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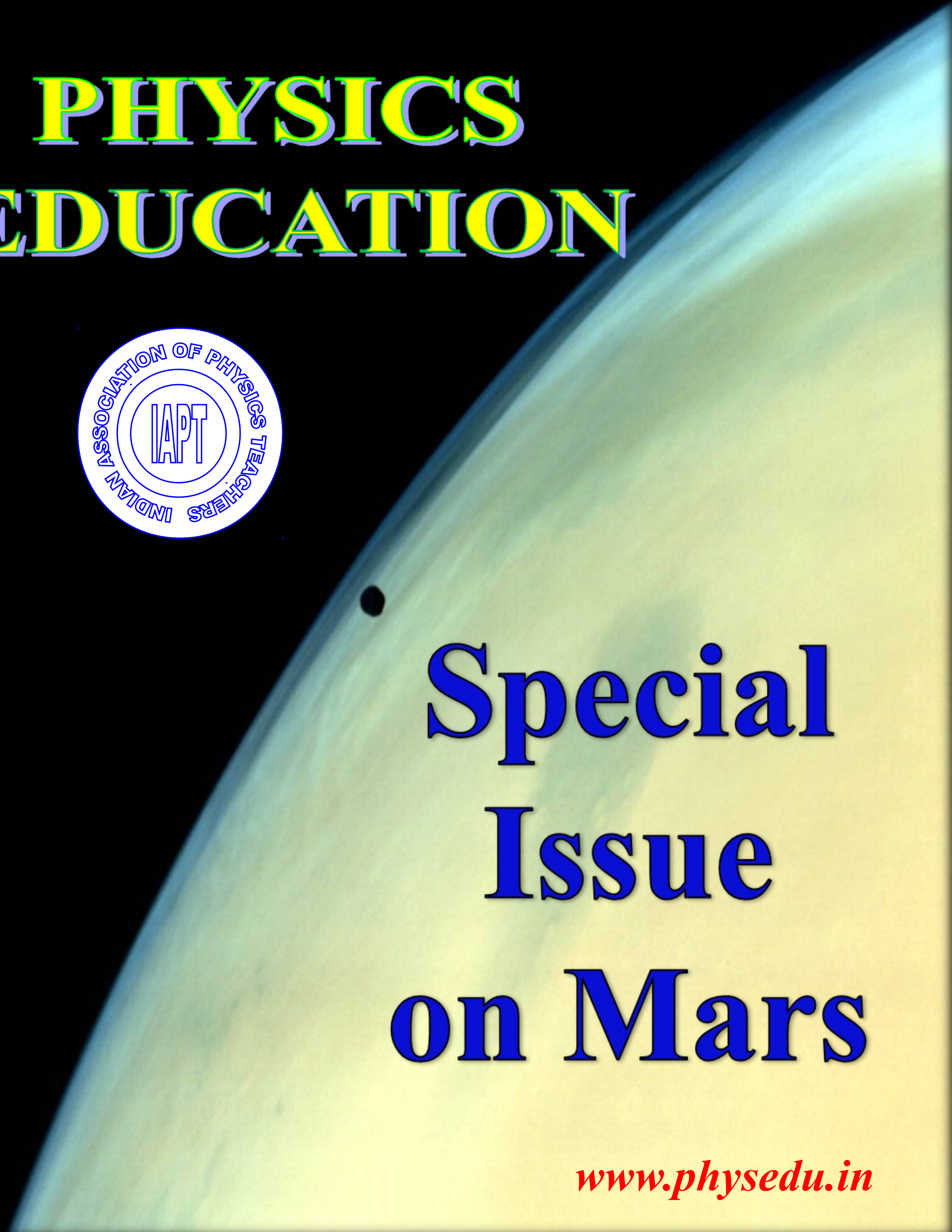

Special Issue on Mars

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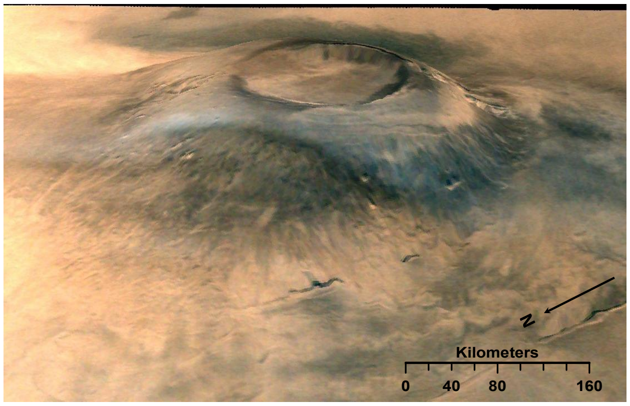
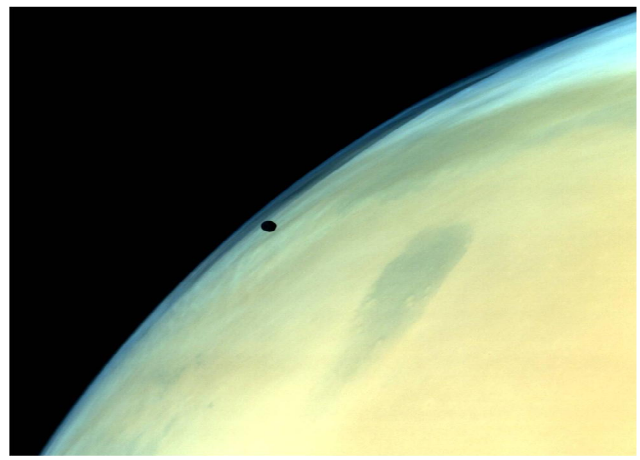
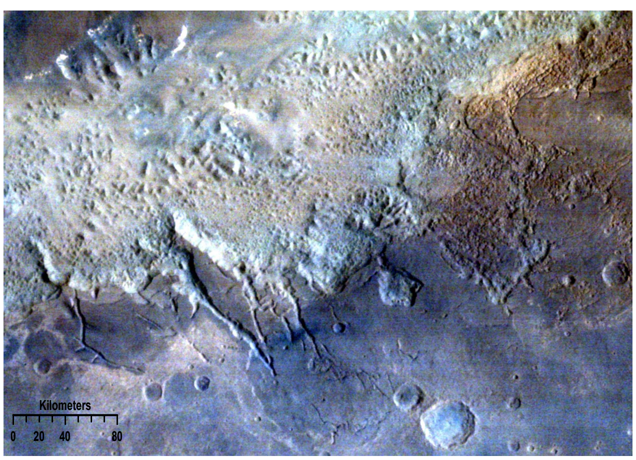
Images Captured by Mangalyaan



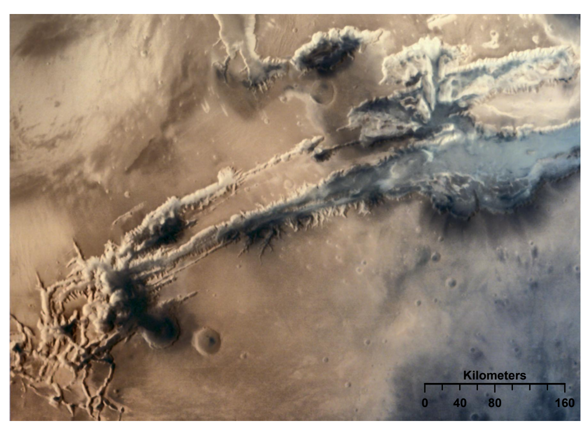
This Image of Arsia Mons, the second highest volcano in the Tharsismons region, has been taken by Mars Color Camera on 4th January 2015, at a spatial resolution of 556 m from an altitude of 10707



Mars has two natural satellites i.ePhobos and Deimos having the mean radius of 11.1 km and 6.3 km respectively.Phobos is the inner and larger one of the two natural satellites of Mars that orbits at an altitude of about 6000 km. Phobos has been imaged by Mars color camera (MCC) on 14th October 2014 at a spatial resolution of 550 m from an altitude of 16057 km. from Mars . Phobos (dark) is seen in the backdrop of Mars (bright) . It is believed to be that these two satellites could be captured bodies from the main asteroid-belt.



``Eos Chaos'' is located in the eastern part of the largest canyon system in the solar system – the Valles Marineris. Images of ``Eos Chaos'' region of Mars taken by Mars color camera on 5th February 2015 at a spatial resolution of 220 m from an altitude of 4403 km. Fracture patterns at the edges of Valles Marineris are clearly seen at this resolution. These images are use full for understanding geological processes at regional scale. Impact Craters of various size are also seen in this image.



The Noctis Labyrinthus, located at the western edge of the Valles Marineris Rift System, is a jumbled terrain composed of huge blocks which are heavily fractured. Images of ``Valles Marineris'' and adjoining regions of Mars taken by Mars color camera on board Mars orbiter mission on 05th December 2014 at a spatial resolution of 1.2 km from an altitude of 24000 km. shows NoctisLabyrinthus at the bottom left corner of the image.

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In this Issue

EDITORIAL

MARS ORBITER MISSION - MANGALYAAN

It is indeed a privilege and honour to present this special issue on the Mars Orbiter Mission - MOM. I was requested to be guest editor for this issue and sincerely hope that we have brought out this issue which will provide insight to all in the findings from the Mars Orbiter Mission-MOM. The mission itself was quite a complex mission involving contributions by thousands of persons in ISRO, in the Indian industry and the whole scientific community. ISRO has been able to achieve successful missions for the Chandrayaan 1 and Mangalyaan in the first attempts. This has certainly been possible due to meticulous execution of all the phases of the missions, adherence to strict quality assurance and quality control practices in the fabrication of the payloads, subsystems, systems, satellites and launch vehicles.

This issue highlights the results and findings from the scientific instruments, generally called as payloads on the MOM Spacecraft. The topics handled here by the scientists / engineers will bring forth the importance of the historic fascinating scientific mission undertaken by ISRO.

ISRO launched the MOM Spacecraft on 5th November 2013 using the Polar Satellite Launching Vehicle C 25. I was fortunate to be there at the Satish Dhawan Space Center at the launch. I was thinking that we were carrying out this mission just a few weeks short of completion of fifty years since we successfully launched the first Nike Apache Rocket from the Thumba Equatorial Launch Station near Thiruvananthapuram, this rocket was expected to reach an altitude of 175 Kilometres in its sub orbital flight for releasing Sodium Vapour in the upper atmosphere. We have certainly come a long way from launching a rocket developed by NASA of USA to launching our own Polar Satellite Launch Vehicle carrying MOM spacecraft. The target this time was reaching up to the Mars and inserting it in to an orbit around Mars. After the successful launch of MOM on 5th November the orbit was raised further and on 1st December 2013 it was inserted in on an orbit around the Sun. The velocity given to the MOM spacecraft was such that it would catch up with Mars and reach there by 24th September 2014.

It reached the desired destination, Mars and was successfully inserted in the orbit of Mars. Since then the MOM spacecraft has been performing exceptionally well. It has completed one year in the orbit around Mars. The MOM satellite has been functioning very well in the Martian orbit. So far the utilization of the propellants has indicated that the MOM satellite will function there for quite few years to come!

The data from Chandrayaan 1 and MOM is now going to be made available to the wider community of students and scientists.Availability of such data to the entire scientific community will be able to generate interest in the students to take up further scientific research work.

Just as we are getting ready to release this issue, news about NASA finding evidence of flowing water on Mars has been widely circulated. This is going to be a very exciting finding. It could lead to renewed interest in the subject of ‘Origin of Water’ and finding ‘Extra Terrestrial Life’.

ISRO has now successfully launched the ASTROSAT satellite this year. This mission is expected to provide multi wavelength imaging capability for the first time. This year also marks completion of forty years since we launched the first scientific satellite ‘Aryabhatta’ and started the Satellite Instructional Television Experiment – SITE.

Space Exploration is a very fascinating subject not just only for the scientists, engineers but also for all persons at any age.In our country earlier we had concentrated mainly on the Applications of the Space Technology for the betterment the day to day life. In the recent years we have undertaken a variety of Space Missions. These have involved Scientific Missions; commercial launches for satellites for other countries, technology demonstrators etc. ISRO has launched so far 51 satellites for other countries.Work is going on for the Chandrayaan 2 and Aditya mission. The Chandrayaan 2 mission involves soft landing on the Moon and deploying a Rover.

We would like to express our sincere thanks to all the authors who have contributed to this issue. They have certainly made great efforts in bringing these comprehensive papers. We would like to express our sincere thanks to Dr. Seetha and Dr. Praveen, ISRO HQ for all of her efforts and follow up done by them. Without their help it would not have been possible to bring out this issue. We would like to express our sincere thanks to our readers whose interest has always encouraged us.

This is to wish all ‘Happy Reading’

Pramod Kale

Former Director, Space Applications Center, Ahmedabad, ISRO
and
Director, Vikram Sarabhai Space Center, Thiruvananthapuram, ISRO

Mars Orbiter Mission

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(*Submitted* 30-08-2015)

Abstract

Mars Orbiter Mission is India's first interplanetary mission to planet Mars. The objectives of this mission are primarily technological and include design, realisation and launch of a Mars Orbiter spacecraft capable of operating with sufficient autonomy during the journey phase of 300 days; Mars orbit insertion / capture and in-orbit phase around Mars. The scientific objectives of the mission are to study the Martian surface features, morphology, mineralogy and Martian atmosphere. The major challenges involved in the design of spacecraft are in radiation environment, thermal environment, communication systems, power systems, on-board autonomy and propulsion systems.

Introduction

Exploration of Space to advance our knowledge of the Universe we live in has always been an important component of ISRO's Space Science Program. India's solar system exploration program was initiated in a major way in October 2008 with the launch of Chandrayaan-1, the first lunar mission of India. Nationally and internationally, Chandrayaan-1 (Ch-1) generated unprecedented enthusiasm and pride among the public. The confirmation of water on Moon was one major result from the Ch-1 mission. In particular, it created excitement in the young minds of this country and firmly established that India can take on any technological challenge. It established a new sense of confidence in our ability to address new frontiers of space exploration. Data from Ch-1 is still being analysed. After the first lunar mission, ISRO is presently working on Chandrayaan-2, an indigenous lunar landing mission.

Beyond the Earth's vicinity, Mars is a natural target of study in India's solar system exploration program. Of all the planets in the solar system, Mars has sparked the greatest human interest. Its orbit lies between the asteroid belt and the Earth. For ages humans have been speculating about life on Mars. The conditions on Mars are believed to be hospitable since the planet is similar to Earth in many ways. Like Earth, it has an atmosphere, though less dense and different in composition. Mars has surface features reminiscent of both the impact craters of the Moon and volcanoes, deserts and polar ice of Earth. But, the question that is to be still answered is whether Mars has a biosphere or ever had an environment in which life could have evolved and sustained.

The Indian Mars Orbiter Mission (MOM) was undertaken primarily to demonstrate India's capability to venture into interplanetary space and make independent exploration of the red planet. All aspects of MOM project, including scientific, technical and managerial, were handled extremely well and it was executed with a tight time schedule of about 2 years. This paper gives primarily the details of the Mars Orbiter spacecraft operations and its challenges.

Mars Missions – Global Scenario

Prior to Indian Mars Mission, there were 51 missions all over the world in the form of fly-bys, orbiters, landers, rovers and a sample return mission. Out of the 51 missions, only 21 missions were successful, which put the success rate at 42%. In this backdrop, it is very pertinent to note that India has been successful, in the very first attempt, to place the Mars Orbiter spacecraft into orbit on September 24, 2014 and thereby has secured a unique place among the space faring nations.

Scientific payloads

Mars continues to be an object of keen interest to scientists in the context of planetary evolution and extra-terrestrial life. Based on our current understanding of Mars, which was thought to be probably a warm and wet planet earlier, is now seen to be dry with a thin atmosphere. How this evolution has taken place is still a topic of research. Properties of the older versus the younger Martian terrains indicate that chemical changes have also occurred in the soil. In the coming decade, Mars is the promising target where search for life can be addressed realistically. It can be visited frequently by robotic spacecrafts paving way for sample return and human exploration. In this backdrop, the Indian Mars Orbiter Mission carried five scientific payloads, as given below:

(a) ***Mars Color Camera (MCC)*** to provide images and information about the surface features and composition of Martian surface.

(b) ***Thermal Infrared Imaging Spectrometer (TIS)*** to map the surface composition and mineralogy of Mars.

(c) ***Methane Sensor for Mars (MSM)*** is designed to measure Methane (CH_4) in the Martian atmosphere. These measurements will trigger further studies to understand the origin of methane.

(d) ***Mars Exospheric Neutral Composition Analyser (MENCA)*** to study the composition of Martian upper Atmosphere.

(e) ***Lyman Alpha Photometer (LAP)*** to measure the relative abundance of deuterium (D) and hydrogen (H) which allows us to understand the process of the loss of water from the Mars planet.

Major challenges of MOM spacecraft

Mars Orbiter Spacecraft was launched onboard PSLV-C25 on November 05, 2013 from Satish Dhawan Space Centre, Sriharikota. After Earth-bound Orbit raising manoeuvres (Fig.1), the Trans Mars Injection manoeuvre was successfully conducted on December 01, 2013 to set the course of the spacecraft towards Planet Mars through a Sun-centric trajectory. Enroute to Mars, three Trajectory Correction Manoeuvres were carried out on December 11, 2013, June 11, 2014 and September 22, 2014 to achieve the precise path towards Mars Orbit. The spacecraft traversed 666 million kilometres of inter planetary space to reach close to Mars.

The most crucial manoeuvre of Mars Orbit Insertion (MOI) was successfully carried out on September 24, 2014 by firing the 440 Newton thrust Liquid Engine along with eight smaller liquid engines, with which the Mars Orbiter Spacecraft successfully entered into an elliptical orbit of 422 kms by 76,994 kms around planet Mars. With this, ISRO has become the fourth space agency to successfully send a spacecraft to Mars orbit.

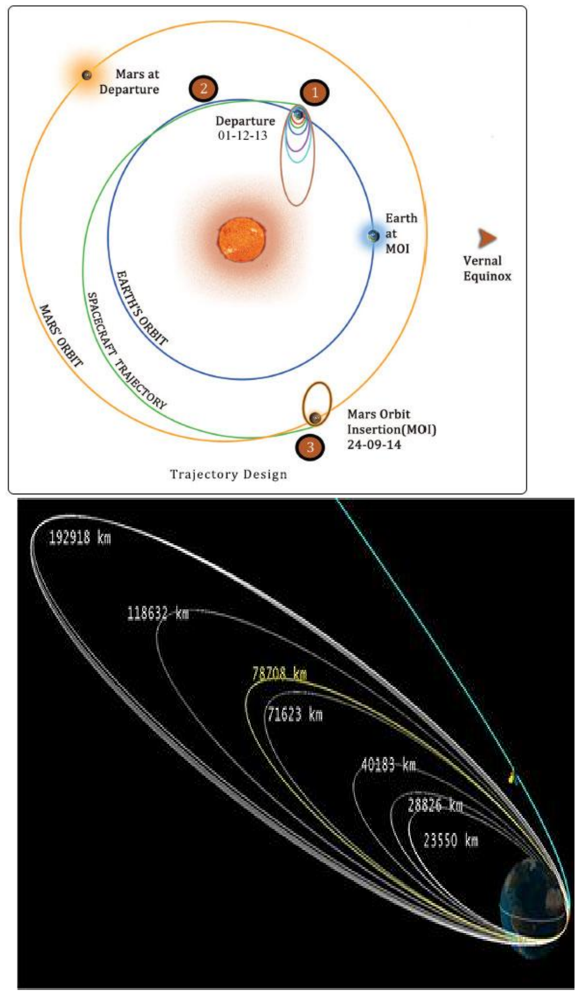

FIG.1: Trajectory design of MOM showing (1) Earth bound orbit, which is zoomed in the right panel (2) Sun-centric trajectory and (3) Mars orbit insertion

ISRO has been continuously monitoring the Spacecraft using its Deep Space Network complemented by that of Jet Propulsion Laboratory of NASA. Mars Orbiter Spacecraft and its five scientific instruments are in good health. All the scientific instruments have been operated and tested successfully. The images of Mars captured by the Mars Colour Camera have been received and are found to be of very good quality. Scientific analysis of the data being received from the Mars Orbiter spacecraft is in progress. Many challenges were involved in the configuration and the subsequent design of the spacecraft (figure 2) which were needed to consider during its mission life. The following subsections details about the major challenges in the design of MOM spacecraft systems / elements.

Mars Orbiter has been technologically a very challenging mission. It has demonstrated technological capabilities of India to reach an interplanetary target like Mars. The spacecraft position prediction and accurate orbit determination with high precision sensors and accurate navigation modelling were critical for successful Mars Orbit Insertion.

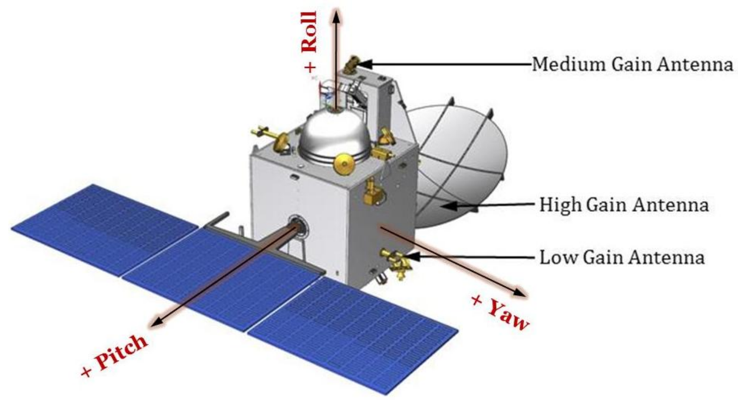

FIG.2: Configuration of MOM spacecraft

Radiation Environment

The main frame bus elements and payloads of MOM are basically designed by considering the radiation environment for the interplanetary missions. The spacecraft bus components were selected pertaining to an accumulated dose of 6 krad for aluminium shielding of standard gauge 22 or below, while the parts have been considered as suitable up to 12 krad with a margin factor of 2.

Thermal Environment

The spacecraft during its journey to Mars undergoes a thermal environment where temperature is highly varying (hot environment at near Earth and cold environment during Earth to Mars cruise). On an average the solar flux at Mars orbit is about 589 W/Sq.m, which is about 42% of solar flux at Earth orbit. Due to the eccentricity of Mars's orbit, the solar flux at Mars varies by +/- 19% over the Martian year and is found to be more than the 3.5% variation compared to Earth. The Albedo fractions at Mars being around 0.25 to 0.28 at the equator and generally increasing toward the poles are similar to that of Earth. The challenges related to varying thermal conditions during different phases of the mission were alleviated to a certain extent by choosing different attitudes.

Power Systems

The spacecraft and payloads during various phases of mission have to be supported by the power system. Power generation, energy storage and power conditioning elements, the essential components of a power system, needs to be carefully designed for an interplanetary mission. The design of power system by considering the power generation under low solar intensity due to the larger distance of the satellite from the Sun is one of the major challenges. The power generation in Mars orbit is reduced to nearly 50% to 35% compared to Earth's orbit. The power generation variation is nearly 15% in a Martian year due to the eccentricity of Mars orbit. The power bus configuration comprises of a single wing of solar array with 7.56 m^2 area generating about 840 W when it is sunlit with normal incidence in Martian orbit, and it is a battery tied single bus of 28-42V.

The single solar array wing consists of three solar panels of size 1.8 m x 1.4 m converts solar energy into electrical energy by photo-voltaic conversion is the power source for the Mars Orbiter Mission. The solar cells convert sunlight to electrical power to operate the spacecraft electrical loads and charge the battery during sun-lit conditions. Design of the solar panels of Mars Orbiter Mission is similar to the earlier IRS missions. The optimized solar array for MOM is designed in such a way to maximise the power generation during extreme environmental conditions (low temperature in the Martian orbit phase and high temperature during earthbound and heliocentric phases).

Mars is away from the Sun as compared to Earth and the distance between Mars and Sun varies from 206 million km (1.38 A.U.) to 249 million km (1.5 A.U.). As a result of it, the solar irradiance near Mars varies from 715 W/m^2 to 470W/m^2 and it leads to a variation in the solar cell operating temperature which varies from 2^oC to -20^oC.

MOM spacecraft is using a single 36 Ah Lithium ion battery in series-parallel configuration and is having a heritage from Chandrayaan-1. The power requirement during launch phase, initial attitude acquisition, during eclipse, liquid engine burns near earth, Mars Orbit Insertion, safe mode and data transmission phases are supported by this battery. Battery charging is done by Taper Charge Regulator and the battery is fully charged before each discharge. Hardware Emergency logic is taking care of battery protection against over discharge. The protection logic opens the Emergency relays to disconnect the battery from the power bus in case of battery emergency.

Communication Systems

One of the challenging tasks is to design the communication systems to meet the requirement for the communication management at a distance of nearly 200 to 400 million km. Communication system consists of Telemetry, Tacking and Commanding (TTC) systems and Data transmission systems in S-band and a Δ-DOR Transmitter for ranging. The TTC system comprises of a near omni coverage antenna system, a High gain antenna system, Medium Gain Antenna, Coherent TTC Transponders, Travelling Wave Tube Amplifiers and feed networks.

Antenna	Beam width	Peak Gain	TM Support (km)/margin (dB)	TC Support (km)/ margin (dB)
LGA	± 90°	0dB	1.4 million /2.4 dB	30 million /2 dB
MGA	± 40°	7dB 3dB @ ±40°	40 million /2.4 dB (with MGA peak pointing to earth)	110 million /2.3 dB (with MGA peak pointing to earth)
HGA	± 2°	31dB	400 million /5.4 dB	400 million /10 dB

Table-1 MOM antennae specifications

Antenna System consists of Low gain Antenna (LGA), Medium Gain Antenna (MGA), and High Gain Antenna (HGA). Coverage details of the antennae are shown in table-1. LGA on the spacecraft consists of two hemispherical coverage antennas with orthogonal circular polarization and provides near spherical radiation coverage. MGA is designed for MOM mission in order to support the TTC up to Mars orbit insertion. HGA is designed on a single 2.2 meter reflector illuminated by a feed at S-band to transmit/receive the TTC or data to/from the Indian Deep Space Network.

Delta Differential One-way Ranging (Δ-DOR)

Delta Differential One-way Ranging (Δ-DOR) is a powerful accurate technique for finding the accurate position of the spacecraft. The pointing direction of the ground station antenna directly gives the angular location of the spacecraft.

However, the accuracy one can achieve using the above technique is insufficient for interplanetary missions with stringent navigation requirements.

Radio signals sent from MOM are received at two different widely separated ground stations at different instances. This time difference corresponds to the angle difference between the lines joining the two ground stations to the spacecraft.

Subsequently the two antennae are pointed towards another standard reference radio source (a 'visually' adjacent quasar) whose angular locations are precisely known. The difference between the measured and known angular position of the reference radio source is the correction required to be made on the angular position of MOM to make it accurate. Delta-DOR measurement is used to improve the Orbit determination accuracy. It is incorporated as a part of RF system as Δ-DOR tones can be down-linked along with TM data.

Propulsion Systems

The propulsion system consists of one 440N Liquid Engine (LE-440) and 8 numbers of 22N thrusters similar to conventional GEOSAT missions. The unified bipropellant system is used for orbit raising and attitude control. The most challenging and critical task in the design of the propulsion system is to restart the main liquid propulsion engine for Mars Orbit Insertion on September 24, 2014 after a dormant period of 300 days (since the Trans-Mars insertion on Dec 01, 2013) and perform to the required stringent/exact specifications. The propellants are stored in Titanium propellant tanks each with a capacity of 390 litres. The tanks have combined storage capacity up to 852 kg propellant. The 67 litre helium pressurant tank is used to pressurize the propellant.

After the Earth bound liquid engine operations are completed the main engine was closed using pyro valves and were successfully made open after about 300 days for propellant supply for Martian Orbit Insertion maneuvers.

On-board Autonomy

It takes about 28 minutes for a radio signal to reach Mars Orbiter Spacecraft and return to Ground Station on Earth. This makes real-time control and communications (as done in earth orbiting satellites) impractical. Therefore, Mars Orbiter had to be built with its own autonomy and intelligence to manage crucial manoeuvres, fault detection, isolation & reconfiguration of systems and operations & controls during non-visible period.

Extended life span of MOM

The designed lifespan of MOM was six months. On completion of six months the lifespan was extended for a further period of six months from March 24, 2015. MOM successfully completed one year in its orbit on 24th September 2015. Normally for a healthy spacecraft, the life limiting parameter under nominal orbital conditions is the availability of propellant to maintain its orbit around the planet. In case of MOM, a reserve of about 35 kg of propellant was available in the satellite. In view of the health parameters of all critical systems of the satellite and the availability of propellant, MOM can survive many years and continues to provide very useful data in the years to come.

The details of the overall mission can be obtained from the special section of Mars Orbiter Mission published in Current Science, Vol.109, No.6, 25 September 2015.

Public Outreach

Mars Orbiter Mission is a mission of national pride which has attracted the attention of students, general public, media and international science/ technical community. Importantly, Mars Orbiter Mission has created enthusiasm among the younger generation in the country, provoked their curiosity to understand and discuss space related techniques and is maintaining the tempo throughout the mission. The Mars Orbiter Mission would go long way in building the scientific human resources in the country in the years to come.

ISRO has been utilizing its website and social media to update and popularise its activities and programmes to the general public. ISRO has made an Announcement of Opportunity (AO) for utilizing the MOM in ISRO website (www.isro.gov.in). The last date for submission of proposals is 10th October 2015. On the occasion of the first anniversary of MOM, ISRO has released a Mars Atlas comprising of images taken by MCC (pdf version is available in ISRO website). Atlas also provides preliminary scientific outputs from MSM and TIS payloads.

Chandrayan-1 data is already available in ISSDC website (www.issdc.gov.in).

ISRO conducts National Space Science Symposium (NSSS) every alternate year to provide a scientific forum for the presentation of new results and to discuss recent developments in space science, planetary exploration and space & ground based astronomy programmes/projects in India. The next NSSS-2016 will be held at Vikram Sarabhai Space Centre (VSSC), Thiruvananthapuram during 9-12 February, 2016. All participants have to pre-register. Last date for submission of abstract is on 30th October 2015.

Details are provided in NSSS-2016 website (http://spl.gov.in/nsss2016)

Acknowlegements

The author thanks Shri. S. Arunan, ISAC, Indian Space Research Organisation, Bengaluru for providing some relevant inputs for preparing this paper.

Mars Colour Camera (MCC)

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(*Submitted* 28-09-2015)

Abstract

Mars Colour Camera (MCC), on-board Mars Orbiter Mission (MOM), is a `true colour' (offering a natural colour rendition) medium resolution camera based on Bayer pattern detector and operating in the visible range (0.4μ to 0.7μ).The camera returns high quality visible images of Mars and its environs. The highly elliptical orbit chosen for the Mars mission allows imaging of localized scenes at high spatial resolution as well as providing a synoptic view of the full globe. MCC has taken a large number of images showing interesting morphological features on the Martian surface and has also captured the two moons of Mars – Phobos and Deimos during its current Martian orbit phase of the mission.

1. Introduction

Mars, one of the terrestrial planets in our solar system, has been an object of general curiosity as well as specific scientific inquiries since time immemorial due to its similarities with Earth in terms of seasonal cycles and thermal environment which is considered to be conducive to the evolution and development of life forms. Even though there have been concerted efforts to gather information about Mars over the years, still much needs to be known about it. ISRO has sent its first orbiter mission to Mars carrying instruments with well-defined scientific objectives. The orbit for the Mars mission is nearly 400km x 72,000km around Mars. Choice of such a highly elliptical orbit facilitates both localized observations with higher spatial resolution as well as observations with large coverage and high radiometric and temporal resolutions.

Mars Colour Camera (MCC) is a medium resolution camera with a RGB Bayer pattern detector. It is a `true colour' (offering a natural colour rendition, i.e., the colours in the image appearing the same way as in the object) and has been designed to return images of Mars, its Moons (Phobos & Deimos) and other celestial objects in natural colour. MCC is designed to meet the following scientific objectives: -

1. To map various morphological features on Mars with varying resolution and scales using the unique elliptical orbit.
2. To map the geological setting around sites of Methane emission source, if any.
3. To provide context information for other science payloads.

MCC is capable of taking images with a spatial resolution of nearly 20m from an altitude of 400km and can acquire complete Martian disc from an altitude of 63000km and beyond. Fig. 1 gives the Instantaneous Geometric Field Of View (IGFOV) and coverage of the camera from orbital heights of 372km (Periareion), 43000km, 63000km and 80000km (Apoareion).

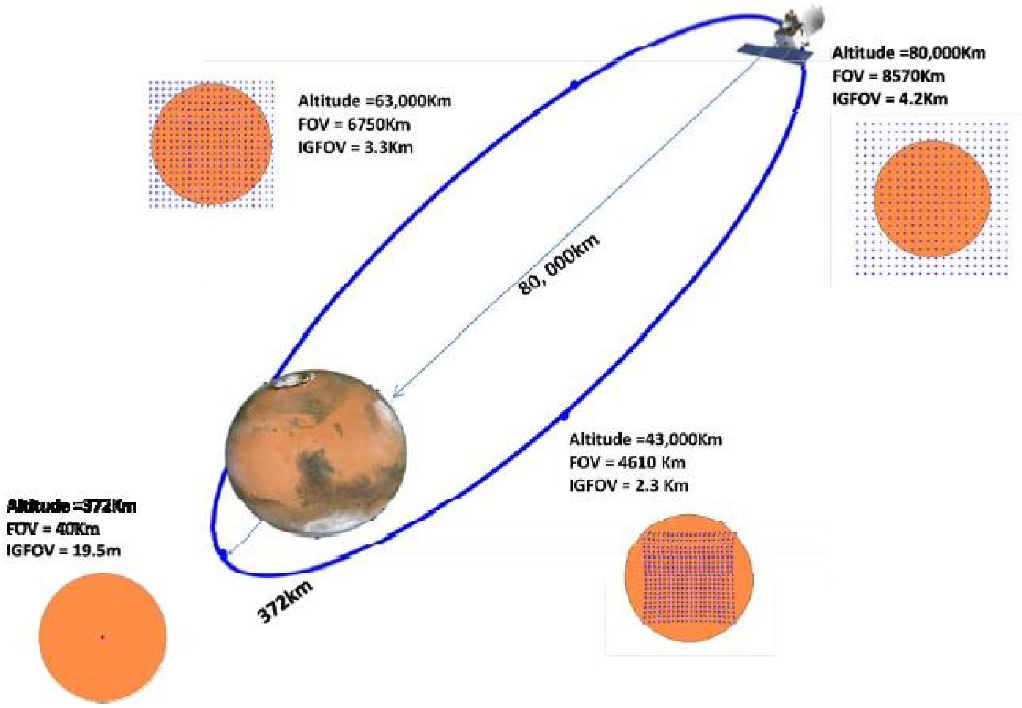

Fig.1: Coverage with MCC from different orbital heights

2. Working Principle

MCC uses a multi-element lens assembly and an area array detector with RGB Bayer pattern to take images just like a typical colour digital camera. The incident light or signal is collected by the lens assembly and focused on to an area array detector (having 2048 x 2048 pixels). As mentioned earlier MCC makes use of a RGB Bayer pattern (Fig.2) in the focal plane with organic R, G or B filter deposited on each pixel to generate colour images.

The incoming light is filtered out at pixel level to acquire information in one band (either R or G or B). Data in other two bands is estimated by interpolating information from surrounding pixels. This approach lends simplicity to the overall system design. The signal from the detector is then further processed by the associated camera electronics. The Camera electronics generates bias for detector and carries out

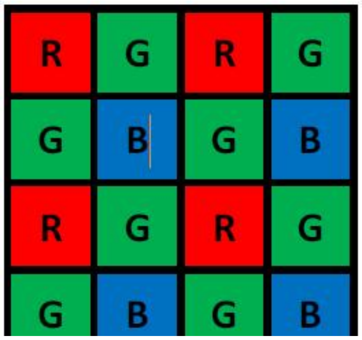

Fig.2: A typical RGB Bayer Pattern

clock generation, data preprocessing and generation of biases from raw bus. The raw data volume is 40Mb/Frame from which colour image is generated at ground using standard demosaicing. MCC hardware is realized with light-weight miniaturized components.

3. MCC Configuration

Table 1 lists the salient features and performance specifications of MCC. Fig.3 gives the schematic of the camera. MCC uses a multi-element lens assembly for collecting the incident radiation from Mars and focusing on the detector. A Commercial Off-The-Shelf (COTS) lens assembly having a focal length of 105mm with an f-number of 4.0, diagonal field of view (±4.4˚) and spectral range (400nm to 700nm) was selected for MCC based on the performance parameters and mission requirements of smaller, size and weight.

Table. 1 Salient Features and Performance Specifications of MCC

Parameter	Value
S/C Altitude (km)	372 x 80000 (Elliptical orbit)
Resolution (m)	19.5 @ Periareion
Frame Size (km)	40 x 40 @ Periareion Full Mars disc from 63000 km to Apoareion
Spectral region (µm)	0.4 – 0.7
Frame time	1s (frame selection at 1s, 8s or 15s period by ground commanding)
Exposure time	Total 16 ground programmable exposures ranging from 34µs to 490ms
Data volume/frame (Mb)	40
System MTF @ 46 LP/mm (%)	>21 (Spec. > 15%)
SNR @ Near Saturation	>95 (Spec. > 50)
Size (mm^3)	346 x 128 x 113 (EOM + LCE) 122 X 105 X 26 (PSE)
Mass (kg)	1.27 (Goal < 1.5kg)
Raw Power (W)	3.0 (Goal < 4W)

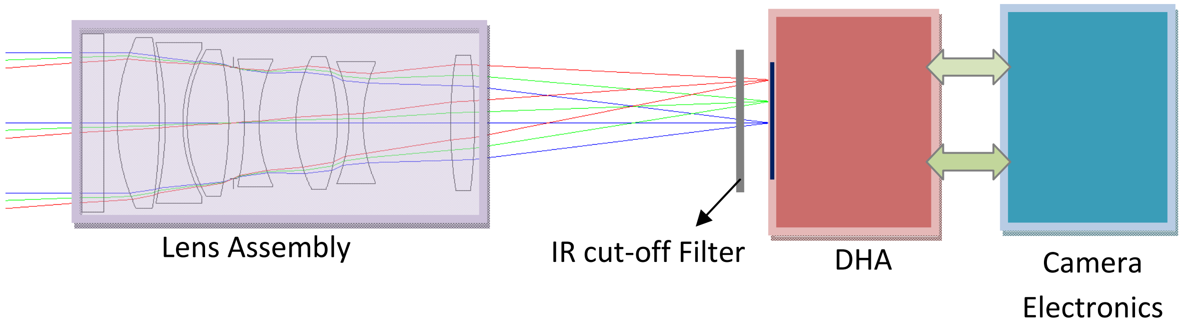

Fig.3: Schematic of MCC payload

An IR cut-off filter (with an average transmission of 95% from 400nm to 700nm with a sharp cut-off at 735nm) mounted on a precisely designed and machined, stress free mounting using flexures was placed in front of the detector to limit the out-of-band response beyond the red region (>700nm) for obtaining colour images with high fidelity.Fig.4 below shows theopto-mechanical lens assembly for MCC payload.

Fig.4: MCC lens assembly

Detector head assembly (DHA) consists of a commercial high speed silicon based snapshot colour CMOS detector and proximity electronics interfaced in a mechanical housing. It is an area array having organic filters. Incoming light is filtered out through Red (R), Green (G) and Blue (B) organic filters deposited on top of each pixel in the form of a RGGB Bayer pattern. Colour imagery is generated by using the property of depth of penetration of light in a silicon wafer.

With this approach, each pixel gets to detect information in one band (either R or G or B). Information on other two bands is estimated by interpolating information from the surrounding pixels. The detector incorporates most of front electronics including analog to digital converter in it. Fig.5 shows the populated fight model detector head assembly.

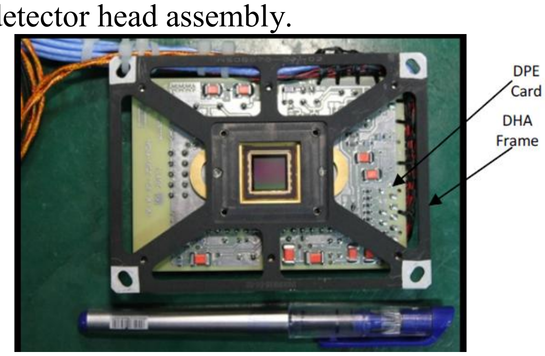

Fig.5: Populated Flight Model DHA

The Camera Electronics (CE) design and development was based on the system and detector requirements of sixteen programmable exposure controls, high speed detector operation (52.5 MHz) and low noise detector bias generation (<1mV) while taking into account the requirements of miniaturization. The miniaturization and performance requirements of Camera electronics are met by selecting state of the art space grade components like Field Programmable Gate Arrays (FPGA) for logic implementation, Low Drop Out (LDO) voltage regulators, compact hybrid DC-DC modules, integrating electronics functions near to the focal plane, usage of Micro-D connectors, Multi-Layer PCBs etc.

The CE consists of three major functional blocks - the Detector Proximity Electronics (DPE) which generates the necessary low noise bias voltages and clock signals for the detector, the Logic and Control Electronics (LCE) which generates the required clocks for detector operation, interfaces with the Base-band Data Handling (BDH) and Tele-command (TC) of space-craft (S/C) bus etc. and the Power Supply Electronics (PSE) which takes the raw power from the S/C and provides low noise (<5mV PARD) regulated power lines to the payload.Fig.6shows the block diagram of camera electronics.

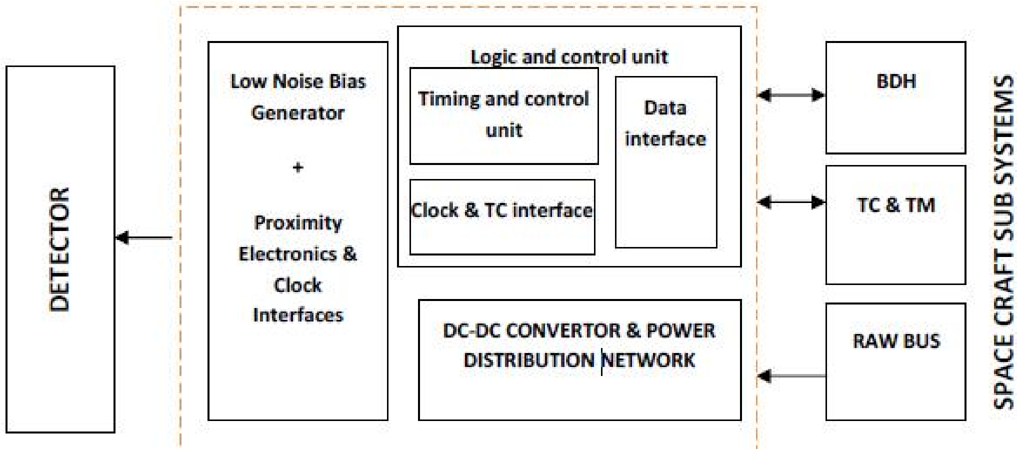

Fig.6: Block Diagram of Camera Electronics

The Electro Optic Module (EOM) structure is designed and analyzed with the objective of keeping the packages and the overall payload light weight and compact while ensuring adequate structural stiffness, electrical shielding and thermal stability to withstand the specified environmental loads and meet the performance requirements. The EOM structure is designed to take the environmental loads like dynamic vibration, shock and temperature excursions during the orbiting period.

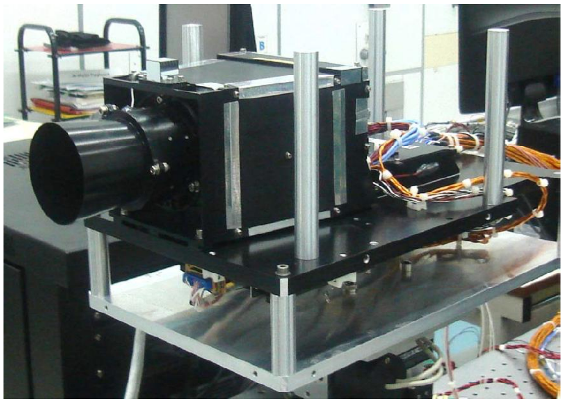

Fig.7:Flight Model of MCC payload

Integrated payload evaluation and characterization: Fig.7 shows the flight model of MCC payload. Performance of the payload has been evaluated at the integrated payload level as per the test & evaluation (T&E) guidelines. Payload performance were verified during Initial Bench Test (IBT), Post Vibration Test, Thermovac tests and Final Bench Test (FBT) phases of T&E. MCC system is optimized to produce best optical and electrical performance for all three bands. MCC payload has been characterized in terms of various performance parameters like Modulation Transfer Function (MTF), payload alignment and its stability, effective focal length (EFL) and distortion, ghost/background analysis, dark noise, Signal to Noise Ratio (SNR) at near saturation etc. Radiometric, spectral and geometric performance meets the requirements with comfortable margins. Performance of MCC payload is found consistent and satisfactory during the development in lab, payload integration, T&E, S/C integration & testing, operation during geocentric, heliocentric and in Martian orbit till the date

4. Post-Launch Performance

Mars Orbiter spacecraft was launched on 5th Nov, 2013. During the long cruise of MOM towards Mars, health parameters were monitored and the performance of the camera was tested. MCC started imaging from 19th Nov 2013. Earth Imaging Experiments (EIE) and Mars imaging experiments (MIE) were conducted during the Earth & Mars Orbit Phase (EOP / MOP) in order to assess the functional and performance aspects of MCC and to assess its application potential vis-à-vis the objectives envisaged. Three imaging sessions on two different dates viz. two sessions on 19th November and one session on 23rd November 2013, were conducted during EOP. This included imaging from varying – altitudes (spatial resolution), -illumination conditions , taking multiple snap-shots of a given area of interest (AOI) etc. in order to view physiographic, morphological and other geological details of our planet so as to ascertain the expected results from highly elliptical Mars Orbit.

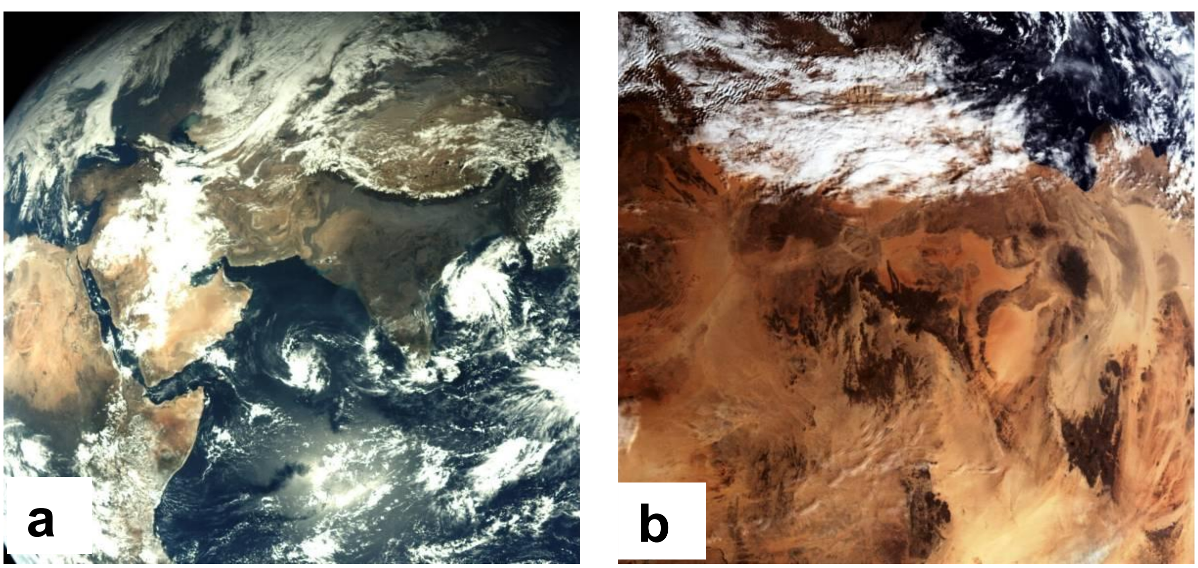

Fig.8: a) First image acquired by MCC on 19 Nov 2013 (left) and b) image on 23rd Nov 2013 over Sahara desert (right)

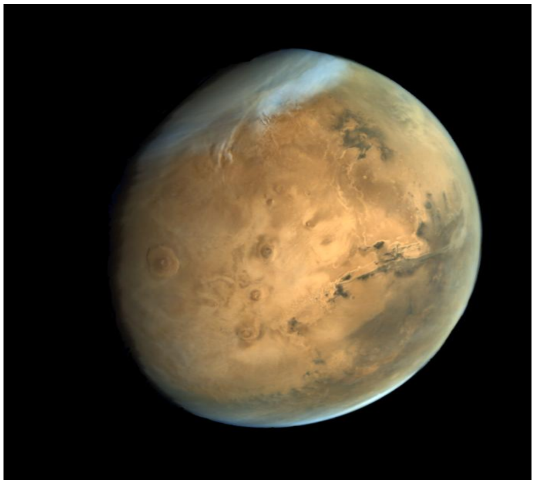

Fig.9: HDR product of the global view of Mars imaged by MCC

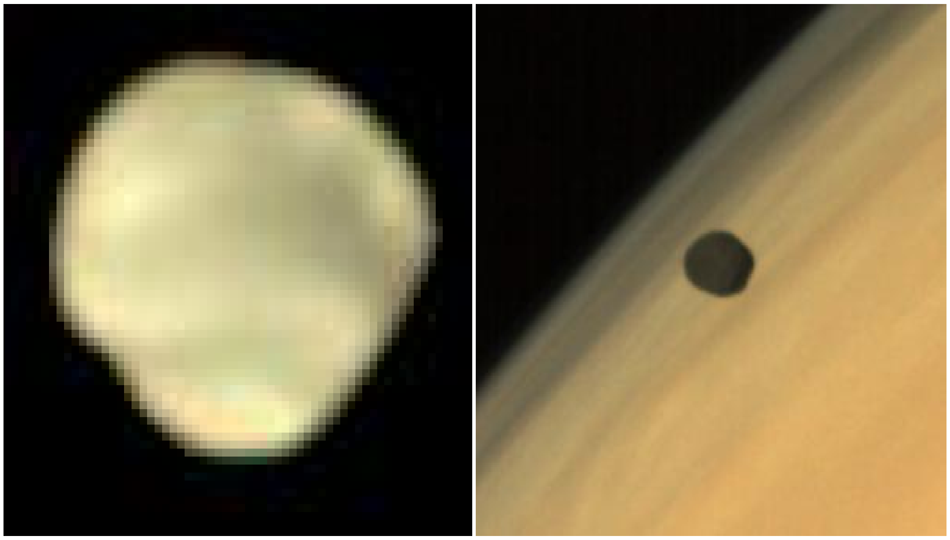

Fig. 10: Deimos (left) and Phobos (right), the two natural satellites of Mars as imaged by MCC. Bright Mars can be seen in the background of darker & smaller Phobos occupying the centre of the frame

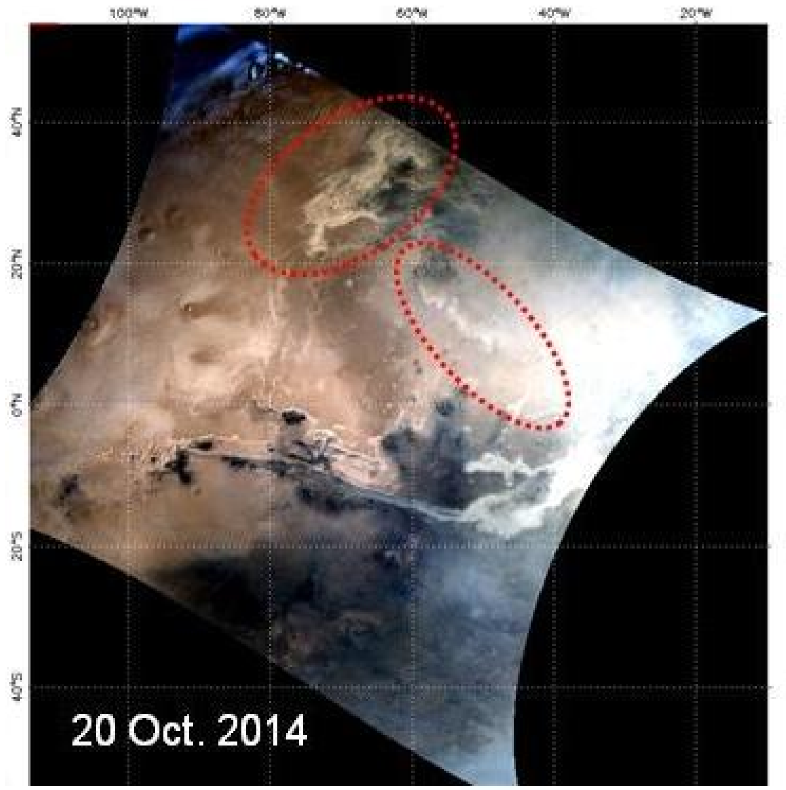

Fig.11: Dust storm (within red dotted circles), north of Vallies Marineries, appears bright.

5. Conclusions

Mars Colour Camera on-board Mars Orbiter Mission is the first camera to acquire a global 2-dimensional image of the surface of Mars. Post launch performance of the payload has been very good. The images generated from MCC are expected to help the scientific community to further understand the static (morphological) Martian features and dynamic processes (Ice-cap changes, Dust devils etc.) during the useful life of the mission.

Acknowledgement The authors wish to thank all the team members involved in the design, realization, test & evaluation and calibration of MCC payload and its various sub-systems. The contribution made by all colleagues from various fabrication and test facilities of Space Applications Centre is also gratefully acknowledged.

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Methane Sensor for Mars (MSM)

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(*Submitted* 11-08-2015)

Abstract

Methane Sensor for Mars (MSM), on-board Mars Orbiter Mission (MOM) is a differential radiometer based on FPE (Fabry-Perot Etalon) filter which measures column density of methane in the Martian atmosphere. It is the first FPE sensor ever flown to space. As MOM mission completes its first 100 orbits around Mars, MSM has already collected large volume of data completely covering the low latitude regions from 30°S to 40°N.

1. Introduction

Mars is a terrestrial planet which lies very close to the habitable zone of our solar system. Like Earth, Mars has an atmosphere, hydrosphere, cryosphere and lithosphere. Thermal environment of Mars is believed to be suitable for the development and evolution of life forms. So, when methane was first discovered on Mars in 2003 by Mars Express Mission of European Space Agency, it generated a lot of interest among scientific community as methane is a potential sign of primitive life. Alternatively, the presence of methane in the Martian atmosphere can also be explained in terms of geological activities.

Since 2003, four research groups have measured methane in the Mars atmosphere, either through terrestrial or satellite based observations.[1-5] The measured concentration was between 5-100ppb. It is found that methane concentration undergoes very rapid temporal and spatial variations with a life time of less than one year. Even though, it is very clear that methane is continuously generated and annihilated on Mars, the processes (biotic or abiotic) by which it is happening is still unknown.

MSM (Methane Sensor for Mars) on-board ISRO/India's Mars Orbiter Mission (MOM) is designed to measure total column of methane in the Martian atmosphere. It is a differential radiometer based on Fabry-Perot Etalon (FPE) Filters with a measurement accuracy of the order of few ppbs (parts per billion). MSM can map the sources and sinks of methane by scanning the full Martian disc from the apogee positions of Mars Orbiter. By correlating the temporal and spatial variations of methane with other geophysical parameters, it may be possible to find out more about the processes, biotic or abiotic which determine the dynamics of methane cycle within the Martian atmosphere.

2. Measurement principle

MSM is a differential radiometer which makes use of FPE filters to measure solar radiation reflected from planetary surface in the SWIR (Short Wave Infra Red) region. FPE is an optical filter that transmits light at extremely narrow, well defined spectral bands which are evenly spaced in the frequency domain. Figure-1A gives the schematic of an FPE filter. It consists of two parallel reflecting surfaces facing each other. When light falls on it from one side it undergoes multiple reflections between the reflecting inner surfaces and emerges from the other side. Depending on the number of reflections that the ray has undergone, its path length /phase changes. Rays having different phases interfere to generate intensity maxima at frequencies at which path difference is an integral multiple of wavelength. So, FPE filter basically transmits light at regular intervals of frequency. Transmittance of FPE is given by,

$$T = \frac{1}{1 + \mathrm{F}\sin^2(\frac{\delta}{2})} \quad \ldots\ldots\ldots\ldots (1)$$

where

$$F = \frac{4\mathrm{R}}{(1-4R)^2}$$

$$\delta = \frac{4\pi\ \mathrm{nd}\cos\theta}{\lambda}$$

d is the separation between the reflecting surfaces, R is the reflectance, θ is the angle of incidence, λ is the wavelength and n is the refractive index of the spacer medium between the reflecting surfaces.

Two parameters which characterize a FPE filter are (1) FSR (Free Spectral Range), the spectral separation between subsequent transmission peaks and (2) FWHM (Full Width at Half Maximum) or band width of transmission bands. It can be shown that,

$$FSR = \frac{1}{2\,\mathrm{n}\,\mathrm{d}} \quad \ldots\ldots\ldots\ldots(2)$$

So, FSR can be modified by varying the refractive index of the spacer medium or the separation between reflecting surfaces. Similarly, FWHM can be varied by varying the reflectance. More the reflectance narrower the transmission peaks. Fgure1B shows estimated transmission of an FPE for the design parameters mentioned therein.

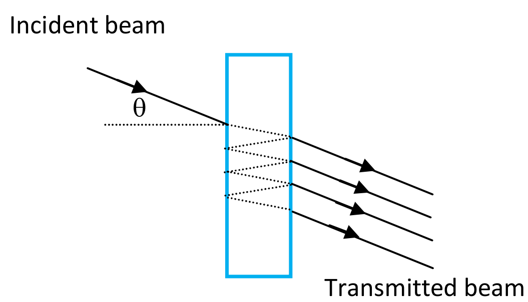

FIG-1A: Schematic of FPE filter

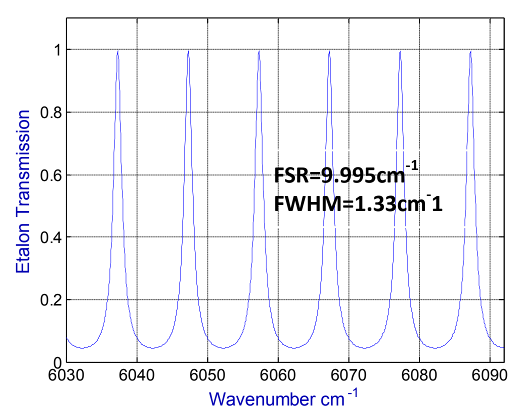

FIG-1B: Transmittance of FPE filter estimated for the design paramereters d=0.03cm, n=1.44 and R=0.85

It may be noted that if absorption lines of the gas to be measured are evenly spaced in frequency space, we can design an FPE sensor which can measure absorption simultaneously at many wavelength positions. Compared to broad band sensors, etalon sensors are very much sensitive to variation in gas concentration since they measure radiation only at those wavelengths where gaseous absorption is large.

Absorption spectrum of methane (CH_4) in the NIR-LWIR region is due to the vibrational and rotational transitions. CH_4 is a non-linear molecule having tetrahedral structure as shown in Figure-2 and does not have any permanent dipole moment. Since it is a non linear molecule, it has 3n-6=9 vibration modes (where n=5 is the number of atoms). Of these, three modes are IR inactive. The remaining modes are triply degenerate with fundamental frequencies centered at $\nu 1=3156.8cm^{-1}$ and $\nu 2=1367.4cm^{-1}$. Apart from vibrational states the molecule has rotational levels. Since energies of rotational levels are relatively small they are occupied even at low temperatures. So vibration-rotation transitions of gases usually consist of thousands of densely packed line intensities. Figure-3 shows the line intensity spectrum of methane in the 1000-10000cm^{-1} region which has more than one lakh lines.

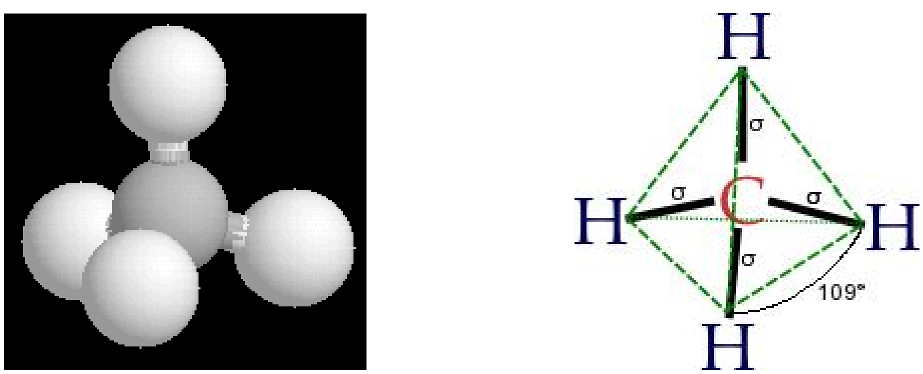

FIG-2: Structure of CH_4 molecule

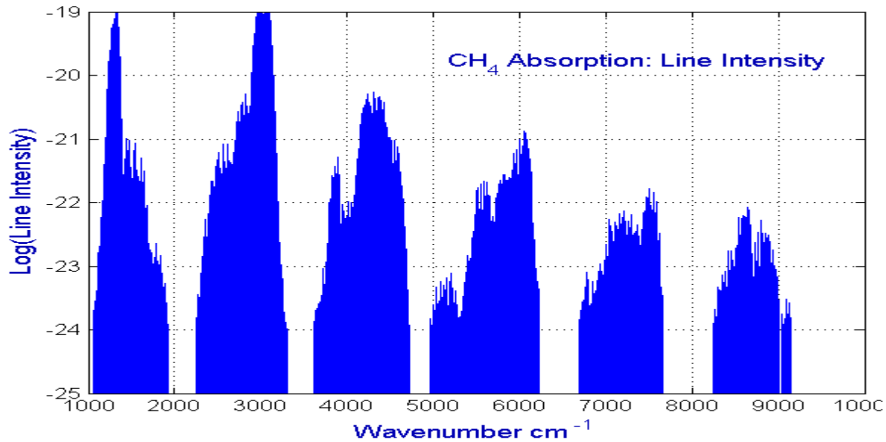

FIG. 3: Line intensities of CH_4 molecule (Source: HITRAN)

In principle, methane can be estimated by measuring radiance anywhere in the spectral region where absorption is significant. The main criteria for choosing an optimum spectral region for gas measurement are (1) absorption line intensities should be sufficiently large (2) absorption by other gas species should be negligible (3) availability and cost of suitable detectors and optical components for the wavelength region. Considering these aspects, a spectral region between 6010-6090cm^{-1} which has six prominent absorption lines is chosen for measurement. Separation between adjacent lines is ~10cm^{-1}. It may be noted that these lines are part of the second harmonic of the fundamental mode centered at 3156.8cm^{-1}. FPE of MSM is designed to measure radiance at these line positions.

Figure-4 gives the optical transmission of FPE filter of MSM (estimated from the design parameters) along with absorption lines of methane. As can be seen, transmission peaks of the filter coincide with the absorption lines of methane. Since radiation is measured only at line positions rather than over a wide spectral band, MSM is very sensitive to variations in gas concentration.

To retrieve gas concentration, the radiance measured by the sensor needs to be corrected for ground reflectance and atmospheric scattering. Conventionally, it is done by measuring radiance in a broad reference channel which is away from gaseous absorption band.[6,7] Since ground reflectance and atmospheric scattering depend on wavelength, it is not possible to correct the data fully. The new sensor design of MSM innovatively circumvents this problem by making use of another FPE filter in the reference channel with its transmission peaks falling in midway between gaseous absorption lines rather than outside the band. Therefore methane absorption in the reference channel is very small (<5% compared to methane channel) whereas ground reflectance and atmospheric scattering remains practically same. Red dotted line in Figure-4 also gives spectral transmittance of reference channel FPE estimated based on design parameters.

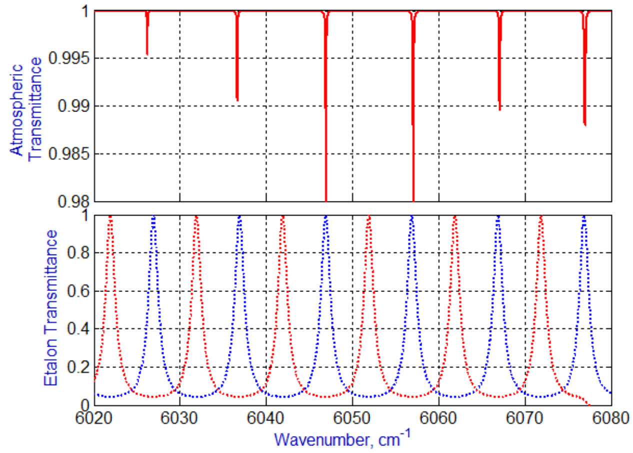

FIG.4: Spectral transmittance of FPEs of methane (blue dotted line) and reference channels (red dotted line) simulated based on design parameters. Red solid curve give atmospheric transmittance due to CH_4 absorption.

3. MSM Configuration

Figure-5 gives the optical configuration of MSM. Fore-optics collects radiance from the scene and focuses it onto a field-stop which limits the FOV (Field Of View) of the sensor to reduce stray radiation. Diverging beam from the field stop is collimated and then divided into two parts by a beam splitter. One part of the beam transmits through FPE filter of methane channel whereas the other part transmits through FPE filter of reference channel and then is focused onto respective focal planes.

FPE filters used in methane and reference channels are identical. But, FPE filter of reference channel is tilted by ~2° with respect to the optical axis so that its transmission peaks are shifted by ~5cm^{-1}, thereby falling mid-way between methane absorption lines. Positions of FPE transmission peaks vary with temperature and angle of incidence. Temperature of FPE is maintained within 0.1K so that frequency shift is less than 0.005cm^{-1}. Similarly, mechanical configuration of the system ensures that alignment stability of etalon is better than 0.01°.

Focal plane assemblies of methane and reference channels consist of eight element InGaAs (Indium Gallium Arsenide) photo diode. So, MSM has eight methane channels and eight reference channels. Detector arrays are aligned in the cross-track direction. Each pixel of methane channel is co-registered with corresponding pixel of reference channel so that they will be looking at the same ground scene. Note that for a non-uniform scene, registration error will cause differential signals which may be wrongly interpreted as methane absorption. So registration error should be as small as possible.

Expected variation in radiance signal due to methane absorption is of the order of 0.005% for 10ppb column density. Measurement of such a small variation requires very high SNR (Signal to Noise Ratio) performance. Also, radiometric resolution in terms of digitization bits should also be high. Readout and processing electronics of MSM has been designed to cater to these requirements.

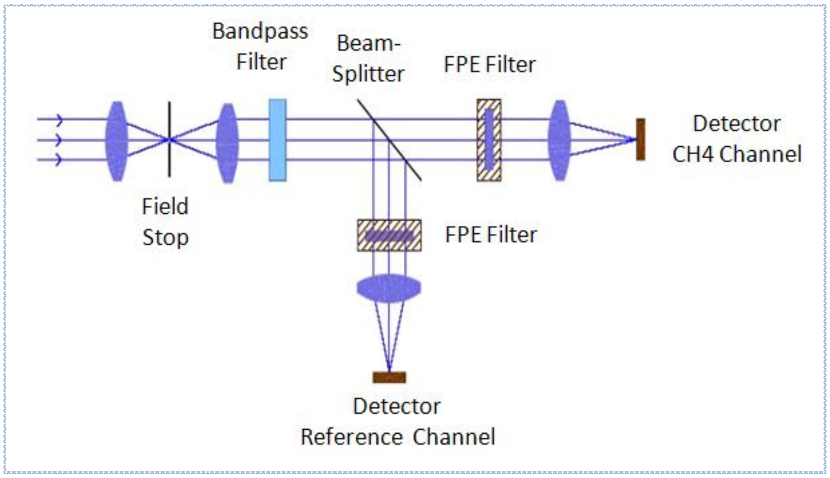

FIG. 5: Optical configuration of MSM

The analog current signal from the photo-diode is converted into a voltage signal, amplified and digitized. The image data having 20 bit resolution is transmitted to the ground station along with other housekeeping parameters. Measured SNR of MSM is better than7000 in all channels at saturation level. Figure-6 shows the flight model of MSM while Table-1 gives its salient features.

4. Post-Launch Performance

Mars Orbiter spacecraft was launched on 5th Nov, 2013. During the long cruise of MOM towards Mars, health parameters of MSM were regularly checked and were found within specifications. MOM was inserted into the Mars orbit on 27th September 2014 and the regular imaging sessions started during the second orbit itself. On 21st June 2015, when MOM completed its 100th orbit around the red planet, MSM had already acquired large volume of data completely covering the low latitude regions. Analysis of data is going on. Figure-7 gives the reflectance map of Mars in the 1.65um region generated from MSM data.

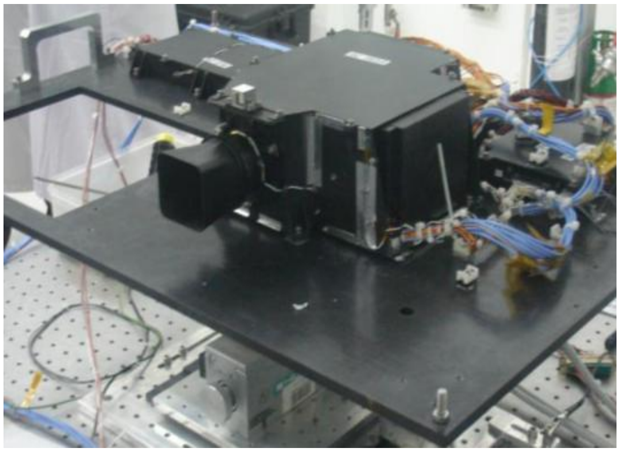

FIG. 6: Flight model of MSM

Optics	Aperture: 5cm, F-number: 1 IFOV: 1.7 milli radians
Spectral Region	6030-6090cm^{-1}
Spectral Resolution	1.4cm^{-1} (0.37nm)
FPE Filters	FSR: 9.995 cm^{-1} , FWHM: 1.4cm^{-1}
Detectors	InGaAs, 85µm pixel, 8 elements
Integration Time	0.25/0.5/1/2msec (selectable)
Digitization	20 bits
Signal to Noise Ratio	> 7000 @ saturation
Methane Sensitivity	38-60 ppb for 10sec intégration
Size	426mm x 355mm x 118mm
Mass	2.95kg
Power	7W

Table 1: Salient features of MSM

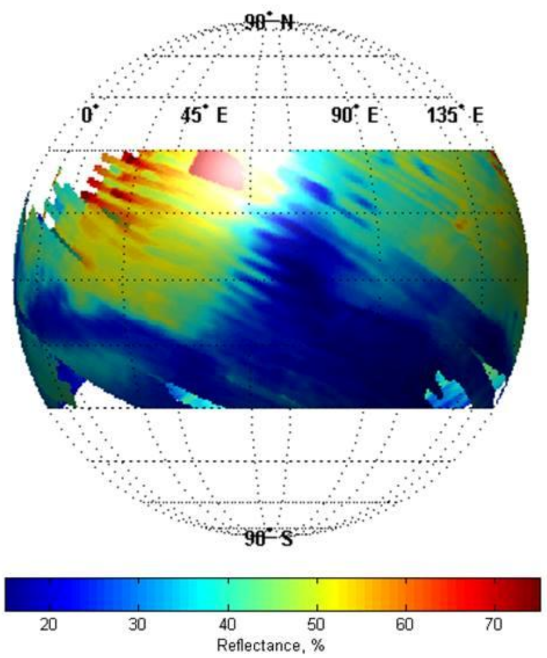

Figure-7 Reflectance map of Mars in the 1.65um region generated from MSM data.

5. Conclusions

Methane Sensor for Mars on-board Mars Orbiter Mission is the first Fabry-Perot Etalon based sensor ever sent to space. The payload has already acquired large volume of data completely covering the low latitude regions from 30S to 30N. The radiometric quality of the data is found to be satisfactory.

Acknowledgement The authors wish to thank all the team members involved in the design, realization, test & evaluation and calibration of MSM payload and its various sub-systems. The contribution made by all colleagues from various fabrication and test facilities of Space Applications Centre is also gratefully acknowledged.

V. **References**

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Lyman Alpha Photometer (LAP) for Water Evolution Studies in Planetary Atmospheres: Instrumentation, Experimentation and Performance Aspects

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Abstract

The evolutionary history of planetary atmospheres especially of non-magnetic planets such as Mars, Venus etc depends on how well one can understand their atmospheric escape process for different gases. Owing to very mild or absence of intrinsic magnetic field, the upper atmosphere of these planets is always exposed to solar wind that triggers photo-dissociation of water by producing hydrogen (H) and deuterium (D), which are subsequently lost to space over time. Measurements of the atmospheric deuterium to hydrogen (D/H) abundance ratio are vital to understand the escape process and further aid to infer the loss process of water in the evolutionary history of planet's atmosphere. The team at '*Laboratory for Electro-Optics Systems-LEOS*' developed a light-weighed (≤ 2 kg) and low power consumption (≤ 8 Watt) ultra-violet photometer; namely, '*Lyman Alpha Photometer-LAP*' that is primarily dedicated for D/H measurements of planetary upper atmospheres. LAP has successfully qualified for space use and is one of the 5 scientific instruments flown in India's maiden mission to the planet Mars, i.e., '*Mars Orbiter Mission-MOM*'. This paper primarily shares details in brief on the instrumentation, theory, and experimental investigations; finally presents the gist on the executed operations in cruise and Martian orbit phase.

1. Introduction

The study of evolution of water in Mars has become an important topic in the investigation of the planet's atmosphere. This study has a significant role in interpreting the content of water that was available during the early history of the planet. It is also useful in investigating the possibility of existence of life-forms and organic matters. Most of the past explorations to Mars have included various kinds of scientific instruments with the objective of mapping the water content and studying its evolution. Using a set of ground based observations (at Mauna Kea observatory) Owen et. al., discovered the presence of deuterated water (HDO) in the atmosphere of Mars [1]. This led to the possibility to use the measurement of isotope ratio (D/H) as a method for investigating the evolution of water. Isotope ratio is obtained by measuring the ratio of number densities of atomic deuterium (D) and hydrogen (H). In upper atmosphere of Mars atomic D and H are produced from molecules H_2 and HD by the process of photo-dissociation caused by solar vacuum ultra-violet radiation. H_2O and HDO molecules present in the middle atmosphere are the major sources for production of H_2 and HD molecules. The measured isotope ratio can be used to estimate the enrichment in water i.e. HDO/H_2O and the fractionation i.e., $(HD/H_2)/(HDO/H_2O)$. By invoking the processes responsible for fractionation a direct relation can be established between the measured isotope ratio and the enrichment of water. The extent of enrichment essentially represents the temporal evolution of water. Observations of D/H ratio measurements of Mars have revealed only local values at certain times or average values over the planet's atmosphere ($9\pm4\times10^{-4}$ by *Owen et. al*, $7.8\pm0.3\times10^{-4}$ by *Bjoraker et. al* and 5×10^{-4} upper limit of D/H ratio by *Korablev et. al*). Analysis of the SNC meteorites which are thought to have come from Mars also provided information of the Martian D/H ratio as $8.1\pm0.3\times10^{-4}$ on the Martian surface. Owing to uncertainties observed in the measured values, the value of the pristine Martian D/H ratio is still considered to be an open question and evidently, the models required to account for the isotopic fractionation is currently a subject of research.

In order to observe the spatial distribution and time variation of D/H ratio in planetary atmospheres, imaging of hydrogen and deuterium Lyman- α coronas from spacecraft is the most effective technique, since the abundances and altitude distributions of H and D atoms can be derived on a global scale. The wavelengths of hydrogen and deuterium Lyman-α lines are 121.566 nm and 121.533 nm, respectively, and thus the separation between the two lines is quite small (0.033 nm). Therefore, a high resolution spectroscopy technique is needed to separate the two lines. A standard UV spectrometer with a diffraction grating, however, is unsuitable for spacecraft measurements because of its large size and heavy weight. Instead, hydrogen/deuterium absorption cells are superior in respect to size, weight and power consumption [2-4].

2. India's Mars Orbiter Mission (MOM) and LAP instrument

In late 2013, the first Indian mission to the red planet i.e., *Mars Orbiter Mission (MOM*) was launched successfully from Sriharikota, India using a Polar Satellite Launch Vehicle and accomplished a meticulous insertion into the Martian orbit during September 2014. The MOM spacecraft revolves around Mars in a highly elliptical orbit (~400 km x 71,000 km). Though the current mission to Mars is primarily of a technological mission, it has been configured in such a way to carry out observation of physical features of mars and execute a limited study of Martian atmosphere. The spacecraft has placed five scientific payloads in an elliptical orbit with the objective of improving our understanding of the Mars based on its morphology and mineralogy using 2 scientific instruments namely Mars Colour Camera (MCC) and Thermal Infrared Spectrometer (TIS); and upper atmospheric studies using 3 scientific payloads namely Lyman Alpha Photometer (LAP), Methane Sensor for Mars (MSM) and Martian Exospheric Neutral Composition Analyzer (MENCA).

Lyman Alpha Photometer (LAP) is essentially a compact far-ultraviolet photometer capable of providing deuterium to hydrogen (D/H) abundance ratio of Martian exosphere from spacecraft observations. LAP is developed on the absorption gas cell based photometry technique [5-6] and is the first Indian space-borne absorption gas cell photometer that operates on the principle of resonant scattering and resonance absorption. Comparison of the present and initial D/H ratio (estimated from observations of the D/H ratio in comets and asteroids, which are believed to be sources of Martian water) should allow us to calculate the amount of hydrogen and, therefore, the water that has been lost over planet's lifetime. Primary scientific objective of the LAP instrument is to determine D/H isotope ratio of Martian upper atmosphere from the ratio of measured Lyman-α intensities. The observations would enable us to *i)* generate spatial and temporal profiles of hydrogen and deuterium Lyman-α intensities, *ii)* study of deuterium-enrichment in the upper atmosphere and *iii)* estimate of the water escape/loss rate. Figure-1 depicts the LAP instrument flown in MOM spacecraft and table-1 presents salient features of the instrument.

FIG. 1: LAP instrument flown in MOM spacecraft

Table-1: Salient features of LAP instrument

Sl. No.	Parameter	Specification
1.	Operational Range	3,000 km – periapsis – 3,000 km
2.	Pointing Direction	Nadir, Limb and Exosphere
3.	Field of View	0.0016 steradians
4.	Dynamic Range	1 - 5 x 10^7 counts per second
5.	Gas Cells	Hydrogen, Deuterium
6.	Weight	1.97 Kg
7.	Power	7.2 Watt (P_{rms})
8.	Dimensions (LxWxH)	276 x 138 x 100.5 (mm)

3. Instrumentation and Challenges

The block diagram of LAP instrument with its sub-units is shown in Figure-2. As shown in the figure, LAP primarily comprises four functional units; *MHU* (Main Housing Unit), *ACU* (Absorption Cell Unit), *OU* (Optics Unit) and *DU* (Detection Unit). The MHU serves as a mounting base for all electro-optic modules of the instrument. The ACU consists of hydrogen and deuterium gas filled cells (H_2-cell, D_2-cell) with tungsten filament coils that can be electrically heated to dissociate the gases in to atoms. H_2-cell and D_2-cell are sealed and isolated from each other by means of MgF_2 windows. OU consists of an MgF_2 collection lens and a coarse Lyman-α filter. The choice of MgF_2 material for the lens as well as for cell windows is mainly due to the fact that this is the only optical material available at the wavelength of Lyman-α without deliquescence. The cylindrical baffle in front of the lens prevents stray radiation reaching the gas cells, while a coarse Lyman-α filter is used to cut-off the undesirable radiation that lies outside the wavelength range of interest. The DU consists of a UV-detector, detection and processing electronics modules. A significant aspect of this configuration is that the LAP detection unit was developed to operate in single-photon counting mode, which was best suited for the low-level incoming scattered flux from the Martian exosphere. The main sub-elements of the Detection Unit are the detector, charge sensitive pre-amplifier, pulse discriminator and time digitizer unit. Considering factors like size, quantum efficiency, speed of response and ease of use, a solar-blind side-on type UV-PMT was chosen as a detector. The resultant output current pulses from the detector are amplified and shaped. A current pulse corresponding to an incident photon is discriminated from noise pulses which have relatively low pulse heights compared to the signal pulses. The arrival time of the pulses was counted by a counter, the value of which was latched at every clock pulse and read by the processing unit.

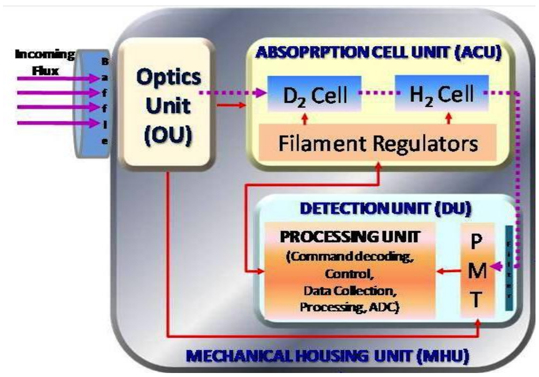

FIG. 2: A cartoon of LAP instrument configuration

The prime challenges of development are: a) realization of absorption gas cells, b) establishment of ultra-high vacuum (better than 10^{-9} Torr) baking, evacuation, gas filling and sealing techniques, c) realization of low-power consumption filament coils, d) design and realization of space-compatible high voltage electronics modules, e) realization of single photon counting detection and processing technique and f) calibration and characterization under ultra-high vacuum environments.

4. Operational Principle and Modes of Operation

As mentioned previously, the LAP instrument works on the absorption cell technique in which power is applied to the filaments to thermally dissociate the hydrogen or deuterium molecules into atoms that absorb the incoming hydrogen or deuterium Lyman-α radiation passing through cells. When the filament in the H_2-gas cell is turned on, the electrons emitted by the hot filament dissociate the hydrogen molecules to produce H atoms. These H atoms resonantly absorb a part of the incoming hydrogen Lyman-α radiation and transmit the remaining part. Similarly, when the filament in the D_2-gas cell is turned on, the electrons emitted by the hot filament dissociate the deuterium molecules to produce D atoms. These D atoms resonantly absorb the incoming deuterium Lyman-α radiation. Thus by turning on the filament of H_2 and D_2 gas cells alternately in a cyclic manner, the ratio of intensities (I_D/I_H) can be measured. The measured intensity ratio can then be used to estimate the isotope ratio i.e., D/H ratio. Figure-3 illustrates the concept of alternately turning on the tungsten filaments for measurement of D/H ratio.

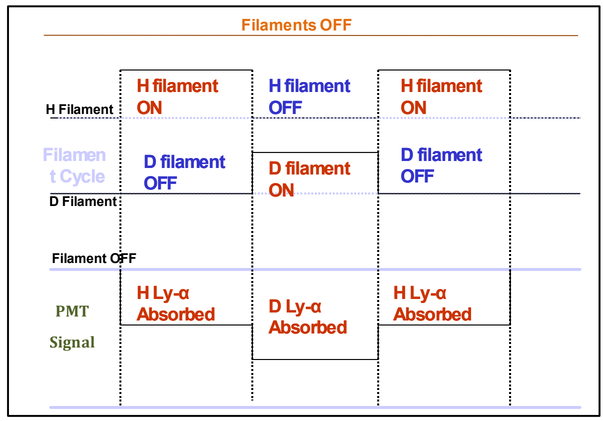

Fig. 3: The concept of alternately turning on/off the tungsten filaments of gas cells for measurement of D/H ratio

LAP can function in two modes i.e., *i) Photometer mode* in which the incoming line-of-sight photon flux within the spectral bandwidth of the Lyman alpha filter is measured without activating the filaments in gas cells. This mode of operation is useful to assess the hydrogen distribution as a function of altitude, *ii) Absorption cell mode* in which, filaments of deuterium and hydrogen gas cells are activated in a cyclic manner to record the relative signal contribution, from which the D/H ratio can be estimated employing the calibration and normalization factors derived from ground based experiments.

5. Experimentation and Performance Aspects

To validate the LAP design and to ensure its operation in Martian orbit, several system-level integration and interface tests are devised and performed. Prior to the instrument level testing and qualification, various kinds of calibration and characterization experiments are carried out in vacuum environment (pressure better than 10^{-5} Torr) at sub-system level. The major test activities were: i) filament stability and survivability along with its characterization in gaseous environment and ii) gas cell spectral absorption investigations. These tests helped to verify the filaments life for the expected on-board operational schedule and yielded calibration factors that to be employed during on-board data processing. Figure-4 shows such a photo-absorption profile of experimental D2-gas cell during its spectral calibration activity. Photo-absorption phenomena as a dip at 121.53 nm can be seen clearly from the gas cell when the set filament current was 465 mA.

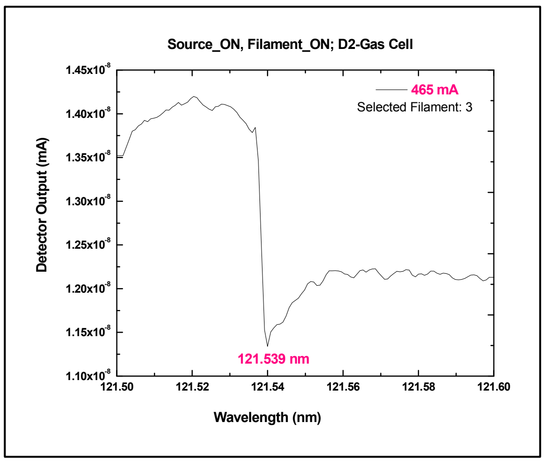

Fig. 4: Registered photo-absorption event in D2-gas cell

Gas cell photo- Cell calibration studies were carried out employing a 1.33 meter vacuum ultraviolet Czerny-Turner configuration based spectrometer that provides a spectral resolution of 0.004 nm. The input radiation source is deuterium lamp. Similar kinds of profiles were recorded during H2-gas cell photo-absorption investigations. These tests are attested the absorption signatures H2 and D2-gas cell at their respective Lyman-alpha wavelengths upon their filament turn_ON. In addition to the retrieval of calibration factors, optimization of filament current required during Martian orbit operations for LAP in 'absorption-cell mode' is devised by these experiments. Figure-5 shows the D2-gas cell calibration setup in the sample chamber of a UV-spectrometer.

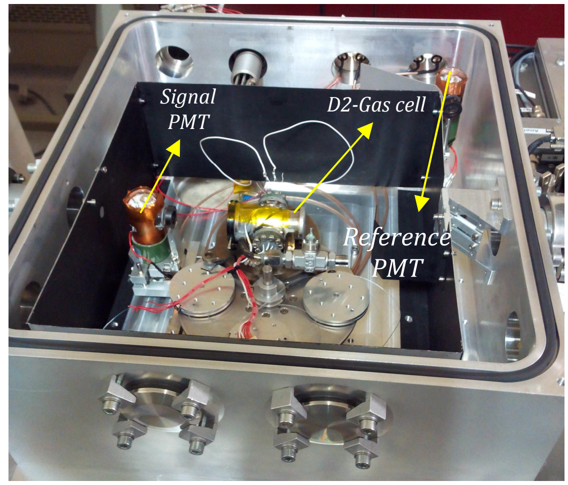

Fig. 5: D2-gas cell in the sample chamber of UV-Spectrometer

Upon the successful testing of sub-modules, all are integrated to the MHU of LAP instrument and is subjected for system level testing. LAP testing include functional (namely initial bench electrical tests), environmental (temperature vacuum cycling test, thermal soak test, vibration test) and end-to-end testing both at the instrument as well as spacecraft levels. Figure-6 shows the LAP instrument on vibration shaker during its acceptance level test subjecting to the frequency levels as defined by the mission (these vibration levels are equivalent to the expected levels experienced by the launch vehicle during launch). Instruments performance is verified by placing it in a thermo vacuum chamber and operated over several thermal cycles between temperatures (-10^0C to+45^0 C). To prevent corona and to ensure reliable operation, the instrument was soaked in vacuum before it was powered. After completion of functional, environmental and end-to-end tests, LAP instrument was integrated to the spacecraft and was tested successfully for its interface, functional and performance checks at various spacecraft-level tests.

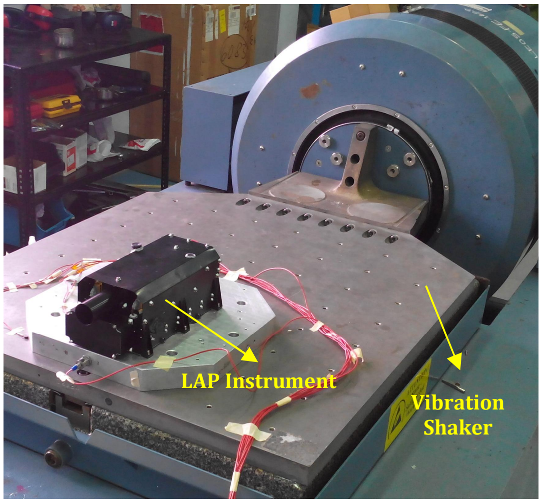

Fig. 6: LAP instrument on Vibration Shaker during it Qualification

6. Retrieval Scheme of Calibration Factors and D/H Ratio Estimation

As explained in previous sections, the hydrogen isotope ratio n_D/n_H can be directly estimated from the ratio of incident fluxes I_D/I_H (intensities received by LAP) of D-L_α and H-L_α. This ratio in principle is determined by measuring the ratio of absorbed intensities $I_{Abs,D}/I_{Abs,H}$. Here, $I_{Abs,D}$ and $I_{Abs,H}$ are the intensities absorbed by D2 and H2 gas cells respectively. The absorbed intensities are related to the respective optical depths τ_D and τ_H by the following relationships (Beer-Lambert law).

By mathematical simplification these relationships can be re-written as,

$$I_{Abs,D} = I_D\left[\tau_D - \frac{\tau_D^2}{2} + \frac{\tau_D^3}{6}\right]$$

$$I_{Abs,H} = I_H\left[\tau_H - \frac{\tau_H^2}{2} + \frac{\tau_H^3}{6}\right]$$

$$\frac{I_D}{I_H} = \xi \, \frac{I_{Abs,D}}{I_{Abs,H}}$$

$$\xi = \left[\frac{I_{Abs,H}}{I_H}\right] \Big/ \left[\frac{I_{Abs,D}}{I_D}\right]$$

Here, where ξ is defined as

$$\xi = \left[\tau_H - \frac{\tau_H^2}{2} + \frac{\tau_H^3}{6}\right] \Big/ \left[\tau_D - \frac{\tau_D^2}{2} + \frac{\tau_D^3}{6}\right]$$

Implying $\xi = \left[\frac{I_{Abs,H}}{I_H}\right] \Big/ \left[\frac{I_{Abs,D}}{I_D}\right]$

that i.e ξ is the ratio of absorption factors, that means, here

ξ = (H Absorption factor) / (D Absorption factor).

The quantity ξ is the calibration factor for the LAP instrument and is determined by recording the absorption factors of H2 and D2 gas cell during their photo-absorption investigations. The 'ξ' is employed in the estimation of Martian atmospheric D/H ratio from the recorded counts by the instrument employing following equation.

$$\mathbf{n_D / n_H = \xi\,(I_{abs,D} / I_{abs,H})}$$

The isotope Ratio is obtained from ratio of absorbed intensities, where

$I_{abs,D}$ (Intensity absorbed by D2- cell) =
I (H-cell off, D-cell-off) - I (H-cell,off, D-cell-on

$I_{abs,H}$ (Intensity absorbed by H2- cell) =
I (H-cell off, D-cell-off) - I (H-cell,on, D-cell-off

7. Summary of LAP Operations in Cruise and Mars Orbit Phase

LAP instrument is planned to be operated in tras-mars orbit and Martian orbit phases. As per schedule, the first on-board operation of LAP in trans-mars orbit phase was carried out on 6th February, 2014 when MOM spacecraft was at a distance of approximately 1,57,04,605 kilometers from the Earth. Functionality checks and health parameters that were monitored during this operational phase attested good health condition of LAP instrument. After the successful insertion of MOM spacecraft in to the desired orbit, LAP instrument has been performing on-orbit investigations flawlessly. Useful scientific data sets are received and are currently under analysis. Analyzed data so far revealed successful registration of the Hydrogen Lyman-alpha brightness as well as clear Lyman-alpha flux absorption signatures of Martian atmosphere. Special operations are in progress to enhance the science yield. Analysis of all such data sets would be utilized in estimating the global average value of D/H ratio of Martian exosphere.

8. Conclusions

LAP kind of instrument is best suited to determine the D/H ratio of a planet's atmosphere, because hydrogen and deuterium gas cell acts as a perfect narrow-band rejection filter at their respective Lyman-alpha wavelengths upon the filament activation. From ISRO's perspective, this kind of instrument development is entirely novel. The performance of the realized instrument matched the desired specifications in all aspects and well within the allowable tolerance limits. LAP instrument is found to be in good health from its first on-board operations. The D/H ratio would be determined from the measured intensity ratio of deuterium to hydrogen during the Martian orbit observations. The determined D/H ratio would be employed further in assessment of the water escape rate.

9. Acknowledgements

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MENCA onboard the Indian Mars Orbiter Mission

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Abstract

The MENCA (Mars Exospheric Neutral Composition Analyser) is one of the science instruments onboard the Mars Orbiter Mission, India's first mission to Mars. MENCA is a quadrupole mass spectrometer, and is also equipped with a Bayard Alpert gauge for total pressure measurements. The quadrupole mass spectrometer is being used to measure the exospheric composition of Mars. In this article, the theory of quadruple mass spectrometery is briefly discussed followed by description of the MENCA instrument. The various processes involved in the characterization and calibration of this mass spectrometer are also described.

1 Introduction

India's first interplanetary mission and the first Indian mission to Mars-the Mars Orbiter Mission (MOM, also known as Mangalyaan) was launched on 5 November 2013 by Polar Satellite Launch Vehicle in its 25^{th} launch (PSLV-C25). MOM escaped from Earth's sphere of influence on 5 December 2013 and after travelling for 10 months in Heliocentric orbit, was inserted into the Martian orbit on 24 September 2014, making India the first country to successfully inject a spacecraft into the Martian orbit in the first attempt. The MOM has successfully completed the planned mission lifetime of 6 months, and it is now continuing in the extended mission phase. Though the primary objective of this mission was technology demonstration, aiming to develop and demostrate the technologies for operations of an interplanetary mission including deep spae communication and incorporation of autonomous features, the satellite carried 5 science instruments to observe the red planet and its atmosphere. These instruments are: (1) Mars Color Camera (MCC) for obtaining images in the visible range, (2) Thermal Infrared Spectrometer (TIS) for mapping the surface composition and Minerology, (3) Lyman Alpha Photometer (LAP) to measure H-Lyman Alpha and the realtive abundances of D and H, (4) Methane Sensor for Mars (MSM) for detecting Methane in the atmosphere of Mars, and (5) Mars Exospheric Neutral Composition Analyser (MENCA) for the measurement of the exospheric neutral composition of Mars. In this article, we will focus on the MENCA instrument.

The MENCA is a quadrupole mass spectrometer-based instrument. In the context of MENCA, the physics of the quadrupole Mass Spectrometry is discussed in detail in section 2. In section 3, the specific feaures of the MENCA instrument are described along with some details about the characterisation and calibration of the mass spectrometer, which enables one to derive the absolute abudances from the observed mass spectra.

2 Mass Spectromety

Basically, mass spectrometers are ion optical devices that can transport, disperse and focus ions which are emitted by an ion source [1]. Mass spectrometers work on the principle that ions get deflected and gain or lose energy/charge (E/q) in electric fields and get deflected in magnetic fields by an amount proportional to their momentum per charge[1]. Basically, a mass spectrometer has three components, viz: *ion source*, *mass analyser*, and *ion detector*. The ion source ionizes the molecules and they are then accelerated to the mass analyser where they are separated according to their mass per unit charge (m/q), and some times according to energy also, by electric and/or magnetic fields. Finally, they are collected by the detector, and the output is an electrical current, which is amplified and detected. There are different methods for realizing a mass spectrometer. Some of these are as follows.

Quadrupole Mass Spectrometers: They are path stability spectrometers as they separate ions of different m/q by selecting only those ions which have stable trajectories in quasi-static electric fields (i.e., $\nabla^2\Phi = 0$, where Φ is the potential).

Ion Trap Mass Spectrometers: In Ion trap mass spectrometers ions are trapped by two end electrodes applied with DC and AC voltages making the ions oscillate in stable orbits. They are selectively thrown out of the cavity with respect to their mass-to-charge ratios and are subsequently detected.

Magnetic Mass Spectrometers: In these spectrometers, combinations of static electric and magnetic fields are used to focus ions of a particular m/q. A special configuration called *Double Focusing* is often used, where ions arriving from the ion source are first directed through an entrance slit and then they are focused in angle and dispersed in E/q using an electrostatic field. Then the ions enter a magnetic field, where they are dispersed according to momentum/charge and focused in energy and angle. Neutral gas is first ionized and then deflected first through an electrostatic filter and then a magnetic filter to a detector, and this double focusing gives a high mass resolution, for instance, it can sepearate N_2 from CO [2].

Time-of-flight Mass Spectrometers: In these spectrometeres, ions leaving the source are accelerated before entering the spectrometer and during their travel through the spectrometer, and they are dispersed in time according to m/q and then focused in time at the detector. The accurate measurement of the time of arrival yields a spectrum with mass discrimination according to m/q.

Mass Spectrometry has been a very useful experimental technique with wide range of applications. Among these instruments described above, quadrupole mass spectrometers gained popularity for space research (which requires rugged construction, high reliablity and high optimization in terms of weight and power), because of their compactness, mechanical simplicity, lightweight, absence of a cumbersome magnet, the linear mass scale, high speed scanning and relatively simple trading off between sensitivity and resolution. They are only limited by their moderate resolution and limited energy range. It may be noted that the usable energy range for the quadrupole spectrometer can be utilized for measurement of thermal paricles and hence sufficient for many planetary science applications, including upper atmospheric and exospheric compositon measurements.

The idea of using quadrupole fields for mass spectrometery was first proposed by Paul and Steinwedel at the University of Bonn, in the early 1950s. This work culminated in a paper on the quadrupole mass filter by Paul et al [3] followed by the construction of a 5.8 m long high resolution mass filter.

A quadrupole mass spectrometer consists of four rods with adjacent electrodes oppositely charged (Figure 1). The applied potential has two components, U and V, where U is the direct current (DC) component, and V is the radio frequency (RF) component, of the form V$cos(\omega t)$. The general form of the equation

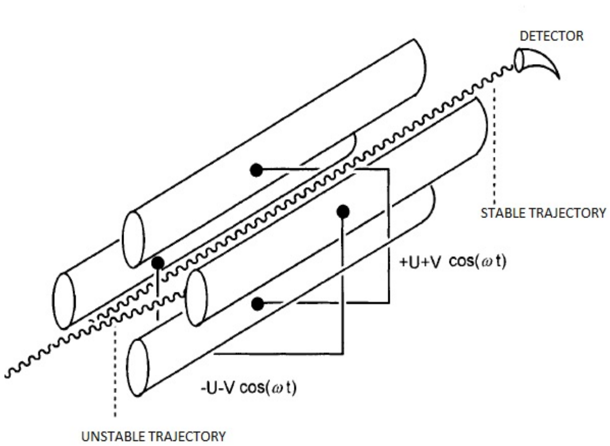

Figure 1: . Quadrupole rod system

of motion can be written as,

$$\frac{d^2u}{d\xi^2} + (a_u - 2q_u cos 2\xi)u = 0$$

where

$$a_u = a_x = -a_y = \frac{4eU}{m\omega^2 r_0^2}$$

$$q_u = q_x = -q_y = \frac{2eV}{m\omega^2 r_0^2}$$

In this, u is the coordinate parameter and ξ is the time expressed in terms of $\omega t/2$.

This is the **Mathieu Equation** in the canonical form [4]. The solutions to this equation reveal that the nature of ion motion depends on a and q and not on the initial conditions. All ions with the same a and q values have the same periodicity of motion.

Furthermore, the solutions can be stable or unstable depending on a and q. For a given quadrupole geometry, r_0 is constant and ω is maintained constant. U and V are the variables. In principle, ω can also be varied keeping U and V constant, but frequency sweeping over extended range is very difficult to realize and is seldom used. For an ion of any mass, x and y can be determined during a time span as functions of U and V. Ions that are resonant with a given field will oscillate close to the z axis and are transmitted through en exit aperture located on the Z-axis. Non resonant ions will undergo unstable oscillations and will eventually strike the quadrupole rods or exit laterally, without entering the detector. The mass number corresponding to the stable trajectory can be changed by varying the magnitudes of U and V, and thus the mass scan can be realized. The mass spectrum thus obtained gives information about the relative abundances of various consituents in the ambience.
As mentioned earlier, mass spectrometers have been used extensively for studying the planetary atmospheres. Some of the early planetary explorations which included mass spectrometery experiments are the Apollo mission to Moon, Viking Mission to Mars and the Pioneer Venus mission. The Apollo-17 mission had a mass spectrometer, the Lunar Atmosphere Composition Experiment (LACE), which was physically deployed by the astronauts on the lunar surface which confirmed the existence of Helium and Argon in the lunar atmosphere [5]. Much of our knowledge about the ioonsphere of Venus was provided by the Ion Mass Spectrometer aboard the Pioneer mission [6]. The Viking landers carried Upper Atmospheric Composi-

tion Explorer mass spectrometers which provided data about the composition of the Martian upper atmosphere from 200 km to 120 km altitude [7]. The ChACE (Chandra's Altitidunal Composition Experiment) onboard the MIP (Moon Impact Probe) of India's Chandrayaan-1 mission had brought out several new aspects about the tenous surface bounded exosphere of Moon [8, 9]. Missions like the Cassini to Saturn and Rosetta to comet 67P/Churyumov-Gerasimenkoalso had sophisticated mass spectrometers [2, 10, 11]. The LADEE mission to Moon had a quadrupole neutral mass spectrometer which provided the first global characterization of He, Ar along with first observations of the diurnal variation of Ne in the lunar exosphere [12]. The ongoing MAVEN mission to Mars also carries a similar mass spectrometer [13], which is expeced to provide data on the upper atmosphere and exosphere of Mars, along with the MENCA aboard the Indian Mars Orbiter Mission [14].

3 MENCA

MENCA is a quadrupole mass spectrometer based instrument. The MENCA instrument consists of two major parts, viz. the sensor probe and the electronics. Figure 2 shows the MENCA instrument in its flight configuration. The mass range is 1-300 amu (programmable through telecommand) with unit mass resolution. Apart from having a quadrupole mass analyser, MENCA has a Bayard Alpert (BA) gauge to measure the total pressure, so that the absolute abundances

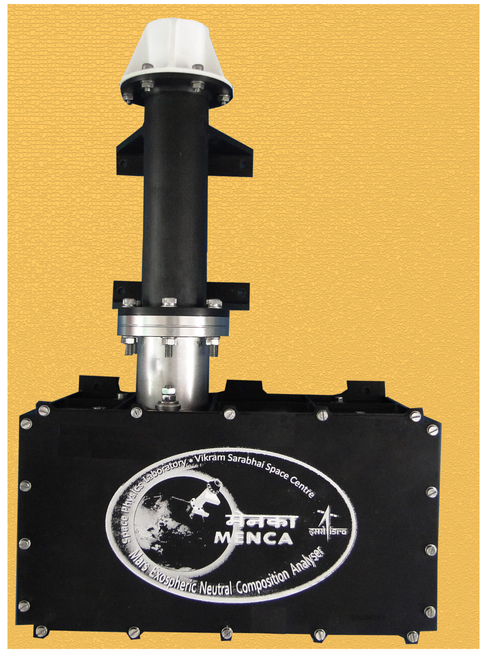

Figure 2: MENCA experiment aboard the Mars Orbiter Mission of India.

of the consituents can be derived from the observations. The BA gauge is operated at pressures below 10^{-4} Torr. The ambient neutrals are ionized by the energetic (typically 70 eV) electrons emanating from a pair of thoria coated iridium filaments operating in hot redundancy.

Within the ionizer region, there is a cylindrical region enclosed by a mesh of wires, known as source grid, which is maintained at a positive potential in order to repel the ions in the medium. The ions which are formed within the source grid region, are accelerated electrostatically along the axial direction by focus grids and enter the quadrupole mass analyser system. The mass discrimination takes place in the quadrupole system, as described in the previous section. The ions entering the detector generate a current which is proportional to the abundance of a partcular species. The MENCA has two types of detectors, viz. Faraday Cup and the Channel Electron Multiplier (CEM). The CEM detector is invoked for pressures lesser than 10^{-7} Torr since it has intrinsic current gain ($\sim 10^5$ for a bias voltage of 2000 V) to amplify the low currents corresponding to the trace constituents. This provides extremely low noise level, enhances the sensitivity in terms of detection of trace species and also facilitates faster mass scans. With both Faraday Cup and CEM, the dynamic range of the instriment is 10^{10}. In addition to Mass Scan mode, MENCA can be operated in Trend (of selected species) Mode wherein the instrument locks in to a set of preselected species and tracks their abundances.

The ionized neutrals which move outside the source grid are collected by a thin wire (BA collector) that is biased negatively to collect the ions situated in a well defined volume and the current is directly proportional to the pressure of the ambient gas. This gives the total pressure in the medium.

The main instrument parameters are as follows.

Emission current : The emission current is a measure of the flux of the thermionically emitted electrons from the filament, which is a part of the built in ion source.

Electron energy : The thermionic electrons are accelerated to 70 eV in order to ionize the ambient neutrals. The instrument has options to operate at other electron energies as well.

Ion energy: The positive ions that are created in the source grid region are directed axially through the quadrupole mass filter region to reach the detector with a potential applied axially.

During operations, several health check parameters are also monitored including power supply voltages, different internal temperatures as well as several digital telemetry parameters.

Several laboratory experiments under High Vaccum conditions (at Space Physics Laboratory, Vikram Sarabhai Space Centre) and Ultra High Vaccum conditions of 2×10^{-11} Torr (at the UHV division, RRCAT, Indore) were conducted in order to characterize and calibrate MENCA. In addition to the calibration under the residual gas enviornments, gas insertion tests were conducted using He, Ar, N_2 and CO_2 gases. Figure 3 shows a mass spectrum the prominent constituents in a residual gas environment and their dissociation products.

The Martian Orbit Insertion (MOI) was on 24 September 2014 and the MENCA instrument was commissioned in the Martian orbit on 29 September 2014. The high voltage commissioning was conducted in phased manner, which was completed on 8 October 2014. Prior to this, MENCA was operated in the Earth-bound phase and in the heliocentric phase for health check. MENCA has been operational in the Mars phase both near

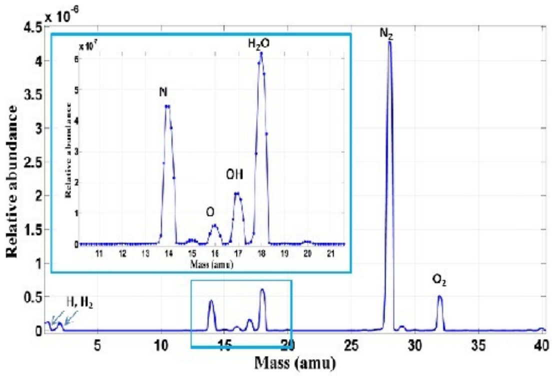

Figure 3: Mass spectrum of the prominent constituents in a residual gas environment and their dissociation products.

the periapsis and near the apoapsis, and the House Keeping (HK) parameters (temperatures, voltages) of the instrument are within the allowable ranges. Currently, the analysis of the MENCA data is in progress, and it is expected that the data would provide useful information about the exospheric consitutents of Mars and their variations.

Acknowledgments

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Thermal Infrared Imaging Spectrometer Onboard Mars Orbiter Mission

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Abstract

Thermal Infrared Imaging Spectrometer (TIS) on-board Mars Orbiter Mission (MOM) is a grating based spectrometer which measures thermal infrared radiation emitted from Mars environment in 7-13 µm spectral range. Observations from TIS help in estimating brightness temperature of Mars surface and in knowing the composition of the surface. TIS is made up of light weight miniaturized components (total weight 3.2 kg) and has power requirement of 6W and uses un-cooled micro-bolometer array for detection.

1. Introduction

Knowledge of Spatial and seasonal behavior of planetary surface temperature is required to understand various thermo-physical processes and associated weather systems. The satellite based observations of surface temperature provides an important boundary conditions for global circulation modeling. Satellite based measurements in thermal infrared spectral region have been used to characterize atmospheric properties, surface composition and detect the surface temperate variability[1-7].Many Thermal infrared spectrometers (IRS, IRIS, ISM, IRTM, TES, THEMIS) onboard different spacecrafts have been flown earlier to Mars to study the thermal ambience and surface composition. The initial infrared spectrometers based experiments were carried during Mariner 6 and Mariner 7 Flybys. In 1971, Mariner 9 began orbiting Mars, and its infrared interferometer spectrometer (IRIS) returned many valuable spectra. Later distinct absorption in the 9 and 20 um spectral regions were observed in Viking Infrared Thermal Mapper (IRTM) data which confirmed basalt like sand surfaces in dark region. It was followed by French built Imaging Spectrometer for Mars (ISM) on the 1989 Russian Phobos 2 flight. In 1997, the Mars Global Surveyor arrived at Mars, carrying the Thermal Emission Spectrometer (TES) and global mineralogical mapping was carried out. The TES was followed by another specialized thermal radiometer (THEMIS) on board Mars Odyssey Mission which is also functioning till date and provided data for more than 12 years. In spite of years of telescopic study from earth and the flights of many spectrometers orbiting around Mars, many processes are still unknown, particularly causes of surface temperature variability and physics of associated dust storm activities on Mars. Thermal Infrared Imaging Spectrometer (TIS) onboard Indian Mars Orbiter Mission (MOM) provides newer opportunity to observe Mars disk as well as specific sites in thermal infrared spectral region from unique elliptical orbit.

2. TIS Configuration

TISis one of the five instruments on board MOM. TIS is designed to detect thermal emitted radiation from Martian environment in 7-13 μm infrared spectral region using micro bolometer detector. The TIS is a plane reflection grating based infrared spectrometer with all refractive optical elements. The spectrometer consists of fore optics, slit, collimating optics, plane reflection grating and focusing optics.

TIS consists of f/1.4 fore optics lens assembly with a focal length of 75mm and a field of view (FOV) of ±3.18°. The f-*number* is an important parameter for any imaging system. The *f-number* is the ratio of the effective focal length to the entrance pupil diameter. The *f-number f/1.4* means that the entrance pupil diameter of fore optics is $1/1.4^{th}$ of the focal length. The irradiance at the image plane is inversely proportional to the square of the *f/no.*

A collimating lens allows the incoming beam of light collected from fore optics and passing through a slit (that defines the input to the spectrometer) to fall on plane reflection grating which then disperses the incident energy into different wavelengths. The first order spectrum of the dispersed emitted Martian infrared radiation is refocused by a focusing optics on 160 x 120 pixels micro-bolometer based area array detector.

A detector is a device that produces an output which depends on the amount of radiation falling on the active area of detector. Thermal detectors make use of heating effect of the electromagnetic radiation. In bolometer type of detector, the change in temperature caused by the radiation changes the electrical resistance. The semi-conductor based bolometer exhibits a much more pronounced resistance variation with temperature change as compared to metals.

The instrument was spectrally calibrated using tunable lasers. The longer axis of the detector is aligned in the cross-track direction. So, 160 detector elements in the cross-track direction define the swath coverage of the sensor while 120 elements in the along track direction define the spectral range. By binning pixels in the along track direction, it is possible to select the required spectral sampling interval as well as number of spectral bands. It is operationally planned to have TIS imaging with 12 bands (Mode-3). The analog current signal from the detector is converted into a voltage signal, which is amplified and digitized subsequently. Digital signals received from TIS is corrected for the drifts due to changing thermal ambience and processed to know the emitted thermal infrared radiation from Mars using prelaunch and earth bound phase calibration studies.

Specific absorption features of surface mineral composition and atmospheric conditions (Aerosol Optical Thickness) manifest in thermal emission spectra observed from TIS. An optical schematic showing the imaging chain of TIS is given in Figure 1and verification and flight model of TIS is shown in Figure 2 and Figure 3 respectively. Table1 shows the important sensor specifications of TIS instrument.

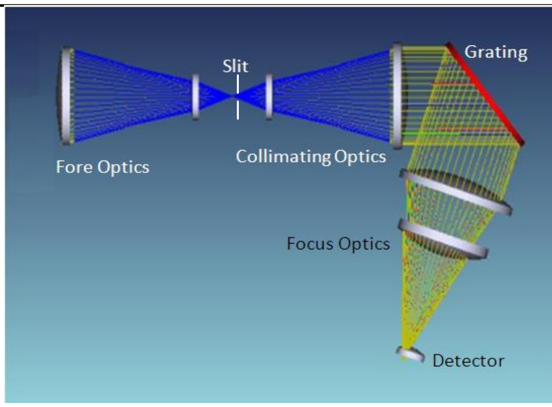

Figure1: Schematic diagram of TIS imaging chain.

Table1: Thermal Infrared Imaging Spectrometer (TIS) Characteristics[8].

Parameter	Value
Spatial Resolution	258m @ Periareion (372km) 55 km @ Apoareion (80000km)
Foot print(Coverage)	41km x 258 m @ Periareion 8800km x 55km @ Apoareion
Spectral range	7µm – 13µm
Spectral resolution	~500 nm (12 bands)
NEDT (Radiometric performance)	< 1K @300K
Data rate	6.56 Mbps
Mass	3.2kg
Power	6W

The thermal imaging spectrometer for such a large span of spectrum in a compact way was designed maximally utilizing the in-house available materials / components and also using COTS (commercial off the shelf) components[8].Signal was maximized by (a) optimizing the signal collection efficiency, (b) maximizing grating efficiency over preferred wavelength region, (c) longer dwell time etc. Back ground was minimized by reduction of stray emissions, tight control of temperatures of sensitive optical and electro-optical components.

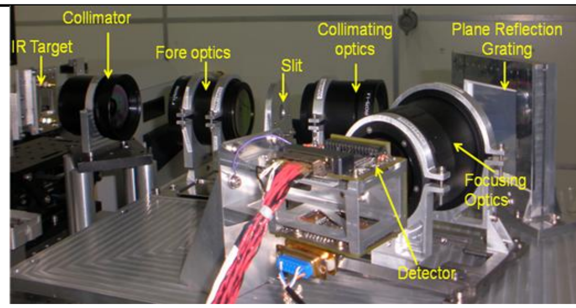

Figure 2: Verification Model of Thermal Infrared Imaging Spectrometer (TIS) instrument showing arrangements of different optical components.

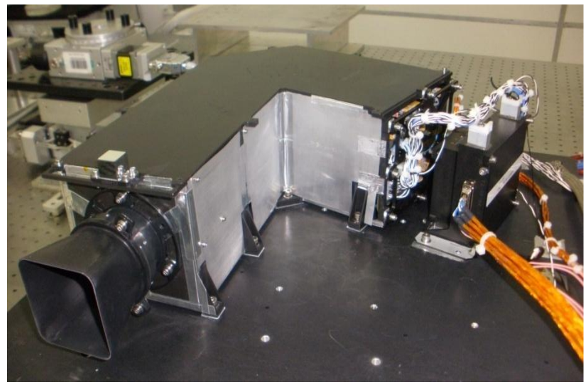

Figure3: Flight Model of Thermal Infrared Imaging Spectrometer (TIS) instrument

3. Measurement Principle

As mentioned earlier, TIS is an un-cooled micro-bolometer detector based spectrometer which uses grating as dispersive element. Emitted thermal infrared radiation from martian surface is collected through fore optics of TIS. Incident thermal infared radiationafter passing through collimated optics in the form of parrallel raysgetsdiffracted and dispersed by reflecting grating.The dispersed spectrum of infrared energy from reflected grating is further refocused by a focusing optics on the micro-bolometer based area array detector. Observed signal at detector is converted into spectral radiance through process of Analog to Digital conversion and calibration.

The diffraction grating is a device which essentially consists of a large number of equidistant lines with separation d. The plane reflection grating with 12 grooves/mm was used in TIS instrument. The following grating equation is used to study the dependence of angle of diffraction (θ) on the wavelength (λ).

$$d \sin\theta = m\lambda; \quad m = 0,1,2 \ldots.$$

where m is the order of diffraction.The zeroeth order of diffraction corresponds to principal maximum occuring at θ=0 irrespective of the wavelength. The first order spectrum of the dispersed beam from grating was refocused on the micro-bolometer area array in TIS. For m=1, the angles of diffraction are different for different wavelength and it is the reason why energy received by TIS in different wavelengths appears at different positions of the micro-bolometer array detector. Tunable laser was used for spectral calibration of the instrument. It may be noted that the energy received from Martian surface at different wavelengths is recorded as a spectrum.

Spectral radiance observed by TIS consists of contribution of surface emitted radiance as well as atmospheric emission which are coupled with atmospheric transmittance. Emitted radiance from any surface depends on the surface temperature and the surface emissivity. The emissivity depends on the composition, surface roughness, and physical parameters of the surface.

Thermal emission radiance received at satellite sensor in given bandwidth (L_{sen} or L_i) can be written as

$$L_{sen} = L_i(T_B) = \varepsilon_i B_i(T_s).\tau_i + L_i \uparrow + (1-\varepsilon_i)L_{DWR}.\tau_i$$

where T_B is the at sensor brightness temperature, τ_i is atmospheric transmittance, $L_i \uparrow$ is upwelling path radiance, ε_i is surface emissivity, B_i (Ts) is Planck radiance at surface temperature T_s and L_{DWR} is down-welling sky irradiance. Here all quantities refer to spectral integration over bandwidth of channel 'i' and depend on the view zenith angle. According to Planck's Law, the spectral radiant exitance (W m-^{2}, um^{-1}) is expressed as

$$B_i(T_s) = \frac{c_1}{\lambda_i^5\left(e^{\frac{c_2}{\lambda_i T_s}} - 1\right)}$$

c1 and c2 are the Planck's radiation constants, with values of 1.19104x10^8 W. μm^{4}m^{-2} and 14387.7 μm.K, respectively. The λ is the wavelength in microns.Spectral radiance received by TIS is modeled to estimate the surface temperature and emissivity. The retrieved spectral signature (in terms of emissivity) helps to know about the composition of different minerals as well as atmospheric turbidity.

4. Post-Launch Observations

Mars Orbiting Mission was launched on 5 Nov. 2013 from SDSC Sriharikota, India. Orbit raising manoeuvres were carried out during Earth orbiting phase before MOM was injected in heliocentric orbit towards mars on 1 Dec. 2013 (Figure 4).The TIS instrument was operated during Earth bound phase[9-11] on 23rd November 2013.The imaging session involved one minute observations of space count, preceded and followed by ten minute observations of Earth surface over Sahararegion. The imaging was carried out at 0900 UTC, at the altitude of 21335.4 km with the Solar Elevation of 52.84 degree. Figure 5 shows the coverage of TIS instrument and Figure6 shows the thermal infrared radiance observed in different bands over Sahara region projected on Mars Colour Camera (MCC) image.

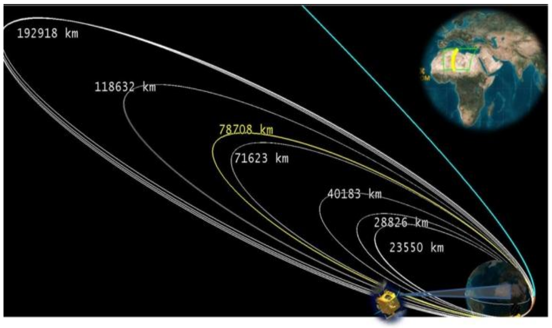

Figure 4: Orbit raising manoeuvres during earth bound phase and TIS imaging of 23rd November, 2013 over Sahara region.

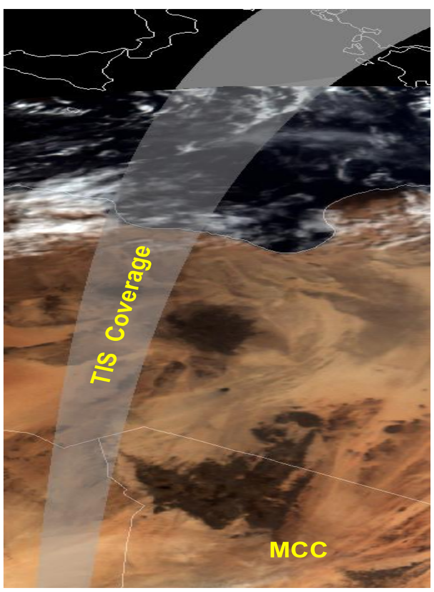

Figure 5: TIS coverage of 23rd November, 2013 over Sahara region shown on Mars Colour Camera (MCC) image

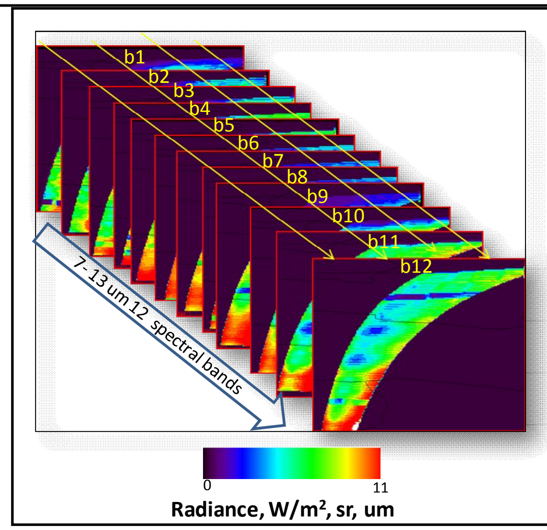

Figure 6: Stack of 12 bands (7-13 μm) spectra of TIS observed radiances on 23rd November, 2013 over Sahara region during Earth imaging

TIS based observations of Martian surface is being collected from 28th September 2014 (solar longitudes (Ls) 204^0) from apoapsisas well as periapsis positions in elliptical orbit (Figure 7). Observations have been taken from satellite altitude varying from 76694 km to 386 km in different imaging sessions. Elliptical Orbit of MOM provides opportunity for scanning of full Mars disk from apoapsis at coarse spatial resolution (Figure 8) as well as site specific surface imaging at relatively high spatial resolution in push broom mode from periapsis (figure 9).

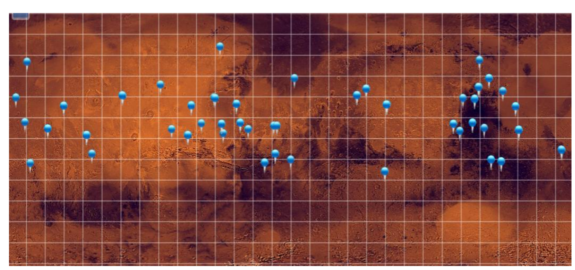

Figure 7: Imaging sessions (between solar longitude Ls 204^0-340^0) of TIS instrument showing the central latitude and longitude of

the different scenes (Source SAC MOM POC Archive)

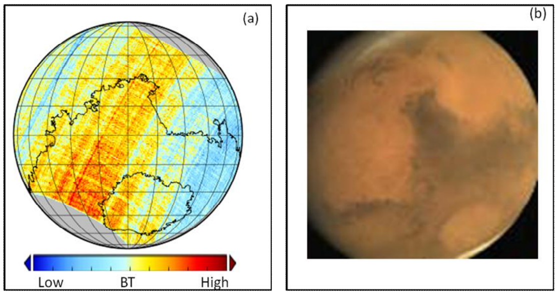

Figure 8: Observations of (a) Brightness Temperature (BT) observed from TIS instrument on 9 Oct. 2014 (Ls=210.7 degrees) in 12.25 um spectral band and (b) corresponding Mars Color Camera (MCC) image taken during same imaging session

The performance of the TIS instrument in Earth-imaging phase, Cruise phase and Mars Orbiting phase have been found in agreement with the laboratory-measurements.

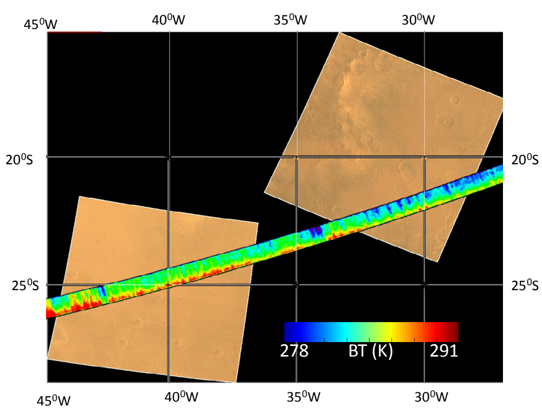

Figure 9: Brightness Temperature (BT) variability as observed from push broom imaging from TIS instrument near Holden Crater on 27 Feb. 2015 (Ls=299.2 degrees) in 10.25 µm spectral band from the altitude of 386 km. TIS observations are draped on background of MCC data.

5. Conclusions

TIS instrument on-board Mars Orbiter Mission is agrating based spectrometer aimed to detect thermal infrared emission from Mars surface in 7-13 µm range and infer thermo-physical characteristics of planet.Elliptical Orbit of MOM provides unique opportunity for scanning full Mars disk from apoapsis as well as site specific surface imaging at relatively high spatial resolution in push broom mode from periapsis. Observed brightness temperatures were found related with surface temperature and solar zenith angle, viewing geometry and atmospheric conditions.

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