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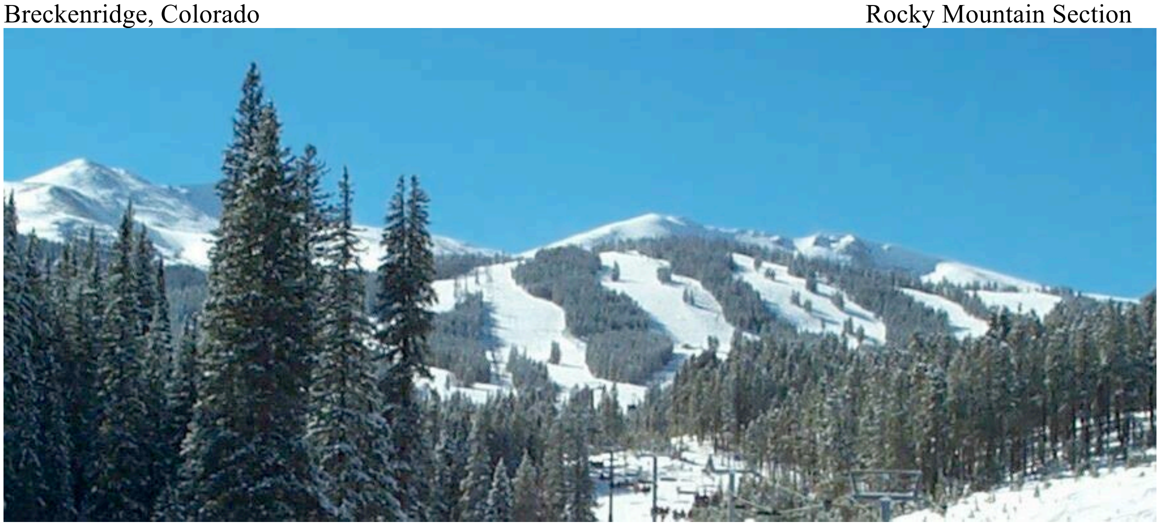

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THE ROLE OF X-RAYS IN FUTURE SPACE NAVIGATION AND COMMUNICATION[*,†]

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Fotis Gavriil[‡‡], Zaven Arzoumanian[§§]

Abstract

In the near future, applications using X-rays will enable autonomous navigation and time distribution throughout the solar system, high capacity and low-power space data links, highly accurate attitude sensing, and extremely high-precision formation flying capabilities. Each of these applications alone has the potential to revolutionize mission capabilities, particularly beyond Earth orbit. This paper will outline the NASA Goddard Space Flight Center vision and efforts toward realizing the full potential of X-ray navigation and communications.

INTRODUCTION

The next decade promises exciting and potentially revolutionary applications of X-rays for space communication and navigation. This will be enabled by existing and emerging technologies in X-ray detectors, commandable sources, and optics. In this paper, we discuss some of the driving forces behind this coming revolution and work at NASA Goddard Space Flight Center (GSFC) that will help pave the way. At the center of this recent technology work is the Neutron-star Interior Composition ExploreR (NICER)/Station Explorer for X-ray Timing and Navigation Technology (SEXTANT) mission—in Phase A through the Spring of 2013—which proposes to bring a powerful X-ray timing instrument to the International Space Station (ISS) to demonstrate, for the first time, on-orbit X-ray Pulsar Navigation (XNAV) and X-ray Communication (XCOM).

THE PROMISE OF X-RAYS

The utility of X-rays for space communication and navigation arises from the following facts: there exist interesting and useful celestial objects with emissions in the X-ray band, the diffraction and penetrating properties of X-rays enable unique applications, and there are existing and emerging technologies for efficiently processing X-rays.

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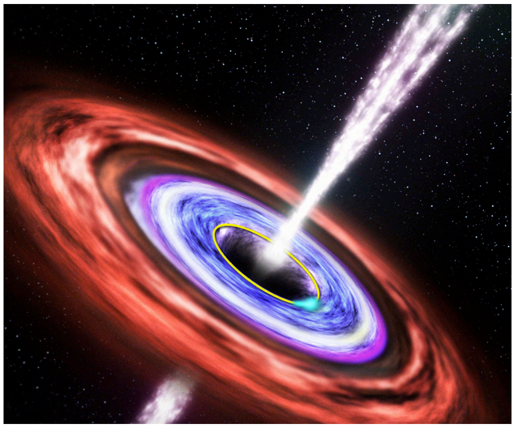


Figure 1: Artist's concept of massive black hole Swift J1644+57 discovered March 28, 2011 by NASA's Swift spacecraft.

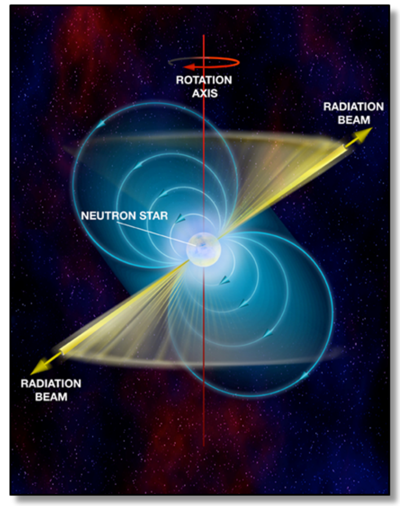


Figure 2: Artist's concept of spinning neutron star with non-coaligned radiation and rotation axes.

Celestial X-ray sources

There are numerous natural celestial objects that are bright sources of X-ray emissions. Black holes, as envisioned in Figure 1, are one such source. Formed through gravitational collapse of very massive stars at the end of their life, black holes can continue to grow by absorbing surrounding matter. This matter forms an accretion disk that can power relativistic jets, perpendicular to the disk, in which particles are accelerated to nearly the speed of light and produce strong X-ray emissions. A second X-ray emitting stellar remnant is the neutron star. Like black holes, neutron stars also form from gravitationally collapsing stars at the end of their life, but lack sufficient mass to become black holes. Often during collapse, conservation of angular momentum will cause the neutron star to rotate rapidly. These highly magnetized, rapidly rotating neutron stars [1], also called *pulsars*, emit a beam of radiation that appears to a distant observer as pulsations at very precise intervals, much like a lighthouse, see Figure 2. A subset of pulsars called Millisecond Pulsars (MSPs) have highly stable pulse timing characteristics that rival atomic clocks in their time-keeping accuracy and stability on long timescales. These MSPs provide numerous signal sources, distributed throughout the galaxy, that are observable from anywhere within the solar system. The soft X-rays emitted do not suffer dispersion in the interstellar medium. In addition, the source distances and properties of X-rays make them very difficult to jam or deny. These properties suggest the feasibility of X-ray Pulsar Navigation (XNAV), and the use of MSPs as navigation beacons throughout our solor system and beyond.

X-ray properties

The extremely short wavelength of X-rays means that they can, in principle, be transmitted and received in very tight beams with very small end terminals. In general, antennas and optics of physical dimension D for transmitting and receiving electromagnetic signals of wavelength λ are subject to a diffraction limit λ/D in their achievable resolving power and beamwidths. Just as optical communications take advantage of these diffractive properties to achieve performance enhancements over Radio Frequency (RF) systems, X-ray communications systems could provide still higher angular resolution and tighter beams to enable reduced transmit power and increased data rates. The tighter beams, for in-space communications, result in reduced receive beam footprints, and provide for considerably more secure physical links. In order to use X-rays for terrestrial, in atmosphere, applications, higher energies are required. At these energies, the penetrating capabilities of X-rays enable the possibility of communications in previously unavailable regimes, e.g. through RF blocking plasma sheaths experienced by hypersonic vehicles, and obstructing materials including RF shielding.

Technologies

Many key technologies for processing X-rays exist or are under rapid development. Efficient, low-cost, non-diffraction-limited X-ray optics are a mature technology. Silicon based X-ray detectors can be made relatively small and improvements in miniaturization of electronics and materials continue. To enable communication via X-rays, commandable or modulatable X-rays sources are required and for efficient operation, such sources must have a fast switching response and emit no X-rays when switched off. Traditional electron impact X-ray sources have very slow modulation timescales on the order of one second or more. Gendreau et al. [2] describe the development of a new kind of electron impact source, the Modulated X-ray Source (MXS), which uses an Ultraviolet (UV) Light Emitting Diode (LED) to liberate photoelectrons from a photocathode, which are then accelerated toward a target at high potential. Thus, modulating the LED output modulates the photoelectron flux, which produces the modulated X-rays. The MXS X-ray output modulation is mostly limited by the LED. Commercially available LEDs support switching timescales on the order of nanoseconds, which make the MXS useful as an XCOM transmitter. Future enhancements will lead to XCOM systems of comparable or higher performance than optical systems.

Finally, largely due to investments by the semiconductor industry in X-ray and extreme ultraviolet lithography, diffraction-limited X-ray optics (e.g., [3]) are an emerging technology that will extract the full potential of X-ray space technologies by focusing X-ray transmitters and receivers. Diffraction limited X-ray optics will enable ultra long-range, high-efficiency high-capacity XCOM links, improve sensor signal to noise ratios, and enable new sensors for high precision attitude determination and relative navigation. Ultimately such Guidance, Navigation, and Control (GN&C) technology will enable revolutionary astrophysics applications including multi-pixel imaging of stars and even event-horizons of black holes [4]. Figure 3 shows how these technologies connect to the many objectives, with Figure 4 showing a projected timeline to reach maturity.

The remainder of the paper focuses on ongoing work at NASA GSFC to advance XNAV and XCOM technologies, including their first on-orbit demonstration as the SEXTANT mission, a proposed enhancement to NICER. The paper is organized as follows. First, we provide a description of the NICER/SEXTANT mission including its payload and primary goals. Next is a review of the concepts and prior research behind XNAV, followed by a description of the GSFC X-ray Navigation Laboratory Testbed (GXLT) developed in support of SEXTANT's XNAV demonstration. After this, we discuss a conceptual practical XNAV sensor for deep space exploration missions, and present some GXLT simulation results. Next, we discuss XCOM and its proposed demonstration, including current preparation work, and layout a technology path

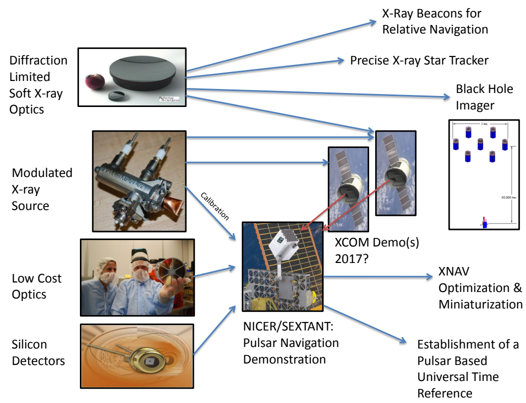


Figure 3: Map of technologies and applications.

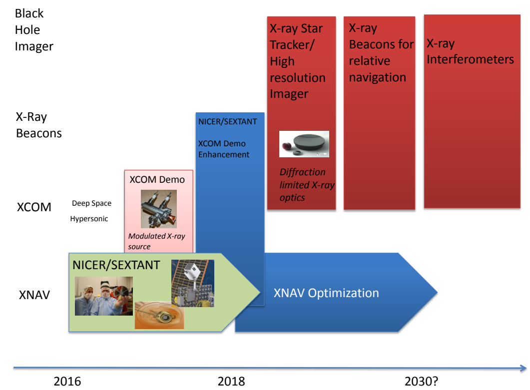


Figure 4: Projected timeline for technology maturation.

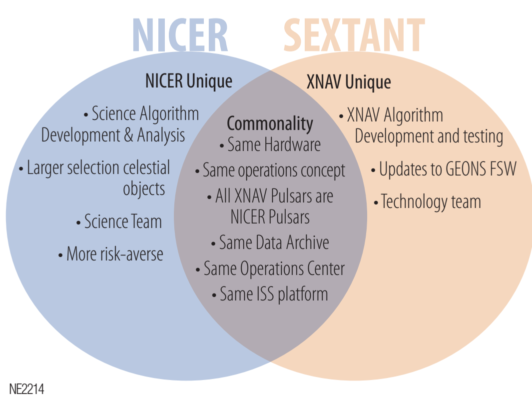


Figure 5: NICER/SEXTANT commonality.

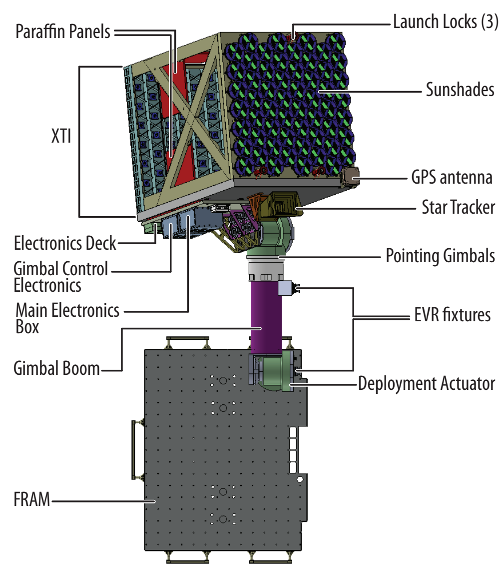


Figure 6: NICER/SEXTANT ISS payload reference representation.

for a practical XCOM system. Finally, we discuss future work and present concluding remarks.

NICER/SEXTANT

In the spring of 2013, NASA GSFC will be completing Phase A for the proposed Neutron-star Interior Composition ExploreR (NICER) mission. NICER's primary objective is to study neutron stars through phase-resolved spectroscopy. The mission will deliver an advanced X-ray timing instrument, Figure 6, to the ISS, which will operate for at least 18 months. NICER will provide more than an order-of-magnitude improvement in timing performance over prior timing missions, and will open up new discovery space in time-resolved X-ray astrophysics. NASA's Science Mission Directorate (SMD) funds the bulk of this mission, which if approved to go beyond Phase A, will launch in December 2016. In parallel, NASA's Office of the Chief Technologist (OCT) has committed to provide additional support under the Station Explorer for X-ray Timing and Navigation Technology (SEXTANT) program to use the same NICER hardware with upgraded algorithms to provide a first demonstration of real-time, on-orbit absolute X-ray Pulsar Navigation (XNAV). This unique partnership is made possible through a substantial overlap of hardware and mission operations, Figure 5. A follow-on technology enhancement will for the first time demonstrate on-orbit XCOM. The following sections describe the NICER/SEXTANT XNAV and XCOM demonstrations and current supporting work, beginning with a brief overview of XNAV concepts.

X-RAY PULSAR NAVIGATION

The stability, distribution, and propagation characteristics of the pulsed signals from millisecond X-ray pulsars make them useful as beacons for absolute and relative spacecraft navigation similar to man-made radio navigation beacons such as those comprising the Global Positioning System (GPS) space segment. This fact was immediately recognized upon the initial discovery of radio Pulsars in 1967 [5], and was reinforced by the subsequent discovery of Pulsar emissions in the X-ray band, and the realization of the benefits of X-rays for space navigation. There has been a significant body of research, funded by the likes of NASA, Defense Advanced Research Projects Agency (DARPA), and National Institute of Standards and Technology (NIST), investigating the potential for solar-system wide absolute and relative XNAV and development of an X-ray pulsar based timescale (XTIM) [6–16]. This work includes recent notable doctoral dissertations focused on XNAV including those of Hanson [8], Sheikh [10] and Emadzadeh [17]. XNAV has the potential to become an enabling technology for very deep space exploration missions and an important augmentation to NASA's Deep Space Network (DSN), the current standard for interplanetary navigation and communication. Early studies estimated that XNAV could achieve three dimensional position accuracy of 150 km [6, 7], while recent estimates incorporating technology improvements in detectors and modeling have estimated kilometer level or better [10, 13].

The predictability of MSP timing signals forms the basis for the XNAV concept. Observed from a hypothetical detector at a location—typically the Solar System Barycenter (SSB)—fixed relative to the X-ray source, the phase of the received signal pulses can be accurately described by a simple polynomial model

$$\phi_{\mathrm{ssb}}(t) = \phi_{\mathrm{ssb}}(t_0) + (t - t_0)f_0 + \frac{1}{2}(t - t_0)^2 f_1, \tag{1}$$

known as the *pulsar spin equation* or *pulsar spin-down law*, where t is a "barycentric coordinate time" and f_0 and f_1 are the pulsar frequency and frequency rate. Such models are fit to data collected from international radio and X-ray observatories and published by the astrophysics community (e.g., the Australia Telescope National Facility (ATNF) [18]) along with best estimates of direction to the source, data on timing irregularities, etc.

Observed from a detector located on a spacecraft in motion relative to the reference point at the SSB, the phase of the received pulsed signal will be shifted relative to that at the SSB by the light-time-delay, τ. To first order, τ is given by

$$\tau(t) = \frac{\hat{\mathbf{n}} \cdot \mathbf{x(t)}}{c}, \tag{2}$$

where $\mathbf{x}(t)$ is the spacecraft's position in barycentric coordinates, $\hat{\mathbf{n}}$ is the unit direction to the pulsar, and c is the speed-of-light in a vacuum. That is, the pulse phase at the spacecraft can be related to model (1), by

$$\begin{aligned}\phi_{\text{sc}}(t) &\triangleq \phi_{\text{ssb}}(t+\tau(t)) \\ &= \phi_{\text{ssb}}(t+\hat{\mathbf{n}}\cdot\mathbf{x}(t)/c),\end{aligned} \tag{3}$$

which can serve as a *measurement equation* connecting the model for the pulse arrival process to the desired spacecraft state $\mathbf{x}$(t). Given the measurement model and statistical/dynamical models for the spacecraft motion, estimation of the spacecraft state can be achieved using a variety of general techniques from statistical estimation and filtering theory.

NASA GSFC'S X-RAY NAVIGATION LABORATORY TESTBED

The NASA GSFC X-ray Navigation Laboratory Testbed (GXLT), developed in support of the SEXTANT mission, is a unique hardware and software test environment, which leverages several GSFC GN&C software tools, and allows for rapid high-fidelity end-to-end simulation and performance evaluation of various spacecraft XNAV scenarios. Figure 7 shows the end-to-end simulation flow with its alternate modes of operation shown as branches in the flow path. We walk the reader through the central path or Hardware-in-the-Loop (HWIL) MSP emulation mode (referred to as *Modeling Scheme 2* in [21]) next, but refer the interested reader to Winternitz et al. [21] for a more detailed description of the GXLT design and capabilities.

The GXLT simulation flow begins with a definition of an XNAV scenario. This includes description of the spacecraft orbital parameters, pulsar description files, pulsar observation schedule, estimation and filter options. Next, a mission design tool (Goddard's General Mission Analysis Tool [22]) is used to generate a spacecraft truth ephemeris from which a set of truth XNAV observables at the spacecraft X-ray detector are obtained. The truth phase and Doppler observables, along with the Pulsar descriptions and observation schedule, are input to the GXLT hardware MXS driver electronics. The MXS driver produces a precision current signal proportional to the pulsar-of-interest instantaneous count rate (or lightcurve) which is modulated by the spacecraft dynamics. This signal is used to drive the input LED to the MXS [2] which results in the production of X-rays with count rates proportional to the input signal. The X-rays travel across a short channel and impinge on the detector/time-stamping module to produce a sequence of X-ray photon detection event times, the fundamental data of the XNAV receiver. The photon events are grouped into batches and processed by parameter estimation algorithms to extract pulse phase and Doppler measurements. These measurements are then passed to the spacecraft Navigation filter (GSFC's Orbit Determination Toolbox (ODTBX) [23] or Goddard's Enhanced Onboard Navigation System (GEONS) [24]) whose output is an estimated spacecraft ephemeris which can be compared to the truth ephemeris generated earlier in the simulation process flow to evaluate performance.

The GXLT also offers two alternate, faster-than-real-time methods for simulating XNAV measurements which are more convenient for use in long-term simulations. These modes are described in detail in [21]. As shown in Figure 7, the interfaces between each major process step are intermediate data files. These file formats have been standardized as described in the

Beyond a measurement equation, the measurement model should describe the statistics of the measurements (often assumed to be additive noise). Developing an accurate statistical model depends on methods for processing the raw observables and many other considerations. The description here is intentionally brief, but we refer the interested reader to [19, 20, 12, 21], for example, for further detail on the statistical models for XNAV measurements.

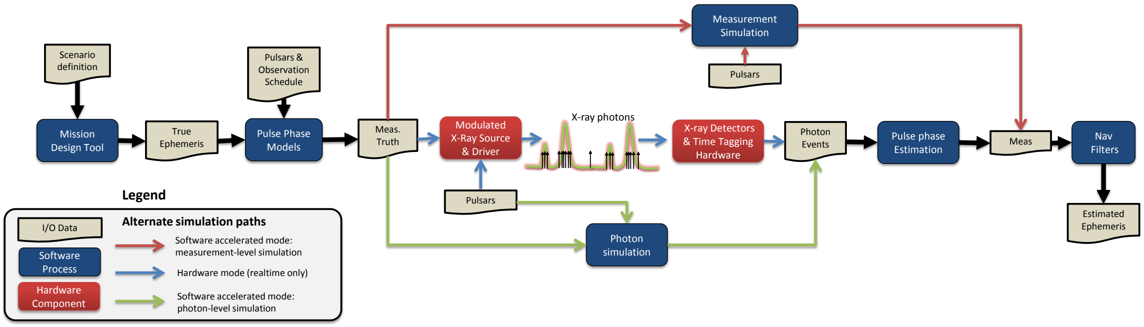
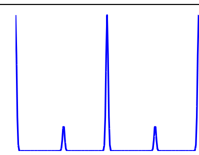
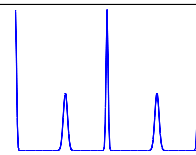
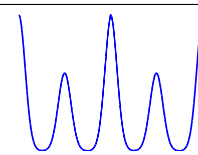


Figure 7: GXLT data-process flow, X-ray photon generation via environment emulator hardware.

Table 1: Preliminary GXLT simulation pulsar data (reproduced from [21])

Name	PSR B1937+21	PSR B1821-24	PSR J0218+4232
Pulse Frequency	641.92 Hz	327.40 Hz	430.46 Hz
Source Photon Rate	0.030 cts/s	0.083 cts/s	0.079 cts/s
Background Photon Rate	0.050 cts/s	0.410 cts/s	0.086 cts/s
Obs Time	2710 s	1940 s	30010 s
Pulse time est. err.	5 μs	10 μs	10 μs
Shape			

Goddard XNAV file exchange format Interface Control Document (ICD) [25], which was developed to foster collaboration and interoperability with complementary simulator and algorithm development by industry and academic partners.

The GXLT has been developed to support the SEXTANT on-orbit demonstration from concept definition to flight. While preliminary operational capability has been achieved, many model and hardware improvements are still planned. Ultimately, the GXLT will be the proving ground for the SEXTANT flight software and many components of the NICER/SEXTANT flight hardware.

Figure 8 shows results of a preliminary GXLT simulation for a scenario modeling the SEXTANT mission (and using the faster-than-real-time mode of operation). The results show 3D Root Sum Square (RSS) position estimation errors at the sub-kilometer level and 3D RSS velocity errors well under 1 m/s. For this simulation, a simple pulsar observation schedule was set to sequentially observe three prominent MSPs in a repetitive cycle, for a total simulation time of 16 days. Each continuous observation of a single pulsar was broken into 10 equal length sub-windows, with the photon events from each used to make a batch estimate of the pulse phase and Doppler. Table 1 gives the pulsar name, count rates, and sub-window observation period for each pulsar, and corresponding predicted pulse time-of-arrival (equivalent to phase) estimation errors. The count rates are estimates provided by the NICER science team using the predicted performance of the NICER instrument.

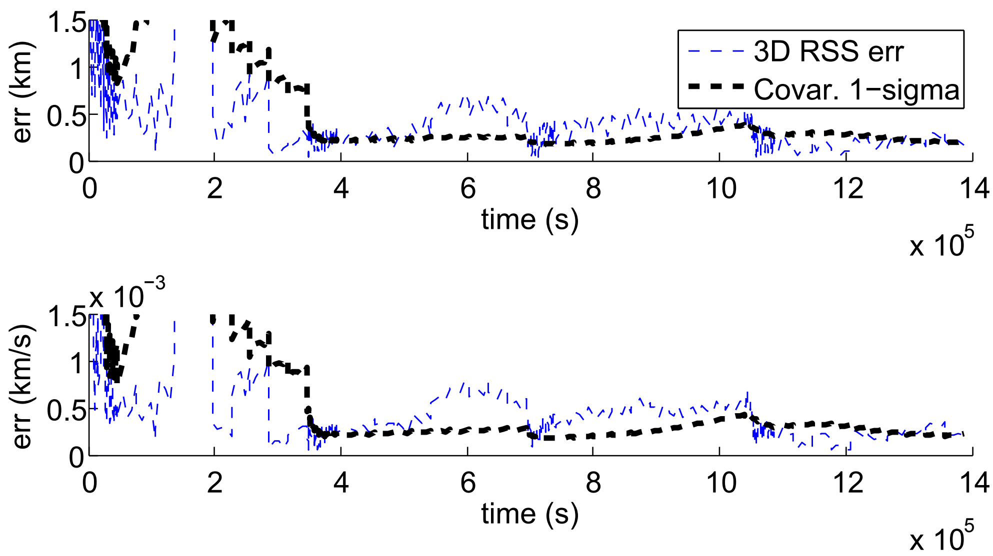


Figure 8: Position and velocity RSS errors and filter root-covariance diagonal for the SEXTANT XNAV simulation.

TOWARD A PRACTICAL XNAV SENSOR

While SEXTANT will demonstrate for the first time, real-time on-orbit absolute XNAV with sub-kilometer accuracy, the NICER/SEXTANT instrument would likely be too large and costly for use on near term deep space exploration missions (as an example use case for XNAV). In this section, we consider simplifications and modifications to the NICER instrument that could make it useful as a near-term XNAV sensor for exploration and estimate its performance within the GXLT end-to-end simulation.

While alternative designs certainly have merit and deserve consideration, scaling down the NICER instrument has the following advantages: 1) if SEXTANT is successful, it will have unique on-orbit heritage as an operational XNAV sensor 2) NICER's focused X-ray optics provide large collecting areas for small physical detector sizes resulting in relatively high signal to background ratios 3) the instrument is inherently scalable, consisting of 56 identical X-ray concentrators and detector pairs (along with an associated array of photon processing electronics).

Here, we take the obvious first approach to scaling down NICER, and consider a single concentrator/detector pair. Like NICER, this instrument would require arcminute level pointing accuracy which we propose to achieve with a combination of bulk spacecraft attitude maneuvers, whose size and frequency would be minimized by optimization of the pulsar observation schedule, and fine-pointing using a small, low-power, 6-DOF hexapod mount which could accurately point the instrument within a 10° cone of sky. We assume the spacecraft attitude control system has sufficient attitude knowledge available. While NICER has access to a precise absolute timescale via its on-board GPS receiver, a practical absolute XNAV sensor would most-likely require an atomic time standard to provide a stable time-base for photon time-tagging. Space borne atomic time and frequency standards have a long heritage especially as a fundamental component of the GPS space segment, and importantly, recent research trends have made great progress in reducing the size, weight, and power requirements of such devices.

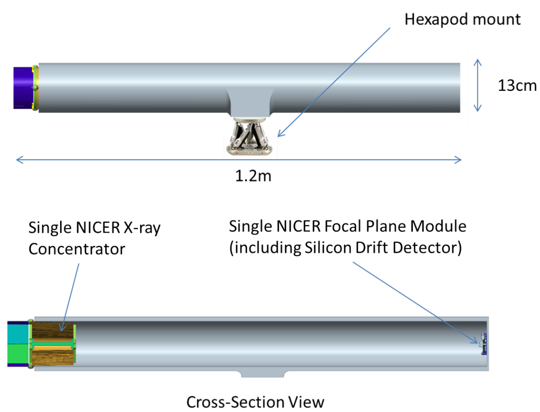


Figure 9: Artist's depiction of practical XNAV sensor using NICER like optics/detector with hexapod mount for limited pointing.

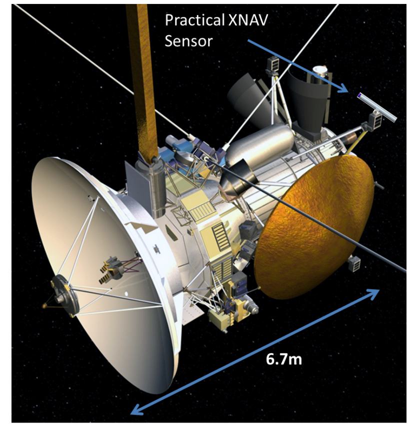


Figure 10: Scale size depiction of practical XNAV sensor with the Cassini spacecraft.

As an example, the JPL Deep Space Atomic Clock (DSAC) [26] provides outstanding stability in a low-mass, low-power package. Once proven, this technology is likely to become a standard component on deep space exploration missions. The resulting sensor would look something like the 1 m long tube as shown in Figure 9 and, for size-comparison purposes, as attached to the Cassini spacecraft in Figure 10. Based on this initial configuration, the concentrator optic, tube, hexapod mount, detector, and timing electronics could be made to occupy a total volume of approximately 22500 cm^3 and weigh less than 4 kg. This weight could be reduced by targeted use of composite structural components, and shielding rather than complete enclosure. Power is more difficult to estimate, due to the NICER detector and timing electronics configuration. However, a very conservative estimate would be less than 4 W for the detector and timing electronics package. This could be improved with further miniaturization of the timing electronics, or improvements in detector technology. One benefit of the current detector electronics configuration is that multiple detectors, which are comparatively low-power, can be driven by the timing electronics package. Consequently, the power scaling for adding detectors is significantly better than a multiple of the minimum single detector configuration.

We conducted a preliminary simulation in the GXLT (in its faster than real-time mode using ODTBX navigation filters) using this conceptual practical sensor in a scenario modeled on the cruise phase of the Cassini-Huygens Saturn-bound mission, starting at a range of about 2 AU from the Sun and running for 2.5 years out to 7 AU. We set the schedule to observe the same sequence of pulsars used in the SEXTANT simulation from Table 1, but with the count rates reduced by a factor of 56, appropriate for the scaled down sensor, and with less accurate pulse time-of-arrival error targets. For a single run, given an initial state estimate accurate to approximately 1 km, the position estimation errors briefly increase, and then quickly settle to about a 10 km 1σ steady state. The time history of position and velocity estimation errors are shown in Figure 11.

For comparison purposes, we used built-in ODTBX simulation capability to evaluate estimation performance for the same spacecraft, reference trajectory, and initial state accuracy, but using DSN radiometric measurements rather than XNAV measurements. We assumed a heavy tracking schedule, providing the filter with DSN range and Doppler measurements whenever

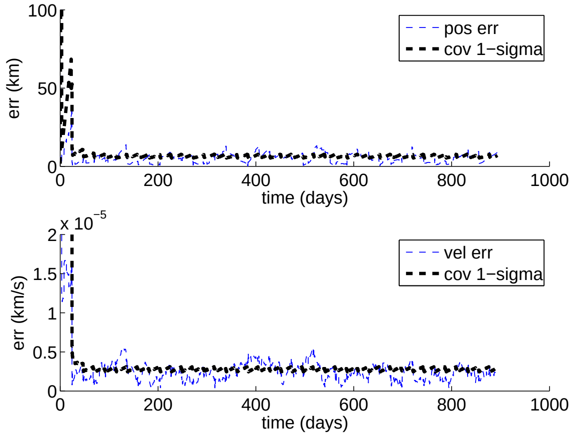


Figure 11: Position and velocity RSS errors and filter root-covariance diagonal for the Cassini cruise-phase simulation using measurements from the notional practical XNAV-sensor only.

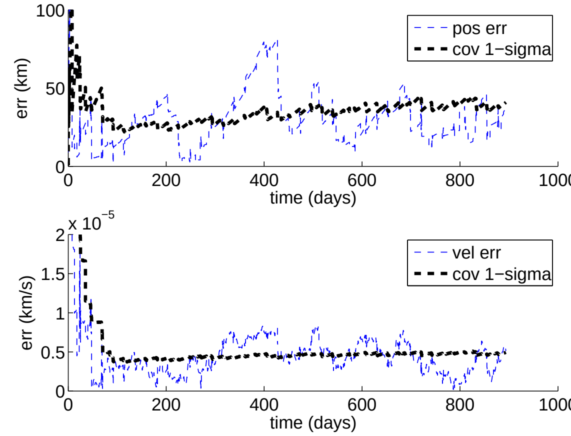


Figure 12: Position and velocity RSS errors and filter root-covariance diagonal for the Cassini cruise-phase simulation using *continuous* DSN range and Doppler tracking arcs, and DDOR measurements scheduled once a week

any DSN station had a line-of-sight view to the spacecraft. We also scheduled Delta Differential One way Ranging (DDOR) measurements between each pair of DSN tracking stations once per week for 24 hours at a time. The measurement noise was set to 1.0 m and 0.05 mm/s (1σ) for range and Doppler, respectively, and to 4 cm (1σ) range accuracy for DDOR, based on values listed in the DSN Services Catalog [27]. The estimation results are shown in Figure 12 achieving 20–30 km position errors, as compared to approximately 10 km with XNAV, that slowly grow during the outbound trajectory, as expected. This result is reasonably consistent with the 20 km performance requirements listed for DSN orbit control accuracy for approach level-1 requirements for the Cassini mission in [28], and supports the idea that XNAV could provide improved performance over DSN for navigation beyond Jupiter.

X-RAY COMMUNICATION

With the growing need for high rate science downlinks in an increasingly crowded RF signal environment, NASA space communication data downlinks have naturally progressed toward higher frequencies, where bandwidth pressure is reduced and high directionality can be achieved with small terminals. Ka-band is currently replacing S-band data links and optical communication systems are being actively developed to replace RF links, e.g., NASA's Laser Communication Relay Demonstration (LCRD) program [26]. X-rays are a next, natural step beyond optical communication frequencies. Soft X-rays, combined with diffraction-limited optics, could provide orders of magnitude tighter beams than optical laser-based systems, with potential benefit for deep space communications. Since X-rays do not suffer dispersion effects, they also hold the promise for more accurate, long-distance range measurements. Furthermore, at higher energies, the penetrating power of X-rays could enable communication with hypersonic and re-entering vehicles, and even penetrate radio-frequency shielding terrestrially.

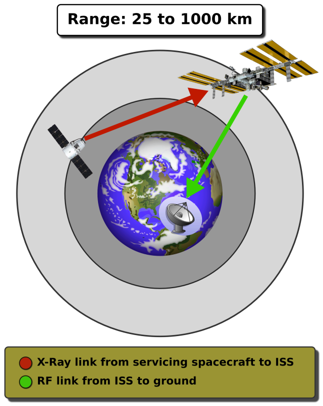


Figure 13: XCOM demonstration scenario.

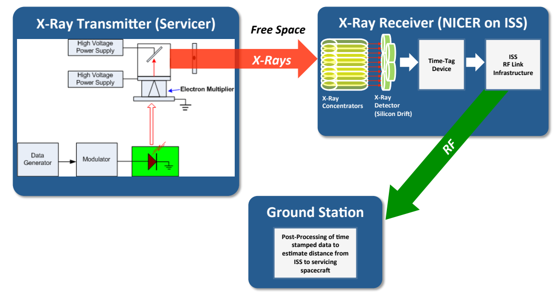


Figure 14: XCOM top-level link system block diagram.

XCOM Demonstration Concept

As an additional technology enhancement to the NICER/SEXTANT mission, scientists and engineers at NASA GSFC are developing a follow-on technology demonstration of XCOM that will use the NICER instrument as a passive X-ray communication receiver. Since radiometric tracking is an important part of deep space communications, the demonstration will include Pseudo-random Noise (PN) sequence ranging.

In the proposed experiment, a PN data sequence modulated X-ray source [2] on board an ISS servicing spacecraft, e.g., SpaceX Dragon or JAXA H-II Transfer Vehicle (HTV), transmits continuously to the NICER instrument on board the ISS. As the servicing spacecraft approaches ISS, the passive detector will time tag the receipt of X-ray photons and transmit this data to the ground via RF link for demodulation and time sequence correlation. On the ground, the arrival events are first processed with a symbol time recovery algorithm, then symbol estimation and PN correlation algorithms. The PN correlation will estimate the beginning of the PN sequence in relationship to the time tag information. The clocks available to the servicing spacecraft and NICER are presumed to be adequately synchronized to enable accurate estimation of the time delay between the PN sequence transmission and reception. This delay estimate is directly proportional to the range between the transmitter and receiver. Illustrated in Figure 13, a servicing spacecraft containing the transmitter is placed into an orbit no closer than 25 km below the ISS with line-of-sight to NICER. In Figure 13, the red arrow from the servicing spacecraft to ISS indicates the one-way X-ray link, while the green arrow indicates the RF link from ISS to a ground station. Figure 14 shows the top-level block diagram of the X-ray transmitter and receiver for the experiment. The X-ray transmitter consists of the data generator, data modulator, MXS, and X-ray concentrator optics. The receiver is the NICER instrument.

XCOM CURRENT WORK AND TECHNOLOGY PATH

An initial study and simulation of the XCOM demonstration concept was developed and executed by engineers at NASA GSFC. This study developed specifications for the communication link and ranging system, developed a specific set of algorithms for the receiver, and evaluated the performance of the system, which used On-Off Keying (OOK) modulation [29], typical for photon counting channels, to transmit a repetitive length 511 PN sequence at 100 kbps symbol rate. The PN sequence length was chosen to ensure *unambiguous* range estimates at the maximum transmitter/receiver range of 1000 km. The symbol rate was chosen conservatively based, on the expected signal and background average photon count rates, taken as 2 cts/s and 10^{-5} cts/s, respectively, and the receiver bandwidth, which is dominated by the bandwidth of the Silicon Drift Detector (SDD). A specific symbol synchronization, detection, and PN-correlation/range-estimation algorithm were developed, all founded on the Maximum Likelihood principle. The performance of these algorithms was demonstrated in a simulation that modeled the statistics of the channel, transmit and receive oscillator instabilities, and errors due to SDD drift delays. The performance analysis focused primarily on range estimation accuracy, which requires effective synchronization and symbol detection as prerequisites. A range accuracy of approximately 10 m was demonstrated using an optimized 40 ms PN correlation time, thus meeting all expectations. A more detailed summary of this simulation and results will be made available in a future technical report.

While preliminary, the results of this work establish the feasibility of an XCOM technology demonstration. Importantly, the point design parameters chosen in this simulation represent technology elements that are either already available or require modest refinement for a successful demonstration.

While a technology capability demonstration is within grasp, there are several areas that require further research and development to establish practical X-ray communication capabilities over long-range, free-space and short-range, high-energy penetrating links. Specific areas for work on transmission include improvements in efficiency and output power for the MXS, advancements in diffraction limited X-ray optics, and better gimbals and platform stabilization for precision pointing. For reception, there is a need for faster detectors and supporting hardware, as well as research and development of algorithms for communication in photon starved channels.

CONCLUSION AND FUTURE WORK

In this paper, we described the emerging and potentially revolutionary applications of X-rays for space communication and navigation and recent technology development work at NASA GSFC in support of these technologies.

At the center of this recent technology work is the NICER/SEXTANT mission for which, in the spring of 2013, NASA GSFC will be completing a Phase A concept study. While NICER's primary objective is to study neutron stars through phase-resolved spectroscopy, as well as open up new discovery space in time-resolved X-ray astrophysics, SEXTANT, an attached technology demonstration enhancement to NICER will demonstrate for the first time, real-time on orbit X-ray Pulsar Navigation (XNAV) achieving absolute orbit determination to better than 1 km. In addition, SEXTANT will lay the ground work for an additional technology demonstration that will provide first ever operational space-based X-ray Communication (XCOM) link.

Beyond NICER/SEXTANT and its XCOM enhancement, emerging technologies in diffraction limited X-ray optics (e.g., [3]), offer the potential for performance and efficiency improvements by fully focusing X-ray transmitters and receivers. This could enable high-efficiency and capacity long-range XCOM links, improve XNAV sensor signal to noise ratios and shrink the size of XNAV sensors. Additionally, it could enable highly precise relative navigation and attitude sensors that track natural X-ray sources or man-made X-ray beacons, which in particular, would revolutionize in-space interferometry missions [4].

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REFERENCES

[1] D. R. Lorimer. Binary and millisecond pulsars at the new millennium. *Living Rev. Relativity*, 4(5), 2001.

[2] K. Gendreau, Z. Arzoumanian, P. Deines-Jones, and R. Koenecke. A modulated X-ray source for in-flight calibration of high-energy astrophysics instrumentation. 2011.

[3] D. L. Windt, S. M. Kahn, and G. E. Sommargren. Diffraction-limited astronomical X-ray imaging and X-ray interferometry using normal-incidence multilayer optics. In *Proceedings of SPIE*, volume 4851, pages 441–450, 2003. URL `http://www.rxollc.com/windt/papers/2002_SPIE_4851_NIML.pdf`.

[4] Keith Gendreau. Black hole imager: What happens at the edge of a black hole? Technical report, NASA GSFC, 2010.

[5] A. Hewish, S. J. Bell, J. D. H. Pilkington, P. F. Scott, and R. A. Collins. Observation of a rapidly pulsating radio source. *Nature*, 217(5130):709–713, 1968.

[6] G. S. Downs. Interplanetary navigation using pulsating radio sources. *NASA Technical Reports, N74-34150*, pages 1–12, 1974.

[7] T. J. Chester and S. A. Butman. Navigation using X-ray pulsars. *Jet Propulsion Laboratory, Pasadena, CA, NASA Tech. Rep. 81N27129*, 1981.

[8] J. E. Hanson. *Principles of X-ray navigation.* PhD thesis, Stanford University, March 1996. URL `http://dx.doi.org/10.2172/877425`.

[9] J. Sala, A. Urruela, X. Villares, R. Estalella, and J. M. Paredes. Feasibility study for a spacecraft navigation system relying on pulsar timing information. *European Space Agency Advanced Concepts Team ARIADNA Study*, 3(4202):23, 2004.

[10] S. I. Sheikh. *The use of variable celestial X-ray sources for spacecraft navigation.* PhD thesis, University of Maryland, 2005. URL `http://hdl.handle.net/1903/2856`.

[11] P. S. Ray, K. S. Wood, and B. F. Phlips. Spacecraft navigation using X-ray pulsars. Technical report, DTIC Document, 2006.

[12] S. I. Sheikh, A. R. Golshan, and D. J. Pines. Absolute and relative position determination using variable celestial X-ray sources. In *30th Annual AAS Guidance and Control Conference*, pages 855–874, 2007.

[13] P. Graven, J. Collins, S. Sheikh, J. Hanson, P. Ray, and K. Wood. XNAV for deep space navigation. In *31st Annual AAS Guidance and Control Conference*, pages 08–054, 2008. URL `http://microcosminc.com/analysis/AAS%2008-054%20XNAV.pdf`.

[14] A. A. Emadzadeh and J. L. Speyer. *Navigation in space by X-ray pulsars*. Springer, 2011. ISBN 9781441980168.

[15] S. I. Sheikh, J. E. Hanson, P. H. Graven, and D. J. Pines. Spacecraft navigation and timing using X-ray pulsars. *Journal of the Institute of Navigation*, 58(2):165–186, 2011.

[16] P. J. Buist, S. Engelen, A. Noroozi, P. Sundaramoorthy, S. Verhagen, and C. Verhoeven. Overview of pulsar navigation: past, present and future trends. *Navigation*, 58(2):153–164, 2011.

[17] A. A. Emadzadeh. *Relative navigation between two spacecraft using X-ray pulsars*. PhD thesis, University of California, Los Angeles, 2009.

[18] R. N. Manchester, G. B. Hobbs, A. Teoh, and M. Hobbs. The Australia Telescope National Facility Pulsar Catalogue. *The Astronomical Journal*, 129(4):1993–2006, 2005. URL `http://stacks.iop.org/1538-3881/129/i=4/a=1993`.

[19] N. Ashby and A. R. Golshan. Minimum uncertainties in position and velocity determination using X-ray photons from millisecond pulsars. In *Institute of Navigation National Technical Meeting*, 2008.

[20] J. Hanson, S. I. Sheikh, P. Graven, and J. Collins. Noise analysis for X-ray navigation systems. In *Position, Location and Navigation Symposium, 2008 IEEE/ION*, pages 704–713. IEEE, 2008.

[21] Luke M. B. Winternitz, Munther A. Hassouneh, John A. Gaebler, Jason W. Mitchell, Fotis Gavriil, Zaven Arzoumanian, and Keith C. Gendreau. An X-ray Navigation Ground Testbed. In *27th Space Simulation Conference*. IEST, November 2012.

[22] S. P. Hughes. General Mission Analysis Tool (GMAT). URL `http://gmat.gsfc.nasa.gov/`. Retrieved Sep 6 2012.

[23] Kenneth M. Getzandanner. Orbit Determination Toolbox (ODTBX). URL `http://odtbx.sf.net/`. Retrieved Sep 12 2012.

[24] A. Long. *Goddard Enhanced Onboard Navigation System (GEONS) Mathematical Specifications*. a.i. solutions Inc., April 2011. Version 2, Release 2.15.

[25] J. A. Gaebler, M. A. Hassouneh, and L. M. B. Winternitz. X-ray navigation testbed interface control document. v2.2.

[26] David E. Steitz. NASA Press Release 11-272: Communications, Navigation and In-Space Propulsion Technologies Selected for NASA Flight Demonstration, 2012.

[27] Tim Pham. Deep Space Network Services Catalog: DSN no. 820-100, rev. e. Technical report, Jet Propulsion Laboratories, 2009.

[28] B. Turyshev. Lecture 10.1: NASA's deep space network: Current status and the future. URL `lnfm1.sai.msu.ru/~turyshev/lectures/lecture_10.1-DSN-Present-Future.pdf`.

[29] C. Georghiades. Maximum likelihood symbol synchronization for the direct-detection optical on-off-keying channel. *IEEE Transactions on Communications*, 35(6):626–631, 1987.