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SPACECRAFT NAVIGATION USING X-RAY PULSARS

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XNAV CONCEPT

The term XNAV (***X***-ray ***nav***igation) is used to describe a variety of means of using celestial X-ray source observations for spacecraft attitude, position, velocity, and time determination. Several classes of source observations can be utilized for different aspects of the navigation process, as shown below.

- **Pulsar Source Observations**: time of arrival and phase (absolute navigation and time correction)
- **Aperiodic Source Observations**: noise intensity correlation across platforms (relative navigation and timing)
- **Bright Source Observations**: occultation by atmospheres or bodies (position and attitude determination)
- **Bright Source Observations**: X-ray band star camera (attitude determination)

For this paper the focus will be primarily on the exploitation of pulsar source observations as position, velocity, and time references.

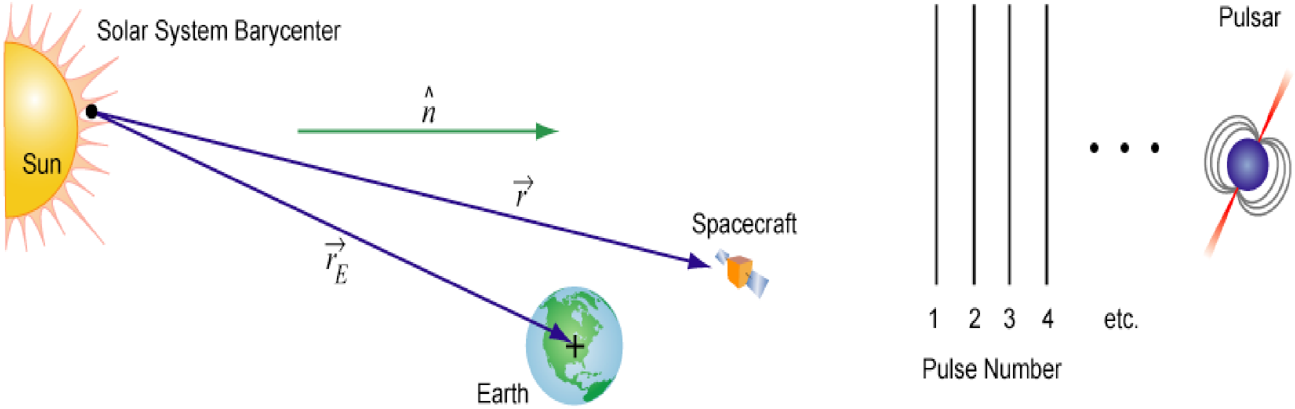

Fig. 1. X-ray Spacecraft Navigation Concept [1, 2]

Fig. 1 illustrates the basic XNAV concept. A neutron star emits highly regular pulses of X-ray photons as it rotates, and is referred to as a *pulsar*. An X-ray sensor on a spacecraft detects the photons emitted from the star. The individually time-tagged photon arrival events are processed to determine the time of arrival of the aggregate X-ray pulse (typically with a pulse period of 10^{-3} to 10^{-1} sec) for the pulsar of interest. Using these time-of-arrival (TOA) estimates and a model of the pulsar timing and ephemeris, range measurements to the spacecraft along the vector from the solar system barycenter (SSB) to the pulsar source can be generated. These range measurements can then be processed through a navigation filter to generate improved ephemeris estimates for the spacecraft.

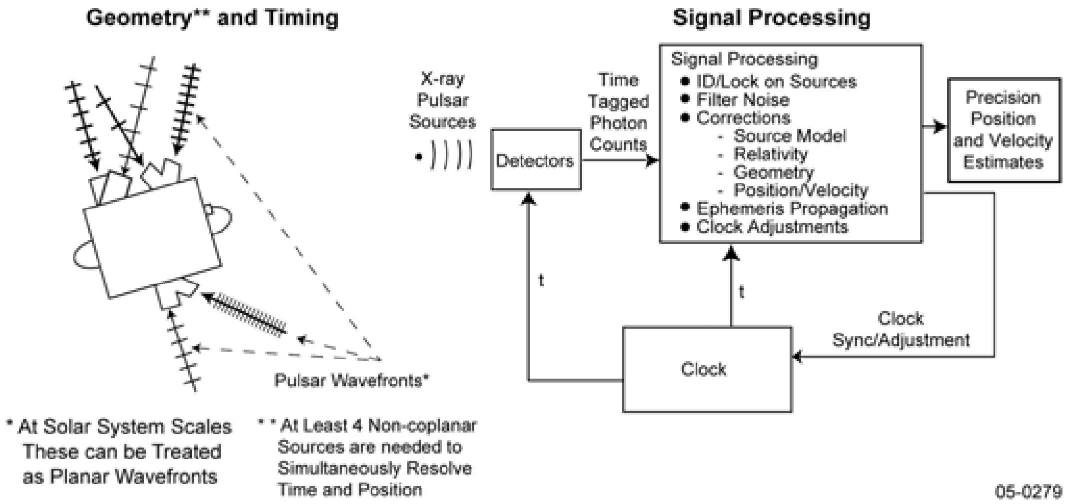

Fig. 2. Geometry, Timing, and Processing [3]

For missions in close proximity to a large body or on a definable interplanetary trajectory, a signal from a single pulsar can be used in conjunction with a model of the local gravitational field and a Kalman filter to produce these estimates [1, 4, 5]. When a minimum of three pulsar signals from geometrically diverse locations and a secondary timing reference (e.g. an ultra-stable local clock, or a ground-based transponder) are available, the position of the spacecraft can be determined directly. In principle, adding a fourth pulsar signal eliminates the need for a local time reference, although there may be some issues with recreating the pulse train over many thousands of seconds without a stable local clock. Fig. 2 provides a notional view of geometry and timing for a spacecraft with multiple XNAV detectors, and a high-level illustration of the basic processing concept.

The historical underpinnings of the concept go back to ancient observations of stars and planets, and their use in navigation, time-keeping and maintenance of accurate calendars. Technologies for exploiting celestial observations have improved tremendously, 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. Some of the key events include:

- 1967: Bell J. & Hewish A. successful discovery of radio pulsar [6]
- 1974: Downs, G.S. from NASA/JPL outlines concept, “Interplanetary Navigation Using Pulsating Radio Sources” [7]
- 1981: Chester & Butman also from NASA, “Navigation Using X-ray Pulsars” [8]
- 1988: Wallace K. from U.K. use of radio stars for navigational systems [9]
- 1988: The NRL Unconventional Stellar Aspect (USA) experiment proposed to DoD (Operated May 1999–Nov 2000)
  - USA experiment explicitly addressed attitude, position, timekeeping
  - Navigation studies detailed in SPIE Proceedings 1940, 105 (1993) [10]
  - Navigation analysis with University of Maryland Aerospace Engineering Department (Sheikh & Pines, 2000–2005) [1, 4, 5]
  - UMD/NRL Patent 7,197,381 on technique awarded March 2007
- 1996: Hanson, J.E. Stanford University Ph.D. dissertation “Principles of X-ray Navigation” [11]
- 2004: ESA Advanced Concepts Team ARIADNA pulsar navigation study [12]

- 2005: Sheikh, S.I. University of Maryland Ph.D. dissertation “The Use of Variable X-ray Sources for Spacecraft Navigation” [4]
- 2005–2006: Defense Advanced Research Projects Agency (DARPA) XNAV Phase I Program
  - Source studies, detector development, navigation algorithms
  - Demonstration system architecture (planned for ISS flight)
  - Did not proceed to Phase II flight demonstration development
- 2006–Present: NASA SBIR with Microcosm, Inc.
  - Studying potential NASA applications of X-ray navigation
  - In Phase II of program as of this writing

Many of the discovered pulsing radio sources also generate X-ray emissions, and fortunately, X-ray detectors are much better suited to spacecraft applications than large aperture radio telescopes. The most recent efforts have largely followed from Naval Research Laboratory (NRL) science and technology development efforts from the late 1980s which culminated in support from DARPA for an XNAV technology development program starting in 2005 and a NASA funded effort which started in 2006.

The following sections will provide further details on how XNAV works as well as discussion of potential applications and status of the technology development effort.

SOURCES

A large number of celestial X-ray sources have been detected. The key types are active galactic nuclei (AGN), supernova remnants (SNR), X-ray binaries, X-ray galaxy clusters, and stellar coronal along with numerous as yet unidentified sources. Fig. 3 provides a map based on the HEAO A-1 observations

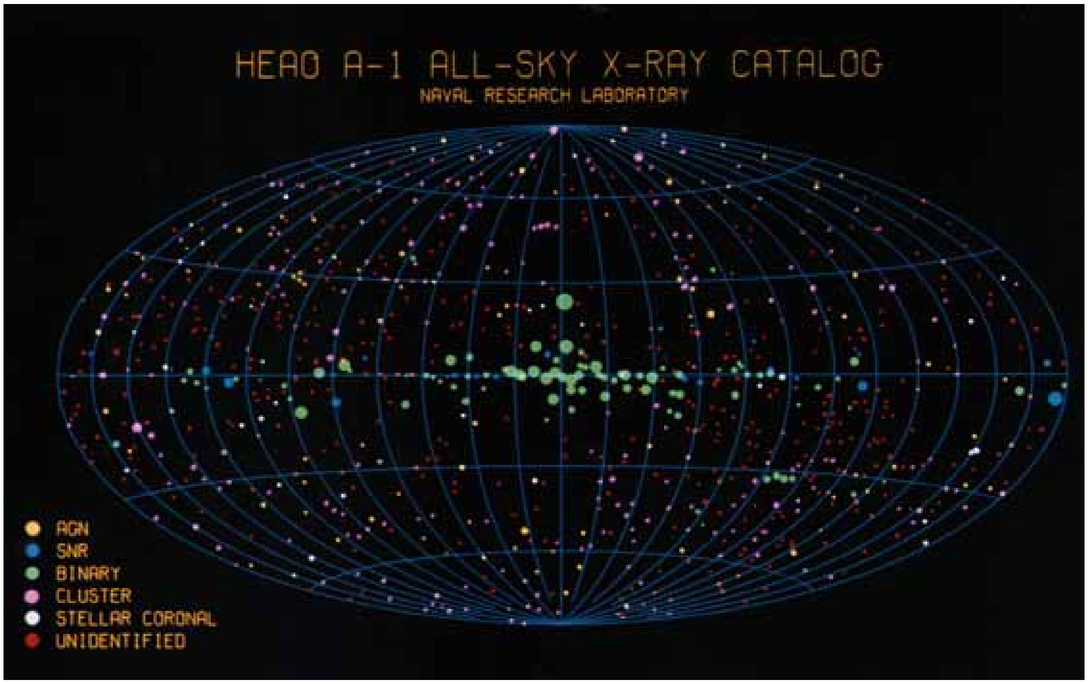

Fig. 3. HEAO A-1 All-Sky X-ray Catalog [2, 13]

Although the use of unstable, highly variable X-ray sources is currently being explored, the fundamental sources for XNAV technology development has been focused upon using millisecond pulsars (MSPs), which typically have stable periods of on the order of 10 milliseconds. MSPs are rapidly rotating neutron stars (NS) with magnetic poles that are not aligned with their rotation axes. X-rays, Gamma-rays and radio beams are swept out along the magnetic poles or from hot thermal surface regions as these stars rotate, and observers who are not aligned with the rotation axis view periodic pulses of these electromagnetic emissions. Fig. 4 provides a conceptual illustration of a pulsar.

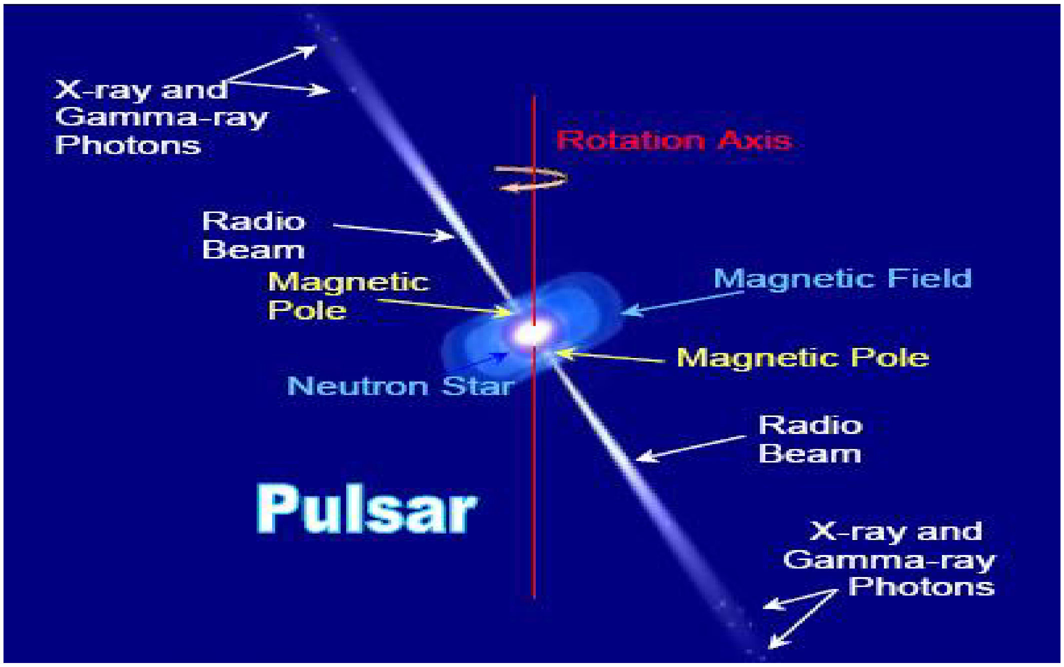

Fig. 4. Illustration of Pulsar, its Neutron Star, Rotation, and Magnetic Axes [4]

Many X-ray sources are found in binary systems and a majority of the detected sources are located in our Milky Way galaxy. Those in our galaxy tend to be clustered near the galactic plane; however a sufficient number of sources are distributed off-plane. Fig. 5 provides a map showing the locations in galactic coordinates of these types of sources: high-mass X-ray binaries (HMXB), low-mass X-ray binaries (LMXB), and Neutron Stars (NS) that are candidates of the XNAV concept.

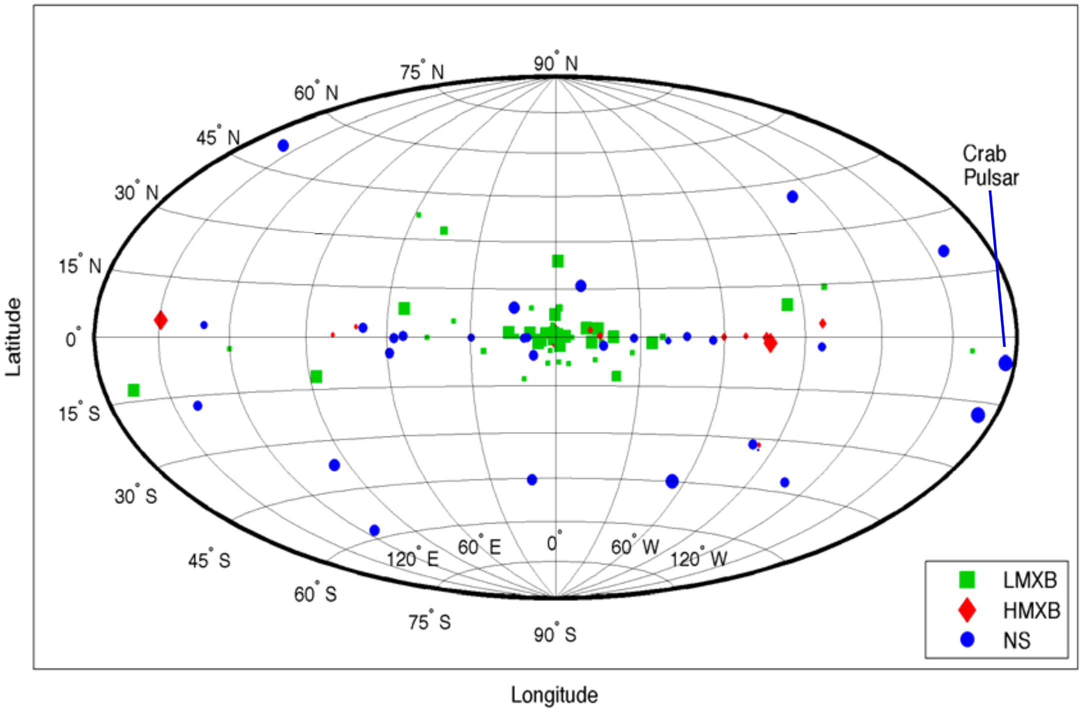

Fig. 5. Galactic Distribution of X-ray Sources [4]

The classifications of pulsars can be further subdivided into accretion-powered pulsars and rotation-powered pulsars. Accretion powered pulsars generate X-rays due to the gravitational acceleration of the material from a disk of orbiting material (known as an accretion disk) or from a neutron star or black hole that has a companion in a binary system. This accreting material can reach relativistic velocities as it approaches the surface of the neutron star, or black hole. 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/donor's orbit [14, 15]. The better timing sources are the rotation powered MSPs — by far the brightest of these sources is the Crab Pulsar. Unfortunately, young bright sources like the Crab tend to have relatively poor timing stability, whereas the best timers tend to be orders of magnitude dimmer. These MSPs have strong magnetic fields (~10^{12} G), and are believed to generate their X-rays via generation of electron-positron pairs which produce X-ray band synchrotron radiation as they accelerate due to the rapid rotation of the body fixed magnetic field. This process dissipates energy and causes the pulsar to spin down over thousands of years from periods of 10s of milliseconds to ~10 seconds, at which point the pulsar may turn off because the dissipative processes that generated the X-rays no longer operate [14, 16].

A subset of these rotation powered pulsars is known as *recycled* MSPs. These are believed to start out as normal rotation powered pulsars in binary systems with a normal star partner. As the partner ages, if its orbit is close enough, it expands and begins to provide new material to accrete and in the process spins the pulsar back up as it accumulates the angular momentum from the influx of material. When the accretion process ends, the resulting pulsar typically has a rotation period of 1 to 15 milliseconds and a significantly reduced magnetic field (~10^{8-9} G). These recycled MSPs are highly stable rotors with much lower dissipation rates than normal MSPs, and thus, lifetimes of millions of years. This lifecycle is illustrated in Fig. 6 [14, 16].

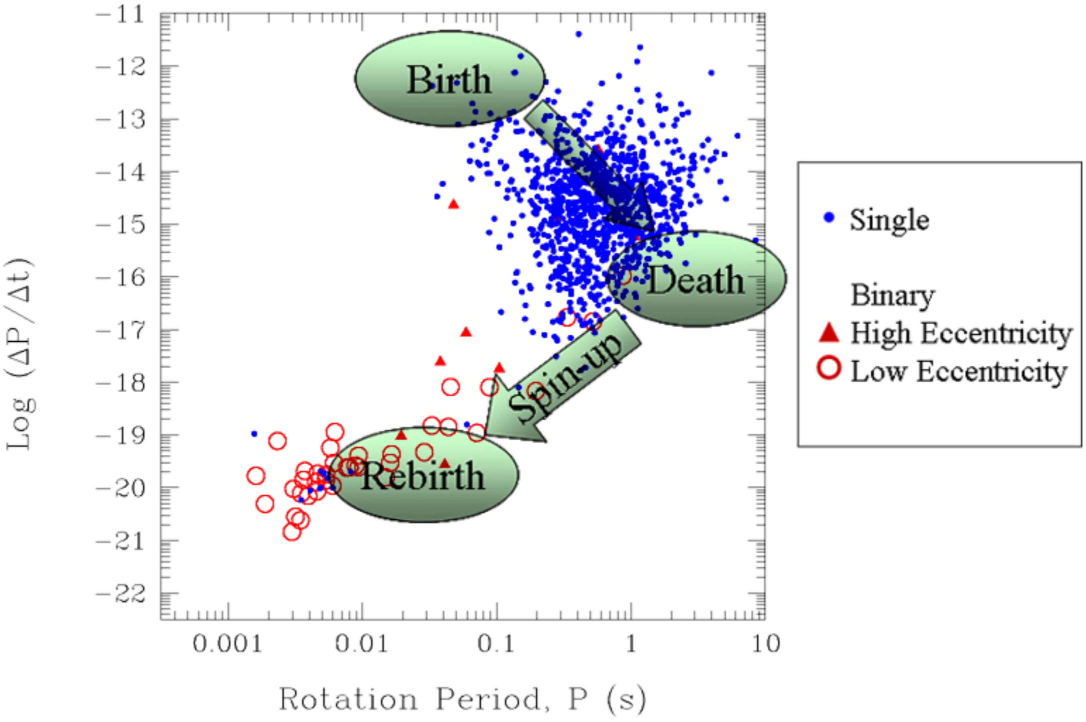

Fig. 6. Recycled MSP Lifecycle [2]

The most stable of these X-ray sources when modeled have timing statistics comparable to those of good atomic clocks. Fig. 7 shows a comparison of PSRs B1937+21 and B1855+09 with several atomic clocks [17]. A unique capability that XNAV 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 [17, 18]. Detection of these sources over long durations could reduce onboard clock errors, or at least stabilize any long-term clock drifts.

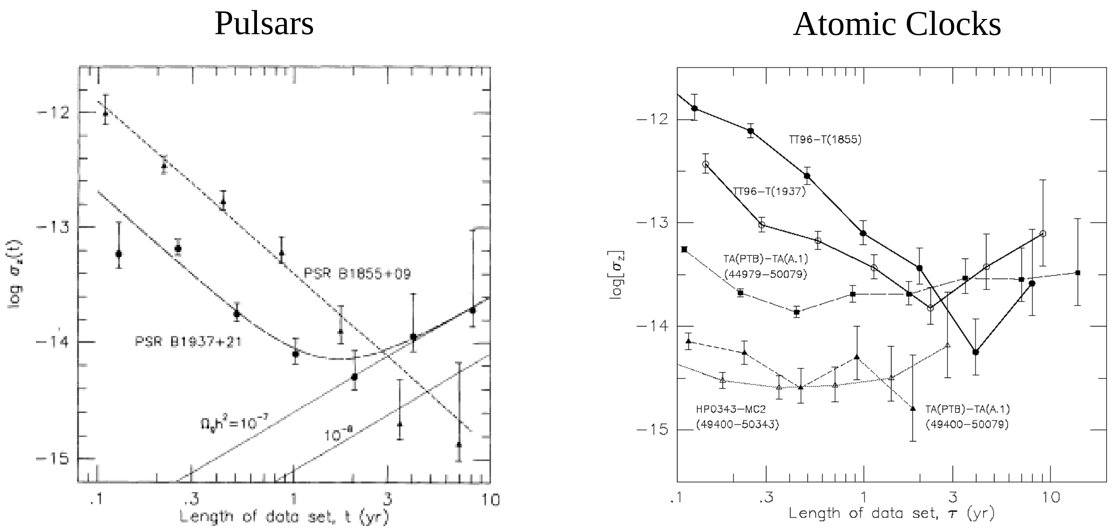

Fig. 7. Comparison Pulsars and Atomic Clocks [17, 18]

Unfortunately, many of the pulsars that provide the most stable long-term timing models tend to be less bright, and visa-versa, the brightest sources tend to be less stable. Table 1 provides data for several candidate sources.

Table 1. Pulsar Characteristics [3]

Source	Galactic Lon (deg)	Galactic Lat (deg)	X-ray Flux 2-10 keV (ph/s/cm^2)	Pulsed Fraction	Period (ms)	RA Error (marcsec)	DEC Error (marcsec)
B1937+21	57.5	–0.290	4.99 x 10^{-5}	0.86	1.56	0.012	0.14
J0218+4232	139.5	–17.53	6.65 x 10^{-5}	0.73	2.32	150	100
B0540-69	279.7	–31.5	5.15 x 10^{-3}	0.67	50.4	450	500
B1509-59	320.3	–1.16	1.62 x 10^{-2}	0.65	150	1350	1000
B1821-24	7.80	–5.58	1.93 x 10^{-4}	0.98	3.05	0.90	12
J1814-338	358.75	–7.59	9.97 x 10^{-2}	0.12	3.18	1*	1*
B0531+21	184.6	–5.78	1.54 x 10^{0}	0.70	33.4	75	60
J1808-369	355.39	–8.15	3.29 x 10^{-1}	0.41	2.49	1*	1*

***Actual data for these parameters was not available**

ERROR SOURCES

The creation of an X-ray navigation instrument and related infrastructure development is a balance of achieving the desired navigation solution accuracy and bandwidth while minimizing the size of detector. As with any new technology, the design space for XNAV instruments is large. In this case, the performance is going to be affected by such parameters as detector area and efficiency, allowable observation time (the inverse of required measurement bandwidth), source strength and pulse temporal profile, and local clock noise, just to name a few. In addition, the character of the optimal XNAV instrument will vary with the mission being considered. The difficulty becomes one of identifying the key design drivers and selecting the best design to achieve the desired performance. To aid in this process, an X-ray navigation noise tree has been created. The purpose of this tool is to provide an estimate of XNAV performance for a particular mission and to provide insight into which parameters drive the system performance, all based on simple rules of thumb and analytical expressions. Table 2 summarizes the key noise sources identified thus far.

Table 2. Summary of X-ray Navigation Noise Tree [3]

Source	Parameters
Source Shot Noise (Periodic Signal)	s: Source strength A: Detector area Δt: Observation time η: Detector efficiency
Source Shot Noise (Steady Signal)	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	$n(f)$: 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	$\Delta\beta$: Source parameter error
Pulse Period Uncertainty	ΔT: Source period error
Source Phase Jitter	$\Delta\psi(\tau)$ Source phase error

For all missions, one critical source of error in the navigation solution is the ability to measure the TOA of the pulse train from each source while contending with shot noise inherent in the faint signal, the diffuse X-ray background, cosmic ray events and detector back ground. The signal-to-noise ratio of the measurement (and hence the accuracy of the TOA estimate) can 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. The problem of predicting the noise in the TOA measurement for a particular design and set of X-ray pulsars was addressed in [19]. It was shown that the TOA measurement accuracy is a function of the area-time product of the detector (the area of the detector and the duration of the observation), the source and background fluxes, and the shape of the pulse itself. Analytical expressions were given that can be used to predict the magnitude of this noise source. Obviously, pulsars with sharp, narrow features will be better beacons than those with broad, ill-defined pulse shapes.

Once the TOAs from three or more pulsars (or four pulsars if the on-board clock is not synchronized to some universal time) have been measured, they can be assembled into a position solution, in a manner similar to that employed by Global Navigation Satellite Systems (GNSS). Uncertainty in the knowledge of the direction to a given pulsar will introduce another error in the position solution, which increases with distance from the origin of the XNAV frame-of-reference [20].

NAVIGATION PROCESSING

The XNAV navigation processing can be separated into the three general areas of *attitude determination*, *position and velocity determination*, and *time correction*. The detector types may be different for each of these solutions, 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 were first proposed using techniques similar to optical star cameras [11]. 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 achievable.

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.

The technique of source *occultation* can be implemented, 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 [10]. As with optical sources and processing techniques, 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 [1, 4]. 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 [21].

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. Many published 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, the goal of the full three-dimensional position determination is to compute the three-axis location 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 [22]. 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 [4, 22]. However, once the cycle ambiguities are resolved, continuous absolute position solutions would be possible. This concept is reminiscent of the similar concepts used to determine absolute navigation using the Earth-based GNSS, or similar trilateration techniques. Although similarities to GNSS techniques 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.

A less complex concept to implement, and one that is appropriate for many missions, would be a single detector technique that provides corrections to estimated range 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 range information with estimated position from an orbit propagator produces corrections to the position and velocity solution, which maintains accurate solutions over time. As presented in the XNAV Concept Section, Fig. 1 shows a conceptual illustration 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 Cramer-Rao lower bound achievable performance [23].

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 [23, 24]. This method can estimate and lock onto the phase and frequency of a source based upon the known pulse timing model. 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 [23]. Digital phase-locked loops can be implemented to insure proper tracking of these signals.

Relative navigation between vehicles has also been explored using variable X-ray sources [25–27]. This application determines a vehicle's location specifically relative to another cooperating vehicle, in order to coordinate observations or communications, as in Fig. 8. In these techniques, bright sources are desired so that high photon flux rates are provided, which reduces the observation durations. Any type of signal variability is usable, thus many other sources other than the highly stable periodic sources can be utilized.

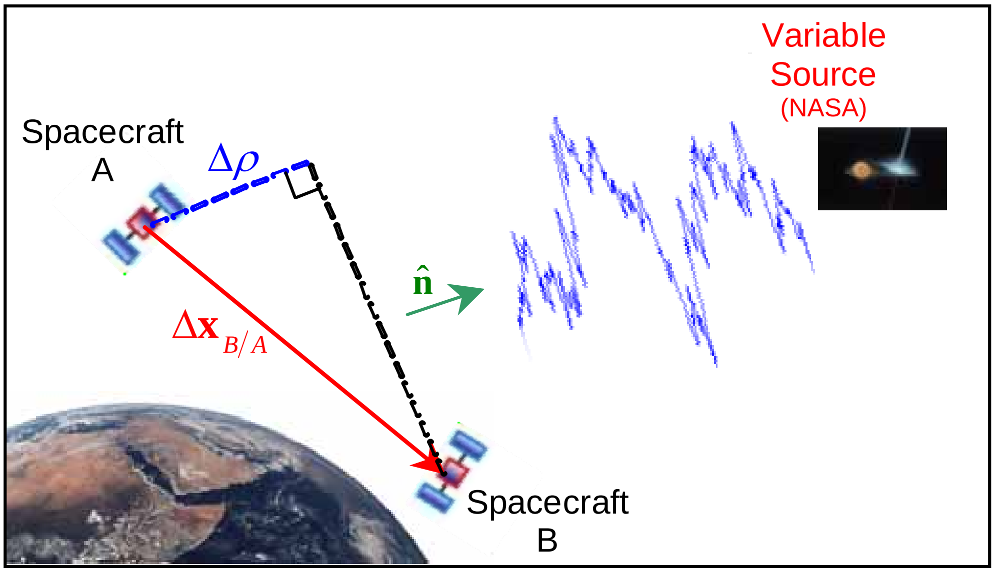

Fig. 8. Relative Navigation Between Two Spacecraft that Observe the Same Variable Celestial Source [25]

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 [4, 5]. 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 [26]. For those spacecraft using NASA Deep Space Network (DSN) tracking, the additional range and range-rate measurements from this Earth-based communication contact would assist with overall accuracy improvements [3, 20]. Furthermore, for deep space missions, the DSN tracking information could be blended with the time-of-arrival information from a pulsar whose line of sight is nearly perpendicular to the line-of-sight from the Earth to the spacecraft being tracked. The XNAV signals are used to augment the extremely accurate DSN position and velocity measurements along one direction with an XNAV measurement that provides information in a direction where DSN accuracy is inherently poorer.

XNAV PERFORMANCE

Previously, the representative accuracies of XNAV for all possible combinations of three pulsars from the given set of eight in Table 3 and the assumed detector and observation characteristics of Table 4 were determined for positions in the solar system from 1 AU to 100 AU in [20]. This analysis did not include the increased performance predicted by [19] that comes about by considering the impact of the pulsar shape on TOA measurement accuracy.

To review, it was shown that the inclusion of the pulse shape improves the accuracy of the TOA measurement: $E\left[t_0^2\right] = \Gamma_s^2 \frac{T}{A\Delta ts} + \Gamma_b^2 \frac{T}{A\Delta ts}\frac{b}{s}$, where A is the detector area, T is the pulse period, Δt is the length of the observation, s is the source strength, and b is the background rate.

Γ_s and Γ_b are called the “Shape Factors” and are related only to the shape of the pulsation as follows:

$$\Gamma_s^2 = \frac{\int f(t,t_0)\left(\frac{\partial f(t,t_0)}{\partial t_0}\right)^2 dt}{\left\{\int\left(\frac{\partial f(t,t_0)}{\partial t_0}\right)^2 dt\right\}^2}, \qquad \text{and} \qquad \Gamma_b^2 = \frac{1}{\int\left(\frac{\partial f(t,t_0)}{\partial t_0}\right)^2 dt}$$

Pulse profile data for B1937+21, J1813-338, and B0531+21 were used to improve the performance prediction. The shape factors for these pulsars are given in Table 3. To be conservative, the pulse shape of pulsar J1813-338 was assumed to be sinusoidal.

Table 3. Pulsars Available for X-ray Navigation [3]

Source	Period (msec)	Intensity (ph·sec^{-1}·cm^{-2})	RA Error (arcsec)	DEC Error (arcsec)	Γ_s	Γ_b	Source Shape Model
B1937+21	1.56	$4.99\cdot10^{-5}$	$1.00\cdot10^{-5}$	$1.00\cdot10^{-4}$	$7.41\cdot10^{-4}$	$3.29\cdot10^{-4}$	Source Data
J0218+4232	2.32	$6.65\cdot10^{-5}$	$1.00\cdot10^{-5}$	$1.00\cdot10^{-4}$	$1.18\cdot10^{-4}$	$1.18\cdot10^{-4}$	Sine
B0540-69	50.4	$5.15\cdot10^{-3}$	$1.00\cdot10^{-5}$	$1.00\cdot10^{-4}$	$2.55\cdot10^{-3}$	$2.55\cdot10^{-3}$	Sine
B1509-58	150	$1.62\cdot10^{-2}$	$1.00\cdot10^{-5}$	$1.00\cdot10^{-4}$	$7.61\cdot10^{-3}$	$7.61\cdot10^{-3}$	Sine
B1821-24	3.05	$1.93\cdot10^{-4}$	$1.00\cdot10^{-5}$	$1.00\cdot10^{-4}$	$1.90\cdot10^{-3}$	$1.10\cdot10^{-3}$	Source Data
J1813-338	3.18	$9.97\cdot10^{-2}$	$1.00\cdot10^{-5}$	$1.00\cdot10^{-4}$	$1.27\cdot10^{-2}$	$1.27\cdot10^{-2}$	Sine
B0531+21	33.4	$1.54\cdot10^{0}$	$1.00\cdot10^{-5}$	$1.00\cdot10^{-4}$	$7.70\cdot10^{-3}$	$3.30\cdot10^{-3}$	Source Data
J1808-369	2.49	$3.29\cdot10^{-1}$	$1.00\cdot10^{-5}$	$1.00\cdot10^{-4}$	$1.26\cdot10^{-4}$	$1.268\cdot10^{-4}$	Sine

As reported in the literature, the poor position knowledge of B0531+21 will result in a significant increase in position error with increasing distance from the sun. If the position knowledge of all pulsars on this list can be improved to match that of B1937+21 (10 μarcsec in right ascension and 100 μarcsec in declination), the XNAV position solution can be used to enhance the DSN solution for missions at or beyond the orbit of Jupiter, as shown in Fig. 9. This plot also provides the representative accuracy of the DSN spacecraft position performance based upon the 1 nrad angular accuracy [28]. It is noted that with this simplified analysis XNAV offers the possibility of improved performance relative to DSN at about 5.5 AU. At 100 AU, XNAV offers 5 km position uncertainty as compared to 15 km for DSN. A further improved solution may be a hybrid, in which the DSN signal is augmented with XNAV information normal to the DSN line-of-sight. The set (B1937+21, B1813-338 and B0531+21) provides the best solution in most cases, but B1821-24 can be exchanged with B1813-338 with a negligible impact on performance. This suggests that when a better model of the B1813-338 pulse profile is used to predict TOA arrival measurement performance, the predicted XNAV performance will improve.

Table 4. Input Parameters [3]

Parameter	**Magnitude**	
Detector Area	1	m^2
Integration Time	100,000	sec
Detector Efficiency	0.95	
Detector Background Rate	0.1	ph/s
Net Cosmic Background	5	ph/s/m^2
Clock Error	0.1	μsec
Diffuse X-ray Background	0.1	ph/s/m^2

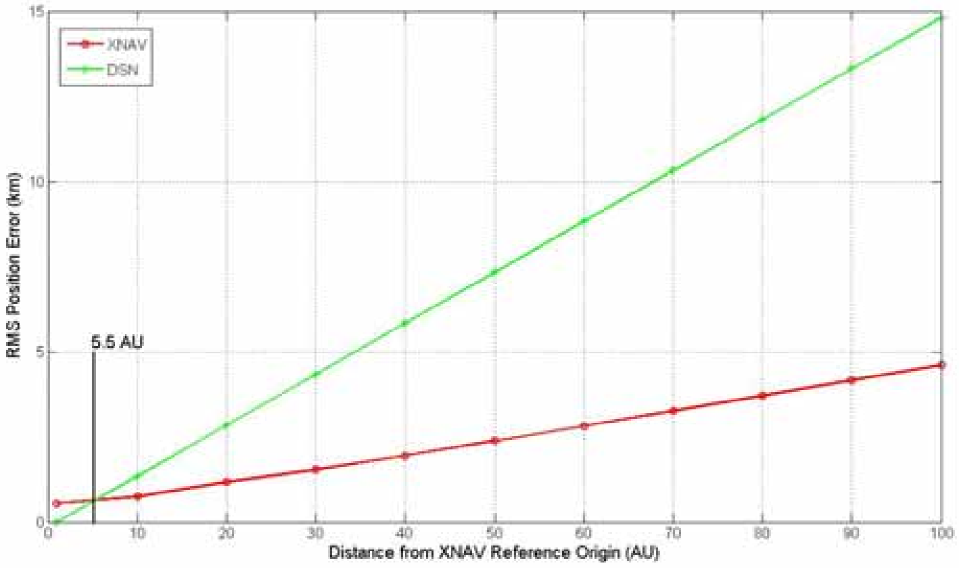

Fig. 9. Position Solution Errors as a Function of Spacecraft Detector Distance from Solar System Barycenter for DSN and XNAV, Using Projected Future Position K nowledge [3]

XNAV AND THE DSN

This section provides a brief overview of DSN capabilities and plans, and begins to provide comparisons of capabilities and a discussion of potential synergies. Table 5 outlines the existing and projected DSN navigation accuracy capabilities for a variety of deep space missions through 2030. For DSN navigation to achieve the goals outlined in Table 5, a combination of incremental improvements and new technology investments will be required. As the XNAV research and development (R&D) program moves forward, it is likely to influence the future direction of DSN tracking R&D investments by enabling autonomous navigation for some missions via XNAV, and providing additional data for improvement of DSN measurements normal to the LOS to the spacecraft

Table 5. DSN Current and Projected Navigation Accuracy (Km, 1-sigma) [20]
Level 1 Long-range requirements (courtesy C. Naudet, JPL)

Mission Type/ Phase	**Year Achieved**			
	2005	**2010**	**2020**	**2030**
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				

Comparisons with the DSN. As described herein, XNAV and the DSN present very different approaches to the deep space navigation problem. They use very different types of data, and except for clock and reference frame errors, they share few common error sources. In addition, XNAV has been pursued as a fundamentally onboard and largely autonomous capability, while DSN navigation is primarily performed via ground based measurements and computations. The performance of DSN degrades with increasing distance from Earth, due to the single LOS measurement from ground-based tracking systems to the spacecraft. The angular resolution of the three-dimensional position solution is in the neighborhood of 1 or 2 nrad [28].

That said, there are some commonalities. They both require specialized and fairly expensive equipment; in the case of the DSN it is specialized radios and clocks/oscillators with much higher stability than would be required for communication only, for XNAV accurate clocks and specialized X-ray detectors with highly accurate photon arrival timing are needed. Both methods also require high precision force and disturbance models for accurate integration of the equations of motion in their navigation filters.

The DSN capability is mature, but has been steadily improving in performance through increases in communications frequencies, better clocks and numerous technological, algorithmic and procedural improvements. Further performance improvements are anticipated as large communications arrays and laser communication solutions are introduced. While XNAV is still a nascent technology, requiring further work in the characterization of sources and the development of navigation algorithms, like many emerging technologies, it offers the potential of a leap in navigation performance for a number of potential applications, particularly when added to the current and anticipated DSN services.

Synergy with the DSN. For missions where relative autonomy is desired and for missions to the outer planets or beyond, a combination of DSN and XNAV should provide the best results. The DSN providing highly accurate range and range rate along the LOS as well as proven clock and time transfer technologies, and XNAV providing good measurements normal to the LOS. Periodic and comparatively brief DSN communications would provide source model and clock updates and return of mission data and XNAV observation data. The relatively time-consuming and complex delta-DOR measurements could largely be eliminated while improving navigation accuracy.

Whether the navigation calculations are performed onboard or on the ground, similar navigation filtering algorithms will be implemented to optimally estimate the navigation states using both the DSN and XNAV measurement data. Development of these filters and associated performance simulations and performance estimates is an important next step in the process of developing and evaluating XNAV.

APPLICATIONS

Several scenarios for which XNAV would be beneficial have been identified [3]. Preliminary assessments have been conducted. However, further work is necessary to determine which scenarios and concepts of operations will be most viable and what levels of performance can be expected.

Fig. 10 shows a wide range of potential applications for XNAV from Earth-orbital to the Moon and Mars, to the outer planets, and beyond.

Fig. 10. XNAV Promises to Provide Primary or Backup Navigation for a Wide Range of Space Missions from Earth Orbit to Beyond Jupiter

Earth-orbital Missions. For Earth-orbiting spacecraft that are not within range of strong GNSS signals, such as GEO or HEO spacecraft, XNAV can provide a fully autonomous navigation solution with coarse to moderately accurate solutions. The XNAV program as proposed by DARPA was intended to provide backup navigation for GNSS for some mission applications and primary navigation for systems that could not rely on GNSS. X-ray signals from pulsars are not susceptible to typical jamming techniques which can interrupt or deny GNSS signals.

Earth-Sun Lagrangian Point Missions/Formation Flying Missions. This class of mission includes Earth-Sun Lagrangian point missions, Earth-trailing missions and others in the neighborhood of Earth's orbit but well beyond the Moon. Initial mission candidates have focused on Earth-Sun L2 halo orbits (E-S L2), but are generally applicable to the broader class. E-S L2 is the point along the Earth-Sun line, opposite the Sun, where the gravitational influence of the Earth and Sun balance such that objects can remain in stable nearby orbits. It is ~1,500,000 km from Earth, and is not entirely stable due to the variable influence of the moon.

For these missions, the principal benefit would be from increased autonomy and reduced reliance and demand on the DSN infrastructure. The capability of the DSN is sufficient to support these missions. However, as these types of missions proliferate, and with high-performance formation based missions under study, autonomous navigation and guidance to conduct station-keeping and maintain knowledge of vehicle locations and trajectories, is likely to provide significant benefits. The potential of XNAV to support autonomous navigation and guidance for loose formations is of particular interest due to the operational demands and complexity of managing them from the ground.

Mars and Moon. This scenario focuses on navigation at Mars and at the Moon as well as trips between Earth and Mars and between Earth and the Moon. These are explored as a special application due to the numerous missions and mission concepts under development.

As with the Lagrangian point missions, the DSN capability and performance for this class of missions is demonstrably more than adequate. Two scenarios have identified the XNAV benefits for this mission. The first is guidance and navigation to and from the Moon and Mars. The benefits and operations would be similar to those of the Lagrangian point missions — namely, increased autonomy and reduced demand for DSN resources. DSN and navigation analysis resources could be concentrated on terminal guidance and orbit insertion.

In future human exploration of Mars and the Moon, where scenarios involve frequent human and cargo missions, XNAV could provide an autonomous navigation solution that eliminates this utilitarian function entirely from the DSN operations.

Very Deep Space. As previously mentioned, XNAV really comes into its own when coupled with missions beyond the orbit of Jupiter — Very Deep Space. XNAV or a DSN/XNAV hybrid could be the enabling navigation technology for several missions, including: [29, 30]

- Pioneer Anomaly Investigation
- Solar System Bow Shock/Heliopause
- 550 AU Mission
- Interstellar Probe

Fig. 11 shows the distance scale of the local interstellar neighborhood. XNAV can provide significant improvement over DSN-only navigation at distances beyond Jupiter. In addition, the very long mission duration of very deep space missions calls for a higher degree of spacecraft autonomy, which XNAV also provides. Most very deep space missions proposed to date with any level of depth and incorporating existing technology go out to distances of several hundred AU. A mission to investigate the Pioneer gravitational anomaly has been proposed, which would require accurate tracking of the spacecraft to distances far beyond Jupiter, measuring the acceleration of the spacecraft very precisely. XNAV could assist in providing more accurate navigation data than can be obtained from DSN alone, and provide real time solutions onboard the vehicle.

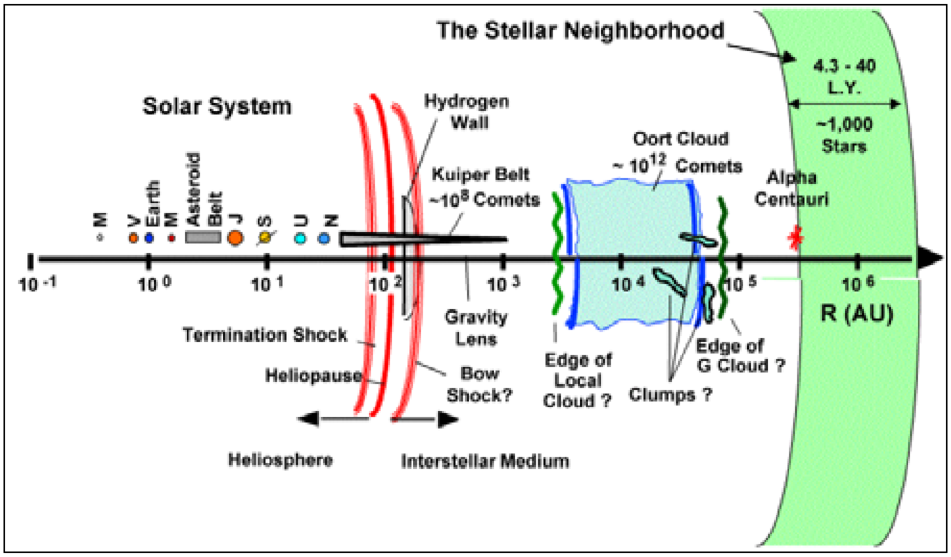

Fig. 11. The Local Interstellar Neighborhood, Shown on a Logarithmic Scale from the Sun to 10^6 AU [29]

The Interstellar Probe mission would travel to a distance of about 400 AU from the Sun, exploring the Kuiper Belt, the boundaries of the heliosphere, and nearby interstellar medium [29]. The 550 AU mission to study the gravitational lens effect of the Sun is indicated in the figure ("Gravity Lens" label) [30]. Both of these missions will need accurate navigation data and XNAV can provide this capability continuously, reliably, and at relatively low cost compared to the cost of mission operations over the very long mission duration required to attain these distances. The Interstellar Probe mission goal is to reach 200 AU in 15 years, and eventually reach 400 AU by the end of mission operations. The 550 AU mission will take even longer.

For these very deep space missions beyond Jupiter, the promise of kilometer-level (or better) accuracy in all directions at these great distances would be enhancing for most missions and enabling for some. The line-of-sight range from the DSN would still be highly accurate, but the normal component accuracy from delta-DOR degrades linearly with range from Earth. For the 550 AU mission, XNAV could provide a factor of 100 to 1,000 improvement in position knowledge. For missions at Jovian distances the improvements would be much more modest, however, it may simplify navigation operations by reducing reliance on DSN or delta-DOR.

Depending on mission requirements including mass, power and cost constraints, XNAV could be conducted with serial observations from a single detector, or via simultaneous observations from multiple detectors. The very long duration of the cruise phase for interplanetary missions, especially very deep space missions, allows extended observation of X-ray pulsars to achieve the highest accuracy available with XNAV. The situation is much more benign and favorable to extended pulsar observations than the Earth orbital scenario with a rapidly changing viewing geometry of available pulsars.

XNAV DEVELOPMENT STATUS

XNAV R&D is still in its early stages. Considerably more work needs to be completed in several areas before it will be sufficiently mature for operational use. The list below identifies some topics where continued development would benefit the XNAV concept.

- **Source Models** — Long-term observations of key sources along with development of associated analytical models is needed. This may ultimately require a new X-ray timing and astrophysics mission.
- **Detectors** — Detector technology is sufficiently mature to support a demonstration or observation focused mission, but considerable additional R&D would be desirable to reduce size, weight and power in order for an XNAV instrument to be practical for a broad range of missions.
- **Algorithms** — Algorithm and signal processing needs are well understood, and have been demonstrated in simulation. The implementation for a particular demonstration mission, however, would require considerable additional development effort to accommodate mission specific hardware and operations.
- **Flight Demonstration** — Plan are continuing to find support for a flight demonstrations, including investigating an opportunity to share the ride of a related science mission if one is selected for funding.

The principal current work on the program is a technology development focused project funded by NASA, and ongoing related science focused work on detector development and source characterization at NASA and the Naval Research Laboratory.

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