The Chandra X-ray Center: a combined science and operations center

Roger J. Brissenden*[a], Jeffrey D. Holmes[b], Edward Mattison[a], Daniel A. Schwartz[a], Daniel Shropshire[c]

[a]Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge MA 02138
[b]Northrup Grumman Mission Systems, c/o 60 Garden St., Cambridge MA 02138
[c]Northrup Grumman Space Technology, c/o 60 Garden St., Cambridge MA 02138

ABSTRACT

The Chandra X-ray Observatory, which was launched in 1999, has to date completed almost seven years of successful science and mission operations. The Observatory, which is the third of NASA's Great Observatories, is the most sophisticated X-ray Observatory yet built. Chandra is designed to observe X-rays from high-energy regions of the universe, such as the remnants of exploded stars, environs near black holes, and the hot tenuous gas filling the void between the galaxies bound in clusters. The Chandra X-ray Center (CXC) is the focal point of scientific and mission operations for the Observatory, and provides support to the scientific community in its use of Chandra. We describe the CXC's organization, functions and principal processes, with emphasis on changes through different phases of the mission from pre-launch to long-term operations, and we discuss lessons we have learned in developing and operating a joint science and mission operations center.

Keywords: Chandra, X-ray astronomy, science center, mission operations, lessons learned

1. INTRODUCTION

The Chandra X-ray Observatory (CXO), the third of NASA's Great Observatory missions is a space-based Observatory containing a high resolution (0.5 arcsecond) X-ray telescope and a complementary set of imaging and spectroscopic instruments, responsive to the energy range 0.1 – 10 keV. Chandra provides an order-of-magnitude advance in spatial and spectral resolution over previous X-ray telescopes. Designed with a minimum mission lifetime of 5 years and a goal of at least 10 years, Chandra is nearing its 7th year of scientific operation without a major anomaly. Chandra was launched on the Space Shuttle Columbia (STS-93) on 23 July 1999. Following launch and orbital insertion, the Observatory underwent a 2-month activation and checkout phase, followed by 2 months of Guaranteed Time Observations. The eighth cycle of General Observer observations is scheduled to begin in December 2006.

The Chandra Program is managed by NASA's Marshall Space Flight Center (MSFC). Science and mission operations for the program are carried out at the Chandra X-ray Center (CXC), which is operated by the Smithsonian Astrophysical Observatory (SAO) under contract with MSFC. The CXC, located in Cambridge, MA, uses facilities of SAO and the Massachusetts Institute of Technology (MIT). The CXC is comprised of the science data system division (CXCDS), the Operations Control Center (OCC), and the scientific, engineering, software and administrative staff required to conduct scientific and mission operations. Observing time is awarded through an annual solicitation of proposals and peer review; selected targets are scheduled in weekly segments; and command loads to carry out the mission schedule are uplinked to the spacecraft from the OCC via NASA's Deep Space Network (DSN). Telemetry and data are downlinked approximately every 8 hours, monitored for state of health at the OCC, and passed to the CXCDS for science processing. The resulting science data products are archived and distributed to the scientific users. In addition to carrying out these scientific and mission activities, the CXC also provides an Education and Outreach program, and administers the Chandra Grants and Fellowship programs.

In this paper we describe the Chandra mission (§2), the CXC operations concept (§3) and the CXC organization (§4), and we discuss lessons we have learned in developing and operating a joint science and mission operations center (§5).

* rbrissenden@cfa.harvard.edu; phone 1 617 495 7387; fax 1 617 495 7411; http://www-cfa.harvard.edu

2. MISSION DESCRIPTION

2.1 Chandra Overview

The Chandra X-ray Observatory represents the culmination of current X-ray astronomy imaging and spectroscopy capabilities. Figure 1 shows the key features of the observatory. The heart of the observatory is the High Resolution Mirror Assembly (HRMA), which creates images with better than 0.5 arcsecond resolution, and instruments that detect the imaged X-rays and analyze their energy. The two imaging instruments are the High Resolution Camera (HRC), which uses a microchannel plate to detect X-rays, and the Advanced CCD Imaging Spectrometer (ACIS), which uses charge-coupled device detectors. Either of two transmission gratings can be inserted into the X-ray path to provide higher resolution energy analysis, or spectroscopy, than is capable with the ACIS or HRC detectors alone.

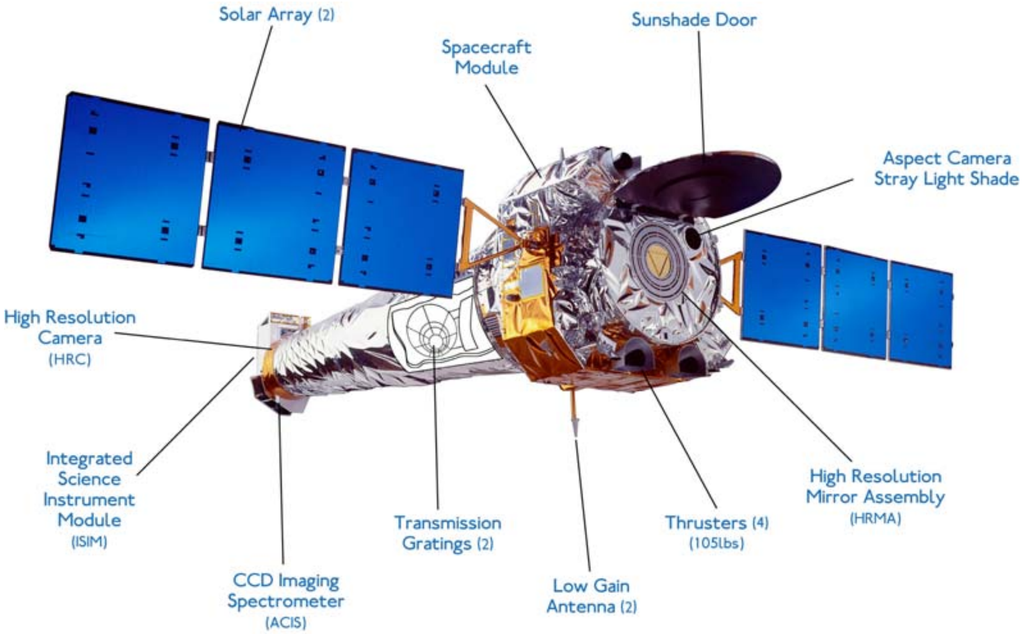

Figure 1. The Chandra spacecraft in its deployed configuration

The spacecraft is 13.8 m in length and 19 m in wing-span, and has a mass of 4,800 kg. The spacecraft is comprised of the spacecraft bus, which contains the communications and electrical power systems, thrusters, solar panels and the HRMA; the integrated science instrument module, which houses the HRC and ACIS focal plane instruments; and a graphite-epoxy optical bench that connects the two modules. The HRMA is a set of four nested pairs of Wolter type I grazing incidence hyperboloidal and paraboloidal cylindrical glass mirrors with a focal length 10 m, coated with iridium to enhance their reflectivity at X-ray wavelengths. The spacecraft's attitude is controlled using a combination of reaction wheels, gyroscopic inertial reference units, sun sensors and an aspect star camera. Chandra orbits the earth in a high earth orbit (28,000 x 120,000 km) with a period 64 hours. The spacecraft spends ~15% of its orbital period passing through the Earth's radiation belts (at an altitude of less than 60,000 km), during which time no observations can be conducted due to the instruments' sensitivity to particles and electromagnetic radiation. Observations are conducted during the rest of the orbit with an average efficiency (including time spent in the radiation belts) of 60-70%, which takes into account time in the radiation belts, time slewing between targets and changing instrument positions, engineering activities, and instrument down-time during, for example, periods of high solar activity.

2.2 Chandra Ground System

The Chandra ground system consists of two principal elements: the Deep Space Network, operated by NASA's Jet Propulsion Laboratory (JPL) and the CXC. Figure 2 shows these elements and the basic data flow for the mission.

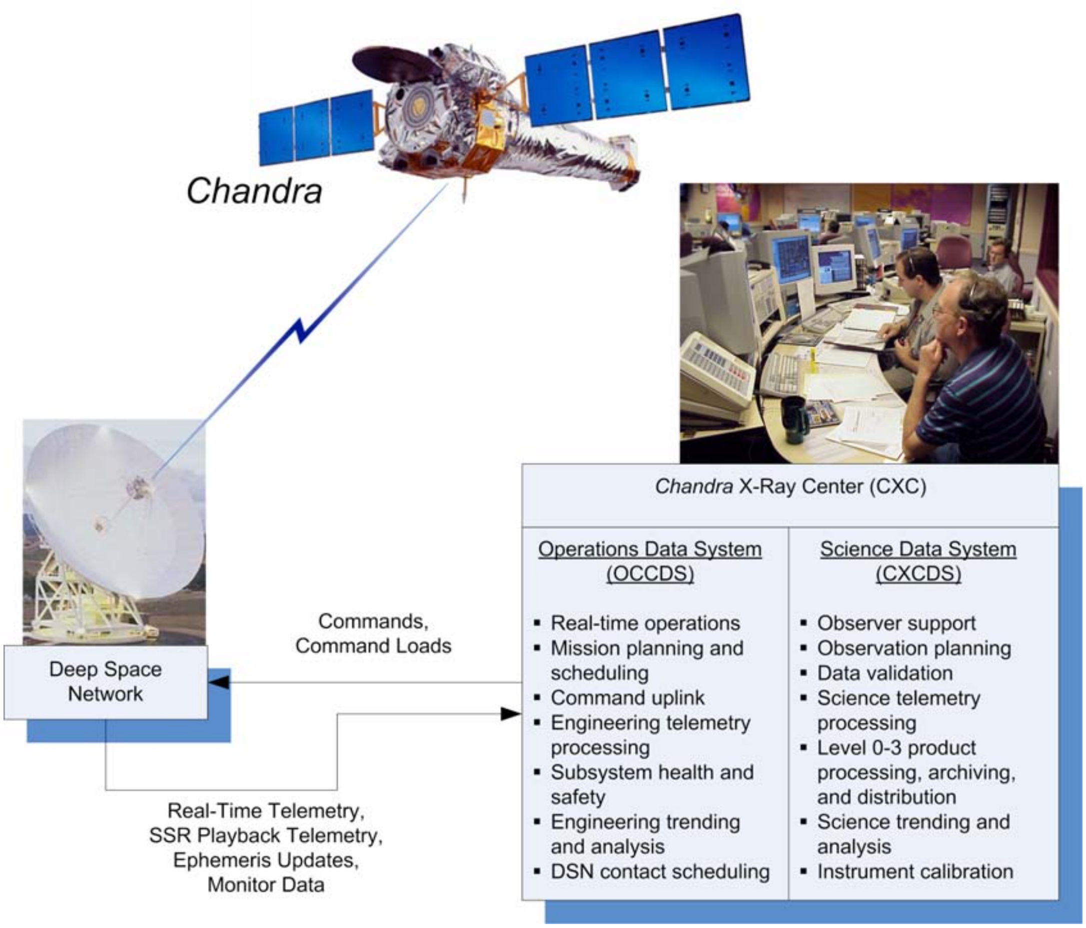

Figure 2. The Chandra Ground System Architecture.

The DSN provides S-band tracking, telemetry, and command services that enable communication with Chandra ~3 times per day. A command link from the OCC to Chandra is provided at 2 kbps. During a communications pass, telemetry is forwarded in real time from Chandra to the OCC at 32 kbps to allow evaluation of current spacecraft and instrument status and health. Data stored on Chandra's on-board solid state recorder is downlinked at a typical rate of 480 kbps (though higher and lower rates are available for operational flexibility) and stored on the DSN Central Data Recorder. Following the pass, the files of stored data are sent to the OCC by means of ftp. Ranging and 2-way Doppler measurements are taken during contacts in parallel with these activities. The DSN's Navigation service incorporates these data into Chandra's orbit solution and sends updated ephemeredes to the OCC twice weekly. Communication with Chandra is principally via DSN's 34 m beam waveguide antennas, but 26 m antennas are also used. Connectivity between the OCC and the DSN gateway at JPL is provided by multilink point-to-point protocol over dual diversely routed T1 lines.

Satellite command and control capabilities are provided by the OCC's Data System (OCCDS), which consists of two software systems, the Online System (ONLS) and the Offline System (OFLS), and an operations database that holds operational data and parameters. The ONLS, which is used primarily for real-time spacecraft command and communications, is a Chandra-specific instance of the Enhanced HOSC System (EHS) developed for MSFC's Huntsville Operations Support Center (HOSC). It currently consists of ~1.5M lines of C, C++, and sql code that provide commanding, display, scripting, ODB maintenance, and time-division multiplexed (TDM) telemetry processing, logging, and retrieval applications. The OFLS, which contains applications for mission planning and scheduling, command load management, attitude determination, and spacecraft clock correlation calculations, was developed by Computer Sciences Corporation (CSC) specifically for Chandra. It consists of ~1.1M lines of C and FORTRAN code. The OCCDS's software runs on 4 sets of equipment: one for operations plus an identical hot backup, one for system test, and one for maintenance. During the last quarter of 2005 the OCCDS was migrated from the original Silicon Graphics platform to a Linux-based platform that has 4 times the performance within ~1/3 the original footprint. The port was driven by considerations of long-term maintenance of the original platform.

The software that makes up the CXCDS was developed by SAO and consists of ~1.9M lines of C, C++, sql, and script code to provide the following scientific processing capabilities:

- interpret ACIS and HRC instrument readout
- determine the precision aspect solution (location on the sky) for each detected X-ray photon
- interpret dispersed spectra from the HETG and LETG
- decommutate telemetry and apply standard processing to observation data, generating a standard set of data products for observers
- archive and distribute standard, custom, special, and ancillary data products to observers
- monitor instrument and spacecraft subsystem performance and trends
- maintain the Chandra Science Plan and Observation Catalog

The CXCDS provides a number of observer support applications, including the portable CIAO data analysis package, which enables observers to locally analyze their Chandra data; and proposal support applications such as ObsVis for simulating proposed observations, and the web-based Proposal Toolkit. CXCDS requirements were developed based on the end-to-end operations thread originally identified during the Chandra concept definition phase and maintained throughout CXC development. The CXCDS software architecture is modular, providing analysis tools with an abstracted view of the underlying data (the Data Model) and allowing the flexible use of the tools within both an interactive environment (CIAO) and a pipelined processing environment (Standard Data Processing) without modification. Further details about the CXCDS software are presented in a companion paper in this volume[1].

3. THE CXC OPERATIONS CONCEPT

3.1 A "Thread"-Based Approach

The CXC is responsible for all operational aspects of the Chandra project, including carrying out mission operations – commanding and monitoring the spacecraft and ensuring its health and safety – and maximizing the program's science return. The overall design of the software and activities needed to fulfill these responsibilities was conceived of in terms of a number of "threads" – sequences of related steps that lead to a particular set of outputs. A thread captures the actions of the CXC staff, the required capabilities of the data system, interactions with external elements, and interactions with other CXC activities. In this section we focus primarily on the operations concept for those activities supported by the CXCDS (i.e., the scientific rather than spacecraft operations), but briefly summarize the spacecraft-oriented activities in §3.3.

3.2 The CXC End-to-End Thread

The primary, or end-to-end, thread for the CXC describes how an observing proposal is transformed successively into an observation request; a scheduled set of instrument settings and spacecraft pointing; commands within a command load sent to the spacecraft; telemetry data sent to the OCC; quality-checked standard data products; a set of data files delivered to the observer; and a set of publicly available data products in the Chandra archive. The end-to-end thread, shown in Figure 3, consists of the “forward thread” running from soliciting observing proposals to commanding the spacecraft, and the “back thread” from down-linking spacecraft telemetry, to delivering data products to observers. The end-to-end thread is supported by the other threads shown in Figure 3: archiving, science flight support (scientific monitoring and trends), instrument calibration, and general user support. The end-to-end thread was developed early in the design phase of the CXC and was a major factor driving the design of the CXCDS architecture and software, and determining the operational processes. The thread also informed the structure of the CXC organization, as discussed in the next section (see Figure 4).

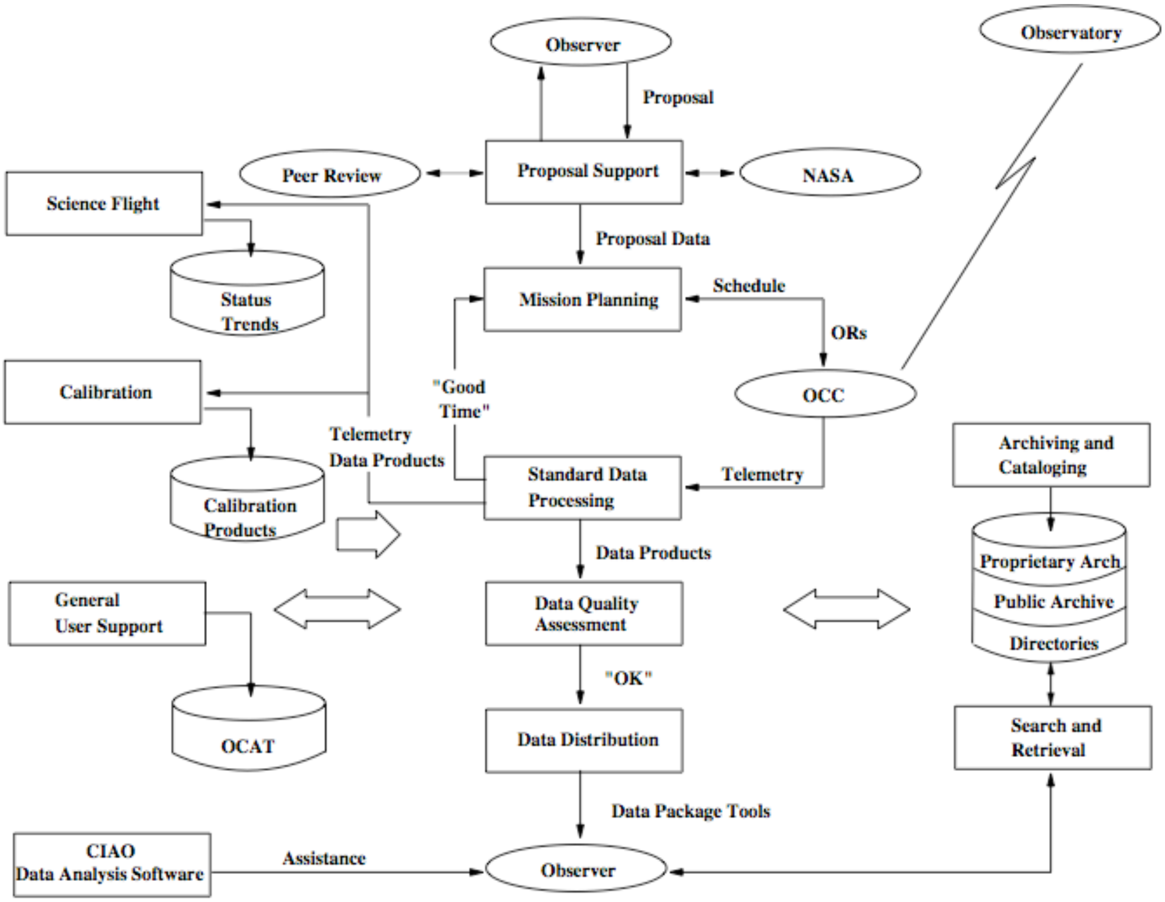

Figure 3. The CXC end-to-end thread

The end-to-end thread begins with an annual solicitation of proposals for Chandra observing time. The CXC’s Director’s Office (CDO), which is the focal point for relations with the scientific community, issues a Call for Proposals and publishes an information guide and Web-accessible software tools for proposers. Typically about 800 proposals are received each year from scientists worldwide. The CDO conducts a peer review, involving about 100 scientific reviewer to evaluate the proposals, of which approximately 200 are accepted for a total of about 20 million seconds (Ms) of observing time per year. Principal investigators of the selected proposals are invited to submit budget proposals for grants that fund data analysis, and a second peer review process, carried out by the chairs of the original peer review panels, evaluates the budgets to determine the amounts of funding to be awarded. The Chandra grants are administered by SAO’s Subcontracts and Procurement department, with technical support from CXC staff.

Following the annual peer review, the Science Mission Planning team generates a long-term (~ year long) schedule from the list of approved targets, taking into account those observations with constraints such as specific spacecraft orientation. A weekly list of Observation Requests (ORs) is generated from the long-term schedule and sent to the OCC’s Flight Operations Team (FOT) as input to the weekly command load schedule generation process. The FOT mission planning group creates a detailed mission timeline taking into account spacecraft constraints and required engineering commanding, and generates a set of command loads for up-link. FOT on-console staff at the OCC transmit the weekly command loads to Chandra via the DSN. Occasionally (roughly once per month) a high-priority time-critical science target (Target of Opportunity) is accepted that requires a rapid (24-48 hour) re-plan of the schedule.

The spacecraft executes the command loads to implement the observing plan and stores the resulting science and engineering telemetry on a solid-state recorder. Chandra's 32 kbps telemetry rate is typically comprised of 24 kbps of science data and 8 kpbs of engineering data, generating 123 GB of raw telemetry per year. The recorder is dumped at high rate (512 kbps or 1 Mbps) during each of the three one- or two-hour real-time contacts per day. During each pass the FOT online operations team checks spacecraft and instrument health and safety, and performs any required real-time procedures. Telemetry dumped from the solid-state recorder is sent to the OCC by the DSN, typically within several hours of the pass, and is made available to the FOT engineering team for trending and analysis, and is passed to the Data Processing Operations team for standard data processing.

The standard data processing pipeline software decommutates the telemetry and processes the data through a series of levels to yield standard data products suitable for further specific analysis by scientific users. Level 0 decommutates telemetry and processes ancillary (non-science) data; Level 1 processes and calibrates X-ray event data (photon arrival time, detector position, and energy), filters the data and reconstructs their aspect (position on the sky); and Level 2 filters data for good X-ray events, applies corrections to positions and energies, and performs an automated source detection. Instrumental corrections that are applied in Level 1 and Level 2 processing, and made available to Observers for more detailed analysis, are determined by the Calibration group through an observing program that utilizes ~4% of the available time.

Following data processing, a largely automated Data Quality Assessment checks that the data products are valid and that no unexpected problems were introduced by the processing, and the data products are archived. In the event of a problem identified with the processing, data may be re-processed. The processed data products are delivered to the proposing observers, typically within about 30 hours of the observations, and are stored in an archive that makes data accessible to users world wide by means of Web-based tools.

In addition to the end-to-end thread, the CXC carries out a variety of other managerial, operational and scientific activities. Project personnel manage the CXC's subcontractors. Director's Office staff exchange information and ideas with the scientific community through a variety of mechanisms, including a help desk to answer users' questions, web pages and electronic newsletters to provide information, and the formal Chandra Users' Committee to obtain feedback on the CXC's scientific effectiveness. The CXC's Data Systems group, in collaboration with the Science Data System Planning team, develops software for standard data processing, as well as the CIAO software package for data analysis by scientific users. FOT personnel maintain the spacecraft's flight software and, with science staff, monitor the performance of the spacecraft and its science instruments[2] and respond to anomalies. The OCC's Operations division operates and maintains the OCC's computer hardware and software systems. The CXC's Education and Public Outreach group, aided by university subcontractors, carries out an active program of formal and informal education and public information. In addition to the data analysis grants for observers, the CXC conducts the Chandra Fellowship program, which funds promising scientists to perform research at institutions of their choice for a period of three years. The Fellowship program annually solicits proposals and administers a peer review process, resulting in the selection of five Fellows per year. Finally, as part of the CXC's mandate to maximize science, CXC scientists carry out their own programs of research, to ensure that operations and decision making is based upon the highest level of scientific expertise.

3.3 The OCC Operational Threads

The threads associated with the OCC are conducted by the OCC's Flight and Ground Operations Teams. These threads implement activities to perform flight mission planning, flight and ground console operations, long-term trending and analysis of spacecraft engineering data, flight dynamics analysis, flight and ground software maintenance, and operation and maintenance of a spacecraft simulator. Supporting threads implement the facilities and systems management activities, and provide for systems engineering functions including configuration management, system compliance and risk management. The systems engineering thread is common to all CXC activities.

4. CXC ORGANIZATION

4.1 Programmatic Organization

The overall management of the mission is carried out for NASA by the Marshall Space Flight Center (MSFC). During the development phase, MSFC managed the prime contractor for spacecraft development (TRW, Inc., now Northrop Grumman Space Technology [NGST]), the science instrument teams, procurement of the Inertial Upper Stage (booster rocket), and development of the operations ground systems (performed in-house at MSFC). SAO was contracted by MSFC to provide scientific assistance (including the ground calibration of the HRMA and science instruments) and for developing and operating the CXC. At one year after launch, SAO subcontracted directly with the ground system maintenance contractors (CSC and Lockheed-Martin and then COLSA) and with the three U.S.-based Science Instrument teams. In practice this latter change had the effect of forging a single team communicating and working together to carry out the science mission for the benefit of the international astronomical community.

SAO subcontracts with several organizations to carry out portions of the CXC's mission. NGST furnishes and manages the Flight Operations Team, and maintains ties with the original spacecraft development team. MIT provides the CXC with scientific expertise in X-ray astrophysics, and also provides scientific and engineering knowledge of the ACIS instrument. The Pennsylvania State University (PSU) and MIT furnish the Principal Investigator (PI) teams that designed the ACIS and the High Energy Transmission Grating instruments and carry out observations and research through the CXC's Guaranteed Time Observer programs. (The HRC PI team is part of the CXC's SAO staff.) Northrop Grumman Mission Systems provides systems engineering services to the CXC, and Tufts University and Rutgers University support the CXC's education and public outreach program.

4.2 Organization

The CXC is organized, as shown in Figure 4, into five Divisions plus the Chandra Director's Office and the Education and Outreach Group. The Grant Awards Section, which is part of an SAO overhead department, works closely with the CXC on Chandra grant administration. During the development phase of the mission, the major focus of the CXC was to develop the software and other infrastructure (hardware, procedures, documentation, calibration plans, initial databases, etc.) needed to carry out the processes defined by the CXC operations concept. During the operations phase, the focus changed to carry out these processes and upgrade and maintain the systems. As was its original intent, the organization shown in Figure 4 has supported both phases well and has required little modification.

The responsibilities of each organizational element map cleanly to the components of the CXC end-to-end thread discussed in §3. The major elements, with their responsibilities, are the Chandra Director's Office (proposal support and scientific community interface), the Science Mission Planning team (mission planning), the FOT and OCC Operations teams (OCC spacecraft operations), the Science Data Systems Division (standard data processing, data quality assessment, data distribution, archiving and cataloging, data search and retrieval, data analysis software), Calibration team (instrument calibration) and Operations Science Support (monitoring instrument performance and participating in anomaly resolution).

4.3 Operational Considerations

A major objective of the CXC organizational design was to create a structure that would connect personnel directly to the required work activities during both the development and operations phases, without significant change. Such a structure would need to accommodate the planned changes in the labor profile as the project moved from planning, through development and construction, to mission operations and data analysis (Phase A/B to E). In addition, it had to allow for the overlay of a real-time on-console command and control structure to support the launch and early activation phase as well as the transition to normal, long-term, operations, including anomaly resolution.

Transition From Development to Operations . In designing the organization, consideration was given to the role of the CXC during the pre-launch phase. In addition to developing the software and systems required to operate the CXC, the

CXC staff supported the ground calibration of the HRMA and the science instruments, ensured that instrument and spacecraft subassembly (pre-launch characterization) data were captured and archived, and participated in a variety of tests including end-to-end tests during spacecraft integration and test. Planning for the support for these "operational" activities pre-launch encouraged a structure that would retain and transition the experience to post-launch. Examples include the Science Division's Operations Science Support team, which has responsibility for the science instruments and scientific monitoring and trends. Before launch, this team focused on capturing the required data and expertise, and developing the necessary instrument operational procedures (including anomaly resolution) that would used for operating the instruments during the post-launch mission. In the case of the Science Data System Division, considerable effort was invested in developing an initial version of the processing and archive system for use during ground calibration. The nascent archive and processing teams gained experience with data formats, algorithms and instrument operations, and the software system was prototyped thereby reducing risk post-launch. Making use of such pre-launch operational opportunities proved valuable in shaping the organization to support both phases.

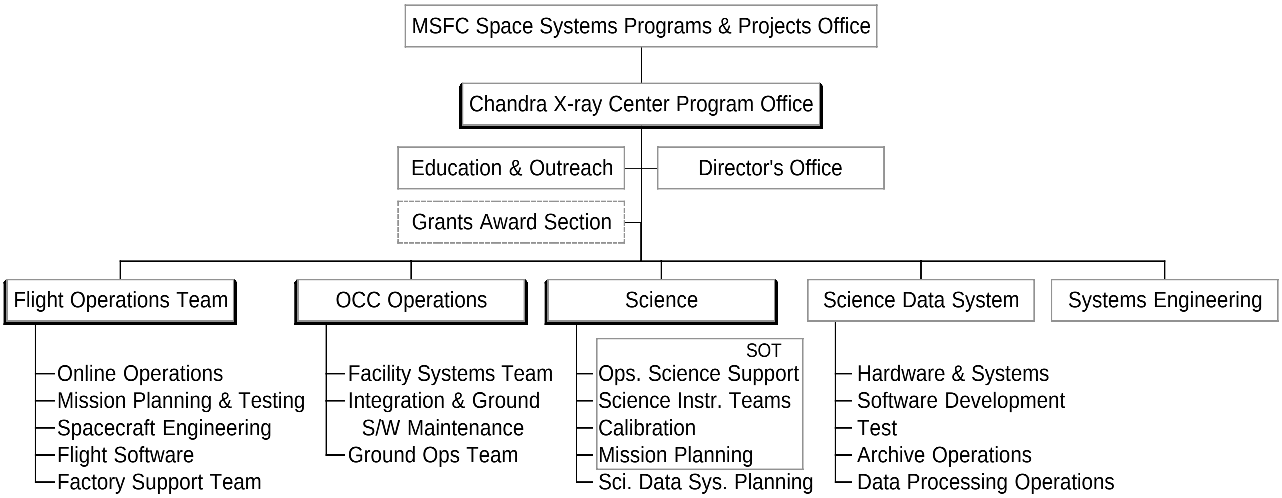

Figure 4. CXC Organization showing operational elements (shadow boxes) and Science Operations Team (SOT).

Required Changes. Three changes to the organizational structure and assigned responsibilities were found to be desirable in transitioning to operations. Prior to launch, the Science Division included a User Support Group with responsibility for general user support, user documentation and the peer review cycle. Following experience with the first observing cycle, some members of the User Support Group were transferred to form the Chandra Director's Office, with responsibility for the observing cycle, grants administration and science policy, while others joined the Science Data System Planning group, which assumed responsibility for user software documentation. This latter change ensured that the documentation was developed by the same science staff who worked to specify the software algorithms. A second change was made in response to a significant number of problems found in the specification of science instrument settings by observers. The Operations Science Support group assumed the new responsibility of "Uplink Support", which checks all instrument settings and user-requested constraints with observers prior to uplink. This change was made shortly after launch and has been operating effectively throughout the mission. The third change, implemented recently, has been to expand the role of the Flight Software Maintenance team within the FOT to take a broader role including the maintenance of the flight simulator and other ground software tools utilized by the FOT. This change also places a more experienced software manager as the lead of the group, acknowledging the increasing importance of flight software management as the spacecraft ages.

Flight Operations Organization. The organization shown in Figure 4 served both as a development and long-term science operations structure, and also as the real-time control and command structure used during launch and mission operations and for responding to anomalous spacecraft conditions. The elements involved in real-time operations, shown as shadowed boxes, include the Flight Director, FOT, OCC Operations team, and Science Operations Team

(SOT). The Flight Director (who also serves as the CXC Program Manager) has overall responsibility for the conduct of mission operations. The FOT and OCC Operations teams fulfill the traditional flight and ground functions. The SOT is comprised of those science groups that are required to perform real-time operational functions. The SOT lead is the Operations and Science Support lead and oversees the real-time activities of the science mission planning, calibration and science instrument teams. These operational teams trained and were certified during launch preparation to operate on-console during real-time spacecraft activities, and undergo on-going training through simulations throughout the mission. This approach is highly efficient since key science and operational roles are filled by the same personnel. This approach, which has been highly successful in the case of the Chandra mission, may or may not be applicable for other missions, but should be considered.

Synergies. Combining the operations and science organizations has resulted in a number of synergies.

(a) A single management structure has allowed the development of common processes for tracking problems and action item, managing configuration control board activity, and assessing and managing mission risk.

(b) A single Systems Engineering group has ensured commonality to compliance, test approach and maintenance of interface and other project documentation.

(c) Science and flight mission planning teams have developed a highly effective level of teamwork and a detailed understanding of each others' processes, working jointly to improve both sets of processes.

(d) Perhaps the most vivid example of a synergistic benefit of combining operations and science in one organization has been the development of the load review process. Following launch a review process was developed for each set of weekly spacecraft command loads. The review, led by the Flight Director, calls for a detailed command level review by each of the operational subsystem teams (pointing and control, aspect camera, electrical power, thermal, mechanisms, and flight software), both science instrument teams (ACIS and HRC)[3], and the science and flight mission planning teams. Each team reviews the loads from its perspective using a variety of specialized software, e.g., checks for constraint violations, instrument settings, final pointing and roll. While these parameters are checked by software during the load generation process, the multidisciplinary load reviews are able to identify subtle but important problems that, when corrected, can result in improved science quality of science, reduced risk, and on occasion, avoided errors. Examples of potential command load problems that can be prevented by the load review include identification of one or more low quality stars selected for use by the star camera, unexpected interaction with real-time engineering procedures scheduled for the upcoming week, timing errors resulting from short-duration events, and improper timing for instrument shutdown either side of the radiation belts. In addition, the load-review team reviews the higher risk schedule changes for rapid Targets of Opportunity. The load review process, coupled with close teamwork between the science and operations staff, has resulted in virtually error-free scheduling during the Chandra mission.

(e) Integrating the Science Instrument teams into the CXC organization has resulted in seamless teamwork during anomaly resolution, changes to instrument flight software, development of calibration plans, and in the formation of effective working groups to resolve or track ongoing technical issues.

5. LESSONS LEARNED

5.1 Lessons from the Development Phase

The following lessons learned were derived from our experience during the development phase.

Scientist Involvement. Involve Science Center scientists and engineers in all aspects of the mission during the development phase.

Operations Planning. Plan early during the development phase (Systems Requirements Review and onward) for operations considerations and make sure that the operations organization (including Science Center) is strongly involved in the requirement definition and in the early design process to assure that the resulting systems and processes are user friendly.

Incremental Data System Releases. Develop the science center data system software as a series of incremental releases, each providing specific functionality. Tie the releases to key milestones such as calibration testing, SI interface testing, and system end-to-end test. This approach reduces risk by demonstrating central data flows early, testing interfaces, providing the team with experience with data formats and operational procedures and, perhaps most importantly, allowing for prototyping of software.

Common Databases. Every effort should be made to ensure common command and telemetry databases between the Integration and Test systems and the operational ground system. This was not the case for Chandra, and resulted in significant effort to synchronize the database content and formats during the test phase. In addition, changes to databases during the operations phase should be anticipated through thread analysis, and processes should be planned to allow for sufficient flexibility.

End-to-End Tests. Before launch, perform end-to-end tests of the flight system with the ground control system using the final flight and ground versions of hardware, software, database and procedures. Flight and ground staff, including Science Center personnel, should perform these tests as an integrated team.

Science Support Contract. In the case of the Chandra mission, NASA contracted with SAO for a Mission Support Contract that provided the Project with calibration support and scientific expertise and review (this was in addition to an excellent Project Science group within MSFC). This support provided value to NASA by furnishing science expertise to support key trade studies between the science requirements and design, which was important to a mission of Chandra's technical complexity.

5.2 Lessons from the Operations Phase

The following lessons have been derived during the operational phase of the Chandra mission.

Plan for Transition from Development to Operations. In planning the science center organization, address carefully the transition from development to operations.

Consider a Combined Operations and Science Center. Consider the advantages in combining science center and operations activities within a single contract and organization. The model has worked well for Chandra, allowing highly integrated approaches for mission planning, operations and engineering studies, anomaly resolution, proactive planning, facility and infrastructure consolidation.

Develop Effective Operational Metrics. A set of metrics was derived from the Level 1 mission requirements that were developed with NASA at the time of launch. The metrics were aimed at measuring science center and mission performance, identifying process problems and trends, and providing feedback for process improvement. The metrics include:

(a) Science Center Metrics: time from observation to delivery of data to user; number of help desk queries and speed of resolution; and time from observation to award of grants.
(b) Science Operational Metrics: observing efficiency, observing time lost due to solar events or other down-time, and data loss due to ground errors or processing problems.
(c) Mission Operations Metrics: consumables usage, subsystem trends, limit violations and many other metrics typically used in operating a spacecraft

Other metrics were developed that have provided additional important insight into CXC operations and success: archive volume and usage, software development and maintenance metrics, analysis software usage by users (downloads, problem reports, platform usage), peer review and proposal statistics, published papers, press statistics, science staff research time and achievement, and programmatic (cost and schedule) metrics. One example of the success of the use of metrics was the reduction in the time from observation to data delivery to users, from over a month at the start of the mission to less than a week. This significant improvement resulted from an end-to-end examination of the performance of the CXC processes and software, prompted by the metric. As improvements were made, the metric provided feedback and allowed the team to reach the optimal performance for the system. Other metrics that are monitored closely and indicate a high level of CXC performance include the completion of five observing cycles with near optimal observing efficiency, the awarding of grants within ~2-3 weeks of data delivery, a continued high degree of over-subscription for observing time (by a factor of 4 to 5 in observers, 6 to 7 in time), increasing trends in analysis software and archive data usage, and increasing trends in published papers.

Involve Instrument Teams Throughout Mission. Plan for continued involvement of Instrument Principal Investigator Teams for the duration of mission. This ensures retention of key science and engineering expertise from the instrument development teams as the instrument and spacecraft ages. Provision of a small amount of guaranteed time for the entire mission duration provides additional motivation for participation by those teams.

Software Lessons.

(a) The software development process should involve scientists during all phases, and not be an "over the wall" requirements-to-developer model.
(b) For long-term maintainability, and to ensure that requirements are met, software development should adhere to a standard paradigm and life-cycle (requirements, specifications, coding, testing).
(c) Allow for software and scripts to be developed by scientists and engineers both in support of rapid prototyping and to allow for specialized tools. "Light weight" standards for coding, documentation and CM should be instituted to ensure long-term maintainability. A more detailed discussion of software solutions developed by the Chandra FOT is provided in a companion paper in this volume[4].

Retain Active Scientists. The CXC model enables scientific staff to continue active research (maintaining and enhancing scientific expertise needed to carry out the required service functions). The CXC contract allows for (PhD) scientists to spend up to 50% their time with the actual average being 32%.

5.3 Long Term Mission Considerations

X-rays are emitted in the hot, violent events which take place in the universe, and whenever particles are accelerated to high energies, which in practice means of order 1% of the speed of light, or greater. X-rays have been observed from every category of astronomical object known. Thus the charter of the Chandra X-ray Center includes making the Observatory accessible to a wide range of astronomers, and to optimize the scientific return. While the specific observations that are done are determined by outside peer review committees, and the scientific merit of the program cannot be measured objectively, it is certain that a key element of maximizing the scientific return of the mission is to prolong the useful observing lifetime. Thus the health and safety of the observatory is considered the highest priority and a set of conservative and self-checking processes have been developed to ensure this. The following are a number of lessons that follow from considering how to maximize the lifetime of the Chandra mission.

Long Range Strategic Plan. The Chandra mission has been successfully operating for over 6 years with exceptional results. To achieve such continued success, a long-range strategic plan must be in place to ensure that the program organization is robust to changes. An effective long range strategic plan must consider vehicle life-limiting items, managing organizational priorities, assessing organizational evolution, maintaining program knowledge, minimizing and planning for staff attrition, providing refresher training, recurrence training and cross training, maintaining ground system hardware and software, planning for requirement changes, managing new or modified mission constraints, and identifying areas for process improvements and opportunities for automation and innovation.

One of the first considerations in developing a long term plan is to identify the operational drivers. The primary drivers for Chandra stem from the needs of the Observatory as it ages. The first step in determining these needs is to perform an analysis of life limiting factors. In 2002 the program completed a comprehensive study of the vehicle's life limiting factors. The factors included: exhaustion of consumables, mechanism wear, contamination, instrument degradation, effects of radiation. The factors were prioritized with the near-time factors given the higher priority. The study resulted in a road map for the operations team that provided guidance on how best to apply resources to minimize future mission risk and maintain the mission's science return. The prioritization also helped guide plans for staffing, training, and overall schedule. One example of a high priority factor was in the area of spacecraft thermal modeling. The study identified the need for improved modeling of several areas of the vehicle that had higher than expected temperature trends. The modeling work led to the identification of several tasks that were needed to avoid damaging spacecraft hardware. The study and resulting actions have led to an assessment that there are no spacecraft or instrument factors that are likely to limit the lifetime of the observatory to less than 15 years (this is impressive given the 5-year life design requirement and 10-year goal).

Another component of a successful long term plan is to perform an organization evaluation and assess whether the organizational structure is sufficient to support a long term mission. As discussed in §4.2, a change was made recently (after 6 years of operations) to strengthen the flight software group and expand its scope. This change was driven by an assessment of the long-term organizational structure and by the expectation of an increasing flight software maintenance activity as the observatory ages. Periodic assessments of both the factors that impact mission lifetime, and the suitability of the organization to best address these factors, are important component of a long range plan.

<u>Knowledge Retention</u>. Another key to successful long-term operations is to develop an effective knowledge retention program. An effort was undertaken shortly following launch to address this question and resulted in three steps. First, the development of a complete database of operations and mission data, together with web-based software to provide easy and rapid access to the data. Second, efforts have been made to minimize staff attrition by providing staff with high levels of responsibility and encouragement to innovate and be creative. Third, a thorough training program was implement designed not only to maintain program knowledge, but also to increase knowledge through simulation exercises, exams, and cross training. For the FOT a training program was designed around specific job requirements, and staff were cross-trained to ensure that at least two staff members could perform each job. The FOT also uses a recurrence training program which ensures that current staff members retain their certifications for each of their job responsibilities. This keeps the team both knowledgeable and current.

<u>Ground System Evolution</u>. Besides having a well-trained staff and a dynamic organization, a successful long term program must also be adaptable to changing requirements and constraints. Typically, ground operations hardware and software are designed to an original set of requirements without the expectation of significant future change. In the case of long-term missions however, it's likely that the ground system will need to be upgraded and ported at least once due to end-of-life of hardware, evolution of operating systems and changes in vendor support. In the case of the Chandra ground system, a major port activity was undertaken in the 4th year of operations to migrate from a Silicon Graphics hardware base to a Linux base. Testing of the system was led by the Systems Engineering team and utilized the operational teams as the testing staff. Careful planning, thorough testing and the involvement of the operations teams resulted in a seamless transition to the new system, with no adverse events.

<u>Mission Constraints</u>. As Chandra has aged, new or modified mission constraints have driven new mission requirements, particularly in the mission planning area. Pro-active management of these mission constraints helps to minimize the impact of requirements changes and tends to reduce the total number of constraints.

ACKNOWLDGEMENTS

The authors gratefully acknowledge the support provided for this work by NASA Contract NAS8-03060.

REFERENCES

1. Evans, J., et al., "The Chandra X-ray Center Data System: supporting the mission of the Chandra X-ray Observatory," SPIE Proc., these proceedings (2006).

2. Virani, S. N., et al., "Improving the science observing efficiency of the Chandra X-ray Observatory via the Chandra radiation model", SPIE Proc., vol. 5165, 530 (2004).

3. DePasquale, J. M., et al, "Optimizing the efficiency of command load inspection for the Advanced CCD Imaging Spectrometer (ACIS) on the Chandra X-ray Telescope", SPIE Proc., vol. 5501, 328 (2004).

4. Shropshire, D., Bucher, S., Rose, J., "Adaptive Software Solutions: Lessons Learned from Chandra Flight Operations," SPIE Proc., these proceedings (2006).