Engineering challenges in the Megha-Tropiques satellite

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Megha-Tropiques is an Indo-French satellite mission for climate research and applications in tropical regions. It is built using ISRO's IRS platform and four high technology payloads: MADRAS, SAPHIR, SCARAB and ROSA. MADRAS is a joint development; CNES provided SAPHIR and SCARAB; ROSA is procured by ISRO. Realization of the satellite was a challenging task for inclined orbit operations, with complex features such as: three mechanically scanning payloads; two payload deployments; large rotating mass (MADRAS); mission-critical power and signal-transfer device. Megha-Tropiques was launched on 12 October 2011 by ISRO's PSLV into a 20° inclined orbit for high observation frequency. It is controlled by ISRO's ISTRAC ground station. Science data is received at ISTRAC and CNES-stations at Kourou and Hartebeeshoek.

Keywords: Flip mode, IRS platform, MADRAS, Moon calibration, TRMM.

Introduction

THE Indian Space Research Organisation (ISRO)–Centre National d'Etudes Spatiales (CNES) Megha-Tropiques (MT) is a unique satellite operating in a low inclined orbit for applications in atmospheric and climate research in the tropics. The only other mission exclusively devoted to the tropics is the US–Japanese Tropical Rainfall Measurements Mission (TRMM), launched in 1997 (see later in the article). While geostationary satellites provide high temporal frequency of observations, their high orbital altitude implies poorer spatial resolution for on-board science instruments. Low-Earth-orbiting satellites of around 1000 km provide a higher spatial resolution but poorer temporal frequency of observations. A low-Earth and low inclined orbit provides both higher spatial resolution and higher temporal frequency of observations over the tropics, and is a good trade-off.

Considering the scientific requirements of the mission, namely detailed observations of tropical convective systems, energy and water budgets and special climate events such as cyclones, floods and droughts, various instrument options were studied. A multi-frequency microwave imager, MADRAS (Microwave Analysis and Detection of Rain and Atmospheric Structures); a millimetrewave humidity sounder SAPHIR (Sounder for Atmospheric Profiling of Humidity in the Inter-tropical Regions); and a radiation budget instrument, SCARAB (Scanner for Radiation Budget) were identified as final payloads, with acceptable spatial resolutions ranging from 6 to 40 km at a nominal orbital altitude of 866 km and 20° inclination. With 4–6 observations per day (about twice that for TRMM), the MT mission thus provides the required data with the highest practical temporal frequency for the tropics. ROSA (Radio Occultation Sounder for Atmosphere) was included later (see article for more detail).

Compared to the earlier Indian satellites, the realization of the spacecraft posed certain special engineering challenges chiefly due to its complex scientific payloads – their design and on-board configuration, the spacecraft design and configuration, special operational features in an inclined orbit, operation throughout the orbit, management of spacecraft operations in space, especially during its transit through hazardous radiation regions (such as chiefly the South Atlantic anomaly) and the accompanying long exposures to such radiation in each orbit.

Initially, while the science data reception was confined to the Indian station, ISRO Space Science Data Centre (ISSDC) in Bangalore, the wide scientific demand for global near-real-time (NRT) data from the satellite requirements necessitated two additional CNES ground stations, one each at Kourou and Hartebeesthoek (HBK), South Africa. Quick data access is being provided to national and international users through communication links from ISSDC to the French ICARE Centre at Lille (France) and the Meteorology and Oceanography Satellite Data Centre (MOSDAC) at Ahmedabad.

This article highlights major engineering challenges encountered during the realization of the spacecraft, payload testing and its operation in orbit.

The Megha-Tropiques compared to TRMM

In terms of mission focus on the global tropical belt, MT is comparable only to TRMM[1]. Table 1 compares the major capabilities of the MT mission vis-à-vis those of the TRMM mission. Table 2 compares payloads of TRMM and MT.

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Table 1. Comparison of MT and TRMM

Parameter	TRMM	MT	Remarks
Launch date	1997	2011	
Orbital altitude (km)	350	866	TRMM was boosted to 403 km in 2001 for increased life
Inclination (°)	35	20	
Science payloads	5	4	

Table 2. Comparison of TRMM and MT payloads

TRMM		Megha-Tropiques	
TRMM Microwave Imager (TMI)		MADRAS	
Frequency	10, 19, 21, 37 and 85 (Note 1)	18, 23, 36, 89 and 157 (Notes 1, 2)	
Spatial resolution (km)	6–50	6–40	
Swath (km)	760 (878) (Note 3)	1700	
Clouds and the Earth's Radiant Energy System (CERES) (Note 4)		SCARAB	
Wavelength (μm)	0.3–5, 8–12 and 0.3–50	0.5–0.7, 0.2–4, 0.2–100 and 10.5–12.5	
Horizontal resolution (km)	25	40	
Swath (km)	Full Earth	2200	
Note 5		SAPHIR	
		Frequency (GHz)	183.31 ± 0.2 ± 1.1, ± 2.7, ± 4.2, ± 6.6 and ± 11
		Vertical resolution (km)	6 layers between 0 and 12 km
		Horizontal resolution (km)	10
		Swath (km)	1740
Note 5		ROSA	
		Frequency (GHz)	1.2 and 1.6
		Vertical resolution (km)	0.5–1.4
		Horizontal resolution (km)	100–300
		Range (altitude; km)	0–60
Precipitation radar (PR)		Note 5	
Frequency (GHz)	13.8		
Horizontal resolution (km)	4		
Vertical resolution (m)	250		
Swath (km)	215 (247) (Note 3)		
Visible and infra-red sensor (VIRS)		Note 5	
Wavelength (μm)	0.63 and 1.6 and 3.75 IR: 10.8 and 12		
Swath (km)	720 (833) (Note 3)		
Horizontal resolution (km)	2		
Lightning imaging sensor (LIS)		Note 5	
Wavelength (μm)	0.7774		
Swath (km)	600		
Horizontal resolution (km)	4		

Notes: (1) All vertical (*V*) and horizontal (*H*), except 21/23 – *V*-only. (2) 157 *V* and *H* first in any mission. (3) At 403 km orbital altitude. (4) Nearly equivalent and (5) No equivalent payload.

ISRO–CNES collaboration and work-sharing

The start of the project was marked by a Project Feasibility Study which began at the same time. Subsequent to a System Requirements Review (SRR) in mid-2000, feasibility studies were completed by late 2002. However, because of the non-availability of the French Proteus bus that had been the basis for the 2002 study, design and configuration of the satellite had to be changed to suit an adaptation of the ISRO-offered Indian Resources Satellite (IRS) bus. Thus, a high-level Joint Task Team recommended a revised work-sharing philosophy followed by a new memorandum of understanding (MoU) between ISRO and CNES. This resulted in three additional responsibilities on ISRO, particularly in

- New engineering interface definition between the platform and payloads;
- Spacecraft control;
- Ground station requirements.

It was quite a challenging task to make the best possible use of the already-designed/developed units and adapt them by re-defining interfaces. However, there were also

Table 3. Comparison of resources between IRS and Proteus platforms

Resource	Proteus	IRS	Remarks
Overall mass (kg)	500	Up to 1500 for IRS	
Payload mass (kg)	250	More than 500	
Maximum payload power (W)	210	More than 350	To end of life
Payload operational life (years)	2	5	All payloads together
Data rate	150 kbps	5 Mbps	

gains to the mission due to the higher spacecraft resources of the IRS platform. Some of these are listed in Table 3, which compares the Proteus and IRS buses. In fact, the additional resources permitted configuring a fourth payload in the form of a new instrument, the Global Positioning System (GPS) ROSA.

Mission objectives

In early 1999, the Indian and French science and technology teams prepared a Mission Rationale and Requirements document, which made detailed proposals for mission objectives, parameters to be measured, possible scientific instruments and their operating frequency bands, spacecraft configuration, and other requirements to meet overall mission objectives.

The main focus of the mission, as it emerged from the document, was to measure a number of atmospheric parameters over the entire tropics with high temporal frequency, specifically up to 4–6 times in the (±) 10–15° lat. band, with spatial resolution ranging from 6 to 40 km depending on the particular instrument and its operating wavelengths, so as to generate the long-term database needed for tropical climate studies. Achieving the scientific objectives required a satellite orbital lifetime of at least three years. The main agreed mission objectives were as follows:

- To collect a long-term dataset on agreed parameters with good sampling and coverage over tropical latitudes to understand better the processes related to tropical convective systems and their life cycle.
- To improve the determination of atmospheric energy and water budget in the global tropical belt on various time and space scales.
- To study tropical climatic events and their predictability, including in particular droughts, floods, tropical cyclones and, more generally, various features of monsoon variability.

The atmospheric and ocean parameters required to be measured were:

- Total cloud liquid water content.
- Cloud ice content.
- Convective/stratiform cloud discrimination.
- Rain rate.
- Latent heat release.
- Integrated water vapour content.
- Profile of water vapour content.
- Longwave and total radiative fluxes at the top of the atmosphere.
- Sea surface wind speeds.

Since the instruments do not require illumination from the Sun for their operation, they are capable of providing the global science data on a 24 h basis over the entire tropics. The finalized list of science instruments included: MADRAS, SAPHIR and SCARAB. In 2007, an additional instrument, ROSA procured from TASI (Thales Alenia Space, Italy) was included among the payloads.

Engineering impact of change in project scenario

Changes that affected realization

Payload instruments module: One of the challenges was to adapt the already-defined payload instruments module (PIM) from Proteus to the IRS platform. While the original design was to interface with the cuboidal structure of Proteus, the IRS design required a circular–cylindrical interface.

Engineering interfaces: Spacecraft payload interfaces had to be redefined to be compatible with IRS. While in the earlier scenario ISRO had to interface only PIM with Proteus, in the new configuration all CNES payload interfaces had to be redefined to enable interfacing with the IRS platform.

Advantages and value-addition

Despite the many changes necessitated on the engineering side, the switch-over from the Proteus to the IRS platform offered several major advantages as given below:

Increased spacecraft peak power: While the Proteus supported a maximum power of 280 W which was sufficient to meet the payload demand at the beginning of life (BOL), the available power would reduce to 220 W at the end of life (EOL), limiting the scope of operation of all payloads to only two years. It had therefore been proposed that one or more instrument/s be switched off after two years. This limitation is overcome by the higher power (> 350 W) capability of the IRS platform.

Addition of GPS-ROSA: Due to the higher resources available on-board the IRS platform in terms of payload mass, volume and data rate, the ROSA payload with about a 30 kg mass and about a 50 W power demand could be accommodated.

Final spacecraft configuration

After the new scenario of the project was accepted in late 2004 and the redesign and redefinition requirements for the interfaces were established, the associated activities started in early 2005. During this phase, CNES offered and proposed the inclusion of Advanced Research and Global Observation Satellite (ARGOS). In addition, several candidates for new instruments, such as precipitation radar, Light Detection and Ranging or Laser Imaging Detection and Ranging (LIDAR), microwave altimeter, lightning detector and GPS occultation sounder were proposed by the Indian Science Team. With due regard to the accepted mission objectives, the new instruments were examined from all aspects of feasibility, including instrument maturity, additional scientific benefits in complementing or supplementing the other data, and effect on criticality of schedule. After studying every aspect of the proposed instruments, only the ROSA payload was finally accepted as the fourth payload instrument in 2007.

The Project faced a number of engineering challenges during the realization phase. These are described in subsequent sections along the following lines:

- Inclined orbit: Power generation, star sensor configuration and thermal control.
- PIM configuration: New interfaces and new design.
- Platform configuration.
- Payloads: MADRAS and ROSA.

System level

The MT spacecraft is configured using standard platform and subsystems with proven heritage. The spacecraft structure has two separate modules, viz. the main platform (MPL) and the payload instruments module (PIM). To the spacecraft are appended two solar panel wings one on either side of the main structure, with each wing having three panels. All the spacecraft subsystems are accommodated on the cuboidal MPL with four equipment panels. The top panel interfaces with PIM, whereas the bottom panel externally interfaces with the launch vehicle. The bottom panel accommodates all propulsion subsystems with the main fuel tank inside the cylindrical structure which supports the main structure.

Three of the four science instruments needed mechanical scanning, thus causing significant mechanical disturbances at the spacecraft level. Apart from the conventional deployment mechanisms, one for each solar panel, the MADRAS and ROSA payloads also had to be incorporated with additional mission-critical deployment mechanisms.

Inclined orbit

Power generation

Due to the inclined orbit configuration, power generated was reduced by cos 43.5° (20° inclination + 23.5° which corresponds to the latitude of the Tropic of Cancer/Tropic of Capricorn) compared to that on polar sun-synchronous orbits. Further, the solar panels closer to the spacecraft body experience shadow, thus reducing the overall power generated. Because of these two factors, the initial design which had only two solar panels on either side had to be modified to accommodate three panels on each side. The shadowed regions were not populated by solar cells to reduce complexity and cost.

Star sensor configuration

In the final optimized layout configuration, a serious problem was encountered in mounting the star sensors on the spacecraft since the Sun entered the field-of-view of the star sensor on 8–10 such occasions per year. The only solution was to periodically yaw-steer the entire spacecraft, i.e. flip the spacecraft around yaw. This called for not only a prediction of such instances on orbit but also implementing the flip manoeuvre in the desired orbit. The satellite is now being routinely operated in this mode.

Thermal control

ISRO and CNES had agreed for the thermal design and analysis of elements internal to the payload units by CNES and those internal to the platform subsystems by ISRO. It was therefore important to implement complete isolation at the interfaces of the payloads and the platform subsystems to enable independent design of each element. This involved a complex design process, as all the coupling factors, including conductive/radiative components had to be addressed for all the possible cases in the inclined orbit through detailed simulation and analyses.

PIM configuration

PIM was one of the most complex units of the spacecraft as it accommodated three major instruments, viz. MADRAS, SAPHIR and SCARAB. PIM required four times as much material as the main satellite structure did. Further, due to the non-availability of the requisite composite material at that time, structural design using aluminium-cored material was necessary, with a 10% (10 kg) penalty on mass. The design was further complicated due to the fact that all the payloads on PIM involved mechanical scanning. Hence for ensuring satisfactory performance, the Structural Model-cum-Flight Model (STM/FM) of PIM had to be qualified using simulated MADRAS, SAPHIR and SCARAB payloads. Detailed tests and qualification procedures were required to provide adequate confidence on on-orbit performance.

Spacecraft realization

After considering all technical and scientific requirements, preliminary design, interface definition and reviews, the realization of the space segment hardware was initiated. The steps involved in this major task are described in the following sections.

Spacecraft platform

Interface with CNES: As in most such major joint projects, the ISRO project team had the challenging but interesting task of interfacing with its partners in all the tasks, including payload integration. While SAPHIR and SCARAB were completely developed/procured and delivered by CNES, MADRAS was a joint development. It was therefore crucial to understand, identify and agree on the technical and managerial responsibilities on each side without any ambiguity till the final integration and testing on the spacecraft and launch. This was the first time in ISRO that a large payload was jointly developed in an international collaboration. Realization of MADRAS called for interaction with not only major ISRO Centres, viz. the ISRO Satellite Centre (ISAC), the Space Applications Centre (SAC), and the ISRO Inertial Systems Unit (IISU), but also CNES and its sub-contractors, including Astrium and several other agencies.

The following are some of the major points that were considered, reviewed periodically and followed till the end of the project.

- Exact definition of work break-up beyond the broad MoU guidelines.
- Technical interfaces, with thorough documentation.
- Techno-managerial meetings, reviews, tele-/video-conferences.
- Participation in joint testing.
- Conflict management: technical and managerial.
- Technical anomaly reports.
- Non-conformances/waivers.
- Test reports and documentation.

All the above stages were interesting experiences, and were managed from time to time with appropriate documentation, meetings and agreements or approvals as necessary.

System design – choice of star sensors against Earth sensor: The user requirement of pointing stability and knowledge were debated for a long time. The pointing requirements for the sensors for ensuring spacecraft stability were stringent, although microwave sensors are considered to have coarser resolution. However, detailed discussions emphasized the demand for pointing knowledge of better than 1 km. The main factor was the need for comparing the MT data with geo-synchronous science data such as new-generation EUMETSAT (European Meteorological Satellite), which have pixel dimensions of 1–2 km. The project eventually met this requirement using star sensors.

Redundancy in spacecraft momentum wheel configuration as contingency for MADRAS momentum compensation wheel (MCW) failure: In order to achieve mechanical stability, MADRAS payload incorporates a momentum compensation wheel to offset the momentum resulting from the rotation (for scanning) of the payload. As a redundancy in case of the failure of MCW, a detailed redesign was made and implemented, with new angular orientations for the main spacecraft momentum wheels. This novel feature strengthened the mission reliability, particularly of MADRAS, through redundancy.

Radiation effects: On-orbit performance of MADRAS indicated certain deviations due to radiation effects and also raised component issues. These were resolved by simulation and by incorporating appropriate corrections in the processing data products. Some of the radiation effects were also overcome with periodic scrubbing of memory devices and field-programmable great arrays (FPGAs).

Field-of-view conflicts between spacecraft and ROSA antennas: There were serious field-of-view conflicts between spacecraft and ROSA instrument antennas with wide view angles, necessitating mission-critical change-over switches for the spacecraft antennas. This has been described in more detail later in the article.

Introduction of features for various modes of MADRAS calibration: End-to-end calibration of a microwave radiometer along with its antenna and receiver is necessary for absolute calibration of the radiometer as well as for inter-comparison of mission data with those from other similar instruments in orbit. Often it is difficult to accurately characterize the radiometers in absolute terms, particularly in the case of those with high absolute accuracy. One option is to steer the spacecraft to facilitate the main antenna to view the cosmic microwave background radiation (CMBR). This provision may be used at appropriate times during the mission, keeping loss of useful science data to the minimum. As a second option, the spacecraft is also designed to view the Moon as a source of blackbody radiation for absolute calibration. There is also a moon-lock mode to keep the moon in view for a short time of a few minutes. However, such a provision appears to be novel and is not reported in the literature. This option would call for a detailed analysis and impact on data loss.

MADRAS

Large number of frequencies: MADRAS[2] instrument makes use of five frequencies (18, 23, 36, 89 and 157 GHz) with large bandwidths for obtaining good temperature sensitivity, and nine receivers (since all except 23 GHz have both vertical and horizontal polarization). The frequencies are chosen to meet specific atmospheric applications as explained in Figure 1. The important challenge was the need of a satisfactory isolation and grounding to prevent electromagnetic interference. The final integrated performance at spacecraft level and also on-orbit was excellent.

MADRAS scan mechanism (MSM): This is a complex mission-critical unit used for rotating the MADRAS front end at 25 RPM. In order to ensure effective performance over a lifetime of 5 years, a life test model was used early in the project and continues to remain in operation on ground, even after launch, to provide reference data. The overall complexity may be perceived by the fact that the number of rotations by the scan mechanism is more than 7 million over a 5-year period.

Dynamic balancing of the rotating element: Any imbalance during rotation creates a 'coning effect' resulting in instability in pointing. There are several causes for the imbalance, including misalignment of the rotation axis

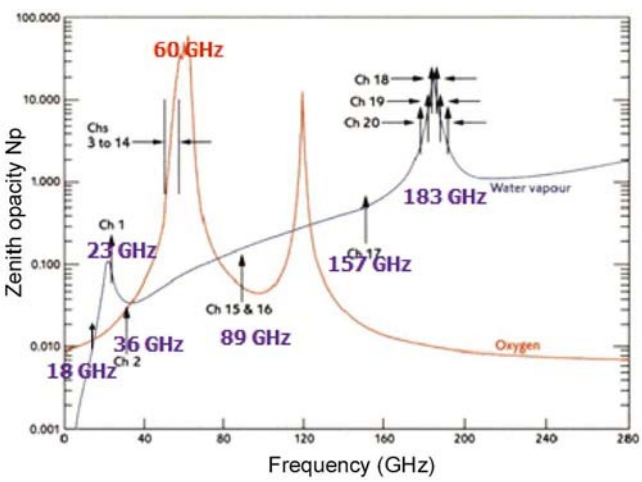

Figure 1. Atmospheric resonance frequencies and window frequencies (MADRAS frequencies are in blue).

during integration. A major task was to balance the rotating part with high accuracy in both dynamic and static conditions. In fact, a specific dynamic balancing facility was procured by ISRO for the purpose. Measurements were needed for ensuring repeatability of the residual imbalance. Another related factor contributing to instability is the possibility of slippage of a multi-layer-insulation material (MLI) fixed on the rotating MARFEQ drum, described in the next section.

Contribution of MLI on rotating parts to instability: From thermal design considerations that demand passive thermal control, the rotating drum of the MADRAS antenna structures is covered with MLI. Initial studies by ISRO brought out serious concerns regarding the stability of MLI (staying intact) due to the antenna rotation and stoppages. The concern was on the residual imbalance and its repeatability. This issue was resolved by CNES by appropriately designing the MLI for reducing the possibility of large slippages.

Large number of PSTD (power and signal-transfer device) – slip-ring contacts: The PSTD is the most mission-critical unit having 92 contacts. This unit interfaces functions of transferring power and signals between the rotating MADRAS RF Equipment (MARFEQ-A) and the static part. The design uses contacting plungers that have three thin gold-plated brush-like wires, with an optimum contact pressure/friction ratio and with low contact resistance of less than 10 milliohms. Further, the 92 contacts are expected to traverse a large distance with these sensitive brush contacts during the 5-year lifetime. The contacts are vulnerable to erosion, possibly due to any mechanical imbalance, by repeated rubbing against the static surface. They are likely to introduce electrical noise. It is possible to correct noisy signals usually by off-line processing of received signals before preparing data products.

Bifurcation of MADRAS backend electronics (MBE) – static and rotating: Early in the project, ISRO and CNES agreed to develop the static and rotating parts of MADRAS respectively. At that time ISRO had agreed to develop the MBE. However, this had to be split into two parts, static and rotating, due to electrical noise considerations. After several discussions ISRO agreed to develop both rotating-MBE (R) and static-MBE (S) parts. This bifurcation introduced difficulties in integration and testing, since MBE (R) was to be integrated along with the MADRAS front-end of CNES, especially in the crucial dynamic balancing at CNES before sending to ISRO, but was managed through a simulated model of MBE (R) at CNES.

Power supply noise due to large cable lengths between MARFEQ and power supply unit (PSU): A new development was concerned with one of the most difficult units on the spacecraft, namely PSU for MARFEQ-A on the rotating segment. The demand was for a power supply with less than 10 mV noise at the end of a more than 1 m-long cable from the static part of the unit. It was also required to provide large start-up (in-rush) current for the RF units, especially for the high frequency local oscillators. Such a sensitive supply is not available commercially, and had to be specially designed and custom-built. The ISRO-made units meet critical specifications beyond the design goals.

Transportation: France–Ahmedabad–Thiruvananthapuram–Bangalore: As the MARFEQ occupied considerable volume (more than 2–3 m on each side, when containerized), no commercial transport could carry it. It was therefore transported from CNES to SAC, Ahmedabad for the first level of integration on an Ilyushin aircraft specially chartered by CNES. From Ahmedabad, it was transported to Thiruvananthapuram by a special aircraft chartered by ISRO in view of greater safety compared to the longer transit by road. Next, it was transported by road to Bangalore.

Hold-down and release mechanism: The rotating part of MADRAS is held down during launch to avoid launch loads acting on the sensitive bearings of MSM. A hold-down and release mechanism (HDRM) was used for this purpose. This final phase of integration at ISAC necessitated use of zero-*g* fixtures for holding MARFEQ in proper position during integration. Strain gauges were used to ensure that no part of the MADRAS units experienced excessive stress.

HDRM is a new and mission-critical unit as the design should allow sufficient gap between the rotating part and the fixed part, during on-orbit rotation after release. A uniform gap of 2.5 mm was present all around the rotating drum and the mechanism was needed with sufficient but uniform gaps at the six hold-down blocks. The planarity and uniformity of the gap were also critical from thermal considerations. It was an arduous task to achieve all the specifications on ground, considering the deflections on ground, repeatability and consistency, and also projecting satisfactory performance in orbit.

Thermo-vacuum testing and ground characterization in large space simulation chamber (LSSC): The MADRAS instrument could be completely configured only on PIM at ISAC. Due to its large volume, thermo-vacuum testing of MADRAS was possible only in LSSC (9 m-diameter) at ISAC. This chamber had to be completely reconfigured and made up-to-date since all the remote sensing satellites launched to date by ISRO are smaller and could be tested in smaller facilities. Therefore, the entire LSSC had to be characterized and also modified with custom-built feed-through connectors for use in MADRAS testing in its full rotating mode of operation. This test also called for new check-out and testing units. Figure 2 shows two views of testing and integration of MADRAS in LSSC.

A crucial phase was the HDRM operations inside LSSC as HDRM needed to be released for rotation tests and held-down thereafter for transportation. The set-up also warranted scaffolding arrangements inside the 9 m chamber (shown in photographs), for accessing the intricate locations of the hold-down blocks for such tasks as alignment, inserting locking pins, etc. without unintended stress and strain. The tests were satisfactorily completed over a span of 16 days, and have provided invaluable reference data for on-orbit performance analysis.

SAPHIR

SAPHIR is unique in terms of its number of channels (six). Because of its large number of channels, sensitivity and hence large bandwidths (up to 7 GHz), there was serious concern on electromagnetic interference (EMI) issues, especially when the entire spacecraft is in operation or testing, with all the platform units emitting power over a wide range of frequencies. Adequate analyses and simulations were conducted by both CNES and ISRO, and appropriate grounding techniques were implemented with satisfactory performance both during pre-launch tests and in orbit.

SCARAB

SCARAB testing (while rotating) necessitated a nitrogen of 99.9995 purity for purging. To meet this very high demand all pollutants such a water vapour, carbon dioxide, methane, etc. had to be reduced to a very low value. Such a test is crucial for SCARAB optics. ISRO installed a special set-up with teflon tubes and 1 μm filter which achieved the required purity successfully.

ROSA

Feasibility: GPS-ROS have demonstrated capability in providing temperature and humidity profiles of Earth's atmosphere with excellent vertical resolution, but with coarser horizontal resolution. Considering their scientific value of providing data that would supplement and complement the other science instruments of MT, a concerted effort was made to commercially procure a suitable unit. A ROSA instrument from TASI was found acceptable and efforts to accommodate it were initiated. Although a similar instrument has already flown on ISRO's Oceansat-2 spacecraft, the payload turned out to be schedule-critical and the project needed to adopt contingency measures, including indigenous development of the entire hardware and software.

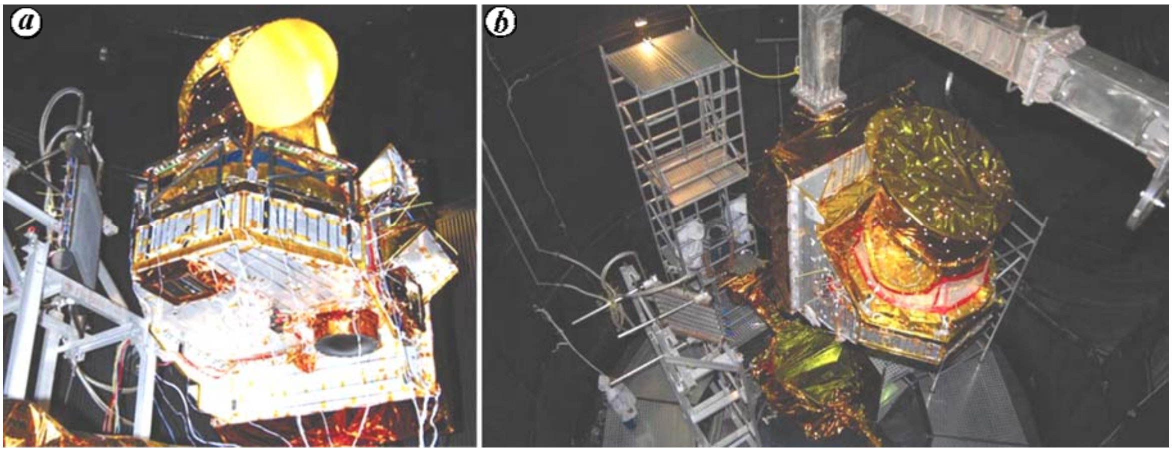

Figure 2. ***a***, MADRAS undergoing thermo-vac tests in LSSC. ***b***, MADRAS integration in LSSC before testing.

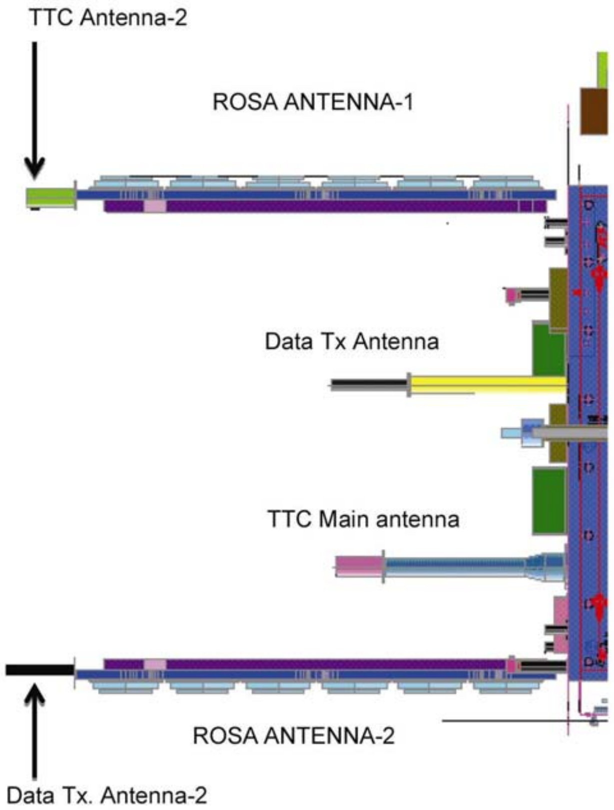

Figure 3. Data transmitter antenna 2 and TTC antenna 2 deployed in orbit.

On-board accommodation and configuration: ROSA posed several engineering difficulties in terms of accommodation, power demand, quality of components used, thermal design, electrical interface and also testability. As it was a late entry, the project team had to rework certain parts of the configuration frozen earlier. They are:

- Introduction of heat pipes (thermal design) in one of the spacecraft panels.
- Introduction of antenna deployment mechanism to overcome serious field-of-view conflicts with spacecraft antennas.
- Insisting that vendor conduct qualification tests to ensure reliable performance in orbit.

Testing/availability of occultation simulator: Testing of ROSA at ISRO laboratories necessitated a special multichannel simulator which was quite expensive and bulky. TASI could therefore complete the testing in stand-alone mode at its own facility. Integrated testing at ISRO posed serious issues with respect to electromagnetic interference due to active sources and also with exact simulation of occultation. A special experimental set-up had to be devised at ISRO to view the orbiting GPS satellites from external antennas, while the occultation signals close to occultation phenomena were simulated by a single-channel simulator. This testing methodology was repeated and successfully executed at the ISRO launch pad also.

ROSA antenna deployment: Another difficult task was to accommodate two antennas, each 130 cm long and about 40 cm wide. When the ROSA antennas, one each for the fore and aft directions, are in the operational mode in space, they severely block the spacecraft telecommand and telemetry (TTC) antenna and also the data transmitter antenna. It was therefore necessary to introduce an additional pair each of TTC and data transmitter antennas. These consisted of one each of body-mounted antennas respectively, for TTC and data transmitter and one each mounted at the edge of the ROSA antenna structure. Figure 3 describes the blockage of the main antennas and Figure 4 shows the deployed view of ROSA antennas along with the TTC and Data Tx antennas (designated antenna '2' – for both TTC and Data transmitter, Data Tx, in Figure 3 and at the tip of the ROSA antennas) that are used in orbit. The configuration permitted the use of body-mounted antennas (before ROSA antenna deployment) during and just after injection, and switching over to the other pair of antennas mounted on the ROSA antenna structure after ROSA antenna deployment in orbit. This scheme has performed well in orbit.

Antenna deployment testing on ground: Since the ROSA antennas were relatively light (less than 1 kg each), testing in zero-*g* condition in the clean room was considered not necessary. But the long and fragile antennas with thermal protective films (sun films) on them made it difficult in handling and testing for deployment. There was also a stringent specification of less than 1° on its alignment in orbit. The antennas were also latched to the main spacecraft after deployment to prevent disturbance during movements.

Realizing all the above was a major task which was successfully completed and satisfactorily tested at the ISRO Satellite Centre as well as at the launch pad at Satish Dhawan Space Centre (SDSC), Sriharikota.

Conclusion

All the engineering challenges taken up during the realization of the MT mission were adequately met as demonstrated by the satisfactory on-orbit performance of the spacecraft and the payloads[2]. All the four science instruments, MADRAS, SAPHIR, SCARAB and ROSA are providing valuable science data, most of which have been used in preliminary scientific studies and applications. MADRAS was a particularly complex instrument with mission-critical elements such as:

- Heavy rotating mass of more than 120 kg.
- Slip-ring assembly, a 92-line slip-ring assembly with sensitive brush contacts.
- High speed of rotation – almost 7 million rotations over a five-year life time.

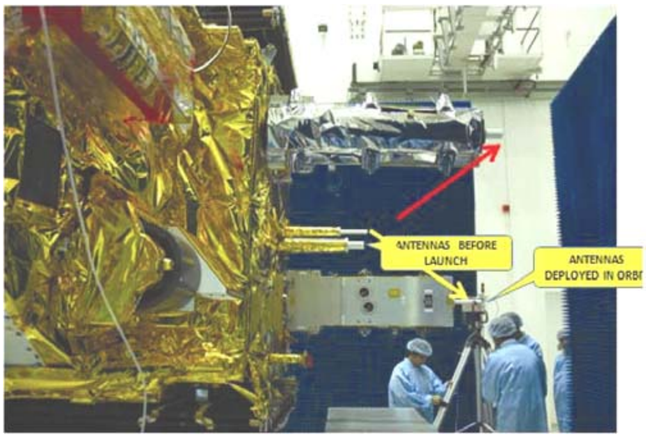

Figure 4. Deployment tests of ROSA antennas. The arrows indicate positions of spacecraft antennas after deployment; box shows body-mounted antennas before deployment.

- A momentum compensating wheel for compensating the MADRAS-induced momentum so as to keep the required stability and pointing.
- Maintenance of a constant and uniform gap between the fixed and rotating parts through the hold-down and release mechanism (HDRM).

In retrospect, it is clear that MADRAS was a complex mechanical design needing to address vital electrical performance specifications. The demands for a low contact resistance (less than 10 milliohms) at the slip-ring contacts and low contact friction over a broad temperature range, and their performance consistency on orbit, the rotation of the scan mechanism at a uniform speed, including maintenance of its alignment with high precision as also a precise alignment have indeed continued to pose technical challenges.

After several months of operation, the MADRAS payload appeared to exhibit some noisy behaviour in several orbits which is suspected to have originated at the component-level. However, the data obtained are correctable and fully recoverable. Detailed studies and simulation have resulted in correction algorithms developed by the project team to effectively recover the instrument data. The latest status indicates satisfactory performance of all the instruments.

MT satellite was launched successfully from Sriharikota, using PSLV launcher on 12 October 2011. A large amount of level-1 science data is already available to users.

1. TRMM website, http://pmm.nasa.gov/TRMM/trmm-instruments
2. Indo-French MT Meeting, Bangalore, India, 17–19 December 2012.

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