2019 STATUS OF GEOMETRIC RESTORATION OF MOON MINERALOGY MAPPER DATA.

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Introduction. More than 95% of the Moon was imaged by the NASA Moon Mineralogy Mapper (M^3) instrument on the ISRO Chandrayaan-1 spacecraft [1-4]. Using Global and Targeted imaging modes (at 140-280 and 70-140 m/pixel spatial resolution, respectively) in 85 channels between 460 and 3000 nm, the M^3 data are uniquely valuable for characterizing surficial water [2, 5] and soil and rock mineralogy [6-9]. Our goal is to improve the geometric registration of the M^3 data to the 3D lunar surface by processing the data with the relatively high spatial resolution (~118 m/pixel) and improved horizontal geodetic accuracy of the LOLA Digital Elevation Model (LDEM [10]).

Figure 1. *Misregistration (~5 km or 36 pixels) of M^3 data to the early LOLA DTM basemap. (a) M3 scene M3G20090731T005012 band 20 (970 nm) centered near Jansen crater (14.7N, 28.9E), Mare Tranquillitatis. (b) Shaded relief image of GLD100 WAC DTM. (c) DTM in red, M^3 in blue.*

We initiated this work because of major misregistrations (up to 5 km or 36 pixels) between version 1 of the M^3 data in the Planetary Data System (PDS) (https://pds-imaging.jpl.nasa.gov/portal/chandrayaan-1_mission.html) and the LDEM and more recent lunar map products (***Fig. 1***). Such misregistrations compromised the accuracy of photometric and reflectance processing of the early M^3 products because these steps rely on registration of the DEM to derive accurate surface orientation parameters at each pixel.

Thus far, we have achieved these goals: (1) Reprocessed M^3 data through the mission's Level 1B (L1B) processing pipeline using the LDEM to improve selenolocation accuracy; (2) Developed USGS Integrated Software for Imagers and Spectrometers (ISIS3) software (v. 3) to ingest and process M^3 data (including a camera model); (3) Controlled the global M^3 dataset with better spatial accuracy and updated two versions of L1B products, one using just the mission L1B pipeline and the second building on that version using ISIS3 *jigsaw* and improved control-point measurements to the LDEM map base; (4) Developed and delivered improved SPICE kernels for the M^3 data; and (5) Initiated Level 2 (L2) processing by performing thermal [11] and photometric correction using the mission procedures [12]. A project status report and updated L1B LOC and OBS files, improved SPICE kernels, and pointers to the supporting ISIS3 software can be found at this project website: https://astrogeology.usgs.gov/maps/moon-mineralogy-mapper-geometric-data-restoration.

Improved Geodetic Control. The LDEM, at pixel spacing of ~118 m, is a good match for the ~140 m pixel sizes of the M^3 data. In 2014, the M^3 L1B IDL pipeline was used to completely reprocess the data through ray tracing and geometric modeling, creating a full-mission orthorectified product. The improvement of geodetic control of M^3 frames used ISIS3 software [see http://isis.astrogeology.usgs.gov/], which allowed us to model the physics and geometry of image formation from the M^3 camera. ISIS3 also supports photogrammetric bundle-adjustment to control M^3 images. The main components of ISIS3 geometric processing for M^3 are (a) a pushbroom camera model, which supports calculation of image coordinates (line, sample) of a known point in three dimensions, or (with elevation information) vice versa; (b) the bundle adjustment software *jigsaw*, which draws on the camera model to compute the relations between image and world coordinates, performing rapid solution of the large M^3 control network, and modeling the trajectory and pointing parameters of the pushbroom observations over long orbit arcs; and (c) image-matching tools for finding image-to-image and image-to-ground correspondences. The ISIS3 *autoreg* program generates such correspondences by comparing patches of pixels from two overlapping datasets (initially registered based on the a priori geometric data) and searching for the position giving the best least-squares fit.

To control the M^3 data, we orthorectified the images (using ISIS3 *cam2map*) and evaluated the consistency of overlapping images in map coordinates to ensure that a consistent solution has been achieved. For the M^3 data, checking the accuracy of registration was made by comparing the position of pixels in the 750 nm mosaic to the LDEM and a WAC "morphology" mosaic [13]. The final M^3 control network is based on 870 images, 176,769 points (including 27,511 constrained points), and 627,052 measurements. The *jigsaw* residual average is 0.67 pixels and standard deviation is 0.55 pixels.

The overall improvement in spatial registration of the M[3] data (***Fig. 2***) indicates that pixel shifts between L1B locations (LOC) and the LDEM were reduced from an average of 12 to ~1.2 pixels. The largest offsets are observed in data from Optical Period 2C (OP2C), when both star trackers were not working and instrument pointing during the Chandrayaan-1 mission was less accurate. Root-mean-squared (RMS) positional errors of the majority of M[3] frames have been reduced from ~200 m relative and 450 m absolute to a pixel (~140 m) or better, and the many images with positional errors of kilometers have been corrected.

Processing Error: Following photometric modeling and development of test mosaics as part of L2 processing, we discovered an offset between the calculated and real opposition surge (the bright region in images that represents zero-phase illumination) locations. Therefore, we have suspended L2 processing while we characterize the magnitude of this error. Starting with orbital modeling, variations in spacecraft altitude of ~190 to 209 km were observed, with frequent perturbations as the orbit progressed. ISIS3 uses a simple polynomial fit to model spacecraft orbit, and it does not allow for independent adjustment of instrument and spacecraft positions, so in many cases it could not handle orbital perturbations of this size and frequency. Users who can or wish to implement improved thermal and/or photometric models in the L2 processing [e.g., 14, 15] can use the updated L1B products and kernels.

Next Steps: The goal of this work was to produce an improved hyperspectral mosaic of all M[3] Global and Target Mode data, along with delivering updated kernels and metadata. These data are essential for characterizing the location and abundance of lunar resources such as water (OH/H_2O), so it is important that we complete the L2 processing and delivery of improved M[3] products to the PDS. We have separately reproduced the full M3 processing pipeline, including bundle adjustment, modeled and characterized M[3] orbits, and have successfully corrected M[3] frame positions and reproduced the photometry for a small number of test frames. Currently we are continuing to evaluate and document the earlier results and will seek additional funds to complete this project.

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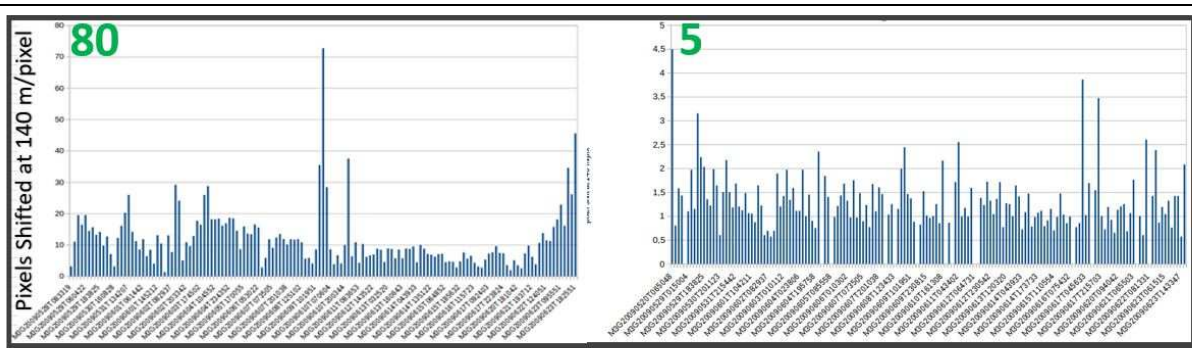

M3 Archived Data **M3 Reprocessed Data**

Figure 2. *Improvement in L1B spatial registration of the M[3] data between pixel locations and the LDEM positions.* ***Left****: Archived product, with shifts >70 (ave. 12) pixels.* ***Right****: Improved (reprocessed) M3 L1B v.2 product, with shifts <4 (ave. 1.2) pixels.*