IMPROVED GEOMETRIC CONTROL OF MOON MINERALOGY MAPPER DATA.
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Introduction. More than 95% of the Moon was imaged hyperspectrally with the NASA Moon Mineralogy Mapper (M^3) instrument on the ISRO Chandrayaan-1 spacecraft [1-4]. Using Global and Targeted imaging modes (at 140 and 70 m/pixel spatial resolution, respectively) with spectral resolution of 20-40 nm 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]. The goal of this work is to use the relatively high spatial resolution (~100 m/pixel) and improved horizontal geodetic accuracy of the Lunar Reconnaissance Orbiter Wide Angle Camera (WAC) stereo-derived topographic model [i.e., the GLD100 digital terrain model or DTM, 10] to improve the positional accuracy of M^3 frames tied to the 3D lunar surface.

This project has seven major goals: (1) Reprocess M^3 data through the mission's Level 1B (L1B) processing pipeline using the improved DTM to improve selenolocation accuracy; (2) Develop USGS Integrated Software for Imagers and Spectrometers (ISIS) software [11] to process M^3 data (including a physically rigorous camera model); (3) Control the global M^3 dataset with better geodetic accuracy and update L1B products; (4) Reprocess improved L1B data through the mission's Level 2 (L2) pipeline to improve thermal and photometric accuracy; (5) Improve the photometric modeling; (6) Create orthorectified frame and mosaicked (Level 3) data products; and (7) Deliver interim and final products, including NAIF SPICE kernels [12] and calibrated, map-projected M^3 products to the Planetary Data System (PDS). Goals 1 and 2 were completed in 2014 and goal 3 is complete as of December 2015. Goals 4 and 5 are underway and will be completed later in 2016. Goals 6 and 7 will be completed in early 2017.

Improved Geodetic Control. The GLD100, at slightly higher resolution post spacing of ~100 m is a good match for the ~140 m pixel sizes of the M^3 data. Geodetically controlling to the GLD100 is a major step forward in improving M^3 data spatial accuracy. 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 makes use of ISIS software [11, http://isis.astrogeology.usgs.gov/], which has allowed us to rigorously model the physics and geometry of image formation from the M^3 camera. ISIS also supports photogrammetric bundle-adjustment to control M^3 images for precision and accuracy that is not only as high as possible but well-understood and documented. The main components of ISIS 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 (***Figure 1)***, 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 ISIS 3 *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.

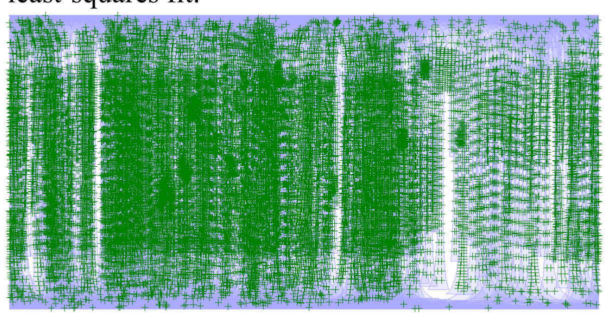

Figure 1. *The control network of the M^3 data comprised of 27,511 constrained points. Equirectangular projection; image extends +90° to -90° latitude and -180° to +180° longitude, with 0° longitude at center.*

To develop a valid control solution for the M^3 data, we then orthorectified the images (using ISIS *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 GLD100 and matching WAC mosaic. In some cases, the test mosaics help to identify poor measurements which are then eliminated or re-measured and the bundle adjustment and rectification steps are repeated as needed. 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.

Figure 2 shows examples of the improvement in control of the M^3 data, where pixel offsets for the examples shown range from 14 to 26 pixels (2.0 to 3.6 km). The largest offsets are observed in data from Optical Period OP2C, when both star trackers were not working during the Chandrayaan-1 mission and instrument pointing was less accurate. Root-mean-squared (RMS) positional errors of the 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.

With the final control solution in hand, the M^3 frames were flipped as necessary to correspond to their respective Level 1B image cubes and the ISIS program *fx* was used to calculate the ground coordinates and geometric parameters needed for updating the mission's location (LOC) and obsesrvation (OBS) ancillary files.

Next Steps: The Level 2 pipeline will be modified and used to compute normalized reflectances from the Level 1B radiances and the improved LOC and OBS files [12]. This process includes (1) scaling for solar radiance and solar distance; (2) statistical polishing; (3) correction for thermal emission; (4) photometric correction; (5) optional ground truth correction; and (6) flagging degraded channels. The initial Lommel-Seeliger photometric correction may be updated by application of the Hapke and/or Akimov photometric models [13]. Once a photometric model is selected, it will be applied to L2 data from which an updated thermal correction has been removed [14].

The goal of this work is to produce an improved hyperspectral mosaic of all M^3 Global and Target Mode data, along with updated kernels and metadata. In 2017, we will deliver individual orthorectified frames, updated SPICE kernels, updated thermal and photometric correction parameters, calibrated mosaics of the data from each observation period, and a calibrated, near-global mosaic of all Global and Target Mode data.

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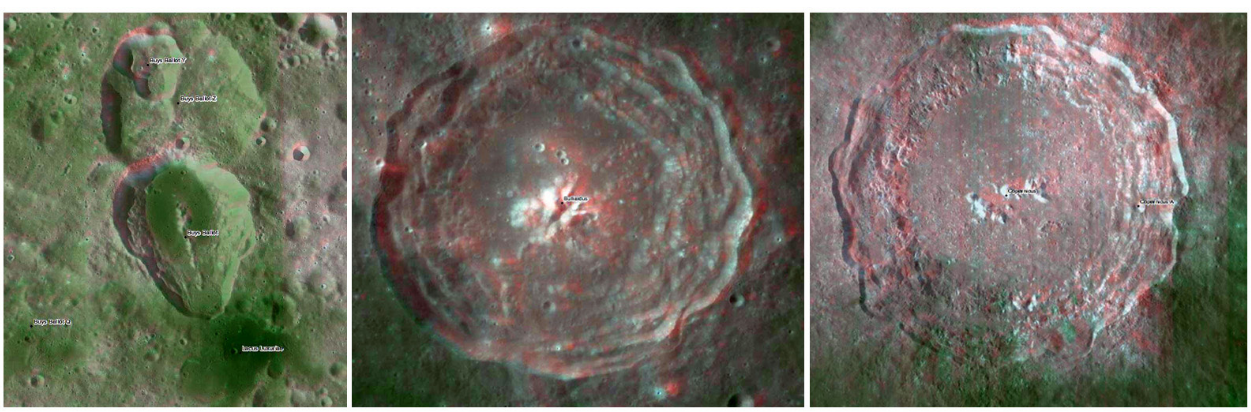

Figure 2. *ISIS test mosaics using M^3 images from OP2C, with the controlled data shown in red and the uncontrolled in blue-green. (Left) Buys-Ballot crater (55 km diam., 20.1°N 174.5°W), (Middle) Bullialdus crater (61 km diam., 20.7°S 22.2°W), (Right) Copernicus crater (93 km diam., 9.6°N, 20.1°W). Pixel offsets in these examples range from 14 to 26 pixels (2 to 3.6 km).*