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Challenges of realizing and operating AstroSat in-orbit

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Abstract. AstroSat, a dedicated Space Observatory of India, has completed five successful years of operation in space on 28th September 2020. AstroSat is a quite complex satellite, as it is a multi-wavelength observatory with many scientific instruments. The saga of many agencies, including Indian Space Research Organisation, the lead agency, and many scientists and engineers has resulted in realizing and operating this mission with excellent performance and highly satisfactory results. This mission generated a lot of observations leading to enhanced research activity for Indian astronomers, as well as international astronomers. It has also kindled interest, as expected, in young scientists and science students. The mission still continues in orbit contributing to celestial observations. AstroSat is a collaborative effort of many agencies not only from India but also from international agencies. The managers and the project team had to face many technological and managerial challenges at various stages of the mission. In this paper we present the challenges in conceiving a space science mission in India, and methods adopted to overcome them to make the mission successful. This may help in planning and executing future space science missions, more efficiently, meeting the growing demands from the scientific community involved in the frontier areas of space research.

Keywords. AstroSat—astronomy—space observatory.

1. Introduction

AstroSat, specialized in simultaneous multi wavelength observations, is the first dedicated Space Astronomy Observatory of India. It was launched on September 28, 2015, with a lift-off mass of 1515 kg, into a 650-km orbit, inclined at an angle of 6° to the equator, by PSLV-C30 (XL) rocket from Satish Dhawan Space Centre, Sriharikota (Seetha & Megala 2017). AstroSat, has completed five successful years of operation in space as a multi wavelength astronomical space observatory. AstroSat is meant to observe galactic and extra- galactic cosmic sources. Complete understanding of these cosmic processes involves enhanced sensitivity, spectral and timing resolution studies which calls for correlation and coordination between various ground-based and space-based observatories. AstroSat observes in a range of wavelengths spanning from UV, soft X-rays and hard X-rays, enabling simultaneous multi-wavelength monitoring with temporal and spectral variability. This multi-wavelength and simultaneous observational capability is the uniqueness of AstroSat.

The spacecraft carries five principal scientific payloads (Singh *et al.* 2014):

(i) Large Area X-ray Proportional Counter (LAXPC) has three identical instruments covering 3–80 keV region.
(ii) Cadmium–Zinc–Telluride Imager (CZTI) with coded mask aperture sensitive in 20–100 keV.
(iii) Soft X-ray imaging Telescope (SXT) uses X-ray reflecting mirrors and X-ray CCD for imaging and spectral studies in 0.3–8 keV.
(iv) Scanning Sky Monitor (SSM) for detecting and monitoring new and known X-ray sources in 2.5–10 keV region. It acts as a survey instrument for identifying transient and new sources.

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(v) Ultra Violet Imaging Telescope (UVIT) consisting of two identical telescopes. One telescope covers Far UV (FUV) band (130–180 nm) and the other covers Near UV (NUV) band (200–300 nm) and visible band (320–550 nm).

The science instruments on AstroSat satellite are shown in Fig. 1. Leading institutions responsible for the design and development of the science instruments are indicated in the parenthesis along with each instrument. LAXPC, SXT and CZTI instruments are developed by Tata Institute of Fundamental Research (TIFR) whereas UVIT instrument is developed by Indian Institute of Astrophysics (IIA). SSM payload is developed by ISRO Satellite Centre (ISAC). AstroSat is a complex mission involving many mission elements as shown in Fig. 2. Well-laid down scientific objectives and specifications of the science payloads (Koteswara Rao *et al*. 2009) have contributed to the success of the mission. Many leading Indian and international agencies/institutions played a key role in building, launching, operating and producing excellent science results by utilizing the observational data. As is the case with many space science satellites, a large number of technological developments were undertaken for both satellite bus and the science instruments.

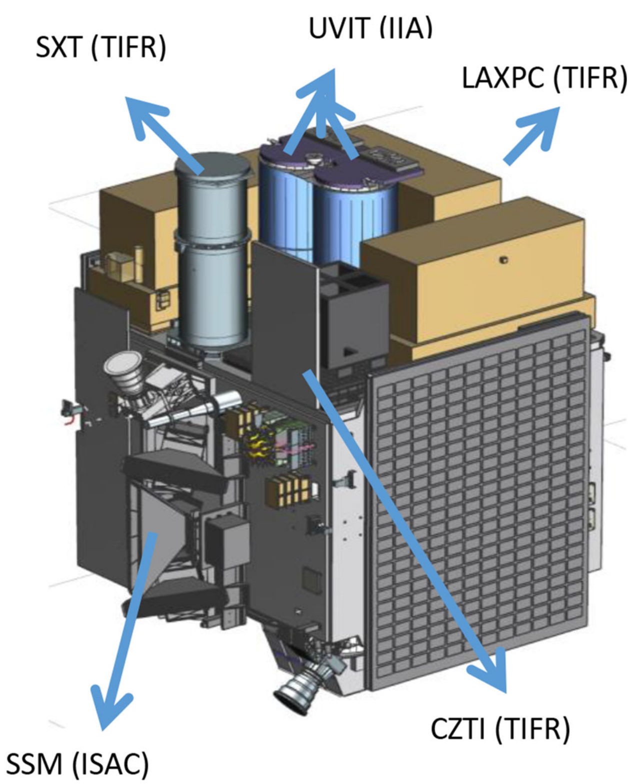

Figure 1. AstroSat with instruments.

2. Background

Aryabhata, India's first satellite, successfully launched into a near earth orbit on 19 April 1975, from a USSR Cosmodrome (Rao 1978), carried an X-ray astronomy payload. This payload was a gas filled proportional counter with a modest effective area of 15.4 cm^2. X-ray observations, on GX17+2 and GX9+9, were made using this payload (Kasturirangan *et al*. 1976).

IRS-P3 satellite, essentially an Earth observation satellite, launched by PSLV-D3 on March 21, 1996 carried proportional counters of the Indian X-ray Astronomy Experiment (IXAE). X-ray observations of the Galactic X-ray transient source GRS 1915+105 were reported, with the pointed payload. which showed remarkable richness in temporal variability (Yadav *et al*. 1999). The observations were carried out on 1997 June 12 to 29 and August 7 to10, in the energy range of 2 to 18 keV and revealed the presence of very intense X-ray bursts.

With this experience of building space grade astronomy instruments and doing advanced research in astronomy with space-based observations, Indian Space Research Organisation (ISRO), being a pioneer in space research, mooted the idea of a dedicated satellite for astronomy. The motive also included the idea of bringing all the Indian astronomers and possibly international astronomers together to build a space observatory and pave way for frontier research in the area of astronomy. The idea also was to kindle interest in young students to pursue science subjects and do good research work in space science. Chairman of ISRO, was firmly behind this idea and vigorously pursued it to take shape.

3. Conceptualization and project formation

Prior to the formal organization of AstroSat project, a lot of work was carried out by scientists from ISRO, TIFR, IIA, RRI and IUCAA. Two working groups discussed the proposals and gave recommendations. Subsequently another committee has conducted a detailed study on a mix of scientific payloads that would bring important contributions to high energy astronomy and astrophysics and would fill the gaps in scientific observations by all global missions present and near future. AstroSat configuration committee has evolved the overall satellite configuration. On April 03, 2003, an office order was issued by Chairman of ISRO/Secretary, DOS, on the organization of AstroSat

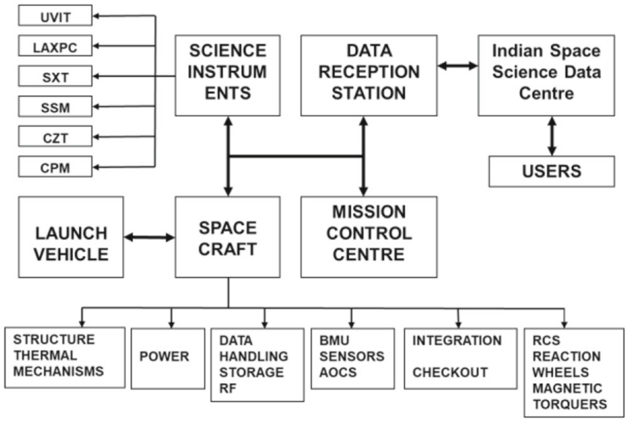

Figure 2. Mission elements of AstroSat.

project. Through this order, a Project Director with responsibility to realize the AstroSat spacecraft, its launch and on-orbit operations; a Principal Investigator with responsibility to realize the total scientific payload and coordinate the developments in respective work centres; two Programme Managers and three Project Managers with responsibility for the development and realization of various payloads; were identified.

The objective of AstroSat is to focus on high-resolution UV imaging for morphological studies of galactic and extragalactic objects, broad-band studies of X-ray sources and other multiwavelength targets ranging from nearby stars to the very distant active galactic nuclei (Koteswara Rao *et al.* 2009). Understanding high energy processes in binary systems, searching for black hole sources in the Galaxy, measuring magnetic fields of neutron stars, studying high energy processes in extragalactic systems and detecting new transient X-ray sources are some of the scientific objectives. Accordingly, AstroSat is configured to be a multi-wavelength astronomy satellite for studying the cosmic sources simultaneously over a wide range of the electromagnetic spectrum (from optical, ultraviolet to high energy X-rays).

Commensurate with the objectives of AstroSat, the salient features of the mission were set as follows:

- Build and operate a multi-wave length space observatory.
- Provide opportunity to academia to build instruments.
- Nurture space astronomy in the country.
- Inculcate scientific temper.
- International co-operation.

Within a few months of the project organization a detailed project report was prepared. Necessary government and financial approvals were accorded within a year.

3.1 *Satellite and science instruments configuration*

In the class of PSLV, XL version has the highest payload delivery capability. A mass of 1500 kg for the AstroSat satellite was contemplated considering the PSLV (XL) capability to place the satellite in the desired orbit. PSLV was a workhorse for all Indian Remote sensing Satellites (IRS). The volume is decided by this class of satellite bus. The mass and size budget for the science instruments (Navalgund *et al.* 2017) is given in Table 1.

As all the instruments with the exception of SSM have to look at the same source at any given time, all the instrument view axes were to be co-aligned and made to look in the same direction.

3.2 *Choice of orbit*

The altitude of the orbit, inclination and mass of the satellite are interlinked and together are dictated by the launch vehicle capability. The science instruments, in operating condition, can get damaged due to the radiations from the South Atlantic Anomaly (SAA) region if the satellite passes over it. From this point of view, a near equatorial orbit is preferred. There is no restriction on orbit height from the science instruments. Altitude selection is mainly based on atmospheric drag which affects the life of the satellite. Considering the PSLV (XL) capability altitude of 650 km and inclination of 8° were contemplated for a 1500 kg satellite. With necessary revisions from time to time the inclination goal was brought down to 6°. Altitude of 650 km and inclination of 6° were achieved for the 1515 kg AstroSat by precise launch. In the five years of operation no orbit maintenance was required.

4. Collaborative effort

AstroSat project is a fine example of an integrated effort not only by national agencies and institutions but also by international agencies and universities. For the first time, in Indian space research programme, all the payloads, with the exception of SSM, were completely designed, realized, tested, qualified, delivered and used by institutes other than ISRO. The national institutes include Tata Institute of Fundamental

Table 1. Mass and size of AstroSat science instruments.

Instrument	Mass (kg)	Size (mm × mm × mm)
LAXPC	415	1193 × 568 × 690 (each of three detectors)
CZTI	56	530 × 510 × 813
SXT	73	382 × 580 × 2482
SSM	75	1200 × 563 × 543
UVIT	230	877 diameter × 3100

Research (TIFR), Mumbai; Indian Institute of Astrophysics (IIA), Bangalore; Inter University Centre for Astronomy & Astrophysics (IUCAA), Pune, Raman Research Institute (RRI), Bangalore and Physical Research Laboratory (PRL), Ahmedabad. The international institutes are Canadian Space Agency, Canada; University of Leicester (UoL), UK and University of Calgary, Alberta, Canada (through CSA). TIFR developed three main x-ray payloads namely LAXPC, SXT and CZTI as well as a Charged Particle Monitor (CPM) instrument. IIA developed the UV payload with twin telescopes, one for far UV and another for NUV and visible, with 375-mm optics for each telescope. Laboratory for Electro Optics Systems (LEOS), a unit of ISRO developed, for the first time in the country, the UV optics with necessary coatings qualified for space application. University of Leicester contributed the detectors for Soft x-ray Telescope (SXT). Canadian Space Agency developed the critical electronics part for the UV payload. TIFR and IIA were funded, for the development of project elements, from ISRO. The costs of manpower, civil works, facilities etc. were borne by respective institutes. In the same spirit of true collaboration there was no monetary transaction of any sort between ISRO and, UOL and CSA. The contributions of the international agencies were acknowledged by means of reserved percentage of observation time. All technical and managerial issues, throughout the project period were amicably solved by mutual discussions and finding suitable solutions. The understanding between scientists and managers from all institutions is definitely one major cause for the grand success of the ASTOSAT mission.

5. Technical challenges

Globally, scientific satellites of the magnitude of AstroSat take longer periods for realization in relative comparison to their counterparts like Earth observation or communication satellites. The results from the scientific satellites are neither tangible in immediate future nor have any commercial value. Naturally they get lesser priority. AstroSat schedule was primarily dictated by the realization and availability of all systems. AstroSat had to be realized in parallel with many other missions. Apart from that the main reason for longer realization time is because of the state of art technologies and in a few cases breakthrough technologies that are required for scientific payloads and the satellite bus. The challenges were many in terms of managerial and technical terms. The space of this article permits a few major challenges to be reported.

5.1 *Detectors for UVIT*

The spatial resolution of the UV payload is set at an ambitious level of less than 1.8 arcsec. Galaxy Evolution Explorer (GALEX), a NASA Small Explorer for performing a survey of the sky in two ultraviolet bands was launched on an Orbital Sciences Corporation Pegasus rocket on April 28, 2003 at 12:00 UT from the Kennedy Space Center into a circular, 700 km, 29° inclination orbit. The instrument is designed to image a very wide 1.25 field-of-view with 4″–6″ resolution (Morrissey *et al.* 2005). The resolution of UVIT is set to be better than GALEX by 2 to 3 times. One of the key factors to achieve this resolution is the detector, configured as shown in Fig. 3. The electrons generated from the photocathode have to enter into the pore of the Micro Channel Plate (MCP) just below it without spilling to the neighboring pores. This can only be achieved if the front gap between the photocathode and MCP is very less. The lesser gap creates a technical challenge in terms of arcing, as a voltage of

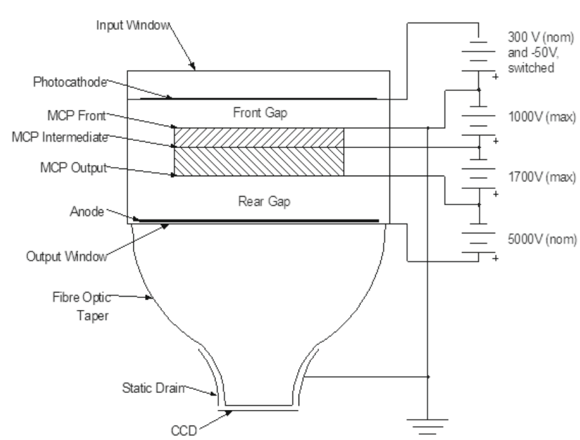

Figure 3. UVIT detector configuration.

300 V is applied between them, and the possibility of their touching each other due to the vibrations and shocks during the launch of the satellite. The credit for the successful development of these detectors goes to M/s Photek, UK. The challenge was taken by the management of Photek as scientific achievement rather than commercial success. It was a magnificent joint effort by Photek, IIA and ISRO teams.

5.2 *Mirrors for SXT*

Wolter-1 geometry optics is used in SXT. Two sections of the geometry with 4 quadrants in each and with a nesting of 40 layers needs a total of 320 mirrors. The mirrors are thin foils (0.2-mm thickness) of Aluminum with replicated gold surfaces on the reflecting side for each section (Singh *et al*. 2017). Each mirror is 100-mm long. The process of realizing these mirrors involves fabrication of a highly polished glass mandrel, sputtering of gold on to the glass surface in vacuum, adhering the aluminum foils to gold with epoxy and removing the foils from the glass. Technology and engineering skills with lot of care and patience are required to do such work. The SXT team at TIFR achieved this and produced the optics for SXT, for the first time in India with great success. This type of optics design is better suited for realizing X-ray payloads with less mass. Only a couple of countries, in the world, have produced such type of x-ray optics so far. Final measurements on these mirrors showed roughness of $\sim$7–10 Å, demonstrating the wonderful quality.

5.3 *Qualification of detectors for CZTI*

CZTI uses the large band gap semiconductor device, i.e. Cadmium–Zinc–Telluride (CZT). The detector has 64 modules divided into four quadrants, each quadrant containing a 4×4 modules. 256 pixelated contacts arranged in a 16×16 array in each module (Rao *et al*. 2017). The detectors were procured from M/s Orbotech, Israel, mainly producing the detectors for health care instruments. At the end of the year 2010, GE has acquired this company. This was the only source of these detectors and the supplier has no experience in space qualification of the products. The team with TIFR, VSSC (ISRO) and Orbotech scientists has mounted a programme to qualify these detectors and weed out the detectors with bad pixels. The testimony of the qualification is that, so far, no detector has failed on-board AstroSat CZTI.

5.4 *Mirrors for UVIT*

In the two telescopes of UVIT, primary mirrors are of 375-mm diameter. and a central hole of 155 mm. Secondary mirrors are of 140-mm diameter. The surface error for all mirrors is better that $\lambda/50$ rms and micro roughness better that 10 Å rms (Kumar *et al*. 2012). Average reflectivity of both the mirrors is better than 60% for the wavelength band of FUV (130–180 nm), better than 70% for the wavelength band of NUV (180–200 nm) and better than 80% for VIS (200–600 nm). Though there are lot of developments in the country for developing optics, all of them are in the visible domain of the optical spectrum and a few are in Infrared domain. There was no institute available within the country which has developed optics in Ultraviolet domain. This challenge was taken up by LEOS (ISRO) team with support from IIA team and produced the required mirrors with better performance than specified. The necessary coating technology was developed inhouse and qualified for rigorous space environment.

5.5 *Structural design*

The five payloads had their own unique mounting requirements on the satellite, with four payloads (UVIT, LAXPC, SXT and CZTI) requiring co-alignment (Navalgund *et al*. 2017). The proven Indian Remote sensing Satellite (IRS) bus was adopted for AstroSat. The real challenge was to accommodate the payloads with a mass of nearly 60% of the total satellite mass. The problem is further complex because the Field-of-View (FOV) clearance requirements for each payload as the others may obstruct the field or reflect/scatter into the instrument. With the skill, experience, long discussions between different teams and excellent understanding, these have been achieved. As the UVIT payload needed higher stability, it has been accommodated in the central cylinder, necessitating shifting of the propulsion system tanks elsewhere. The rotating platform for SSM payload carried more than 100 electrical wires to be connected to the inside electrical systems. Normal practice is to have these connections through rotating slip rings. But the size and mass of the rotating shaft becomes unwieldy. After careful consideration it was decided to rotate the platform in both clockwise and anticlockwise directions and avoid continuous rotation of more than 360°. The bunched twisted harness was qualified for the required number of rotations expected in the life of the mission.

5.6 *Thermal design*

Thermal requirements of UVIT payload are very stringent. Temperature of telescope tubes are to be maintained between 18°C and 22°C. Axial variation of temperature on telescope tubes is to be within +/−2°C. Circumferential variation of temperature on telescope tubes is to be within 5°C (Kumar *et al*. 2012). The telescopes are of nearly 2 m in length. One end of the telescope may be exposed to the sunlight when the other end is exposed to deep space. The surface areas for any passive control are limited. Prudent and exceptionally brilliant design of thermal team has achieved these stringent requirements and the proof is the on-orbit performance. But this is with a cost of increased number of heaters along the body of the telescopes and their control automatically. Special inorganic black coatings were developed yielding ultra-high emittance and absorptance which are employed for the Invar and aluminum tubes of UVIT payload.

SXT and CZT detectors are to be cooled. In CZT case passive cooling with heat pipes and radiator are adequate. In case of SXT in addition to heat pipe and radiator, an active cooling with a thermo electric cooler is used. The large size radiators are realized with honeycomb structures for low mass. The radiators are fixed to the spacecraft body using specially designed flexures for providing high thermal resistance and required structural stability. The ΔT requirement in case of SXT is beyond the limits of the existing heat pipe technology using ammonia. New heat pipes with ethane were developed for first time and successfully used to meet the requirements.

5.7 *Special mechanisms*

Special mechanisms were developed for payload systems. UVIT and SXT telescope have one-time operated deployable cover mechanisms and SSM has hold down, release and steering mechanism. Both UVIT and SXT employed paraffin wax-based actuators whereas SSM employed pyro cutter-based actuator. Both UVIT and SXT deployable covers are at the top end of the external baffle tubes and act as contaminant covers for the optical elements of the telescope on ground and during launch. In orbit, these covers are deployed exposing the telescope optics for imaging. In case of UV telescopes the deployed covers also act as Sunshades and the covers are deployed to 95 degrees while in SXT payload, the telescope cover deploys to 256 degrees. After deployment the covers are to be locked in position. The door mechanisms were accordingly designed and qualified for these functions.

5.8 *Contamination control*

Neither ISRO nor IIA had previous experience of fabricating, handling, transporting, assembling and testing of UV optics. The surface reflectivity and transmission of UV optical elements degrade with contamination in terms of deposition of particles or molecules. The absorption cross-sections in ultraviolet are very large, and great care needs to be taken to avoid any contamination (Kumar *et al*. 2012). The particulate contamination can be reduced by control of cleanliness during all phases of operation. The molecular contamination is controlled by using materials with low Total Mass Loss (TML <1%) and Collected Volatile Condensable Material (CVCM <0.1%). The materials passing these criteria are further tested for their potential for contamination before being accepted for use. Purging with high purity nitrogen gas is used at various stages of transport, assembly and even at launchpad. All optical components are open only in clean rooms of class 100. The thermo-vacuum chambers used for testing the payload and the satellite were thoroughly tested for cleanliness before loading the payload/ satellite. All the subsystems delivered to get integrated on to the satellite were baked at higher temperature for sufficient time to avoid any degassing in further tests/operations. 20-mm diameter × 2 mm thick windows of MgF_2 were used as witness samples for measuring possible contamination at every stage. The transmission of the window in UV range (120 nm to 180 nm) was measured and compared with its original transmission. The degradation in transmission gives the measure of potential of contamination. The witness samples were periodically checked for its transmission/reflection in 120–180 nm range. The goal for overall cumulative transmission/reflection loss on a witness sample was set to be <5%. It is gratifying that the witness windows kept with the detectors and the mirrors have not shown any measurable loss of transmission during the life cycle of AstroSat.

5.9 *Data storage and handling system*

The payloads are always ON and continuously obtain science data. The peak data rates vary differently and it depends on mode of observation. The volume and data rate is high for UVIT payload. There is no direct real time transmission of payload data to ground station. The data is always recorded onboard storage and played back. A single ground station, located at Byalalu, Bengaluru, was contemplated to receive the data stored from all the payloads. The data storage and handling systems so far developed by ISRO operated in exclusive mode of either 'recording' or 'playback'. When it came to AstroSat the observations continue during the play back of the data also and this data at any cost cannot be lost. Therefore, the system was newly designed with the feature of simultaneous playback and recording capability. After AstroSat this type data storage system has become normal for almost all the subsequent satellites of ISRO. For the same reason of downloading the data from satellite to the ground station, during radio visibility, a fixed orientation RF antenna would not be sufficient as the observation direction and the ground station direction vary from time to time. Two-phased array antennae were configured, with electronic beam steering capability, each having a coverage of one hemisphere.

5.10 *Integration and testing*

Each model of payload instrument at unit level underwent electrical interface compatibility tests, vibration, and thermal-balance and EMI-EMC tests. A very well chalked out sequence of integration of systems is followed totally in lines of contamination control. During the integration activity and disassembled mode all systems are tested for functional performance. The totally assembled spacecraft underwent functional and performance tests, end to end tests before and after the environmental tests, vibration and thermo-vacuum, autonomous tests, mass properties check, field-of-view and polarity checks, alignment tests, acoustic testing, fit check with launch vehicle adapter, clamp-band release and mechanisms functional tests, solar panel deployment and payload cover deployment tests. Compatibility with communication with ground station equipment is also tested. Thermal-balance tests is carried out to validate the thermal mathematical models and to verify the ability of the thermal control subsystem to keep payloads and spacecraft equipment within specified temperature limits under simulated extreme expected orbital conditions. Minor failures of systems, electrical or mechanical, that occurred during these tests are fixed using special procedures and tools different from conventional methods complying to the contamination control procedures. UVIT, SXT, SADA are continuously purged. The LAXPC and SSM units are bagged and continuously purged. All the tests, including vibration tests and mass properties measurements, are conducted in 10,000 class clean room.

6. Managerial challenges

Apart from many technical challenges, some of which are briefed in the previous section, AstroSat mission had its own peculiar managerial challenges also. Again, without going in to the details of all the challenges a few of them are listed in this section.

6.1 *Collaboration of many agencies*

As told earlier, AstroSat is a fine example of collaborative effort involving many Indian and international agencies/institutes. It harnessed and synergized the expertise of the individual agencies. It brought international character to an astronomical observatory in space. It also brought some cost benefits to the project and the project was realized within the budget allocated. During the initial period of the project, there were wide differences of opinions among different teams. The authors' firm opinion is that they are mainly due to the cultural differences between scientists/engineers from different institutes. The challenge of the project team was to see that they do not grow and act as moderators between teams. This was a delicate and strenuous job requiring lot of patience and balance of mind. This job, nevertheless, was meticulously achieved by the small project team. After AstroSat, handling of such collaborations have become much easier as the cultural differences were narrowed and each team understood them in proper perspective. AstroSat project, in a way, paved a path for managing larger collaborative missions.

6.2 *AstroSat payload monitoring committee*

At some stage, luckily almost in the beginning phase of cutting metal for the payloads, it was felt that monitoring and reviewing of the payloads is not going to be a simple task. Recognizing this, AstroSat Payload Monitoring Committee (APMC) was constituted, under the chairmanship of Dr. George Joseph, Former Director of Space Application Centre, ISRO. This committee had eminent scientists as members. The credit for excellent reviews, controlling and managing the schedules, overseeing the testing and calibration goes to this committee. Constituting 'Payload Monitoring Committees' has become a norm in ISRO for subsequent science missions.

6.3 *Contamination control committee*

The need for contamination control has already been briefed in Section 5.7. Though the requirement was known, very little was known about the methodology to achieve it in a systematic manner. In order to streamline this activity, a new committee (this type of committee did not exist for any previous missions of ISRO) was constituted. This committee has done a wonderful job of budgeting the contamination down to each subsystem and taking stock of bill of materials in terms of quantity used and their contribution. The contamination budget was done for the first time. The committee also chalked out procedures for controlling the contamination at various levels starting from component to launch of satellite. This definitely was a new learning and done meticulously. The proof is in seeing the performance of the instruments in space and more evidently from the measurements carried out on the witness samples on ground. Needless to say, some of these practices have now become routine in the U R Rao Satellite Centre.

6.4 *Managing the observation proposals*

The first six months of the AstroSat observations were designated as 'Performance Verification' (PV) phase. The next six months were 'Guaranteed Time' (GT) phase. A year later, regular observations started with reduced time for GT. The observation time allocation is based on the merit of the proposals, Percentage of time allocated for various groups of observers and technical feasibility. The users are divided in to seven groups:

(i) AstroSat instrument teams,
(ii) Canadian Space Agency,
(iii) University of Leicester,
(iv) Indian astronomers,
(v) International astronomers,
(vi) Targets of Opportunity (ToO) and
(vii) Calibration.

Each group is allocated with a fixed percentage of observational time. As the time allocation and studying the feasibility of observation are quite involved, the need for managing this is quite evident. In order to manage this efficiently and effectively two committees, AstroSat Time Allocation Committee (ATAC) and AstroSat Technical Committee (ATC) were formed. Submitted proposals were reviewed and approved by the ATAC with the help on technical feasibility assessment provided by the ATC. ATC considers payload operation constraints like avoidance of bright objects, constraints on source location with respect to Sun, Moon, etc, and source detectability in various instruments. Based on these approvals, the mission and operations team at U R Rao Satellite Centre and ISRO Telemetry, Tracking and Command Network (ISTRAC) creates the necessary list of targets to be observed. This proposal management system worked very well over the past five years and continues to work with enhanced enthusiasm.

7. Establishment of new facilities

Many new ground systems and facilities have been established under the scope of AstroSat mission. A couple of important facilities are listed here.

7.1 *Indian Space Science Data Centre*

AstroSat is operated as Space Observatory. The data received from the ground station is to be validated, archived, stored and disseminated. The data is to be transferred to the corresponding groups as listed in Section 6.4 after a certain level of processing. The user groups process the data further and post it back to the repository. In order to cater to this requirement on a routine basis an Indian Space Science Data Centre

(ISSDC) is established under the management of ISTRAC, ISRO. This data centre maintains the lock-in rules provided to the instrument scientists and the proposers. After the lock-in period the data is made available all the interested scientists including university students. Both raw data and the processed are accessible for any user, either on dedicated lines or through internet. ISSDC, now, has grown in stature. Apart from AstroSat, it is catering to all science missions of ISRO including Chandrayaan, Mars Orbiter Mission and Meghatropiques.

7.2 *M.G.K. Menon Laboratory for Space Sciences*

IIA has set up a world class facility, with ultra-high clean rooms including a class 100 room, for assembly and testing of optical instruments especially UV optics. This was necessary for the development UVIT payload of AstroSat. This facility is in Hosakote, now outskirts of Bengaluru. This facility is declared as a national facility. All future optical instruments, where cleanliness is of importance, can be assembled here and tested using the test equipment available. With further improvements by IIA, work is already in progress, for the development and testing of Visible Emission Line Coronagraph (VELC) payload for Aditya-L1 satellite.

8. Results

The proof of success of any mission can be evaluated, to a large extent, by means of the results achieved. By this standard, AstroSat mission achieved a grand success. More than 1500 scientific papers/announcements are published just prior to the completion of five years of the satellite launch. Out of this, at least 150 papers are in refereed journals. Currently, AstroSat has nearly 1500 users from 48 countries around the globe. It is heartening to note that half of them are from India. These users also include, academicians and students. To the best of our knowledge, 15 PhD theses, so far, are based on AstroSat data. Over 900 unique fields were observed by AstroSat over the last five years.

There are numerous headlines, some of them are sensational like “India’s AstroSat makes rare discovery”, in both print and electronic media in India and abroad. Many of them surely are/will be reported by means of scientific papers.

9. Conclusion

AstroSat mission is conceived, designed, managed, executed and operated satisfactorily. The mission was managed without any cost over runs in spite of a little time over run. The technical, managerial and techno-managerial skills employed in this mission are unique for Indian Space Science mission. It is a great experience to the project team with several lessons learnt. Some of these skills, tools and techniques may be useful for next generation of scientists, engineers and others if they can adopt, improvise and employ them. AstroSat, though designed for an operational life of five years, is in still good health. Hardly any fuel is used for the orbit maintenance., AstroSat is expected to serve for many more years to come, subject to no component failures. The mission accomplished all its objectives. It is heartening to note it energized the Indian astronomy community and kindled the interest of science in many young students.

Acknowledgements

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