Uncertainty	$\hat{n}$

ters, clock errors, and instrument noise will introduce errors into the TOA measurement. Furthermore, the signal being measured (the pulsar emission), being a weak signal, is dominated by photon noise. The measured TOA must be corrected for changes in spacecraft velocity and position during the observation as well as the impact of relativistic effects on the X-ray photons. Errors in the estimated spacecraft velocity and position introduce errors of their own. Finally, the knowledge of the position of the pulsar in the sky is used to determine the position of the spacecraft in the X-ray navigation frame-of-reference. Uncertainty in the position of the pulsar will introduce a final error whether a system using observations of a single pulsar and a gravitational model are used, or whether four or more pulsars are used to create an instantaneous position measurement.

For most missions, the primary source of error in the navigation solution is the ability to measure the TOA of the pulse train from each source while contending with the shot noise that is inherent in the faint signal, the diffuse X-ray background, cosmic ray events, and detector background. The SNR of the measurement (and hence the accuracy of the TOA estimate) can always be improved by using a larger detector, or increasing the observation time. However, physical limits of the spacecraft and mass considerations will limit the maximum possible collection area of the detector. The particular mission being considered will place limits on the duration of any observation through changes in the spacecraft velocity or orbit parameters, or through occultation of sources being observed by planetary bodies or asteroids. Thus, the problem becomes one of extracting the most information from an observation in order to minimize the required detector area and observation time.

This is complicated by the fact that the intensities of the pulsars are a function of photon energy (as a general rule, the flux decreases as a power law with energy), making the detector sensitivity as a function of energy an important parameter in predicting the performance of an XNAV system.

Several methods have been used to estimate the impact of these noise sources on XNAV performance. In general, three analytical approaches have been used, each of which has been verified with some form of Monte-Carlo simulation:

- A simple relationship between the SNR and the width of the pulse [12, 17];
- A least-squares (LS) fit of the pulse shape to the X-ray data assuming the photons are collected into finite duration time bins over the length of the observation and folded perfectly at the pulse period [23]; and,
- A Cramer-Rao lower bound to the performance of an MLE, assuming that the photons are time-tagged, but not binned [26].

The total number of photons in an observation bin can be characterized by the mean number of photons expected, y_i, as

$$y_i = [b + s \cdot h(t_i, t_0)]A \cdot N \cdot \eta \cdot t_{bin} \tag{5}$$

where b is the background rate (including detector noise, the diffuse X-ray background, uncancelled cosmic ray events, and steady emission from the pulsar), s is the source flux, $h(t_i,t_0)$ describes the shape of the pulse, t_i is the time at the center of bin i, t_0 is the time of arrival of the pulse, A is the collection area, t_{bin} is the size of the bins used to count photons, N is the number of waveforms folded, and η is the detector efficiency. A useful and very simple relationship for the expected pulse TOA accuracy (σ_{TOA}) as a function of the instrument SNR and the full-width-half-maximum of the pulse shape is presented as [12, 17, 46],

$$\sigma_{TOA} = \frac{\frac{1}{2}FWHM}{SNR} \tag{6}$$

In Eq. (6), *FWHM* is the full-width at half-maximum of the main peak in the pulse profile. This approach can be used to approximate TOA performance in observing a particular pulsar, but it neglects the full contribution of pulse shape to performance. For example, two pulses might have the same FWHM value, but if one pulse is sharper than the other, one would expect a more accurate TOA measurement.

This simple TOA accuracy concept was further extended to include the pulse shape for the LS estimator case [23]. In this case, the following assumptions are made:

- The pulse shape and pulse period are known;
- The photons are time-tagged and collected into bins of fixed time width (e.g., 0.1 msec);
- The photon arrival times are corrected for relativistic effects;
- The series of N pulses, measured over the total time Δt, are folded together to form a light-curve profile that is the sum of the individual pulsations; and,
- After folding, the number of photons in any bin are sufficiently large such that the Poisson distribution of the number of photons in a bin can be approximated by a Gaussian distribution (i.e. $n_{photons} > 20$).

The error in the time-of-arrival estimate of a pulse train from a pulsar has two components, one describing the shot noise inherent in the signal itself and one describing the added shot noise due to all background photons, including the steady emission from the source, the diffuse X-ray background, cosmic rays, and detector noise:

$$E\left[t_0^2\right] = \Gamma_s^2 \frac{P}{A\Delta t s} + \Gamma_b^2 \frac{P}{A\Delta t s}\frac{b}{s} \tag{7}$$

where the two parameters Γ_s and Γ_b (the pulse shape factors) describe the impact of the pulse shape on the estimate error for source shot noise and background shot noise, respectively, as,

$$\Gamma_s^2 = \frac{\int h(t,t_0)\left(\frac{\partial h(t,t_0)}{\partial t_0}\right)^2 dt}{\left\{\int \left(\frac{\partial h(t,t_0)}{\partial t_0}\right)^2 dt\right\}^2} \tag{8}$$

$$\Gamma_b^2 = \frac{1}{\int \left(\frac{\partial h(t,t_0)}{\partial t_0}\right)^2 dt} \tag{9}$$

The error in the TOA estimate of a pulse train is inversely proportional to the square root of the product of the detector area and the observation time. In addition, The pulse shape factors for several promising X-ray pulsars have been computed and used to predict performance [23, 69].

While the previous analyses provide performance predictions for XNAV systems using binned photon data with LS estimators, a different approach is necessary if the performance of single photon processing systems is to be evaluated. In this case, the Cramer-Rao Lower Bound (CRLB) provides a lower bound to the performance of an XNAV system using an MLE [26]:

$$Var[t] \geq \left\{ f^2 \Delta t \int_0^1 \frac{\left[sp_f\left(\partial h(\phi)/\partial\phi\right)\right]^2}{sp_f h(\phi) + \left[s(1-p_f)+b\right]} d\phi \right\}^{-1} \tag{10}$$

where the profile shape function, h, is written in terms of cycle phase, ϕ, and pulsed fraction, p_f. This theoretical technique provides a lower bound (i.e., optimistic) estimate to the error in an MLE. Several sources have been analyzed and it was determined that the CRLB is very sensitive to source flux and profile and these must be modeled appropriately to obtain the best analytical estimates. This also suggests that the performance of XNAV is highly dependent on accurate, high SNR models of the pulse profiles and source strengths and that current XNAV models may underestimate the accuracy achieved when using sources with shorter historical observations. The CRLB analysis can be employed to verify the potential performance of several processing techniques, such as MLE, LS, and non-linear LS.

The results of Monte-Carlo simulations and LS analytical data are shown in Figure 10, and the LS technique compares well after the initial break portion of the plots. This break in the plot of the Monte Carlo simulated accuracy indicates that the actual system accuracy is poorer than the model predicted accuracy when considering area-time products less than $5{\cdot}10^4$ m$^2{\cdot}$s for PSR B1821+24. This may be due to a low signal-to-noise ratio resulting in poor performance of the gradient search algorithm used in the Monte Carlo simulation. This behavior was also seen in the Monte Carlo simulations of [26] and is a subject of ongoing research in the field. The CRLB method also demonstrates good comparisons to the LS analytical solution, typically showing only a 10–20 percent improvement over LS in accuracy at low flux, and a 20–40 percent improvement in observation time. There is a possible improvement in the location of the threshold point of the break, where the

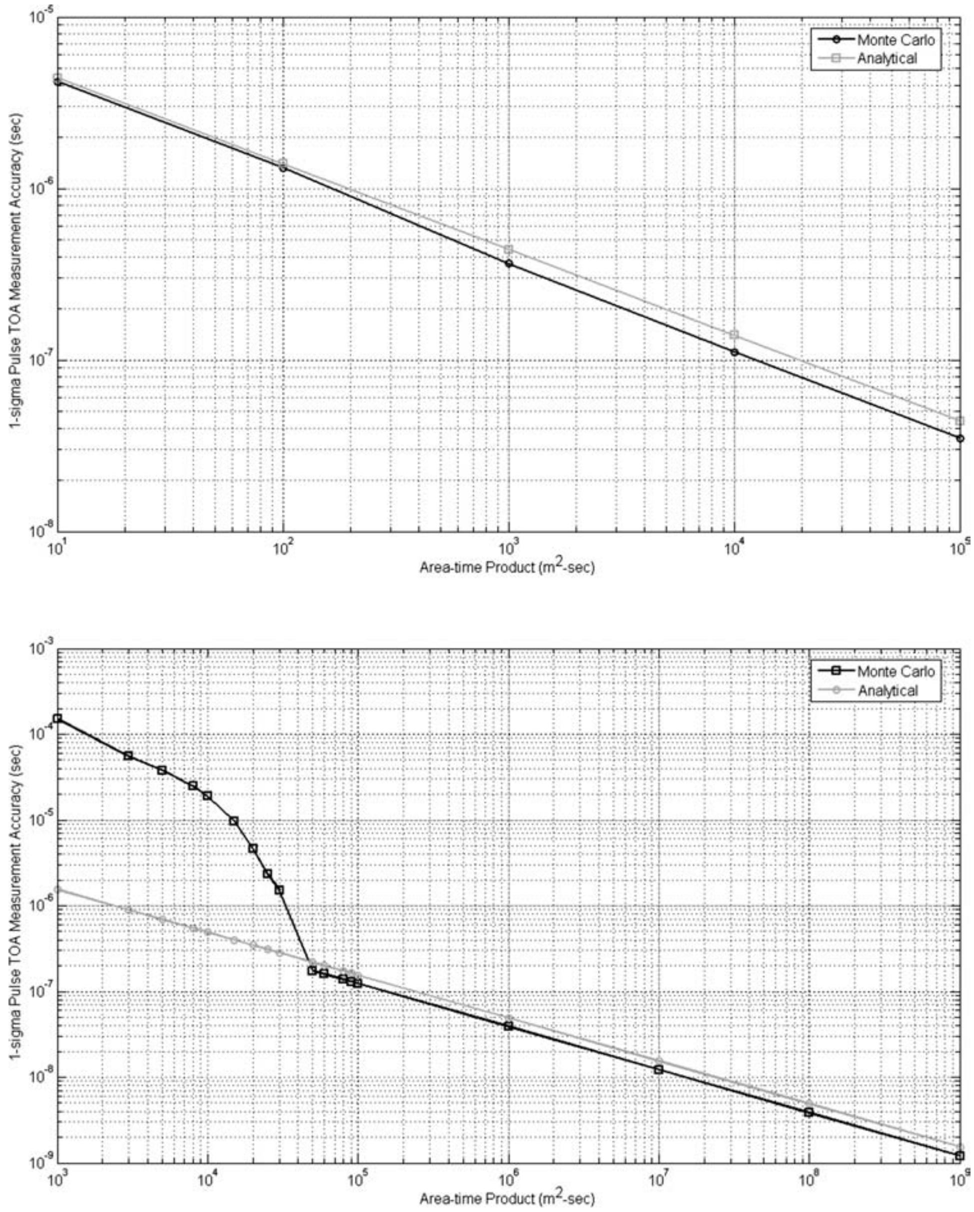

Fig. 10–Comparison of monte-carlo simulation and least-squares photon processing approaches, with parameters in Panel A for the Crab pulsar (PSR B0531+21) and Panel B for PSR B1821+24 [23]

LS method approaches the theoretical CR limit. A similar comparison shows an asymptotic convergence at high area-time products [25]. These results indicate that the single photon algorithms may reduce the time-area product required for a given accuracy.

As presented in the accuracy equations above, the overall performance of an XNAV system is highly dependent on the detector area, the observation time, and the pulsar being observed. In general, the TOA measurement error is inversely proportional to the square root of the product of the detector area, observation time, and source intensity. Hence, a four-fold increase in detector area or observation time will result in a halving of the TOA measurement error. A 1000 cm^2 detector making a 1000 second observation of the Crab pulsar would have a TOA measurement error of approximately 1.5 μsec.

Mission Applications

Among the most promising applications for this X-ray navigation technique are science and exploration missions far from Earth. These types of missions can combine relatively small detectors ($\sim$1000 cm^2) and relatively long observation times (10^3–10^5 seconds), along with a benign disturbance environment to achieve useful navigation estimates. Additionally, for missions that pass close to the Sun, spacecraft emergencies, and landing on or orbiting asteroids or comets, it is desirable, and in certain cases essential, to provide an autonomous capability for the position and velocity determination in real time onboard. In such circumstances, for the execution of orbit correction maneuvers in a timely manner, the ability to estimate an onboard position, as well as maintain a very accurate clock, is essential and mission enabling.

Augmentation with existing systems, such as DSN, further enables missions to succeed or operate at lower cost. For example, orbits in the vicinity of the Earth-Sun L2 point are considered fairly stable; however, they will diverge after approximately 23 days without periodic maintenance burns. Thus, for these L2 orbit applications, XNAV could provide increased autonomy and potential reductions in DSN operation costs. Another mission is one to investigate the Pioneer anomaly – an apparent deviation of Pioneer's anticipated trajectory from model predictions [72]. Navigation with XNAV would provide both significantly improved navigation accuracy over DSN alone, and an independent measurement from radiometric techniques.

Formation flying and relative navigation with XNAV shows promise in a few different ways, primarily by opening up the realm of potential sources to include bright, aperiodic sources, which cannot be easily modeled for independent use, but can provide excellent relative results by correlating observations between multiple spacecraft [25, 71]. With the inclusion of an accurately navigated X-ray observatory platform and the ability to communicate observations, this approach could be used to support navigation of individual spacecraft.

Along with these documented benefits for spacecraft navigation, accurate pulse timing from pulsars is beneficial for future science observations that utilize these signals, such as gravitational wave detection [73–75] and planetary mass and ephemeris calculations [76].

Operational Benefits and Challenges

There are numerous potential benefits from this technology. A navigation and/or timing system utilizing X-ray pulsars would be available anywhere cosmic X-ray sources can be observed, from low Earth orbits to interplanetary trajectories and planetary orbits. The system is passive, requiring only infrequent pulsar ephemeris updates, and can operate in an autonomous mode, independent of GNSS and NASA DSN systems. In addition, it can be used in modes where it supplements or enhances DSN capabilities by stabilizing onboard time references for accurate range computations. It can provide measurements that are in a direction perpendicular to the line of sight from Earth to the spacecraft. The detectors are highly resistant to blinding or contaminating events. Detectors used within the XNAV system are intrinsically radiation hardened due to their design for recording X-ray photon events. Previous research on this technology has shown that the achievable navigation performance using these sources can be on the order of existing navigation technologies. Even with these numerous benefits, significant challenges remain that must be addressed before an operational system can be deployed.

Through five decades of X-ray astronomy both source characteristic knowledge and sensor detector system concepts continue to mature. New radio MSPs are continually being discovered but few of these have been adequately investigated for mere detection of X-ray millisecond pulsations. With newly proposed X-ray astronomy missions, detector concepts are undergoing major revisions to achieve performance beyond current day capabilities. Many future designs center on solid-state detectors combined variously with collimators, coded apertures, or concentrators. X-ray detectors with high quantum efficiency, low-power, low-noise, accurate time resolution, and minimum size and mass will be needed to make broad adoption practical.

A navigation system that utilizes pulsed emissions from pulsars will have to address the faintness, transient, flaring, bursting, and glitching aspects of these sources, in addition to the number of signal phase cycles received and the presence of the noise from the X-ray background, cosmic ray events, and detector noise [15]. An operational system would require a pulsar almanac database with current source characteristics and profile information. Faint, noisy sources drive solutions toward large detectors and long integration times to precisely resolve TOAs, but this comes as a tradeoff between available payload mass and power usage versus the overall mission spacecraft size and objective. Bright sources such as the Crab pulsar have relatively poor timing stability and are a challenge to be modeled accurately for long-term predictions. Motion of sources relative to the ECI frame requires accurate measurement and modeling of source position, proper motion, and binary orbit parameters. Source frequency drifts due to a pulsar's slow energy loss and must be modeled. Maintaining accurate timing models will require either a dedicated observatory spacecraft or development of a capability to predict X-ray behavior based on ground-based radio band observations. General and special relativity effects must be accounted for because the vehicle is moving and is influenced by gravity.

A stable onboard clock would be an essential part of a complete XNAV system, which increases mass and cost to any vehicle. Although data from actual X-ray astronomy missions have been used to demonstrate the capability, a dedicated flight experiment is yet to be built and flown.

CONCLUSIONS

The novel concepts of XNAV and XTIM hold great promise for future deep space exploration and for the developing user community because they are enabling technologies for fully autonomous planetary orbiting and interplanetary navigation. These new systems will provide significant future mission operating enhancements as an adjunct to the DSN and ground-based navigation methods. Even with the noted challenges that this system faces, the conceived benefits of this new X-ray navigation and timing technology warrants its continued investigation.

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