Deep Space Navigation Using Celestial X-ray Sources

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BIOGRAPHY

Paul Ray is an Astrophysicist in the Space Science Division of the Naval Research Laboratory. He received his Ph.D. in Physics from Caltech in 1995 for research on radio pulsars. Currently he is active in X-ray timing studies of neutron star and black hole sources, including pulsars and accreting binary systems.

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Michael Wolff is an Astrophysicist in the Space Science Division of the Naval Research Laboratory. He received his Ph.D. in Astronomy from Indiana University in 1985. He has investigated the properties of a wide range of compact object binary systems, including white dwarf, neutron star, and black hole systems.

Kent Wood is Head of the X-ray/UV Astrophysics and Applications Section at the Naval Research Laboratory. He received his Ph.D. from the Massachusetts Institute of Technology in 1973. He was Principal Investigator of the NRL USA experiment on ARGOS, which conducted timing studies and explored applications of X-ray astronomy.

Keith Gendreau is an astrophysicist in the Science Exploration Division at NASA's Goddard Space Flight Center. He received his PhD from MIT in 1995 calibrating and modeling radiation damage mechanisms of CCDs for the ASCA X-ray astrophysics mission. He also studied the Cosmic X-ray background for his thesis. Since then he has been the study scientist for the MAXIM black hole imager mission concept and has demonstrated X-ray interferometry in the laboratory. He also works on applications of X-ray astrophysics developed technology for such fields as spacecraft navigation, material analysis, and communication.

ABSTRACT

Spacecraft traveling into deep space operate well beyond the useful range of the Global Positioning System (GPS) and yet still may have requirements for precise navigation information for trajectory calculations, instrument operations, or communications. The current predominant source of navigation information for deep space probes is range and range rate information obtained as part of the uplink and downlink communication with ground stations such as NASA's Deep Space Network (DSN). These systems are expensive to build and maintain and time on them is a scarce resource because of their support of many concurrent missions. In addition, the navigation information obtained naturally achieves much higher precision in the radial dimension than in the two transverse directions. Consequently, a source of navigation information that does not rely on frequent communications with Earth-based assets and that attains high accuracy in all directions would be highly desirable.

In this paper, we describe one such source of navigation information: celestial X-ray sources. Several classes of X-ray sources, particularly X-ray pulsars, produce regular time signatures that can be predicted with very high accuracy over long timescales. By observing the arrival time of pulses at a spacecraft from several pulsars in different directions, a spacecraft could autonomously determine its location with respect to an inertial origin in a manner similar to GPS.

This technique is applicable anywhere in the Solar System, and beyond. The relatively low disturbance environment of deep space, as compared with low-Earth orbit, allows pulse times-of-arrival (TOAs) to be measured using long integrations in order to make useful position determinations.

Source characteristics and X-ray detector techniques are described herein, along with methods to use this source signal to supplement ground tracking observations to enable greater autonomy, increased navigation performance, and reduced resource requirements for future deep space missions.

INTRODUCTION

Observations of celestial sources have been employed for navigation for millennia. Modern day instruments such as star cameras operate in the visible band where the stars in the sky are essentially constant in number and steady in brightness. The situation is completely different in the X-ray band (photon energies in the ~keV range) where there are effectively *no* steady point sources and several of the bright sources in the sky at any given time are likely to be transients that make appearances lasting anywhere from seconds to decades. In addition, some classes of X-ray sources exhibit stable periodic modulations.

There are several ways in which these fluctuating X-ray sources can be used to provide navigation information for spacecraft with the appropriate sensors[1]. For the bright and highly variable sources, detectors on two separate spacecraft can be used to correlate the signal from the same source. This yields information about the relative position of the two spacecraft [21]. Alternatively, observations of pulsars can be used to measure individual arrival times of pulses. Pulsars are rotating neutron stars that produce highly regular, very stable pulses, which are able to be accurately predicted. This arrival time information provides a measure of the location of the spacecraft relative to the Solar System barycenter. These techniques are most promising for deep space applications, which is defined here as those distances from Earth beyond geostationary orbit. In the following sections, we describe the characteristics of the pulsar sources that could be employed, the X-ray detectors that are required, the navigational algorithms that are needed, and several potential applications where this technique could provide improvements over current techniques.

SOURCES

To be useful for the direct position determination techniques, sources must exhibit stable predicable pulsations that can be measured with an X-ray detector and compared to an onboard timing ephemeris. The most promising class of sources is rotation-powered X-ray pulsars. A significant number of young pulsars are found to exhibit bright X-ray pulsations. However, these young pulsars have strong magnetic fields that exert torques on the stars, spinning them down rapidly and causing their pulse periods to be rather unstable in their evolution. For these to be used, their timing ephemerides would have to be updated frequently and the accuracy would be limited. Alternatively, there is a class of pulsars known as millisecond pulsars (MSPs) that have much weaker magnetic fields and ages in the Gyr range. These sources are *much* more stable and several have been timed to accuracies approaching 100 ns over periods of years. A sample of known millisecond pulsars with detected X-ray pulsations are included in Table 1.

Table 1. Basic parameters of several useful pulsars for X-ray navigation. Source count rates and TOA accuracies are applicable to the *NICE* mission concept described in the text, with an integration time of 10 ks.

Pulsar	Period (ms)	Count Rate (cts/cm^2/s)	FWHM (%)	σ_{TOA} (μs)
B1937+21	1.56	1.31E-05	2%	0.4
J0218+4232	2.32	3.74E-05	11%	3.3
B1821-24	3.05	4.23E-05	3%	0.5
J0751+1807	3.48	1.13E-05	31%	53.6
J0030+0451	4.87	8.75E-05	15%	6.4
J2124-3358	4.93	3.35E-05	40%	50.8
J1024-0719	5.16	6.67E-06	30%	116.6
J1012+5307	5.26	2.10E-05	10%	9.3
J0437-4715	5.76	1.29E-04	28%	23.7
Crab Pulsar	33.00	6.32E-01	5%	0.3

The X-ray emitting MSPs fall into two basic spectral categories [10], those that emit predominately thermal radiation from hot spots on the surface and those whose emission is dominated by power-law spectrum generated in the magnetosphere (see Figure 1). The power-law sources (e.g. the first three sources in Table 1) 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. The thermal sources tend to be intrinsically fainter and have broader pulse widths. Their soft spectra are best detected in the 0.5–2 keV soft X-ray band.

By virtue of their stable, compact structure, pulsars tend to be very good clocks. The millisecond pulsars have been shown to have timing stabilities rivaling that of modern atomic clocks [13]. Younger pulsars, such as the Crab Pulsar, with higher magnetic field strengths, tend to be more unpredictable in their spindown behavior. These sources can also be utilized, but they will require more frequent ephemeris updates and result in a lower performance system. However, since they are brighter this can be accomplished with a smaller detector system.

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[1] Note that X-rays don't penetrate deeply into the Earth's atmosphere so these techniques aren't applicable to ground-based terrestrial applications.

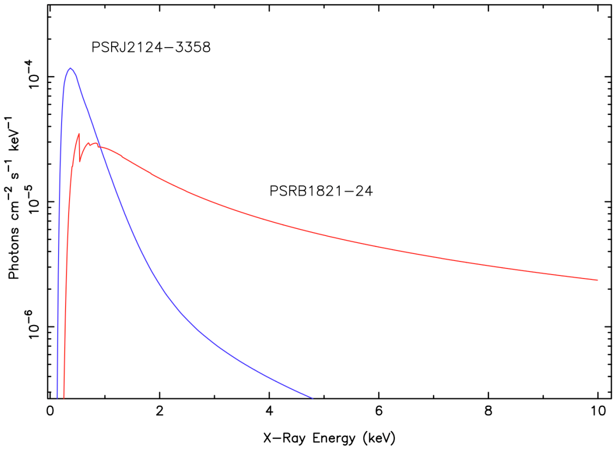

Figure 1. Comparison of the X-ray spectra of two millisecond pulsars showing the distinct difference between the two classes.

DETECTOR TECHNOLOGY

The key function of the X-ray detector in an X-ray navigation (XNAV) system is to detect as many photons as possible from the source being observed while minimizing the number of non-source events, whether they are from particle events in the detector or from the diffuse X-ray background. Each photon detected must be time stamped to a precision such that the uncertainty in the time is small compared to the statistical error in the pulsar measurement. Time resolutions of 1 μs will enable positional measurements of 300 m. The design of a detector system to optimize the detectability of these sources depends on the energy spectrum of the emitted X-rays, as shown in Figure 1. Thus, the key performance metrics for comparing detector systems are energy range, efficiency (i.e. effective area per unit geometric area), background rate, and time resolution. In addition, the volume, weight, and power of the system will be critical for practical applications.

One class of instruments is based on large area X-ray detectors with collimators that allow only photons coming from the direction of the source. In the past, these were based on gas proportional counters, which are heavy and subject to gas leaks, breakdowns, and other problems. A newer approach is to use solid state detectors such as silicon pixels, which are much more robust. The primary benefits of this class of instrument are broad energy coverage, high efficiency, and compactness. The drawbacks can include high background rates caused by the large detector area, and high power usage. In addition, the electronics noise inherent in low power front-end electronics can make achieving low energy thresholds below ~1.5 keV difficult.

An alternative approach is to use a focusing optic in front of a small solid state detector. This can greatly reduce the background contributions from both charged particles and the diffuse X-ray background. Standard X-ray imaging systems have employed grazing incidence optics in a Wolter I configuration with two reflections in the optical path. This requires long focal lengths and achieves rather poor efficiencies. Since this application requires only *concentrating* the X-rays from the source, not true focusing, a simpler and more effective and more compact design can be based on small-diameter single-bounce X-ray optics.

An instrument of this type has recently been developed in detail for a proposal to NASA for a Mission of Opportunity flight to the International Space Station in 2012. The *Neutron star Interior Composition Explorer* (*NICE*; Principal Investigator K. Gendreau of NASA's GSFC) is designed to make deep exposures of neutron stars in the 0.5–10 keV band with ~100 ns timing precision on each photon. These observations promise to answer fundamental questions about the structure of neutron stars and the equation of state of matter at super-nuclear densities. In addition, the same data will provide a direct demonstration of the X-ray navigation concept and flight qualify several of the key technologies that would be employed in an operational system. If *NICE* is selected for flight, it will represent a critical step in the development of critical technologies for X-ray navigation.

NICE consists of 56 telescope assemblies, each made up of 27 concentric gold-plated mirror shells backed by an avalanche photo-diode (APD) focal plane array (see Figure 2). By keeping the largest mirror diameter small (10 cm), the focal length can be kept to only 115 cm so that the volume requirements are modest. The APDs have high quantum efficiency, low dead time and good energy resolution (5% @ 6 keV) at modest power consumption.

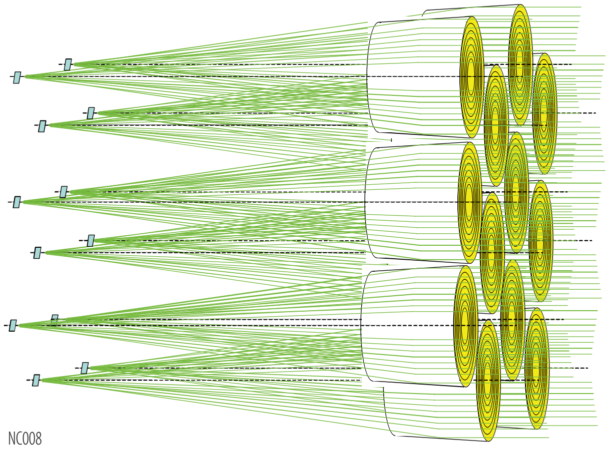

Figure 2. Array of X-ray concentrators as proposed for the NICE mission.

HISTORY AND GENERAL CONSIDERATIONS

Variable celestial X-ray sources provide unique opportunities to create accurate spacecraft navigation solutions. Full three-dimensional solutions are achievable from these sources, including vehicle attitude determination, position and velocity determination, and clock corrections for maintaining accurate time. It is this potential for the full suite of onboard navigation solutions from these periodic sources that is currently driving the interest and research into their utility. Concepts of navigation using radio emitting pulsars began shortly after their discovery in 1967 [7, 2]. Benefits of smaller sized detectors quickly identified X-ray sources as having greater practical utility to spacecraft than those emitting in the optical or radio bands [1,23,6]. In particular, [23] examined use of all kinds of X-ray sources for a range of space-based applications including but not restricted to navigation, and the latter including but not restricted to pulsars, and this reference contains a description of the USA Experiment on flown by the Navy on the Air Force *Advanced Research and Global Observation Satellite* (*ARGOS*) under the Space Test Program. That experiment was the first flight test of these ideas. A patent [20] was later granted covering this method of navigation. It is worth mentioning that pulsars are a small fraction of the bright X-ray-emitting objects, which include both stars in our own Galaxy and other extragalactic objects, and that rotation-powered millisecond pulsars are only one of several classes of sources exhibiting periodicities. In any case, the USA Experiment was already well under way when rotation-powered millisecond pulsars (the fastest and least noisy clocks) were conveniently found to pulse in X-rays as well as radio, the latter being the band of their initial discovery. For further discussion of the development of space-based X-ray applications and of the associated astronomical background see [23 and 24]. An overview of current concepts for how signals from these celestial X-ray sources may be used to derive spacecraft navigation products is presented in the following section.

NAVIGATION ALGORITHMS AND TECHNIQUES

The fundamental measurable component of the X-radiation from these sources are the individual X-ray photons detected by an instrument on a spacecraft. All navigation solutions are derived from these photon detection times. 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.

The pulse arrival times from pulsars can be measured with high accuracy and modeled using a timing ephemeris with only a few free parameters. It is precisely this predictable behavior that allows pulsars to be considered as navigation beacons. 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 over a period of up to several decades, in some cases. The model output is the total accumulated phase, Φ as a function of time. The primary model parameters are the pulse frequency, f, and its low-order derivatives,

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

The time, t, is the coordinate time (typically TDB or TCB) and t_0 is the chosen reference epoch for the model parameters [12,17]. 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.

During an observation of a source, the detected photons are average synchronously, or *folded*, based upon the known pulse period from its pulse-timing model. An ensemble of these folded photons creates well-defined and stable pulse shapes. Figure 3 shows the pulse profile detected from the Crab pulsar (PSR B0531+21) by the Naval Research Laboratory's Unconventional Stellar Aspect experiment [26]. It is noted that the pulse shape includes a sharp main pulse and a prominent second, inter pulse.

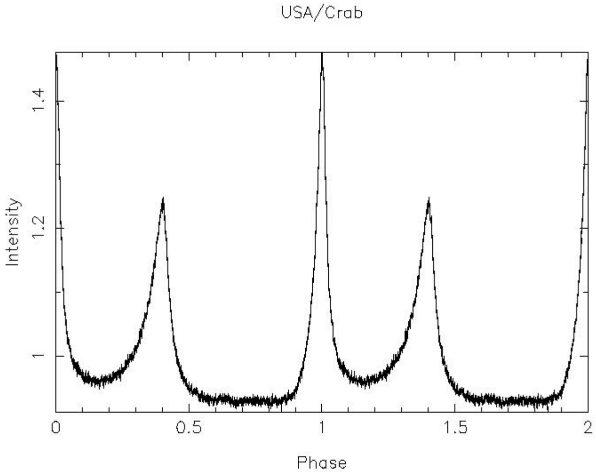

Figure 3. Pulse profile for Crab Pulsar. Two periods are shown.

Any errors in the pulsar timing model will directly translate to errors in the navigation solution determined from them. For example, in order to achieve 1 km accuracy throughout the Solar System, the source direction must be accurate to ~0.0005 μrad. Fortunately, these parameters are typically determined directly from the pulse timing observations of the source and thus are continually being improved by more and higher quality observations. It is worth noting that nearly all of the useful pulsars are also bright radio pulsars and are routinely timed as part of long term pulsar timing studies with large ground-based radio telescopes.

For an operational XNAV system, it will be necessary to continuously monitor, catalog, and disseminate the timing models for existing and newly detected sources to spacecraft that rely on this information. In addition to ground-based radio timing, it is envisioned that an orbiting X-ray observatory, serving as both an astrophysics science research instrument and a navigation base station could be of great value for long term XNAV operations. Existing X-ray astrophysics missions, such as the *Rossi X-ray Timing Explorer* (RXTE) [8] and XMM-Newton, can be employed to partially demonstrate this function; however, a dedicated X-ray observatory that can communicate this critical pulsar almanac information will likely someday be required.

Several of the techniques designed for navigation use the difference between the pulse time of arrival (TOA) measured onboard a spacecraft to the predicted arrival time based upon the model. This difference, or *timing residual*, provides the input data for the navigation solution determination. The accuracy of each of these TOA measurements is critical in determining the accuracy of the derived navigation solution.

Earlier work has utilized a simple signal-to-noise ratio (SNR) scaling in order to compute the expected TOA accuracy (σ_{TOA}) of an individual observation [19,15,16] in the form,

$$\sigma_{TOA} \cong \frac{\frac{1}{2} FWHM}{SNR} = \frac{HWHM}{SNR}$$

where HWHM and FWHM are the full and half widths and half maximum of the main peak in the pulse profile. Improved estimates of the TOA accuracy, however, can be computed using the theoretically achievable limits of this pulsar signal by computing the signal's Cramer-Rao lower bound (CRB) [4]. Given expected pulsar photon flux, expected pulse frequency, and the expected X-ray background flux, this CRB process places a lower bound on the variance of the estimation of pulse phase based upon observation duration and detector area.

The XNAV navigation processing can be separated into the three general areas of *attitude determination*, *position and velocity determination*, and *time correction*. The detectors used for each of these solutions may be different, as those used for imaging in attitude determination may have different characteristics than those used for high accuracy photon timing. Additionally, the algorithms and techniques for each of these types of navigation solutions will be different.

Methods of attitude determination using these variable sources was first proposed using techniques similar to optical star cameras [6]. X-ray image detectors located on the spacecraft body are used to produce images within their field of view. If three-dimensional attitude is completely unknown, then the detected field image must be matched within those stored in an X-ray source image database. If coarse attitude solutions are known, then comparisons to an expected image in the field of view can be computed, and any estimated attitude can be corrected by the computed offsets. Full three-dimensional attitude can be computed using multiple detectors oriented toward different sky directions. Convolution of images using coded masks can help with the image resolution process. Accuracies comparable to star cameras are expected to be achieved.

There are several methods of position and velocity determination that have been researched. They can be categorized in an *absolute* sense and a correction, or *delta*, sense. In the absolute mode, methods are created to determine the absolute three-dimensional position and/or velocity in an inertial reference frame. In the delta mode, updates to estimated position and velocity values are generated from the pulsar measurements. Either of these methods contributes to maintaining a continuous, accurate navigation solution.

A concept that borrows from optical source methods is the concept of *occultation*, where a variable 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 [23]. 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 [19, 15]. Using accurate ephemeris information of the body and the unit direction to the source, estimated position (or more likely accurate *range* from 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 [25].

For many deep space mission applications, where contact from Earth may be limited and few planetary bodies in the near vicinity, methods to uniquely determine the full three-dimensional position solution are sought. As discussed here, most position determination corrections methods used the measured TOA from a pulsar to provide position, or range, information with respect to a specific origin, planetary body, or even another spacecraft. However, in the full three-dimensional position determination objective, the goal is to compute the three-axis position information with respect to an inertial origin without requiring knowledge of other nearby bodies or information in a relative sense. To compute this solution using pulsars it is necessary to monitor several pulsar simultaneously and merge their pulse TOA information into a single solution [16]. This 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. Uncertainties in the pulse cycles with respect to the reference origin would exist and must be resolved to declare a solution valid [15,16]. However, once the cycle ambiguities are resolved, continuous absolute position solutions would be possible. This concept is reminiscent of the similar concepts used within the Earth-based Global Navigation Satellite Systems (GNSS), and liken pulsar-based navigation to GPS, or similar trilateration techniques, absolute navigation. Although similarities to GPS do exist, the absolute method of navigation using variable celestial sources is actually more challenging to implement, primarily due to the requirement of multiple detectors and processors, and thus must be considered as an evolutionary advancement to future XNAV systems.

Perhaps the most readily achievable and most straightforward concept to implement would be single detector techniques that provide corrections to estimated range, and hence position, solutions. The most common approach is the computation of a TOA-difference. When viewing a single pulsar, with its known pulse timing model, the computed TOA difference between the predicted TOA of the model and the measured TOA by the detector 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 4 shows the concept where arriving pulses are used to help update the spacecraft position with respect to the Solar System barycenter reference frame. To produce accurate TOA measurements would require long observation durations (many thousands of seconds) from sources based upon the CRB achievable performance [4].

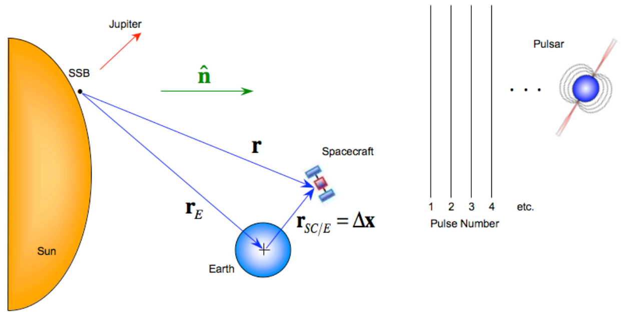

Figure 4. Position of spacecraft as pulses arrive into Solar System from distant pulsar.

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 [4]. This method can estimate and lock onto the phase and frequency of a source based upon the known model of Eq. . 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 [4]. Digital phase-locked loops can be implemented to insure proper tracking of these signals.

A frequent aspect of navigation for some applications is determining a vehicle's location specifically relative to another cooperating vehicle, in order to coordinate observations or communications, as in Figure 5. Thus, relative navigation between vehicles has been explored using variable X-ray sources [21, 3]. 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 [21].

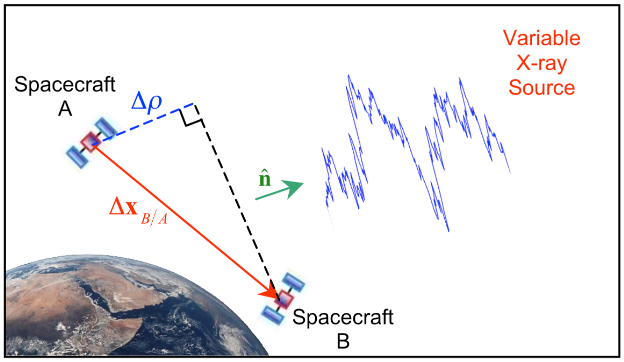

Figure 5. Relative navigation between two spacecraft that observe the same variable celestial source.

A very unique aspect that stable pulsars can provide to improve spacecraft mission operations is the ability to provide atomic clock quality time. This has been demonstrated with several highly stable sources [13, 9]. Detection of these sources over long durations could reduce onboard clock errors, or at least stabilize any long term clock drifts.

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 [15, 18]. 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 of gyros and accelerometers allows attitude, position, and velocity processing [3]. Incorporating attitude sensors such as optical star trackers, sun sensor, horizon sensors, etc. improve not only the overall spacecraft navigation solution, but can aid in X-ray detector inertial pointing as well. For those spacecraft using DSN tracking, the additional range and range-rate measurements from this Earth-based communication would assist with overall accuracy improvements [5].

INTERPLANETARY APPLICATIONS AND PERFORMANCE EXPECTATIONS

Among the most promising applications for XNAV are science and exploration missions far from Earth. These types of missions can combine relatively small detectors (~1000 cm^2) and relatively long observation times (10^3–10^5 seconds), along with a benign disturbance environment to achieve useful navigation estimates. Several of the authors are supporting or participating in a Phase II NASA SBIR project to explore these types of applications and to assess XNAV's potential utility. Some specific applications are discussed in detail below.

Earth-Sun L2 Point

The Earth-Sun L2 point is about 1,500,000 km from Earth, opposite the Sun along the Earth-Sun line, as illustrated in Figure 6. Orbits in the vicinity of L2 are considered fairly stable; however, they will diverge after approximately 23 days without periodic maintenance burns. A number of missions including *Wilkinson Microwave Anisotropy Probe* (*WMAP*) and the *James Webb Space Telescope* (*JWST*) benefit from the L2 location. Benefits include: a stable position relative to Earth, minimal interference from Earth or Moon for celestial observations, and a stable thermal environment.

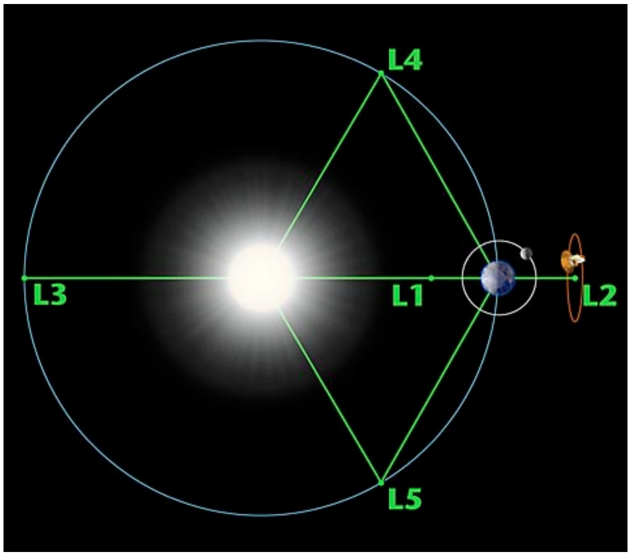

Figure 6. Earth-Sun Lagrangian Points (Source: NASA Website)

The principal XNAV application would be for autonomous navigation and orbit maintenance. DSN based radiometric techniques provide the current baseline approach, however, they require regular, multi-hour tracking observations and maneuver calculations and commands from the ground. Thus, for the L2 application, XNAV could provide increased autonomy and potentially reductions in operations costs, but alone cannot be considered mission enabling.

Planetary Approaches and Orbits

For planetary missions XNAV also would provide principally autonomy and operations cost benefits. Current radiometric methods in combination with optical methods near the destination have proven extremely successful for NASA and ESA planetary missions. XNAV would enable an autonomous cruise phase with periodic course corrections. For orbiters without precision insertion requirements, XNAV could provide primary navigation for all phases of the mission.

Asteroid missions and planetary landers could also benefit from XNAV during cruise but would still require radar and/or optical instruments for final insertion/capture and landing, if required.

Additionally, XNAV could be used to improve planetary ephemeris and gravity models, particularly in conjunction with parallel XNAV observations from Earth.

Outer Planets and Deep Solar System

Missions to the Solar System's outer planets and beyond appear to provide the highest potential payoff applications using XNAV concepts. The DSN's tracking capability normal to the line of sight from Earth is currently accurate to about 1 nanoradian, and thus, XNAV begins to become competitive in terms of accuracy *in the vicinity of the distance to Jupiter.* Jupiter's orbit averages just under 800,000,000 km from the sun, so the distance from Earth oscillates between around 700,000,000 km and around 900,000,000 km. Thus, at Jupiter, DSN tracking accuracy normal to the LOS (line-of-sight) to Earth is a little better than 1 km. Current estimates of XNAV performance are also in the neighborhood of 1 km or better depending on sources, detector, observation time and disturbance environment. It is currently believed that XNAV will provide comparable accuracy at Solar System scale distances. Detailed error budget analysis is underway to validate this. Thus, at distances well beyond Jupiter, XNAV accuracy is expected to increasingly dominate the DSN capability.

Similar autonomy and operations cost reduction arguments also apply to these missions, however, for some applications the improved navigation capability could be mission enabling. One such mission under consideration is a mission to investigate the Pioneer anomaly – an apparent deviation of Pioneer's anticipated trajectory from model predictions [14]. Navigation with XNAV would provide both significantly improved navigation accuracy, and an independent measurement from radiometric techniques.

Formation Flying and Relative Navigation

Formation flying and relative navigation with XNAV involves simultaneous observations of XNAV sources by two (or more) platforms to provide improved relative navigation performance through cancellation/elimination of common mode errors. This approach shows promise in a few different ways. Research has shown that it opens up the realm of potential sources to include bright, aperiodic sources which can not be easily modeled for independent use, but can provide excellent relative results by correlating observations from multiple spacecraft [21]. With inclusion of an accurately navigated (relative to the ECI or SSB frame) observatory platform and ability to communicate observations, this approach could be used to support navigation of individual spacecraft in a similar manner to that envisioned for X-ray pulsar based XNAV.

COMPARISON TO OTHER METHODS

The primary method of navigation for deep space missions is radiometric tracking using the Deep Space Network (DSN) [22]. The DSN provides range and range rate measurements along the line-of-sight (LOS) from Earth via time-of-flight and Doppler measurements from S and/or X and/or Ka band communications with progressively improved performance due to increasing frequency. Currently, range and range rate can be determined to better than 60 cm and 0.03 mm/s for a 60-second X band observation. With long observation times, several hours, ~50 nrad knowledge normal to the LOS without VLBI (very long baseline interferometry) can be achieved.

Table 2. DSN current and projected navigation accuracy (1-sigma) for various mission applications (all values in km; courtesy C. Naudet, JPL)

Mission Type/ Phase	Year Achieved			
	2005 (km)	**2010** (km)	**2020** (km)	**2030** (km)
Orbit control (OCA) on approach -Mars/ terrestrial bodies	2	2	1	0.5
OCA on approach, Outer planets	20	20	10	2
OCA in orbit	6.75	1.5	1	0.25
Orbit reconstruction, radial	0.33	0.0005	0.0001	< 0.0001
Landing on surface, terrestrial bodies*	21×5	7×7	1×1	0.1×0.1
Landing on surface, small bodies*	N/A	0.003 × 0.003	0.025 × 0.025	0.025 × 0.025
Position determination of landed vehicle	0.010	0.010	0.001	0.001
* landing error ellipse size				

The use of VLBI with two of the three primary DSN tracking stations (Goldstone in California, Madrid in Spain, and Canberra in Australia) along with temporally close observations of nearby quasars to reduce some error contributions, called Delta-DOR (differential one-way ranging), angular measurements with accuracies near 1 nrad can be achieved [11]. Table 2 presents current and projected navigation performance for the DSN at long ranges.

CHALLENGES AND PROGRAMMATIC DIRECTIONS

One might imagine that after nearly five decades of X-ray astronomy that both source knowledge and sensor system concepts would be mature enough that deep space systems could be assembled without further fundamental development. In fact, new radio millisecond pulsars are continually being discovered and not even 25% of those known have been adequately investigated for mere *detection* of X-ray millisecond pulsations. Once sources are found pulsing in X-rays there remains a vital task of observationally determining intrinsic noise levels, which limit timekeeping or pulsar-based navigation positional accuracy. The detector concepts are undergoing a major upheaval at this time. Although gas-based detectors are still gathering data, future designs center on solid state detectors combined variously with collimators, coded apertures or concentrators, yet few systems of these kinds have any flight experience at all. The first instances of the concentrator-plus-APD designs are only at proposal stages. Only a few cases of algorithm development for signal processing have been pursued to realistic levels such as Kalman filter simulations. In any actual implementation filters need to be designed to requirements, then tested and refined. Optical avionics systems are still evolving to incorporate new ideas even though optical astronomy has been pursued professionally for centuries. Since X-ray sources have only been studies since the 1960s, navigation system concepts based on them are necessarily in their infancy. For all these reasons X-ray navigation needs a stable level of investment to arrive at end products.

Perhaps the most useful point to make in closing is this: the first practical flight X-ray navigation systems are *not* likely to be simple change-outs with form, fit, and functional equivalence for existence avionics and navigation systems based on other physics such as GPS or star trackers. Rather they will probably arrive as special-purpose systems tailored to requirements of specific niches. The loads envisioned for the DSN system and its potential replacements and the accuracies achievable in the outer Solar System create one of those niches, one where X-ray methods may well be the path of choice. Even in this instance work will be needed to establish which of several X-ray approaches – or perhaps an approach melding X-rays with other technologies – provides the best system solution. A programmatic vehicle that provides funding to gather and analyze data and also for competitive exploration of candidate technologies would be a constructive next step.

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