Mars Colour Camera: the payload characterization/calibration and data analysis from Earth imaging phase

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Mars Colour Camera (MCC) on-board Mars Orbiter Mission is considered the 'eye' of the mission, taking photographs (imageries) of the surfacial features on Mars, and the cloud and dust around it. MCC is an important contextual camera for other non-imaging sensors like MSM, TIS, LAP, etc. The camera has been designed, characterized, calibrated and qualified at the Space Applications Centre, ISRO, Ahmedabad by a team of professional engineers and scientists. It has been miniaturized, ruggedized and space-qualified to match the weight and power budget of the mission. During Earth orbit phase, the images returned by the camera have been analysed qualitatively and quantitatively. The results show that MCC has been working as expected in terms of radiometry, geometry and application potential to discern various morphological features. The present article discusses these facts in detail.

Keywords: Detector, Earth imaging phase, payload, Mars colour camera.

Introduction

MARS Colour Camera (MCC) is a medium-resolution camera, with RGB Bayer pattern detector. It is a 'true colour' (offering a natural colour rendition, i.e. colours in the image appear the same way as in the object) camera flown on-board Mars Orbiter Mission (MOM). MCC has been designed to return images of Mars, its Moons (Phobos and Deimos) and other celestial objects in natural colour. It is also 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 designed to image the complete Mars disk with a spatial resolution of nearly 4 km from an altitude of 80,000 km and localized scenes at higher spatial resolution of nearly 19 m from 370 km. It can provide a synoptic view of the full globe from the orbital altitudes ranging from 63,000 to about 80,000 km around Mars[1]. Figure 1 shows a photograph of the MCC payload developed at Space Applications Centre (SAC), ISRO, Ahmedabad and Figure 2 gives the instantaneous geometric field-of-view (IGFOV) and coverage (field-of-view, FOV) of the camera from various orbital heights.

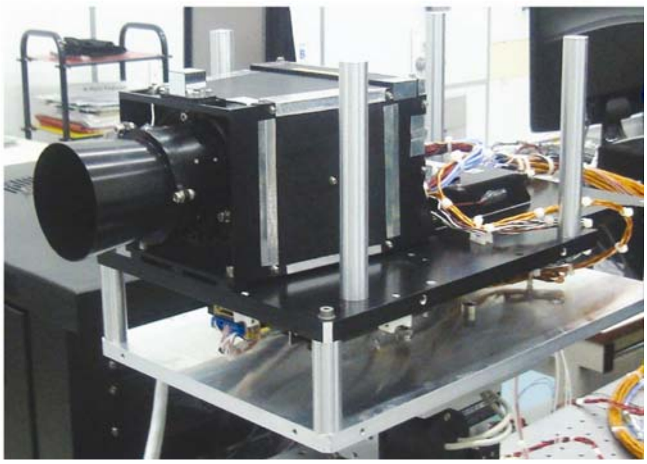

Figure 1. Mars Colour Camera (MCC) payload.

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MCC payload

The design and development of MCC was a challenging task. MCC payload was designed and realized with the constraint of low power (< 4 W), smaller size and weight (<1.5 kg) and extremely short time for realization (within a year). It was designed with the available materials/ components and with commercial off-the-shelf (COTS) components wherever new components were required. COTS components were adequately ruggedized and thoroughly tested to establish their space worthiness. The high level of miniaturization in terms of size and weight was achieved for all major sub-systems like optics, detector head assembly (DHA), camera structure and camera electronics (CE) and the same was translated to integrated payload level (details given subsequently in the text). Concurrent engineering practices were extensively followed. Three models were developed. 'Verification model' was developed for demonstration of proof of concept. 'Flight model like' and 'flight model' were developed identical to each other and were subjected to qualification and acceptance level tests respectively. The development of these models ran almost parallel with feedback from one model incorporated onto the other and verified quickly. Figure 3 shows the CAD simulation of the MCC payload.

MCC used a multi-element lens assembly for collecting the incident radiation from Mars and focusing on the detector. A COTS lens assembly having focal length of 105 mm with f-number of 4.0, diagonal field-of-view (±4.4°) and spectral range (400–700 nm) was selected for MCC based on the performance parameters and mission requirements of smaller size and weight. The lens was customized through in-house development to bring down its mass and size. It was qualified at subsystem level to establish its suitability for space use by subjecting it to specified environmental conditions (temperature excursions in vacuum and vibration loads). Figure 4 shows the COTS lens and the ruggedized flight model MCC lens with more than 50% mass reduction. This was made possible by employing new materials like Al 6061-T6 alloys which used a novel technique of mounting the lenses in the barrels using stress-free lock rings aided by elastomeric joints separated 120° apart on their radial periphery.

An IR cut-off filter (with an average transmission of 95% from 400 to 700 nm with a sharp cut-off at 735 nm) mounted on a precisely designed and machined stress-free mounting using flexures was placed in front of the detector to limit out-of-band response beyond the red region (>700 nm) for obtaining colour images with high fidelity. Figure 5 shows the IR cut-off filter assembly for MCC. Detector head assembly (DHA) (Figure 6) consists of a commercial high-speed snapshot colour CMOS image sensor with a pixel size of 5.5 μm. It is an area array having red (R), green (G) and blue (B) organic filters deposited on top of it in the form of RGGB Bayer pattern[2]. The detector is an active pixel sensor and incorporates most of front electronics, in it including ADC.

The detector and processing card were mounted on a low-mass and scooped Al alloy structure (Figure 7). This reduced the hardware complexity, improved feasibility in electrical interconnection and significantly reduced the mass eliminating the possibility of stress on the dissimilar metallic joints. The incoming panchromatic photons are converted to electrons at pixel level having either 'R', 'G' or 'B' filter (according to RGB Bayer pattern laid down on the top of the pixel) and photodiode. Subsequently, photo-generated electrons are converted to voltage using pixel-level charge to voltage amplifiers. These signals are digitized at column-level analog to digital converters (ADCs) using row and column-level multiplexers and decoders[3]. Like the optics, the detector underwent the entire process of ruggedization and qualification for development of flight model. Detector head assembly incorporated necessary electrical, mechanical

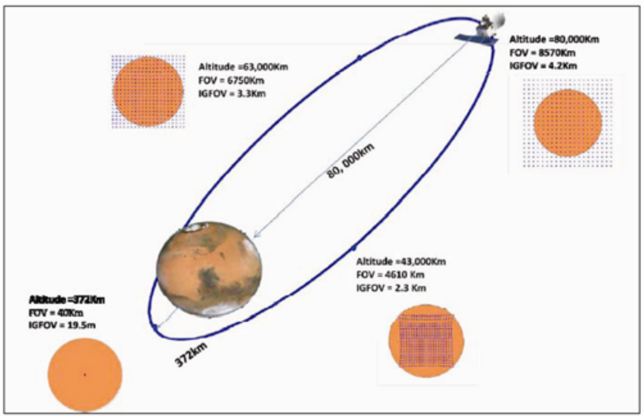

Figure 2. Coverage by MCC from different orbital heights.

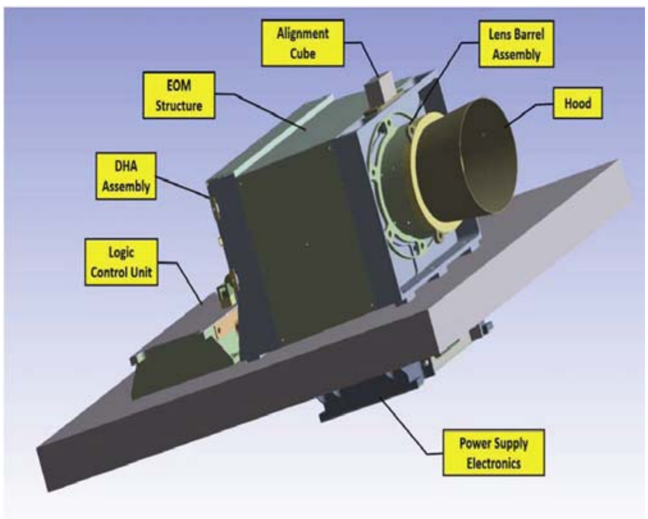

Figure 3. CAD simulation of MCC payload.

Figure 4. Commercial off the shelf lens (620 g) and MCC FM lens (310 g).

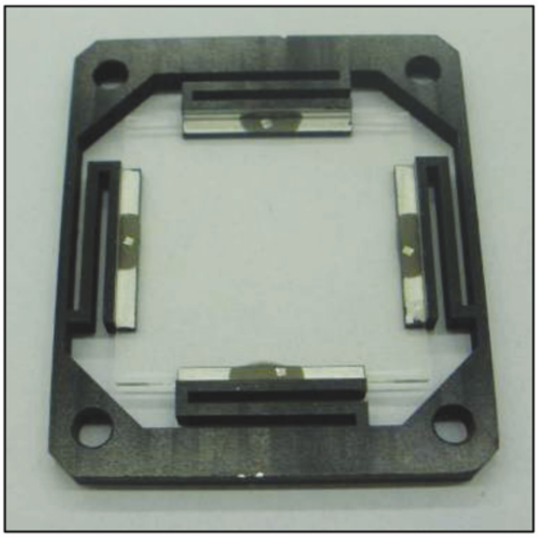

Figure 5. Infrared cut-off filter assembly.

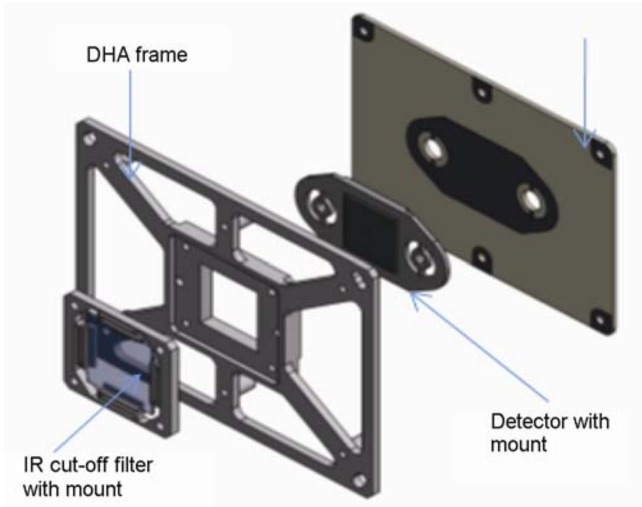

Figure 7. Detector head assembly/mount/filter.

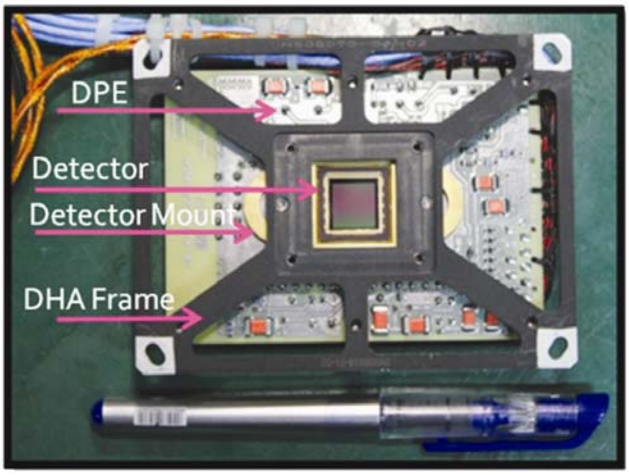

Figure 6. MCC detector head assembly.

and thermal interfaces. Figure 6 shows a photograph of the actual realized FM detector head assembly.

The design and development of camera electronics (CE) was based on the system and detector requirements of 16 programmable exposure controls, high-speed detector operation (52.5 MHz) and low-noise detector bias generation (<1 mV), while taking into account the requirements of miniaturization (low weight (~0.4 kg) and raw power (~3 W)) and usage of available space-grade components to meet the realization schedule in the shortest possible time. The miniaturization and performance requirements of camera electronics were met by selecting state-of-the-art space-grade components, field programmable gate array (FPGA) for logic implementation, low drop-out (LDO) voltage regulators, compact hybrid DC–DC modules, integrating electronics functions near 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 spacecraft (S/C) bus, etc. and the power supply electronics (PSE) which takes the raw power from S/C and provides low-noise (<5 mV PARD (periodic and random deviation)) regulated power

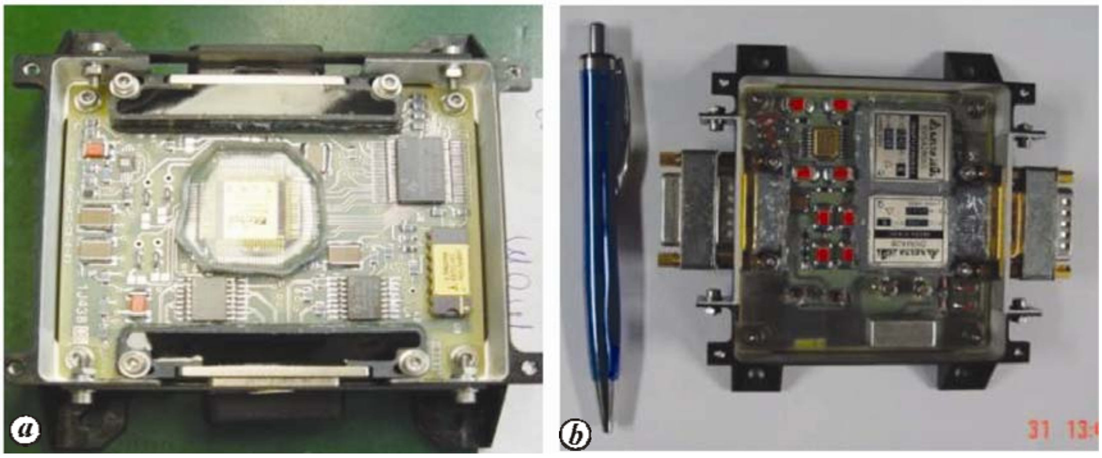

Figure 8. ***a***, MCC FM LCE card; ***b***, MCC FM PSE card.

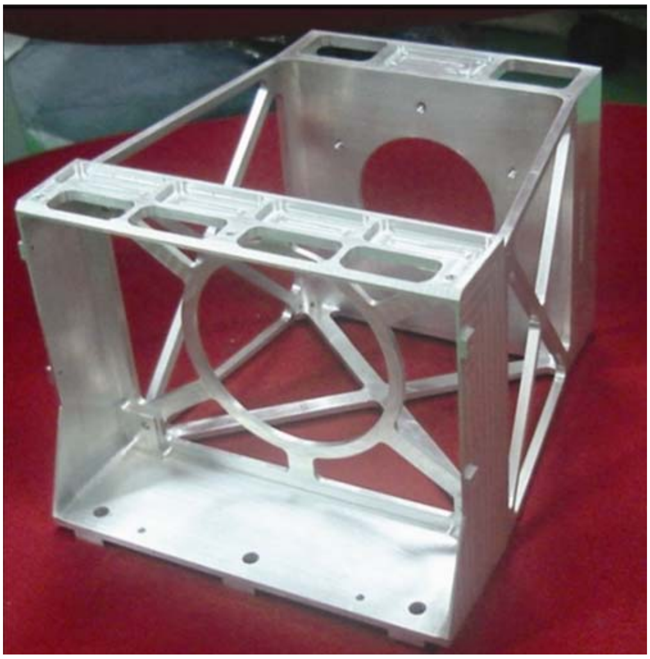

Figure 9. Light-weight EOM structure.

Table 1. Salient features and performance specifications of Mars Colour Camera

Parameter	Value
S/C altitude (km)	372 × 80000 (elliptical orbit)
Resolution (m)	19.5 @ periapsis
Frame size (km)	40 × 40 @ periapsis Full Mars disc from 63,000 km to apoapsis
Spectral region (μm)	0.4–0.7
Frame time	1s (frame selection at 1, 8 or 15 sec period by ground commanding)
Exposure time	Total 16 ground programmable exposures ranging from 34 μs to 490 ms
Data volume/frame (Mb)	40
System MTF @ 46 LP/mm (%)	>21 (specification > 15%)
SNR @ near saturation	>95 (specification > 50)
Size (mm^3)	346 × 128 × 113 (EOM + LCE) 122 × 105 × 26 (PSE)
Mass (kg)	1.27 (Goal < 1.5kg)
Raw power (W)	3.0 (Goal < 4W)

lines to the payload. Figure 8 *a* and *b* shows the actual realized FM LCE and FM PSE cards respectively. The CE incorporates exposure control logic to facilitate matching detector dynamic range with intended scene dynamic range.

The electro optic module (EOM) structure was designed and analysed 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 was designed to take environmental loads like dynamic vibration, shock and temperature excursions during the orbiting period. The structure has been optimized for thermo-structural stability (20 g RMS for structural and –40°C to 60°C for thermal) for minimum deformation (change of distance between lens-mounting plane and DHA-mounting plane) of the order of 20 μm. The structure was machined from Al 6061-T6 alloy solid block into an ultra-light weight structure (mass less than 200 g) with alignment accuracy better than 10 μm (parallelism between lens and detector mounting planes and perpendicularity of these planes with respect to structure base). Figure 9 shows the realized EOM. The achieved fundamental mode is higher than 400 Hz and survived the temperature excursions (0–40°C) without any deformation higher than 0.01 μm.

Payload checkout system for MCC consisted of four subsystems: spacecraft interface simulator (SIS), payload status indicator (PSI), payload data acquisition system (PDAS), and application software (AS). SIS generated all the commands required for the operation of the payload

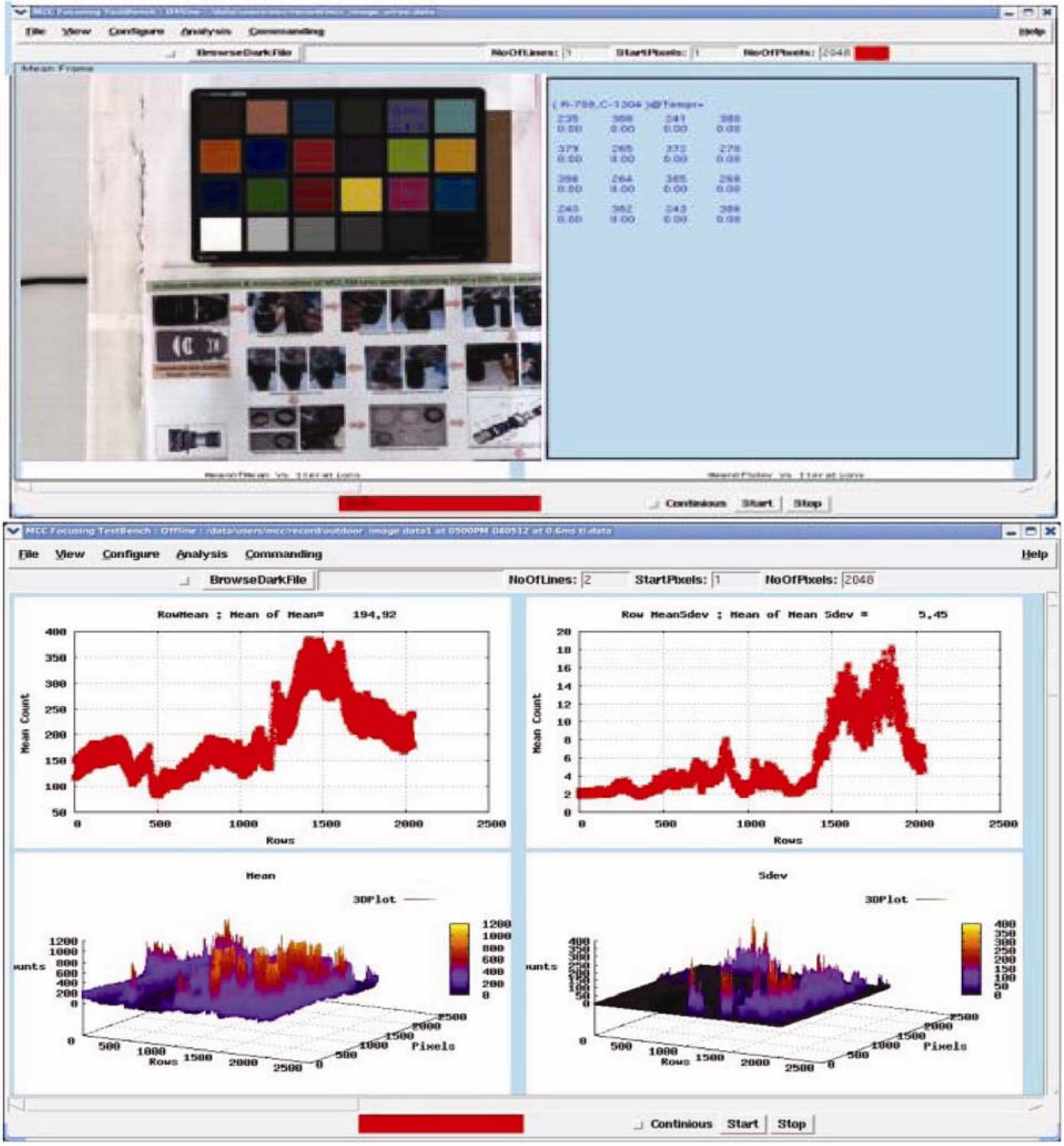

Figure 10. Screenshot of MCC user-interface module.

and control signals in the absence of actual satellite. PDAS acquired the data from the payload using in-house developed PCI-based data acquisition card (DAQ), formatted the same and make them available on network. Application software consisted of core libraries developed in C/C++, configuration data, parameter computation and analysis tools, supporting scripts, user interface (UI) for data visualization and test results display. PSI received and processed all the analog and digital telemetry information from the payload for health monitoring. Figure 10 shows the screen-shot of UI module of application software system. Table 1 gives the salient features and performance specifications of MCC.

Integrated payload characterization

MCC system was optimized to produce best optical and electrical performance for all three bands. MCC payload was characterized in terms of various performance parameters like modulation transfer function (MTF), payload alignment and its stability, effective focal length and

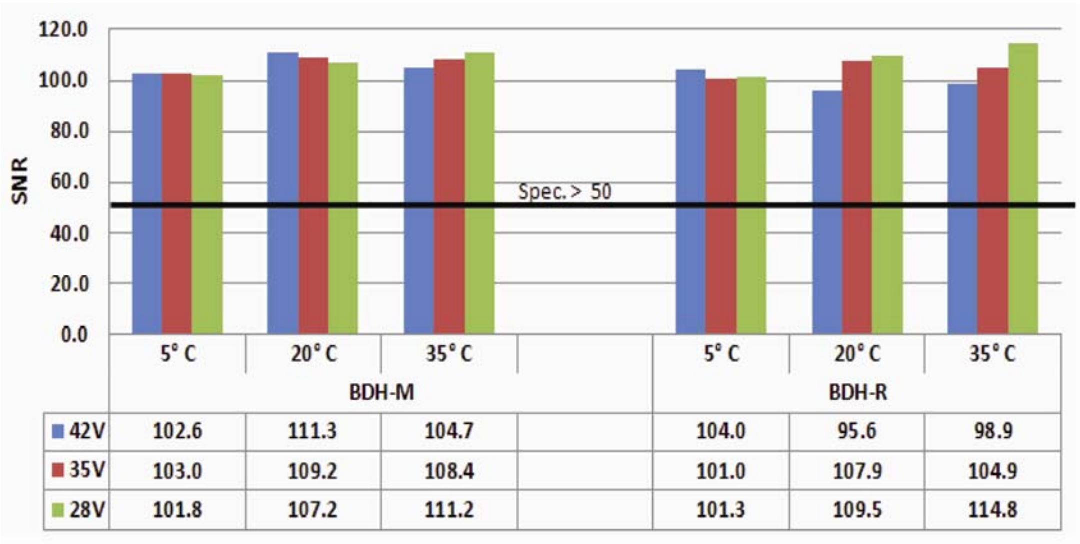

Figure 11. Signal to noise ratio versus temperature.

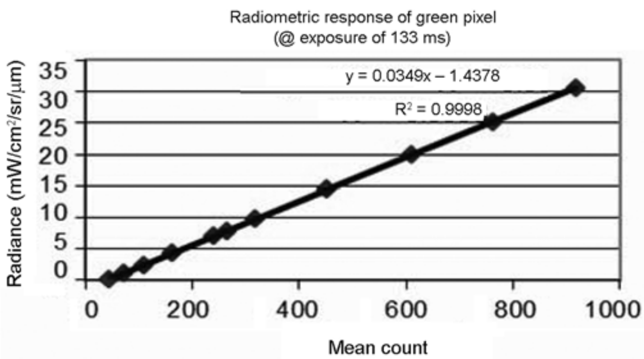

Figure 12. Radiometric linearity.

distortion measurement, ghost/background analysis, dark noise, signal to noise ratio (SNR) at near saturation, etc.

MCC employed multiple levels of exposure settings varying from 34 μs to 490 ms to meet the imaging requirements of various targets and varying illumination conditions. Extensive radiometric calibration was carried out using an integrating sphere (uniform illumination source) to establish radiometric performance for various exposure settings. Light transfer characteristics (LTC) of all three bands was carried out with multiple exposure modes and suitable radiance level to cover complete dynamic range of the payload. Radiometric response for each band was established. Figure 11 shows the SNR performance at ~850 counts (10 bit digitization) for both data chains (BDH systems – main and redundant) and for different raw bus voltages (28, 35 and 42 V) during thermo-vacuum test.

Figure 12 shows radiometric response (typical for the green band) at exposure setting of 133 μs for the MCC payload. Colour reproduction capability of MCC was determined largely by accurate spectral calibration of the payload in the complete spectral range. The spectral response measurement of MCC was carried out using a monochromator source and standard spectro-radiometer for the spectral range 300–1100 nm. The in-band measurements were carried out in step size of 2 nm interval and the out-of-band data were acquired at 10 nm interval. The spectral response measurement was carried out to cover all the zones of the detector array at the focal plane. Figure 13 shows the spectral response of all three bands. The geometric performance of MCC was carried out in a detailed manner in the laboratory as well as thermovac conditions. The performance was consistent. Figure 14 shows the MTF performance data. Radiometric, spectral and geometric performance meets the requirements with a comfortable margin.

Data product scheme

Level-1 product (calibrated data) generation involves detector-wise photo response non-uniformity model correction as understood from pre-launch laboratory calibration exercises; line/pixel loss correction and tagging the geographic coordinates to each pixel. An MCC image is a Bayer filter mosaic, a colour filter array (CFA) for arranging RGB colour filters on a square grid of photo sensors. The demosaicing algorithm was developed to reconstruct a full colour image. The software pipeline to produce minimum planetary data system (PDS) compliance product in the active archive was developed, tested, evaluated and readied at ISSDC, Bangalore. Software for data products included reference datasets and utilities to help ascertain radiometric and geometric accuracies, and a tool to produce a high dynamic range colour image from multiple MCC frames called bracketed exposures.

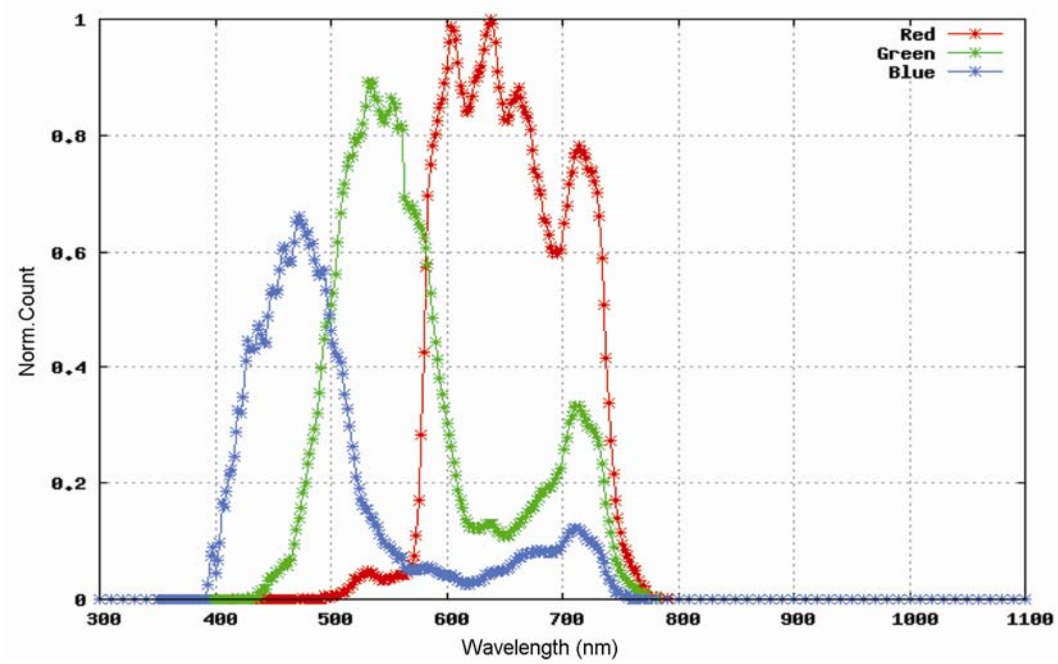

Figure 13. Relative spectral response of MCC.

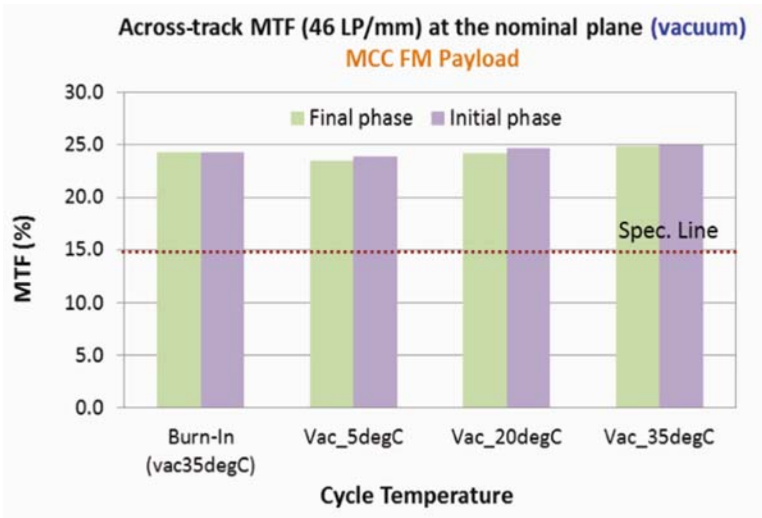

Figure 14. Modulation transfer function at various temperatures (MCC).

Earth imaging experiments

MOM was launched on 5 November 2013 and MCC started imaging from 19 November 2013. Earth imaging experiments (EIE) were conducted during the Earth orbit phase (EOP) in order to assess the functional and performance aspects of MCC and assess its application potential vis-à-vis the objectives envisaged. Three imaging sessions on two different dates, viz. two sessions on 19 November 2013 and one on 23 November 2013 were conducted. This included imaging from varying altitudes (spatial resolution), illumination conditions, taking multiple snapshots 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. The modes of operation also ranged from mode-3, having integration time of 0.4 ms to mode-13, having integration time of 0.133 ms for MCC.

The imaging sessions were chosen to get favourable illumination and viewing geometry: During EIE, there were five major objectives: (1) To image India for outreach purpose; (2) To image Earth from Mars Apoapsis equivalent (about 60,000–70,000 km) altitude; (3) To

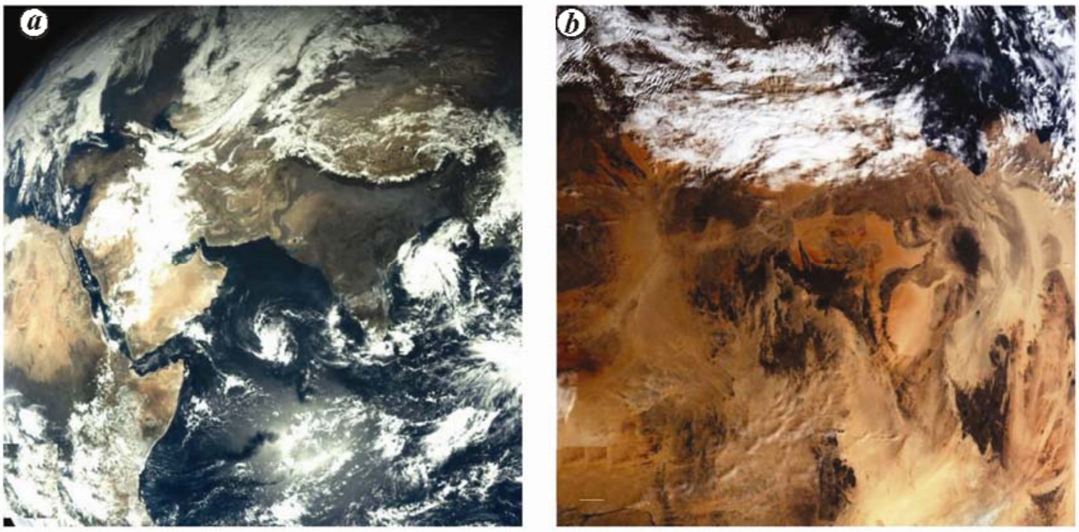

Figure 15. ***a***, First image acquired by MCC on 19 November 2013. ***b***, Another image on 23rd November 2013 over Sahara desert.

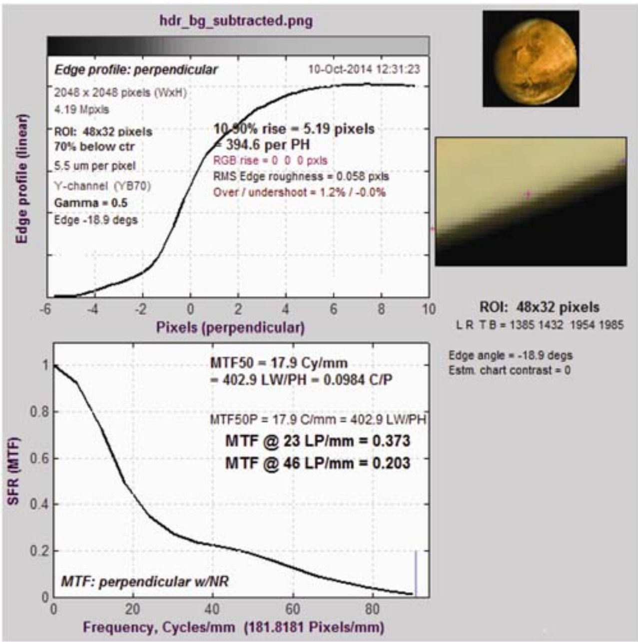

Figure 16. MTF estimation across land/ocean boundary.

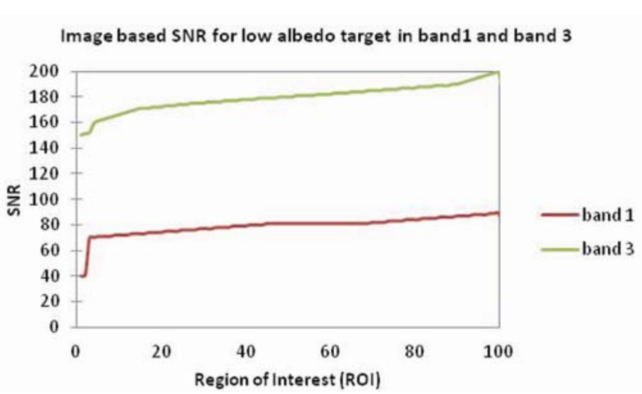

Figure 17. SNR of MCC in one mode for bands 1 and 3.

image from geo-stationary equivalent altitude (36,000 km); (4) To image at a resolution of 1 km; (5) To analyse and evaluate the data.

Qualitative analysis

The first photograph (Figure 15 *a*) was taken on 19 November 2013 (0820 UT) from an altitude of 67,975 km with 3.5 km spatial resolution. It was the first MCC image showing parts of Asia and Africa, including India. The swath of the image was about 7240 km and it was taken using 0.4 ms integration time. Three snapshots, each shot per second, were taken. Another imaging session over the Sahara desert was carried out on 23 November 2013 (0900 UT) from an altitude of 18,746 km (Figure 15 *b*). The spatial resolution was 0.91 km. Visual interpretation of the image was carried out and many Martian morphological analogues like barchans, longitudinal sand dunes, parabolic dunes, volcanic rock outcrops and aeolian corridors (streaks) could be clearly mapped.

In the first image (Figure 15 *a*), most of India could be covered with minimal cloud cover. The four major physiographic zones of India, viz. Himalayan range (white snow), the Indo-Gangetic plain (greyish), Thar desert (beige colour) and the southern peninsula (dark) were picked up distinctly with textbook precision by the maiden image taken by MCC. The cyclone ‘Helen’ (white), off the eastern coast, was picked up before its landfall. Additionally, the dispersal pattern of the suspended sediments discharged by rivers into the Gulf of Khambhat and Gulf of Kachchh was also seen in light blue colour, off the Gujarat coast. Holy lake ‘Mansarovar’ was also visible across the Himalayan snow peaks. Other features in the image show parts of Sahara and Arabian deserts (bright colour), Trans-Himalayan Tibetan plateau, fertile Indus valley and a variety of cloud patterns.

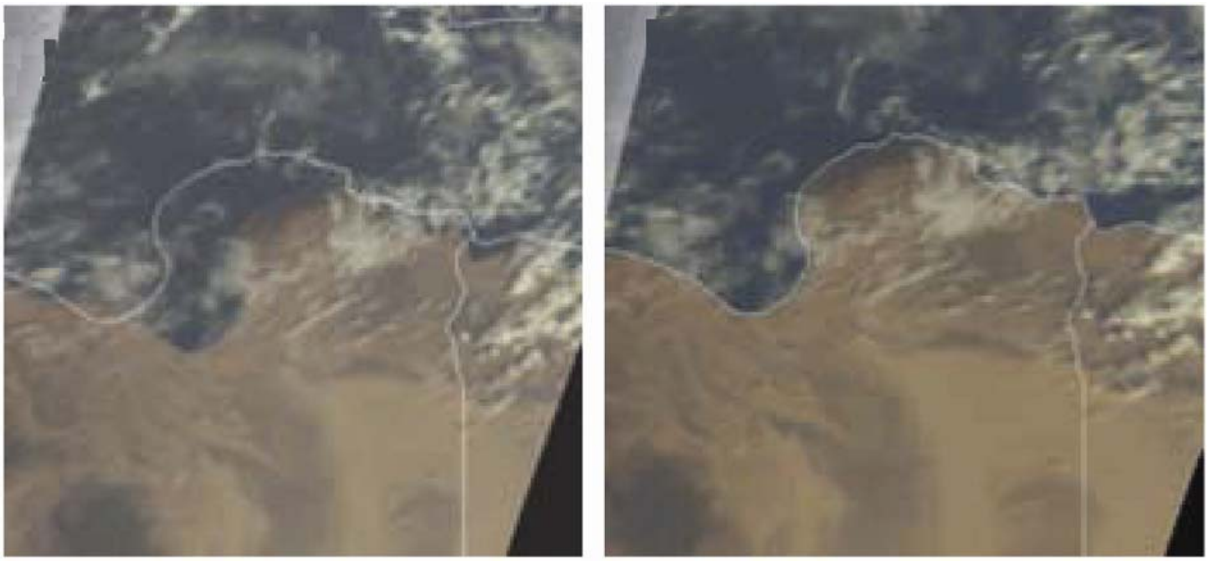

Figure 18. Images showing match between coastal and land boundary before (left) and after (right) improvement.

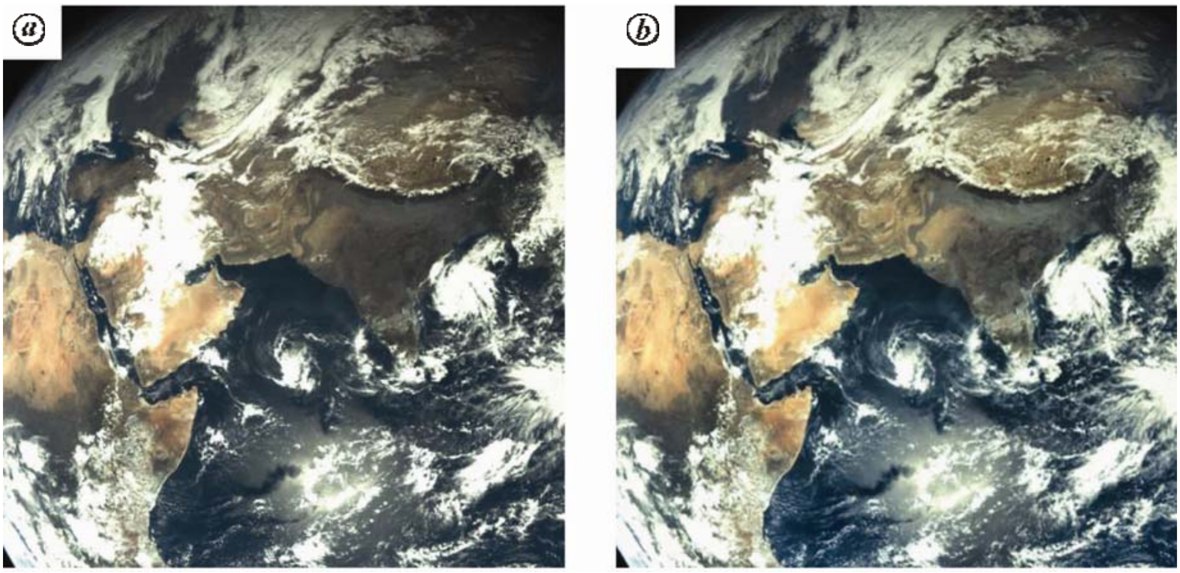

Figure 19. Single frame (***a***) and three-frame (***b***) high dynamic range (HDR) images.

Quantitative analysis

MCC data, acquired on 19 and 23 November 2013 were analysed for the following aspects: (1) MTF measurement (2) Signal-to-noise-ratio; (3) Dynamic range of the data (in radiance domain); (4) Inter-sensor comparison.

Image-based MTF computation: MTF was estimated at land/ocean boundary (Figure 16, indicated by dotted-square off the Saurashtra coast, Gujarat). It measured 20.3%, which conforms to the pre-launch laboratory tests of MCC.

Image-based signal-to-noise ratio computations: Systematic analysis of SNR was carried out separately for various targets, viz. low albedo target (deep ocean) and high albedo target (sand/cloud). Homogenous areas were identified and SNR assessed using the procedure described in the literature[4,5]. The assessed average SNR ranges from 80 to 180 among different bands. SNR values show that we can expect good discrimination of Martian features. Figure 17 shows the typical SNR computed from MCC image in mode 13. As expected from ground LTC data, saturation count (DN) was found to be about 850.

Geometric performance evaluation: An elaborate exercise was carried out to establish the geometric accuracy of MCC datasets acquired over Earth bound phase. Terrestrial surface features were distinctly discernible by direct visual analysis in MCC image. Geometric accuracy

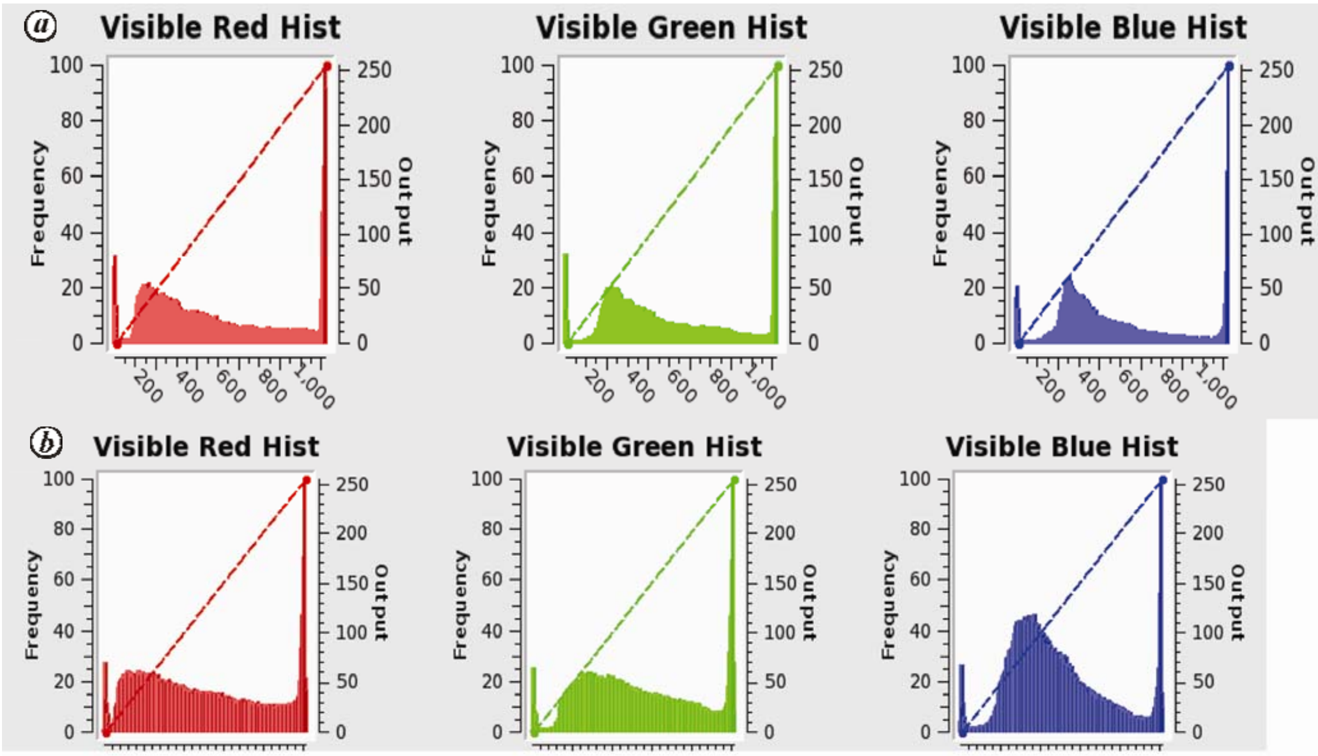

Figure 20. Histogram of red, blue and green bands (***a***) before and (***b***) after generation of HDR.

evaluation was carried out using ground control points collected from ortho-rectified images acquired from 'True Marble' (NASA) and IRS-Resourcesat-2 AWIFS datasets. After estimating the residual errors of orbit/MCC images using reference data, additional corrections were applied. Thereafter, the world coastal and land boundary data were overlaid on MCC data which were found to match (Figure 18). Accuracies achieved were of the order of +/– 0.5 MCC pixel resolution at various altitudes.

Image-based radiance range of the data: Radiance range is an important element of the datasets used for evaluating the quality of the data. The radiance range comprised of data from low-albedo targets which in this case was deep ocean and high-albedo target which was sand/cloud in all the three datasets. The data acquired by the payload experienced varying viewing geometry and solar illumination and hence the data were normalized for both the effects. It was observed that radiance range lay between 2 and 50 $mW/cm^2/sr/\mu m$ for red band, 5 and 38 $mW/cm^2/sr/\mu m$ for green band, and 7 and 28 $mW/cm^2/sr/\mu m$ for blue bands. The saturation radiance for the three bands was 54.71, 50.65 and 48.41 $mW/cm^2/sr/\mu m$ respectively, for the modes selected for operation. The data do not get saturated in this mode of operation and the same is expected in Mars imaging phase.

In order to check the radiance value and top of atmosphere reflectance with the contemporary satellite, an analysis was done by taking observations from geostationary satellite INSAT 3A CCD red band only, as it is the only band common in both the payloads. The data were so selected such that the time of observation nearly matches in both cases. As was done for MCC, normalization for viewing geometry and solar illumination was also done for INSAT 3A CCD datasets. MCC and CCD radiance showed close approximation in values ($R^2 \sim 0.69$).

High dynamic range data product: A specialized high dynamic range (HDR) product was generated using three frames imaged consecutively to enhance the land features. The difference between the single-frame and three-frame image was clearly visible (Figure 19 *a* and *b* respectively). The same is represented by histograms of red, blue and green bands before and after generation of HDR (Figure 20 *a* and *b* respectively).

The surface features on land was enhanced in the HDR image, e.g. Thar Desert, India.

Conclusion

The payload could be realized within the weight and power budget of the mission. Three models of the payload were made, characterized, calibrated and space-qualified in a record period of one year. Indigenous miniaturization of the flight model of MCC brought down its mass by 50%. The MCC data generated during the Earth orbit phase at different altitudes were of professional quality and found to be mostly conformal with the calibration values of LTC data generated during laboratory tests of MCC. Visual interpretation of the MCC images could be used to identify Martian analogous features on the Earth surface with satisfactory quality. Post-launch performance of the payload has been excellent. The data pipeline has been established. MCC is expected to give images of desired quality during rest of the Mars mission, which will 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.

1. Anon., Pre-shipment review document, Mars Colour Camera, Document No. SAC-MOM-04-April 2013.
2. Hua, L. and Chen, H., A color interpolation algorithm for Bayer pattern digital cameras based on green components and color difference space. Informatics and Computing, IEEE International Conference, Shanghai, 10–12 December 2010, pp. 791–795.
3. El Gamal, A., CMOS image sensors. *IEEE Circuits Dev. Mag.*, 2005, **21**, 6–20.
4. Zhang, L., Automatic digital surface model (DSM) generation from linear array images. Ph D dissertation. Institute of Geodesy and Photogrammetry, Zurich, Switzerland, 2005.
5. Baltsavias, E. P., Pateraki, M. and Zhang, L. Radiometric and geometric evaluation of IKONOS geo images and their use for 3D building modeling. In Proceedings of Joint ISPRS Workshop on High Resolution Mapping from Space 2001, Hannover, Germany, 19–21 September 2001.

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