FULL-MISSION SELENOLOCATION PROGRESS FOR THE MOON MINERALOGY MAPPER ON CHANDRAYAAN-1. Joseph W. Boardman[1*], C. M. Pieters[2] and R. Green[3], S. R. Lundeen[3], P. Varanasi[3], J. Nettles[2], N. Petro[4], P. Isaacson[2], S. Besse[5], and L.A. Taylor[6] [1]Analytical Imaging and Geophysics, LLC, 4450 Arapahoe Ave. Suite 100, Boulder, CO 80303, [2]Dept. Geological Sciences, Brown Univ, [3]Jet Propulsion Laboratory, [4]NASA Goddard Spaceflight Center, [5]University of Maryland, [6]Planet. Geosci. Inst., Univ. of Tennessee, *(boardman@aigllc.com).

Introduction: The Moon Mineralogy Mapper (M^3) was a NASA imaging spectrometer flown onboard India's inaugural mission to the Moon: Chandrayaan-1 [1]. Here we present an overview of the mission, our current results and methods regarding the selenolocation and observation geometry characterization and suggestions for future improvements and processing of the M^3 data.

M^3 Mission Overview: M^3 was planned to operate for a two-year mission at the Moon in a 100-kilometer orbit, collecting the whole Moon in Global Mode and up to 30% of the Moon in higher spatial and spectral resolution Target Mode. The Global Mode data were planned for 85-band spectra and 140-meter pixels. Target Mode data were to have 259 spectral channels and twice the spatial resolution, with 70-meter pixels. M^3 was to operate during four Optical Periods when the solar β angle was less than 30 degrees.

The Chandrayaan-1 mission was cut short at ten months in August 2009, when contact was lost with the spacecraft. Despite the abbreviated mission, M^3 was able to meet its mission requirements: collecting more than 95% of the Moon in Global Mode along with a small number of Target Mode images. Figure 1 shows a summary image of the full-mission Global Coverage.

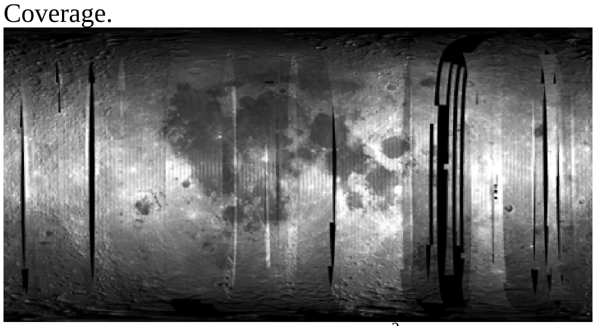

Figure 1. Composite full-mission M^3 Global Mosaic.

However, certain operational issues with the spacecraft made our initial efforts at selenolocation less than satisfactory, with errors up to tens of kilometers. These issues include absolute attitude knowledge, the on-board clock and the original ephemeris data. We have spent the last sixteen months developing modified methods to bootstrap acceptable selenolocation results.

Chandrayaan-1 Mission Challenges: While the Chandrayaan-1 mission was undoubtedly a remarkable success, it experienced a number of operational and spacecraft issues that directly impacted our selenolocation plans and processing. Upon arrival at the Moon, the spacecraft began experiencing unexpected thermal issues and overheating. Before the first M^3 data could be collected one of the two star trackers was lost together with one of the Bus Management Unit CPUs.

ISRO mission operations personnel began developing, in real time, a modified mission time-line and plan for operations. For M^3, this resulted in an extended commissioning phase, as well as a modified duty cycle during much of the mission, as compared to the plan.

In late April 2009, the second and last star tracker was lost and with it any detailed and accurate attitude knowledge. ISRO, working with the coarse Sun sensor and high-gain antenna, did a remarkable job estimating attitude and controlling the spacecraft for the remainder of the mission. Shortly after the loss of the last star sensor, ISRO decided to raise the orbit to 200 kilometers from the nominal 100-kilometer orbit, so as to minimize the orbit-keeping requirements.

Auxiliary Data Employed: We have been able to leverage two auxiliary data sets that made it possible for us to overcome our attitude knowledge problems and bootstrap the spacecraft attitude history directly from the image data themselves. Using the best available LOLA topography [2] and a new Chandrayaan-1 ephemeris created by the JPL Navigation Team [3], along with an improved clock kernel, we had adequate data for all the required ray-tracing inputs other than the camera calibration and the attitude history of Chandraaayn-1. We were forced into developing a self-calibration strategy that derives the attitude history of the spacecraft and the in-flight M^3 camera model from the data themselves, by forcing overlapping areas to be seamless and the overall mosaic to tie to the LOLA-defined selenodetic frame.

Current Methodology and Results: We have developed three successively more complex models for attitude retrieval and selenolocation optimization of the M^3 data. As the mission progressed, the attitude data became more unstable and the management of the spacecraft state became more difficult. In each of the three models we employ a joint non-linear inversion to minimize error on image-to-image tie points and image-to-LOLA pseudo-control points. This suite of control points is created automatically via image matching of M^3 images for the tie points and M^3 images and fly-over-time-illuminated LOLA topographic models for the control points.

The three attitude models range from: 1) a simple fixed roll, pitch and yaw bias per orbit; to 2) attitude biases augmented with attitude rates; to 3) an initial attitude state coupled with an arbitrary J2000 rotation axis and rotation rate. The third and most complex model was required for the Optical Period 2 data from the 200-kilometer orbit with no star tracker data.

Despite the challenges imposed by the data, we have been able to achieve image-to-image rms error on the pixel level (<200m rms) and matches to the illuminated LOLA images with rms errors of only slightly greater amplitude (<450m). We suspect, though cannot prove, that the absolute LOLA fit is better than this and the larger control point rms reflects the sparse LOLA coverage and imprecise control point creation inherent in this process. In any case, the end-user should assess the selenolocation accuracy by comparing the M^3 imagery with Band 10 of the *_OBS.IMG file (a cosine incidence angle rendering of the LOLA topography, as sampled by the M^3 pixel centers). Figure 2 shows a mosaic of 31 strips of M^3 imagery.

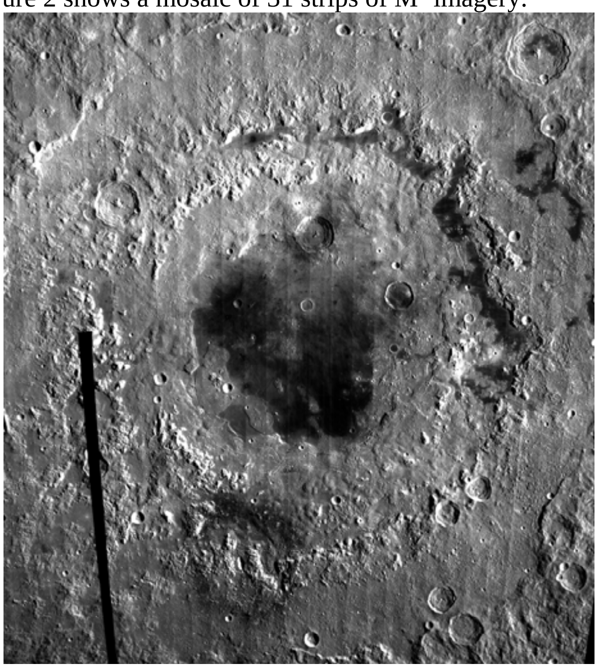

Figure 2. M3 mosaic at Orientale.

PDS Level 1B Deliveries: In June, 2010 and December, 2010, we delivered the Optical Period 1 and Optical Period 2 M^3 Level 1B data to the Planetary Data System Imaging Node. These Level 1B deliveries are comprised of our calibrated spectral radiance image cubes along with supporting images, or backplanes, that supply selenolocation and observational geometry parameters on a pixel-by-pixel basis.

The first backplane image (*_LOC.IMG) is a three-band image that supplies the pixel center longitude, latitude and radius values in the selenodetic MOON_ME frame common to LRO data sets [4]. The second backplane image (*_OBS_.IMG) provides ten observational geometry parameters that fully characterize the incoming ray, the reflected ray and the local slope and aspect, as determined by the M^3 ray tracing to the LOLA data current at the time of our processing.

Proposed Future Processing and Improvements: While we have delivered a full-mission data set that meets our mission requirements, there are still improvements that could be made with future processing and auxiliary products. The current M^3 Level 1B archive has three different attitude bootstrapping models and was built piecemeal through time as we worked to narrowly meet our June 2010 and December 2010 PDS delivery deadlines.

As we developed the M^3 Level 1B products for selenolocation and observational geometry characterization we used the most current LOLA coverage available as the underlying topography. These data sets were incomplete as LOLA is still mid-mission and collecting altimetry. Furthermore other complementary lunar topography products such as the LROC WAC stereo models [5], the Kaguya altimetry [6] and Kaguya Terrain Camera stereo models [7] should be included in the lunar topographic model.

We suggest the entire M^3 data set should be reprocessed once these new sources of lunar topography are finalized and combined. Not only would this improve the underlying topography for ray tracing, it would provide a chance to unify the attitude, timing, camera and ephemeris models used in the current M^3/Chandrayaan-1 processing. Beyond any improvements in selenolocation, such a reprocessing would have direct benefit for reflectance retrieval, thermal modeling, photometric studies and all other quantitative uses of the M^3 archive in the future.

References: [1] Pieters C.M. et al. (2009) The Moon Mineralogy Mapper (M^3) on Chandrayaan-1, Curr. Sci, Vol. 96, No. 4, 500-505. [2] Smith D. E., et al. (2010), Initial observations from the Lunar Orbiter Laser Altimeter (LOLA), *Geophysical Research Letters*, Vol. 37, 6 pp. [3] Mottinger M., (2010), JPL personal communication. [4] LRO Project and LGCWG, (2008), A Standardized Lunar Coordinate System for the Lunar Reconnaissance Orbiter and Lunar Datasets, Version 5, GSFC. [5] Scholten F. et al. (2010) Towards Global Lunary Topography Using LROC WAC Stereo Data, LPSC 41, Abstract 2111. [6]Araki H. et al. (2009) Lunar Global Shape and Polar Topoigraphy Derived from Kaguya-LALT Laser Altimetry, Science, Vol. 323, Issue 5916, pp. 897. [7] Haruyama J. et al. (2009) Selene (Kaguya) Terrain Camera Observation Results of Nominal Mission Period, LPSC 40, Abstract 1553.