Spacecraft System Design For an Advanced X-Ray Monitor (AXM) Mission

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Abstract. This paper describes a system concept for a NASA Small Explorer Mission to develop an all-sky-viewing Advanced X-ray Monitor (AXM). The spacecraft is configured to be launched from a Pegasus XL vehicle. AXM is designed to provide unprecedented sensitivity to cosmic explosions seen in X-rays. These include the ejections of relativistic jets by black holes in the Galaxy, and the fireballs of gamma ray bursts that originate in distant Galaxies. Such events are captured with 31 cameras mounted on the AXM spacecraft to continuously view 97% of the celestial sphere, excluding occultations by the Earth. The camera detectors are Gas Electron Multiplier (GEM) devices, developed at CERN and used with coded masks for X-ray astronomy. The pointing orientations for the cameras presented a challenge to provide 4p steradian viewing, while accommodating spacecraft subsystems and deployable solar arrays for power. The mounting orientation resembles the 32 faces and vertices of a soccer ball, with one camera eliminated to avoid the saturating effect of solar X-rays. The objective of continuous, all-sky viewing is accomplished with a three-axis stabilized attitude control subsystem with the solar panels pointed close to the Sun. The AXM mission is designed for launch into a ~600-km altitude, circular, equatorial orbit. An approximately 1 degree spacecraft maneuver once per day will maintain the solar panels aligned with the Sun. The spacecraft is powered by solar arrays that deploy after launch and are then fixed for the mission duration. Within limitations, the AXM spacecraft has been designed to gracefully tolerate many kinds of anomalies.

Science Overview

X-ray astronomy is a primary window to the portion of the Universe characterized by high temperatures and explosive behavior. As one progresses from the visible band to the extreme UV, view of the cosmos beyond the local region in the Galaxy is increasingly attenuated by interstellar absorption. However, as the 1 keV and the X-ray band is approached, the long-range view becomes clear again. And since the spectra of X-ray sources generally yield fewer photons at higher energy, it is no wonder that X-ray astronomy missions historically favor the energy range of 2-10 keV.

In the Galaxy, the X-ray sources with the highest luminosity are black holes and neutron stars that are accreting material from companions in binary systems. Some X-ray binary systems are further distinguished by the capacity to produce violent mass ejections at relativistic speeds, as seen in bipolar radio jets. Other types of more common, yet less luminous Galactic X-ray sources include accreting white dwarfs ("cataclysmic variables") and stars with hot coronae, which can be far more luminous in X-rays than the active Sun.

Beyond the Milky Way, the X-ray sky is dominated by super-massive black holes at the centers of other galaxies. These "active galactic nuclei" (AGN) include distant quasars, Seyfert galaxies, and "blazars," in which galaxy-size jets are directly viewed.

The X-ray sky is extremely variable. This variability ranges from <1 ms to days to years; intensity changes by factors up to ~ 10^{12} are seen in some cases. Space missions in the last decades developed productive science applications related to X-ray monitoring. Recently, X-ray source variability has been witnessed with unprecedented clarity during the four years of NASA's *Rossi X-ray Timing Explorer* (RXTE, launched 12/95). This mission includes a scanning All Sky Monitor (ASM) and pointed instruments that provide 1 μs time resolution. Additional insights have been gained from the Italian-Dutch *BeppoSAX* Mission (launched 5/96). Scientific advances from these observatories substantiate the perspective that high energy astrophysics often requires a joint consideration of temporal and spectral variability and a strong commitment to multifrequency observations.

Another historical advance is occurring in the form of X-ray imaging instruments. *Chandra* is a NASA Great Observatory Mission (launched 7/99) that provides 0.5 arcsec images and X-ray spectra with resolving power, R ~ 1000. *XMM-Newton* is an ESA Cornerstone Mission (launched 12/99), with modest spatial resolution (20 arcsec), but with five times the collecting area of *Chandra*. Both will provide fundamental advances in the science of quasars, the cosmic X-ray background, clusters of galaxies, accretion disks, and supernova remnants.

These large missions will investigate exceedingly fine details in a wide range of astrophysical systems, and yield exciting new discoveries. However, they are designed to focus on small fields of view for limited intervals of time, and they will not continue the groundbreaking work of discovery and comprehension related to unpredictable X-ray behavior achieved by the *Compton Gammay-ray Observatory*, *RXTE*, and other missions in the last few years.

The "Advanced X-ray Monitor" (AXM) mission will perform important observations that cannot be done by the large imaging missions. Recently launched X-ray missions, ground-based monitoring programs, and observatories of the future will be substantially more productive given the continuity and improvements of an advanced X-ray monitor.

AXM will generate self-contained science investigations and will further provide invaluable and rapid guidance to other programs for scheduling observations and for interpreting results. AXM has two primary mission goals:

1. To observe nearly the entire sky, continuously, so as to measure temporal and spectral properties of outbursts and flares which last from seconds to hours.

2. To monitor "persistent" X-ray sources with sufficient sensitivity to provide detailed light curves for many accreting compact objects in the Galaxy and extragalactic AGN.

Science Implementation

AXM Cameras

The choice of 31 cameras combines an aggressive approach to all-sky viewing with considerations of feasibility. Having more cameras would reduce the effect of the cosmic X-ray background, which reduces the detection threshold for cameras with wide FOV.

Only one instrumental approach is presently capable of satisfying the wide-ranging objectives of X-ray position and intensity measurements, i.e., coded-aperture cameras. The performance of coded-aperture cameras is amply demonstrated by several flight instruments, recently the *RXTE* ASM (Levine *et al*. 1996) and the *BeppoSAX* WFC (Jagger *et al*. 1997). The use of focusing optics, that have narrow FOVs, low effective areas, and spectral range, and single-pinhole designs were considered and rejected.

Each AXM camera comprises a coded mask which is an opaque sheet perforated by many holes, and a position-sensitive X-ray detector which is capable of recording the positions, energies and times of individual X-ray photons. The detector entrance window, a thin (~75 µm) Be foil, and the gas-fill of the detector (Xe-CO_2) set the sensitive energy range to 1.5-12 keV. The detector active area will be 15 cm by 15 cm. It is estimated that the window strongback will block about 10% of this so that 200 cm^2 will be useful. The coded mask will be 20 cm by 20 cm. The mask open fraction will be ~1/3 so that an effective area of ~70 cm^2 will be presented to sources near the center of the field of view (FOV). The azimuth-averaged camera FOV has a radius of 20 degrees (to half-maximum response).

The use of position-sensitive proportional counters has been baselined using recently developed technology (in high-energy physics), viz., gas electron multipliers (GEMs) and passive grid readout planes. This detector concept promises substantial advantages in cost, speed of construction, and reliability over more standard wire-based designs. Development of flight qualified GEM detectors will make available "smaller, faster, cheaper" detectors for future X-ray astronomy missions.

The AXM design comprises 31 cameras that view *continuously* 97% of 4p steradian of which Earth occults 33% at any given time. The region within 20 degrees of the sun is excluded. Thus 65% of the celestial sphere is viewed at any time with roughly uniform sensitivity because of the overlapping camera FOVs. An alternative plan to build fewer cameras and roll the spacecraft in phase with the orbit was rejected because of severe complications for operations and data analysis.

Performance calculations conservatively assume, for the proposed ~600 km equatorial orbit, that 5% of the time will not be available for observations due to high background. Every point on the sky (except those within 20 degrees of the sun) will thus be observed from 57% to 95% of the time, depending upon the celestial declination.

Detectors and Camera Electronics

The X-ray detectors for AXM are required to have a large sensitive area (15 by 15 cm), spatial resolution better than 1 mm in two dimensions, good quantum efficiency over the 1.5-12 keV energy range, and to survive launch and operate for years in the space environment. Note that the detectors used in the RXTE ASM would not satisfy these requirements.

Position-sensitive proportional counters have been used in many previous space-borne telescope and coded-aperture instruments for X-ray astronomy, including those in the Einstein Observatory, ROSAT, ASCA, BeppoSAX and HETE observatories. However, the procurement of position-sensitive detectors that will satisfy the requirements for AXM is not routine; their construction still requires significant time, expertise, and the product often has problems. Therefore the use of counters have been baselined that incorporate recent technological developments in high-energy physics that promise significant improvements in simplicity and reliability which would make feasible the production of a large number of detectors in a timely fashion. If successful, this new technology would be highly advantageous to future x-ray astronomy missions. However, if early prototyping reveals unexpected and insurmountable hurdles, other more standard anode-based systems would be explored in an effort to meet mission objectives.

In the last few years, workers at CERN have developed the Gas Electron Multiplier (GEM) for use in gas-based particle and X-ray detectors (see Bachmann et al. 1999 and references therein). Early position-sensing detectors utilized a microstrip readout consisting of multiple plated conductive strips on an insulating substrate like a printed circuit board. Attempts to apply high voltages between the conductors of a microstrip readout, and to thereby build a device that would provide both the necessary charge multiplication and the readout electrodes have been plagued by high-voltage breakdown problems. The GEM was invented to provide the charge multiplication remotely and thus reduce or eliminate the voltages on the microstrip readout. It has been eminently successful in achieving this goal and GEM detectors are planned for use in high-energy physics experiments at accelerator facilities.

The GEM detector design promises to reduce the cost and time required to build each unit, and also promises a substantial increase in reliability. Since the recent advances in the development of large area imaging GEM-based detectors are encouraging, a dual GEM with passive 2-D grid readout for the AXM detectors has been baselined. It should be emphasized that the design only assumes technical capabilities that have been demonstrated to date; detectors which use double GEMs and 2-dimensional readouts have been built, and GEMs with active areas as large as 1000 cm^2 have been utilized (Bachmann et al. 1999).

A partnership with Metorex International Oy for the development and manufacture of the detectors (as was done for the ASM on RXTE) has been formed. The requirements for proportional counters that are used in space applications are very similar to the requirements for counters used in portable X-ray analyzers, the main commercial products of Metorex. They have provided proportional counters for many space instruments, including the RXTE ASM, the WXM on HETE II, the SXRP instrument of the SXG mission, and the XGRS instrument of the NEAR mission. Metorex is currently manufacturing large area, high-pressure MSGC detectors for the JEM-X instrument of the INTEGRAL mission. Metorex had been planning to start development of GEM detectors.

The configuration for the AXM detectors utilizes two GEM charge-multiplication stages to obtain high gain (10^4). This gain will provide sufficient signal to noise ratio for the signals associated with X-rays in the 1.5 to 12 keV energy range. The detectors for AXM will be filled with a 95% Xe-5% CO_2 gas mixture to a pressure of 1.2 atm and permanently sealed so that no gas flow system is required. The inside surface of the 75 µm thick Be window will act as the upper electrode of the drift region which will be 1 to 1.5 cm deep. These design characteristics will yield good quantum efficiency in the 1.5 to 12 keV energy band.

Each camera will contain a high voltage power supply to provide the expected window-to-readout grid potential difference of about 2000 V and, through the use of a resistive voltage divider, the intermediate potentials for the multiplication stages. The divider chain resistances will be adjusted for each detector during the manufacture and calibration stages of each camera. Each camera assembly will contain a power system that will supply regulated voltages to the camera electronics.

Conductive “X” and “Y” grids are plated onto the readout substrate surface, but are isolated from each other by a thin insulating layer. The X grid traces are arranged into three groups (A, B and C). Each group is made up of multiple sets of a small number (provisionally 4) of adjacent traces. The traces for each group are connected to a resistive strip, each end of which is, in turn, connected to readout amplifiers. The traces forming the Y grid are also subdivided into groups and connected to resistive strips. The charge produced by each event will be split among various X and Y traces and then further split between the amplifier chains at the two ends of the associated resistive strips. Signal charge that reaches each end of each resistive strip will be amplified for subsequent processing including threshold detection, background event identification, event energy and position determination, and digitization. The camera electronics design is straightforward and will be implemented through the use of highly integrated devices.

Non-X-ray background will be rejected by two methods. First, the total charge generated by most non-X-ray events will exceed the high-level threshold setting. Second, energetic charged particles, as opposed to X-ray photons, will normally produce an extended cloud of electrons at the readout grid resulting in a charge signal being produced in many of the sensing grid traces. Background events can then be rejected by identifying coincidences among all 3 of the A, B, and C outputs. This approach is expected to achieve the desired particle rejection efficiency of 95%.

A digital processing system in each camera will produce fixed-length CCSDS packets containing event, background, timing, and housekeeping data. Each X-ray event will be described by a 32 bit word (energy, 6 bits; X, Y positions, 9 bits each; time, 8 bits). The packets will be generated asynchronously at a variable rate depending on background and source count rates. Each packet will contain a secondary header with camera ID and start time. The time bits of each event will give the time since the previous event (or the start of the packet for the first event) in units of 2^{-13} s (122 us). Marker events will be inserted into the event stream as needed to avoid time-tag rollovers. Each camera assembly will communicate with the spacecraft via a dedicated 1553 serial communication port.

Particle Background and Solar X-ray Monitors

The AXM instrumentation will include two very small detectors that will act as particle background and solar X-ray monitors. Particle background and solar X-ray intensity information will be sent to the S/C computer, which will turn the appropriate detectors off/on according to prevailing conditions.

Mission Implementaion

Launch and Orbital Requirements

AXM is designed to be launched on a Pegasus XL (Orbital Sciences) into a ~600 km circular equatorial orbit from the vicinity of Kwajalein. Much higher orbits that avoid Earth occultations and the van Allen belts do not appear to be feasible for a NASA Small Explorer program. The objective of continuous, all-sky viewing is then best served in a low-altitude orbit where passages through high flux ionizing particle background regions are relatively rare. Table 1 shows mission and spacecraft requirements for the AXM mission.

The AXM spacecraft design accommodates all 31 cameras according to the requirement of nearly all-sky coverage (See Figure 1).

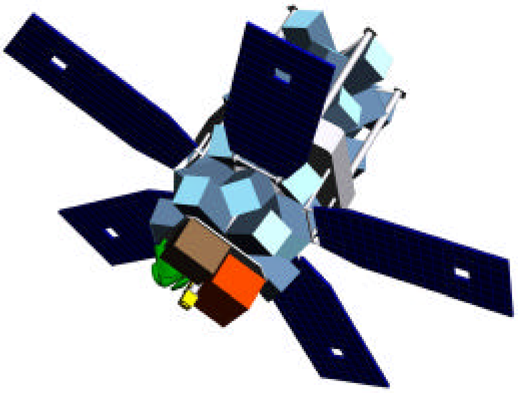

Figure 1. Deployed AXM Spacecraft

The spacecraft concept includes solar arrays that deploy after launch and which are then fixed for the mission duration. The solar arrays point in a common direction that will be maintained within a few degrees of the Sun. Because of restrictions imposed by the complement of antennae and thermal design, the roll angle of the spacecraft around the sun line will be restricted to ±40 degrees.

Table 1. Mission and Spacecraft Requirements

Parameter	Requirements	Capability
Mission Life	3 years	>5 years
Science Observation	All-sky, continuous viewing with minimum radiation/SAA exposure	600 km equatorial circular, Pegasus-XL
Science Instrument Stabilization	Sun fixed, non-rotating spacecraft	Zero momentum, 3-axis stabilized
Attitude Control	<30" attitude drift over 1000s period	<15" control with disturbance torques
Attitude Knowledge (ex post facto)	<10" per axis absolute attitude determination	<15" pitch and yaw <10" roll
Momentum Storage	>0.5 Nms	2.0 Nms
Control Torques	>0.008 Nm	0.04 Nm
Mass Memory	>0.25 GB	2.0 GB
Maximum Power	>478 W	575 W EOL
Total Mass to Orbit	<363 kg	292 kg baseline s/c
Science Data Time Tagging	Precision master clock with <3ppm stability	0.13 ppm stability with TCXO
Science Data Downlink	<3dB Link Margin with 10^{-6} BER	6.3 dB with 10^{-6}BER at 3.1 Mbps data rate

In normal operations, the spacecraft will maintain an inertially stationary attitude with the solar panels pointed close to the sun. This facilitates analysis of the data, keeps operations simple, and provides a stable thermal environment. A ~1 degree maneuver once per day will keep the solar panels aligned with the Sun.

The spacecraft attitude determination and control system (ADCS) will limit attitude drift between maneuvers to 30 arcsec per 1000 s. The absolute attitude determination should be 10 arcsec or better, ex post facto. These requirements are derived from the goal of obtaining X-ray positions as accurate as 1 arcmin for bright sources, and of being able to detect and locate weak sources that are not far from strong sources. The latter implies the need to accurately model the mask-pattern response to strong sources, and this demands accurate camera aspect knowledge.

It will be possible to determine the spacecraft attitude ex post facto using the positions of known X-ray sources. This capability will act both as a supplement and as a backup to the spacecraft ADCS system attitude determination. Calibration of camera pointing directions and angular scales will be obtained from observations in orbit of catalogued X-ray sources with accurate locations from optical, radio, or X-ray telescopes.

During each orbit, AXM cameras will be turned off while they are primarily viewing the Earth, or if they experience very high-count rates from either scattered solar X-rays or a high flux of charged particles. Small background monitors will be included as part of the instrument complement for this purpose.

The AXM spacecraft and cameras are designed for a 3-year mission life. However, the mission concept does not include any consumable materials that preclude operation for a more extended period of time.

Spacecraft Design

The AXM spacecraft is a conservative design that uses flight proven industry standard components. No new spacecraft technologies are required to meet the AXM mission requirements. A summary of the mass and power for the major spacecraft subsystems is shown in Table 2.

Table 2. Mass and Power Summary

Item	Mass (kg)	Power (watts)
Science Instruments	126.0	159.0
Power Electronics	79.0	10.5
Power Harness	6.0	-
S-Band/X-Band Communications	9.8	4.0*
Command & Data Handling	11.5	25.5
Attitude Determination and Control	21.9	58.1
Thermal Control	5.0	10.0
Structure	31.7	-
Battery Charging	-	210.9*
Total	290.9	478.0
Solar Array Power (EOL)	-	574.8
Pegasus-XL mass to orbit (600km)	363	
Resource Margin	24 %	20 %
Note: Power allocation for S-Band/X-Band downlink transmission included in Battery Charging line item.		

Attitude Determination and Control Subsystem

The ADCS provides 3-axis control of the spacecraft, using reaction wheels for precision pointing. A tetrahedral assembly of four reaction wheels supplies attitude control torques and stores disturbance angular momentum. Magnetic torquer bars are used for momentum unloading. Disturbance torque analyses show adequate wheel capacity to store up to four orbits of accumulated momentum, and there is substantial wheel control torque margin. Precise 3-axis attitude determination is accomplished with a stellar-inertial implementation using two wide field-of-view (20? x 20? cameras and an inertial measurement unit (IMU). The star camera quaternions are Kalman filtered with IMU gyro data to provide optimal attitude estimates at a 5 Hz rate. Analysis indicates ADCS performance well within the required accuracy (10 arcmin). The ADCS architecture also includes a 3-axis magnetometer and multiple analog coarse sun sensors; the magnetometer and sun sensors are used with the gyros for rate damping and preliminary attitude determination after separation from the launch vehicle; initial rate damping is done using the torquer bars. The star cameras are flight-proven "starlight in – quaternion out" units with embedded star catalog and internal processing; they can acquire, track, and identify stars from a "lost in space" condition provided that vehicle rates are less than 0.5 deg/sec.

Electrical Power

Primary 28V electric power is provided by a total of 3.5 m^2 of deployed, gallium arsenide (GaAs) solar arrays that generate 605 W (end-of-life). A power controller and rechargeable battery storage complete the power subsystem. The solar arrays have been sized to provide adequate power including battery charging with 20% margin at end-of-mission life. The Super NiCd batteries (four 250 watt-hr batteries) provide adequate power during the 36-minute maximum eclipse period with a 20% depth of discharge.

Structure

The spacecraft is designed to fit within the Pegasus XL payload static envelope as shown in Figure 2, and to be capable of surviving launch and shock loads with a margin of 1.5 safety factor (SF). The lightweight aluminum-alloy structure provides high mass-to-bending stiffness that minimizes the controls/structure interaction during maneuvers, and adequate thermal inertia to minimize thermal distortions. The innovative spacecraft design accommodates all 31 X-ray cameras in the allotted volume with unobstructed fields of view.

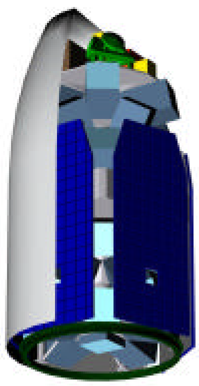

Figure 2. Stowed AXM Spacecraft Fits within Pegasus-XL Static Envelope

Command and Data Handling

The Command and Data Handling Subsystem (C&DH) for AXM uses a heritage design to perform realtime/stored command execution, telemetry data collection/formatting, ADCS processing, and science data management/storage. The C&DH also interfaces with the communications system. The C&DH system consists of a single 32-bit processor on which all flight software resides, 2 Gbytes of solid state memory for science data storage, a highly stable spacecraft master clock, and Mil Std 1553B subsystem interfaces (an RS422 for the RF subsystem). The processor operates with 21 MIPS throughput. Flight software will include all functions for autonomous mission operation, as well as uplink command execution. Normal spacecraft operations will follow sequences developed prior to launch; however, on-board stored command execution allows uplink and autonomous execution of stored command sequences for several days. The C&DH design has the capability for both flight software code patches and parameter updates, e.g., ACS gain and filter coefficients, or updates. Reprogrammability will be used to accommodate evolving mission requirements and contingencies. The science data memory can hold up to 8 orbits of data, so that, should a downlink pass be missed, the data can be stored for later transmission.

Communications

Communications is accomplished with body-fixed, high-bandwidth multi-element antennas for X-band downlink and body-fixed patch antennas for S-band uplink and downlink communication. Satellite link budgets assume a single 3-m diameter dual-frequency antenna at the ground station. The communication system has been designed to provide greater than 3.1 Mbps downlink capability (>230 Mbytes per 10 minute pass). Link margins are 6.3 dB for the X-Band science downlink, 17 dB for the S-band command uplink, and 10.6 dB for the S-band telemetry downlink at 40 kbps.

Thermal Control

Thermal control is primarily passive and is implemented with standard multi-layer insulation (MLI) blankets, selected coatings, thermistors, and heaters. Preliminary thermal studies indicate an adequate temperature margin for the worst-case exposures and an operating mode with a 100% margin. Thermal control is provided by highly reflective coverings on those faces that see the sun or earth, and radiators on the anti-solar faces of the solar arrays. Adequate thermal mass exists in the spacecraft to provide damping of temperature swings and distribute heat uniformly throughout the structure, so as to avoid hot or cold concentrations within the spacecraft, and to minimize thermal distortion.

Fault Tolerance

Within limitations, the AXM spacecraft has been designed to gracefully tolerate many kinds of hardware malfunctions. If any of the 5 solar panels fails, there is still adequate power; if a second fails, the cameras whose view are occulted by the earth can be turned off to reduce the power requirements so that 3 panels will provide sufficient power. The same power conservation strategy will make it possible to run on 3 of the 4 batteries. Two star cameras have been included because loss of accurate attitude information would result in loss of mission. The design has four reaction wheels mounted in a pyramid that will still provide 3-axis control capability with the loss of any one wheel. The magnetic torquer rods have redundant coils and also provide a backup attitude control capability. An on-board magnetic field model has been included, which in conjunction with the S/C ephemeris will provide backup capability for the 3-axis magnetometer. It was also considered to include a MEMs gyro package as a technology demonstration that will also provide backup for the IMU.

The computer assembly will communicate with the various instruments and sub-systems over two 1553 busses. The instruments will be assigned to the busses in such a way that loss of a bus will result in loss of half the instruments in an alternating checkerboard fashion. By rolling the S/C about the sun vector, the cameras connected to the operational bus would obtain coverage of most of the sky, but with some degradation in temporal coverage. Obviously, the loss of a few X-ray cameras still allows for substantial observations to be made. There are 4 X-band antennas on the S/C that allow communications to occur on every pass. If one antenna fails, sufficient memory capacity is available in the computer to store data that would have been sent using the failed antenna. The stored data is retained until such a time that a functional antenna is available for downlink. Failure of the X-band transmitter will be dealt with by using the S-band system with reduced data rates compatible with the capacity of the link. A ground commandable selection list will be used to identify the data that will actually be sent down over the reduced bandwidth system. The computer has dual redundant power supplies. If the high accuracy clock fails, the regular computer clock will be used, but precluding high precision timing observations.

Spacecraft Integration and Test

The spacecraft bus will be assembled and then the 31 cameras will be integrated. Hot bench testing will be performed on each subsystem prior to integration into the bus. A full up test of the integrated spacecraft will be performed prior to and following environmental testing. Environmental testing would be performed at GSFC.

Ground Data System

The X-band downlink telemetry is sized to allow for 10,000 counts/s (expect 7-10,000 counts/s). This generates a data stream of up to 230 Mbytes/orbit that will be downlinked to an equatorial ground station once per orbit. The ground station will be outfitted for both X and S-band communication using a 3-meter diameter dish. The specific location of the ground station will be chosen taking into account political stability, infrastructure, internet accessibility and US export control laws. It is planned to co-locate the ground station with those of other missions. Positive preliminary discussions have occurred about locating the AXM station at the site in Malindi, Kenya, which will also be the location for the ground station for the Swift mission. The sites for the three primary groundstations for HETE II at Kwajalein, Cayenne and Singapore will also be evaluated. The baseline plan is to analyze the data at the ground station, and send solutions and selected raw data to MIT over the Internet. The complete telemetry stream for each week will be archived on a DVD disk, which will be sent to MIT. The use of multiple, smaller groundstations to improve reliability and response time can also be evaluated.

Operations

The AXM mission has been conceived with operational simplicity in mind. Nearly all operational functions will be partially or fully automated in flight or ground software. The satellite will be controlled from MIT via an Internet connection to the equatorial ground station. Operations need to perform the following:

1) The S/C will perform a 1degree maneuver each day to keep the solar panels pointed at the Sun.
2) Camera high voltage will be turned on and off according to the strength of the particle background and solar X-ray flux scattered in the Earth's atmosphere. The onboard particle and solar X-ray monitors will act with the S/C computer to do this autonomously.
3) Orbital ephemeris data will be uplinked.
4) The S/C clock must be correlated to UTC.
5) Downlink operations will be done once per orbit. This will include sending data to the ground and uplinking confirmation of receipt to the S/C to help with memory management.
6) System functionality and housekeeping data will be monitored.

Summary

This paper presents a novel spacecraft system design that is capable of viewing 97% of the celestial sphere, excluding occultations by the Earth. The AXM mission will increase the productivity of high-energy missions such as Chandra, XMM, Swift, INEGRAL, and GLAST. The results will also provide direction for ground-based observatories, such as the TeV telescopes and monitoring networks at radio and optical frequencies.

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