NASA SEXTANT Mission Operations Architecture

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Abstract

The Station Explorer for X-Ray Timing and Navigation (SEXTANT) mission 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) that was launched in June of 2017. The NICER instrument is a precision pointing X-ray telescope that times pulsar sourced photon arrivals which the SEXTANT mission uses to perform autonomous onboard X-ray Pulsar Navigation (XNAV). By comparing the detected time of arrival of X-ray photons to a reference of expected pulsar timing models, one can infer a range and range rate measurement based on light time delay. Since both timing and orientation information comes from a celestial source, this technology could provide a GPS-like navigation capability available throughout our Solar System and beyond. Applications that XNAV can support include outer planet and interstellar missions, manned missions, libration orbit missions, and current infrastructure such as the Deep Space Network (DSN). The SEXTANT team successfully completed a first demonstration of in-space and autonomous XNAV in November 2017. NICER and SEXTANT have separate teams, with NICER being the primary team with its own science objectives. Operational modes for both missions must have concurrent and independent components as well as an integrated ground system. This paper describes on the operational infrastructure and successful operations for performing X-ray Pulsar Navigation with the Station Explorer for X-ray Timing and Navigation Technology (SEXTANT) demonstration. This paper first details the infrastructure implemented, then the concept of operations, and finally the operations for the SEXTANT demonstration and lessons learned.

Acronyms/Abbreviations

AGS	Attitude Ground System
GCD	Game Changing Development Program Office
GPS	Global Positioning System
GSFC	Goddard Space Flight Center
ISS	International Space Station
JSC	Johnson Space Center
MSFC	Marshall Space Flight Center
NICER	Neutron star Interior Composition Explorer
NRL	Naval Research Laboratory
SEXTANT	Station Explorer for X-ray Timing and Navigation Technology
SMOC	Science Mission Operations Center
SMD	Science Mission Directorate
STMD	Space Technology Mission Directorate
TOA	Time-of-Arrival
XNAV	X-ray Pulsar Navigation

1 Introduction

SEXTANT is a NASA Goddard Space Flight Center (GSFC) 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 International Space Station (ISS) which launched in June 2017. The NICER fundamental science studies the modulation of soft X-ray light curves from the rotation of neutron stars. Within that stream of observed NICER data, the SEXTANT mission will utilize, on board and in real time, the same raw data to generate navigation measurements and maintain position knowledge of an initially degraded ISS state from the NICER Global Positioning System (GPS) receiver. Previous publications on SEXTANT include the mission system architecture [1] in 2015, the SEXTANT flight system testing [2] in 2016, and initial flight demonstration [3] / additional results [4] in 2018.

In this paper, we focus on the ground system and operations used to successfully implement the SEXTANT mission. It is a mission that requires interfaces with a NASA science mission (NICER) within GSFC, the astrophysics community for ground software updates (such as Naval Research Laboratory (NRL)), as well as the Johnson Space Center (JSC)/Marshall Space Flight Center (MSFC) operations team for the interface to the ISS as an external payload. The mission was launched in June 2017 and is currently in operation on the ISS. A recent photo of the NICER instrument payload can be seen in Figure 2.

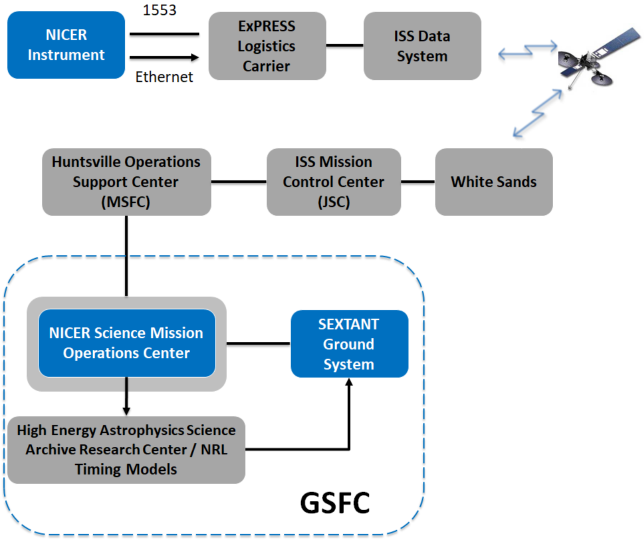

Figure 1: Overall Ground System Architecture including the SEXTANT Ground System

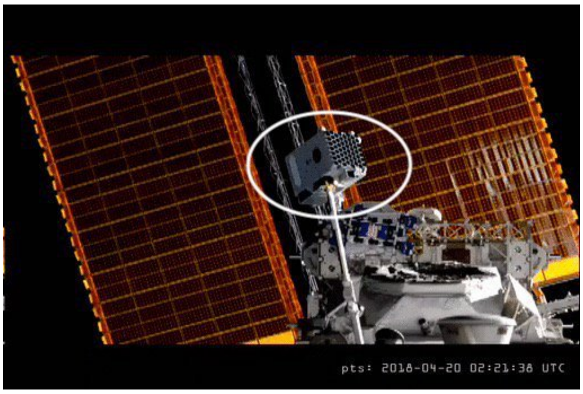

Figure 2: Circled NICER Instrument Image on the ISS

2 Demonstration Requirements

The technology demonstration requirements derived from the mission objectives are detailed in reference [1]. While all requirements are supported by the ground system, the primary drivers of the ground system design and concept of operations are quoted below:

XNAV-01 The X-ray Pulsar Navigation (XNAV) instrument shall be provided with an initial position and time estimate accurate to 10 km and 1 μs root mean squared, respectively.

XNAV-03 The XNAV instrument shall achieve the per-pulsar sourced pulsed count rates listed in the SEXTANT pulsar catalog (see Table 1) within a factor of 2. Though technically called the unpulsed X-ray photon rate, the term background rate is used interchangeably in this paper for the same meaning.

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

Requirements listed are unique to SEXTANT and are within NICER requirements. From a ground systems perspective, requirement XNAV-01 drives the frequency of on orbit software configuration uploads and XNAV-02 drives the necessary pulsar source data needed for upload for the demonstration. The SEXTANT team is allocated a 2-week period stated in XNAV-03 to drive operations on the instrument so the team can actively generate XNAV measurements for the on-board filter. It is within this window that the demonstration was attempted. In general, the NICER operations team drives the instrument for its nominal 18-month mission lifetime[5]. Outside of the 2 week period, further SEXTANT research opportunities can be pursued in conjunction to NICER nominal operations.

3 Operations Architecture

The following sections detail the SEXTANT ground system and the planned concept of operations for SEXTANT on orbit operations. As the XNAV demonstration is real time and on board on a science payload, the ground system is designed for the flight software to work autonomously alongside science operations. The ground system uploads command data to the flight software while simultaneously providing the NICER operations team commands for the instrument. The flight software then performs orbit tracking of the ISS autonomously until the next upload.

3.1 Ground System Overview

Starting from the general ground infrastructure, the SEXTANT ground system is a component connected to a sequence of other operational components to drive the demonstration on the NICER instrument. Seen in Figure 1, the spacecraft commanding passes from instrument to ISS ELC hardware to the ISS operations facility at JSC to the payload operations team at MSFC prior to the NICER/SEXTANT science mission operations center. Commands and uplinks to the instrument are dependent on approvals and protocol coming from these command centers.
The SEXTANT ground system processes multiple products described here: pulsar timing knowledge from other observatories (called the pulsar almanac in this

Table 1: List of SEXTANT Pulsars for Navigation [6]

Name	Period (ms)	Source Pulsed Rate (α, cnts/s)	Total Unpulsed Rate (β, cnts/s)
Crab Pulsar	33.000	660.000	13860.20
B1937+21	1.558	0.029	0.24
B1821-24	3.054	0.093	0.22
J0218+4232	2.323	0.082	0.20
J0030+0451	4.865	0.193	0.20
J1012+5307	5.256	0.046	0.20
J0437-4715	5.757	0.283	0.62
J2124-3358	4.931	0.074	0.20
J2214+3000	3.119	0.029	0.26
J0751+1807	3.479	0.025	0.22
J1024-0719	5.162	0.015	0.20

paper), X-ray photon and radiation background events / telemetry from the NICER instrument, and commands and planned observation schedules from the SEXTANT flight software. The pulsar almanac is a flight software input compilation of applicable pulsars for XNAV measurements as listed in requirement XNAV-02 for timing models, light curve templates, pulsar source, and background photon count rates. X-ray photon/background events and telemetry from the NICER instrument are inputs used to tune the filter and flight software between experimental runs. With these products, the SEXTANT ground system generates observation schedule products and a separate flight software upload for the NICER operators to perform and upload to the NICER instruments. From there, the instrument makes its observations and the flight software resets and performs its onboard autonomous processing of XNAV measurements.

The following sections detail the initial ground system delivery process, the SEXTANT and NRL operational interface, and the SEXTANT and NICER interfaces.

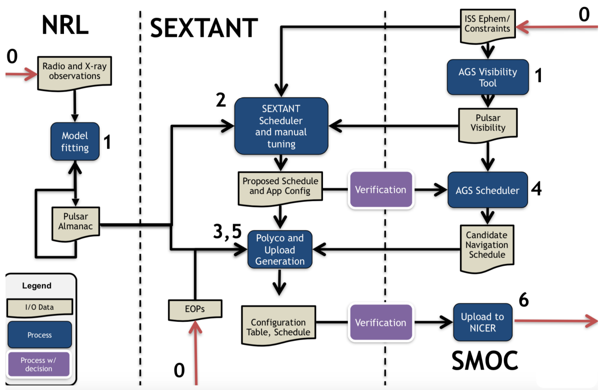

Figure 3: Primary Flow Diagram of NICER SMOC and NRL interfaces with SEXTANT operations

This section focuses on the GSFC component of Figure 1, detailed in Figure 3. In broad terms, two inputs are generated and two outputs are produced for upload to the instrument and the NICER operations team to implement. First, input from NRL to NICER generates

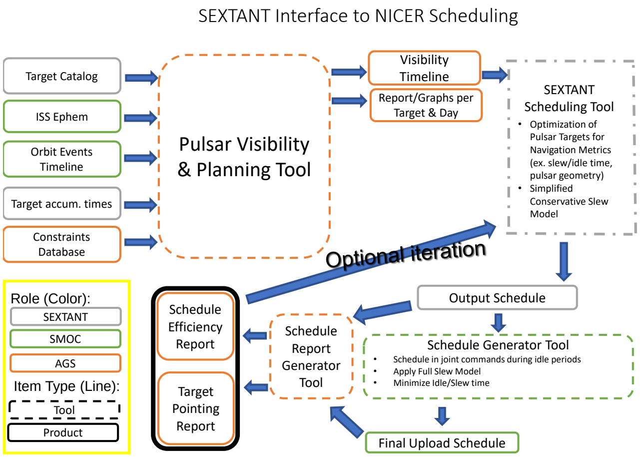

Figure 4: Secondary Flow Diagram detailing NICER and SEXTANT Operations with ISS interfaces

the pulsar almanac data/telemetry/X-ray background processing. Second, input from the ISS to NICER generates the attitude and state prediction data. These inputs come into Figure 3 from *Step 0* where the red arrows point into the flow chart. These two datasets are then processed together through the flow diagram to produce two outputs: the flight software upload (pulsar almanac, timing model polynomial coefficients, commands, etc.) for the SEXTANT flight software as well as products for the NICER operations team to drive the telescope to the appropriate observations. This final product can be seen as a red arrow pointing out of the flow chart in Figure 3 as *Step 6*. The SEXTANT team performs this process in the flow diagram in a 3-day cadence. Further information on the flow diagram is detailed in reference [1].

Elaborating on the first input from the NRL section of Figure 3, Figure 5 displays the interface that generates the NRL pulsar almanac. The data starts from reference time fitted models from radio sources and X-ray photon data from the NICER instrument as a

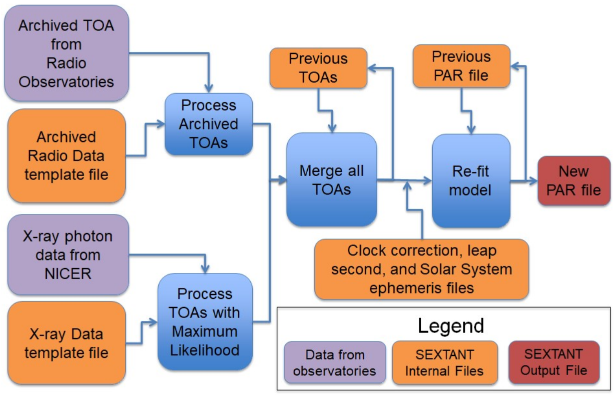

Figure 5: Secondary Flow Diagram detailing NRL and SEXTANT Operations

baseline to generate the Time-of-Arrival (TOA) models. The SEXTANT flight software then takes the data and generates a software upload with on-board TOA data. Corrections are included at this stage with on-board telemetry on clock corrections, leap seconds, and solar system ephemeris data. Finally, the data is fitted one more time and delivered for processing. Once the pulsar files are delivered, the data is used to model any recent changes to the pulsar timing models.
Elaborating on the second input in the SEXTANT and SMOC sections of Figure 3, Figure 4 details the ISS delivery process to the NICER and SEXTANT operations team for processing and planning. This includes the predictive ISS state ephemeris and the predictive ISS attitude history data. The NICER science team also submits a pulsar target catalog and visibility constraints file to specify additional targets and changes to the visibility threshold on multiple occultation sources. A cone angle restriction of visibility along the pulsar target line of sight is applied to ISS hardware, celestial body, solar glint, and South Atlantic Anomaly/Polar Horn regions. These data products allows both the NICER and SEXTANT teams can plan adjacent target observations during all operational modes of the mission.
The final product generated for upload is the target observation optimization itself. A SEXTANT configured and NICER configured scheduling algorithm is incorporated through a GSFC ground system configuration called the Attitude Ground System (AGS). Each is configured for its optimization space of about 10 pulsar targets for SEXTANT and greater than 100 targets for NICER. Nightly runs are performed on the SEXTANT ground software in order to predict filter performance and manage any ground system issues[1].
All these products are reviewed and confirmed through the *Verification* flow block of Figure 3. NICER operations team then uploads both SEXTANT and NICER data.

3.2 Concept of Operations

The flow diagram of SEXTANT operations at its baseline has two operational modes: demonstration (independent operations from NICER) and opportunistic (concurrent operations with NICER). The 2-week demonstration period is the primary SEXTANT concept of operations, but opportunistic mode was set to use NICER operations to perform SEXTANT calibration and other research prior to and after the demonstration.
Both modes consist of the same data processing of observation schedules and timing models; the process repeats for a 3-day cycle. During opportunistic mode, the SEXTANT team reviews daily Monte Carlo runs and other telemetry data from the flight software to determine if the SEXTANT team will upload data or propose an observation schedule for the next 3-day cycle.
Prior to the demonstration mode, the date for the demonstration was negotiated months before with the NICER team. To determine a candidate period for a demonstration, both operation and performance metrics were considered. For operations, the seasonal visibility as well as statistical day to day visibility was evaluated for all pulsar targets. The timing model accuracy testing during calibration was also factored in determining a demonstration date [3]. Finally, timing model glitches and any hardware performance was evaluated alongside the NICER team. Once the date was determined, the demonstration repeated the same 3-day cycle, with the exception that the maximum allotted time was scheduled for SEXTANT observations. In summary, Figure 6 constitutes the 2-3 month planning cycle to determine the 2-week demonstration, and Figure 7 constitutes the operations timeline for the 2-week demonstration.

4 On Orbit Events

The implementation of the concept of operations and products was modified while on orbit to accommodate for on orbit operations. The first section describes those changes. The last section will describes the operations timeline around November 9th, 2017 that successfully demonstrated on orbit autonomous X-ray pulsar navigation.

4.1 Demonstration Preparation

While on orbit, changes to the SEXTANT operations architecture in preparation for the demonstration involved calibration, pulsar visibility, and ISS operations modeling.
Calibration of the photon processing and instrument observations pulsar targets was performed from data

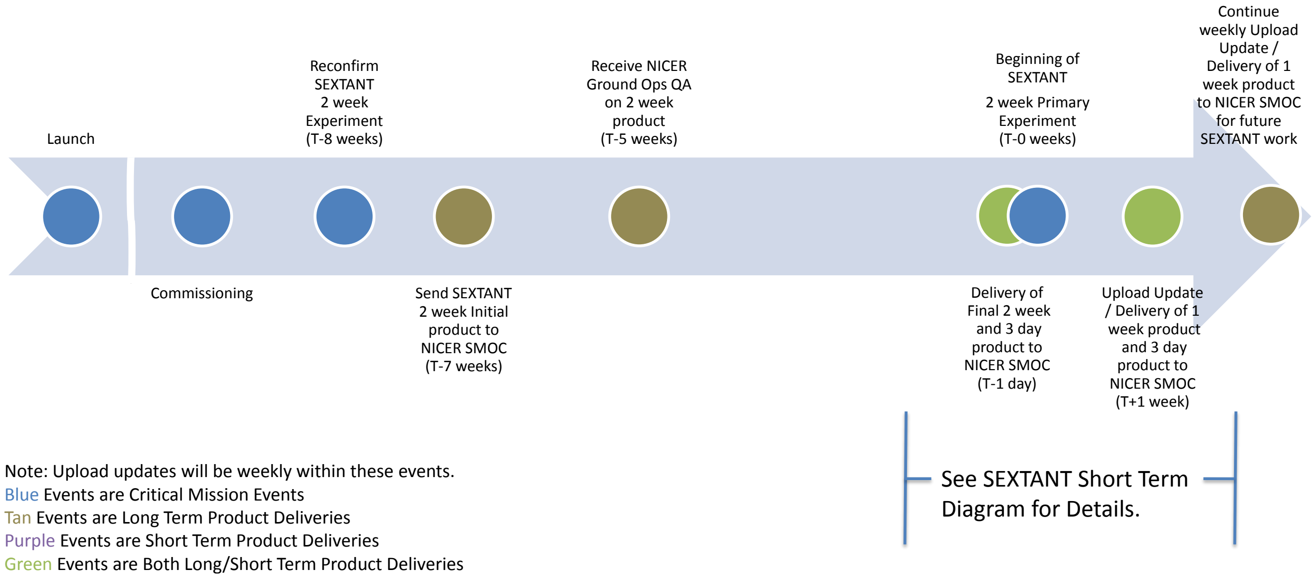

Figure 6: Long Term Operation Timeline Concurrent with both NICER/SEXTANT Operations

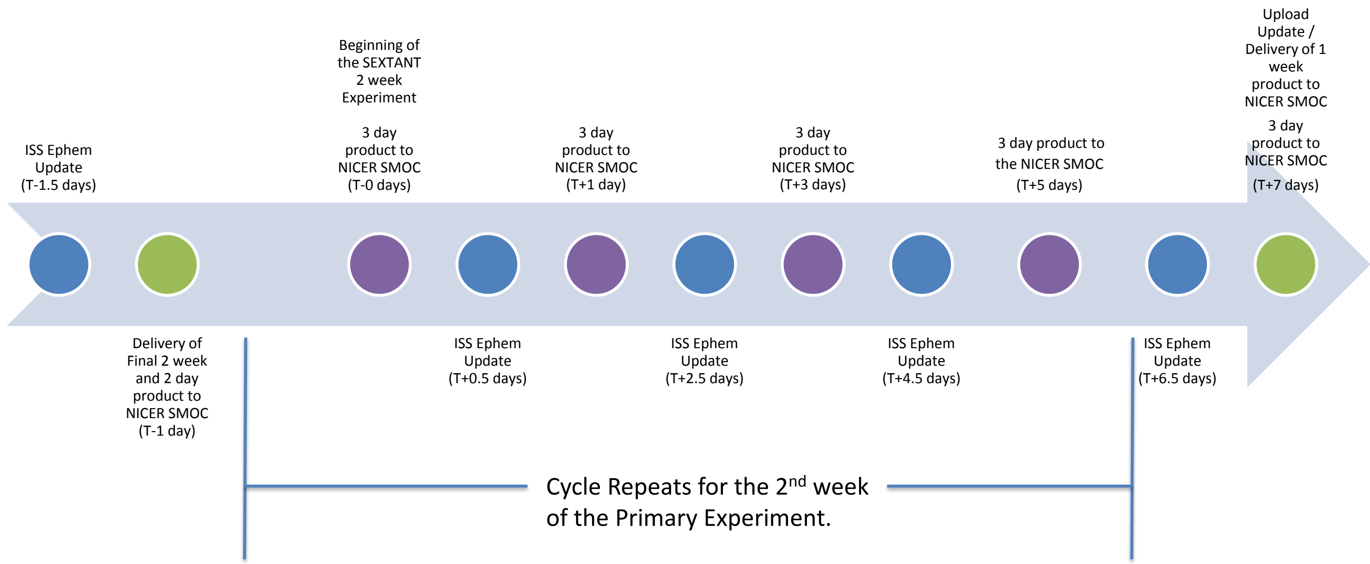

Figure 7: Short Term Operation Timeline during the SEXTANT demonstration

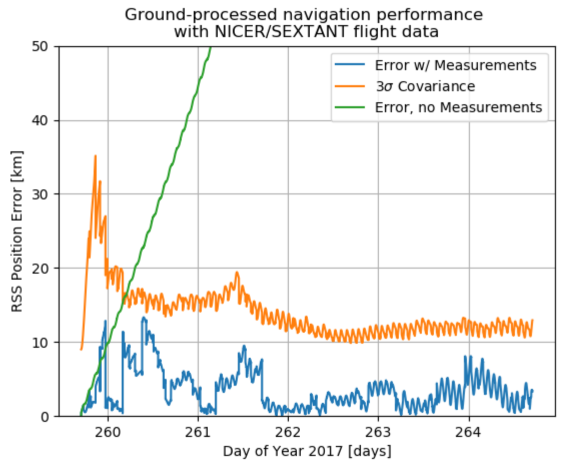

Figure 8: Day of Year 259-265 Ground Calibration Demonstration Test

sets day of year 259 to 265. The results were presented in reference [3] and was based on a proposed schedule plan driven by NICER to capture timing data prior to solar occultation in mid November. End to end ground processing of the flight data was generated alongside calibration and is shown in Figure 8.

With multiple science goals on the NICER hardware and ISS operations, about a 87% duty cycle was capable for all on orbit pulsar observations. With celestial occultations and hardware constraints, the NICER instrument's single target design requires slew times which take the majority of the duty cycle efficiency. After calibration testing, the SEXTANT team decided to reduce pulsar observations based on a 2D ground orbit ground track to reduce background noise from high X-ray energy. The resultant SEXTANT observation keepout regions within the ISS ground track is seen in Figure 15 as colored regions. In general, these depict the South Atlantic Anomaly and northern and southern polar horn regions in low Earth orbit. During the demonstration, the NICER team used the transit time in these regions to make other observations outside of the SEXTANT schedule. Out of the 87% pulsar schedule efficiency, these adjustments resulted in an average 32% schedule efficiency on SEXTANT targets during the demonstration.

ISS operations, being a priority, also drove SEXTANT operations. The ISS docking schedule resulted in changes in the delivery and content of ephemeris and attitude products of the ISS for planning any instrument pointing on the space station. All major ISS events from the NICER launch until the SEXTANT demonstration are listed below[7]:

1. 6/05/2017: SpaceX dragon capsule docks with ISS (with the NICER instrument on board)
2. 6/16/2017: Progress 67 resupply ship docks
3. 7/03/2017: SpaceX dragon capsule departs
4. 7/20/2017: Progress 66 departs
5. 7/28/2017: Soyuz MS-05 docks
6. 8/16/2017: SpaceX dragon docks
7. 9/17/2017: SpaceX dragon departs
8. 9/27/2017: ISS orbital reboost
9. 10/16/2017: Progress 68 docks

Each of these events modified the mass, atmospheric drag, attitude profiles, and other ISS properties. Figure 9 shows the property changes of the ISS, starting at the week of the demonstration. The y axes include the mass, drag area, coefficient of drag (Cd), and solar beta angle of the ISS. The asterisks indicate the predicted epoch of that property change. As seen, the ISS mass can vary by thousands of kilograms and hundreds of km^2 of drag area within a day or two of propagation. While acceptable to the filter design, predictive and definitive navigation accuracy for the telescope requires updates 2 to 3 days after upload.

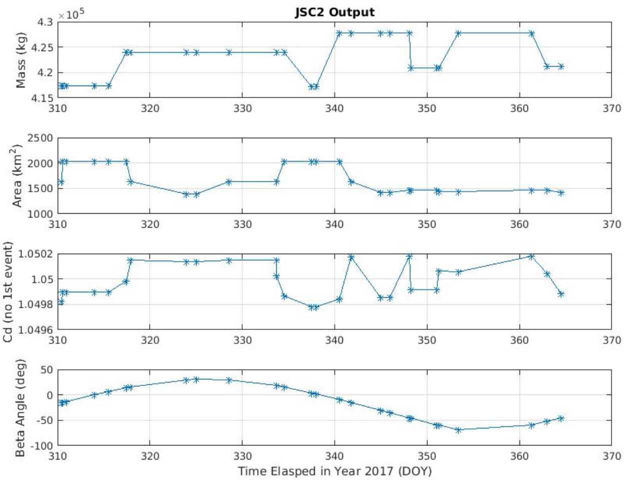

Figure 9: ISS Properties vs. 2017 Day of Year

Finally, the physical structure of the ISS also drove changes in the visibility models after launch. Modifications were made to accommodate shape models of solar panels and radiators to avoid any singularity in ray tracing pulsar line of sight. The Soyuz vehicle also provided an additional radiation occultation due to its gamma altimeter. Also, celestial occultations of 15/30/45 degrees keep out cone angle zones for Moon/Earth/Sun were tuned values to trade observation time and signal noise. The resultant chart for ideal SEXTANT target visibility is seen in Figure 14.

4.2 SEXTANT Demonstration

The demonstration planning period was scheduled for 11/8/2017 to 11/22/2017, with the formal demonstration achieving SEXTANT requirements between 11/10/2017 and 11/15/2017. The date was chosen to

Figure 10: NICER/SEXTANT 3D Model simulation during the SEXTANT demonstration

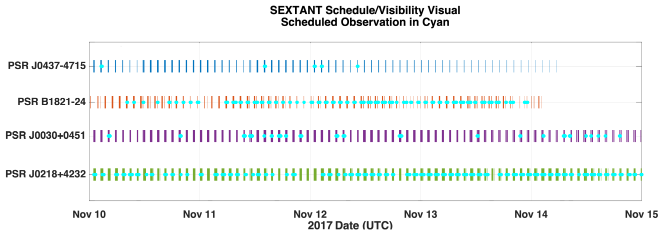

Figure 11: SEXTANT Experiment Performance Visibility and Schedule

maximize the number of available SEXTANT targets to be visible; in particular, the B1821-24 pulsar target would be unavailable after 11/12/2017 for two months, eliminating the chance to use the pulsar. With the date chosen, planning started with the delivery of ISS products by 5:00 UTC on 11/8/2017. The NICER operations team provided an initial visibility report and planned observations at 8:56 UTC to SEXTANT and other science partners. SEXTANT drove the schedule, with unscheduled time by the SEXTANT team used for coordinated observations between NICER and other science partners. After testing visibility constraints for other science observations, the first draft observation schedule from the SEXTANT team was submitted for review at 17:33 UTC that was optimized with SEXTANT targets. The second draft was updated by the NICER team with their targets between SEXTANT observations. At 17:45 UTC, an unplanned update to the ISS attitude file was provided so a third draft with SEXTANT and NICER updates was included. Finally, after the addition of short but high source flux Crab pulsar (B0531+21) observations, the final product was uploaded to the instrument by 21:38 UTC. The next day on 11/9/2017, the flight software upload was sent and some diagnostics were performed on the NICER X-ray telescopes prior to the demonstration.

As a result, the final demonstration's schedule and XNAV measurements were generated in Figure 11 and 12. Figure 11 shows the availability of pulsars as colored bands with a cyan mark for the pulsar that is

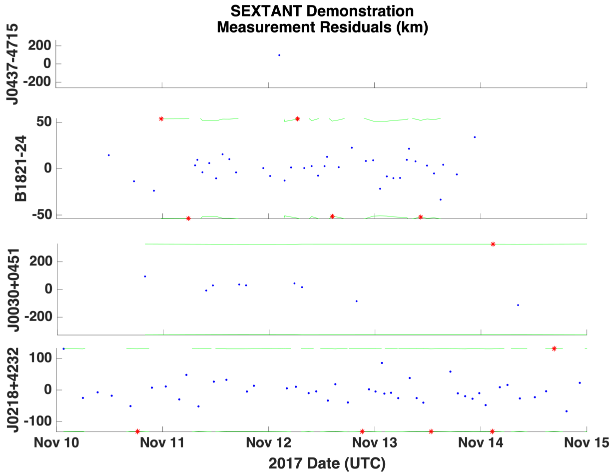

Figure 12: SEXTANT Experiment Performance XNAV Measurement Residuals

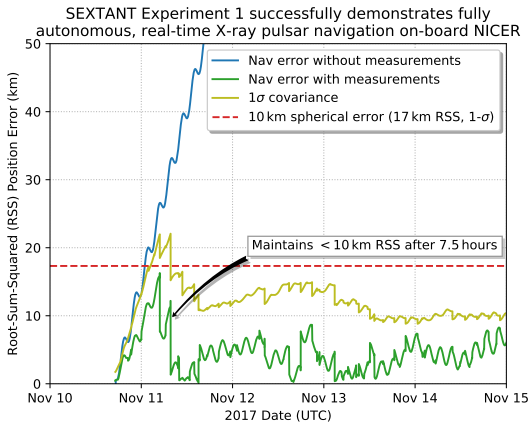

Figure 13: SEXTANT Experiment Performance Results

scheduled. J0218+4232 and B1821-24, with its evenly timed cadence of slews and timing accuracy, dominated the optimized schedule for the first 4 days (11/8 to 11/12), after which the other pulsar targets took over as B1821-24 was occulted. About 33% of the total observations made in the schedule were for SEXTANT targets. Figure 12 shows the resultant measurement residuals from each pulsar in blue, with the sigma residual limit in green and the rejected measurements marked as red asterisks. The pulsar measurements were edited with a 10-60 km wavelength sigma edit for an average measurement rejection rate of 15% resulting in a couple hundred XNAV measurements. Finally, the flight hardware telemetry playback is shown in Figure 13. Four pulsar targets were used: J0437-4715, B1821-24, J0030+051, and J0218+4232. Using these pulsars, the 10 km RSS performance requirement was achieved in about 7.5 hours, with the potential to get to potentially less than a 1 km error point solution. A 3D graphical visual that displays the in-situ data during the demonstration can be seen in Figure 10.

5 Conclusions

The Station X-ray Timing and Navigation Technology(SEXTANT) demonstration is a software enhancement to the Neutron star Interior Composition Explorer(NICER) X-ray timing telescope science mission onboard the International Space Station(ISS). Using the same timing data as NICER, the SEXTANT mission will utilize, on board and in real time, the same raw data to generate navigation measurements and maintain position knowledge of an initially degraded ISS state from the NICER GPS receiver.

This paper presents the SEXTANT ground system; an integrated system with the command chain from the ISS JSC and MSFC operations teams. The ground system handles both the need to accommodate operational events onboard the space station as well as the science demands required for the NICER science team. The ground system is run on two modes of independent and concurrent operations alongside the NICER team. The system collects the pulsar timing data and generates observation schedules and the software upload with timing data and calibration parameters to allow the onboard flight software to successfully demonstrate X-ray pulsar navigation.

Overall, the SEXTANT ground system underwent a series of changes on orbit which were lessons learned for future missions. The ISS operations environment requires a greater degree of flexibility in product delivery and uncertainty than originally designed; daily critical events can change the mass, attitude, and configuration of the station. Combined with the background and visibility environment, pulsar observation time for SEXTANT was around 33% for the demonstration. ISS predictive knowledge to plan telescope observation schedules and XNAV products was effective for 2 to 4 days. Even with these changes, SEXTANT successfully demonstration on board, real time X-ray pulsar navigation.

The resultant demonstration performed from 11/10/2017 to 11/15/2017 achieved the SEXTANT performance requirement of 10 km, worst direction RSS tracking within its two week demonstration period. The 10 km settled RSS performance criteria was achieved with 7.5 hours and point solutions achieved lower than 1 km error with XNAV measurements.

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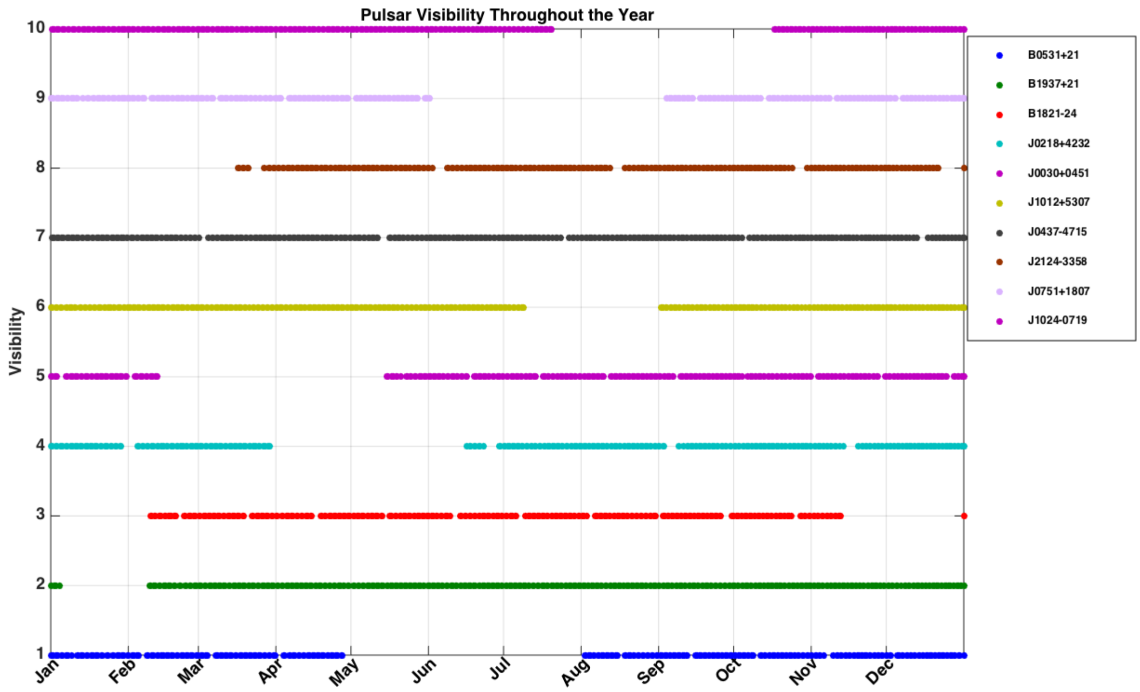

Figure 14: NICER/SEXTANT Available Visibility of Pulsars throughout the Year

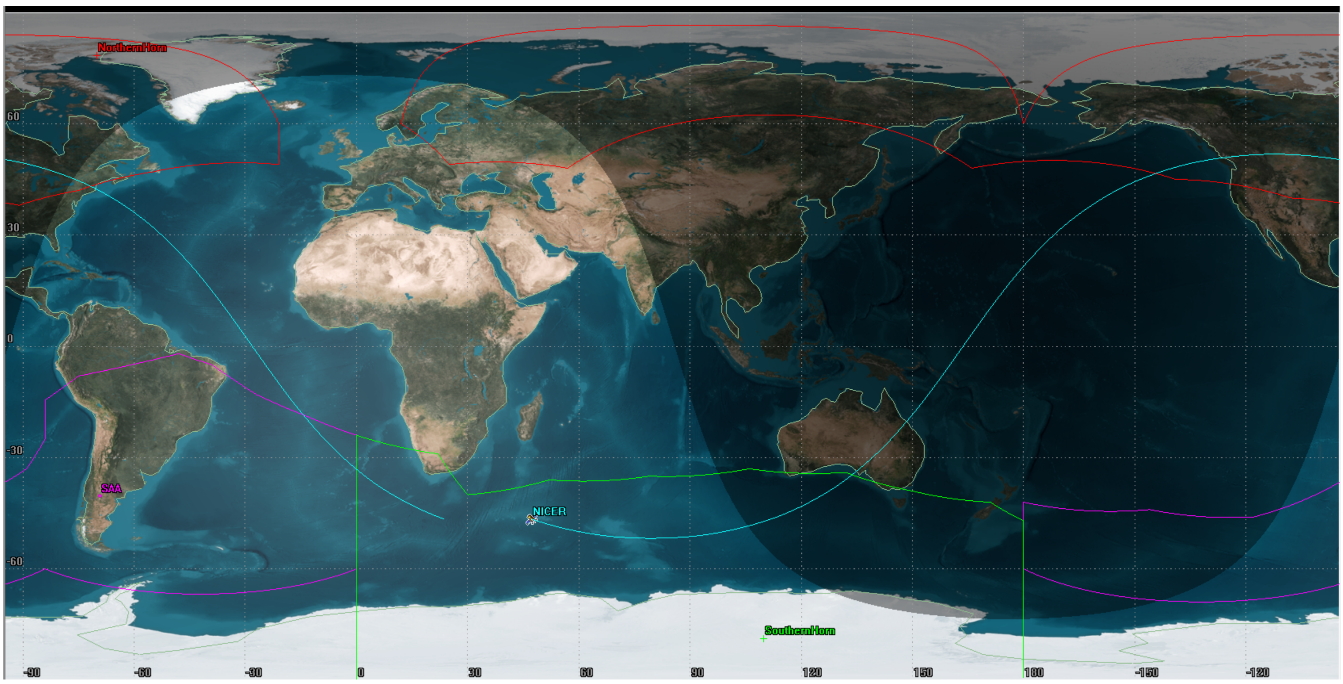

Figure 15: ISS/NICER instrument 2D Ground Track with Background Radiation Energy Keepout Regions during the SEXTANT demonstration