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Overview of the XNAV Program, X-ray Navigation Using Celestial Sources

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1.0 ABSTRACT

Satellite navigation systems rely heavily upon the Global Positioning System (GPS). GPS provides unrivaled performance in measurements of satellite ephemerides. Due to the increasing number of GPS system threats other options are now being evaluated, these new technologies are designed to augment or back-up the GPS system and be applied on other deep space missions. The Defense Advanced Research Projects Agency (DARPA) is developing one such navigation system, referred to as XNAV - "***X***-ray Source Based ***NAV***igation for Autonomous Position Determination". Theoretically, this system can use celestial X-ray sources to determine spacecraft attitude and position knowledge anywhere in the solar system.

DARPA has contracted with Ball Aerospace & Technologies Corp. (BATC), Los Alamos National Laboratories (LANL), Johns Hopkins University – Applied Physics Laboratory (JHU-APL), and the National Institute of Standards & Technology (NIST) to develop a celestial navigation system for an on-orbit demonstration. The XNAV program is currently half-way through the 18-month feasibility study.

The goal of the XNAV program is to prove the feasibility and viability of this approach through a culmination of detailed analyses and hardware demonstrations. This paper will provide an overview of the XNAV system and its expected capabilities; identify the development milestones; examine possible applications; and provide a top-level technical approach.

1.1 BACKGROUND

The X-ray astronomy groups at NASA Goddard Space Flight Center (GSFC), the Naval Research Laboratory (NRL) and others have proposed various concepts using celestial X-ray sources for navigation. Multiple X-ray experiments have been carried out since the beginning of the space age (1960's). Since X-rays do not penetrate the Earth's atmosphere, these experiments can only be simulated in unique laboratory and space environments. Some previous X-ray astronomy missions include HEAO 1, ARGOS, ALEXIS, BBXRT, EXOsat, HEAO-1, RXTE (HEXTE instrument), ROSAT, Chandra (AXAF), and XMM-Newton. Each of these missions has laid the ground work for the XNAV mission. Two key missions with relevance to the XNAV program include:

ROSAT

The Roentgen Satellite (X-ray satellite) provided the first all-sky survey with an imaging telescope in the X-ray band of 0.1 keV - 2 keV. While in the scan mode, the ROSAT instrument detected more than 60,000 new X-ray sources. The instrument has the capability to locate these sources with an accuracy of at least 10 arcsec while operating in a pointing mode.[1]

RXTE

The Rossi X-ray Timing Explorer (RXTE) mission had three primary instruments; the Proportional Counter Array (developed to detect the lower part of the X-ray energy range), the High Energy X-ray Timing Experiment (HEXTE) developed to observe the upper energy range, and an All-Sky Monitor (ASM). The HEXTE instrument demonstrated the ability to time tag X-ray photons (15 to 250 keV) with an accuracy of 8 microseconds.[2]

Another important discovery necessary for the implementation of the XNAV navigation system is millisecond pulsars. In 2002, researchers combined Hubble Space Telescope images with radio observations to detect a fast spinning millisecond pulsar. It is theorized that a millisecond pulsar consists of a spinning pulsar and a red giant sun as shown in **Figure 1-1 .**[3]

Figure 1-1 "This artist's impression shows the pulsar (seen in blue with two radiation beams) and its bloated red companion star in the globular cluster NGC 6397. Scientists believe that the best explanation for seeing a bloated red star instead of a 'quiet' white dwarf in the system is that the pulsar only recently has been spun up to its current rotation speed of 274 times per second by the gases transferred by the red star. It is the first time such a system has been observed. Credit: European Space Agency & Francesco Ferraro (Bologna Astronomical Observatory)"

Each of the above experiments and associated discoveries are important factors for the development of a celestial-based navigation system. These elements are required for spacecraft attitude and position determination in LEO, GEO, lunar and deep space missions.

2.1 XNAV PROGRAM OVERVIEW

DARPA is funding the effort to develop the next generation navigation system, referred to as XNAV. The XNAV system is intended to serve as a back-up to GPS and in Exo-Earth Orbits (EEO) where GPS is not available. This system will detect and track X-rays from stable pulsars and other bright sources and use them for attitude and position determination.

DARPA has contracted with the BATC lead team to develop this innovative celestial navigation system. The next phase of the program will further develop and build the sensors for the on-orbit demonstration. The XNAV team and responsibilities are shown in **Figure 2-2**. The XNAV payload is currently scheduled to be demonstrated on-board the International Space Station (ISS) in March of 2009.

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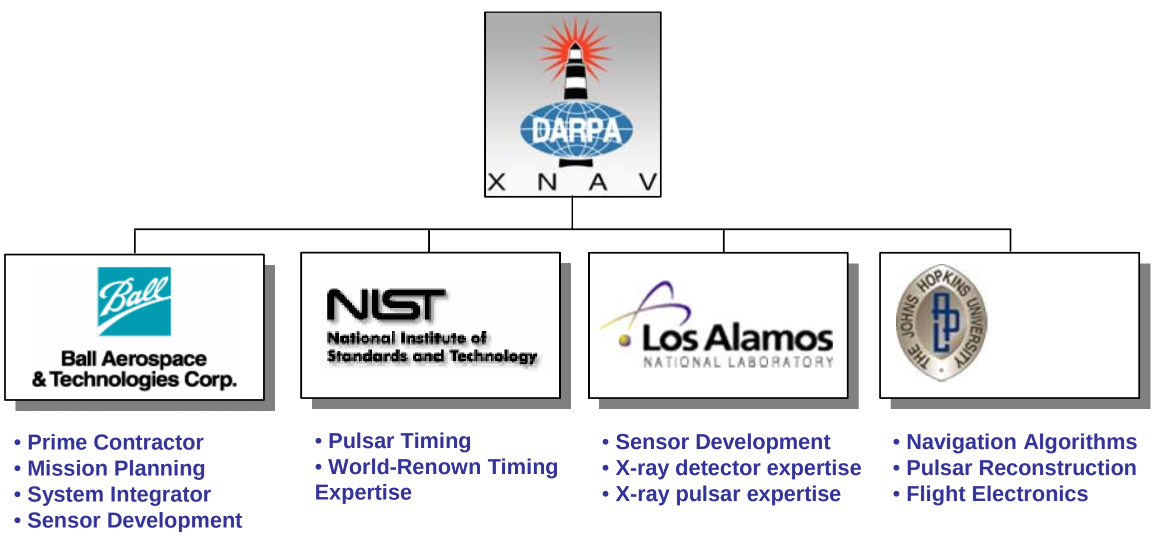

Figure 2-2 XNAV Team and Responsibilities

The primary goal of the XNAV program is to provide an autonomous spacecraft navigation capability with a position accuracy less than 100 m SEP (Spherical Error Probability) anywhere in the solar system. This is a revolutionary navigation capability which may exceed the capabilities of current deep space navigation methods. During the Phase I feasibility study, detailed analyses and hardware demonstrations will be performed to determine the viability of the concept. Four task areas have been established for Phase I of the program,

1) Pulsar Cataloging and Modeling
2) Detector Design, Development, and Characterization
3) Navigation Algorithm Design and Development
4) Integrated System Design and Mission Studies

Some expected results from the study are;

- Development of a high fidelity catalog of candidate sources (stable pulsars and other bright sources)
- Development of new X-ray sensors to meet imaging and timing requirements
- Development of advanced navigation algorithms
- Development of a system design for the XNAV sensor suite
- Evaluate utility for other missions (LEO, GEO, HEO, Lunar, Deep Space). A sample concept of operations (CONOPS) for multiple missions are shown in **Figure 2-1**

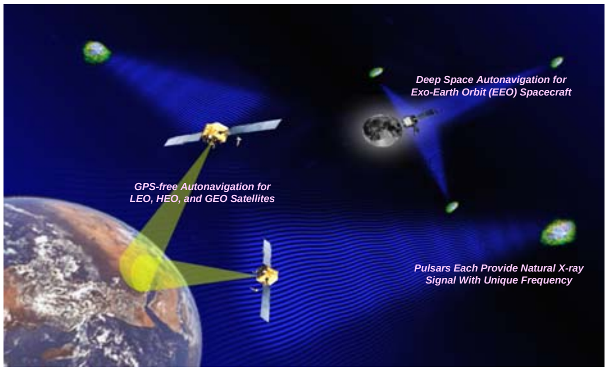

Figure 2-1 Potential XNAV Mission Concept of Operations (CONOPS) [4]

System and sensor design and navigation trade studies are active at this time and will not be discussed in this paper. It is expected that at the completion of the Phase I activities, additional details will be made available in subsequent papers.

2.1.1 X-RAY SOURCE AND NAVIGATION CONSIDERATIONS

There are many X-ray pulsars and other bright sources that have been identified for potential use by the XNAV system. These sources are shown in **Figure 2-3**. **Figure 2-4** is an artist's depiction of what a pulsar may look like. A previous technical paper [8] clearly describes the dynamic processes associated with a pulsar.

> "Rotation-powered pulsars are theorized to be rotating neutron stars that emit electromagnetic radiation along their magnetic field axis. As the star rotates about its spin axis, the radiation appears to *pulse* towards an observer as the magnetic pole sweeps past the observer's line of sight to the star. The pulsations from many of these sources have been shown to be very stable and predictable. [5, 6] These stars emit pulsed, or variable, radiation in all bands of the electromagnetic spectrum, however detection within the X-ray band allows for the development of more compact detectors than other bands, including radio and optical. There are several types of variable X-ray celestial sources, but pulsars, with their stable, periodic, predictable signatures, are the most attractive for use in position determination. [7,8]

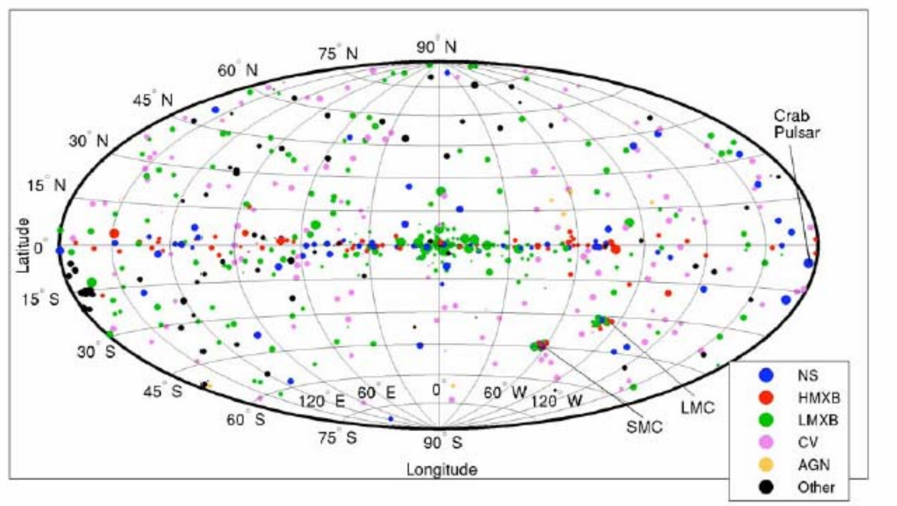

Figure 2-3 X-ray Sources in the Galactic Plane [4]

NS = Neutron Star
HMXB = High Mass X-ray Binary
LMXB = Low Mass X-ray Binary
CV = Cataclysic Variable stars - binary stars containing a white dwarf and a normal star AGN = Active Galactic Nuclei

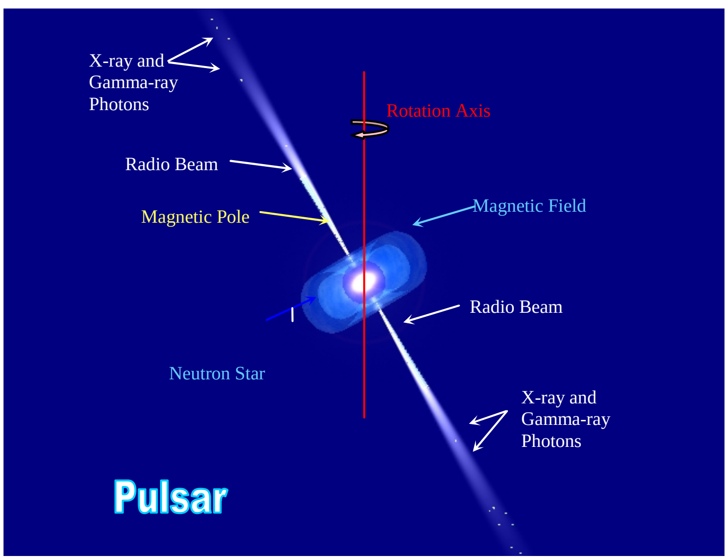

Figure 2-4 Theoretical Pulsar Structure [4]

There are many pulsars that have been identified and evaluated in our galaxy. Their characteristics are well known in the radio band but not in the X-ray band due to atmospheric absorption of X-rays. During Phase I of the program, we plan to compare radio observation data with X-ray data from previous spacecraft missions to determine the correlation between pulse profiles. It should be noted that not all pulsars emit X-rays and radio waves simultaneously. In a recent paper [9], NRL details the limitations associated with radio pulsars and the benefits of using X-ray pulsars.

"These periodic sources are seen both in radio and X-rays, but the radio pulsars are very faint and can only be studied with the world's largest radio telescopes, such as the 305-m Arecibo telescope in Puerto Rico, or the 100-m Green Bank Telescope in West Virginia. The requirement for huge antennas makes a navigation system based on radio observations of pulsars impractical for most conceivable applications. In addition, propagation of radio signals through the interstellar medium results in frequency-dependent delays that set a limitation on achievable accuracy. However, a modest number of pulsars, distinguished by having the most precise known periodicities, emit pulsed X-rays as well. They can be detected by an X-ray instrument that is less than one square meter, far smaller than the antenna size needed for radio detection. The X-ray signal, at effectively infinite frequency, is not affected by the interstellar medium like the radio signal, hence several limitations to the precision of the timing measurements are removed." [9]

There are multiple factors considered in the navigation solution. These include, pulsar intensity (brightness), pulse shape, pulse stability, speed of pulsar rotation, position of the X-ray source with respect to the galactic plane, position knowledge/accuracy of the X-ray source, knowledge / predictability of pulsar glitches, ability of the sensor to obtain a fix on the pulsar and lock onto its signal. The pulsars of greatest interest are the millisecond X-ray pulsars (MXP) because of their timing stability. MXPs are defined as a group of pulsars with spin periods between 1.5 ms and 30 ms and spin slowdowns of less than 10-19 s/s [10]. However, most of these pulsars are weak and may be difficult to detect because of their low energy photons. In addition, most of these sources are centered on the galactic plane which adds to the difficulty of obtaining an attitude solution. A paper written by members of our team [11] clearly describes the challenges of using pulsars for navigation.

> "The periodic pulsations from these sources essentially emulate celestial *lighthouses*, or *clocks*, and can be used as navigation beacons in methods similar to Earth-based navigation systems, such as the Global Positioning System (GPS) and the Global Orbiting Navigation Satellite System (GLONASS). Pulsars are extremely distant from the solar system, which provides good visibility of their signal near Earth as well as throughout the solar system. However, unlike GPS or GLONASS, the distances of these sources cannot be measured such that direct range measurements from the sources can be determined. Rather, indirect range measurement along the line of sight to a pulsar from a reference location to a spacecraft can be computed. Recent studies have presented these concepts, as well as demonstrated some preliminary experimental results. [10, 11] Presented here is the use of these range measurements to recursively update, or correct, the position of a spacecraft in orbit about Earth to provide a continuous, accurate navigation solution. Several orbits are investigated, including spacecraft in LEO, MEO, and GPS orbits, as well as orbits about Earth's Moon." [11]

2.1.2 X-RAY SENSOR AND SYSTEM CONSIDERATIONS

The XNAV sensor suite development is one of the most challenging aspects of the program. There are a multitude of design considerations that need to be accounted for in the final concept. These include,

1) The motion of the on-orbit platform during data collection events
2) Limitations of the sensor field of view (FOV) due to surrounding ISS modules
3) Size and mass of the aperture
4) Effects of the background radiation (charged particles, and galactic cosmic rays) on the sensor SNR (Signal to Noise Ratio)
5) The sensitivity (energy range) of the sensor
6) The speed of the readout electronics
7) Thermal management requirements

8) Sensor power consumption
9) Other relativistic effects
10) Validation of the data received

Additional information may be provided in subsequent papers. The demonstrator payload is scheduled to fly on the ISS Express Logistics Carrier (ELC). Therefore, Manned Safety requirements are imposed on the XNAV mission. BATC is working with NASA to address safety issues early to ensure compliance.

2.1.3 XNAV MISSION APPLICATIONS

As the XNAV program progresses, additional applications are being identified by the technical community. One recent application explored the use of XNAV to provide a GPS-like constellation around the moon. For Phase I, BATC is focusing only on the ISS mission experiment. Other candidate XNAV missions include LEO, GEO, HEO, lunar, and interplanetary missions. A few of the system level navigation considerations for these various missions are captured in **Figure 2-5**.

	LEO	GEO	Interplanetary
• Earth Keplerian Parameters • Solar Keplerian Parameters • Stabilization of Host platform	Yes No Nadir pointing	Yes Yes Nadir pointing	No Yes Spin-stabilized or three-axis
• dω/dt and dΩ/dt (due to inhomogeneous gravity effects)	Yes	Yes	No
• Atmospheric drag • Third-body effects • Solar-radiation pressure	Yes No No	No Yes Yes	No Yes Yes
• Pulsar visibility	Sometimes Obscured	Considerably Less obscured	Seldom obscured

Figure 2-5 System Level Navigation Considerations [12]

3.0 PROGRAM SCHEDULE

DARPA has provided a top-level XNAV schedule of the program that is shown in **Figure 3-1**.

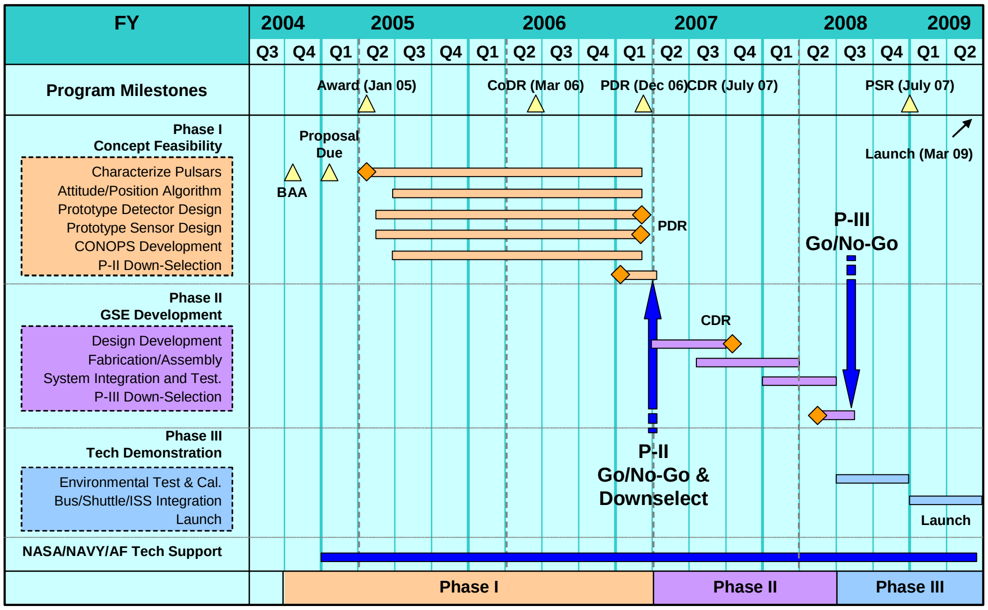

Figure 3-1 XNAV Program Schedule

4.0 SUMMARY AND CONCLUSIONS

The BATC team has many challenges associated with developing a new X-ray based navigation system. During the Phase I feasibility study, we expect to mitigate many of the high risk areas with sensor prototypes and multiple analyses. This system has the potential to revolutionize how interstellar navigation is achieved. It is expected that multiple papers will be presented in the future as this program proceeds forward into a flight demonstration.

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