Thermal Infrared Imaging Spectrometer for Mars Orbiter Mission

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Thermal Infrared Imaging Spectrometer (TIS), which operates in the infrared spectral region (7–13 μm), is one of the five instruments on-board the Mars Orbiting Mission (MOM). TIS was designed to detect emitted thermal infrared radiation from the Martian environment, which would enable the estimation of ground temperature of the surface of Mars and also map its surface composition. TIS instrument is a grating-based spectrometer which has spatial resolution of 258 m at periapsis (372 km). TIS hardware was realized with light-weight miniaturized components (total weight 3.2 kg) with power requirement of 6 W. Observations from TIS instrument were carried out during Earth-bound manoeuvres and cruise phase operations of MOM and the results were found to be in agreement with the laboratory measurements.

Keywords: Aerosol optical thickness, Mars Orbiter, minerals detection, thermal infrared spectroscopy.

Introduction

KNOWLEDGE on type of minerals present in any planetary system provides information on the conditions under which minerals are formed and the processes by which they are weathered. Specific absorption features of surface mineral composition manifest in thermal emission spectra observed from thermal infrared spectrometers. Precise detection of specific spectroscopic features allows estimation of surface composition and atmospheric parameters (aerosol optical thickness) of a planet, for example Mars[1–5]. Many early spacecraft missions carrying infrared spectrometers (IRS, IRIS, ISM, IRTM, TES, THEMIS) had been flown to Mars to study its surface composition. Distinct absorption in the 9 and 20 μm spectral regions was observed in Viking Infrared Thermal Mapper (IRTM) data, which confirmed basaltic sand surfaces in dark regions. The Thermal Emission Spectrometer (TES) on Mars Global Surveyor and the thermal radiometer (THEMIS) on-board Mars Odyssey Mission have also collected data of Martian surface. However, our understanding on the mineral composition of the Martian surface is still far from complete. The Thermal Infrared Imaging Spectrometer (TIS) is one of the five instruments on-board the first Indian Mars Orbiter Mission (MOM) launched on 5 November 2013. TIS was designed to detect thermal emitted radiation from the Martian environment in the 7–13 μm infrared regions using microbolometer device[6].

Configuration of TIS instrument and its realization and performance based on pre-launch calibration are presented in this article. Information on data products of TIS is also given along with a discussion on the science objectives and optimized strategy of TIS for realizing science goals with minimum requirement on mission. Post-launch performance of the sensor is also presented.

TIS configuration

TIS is a plane reflection grating-based IR spectrometer with all refractive optical elements. It uses an uncooled microbolometer detector operating in 7–13 μm infrared wavelength range and was flown on the Indian MOM. TIS consists of $f/1.4$ fore optics lens assembly with a focal length of 75 mm and a field of view (FOV) of ±3.18°. A slit is placed at the focal plane of fore optics, which is input to the spectrometer. A collimating lens allows the beam to fall on plane reflection grating which then disperses the incident energy into different wavelengths. The dispersed spectrum is then refocused by a focusing optics on 160 × 120 pixels microbolometer-based area array detector. Figure 1 shows the flight model TIS instrument, and Table 1 lists the major features/specifications of the instrument.

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Development and realization of TIS payload

The design and realization of TIS in a span of two years was a challenging task. It was realized from conception to delivery. One of the important goals of instrument design was to measure narrow-band spectral radiances of full Martian disc in the wavelength range 7–13 μm with targeted NEDT of <1 K @ 300 K in a minimum period of time and to realize a payload with mass of <3.2 kg, power <6 W and minimum size. Many innovative ideas and approaches were exercised through all stages of development to realize the goals.

The design of TIS for such a large span of spectrum in a compact way was realized maximally utilizing the in-house available materials/components and also using commercial off-the-shelf (COTS) components. TIS optical system design and feasibility analysis were carried out according to the COTS available optical components to help fast realization. Signal was maximized by (a) optimizing the signal collection efficiency (F-number:1.44), (b) maximizing grating efficiency over preferred wavelength region, (c) longer dwell time, etc. background was minimized by reduction of stray emissions, and tight control of temperatures of sensitive optical and electro-optical components. Precise measurement of temperature of the detector and other surround surfaces was incorporated to help estimate the background accurately after due calibration. Adequate dynamic range was provided in the electronics to cater to background and signal. Noise was minimized by optimizing spectral bandwidth, accurate control of detector temperature, multiple sampling and binning, electronics, bandwidth optimization, low-ripple power supply, multilayer PCBs, etc. The staring capability of the satellite can be made use of to improve the sensitivity further. Considering the possible uncertainties and improvements associated with the development of a new instrument with a new set of components, a large number (8) of operating modes were incorporated to characterize and assess performance of the components like grating, bolometer, etc. This also helps in measurements on Mars to maximize the information based on scientific interest.

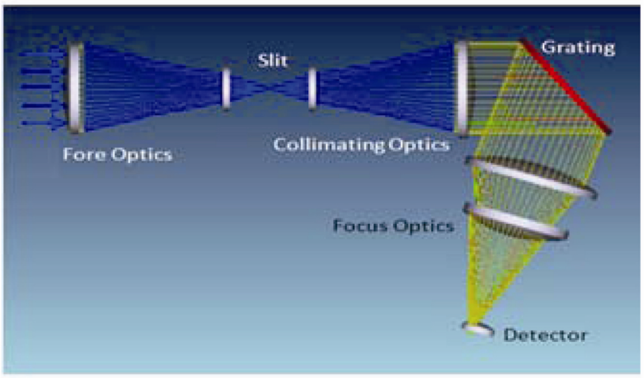


Figure 1. TIS optical layout

Table 1. Major specifications of TIS instrument

Parameter	Value
IGFOV	258 m @ periareion (@ 372 km) 55 km @ apoareion (@ 80,000 km)
Foot print (coverage)	41 km × 258 m @ periareion 8800 km × 55 km @ apoareion
Spectral range	7–13 μm
Spectral resolution	~500 nm (12 bands)
NEDT (radiometric performance)	<1 K @ 300 K
Data rate	6.5625 Mbps
Mass	3.2 kg
Power	6 W

All the optical elements, i.e. fore optics lens assembly, collimating lens assembly, slit, plane reflection grating and focusing lens assembly of TIS were COTS-type. In-house developed lens mounts and barrel were made to have a suitable interface and provide sufficient stiffness in the hardware of all the lens assemblies, grating and slit. Each assembly was optimized to achieve light weight. The performance characteristics of lens assemblies were ascertained through precise measurements using in-house developed test set-ups.

The focal plane assembly of the TIS payload was developed around vanadium oxide (VOx)-based bolometer array detector. It had 160 × 120 grid array with pixel pitch of 52 μm and pixel size of 50 μm in each direction. The detector array was packaged in an alumina ceramic cavity vacuum sealed with AR-coated germanium window optimized for transmission of the TIR radiation in 7–13 μm wavelength band. The detector had integrated thermo electric cooler (TEC) and precision temperature sensors. It also incorporated blind pixels for dark performance evaluation. Detector was in-house qualified for space use. Differential operating mode was selected as it provides first-order correction for detector dark signal. The detector head assembly (DHA) consisted of low noise bias generator and digitizer electronics section and a mechanical structure to hold the detector in place along with a heat sink for thermal management.

The analog current signal from the photo-diode was converted into a voltage signal, amplified and digitized. Customized and indigenously developed camera electronics (CE) was configured to perform these tasks. The design and development is based on the system and detector requirements taking into account the considerations of miniaturization, low weight and power, and usage of available components to meet the realization schedule in the shortest possible time. The CE consists of four major functional blocks – the Detector Proximity Electronics (DPE) which generates the necessary biases for the detector; TEC Control Electronics (TCE) which consists of Proportional-Integration and Differential (PID) controller for driving in-built TEC of detector and controlling detector temperature in closed loop with 10 mk accuracy;

Logic and Control Electronics (LCE) which interfaces with the other spacecraft subsystems and generates the required clocks, programmable exposure controls, etc. and the Power Supply Electronics (PSE) which takes the raw power from the spacecraft and provides regulated power lines to the payload according to the requirements. The CE design incorporates multiple sampling of the same video pixel and averaging to minimize pixel-level noise. It also provides eight modes of operation which can be selected by ground commands. These modes include raw data (120 bands) at frame level, raw data with 4/16/64 frames binned, spectrally binned data (12 bands) at each frame, and spectrally and frame-wise binned data. These modes are used during ground testing. It is planned to use the spectrally binned mode on-board. Mechanical, structural and thermal design and realization are critical towards fulfilment of the mission objectives. The realized instrument is light in weight, compact in size and volume, structurally stiff, thermally stable involving multi-materials and multi-constraint joints. It is a major effort to design light-weight optical assemblies while keeping the original optical performance intact. Precise dimensional performance was realized by incorporating design for manufacturability and also precision machining. The precision alignment requirement of a large number of spectrometer optical elements called for the development of accurate jigs. All functional parts were precisely manufactured to the required optical precision and perfectly assembled/aligned to perform the intended optical function of the instrument. Mechanical design and realization was done with the aim of developing a robust design and synergizing the requirements into a well-defined flight-worthy realizable hardware. Figure 2 shows the flight model TIS instrument.

Thermal design was an involved task as the detector was required to be controlled with few mK and minimum variations from surrounding surfaces. TIS is an uncooled longwave infrared spectrometer; measurement and control of drift in its self-emissions are a major challenge to achieve radiometric performance. Weight and power are the major limitations for having dedicated multiple precision thermal controllers for the spectrometer, and, background signal of the spectrometer varies dynamically, which has been modelled and experimentally confirmed. Based on these studies, precision thermal sensor was implemented at a strategic place in the vicinity of detector frame. A shield was incorporated around the input port of detector to minimize thermal drifts due to the surroundings. A separate methodology was adopted for off-line estimation and correction of dynamic background. In addition, TIS was planned to look at deep space at adequate intervals of time to measure absolute value and drift rates of instrument background, which will be used in final image/spectrum extraction.

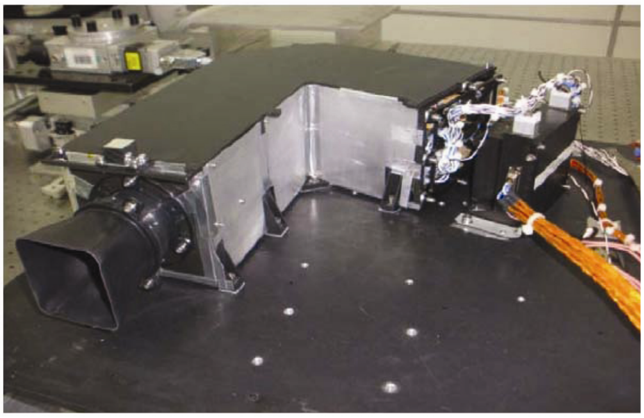


Figure 2. Flight model TIS payload

Performance of TIS was characterized both at system as well as sub-system levels during the development period. The instrument was successfully subjected to environmental tests like thermal storage, vibration, and thermo-vacuum tests. Detailed measurements during these tests showed the consistency of the performance as well as the margins in the performance. The instrument also underwent similar environmental tests as part of integrated spacecraft-level testing. The instrument alignment and spectral stability were measured at all stages in addition to other parameters.

The instrument was spectrally calibrated using tunable lasers. Figure 3 shows the spectral dispersion of TIS for 10.1 μm. Absolute signal of the instrument is inversely proportional to the incident radiance, the dip indicates the response.

Instrument distortion was characterized and optical smile of the spectrometer was measured. Figure 4 shows the measured optical smile at 10.3 μm, while Figure 5 shows spectral linearity plot for central wavelength.

During the radiometric performance optimization and calibration, a blackbody was used inside a thermo-vacuum chamber. The instrument was maintained at a constant temperature (20°C), using payload and external heaters. The integrated payload performance was characterized for 10°C to 30°C payload temperature. For each setting, the instrument performance was characterized by simulating a variable target temperature range from 180 to 320 K. Figures 6 and 7 show TIS instrument set-up inside a thermo-vacuum chamber and instrument response at different target temperatures respectively.

Checkout and evaluation software system for TIS-like payload was developed. Even though it had some similarity with other hyper spectral payloads in the near-visible region, its characterization and parameter computation were complex in nature. The MOM TIS has eight modes for different kinds of binning, which has increased the complexity further, starting from data acquisition to data processing stage. As TIS payload does not have any cooling system, the background behaviour was studied and its characterization implemented in the evaluation system.

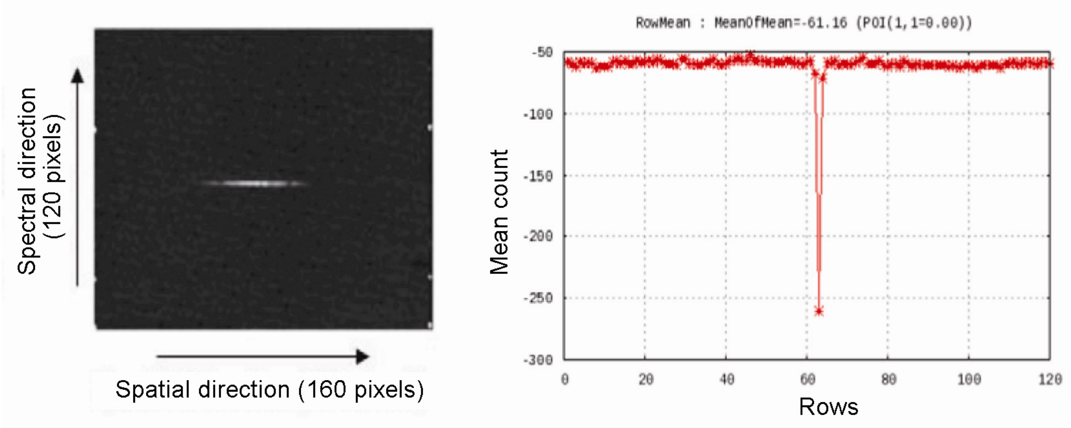


Figure 3. Spectrometer aligned slit at 10.1 μm.

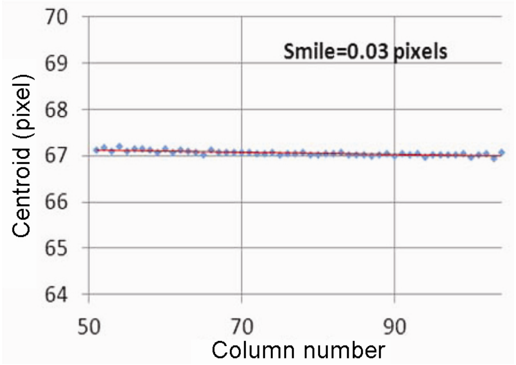


Figure 4. Optical smile at 10.3 μm

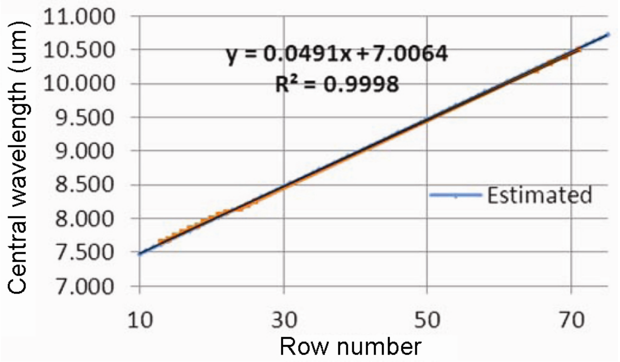


Figure 5. Spectral calibration linearity plot

Many new Test Benches were developed like Noise/NEdT Characterization Test Bench, Smile and spectral response measurement, etc. Figures 8 and 9 show the simulation test bench and plots of thermal behaviour respectively.

Data processing

TIS data products are defined as level-0 and level-1 products. Level-0 processing produces edited data using

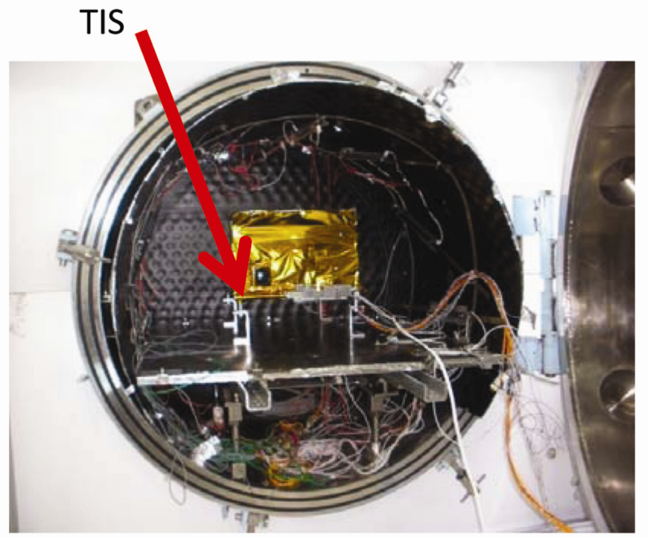


Figure 6. TIS instrument set-up inside the thermo-vacuum chamber.

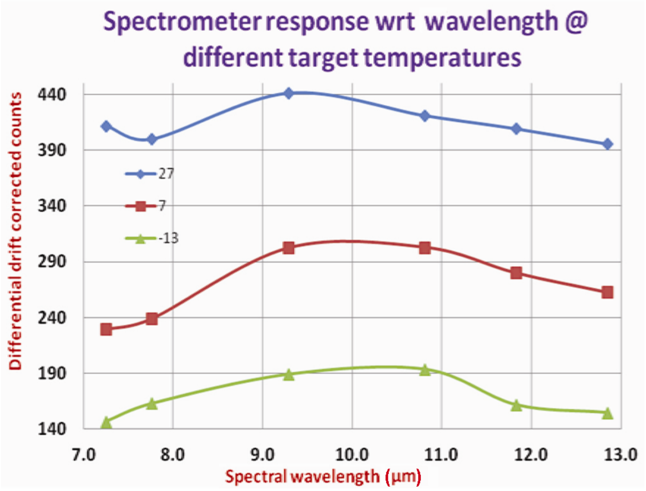
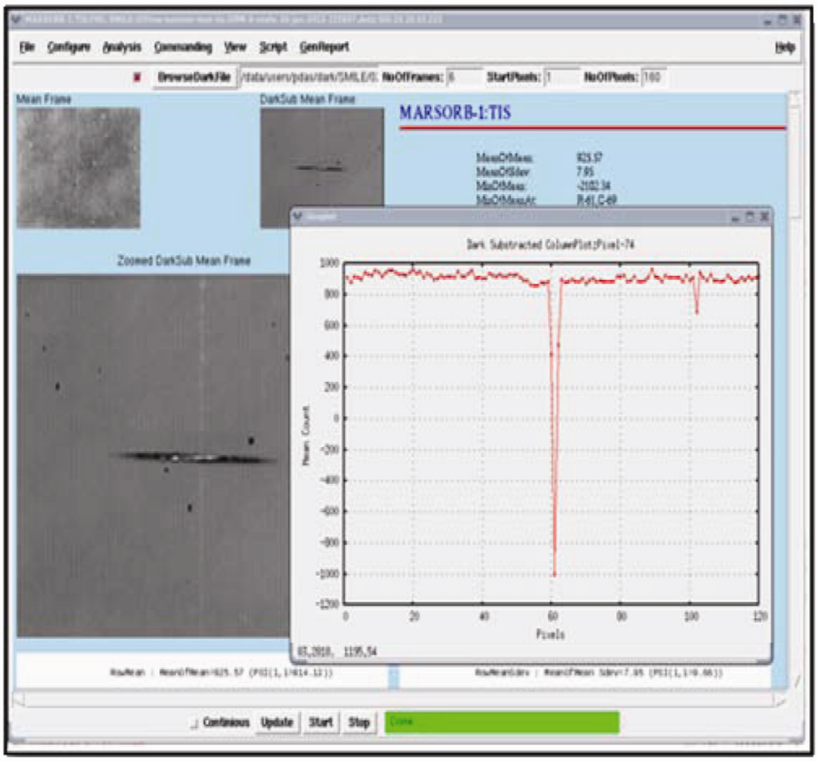


Figure 7. TIS response at different target temperatures (–13°C, 7°C and 27°C).



/data/users/pdas/dark/SMLE/S NoOfFrames: 6 StartPixels: 1 NoOfPixels: 160

MARSORB-1:TIS

MeanOfMean 925.57
MeanOfSdev 7.95
MinOfMean -2102.34
MinOfMeanAt R-61,C-69

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Figure 8. Spectral characterization test bench.

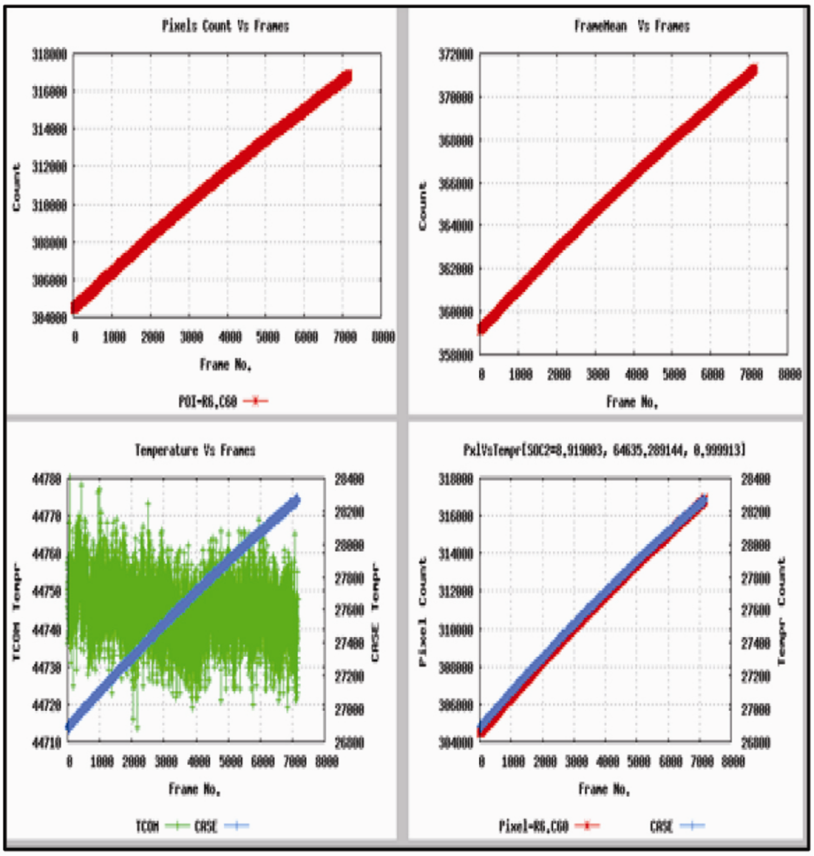

Figure 9. Thermal behaviour plot with video.

telemetry and payload data. It involves corrections for telemetry errors, reformatting based on payload data records, tagging with time and location of acquisition. Level-0 product consists of payload data from both the channels, calibration data for correction, ancillary data and Meta information. Further, level-1 processing uses level-0 data as input and produces radiometric-corrected and geometric-tagged output. These two levels, i.e. level-0 and level-1 are mapped to international standard based on Committee on Data Management and Computation (CODMAC) level-2 and level-3 respectively, and are archived according to Planetary Data System (PDS) philosophy at the Indian Space Science Data Centre (ISSDC), Bengaluru, that may be obtained for analysis by users.

Science objectives and methodology

TIS is useful in mapping important mineral compositions and surface temperature during periapsis imaging and in deriving global surface temperature distribution and aerosol turbidity in the Martian atmosphere during apoapsis viewing. The important science goals of TIS are as follows[7]:

- To estimate ground temperature of the surface of Mars.
- To map surface composition and mineralogy of Mars.
- To detect and study the variability of aerosol/dust in the Martian atmosphere.

Various laboratory-based and space-based studies over four decades have demonstrated the uniqueness of vibrational spectroscopy for detection of surface composition and mineral mapping over planetary surfaces. The fundamental frequencies of vibrational–rotational transitions of crystal lattice of minerals are linked to their structure and elemental composition. Geological minerals exhibit a unique thermal infrared response in 7–13 μm spectral range and TIS is specifically designed to detect these spectra from the orbital platform. Individual mineral components and rock types can be distinguished based upon their spectral characteristics as well as their ability to resist the change in the diurnal temperature variations.

The analysis of TIS data involves estimation of brightness temperature from thermal radiance data. It is followed by retrieval of surface temperature and emissivity spectra for different regions. The approach involves theoretical modelling study using a radiative transfer (RT) modelling in the thermal region at different atmospheric conditions of the Mars atmosphere.

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

$$L_{\text{sen}} = L_i(T_{\text{B}}) = \varepsilon_i B_i(T_{\text{s}}) \cdot \tau_i + L_i \uparrow + (1-\varepsilon_i) L_{\text{DWR}} \cdot \tau_i,$$

where T_{B} is the at-sensor brightness temperature, τ_i the atmospheric transmittance, $L_i \uparrow$ the upwelling path radiance, ε_i the surface emissivity, $B_i(T_{\text{s}})$ the Planck radiance at surface temperature T_{s} and L_{DWR} is the downwelling 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}, μm^{-1}) is expressed as

$$B_i(T_{\text{s}}) = \frac{c_1}{\lambda_i^5 \left(e^{\frac{c_2}{\lambda_i T_{\text{s}}}} - 1 \right)},$$

where c_1 and c_2 are the Planck's radiation constants, with values of 1.19104×10^8 W.$\mu\text{m}^4\,\text{m}^{-2}$ and 14387.7 μm K respectively. λ is the wavelength (μm).

The planetary surface temperature (T_{s}) is estimated from the above relation using TIS data.

The a priori input such as emissivity of the Martian surface for a given wavelength is used from the literature survey and by conducting experiments on different mineral compositions. Estimated emissivity spectra obtained over the Martian surface would be compared with different analogue mineral emissivity spectra of Mars. Thermal infrared spectrum of a mixed surface will be modelled as a linear combination of the end-member spectra weighted by the area-weighted concentration of each end-member. Mineral end-members based on spectral library will be used to generate the mineral composition using TIS data.

Laboratory-based Fourier Transform InfraRed (FTIR) spectrometer was used to generate the emissivity spectra between 7 and 13 μm for selected minerals such as, olivine, serpentine, etc. that are known to exist on the Martian surface. It can be seen from Figure 10 that minerals are associated with lower emissivity in 9–10 μm range in comparison to 8 μm wavelength. Serpentine has lower emissivity in comparison with olivine near 10 μm wavelength.

Theoretical simulations of satellite-level radiances for TIS spectral bands were carried out to model the expected radiances to be observed by TIS in the Martian environment at different surface temperatures. The top-of-atmosphere (TOA) radiances were simulated at different surface temperatures of Mars by adapting the MODTRAN radiative transfer code for the Martian atmospheric and surface conditions. The Martian atmospheric profiles were generated from the Mars-GRAM model. TOA radiance calculations were performed for these atmospheric profiles having atmospheric boundary layer temperatures ranging from 170 to 290 K over the Martian surface assumed to be covered dominantly with serpentine. Theoretical simulations show that emitted peak thermal radiance can vary from 0.5 to 8 W/m^2-μm-sr depending on surface temperature variability from 170

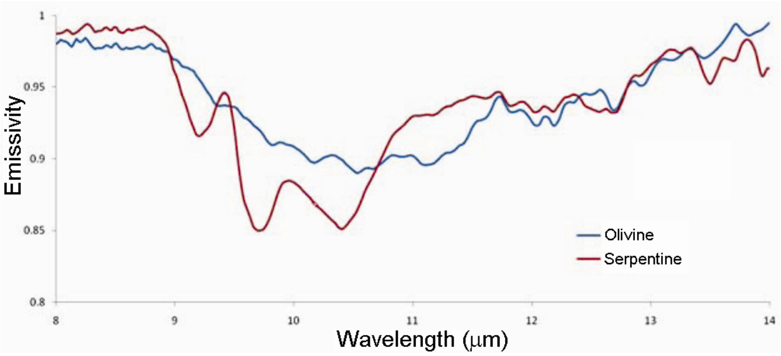

Figure 10. Emissivity spectra of olivine and serpentine measured through FTIR in the laboratory.

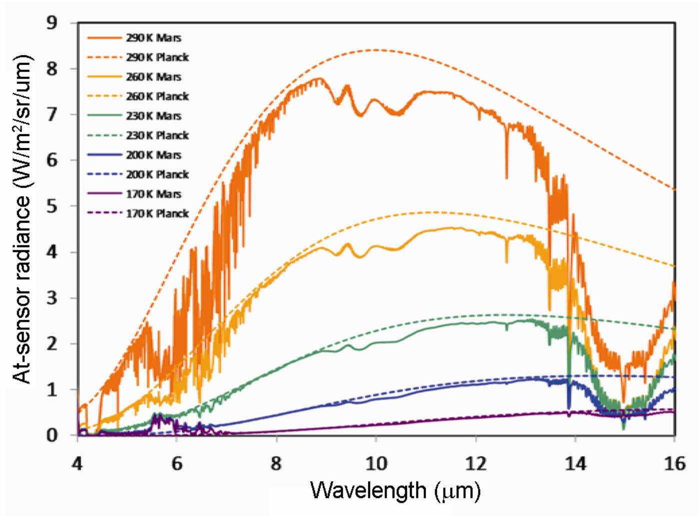

Figure 11. Simulated at-sensor radiance at different Martian surface temperatures using RT modelling.

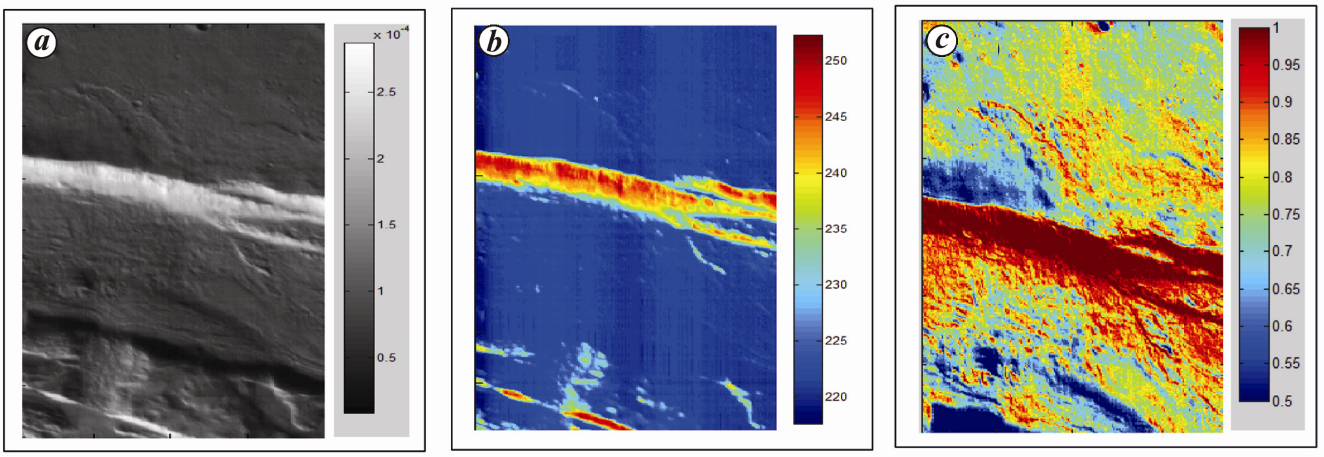

Figure 12. Mars thermo-physical parameters: ***a***, radiance (W/cm^2/μm/sr); ***b***, surface temperature (K); ***c***, surface emissivity estimated from THEMIS observations from band 3 (7.93 μm).

to 290 K (Figure 11). Dashed lines on the figure show ideal blackbody curves at surface temperature ranging from 170 to 290 K.

Algorithm of geophysical parameter retrieval was developed to estimate the surface temperature and emissivity spectra from TIS observations. Overall approach was implemented on Mars radiances observed from THEMIS instrument on-board Mars Odyssey Mission. The THEMIS data image acquired over north of Olympus Mon centred at lat. 37.17°, long. 228.54° was used for

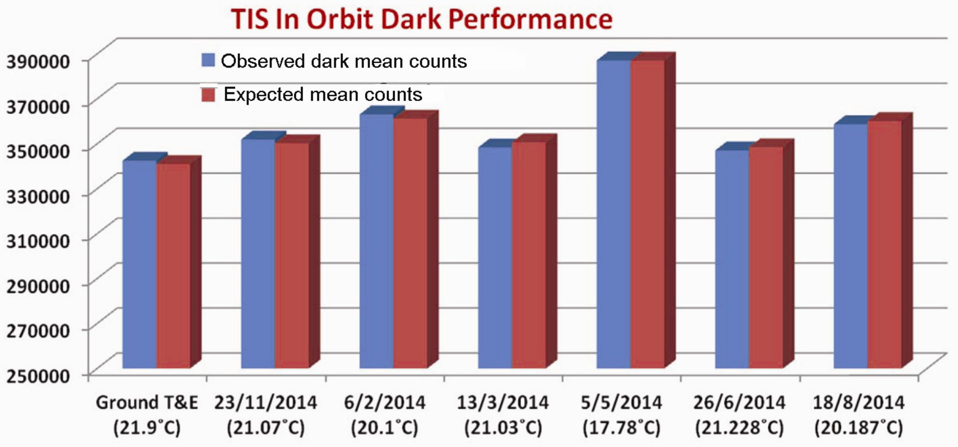

Figure 13. TIS in-orbit performance in terms of dark counts.

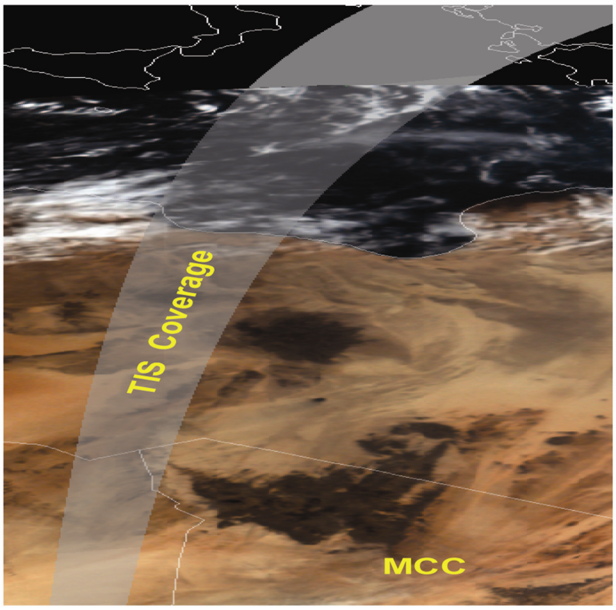

Figure 14. TIS coverage of 23 November 2013 over Sahara region shown with MCC image.

implementation. The image was taken at Mars year 25, solar latitude 329.63 at local solar time 15.266 with maximum dust opacity of 0.183. Figure 12 provides an analysis of THEMIS data on representative scene showing the variability of surface temperature from 220 to 250 K and emissivity from 0.5 to 1 in spectral channel centred at 7.93 μm.

Post-launch observations during Earth-bound and cruise phase

MOM was launched on 5 November 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 December 2013. The TIS instrument was operated during Earth-bound phase[8] of MOM orbiting on 23 November 2013. This was followed by observations of dark counts five times (6 February, 13 March, 5 May, 26 June and 18 August 2014) during cruise phase. Figure 13 shows the dark counts observed from laboratory conditions to cruise phases. The Earth imaging session involved 1 min observations of dark space count, before and after 10 min observations of Earth surface over Sahara region. The objective of this imaging was to compare the TIS counts observed in the Earth-bound phase to that of laboratory measurements and other synchronous satellite observations. The imaging was carried out at 0900 UTC, at the altitude of 21,335.4 km with the solar elevation of 52.84°. The across-track resolution was 13.93 km with a swath of 2229 km. The image was acquired in 7219 frames in mode-3 in which on-board processer acquired image in 12-bands mode with detailed information of T_{case} (temperature of the instrument case) for each frame. Figure 14 shows the coverage of TIS instrument over Sahara region projected on Mars Colour Camera (MCC) image. Estimation of differential counts using space-look and earth-look data was carried out including normalization of these datasets with varying T_{case} information. The differential counts of TIS (band 8:10.75 μm) were calibrated ($r^2 = 0.68$) with the actual radiances observed from the MODIS sensor (11 μm band) over the same region[9,10]. Figure 15 shows variability of the observed radiances (geographically resampled at 0.03° × 0.15° after spatial filtering) in different spectral channels of the TIS instrument over the Sahara region. The performance of the TIS instrument in Earth-imaging and cruise phase was found to be in agreement with the laboratory measurements.

TIS payload has been operated several times to validate the health and reference dark performance. All functional parameters were verified and found to be satisfactory. The retrieved spectral information shows the potential of the instrument for Mars investigations.

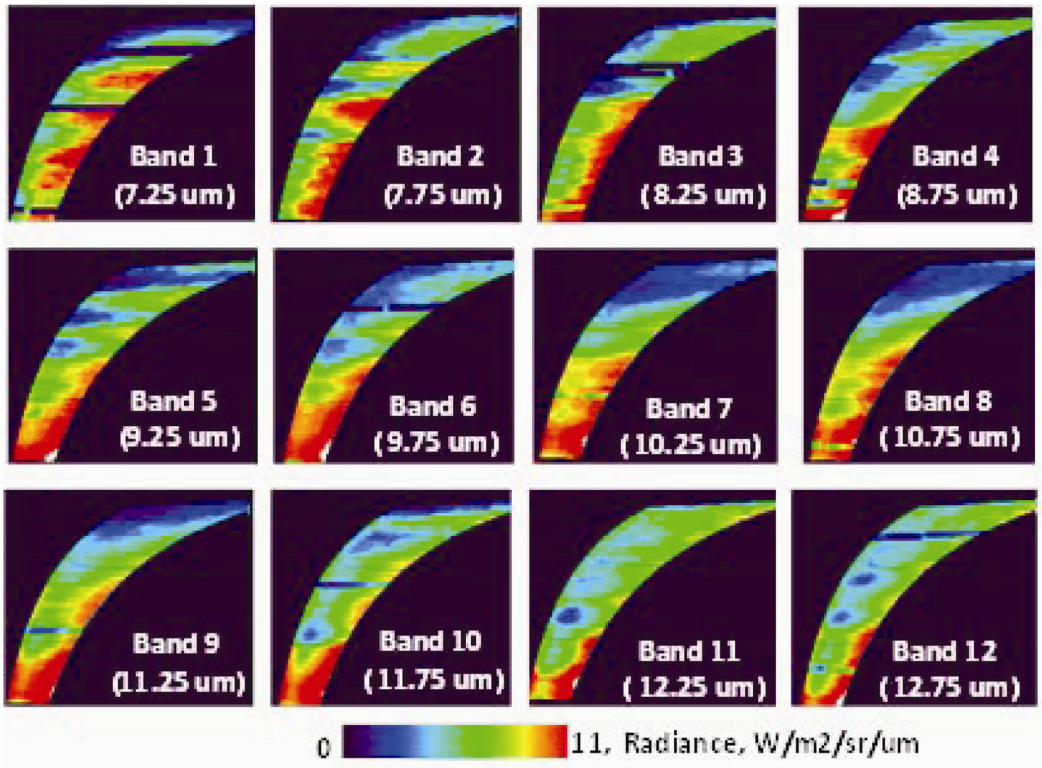

Figure 15. TIS observations in 12 spectral channels over the Sahara region during Earth-imaging phase of MOM on 23 November 2013.

Conclusion

The design, development, realization and qualification of the compact TIS for MOM was a challenging task which was accomplished by adopting innovative approaches and implementing concurrent engineering practices. The performance was satisfactory as seen through test results. Development of data products and retrieval algorithms for this type of instrument is challenging as it requires thorough understanding of the intricacies of the instrument and interaction of radiation with coupled surface and atmospheric characteristics of Mars. A spectral library was developed for specific minerals (available on Earth) that are analogues to reported Martian minerals based on FTIR spectrometer studies. The readiness of the ground processing and remotely sensed data processing system was checked using Earth-bound and cruise-based data.

1. Bandfield, J. L., Global mineral distributions on Mars. *J. Geophys. Res. E*, 2002, **107**, 5042; doi:10.1029/2001JE001510.
2. Herr, K. C., Forney, P. B. and Pimentel, G. C., Mariner Mars Infrared Spectrometer. *Appl. Opt.*, 1972, **11**, 493–501.
3. Salisbury, J. W. and Walter, L. S., Thermal infrared (2.5–13.5 µm) spectroscopic remote sensing of igneous rock types on particulate planetary surfaces. *J. Geophys. Res.*, 1989, **94**, 9192–9202.
4. Pleskot, L. and Kieffer, H., The infrared photometric function of Mars and its bolometric albedo. *Icarus*, 1977, **30**, 341–359.
5. Christensen, P. R. *et al.*, Evidence for igneous diversity and magmatic evolution on Mars from infrared spectral observations. *Nature*, 2005, **436**; doi:10.1038/nature03639.
6. SAC, Mars Orbiter Mission Pre Shipment Review document on Thermal Infrared Imaging Spectrometer, SAC-MOM-05-MAY2013, 2013.
7. Singh, R. P., Pandya, M. R., Gujrati, A. and Shah, R. D., Mars science plan for thermal infrared spectrometer (TIS) instrument. In National workshop on Lunar and Mars Geosciences, SAC, Ahmedabad, 30–31 July 2013.
8. Singh, R. P., Pandya, M. R., Gujrati, A., Shah, D. and Shah, R. D., Thermal infrared spectrometer (TIS) instrument. *PLANEX*, 2014, **4**(1), 21–23.
9. Singh, R. P., Thermal Infrared Imaging Spectrometer (TIS) onboard Mars Orbiter Mission. In National Space Science Symposium, NSSS 2014, abstr., Dibrugarh, 29–31 January 2014.
10. Singh, R. P., Pandya, M. R., Gujrati, A. and Shah, D., Observations from Thermal Infrared Imaging Spectrometer (TIS) instrument onboard Mars Orbiter Mission during Earth bound phase. In Procedings of the Workshop on Mars Orbiter Mission–Data Analysis and Science Plans, PLANEX, Physical Research Laboratory, Ahmedabad, 20–21 August 2014.

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