The Neutron Star Composition ExploreR (NICER) Project

Data Management Plan

NICER
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Goddard Space Flight Center
Greenbelt, Maryland

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CM FOREWORD

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COMPLIANCE IS MANDATORY

In this document, a requirement is identified by “shall,” a good practice by “should,” permission by “may” or “can,” expectation by “will,” and descriptive material by “is.”

WAIVERS AND DEVIATIONS

Waivers and deviations against this document can be found in the NICER library TBD under this document record.

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NICER PROJECT

DOCUMENT CHANGE RECORD

Sheet: 1 of 1

REV LEVEL	DESCRIPTION OF CHANGE	APPROVED BY	DATE APPROVED
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List of TBDs/TBRs

Item No.	Location	Summary	Ind./Org.	Due Date

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1.0 INTRODUCTION

1.1 SCOPE

This Data Management Plan (DMP) for the Neutron Star Interior Composition Explorer (NICER) provides a description of the end-to-end data flow from the instrument to the users and data archive. All basic components needed for managing NICER data are described, including:

- A brief overview of the mission
- The ground system organization
- The mission operation and data policies
- Data processing and data format
- Software and calibration approach
- The data archive
- Data management schedule and cost

1.2 APPLICABLE DOCUMENTS

Documentation applicable to the NICER Data Management Plan includes:

EXP-NICER-RQMT-0001: Mission Requirements Document

EXP-NICER-MSP-SPEC-0017: Measurement System Performance Specification

EXP-NICER-OPT-SPEC-0019: X-ray Concentrators Specification

EXP-NICER-FPMMPU-RQMT-0005: Detector System Specification

EXP-NICER-FPMMPU-ICD-0015: Detector System Interface Control Document

EXP-NICER-EXP-NICER-MSN-PLAN-0014: Calibration Plan

EXP-NICER-GSO-PLAN-0010: Concept of Operations

EXP-NICER-GSO-RQMT-0009: Ground System Requirements Document

1.3 DATA MANAGEMENT PLAN EXECUTION

The NICER mission development team at GSFC will develop plans for the Science and Mission Operations Center (SMOC) in coordination with the High Energy Astrophysics Science Archive Research Center (HEASARC) to take full advantage of the extensive experience within GSFC's Astrophysics Science Division (ASD) in developing similar operations centers.

This DMP document will be under configuration management and will be updated as necessary.

2.0 NICER DATA SYSTEMS

As described in this document, NICER's data systems comprise the payload instrumentation, ground command and telemetry, data pipeline processing, software development, and archive systems. These systems function together to produce scientific, engineering, and ancillary data from observations of astrophysical targets; the data will be analyzed to achieve Level 1 mission science requirements.

The NICER project, under the direction of the Principal Investigator, validates, calibrates, and delivers scientific, engineering, and ancillary data to the HEASARC for archiving and dissemination to the scientific community. NICER also delivers to the HEASARC software and calibration products required for scientific data reduction, enabling the NICER science team and the public scientific community to analyze NICER data, publish findings, and communicate results to the general public.

3.0 NICER MISSION OVERVIEW

3.1 SCIENCE

NICER seeks to study the structure, dynamics, and energetics of neutron stars using the unique combination of high timing resolution and moderate spectral resolution of its X-ray Timing Instrument (XTI). These NICER characteristics enable, for the first time, resolution among competing models of the dense matter within neutron star cores and of the high-energy emission mechanism within neutron star magnetospheres, through rotation-resolved spectroscopy of the X-ray emissions of rapidly spinning neutron stars.

NICER also provides continuity of *Rossi* X-ray Timing Explorer (RXTE) science through its ability to monitor known time-variable X-ray sources, to discover new timing phenomena in the 0.2–12 keV band, and to rapidly re-point to track transient activity in the dynamic X-ray sky.

3.2 NICER LAUNCH AND TRANSFER VEHICLE, OPERATING PLATFORM

NICER is a Mission of Opportunity (MO) destined for the International Space Station (ISS). NICER leverages existing ISS/ExPRESS Logistics Carrier (ELC) infrastructure to provide high quality science at a fraction of the cost of a free-flyer mission.

NICER is built and tested at GSFC. After instrument-level testing and verification, the NICER instrument is integrated onto a Flight Releasable Attachment Mechanism (FRAM), a government furnished standard ISS/ELC interface. The FRAM is also NICER’s interface to the transfer vehicle that will ferry the NICER payload to the ISS.

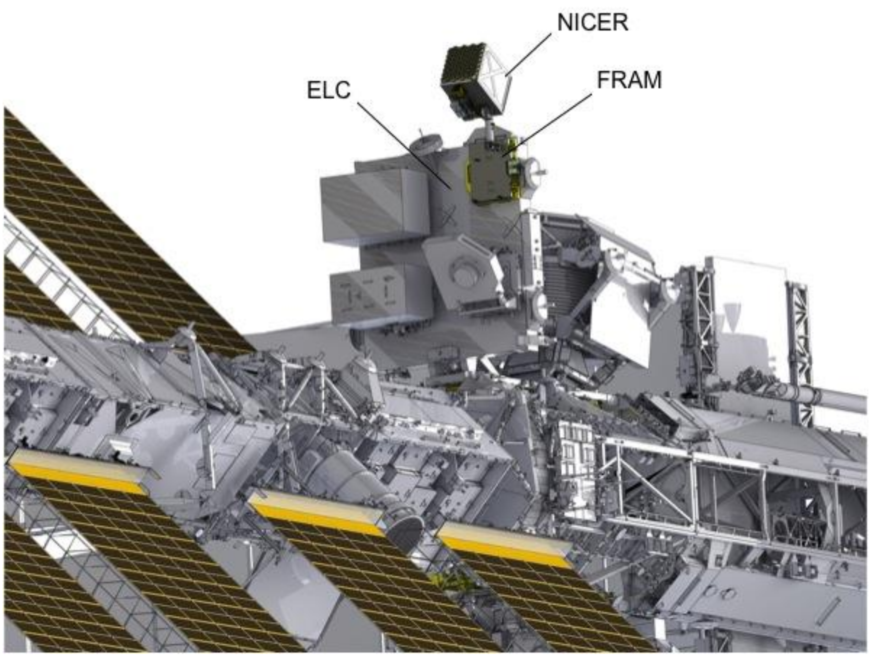

Figure 1. The NICER payload, integrated with a standard Flight Releasable Attachment Mechanism (FRAM), is attached to one of the International Space Station's zenith-side ExPRESS Logistics Carriers (ELC). The ELC provides power and a telemetry interface; installation is accomplished robotically. Shown in its deployed state, NICER offers nearly a full hemisphere of sky coverage with high viewing efficiency even when obscurations by ISS components (such as the solar arrays) and interruptions due to ISS operations (such as spacecraft docking) are taken into account.

NICER is launched by a Space-X Falcon 9 launch vehicle, integrated with the Dragon transfer vehicle within its unpressurized Trunk. After the transfer vehicle berths with the ISS, the NICER payload is preheated using ISS power. NICER is then transferred robotically to its zenith-side ELC location. NICER is deployed from its stowed state for nominal operations (Figure 1). At the end of its science mission NICER can either be re-stowed and de-orbited, or indefinitely turned off and left on the ELC.

3.3 NICER SCIENCE INSTRUMENT OVERVIEW

The XTI consists of an aligned collection of 56 X-ray concentrator (XRC) optics with paired silicon drift detectors (SDDs). The Instrument Optical Bench (IOB) holds these optic/detector pairs together in a compact bundle while maintaining the alignment requirement. Sunshades, coatings, and multi-layer insulation mitigate solar loading.

Each XRC collects photons from a large area over a ~28 arcmin^2 region of the sky, and focuses them onto a small, thermoelectrically cooled SDD. The SDD detects individual X-ray photons, recording their times of arrival to high precision as well as their energies.

The XTI provides a photon counting capability with large effective area, high time resolution, moderate energy resolution, and low background in the 0.2–12 keV X-ray band matching the typical spectral and temporal properties of many pulsars as well as those of many other astrophysical sources. The instrument is calibrated so that flux is known to better than 5%, energy resolution to better than 10%, and absolute time resolution to better than 10%.

A pointing and deployment system extends the XTI above the ELC. The system uses high heritage components including a star tracker, gimbals, and software that enable the XTI to track celestial objects as the ISS orbits the Earth.

A Main Electronics Box (MEB) hosts the instrument's command and data handling system (C&DH), power distribution and switching boards, and GPS electronics. The MEB interfaces to the ELC via 1553 for uplink of commands, via Ethernet for high-rate downlink of science data, via 1553 for housekeeping downlink, and for power through the High-Power Swithing (HiPoS) and ExPA Power Interface Controller (EPIC) boxes. The GPS system provides position and time, which are critical to interpreting the X-ray data from neutron stars.

4.0 GROUND SYSTEMS

The NICER Science and Mission Operations Center (SMOC) provides all ground operations, including preparation of the observing plan, telemetry monitoring, data processing and distribution, analysis software, and staging for archiving. The SMOC is located within GSFC's existing Science and Planetary Operations Control Center (SPOCC). The established infrastructure of the HEASARC hosts the NICER archive and data distribution functions, and the HEASARC software and calibration environment are used to distribute NICER-specific science software and calibration information, and associated documentation.

4.1 SMOC

The SMOC integrates the payload and scientific operations aspects of the NICER mission, with common staffing supported by the NICER science team.

4.1.1 Payload Operations

The SMOC supports pre-launch, launch, on-orbit activation, calibration, nominal, and contingency operations. The SMOC is responsible for commanding of the NICER payload and for high-level health and safety monitoring. Routine command uploads consist of science target observing sequences developed by the SMOC with input from the NICER science team, and with the PI's concurrence. During normal operations, the SMOC is staffed for 8 hours, five days a week, with automated alarm notification to on-call staff, including science team members, during off-hours.

As its interface to the ISS communications infrastructure the SMOC uses the mature Telescience Resource Kit (TReK) software. TReK was developed by MSFC for ISS payload operations; it provides basic command, telemetry, and display functions through the Payload Operations Integration Center (POIC) at MSFC. TReK and SMOC personnel are employed during NICER integration and test (I&T), simplifying the transition to operations. The SMOC's mission and science planning tool generates the command sequence from a list of targets prioritized by the science team, taking into consideration the times at which targets are visible as well as pointing constraints for solar, lunar, and ISS structure avoidance.

NICER's orbit-average science data downlink rate is 4.5 kbps, with a maximum of 2.5 Mbps for periods of up to 1,000 seconds. (For reference, the Crab Nebula produces a data rate of approximately 800 kbps.) Each ELC has a downlink capacity over Ethernet of 6 Mbps (potentially shared among 2–4 payloads), as well as a 1 Mbps up- and downlink capability over 1553 for commanding and housekeeping telemetry. There are data buffers on the ISS for the approximately 20% of the time that the ISS is not in contact with the ground through the Tracking and Data Relay Satellite System (TDRSS); such latency of NICER data acquisition on the ground is of no concern during normal operations. In addition, the MEB has on-board storage capacity sufficient for holding one month's worth of data at typical rates.

The NICER TReK workstation in the SMOC will continuously receive data from the payload through the ISS TDRSS link and the POIC. Buffered data accumulated when real-time TDRSS access is unavailable are easily sent down when the TDRSS link is re-established. Real-time and delayed data can be seamlessly combined.

The SMOC performs Level 0 processing on data captured from the POIC within 24 hours. This includes time ordering of the raw CCSDS packets and basic quality checks, such as removal of duplicate packets. These data are then ready for science processing.

4.1.2 Science Operations and Data Processing

Science processing activities within the SMOC are designed to maximize NICER science. The SMOC's responsibilities in this area include the development and maintenance of (i) science planning tools and their application for formulating target observing schedules; (ii) software to convert the science and housekeeping (HK) telemetry data into Flexible Image Transport System (FITS) files; (iii) software to calibrate and process science data into Level 1, 2, and 3 products, described below; (iv) the processing pipeline; (v) calibration data; and (vi) metadata for the NICER archive.

During normal operations, designated members of the NICER science team, in consultation with the wider team, meet at least weekly to formulate a short-term (next 2–3 weeks) observing plan and effect any necessary changes to the long-term (several months) observing plan. These plans are typically dominated by NICER's key science targets—millisecond pulsars (MSPs) such as J0437–4715 and J0030+0451—and others that are monitored for long-term variability (such as magnetars) or bursting behavior. Consideration is also given to targets of timely interest, such as accreting binary systems in outburst, or in a cooling state following a recent outburst. Finally, monitoring of targets such as the Crab Nebula for calibration tracking purposes also plays a role in routine scheduling. SMOC staff work with the scientists to guide decision-making with input on target visibility and other criteria. The SMOC staff then produces, typically, a week-long command schedule for upload to the NICER payload. To enable an informed rapid-response capability for NICER, at least one member of the SMOC staff and one science team member are assigned to be on-call to assess the significance of transient events—such as outbursts or flares from neutron star systems—not anticipated in the planned observing schedule and that warrant its interruption. Real-time command uploading capability to NICER is typically available through the TReK-based POIC connection for several hours, during several opportunities, each day; during such periods, the payload is able to respond within minutes. When real-time commanding is not available, NICER can be rescheduled to observe an interesting transient within 12 hours of receipt of its coordinates on the sky at the SMOC.

For data processing, Level 0 telemetry is the input to a software pipeline that produces higher-level data products (see Section 5 for details). Raw science and HK telemetry data are converted into FITS format, with science data transformed into FITS 'Event Tables,' and the HK into time-ordered FITS tables. The Level 0 science data are processed using both mission-specific and multi-mission tools; together with NICER calibration data, the pipeline generates calibrated "event lists" (Level 1). Also in Level 1, data are organized by observation intervals, where each "observation" encompasses data for a single target even though they may span, for example, multiple orbits that interleave multiple targets. The event list is then screened (Level 2) to exclude low-quality data—intervals of passage through the South Atlantic Anomaly and its associated elevated particle background levels are excluded, for example. Level 3 files contain refined information in the form of lightcurves and spectra automatically extracted from the screened event lists, as well as metadata such as processing logs and quick-look products to support archiving. The high-level products are then analyzed and modeled to achieve NICER's science objectives. Figure 2 illustrates the data processing.

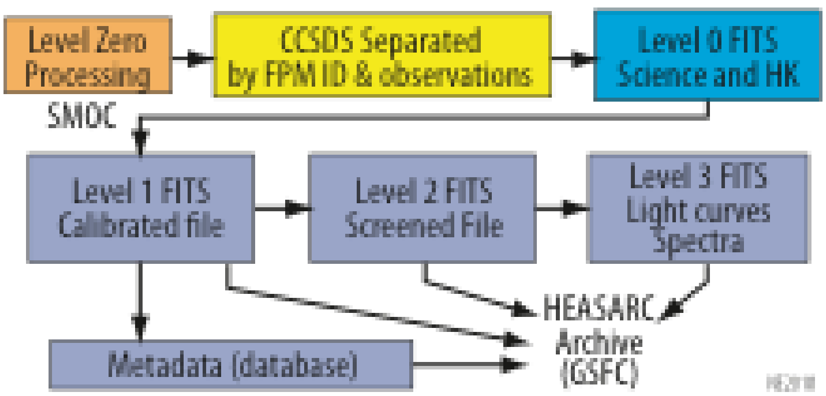

Figure 2. NICER adapts existing pipeline processing software and tools to deliver products to the archive as quickly as possible.

The processing pipeline is based on the design successfully used for ASCA, *Swift*, and *Suzaku*, and currently planned for Astro-H. It runs automatically and minimizes the time between delivery of telemetry data and archiving. The pipeline uses scripts to combine a large number of existing multi-mission FITS tools (FTOOLS), maintained by the HEASARC, with NICER-specific algorithms to yield the resulting higher-level data products. Similar scripts have been used on a large number of missions. The SMOC is responsible for the development and maintenance of NICER-specific FTOOLS to handle the unique aspects of NICER analysis, primarily those related to calibration of the data, and to provide user documentation.

The SMOC and NICER science team members update instrument calibration files (response matrices containing throughput, time adjustment, gain, and energy resolution functions) and tools based on regular in-flight calibration measurements. The NICER target catalog includes a number of calibration targets to monitor any instrument aging. The optics team, led by Dr. Takashi Okajima, is responsible for the development and maintenance of the XRC response modeling, including ray-tracing code. The XRC response code is derived from similar code developed for BBXRT, ASCA, and *Suzaku*. The detector team, led by MIT's Dr. George Ricker, is responsible for the detector response matrices, which are very similar to existing matrices for most silicon-based X-ray detectors such as X-ray CCDs and photodiodes. The SMOC ensures that calibration data are included in the Calibration Database (CALDB) as soon as they are made available and included in the pipeline. Dr. Craig Markwardt is responsible for the pipeline processing of raw data into higher-level products (Levels 1, 2, and 3) and delivering the products to the HEASARC archive. Drs. Michael Corcoran and Steven Drake of the HEASARC are responsible for the archiving of data, software, and documentation, and disseminating them to the scientific public and science/instrument teams.

4.2 HIGH ENERGY ASTROPHYSICS SCIENCE ARCHIVE RESEARCH CENTER (HEASARC)

The HEASARC, located at GSFC, is the data repository for NICER during the mission lifetime and acts as the long-term archive after the end of mission operations.

The HEASARC maintains the NICER science and calibration data archives, provides data access to the astronomical community via the standard HEASARC Web search facility and FTP interface, provides and maintains the software environment and infrastructure to develop NICER-specific software, hosts multi-mission analysis software, provides a Web server facility for documentation produced by the SMOC, and a database system for NICER data tables such as metadata or catalogs that NICER produces.

4.3 SCIENCE AND INSTRUMENT TEAM RESPONSIBILITIES

The instrument team, led by the Principal Investigator, is responsible for designing, building, testing, and delivering the NICER instrument, and provides the scientific and engineering expertise concerning the instrument and NICER science. The instrument team implements the specific algorithms and software tools for calibration of NICER data. The team is engaged in pre- and post-launch instrument calibration and in maintaining the calibration products required for scientific data analysis. The instrument team is responsible for validating the software and calibration products.

The science team is led by the Principal Investigator. The science team includes Co-Investigators and Collaborators at GSFC and from universities and other institutions.

Upon completion of science data processing, the data are deposited in the HEASARC archive and made available to the science team in an encrypted form for validation. For astrophysical targets, science team members are responsible for performing initial analysis and validation of science data sets and for disseminating the results to the scientific community. The responsibility for individual and/or classes of astrophysical targets is established by science team working groups, as formed by the Principal Investigator. Unencrypted versions of the validated data sets are delivered to the HEASARC for availability to the public scientific community.

5.0 <u>MISSION OPERATIONS</u>

NICER begins operations upon installation on the ELC. There is an initial on-orbit checkout and calibration period that lasts one month, after which normal observations begin. NICER operations generally occur independently of other ISS payloads, but may be interrupted for safety reasons such as visiting spacecraft or astronaut extravehicular activity. The NICER mission life for baseline science is 18 months.

5.1 MISSION PLANNING

The NICER observation schedule is planned in advance to optimize the science data collection. The pre-planned schedule incorporates and accounts for radiation belt passages, contamination constraints (such as when re-supply vehicles are present), viewing constraints imposed by the Earth, Moon, Sun, and ISS structures, and any other constraints to preserve the instrument's health.

The NICER science team generates the observation list and the SMOC converts the target lists to command loads. These are typically generated weekly but the capability exists to perform this daily as needed. The SMOC delivers the command list to the POIC at MSFC. The POIC uploads the new plan for the NICER instrument via the ISS command system well in advance of the currently executing command plan's expiration. The NICER instrument executes these chronological sequences, buffers the resulting science data, and then downlinks them to the POIC. The POIC forwards the data to the NICER SMOC. Timely arrival of mission science data to the SMOC is not critical.

5.2 OBSERVING STRATEGY

During normal operation, NICER tracks up to three or more targets within an ISS orbit. The first target is monitored until viewing constraints require repositioning; with a rapid slew, NICER begins observing the second target, and so on. The NICER minimum science objectives are achieved through a net integration time of 10 Msec (the equivalent of four uninterrupted months). The total observation time is accumulated over a year due to viewing constraints. Over an 18-month span NICER will achieve or surpass its baseline science requirement of 15 Msec of valid observing time.

After the initial on-orbit checkout, NICER carries out calibration observations. These consist in observing standard reference targets to validate flux and timing performance, as described in the NICER Calibration Plan. Several NICER science targets (e.g., the Crab Nebula and pulsar) are standard flux references. These observations serve as verification of the NICER ground calibration and to cross-calibrate NICER with other X-ray observatories that may be active at the same time. After initial calibration, NICER will perform periodic maintenance calibration observations in order to determine trends and to refine the calibration models.

As part of NICER's Science Enhancement Option (SEO) a Guest Observer (GO) program will be instituted and—pending a successful review of science progress 12 months into Phase E—the mission will be extended by 6 months, allowing the astronomy community at large to propose, through a peer-review process, observations of targets not part of NICER's core science agenda. The mission's second year of scheduled observations will then consist of a mix of core science and GO targets. Science targets accepted through the GO process are incorporated into the science target list in the same manner that targets from the PI and science team are.

5.3 OBSERVATION DEFINITION

To achieve NICER's science objectives, key targets are monitored for a long period of time, essentially the entire mission lifetime, with data stitched together through precise timing traceable to UTC via the onboard GPS system, a technique that the Fermi gamma-ray telescope has validated for pulsar observations. NICER data for any particular target will be divided across several disjoint time intervals because of interruptions due to visibility (such as Earth occultation), data filtering (e.g., passages through the South Atlantic Anomaly), or ISS operations that require stowing of NICER. To maintain some cohesiveness of data, an observation of a target is defined as the accumulated exposures across multiple *segments*, which each have an elapsed time of one or more days. Each such observation segment is identified with a unique sequence number. This is similar to the observation definition adopted by *Swift* for data acquired while monitoring gamma-ray burst afterglows. During scientific analysis, it will be possible for scientists to combine multiple observations into a single large data set, in order to achieve the ultimate expected sensitivity for long observations of faint targets. A science observation of a target is complete, when the last planned observation segment has been observed.

5.4 DATA RELEASE POLICY

NICER science data, engineering data, ancillary data, calibration data, data-reduction software, and documentation are made available to the scientific community without restrictions or exclusive data rights. After completion of an observation, data undergo a validation. NICER data acquired during the initial checkout and calibration period will be delivered to the public archive after a validation period of 6 months, in order to allow the team to fully shake down the instrument and to derive final calibration products. After the first 6 months, data acquired during normal operations will be validated by the science team and placed unencrypted in the public archive with at most a two-week delay from the end of the observation.

6.0 DATA PROCESSING

Data processing at the SMOC begins as soon as Level 0 data are retrieved from the POIC. The data are organized by target and divided into segments that span an interval of one or more days. The SMOC will maintain a local archive of the Level 0 data organized by segment. Pipeline processing begins when a segment is complete. The NICER data pipeline is a script that includes several steps. First, the telemetry and any auxiliary information are converted to FITS files; the conversion retains all telemetered information. Next, the photon (“event”) data are calibrated (Level 1) and screened (Level 2), and derived science products such as lightcurves and spectra (Level 3) are created. Finally the data are encrypted, organized in directories, and delivered to the HEASARC archive. The science team retrieves the data directly from the HEASARC. The pipeline uses multi-mission and NICER-specific software together with calibration data as stored in the CALDB. The same software and calibration products are also publicly distributed by the HEASARC.

After an observation segment is completed, the pipeline processes and populates the HEASARC archive within a few hours, depending on the size of an observation (for example, a one-day dataset requires approximately 3 hours).

Initial unvalidated data products are delivered to the HEASARC in encrypted format. After the science team completes validation, unencrypted versions of the products are made available. If the initial products were valid as delivered, then the HEASARC simply unencrypts the data in-place. If, after validation, new products are required, the NICER project redelivers new validated products to the HEASARC which are made publicly available immediately.

6.1 DATA VALIDATION

NICER data products are validated in order to ensure high quality data products reach the public archive.

During the validation period, unvalidated NICER products are only available to the science team in encrypted format, for the purposes of validation.

Validation of science data sets consists of both automated and human-involved quality checking processes. The data processing pipeline produces automated quality reports. These reports indicate such quantities as data completeness, X-ray count rates, detector status, instrument pointing and stability, etc. A data quality scientist reviews these reports and approves the validity of data sets on an approximately weekly basis.

During the first six months after check-out, the NICER science software and calibration data products themselves are validated. NICER observations of calibration targets (as well as science targets) are used by the instrument and science teams to adjust and ultimately validate the calibration products and software algorithms. Data sets are processed initially with pre-launch calibration products and software, and are reprocessed as needed, as these are incrementally improved. After a review of data quality and performance, the Principal Investigator declares the calibration and software validated.

When the validation of science data sets, software, and calibration are established, the data are reprocessed if necessary and delivered immediately in unencrypted format to the HEASARC public archive.

In summary, the data validation period is six months or less during the first six months after check-out is complete, and two weeks or less thereafter.

6.2 DATA INTEGRITY

The NICER Project designs its systems to maintain data integrity.

According to the NICER Concept of Operations, space-to-ground data handling is expected to achieve 99.5% data transmission completeness. Beyond this, the system also has the legacy capability to re-transmit data from on-board storage in the case of lost or missing data.

Within the ground system, no data losses are expected due to transmission or storage. Data is transmitted with reliable and secure protocols with automatic error-checking and data correctness. Data are stored on redundant storage systems with remote storage backup, as well as backup power in case of power outage.

During data processing from Level 0 files until final delivery to the archive, less than 0.5% of additional data loss is expected. Such losses could occur when VCDUs (CCSDS transfer frames) are lost or dropped due to uncorrectable errors. The fragments of CCSDS packets of VCDUs that do survive would also likely be discarded. NICER science data analysis is tolerant to such data dropouts. Missing/dropped data packets or VCDUs ultimately show up as missing “good time intervals,” which are handled properly by standard downstream processing software without additional intervention. Scientific analysis of the data that survive can still be accomplished, even if small amounts of data are lost. In the cases of lost data around the epoch of time-sensitive scientific events such as X-ray eclipses, X-ray bursts, or pulsar glitches, the operations team may make an extra effort to retransmit data from on-board storage.

6.3 DATA FORMAT

NICER science, housekeeping, and auxiliary data are formatted in FITS, the NASA standard for astrophysics data. The HEASARC has developed a number of data structure and keyword conventions, known as the GSFC Office of Guest Investigator Programs (OGIP) conventions, which are the de facto standard in high-energy astrophysics. The NICER FITS files adopt these standards for both science and HK data. Science data are organized in a FITS Table extension as an "event list" where each row records all information (time of detection, energy, rise time, etc.) relevant to a single photon. The HK (and auxiliary) data are FITS Table extensions time-ordered where each time-ordered row records in multiple columns the specific housekeeping quantities captured at that time. Science housekeeping and auxiliary information (such as orbital position) are stored in separate FITS files. NICER science Level 0, 1, and 2 files are in the standard FITS "event file" format, Level 3 derived lightcurve and spectra are in the OGIP standard lightcurve and spectrum FITS formats. The NICER SMOC team works with the HEASARC to ensure that the standard FITS format is followed for all data levels.

6.4 DATA DESCRIPTION

Each of the photons detected by NICER is described by several quantities, including at Level 0 photon arrival time and pulse height amplitudes (PHA, a proxy for photon energy) from two readout channels; the Detector System Interface Control Document provides additional detail. After the original data are written to FITS, supplementary information is added for each event in subsequent pipeline steps. The Level 1 data files are event lists containing for each event all fundamental quantities telemetered as well as their derived "calibrated" information (e.g., the PHA corrected for gain and thereby representing the photon energy). Therefore, the Level 1 files suffer no loss of information and may be used to recalibrate the data when improved calibration is available. The Level 2 files are the screened event data representing good-time intervals (GTI) defined according to instrument-specific criteria (e.g., effective pulse rise-time) or mission events such as high particle-background episodes, a combination of science selection and observing conditions. Lightcurves and histograms of pulse heights (Level 3 products) are extracted from the Level 2 files. These are the basic products for science analysis. A science analyst may wish to extract different Level 3 products based on different assumptions (such as extraction time intervals or detector selections). Analysts can use the standard software tools with different parameters to accomplish this. Lightcurves are used to search for periodicity, its possible variation with time, and other fundamental quantities via modeling of the lightcurve shape. Modeling of spectra together with the instrument energy response enables characterization of the emissions of neutron stars. Catalogs of summary information such as pulsation periods, their rates of change, spectral and timing indices as well as source flux may be compiled from the lightcurve and spectral analysis of each target.

6.5 PIPELINE PROCESSING SYSTEM

The purpose of the pipeline processing system is to implement, in a nearly automated way, the calibration, screening, and extraction of high-level data products. The pipeline infrastructure is implemented as a group of Unix shell and Perl scripts, which run as daemons, as 'cron' jobs, or are activated by the receipt of input into the system. The pipeline is designed to be automated, and benefits from heritage processes from RXTE, ASCA, *Suzaku*, and *Swift*. The majority of the code involved in the data processing and archiving scripts is mission-independent and, wherever possible, legacy code is used to perform common tasks. The NICER data stream will employ these established processes as well as mission-specific tasks via an existing common interface that includes file naming conventions, FTOOL execution, FITS access, and error handling.

Other outputs from pipeline processing include: HTML log files that include details of the processing and any errors encountered during the processing run. The software chain to calibrate and screen the data uses the mission-independent and mission-specific tools as well as the NICER calibration data in CALDB. This software resides in the HEAsoft software package and is distributed via the HEASARC together with CALDB; it is therefore always accessible to end-users. If calibrations are updated or new screening criteria are defined at any stage of the mission, users may re-calibrate and re-screen data starting from the archived Level 1 products without waiting for new reprocessing to occur at the SMOC. The system also logs errors that occur while the pipeline processing is running. Depending on the severity, the processing continues or stops, and may require manual intervention by a SMOC data manager to resolve the problem and continue.

The pipeline output for a given observation of a target is organized in a directory structure named according to the observation identifier and contains all the Level 1, 2, and 3 science files as well as HK and auxiliary information and the processing logs. The entire package is delivered to the HEASARC.

As the calibration and software are updated, the processing script is revised, and earlier data are re-processed with the new system. Before running data through an updated processing script, the output of updated tools used in the pipeline is compared to the previous pipeline output, on the same standard input data. The new products of any reprocessing are delivered by the SMOC to the HEASARC to replace old products in the NICER archive. Version numbers, included as keywords in the FITS products, are used to distinguish between different revisions of the processing script and calibration data sets.

Configuration changes are developed in a parallel "development" pipeline, so as to not disturb the operational production pipeline. When a revision is complete, the new configuration is operated in the "test" pipeline in order to verify performance. When performance is verified, the new configuration is installed in the production pipeline at a well-defined time. Configuration changes are documented and tracked.

6.6 PROCESSING HARDWARE

Data processing takes place at GSFC on a hidden LAN. The actual processing work is performed on a virtual-environment system and uses multiple virtual processing nodes to improve reliability, enabling multiple observations to be processed simultaneously and to create a development environment in which new features can be tested without interrupting the main processing. System administration is provided within the ASD at GSFC. Two dual-processor virtual machines carry out the NICER production pipeline processing. Additional virtual machines can be configured for development and testing, or as a backup if one of the main machines malfunctions. This hardware is based on the estimate of a daily average of 600 Mbytes of data volume, which is less than the data rates from other missions, such as *Swift*, that successfully use similar facilities.

7.0 SOFTWARE AND CALIBRATION

NICER uses the same approach for its mission-specific pipeline software and calibration as did ASCA, *Swift*, *Suzaku*, and RXTE. The NICER software is written in the HEAsoft environment and the calibration data are placed in the CALDB. HEAsoft and the CALDB are environments maintained by the HEASARC. NICER data stored in FITS benefit from the extensive HEAsoft libraries of multi-mission tools that operate on FITS files; for example, data screening is achieved with existing software to create a "filter file" from which GTIs are extracted. HEAsoft also includes standard analysis software packages, such as for spectral (XSPEC) and timing (XRONOS) studies, that are re-usable with NICER's high-level data products. NICER software development is thus mostly limited to mission-specific code to derive gain-calibrated PHA or to calculate response functions, taking into account the XTI's modularity (56 optics and detectors, each individually calibrated). Well-established standard libraries simplify this development task: management of input parameter files (API), reading and writing of FITS files (CFITSIO), and interfaces with CALDB. All code is written in C or Perl and is portable to different operating systems. The HEASARC provides a CVS system, and NICER uses this system for revision control.

All instrument parameters required to calibrate the data or to generate calibration products reside in CALDB files rather than being hard-coded in software. CALDB is a multi-mission database with well-defined interfaces to mission-specific calibration tools; such tools query the CALDB to retrieve appropriate files. Consequently, when calibration information is improved, users need only update their calibration files, not the software that generates the products.

NICER software, calibration data, and documentation are delivered by the SMOC to the HEASARC. The HEASARC is responsible for making public the calibration data in CALDB and preparing the software for distribution.

As part of the HEAsoft system, software, documentation and calibration products are made available to the scientific community at no direct cost. Software is distributed both in binary (compiled) form as well as in source code form, which allows scientists in the community to examine the data processing logic in detail. These components are made available with a liberal license that allows copying and redistribution, and no exclusive ownership rights or utilization restrictions are imposed. Excluded from routine public distribution will be high-level analysis algorithms, models, and software tools developed (often prior to the start of the NICER project) by members of the NICER science team and affiliated scientists for core science investigations such as lightcurve modeling, high-precision pulse timing, pulsation searches, and others. These will be shared within the project to facilitate achievement of NICER's Level 1 science requirements, but intellectual property rights for these high-level capabilities will be retained by the original developers, consistent with past practice.

8.0 THE NICER ARCHIVE

NICER archives all science, housekeeping and auxiliary data files at the HEASARC. The HEASARC archive is populated from the start and serves as the data repository and distribution venue for the instrument team, the science team, and unaffiliated scientists at all phases of the mission and beyond.

The HEASARC contains all information, data, and software needed so that analysis of NICER data by the community is straightforward, well documented and understood, and well supported. All of the data in the archive are in FITS format in conformance with OGIP standards. Other standard formats, such as HTML, are used for previewing products or recording a log of the processing. The NICER Web site, which is hosted by the HEASARC, includes a data analysis guide, software documentation, data files populating the NICER archive, details of the calibration, and information on the GO Program.

Data and databases (metadata) are delivered to the archive after processing at the SMOC, and they are stored on active, online storage media (hard drives) at the HEASARC. During the validation period, the data are encrypted. The encryption key is distributed as appropriate (e.g., to instrument or science team members). Upon termination of the validation period, data are decrypted and worldwide access is enabled. This practice has substantial heritage in many of the current high-energy missions, such as *Suzaku*.

Data are organized by identified observation segments. A sequence number is assigned to each segment and all data files and standard products belonging to that observation are stored in a directory labeled with the sequence number.

Access to the NICER archive is available through the HEASARC Browse Web facility as well as other channels such as ‘wget’ or FTP. The Browse facility enables searches for data in the archive through queries of the NICER database by sky coordinates, observation date & time, or any specific parameter that characterizes a NICER observation. The Browse interface is multi-mission and is used extensively for all high-energy missions archived at the HEASARC. Expert users can opt instead to access the archive using ‘ftp’ and ‘wget’ protocols; in this mode, knowing the sequence number of the data, users can download data by invoking their preferred protocol from a script or terminal command line. Finally, NICER data is made available through the HEASARC’s HERA interface, for remote processing that doesn’t require local installation of software or waiting for lengthy data downloads.