SEXTANT - Station Explorer for X-ray Timing and Navigation Technology[*][†]

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The Station Explorer for X-ray Timing and Navigation Technology (SEXTANT) is a technology demonstration enhancement to the Neutron-star Interior Composition Explorer (NICER) mission, which is scheduled to launch in late 2016 and will be hosted as an externally attached payload on the International Space Station (ISS) via the ExPRESS Logistics Carrier (ELC). During NICER's 18-month baseline science mission to understand ultra-dense matter though observations of neutron stars in the soft X-ray band, SEXTANT will, for the first-time, demonstrate real-time, on-board X-ray pulsar navigation, which is a significant milestone in the quest to establish a GPS-like navigation capability that will be available throughout our Solar System and beyond. Along with NICER, SEXTANT has proceeded through Phase B, *Mission Definition*, and received numerous refinements in concept of operation, algorithms, flight software, ground system, and ground test capability. NICER/SEXTANT's Phase B work culminated in NASA's confirmation of NICER to Phase C, *Design and Development*, in March 2014. Recently, NICER/SEXTANT successfully passed its Critical Design Review and SEXTANT received continuation approval in September 2014. In this paper, we describe the X-ray pulsar navigation concept and provide a brief history of previous work, and then summarize the SEXTANT technology demonstration objective, hardware and software components, and development to date.

I. Introduction

The ubiquity, reliability, and accuracy of the Global Positioning System (GPS) has revolutionized terrestrial navigation over the past two decades. Space users, within the GPS Space Service Volume (SSV), have also benefited from the abundance of GPS radiometric measurements to autonomously obtain position, velocity and time on-board and in real-time. The use of GPS for

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space navigation is well established in Low-Earth Orbit (LEO) (e.g., [1–3]). More recently, its use has been extended to Geosynchronous Earth Orbit (GEO) and Highly Eccentric Orbits (HEOs), see for example [4–8]. It has also been explored for lunar libration point and lunar transfer orbits (e.g., [9, 10]). Unfortunately, GPS is available only to space users within Earth's vicinity. To enable autonomous navigation for future missions operating far from Earth-based navigation beacons, the Station Explorer for X-ray Timing and Navigation Technology (SEXTANT) will use rapidly spinning neutron stars to demonstrate a GPS-like navigation capability available throughout the Solar System. This technology also holds the ultimate promise of enabling travel beyond our Solar System, to other stars.

SEXTANT is a NASA Space Technology Mission Directorate (STMD) Game Changing Development Program Office (GCD) funded technology demonstration enhancement to the Neutron-star Interior Composition Explorer (NICER) mission. NICER is a NASA Science Mission Directorate (SMD) Astrophysics Mission of Opportunity to the ISS, with launch planned for October 2016, funded by SMD with an STMD cost-share. NICER's fundamental science will probe the interior composition of neutron stars through stellar radius and mass measurements obtained by careful study of the modulation of soft X-ray brightness as the neutron stars rotate. The modulation of these *light-curves* is influenced by relativistic light-bending and Doppler shifts, as well as relativistic effects on the pulsation arrival times, measured at Earth, induced within binary systems. SEXTANT will use the NICER science data stream, when observing millisecond-period neutron stars, to develop measurements, *on-board* and in *real-time*, that will be input into a navigation filter to maintain knowledge of position after receiving an initial state, intentionally degraded, from the NICER GPS receiver.

In this paper, we describe the concept of X-ray Pulsar Navigation (XNAV) and briefly summarize the history of XNAV. Next, the SEXTANT demonstration objectives and requirements are presented. This is followed by an architecture overview that includes details about the NICER instrument and concept of operation. Then, a current project status is given. Finally, the paper concludes with a brief summary and discussion of future work.

I.A. X-ray Pulsar Navigation Concept

Rapidly-spinning neutron stars, *pulsars*, emit powerful, but anisotropic, photon beams across a range of wavelengths, so that to an observer they appear to pulsate, that is, the received emission is periodically modulated at the spin period. One class of pulsars, Millisecond Pulsars (MSPs), rival atomic clocks in timekeeping accuracy and stability on timescales longer than a few weeks. A sequence of phase determinations made by observing these pulsations with a sensor on a space platform provides navigational information to that platform, employing principles similar to those underlying the GPS. Pulsar navigation can be used either by itself or as an augmentation to other methods, such as NASA's Deep Space Network (DSN), to achieve navigation over large volumes of space. In an augmentation mode, a small X-ray system performing pulsar-based navigation on an interplanetary spacecraft could improve accuracy in the plane normal to the line connecting Earth-based transmitters with that spacecraft. Acting alone, a suitably-engineered pulsar navigation system could operate over a volume much larger than the Solar System, extending into nearby interstellar space.

Pulsars have been detected in radio, infrared, visible, X-ray, and gamma-ray wavelength bands. Particular pulsars may be seen in most of those bands or in some bands and not others. From current astrophysical understanding, the X-ray band enjoys advantages for satellite navigation in that fluxes from pulsars of interest, i.e., the best clocks, are sufficiently high to be detected with instrument systems of practical size. NICER, optimized for scientific study of these same pulsar targets, is admirably suited as a receiver for a concept demonstration.

One approach to extracting navigational information from pulsar signals proceeds in two steps. First, the approximate spacetime coordinates of each detected X-ray photon are recorded over an extended observational interval, which need not be continuous but may have interspersed gaps. Next, this collection of event coordinates are batch processed to extract a pulse phase and optionally a Doppler estimate. Then, in the second step, the phase measurements and Doppler estimates are passed to a filtering algorithm that relates them to the spacecraft state through a predictive phase *measurement model* of each pulsar and merges them with a spacecraft orbital dynamics model to form state vector estimates. These predictive models must be provided to the filter externally. In most cases, this *pulsar almanac* is expected to be maintained and provided by a supporting ground system, but, in principle, could be generated on board by a sufficiently advanced XNAV system.

The concept must be grounded in sound astrophysical understanding of the pulsar ensemble, in particular knowledge of which pulsar classes provide the best phase information. This depends upon factors such as the brightness of the various pulsars, their pulse periods, the duty cycles and modulation depth of pulses, and the rotational stability of the pulsar. Each element is determined observationally. The clock stability may be thought of as the accuracy to which the phase can be predicted in the future using a deterministic ephemeris. The clock stability limitation arises from the fact that internal dynamics in the neutron star and torques acting on it produce stochastic phase variations. The level of such noise governs how long into the future pulse phase can be predicted, after which time it becomes stale and must be updated. These considerations govern achievable navigational accuracy for a given measurement paradigm. In the pulsar navigation concept sketched above, ephemeris data are provided from major observing facilities that presently consist almost entirely of radio telescopes on Earth. The radio ephemeris for pulsar phase, period, and period derivative(s) is applied to the X-ray pulsar navigation measurements. Transfer from radio incurs two further sources of uncertainty. First, there is a phase offset between the X-ray and radio pulse that must be calibrated. Second, the radio measurements are themselves subject to an additional noise source, having to do with radio signal propagation through the interstellar medium, to which the X-ray sources are immune. However these penalties are, for now, preferable to the alternative of creating a master X-ray observatory in near Earth orbit to provide the ephemerides. Further algorithmic details are found in [11].

Considering the pulsar populations known today, the X-ray MSP class emerges as the most suitable foundation for pulsar navigation, although at least one particular pulsar not belonging to that class, the X-ray pulsar in the Crab Nebula, provides complementary information, being disadvantaged by a longer pulse period and a higher clock noise level than the MSPs, but more than a thousand times brighter. It can thus provide high-cadence measurements, as long as frequent ephemeris updates are available, while MSPs provide high precision over longer integration times. We now briefly review how X-ray pulsar navigation has evolved.

I.B. X-ray Pulsar Navigation History

Use of radio pulsars as navigation beacons was first considered shortly after their discovery [12]. The idea was later extended to X-rays using the earliest established X-ray pulsars [13] but the achievable accuracy was severely limited by the noise characteristics of the X-ray pulsars known at the time. X-rays do not penetrate the Earth's atmosphere to sea level. Thus, the X-ray form of the concept is inherently limited to operations above atmospheres and perhaps planetary surfaces with thin atmospheres or none, but has the advantage that it permits comparatively small sensors to be used. The first X-ray satellite instrument developed with a specific goal of exploring the feasibility of X-ray satellite navigation techniques was the Unconventional Stellar Aspect (USA) Experiment flown in 1999 on the DoD ARGOS Satellite, under the Space Test Program [14]. This experiment explored a broader vision of X-ray navigation, not limited to use of pulsars for position determination, but also studying use of occultations, which require no pulses and may use bright sources, a technique suitable for satellites in orbits near planets. It furthermore was not limited to position determination but also evaluated X-ray sensors for attitude determination and time transfer. For these applications it primarily conducted feasibility assessment exercises rather than full operational demonstrations.

During the late 1990s X-rays began to be detected from MSPs, which had previously been known only as radio pulsars [15]. This removed the earlier limitation associated with the intrinsic pulsar clock noise but entailed observing a considerably fainter class of X-ray sources. The USA Experiment lacked sufficient sensitivity and on-board timekeeping accuracy to study this source class effectively, but it was recognized that X-ray MSPs would greatly improve the accuracy of an X-ray pulsar-based navigation system, hence the conceptual development path was laid out in paper studies [16, 17] and a patent (US Patent 7,197,381). A DARPA program emphasizing MSP navigation represented the next phase of DoD development and introduced the term *XNAV* for the specific pulse timing based methodology. The deep space navigation application of XNAV described above was also analyzed [18]. During this program the first laboratory facility to simulate X-ray pulsars was built at NASA GSFC and used to test sensor prototypes. As of 2014 the concept of X-ray navigation is being widely discussed, in several other countries as well as the US [19, 20].

As the DARPA program advanced, it became increasingly clear that the detector concept most appropriate for the X-ray MSP population would need to include optics to enhance Signal-to-Noise Ratio (SNR). Optical systems that focus X-rays have been developed for many different astronomical purposes. High performance systems provide full imagery for extended sources or groups of point sources. A by-product of the focusing is that SNR is greatly improved because photons are collected over the full aperture of the focusing system while background is collected only over the much smaller active area of the detector; SNR is enhanced, roughly, by the ratio of those areas. When the goal is to obtain the spectrum or time history of a single source, it is possible to obtain the latter benefit without the cost of the former by using optics of lower performance that can be made low weight as well as low cost. NASA GSFC has broad experience in such designs, dating back to the Broad Band X-ray Telescope, flown on space shuttle Columbia in 1990. A modern, low-cost and low-weight optic combined with a Silicon Drift Detector (SDD) emerged as an excellent design for observing X-ray MSPs for navigational purposes. This same design was also ideal for the science that forms the NICER mission goals in astrophysics. In this way, a scientific mission (NICER) and an engineering demonstration (SEXTANT) became realizable in a single package. Moreover, the driving technical requirements flowing down from the scientific objectives were able to cover the requirements for SEXTANT, i.e., the latter did not levy additional requirements beyond those imposed by the purely scientific mission goals.

II. Demonstration Objective

The SEXTANT technology demonstration objective is to perform *real-time, on-board* XNAV-only orbit determination, via sequential observation of multiple MSPs, see Table 1. In the highly dynamic ISS orbit, SEXTANT will use an intentionally degraded initial orbital position, provided by NICER's GPS receiver, then maintain its orbital position knowledge by processing only XNAV measurements. The demonstration will be considered successful if the on-board position knowledge error reaches $\leq 10\,\mathrm{km}$, worst direction, with two weeks of valid measurements derived from a navigation focused observation schedule. The baseline experiment includes two attempts to achieve this objective: one early in mission operations using ground-based radio observatory derived pulsar timing models, and one later in mission operations using NICER augmented timing models. The performance of the XNAV system will be determined by comparison with the available on-board GPS solution.

If time permits during NICER mission operations, and with complementary observation schedules, a number of additional objectives will be pursued. In line with the primary objective previously stated, a *stretch* primary objective is to attempt to reach $\leq 1\,\mathrm{km}$ on-board position knowledge error, worst direction, with up to 4-weeks of valid measurements from a navigation focused observation schedule. This presents a supreme challenge in the highly dynamic ISS orbit.

The study of long-term pulsar clock stability is a secondary objective that is shared with NICER's fundamental science. Since MSPs rival terrestrial atomic clocks, XNAV observations may be used to support spacecraft time and frequency maintenance, or spacecraft clock synchronization for coordinated measurements over long distances.

Since all NICER photon data will be telemetered to the ground and archived, it will be available for use in ground experiments in which SEXTANT will explore variations and enhancements to its on-board algorithms. Planned ground investigations include exploring the effect on navigation performance of intentionally degrading photon event timestamps resulting from an imperfect spacecraft clock, and attempting to eliminate the need for an initial seed state by batch processing an extended observation sequence—Event times are referenced to GPS time as described in Section IV.A.

III. Requirements

Demonstrating XNAV-only navigation in LEO on ISS is a considerable challenge. Several factors work to limit the available time to observe MSPs: 1) the highly dynamic perturbation-rich ISS orbit, 2) payload mechanical pointing limitations, 3) ISS structural interference and source occultations, and 4) Sun, Earth, and Moon exclusion zones. This is exacerbated by the faintness of the most desirable MSPs for navigation. Consequently, this objective is less than the ultimate potential accuracy of XNAV-only position determination, which is expected to be on the order of hundreds of meters with a NICER-like instrument in lower dynamic environments, e.g., an interplanetary cruise phase.

To achieve SEXTANT's technology objective, a set of basic technical requirements were developed. The requirements, enumerated below, assume a detector capable of providing source and background count rates as specified in Table 1.

Table 1. SEXTANT pulsar catalog with source and background count rates for a NICER-like detector.

Name	Period (P, ms)	Source Pulsed Rate[a] (α, cnts/s)	Total Background Rate[a] (β, cnts/s)
Crab Pulsar	33.51	660.000	13 860.20
B1937+21	1.56	0.029	0.24
B1821−24	3.05	0.093	0.22
J0218+4232	2.32	0.082	0.20
J0030+0451	4.87	0.193	0.20
J1012+5307	5.26	0.046	0.20
J0437−4715	5.76	0.283	0.62
J2124−3358	4.93	0.074	0.20
J2214+3000	3.12	0.029	0.26
J0751+1807	3.48	0.025	0.22
J1024−0719	5.16	0.015	0.20

[a] Source and background count rates for a NICER-like detector configuration include consideration of effective detector area, field of view, energy band, operational regime background radiation, etc.

XNAV-01 The XNAV instrument shall be provided with an initial position and time estimate accurate to 10 km and 1 μs RMS, respectively.

Rationale: Provides for suitable initial state and time.

XNAV-02 The XNAV instrument shall achieve the per-pulsar total background count rates listed in the SEXTANT pulsar catalog (Table 1) within a factor of 2 outside of the South Atlantic Anomaly (SAA) and magnetic poles.

Rationale: Establishes expected instrument rejection performance.

XNAV-03 The XNAV instrument shall achieve the per-pulsar source pulsed count rates listed in the SEXTANT pulsar catalog (Table 1) within a factor of 2.

Rationale: Establishes expected instrument effective collecting area.

XNAV-04 The XNAV instrument shall provide time-tagged photon events with no more than 1 μs RMS error traceable to UTC.

Rationale: Establishes event time-tagging accuracy.

XNAV-05 The XNAV instrument shall observe a sequence of pulsars based on a SEXTANT provided schedule for one 2-week period.

Rationale: For the general case, an observation schedule to support navigation is required. In the specific case of SEXTANT operation within the NICER mission, a science and navigation commensurate schedule will be required, particularly early in the mission.

While these requirements satisfy SEXTANT, they are not specifically levied as elements of the NICER mission requirements because the requirements that drive NICER science objectives meet

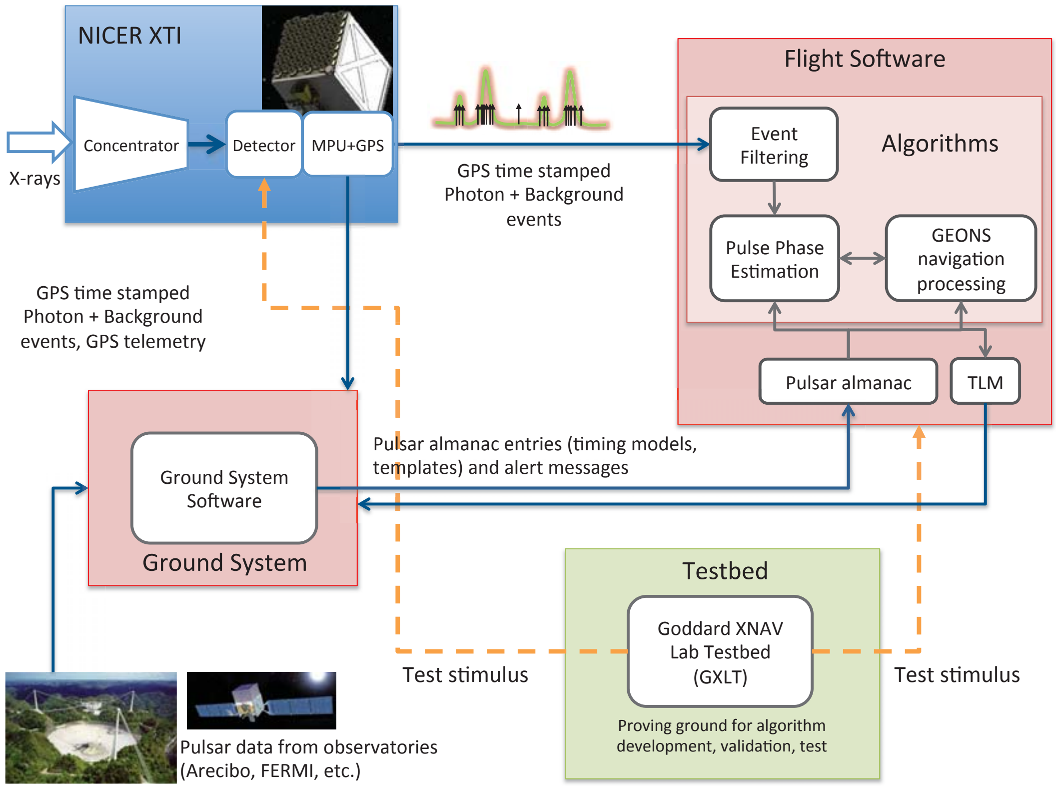

Figure 1. SEXTANT system architecture showing the four main components.

or exceed the SEXTANT requirements specified above. Further, a dedicated period of observing time will be made available wherein SEXTANT objectives receive consideration in optimizing the target observation schedule. The interval will be long enough to realize the requirements given above.

The NICER X-ray Timing Instrument (XTI) is briefly described in Section IV.A. A more detailed description of the instrument that includes a discussion of driving technical and derived requirements can be found in [21].

IV. Architecture Elements

The SEXTANT system architecture is comprised of four main components: 1) the NICER XTI, 2) the flight software and algorithms, 3) the ground system, and 4) the ground testbed; see Figure 1 and [22]. In this section, we give a brief description of these elements.

IV.A. X-ray Timing Instrument

NICER's XTI is an array of 56 identical X-ray telescopes optimized for observations of neutron stars with high time resolution, good throughput, and low background. The XTI is described in more detail in [11, 21].

Briefly, the XTI operates in the $0.2 - 12\,\mathrm{keV}$ X-ray band with a peak effective area of $1800\,\mathrm{cm}^2$ at

1.5 keV. The detectors are Amptek, Inc. SDDs with dual, fast and slow, readout electronics chains that simultaneously provide excellent time resolution (100 ns) and energy resolution (120 eV). The single-reflection optics are highly efficient and minimize radiation backgrounds by concentrating incident X-rays from a 10 cm diameter aperture down to a 2 mm diameter detector area. The expected background rate is < 0.2 counts per second in the critical $0.4 - 2$ keV band. Because the instrument does not require good imaging performance, the additional size, weight, and complexity and poorer efficiency of true imaging optics are not needed. The modularity of the design facilitates scaling to a large range of eventual applications, e.g., [23].

Event times recorded by the XTI are referenced to GPS time provided by NICER's GPS receiver system, which gives absolute timing accuracy referenced to UTC to an accuracy of 100 ns RMS. In a future XNAV application outside of Earth orbit, this simplification would not be available. Such an XNAV system would require a stable clock that is either synchronized with UTC time via two-way time transfer, or steered based on XNAV pulsar observations to a pulsar-based time standard. This additional degree of freedom can be accommodated by observing more than the minimum 3 pulsars required to determine position alone.

IV.B. Algorithms and Flight Software

Photon events, timestamped with GPS time, with associated pulse heights, which are proportional to photon energy, are the fundamental data provided by the NICER XTI to the SEXTANT X-ray Pulsar Navigation Flight Software (XFSW) application. The observed photon events are modeled as the arrival times of a Non-Homogeneous Poisson process (NHPP) with time varying mean cumulative count function. The photon arrival process at the detector is modeled as a delayed version of that at a hypothetical reference observatory, e.g., located at the Geocenter or at the Solar System Barycenter (SSB), with a delay given by the light propagation time of the pulse wavefront moving from the detector to the reference observatory. The relationship between the rate of the arrival process at the spacecraft and that at the reference observatory furnishes a measurement equation that connects the statistical model for the fundamental photon arrival process to the desired spacecraft state parameters. The phase evolution at the reference observatory is provided by the pulsar timing software Tempo2 [24]. Section IV.D provides more detail SEXTANT's use of Tempo2.

The XFSW implements the XNAV algorithms in C and runs as a single application hosted by the NICER Instrument Flight Software (IFSW), which is based on the NASA GSFC Core Flight System (CFS) [25]. As an application within the IFSW, it receives commands and sends telemetry via the CFS provided publish-and-subscribe software message bus. These messages include the photon events generated by NICER's XTI, the ground commands to configure and manage the on-board pulsar almanac, and the GPS receiver position, which is used to initialize the orbit propagator. The XFSW algorithms are included in the application as a shared library containing two core components: photon processing algorithms, specially developed for SEXTANT, and navigation filter software based on an XNAV-enhanced version of the Goddard Enhanced Onboard Navigation System (GEONS) flight software package [26]. The shared library allows the flight source code to be tested from within MATLAB via the C shared library interface. More details about the XNAV algorithms and the XFSW are given in [11].

SEXTANT XFSW operates as follows. Several MSPs from the SEXTANT catalog are observed in a sequence taking into account observation schedule and visibility constraints. After accumulating

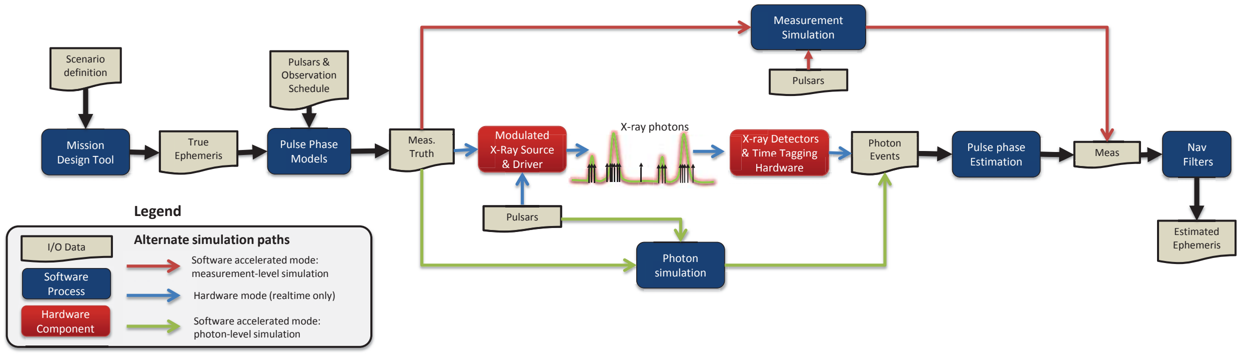

Figure 2. SEXTANT ground testbed architecture showing the three simulation flows from orbit simulation through truth measurement simulation, photon processing and navigation filtering algorithms. The three levels of simulation split at measurement truth and primarily differ in the way estimates are produced. In Level 0, red (upper path) arrows, the measurements are simulated using the measurement model. In Level 1, green (lower path) arrows, the measurements are produced from software simulated photon events. In Level 2, blue (central path) arrows, the measurements are produced from HWIL simulated photon events.

a sufficient number of photon events from a given MSP, the collected events are batch processed to extract pulse phase and Doppler measurements. These measurements are then passed to the GEONS navigation filter, where they are blended with models of the spacecraft dynamics to update an estimate of the spacecraft state.

IV.C. Ground Testbed

The GSFC X-ray Navigation Laboratory Testbed (GXLT) is a unique hardware and software test environment developed in support of the SEXTANT mission. The GXLT leverages several GSFC Guidance, Navigation, and Control (GN&C) software tools and X-ray source and detector technologies, and allows for rapid, high-fidelity, end-to-end simulation and performance evaluation of various spacecraft XNAV scenarios.

The overall end-to-end simulation architecture of the SEXTANT ground testbed, depicted in Figure 2, provides three simulation process flows which are indicated by the colored arrow paths. A simulation scenario definition specifies the simulation level and length, X-ray detector parameters, observation schedule that takes into account visibility constraints and observation times, pulsar target list and their models, a truth ephemeris file, event simulation options, photon processing algorithms, and orbit propagator parameters and navigation filter options.

The three simulation process flows, or *levels*, differ primarily in the fidelity and way XNAV measurements are estimated. The simulation levels are described below.

Level 0: Pulsar pulse phase and Doppler measurements are generated by the XNAV measurement model used by the navigation filter. Noise is intentionally added to these measurements based on expected uncertainty in generating the phase and Doppler estimates from the photon data. Simulation of measurements is a standard operating procedure for fast simulations and for navigation performance evaluation, i.e., no hardware-in-the-loop. This flow is indicated by the red (upper path) arrows in Figure 2.

Level 1: Measurement generation fidelity is increased by simulating the photon arrival process in software, then extracting the realized pulse phase and Doppler estimates. This flow

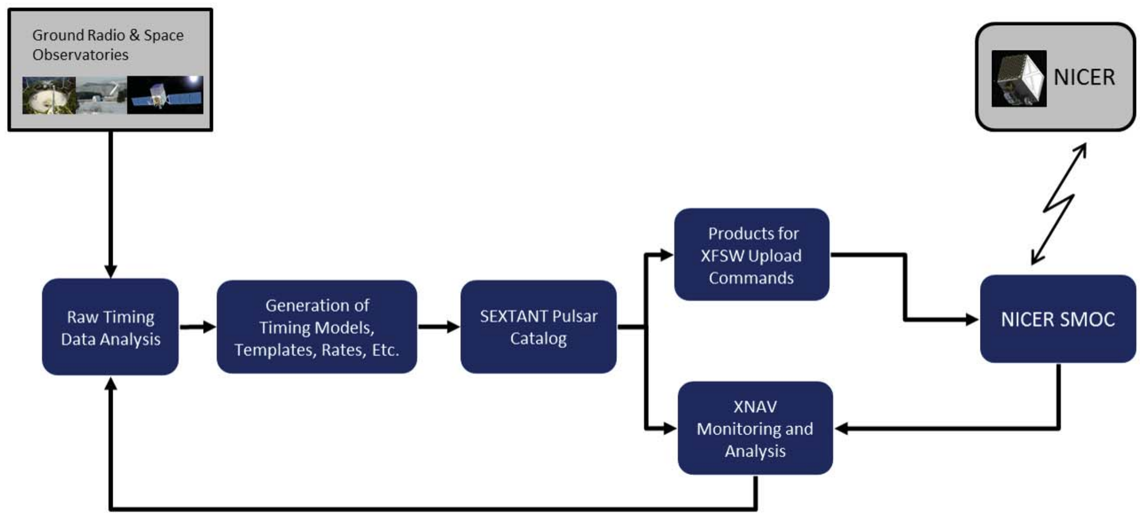

Figure 3. SEXTANT Ground System: Pulsar catalog and almanac maintenance process.

is indicated by the green (lower path) arrows in Figure 2.

Level 2: Measurement fidelity is further increased by replacing the software simulated photon process with a Hardware-in-the-Loop (HWIL) process obtained from the GXLT X-ray pulsar simulator hardware, which is driven by various XNAV pulsar observation scenarios. This flow is indicated by the blue (central path) arrows in Figure 2.

More detailed descriptions of the simulation levels along with the various software and hardware components is given in [11, 27].

IV.D. Ground System

The NICER ground system will reside in a Science Mission Operations Center (SMOC) at NASA GSFC, and will have responsibility for the health and safety of the NICER payload, as well as the scheduling of observations in a manner designed to meet the primary mission science objectives. The SEXTANT ground system is comprised of two components: a monitoring and trending element, which resides within the NICER SMOC, and an external component that maintains the pulsar almanac and provides scheduling recommendations to NICER. Since the primary pulsar targets are common between NICER and SEXTANT, scheduling needs can be met within the constraints of NICER's nominal operations concept.

The primary function of SEXTANT's ground system is to generate and maintain the pulsar information needed to support the XNAV demonstration objectives. This includes parameterized pulse timing models, polynomial-based pulse phase predictions used by the flight software, X-ray profile templates, and count rate estimates. The ground system receives pulsar timing data from ground-based radio telescopes, X-ray telescopes, and NICER itself. The SEXTANT ground system also collects telemetry data and analyzes it for navigation performance monitoring purposes, see Figure 3.

The SEXTANT pulsar catalog, consists of pulsars that have been identified as suitable for navigation. The pulsar selection criteria are based on predictive accuracy of the timing model and the precision of Time-of-Arrivals (TOAs) measured with XTI in a 30 minute observation, which is determined from the X-ray brightness, pulse period, lightcurve shape, and unpulsed background rate. The current SEXTANT pulsar catalog contains 11 pulsars, shown in Table 1 and Figure 4, and will be supplemented by new pulsars discovered and characterized before launch and by NICER once operational.

The SEXTANT ground system uses the TEMPO2 pulsar timing software [24, 28] to generate timing models by fitting parameterized models to measured radio and X-ray pulse TOAs. During SEXTANT operations, the ground system will measure the phase relationship between the radio and X-ray templates and track variations in the pulsar dispersion measure to maintain alignment.

The TEMPO2 timing model parameters are not suitable for direct use by the flight software due to computational complexity. Instead, we use TEMPO2 in its predictive mode to generate piecewise polynomial approximations to the full timing model that can be rapidly evaluated. These polynomials, together with astrometric parameters estimated as part of the timing model update, comprise the pulsar almanac that will be uploaded to the XFSW at regular intervals.

V. Concept of Operation

The NICER XTI will be attached to and operate from the ISS. While there are more than 200 currently identified and astrophysically interesting targets for NICER, the number of MSP targets of interest for SEXTANT, shown in Figure 4 and Table 1, is considerably smaller. As stated in Section II, navigation measurements will be developed by sequentially observing these MSPs.

In the following, the concept of operations is described.

V.A. Launch and Installation

NICER is planned to launch in October 2016, and will arrive at ISS on SpaceX, Inc.'s twelfth resupply mission via the Falcon 9 and Dragon vehicles. Once berthed, NICER is installed robotically via the Space Station Remote Manipulator System (SSRMS), or robot arm, and the Special Purpose Dexterous Manipulator (SPDM), or Dextre. During this process, NICER must be able to survive for at least 6 hours without power, when provided sufficient notice to allow for pre-heating of the payload. The robot arm and Dextre will transfer NICER to its operational location, Site 7 on ELC 2, which is zenith, outboard, and ram on ISS. Once the payload Flight Releasable Attachment Mechanism (FRAM) is mated to the ELC 2's FRAM and powered on, engineering assessment will begin. Assessment will continue through deployment and science calibration of the instrument. Once commissioned, primary mission operation will commence.

V.B. Observing Strategy

SEXTANT will have two modes of operation during the NICER mission. Whenever NICER is observing MSPs, SEXTANT will attempt to make X-ray pulsar measurements and produce a navigation solution in an opportunistic mode. There will also be a dedicated two week window in

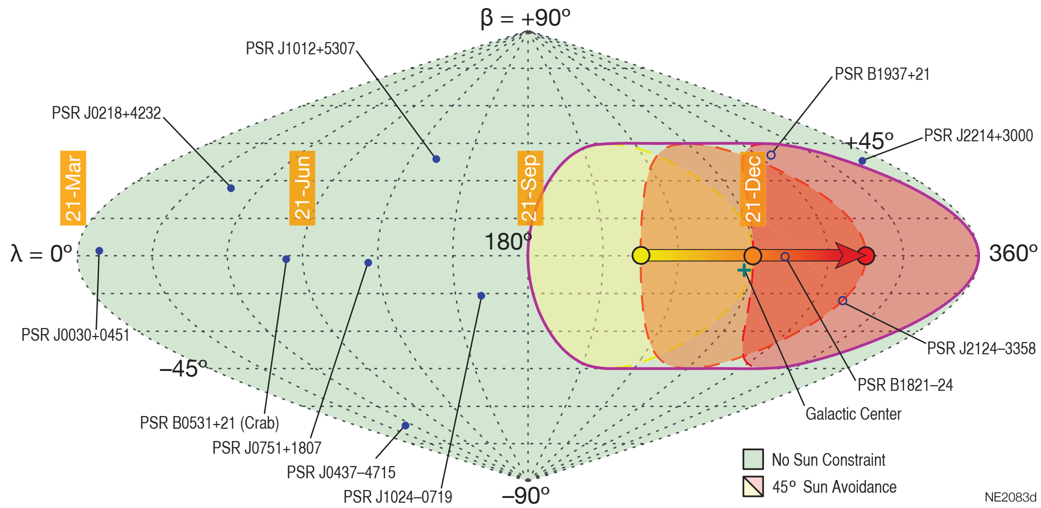

Figure 4. The sky locations, in ecliptic coordinates, of SEXTANT's top 10 navigation targets, and the Crab pulsar, are labeled around the figure and indicated as blue circles. The enclosed purple region represents the effect of a 45° Sun avoidance angle on a 3-month period, centered on December 21, with the exclusion zones shown at the beginning (yellow), middle (orange), and end (red). Targets that are unavailable due to Sun avoidance constraints appear as unfilled blue circles, while targets that remain visible during the period are filled.

which SEXTANT will directly influence the observation schedule in order to achieve the previously stated technology demonstration objective. The schedule must provide adequate observation time for each pulsar while obeying the visibility constraints of the pointing system. A navigation focused observation schedule will be developed to maximize navigation performance during this two week window.

Typical observation times will range from 10 min to several hours to produce navigation measurements. Ideal observation windows are often broken up by visibility restrictions either due to physical blockage of the pulsars or hardware constraints. For example, in a 90 minute ISS orbit, the Earth can block the line of sight to a pulsar for up to 45 minutes. Annually, the portion of the celestial sphere in the neighborhood of the Sun is also blocked from view of NICER, see Figure 4. Pointing restrictions from the hardware include gimbal actuator limits and ISS structure exclusion zones.

Even with these visibility restrictions, generally, at least one pulsar is available for observation. Careful selection of pulsar sequencing in this challenging environment will produce a good navigation solution. The final observation schedule is created by weighing the impact of pulsar availability against the navigation quality of the measurements produced. Verification of the schedule's impact on navigation performance is done in the high fidelity end-to-end simulation environment, see Section IV.C. Initial results have shown navigation performance meeting or exceeding SEXTANT's goals [11].

V.C. Ground System Operations

The SEXTANT ground system will receive telemetry which will be input into the monitoring and trending functions located in the NICER SMOC.

On a monthly cadence, the SEXTANT ground system will retrieve new radio and NICER pulse TOAs for all catalog pulsars, then update the pulsar almanac. More frequently, a new pulsar upload ephemeris will be generated and sent to the XFSW. The upload period is expected to be weekly, except for the Crab pulsar which requires more frequent updates.

VI. Current Status

The NICER mission was formally selected for Formulation in April 2013 after completing Phase A, Concept and Technology Development [29], and holding a very successful Phase A site visit in January 2013 conducted by a standing review board. Proceeding to Phase B, Preliminary Design and Technology Completion, NICER/SEXTANT successfully completed a Preliminary Design Review (PDR) in December of 2013. NICER's Key Decision Point (KDP)-C review was held in late February 2014, and shortly there after, NICER was confirmed to proceed to Phase C, Final Design and Fabrication. Recently, NICER/SEXTANT successfully passed a Critical Design Review (CDR) in September 2014, after completing the design. While completing the XTI design, a number of Engineering Test Units (ETUs) were developed and subjected to preliminary environmental testing, e.g., X-ray Concentrator (XRC), detector packaging. Currently, NICER is preparing for its ISS Phase II Safety Review.

The initial version of the SEXTANT XFSW was delivered to and integrated with the initial build of the NICER IFSW in April 2014. IFSW Build 1 testing commenced in June 2014 and will continue through November 2014. During the early testing, an XFSW clean-up build was delivered to and integrated with an IFSW Build 1.1, which was used for continued testing. Initial IFSW testing was successfully performed on a Commercial Off-The-Shelf (COTS) development version of the flight processor. Supporting documentation accompanying the initial XFSW software included: the Algorithm Description Document (ADD), the software Version Description Document (VDD), and the Command and Telemetry Interface Control Document (ICD). Much of the content of the ADD can be found in [11]. Currently, NICER IFSW Build 1 testing is transitioning to an Engineering Model (EM) of the flight processor.

VII. Summary and Future Work

In this paper, we described the SEXTANT technology demonstration and its primary objective to perform real-time, on-board, orbit determination using XNAV-only measurements, while hosted on the NICER XTI payload. The SEXTANT demonstration will be a technology first, and XNAV holds the promise of a GPS-like capability available throughout the Solar System and beyond.

The central elements of the architecture established to achieve this demonstration have been presented, along with a description of the operations concept. Finally, a brief review of NICER and SEXTANT's progress has been given, including their current status.

A significant strength of this technology demonstration is the extensive simulation development that preceded the current flight work. The unique SEXTANT ground testbed, which includes end-to-end software capability as well as hardware-in-the-loop capability using dynamically modulated X-rays, has been used to establish, with high confidence, that this demonstration will successfully complete the primary objective.

In the near-term, the second flight build of the SEXTANT XFSW will be integrated in the second

IFSW build in early March 2015. NICER IFSW Build 2 testing will begin in mid-April 2015 and continue through August 2015. IFSW system testing will continue in payload integration and test through early 2016. In parallel with the flight software work, ground system development and coordination with NICER will continue through November 2015. Combined ground system testing will take place from late November 2015 to mid-March 2016. This work will culminate in a launch in mid-October 2016, and after a successful commissioning and calibration phase, NICER will commence mission operations, so enabling the SEXTANT technology demonstration.

In the longer-term, the wealth of data provided by SEXTANT will be essential in maturing XNAV technology for operational use in both flight and ground segments. Leveraging these data with the unique SEXTANT ground testbed will enable the study, with unprecedented fidelity, of XNAV performance for infusion of the technology into future missions.

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