AstroSat: I. The Scientific Instruments*

AstroSat Payload

Kulinder Pal Singh

AstroSat, India's first UV and X-ray astronomy satellite, has completed over six years of observations while in orbit around the Earth. It has carried out detailed studies of all kinds of objects in the Universe ranging from single stars, stars in clusters, binary stars with compact companions like neutron stars and black holes, star formation in galaxies, supermassive black holes in active nuclei of galaxies, etc. Here, I give a short description of its UV and X-ray telescopes and detectors. Some of the most important results obtained using AstroSat will be described in Part II.

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Introduction

AstroSat is India's first satellite for astronomical studies. It was launched on a Polar Satellite Launch Vehicle (PSLV-C30) on 28 September 2015 at 10 AM (IST) from Sriharikota Range north of Chennai on the eastern coast of India. The satellite weighing 1513 Kg was injected into a near-equatorial and nearly circular orbit around the Earth with an apogee of ~650 kilometers and inclination of 6° with respect to the equator. Specifically designed to study stars and galaxies simultaneously in the ultraviolet (UV) and a broad range of energies in X-rays, AstroSat carries four co-aligned telescopes and detectors, which are mounted on the same deck of the satellite. A fifth instrument with three X-ray detectors mounted on a rotating platform oriented 90° with respect to the other four scans the sky for X-ray transients (sources that brighten unexpectedly in X-rays). The five scientific instruments, in all, weigh ~855 Kg and are briefly described below. For a general

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AstroSat, astronomy, X-rays, ultraviolet, payload.

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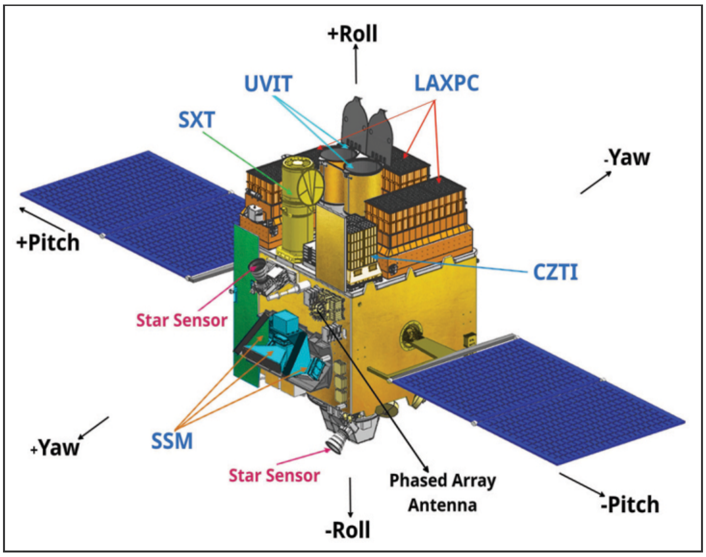

Figure 1. A schematic of the AstroSat. Credits: V. Girish, ISRO HQ, Bengaluru.

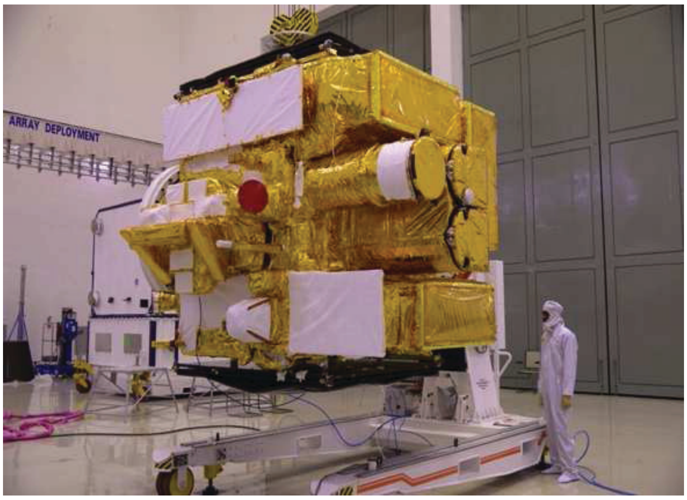

Figure 2. Fully assembled AstroSat in a clean room in Shriharikota, before mating with the PSLV. Credits: ISRO.

description of the principles and types of X-ray telescopes and X-ray detectors used in X-ray astronomy, please see my articles in *Resonance*[1]. For a description of AstroSat before the launch, see Singh et al. (2014) [1].

[1]Techniques in X-ray Astronomy, Vol.10, No.6, pp.15–23 & No.7, pp.8–20, 2005.

The Satellite and Its Sub-systems

The scientific payload carried by the satellite consists of two ultraviolet imaging telescopes (UVIT), three large-area X-ray proportional counters (LAXPC), a soft X-ray focusing telescope (SXT), cadmium–zinc–telluride imager (CZTI), a scanning sky monitor (SSM), and an auxiliary detector called the charged particle monitor (CPM) as shown schematically in *Figure* 1. A picture of AstroSat with its entire payload (scientific and auxiliary instruments) in a clean room in Sriharikota, before mounting on the launch vehicle (rocket) is shown in *Figure* 2. The view axis of the four co-aligned instruments is called the positive roll axis, as the entire satellite can be rotated around this axis. Two solar panels made of triple-junction solar cells, deployed after the satellite is injected into its desired orbit, generate about 2.2 kW power. The panels can be rotated around an axis known as the pitch axis and are kept oriented in a direction normal to the Sun in order to generate maximum power. The other axis perpendicular to both the roll and pitch axes is called the yaw axis. Some main auxiliary instruments comprise the following:

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Two Li-ion batteries serve as a backup source of power when the orientation is such that the solar panels are not working at full efficiency. A power management system supplies power to all the payloads. A thermal control system ensures that all the scientific payloads are maintained within a comfortable temperature range as specified by the scientists and engineers, while the satellite goes through extreme hot (day) and cold (night) cycles (~14) as it goes around the Earth every ~98 minutes. Four reaction wheels and three magnetic torquers make up the attitude and orbit control system (AOCS) to orient the satellite towards any source in the sky and maintain the pointing direction for the duration of an observation, which can last from a fraction of an hour to several days continuously. A backup system of tiny jets (thrusters) is also available for orientation but to be used only in case of emergency to avoid chances of contamination of the optical elements of telescopes. Two star sensors operating in a closed loop along with gyro wheels control the attitude of the satellite and maintain it within ~2 arcmin. Finer attitude determination is provided by the visible channel of one of the UVIT telescopes. A pointing accuracy of $\leq 0.05^{o}$ in each axis, an attitude drift rate of ~1.1 arcsec per sec, and a jitter of ≤ 0.3 arcsec is thus obtained.

A satellite bus management unit (BMU) integrates the main functions, including AOCS, telemetry, command and sensor processing, etc. A solid-state recorder with 200 Gb storage capacity is used for onboard storage of data. Data from all the payloads are transmitted to the Mission Operations Complex, ISRO Telemetry Tracking and Command Network (ISTRAC) by two X-band carriers using phased array antennae. The same station operates the satellite. Data are processed, archived, and distributed by the Indian Space Science Data Centre (ISSDC) near Bengaluru to all the observers. All data are transmitted in 11 or 12 orbits (out of ~14 orbits per day) over a day generating ~700 GB of scientific data every month. For more details on auxiliary instruments and please see [2, 3]. The scientific payloads are described in the next section.

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Telescopes and Detectors Onboard AstroSat

Ultraviolet Imaging Telescope (UVIT)

UVIT consists of two co-aligned telescopes each having a primary mirror of aperture 375 mm, focal ratio of $f/12$ in Ritchey–Chretien optical configuration, with filters and detectors in their respective focal planes. One telescope is designed to observe in the far-ultraviolet (FUV) band of 1300–1800 Å, while the other one detects photons in both the near-ultraviolet (NUV) band of 2000–3000 Å and visible (VIS) band of 3200–5500 Å. The VIS channel is used primarily as a very fine star tracker and to obtain an accurate aspect of the UVIT telescopes. A schematic diagram of the UVIT telescopes is shown in *Figure* 3. A filter or a grating for a low resolution dispersed spectra, as desired by an observer based on the scientific objectives, is selected from a large selection of filters or gratings mounted on a wheel, one each in front of the FUV and NUV detectors, respectively. The detec-

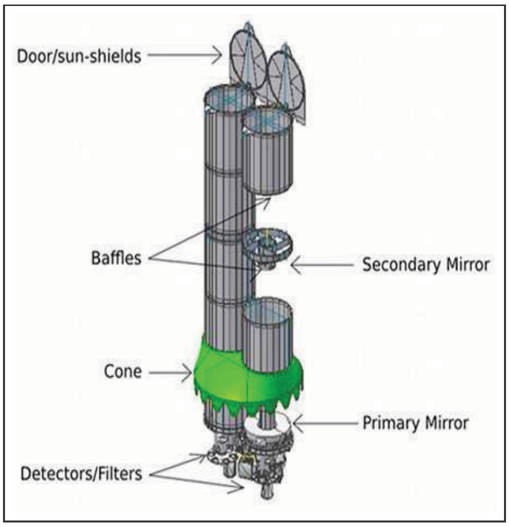

Figure 3. A schematic of the UVIT. Credits: UVIT team at IIA Bengaluru and Tandon et al., 2017a [4].

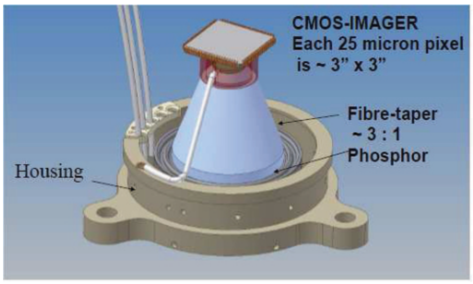

Figure 4. A schematic of the detectors used in the UVIT. Credits: UVIT Team at IIA, Bengaluru.

tor (or camera) in each of the channels is made of an intensified CMOS (Complementary metal-oxide–semiconductor) of 39 mm aperture, which can work either in photon counting mode or in integration mode. A schematic diagram of one of the detectors used in the UVIT is shown in *Figure* 4.

An appropriate photo-cathode material is used in each detector to detect the photons in different bands. UVIT takes images of ~28 arcmin diameter (only slightly less than the diameter of the moon) of the sky centered on the direction in which it is pointed. It has a spatial resolution of ~1.5 arcsec. The sensitivity in the FUV is such that it can detect a 20 magnitude (AB magnitude system) star in a 200 s exposure[2]. The time resolution is 1.7 msec. For more details about the UVIT, the reader is referred to [4, 5].

[2]The AB magnitude system is based on flux measurements that are calibrated in absolute units, namely spectral flux densities at a given wavelength.

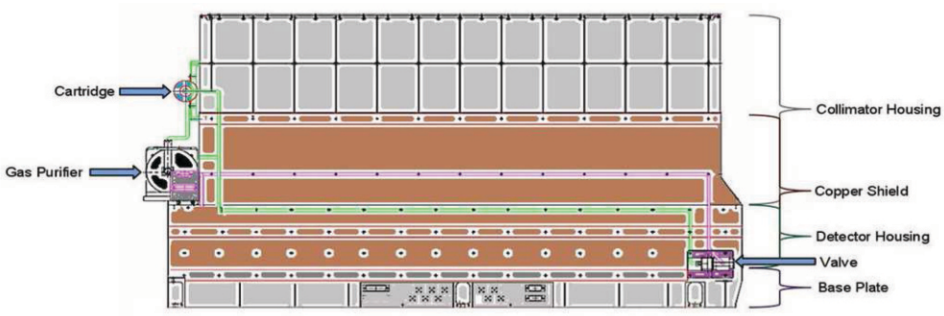

Figure 5. A schematic of one of the units of LAXPC. Credits: LAXPC POC website at TIFR Mumbai.

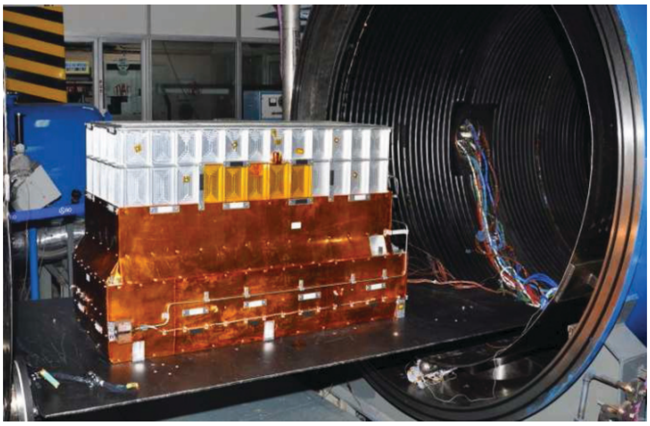

Figure 6. One fully assembled LAXPC unit undergoing testing. Credits: LAXPC POC website at TIFR Mumbai.

Large-area X-ray Proportional Counters (LAXPC)

The LAXPC consists of three co-aligned identical multi-layered and multi-cell proportional counters (PC). Each PC has 12 anode cells per layer, with each cell being 100 cm long and having a cross-section of 3 cm × 3 cm. There are five layers in all, giving each PC a depth of 15 cm. The top two layers are divided into two parts, and alternate cells (odd and even sets) are connected for high voltage and output signals. There are thus seven anodes—two each in the top and second layer, one each from the remaining three layers.

There are three veto layers, each surrounding the left, right, and bottom sides to reduce background, and each veto layer consists of 1.5 cm × 1.5 cm × 100 cm anode cells. The outputs from the seven main anodes and three veto anodes are fed to 10 charge-sensitive preamplifiers (CSPAs). High voltage (2000–2500 Volts) is supplied to all the main anodes (A1–A7) at the same point, and its value is, therefore, the same and can be controlled from the ground. The veto anodes have a lower voltage but they cannot be controlled separately.

All PCs are filled with a mixture of xenon gas (84.4%), methane (9.4%), and argon (6.2%) at ~2 atm pressure. A gas purification system is included in each PC, which is used from time to time to maintain the properties like energy gain and resolution of the detectors close to the optimum value. Each detector is sealed on the top by a 50 μm thick aluminized Mylar sheet, which allows X-rays with energy >3 keV to pass through and dictates the low-energy threshold of the detectors. A collimator made of slats sits on top of the Mylar window and defines the field of view of $1^\circ \times 1^\circ$ for X-rays incident on top. The collimator on top of each PC has ~7000 square cells of 7 mm × 7 mm size.

The geometric area of each PC is 3600 cm^2, which reduces to 2800 cm^2 after considering the blockage by the collimator. Each PC has its own independent front-end electronics, high voltage supply, and signal processing electronics. A system-based time generator (STBG) is common for all three LAXPC detectors to provide a timestamp with an accuracy of 10 μsec for all the accepted events. Data from each unit of LAXPC are acquired and stored independently.

The efficiency of detection for photons is a function of energy and peaks at ~2000 cm^2 between 3–30 keV. The total effective energy bandwidth has detection efficiency above 25% and is 3–80 keV. The energy resolution of the detectors is ~22% at 6 keV and between 10–20% from 20–80 keV. Each unit of LAXPC has a large mass and size offering a large cross-section for background particles and also a large Compton scattering cross-section for energy photons above 80 keV in its walls and surrounding materials. The veto layers are very effective in reducing these backgrounds in the useful energy band of 3–80 keV. However, many background events still get registered, making the PC's background domi-

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nated for weak sources, thus affecting the sensitivity for source detection.

The total number of background counts averaged over an orbit is ~ 200–250 counts s^{-1} per PC with a variation of ~20% around the average value. All PCs are switched off during the passage of the satellite through the South Atlantic Anomaly just south of the equator for safety as the background is very high and can lead to discharge inside the PCs. A LAXPC unit has been able to detect a source of ~ 0.5 milliCrab (1 Crab = 2.4 × 10^{-8} erg cm^{-2} s^{-1} in 2–10 keV energy band) strength at 3σ level in ~10000 s of exposure. A schematic diagram of one LAXPC unit, including the collimators and shields, is shown in *Figure* 5. A fully assembled unit of LAXPC undergoing tests in a vacuum chamber is shown in *Figure* 6. For more details of the LAXPC, see [6].

Soft X-ray Telescope (SXT)

Soft X-ray telescope, India's first X-ray focusing telescope, consists of a set of conical shells of mirrors approximating paraboloidal and hyperboloidal shapes and arranged confocally and coaxially behind each other in Wolter I geometry.

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X-rays are incident grazingly, are first reflected by approximate paraboloidal mirrors (known as 1α section defined by the cone), and then reflected to the prime focus of the telescope by approximate hyperboloid surfaces (known as 3α section of the cone). Mirrors were made of very thin (0.2 mm thickness) Al foils covered with replicated gold surfaces. Replication of gold surfaces from a glass mandrel provided surfaces with a roughness of only ~ 10 Å thus producing mirrors with a low scattering of X-rays. Each mirror was made for a quadrant of a shell. Thus, four of them made one shell of 1α section, and another four made one shell of 3α section. Thus, eight mirrors made up one complete shell of the telescope. In all, SXT has 40 such complete shells nested within each other to increase the reflecting area for X-rays and, therefore, consists of a total of 320 mirrors.

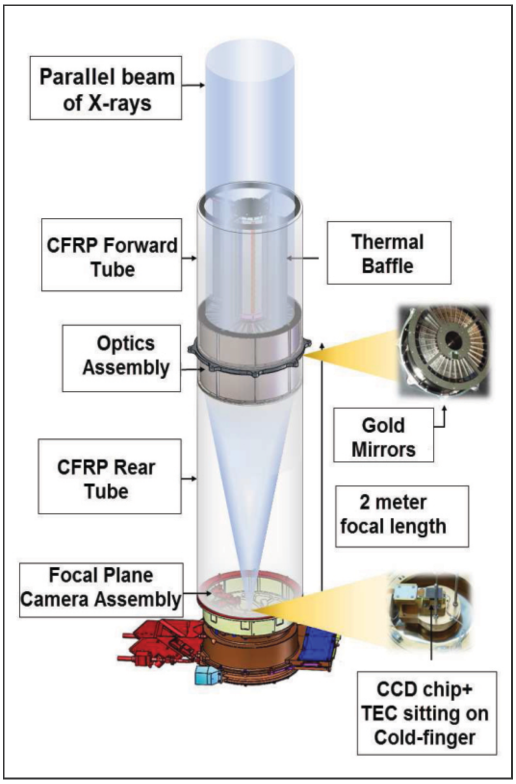

Figure 7. A schematic of the SXT. Credits: V. Navalkar et al., 2021 [7], and Singh et al., 2017 [8].

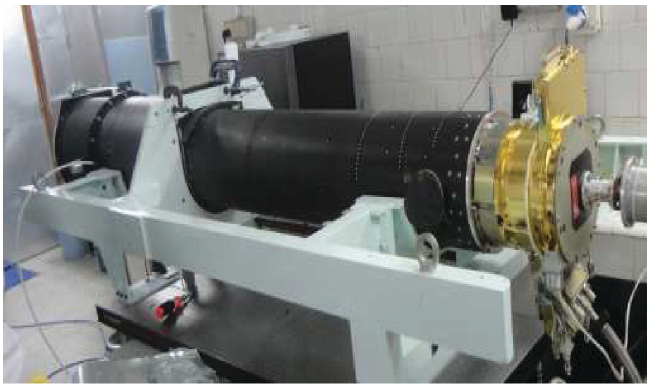

Figure 8. Fully assembled SXT in the laboratory. Credits: SXT Team at TIFR.

Each mirror is 100 mm long, with the radius of the outermost and innermost shell being 130 mm and 65 mm, respectively, with other mirrors having radii in between these values as determined by ray-tracing to provide a clear path for the X-rays after reflection. A specially machined holder was made to house each mirror so that all the mirrors in all the shells were mounted coaxially. The overall performance of mounted mirrors was measured on the ground using optical light—targeting each foil with a pencil beam for adjustments followed by a broad parallel beam from an inverse optical telescope for the overall performance (see [7] for more details).

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The CCD in the focal plane camera is operated at -82°C using a thermo-electric cooler. The CCD has 600×600 pixels with each pixel of size 40×40 microns corresponding to 4×4 arcsec^2. Photons from a source reach the CCD through a very thin and fragile window made of a polyimide film (184 nm thick and coated with 48 nm of aluminum on one side), which blocks the ultraviolet and visible photons but allows the X-rays to enter. The CCD is surrounded by a proton shield to block the charged particles from all other sides. The performance of the CCD and its associated processing electronics is monitored in real-time using radioactive Fe^{55} sources (at the 4 corners of the detector). Another calibration source mounted on the inside of the camera door was used for ground tests and during the flight until the door was opened permanently on 26 October 2015.

SXT has a field of view of ~40 arcmin. Its spatial resolution was measured in-flight by observing point sources in the universe and found to be 2 arcmins (full width half maximum) and 10 arcmins (half power width).

The electronics is designed to read out the CCD in several modes, the most commonly used one being the photon counting (PC) mode with a time resolution of 2.3775 s, and a faster mode provides a time resolution of 0.278 s for the central 15 arcmin^2 window. The energy information for each photon is made available in both modes. The energy resolution is ~2.5% at 6 keV and 5–6% at 1.5 keV.

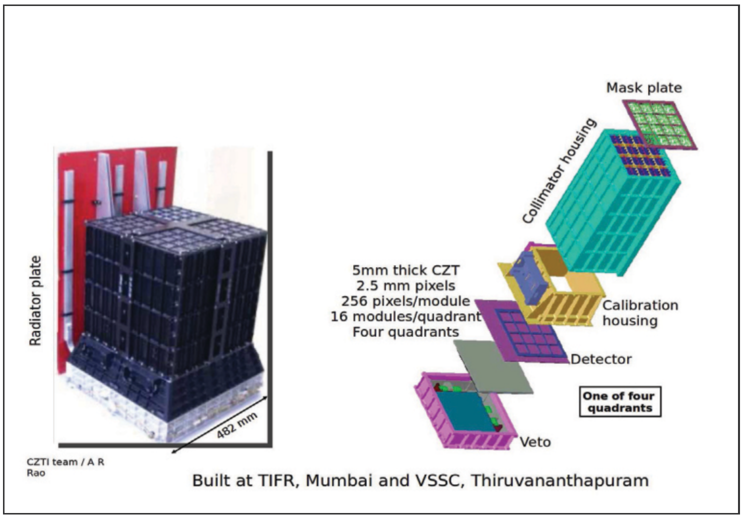

Figure 9. Fully integrated CZTI on the left and a schematic of one of its quadrants on the right. Credits: CZTI team at IUCAA.

The background is extremely low (<0.2 counts per sec over the entire field of view) due to focusing on a detector with a very small size and mass, and thus providing good sensitivity, particularly for sources with an X-ray spectrum between 0.3–2.0 keV, where the effective area of the SXT is maximum.

The natural ability of a pixelated detector like CCD to distinguish between patterns of charge deposited by X-rays and particles helps to further reduce the background. SXT has been able to detect sources ~20 microCrab intensity in a cumulative exposure time of ~30000 s with a confidence of $>5\sigma$. Considering that SXT has a peak effective area of only ~80 cm^2, it provides nearly two orders of magnitude better sensitivity than a detector of similar area but without any focusing. Further details about the SXT can be found in [1, 8] and references therein.

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Cadmium–zinc–telluride Imager (CZTI)

CZTI consists of sixty-four detector modules made of 5 mm thick crystals of compound semiconductor $Cd_{0.9}Zn_{0.1}Te_{1.0}$ (CZT). A continuous anode made of 50 μm thick aluminized Mylar runs across each module. The cathode is divided into a grid of 16×16 pixels, which are directly bonded to two application-specific integrated circuits (ASICs) for readout. The ASIC signals are further read and processed by the main electronics unit. The modules are arranged in four quadrants, with 16 of them in each quadrant. Scintillation detectors made of CsI(Tl) are located below the CZT modules and serve as active anti-coincidence shields to reject charged particle events and very high-energy photons. All the detectors are connected to a passively cooled radiator plate located on a side of the satellite facing the satellite's +yaw axis. The CZT detectors are thus maintained at a temperature of ~0°C to reduce the thermal noise. X-ray events detected by CZTI have a time resolution of 20 micro sec.

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The imaging capability is provided by a coded aperture mask located 481 mm above the detector plane giving 17 arcmins resolution over a $4.6^\circ \times 4.6^\circ$ field-of-view. The mask for each quadrant is made of a 0.5 mm thick tantalum plate with square and rectangular holes matching the pitch of the CZT detector pixels. These holes cast a unique shadow on the detector plane for each source direction. The patterns are based on a 255-element pseudo-noise Hadamard set of uniformly redundant arrays. ^{241}Am alpha-tagged radioactive sources are mounted alongside the detector housing and are used as energy response calibrators. The energy bandwidth of the CZT detectors is 20–200 keV X-rays. CZTI has an unobstructed view of the sky for energies >100 keV and is, therefore, sensitive to gamma-ray bursts and other bright transients occurring anywhere in 30% of the sky around the observing axis of the satellite. The detectors being pixellated are sensitive to tracks made by the polarized component of X-rays above 100 keV. CZTI has demonstrated its capability to measure hard X-ray polarization from bright persistent sources, e.g., Crab Nebula. For more details, please see [9].

SSM comprises three nearly identical units of position-sensitive gas-filled proportional counters each having a coded mask.

Scanning Sky Monitor (SSM)

SSM comprises three nearly identical units of position-sensitive gas-filled proportional counters each having a coded mask. Each SSM, with its associated electronics, is mounted on a rotating platform to scan the sky. Each unit has eight anodes with a high

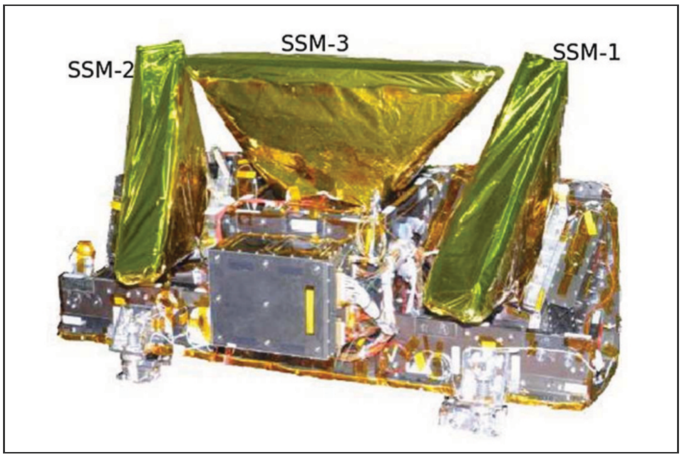

Figure 10. Fully integrated SSM with all its 3 units mounted on a single platform. Reproduced with permission from Ramadevi et al.,(2017) [10].

voltage of ∼1500 volts. The effective area of SSM is 51 cm^2 at 5 keV (11 cm^2 at 2.5 keV). Each SSM contains a mixture of argon and methane held by a window of aluminized Mylar of thickness 50 microns. Coded mask patterns with 50% transparency joined sideways provide a spatial resolution of ∼1 mm at 6 keV (angular resolution ∼12 arcmins on the sky) in one direction. In a direction perpendicular to the coding direction, it is 2.5°. The energy resolution is 25% at 6 keV, and its sensitivity is ∼ 28 mCrab for 600 s exposure time. Each SSM unit scans the sky in one dimension over a field of view of $22^\circ \times 100^\circ$. *Figure* 10 shows all three units of SSM mounted on a single platform.

Charged Particle Monitor (CPM)

An auxiliary scientific payload that is used to warn other scientific instruments about the passage through high particle background regions, like the South Atlantic Anomaly, is the charged particle monitor (CPM). It measures the count rates above a specified energy threshold of ∼1 MeV (programmable from the ground), and is used for screening events in the SXT and for changing high voltages on the LAXPC or CZTI. It is made of a CsI (Tl) scintillation detector read by a Si-Pin photodiode. It has a thin entrance window of 0.12 mm Teflon reflector along with a 50 micron aluminized Mylar on top.

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Figure 11. Launch of PSLV C-30 from Sriharikota on 28 September 2015. Credits: ISRO HQ.

Observing With AstroSat

The safety of the payloads imposes certain constraints on the directions in which all the four co-aligned telescopes and detectors can point and observe while in orbit. These are as follows: (a) the Sun is kept mostly along the negative yaw axis such that the angle between payload-pointing axis (roll axis) and the Sun is maintained ≥65° to avoid the intense direct and scattered sunlight into the payloads while maintaining maximum power; (b) ram angle, defined as the angle between the roll axis to the velocity vector direction of the spacecraft, is kept ≥ 12° to avoid the optical elements of the telescopes getting hit by any residual molecules and atoms trailing the satellite in its orbit; (c) angle between roll axis and bright limb of the Earth is kept ≥12°, and d) the angle between star sensor and the Sun is always to be ≥50°.

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AstroSat can be used by anyone in the world for observations through a proposal system called APPS (AstroSat Proposal Processing System) handled by ISRO. Proposals are accepted based on a yearly cycle of submission and peer review. All data are archived and made accessible free of charge via the internet to anyone after one year of lock-in period reserved for the principal observer of the proposal. Proposal for targets of opportunity for urgent and/or new targets are accepted round the clock throughout the year. Its operation has been guaranteed by ISRO for several more years, depending on the health of the payloads. Currently, the near UV instrument and two of the three LAXPC units are not functional, while all the other units and scientific payloads are performing as expected.

Conclusion

AstroSat, India's first astronomy satellite that can observe simultaneously in UV and a broad energy range of X-rays from 0.3–100 keV, has now spent 6 years in orbit around the Earth and has demonstrated the capability of Indian scientists and engineers to realize and operate a complex observatory in space, paving the way for more such satellites to be made in India. Its easy access to researchers has made high-energy astrophysics accessible to everyone in India and has produced several new discoveries reported in many international journals of high repute.

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Acknowledgement

I acknowledge the efforts of all the scientists and engineers in TIFR, IIA, IUCAA, ISRO, ISSDC, RRI, PRL, VSSC, University of Leicester, UK, Canadian Space Agency, and several private contractors who made *AstroSat* a reality. I also acknowledge ISRO and the Payload Operation Centres (POCs) for allowing me to reproduce the pictures and figures of the payloads here. The work of all the people at the ISSDC and at the POCs of individual payloads, who are scheduling observations round the clock, and providing data to all the observers, is cheerfully acknowledged.

Suggested Reading

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