The Neutron star Interior Composition Explorer (NICER): design and development

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ABSTRACT

During 2014 and 2015, NASA's Neutron star Interior Composition Explorer (NICER) mission proceeded successfully through Phase C, *Design and Development.* An X-ray (0.2–12 keV) astrophysics payload destined for the International Space Station, NICER is manifested for launch in early 2017 on the Commercial Resupply Services SpaceX-11 flight. Its scientific objectives are to investigate the internal structure, dynamics, and energetics of neutron stars, the densest objects in the universe. During Phase C, flight components including optics, detectors, the optical bench, pointing actuators, electronics, and others were subjected to environmental testing and integrated to form the flight payload. A custom-built facility was used to co-align and integrate the X-ray "concentrator" optics and silicon-drift detectors. Ground calibration provided robust performance measures of the optical (at NASA's Goddard Space Flight Center) and detector (at the Massachusetts Institute of Technology) subsystems, while comprehensive functional tests prior to payload-level environmental testing met all instrument performance requirements. We describe here the implementation of NICER's major subsystems, summarize their performance and calibration, and outline the component-level testing that was successfully applied.

Keywords: X-ray astrophysics, Neutron stars, Timing spectroscopy, International Space Station, SEXTANT, X-ray pulsar-based navigation (XNAV)

1. INTRODUCTION

The Neutron star Interior Composition Explorer is a Mission of Opportunity—an external attached payload on the International Space Station (ISS)—within NASA's Astrophysics Explorers program. Approved for implementation in April 2013, NICER is currently scheduled for launch in early 2017. In keeping with the early stages of the lifecycle of NASA space missions, we have previously described NICER's mission concept and scientific motivation,[1] as well as the set of requirements[2] that define the payload's performance, drive its design, and ultimately enable the desired scientific outcomes. The present paper outlines the development of the NICER payload through summary descriptions of the major flight hardware systems and the mission's ground segment.

2. THE NICER PAYLOAD

Figure 1 shows an illustration of the NICER payload, and Figure 2 a photo of the nearly complete flight assembly.

2.1 X-ray Timing Instrument (XTI)

NICER will achieve its science objectives by providing unprecedented timing-spectroscopy capability, with high throughput and low background, in the 0.2–12 keV (soft X-ray) band. The XTI, NICER's sole science instrument, is a highly modular collection of X-ray "concentrator" optics, each with an associated detector. These subsystems are described in detail elsewhere; we touch upon them briefly here.

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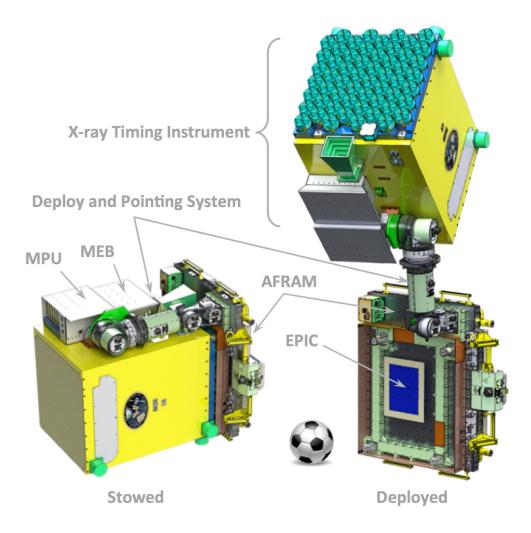Z.A. e-mail: zaven.arzoumanian@nasa.gov

Figure 1. NICER in its stowed and deployed configurations.

2.1.1 X-ray Concentrators (XRCs)

The XTI collects cosmic X-rays using grazing-incidence, gold-coated aluminum foil optics. Each of the 56 optic modules (Fig. 3) consists of 24 nested foils that are precisely shaped to form parabolic surfaces of a common focal length. The flight XRCs alone (not accounting for losses elsewhere in the optical path) provide nearly 2,500 cm^2 of effective area at 1.5 keV. Ref. 3 covers the fabrication methodology for the NICER XRCs, and Ref. 4 (this volume) describes their performance, coalignment, and calibration.

2.1.2 X-ray Detector System

Ref. 5, in this volume, provides a thorough exposition of NICER's X-ray detection system, which consists of commercially available (Amptek, Inc.) silicon-drift detectors integrated with custom pre-amplifier circuitry in Focal Plane Module (FPM) housings, and the Measurement/Power Unit (MPU), the readout and supporting electronics for the ensemble of detectors. The Detector System surpasses, with significant margin, minimum XTI performance requirements for photon energy resolution and time-stamping; see, e.g., Figures 8 and 13 of Ref. 5.

2.2 Mechanical/Structural System

NICER's Mechanical System comprises the structural elements of the XTI (principally, the Instrument Optical Bench that houses the optics and detectors), the Deploy and Pointing System (DAPS; see Sec. 2.3), and the

Figure 2. The NICER flight payload in a nearly fully integrated configuration, blanketed and stowed against the flight A-FRAM plate.

Adapter Plate, through which NICER is connected to the ISS-provided Active Flight Releasable Attachment Mechanism (A-FRAM) for eventual attachment to a Passive (P-FRAM) counterpart on the ISS. The Adapter Plate supports the launch-lock mechanism that secures the XTI during launch and releases it once NICER is installed on the ISS.

NICER's structures play a role in the mechanical, electrical, and thermal interfaces for all subsystems and components.

2.2.1 Instrument Optical Bench (IOB)

The IOB's purpose is to keep the XRC optics and FPM detector housings co-aligned, to maintain the focal distance of 1085 mm, and to support secondary structures. It is a bolted structure that consists of five machined aluminum plates and two honeycomb panels. All through-hole joints, match-drilled at the time of assembly, are fastened using close-tolerance bolts, with washers and nuts on the inside of the IOB. Blind holes were used when through-holes could not be accommodated. All corner connections were match-drilled and pinned (with press/interference fit) to minimize movement during launch vibration loads.

The IOB's Concentrator Plate (Figure 3) holds the 56 XRCs, their thermal filters, and composite sunshades along with four Frangibolt launch-lock actuators (see below). At the other end of the IOB, the Detector Plate supports the 56 FPMs and the localized radiation shielding (silver/gold-plated aluminum cones, lead disks and collars) associated with them. Essentially, the IOB supports 56 parallel "telescopes." The two side plates, the top plate, and the honeycomb baseplates—which provide a stiff and thermally resilient structure to hold electronics boxes, the star tracker, and harnessing—make up the remainder of the IOB.

2.2.2 Adapter Plate

This shaped aluminum plate, 50 mm thick, serves as the interface between NICER and the ISS program-provided A-FRAM. In addition to lending additional stiffness to the A-FRAM, the adapter plate holds the launch-lock
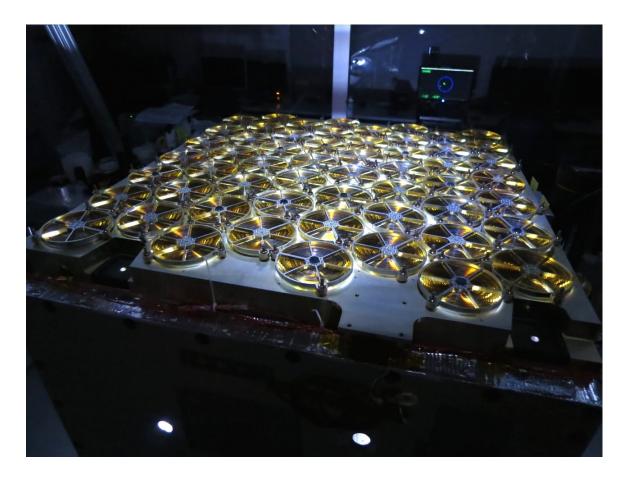
Figure 3. NICER's 56 X-ray Concentrator optics integrated onto the Concentrator Plate in NICER's dedicated coalignment facility.

towers and is the base for the DAPS.

Four launch-locking mechanisms, the $3/8''$ fastener-diameter FC6 Frangibolt system from TiNi, Inc., are used to hold the payload in the stowed configuration during launch and to release it on command once in orbit. The Frangibolt actuator is a non-explosive release device that uses shape memory alloy (SMA) to forcefully break a bolt in tension. When the SMA is heated above approximately $80°$ C by heater elements bonded in a cylinder around the bolt, it recovers its original length, stretching the bolt to failure.

2.2.3 Decks and Brackets

The Instrument Electronics Deck attaches to the IOB via four titanium flexures, to accommodate thermal-mechanical stresses, and serves as the mount point for the star-tracker Data Processing Unit and the detector MPU. The Deck is a sealed volume containing Phase Change Material (PCM; see Sec. 2.5).

The Avionics Deck also attaches to the IOB via four titanium flexures and serves as the base for the Main Electronics Box (MEB) and Gimbal Control Electronics (GCE). Similar to the Instrument Electronics Deck, the Avionics Deck contains PCM for thermal management.

The Star Tracker Bracket supports the star tracker camera head and baffles.

2.2.4 Mechanical Component-Level Testing

During the component-level development phase of NICER, several subsystems and components were tested to ensure they would survive future payload-level environmental testing and launch and on-orbit environments. The

most significant of these tests, the Structural Verification Unit (SVU) vibe test, was carried out to verify that our IOB structure design and assembly processes would maintain the co-alignment of the 56 telescopes after launch. A duplicate IOB was fabricated for test purposes, and mass simulators were used in place of the flight instruments in most locations to minimize risk to expensive or one-of-a-kind flight hardware. Because NICER was prohibited from using the Flight A-FRAM during environmental tests, a unique simulator was designed and built to mimic its structural integrity and stiffness. This test was successful, showing total telescope misalignments that were below the predicted values. This test also validated the Finite Element Model (FEM) that was developed for NICER payload-level analyses. Earlier, vibration tests were performed on subsets of the XRCs to develop effective co-alignment, torquing, and staking procedures. Vibe and acoustic tests were also performed on Engineering test-unit (ETU) FPMs and thermal filters to ensure they would survive the predicted environments.

Because NICER will be installed on the ISS, unique requirements were addressed relating to astronaut and robotic equipment maneuvers. NICER is required to withstand astronaut kick loads as well as 1 Joule impact loads on nearly all external structures. Large openings in the IOB are covered with multi-layer insulation (MLI), so a specific test article was fabricated to prove that the MLI in these areas could withstand such loads. ETU composite sunshades were also tested to verify that these requirements were met. All other NICER structures were analyzed to demonstrate compliance with requirements. The component-level tests aided in the success of the NICER payload-level integration and testing processes by reducing risk and allowing the team to develop procedures and processes in a more flexible manner than if they had been developed later.

2.3 Pointing System (PS)

The NICER PS points the XTI at celestial targets and tracks them as the ISS rotates to maintain its local-vertical/local-horizontal (LVLH) attitude. When one target sets (or moves beyond the actuator range limit), the PS slews to the next target upon command and repeats the tracking operation until the next slew command is received. In addition to supporting NICER science observations, the PS is also responsible for deploying the XTI above its FRAM installation point on the ISS ExPRESS Logistics Carrier 2 (ELC2) to enable a nearly hemispherical field of regard about the zenith, and for stowing the instrument when needed (e.g., during dockings of visiting spacecraft and astronaut or robotic extravehicular operations).
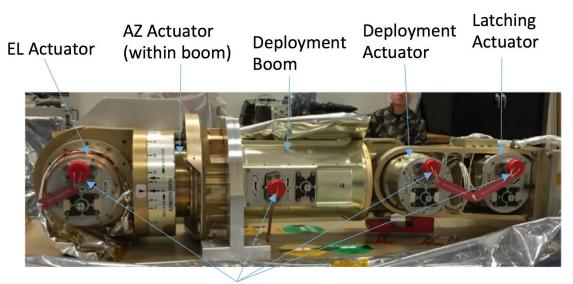
2.3.1 Pointing System Hardware

The PS hardware consists of a deployment and pointing system (DAPS) mechanism assembly, actuator and gimbal control electronics (GCE), a star tracker (ST), and tuned mass dampers (TMDs). The DAPS mechanism was designed and built by Moog Chatsworth, Inc. The GCE was procured from Moog Broad Reach Engineering, Inc., with design heritage from NASA's Lunar Reconnaissance Orbiter (LRO) mission. The National Space Institute of the Technical University of Denmark (DTU Space) provided the integrated ST and micro-inertial reference unit (IRU) for NICER.[6] Moog CSA, Inc., designed and delivered the TMDs to provide damping of resonant responses from low-frequency NICER structural modes.

The DAPS mechanism assembly has five major components:

1. a deployment actuator that raises the boom, gimbal assembly, and XTI above the ELC to clear most of the ISS structural viewing obstructions,

2. a latching actuator that is capable of releasing and re-locking the deployment actuator in both the stowed and deployed configurations,

3. a deployment boom that provides the requisite height for raising the XTI above the ELC and supports the gimbal actuator assembly,

4. gimbal actuators that are oriented in an elevation (EL) over azimuth (AZ) configuration to enable target tracking, and

5. an ISS robotics interface for each actuator that allows external manipulation of the NICER actuators in the event of a contingency requiring robotically executed re-stow of the payload.

The major components of DAPS are shown in Figure 4. The deployment, AZ, and EL actuators are Moog Type 5 stepper-motor Rotary Actuators, customized to reduce detent torque, whereas the latching actuator is a Moog Type 3. Each has a potentiometer on its output side to provide coarse joint-angle positions with accuracy better than ±0.25°. The AZ and EL actuators also incorporate Hall-effect sensors on the actuator input side to provide home position information with high accuracy (±1 actuator step).

Figure 4. DAPS mechanism assembly, developed by Moog Chatsworth, Inc.

The GCE receives commands from either the pointing control flight software (PCFS) or the Ground System through NICER's Main Electronics Box (MEB). It drives each actuator accordingly, and stops any actuator when potentiometer voltage limits are exceeded, to prevent the actuators from hitting their hardstops. The GCE also provides joint angle telemetry information through potentiometer voltages, Hall sensor trigger status, and step counts back to the MEB.

The ST assembly includes the camera head, baffle, and data processing unit. The camera head and baffle (Figure 5) are mounted on the XTI with the optical boresight co-aligned with the XTI's X-ray boresight. The ST provides the attitude of the XTI with respect to the inertial frame at a 5 Hz rate. It also incorporates internal micro-electromechanical gyros and accelerometers that are used to propagate the star tracker solution at a 10 Hz rate, minimizing the time delay in attitude measurements and providing attitude information when the ST data is temporarily unavailable due to Sun or ISS structure occultation.

The TMDs are resonant devices designed to dissipate vibrational energy from the structure. They are passive mechanical devices that do not require electronics or power. The TMDs are particularly effective for NICER in that they suppress low-frequency vibrations excited by both DAPS stepper-motor and ISS-induced disturbances. The NICER TMDs were designed to provide 1–3% damping ratio for the first three flexible-body modes. They are oriented to reduce vibrations along the axes where the vibrational displacements occur; NICER's TMDs, located at certain corners of the moving XTI volume, are shown as green cylinders in Figure 1.

2.3.2 Pointing System Software

The PS uses both ground and flight software commands to accomplish various functions including deployment and stowing of the instrument, slewing to a new target (in either joint or inertial space), tracking a new target, and stopping the actuators from moving when problems are detected through the flight software Fault Detection and Correction (FDC) system. The Pointing Control Flight Software (PCFS) supports the slewing, tracking,

Figure 5. NICER's μASC star tracker, developed by the Technical University of Denmark. The camera head and baffles are shown mounted on an IOB bracket.

and fault-protection aspects of the PS functionalities and uses commands from the Ground System to perform Stow and Deployment operations.
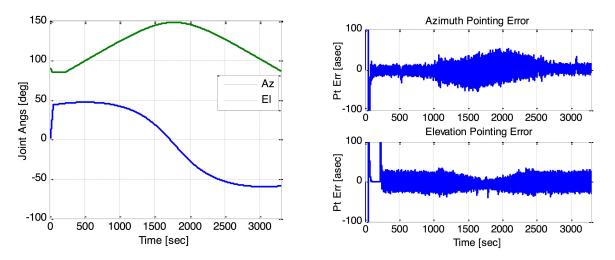

Figure 6. Joint angles (*left*) and pointing error (*right*) from the high-fidelity NICER pointing simulation.

The PCFS was developed in-house at NASA GSFC using the Mathworks auto-generated code process. The PCFS is part of a high-fidelity pointing simulation created in MATLAB Simulink that includes ISS and NICER dynamics, actuator and sensor models, and interfaces to flight hardware models. The control algorithm includes a heritage proportional-integral controller, augmented with a low-pass filter to reduce the low-frequency structural mode responses in the control loop. A representative slew-to-track scenario is shown in the left-hand panel of Figure 6, where the AZ and EL travel ranges are $+47°$ to $-57.5°$ and $85°$ to $148.5°$, respectively, where the coordinate system is defined such that AZ $= 0°$ is the starboard direction and EL $= 180°$ is within a few degrees of the zenith. The tracking portion of the simulation begins at approximately 250 seconds, after the target rises above $85°$ in EL. The right-hand panel of Figure 6 shows the pointing error during tracking to be less than ~ 50 arcsec versus a requirement of 66 arcsec.

Figure 7 shows the top-level PCFS mode transition diagram. The PCFS has an Operations State for nominal operations and a Safe State for when faults are detected. Within the Operations State, there are three control modes: Joint Control Mode (JCM), Science Control Mode (SCM), and Stop Mode. The JCM and SCM each

have separate slew and track sub-modes in order to allow different controller designs for each control mode and smooth transitions between the sub-modes. For the JCM, the track sub-mode serves as a hold mode, which aims to hold the commanded joint position.
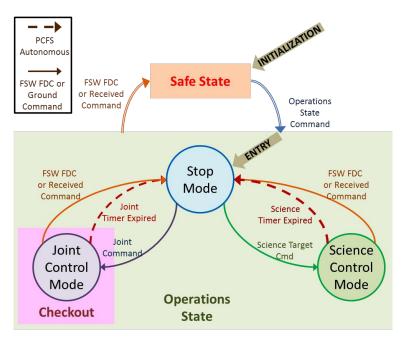

Figure 7. Pointing Control Flight Software mode transition diagram.

For PCFS mode transitions, the PCFS initializes into the Safe State and can transition to the Stop Mode in the Operations State via ground command. In the event of error detection, the PCFS can transition from any of the control or stop modes back to the Safe State. A ground command must be sent to allow PCFS to exit the Safe State, whereas autonomous exit is allowed from the Stop Mode via a Science or Joint Target command to the control modes. If either the JCM or SCM timer expires (i.e., programmed maximum slew and tracking durations are exceeded), the control modes transition autonomously to the Stop Mode and wait for the next Joint or Science target command.

The PCFS has been tested in several independent NICER flight software build tests. The entire NICER PS design has been implemented with all hardware components procured and integrated. Substantial effort was put into modeling, analyzing, testing, and optimizing several subsystem designs and operations to reduce pointing jitter, and the PS meets the mission's functional and performance requirements.

2.4 Electrical System

The Electrical System handles power, computations, and communications within the NICER payload and supports multiple interfaces with ISS:

- 28 V Operational Power

- 120 V Operational and Heater Power

- MIL-STD-1553 Communications Bus for command uplink and housekeeping telemetry downlink

- Ethernet science telemetry downlink

- 5 V discrete signals for power switching

- Analog signals for temperature monitoring.

NICER can be operated either directly from ISS-provided 28 V power or from ISS 120 V power by way of a GSFC-developed electrical box called EPIC. From EPIC, 28 V power is delivered to the MEB, which was developed by Moog Broad Reach Engineering. The MEB contains the single-board computer, in which the Flight and Pointing Control Software reside, and the GPS electronics. The MEB also handles communications (1553, Ethernet, RS-422, and the GPS "1 Pulse Per Second" signal over a low-voltage differential signaling [LVDS] line) and is responsible for controlling power to the various electrical components that make up the NICER payload. This includes elements of the pointing, deployment, thermal, and detector subsystems.

2.4.1 ExPA Power Interface Controller (EPIC)

EPIC is responsible for converting 120 V DC operational power from the ISS ExPRESS Payload Assembly (ExPA) and distributing up to 500 W of 28 V DC operational power to the rest of NICER. EPIC contains three DC-DC 120 V to 28 V isolated converters to meet the load demand. The converters are enabled and disabled via a 5 V (level) discrete command from the ExPA. EPIC also provides a maximum of 105 W of unswitched 120 V power from ExPA to the High Power Switching (HiPoS) Box for pre-survival (see Sec. 2.5) heater power. The EPIC design contains a non-latching relay that optionally bypasses the DC-DC converters to select the ExPA 28 V operational power as the power feed for NICER.

2.4.2 Main Electronics Box (MEB)

The MEB's multiple printed circuit boards make up the avionics for the NICER payload. The MEB includes all necessary electrical components, circuits, software/firmware, interface connectors, and structural chassis to command, control, distribute power to and provide telemetry from all other components of NICER. The MEB Single Board Computer (SBC) is the main processing unit for NICER and is responsible for all uplink and downlink ISS communication interfaces. The MEB serves as the main data communication hub with all other electronics on NICER, using RS-422 based Universal Asynchronous Receive/Transmit (UART) nodes for data transfer.

The environments that apply to the MEB include self-generated, conducted, and radiated electromagnetic noise; the radiation environment found outside the ISS where NICER will be docked; the thermal and mechanical environments of integration and test, launch, orbit, and end-of-mission disposal.

2.5 Thermal Control

NICER's Thermal Control System (TCS) is designed to maintain all parts of the payload within their required temperature limits for all phases of the mission. The TCS employs a combination of thermal control hardware elements including dedicated radiators, phase change material (PCM), heaters (both software- and mechanically-controlled), interface material, coatings, and multi-layer insulation.

One of the biggest challenges for the TCS is to dissipate the relatively large amount of electronics power during nominal science operations, yet maintain those same components within survival temperature limits during the translation from the ISS transfer vehicle (the SpaceX *Dragon*) to NICER's installed location on the ISS at ELC2. During the translation, NICER must survive up to 6 hours without any internal power dissipation or heater power. This is achieved by utilizing PCM that releases stored energy while changing from a liquid to a solid state. The PCM is sealed within mounting decks that are thermally coupled to the payload's electronics boxes.

Another challenge for NICER thermal control is to maintain alignment between the XRC optics and their corresponding detectors on the focal plane, just over 1 m away. Thermal-mechanical distortions can cause misalignments—through tip-tilt motions of the XRCs, lateral displacements of the detectors, or both at the level of tens of arcseconds—that violate the XTI's pointing and alignment budget. Therefore, flight software-controlled heater circuits have been incorporated into both the Concentrator and Detector Plates, each of which is designed to maintain positive temperature control. Based on detailed Structural/Thermal/Optical (STOP) analysis that included realistic science target pointing sequences (Figure 8) across multiple ISS solar illumination conditions, the Concentrator Plate heater circuits are set to match the temperature of the Detector Plate, thus minimizing distortion through the meter-long aluminum optical bench.
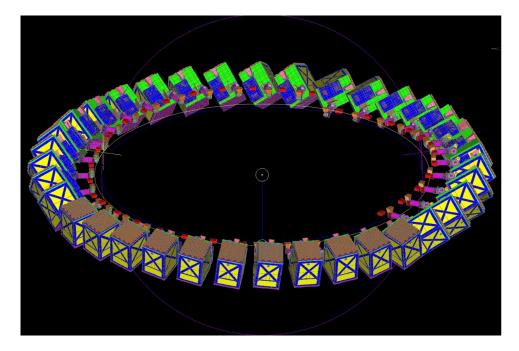
Figure 8. Solar illumination simulation for a representative sequence of three target observations with NICER for an ISS orbit beta angle of +25°. The view is from the Sun, with orbit noon at bottom and the sequence progressing counterclockwise.

2.6 Flight Software (FSW)

NICER's FSW fulfills command and data-handling (C&DH) as well as pointing control functions, and runs on the MEB processor with the VxWorks real-time operating system (Figure 9). The FSW handles:

- Communications between the ISS and NICER via the 1553 interface

- RS-422 communication with the star tracker, detector MPU, and GCE

- Packaging of housekeeping and science data for downlink

- Executing instrument commands in real time and by providing a stored command capability to enable autonomous operations

- Pointing Control.

The FSW system is connected to the external environment (i.e., ISS) through the 1553 bus and Ethernet interfaces. All FSW resides in the memory available to the MEB's single-board computer. The FSW uses the *C* language and assembly-level programming. The FSW is highly table-driven and supports inflight memory, table, and image uploads. The Core Flight Executive (cFE) and Core Flight System (CFS) components provide the majority of the C&DH capabilities. GSFC has developed these open-source components[*] specifically for re-use on multiple missions; they are fully tested and are considered off-the-shelf with flight heritage on prior missions including LRO, SDO, GPM, and *Swift*.

Observation sequencing control is handled with the existing Stored Command sequencing FSW components. The Stored Command processor is configured to hold up to one week of observation commands. An instrument control application specific to NICER forwards commands to the MPUs, receives science and housekeeping data from them, and packages the data for downlink through the 1553 and Ethernet interfaces. Limit Checker and Stored Command Processor provide functionality for mission operations, including fault detections and
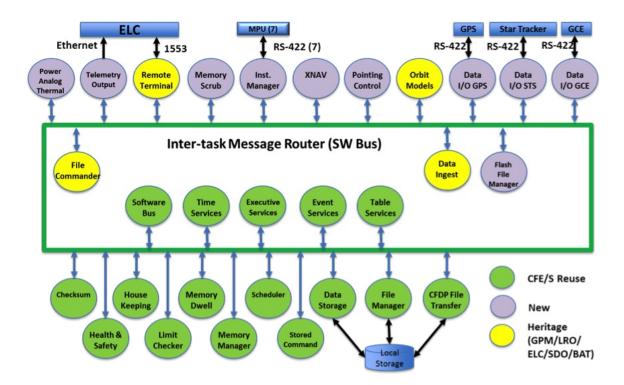
[*]https://cfs.gsfc.nasa.gov/

Figure 9. NICER flight software architecture.

corrections, such as Sun avoidance for the instrument boresight. The pointing control software was co-developed by NICER's Pointing and FSW teams using Mathworks modeling tools. The Pointing System team modeled the pointing control algorithm using MATLAB Simulink; once the algorithm was fully designed under this high-fidelity simulation environment, the PS team used the MATLAB Real-time Workshop tool to generate the flight code and deliver it to the FSW team for integration and test under the embedded system environment. High-fidelity simulation test results from the embedded system are compared and used for final system checkout.

The NICER FSW team uses a testbed for development and test, initial interface verification, and for operations preparation. The high-fidelity testbed is maintained for FSW system testing as well as sustaining engineering. The FSW testbed reduces risk through high-fidelity simulation of the operational interfaces.

3. PAYLOAD-LEVEL ENGINEERING

3.1 Systems Engineering

NICER is a Mission of Opportunity led by a Principal Investigator (PI). The PI delegates day-to-day execution of the project to a Project Manager (PM), but the PI exercises final authority on all decisions and is ultimately responsible for the mission's success. The Project Systems Engineer (PSE) provides technical input to the PI and PM for decisions that affect mission implementation. The PSE makes mission-level technical decisions as delegated by the PM. The PSE, as Technical Authority, has a reporting chain through the NASA GSFC engineering organization, and uses this path to elevate issues as appropriate to ensure mission success. Also as Technical Authority, the PSE encourages diverse perspectives and minority opinions from the engineering team, and raises those opinions as appropriate with the project management through a risk management system, monthly reporting, and informal communications pathways.

The NICER Systems Engineering (SE) team integrates the technical work of the instrument, pointing, electrical, and mechanical systems, as well as ground operations, to meet mission science objectives within programmatic constraints. This technical leadership ensures the entire team focuses its resources on building a system that achieves the science requirements. This focus is essential to contain costs while achieving scheduled milestones

throughout the development with PSE oversight. The SE team utilizes GSFC's standard process, documented in Goddard Procedural Requirement 7123.1A and demonstrated on missions such as LRO and SDO.

As a *Class D* mission, NICER benefits from clear lines of accountability, with technical and programmatic authority residing at the Project level, minimal reporting overhead, a product-oriented focus with a streamlined reliability approach, and advice and stewardship made available by NASA GSFC management for execution-to-cost best practices.

3.2 Integration and Test

The Flight Systems Integration and Test (I&T) team at NASA GSFC led the effort to mechanically and electrically integrate instrument and payload components, and then conduct functional and performance testing. I&T management also arranged for facilities, resources, and personnel needed to support the entire NICER I&T program. This necessitated both long-term strategic planning and short-term tactical coordination of people and equipment, culminating in a fully integrated and tested payload.

3.3 Safety and Mission Assurance (S&MA)

NICER System Safety provided technical assistance to ensure compliance with ISS and GSFC safety requirements, prepared safety data and hazard reports for ISS Payload Safety Review Panel approval, and processed non-compliances through the responsible ISS organizations at NASA's Johnson Space Center (JSC). NICER System Safety assisted in NICER assembly and test planning, and provided oversight during hazardous operations.

NICER Quality Assurance (QA) engineering provided technical assistance for hardware assembly and test planning, and ensured hardware configuration control was maintained and verified through detailed documentation in Work Orders and Procedures. QA provided independent oversight to verify critical operations and measurements. QA inspected or provided oversight of workmanship for NICER assembly, handling, and test configuration. QA ensured anomalies and non-compliances were documented and dispositioned by the development, S&MA, and NICER management teams.

Electrical, Electronic, and Electromechanical (EEE) Parts engineering provided technical expertise for parts selection, screening, and failure analysis. EEE Parts approved supplier parts lists and responded to Government-Industry Data Exchange Program (GIDEP) alerts.

A Materials and Processes Control Plan was implemented that was appropriate for a Class D mission. Both in-house and out-of-house developers worked to their standard procedures. Materials and Processes Engineering (MPE) provided technical expertise to subsystem leads for process development and qualification; reviewed drawings, work-order authorizations, and statements of work as necessary; and supported NICER reviews. GSFC Materials Engineering Branch laboratory activities for NICER included: evaluation of printed wiring board (PWB) coupons, radiographic examination of parts or assemblies, outgassing tests, analysis of cold fingers and scavenger plates for Contamination Engineering, polymers processing, evaluation of material and component properties, and failure analyses. Project deliverables included an As-Designed and As-Built Materials Identification Usage List (MIUL), approved Materials Usage Agreements (MUA) for non-compliant materials and processes, as well as reports and memos that document testing and analyses performed. As part of the Class D approach, a risk assessment was performed for all PWBs with non-conformances, allowing the acceptance of 12 of 18 PWB panels with little-to-no risk to NICER.

4. NICER GROUND SYSTEM

The NICER Science and Mission Operations Center (SMOC), located at NASA GSFC, provides the ground system functionality required to plan science target observations, issue commands to the payload, and interpret and display payload engineering telemetry as well as generate science data products from the downlinked science telemetry.

The SMOC hosts multiple Ground System components, network interfaces, and supporting infrastructure that enable two-way communications with the ISS Payload Operations Integration Center (POIC) at NASA's Marshall Space Flight Center (MSFC) to perform all operations required to conduct the NICER science mission.

The SMOC communicates with the POIC via GSFC's Science and Engineering Network (SEN), which is peered directly to the POIC network for payload operations. An Attitude Ground System (AGS) is used in the SMOC to plan and schedule observations of celestial targets and to determine the pointing parameters for slewing the payload to the pre-planned targets. The SMOC real-time telemetry and command processing system, the Advanced System for Integration and Spacecraft Test (ASIST), is used to build tables containing the target lists generated by the AGS and all other commands for transmission to the POIC for uplink, in turn, to NICER via the Tracking and Data Relay Satellite System (TDRSS). ASIST also processes the raw engineering and science telemetry received from NICER via TDRSS and the POIC, and transfers those data to an Integrated Trending and Plotting System (ITPS), which enables detailed long-term subsystem performance analysis and characterization, as well as a science data processing system that processes the telemetry into high-level products for analysis by the scientific community and transfer to a permanent archive in NASA's High Energy Astrophysics Science Archive Research Center (HEASARC)[†].

The SMOC also hosts software tools to alert operations personnel of telemetry violations and/or anomalies during weekend and off-hours, and provides Voice over IP (VoIP) and video display and distribution systems to enable real-time communications with on-console operations personnel in the POIC and for observing the payload during deployment operations and scheduled special surveys throughout the NICER mission.

5. SEXTANT

The Station Explorer for X-ray Timing and Navigation Technology (SEXTANT) is a technology-demonstration enhancement to the NICER mission. SEXTANT will, for the first time, demonstrate real-time, on-board X-ray pulsar-based navigation (XNAV), representing a significant milestone in the quest to establish a GPS-like navigation capability available throughout our Solar System and beyond.[7–9]

XNAV is the concept of navigating in space using millisecond pulsars (MSPs), distributed across the Galaxy, as navigational beacons. Some MSPs rotate so regularly that they rival terrestrial atomic clocks in their stability, similar to the clocks flown in each GPS satellite. By using a sensitive XNAV receiver to carefully time the faint pulsations from MSPs, a spacecraft can autonomously determine its absolute position, with approximately uniform accuracy, anywhere within our Solar System. This is in contrast to conventional position determination using Earth-based tracking, in which a communication link back to Earth is required and accuracy degrades as the distance from Earth grows.

NICER's XTI is exceptionally well suited for an XNAV demonstration, providing a large collecting area and low background rate (and thus a high signal to noise ratio), with high-resolution photon time-stamps (better than 100 ns RMS), precisely what is needed to extract high-quality navigation information from faint MSP signals. Taking advantage of NICER's science program, which targets all of the most stable X-ray emitting MSPs known, the stated goal of the SEXTANT XNAV system is to demonstrate real-time, on-board orbit determination with error better than 10 km in any direction, through measurements made over 2 weeks or less. The performance of the SEXTANT XNAV system will be assessed through a comparison with the available on-board GPS-derived position. In many ways, the SEXTANT ISS demonstration is a challenging case for XNAV due to the highly dynamic, perturbation-rich ISS orbit, ISS structural interference, and source occultations induced by the Sun, Moon, and especially Earth exclusion constraints.

The SEXTANT project includes an augmentation to NICER's flight software. The X-ray Pulsar Navigation Flight Software (XFSW) is a single application hosted by the NICER Instrument FSW. In addition to supporting command, telemetry, and configuration management, the XFSW divides into three key algorithmic functions: photon event conditioning and filtering, batch photon processing to generate phase and Doppler measurements, and spacecraft state estimation via an extended Kalman filter. The latter component uses an XNAV-enhanced version of the heritage Goddard Enhanced Onboard Navigation System (GEONS) navigation filter software,[10] while the first two components are custom for SEXTANT.

The second critical element of SEXTANT is its ground system.[9] In addition to commanding, data telemetry, and performance monitoring, the key function of the SEXTANT ground system is to maintain the "pulsar

[†]http://heasarc.gsfc.nasa.gov

almanac," consisting of MSP timing models, pulse shape templates, and count rate models. The almanac is updated by periodically incorporating data from MSP observations using radio telescopes, other X-ray telescopes, and the NICER XTI itself (once operational). A compressed version of the almanac will be provided to the XFSW on a periodic basis, as needed for onboard processing. For SEXTANT, the onboard almanac may only need to be updated every few months. Future XNAV systems may be able to autonomously update an onboard pulsar almanac, thus reducing or eliminating reliance on a ground system.

As a key part of SEXTANT development and validation, the SEXTANT team has developed the Goddard XNAV Laboratory Testbed (GXLT).[8,9] The GXLT provides a multi-level, high-fidelity simulation environment for modeling XNAV scenarios. At the first level, a software simulation of XNAV measurement processes can be used to develop navigation algorithms and study multi-year scenarios. At the next level of fidelity, the GXLT software simulates photon event times as seen by a model detector aboard a spacecraft observatory viewing a sequence of MSPs. This mode is useful for development and test of photon event processing algorithms. Finally, at the highest level of fidelity, the GXLT provides for real-time hardware-in-the-loop simulation through precision control of NASA GSFC's unique Modulated X-ray Source (MXS) using the GXLT pulsar simulator, whereby the NICER XTI running SEXTANT flight software could be made to perform as though it were flying on the ISS observing a sequence of MSPs exactly as planned on orbit. This test-as-you-fly mode was used as the final preflight verification of the SEXTANT XNAV system.

ACKNOWLEDGMENTS

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