Performance as Promised: How the Chandra X-ray Observatory accomplished one of NASA's most challenging missions for billions of dollars less than originally planned

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I. Introduction

On July 23, 2004 the Chandra X-ray Observatory completed its prime mission for billions of dollars less than originally planned. Chandra continues to be the world's premier x-ray observatory in its extended mission, but the completion of the five year prime mission also marks a significant accomplishment for NASA in the development of a challenging space system. From its highly elliptical orbit between 10,000km and 140,000km, Chandra has made 4,662 observations, with 28,403 hours of on-target science observing. From initial on-orbit check-out which was completed ahead of schedule and demonstrated that the system had "*fully satisified or bettered*" all 21 key performance measures, to current on-orbit performance which remains significantly better than requirements, the Chandra flight system has fully achieved its scientific goals. But perhaps even more remarkable was the cost to achieve this exceptional performance.

NASA's 1985 Non Advocate Review (NAR) predicted that Chandra would be at least as challenging as HST. Chandra originally resembled Hubble in having a 15 year prime mission lifetime accomplished by shuttle servicing. However, where as Hubble had one paramount technical challenge with the primary mirror, Chandra was seen as having two challenges equal to

Figure 1. Shuttle Columbia Captained by Eileen Collins, carries Chandra to orbit on 23 July 1999.

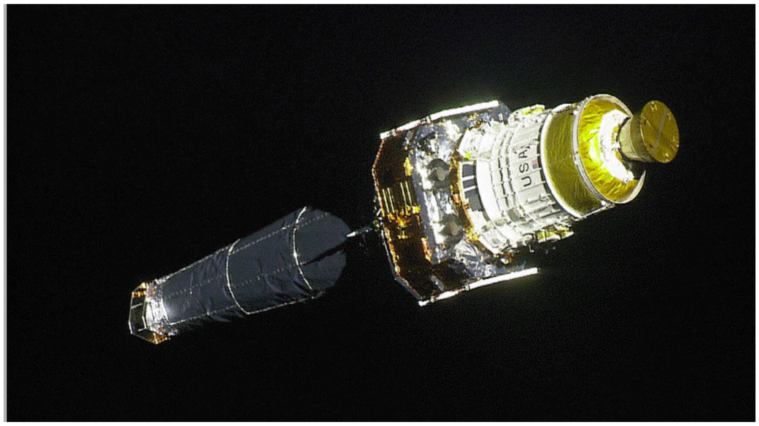

Figure 2. Chandra and Inertial Upper Stage as deployed from Columbia, 24 July 1999.

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[*] Where a change in program or organizational names has occurred over Chandra's history (e.g., renaming the Advanced X-ray Astrophysics Facility as the Chandra X-ray Observatory), the current names are used in describing events that took place before the new names were in place. Organizational examples are Northrop Grumman (previously TRW), ITT (previously Kodak), and Goodrich (previously Hughes Danbury Optical Systems).

that of the Hubble mirror: the cylindrical x-ray mirrors and the assembly needed to hold these mirrors in precise alignment. It turns out that Hubble has cost significantly more than anticipated in the mid-1980's. But the Chandra development program was accomplished within the cost range set by NAR for Phase C/D costs - in the FY85$ used by the NAR, Chandra's $1,120M development costs are well within the $950M-$1,200M range provided in 1985.

Chandra's greatest savings were with respect to life cycle costs. Estimates of life cycle costs varied in the early years, but just before elimination of the shuttle servicing mode the life cycle costs were estimated at $5.6B (Real Year $), plus the costs of three shuttle missions, international contributions, and civil servant support. By 1992, cost savings had been achieved through elimination of two shuttle flights, but the cost of this plan would still have been over $7B (RY$), and the actual costs may have been higher. The expected full life cycle costs of Hubble through April 2005, the completion of its 15 year prime mission, are over $14B in FY05$. Chandra completed its prime mission at a full life cycle cost of $3.7B in FY05$.

The American taxpayers got the performance as promised from Chandra for a significantly lower cost than anticipated. A number of exceptional accomplishments contributed to this performance, such as the highly successful mirror technology demonstration that won approval for the completion of the program in September 1991. This paper will focus on two areas that contributed to Chandra's performance as promised: the 1992 "restructuring," and a series of approaches that enabled effective implementation.

II. Chandra's 1992 Restructuring

NASA Headquarters decided to restructure Chandra in January 1992 despite the highly successful mirror technology demonstration in September 1991 that won Congressional approval for the completion of the Chandra program. Associate Administrator for Space Science Len Fisk and Astrophysics Director Charles Pellerin determined that Congress would not fund the originally planned Chandra program and they challenged the entire team to develop dramatically less expensive options to conduct the mission.

The restructuring was completed in less than four months - from the first mention on January 6, 1992 to approval of the new baseline by April 30, 1992. While such exercises are unfortunately all too common, the identification of significant savings (and the later realization of those savings) is almost unprecedented. This was accomplished by a combination of team-work, systems engineering, and advanced technology insertion.

A very broad team came together to achieve the Chandra restructuring. NASA's MSFC Observatory Projects Office led the overall effort, but there was also significant in-house MSFC effort at the X-Ray Calibration Facility that would be used to test and calibrate the optical system and instruments. Science leadership was provided by the MSFC Project Science Office, working with science support from the Smithsonian Astrophysical Observatory (including Chandra Science Center which operates the observatory), with additional science input from four Principal Investigator teams (from the two focal plane instruments and the two grating instruments). The industry team was led by Northrop Grumman Space Technology, with subcontractors ITT, Ball, OCLI and Goodrich.

Restructuring the program was not easy. Many individuals had entrusted a substantial portion of their lives (and aspirations) to the original conception of the program. Headquarters was pushing for deep budget cuts, the science community was vociferously resisting, and Marshall was working hard to recover a viable and sustainable program. Northrop Grumman worked with MSFC to build team-work not by holding team-building off-sites, but by fair and rigorous analysis of a broad trade-space. This broad system architecting approach yielded some surprising innovations in terms of the final design selected, but it also served to bring the entire team together. By considering a wide range of alternatives and making decisions based on data and analysis, what could have been a contentious decision evolved to consensus.

"[NGST] did a tremendous job in the middle of difficult and emotional arguments between headquarters, the science community, and Marshall. By gaining the confidence of all three groups, [NGST] made the restructuring work."

-Art Fuchs, former NASA HQ program manager

The systems engineering approach was to trade a broad set of parameters including number of mirrors, launch vehicle and orbit, servicing, combinations of payloads, and alternate technologies. Cost, schedule, performance and risks from each option were evaluated. The thorough tradeoff of science utility vs. cost led to the selection of a highly elliptical orbit with uncrewed robotic delivery, deployment, and maintenance. A proposed 100,000km apogee orbit would provide much greater science observing time, since the Earth would block the telescope's line of sight for a much smaller fraction of each orbit, however two alternate technologies were necessary to reach this orbit. Composite materials were used extensively to reduce observatory mass from over 32,000 lbs to 10,110 lbs, and a high Isp liquid bi-propellant system was built into the observatory to take the vehicle from an apogee of under 40,000km to its final operating orbit.

Certain features were eliminated in the restructuring. Four of twelve mirrors were eliminated, although neither the smallest or the largest (which minimized the impact on any particular part of the x-ray spectrum being observed). Two of four focal plane instruments were eliminated - one was primarily a low risk back-up; the other did not require mirrors of Chandra's quality and was assigned to fly on another spacecraft. Shuttle servicing was also eliminated, which precluded a mission to repair failures or upgrade capabilities further.

However, there were also significant performance improvements achieved through the restructuring and over the development and operational lifetime including better photon collecting due to iridium mirror coating (doubled), high efficiency detectors (doubled efficiency at 1 keV; even more performance at lower energies) and better than expected mirror coating reflectivity (~10%). Mirror smoothness provided high energy angular resolution (focus) three times sharper than requirements, and the array size of best detectors increased by a factor of 3.5 (detectors in 2x2 imaging array: 640x640 format increased to 1K x 1K). Chandra achieved 11,400 more hours on target performing science observations during the prime mission than anticipated at the time of the restructuring, by lower than anticipated observatory overheads (slewing, safemodes, scheduling inefficiency, etc.) and by raising apogee from 100,000km to 140,000km to spend less time in the radiation belts.

Figure 3. Extensive use of composite materials helped cut mass from 32,000 to 10,110 lb.

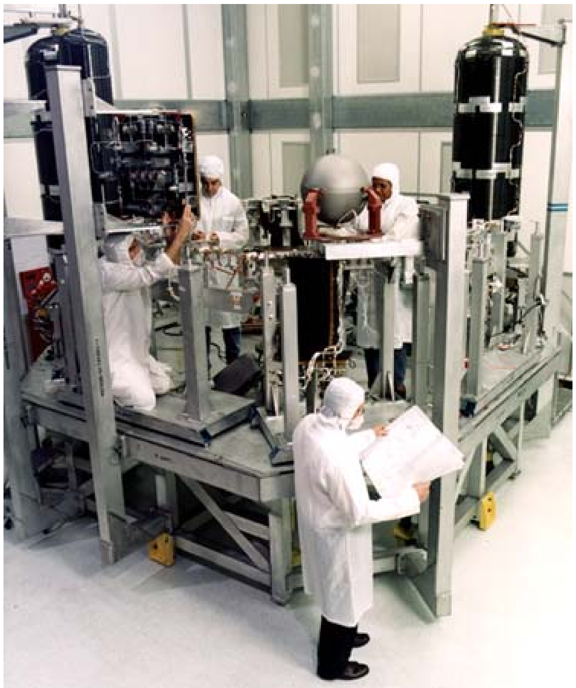

Figure 4. Innovative mission design enabled by high Isp bi-prop propulsion system.

The performance enhancements brought more photons reflected more sharply onto more sensitive detectors, while the improvements in operational efficiency after the restructuring provided 67% more science observing time in the prime mission. Chandra provided substantially more performance than promised for the budget.

The restructuring could not have happened without real courage demonstrated by NASA decision-makers. Almost exactly two years after the launch of the Hubble Space Telescope with a flawed primary mirror, NASA had the option of a much lower performance architecture (a single pair of mirrors in LEO) that could be shuttle serviced. NASA selected the HEO architecture based on an assessment of risk and return. According to the notes of Chandra Program Executive Pete Ulrich, NASA Associate Administrator Len Fisk concluded the restructuring decision meeting as follows: *"What are the negatives with HEO? You can't get to it to fix it. However, this is just part of doing space astrophysics, and furthermore, [NGST] successfully does this sort of thing all the time. Therefore, decision to exercise the HEO option."*

The restructuring saved the American taxpayers $3.6B, but it also left the program with a very lean budget. NASA was entering an era of "faster, better, cheaper," and while Chandra was still a large program, it was given very limited flexibility. When Chandra was restructured (two years before PDR), program cost reserves were set at a very aggressive 21%, mass margin was 20%, and schedule margin was only 6%. Concerns over the ability to accomplish this technically challenging mission with less than 30% cost reserves even led to a 1993 audit of Chandra by the General Accounting Office. This audit called upon the NASA Administrator to review whether "funding reserves are realistic in light of the program's uncertainty and risk." The 20% reserves were the baseline that the Chandra program ultimately overran by 3%. This level of overrun was still only half the size as the average for the other 6 NASA Space Science programs launched in FY 1999 (note: three of those six missions failed), and less than 1/3 of the metric set for NASA missions in accordance with the Government Performance and Results Act. The other key element in the Chandra story was how the project managed to these lean reserves.

III. Implementation Approaches

The Chandra team was able to execute the lean program due to a combination of a system-level approach to program management and a culture that emphasized high value investments or savings. The program management approach provided the entire team with an understanding of the system drivers and constraints, and allowed effort to focus on mitigating the key risks. The culture influenced individual, organizational and team behavior to focus efforts on what was best for the program.

The Project identified and managed the depletion of reserves. A comprehensive list of program risks were identified and based on weighted probabilities, budgetary liens were set aside and the remaining risks tracked as threats. In 1994, it was recognized that schedule reserves were significantly tighter than cost reserves, and so the Project authorized a schedule acceleration initiative where all project elements had an opportunity to request additional funds in they could add 1-2 months of slack to their critical path. Reserves were allocated to investments associated with mirror fabrication, coating and optical testing, and some relatively small investments had a substantial payoff in terms of contributing to the 5 years of optical development occurring on schedule.

The project managed by margins even with respect to technical performance. Since Chandra was shuttle launched, the possibility was raised of astronaut servicing during the initial deployment operations - a potential cost driver both for analysis and for redesign to make Chandra astronaut-friendly (no sharp edges that might tear a space suit, etc.). The only potential failure easily remedied by astronaut servicing was the potential deployment failure of either of Chandra's low gain antennas. Fortunately, the team had a good understanding of the potential impact of a failure of one or both deployments (6%-12% of mission data) as well as recognition that post-restructuring improvements in efficiency had already provided 30% more observation time, and thus there no further expenditures were needed in this area.

Pro-Active Risk Management

Chandra demonstrated the value of developing technology risk reduction pathfinders. In the mid-1980's, MSFC developed a Technology Mirror Assembly that demonstrated the capabilities required for the Chandra mirrors on a small scale. Chandra's approval for a New Start was conditional on on-cost, on-schedule development of the largest pair of mirrors. The Verification Engineering Test Article (VETA) 1 had the two largest flight mirrors held in a non-flight mirror assemby. The VETA-2 had flight mirrors in a flight-like mirror assembly. From every step of the way, lessons learned were passed forward not only in regard to matters such as materials and designs, but also with respect to assembly and testing processes.

Figure 5. VETA-1 technology pathfinder developed to reduce cost, schedule and technical risk.

The team proactively conceived a pathfinder for the spacecraft central cylinder as a risk mitigation approach that provided cost avoidance by preventing a 2-3 month schedule hit on the program critical path. Despite the very tight budget, the Project allocated reserve funds to produce a composite model of a key portion of the Structural Test Article (STA), which was a high fidelity model of the spacecraft structure. The pathfinder uncovered a problem with resin out-time (resin partially cured at room temperature during the 46 day lay-up, precluding adequate resin consolidation during the elevated temperature cure). If there had not been a pathfinder, this problem would have emerged in the development of the equipment compartment for the Structural Test Article leading to a 2-3 month delay. These lost months would have led to a late start of mechanical integration of the flight spacecraft, and ultimately may have threatened the program critical path

Lessons learned from the central cylinder pathfinder were folded into the STA development. Later, the team used the static loads test of the Structural Test Article (STA) to develop ways to reduce the schedule for the static test of the Flight Structure by four months. The flight structure was instrumented in parallel during manufacturing prior to delivery for I&T, and the approach for applying loads was simplified to minimize time-consuming configuration changes. These measures reduced required testing from 30+ weeks on the STA to 7 weeks for the flight structure. Ultimately, the STA was combined with the VETA-2 (populated with aluminum surrogate mirrors) to perform observatory loads testing without having to use any flight hardware.

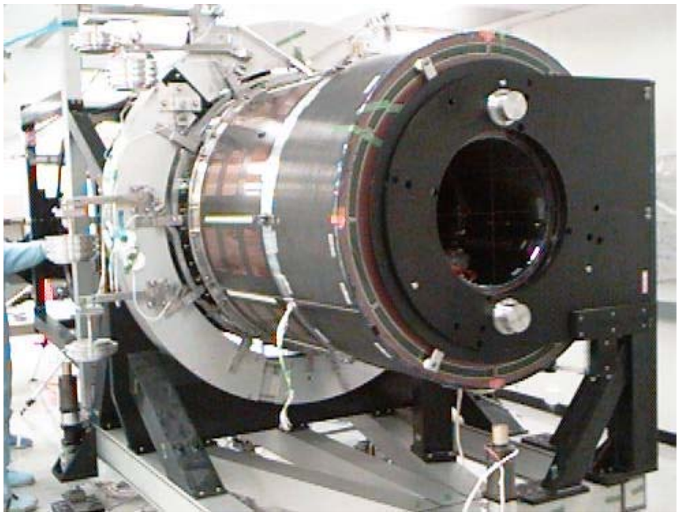

Figure 6. VETA-2 populated with aluminum mirror surrogate used for observed loads testing.

Chandra avoided many pitfalls that have impacted similar programs in the past. One of the key risks for large space observatories is late delivery of advanced scientific instruments. On Chandra, the most challenging instrument was the Advanced CCD Imaging Spectrometer (ACIS). When mirror fabrication was completed without consuming all slack, the delivery of ACIS for integration into the Science Instrument Module (SIM) became the critical path. This integration was needed prior to the critical five month period of x-ray testing of the telescope and its instruments. However, the Chandra team recognized the risks and potential impacts of an ACIS slip. The first pro-active risk reduction step was to save several months of critical path schedule by deferring integration into the flight SIM until after x-ray calibration was completed. The Late ACIS Surrogate SIM (LASS) was conceived, salvaging the SIM designs while switching to stainless steel to avoid the unacceptably long delays that would have been required by the flight composite design. The LASS effort was not trivial, as significant SIM functionality had to be provided on a dramatically shorter timeframe (e.g.; a GSE mount with 5 degrees of freedom. a duplicate set of harnesses that worked with the flight HRC instrument and the flight ACIS avionics, etc.).

Later, it became clear that even those three additional months would be inadequate. The team developed a concept for an ACIS 2-chip (A2C) detector that would use flight-quality CCD's to make as much progress in calibration as possible without the flight instrument. Scientists and engineers, industry and in-house personnel, all worked to develop the liquid N_2 moveable plumbing, the vacuum vessel and all its interfaces, and the critical high-speed data link.

The ACIS instrument was delivered in early April, 7-months behind schedule. Through effective use of AC2, rapid integration into LASS, and a well-conceived plan of cross calibration, all of the originally planned X-ray calibration activities were completed on time. When the Chandra restructuring was approved by Len Fisk on April 30, 1992, the team was given exactly five years to complete x-ray calibration. Five years later, the job was complete. The project elected to use an additional five days of calibration for new activities to improve science performance (a decision that takes nothing away from the on-time accomplishment of a suite of activities that many observers believed might take 1 to 2 years longer than planned).

In the immediate aftermath of the problems with the Hubble Space Telescope mirror, the Chandra Project did not take the easy approach of funding to mitigate every risk. One key decision that helped shape the culture was the leadership to select a non-serviceable mission concept. Regardless of origin, the Chandra team had a culture that encouraged efforts to push back against certain risk reduction expenditures. Examples include working closely with the Johnson Space Center to get a test exemption for the composite mirror support sleeves (the elements that bore the loads of the 500 lb Chandra mirrors). Another key test that was eliminated was the horizontal testing of the High Resolution Mirror Assembly (HRMA) testing. A gravity off-load approach was developed that allowed the test to be conducted along with testing at the X-Ray Calibration Facility, instead of extended the stay at ITT in Rochester. Finally, industry made a compelling case to eliminate bake-out of the Optical Bench Assembly (the massive telescope "tube") which saved several million dollars and a month of schedule.

High Performance Culture

Chandra's program performance was remarkably different from the predictions early in Chandra's development, and different from beliefs about current and future programs. Cynics assume that team members will play "project manager's poker" and exploit problems elsewhere in the program. Projects are assumed to fail to identify and address risks early, leading to huge marching army costs while resolving surprise show-stoppers. It is taken as a given by some that industry can be counted on to exploit government changes, and that there will be waste and inefficiency because Project organizations can't work as a team ("throwing problems over the transom"). If these behaviors had occurred among the Chandra team, the program might have slipped many years and suffered high percentage overruns.

Figure 7. Chandra at NGST Thermal Vacuum Chamber

Throughout many of these examples discussed earlier, it is noteworthy that the entire team worked in the program's interest, even when it was not necessarily in their direct financial interest. The prime contractor would have benefited significantly from a financial perspective if the whole program had slipped out in accordance with the 7 month slip in the Government-Furnished Equipment (GFE) ACIS instrument. Or perhaps the biggest "lost financial opportunity" for industry - if the program had remained with the shuttle servicing mode, and if Hubble is any basis, the prime contractor might have been eligible for an additional billion dollars in sales.

One of the authors of this paper witnessed an exceptional illustration of this culture at a monthly meeting at the Telescope subcontractor ITT in Rochester, NY. An engineer from ITT announced that a problem had emerged in meeting a Level 3 spec for the obscuration caused by thermal baffling of the HRMA. An effective fix had been developed to meet the science requirements with no schedule impact, at a cost of $282K, and the team was ready to move forward. Four remarkable things happened in rapid sequence.

1. a representative of the Science Center was actually in the audience
2 he had the engineering insight to understand the validity of both the requirements violation and proposed fix, and he had the science insight to understand that the requirements violation was trivial
3 the Science Center representative was willing to stand up in a room of 50 people and say "That is the stupidest thing I ever heard" and to recommend taking no action and saving the money
4. the team listened to him; quickly verified the facts; and eliminated any further efforts on this issue

This is a significant contrast to other programs where every team member fiercely guards their turf, and no scientist would yield on a requirement affecting performance, no matter how trivial. This also demonstrates a culture where broad technical participation was welcomed, and dissenting opinions encouraged.

Many times on Chandra, the team took actions that avoided unnecessary expenditures. Often the savings were just a few hundred thousand dollars, and even in the aggregate they amounted to a small percentage of the total program budget. However, the culture that had everyone trying to avoid investments of effort with negligible returns was combined with a culture that put additional money where it might have a high payoff. The tripling of image clarity for hard x-rays was achieved through ~$1M investment in mirror polishing research; the additional 30% observing time achieved by boosting apogee from 100,000 km to 140,000 km also was accomplished for roughly $1M.

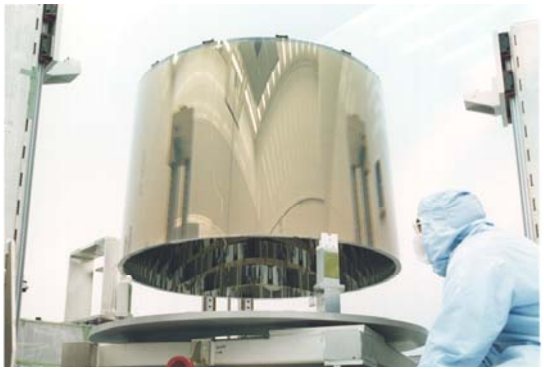

Figure 8. Investment in polishing technology provided high energy angular resolution three times sharper than requirement.

If culture is a key driver of outstanding program performance, then the critical question is how to instill a high performance culture. On Chandra, the ingredients included experienced science team that was fully integrated into the Project. The science culture of skeptical inquiry and focus on ultimate mission utility was a core part of the overall Chandra culture. The industry team was led by a prime contractor with the responsibility for aligning corporate incentives and behavior in accordance with program goals. The NASA Project Office selected team members and assigned roles based on best value to the program, and led by example in managing the broad team in a collaborative and constructive fashion. And, after the restructuring, NASA Headquarters and Congress were able to provide stable funding and top-level requirements to enable the Project to focus on execution.

Summary

As the nation looks toward bold new ventures in space, the Chandra X-ray Observatory program offers an example of how billion-dollar missions can be successfully developed within tightening fiscal constraints. Chandra experienced many of challenges facing bold space programs (state-of-the-art technical requirements and budget-induced slips and restructurings), and yet the Chandra team achieved essentially all the originally envisioned performance for dramatically lower cost. This was accomplished by a combination of team-work, systems engineering, advanced technology insertion, and effective approaches for program implementation, combined with a high performance culture that aligned goals and focused on mission success. As Chandra now enters the extended mission, the observatory continues to provide superb scientific performance.

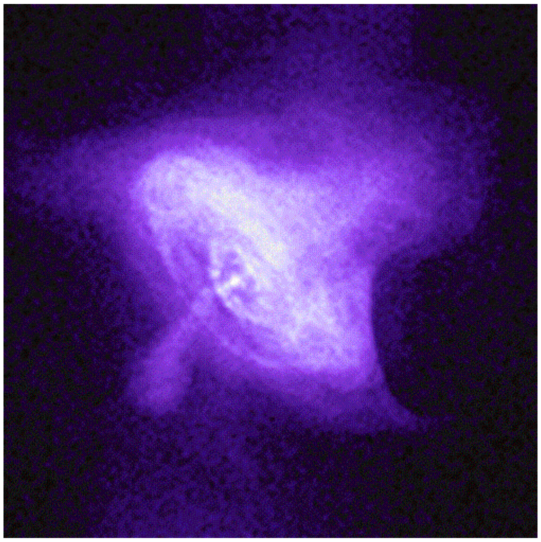

Figure 9. Chandra image of the Crab Nebula