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CHANDRA X-RAY OBSERVATORY POINTING CONTROL SYSTEM PERFORMANCE DURING TRANSFER ORBIT AND INITIAL ON-ORBIT OPERATIONS

Peter Quast*, Frank Tung*, Mark West**, and John Wider*

The Chandra X-ray Observatory (CXO, formerly AXAF) is the third of the four NASA great observatories. It was launched from Kennedy Space Flight Center on 23 July 1999 aboard the Space Shuttle Columbia and was successfully inserted in a 330 x 72,000 km orbit by the Inertial Upper Stage (IUS). Through a series of five Integral Propulsion System burns, CXO was placed in a 10,000 x 139,000 km orbit. After initial on-orbit checkout, Chandra's first light images were unveiled to the public on 26 August, 1999.

The CXO Pointing Control and Aspect Determination (PCAD) subsystem is designed to perform attitude control and determination functions in support of transfer orbit operations and on-orbit science mission. After a brief description of the PCAD subsystem, the paper highlights the PCAD activities during the transfer orbit and initial on-orbit operations. These activities include: CXO/IUS separation, attitude and gyro bias estimation with earth sensor and sun sensor, attitude control and disturbance torque estimation for delta-v burns, momentum build-up due to gravity gradient and solar pressure, momentum unloading with thrusters, attitude initialization with star measurements, gyro alignment calibration, maneuvering and transition to normal pointing, and PCAD pointing and stability performance.

INTRODUCTION

The Chandra X-ray Observatory (CXO) is the third of the four NASA great observatories. Its predecessors include the Hubble Space Telescope and the Compton Gamma Ray Observatory. Chandra was formerly known as AXAF, the Advanced X-ray Astrophysicas Facility, and was renamed in December 1998 to honor Subrahmanyan Chandrasekhar, the late Indian-American Nobel laureate.

The CXO is a space astronomy mission for the observation of celestrial object radiating at x-ray wavelengths between 1.15 angstroms and 115.7 angstroms (~ 0.1 to 10 keV energy range). The CXO was designed and built by TRW with team members Ball and Kodak. The program is sponsored by NASA Marshall Space Flight Center.

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An isometric drawing of the CXO design is shown in Figure 1 (Reference [1]). CXO is composed of four elements: the spacecraft system, the telescope system, the science instrument module, and the science instruments. The flight sheet of each element can be found in the Appendix. The spacecraft system constitutes the core vehicle and houses the avionics and power generation and distribution functions. The telescope system provides the high resolution mirror assembly (HRMA) and the optical bench assembly. The science instrument module (SIM) is placed at the aft end of the telescope. In addition to support for the two focal plane science instruments, the SIM provides the mechanism for interchanging the instruments and adjusting their position at the focal plane of the HRMA. There are two objective transmission gratings mounted at the aft end of the HRMA.

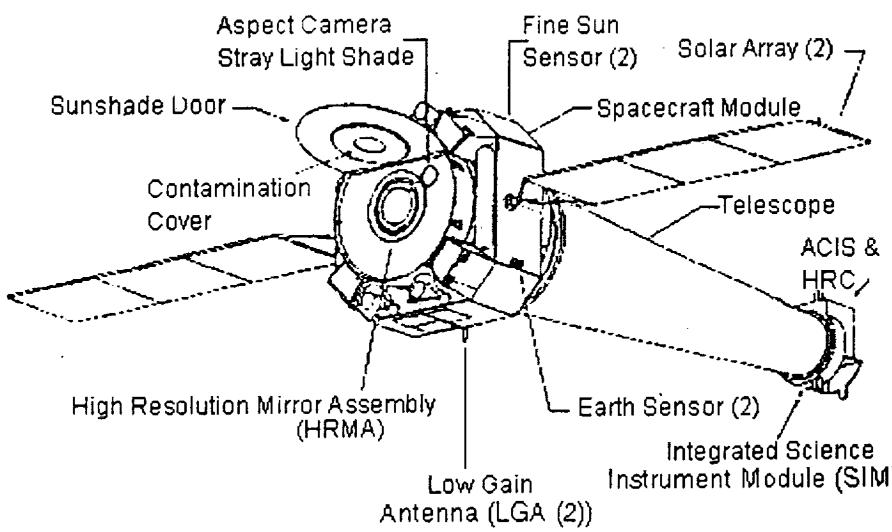

Figure 1. The Chandra X-ray Observatory

POINTING CONTROL AND ASPECT DETERMINATION SUBSYSTEM

The Pointing Control and Aspect determination (PCAD) subsystem points the CXO at desired science targets, slews it to new targets, supplies data and algorithms for post-facto image reconstruction, and provides safe modes in response to detected failures. PCAD also performs the attitude control and determination functions during both powered flight and coast phases of the transfer orbit.

Subsystem Configuration

The PCAD hardware configuration is shown in Figure 2. The algorithms for the normal operational modes are implemented in the on-board computer (OBC). Attitude control during safemode contingency operations is performed by the Control Processing Electronics (CPE) of the Control Electronics Assembly (CEA). The PCAD equipment list is presented in Table 1.

Table 1. PCAD Equipment List

EQUIPMENT	TOTAL WEIGHT (LB)	TOTAL POWER (W)	QUANTITY	SOURCE	HERITAGE
Inertial Reference Unit (IRU)	28.8	28.5	2	Kearfott	Classified
Aspect Camera Assembly (ACA)	68.1	14.1	1	BASD	CT-601
Fiducial Light Assembly (FLA)	1.3	0.1	14	TRW	New
Fiducial Light Controller Assembly (FLCA)	6.3	4.8	1	TRW	New
Fine Sun Sensor Assembly (FSSA)	8.8	2.2	2	Adcole	TRMM
Coarse Sun Sensor Assembly (CSSA)	0.2	0	4	TRW	GRO
Reaction Wheel Assembly (RWA)	116.4	130.6	6	Teldix	GOES
Wheel Drive Assembly (WDA)	23.6	98.4	1	TRW	IRAD
Control Electronics Assembly (CEA)	16.8	19.6	1	TRW	IRAD
Drive Electronics Assembly (DEA)	13.8	14.5	1	TRW	IRAD
Solar Array Drive Assembly (SADA)	34.0	42.6	2	TRW	WCP
Earth Sensor Assembly (ESA)	11.3	7.0	2	Ithaco	New
Reaction Wheel Isolator Assembly (RWIA)	24.0	0	6	TRW	New
Total	353.4				

The aspect camera and two inertial reference units (IRUs) are mounted on the HRMA support structure. Each IRU has two 2 degrees of freedom dry-tuned gyros. The IRUs are skewed such that any two gyros can provide three-axis rate measurements. The IRU supports two rate ranges. At low rate it provides a resolution of 0.02 arcsec/pulse; and at high rate it supports a maximum rate of 4 deg/sec. The aspect camera has two (primary and redundant) 1024x1024 pixels CCD detectors and 1.4°x1.4° field of view. The IRU with star updates from the aspect camera provides the primary attitude reference.

Six reaction wheels, arranged in a pyramidal configuration, provide torquing and momentum storage. Each wheel is mounted on a reaction wheel isolator assembly (RWIA) to reduce the transmission of RW disturbances to the telescope and science instruments. A brief description of the RWIA is presented in Reference [2]. Each wheel is capable of generating 20 in-oz of torque and storing 50 ft-lb-sec of momentum. Secular momentum unloading is accomplished using thrusters. Four array mounted coarse sun sensors with overlapping field of views provide full sky coverage. Fine sun sensor assembly provides more accurate sun position data and it also performs the bright object detection function (determination of improper sun attitudes). Earth sensor and fine sun sensor provide the ground with the necessary telemetry required for ground attitude determination during transfer orbits.

Subsystem Modes

PCAD provides 6 normal modes and 3 safe modes for various phases of the CXO mission. The normal modes implemented in the OBC, support all planned operations in both transfer orbit and on-orbit phases. The safe modes, implemented in the CPE, provide contingency operation when an on-board anomaly is detected. All PCAD operational modes are summarized in Table 2. Figure 3 depicts the PCAD mode transition for normal operations.

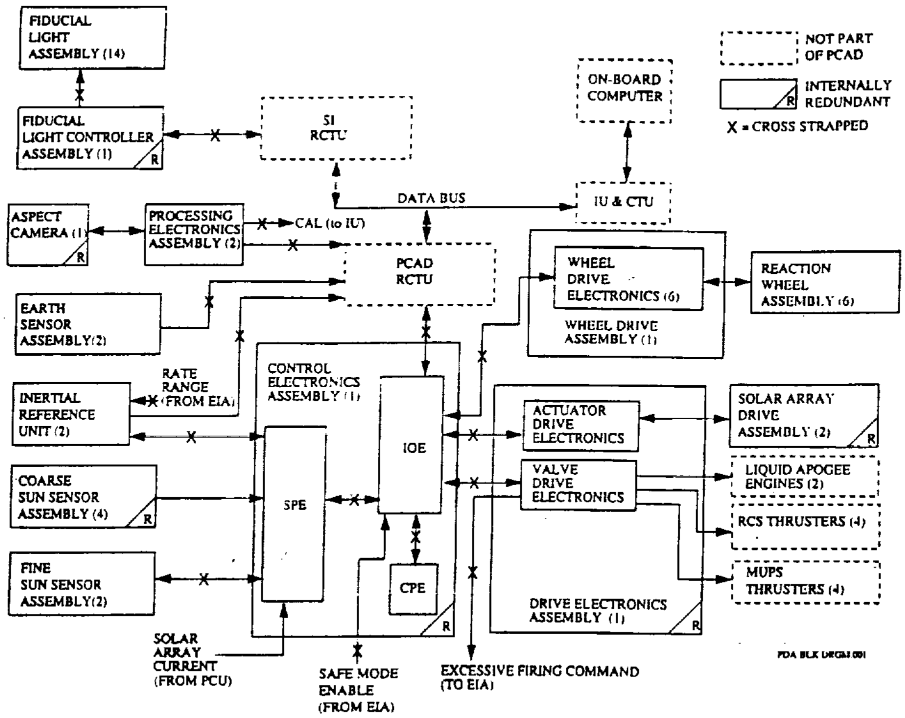

Figure 2. PCAD Hardware Configuration

Table 2. Summary of PCAD Operational Modes

Mode	Sensors/Actuators	Processor	Function
Standby (SBM)	IRU, FSSA, CSSA	OBC	• Process sensor data • No OBC command to actuators
Normal Pointing (NPM)	IRU, ACA, RWA, MUPS, FLA, FLCA	OBC	• Points to science target • Provide star and fiducial pixel data for posto-facto image reconstruction • Provide dither function • Acquire guide stars
Normal Maneuver (NMM)	IRU, RWA, SADA, MUPS	OBC	• Slew to new science target • Slew for ESA data collection
Normal Sun (NSM)	IRU, CSSA, FSSA, SADA, RWA, MUPS, RCS	OBC	• Acquire sun to solar arrays • Position solar arrays to –Z • Point –Z to sun • Hold attitude during eclipse • Rotate about sun line
Powered Flight (PFM)	IRU, RCS, LAE	OBC	• ΔV
RCS Maneuver (RMM)	IRU, RCS	OBC	• Slew to ΔV attitude
Safe Sun (SSM)	IRU, CSSA, SADA, FSSA, RWA, MUPS	CPE	• Acquire sun to solar arrays • Position solar arrays to –Z • Point –Z to sun • Hold attitude during eclipse • Rotate about sun line
RCS Safe Sun (RSM)	IRU, CSSA, SADA, FSSA, RCS	CPE	Same as above
Derived Rate Safe Sun (DSM)	IRU (1 gyro), CSSA, SADA, FSSA, RWA, MUPS	CPE	• Acquire sun to solar arrays • Position solar arrays to –Z • Point –Z to sun • Hold attitude during eclipse

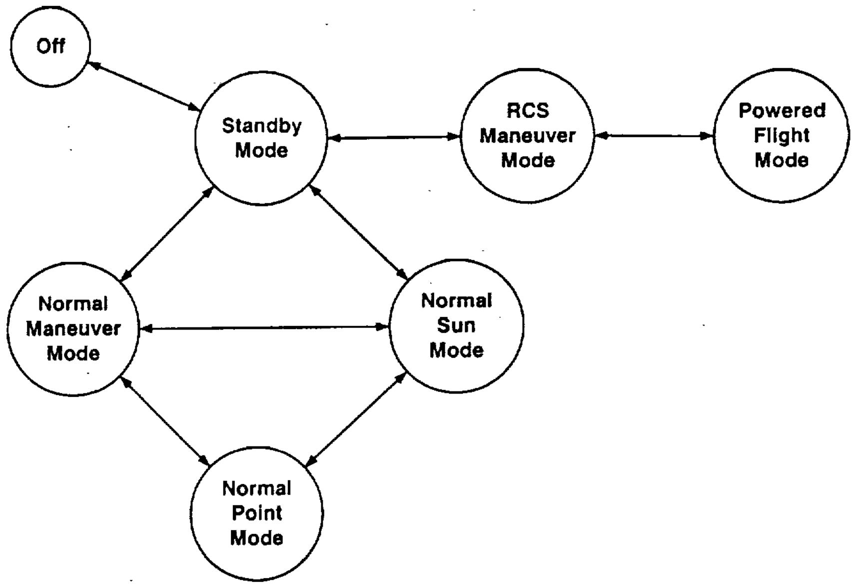

Figure 3. PCAD Normal Mode Transitions

Operational Constraints

Although there are many sun exclusion constraints for the observatory, the constraints can be generalized to the following:

- Keep the sun within +/-20° roll of a nominal roll attitude. (Nominal roll is defined as orientations for which the center of the sun is on the –Z half of the XZ plane). This constraint is determined primarily by the geometry of sun shades which are used to shield science instruments.
- Maintain sun shade door shadowing of the High Resolution Mirror Assembly (HRMA). For nominal roll orientations, this corresponds to not allowing the sun to get within 45° of the +X axis.

Key PCAD Performance Requirements

Key system level performance requirements and their allocations to PCAD is summarized in Table 3.

Table 3. Key PCAD Requirement

Requirements	System Level Requirements	PCAD Allocation
Absolute LOS Pointing	Within a radius of 30 arcsec 99% of the time	4 arcsec (1σ) per axis
Pointing Stability	Less than 0.25 arcsec (rms) half-cone angle 95% of all 10 second periods	Less than 0.12 arcsec (rms) per axis 95% of all 10 second period
Maneuver Time	Maneuver 90 deg in 45 minutes with no wheel failure	Maneuver 90 deg in 45 minutes with no wheel failure

TRANSFER ORBIT OPERATIONS

PCAD was activated 13.5 minutes prior to separation from IUS. One minute after separation from IUS, PCAD entered normal sun mode to damp out separation rates and maintain solar arrays at a sun pointed attitude. PCAD stayed in the normal sun mode for most of the transfer orbit except for earth viewing maneuvers and Delta-V burns. A depiction of the Chandra transfer orbit history is presented in Figure 4.

Significant Events and Timeline

Date	Event
23 July 04:31	Liftoff of STS 93
23 July 11:47	Chandra/IUS Deploy from Space Shuttle (268 km x 295 km)
23 July 12:54	IUS Burns Complete (330 km x 72,000 km)
23 July 13:49	Separation of Chandra from IUS
25 July 01:15	IPS 1 (1190 km x 72,000 km)
26 July 01:52	IPS 2 (3464 km x 72,000 km)
31 July 22:51	IPS 3 (3480 km x 139,000 km)
4 August 16:35	IPS 4 (5650 km x 139,000km)
7 August 05:43	IPS 5 (10,000 km x 139,000km)
12 August 17:59	Sun Shade Door Open
12 August 21:00	Fine Attitude Initialization Complete

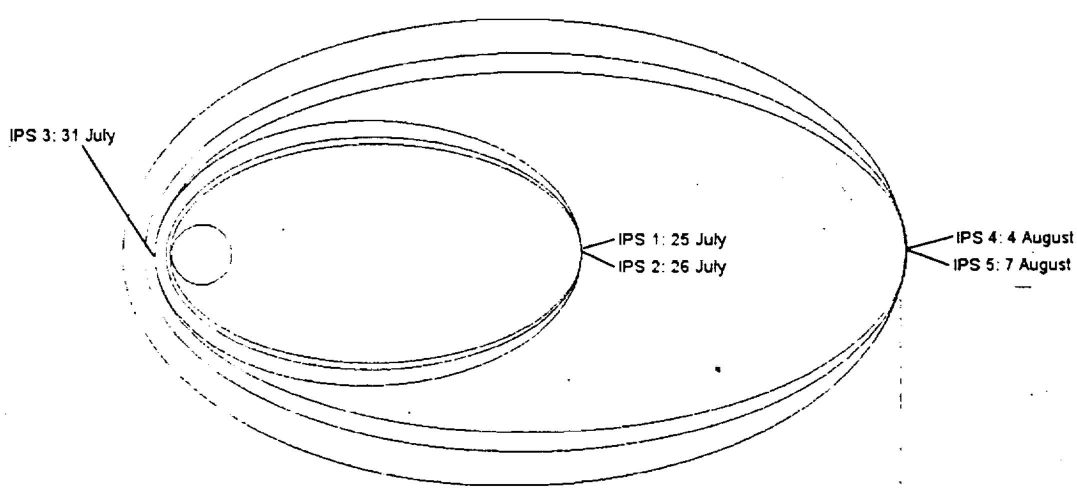

Figure 4. Chandra Transfer Orbit History

Orbital Data

Perigee altitude: 10,000 kilometers
Apogee altitude: 139,000 kilometers
Inclination: 28.5 degrees
Right Ascension of the Ascending node: 200 degrees
Argument of perigee: 270 degrees

Delta-V Burns

After deployment by the Space Shuttle Columbia on 23 July 1999 at 7:30 MET, a two stage Inertia Upper Stage (IUS manufactured by Boeing) was used to transfer the Chandra Observatory from the shuttle parking orbit (268 x 295 km) to an intermediate orbit of 330 x 72,000 km with a period of 24.3 hours. A series of 5 burns were then performed over the following 14 days using Chandra's integral propulsion system (IPS) to transfer the observatory to an orbit of approximately 10,000 x139,000 km and period of 63.5 hours. The burns were each performed at inertially fixed attitudes with the first two performed at apogee followed by one performed at perigee and two more performed at apogee.

After each burn, detailed analysis was conducted to assess the performance of the IPS and attitude control subsystem. The four liquid apogee engines (LAEs) on Chandra are grouped into sets of two diagonally opposed primary engines and two diagonally opposed redundant engines. Each engine produced approximately 106 lbs of thrust. During LAE burns, only the primary or redundant set of LAEs were used at one time. Attitude control was maintained using the four 25 pound thrusters of the reaction control system (RCS). After the third IPS burn , it was determined by analysis that there was a likely asymmetric degradation of the thrust produced by each of the primary LAEs. This determination was made using several calculations:

- The net delta-V vector for each burn was determined by the Jet Propulsion Laboratory (JPL). These results indicated that slightly less than expected thrust was produced by the LAEs. The overall net thrust degradation for both engines at the conclusion of IPS burn 3 was estimated to be approximately 2%.
- Based on the RCS firings commanded during the burn and accounting for cg migration, an asymmetric thrust developed during the IPS 3 burn which amounted to a difference in thrust at the end of the burn of approximately 0.7% between the engines.

Although the exact cause of the degradation of LAE thrust was not ascertained, the future behavior of the primary engines was not certain. It was decided to use the redundant set of LAEs for the remaining burns. The subsequent burns were performed satisfactorily.

During the burns, the sun-orbit configuration at the date of the burns resulted in the sun position being in the XZ plane of the observatory and within 20° of the –Z axis. This sun position in the body frame resulted in the relatively accurate inertial attitude knowledge provided by the fine sun sensors translating to very accurate attitude knowledge predominately about roll and pitch during the burns. The less accurate inertial

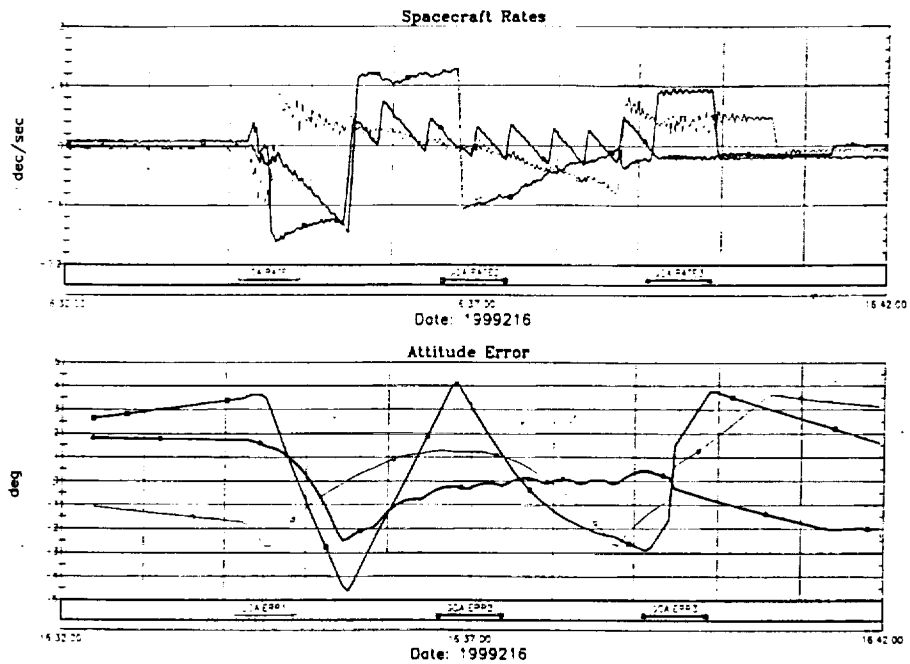

Figure 5. Rate and Attitude Error During IPS 4

attitude knowledge about the sun line provided by the earth sensors resulted in slightly less accurate attitude knowledge about the yaw axis during the burns.

The rate and attitude error history during IPS 4 is presented in Figure 5. The performance illustrated is typical of that observed during all IPS burns. Note that although the deadband behavior produces attitude errors greater than 1°, the overall averaged effective attitude error over the entire burn is less 1°. Indeed, based on the assessment of the delta-V vector after each burn provided by the JPL, the resultant true delta-V vector generated during each burn was within on the order of 1° of that desired. This was well below the tolerance needed for suitable attainment of the final orbit desired and indicated very good attitude control performance as well as very accurate onboard attitude knowledge during all burns.

Attitude and Gyro Bias Estimation

Attitude knowledge is maintained by propagation of spacecraft rates as measured by Kearfott SKIRU V gyroscopes. During transfer orbit, updates to the onboard estimated attitude and gyro bias were made periodically by the ground. The onboard attitude was initially updated based on the attitude reported by the IUS at time of separation. Throughout the duration of transfer orbit, the attitude and gyro bias updates were calculated by the ground using data from the fine sun sensors and earth sensors. Since the sun shade door was closed during transfer orbit, aspect camera information was not available for updating attitude and gyro bias knowledge.

Using fine sun sensor data, the inertial attitude knowledge of the observatory about axes orthogonal to the sun line was determinable to within approximately 0.01°. However, the sun sensors are in general unable to provide accurate inertial attitude knowledge about the direction of the sun line. Attitude knowledge about the sun line was updated by determination of earth nadir vector locations calculated using measurements made with earth sensors during earth scan maneuvers. These maneuvers were performed on both the ascending and descending legs of each orbit during transfer orbit between optimal altitudes of approximately 15,000 km and 60,000 km. Based on the inherent accuracy of the earth sensors combined with the degree of precision recoverable by calibration, the observatory attitude knowledge about the sun line, as determined by the earth sensor measurements, was accurate to within approximately 0.5°.

The earth sensors were manufactured by Ithaco Corporation (formerly Space Sciences) and calibrated by TRW. The instantaneous field of view of each earth sensor subtends an arc of approximately 1.5°. While scanning, this field of view prescribes a cone which has an angle between the symmetric axis and the cone surface of approximately 45°. Each scan cone was electronically blanked over an arc of approximately 200°. The earth sensors were oriented on the observatory such that the center of the remaining unblanked arc is centered near the +Z axis of the observatory. The earth viewing attitudes were constructed so that the earth would pass across the scan cones while the observatory maintained sun exclusion constraints.

ON-ORBIT ACTIVATION AND CHECKOUT

Fine Attitude Initialization

For the initialization of attitude knowledge after sun shade door opening, the attitude uncertainty resulting from the accuracy of the Fine Sun Sensor and Earth sensor prohibited the identification of the first star acquisition using the on-board point mode software. Ground software was developed which utilized Aspect Camera telemetry of acquired star positions to generate a fine attitude update, which could be uploaded to the spacecraft. Due to concerns with the first use of the nominal fine attitude initialization ground software and the initial Aspect Camera star acquisition, a backup manual attitude determination ground software capability which relied on visual pattern recognition was developed based upon a similar system developed for the NASA Spacelab Astro-2 mission. The backup fine attitude determination system was successfully utilized to remove the initial fine attitude error of approximately 7 degrees about the sun line. Figure 6 shows the pattern recognition display after the successful attitude initialization, the rectangles indicate the ACA real-time field of view position telemetry for the eight successfully acquired stars.

Hardware failures or ground commanding problems leading to safemode or failure of the autonomous on-board acquisition of pointing objectives will require subsequent fine attitude initialization procedures. The nominal ground software attitude initialization software was successfully utilized to provide an attitude update to the CXO after a safemode recovery on 19 August 1999.

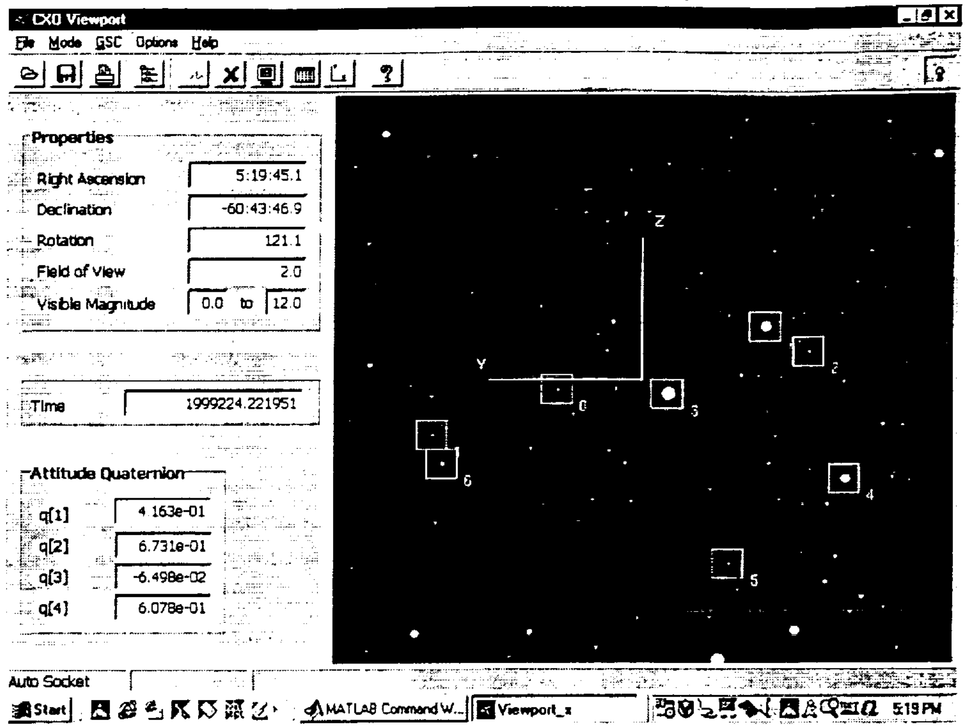

Figure 6. Star Pattern Matching for Attitude Initialization

Pointing and Stability Performance

Because the photon flux from most x-ray sources arrives at relatively low rates, long exposure times ranging from several minutes to hours will be required for most observations. Photon arrivals are time-tagged and with the aid of time-tagged attitude and fiducial light data from the IRU and aspect camera respectively, the image is reconstructed on the ground. Rather than requiring the observatory to maintain precision target pointing over long observation intervals, CXO has a relatively relaxed absolute pointing requirement but a very tight pointing stability requirement. These requirements apply to Normal Pointing Mode, including during dither motion, but excluding the transition time after a maneuver. These requirements also apply for 15 minutes after completion of momentum unloading.

PCAD Absolute Pointing Performance. The CXO is required to point the telescope line-of-sight (LOS) to within a radius of 30 arcsec of the commanded direction 99% of the time. PCAD's share of the error budget is 4 arcsec (1σ, per axis). Figure 7 shows pitch and yaw pointing error in a 4 hour period after a maneuver. Dither mode with dither magnitude of 8 arcsec is active during this period. The pointing errors are less than 0.2 arcsec for most of the time.

PCAD Pointing Stability Performance. The top level relative LOS stability is required to be less than 0.25 arcsec (rms) half-cone angle with respect to the commanded direction over 95% of all 10 second periods. The error budget allocation to PCAD is 0.12 arcsec (rms) per axis for 95% of all 10 second periods. The PCAD pointing stability for the same 4 hour period is presented in Figure 8. The plots represent rms values of pointing errors, computed in a 10 second moving window. The plots show pointing stability is less than 0.05 arcsec with the most of the errors below 0.03 arcsec.

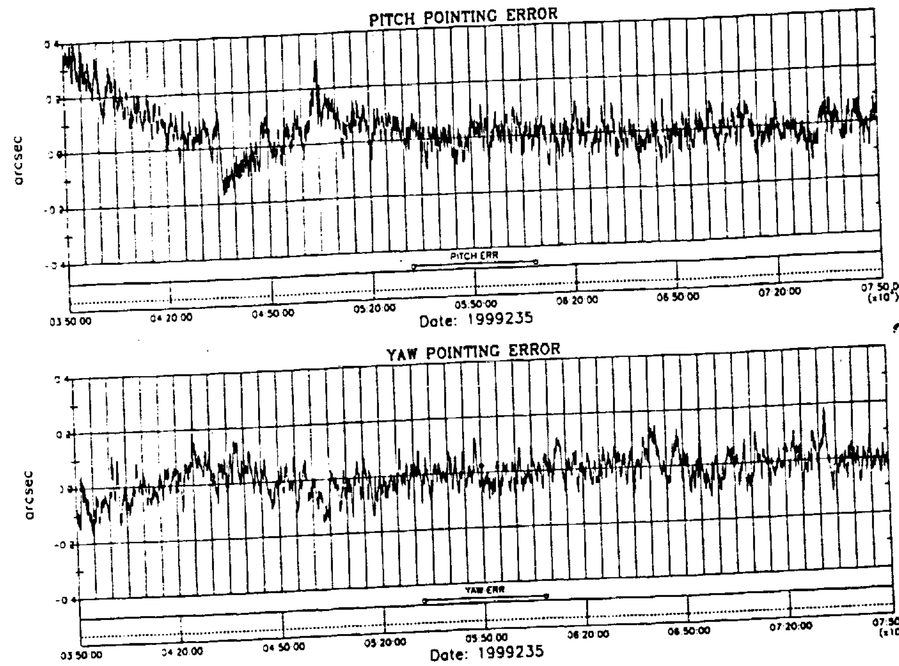

Figure 7. Pitch and Yaw Pointing Error

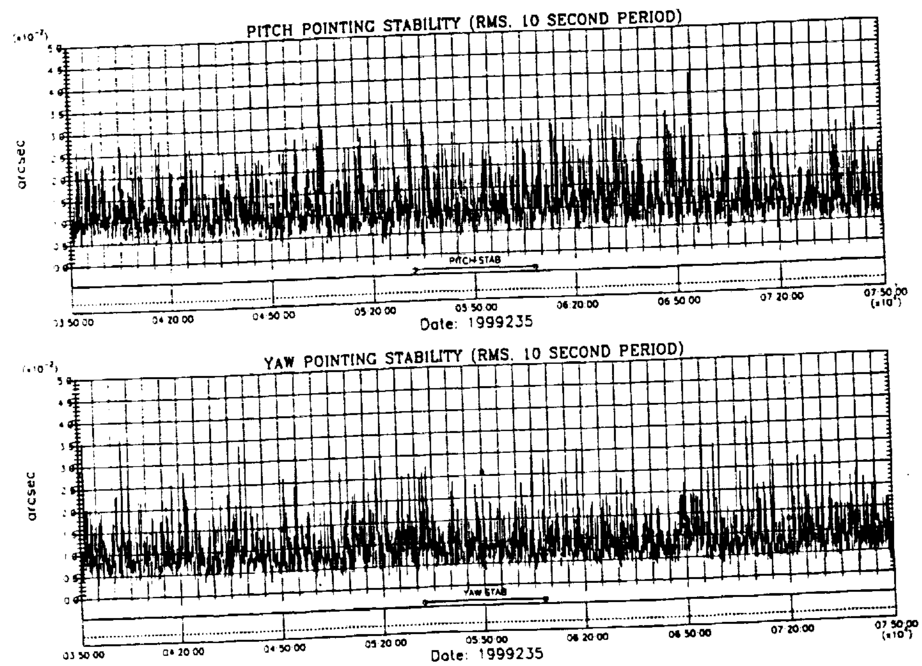

Figure 8. Pitch and Yaw Pointing Stability

Momentum Unloading

Reaction wheel momentum accumulated due to disturbance torques is dumped using Momentum Unloading Propulsion System (MUPS) thrusters. Fed by a blowdown system, the nominal beginning of life thrust is 0.26 lbf. A maximum of 3 thrusters are used at any given time, with each thruster individually pulsewidth modulated so as to align the unloading torque as closely as possible opposite the direction of momentum. The time to commence unloading and the desired final momentum state are commanded by the ground and the selection and firing of thrusters are performed on board. For minimum disruption to science data gathering, the unloading can be performed at the beginning of a long maneuver. If the accumulated momentum exceeds a pre-set value, the unloading function is performed autonomously.

Prior to launch, the largest secular disturbance torque was predicted to be solar. The actual solar torque, however, is only about one-half that predicted. Instead, cyclical gravity gradient torque tends to dominate the timing of momentum unloads. Thus far in the mission, unloading performance has been nominal, with the unloading control laws selecting appropriate on-times and thrusters producing expected torque. PCAD's allocation for pointing (4 arc-sec) and stability (0.12 arc-sec) apply 15 minutes after completion of momentum unloading. However, the above requirements are actually met within 2 minutes following unloading, with pointing is maintained within 0.4 arc-sec starting 3 minutes after unloading ends.

Slew Maneuvers

The observatory maneuvers by direct eigen slews from a given commanded attitude to the next target attitude. The trajectory of eigen slew angle, angular rate and acceleration about the eigen axis is generated consistent with the following maneuver parameters:

Jerk Time 60 seconds (time over which the acceleration increases to a maximum)
Maximum Angular Acceleration 1.25e-4 deg/sec^2
Maximum Angular Rate 0.075 deg/sec

The resulting maneuver times over all maneuver angles is depicted in Figure 9. Throughout all Chandra flight operations, maneuver performance has been nominal.

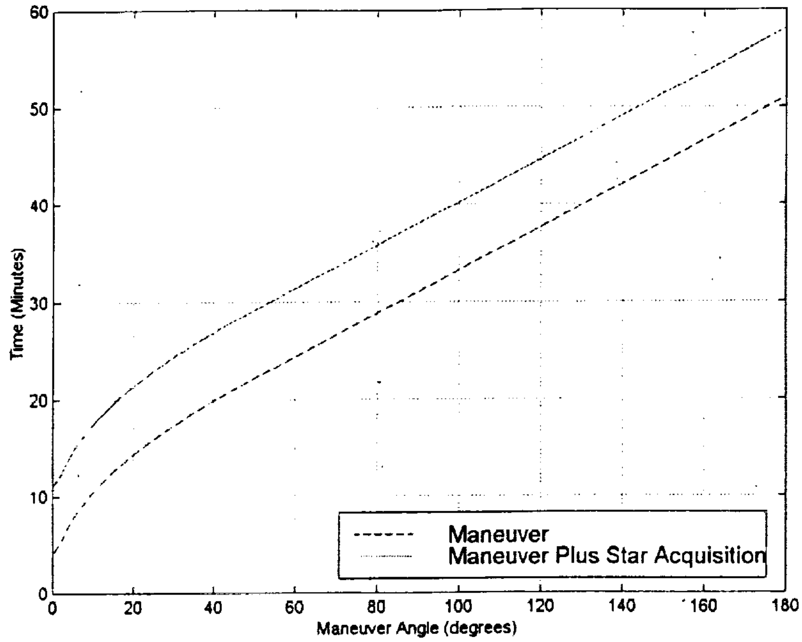

Figure 9. Maneuver Time versus Maneuver Angle

Spacecraft Rate Determination and Gyro Scale Factor and Misalignment Compensation

The estimation of the gyro axis rates is performed by the flight software each sampling period using a back difference of the gyro counts along with nominal gyro scale factors. The calculation of the estimated body axis rates using these gyro axis rates is then performed by the flight software using the following calculation:

$$\omega_{body} = [\ I+M\ ]G\ \omega_{gyro}$$

where I is the identity matrix, M is a misalignment matrix and G is the pseudoinverse matrix which maps gyro rates in each of the 4 gyro axis in use to the 3 body axis. The pseudoinverse matrix includes known misalignments of the IRUs as measured in calibration on the ground.

In order to account for further uncompensated gyro misalignment and scale factor differences from those already accounted for, the flight software uses the misalignment matrix M to modify the calculation of estimated body axis rates. Determination of this matrix was made during a calibration performed soon after sun shade door opening. The calibration consisted of a series of large maneuvers for which each eigenaxis was near the observatory roll, pitch or yaw axis and for which sun exclusion constraints were maintained. Before and after each maneuver, a full field search of the aspect camera was commanded and stars were acquire. Using the ground software, the precise attitude of the observatory at each star acquisition was then determined. By knowing the precise attitude before and after each maneuver as well as the time history of the gyro counts during each maneuver, the best fit estimation of the misalignment matrix M was made.

Based upon on orbit performance results, the calibration was very successful. The resulting attitude knowledge errors, even after very large maneuvers, have only been on the order of tens of arc seconds.

Star Acquisition and Kalman Filter Performance

Since the sun shade door was opened, the spacecraft attitude and gyro bias estimation updates have subsequently been determined by a Kalman filter using inertial attitude data provided by the aspect camera. The aspect camera has the capability to track eight images simultaneously. For typical science operations, five stars and three fiducial lights are tracked by the aspect camera. The fiducial lights are located on the translational table (SIM Table) to which the science instruments are attached within the science module at the –X end of the observatory. The fiducial light images are reflected into the aspect camera by a series of mirrors and used for a posteriori reconstruction of the true position of the science images relative to the inertial reference of the tracked stars. Star catalogs are uploaded for each observation and logic in the flight software is used to command the aspect camera to acquire stars. After stars are acquired by the aspect camera, the position and magnitude information of the stars which were found is evaluted by the flight software logic. The data is screened to ensure that only stars which were correctly acquired by the aspect camera are actually used. A Kalman Filter implemented in flight software uses the aspect camera star measurement data to determine updates to the onboard estimates of attitude and gyro bias. Attitude and bias updates are performed by the flight software each time new data becomes available from the aspect camera. The period of updates is driven by the integration period selected for the aspect camera, but typically is between one and five seconds.

Inertial Reference Unit Performance

Both IRUs are powered in high rate range prior to IUS separation, with near zero null measurement vectors demonstrating proper operation by each unit. Science operation uses IRU-1 in low rate range. IRU-2 is left off, except when powered on by autonomous safing action. IRU acceleration insensitive drift rate (AIDR) performance specifications include:

- 7.2 arc-sec/sec absolute
- 1 arc-sec/sec life time variation
- 0.1 arc-sec/month variation

All operations are within the above specifications. Current draw has increased about 5 mA for both IRU-1 gyros. In addition, gyro number 2 experiences periodic jogs associated with lubricant redistribution. A momentum peak 22 mA above initial current was observed on 10 November and numerous self correcting AIDR changes of 0.05 arc-sec/sec occurred in December.

Safe Mode Performance

For safing configuration, the observatory has a backup string of sensors hardware, Communication, Command and Data Management (CCDM) hardware and On Board Computer (OBC). In safemode, there is also a dedicated processor called the Control Processing Electronics (CPE) used for attitude control. A series of monitors implemented in flight software continuously evaluate spacecraft performance and will command a failover to the redundant set of hardware as well as attitude control by the CPE in the event anomalous behavior is detected.

There have been two transitions to safe mode in the Chandra X-Ray observatory. Both have been related to ground processing errors and did not involve hardware failures.

The first transition to safemode occurred on 17 August and resulted from a timing problem in the sequencing of maneuver commands. Each maneuver sequence has a series of commands associated with it, namely updating the target quaternion and commanding the start of the maneuver. If the maneuver is to be followed by a star acquisition, the star catalog is also updated at the beginning of the maneuver and a flag is set to enable the autonomous transition from NMM to NPM at the end of the maneuver. This first safemode transition occurred on the occasion of the first ever execution of a segmented maneuver by the ground software. The maneuver was segmented for sun exclusion purposes and was to involve a maneuver to an intermediate attitude after which stars were not to be acquired, followed immediately by a second maneuver to the desired target attitude after which stars were to be acquired. Not enough time was allocated by the ground system after the completion of the first maneuver sequence prior to the beginning of the second manuever. In this case, the command to enable autonomous transition from NMM to NPM at the end of the second maneuver was incorrectly issued just seconds prior to the end of the first maneuver. At the time the target quaternion was updated for the second maneuver, the observatory was already in NPM. This updating of the target quaternion while in NPM had the effect of creating a very large attitude error resulting in the tripping of the Attitude Error Rate Error Monitor and subsequent transition to safemode. The observatory was successfully recovered from safemode in 48 hours which included a thorough reevaluation and retesting of existing safemode recovery procedures.

The second transition to safemode occurred on 26 September and resulted from a incorrect issuance of commands during a recovery from a Bright Star Hold event. Bright Star Hold occurs when the stars which were to be acquired for an observation cannot be found. In this case, the camera is commanded to search for the brightest stars it can find and then the flight software "holds" on these stars until recovery by the ground. As a result of a very slightly incorrect star catalog computed by the ground system, an attitude knowledge error of approximately 400 arc seconds was systematically introduced into the flight software during an observation. At the next observation, the desired stars were not acquired as a result of this attitude error and the observatory went to Bright Star Hold. In the process of recovery by the ground during the next DSN contact with the observatory, the process of fine attitude initialization was performed to correct the attitude knowledge error. However, the onboard attitude was inadvertently updated while in NPM. While not resulting in enough attitude error to trip Attitude Error Rate Error

Monitor, there was enough of an attitude error for the Kalman Filter logic to conclude that the bright stars that it was currently tracking were not valid. In this case, the observatory transitioned to NSM as a safing action. As part of this transition, the SIM table was moved to a safe location. The angular momentum discrepancy associated with moving the SIM table would ordinarily by enough to trip the Spacecraft Momentum Monitor, and therefore this monitor is disabled during all SIM table moves during normal science operations. However, this disabling of the Spacecraft Momentum Monitor was not originally part of the onboard sequence to move the SIM table during transition to NSM as a safing action. Therefore, in this case, the Spacecraft Momentum Monitor tripped and a transition to safemode resulted. The observatory was successfully recovered from safemode in 12 hours.

IMPROVEMENTS

Enhanced Dither

The Chandra X-ray Observatory currently has the capability to dither during observations. The originally intended purposes of the dither capability was to ensure that X-ray sources do not steadily irradiate individual pores of the Micro Channel Plate (MCP) in the High Resolution Camera (HRC) during observations. Steady irradiation of the same pores while HRC voltage is ramped up could cause permanent degradation of the HRC instrument. In addition to this originally intended purpose of dither, the dither capability is now used for all observations (ACIS and HRC) and is considered particularly important for ACIS bias calibrations which occur regularly.

Originally, the Chandra flight software did not dither the observatory and would not allow HRC voltage to ramp up until after stars had been acquired at the observation attitude. Further, once a maneuver began, dither stopped and HRC voltage was ramped down. In order to enhance science efficiency and reduce mission planning complexity, the dither capability has been changed to superimpose a dither pattern onto the commanded attitude while maneuvering as well as while pointing "steadily" at a target. This capability now allows ACIS and HRC to perform science at all times, including during maneuvers, as well as allow ACIS to perform bias calculations at any time. The typical dither profile is a Lissajous Pattern with maximum amplitude of 20 arc seconds.

Reaction Wheel Configuration Study

The PCAD baseline design operates all six reaction wheels. When the OBC detects a wheel failure (delta wheel speed inconsistent with torque command), the failed wheel is powered off and the CXO attitude is maintained with the remaining five wheels. The ground reconfigures PCAD to a four wheel operation by powering off the opposite wheel in the pyramidal configuration and loading in the appropriate four wheel distribution matrices in the OBC.

A study has been initiated to study the benefit of changing the baseline to a four wheel configuration with two wheels as spares. The study will consider the actual wheel speeds and disturbance data that CXO experienced in orbit along with vendor experience with this wheel design on other platforms.

CONCLUSION

The Chandra X-ray observatory was successfully activated and configured for normal operation during transfer orbit with no significant difficulties. The observatory has since performed its mission in all respects in an exemplary manner, equaling or surpassing all specifications and expectations for a successful mission to date.

ACKNOWLEDGEMENT

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APPENDIX

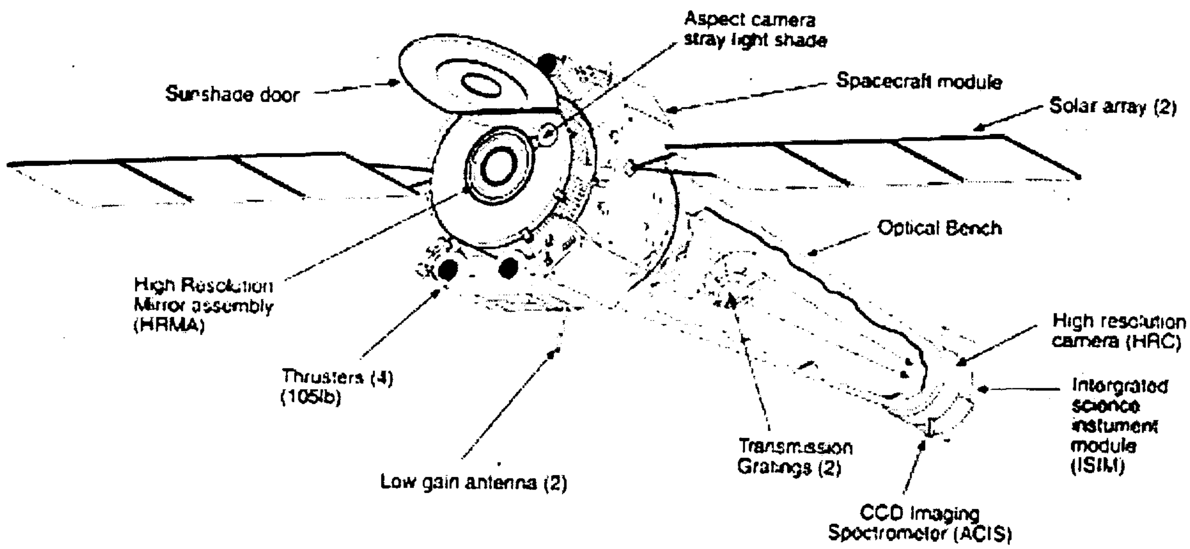
NASA'S ADVANCED X-RAY ASTROPHYSICS FACILITY (AXAF)

Overall Specifications

Size:	45.3 ft x 64.0 ft (solar arrays depolyed)
Weight:	10,560 pounds
Orbit:	6,200 x 86,000 miles 28.5 deg. inclination
Ascending node:	200 degrees
Argument of perigee:	270 degrees
Life:	minimum 5 years

Spacecraft Specifications

Power:	two 3-panel silicon solar arrays (2350W) three 40 amp-hour nickel hydrogen batteries
Antennas:	two low-gain, conical log spiral antennas
Frequencies:	transmit 2250 MHz, receive 2071.8 MHz
Command Link:	2 kilobits per second (kbps)
Data Recording:	solid state recorder; 1.8 gigabits (16.8 hours) recording capability
Downlink options:	selectable rates from 32 to 1024 kbps
Downlink Operations:	downloaded typically every 8 hours
Contigency Mode:	32kbps
Saling:	autonomous operation



Telescope System

High Resolution Mirror Assembly:	4 sets of nested, grazed incidence mirror pairs
Length:	each 83.3 cm long
Weight:	2104 pounds
Focal Length:	10 meters
Outer diameter:	1.2 meters
Field of view:	1.0 degree diameter
Ang. resolution:	0.5 arc sec
Altitude Control:	6 reaction wheel control 2 inertial reference units
Aspect Camera:	1.40deg x 1.40deg field of view
Poining Stability:	0.25 arc-sec (RMS) radius over 95% of all 10 second periods
Pointing Accuracy:	30 arc-sec 99% of viewing time
Remarks:	Mirrors have an effective area of 400 sq. cm. @ 1 keV; 330 A iridium coating

Science Instruments

AXAF Charged Coupled Imaging Spectrometer (ACIS):	Ten CCD chips in 2 arrays provide imaging and spectroscopy; over an energy range 0.2 - 10 keV; sensitivity: 4×10^{-15} ergs-cm^{-2} sec^{-1} in 10^5 s
High Resolution Camera (HRC):	Uses large field-of-view micro-channel plates to makes X-ray images: ang. resolution < 0.5 arc-sec over field-of-view 31x31 arc-min; time resolution: 16 micro-sec sensitivity: 4×10^{-15} ergs-cm^{-2} sec^{-1} in 10^5 s
High Energy Transmission Grating (HETG):	To be inserted into focused X-ray beam; provides spectral resolution of 60-1000 over energy range 0.4 - 10 keV
Low Energy Transmission Grating (LETG):	To be inserted into focused X-ray beam; provides spectral resolution of 40-2000 over the energy range 0.09 - 3 keV

The AXAF program is managed by the Marshall Center for the Office of Space Science, NASA Headquarters. TRW is the prime contractor and has assembled and tested the observatory for NASA.