The Moon Mineralogy Mapper (M³) on Chandrayaan-1

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The Moon Mineralogy Mapper (M³) is a NASA-supported guest instrument on ISRO's remote sensing mission to Moon, Chandrayaan-1. The M³ is an imaging spectrometer that operates from the visible into the near-infrared (0.42–3.0 μm) where highly diagnostic mineral absorption bands occur. Over the course of the mission M³ will provide low resolution spectroscopic data for the entire lunar surface at 140 m/pixel (86 spectral channels) to be used as a base-map and high spectral resolution science data (80 m/pixel; 260 spectral channels) for 25–50% of the surface. The detailed mineral assessment of different lunar terrains provided by M³ is principal information needed for understanding the geologic evolution of the lunar crust and lays the foundation for focused future in-depth exploration of the Moon.

Keywords: Imaging spectrometer, lunar composition, mineralogy.

Introduction

THE history of the Earth and the Moon is intimately linked since their formation, 4.5 billion years (Gy) ago. The scientific advancements from the Apollo era included recognition of major planetary processes such as formation of a magma ocean and pervasive differentiation. These early events of planetary evolution were dated with returned *Apollo* and *Luna* samples. We have learned that many other processes active on the early Moon are also common to most terrestrial planets, including the record of early and late impact bombardment[1,2]. Since most major geologic activity ceased on the Moon ~3 Gy ago, the Moon's surface provides a nearly unaltered record of the earliest era of terrestrial planet evolution.

The type and composition of minerals that comprise a planetary surface are a direct result of the planetary body's initial composition and its subsequent thermal and physical processing. Lunar mineralogy seen today is thus a direct record of the early evolution of the lunar crust and the subsequent geologic processes acting upon it. In particular, the distribution and concentration of specific minerals is closely tied to magma ocean products, lenses of intruded or remelted plutons, basaltic volcanism and fire-fountaining, and any process (e.g. cratering) that might redistribute or transform primary and secondary lunar crustal materials. In spite of the success of the 1994 Clementine and 1998 Prospector remote-sensing missions to the Moon, we still lack detailed information characterizing the mineralogy across the lunar surface.

The Moon Mineralogy Mapper (M³, or m-cube) is a state-of-the-art imaging spectrometer that is designed to identify and map the minerals and rock compositions across the lunar surface. The M³ developed for flight on Chandrayaan-1, the Indian mission to the Moon, as one of several foreign instruments chosen by the Indian Space Research Oragonization (ISRO) to complement the strong ISRO payload package. After a detailed NASA peer-review, M³ was selected in February 2005 for funding through NASA's Discovery Program as a Mission of Opportunity.

M³ instrument concept

Common rock-forming minerals are known to exhibit highly diagnostic spectral properties in the near-infrared (700–3000 nm). The physical principles that produce these absorption features are well defined and are controlled by the specific atoms and structure of a mineral[3]. Since these are the properties that make a mineral unique, the spectral signature of individual minerals can be used to identify a mineral and its composition. Rocks are a mixture of minerals, and spectra of rocks contain a superimposed combination of the diagnostic spectral signatures of mineral constituents, although the spectral mixture is typically nonlinear.

Shown in Figure 1 are reflectance spectra of well-characterized lunar minerals and soils returned to Earth for analysis during the Apollo program. Lunar soils have significantly reduced spectral contrast due to a variety of space weathering effects[4], but nevertheless retain weak features that remain diagnostic of the minerals present. The most prominent mineral absorption features are due to various compositions of pyroxene and olivine present in local rocks found at fresh craters or other surfaces devoid of well-developed space-weathered soil.

The M³ operates as a pushbroom grating spectrometer with a slit oriented orthogonal to the spacecraft orbital motion. Measurement geometry is fixed with nadir pointing. Measurements are obtained simultaneously for 640 cross-track spatial elements along the slit and 260 spectral elements. Twenty pixels are masked on both sides of the slit to provide continuous background measurements, leaving 600 cross-track spatial pixels. This translates to ~70 m/pixel spatial resolution from a nominal 100 km polar orbit for Chandrayaan-1. The M³ field of view (FOV) is

24 degrees, which translates to ~40 km on the surface from a 100 km orbit. This FOV allows contiguous orbit-to-orbit measurements at the equator and data mosaics will thus minimize variation in lighting conditions. The M³ design has exceptionally high uniformity: spatial and spectral elements are co-registered to within 0.1 pixel. The resulting 'image cubes' of data (two spatial dimensions, one spectral dimension) allow spectral features diagnostic of mineralogy to be identified in a detailed spatial context. The high-resolution compositional information provided by M³ for surface mineralogy is fundamental information for assessing the geologic character and history of the surface of the Moon. The M³ image cube concept is illustrated in Figure 2.

The M³ design requirements are specified to cover the spectral range 700–3000 nm with high SNR (>400) for
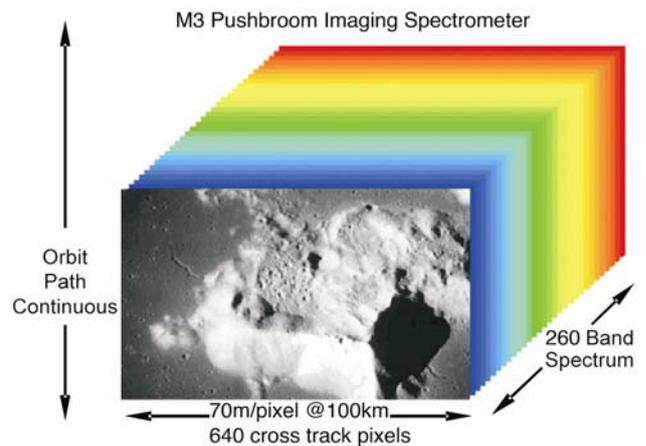

Figure 2. The M³ pushbroom instrument concept. An 'image-cube' of data is produced that consists of two dimensions of spatial information and one dimension of spectral information.
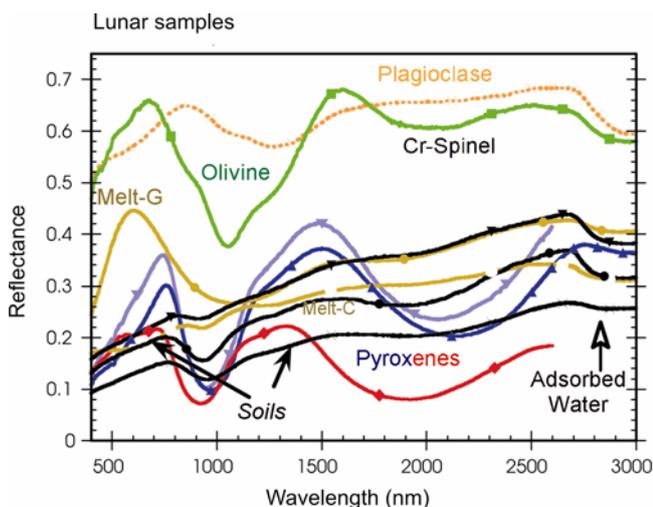

Figure 1. Reflectance spectra of lunar minerals and soils over the spectral range of M³. High spectral resolution allows superimposed features to be deconvolved for identification. The weak feature near 2900 nm is due to trace amounts of (terrestrial) water remaining on the samples even in a purged laboratory environment.
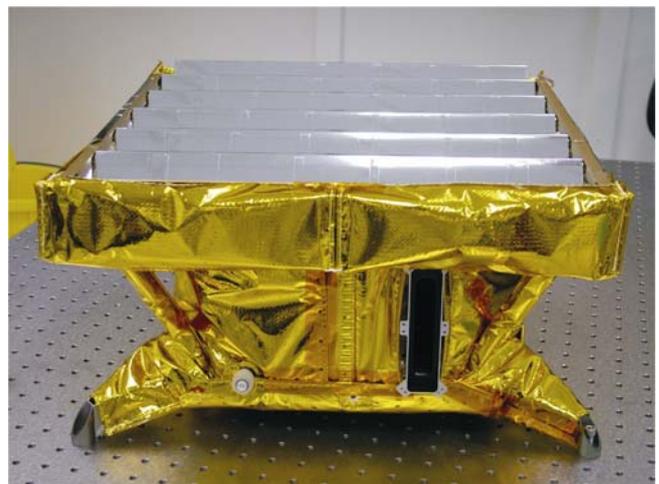

Figure 3. The M³ Optical Bench Assembly (spectrometer). The radiator is on top with the entrance aperture in front. This side faces the Moon. Dimensions of the OBA are approximately 420 W × 350 D × 220 H (mm).

Table 1. The M^3 Instrument parameters and measurement modes

Overall
  40 km FOV (allows contiguous orbit overlap)*
  405–3000 nm spectral range
  12 bit/pixel

Target Mode (full resolution):
  600 spatial pixels (70 m/pixel)*
  260 spectral channels (10 nm/channel)
  1 GB/orbit downlink: 10–12° longitude swath

Global Mode (reduced resolution):
  300 spatial pixels (140 m/pixel)*
  86 spectral channels (mixed 20 and 40 nm/channel)
  1 GB/orbit downlink: 135° longitude swath (alternating poles)

*For 100 km lunar polar orbit.

equatorial latitudes. The M^3 lower wavelength range is intended to allow maximum overlap with ISRO's Hyper Spectral Imager (HySI) instrument while the higher spectral range extends the spectral coverage across and into the near-infrared. All wavelengths are collected on a single two-dimensional detector and the detector is cooled using a passive radiator. The M^3 flight instrument (spectrometer and radiator) is shown in Figure 3. The integrated design (Green *et al.*, in preparation) easily met the specified requirements and was able to achieve the desired broader range of overlap. Calibration tests indicated that the M^3 nominal operation will be from 405 to 3000 nm at approximately 10 nm spectral resolution, although the first few channels (<434 nm) may be below the required SNR.

Since the M^3 has no moving parts, operation is relatively simple. However, the M^3 is a high data-rate instrument (44.4 Mbps at full resolution), and to fit data measurements within realistic downlink guidelines, the M^3 Science Team developed two operational modes to be used over the two-year Chandrayaan-1 mission (with 1.5 loss-less compression). These data operation modes are summarized in Table 1. Both modes maintain the same FOV and spectral range, but with different spatial and spectral resolution. The M^3 Target Mode is full spatial and spectral resolution and will be used to acquire prime science data. The M^3 Global Mode is substantially lower spatial and spectral resolution and will be used to acquire a base-map to provide context for the higher resolution prime science data. The overall science measurement strategy using these two modes is discussed in the next section.

Overall, the M^3 is a unique instrument that has benefited from major technical improvements previously unavailable for planetary imaging spectrometers. First, the spatial and spectral uniformity achieved (essentially the near-perfect alignment of elements across the detector chip) assures that the spectral data are co-registered from the beginning. This greatly simplifies the processing steps and allows the data to be used for science analysis almost immediately after basic calibrations. Secondly, the broad spectral range (430–3000 nm), which normally requires two or more separate detectors, is all measured on the same detector chip, eliminating the need to fit together different parts of the spectrum measured separately. Coupled to this latter characteristic is a special optical design that allows a nominal measured signal to normally be within a factor of 2 across the entire spectrum, simplifying measurement strategy.

Science and measurement strategy

The primary *science* goal for the M^3 is to characterize and map the lunar surface composition in the context of its geologic evolution. This translates into several science objectives to be addressed. Similarly, the primary *exploration* goal of the M^3 is to assess and map the lunar mineral resources at high spatial resolution to support planning for future, targeted missions. The science goals address several issues important to planetary science and in particular those related to understanding the origin and evolution of the lunar crust and mantle. Specific science objectives include the evaluation of primary crustal components and their distribution across the lunar highlands, characterization of the diversity and extent of different types of basaltic volcanism, mapping of fresh craters to probe the interior as well as impact record, identification and assessment of lunar deposits containing volatiles, and identification and evaluation of concentrations of unusual/unexpected minerals.

The science emphasis of the M^3 relies on measurement and mapping of surface mineralogy at high spatial resolution using the diagnostic features identified with high spectroscopic resolution for common rock-forming minerals illustrated in Figure 1. Since most lunar rocks are mixtures of minerals, spectral analysis involves the deconvolution of superimposed features, often with subtle band-to-band deviations. The prime science data for the M^3 is thus acquisition of high spectral resolution (10 nm) data across the mineral features in the near-infrared at the highest spatial resolution possible. This is achieved through the M^3 Target Mode measurements, but global coverage is not possible during a two-year mission.

In addition, by extending the spectral range to 3000 nm the M^3 can also address the issue of whether the hydrogen observed at the poles[5] is in the form of water–ice. The highly diagnostic fundamental absorption of H_2O near 2.8 μm shown in Figure 1 will allow the detection of H_2O even in trace amounts if it exists within the upper mm or two of the surface. Meteoritic impact induced 'gardening' of upper layers of lunar regolith would expose near-surface materials. In permanently shadowed areas at the base of craters in the polar regions, scattered light from crater walls provide faint illumination that is expected to allow sufficient signal over the course of the mission to test the hypothesis of presence of H_2O in such areas. Detection of H_2O, if seen, would be unambiguous. On the other hand,

lack of detection (the null hypothesis) places limits on the uppermost surface, but leaves the character of deeper layers of the regolith at the lunar poles to be resolved by other techniques including the imaging radar instrument (mini-SAR) onboard Chandrayaan-1.

The ground track of Chandrayaan-1 passes over all 360 degrees of lunar terrain each month. The sub-spacecraft lighting conditions for such a circular lunar polar orbit evolves over several months resulting in two periods each year when optimal illumination geometry is available for optical measurements. During the two-year Chandrayaan-1 nominal mission there are thus four 'optical periods', each of several months duration, during which the M^3 will acquire science data. Other months have slightly lower solar elevation and could be used for observations of polar region. Within anticipated downlink constraints, the M^3 Science Team has developed a two-stage measurement plan using a combination of a full resolution Target Mode with a lower resolution Global Mode data acquisition strategy.

During the first optical period, the M^3 initial measurement priority is full global coverage with low resolution M^3 Global Mode data. Since the M^3 FOV provides orbit-to-orbit overlap, full coverage can be achieved with contiguous orbits (alternating pole to ~60° in the opposite hemisphere), and it is anticipated that this valuable global base-map could be acquired during the first optical period. The M^3 switches to the prime science Target Mode for any remaining part of the first optical period and optical period 2, 3 and 4. Over the course of the two-year nominal Chandrayaan-1 mission approximately 25–50% of the lunar surface can be covered with M^3 Target Mode. For implementation of the M^3 Target Mode data acquisition, the M^3 Science Team developed a prioritized measurement plan for the highest priority science targets. Since it is unknown just what operational constraints might appear over the two-year mission, our targeting sequence is driven by science interests for individual targets. This sequence will continually be updated as M^3 global base-maps are available and new science priorities identified.

M^3 calibration

Laboratory calibration measurements to determine the spectral, radiometric, spatial and uniformity characteristics of M^3 were acquired in April of 2007. Initial results were reported in Green *et al.*[6]. The spectral range for the 260 channels was determined to actually span from 404 nm to 2993 nm with 9.96 nm sampling. The absolute radiometric calibration was determined with respect to a US National Institute of Science and Technology (NIST) traceable standard at the 5% uncertainty level. The radiometric precision or signal-to-noise ratio was calculated from the M^3 measured performance; it was shown to meet the requirement with respect to the M^3 equatorial and polar

reference radiances for 434–2993 nm. From the calibration measurements, the FOV of the M^3 was measured to be 24.3 degrees, and the cross-track sampling was measured as 0.698 milli-radians. Spectral cross-track uniformity and spectral instantaneous-field-of-view uniformity of the M^3 are critical calibration characteristics. All uniformity requirements of better than 0.1 pixel deviation end-to-end across the target were met. An example is shown in Figure 4.

The M^3 ground calibration data files will allow M^3 data to be calibrated to radiance at sensor (level L1b described below). The data needs to be further calibrated to the equivalent of reflectance data similar to that shown in Figure 1 for useful scientific analysis. This involves dividing the radiance data by a solar spectrum and photometrically correcting all data to the same viewing geometry to eliminate variations due to lighting conditions. Experience has shown that even with the best starting models, both steps contain significant errors and require some iteration and additional in-flight calibrations. There is an additional complicating factor for warm sunlit surfaces, which may include an additional small thermal component at wavelengths longer than 2000 nm.

We use a 'ground truth' procedure that has been successful for telescopic observations of the Moon and relies on the fact that we have samples of the Moon available for measurement in earth-based laboratories. If a sample can be identified that is representative of the region from which it was collected, then its properties can be used to calibrate those observed remotely under similar conditions. The Apollo 16 site is well suited for this because it is largely dominated by one type of material (feldspathic breccias) unlike most other landing sites that contain diverse lithologies. A well-developed soil from Apollo 16 (62231) was selected for this procedure and a large nearby region of undisturbed soil selected for the calibration target. This concept and the procedures are summa-
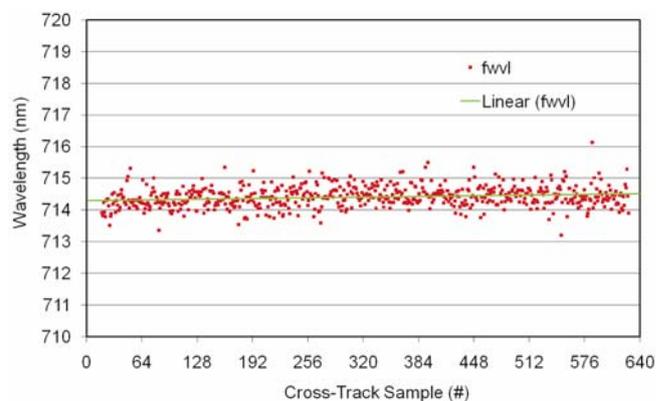

Figure 4. The M^3 cross-track spectral uniformity measured from a Nd spectral target during laboratory calibration tests. Each spectral channel is 10 nm, and there is less than 0.5 nm spectral variation across the 600 cross-track elements.
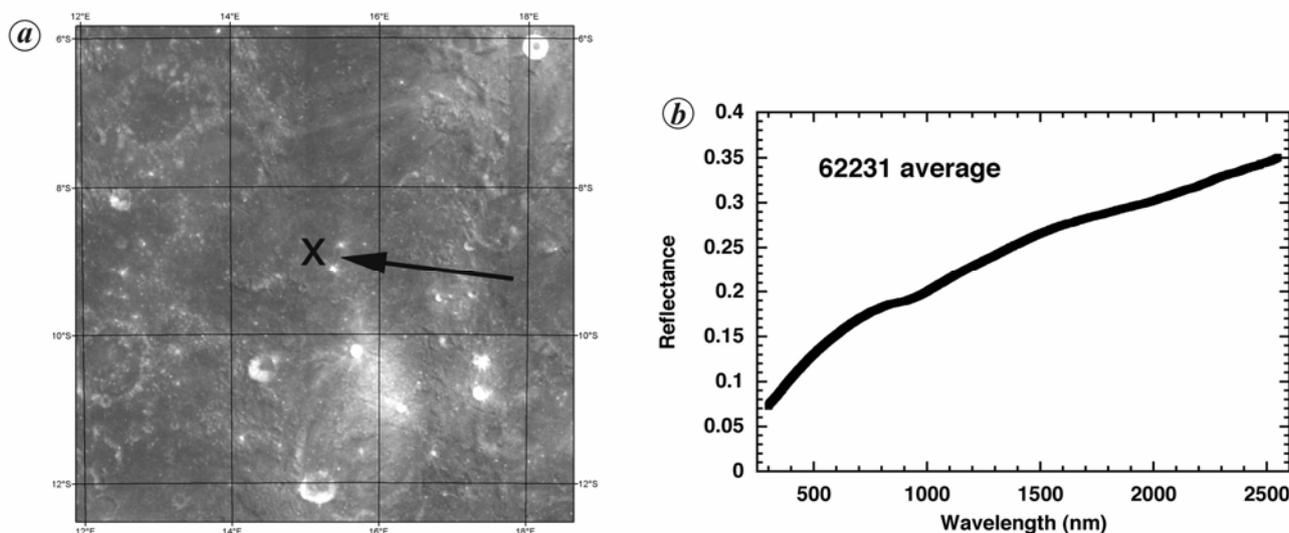
Figure 5. *a*, Clementine 750 nm image of the Apollo 16 LISCT calibration site ($\sim$ 200 km in diameter). The actual landing site is indicated with an arrow, and the region of well-developed soil used as a calibration site is indicated with the 'X'. *b*, Bi-directional reflectance spectrum of Apollo 16 soil 62231 measured at $i = 30°$, $e = 0°$ and used as a reference (ground truth). This soil is representative of well-developed soils found at the site and undisturbed soils observed remotely.

rized in Pieters[7]. The Apollo 16 region, shown in Figure 5 *a*, is one of the prime Lunar International Science Calibration/Coordination Targets (LISCT) proposed for cross calibration of lunar data obtained by various missions[8].

The spectrum of well-developed soil from the Apollo 16 site measured in the laboratory at $i = 30°$, $e = 0°$ is shown in Figure 5 *b*. This spectrum can be obtained in digital form at http://www.planetary.brown.edu/relabdocs/Apollo16_62231.html. What makes lunar soil a particularly valuable calibration standard is that it is smoothly varying with wavelength, and absorption features present are weak and well defined. This property is particularly useful for calibrating residual multiplicative errors in either the solar spectrum or minor instrumental errors un-identified during ground calibration.

It is also important to account for viewing geometry. Not only are there prominent brightness variations due to illumination, but there are also smoothly varying colour effects with viewing geometry, where lunar soils become 'redder' (more steeply sloped toward the near-infrared) with increasing phase angle. Both must be accommodated with an accurate photometric model to compare one area on the Moon to another. We have developed[9] an initial wavelength-dependent photometric model that will be tested and modified as data are accumulated during Chandrayaan-1 and other lunar missions.

M³ data products

The principal Target Mode data product from M³ will be a fully calibrated image-cube with 600 cross-track elements and 260 spectral channels and as many lines as

were acquired in the specific data set. Typical aspect ratios are 1 : 10. Global Mode image-cubes will have 300 cross-track samples and 86 spectral channels, and will span ~135 degrees of latitude. These calibrated data are designated level 1b and include full spectral, radiometric and spatial calibration. In addition, these data will be delivered with full seleno-rectification including latitude, longitude and elevation for every spectrum (spatial pixel) in the data set.

As discussed above, M³ level 2 data will be derived from L1b but contain additional calibration steps (solar correction, ground truth correction, photometry correction). Each of these corrections is expected to be improved with flight data experience as the mission progresses.

All L1b and L2 data are prepared to PDS standards and can be read with common software packages available for imaging spectrometer data. M³ data are available to the Chandrayaan-1 team as it is produced. As specified by Chandrayaan-1 data policy, M³ L1b data will be released into the public domain one year after generating data in a useful form (calibrated). M³ L2 data follow a similar path, but may take a little longer due to required refinements in calibration. Thermal corrections, corrections for local topography, and data mosaics are higher order data products.

The data obtained by M³ will permit the detailed mineralogical characterization of the lunar surface in a geological context. These data, in conjunction with data from other Chandrayaan-1 instruments, provide critically important information regarding the mineralogic and petrologic evolution of the Moon, a cornerstone in understanding the evolution of the terrestrial planets, Mercury, Venus, the Earth and Mars. The Moon's geological record preserves

the formative years of planetary history, a period largely lost on the Earth. Knowledge of the distribution and configuration of the mineralogy of the lunar crust will enable sophisticated and far-reaching scientific exploration of the Moon in the future. These data will also be crucial to identify and characterize landing and exploration sites and to locate resources necessary to help support future explorers of the Moon and Mars.

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