SEXTANT X-RAY PULSAR NAVIGATION DEMONSTRATION: INITIAL ON-ORBIT RESULTS^{*,†}

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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. SEXTANT will be a first demonstration of in-space, autonomous, X-ray pulsar navigation (XNAV). Navigating using millisecond X-ray pulsars which could provide a GPS-like navigation capability available throughout our Solar System and beyond. NICER is a NASA Astrophysics Explorer Mission of Opportunity to the International Space Station that was launched and installed in June of 2017. During NICER's nominal 18-month base mission, SEXTANT will perform a number of experiments to demonstrate XNAV and advance the technology on a number of fronts.

In this work, we review the SEXTANT, its goals, and present early results from SEXTANT experiments conducted in the first six months of operation. With these results, SEXTANT has made significant progress toward meeting its primary and secondary mission goals. We also describe the SEXTANT flight operations, calibration activities, and initial results.

BACKGROUND

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, a NASA Astrophysics Explorer Mission of Opportunity to the International Space Station (ISS), [1–4]. During NICER's nominal 18-month base mission, SEXTANT will perform the world's first demonstration of real-time, on-board, autonomous, X-ray Pulsar Navigation (XNAV): the concept of navigating by precise timing of the pulsations from Millisecond Pulsars (MSPs), rapidly rotating neutron stars that pulsate in the X-ray band.^{††} In principle, XNAV provides a Global Positioning System (GPS)-like navigation capability available throughout our Solar System and beyond. The concept of navigating by pulsar has a rich history that dates back several decades [5, 6]. For further detail on the history and concepts of pulsar navigation see [7, 8] and references therein.

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^{††}MSPs emit broadband electromagnetic radiation, but the X-ray emission offers several advantages for navigation including far smaller detectors than radio or optical and immunity to interstellar propagation effects, e.g., time-variable dispersion and scattering, that affect the radio signals.



Figure 1: SEXTANT system architecture

SEXTANT requires that an XNAV demonstration be performed in *real-time* through the sequential observation of multiple MSPs and *on-board* NICER. The on-board navigation demonstration is initialized with an intentionally-degraded orbit position and velocity, based on data provided by NICER's GPS receiver, and then must maintain orbit knowledge by processing *only* X-ray pulsar measurements. The primary performance goal of the mission—its so called Key Performance Parameter (KPP)—is to to achieve real-time, onboard, navigation position accuracy of 10 km worst-direction, using up to two weeks of dedicated navigation-focused MSP observations. By convention, this uncertainty is treated as < 17.3 km Root-Sum-Squared (RSS) error^{‡‡} compared to the on-board GPS solution whose accuracy is several orders of magnitude better than this. 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 [2]. During the mission all NICER photon data will be telemetered to the ground, archived, and made public for use in ground based investigation and experiments.

In addition to its primary goal, SEXTANT has the following secondary goals: a) validate and enhance the XNAV Laboratory Testbed (XLT) and its end-to-end simulation, b) develop and test alternative and enhanced algorithms for XNAV, c) use the ground testbed to study real-world XNAV scenarios, e.g., small detectors on deep space trajectories, d) study the use of XNAV and pulsars for time keeping and clock synchronization, e) discover new pulsars useful for XNAV, and finally, f) infuse XNAV technology into near future applications. These goals are being pursued through a series of ongoing ground-based experiments and activities.

In the remainder of this paper, we first recall the basic architecture of the SEXTANT navigation system, then describe key aspects of SEXTANT operations, planning products, and scheduling flow with respect to ISS and NICER activities. Next, we describe the calibration of the SEXTANT *pulsar almanac*. Results from selected navigation experiments are presented including an early result obtained by processing NICER telemetry through a ground-based version of the SEXTANT navigation software, as well as a real-time, on-board experiment that fulfills the primary goal and KPP of the SEXTANT mission.

^{‡‡}This *convention* makes the convened assumption of a spherically symmetric error so that the error in any one direction would be divided by $\sqrt{3}$.



(a) Diagram of NICER Instrument



(b) NICER On-orbit with the ISS starboard solar panels in the background [9]

Figure 2: Neutron star Interior Composition Explorer (NICER) payload.

SEXTANT SYSTEM ARCHITECTURE

Figure 1 depicts the four main components of the SEXTANT flight system—the NICER X-ray Timing Instrument (XTI), the SEXTANT X-ray Pulsar Navigation Flight Software (XFSW), the SEXTANT ground system, and the SEXTANT XLT—as well as the data flow relationship among the components. We briefly describe each below and refer the reader interested in more detail to previous SEXTANT publications [3, 4].

NICER's XTI, depicted in Figures 2a and 2b, is a gimballed array of 56 co-aligned X-ray concentrator optics (52 functioning on orbit), each paired with an associated Silicon Drift Detector (SDD) and GPSsynchronized timing electronics, offering an unprecedented combination of time and energy resolution and sensitivity making it a superb sensor for X-ray pulsar navigation [10]. The XTI detects individual X-ray photons from the target source and feeds them to the SEXTANT XFSW, a Core Flight System (CFS) [11, 12] application hosted by the NICER Instrument Flight Software (IFSW). The XFSW collects groups of GPStime-tagged events from each source, applies a carefully constructed array of filtering criteria to optimize signal-to-noise ratio, and then batch processes these into pulse phase and frequency measurements, using models of the pulsar timing and pulse shape, which are then fed to a sequential navigation filter. The XFSW navigation filter is an XNAV-enhanced version of the Goddard Space Flight Center (GSFC) high heritage GEONS flight software [13] used in numerous National Aeronautics and Space Administration (NASA) and non-NASA missions. The SEXTANT XNAV Ground Segment/System (XGS) is responsible for maintaining the onboard pulsar models, as well as XFSW tuning parameters. In principle, updates to the pulsar almanac can be as infrequent as once every several months, or even years, for many of the highly-stable SEXTANT target pulsars. Finally, verification of the upload products and performance predictions are provided by highfidelity XLT simulation environment.

SEXTANT FLIGHT OPERATIONS

Operations Flow

This section describes the SEXTANT flight operations which consists of a number of actions synchronized to the nominal 3-day NICER target schedule planning cycle. The majority of this workflow happens within a single workday, while critical products are delivered every 3-days. The following sections describe each step in the the operations workflow, shown in the enumerated flow diagram in Figure 3.

External Product Input First, external products are ingested into NICER repositories (*NRL*, *SEXTANT*, *Science Mission Operations Center (SMOC): step 1*). These products include an ISS Mission Control Cen-

ter (MCC) predictive ephemeris, ISS hardware joint state file, ISS events file, and Earth Orientation Parameters (EOP). In general, these products provide predictive information on the ISS for SEXTANT product uploads. Further information on ISS products for ISS payloads are summarized in reference [14]. Additionally, external radio and space observatories' timing products are directly delivered to Naval Research Laboratory (NRL) repositories for fitting the timing models. The timing models are updated much less frequently than the regular operations tempo.

Pulsar Information Processing After processing external products, the NRL team uses pulsar timing data from various observatories to perform model fitting and calibration for each SEXTANT target to minimize modeling errors (*NRL: step 2*). This approach is described in more detail in the pulsar calibration section. Next, the team evaluates pulsar visibility as a function of time along the predicted orbit (*SMOC: step 2*). The visibility product determines solar, lunar, Earth, ISS structure, glint, and South Atlantic Anomaly/Polar Horn incursions for up to 2 weeks. Both the visibility and scheduling products for SEXTANT are processed through the NICER scheduling Attitude Ground System (AGS), an integrated ground systems tool that has operational heritage from over two dozen missions [15].

NICER and SEXTANT Scheduling tools With pulsar visibility as an input, a candidate observation schedule is generated. Due to the complex scheduling constraints, two scheduling algorithms are used: a SEXTANT-developed scheduling algorithm (*SEXTANT: step 3*) and the NICER AGS algorithm (*SMOC: step 6*). The final schedule may be based on either algorithm depending on predicted performance. The SEXTANT tool builds an observation schedule for each measurement by locally optimizing the position error covariance performance with potential XNAV measurements. Each potential measurement is based on an observation schedule designed to minimize time between measurements. The NICER AGS uses a global genetic algorithm. The objective function minimizes slew time and a first order SEXTANT metric based on position error covariance through the entire schedule [16]. The two schedules are then evaluated in nightly Monte Carlo runs using the full SEXTANT end-to-end simulation to generate higher fidelity navigation performance predictions for validation (*SMOC: step 4*).

Product Validation, Flight Software Configuration, and Product Upload The XNAV simulation runs nightly to evaluate scheduling, automating the generation of the compressed timing models and upload parameters (*SMOC: step 4*). The resulting configuration table provides an archive of the XFSW state during verification. After producing the configuration table, the observation schedule and software configuration is verified (*SMOC: step 5*). Verification consists of analyzing simulation performance predictions and verifying that the candidate configuration table is accepted without error by the XFSW running on a ground system. The observation schedule is sent to the NICER science team and negotiated to obtain the final product upload schedule (*SMOC: step 6*). At this point, the XFSW configuration table is regenerated and the SEXTANT team verifies the NICER approved schedule in a ground simulation (*SMOC: step 7*). If the verification fails at *SEXTANT: step 5* or *step 8*, then operations restart at *SEXTANT: step 3*. Finally, the configuration table and schedule products are sent to the NICER SMOC for upload (*SMOC: step 9*) to the NICER flight computer.

CALIBRATION

Pulsar Model Calibration

The measurements that feed the navigation filter critically depend on accurate predictions of the pulse arrival times from the MSP observations. These are provided by physically-motivated timing models that are fitted to measurements made at ground- and space-based observatories. A discussion of the characteristics of the pulsars useful for navigation and the factors that determine the accuracy of both the measurements and the model predictions can be found in [17].

The SEXTANT *pulsar almanac* consists of a list of the most applicable pulsars for XNAV and all data needed to model the signals from these pulsars to sufficient accuracy to execute the SEXTANT algorithms. The almanac contains timing models, source and background count rates, light curve templates, and raw data



Figure 3: Nominal Operations Flow

used to generate these.

The basic criterion for a pulsar to be included in the SEXTANT pulsar almanac is that its predicted Timeof-Arrival (TOA) accuracy in a 5000 s observation, i.e., approximately one ISS orbit, should be $< 333 \,\mu$ s, corresponding to a range uncertainty of 100 km. Pulsars that do not meet this requirement do not make a useful contribution to the navigation solution.

The almanac is kept updated using data from radio telescope timing observations and NICER observations, as described below. For the initial flight experiment, the timing model fits were developed using radio data exclusively and NICER data were only used to determine X-ray template profiles and absolute phase of the X-ray pulses. Now that NICER has collected substantial amounts of timing data on many of the SEXTANT pulsars, e.g. [18], in future experiments, the timing models can be updated using NICER data.

Radio observations To determine the timing models for the SEXTANT pulsars, we used data from ongoing long-term pulsar timing programs at the Nançay Observatory, the Green Bank Telescope (GBT), the Arecibo Observatory, and the Parkes Telescope. These programs are largely motivated by searches for gravitational waves using pulsar timing, requiring extremely high timing precision, rapid cadence and very careful removal of interstellar propagation effects, so the data meets our needs for deriving models useful for navigation.

Our Nançay Observatory data were taken at three radio frequencies, as documented in [19]. The GBT and Arecibo data were taken by the North American Nanohertz Observatory for Gravitational Waves (NANOGrav) project as documented in [20]. We made use of more recent data (up through March 2017) processed using the same nanopipe^{§§} pipeline. The Parkes data for PSR J0437–4715 were taken by the Parkes Pulsar Timing Array (PPTA) project [21]. In all cases, the data delivered to SEXTANT were TOA measurements of each pulsar spanning multiple years.

Timing model generation Current timing models are determined, and predictive polynomial coefficients are generated, using the TEMPO2 pulsar timing software [22, 23]. We fit models to the radio TOAs that are appropriate for our purpose of extrapolating models into the future. We use the DE421 JPL planetary ephemeris, the TDB time scale, and do not include red noise or other non-deterministic parameters. We model Dispersion Measure (DM) variations with simple low-order polynomials. The residuals to these model fits are shown in Figure 4b.

^{\$\$}https://github.com/demorest/nanopipe



Figure 4: Pulse profiles, left, and TOA residuals (in μ s), right, for the MSPs used in the SEXTANT experiments. The residuals show the difference between the radio measurements and the timing model, for all of the radio data used to construct our models. The colors denote which radio telescope took the data (magenta = Arecibo, blue = GBT, green = Nançay, red = Parkes). Note that the vertical scales are all $\pm 33\mu$ s, which is equivalent to ± 10 km. The frequency-dependent drifts near the end of the B1937+21 data is caused by the complex DM variations seen in the pulsar. The orange vertical stripe marks the dates of the SEXTANT flight experiment.

NICER data processing The spin evolution of the pulsars is fully determined from the radio data, but to be able to precisely predict the time of the X-ray pulses, we needed to acquire sufficient data on each pulsar using NICER. Previous X-ray data from other missions were insufficient since NICER has far better time resolution and time stamp accuracy than any prior mission. As part of the early mission goals, NICER acquired substantial exposure on each of the SEXTANT pulsars, which allowed us to validate our pre-launch estimates of source and background count rates, optimize the time and energy cuts to maximize the signal to noise of each pulsar, and derive a pulse template for each pulsar to be used in the onboard processing.

To process the NICER data, we filtered out non-photon events and those likely to be background based on the pulse height ratio between the slow and fast shaper. We selected good time intervals according to several criteria: pointing mode, offset from target $< 0.015^{\circ}$, cutoff rigidity > 4.5 GeV, elevation above the Earth limb $> 30^{\circ}$, and ISS location outside of geographic regions that correspond to the South Atlantic Anomaly and the polar horn regions where backgrounds are often elevated (see Figure 5).

For each of the filtered photon events during our good time intervals, we assign pulse phases using the photonphase code in PINT [24]. We then determined minimum and maximum energy cuts that optimized the signal-to-noise ratio for the pulsar, as determined by the H-test detection statistic. The total NICER exposure for each pulsar, available at the time, was used to compute the pulse templates and perform absolute phase calibration, as well as the average pulsed count rate (α) and the average total background count rate (β), which includes unpulsed counts from the source, diffuse X-ray background, and radiation backgrounds.

Template generation For each pulsar, we generated an analytic pulse profile template by fitting multiple wrapped gaussian components to the NICER phased photon dataset using an unbinned maximum likelihood fitter, as in the *Fermi* Second Pulsar Catalog [25]. Each template is rotated in phase so that the peak of the largest gaussian component is at phase 0. Binned versions of these templates are used for the onboard fitter



Figure 5: Map showing the high background regions of the NICER (ISS) orbit. The color scale shows the count rate of particle background events as indicated by the pulse height ratio between the slow and fast shapers in the NICER detector electronics. These events are filtered out during NICER data processing. The dashed lines are the borders of the geographic region excluded from our analysis.

(see Figure 4a).

Absolute phase measurement To measure the absolute time of the X-ray pulse arrival, we used the templates to generate pulse TOA measurements from each day of NICER observations using unbinned likelihood fits, as described in [26]. These TOAs are referenced to the Solar System Barycenter at infinite frequency. The final reference time of arrival is determined by a TEMPO2 fit to this set of TOAs. This value (TZRMJD) defines phase 0 for the pulsar in MJD (TDB) units. When inserted into the spin ephemeris derived from the radio data, we obtain a timing model that predicts absolute time of arrival of the X-ray pulses to high accuracy for use in the onboard algorithm.

For the onboard processing, we do not evaluate the full timing models but rather use sets of predictive polynomial coefficients (referred to as *polycos*), generated by TEMPO2, that can be quickly evaluated to give pulse phase as a function of time.

NAVIGATION EXPERIMENTS

In this section, we describe results from a SEXTANT ground navigation experiment, as well as results from the first SEXTANT real-time, on-board flight experiment. In ground experiments, raw telemetry packets from the payload are collected over the period of interest and *replayed* through the XFSW application running on a computer or through the XLT end-to-end simulation. In addition to replaying flight telemetry, the XLT end-to-end simulation can also simulate all necessary telemetry. XFSW flight replay mode is numerically equivalent to the on-board XFSW and is useful for predicting and tuning on-board performance, while XLT end-to-end simulation ground processing is useful for Monte-Carlo simulation and algorithm development. Ground mode allows faster-than-real-time processing, iterative retuning of algorithms, variation of initial conditions, and enhanced telemetry. Flight mode, however, is required to fulfill the primary SEXTANT mission objective of demonstrating autonomous XNAV in space.

During early operations, the SEXTANT team worked with the NICER schedulers and advocated for MSP observations in support of navigation. Prior to the flight experiment, SEXTANT operated in *opportunistic* mode with the XFSW on-board typically run in *calibration* mode, where XNAV measurements are computed when available, but not processed by the filter, and the navigation solution is kept accurate by feeding GPS point solutions to the filter. During this time, the NICER team's scheduler accommodated SEXTANT inputs when possible: sometimes specific SEXTANT requests were accommodated, other times MSPs were included in the scheduler at higher priority to be scheduled at random, and other times SEXTANT requests were not accommodated.



(a) SEXTANT ground experiment starting day 259 of 2017 (b) SEXTANT flight experiment starting day 313 of 2017

Figure 6: MSP visibility and observing schedules from the SEXTANT ground and flight experiment

SEXTANT navigation experiments, especially during initial convergence, require a high density of SEX-TANT MSP observations over a period of one to two days. While not the typically the case, due to NICER science priorities, sufficient SEXTANT MSP observing density was obtained several times during early operations. Due to their sharp pulse shapes, as can be seen in Figure 4a, B1937+21 and B1821–24 standout from the rest of the SEXTANT MSPs as the most useful for navigation performance. The experiments described below each include significant time on of one of these MSPs, although not both simultaneously (see Figures 6a and 6b).[¶]

Ground experiments

SEXTANT was able to conduct a few successful ground experiments in the first six months of the mission by replaying flight telemetry into the XFSW and/or playing the events back through the SEXTANT XLT endto-end simulation. In this section, we present results from the most successful SEXTANT ground experiment to date, which was conducted using observations and telemetry over the period 2017 day-of-year 259.5 to 264.5. This period was preplanned as a ground calibration period for the SEXTANT team during which many SEXTANT observation requests were incorporated into the operational schedule. Figure 6a shows scheduled observations of the SEXTANT MSPs over the time period of the ground experiment, where a high density of B1937+21 observations can be seen.

Figure 7a shows position RSS errors (XNAV vs. GPS solution) and 3σ RSS filter root-covariance obtained during this experiment, which replayed the flight telemetry over this period through the SEXTANT XFSW on a computer on the ground. A Radial, In-track, Cross-track (RIC) decomposition of the errors show, perhaps as-expected, that these errors are largely in-track. Here, the state was initialized from a GPS point solution with a fixed Earth Centered Earth Fixed (ECEF) error of (250 m, 250 m, 250 m, 0.25 m/s, 0.25 m/s) added. This level may appear small compared to the target performance level of 10 km, but it is sufficient to lead to divergence far beyond the target level when propagated without measurement processing over the period of interest, as shown by the dotted trace in Figure 7a. A discussion of initialization errors is provided in the following subsection . Over this five day period, RSS position errors rapidly reduce to below 10 km after a brief initial convergence period, well below the KPP level of 17.3 km RSS. Plots of measurement residuals (omitted for limited space) show consistency with filter measurement variance.

A key secondary goal of the SEXTANT project is to validate and enhance the SEXTANT XLT and its endto-end simulation, described in detail in references [3, 4], and to evaluate its ability to accurately predict on-board performance. Figure 7b shows the predicted performance from the end-to-end simulation over the same period, using the same MSP models (timing, templates, and count rates) as in the XFSW, the ISS predictive ephemeris from the given period as truth, and the NICER observing schedule over the period of interest, and running the same flight algorithms with consistent algorithmic tuning parameters. The simulation

^{III} The high-flux, but noisy, Crab Pulsar further stands out from the rest of the SEXTANT pulsars. While NICER has spent significant time observing the Crab, and the SEXTANT XFSW has a special Crab processing mode, we do not yet include results from SEXTANT Crab processing.



(a) Ground experiment RSS position errors (XNAV vs. GPS solution) and 3σ RSS filter root-covariance. The dashed line gives the RSS error obtained by simply propagating the initial degraded state without processing XNAV measurements.

(b) XLT end to end simulation Monte-Carlo RSS position errors and mean 3σ RSS filter root-covariance for the ground experiment scenario.

Figure 7: Results from the SEXTANT ground experiment starting on day 259; flight data are shown in the left hand plot, XLT end-to-end predictions on right hand plot.

includes 20 Monte-Carlo cases where the initial state errors, photon arrival process, and pulsar timing model parameters are varied. The timing models were varied within the statistical uncertainty of radio-based timing model parameters and the initial state errors were randomized with Gaussian errors whose 1σ diagonal root-variance was set to (250 m, 250 m, 250 m, 0.25 m/s, 0.25 m/s, 0.25 m/s) for consistency with the ground experiment. Here they were added to the truth *inertial* state rather than ECEF state (used in the XFSW), but nonetheless, generate initial errors consistent with the ground experiment. Given this setup, by comparing left and right plots, it can be seen that the on-board result is in-family with the simulation, suggesting useful predictive power of the XLT end-to-end simulation. This result is a step toward fulfilling the validation component of the aforementioned secondary SEXTANT goal, although there is continuing effort to further enhance the simulation's fidelity.

Discussion of initialization errors The current XFSW implementation requires initial errors be specified in ECEF (matched to the GPS point solution), as opposed to a more natural RIC frame. XLT investigations have confirmed that relatively large initial in-track errors (tens of kilometers) can be tolerated, but that the filter is sensitive to initial radial position and in-track velocity error, which contribute directly to Semi-Major Axis (SMA) error. This makes sense since the SEXTANT photon processing algorithms rely on the ability to coarsely predict the state of the detector over each observation period (10 minutes to hours) [3, 4], and prediction error is largely governed by SMA estimation error [27]. Large initial SMA errors can lead to very large prediction errors for the initial XNAV measurement intervals, potentially leading to failure of the pulse phase estimation process with correspondingly large measurement errors, and then ultimate failure of the navigation process. While we chose to be conservative in our early experiments, XLT investigations have shown that significantly larger initial SMA errors than used in our initial experiments are generally tolerable in the SEXTANT XFSW, in MSP-rich observation scenarios. On-going SEXTANT investigations are exploring aspects of initialization and initialization errors in more depth, and may look at new cold-start algorithms.

Flight Experiment

In this section, we describe a flight navigation experiment conducted between 2017 days of year 314-316, where SEXTANT met its primary goal or KPP by achieving autonomous XNAV navigation performance better than 10 km, worst direction, on-board and in real-time. Figure 6b shows NICER's scheduled observations of the SEXTANT MSPs over the time period of the flight experiment. At this point, final SEXTANT calibration issues had been recently sorted out, and SEXTANT MSP visibility was sufficient, although not ideal since B1937+21 had passed behind the Sun, for the team to have high hopes for a successful on-board experiment.



(a) Flight experiment RSS position errors (XNAV vs. GPS solution) and 3σ RSS filter root-covariance. The dashed line gives the RSS error obtained by simply propagating the initial degraded state without processing XNAV measurements.

(b) XLT end to end simulation Monte-Carlo RSS position errors and mean 3σ RSS filter root-covariance for the flight experiment scenario.

Figure 8: Results from the SEXTANT flight experiment starting on day 313; flight data are shown in the left plot, XLT end-to-end prediction on right plot.

Figure 8a shows RSS position actual (vs. the NICER GPS solution) and filter formal errors (RSS rootvariance). Here, the filter state was initialized from a GPS point solution at 20:33:27 UTC of 2017 day of year 313, again, with a fixed ECEF error of (250 m, 250 m, 250 m, 0.25 m/s, 0.25 m/s) added. It can be seen in Figure 8a that the actual errors initially grow, but are then quickly reduced to and maintained below 10 km. The filter 3σ root-variance (formal error) settles to below 30 km after about one day. As above, the dotted trace of Figure 8a shows the rapid error growth obtained when simply propagating the initial state over the period of interest. Figure 8b shows a 20 case XLT end-to-end simulation Monte-Carlo prediction corresponding to this orbit and observing schedule. Here, the errors appear consistent with the flight results, but there were a small fraction of cases that diverged. The cause of these divergence cases is still under investigation. Current considerations are conservatism in the simulation, or perhaps a possibility inherent in the scenario's observing schedule, initialization, and algorithm parameters.

CONCLUSION

In this paper, we described early results from the Station Explorer for X-ray Timing and Navigation Technology (SEXTANT) demonstration. As a first time in-space technology demonstration, SEXTANT has firmly established the feasibility of real-time, autonomous X-ray pulsar navigation. Specifically, we presented both ground and flight experiments that have exceeded the primary mission performance goal by maintaining < 10 km root-sum-squared navigation error once converged. We also described the flight operations and in-orbit calibration activity, and reviewed the mission goals and system design.

As future work, we are preparing for a second SEXTANT navigation experiment, where timing models are generated from NICER-only data. In addition, we will continue to execute ground and opportunistic flight experiments, as well as tune and modify our algorithms to improve performance. Further, we will continue to pursue infusion activities for future applications of this technology for autonomous deep-space and crewed navigation.

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Software Routines from the IAU SOFA Collection were used. Copyright © International Astronomical Union Standards of Fundamental Astronomy [28].

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