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Review

AstroSat: From Inception to Realization and Launch

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Abstract. The origin of the idea of AstroSat multi wavelength satellite mission and how it evolved over the next 15 years from a concept to the successful development of instruments for giving concrete shape to this mission, is recounted in this article. AstroSat is the outcome of intense deliberations in the Indian astronomy community leading to a consensus for a multi wavelength Observatory having broad spectral coverage over five decades in energy covering near-UV, far-UV, soft X-ray and hard X-ray bands. The multi wavelength observation capability of AstroSat with a suite of 4 co-aligned instruments and an X-ray sky monitor on a single satellite platform, imparts a unique character to this mission. AstroSat owes its realization to the collaborative efforts of the various ISRO centres, several Indian institutions, and a few institutions abroad which developed the 5 instruments and various sub systems of the satellite. AstroSat was launched on September 28, 2015 from India in a near equatorial 650 km circular orbit. The instruments are by and large working as planned and in the past 14 months more than 200 X-ray and UV sources have been studied with it. The important characteristics of AstroSat satellite and scientific instruments will be highlighted.

Keywords. Multi-wavelength satellite—X-ray astronomy—ultraviolet astronomy—high energy astrophysics mission—X-ray timing and spectral studies—UV imaging studies.

1. Introduction

X-ray astronomy was born in 1962 with the serendipitous discovery of the brightest X-ray star Scorpious X-1 (Sco X-1) in a rocket flight experiment (Giacconi *et al*. 1962). Giacconi was awarded the Nobel Prize in Physics in 2002 for this important discovery which opened up the new field of X-ray astronomy and revolutionized the discipline of high energy astrophysics. A large number of X-ray sources were discovered by 1970 but their nature and mechanism responsible for producing their high X-ray intensity remained a mystery. A breakthrough occurred by the launch of the first X-ray astronomy satellite UHURU in 1971 when it detected 4.8 s X-ray intensity variations and also detected dips in the X-ray intensity of Cen X-3 every 1.8 days. This immediately suggested that Cen X-3 was a binary system in which the X-ray emitting object gets eclipsed by the larger companion star during their orbital motion. The discovery of another X-ray pulsar Her X-1 with 1.24 s pulsation period followed soon after. Optical companions of both the X-ray pulsars were soon identified. These discoveries solved the mystery of the nature of X-ray bright stars. Unlike the radio pulsars, the X-ray pulsars are accretion-powered sources. A fraction of the mass loss from the optical companion is captured by a neutron star or a black hole in the binary and due to their very strong gravity, the accreting matter releases enormous energy resulting in their high X-ray luminosity. The X-ray emitting neutron star has a strong magnetic field of $\sim 10^{12}$–10^{13} Gauss and as it spins the matter accreting at its magnetic poles results in pulsations. Following UHURU, a series of X-ray satellites launched by USA, ESA and its member states, Japan etc. in the following 3 decades studied in great details the morphological, timing and spectral characteristics of different types of sources with a variety of detectors. A major advancement in the sensitivity for X-ray detection was achieved with the Einstein X-ray Observatory which carried an X-ray imaging telescope with several focal plane instruments for imaging and spectroscopic studies. High resolution timing capability of Proportional Counter Array (PCA) on the Rossi X-ray Timing Explorer (RXTE) resulted in discovery of millisecond accreting X-ray pulsars, kHz quasi-periodic oscillations, measurements of the spin periods of the neutron stars in Low Mass X-ray Binaries (LMXBs), etc. The advent of X-ray Charge Coupled Devices (CCDs) and their use in observatories like ASCA, Chandra X-ray Observatory of NASA and ESA's XMM-Newton Observatory in the 20th century and early part of 21st century, contributed enormously to the advancement of X-ray astronomy.

2. Indian scenario before the advent of AstroSat

Five years after the discovery of Sco X-1, research in X-ray astronomy in India began with balloon-borne observations at Tata Institute of Fundamental Research (TIFR), Mumbai and rocket-borne experiments by Physical Research Laboratory (PRL), Ahmedabad. TIFR group conducted a series of balloon experiments with collimated NaI (Tl) detector of about 100 cm^2 area during 1967–75 and measured temporal and spectral characteristics of bright X-ray sources like Sco X-1, Cyg X-1, etc. in 20–100 keV. Several new results like the presence of non-thermal hard component in ScoX-1, rapid variations in the intensity and hard X-ray flaring activity in Cyg X-1, etc. were reported by the TIFR group. The advent of several X-ray astronomy space observatories after 1975 made it possible to probe timing and spectral features in great detail by long observations of discrete objects. This was not possible with balloon and rocket experiments and hence after 1980 these experiments became largely unviable. A proposal was jointly made by TIFR and ISRO Satellite Center (ISAC), Bengaluru in 1981 for a satellite experiment using collimated PCs of about 1200 cm^2 area weighing about 40 kg. The launch of this payload had to wait till the successful development of Polar Satellite Launch Vehicle (PSLV) in mid-1990, which is the workhorse of Indian space programme and capable of launching about 1.6 ton satellite in the near-Earth orbit. ISRO approved the launch of the X-ray astronomy experiment aboard Indian Remote Sensing Satellite IRS-P3. This payload named as Indian X-ray Astronomy Experiment (IXAE), was developed in 18 months and successfully placed onboard IRS P-3 in a polar 800 km orbit in March 1996. Despite a high background orbit and only 2–3 months of observing time in a year, the IXAE studied about 20 X-ray sources including neutron star and black hole binaries. The main results of IXAE included $\sim$50 s quasi-regular intensity bursts from the black hole binary GRS 1915+105 now termed as the 'heartbeat of black hole' (Paul *et al*. 1998), accretion torque reversal in X-ray pulsar 4U 1907+09 (Mukerjee *et al*. 2001), change in 4.8 h binary period of Cyg X-3 (Singh *et al*. 2002), etc. After 5 years in orbit, IXAE was switched off.

3. International scenario at the time AstroSat was conceived

When the idea of AstroSat was taking shape during late nineties, RXTE was operational making important discoveries. NASA's Chandra and ESA's XMM-Newton observatories, sensitive in 0.1–10 keV, had become just operational. Both these missions operating since 1999 have unprecedented capability for imaging and spectroscopies studies. ESA's INTEGRAL satellite with Cadmium Telluride (CdTe) array equipped with coded mask aperture, has hard X-ray imaging capability in 15–200 keV. These missions, except RXTE, have limited capabilities for investigating rapid variability phenomenon. It was noticed that all the operational X-ray observatories, except XMM-Newton which also has a UV telescope for simultaneous UV observations, work in limited spectral bands and hence lack wide multi wavelength (MW) observation capability. Understanding complex emission processes in Active Galactic Nuclei, X-ray binaries, etc. require not only observations in the extended X-ray region but also in the UV and optical bands. Such MW studies have been attempted by making coordinated observations with several satellites sensitive in different bands but has met with only limited success due to logistic problems arising from widely different orbits. The goal of MW observations is best achieved by making simultaneous observations with several coaligned instruments mounted on the same platform. One of the important objectives of AstroSat was to realise MW capability by having several coaligned instruments with wide spectral coverage. This makes AstroSat a unique mission.

4. Birth of the concept of AstroSat and its principal objectives

In spite of the lack of opportunity for satellite experiments with sufficient mass during 1980–85, the TIFR group embarked on the development of a large area ($\sim$2500 cm^2) hard X-ray instrument for balloon-borne studies of 20–100 keV emission from X-ray binaries. This employed two multi-anode, multilayer PCs filled with xenon at a pressure of about 1200 torr having an interaction depth of 15 cm to achieve high detection efficiency (Rao *et al*. 1987). This instrument was successfully used in a series of balloon experiments to measure energy spectra of Cyg X-1, Cyg X-3, pulsar 4U 1907+09, etc. (Chitnis *et al*. 1998). This experience proved very valuable in the development of Large Area X-ray Proportional Counter (LAXPC) instrument on AstroSat.

The success of the IXAE experiment on IRS-P3 bolstered confidence that we can design and develop instruments that will work in the harsh space environment. Encouraged by this, a proposal was made by this author in July 1996 to the Chairman of ISRO, for a full-fledged satellite experiment using large area xenon-filled detectors of high efficiency for hard X-rays aimed at studies in 2–80 keV. The Chairman of ISRO responded promptly and suggested a brain-storming meeting at ISRO headquarters by inviting a wide section of astronomy community representing different fields of astronomy. The meeting held during July 1996, discussed a large number of proposals and ideas put forth by the participants over 2 days. Based on the summary of the discussion, the Chairman constituted two Working Groups (WGs), one for proposals in X-ray and gamma-ray astronomy and the other covering optical, infrared and ultra-violet (UV) astronomies. The mandate of the WGs was to critically discuss various proposals and at the end have a joint meeting to short list instruments for the proposed satellite keeping in mind that the mission should be internationally competitive and Indian astronomers should be able to carry out research in frontier areas of astronomy. The WGs held several meetings for over 2 years and at the joint meeting a consensus was reached about principal scientific goals of the mission and most suitable instruments to realise the objectives. The following considerations were kept in mind in defining goals and instruments for the proposed satellite:

(a) The mission should have some unique features not found in any other operational mission. Multi wavelength astronomy was found to be a niche area in which the proposed mission will have unsurpassed capability.
(b) It should have broad spectral coverage covering 0.5–100 keV in X-ray band to characterize complex continuum and line spectra.
(c) The main X-ray instrument should have large area with high count rate capability to investigate high-frequency variations in X-ray binaries. It should have high collecting area and high detection efficiency in 20–80 keV, surpassing other missions, to study millisecond variability and kHz Quasi-Periodic Oscillations (QPOs) above 20 keV.
(d) To achieve the MW capability the mission was envisaged to have a sensitive state-of-the-art UV-optical instrument to probe origin of radiation in different spectral bands and inter-relationship between them from simultaneous observation over 5 decades in energy covering optical, near-UV, far-UV, soft X-rays and hard X-rays. This is very important to decipher the radiation processes in Active Galactic Nuclei (AGNs), X-ray binaries and Cataclysmic Variables (CVs). The UV instrument has additional objective of studying UV bright objects.
(e) For monitoring the variability of known X-ray sources and to detect new transients, inclusion of an X-ray monitor was necessary which will also provide alerts to other instruments when a new source is detected or a known object undergoes outburst to enable pointed mode observations by the co-aligned instruments.

Selection of the instruments was made to achieve the above objectives based on the considerations discussed in the following section.

5. Science instruments for the AstroSat

The following consideration were kept in mind in the selection of the payloads:

(I) The main X-ray instrument should be based on proven technology in which experience and expertise exist within the country to design and fabricate it. The TIFR group had experience in the development of large area PCs for the balloon and satellite experiments and hence it was entrusted the responsibility for the development of large area PCs with 3–80 keV response and high detection efficiency in 20–80 keV hard X-ray band. Four multilayer PCs of 15-cm depth filled with xenon at about 1500 torr, having a total effective area of >6000 cm^2 in 5–20 keV were included in the proposed mission so that this instrument named as Large Area X-ray Proportional Counter (LAXPC) experiment would have the largest area among all the operational X-ray astronomy missions, for timing studies. The use of multiple LAXPC units also provides redundancy. Each LAXPC unit would have independent high voltage supply and signal processing electronics. Its time resolution would be about 10 μs and have a high count rate (25 counts/s) handling capability to investigate rapid variability on kHz scale.

(II) A proposal of TIFR for inclusion of a Soft X-ray Telescope (SXT) based on X-ray reflecting optics using conical foil mirrors (similar to the one on highly successful ASCA satellite of Japan) with an X-ray CCD as the focal plane detector, was accorded high priority as it would provide high detection sensitivity in 0.3–8 keV as well as provide imaging on a few arc minute scale and medium energy resolution spectroscopy. This would be a new technology instrument and experience gained from development of the X-ray reflecting telescope would also prove valuable for future Indian X-ray missions.

(III) The Indian Institute of Astrophysics (IIA), Bengaluru had proposed inclusion of an UltraViolet Imaging Telescope (UVIT) sensitive in Optical, NUV and FUV bands with several filters and prism for low resolution spectroscopy for MW studies of AGNs and other sources radiating over a wide spectral band as well as measuring characteristics of UV bright objects on stand-alone basis. This was included in the proposed mission as it would enable wide spectral coverage. The proposed UVIT was originally based on the use of a single telescope but later changed to a twin telescope configuration, one covering visible and NUV and the other telescope dedicated to FUV observations. The use of photon counting imaging detectors was envisaged as the focal plane detectors.

(IV) The astronomy group at ISAC suggested inclusion of a Scanning Sky Monitor (SSM), similar to the All-Sky Monitor (ASM) on RXTE, for continuous scanning of X-ray sky to detect intensity variations of known and new sources. SSM was included for providing alert to making pointed mode instruments for observations.

(V) Originally, three co-aligned instruments namely LAXPC, SXT and UVIT and the fourth instrument SSM, were included in the proposal. At the time of review of the proposal by the Chairman of ISRO at TIFR in September 2000, it was proposed to include a hard X-ray imager based on the use of pixellated Cadmium–Zinc–Telluride (CZT) detector, with a Coded Aperture Mask (CAM) placed above the detector plane for hard X-ray imaging in 10–100 keV to an accuracy of $\sim$8 arcmin. This was similar to CdTe imager on INTEGRAL satellite launched in 2001 but with a modest effective area of about 500 cm^2. The proposal was based on the use of new generation detectors which required only modest cooling of CZT from $\sim$0°C–15°C and had the merit of resolving hard X-ray sources in the crowded fields like the one near the galactic center region. The instrument named as CZT Imager (CZTI) was included as part of the LAXPC instrument by reducing the number of LAXPC units from 4 to 3.

Reports of the WGs were submitted to the ISRO Chairman in 1998 who approved it and requested this author to prepare a detailed scientific and technical proposal for the proposed satellite mission. Due to reasons beyond our control, it took nearly two years to write a detailed proposal. An important aspect of the proposal was that it described in detail the designs of the instruments and associated signal processing electronics as well as technical plans for the realization of the instruments. The composition of the scientific and technical team of each instrument was also defined and a team leader for each of the instrument was identified. The proposed mission was named as AstroSat and the proposal was submitted to the Director, TIFR on behalf of the participating institutions, who recommended it to the ISRO Chairman for consideration.

The Chairman responded promptly and decided to have a review of the proposal at TIFR in September 2000 by leading astronomers and other scientists. The detailed proposal with its science objectives and proposed instruments was discussed critically at the review held on September 20, 2000. At the end of the discussion there was unanimity that the proposed AstroSat mission was well thought out and it will enable Indian astrophysics community to make outstanding contributions in a frontier area of science. It was recognized that AstroSat has the potential of propelling India to a leading position in high energy astrophysics.

By the end of 2000, the AstroSat proposal was approved by the Space Commission for development of science instruments and first instalment of development fund was received by TIFR. The Project Director was appointed in 2003 and he prepared a detailed Project Report for the approval of the Government. Finally the AstroSat project was approved by the Government of India in October 2004 for the development and launch.

An early description of the AstroSat instruments is presented by Agrawal (2006) and a more recent account of the AstroSat instruments and the mission can be found in Singh *et al*. (2014). The main characteristics of the 5 instruments are presented in Table 1.

Table 1. Summary of characteristics of AstroSat instruments.

Instrument characteristics	LAXPC	SXT	CZTI	UVIT	SSM
Detector	Multilayer, multi anode proportional counters	Conical foil mirrors in Wolter-1 geometry with X-ray CCD at the focus	CZTI pixelleted detectors of 5 mm thickness with 2D coded apert-ure mask	Twin RC telescopes of 38 cm aperture each with intensified CMOS detectors in photon counting or integration mode	Position sensitive proportional counters with 1-D coded aperture mask
No. of units	3	1	1	2	3
Field-of-view	$0.9° \times 0.9°$	40 arcmin. dia.	$4.6° \times 4.6°$ (10–100 keV) $17° \times 17°$ (at 150 keV)	28 arcmin. dia.	SSM1 and 2—$26.8 \times 100°$; SSM3—$22.1 \times 100°$, FWHM
Angular resolution	1–5 arcmin. (depends on source intensity) in scan mode only	~2 arcmin	17 arcmin (8 arcmin for bright sources)	~1.5 arcsec in 130–180 nm and 200–300 nm	~10–13 arcmin in coding direction and 2.5° across
Time resolution	10 μs	2.4 s and 278 ms	20 μs	2.0 ms	0.1 ms
Energy/wave band response	3–80 keV	0.3–8 keV	20–100 keV	130–180, 200–300 and 320–550 nm	2.5–10 keV
Energy resolution (FWHM)	~12 % in 20–80 keV	150 eV at 6 keV	~ 11% at 60 keV	<100–500 Å, depends on choice of filters	~ 25% at 6 keV
Geometrical area	10800 cm^2	250 cm^2	976 cm^2	1250 cm^2	57.6 per SSM cm^2
Effective area	~6000 cm^2 in 5–20 keV, ~5000 cm^2 in 33–50 keV	128 cm^2 at 1.5 keV, 22 cm^2 at 6 keV	480 cm^2in 10–100 keV	~10 cm^2 at 150 nm, ~40 cm^2 in 200–300 and 320–550 nm	~2.5 cm^2 at 2.0 keV, 51 cm^2 at 5 keV for 3 SSMs
Detection sensitivity	0.1 mCrab in 1000 s (3 σ)	$\sim 10^{-13}$ ergs $cm^{-2}s^{-1}$ (5 σ) (20000 s)	0.5 milliCrab (3 σ) (10000 s)	20th mag. in 200 s in 130–180 nm (5 σ)	~25 milliCrab for SSM1 and ~28 milliCrab for SSM3 (3 σ, 600 s)
Mass of instrument	419 kg	70 kg	56 kg	230 kg	65.5 kg
Required power (Watts)	65 W	53 W	50 W	87 W	41 W
Principal institution for the instruments	TIFR	TIFR	TIFR	IIA	ISAC
Typical observing time in pointed mode	1–2 days	0.5–1 day	2 days	30 min	10 min per FoV

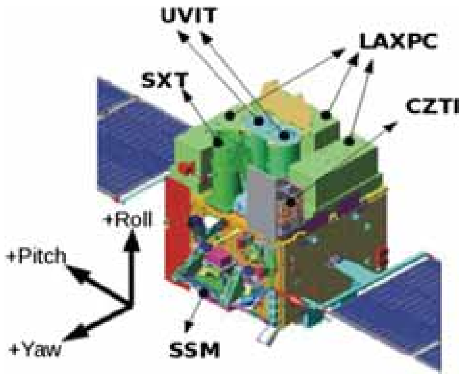

Figure 1. Schematic view of instruments on the top deck of the AstroSat satellite.

A schematic view of the 5 payloads mounted on the satellite is shown in Fig. 1. Note that the 4 co-aligned instruments (LAXPC, SXT, CZTI and UVIT) are mounted on the top deck of the bus with their view axes along the roll axis of the satellite. The UVIT is a single integrated instrument with twin telescopes. Similarly SSM instrument is a single unit with 3 detectors mounted on the side panel of the satellite with center of its view axis normal to the roll axis of the satellite. The SXT and UVIT instruments have one shot removable covers at their entrance aperture which are in closed position, at the time of launch. After a period of about a month for SXT and about 2 months for the UVIT, when outgassing becomes negligible, the covers of these two instruments were deployed in permanently open condition by radio commands. A detailed description of the individual instruments are presented in separate articles in this issue of the journal by the instrument teams.

6. Challenges in the development of the AstroSat science instruments

The realization of the AstroSat science instruments posed several technical challenges which took a long time to overcome and the instruments were finally successfully fabricated. The main technical challenges encountered for the different instruments are summarized below:

(a) *LAXPC Instrument*: The four LAXPC units, 3 for the flight and one engineering cum flight spare model, were to be fabricated. Each LAXPC has X-ray detection volume of 60 anode cells arranged in 5 anode layers, each 3 cm deep, surrounded on 3 sides by 46 number of veto anodes with cross-section of 1.5 cm $\times$ 1.5 cm to reject background events resulting from interaction of cosmic rays in the walls of the detector. This implies 106 anode cells of 37 μ diameter gold-coated stainless steel wires with of $\sim$2.5 to 3 kV HV. There are nearly 1200 cathode wires shielding the adjacent anode cells. Wiring of anode frames was a very painstaking and delicate work requiring care and precision to ensure proper tension in the wires and no dry solder. Each LAXPC wiring took nearly 9 months. To ensure light weight structure and no possibility of leakage, all the main detector parts were fabricated by milling from heavy aluminium alloy forgings. Fabrication of the 4 LAXPC parts took nearly 4 years in the TIFR Workshop. The most challenging part was fabrication of Field-of-View Collimator (FoVC) with FoV of about 0.9° $\times$ 0.9° opaque to X-rays of up to 80 keV within 30 kg weight. A detailed description of the LAXPC hardware and the collimator designs can be found in Roy *et al*. 2016. After intense efforts of about 3 years the FoVC design was evolved. The slats used in FoVC were made from 5 layers of Sn + Cu + Al, with thickness of 175 μ, glued with a very low outgassing epoxy and slits cut by laser cutting. A 50 μ thick Mylar film has been used as gas barrier that also serves as X-ray entrance window. When exposed to the atmosphere, molecules of oxygen, water vapour and carbon dioxide diffuse through the Mylar film and degrade the energy resolution. This necessitated inclusion of an on-board gas purifier unit based on the use of a bellow-based mini pump which forces the xenon gas through an 'Oxisorb' cartridge that can remove the impurity molecules. This was a new development which was successfully carried out by ISRO Inertial System Unit (IISU) and the purifiers are working well in orbit.

(b) *SXT*: This was technologically one of the most challenging part of AstroSat as there was no prior experience in India for the design of the X-ray reflecting optics. The SXT design required fabrication of about 320 gold-coated aluminium foil mirrors of paraboloid and hyperboloid shapes. The SXT team successfully developed the technique of making thin gold-coated foil mirrors approximating parabola and hyperbola surfaces by setting up a RF gold sputtering machine. Fabrication of mirror holder with precision machining to house 8 quadrants of mirrors and their alignment for a 2-meter focal length X-ray reflecting telescope to achieve about 2–3 arcmin angular resolution, was challenging but successfully realised by the SXT team. A Carbon Fibre Reinforced Plastic (CFRP) tube to house the SXT telescope optics was developed in-house by Vikram Sarabhai Space Center (VSSC) of ISRO meeting the exact specifications. The SXT needed an X-ray CCD cooled to about $-80°$C by a thermoelectric cooler and a heat pipe, as the focal plane detector. X-ray CCDs are custom-made devices as they need $\sim$30 μ deep depletion region. An agreement was reached with the X-ray astronomy group of University of Leicester (UoL) to fabricate the X-ray CCD camera with front-end amplifier as they had successfully developed a similar unit for the XMM-Newton mission. FPGA-based signal processing electronics of CCD camera was designed by the TIFR group. To ensure good energy resolution, electronic noise has to be kept very low which needed lot of efforts to achieve it. Alignment of the 4 mirror segments to achieve good image quality was also a challenge which was met successfully. In lieu of its contributions UoL was guaranteed 3% of AstroSat time.

(c) *UVIT*: Like the SXT, there was no prior experience in making UV reflecting mirrors in India which need very precise polishing to realise high reflectivity and low scattering for the UV photons. This challenge was successfully met by ISRO's Laboratory for Electro-Optics System (LEOS) which set up new facilities to meet the exact requirements of the UVIT mirrors and delivered the mirrors, meeting the design goals. The UVIT needed imaging photon counting detectors at the focal plane. It was realised that development of photon counting UV detectors with associated HV units in India, will need considerable time and efforts. Therefore, an offer from the Canadian Space Agency (CSA) to design and fabricate the 3 sets of detectors for the visible, FUV and NUV channels along with the associated electronics for the UVIT, was accepted. For its contribution, CSA was guaranteed 5% observing time on AstroSat. The fabrication of Invar tubes for the two telescopes of the UVIT and a titanium cone, holding the twin telescopes and used as interface for mounting the UVIT on the satellite deck, were other major hurdles which were successfully overcome.

An important goal of UVIT was to achieve angular resolution of $\leq$1.8 arcsec to probe deeper in the UV sky. This needed mirrors with very low scattering, baffles around the mirrors with very low scattering, stringent temperature control of the UVIT instrument, precision alignment of the optics and detectors, and strict contamination control. Integration, alignment, testing and calibration of the UVIT required setting up of a vacuum facility in a clean room of 100–1000 class with strict contamination control. After a lot of efforts this facility was successfully set up and made operational. This facility set up at Hoskote campus of IIA and known as M.G.K. Menon Laboratory, played a crucial role in the realization of 1.5 arcsec resolution in the FUV and NUV band of UVIT in orbit.

(d) Similar difficulties were encountered in the realisation of CZTI and SSM instruments. The design and fabrication of 0.5 mm thick tantalum CMA for the CZTI, which can withstand shock and vibration levels at launch, was also complex but successfully achieved. The characterization and calibration of each of more than 16 k pixels of CZTI detector was also a time intensive job done successfully.

SSM used position sensitive PCs in which carbon-coated quartz fibres of 25 μ diameter were used as anodes to locate position of each detected X-ray along wire length by charge division technique. Bonding of quartz fibres to feedthroughs by using electrically conducting epoxy required a lot of trial and errors but with persistent efforts the technical problems were overcome.

Ultimately by overcoming all the technical challenges, the 5 instruments were successfully installed, qualified and delivered to ISAC in time for integration with the satellite bus.

7. Major requirements of AstroSat mission and launch

A minimum mission life of 5 years was essential to achieve the science objectives. To achieve this and a low unvarying background, requirement of a low ($\leq 6°$) inclination 650 km circular orbit was projected. A near-equatorial orbit of 650 km has the advantage of (a) high cut-off rigidity for cosmic rays which implies little variation in their flux in the orbit, (b) density of atomic oxygen which can damage the optics of UVIT and SXT, is rather low in this orbit. AstroSat is a 3 axis stabilized satellite whose orientation can be changed by using magnetic torque and reaction wheels which get input from the 3 rate gyros and 2 star trackers. It can be pointed towards any target in the sky and a pointing precision of about two arcsec can be realised using data from the optical channel of the UVIT. In a day, 3–4 orbits of AstroSat are below the radio horizon and hence a 200 Gb solid state recorder is essential for storing data of 4 orbits. Requirement of a large number of ON/OFF, time-tagged commands and data commands was projected for the control and operation of the instruments in-orbit. A downlink of 105 Mb is required to download the stored data.

The AstroSat science payloads weighed about 855 kg and the fully integrated satellite has a mass of 1513 kg. Placing this satellite in 650 km near-equatorial orbit required PSLV XL version. The AstroSat satellite was successfully placed in the desired orbit by PSLV-C30 XL launch from Satish Dhawan Space Center, in India on September 28, 2015. Over a period of 2 months, one by one the instruments were turned ON. AstroSat instruments have been working for the last 15 months and have so far observed more than 200 targets. The analysis of data are progressing and several new results and discoveries are expected to emerge in the coming months. A glimpse of some new results is provided in articles on the 5 payloads.

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