# XNAV Beyond the Moon

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## BIOGRAPHIES

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## ABSTRACT

In 2006, Microcosm executed a Phase I Small Business Innovative Research (SBIR) project for NASA exploring applications for XNAV beyond geosynchronous orbit. This paper provides a brief overview of the basic principles of XNAV, followed by a discussion of elements of the navigation error budget. Then various applications will be explored, including Earth-Sun L2, planetary and very deep space missions. Performance comparisons relative to current solutions are presented.

Phase I results demonstrated approximate, first-order navigation accuracy achievable using periodic X-ray sources that have been characterized and catalogued in recent years, demonstrating utility for some NASA mission applications. Sample use cases of interest to NASA were identified and investigated for implementation of XNAV either as an autonomous navigation capability or as an augmentation to current interplanetary navigation capability via the Deep Space Network (DSN). A first order error budget was developed that identified the key error sources and how they contribute to overall navigation error. The potential benefits of employing XNAV for future missions were also investigated for both relatively near and very far interplanetary missions.

Microcosm is currently under a follow-on Phase II SBIR contract that will build upon the Phase I activities. This new phase will develop a detailed XNAV simulation capability to assist evaluating navigation performance for specific missions of interest, and create an XNAV flight software experiment ready to integrate on an appropriate near-term flight demonstration mission in Phase III of the program. The simulation will be targeted for integration with Goddard Space Flight Center's GPS Enhanced Onboard Navigation System (GEONS) software. The XNAV error budget begun during Phase I will be developed in more detail to support the algorithm and simulation work.

## 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 Global Positioning System (GPS)" signal. Accurate pulse time-of-arrival estimates from multiple non-coplanar sources allows 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 and monitoring the long-term stability of several well-studied 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 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 from Earth. The detectors are highly resistant to blinding or contaminating events. Detectors used within the XNAV system are intrinsically radiation hard due to their design of recording photon detections.

In a Phase I Small Business Innovative Research (SBIR) program carried out in 2006, the Microcosm team investigated achievable XNAV accuracy for various interplanetary applications, developed a preliminary, detailed source catalogue, constructed an XNAV error budget, and identified potential implementation options for XNAV. The Phase II program will develop 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 a 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 GPS”. 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. Issues exist with these sources including the fact that the signals are faint, noisy, and they are not tagged with time and 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 process is provided in Figures 1 and 2.

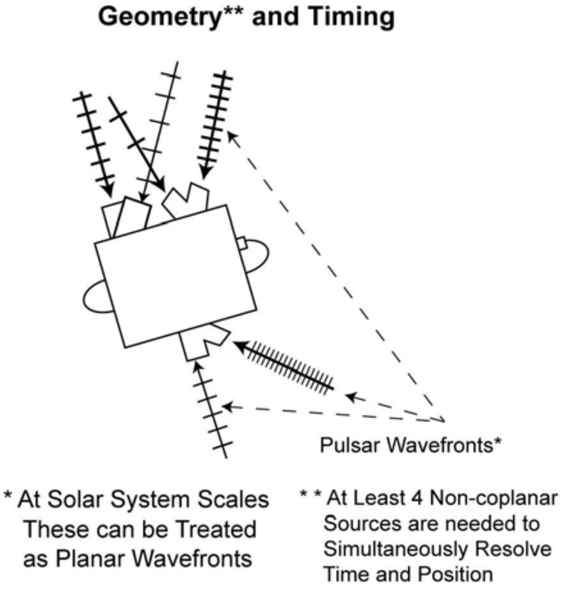

**Figure 1. XNAV Essential Geometry**

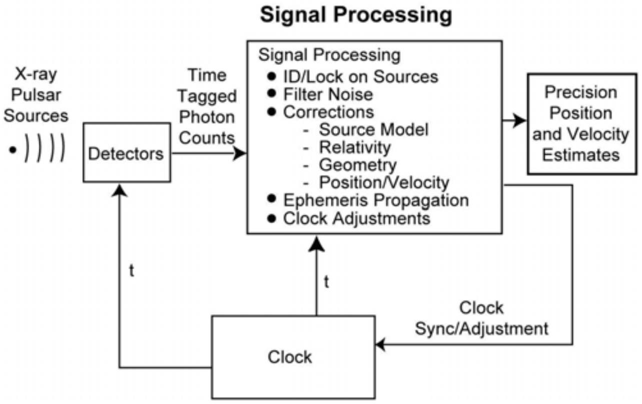

**Figure 2. XNAV Processing Algorithms**

For a subset of missions, such as very deep space missions to the outer planets and beyond, 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. 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,.

There are current alternatives to DSN for navigation and accurate time determination. Unfortunately, they all suffer from significant drawbacks:

- **Navigation [Wertz]**

  - **Ground tracking** can be done with 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). It can be useful for short-term solutions, but its accuracy degrades rapidly without an external reference.

- **Time Keeping**

  - **Ground updates** are resource intensive, periodic, non-autonomous, and have a fundamental accuracy limit of ~10 nanoseconds due to unmodelable ionospheric delays.
  - **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 new missions cannot be satisfied by GPS, DSN or their current alternatives.

The principal scientific and technical advances that make the X-ray based approach feasible have come about fairly recently:

- Characterization of sufficient numbers of highly stable X-ray pulsar sources to provide the basis for a timing system
- Development of new X-ray detector technology with high time resolution of recorded events.

***Time and Position Determination***

A simple way to understand the spacecraft navigation problem solved using XNAV concepts is to imagine a stationary vehicle with several extremely distant stationary point sources each broadcasting a different frequency that is perfectly stable and has a perfectly clean signal. If these signals had been previously characterized, and there was a perfect clock on-board, observation of one source would constrain the possible locations to a series of equally spaced planes normal to the direction of the source. Adding another source would constrain possible locations to the lines of intersection of the planes. The next source would constrain them to a set of points. This is sufficient if the initial uncertainty in position is much less than the distance between the wavefronts. If not, adding the fourth source resolves the ambiguity except in degenerate cases where the sources are coplanar or the frequencies have integer ratios (the degenerate cases do not apply for actual X-ray pulsar sources).

If the time is not known, but the clock is stable, then differencing the arrival times between wavefronts from pairs of sources creates a new set of planes that can be intersected in a similar fashion to define points with four sources and uniquely identifies the location with five (with similar caveats). Although absolute time can not be recovered since no identifying code is attached to any pulsar signal, interestingly, once the position is determined, time relative to the wavefront arrival can be recovered uniquely from the time difference of arrival (TDOA) among the sources. Again, fewer sources will suffice if the clock error is small compared with the time between wavefronts. Once the clock is recovered, a single source is sufficient to prevent clock divergence if the position is known.

An analogous process is required for position and time determination using actual pulsar signals. It is, however, considerably more complicated in implementation because:

- **Noisy sources** drive solutions toward large detectors and long integration times to precisely resolve times of arrival.
- **Motion of sources** relative to the ECI frame requires 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.
- **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 unmodeled disturbances.
- **State-of-the-art atomic clocks** for space applications are insufficiently stable for autonomous use as long-term references. Thus, ground-based, or even pulsar source-based, clock corrections will still be required periodically.

Initial performance projections were developed during Phase I and will be refined in much greater detail during Phase II, with more fidelity in the error modeling.

***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 [Matsakis]. Kaspi, Taylor, & Ryba show 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. In their 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.

## SOURCE CATALOG DEVELOPMENT

As part of the Phase I SBIR program, an X-ray source catalogue was compiled to identify the most up-to-date physical characteristics available on all relevant sources that could be used for estimating a spacecraft's position and velocity in space. Identifying variable celestial sources that are sufficiently bright is critical for the success of XNAV. After investigating existing catalogues, several lists of candidate sources were presented. Further investigation into the utility of each source will be undertaken on the current NASA Phase II SBIR program.

The catalogue developed provides three datasets separated by source category, which include *Rotation-Powered Pulsars*, *Accretion-Powered Pulsars*, and *Other Sources of Interest*. The data is separated into several sections, including the *Install Number*, *Name and Type*, *Position*, *Energy*, *Stability*, *Periodicity*, and *References*. This catalogue will continue to evolve and expand during the Phase II activity to support Phase II simulation work.

The sources listed within the XNAV Source Catalogue were chosen based upon several criteria and requirements developed for the project. Most importantly, the sources must be a known X-ray source –many candidate pulsars were first identified through ground-based radio observations. Consequently, they must have been observed by an X-ray astronomy mission. Sources within this catalogue typically have well measured flux. For navigation, it is desired that the sources produce high amounts of X-ray flux in order to help reduce the required observation times. However, the Catalogue lists several sources that are very faint, which are still viable candidates for navigation, due to their signal stability.

Catalogued sources must also have a known position, and it is desired that this position be known to high accuracy. The source should also produce measured variability in its signal. This variability is highly important for the planned navigation algorithms. Although a short period duration in this variability is desired, typically less than one second, some longer period but brighter sources are also listed, since their higher X-ray flux is also attractive for some XNAV techniques.

## XNAV ERROR BUDGET DEVELOPMENT

In Phase I, a top-level XNAV error budget was formulated. This initial cut at developing an error budget includes key error components that are more easily estimated. There are additional contributors to the overall navigation error, including those with second order effects, and these will be incorporated into the detailed XNAV simulator to be developed in Phase II. Table 1 shows a complete list of error components identified to date, with items highlighted in italics that are included in the current top-level error budget. The preliminary error budget results show line-of-sight position determination errors on the order of a kilometer to a few 10's of km. The error budget will be refined and worked in much more detail during Phase II to gain a more accurate estimate of the expected errors for various types of deep space missions utilizing XNAV.

**Table 1. XNAV Error Sources Contributing to Overall Navigation Error.** Italicized items are included in the top-level error budget developed in Phase I.

| **Detector Errors** | |
|---|---|
| | Photon Time Arrival Resolution |
| | *Noise - Shot Noise (source and background), Readout Noise (or equivalent)* |
| | *Detector Efficiency* |
| | *Background Rejection Efficiency* |
| **Source Measurement Errors** | |
| | X-ray Pulse Width |
| | *Source X-ray Flux* |
| | *Source Period* |
| | Transient Characteristics of Source (whether high discharge or quiescent) |
| | Flaring or Bursting effects |
| | *Diffuse background* |
| | Compensation for pulsar glitches and recovery (corrections to pulse arrival time, & width of X-ray pulse) |

| | |
|---|---|
| **Source Model Errors** | |
| | Pulse Timing Model |
| | Radio vs. X-ray phase lag in the time model |
| | *Estimated unit direction of pulsar within solar system* |
| | *Source Distance (relative to solar system barycenter)* |
| | *Proper motion of pulsar* |
| | Relativistic Time Transfer Equation |
| | Binary or Multiple star systems Complexity |
| | Source frequency drifts |
| **Spacecraft System Errors** | |
| | *Spacecraft clock* |
| | Spacecraft Proper-time to Coordinate-time Conversion (general and special relativity effects due to spacecraft clock in motion relative to inertial frame and within gravitational field) |
| | Gimbal Tracking Accuracy |
| **Other Modeling Errors** | |
| | *Solar System Barycenter Estimated Position* |
| | Solar System Barycenter Estimated Velocity |
| | Earth Ephemeris Position Error |
| | Earth Ephemeris Velocity Error |
| | Interstellar Dispersion Effects on All Measurements (radio; X-ray assumed zero) |
| | Dynamic model of spacecraft orbital motion |
| | Gravitational Potential of Sun and Planets |

## DSN OVERVIEW

This section provides background on the operation of the Deep Space Network, which is the current system employed for navigation of NASA interplanetary space missions. This includes a discussion of current and future DSN navigation performance to compare with expected XNAV performance to understand where XNAV may offer an acceptable alternative to DSN or provide a backup navigation solution.

### *Description and Architecture*

Figure 3 shows the basic elements of the DSN, all key nodes of the system, and data flow. Figure 4 shows the geographic makeup of the DSN. The principal ground tracking facilities are located in Canberra, Australia; Madrid, Spain; and Goldstone, California, USA.

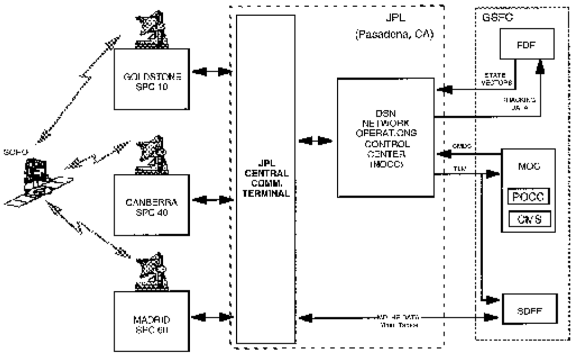

**Figure 3. DSN Basic Operation**

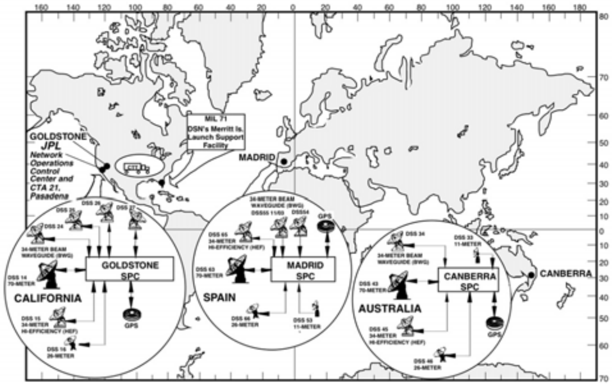

**Figure 4. DSN Global Array of Antennas**

### *Navigation Process*

The process of spacecraft navigation via the DSN is illustrated in Fig. 5. The two primary navigation functions are orbit determination and guidance. The orbit determination process is an iterative procedure requiring an a priori estimate of the spacecraft trajectory, referred to as the nominal orbit. Expected values of the tracking observables are calculated based upon nominal values for the trajectory and precise models of the tracking observables. These calculated observables are differenced with the actual values obtained from the tracking system to form the data residuals. Guidance involves the calculation of optimal maneuvers and commands needed to deliver the spacecraft to the desired target.

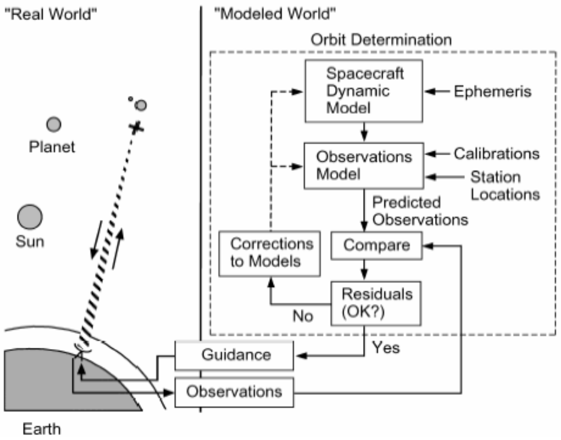

**Figure 5. The navigation process.**

If the trajectory and the data models were perfectly known, the residuals would exhibit a purely random, essentially Gaussian, distribution due to uncorrelated measurement errors (for example, thermal noise in the tracking receiver). However, errors in the trajectory and the observable models introduce distinctive signatures in the residuals. These signatures enable an adjustment to the model parameters through weighted linear least-squares estimation or other optimization/parameter identification approaches.

Delivery accuracy requirements vary from mission to mission, but typically become increasingly more challenging as demonstrated navigation performance improves. For example, the one sigma (standard deviation) delivery requirement for the Voyager Io encounter was approximately 900 km. The comparable value for the first Galileo Io encounter was about 100 km.

### *Radiometric Tracking*

Radiometric tracking is normally performed as part of the periodic communication process with the spacecraft, and may include tracking focused modes with longer durations than would be required for communication alone to enable improved tracking accuracy. It uses Doppler and time-of-flight to derive range and velocity estimates which can be filtered in conjunction with a dynamic model to estimate spacecraft position and velocity.

### *Delta-DOR*

Delta-DOR (differential-one-way-range) is a specialized radiometric tracking mode used to enable high accuracy angular measurements, those normal to line-of-sight (LOS) to the vehicle. It uses two widely separated ground based receivers and alternates tracking the vehicle and a nearby quasar. The quasar measurement provides a reference range difference, mitigating many sources of error. Delta-DOR can provide accuracies in the neighborhood of a millionth of a degree (~4 km at 150,000,000 km).

### *Future Capabilities and Infrastructure*

NASA and ESA continue to invest in infrastructure and research and development (R&D) to improve both communication bandwidth and tracking capability. Among the options being pursued are use of laser communication links, and large aperture antenna arrays with long N-S and E-W baselines.

Table 2 outlines the existing and projected DSN navigation accuracy capabilities for a variety of deep space missions through 2030.

**Table 2. DSN Current and Projected Navigation Accuracy (1-sigma) for Various Mission Applications (all values in km).** Level 1 Long-range requirements (courtesy C. Naudet, JPL)

| Mission Type/ Phase | Year Achieved | | | |
|---|---|---|---|---|
| | 2005 | 2010 | 2020 | 2030 |
| Orbit control accy. (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 accy., radial | 0.33 | 0.0005 | 0.0001 | < 0.0001 |
| Landing accy. on surface, terrestrial bodies* | 21×5 | 7×7 | 1×1 | 0.1×0.1 |
| Landing accy. on surf., 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 | | | | |

If the XNAV R&D program proves successful, 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.

## OVERVIEW OF XNAV APPROACHES

XNAV can be utilized in a variety of potential applications, such as a totally autonomous onboard system, a system that can be periodically updated with improved X-ray source model information, a system that will work in conjunction with DSN, a system that enhances nominal DSN navigation solutions, or one that acts as a DSN backup.

### *Fully Autonomous XNAV*

Fully autonomous XNAV uses pulsar that have sufficiently long-term timing models. Such sources are typically relatively dim, and require longer observation times to approach their accuracy limit for a given detector area. It can be accomplished via serial observations of an appropriate set of sources using a single detector, or via simultaneous observations from multiple onboard detectors.

### *Observatory XNAV/Relative Navigation*

This approach enables the use of brighter, more variable, more poorly modeled or unmodelable sources – including bright, aperiodic sources. In this case, space or ground based observatories gather data for shorter-term modeling and/or for noise correlation. Models and/or data can then be shared on a frequent basis with the target spacecraft to provide accurate retrospective models/data and improved predictive model parameters. This would enable a broader set of sources and potentially allow smaller detectors or shorter observation times to reach each source's accuracy limit. It would, however, require significantly more infrastructure investment and would add operational complexity.

### *DSN Augmentation*

This mode of use could be applied in either of the aforementioned cases. It leverages the current DSN capability and infrastructure, and augments it with XNAV to improve performance, increase autonomy, and/or to reduce cost. The DSN and associated navigation analysis can provide very accurate measurements/estimates along the LOS, but performance degrades and resource requirements are typically higher for directions normal to the LOS. In addition, many current and planned missions require frequent guidance inputs which in-turn requires frequent access to the DSN infrastructure. The particular method depends on the specific application and will be discussed further in the upcoming section on scenarios.

## BEYOND THE MOON MISSION SCENARIOS

Several scenarios for which XNAV would be beneficial have been identified. 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. Table 3 outlines the various mission scenarios considered, mapped against the alternative navigation approaches discussed in the previous section, with attendant performance issues.

### *Very Deep Space*

For this discussion, very deep space includes missions to Jupiter and beyond, but will focus on missions and mission concepts well beyond Jupiter. For example:

- 500 AU
- Solar System Bow Shock
- 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.

### *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. Discussion will focus 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.

**Table 3. Potential High Priority XNAV Mission Applications.**

| Mission Type | Classic XNAV*, No DSN | Observatory XNAV**, No DSN | Classic XNAV, with DSN | Observatory XNAV, with DSN | XNAV Enabling or Enhancing Features |
|---|---|---|---|---|---|
| **Earth-Sun L2 Navigation** | Achieve navigation accuracy on the order of few 10's of km, fully autonomous, low frequency (few times per day to once per day) | Nav. accuracy of 10's of km to 1 km, with higher frequency. | Achieve nav. accuracy on the order of 1 to 10 km, with DSN fix at regular frequency, improve the cross-track nav component accuracy over DSN standard capability, improve clock error | Improved accuracy over observatory XNAV alone- 1 to 10 km error. Higher frequency than using classic XNAV. | Reduce DSN work load. XNAV-only eliminates DSN transponder from spacecraft. Provides additional spacecraft attitude reference. Useful for course relative navigation applications, where intersatellite distances are large. |
| **Deep Space Missions (Past Jupiter)** | Achieve navigation accuracy on the order of few 10's of km consistently for mission duration, fully autonomous, low frequency- OK due to long cruise periods in interplanetary space. | Potentially useful for mission phases requiring higher frequency nav solutions, e.g. planetary orbit capture, but assessment of achievable accuracy and solution frequency must be made, to compare with typical requirements for these applications. | Achieve nav. accuracy on order of few km, with DSN fix at regular frequency, improve the cross-track nav component accuracy over DSN capability, and accurate external timing reference | Nav. accuracy of few km, higher frequency than classic XNAV. | Reduce DSN work load. XNAV-only eliminates DSN transponder from spacecraft. Provides additional spacecraft attitude reference. |
| **Mars Missions** | Achieve navigation accuracy on the order of few 10's of km consistently for mission duration, fully autonomous, low frequency- OK due to long cruise periods in interplanetary space. | Investigate potential scenario including observatories in both LEO and in Mars orbit. Potential course nav utility for Mars surface assets communicating with observatory in Mars orbit. | Achieve nav. accuracy on the order of few km, with DSN fix at regular frequency, improve the cross-track nav component accuracy over DSN capability, and accurate external timing reference | Nav. accy of few km, higher frequency than classic XNAV. | Reduce DSN work load. XNAV-only eliminates DSN transponder from spacecraft. Provides additional spacecraft attitude reference. Enables lower cost navigation option for routine, autonomous operations. |
| **Cis-Lunar Missions** | Classic XNAV does not meet nav accuracy or frequency requirements for some applications, like Earth and Moon orbit departure and capture, and on-orbit rendezvous and docking. | Missions have close relative proximity to LEO Observatory. Potentially useful for mission phases requiring higher frequency nav solutions, such as Earth and Lunar orbit departure and arrival. | Achieve high accuracy nav. solutions, with DSN fix at regular frequency, improve the cross-track nav component accuracy over DSN capability, and accurate external timing reference. | DSN augmentation can provide higher nav accuracy. | Reduce DSN work load. XNAV-only eliminates DSN transponder from spacecraft. Provides additional spacecraft attitude reference. Enables lower cost navigation option for routine, autonomous operations. |

*Classic XNAV: utilize dim, very stable pulsars, very predictable, models onboard spacecraft, no regular or frequent updates needed

**Observatory XNAV: utilize brighter, aperiodic x-ray sources, model updates broadcast to spacecraft at regular frequency, removes common mode errors

Another more speculative application of XNAV would be as part of a Mars navigation constellation. XNAV would allow continuous navigation updates for Mars orbiters. It would also provide additional reference data to tie the Earth and Mars frames. Flight experiments could be conducted as part of the revitalized lunar program.

## ISSUES

There are still numerous issues to be resolved before XNAV becomes a viable navigation alternative for NASA or other users. Among them:

- Bright sources such as the Crab pulsar have relatively poor timing stability and can not yet be modeled accurately for long-term predictions
- The most stable sources are relatively very dim, requiring large detectors and/or long observations –both of which can have significant mission impacts
- Maintaining accurate timing models will require either a dedicated observatory spacecraft or development of a capability to predict x-ray behavior based on radio observations
- High quantum efficiency, low-power, low-noise, accurate time resolution detectors will be needed to make broad adoption practical
- Fast-timing electronics, and large-memory, fast-processing computers onboard
- A flight experiment to validate hardware, algorithms, and overall system utility will also be necessary

The Phase II program will target key issues specific to NASA applications as-well-as, resources permitting, other gaps identified as the nature and level of other XNAV investments are determined.

## CONCLUSIONS

XNAV shows considerable promise for a broad range of civil space applications, contributing to:

- Navigation performance
- Autonomy
- Operations cost reductions

However, considerable work is yet to be done both to develop the basic technology and to explore implementation and performance details for the most promising applications.

Microcosm, working with it's team of consultants on the current Phase II SBIR sponsored by NASA, will continue development of XNAV algorithms to work toward a flight software experiment that can fly with an appropriate XNAV sensor on a future technology demonstration mission. The team will coordinate activities with the DARPA XNAV program to the extent possible, and will continue discussions with NRL on ongoing XNAV development work.

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