Challenges in design and development of very high resolution Cartosat-2 Series imaging systems for earth observation

Arti Sarkar[1], B N Sharma, Manish Saxena, Ravi Atreya, Anish Saxena, H K Dave, S S Sarkar
Electro-optical Payload Integration Division, Electro-Optical System Design and Integration Group, SEDA
Space Applications Centre (ISRO)
Ahmedabad- 380015, India
[1]Email arti@sac.isro.gov.in

ABSTRACT: Cartographic missions' demand sub meter resolution imaging systems with very high revisit capability for cadastral level mapping and host of other applications. Indian Space Research Organization (ISRO) has launched and operationalized Cartosat-2 series of satellites for these purposes with 0.8 m Panchromatic (PAN) imageries from a highly agile platform. In order to augment these services with enhanced imaging capabilities and provide sustainable services, Cartosat-2S series payloads have been designed and developed. With the incorporation of state-of-the-art technologies, three payloads were realized to provide both PAN and Multispectral (MX) coverage with improved GSD (0.65m PAN & 1.6m MX), SNR and imaging efficiency by using TDI detectors within the constraint of previous Cartosat-2 series telescope and mainframe configuration. In order to achieve 10 km swath using available small format detectors, an innovative optical butting configuration was worked out and 5 TDI detectors for MX and two for PAN were accommodated in the available focal plane. Additionally, video capturing capability was introduced in this mission by accommodating two event monitoring cameras in the focal plane. All these posed great challenges in design and realization of focal plane assemblies, electronics systems, mechanical system and assembly integration and testing (AIT) of Cartosat-2S payloads.

In this paper, authors bring out various design challenges in accommodating large number of components in the existing Cartosat-2 payload envelope. Criticality in development of each subsystem is discussed with emphasis on new elements used. Challenges in realization of optically butted focal plane assemblies is presented. Development of various tests setups for payload realization is discussed in detail. Criticalities in Assembly, Integration and testing (AIT) aspects are brought out. Results obtained as part of performance evaluation tests of integrated payload are analysed and presented.

I. INTRODUCTION

Recent years have seen major thrust in development of very high resolution space borne imaging systems across the globe with both public and private players seeing the potential usage of high resolution imageries for development of various cartographic applications. Indian Space Research organisation (ISRO) had successfully deployed sub meter class Cartosat-2 series payloads to meet national demands. To meet the increasing user demands for cartographic applications at cadastral level for the development of various urban and rural resource management, coastal land use and regulation, utilities mapping, LIS and GIS applications with increased revisit capability etc., ISRO envisaged development of Cartosat-2S series mission with enhanced imaging capabilities to augment the data services. The stride taken by the ISRO resulted in successful launch of three payloads in the current series, which are providing excellent imageries.

Major challenges in the design and development of the current series was to enhance the existing imaging capabilities in terms of better resolution, increased imaging time, improved SNR, incorporation of multispectral imaging chain and include video monitoring features within the constraint of retaining the telescope and mainframe configuration same as previous mission. This posed great design challenge and was overcome by configuring the system with the selection of state-of-the-art technological components, innovative utilization of focal plane using optical butting technique, optimum utilization of real estate near focal plane to accommodate Focal Plane Assembly (FPA) and associated electronics systems, usage of flexi PCBs to reduce volume of interconnections etc. The realization process was equally challenging as large number of systems were to be assembled and integrated with very tight margins, newer components and processes needed to be qualified, bread board models to be developed to demonstrate adequacy of new techniques used, subsystem level interface tests to be carried out to bring out compatibility issues and so on. And all these were required to be carried out within a very tight project schedule.

The above aspects required thorough validation of designs and processes, identification of error sources and handles to control the errors, proper assembly and integration sequences, development of test setups for exhaustive testing and characterization, meticulous planning and execution of the activities to realize three payloads within a short span of 1 year.

This paper, in subsequent sections, highlights design challenges and finalized configuration details to meet user requirements, subsystem design and development aspects with emphasis on newer components, test setups, challenges in AIT of payload, test and evaluation aspects, performance characterization and at the end presents the results and data analysis outcomes.

II. SYSTEM DESIGN CONSIDERATIONS

As stated earlier, payload system design was constrained with retaining the similar telescope and mainframe configuration, it was very challenging from system design point of view to achieve enhanced electro-optical design and performance parameters compared to Cartosat-2 series as shown in Table 1.

Table 1: System design goals for Cartosat-2S

Parameters	Cartosat-2/2A/2B (630 km orbit)	Cartosat-2S (505km orbit)	
		PAN	MX
GSD (m)	0.79	~ 0.65	~ 1.6
Swath (km)	~ 10	~ 10	~ 10
Spectral Bandwidth (µm)	0.5-0.85	0.45-0.9	B1: 0.45-0.52 B2: 0.52-0.59 B3: 0.62-0.68 B4: 0.77-0.86
SWR (%) @ Nyquist freq.	> 10	> 10	> 20
Saturation Radiance (mW/cm2-str-µm)	55	55	B1: 53 B2: 53 B3: 47 B4: 31.5
Quantization (bits)	10	11	11
SNR at Saturation	> 180	> 180	> 300
Envelope (mm) R x P x Y	775 x 775 x 1415	775 x 775 x 1415	
Weight of EO module (Kg)	105	< 120	
Unregulated power (W)	57	<70	<130
Data rate generated (Gbps)	0.336	2.4	1.5
Compressi-on ratio	3.2:1	Variable CR	

To meet above design goals various trade off studies on designs of different elements in the EO imaging chain were carried out and final configuration was arrived which meets the above design goals with adequate margins.

The primary goal was to achieve 0.65 meter GSD for Panchromatic chain. For this the orbital height was reduced to 505 km from 630 km as it was constrained to increase focal length further and/or decrease pixel size of the detector. However, reducing the orbital height reduces the field of view and hence swath coverage. In order to retain the swath, the field correcting optics in the telescope was modified to increase the field of view from +/-0.5 degrees to +/-0.6 degrees. Also to increase number of pixels from 12K to 15K, two PAN TDI detectors were used in optical butting configuration. Similarly, for MX chain 1.6m GSD and 10 km swath was achieved by using 5 optically butted TDI detectors in the focal plane. Quad line TDI detectors were selected for MX chain to form four bands using strip filters. This approach drastically reduced the resource requirements associated with the usage of individual TDI detectors. In the innovative optical butting configuration, main telescope rays reaching the focal plane was spilt in along-track direction using two fold mirrors to form PAN and MX focal planes. And by using one butting mirror in the path of converging rays just before the focal plane, two 8K TDI detectors were accommodated in two orthogonal planes. Similarly, 3 and 2 detectors of MX chain were accommodated in two orthogonal planes by using two butting mirrors. In order to accommodate two Event monitoring camera chains, two individual fold mirrors were used in the across track direction at both ends of the focal plane. This kind of optical arrangements required sub-micron level accuracy in the alignment of individual mirrors and detectors in the focal plane. This also considerably increases complexity in mechanical design of the focal plane and accommodation of 9 detectors, 7 fold mirrors and their associated electronics packages in the available real estate. The mechanical design should ensure structural integrity and also provide provisions for alignment and easy assembly & integration of individual subsystems. Thermal management of the focal plane also became critical as large number of detectors were required to be operated simultaneously resulting in high dissipation in the focal plane. All these aspects were adequately addressed and included in the design.

This complex system design involving increased GSD and usage of new TDI detectors, posed great challenge in the design of Electronics systems to meet architectural clocking, biasing and read out requirements of two different type of TDI detectors. The increase in GSD resulted in increase of line frequency to 11.2 kHz from 2.7 kHz in the previous mission. In addition, 11-bit quantization was envisaged to provide better radiometric resolution with high dynamic range coverage. These two factors required design of very high speed and low noise electronics systems to meet 11-bit performance. All these design challenges were met with usage of state-of-the-art components like high-speed low noise analog front-end devices, high speed SerDes interfaces for ~4 Gbps data link etc.

Considering the dense accommodation near the focal plane, innovative interconnection technology and assembly, integration and testing (AIT) approach was required to carry out error free AIT and thorough characterization of the developed system.

In the system design phase, reliability and quality aspects were also addressed. Redundancy at detector level would increase the real estate requirements. Within each chain, the full swath is realized using multiple detectors. Thus this configuration provides inherent immunity against single point failures. Configuration of camera electronics and payload power is kept modular and separate for each detector. Thus, failure of any detector would reduce available swath and not lead to loss of entire band. Figure 1 below shows the envisaged payload chain and Figure 2 shows the optical schematic of the payload and arrangements in the focal plane.

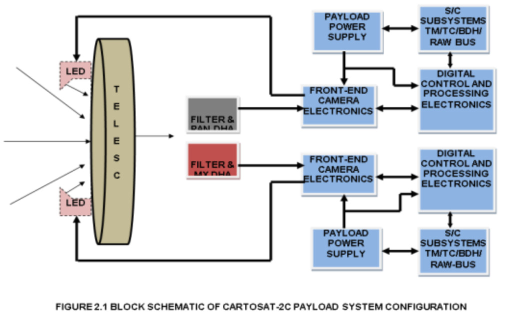

Figure 1: Camera Chain

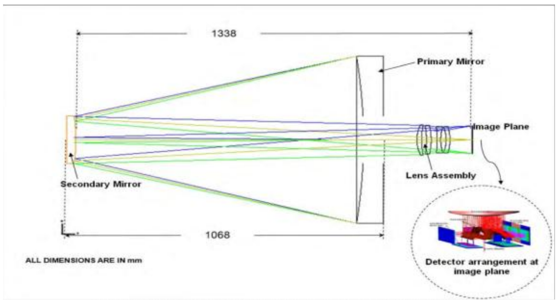

Figure 2: Optical Schematic and Focal Plane Arrangements

III. DESIGN AND DEVELOPMENT OF PAYLOAD SUBSYSTEMS

With the detailed trade-off studies a realizable payload configuration was worked out. The next challenge was to develop various subsystems independently and make them available for final integration and testing. This section discusses briefly the realization of different subsystem and brings out challenges.

TELESCOPE DEVELOPMENT:

As mandated similar modified RC telescope system consisting of a two-mirror telescope, four-element lens assembly (FCO) and a band pass filter was used. The FCO is used to correct the aberrations at the larger field of view (+/-0.6°) and also to flatten the image. Band pass filters placed close to the CCD define the band shape. A 700mm diameter Primary mirror collects the earth radiation and reflects it onto the secondary mirror. The reflected radiation from the secondary mirror is focused on the TDI detectors kept at the focal plane of the system after passing through the FCO. Both Primary and Secondary mirrors are light weighted. Five short format TDIs and two short format TDIs are used to realize the Multi-spectral and the Panchromatic bands respectively. Quad TDI detectors are used for MX forming four bands. Each active area consists of 1340 vertical columns and 45 horizontal TDI stages of 17.6 X 17.6 µm pixel size. Two 8k TDI detectors are used for panchromatic band each consisting of a single array of 8192 vertical columns and 80 horizontal TDI stages of 7 X 7 µm pixel size. The multi-spectral bands and the panchromatic band are separated by 22 mm in the focal plane which corresponds to 1.98 km on ground. Multi-spectral bands are leading while the panchromatic band is trailing. Complete telescope design was carried out and expected telescope MTF performance was derived considering effect of baffles, assembly stresses, gravity effects, assembly and integration aspects etc. Back focal length was also determined with the new FCO design. Detailed tolerance analysis on all performance parameters was also carried out for the finalized design.

Based on the design, individual mirrors and FCO was fabricated at LEOS and delivered for telescope realization after satisfactory component level and bench level global test and evaluation. Primary Mirror mounts were first assembled on CFRP base plate and then PM was bonded to the mounts. Similarly, Secondary mirror was also bonded to its mounts. Special interferometry based test setup was developed and extensively used to carry out pre and post boding interferometry tests on the mirrors. Bonded mirrors were subjected to environmental test to release bonding stresses. All the components were then assembled to indigenously developed CFRP light weighted structure to realize the telescope. Throughout the development phases interferometry tests were conducted to ensure designed optical performance. Interferometry test setup is shown in Figure 3.

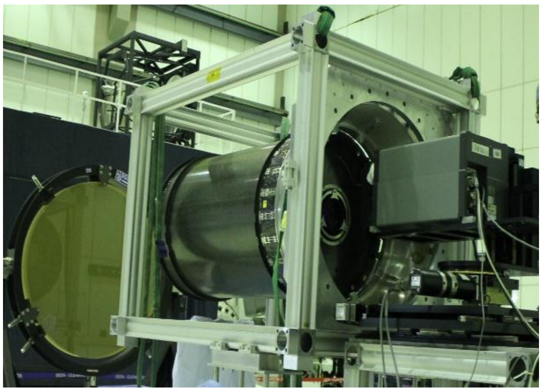

Figure 3: Interferometry Test Setup

FOCAL PLANE ASSEMBLY (FPA) DEVELOPMENT:

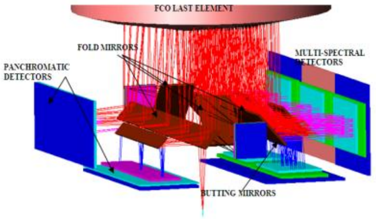

Figure 4: Focal Plane Assembly Model

In the focal plane of telescope, detectors are placed to convert light energy into electrical signal for further processing. Physical size of the detectors selected for this mission are almost twice the active size and therefore when placed inline, results in discontinuous swath and also exceeds the field of view of ±0.6º. Challenge lies in positioning the detectors within field of view of ±0.6º while ensuring continuous swath. This requirement is met by using optical butting technology in which the optical image is divided into the required number of segments and a corresponding image sensor receives each of the sub images. An optical device like a flat mirror can be used to divide the image line into segments. A high-resolution large format image can be obtained by compositing the separate image parts together. The same model is shown in Figure 4. It may be noted that alignment of detectors is very crucial and also the fold mirrors used in the optical path causes secondary diffraction effects. However, all these aspects have been very well studied in a development model butting module and required tools and expertise have been developed.

Figure 5: Realised Focal Plane Assembly Model

The development of focal plane assembly (FPA) was carried out in parallel with telescope, so that both are available at the same time for integration. For this, all the small size fold and butting mirrors were bonded to their respective mounts with high precision. Individual detectors were also glued to their mounts. For MX chain two Interface plates (IPs) were developed each accommodating two and three MX detectors respectively. These two IP plates were assembled to the FPA box. Similarly, two detectors of PAN were also mounted on the box. Active and passive alignment methodology was developed and used extensively for aligning MX and PAN detectors, EVM-1 & 2 detectors were also assembled on FPA box at their respective locations. Refer Figure 5.

PAYLOAD ELECTRONICS (PLE) DECK DEVELOPMENT:

All the payload electronics packages need to be accommodated near the focal plane. For this a CFRP based honeycomb deck with Al face sheet on both sides was developed. This deck has provisions for mounting all the power supplies on the one face (front face) and all electronics packages on another face (rear face) as shown in Figure 6 and 7 respectively.

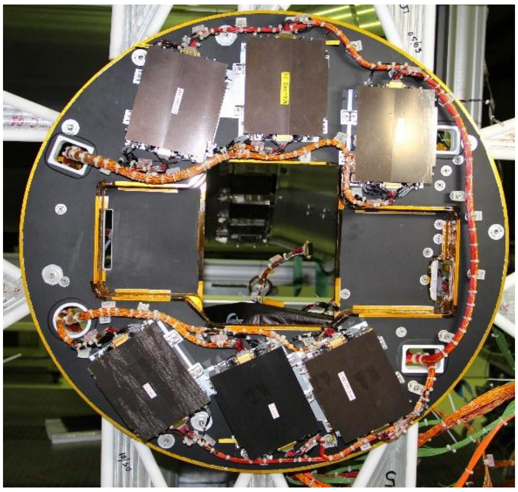

Figure 6: PLE Deck Rear Face (PLE Side)

Before the realization of the deck, various design studies have been carried out to locate various packages and appropriate provisions were made from accessibility point of view. The study revealed that the interconnection from MX detectors to Front end electronics needs to be with flexi PCB. Further, requirement of Flexi PCBs for interconnecting front end to back end electronics was also realized due to the less real estate available near the focal plane for supporting conventional harness. 20 flexi PCBs of different shape and length was realized to interconnect 20 modular MX electronics chains. Interconnection sequence was also decided during design phase as these PCBs cannot be crisscrossed as they are twisted. Provisions for supporting these flexi-rigid PCBs were also worked out. Special provisions were made for the harness passage between subsystems. After the PLE deck layout and design finalization, a dummy deck was used as harness zig and plan was worked for parallel development.

This PLE deck has interface with spacecraft cone through eleven Al brackets at multiple locations. Special grounding schemes were implemented in the PLE deck. Three ground posts were connected from both rear and front side to provide electrical contact. All EMI/EMC guidelines were followed during harness fabrication. After receiving all electronics packages, PLE deck was populated with these packages as per layout drawing. All the harness assemblies were transferred to this FM PLE deck from the dummy deck. This approach was extremely helpful as it avoided excess length in the harness, no rework in the routing path was required. Clear routing Electrical input/output verification was carried out and packages were powered through the active setup and package level performance was satisfactory. With this PLE deck was made available for integration with telescope. Refer Figure 8.

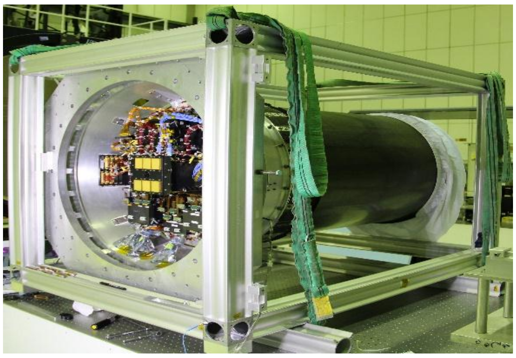

Figure 8: PLE Deck Integrated with Telescope

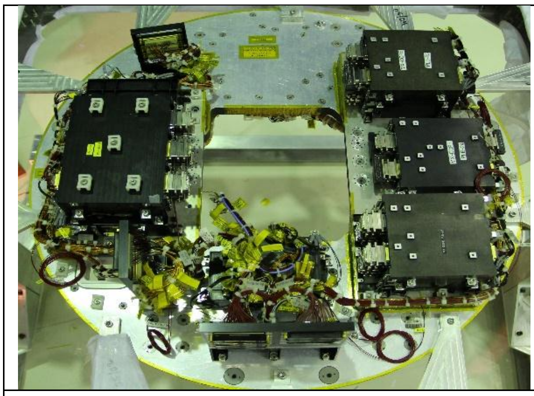

Figure 7: PLE Deck Front Face (PPS Side)

IV. DEVELOPMENT OF TEST SETUPS:

Various tests setups are required to facilitate assembly, integration, testing and characterization of EO imaging payloads. These setups simulate the spacecraft interfaces, operating conditions, simulate input scenes, provide ground support for AIT activities, help in monitoring and measurements of various EO parameters, help in carrying out spectral and radiometric calibration of the final integrated system etc. apart from these, the setups should be designed to be fault tolerant so that error should not propagate and damage the EO system. For development of Cartosat-2S imaging system large no of test setups, zigs etc have been developed. Detailed characterization and calibration of these setups have been carried out and safety aspects were ensured before their use with FM system.

Figure 9: Integrated Test Setup

In order to operate the payload and carry out various tests, integrated payload test setup was developed as shown in Figure 9. This setup has all the ground checkout units, which simulate the mainframe electrical interfaces in absence of the spacecraft during payload testing. The setup is used to power ON the system, operate the payload in various configuration, acquire data and analyse the data. Various health parameters of the payload have also been acquired and processed by the setup. The setup also include various interconnection harnesses required for payload and setup interfaces. Individual units of the setup have undergone test and evaluation exercise.

Zygo interferometer based test setup has been developed to facilitate testing of various optical components and also the assembled telescope during the entire development cycle. Optical wavefront quality during various assembly processes are analysed to ensure no stresses are introduced in the system. This setup helps in estimating MTF performance of the payload.

A 1.2 m diameter two mirror based Scene simulator as seen in Figure 10 have been used to test the developed telescope and later integrated payload. In the focal plane of the scene simulator different target patterns such as SWR patterns for different Nyquist frequencies are kept and projected on to the payload. This scene simulator is aligned and characterised for its performance before using it for FM payload optimization. Refer Figure 10.

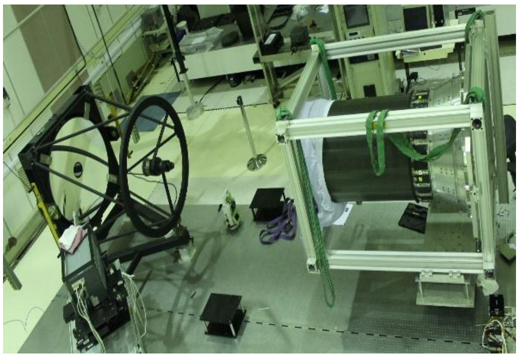

Figure 10: Integrated Optical Test Bench

In order to develop and characterize the focal plane assembly both passive and active test setup have been developed. Passive setup is based on a very high resolution microscope and fixtures for mounting the FPA with provisions to align individual small mirrors and detectors. The active setup is developed to operate the individual detectors to confirm and refine the alignment achieved through passive setup. The active setup consists of electrical system to operate two detector chains and acquired data carry out data analysis and derive alignment parameters.

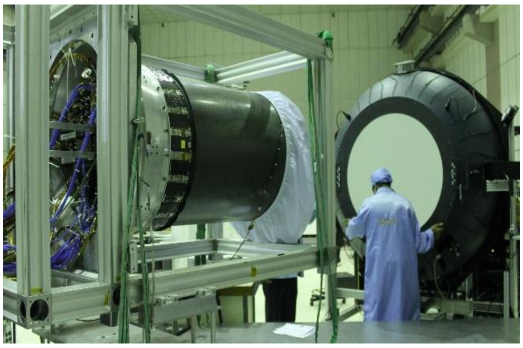

Figure 11: Calibration Setup

LED based light source has been developed and used innovatively to facilitate area array mode of operation of TDI detectors. This is achieved by operating the LEDs in strobed mode and in sync with TDI operation. This allows to acquire the data in area array mode and precise target location (x,y co-ordinate) in the image plane is known with 0.01 pixel accuracy.

A large aperture Integrating sphere (Figure 11) with its output spectrum and radiance traceable to NIST standards has been used to carry out radiometric performance of the system. A monochromator based spectral calibration setup was also used for calibration of the EO imaging system. In order to demonstrate and evaluate TDI imaging capability, relative motion is required between object and the imaging system. For this a special test setup, consisting of a rotating target with matching speed of TDI line rate, was developed to demonstrate the TDI imaging capability on ground. Different images were put on a drum structure and were mounted on a motorized rotary platform. This rotary was put in the focal plane of the scene simulator and images were acquired by the payload. This setup was used extensively during payload level testing and spacecraft level testing also to evaluate end-to-end performance. All these setups were successfully developed, individually characterised and used extensively during testing.

V. INTEGRATED PAYLOAD DEVELOPMENT

Integrated payload development is a multi-disciplinary activity involving assembly, integration, testing and characterization (AIT) of the EO imaging system. A meticulous AIT plan and sequences helps in understanding interaction among different subsystems and helps in solving interface compatibility issues. It also helps in achieving good control on system performance degradation factors such as stresses arising due to assembly processes, EMI/EMC environment due to setups and interconnecting harnesses etc. A detailed AIT plan for Cartosat-2S series payloads was prepared and assembly sequences were worked out. During the design phase itself it was realized that the assembly and test sequence is very crucial as any kind of rework can lead to complete dis-assembly of the payload. For the first time detector soldering process was part of the integration sequence and was achieved using specially designed fixtures with excellent workmanship. Refer Figure 12. All thermal implementation such as heat pipe fixing, LE tape fixing, thermal tape/grease implementations etc. were carried out as per sequence. All the electronics packages and power packages were assembled onto the PLE deck and interconnecting harness routing was carried out. All electronics chains were powered and verified for input output functionality before assembly of PLE deck with telescope. At this stage focus optimization was carried out to determine the best focus. PLE deck assembly with telescope was a very challenging job as at this stage complete FPA is assembled with telescope and it has to pass through a cut-out on PLE deck with very tight margins. Flexi PCBs were adequately supported on the PLE deck using kapton tapes. Final harness routing and supports were provided as per harness routing layout.

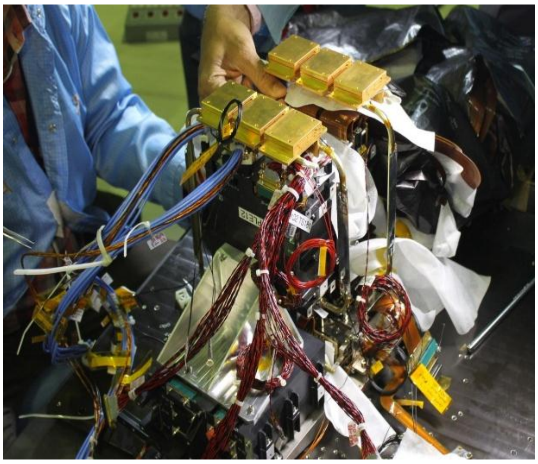

Figure 12: FPA integration stage

The final integrated payload was then subjected to test and evaluation in lab and space environmental conditions. Detailed laboratory characterization was carried out. Large amount of test data has been acquired and processed. Results obtained are discussed in the next section.

VI. RESULTS AND DISCUSSIONS

Integrated payloads have been subjected to test and evaluation as per project requirements. Tests have been carried in lab and other environmental conditions such as vibration and thermo-vacuum conditions. Vibration levels and thermal excursions were derived based on various launch loads and in-orbit loads. Various electro-optical parameters such as SNR, dark offset, dark noise, SWR, effective focal length (EFL), power etc were measured in different test phases. Spectral and radiometric calibration have been carried out at the final stage. Cartosat-2S imaging system is photon noise limited system. SNR specification of 180 at saturation has been adequately met. Observed SNR at near saturation radiance for PAN chain is 225 and MX chain is 500 as shown in Figure 13. SNR performance at other radiance levels were also evaluated and are observed to be as per the design.

Dark offset and noise behaviour has been characterized using the data generated during various test phases. It has been observed that the dark offset and noise are consistent indicating stable system behaviour in various environmental test condition as shown in Figure 14. Ensuring this consistent behaviour of the system offsets are very crucial as it can lead to radiometric errors after the launch. Square Wave Response (SWR) is a measure of contrast transfer capability of the system. SWR measurements for all detectors were carried out during various phase of testing. For MX detectors the measurements are done at Nyquist and for PAN at Nyquist/2. Measurements for SWR are carried out at pre and post dynamic test. The SWR values given are without any correction for target contrast and collimator performance and will increase the values further after corrections. Measured SWR for one of the detector of MX chain during initial and final bench tests (IBT & FBT) is shown in Figure 15.

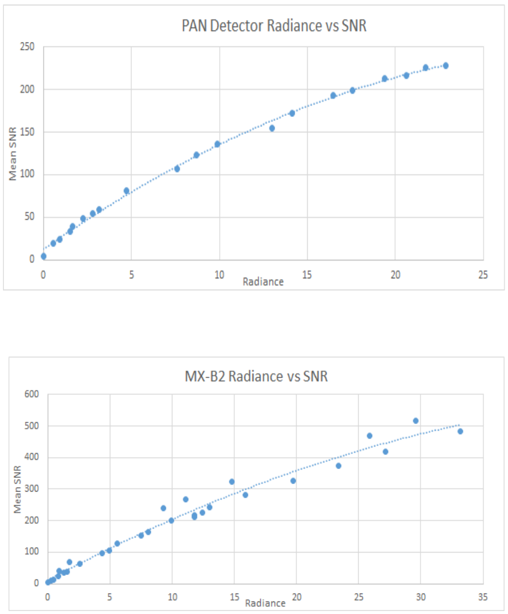

Figure 13: PAN and MX SNR vs Radiance Plot

Effective focal length measurements were carried out at different field locations and are observed to be within specification. The total power consumption of PAN chain is about 60 watts and MX chain is about 94 watts as expected. Results are shown in Table 2.

Table-2: Performance Results

	Specification	Achieved value
SNR	>180	220 PAN 400 MX
SWR	>10 PAN >20 MX	15 PAN 40 MX
EFL (mm)	5600+/-5	5601
Power (watts)	<70 (PAN) <130 (MX)	60 PAN 94 MX

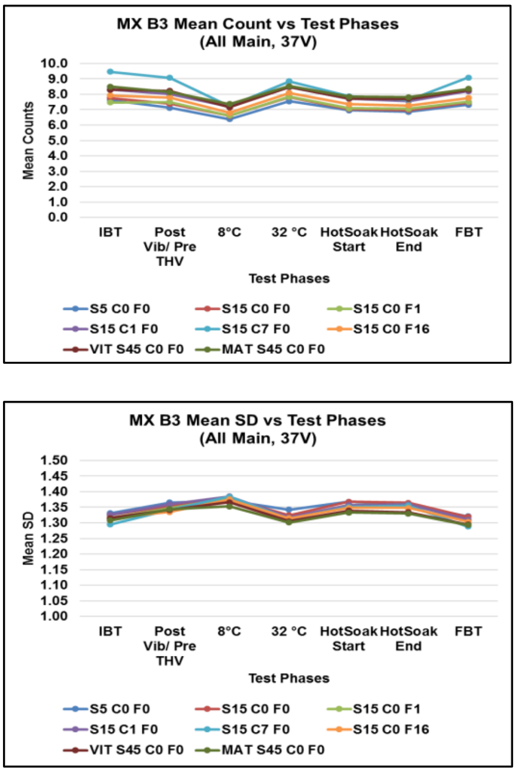

Figure 14: Dark Offset and Noise behaviour

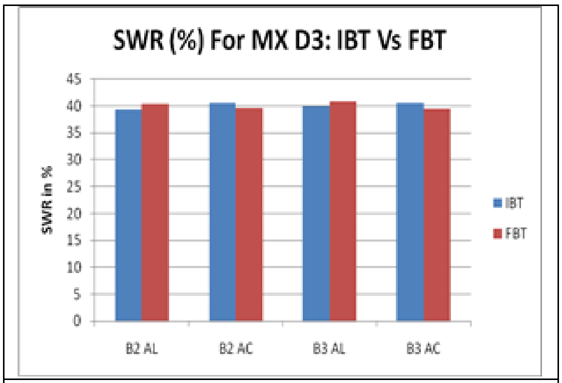

Figure 15: SWR for MX Detector 3

VII. CONCLUSION

Cartosat-2S payloads design and development posed extreme challenges. Accommodation of PAN, MX and Event monitoring chains within the Cartosat-2 envelope was accomplished with innovative design and realization approaches. Meticulous planning and execution of AIT processes helped in achieving the design goals.

All the payloads are successfully launched and operationalized. Extremely high quality images obtained from these payloads speaks volumes about the payload quality.

VIII. REFERENCES

Internal SAC/ISRO documents