Terrain Mapping Camera: A stereoscopic high-resolution instrument on Chandrayaan-1

A. S. Kiran Kumar*, A. Roy Chowdhury, A. Banerjee, A. B. Dave, B. N. Sharma, K. J. Shah, K. R. Murali, S. R. Joshi, S. S. Sarkar and V. D. Patel

Space Applications Centre, Jodhpur Tekra, Ahmedabad 380 015, India

Chandrayaan-1, India's first lunar mission, has the prime objective of simultaneous chemical, mineralogical and photo-selenological mapping of the lunar surface. In keeping with the mission objectives, Chandrayaan-1 carries the Terrain Mapping Camera (TMC) designed to map the entire lunar surface during the planned two-year mission. TMC data will enable preparation of a three-dimensional lunar atlas with 5 m sampled spatial and altitude data of 12 bit digitization. The TMC will image in the panchromatic spectral band of 0.5–0.75 μm with a stereo view in the fore, nadir and aft directions of the spacecraft movement and have a base to height ratio of one.

Keywords: Active pixel sensor, digital elevation map, Moon, stereoscopic view.

Introduction

THE Terrain Mapping Camera (TMC) on India's first satellite for lunar exploration, Chandrayaan-1, is intended for systematic topographic mapping of the entire lunar surface, including the far side and the polar regions. The aim is to prepare a three-dimensional atlas of the Moon with high spatial and altitude sampling for scientific studies. The 5 m sampling of the camera is chosen to be commensurate with 1 : 50,000 scale mapping and desirable contour interval of less than 10 m for height information. Such high resolution imagery of the entire Moon will help detailed study of specific lunar regions of scientific interests and further our understanding of lunar evolution. The digital elevation model available from TMC will also provide important inputs for analysing data from the other instruments on Chandrayaan-1 namely, HySI, MMM, SIR-2, LLRI and mini-SAR. TMC will image the lunar surface in push-broom mode in the panchromatic spectral band of 0.5–0.75 μm. For obtaining the elevation information the camera will have along-track stereo viewing, acquiring stereo triplet of the target scene in the fore, nadir and aft views, as the spacecraft moves in a 100 km circular polar orbit. With this arrangement, the entire lunar surface can be imaged without occlusion with at least one stereo pair. The base to height ratio (B/H) of the camera is 1. For the 100 km polar orbit, the equatorial shift of the Moon between two orbits is about 32.62 km. The swath of the instrument is 20 km and with orbital shift of 17 km between two imaging seasons, total coverage of lunar surface at equator with adequate overlap is ensured. The viewing geometry is shown in Figure 1.

Scene illumination over the moon varies as the solar aspect angle goes through a yearly cycle. Limiting the solar aspect angle to ±30° at the equator to minimize variation of illumination conditions will provide about two months of prime imaging period every six months leading to four prime imaging seasons during the two-year mission life. During the prime-imaging seasons, regions between 60°N and 60°S will be covered. This requires 20 min imaging per orbit for six orbits per day. The solar illumination at polar regions (above 60° latitude) is poor in all seasons, and these regions will be covered during the remaining periods, termed as the secondary imaging seasons.

TMC will measure the solar radiation reflected/scattered from the Moon's surface. The dynamic range of the

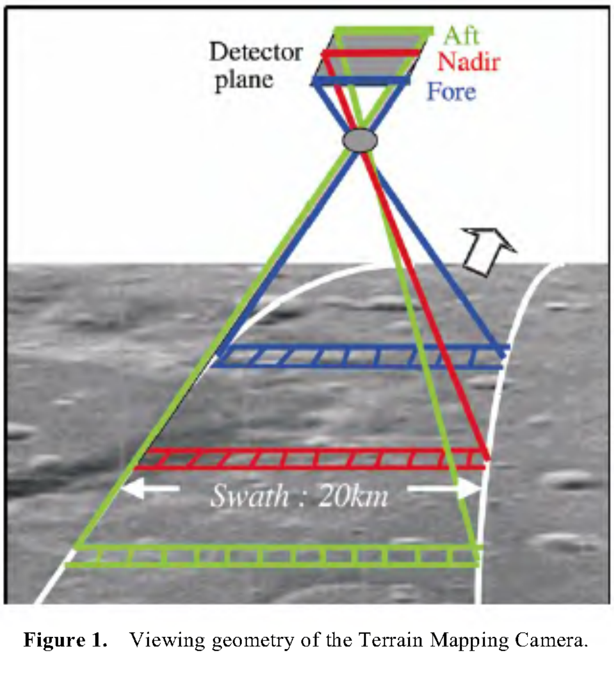

Figure 1. Viewing geometry of the Terrain Mapping Camera.

*For correspondence. (e-mail: kiran@sac.isro.gov.in)

reflected signal is quite large (>300), represented by the two extreme targets – high albedo fresh anorthosite and low albedo mature mare soil. The other factors affecting the illumination are the seasonal variation, latitude–longitude of the scene, topography and anisotropic reflectance of lunar surface. TMC's radiometric range of 4096 levels will cover the total dynamic range. Four programmable gain and exposure settings are also available. For low illumination conditions, improved SNR is achievable by increased integration time.

In a 100 km polar orbit, the visibility time from earth is approximately 70 min. For nearside observations, 20 min will be used for imaging and the remaining 50 min for data transmission. For farside observations, data will be transmitted when the spacecraft comes in earth's view. In this case, 28 min of imaging data can be acquired as the full 70 min is available for data transmission. Considering the generated data volume in 20 min and the transmission rate, data compression of the order of 2.5 : 1 is required.

Table 1. Key features of Terrain Mapping Camera

Spatial sampling	$5 \times 5m^2$ (from 100 km orbit)
Swath	20 km
Spectral band	Panchromatic (0.5–0.75 μm)
Stereo mode	Alongtrack triplet, $B/H \approx 1$
No. of gains and exposure	4 each
Quantization	12 bits
Square wave response	>25
Signal to noise ratio	>350
Operating temperature	20 ± 10°C
Power	1.8 W
Weight	6.3 kg

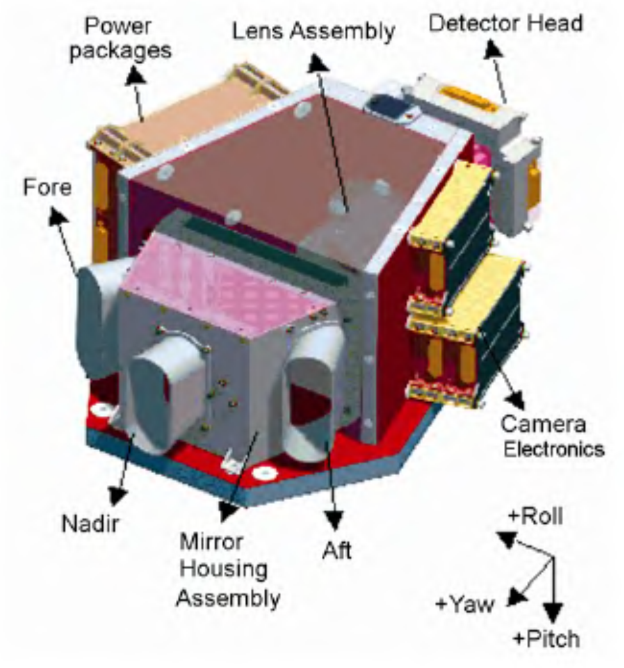

Figure 2. Schematic of the Terrain Mapping Camera.

The TMC data are losslessly compressed before transmission. Table 1 summarizes the key features of the instrument.

Instrument description

The subsystems of the TMC instrument are: Optical assembly; detector assembly; electronics; mechanical system.

The schematic of TMC is shown in Figure 2. The TMC is highly compact, low weight, low power dissipating instrument. The stereo data is collected by triplet imaging in the along-track direction with three linear detectors.

Optical subsystem

The optical configuration for TMC comprises a single multi-element f/4 lens assembly with a focal length of 140 mm. The required along track field angle of ± 25° is achieved with the help of a pair of plane mirrors placed strategically on either side of the 0° field (see Figure 3). The mirrors fold the incoming beams entering at ± 25° such that the lens assembly receives the same at a

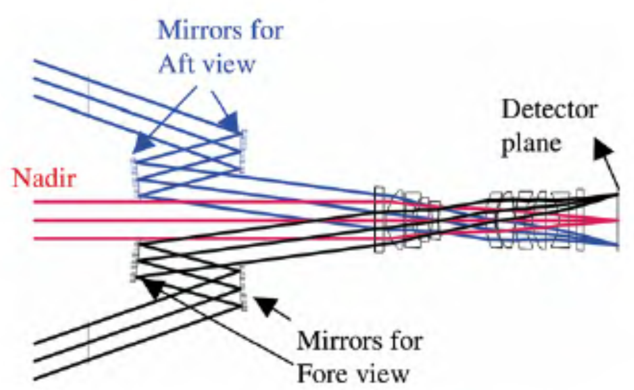

Figure 3. Optical schematic of Terrain Mapping Camera.

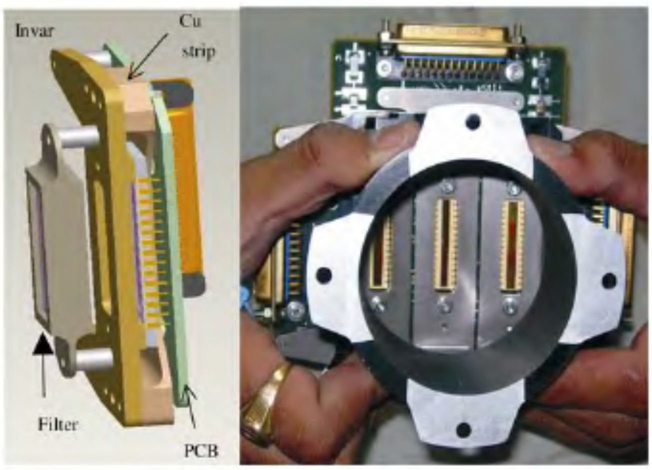

Figure 4. A close-up of the Terrain Mapping Camera Detector head.

reduced angle of ±10°. This enables spherical surface profiles for the lens elements used. The design of the mirror mounts and other mounting interfaces, the bonding and assembly procedures followed ensured that there was negligible change in system Modulation Transfer Function (MTF).

Detector subsystem

The TMC detector head is built around monolithic Complementary Metal–Oxide–Semiconductor (CMOS) linear array Active pixel Sensor (APS). The APS has integrated sensing elements, timing circuitry, video processing and 12-bit analog to digital conversion. Three detectors are kept in the focal plane for the fore, nadir and aft views. Figure 4 shows the detector assembly.

Electronics subsystem

The electronics for the instrument is designed to meet the detector and system requirements. It is modular and separate for the three detectors. The electronics is miniaturized and low power dissipating, providing necessary stimuli to the detector and outputting the 12-bit data with hot redundancy. Additionally, four gains and exposure settings are also available. The settings can be exercised through ground commanding. In addition, a feature allowing increased scene dwell time to improve signal to noise ratio is also present. Figure 5 shows the front-end electronics for a detector.

Mechanical subsystem

The mechanical subsystem consists of the structure and the electronics packaging. The main consideration is to meet the system performance by providing the stability for the static, dynamic and thermal load conditions with minimum weight and size. The structure is made of composite material of sandwich construction with face skins of high modulus carbon fiber material and core of aluminum alloy honeycomb. The electronics are packaged in trays and are mounted on the structure.

The TMC instrument (Figure 6) has a power dissipation of 1.8 W and weighs 6.3 kg. The performance of the instrument has been verified over the operating temperature limit and is meeting the requirements with sufficient margin.

Integration, testing and ground performance

The instrument flight model was realized using subsystems, after each has undergone detailed testing and qualification. The integrated payload underwent optimization and detailed characterization before going through the test and evaluation at acceptance test levels. During the various stages of testing, the payload was evaluated using an indigenous test unit, iSPACE – Instrument for Small Payload Checkout and Evaluation.

Focusing

Since the TMC employs three individual linear array APS detectors for three different camera views, the focusing of TMC involved accurate placement of the detectors at the focal plane of the imaging optics. The required plane for each of the three views – fore, nadir and aft – was determined by measuring the Square Wave Response (SWR), a measure of image contrast, as a function of defocus in the image plane. The SWR profiles were also generated during thermo-vacuum testing for 5°C, 20°C and 35°C temperatures. The SWR for all three views is greater than 25.

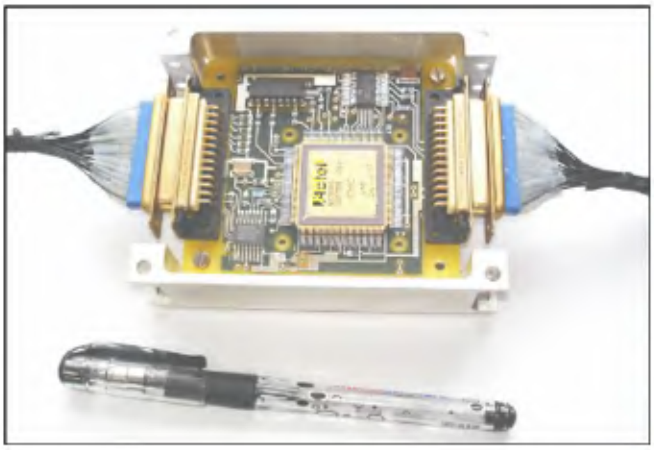

Figure 5. Front-end electronics of Terrain Mapping Camera.

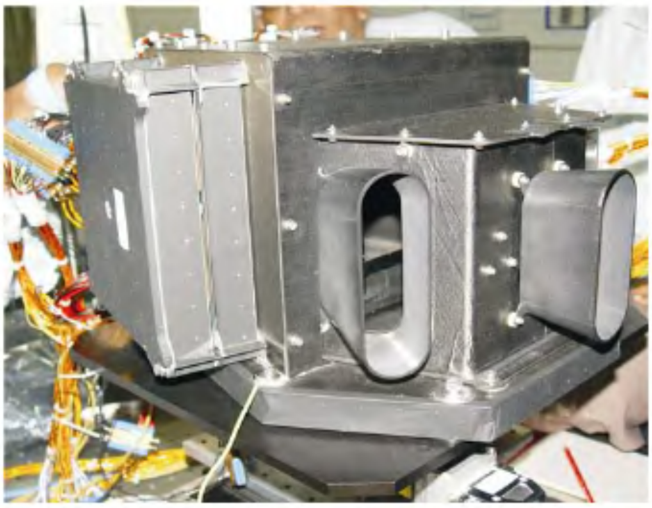

Figure 6. Flight model of the Terrain Mapping Camera.

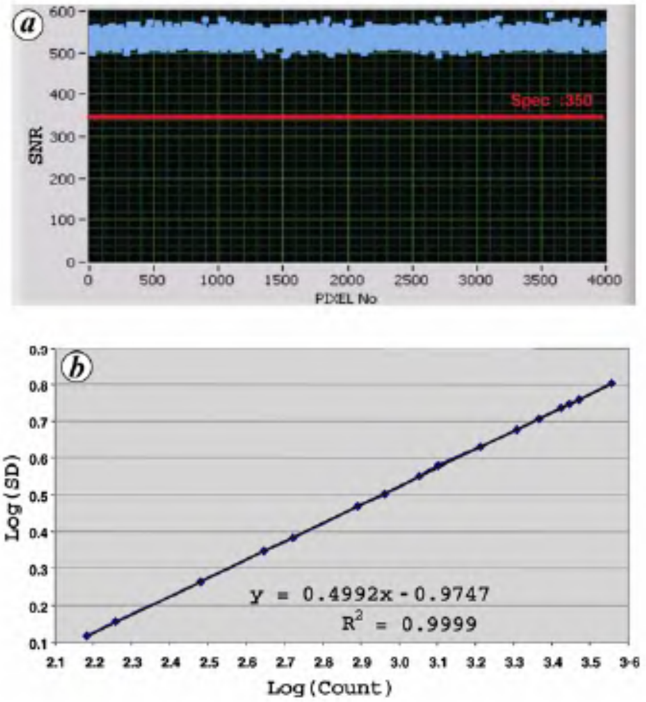

Figure 7. ***a***, Signal to noise ratio at saturation; ***b***, Terrain Mapping Camera noise behaviour.

Alignment

The alignment of the TMC payload involved alignment of individual detector for each of the camera views – fore, nadir and aft – with respect to the lens assembly and the mirrors (for fore and aft) as well as inter-alignment among the detectors. The central pixel correspondence between the fore, nadir and aft views was measured as 1995, 2001 and 1998 pixel respectively. The along track look angles for the fore and aft views with respect to nadir are 26.01° and 25.22° respectively.

Signal to noise ratio (SNR)

The noise performance of the instrument was measured during all stages of testing. Figure 7 *a* shows the SNR performance of the pixel array at saturation in minimum gain and maximum exposure setting condition. The count vs noise (standard deviation) is plotted in logarithmic scale in Figure 7 *b*. The slope of the plot is 0.499, which indicates that the system performance is limited by photon noise.

Radiometric performance

The radiometric performance was evaluated using a source that was sequenced through a set of different radiance levels at different exposure and gain settings for nadir/ fore/aft views. Spectral radiance was measured using a thermo-electric cooled silicon-based radiometer. The spectral radiance so measured was confirmed using another radiometer calibrated against a reference standard with its output traceable to NIST primary standards. The source radiance stability is better than 99.9% and the angular uniformity is 98% within ± 45°. With the four gain settings (× 1, × 2, × 3 and × 4) and the four exposure settings (100%, 90%, 80% and 70%) the saturation radiance of the instrument can be set in a wide range from about 6–30 mW/cm^2-sr-μ, thus ensuring optimum coverage of different features. The ground test result indicates satisfactory performance of the instrument.

The flight model of the TMC, developed for the Chandrayaan-1 mission, has met all the design specifications. Observational plans have been worked out to realize the mission goal of having a three-diemnsioal atlas of the entire lunar surface during the mission life of two years.

1. Lucey, P. G., Spudis, P. D., Zuber, M., Smith, D. and Malaret, E., Topographic-compositional units on the moon and the early evolution of the lunar crust. *Science*, 1994, **266**, 1855–1858.
2. Stertel, D., Lucey, P. G. and Gillis, J. J., Near infrared spectral properties of selected nearside and farside sites. *Lunar and Planeary Science XXXV*, 2004 (CD Rom).
3. Tompkins, S. and Pieters, C. M., Mineralogy of the lunar crust: Results from Clementine. *Meteor. Planet. Sci*., 1999, **34**, 25–41.

ACKNOWLEDGEMENTS. Several units of ISRO are involved in the development of the Terrain Mapping Camera. The Sensors Development Area at Space Applications Centre is the lead area responsible for overall design, development, testing, qualification and delivery of the instrument. The lens assembly and mirrors are fabricated at LEOS, Bangalore. The structure is developed at CMSE, Thiruvananthapuram. The power subsystem is designed and developed at ISAC, Bangalore. We thank all colleagues for their contribution in the realization of the instrument. We also gratefully acknowledge the constant encouragement and guidance received from Dr Ram Rattan, Associate Director and Dr R. R. Navalgund, Director, Space Applications Centre.