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XNAV for Deep Space Navigation

P. Graven[*], J. Collins[*], S. Sheikh[**], J. Hanson[†], P. Ray[‡], K. Wood[‡]

[*]Microcosm, Inc.; [**]ASTER Labs Inc.; [†]CrossTrac Engineering,
[‡]Naval Research Laboratory

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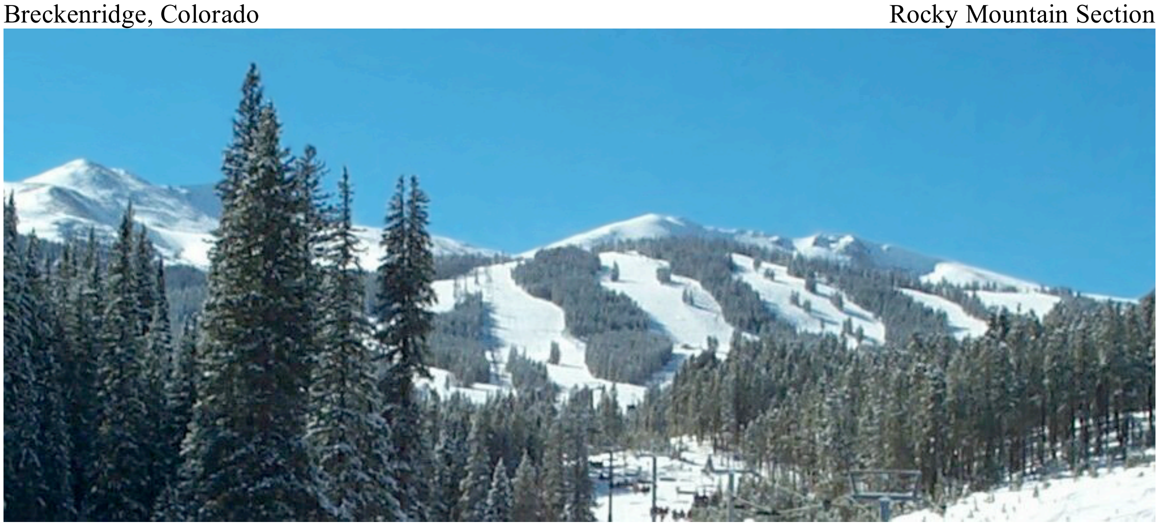

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XNAV FOR DEEP SPACE NAVIGATION

P. Graven[*], J. Collins[*], S. Sheikh[**], J. Hanson[†], P. Ray[‡], K. Wood[‡]
[*]Microcosm, Inc.; [**]ASTER Labs; [†]CrossTrac Engineering,
[‡]Naval Research Laboratory

The concept of utilizing pulsars for spacecraft navigation has been in development since the discovery of these rapidly rotating neutron stars in the 1960's [1]. The Jet Propulsion Laboratory (JPL) conducted studies in the 70's and 80's proposing the use of the pulsar signals as navigation beacons in both the radio and X-ray bands of the electromagnetic spectrum [2, 3]. Since the 80's, the Naval Research Laboratory (NRL) has researched X-ray sources and developed detectors providing the foundations for X-ray source spacecraft navigation development. Several important dissertation researches were pursued within the 90's and 00's [4-7]. During the last several years the Defense Advanced Research Projects Agency (DARPA) and NASA have supported more in depth development focused on the preparation of an operating instrument for an eventual space flight demonstration. Preliminary results suggest that XNAV becomes competitive with current radiometric methods, in terms of navigation performance, at ~10^9 km – near the range to Jupiter when Jupiter and Earth are in opposition. As range from Earth grows from there, XNAV becomes an increasingly attractive alternative, and may be mission enabling for very deep space applications such as investigation of the Pioneer Anomaly [8], as well as unique orbit applications such as the Earth-Sun Libration (L2) point.

This paper provides an overview of the basic principles of X-ray pulsar source based navigation and timing (XNAV), followed by a discussion of elements of a navigation error budget focused specifically on deep space applications. Several potential NASA applications are identified, including Earth-Sun L2, outer planetary, and very deep space missions. Finally, some preliminary comparisons with Deep Space Network (DSN) based radiometric methods are presented.

INTRODUCTION

The novel technologies of the XNAV concept hold great promise for NASA and the developing user community because it is an enabling technology for *fully autonomous planetary orbiting and interplanetary navigation.* Alternatively, it could provide significant future mission operating enhancements as an adjunct to the DSN and ground based navigation methods. XNAV has the potential to greatly enhance space system autonomy, while helping reduce DSN operations and infrastructure costs. The baseline XNAV approach uses observations of the X-ray emissions of highly stable, rotation powered, millisecond pulsars as a kind of *natural celestial beacon*. 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 through the use of onboard atomic clocks or the monitoring of the long-term stability of several well-characterized pulsars. In addition, brighter, less stable X-ray sources may have utility as well, particularly in applications that require only relative navigation information.

There are numerous potential benefits from this technology. A navigation/timing system utilizing X-ray pulsars would be available anywhere that cosmic X-ray sources can be observed, from Low Earth Orbits (LEO) 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 Global Positioning System (GPS) and 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 (LOS) from Earth to the spacecraft. The detectors are highly resistant to blinding or contaminating events. Detectors used within the XNAV system are intrinsically radiation hard due to their design for recording photon events.

In a Phase I Small Business Innovative Research (SBIR) program carried out in 2006, a Microcosm, Inc. led team investigated achievable XNAV accuracy for various interplanetary applications, developed a preliminary detailed source catalogue, constructed an initial XNAV error budget, and identified potential implementation options for XNAV. The Phase II program which began in March, 2007 is developing a detailed XNAV simulation to evaluate XNAV performance for specific missions of interest, and plans to develop a flight experiment software package that could be flown on an XNAV demonstration mission.

Recent developments in solid state X-ray sensor technology, combined with an extensive characterization of the X-ray pulsar population using several recent scientific spacecraft (RXTE, USA, ASCA, Chandra, ROSAT XMM/Newton, and others), have provided the fundamental building blocks for such an XNAV system, and their culmination provides a unique opportunity for developing a new navigation and timing system for spacecraft.

X-ray Navigation Background

Highly stable pulsars can be viewed as *nature's celestial lighthouses*. They provide an oscillating signal with long-term stability comparable to current state of the art atomic clocks. These signals can be utilized to help resolve time and position in a fashion similar to GPS. Figure 1 shows a typical pulsar with emission jets that radiate in the high energy spectrum. Challenging issues exist with these sources, including the fact that the signals are faint, noisy, and they are not tagged with time or ECI position of origin. These factors can be overcome via source timing models, adequate collection time, adequate collection area, and Kalman-Filter-based signal processing. A conceptual illustration of the XNAV measurement and solution process is provided in Figure 2.

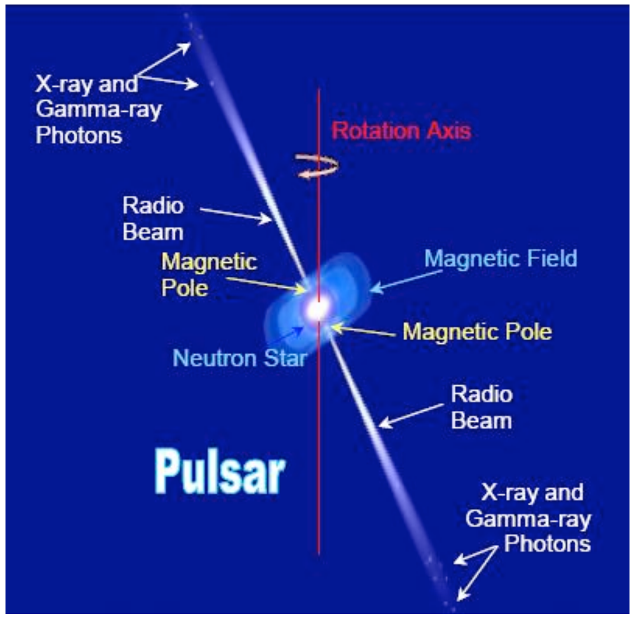

Figure 1. Pulsar Physics Yielding Regular Signals Detectable to High Precision in the X-ray Band.

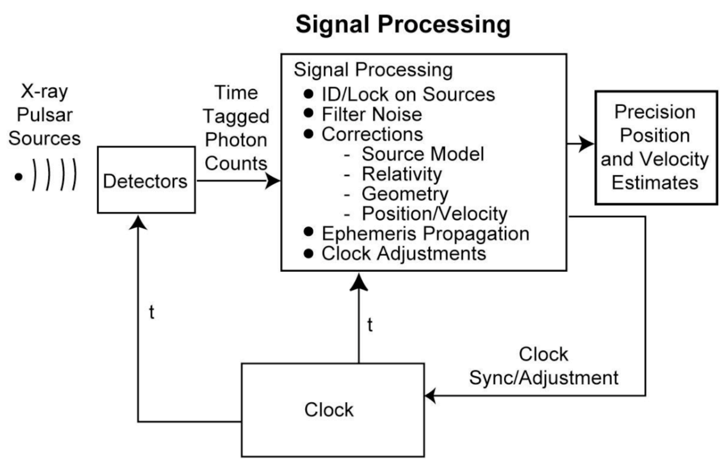

Figure 2. XNAV Processing Algorithms.

For a subset of missions, such as very deep space missions to the outer planets and beyond, missions that pass close to the sun, spacecraft emergencies, and landing on or orbiting small solar system bodies, such as asteroids and comets, it is desirable, and in certain cases essential to provide an autonomous capability for the spacecraft to determine its position and velocity in real time onboard. For instance, in the case of landing on or orbiting an asteroid, the interaction of a spacecraft with an irregular gravity field will cause an initially circular orbit to transition to an unstable, impacting, or escaping orbit within a short time, in some cases, within hours. In such circumstances for the execution of orbit correction maneuvers in a timely manner, the ability to estimate an on-board position, as well as maintain a very accurate clock, is essential and mission enabling.

Most deep space missions rely heavily on operational DSN communication contact to maintain onboard clock stability and post process ground-based navigation solutions based upon precise range and range-rate measurements [9]. With many active and proposed missions, the use of DSN tracking stations can be over-subscribed, which increases mission operations cost. There are existing current alternatives to DSN for navigation and accurate time determination. Unfortunately, many suffer from major drawbacks:

- **DSN Navigation and Timing Alternatives** [9]
  - **Ground tracking** can be done with antenna resources other than DSN; however, this option is impractical and equally resource intensive except in the case of near-Earth trajectories.
  - **Optical autonomous navigation** uses observations of planets or other bodies (e.g., Sun, moons, asteroids) and star tracking, along with Kalman filtering on-board to estimate position. This option is workable in circumstances where geometries are favorable, and the motions of the observed bodies are well characterized. It is highly dependent on mission timing.
  - **Dead reckoning** uses force models and inertial sensing (gyros and accelerometers). This numerically integrated orbit propagation can be useful for short-term solutions, but its accuracy degrades rapidly without external reference information.
  - **High accuracy, high stability clocks** are expensive to fly and still require frequent ground updates due to secular drift. For example, the highly accurate clock onboard GPS satellites are updated daily to maintain synchronization.

Therefore, emerging accuracy and autonomy requirements for future missions cannot be satisfied by GPS, DSN or their current alternatives alone.

Background on Sources

Of the known X-ray source types, pulsars represent the most favorable type of source for use for determining time and computing vehicle navigation solutions. From existing X-ray source catalogues, candidate X-ray pulsars can be chosen that will meet the required characteristics for this proposed system. Although some long period pulsars may have sufficient brightness in the X-ray domain, only the short period, most stable pulsars provide the most value. Long period pulsars would require long observation times, and unstable pulsars would not meet the stringent time synchronization requirements. Sources that show significant transient behavior or timing noise, which renders them unusable as time and navigation references, have been excluded. Certain brighter, unstable X-ray sources may have useful application for relative navigation by correlating the observations from the two platforms.

Several studies have determined the long-term stability of pulsar signals. The key parameter is the residuals, differences between the measured time of arrival (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 [10]. 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 [11]. 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. These stability values are comparable to current terrestrial atomic time standards.

Figure 3 provides an image of the Galactic sphere in Galactic Longitude and Latitude coordinates. The different types of sources are identified, and the size of the marker provides the relative magnitude of the source's flux in a logarithmic scale. Sources such as low-mass X-ray binaries (LMXB), high-mass X-ray binaries (HMXB), and neutron stars (NS) are shown. This image begins to show the concentration of sources located along the Galactic plane and near the Galactic center. Figure 4 provides another representation of the position coordinates of the sources using the Right Ascension and Declination (J2000) coordinates.

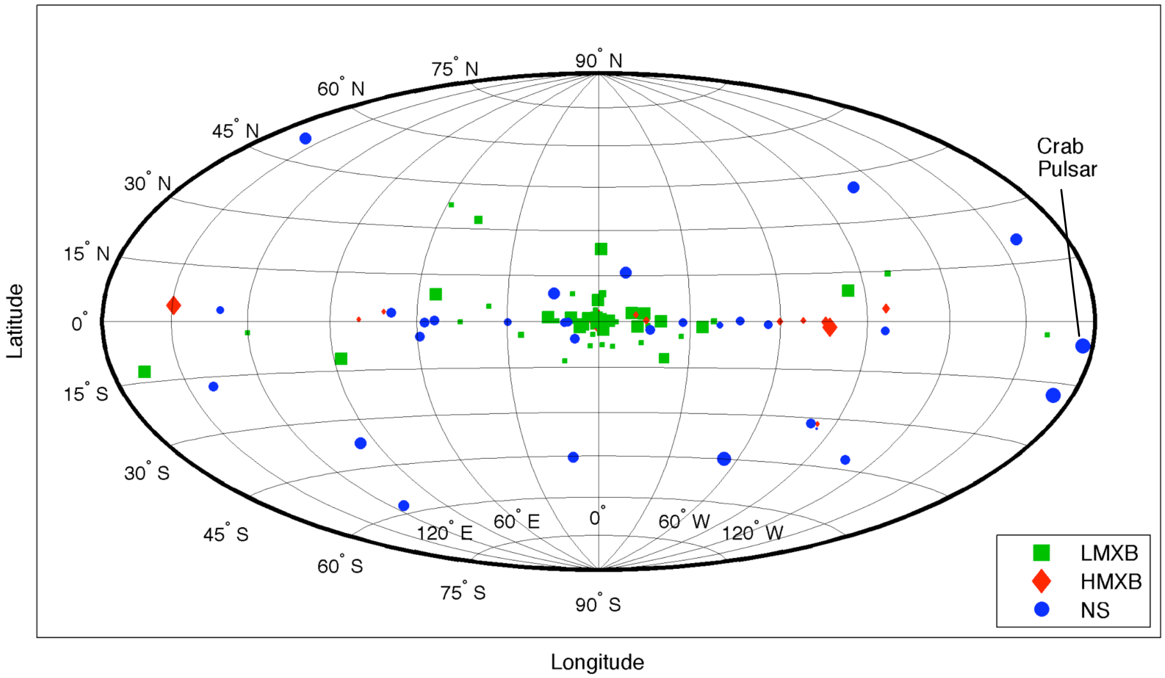

Figure 3. Galactic Longitude and Latitude Plot of X-ray Sources.

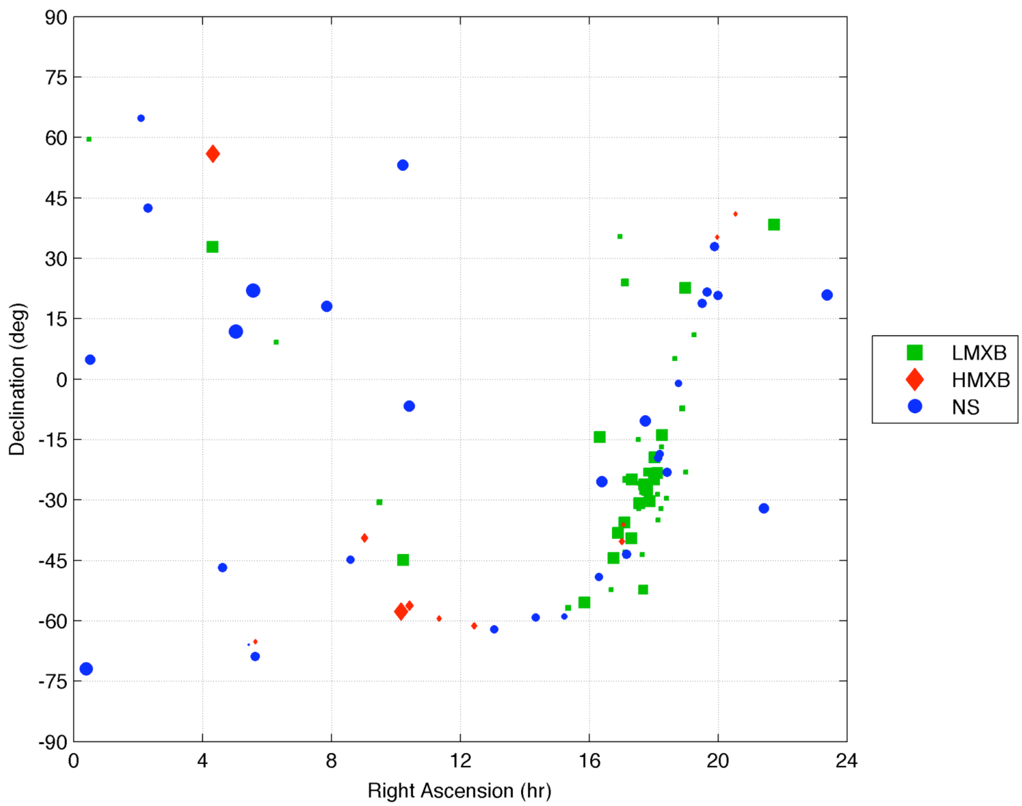

Figure 4. Right Ascension and Declination Plot of X-ray Sources.

Time and Position Determination

Variable celestial X-ray sources provide unique opportunities to create accurate navigation solutions of spacecraft. 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 of the full suite of onboard navigation solutions from these periodic sources that is currently driving the interest and research into their capabilities.

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 LOS direction, 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; and any known transient, flaring, or bursting aspects of the source. One source characteristic that appears in nearly all navigation algorithms is the unit light of sight, or *apparent position*, of the source. Many techniques use this direction information within their equations, thus any unknown errors in this term reduces 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, several commonly utilized pulsars within these research studies have this sufficiently accurate position knowledge. However, since their position accuracy is connected to their timing accuracy, or *timing noise*, several interesting potential pulsar 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.

In order for an eventual XNAV system to operate with high efficiency and accuracy, just as it is important to monitor and catalog the defining characteristics of optical stars for on-Earth navigation and spacecraft attitude determination, it will be necessary to continuously monitor, catalog, and disseminate the information of existing and perhaps newly detected sources at regular intervals to XNAV users. 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 XNAV operations. Existing X-ray astrophysics missions can tentatively serve this function, such as the Rossi Timing Explore (RXTE) [12] and XMM-Newton. However, a dedicated X-ray observatory that can communicate this critical pulsar almanac information will someday be required.

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.

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 [13]. 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 [5, 13]. 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. 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 LOS 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. The diagram of Figure 5 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 [14].

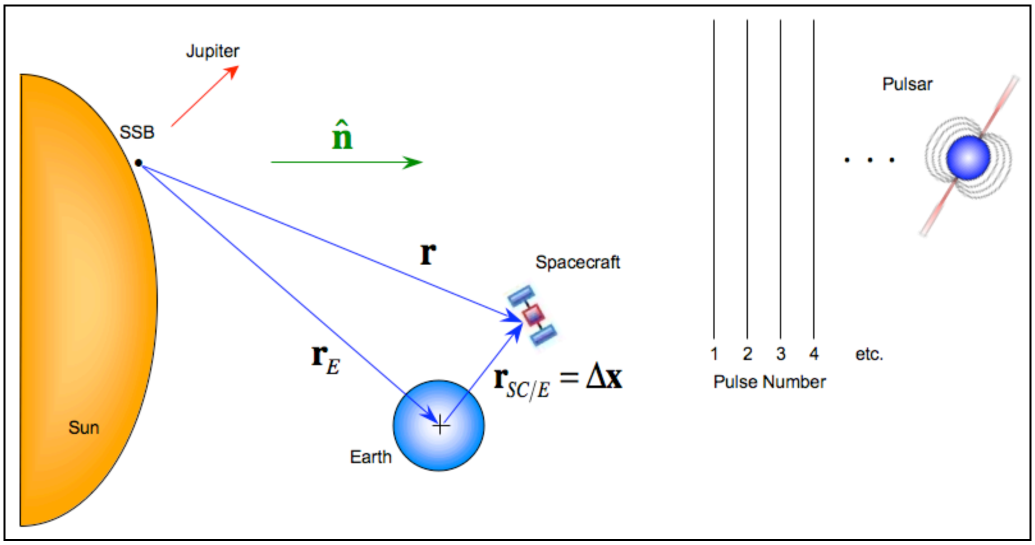

Figure 5. Position Of Spacecraft As Pulses Arrive Into Solar System From Distant Pulsar.

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 [14]. 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 [14]. 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 6. Thus, relative navigation between vehicles has been explored using variable X-ray sources [15, 16]. 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 [15].

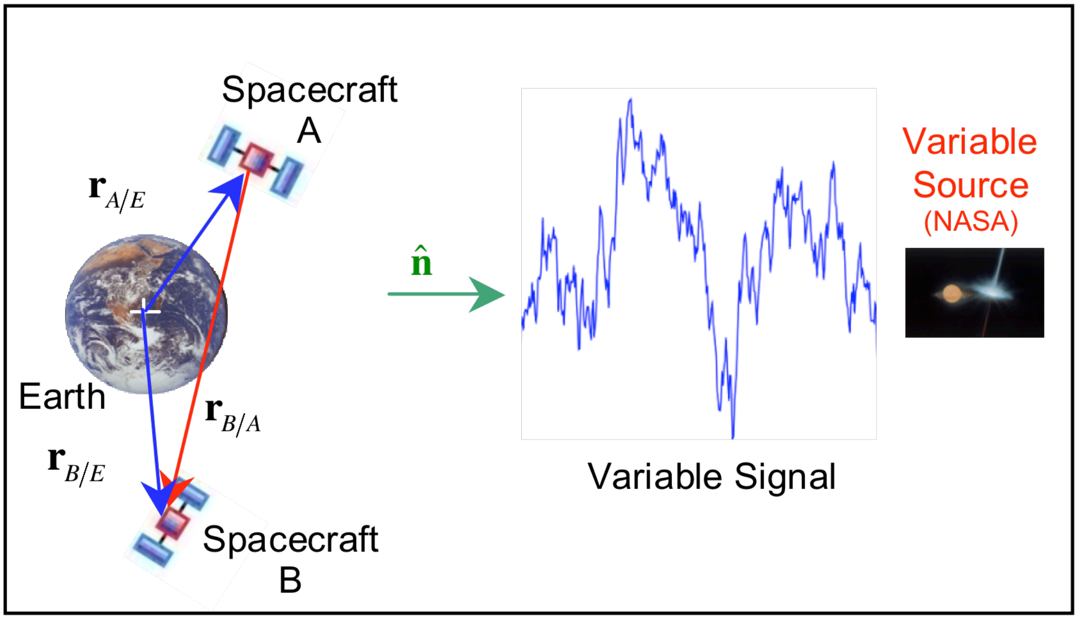

Figure 6. Relative Navigation Between Two Spacecraft That Observe The Same Variable Celestial Source.

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 [10, 11]. 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 [5, 7]. 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 [16]. 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 contact would assist with overall accuracy improvements [17].

Significant challenges yet remain for full XNAV implementation, including:

- **Faint, noisy sources** drive solutions toward large detectors and long integration times to precisely resolve times of arrival. Bright sources such as the Crab pulsar have relatively poor timing stability and can not yet 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 that 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.
- **Orbit propagation** is imperfect due to unmodelable disturbances.
- **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
- **State-of-the-art atomic clocks** for space applications are insufficiently stable for autonomous use as long-term references. Thus, ground-based or potentially pulsar source-based, clock corrections may be required periodically.

XNAV POSITION ERROR ANALYSIS

The three-dimensional position of a spacecraft relative to the chosen XNAV inertial frame origin can be established by measuring the phases of at least three different pulsars [5, 13]. Once any integer phase cycle ambiguity has been resolved, in a manner similar to that of the GPS these phase measurements can be combined to form the instantaneous position of the spacecraft independent of its trajectory or mission. In addition, it may be able to provide a correction to onboard clock time, when four or more pulsars are included. However, since at least three pulsar observations are required, the position accuracy will be limited by the observation performance of the poorest performing source, such as those that are faint, noisy, or unstable.

It has been shown that by using a model of the spacecraft's trajectory, a single pulsar can be used to resolve position if the spacecraft is in Earth orbit, since the spacecraft position vector is changing significantly with respect to the Earth inertial frame when observing the pulsar [5, 7]. To consider the use of XNAV for interplanetary trajectories, it may not be sufficient to use a single pulsar in conjunction with a numerical orbit propagator, since the spacecraft's trajectory relative to the pulsar may not be changing appreciably over the mission duration. However, it may be assumed that the onboard clock is synchronized to an Earth reference, reducing the number of observed pulsars to just three for position resolution.

A straightforward error analysis identifying the potential position determination performance is described here to access the navigation accuracy using multiple pulsars. This error analysis does not blend the orbit dynamics with sequential pulsar measurements as completed previously, however, it does provide a representative measure of performance if instantaneous multiple measurements are combined [7]. The errors considered here are associated to the capabilities of computing accurate pulse phase observations and how these relate to spacecraft position. Although multiple detectors may be required to instantaneously perform observations of multiple pulsars, it is assumed here that all observations are aligned to provide measurements at the same epoch.

Calculating the error in the measured position of the spacecraft requires the range errors to each pulsar to be combined with the pulsar geometry. For a deep space trajectory, individual pulsars are unlikely to be obscured by a planet or the sun, so the best set of three available sources can be used to characterize the XNAV performance. The position of the spacecraft, $\vec{R}$, based on the measured phases from three pulsars, ϕ_I, is:

$$\vec{R} = \begin{bmatrix} x_1 & y_1 & z_1 \\ x_2 & y_2 & z_2 \\ x_3 & y_3 & z_3 \end{bmatrix}^{-1} \begin{Bmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \end{Bmatrix}$$

where $[x_i, y_i, z_i]$ are the unit vectors describing the positions of the three pulsars. The error in the position measurement will be due primarily to the error in the measurement of pulsar phase, $\Delta\phi$, and the error in the knowledge of pulsar position, ΔI, as:

$$\Delta\vec{R} = \begin{bmatrix} x_1 & y_1 & z_1 \\ x_2 & y_2 & z_2 \\ x_3 & y_3 & z_3 \end{bmatrix}^{-1} \begin{Bmatrix} \frac{cT_1}{2\pi}\Delta\phi_1 \\ \frac{cT_2}{2\pi}\Delta\phi_2 \\ \frac{cT_3}{2\pi}\Delta\phi_3 \end{Bmatrix} - \begin{bmatrix} x_1 & y_1 & z_1 \\ x_2 & y_2 & z_2 \\ x_3 & y_3 & z_3 \end{bmatrix}^{-1} \left[\Delta I\right]\vec{R}$$

where T_i are the periods of the pulsar signals.

The terms that contribute to the errors in pulse phase measurement are summarized in Table 1. These terms are ultimately limited by the shot noise inherent in such faint sources. In addition, contributions from shot noise contributed by the diffuse x-ray background, the cosmic ray background, and detector thermal noise affect the error magnitudes.

Table 1.
PRIMARY PHASE NOISE CONTRIBUTORS.

Source	Phase Noise	Parameters
Source Shot Noise (Periodic)	$\phi_{sp} = \frac{1}{\left[sA\Delta t\eta_d\right]^{0.5}}$	s: Source strength A: Detector area Δt: Observation time η_d: Detector efficiency
Source Shot Noise (Steady)	$\phi_{ss} = \frac{1}{s}\left[\frac{b_s}{A\Delta t\eta_d}\right]^{1/2}$	b_s: Source background
Diffuse X-ray Background Noise	$\phi_b = \frac{1}{s}\left[\frac{b_d}{A\Delta t\eta_d}\right]^{1/2}$	b_d: Diffuse X-ray background
Cosmic Background Noise	$\phi_{cb} = \frac{1}{s}\left[\frac{b_c}{A\Delta t\eta_d}\right]^{1/2}$	b_c: Cosmic X-ray background (after rejection)
Detector Noise	$\phi_d = \frac{b_{\det}^{0.5}}{sA\Delta t^{0.5}}$	b_{det}: Detector noise
Total Phase Noise	$\phi_{tot} = \left[\phi_{sp}^2 + \phi_{ss}^2 + \phi_b^2 + \phi_{cb}^2 + \phi_d^2\right]^{0.5}$	

During the Phase I effort of the Microcosm SBIR program, eight pulsars were identified that have characteristics necessary to be used in XNAV, these being that they are relatively bright, have short periods and, most importantly, their pulsations are known and stable over long periods. The characteristics of these pulsars are summarized in Table 2. The design parameter that most affects the accuracy of the XNAV solution is the area-time product of the detector, $A\Delta t$. Long observations or large collecting areas result in reduced shot noise relative to the signal of interest, as shown in Figure 7. An observation of the Crab pulsar B0531+21 made at 1 AU with a area-time product of 10^4 sec-m^2, gives a range error of approximately 200 m, while the faintest source considered, B1509-58, results in a range error of approximately 9 km under the same conditions. Table 3 provides the assumed detector and background characteristics used in this error analysis.

Table 2.
PULSAR CHARACTERISTICS.
(*Actual data for these parameters was not available)

Source	Galactic Lon (deg)	Galactic Lat (deg)	X-ray Flux ($ph/s/m^2$)	Pulse Fraction	Period (ms)	RA Error (marcsec)	DEC Error (marcsec)
B1937+21	57.5	-0.290	4.99×10^{-5}	0.86	1.56	0.012	0.14
J0218+4232	139.5	-17.53	6.65×10^{-5}	0.73	2.32	150	100
B0540-69	279.7	-31.5	5.15×10^{-3}	0.67	50.4	450	500
B1509-58	320.3	-1.16	1.62×10^{-2}	0.65	150	1350	1000
B1821-24	7.80	-5.58	1.93×10^{-4}	0.98	3.05	0.90	12
J1814-338	358.75	-7.59	9.97×10^{-2}	0.12	3.18	1*	1*
B0531+21	184.6	-5.78	1.54×10^{0}	0.70	33.4	75	60
J1808-3658	355.39	-8.15	3.29×10^{-1}	0.41	2.49	1*	1*

The representative accuracies of XNAV for all possible combinations of three pulsars from the given set of eight of Table 2 and the assumed detector and observation characteristics of Table 3 were determined for positions in the solar system from 1 AU to 100 AU. At distances close the Earth, the best performance (~2.2 km) is achieved by using the pulsar set: B1939+21, J1814-338, B0531+21. However, the poor position knowledge of B0531+21 results in a significant increase in position error with increasing distance from the sun. At 100 AU, a position error of 1,360 km is achieved using the pulsar set: B1939+21, J1814-338, J1808-3658. However, the error is dominated by the uncertainty in the knowledge of the pulsar positions. If the position knowledge of this set of pulsars can be improved to match that of B1939+21 (10 μarcsec in right ascension and 100 μarcsec in declination), the spacecraft position error due to pulsar position knowledge can be reduced significantly as shown in Figure 8. This plot also provides the representative accuracy of the DSN spacecraft position performance based upon the 1 nrad angular accuracy [18]. It is noted that based upon current source position knowledge XNAV improves performance over DSN at about 15 AU. At 100 AU, XNAV offers 5 km position uncertainty as compared to 15 km for DSN.

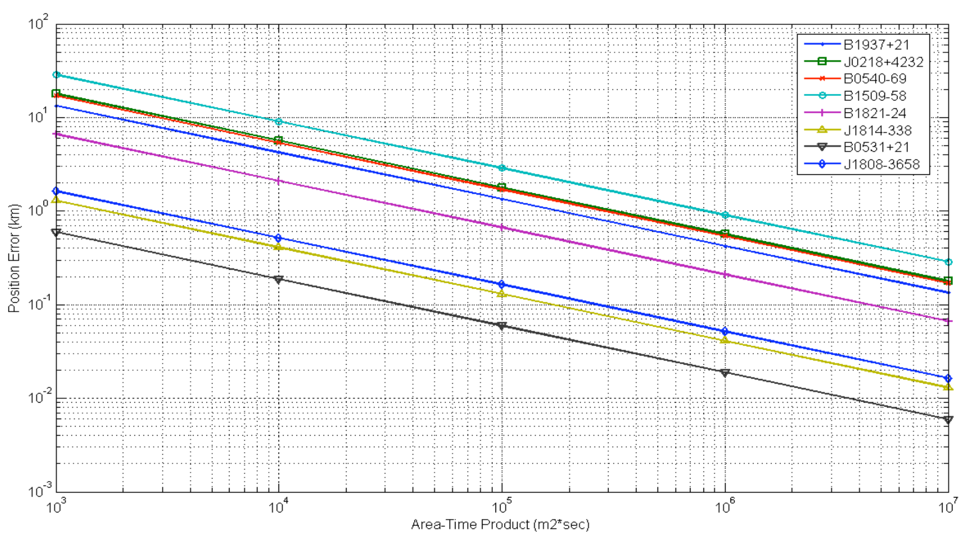

Figure 7. Pulsar Range Error as a Function of Area-Time Product (1 AU).

Table 3.
INPUT PARAMETERS.

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

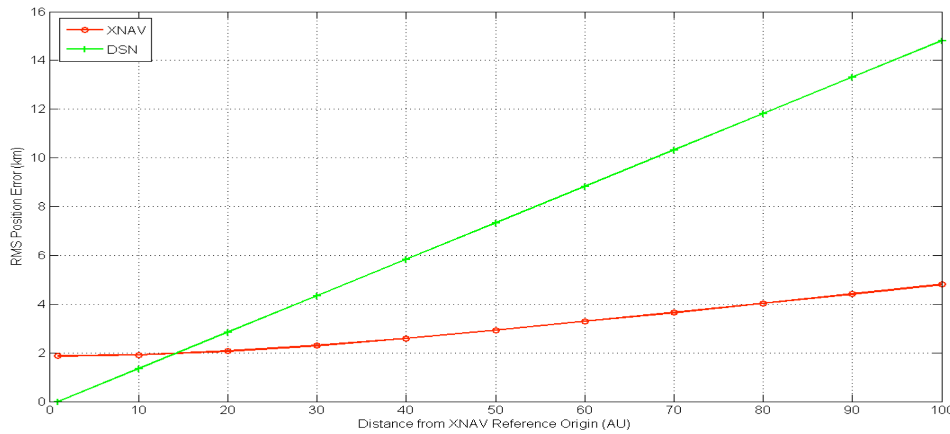

Figure 8. Position Solution Errors As A Function Of Spacecraft Detector Distance From Solar System Barycenter For DSN And XNAV, Using Projected Future Position Knowledge.

DSN and XNAV

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 4 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 4 a combination of incremental improvements and new technology investments will be required. As the XNAV 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 4.

DSN CURRENT AND PROJECTED NAVIGATION ACCURACY (KM, 1-SIGMA)

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				

Level 1 Long-range requirements (courtesy C. Naudet, JPL)

Comparisons with the DSN. As described herein and in other papers in this session, 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 on the order of 1 or 2 nrad [18].

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. Significant further performance improvements are anticipated as large communications arrays and laser communication solutions are introduced. In contrast, XNAV is still a nascent technology with considerable development required for a flight demonstration and considerably more work on source observations and modeling as well as detector and algorithm development required to make it an operational capability.

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.

POTENTIAL MISSION APPLICATIONS

Several scenarios for which XNAV would be beneficial have been identified [17]. Preliminary assessments have been conducted. However, considerable further work is necessary to determine which scenarios and concepts of operations will be most viable and what levels of performance can be expected.

Earth-Sun Lagrangian Point Missions. This class of mission includes Earth-Sun Lagrangian point missions as-well-as Earth-trailing and other missions 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 is 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/demand on the DSN infrastructure. The capability of the DSN is more than adequate to support these missions. However, as these types of missions proliferate, and with constellation/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/constellations is of particular interest due to the operational demands and complexity of managing them from the ground.

Mars. This scenario focuses on navigation at Mars as well as trips between Earth and Mars. 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 these 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 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.

Very Deep Space. Very deep space includes missions to Jupiter and beyond, but focuses on missions and mission concepts well beyond Jupiter. For example:

- 500 AU
- Solar System Bow Shock (Heliopause)
- Pioneer Anomaly
- Interstellar

For these missions, the promise of kilometer-level accuracy in all directions at these great distances, would be enhancing for most missions and enabling for some. The LOS 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 500 AU mission XNAV could potentially provide a factor of 1000 improvement in position knowledge. For missions at Jovian distances the improvements would be much more modest, however, it may also simplify navigation operations by reducing reliance on DSN/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.

CONCLUSIONS

There is considerable work yet to be done to determine the performance limits for XNAV, and to validate its potential operational utility. The combined efforts supported by the University of Maryland (UMD), NRL, DARPA, and NASA over the past several years to develop the science and technology suggest that 3-D navigation accuracy in the neighborhood of 1 km or better will be achievable. This begins to compete favorably with the DSN's delta-DOR angular measurements at the range of Jupiter, and would increasingly perform beyond DSN's capability at distances in the neighborhood of 10 AU or greater from Earth. Thus, XNAV could prove to be mission enabling, and would likely be mission enhancing for a variety of deep space missions.

The recommended solution for most relevant NASA missions would be a combination of DSN and XNAV technologies, each complementing the other's navigation solution. Combining DSN's high accuracy range and range-rate measurements along the LOS from Earth to spacecraft, DSN's time reference/transfer capability, and XNAV's measurements along multiple LOS directions would create a significantly enhanced deep space navigation system. Tracking accuracy for many deep space missions would be significantly improved, while dramatically reducing frequency and duration of DSN observations.

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