

Thermal Control System of the Moon Mineralogy Mapper Instrument

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ABSTRACT

The Moon Mineralogy Mapper (M3) instrument is one in a suite of twelve instruments which will fly onboard the Indian Chandrayaan-1 spacecraft scheduled for launch in 2008. Chandrayaan-1 is India's first mission to the Moon and is being managed by the Indian Space Research Organization (ISRO) in Bangalore, India. Chandrayaan-1 overall scientific objective is the photo-selenological and the chemical mapping of the Moon. The primary science objective of the M3 instrument is the characterization and mapping of the lunar surface composition in the context of its geologic evolution. Its primary exploration goal is to assess and map the Moon mineral resources at high spatial resolution to support future targeted missions. It is a "push-broom" near infrared (IR) imaging spectrometer with spectral coverage of 0.4 to 3.0 μm at 10 nm resolution with high signal to noise ratio, spatial and spectral uniformity. The nominal on-orbit mission lifetime for the instrument is 2 years with 2 months of primary science imaging every 6 months. The Chandrayaan-1 spacecraft will be placed in a near-circular Moon polar orbit with an inclination of 90 degrees, mean altitude of 100 km, and 118 minute orbit period.

The thermal control system consists of passive elements to maintain the instrument within allowable flight temperature (AFT) limits. Passive thermal control includes multi-layer insulation blankets, thermal straps, and surface coatings to manage the transfer of waste energy from sources through structures and ultimately to radiators. The detector is cooled to 150 K by means of a three-stage passive cooler which also cools the optical bench and telescope to near 180 K. This paper describes the instrument thermal requirements, top-level thermal design and analysis approach, key design drivers and analysis results.

INTRODUCTION

The M3 instrument, designed and built by the Jet Propulsion Laboratory for NASA, will fly onboard the Chandrayaan-1 spacecraft scheduled to be launched in 2008 aboard a Polar Satellite Launch Vehicle XL

(PSLV-XL) from Satish Dhawan Space Center in Sriharikota, India. Chandrayaan-1 will utilize the flight proven KALPANA-1 (METSAT) spacecraft bus successfully flown in 2002. The Chandrayaan-1 project is managed by ISRO for the Indian Government. Spacecraft communication will be done using ISRO's telemetry, tracking and command network in Bangalore, India. As India's first mission to the Moon, the Chandrayaan-1 satellite hosts a suite of scientific instruments designed to make the most comprehensive measurements ever undertaken of Moon's surface. Chandrayaan-1 suite of instruments have unique and complementary capabilities to map on a global scale data on the Moon's surface. The M3 instrument is a state-of-the-art high spectral resolution imaging spectrometer that will characterize and map the mineral composition of the Moon. M3 was developed in-house with major procurements from Rockwell Scientific for the detector and Barr Associates, Inc. for key aluminum optics. It will provide a significant improvement in the information quality available both for global and high resolution targeted mapping of the Moon.

India is developing the primary science instruments while the US will provide two opportunity science instruments and the remaining four are being developed by other foreign countries. MiniSAR being developed at Applied Physics Laboratory in Laurel, Maryland for NASA, is the second US instrument. A brief description of all twelve instruments is provided in Tables 1-2. A detailed description of M3 and its science capabilities is found in Ref. 1. An artist's conception of the Chandrayaan-1 spacecraft mission scenario is shown in Fig. 1. A CAD solid model of the spacecraft without external multi-layer insulation blankets is shown in Fig. 2 with its coordinate system. This figure identifies all the instrument payloads and their accommodations on the spacecraft bus.

Due to the challenging thermal requirements, tight mass and power budgets, restrictive spacecraft accommodations and widely varying mission conditions, the M3 instrument posed a challenging thermal design opportunity. Further compounding this challenge was the tight temporal detector temperature stability and

spectral stability requirements for the optical bench operating near 180 K.

Instrument	Description
TMC	Terrain mapping stereo camera, 5m spatial resolution with 20km swath, 0.5-0.85µm, 6.0kg, 13W
HySI	Hyper spectral wedge filter camera, 80m spatial resolution with 20km, 15nm spectral resolution, 64 channels, 3.1kg, 16W
CIXS	An X-ray fluorescence spectrometer covering 1- 10 keV with a ground resolution of 25 km, <10kg, <15W
HEX	High energy x-ray spectrometer, 40km footprint, 15.5kg, 34.2W
LLRI	Laser ranging instrument, 10m topographic resolution
MIP	Moon Impact probe, prove out soft landing technologies

Table 1. Chandrayaan-1 spacecraft suite of primary science instruments from India (Refs. 2-6)

Instrument	Country	Description
SXM	UK, India	Solar X-ray Monitor to detect solar flux in the 1–10 keV range, 5.2kg, 28W
RADOM	Bulgaria	Radiation Dose Monitor from Bulgaria to map the radiation environment around the moon, 0.16kg, 0.8W
MiniSAR	US	S-band miniSAR is the active SAR system to map lunar polar ice, 5.8kg, 50W
SARA	Sweden, India, Japan, Switzerland	Sub-keV Atom Reflecting Analyzer will map composition using low energy neutral atoms in the 10eV – 3KeV range sputtered from the surface, 3.5kg, 3.0W
SIR-2	Germany, Poland, Norway	A near IR spectrometer will map the mineral composition using an infrared grating spectrometer, 2.8kg, 10W
M3	US	Imaging spectrometer to map the surface mineral composition, 8.0kg, 13W

Table 2. Chandrayaan-1 suite of opportunity payload science instruments (Refs. 2-6)

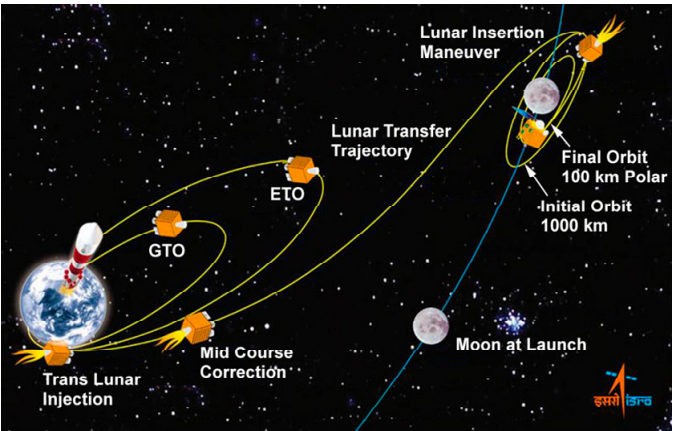


Figure 1. Chandrayaan-1 mission scenario to the Moon

INSTRUMENT DESCRIPTION

M3 makes nadir observations with a spatial resolution of 0.53 by 5.3 km with a swath of 5.3 by 8.5 km. M3 is capable of making observations only on the day-light side of the Moon. This instrument makes use of reflected sunlight to provide day coverage of the Moon's surface.

The primary science imaging will occur during a two-month period where the sun is within ± 30 degrees from the orbit plane. During preliminary interface discussions with the Chandrayaan-1 spacecraft, an extended science imaging period was identified for M3 which will extend coverage to ± 45 degrees from the orbit plane. This will provide an additional month of observations every six months.

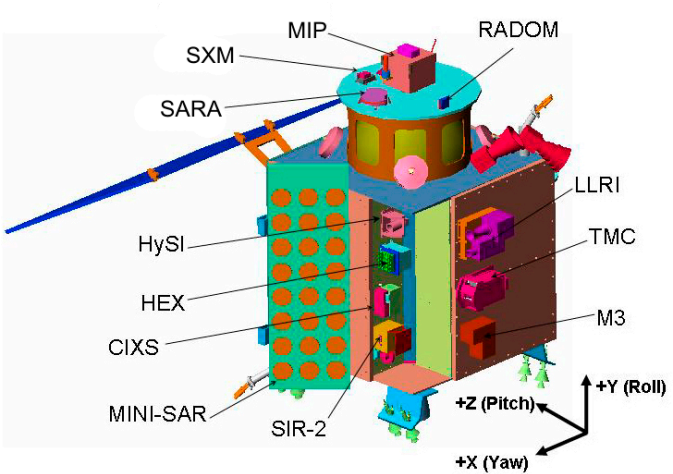


Figure 2. Chandrayaan-1 spacecraft concept with all twelve science instruments

The heart of the M3 instrument is a focal plane array (FPA) cooled to 150 K by the third-stage of a three-stage passive cooler. The spectrometer optics, including the telescope, is maintained at 180 K by means of the passive cooler second-stage. The first-stage cools a thermal shield which intercepts parasitic heat leaks from the surrounding environment near 300 K. The instrument thermal block diagram with the required temperature zones is shown in Fig. 3.

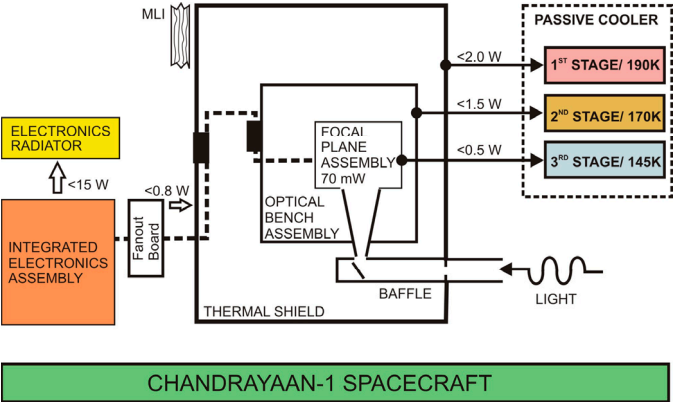


Figure 3. Instrument thermal schematic diagram with passive cooler

The instrument is comprised of the optical bench assembly and the instrument electronics assembly. The OBA includes a thermal shield surrounding the optics bench to intercept heat from the ambient surrounds and provides a cold environment for the optics bench. The optics bench is comprised of the telescope and secondary mirrors including the FPA support structure.

The optics bench and mirrors are built primarily from optics grade aluminum. The total instrument heat load on the passive cooler is nominally 2.0 W to the first-stage at 190 K, 1.5 W to the second-stage at 170 K and 0.5 W to the third-stage at 145 K. The passive cooler radiator surfaces are constructed from high conductivity pyrolytic graphite-aluminum composite material. The OBA envelope is 0.5 m by 0.5 m by 0.3 m and the integrated electronics assembly (IEA) is 0.3 m by 0.3 m by 0.1 m. The allocated mass and orbit average operating power is 8.0 kg and 13 W, respectively.

Early trade studies between passive and active cryogenic cooling led to the selection of a passive cooler for the instrument. The small Ricor 508 tactical cryocooler with flight heritage was considered for this application. This cooler has an acceptable system efficiency of ~7.5 W input power per Watt of refrigeration at 145 K. The Chandrayaan-1 mission lifetime is 2 years and the instrument is expected to be operating in science mode for a total of twelve months. The Ricor cooler expected lifetime exceeds one year, and therefore, was compatible with lifetime requirements for this application. The cryocooler mass is approximately 0.65 kg. The spacecraft bus voltage range is 35-42 V, whereas the cryocooler specification range is 18-28 V. This application would have required the implementation of power conditioning electronics including EMI/EMC filtering, current ripple suppression and an increase in instrument power allocation for the cooler subsystem. The Chandrayaan-1 spacecraft power bus configuration consists of a solar array and battery clamped single bus of 28-42 V. However, the expected minimum operating voltage for the payloads is 35 V. If the bus voltage drops below 35 V, the power subsystem will shed loads and put the payloads in survival mode. A mass estimate for the additional electronics hardware required for the cooler was in excess of 1 kg. It was estimated that the required system input power for the cooler to provide sufficient refrigeration in this application would far exceed the allocation. The instrument electronics power requirements was high and took up the majority of the allocated power. The cryocooler mass and power requirements were high and this led to the selection of a passive cooler as the baseline.

KEY SPACECRAFT PARAMETERS

Key drivers for the M3 thermal control system are as follows:

- Orbit parameters: polar elliptical orbit, 100 ± 20 km altitude, 90 degree orbit inclination,
- 0 to ± 45 degree orbit plane to solar vector (beta angle) for science mode,
- ± 45 to ± 135 degree beta angle for survival mode,
- Spacecraft interface temperatures: 0 to +40°C for operating (science) and -20 to +50°C for non-operating conditions (survival),

- Heat transfer to spacecraft is limited to less than 20 W/m², which includes radiation and conduction heat transfer,
- Spacecraft accommodations may add a maximum of 3.5 W/m² heat flux to the passive cooler radiators.

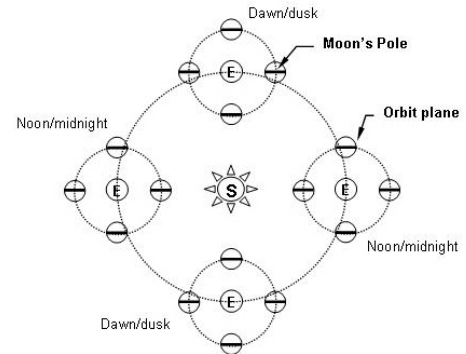


Figure 4. Spacecraft polar orbit relative to Earth and Sun positions

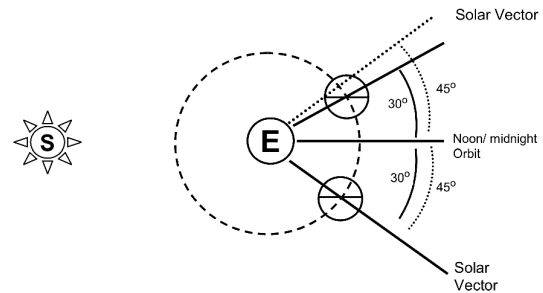


Figure 5. Science orbit definitions: primary is ± 30 degrees, secondary is ± 45 degrees

The low lunar orbit planned for this mission is nominally circular and polar and very nearly perpendicular to the ecliptic plane as shown in Fig. 4. The orbit plane is inertially fixed due to the small oblateness of the Moon. The solar incidence angle, with respect to the surface normal, changes at about 1 degree per day. Therefore, the primary imaging periods, where the sun vector is within ± 30 degree from the surface normal, will take place during the two months centered on the noon/midnight orbit. The extended imaging period occurs when the sun angle is between ± 30 to ± 45 degrees. This provides an additional month of science observations. Figs. 5-7 define the primary and secondary science orbits with the beta angles. Fig. 7 shows the sun vector relative to the orbit plane for the entire year. Consequently, imaging within the ± 45 degrees will take 90 days to complete and will repeat every six months. The orbit path will change direction from pole to pole every six months. Complete coverage of the Moon surface with a 20 km swath will take 3 months to complete. This will potentially occur within the first six months of the mission. To maximize solar illumination on the solar array, the spacecraft will rotate 180 degrees about the X-axis every six months. The spacecraft will rotate 180 degrees about the X-axis every six months.

axis (yaw rotation) every six months. The solar arrays are flipped 180 degrees (pitch rotation) every six months also for the same purpose. Table 3 shows all the annual planned maneuvers which result in an efficient utilization of sun illumination for power generation.

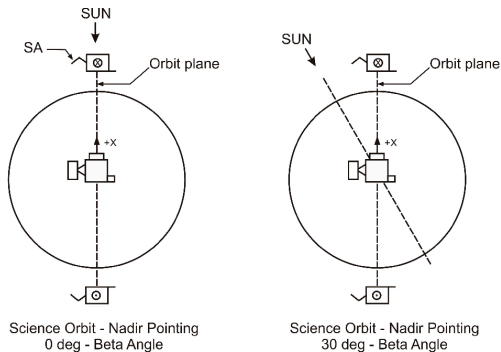


Figure 6. Beta angles for science orbits

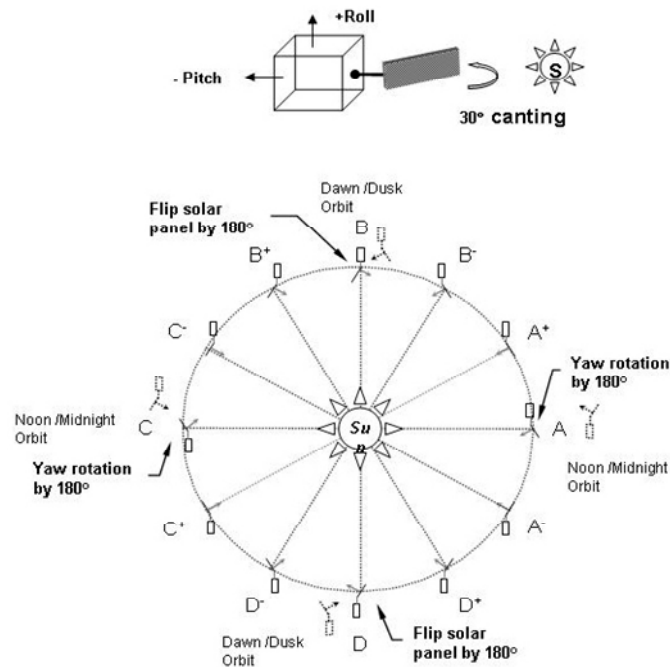


Figure 7. Spacecraft annual on-orbit maneuvers to maximize solar illuminations on solar arrays

The parameters and conditions of each spacecraft state defining the hot and cold mission environments, and survival spacecraft attitudes and the solar vector to orbit plane (beta) angle is shown in Table 4. The environmental constants used are defined in Table 5.

After injection into the transfer orbit by the PSLV, approximately 7 days are required for lunar capture at an orbit altitude of 1000 km. The time required to lower the orbit to 200 km is estimated to be 3 days. Subsequent liquid motor burns will be carried out to achieve the nominal 100 km orbit altitude. Launch to nominal orbit acquisition may take up to a couple of weeks to complete.

Orbit	Position	Solar Panel Rotation–Pitch (deg.)	Satellite Rotation–Yaw (deg.)	Sun Incidence on Solar Array (deg.)
Noon/Midnight	A ⁻			0
	A		180	30
	A ⁺			0
Dawn/Dusk	B ⁻			30
	B	180		60
	B ⁺			30
Noon/Midnight	C ⁻			0
	C		180	30
	C ⁺			0
Dawn/Dusk	D ⁻			30
	D	180		60
	D ⁺			30

Table 3. Sun incidence on solar array

Mode	Beta angle (degrees)		S/C Attitude	Description
	hot	cold		
Launch/Orbit insertion	Varies	Varies	Varies	Includes ascent, cruise to orbit insertion prior to nominal science orbit acquisition. Instrument off.
Science	0	±45	+X Local Vertical (Nadir Pointing)	Nominal science orbit: 80-120km altitude
Decontamination	0	±45	+X Local Vertical (Nadir Pointing)	Nominal science orbit: 80-120km altitude
Survival	0	±90	+X Local Vertical (Nadir Pointing)	Nominal science orbit: 80-120km altitude, Instrument off
	Sun-pointing	Space view	±Z solar intertial	Instrument off

Table 4. Chandrayaan-1 spacecraft mission environments

Parameter	Cold Case	Hot Case
Solar Flux	1290 W/m ²	1420 W/m ²
Albedo (ratio)	0.06	0.13

Table 5. Mission environmental parameters (Ref. 7)

The desired nominal orbit for this mission is a 100 km altitude circular polar orbit needed to meet the scientific objectives. However, orbital perturbations arise from gravitational and non-gravitational forces. The most significant source of this orbit perturbation is the asphericity of the Moon. The non-gravitational perturbations are due to solar radiation, Moon IR flux and albedo radiation. Consequently, periodic orbit corrections will be carried out to maintain the nominal orbit. The nominal scenario is to carry out orbit corrections every 28 days which will result in altitude variations of less than ± 20 km from the 100 km nominal orbit. This orbit may be adequately modeled as an elliptic orbit with a periapsis and apoapsis of 80 km and 120 km, respectively. The orbit maintenance period was selected to ensure the spacecraft was in view of the Bangalore Deep Space Network (DSN). The maneuver