PRELIMINARY STEREO RECONSTRUCTION FROM APOLLO 15 METRIC CAMERA IMAGERY. M. J. Broxton[1], Z. M. Moratto[2], A. Nefian[1], M. Bunte[3], M. S. Robinson[3] [1]Intelligent Robotics Group, Carnegie Mellon University/NASA Ames Research Center (michael.broxton@nasa.gov), [2]Automated Vehicle Systems Lab, Kansas State University, [3]School of Earth and Space Exploration, University of Arizona.

Introduction: The NASA ESMD Lunar Mapping and Modeling Project (LMMP) has been charged with producing cartographic products for use by mission planners and scientists in NASA's Constellation program. As part of the LMMP, we have produced 70 preliminary Digital Terrain Models (DTMs) and ortho-images derived from Apollo 15 Metric Camera (AMC) orbit 33 imagery using the Ames Stereo Pipeline (ASP); a software tool that generates high quality DTMs from orbital imagery using a fully automated process. This is the first milestone in a 3-year effort to process the entire AMC data set consisting of over 8,000 stereo image pairs. The AMC data set was selected for processing based on the following criteria:

- AMC imagery approaches the resolution (10 m/pixel) and the data volumes (1's-10's of Terabytes) of modern lunar data sets, thus it exercises the infrastructure necessary to process the rapidly increasing volume of lunar data.
- The wide field of view (~74°) and significant overlap between adjacent frames (80%) mean that AMC imagery is well-suited for stereo processing.
- AMC imagery contains a full range of lighting angles in each orbit, thus exercising algorithms for image matching, stereo correlation, and stereo blunder detection under various lighting conditions.
- There is substantial scientific value in producing DTMs and ortho-images from AMC data.

A joint effort between Arizona State University (ASU) and NASA JSC is underway to scan the original film negatives from Apollo-era mapping cameras, including the AMC [1]. These archival scans are of exceptional quality, resulting in digital files that capture the full dynamic range and resolution of the original film. The scans have been geometrically controlled, making them ready for rigorous cartographic analysis.

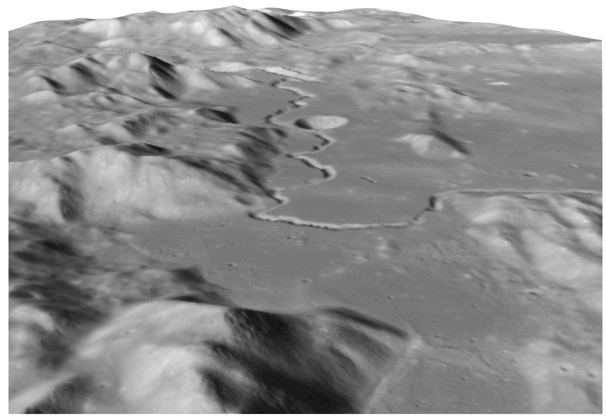

Figure 1: *This oblique view of Hadley Rille, produced using our automated stereogrammetric technique, was derived from high resolution scans of Apollo Metric Camera frames AS15-M-1135 and AS15-M-1136.*

Below we discuss some characteristics of this data set as well as some essential improvements to the ASP software that were necessary to process the scanned Apollo data. More general information on our stereogrammetry techniques can be found in [2] and [3].

Approach: Stereo reconstructions were carried out using 71 images from from orbit 33 of the Apollo 15 Command/Service Module's Metric Camera. Images were subsampled by a factor of 4 to reduce the deleterious effect of noise from the film grain. This resulted in an effective input resolution of 40-m/pixel.

Geo-registration. Preliminary Apollo spacecraft ephemerides extracted from historical documents were provided by ASU; however due to the low accuracy of

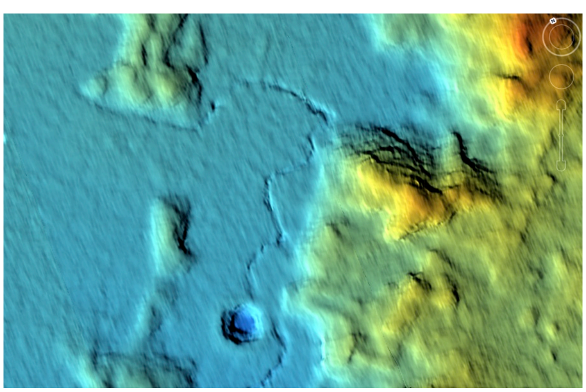

Figure 2a: *Colorized, hill-shaded DTM of Hadley Rille. Notice the visible "terracing" artifacts on sloped surfaces. These are characteristic of sub-pixel matching by means of fitting a quadratic surface in the correlation cost space.*

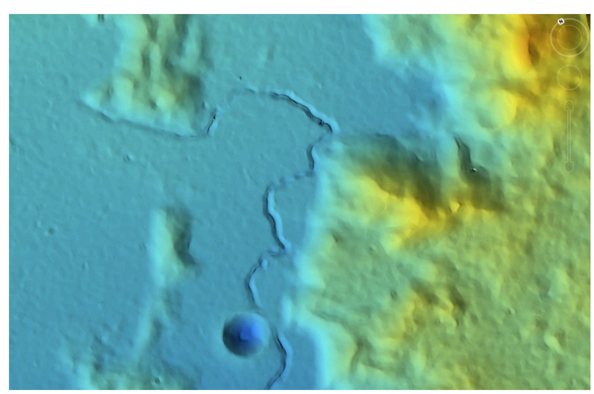

Figure 2b: *Improved DTM produced using affine adaptive window sub-pixel correlation. In this method, the correlation window itself can be scaled an rotated to produce a more accurate match on slopes where foreshortening is severe.*

the Apollo-era satellite tracking network, these data contained significant errors in satellite position and pose. Historical estimates of error are recorded as sigma uncertainties of 2.04-km for position and 0.002 degrees for pose in a typical Apollo 15 image [4]. Such errors propagate through the stereo triangulation process, resulting in systematic position errors and distortions in the resulting DTM (see Figure 3, top).

Tie-points were automatically extracted from input imagery using the SURF automated feature detection algorithm [4], and used in least-square bundle adjustment [5] to correct pointing and pose errors. This greatly improved consistency between adjacent DTMs (Figure 3, bottom).

Stereo Matching. Consecutive images were grouped into stereo pairs and processed using the Ames Stereo Pipeline on an 8-core workstation. Stereo processing took less than an hour for each pair, and required no human intervention. The final DTMs were colorized, hill-shaded, and mosaicked together for visualization in Google Earth.

Improved Sub-pixel Correlation. In our early tests, we noticed an unexpected "terracing" artifact in AMC-derived DTMs (Figure 2a). This was particularly pronounced on mountain slopes and crater walls. Subsequent research into the issue suggested that this was characteristic of our sub-pixel correlation algorithm, which derives sub-pixel disparity estimates by fitting a quadratic surface to the 8-connected neighborhood around the minimum (i.e. best match) location in the correlation cost surface.

On slopes that appear drastically different in adjacent images due to foreshortening, this technique breaks down – leading to our problem, which is referred to in some stereo literature as *pixel locking.* It can be corrected by adopting an affine adaptive window sub-pixel correlation technique [6][7]. Figure 2b shows our improved results using this method.

Conclusion & Future Work: We have demonstrated that automated stereo reconstruction is a viable technique for processing AMC stereo data. However, processing all 8,000 stereo images pairs will require significant computational resources, so we are currently testing our processing pipeline on NASA's Columbia Supercomputer. An effort is also underway to improve our algorithm's immunity to image noise, especially to film grain, dust, and lint that appear in AMC scans. We hope that this will allow us to process full-resolution images without subsampling the input imagery. Finally, although geometric consistency has been achieved within the AMC data set using bundle adjustment, the images still need to be geodetically controlled to a lunar network such as the Unified Lunar Control Network (ULCN) 2005.

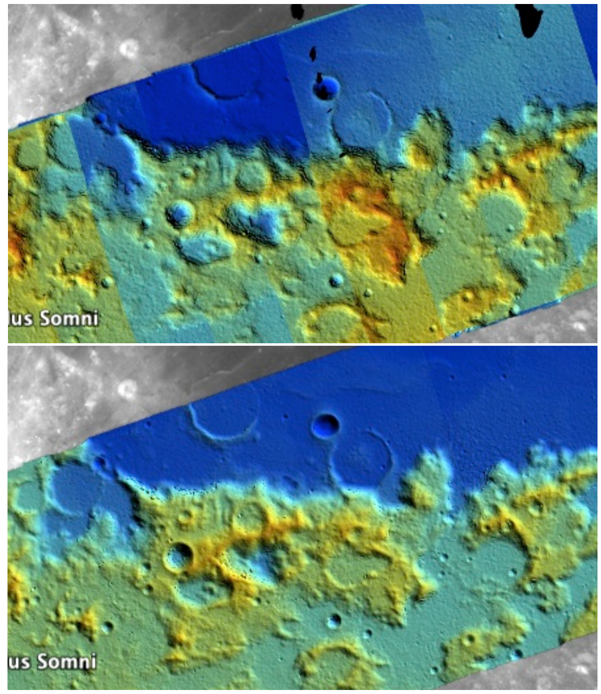

Figure 3: *Mosaic of colorized, hillshaded DTMs from orbit 33.* Top*: Using uncorrected hisorical Apollo spacecraft ephemerides results in mis-alignment between overlapping DTMs.* Bottom*: Results improve after camera parameters are corrected using least-squares bundle adjustment.*

References: [1] S.J. Lawrence et. al. (2008) NLSC Abstract #2066. [2] M. Broxton and L. Edwards (2008) LPSC XXIX Abstract #2419. [2] L. Edwards and M. Broxton. (2006) "Automated 3D Surface Reconstruction from Orbital Imagery", In Proceedings of AIAA Space 2006. [3] W.S. Cameron and M.A. Niksch (1972) "Apollo 15 Data User's Guide", NSSDC 72-07. [4] H. Bay et. al. (2008) "SURF: Speeded up Robust Features", Computer Vision and Image Understanding, Vol. 110, No. 3, pp. 346-359. [5] B. Triggs et. al. (1999) "Bundle Adjustment - A Modern Synthesis", Proc. of the International Workshop on Vision Algorithms. [6] B.D. Lucas and T. Kanade. (1981) "An Iterative Image Registration Technique with an Application to Stereo Vision". Proc. of the DARPA Image Understanding Workshop. [7] A. Stein et. al. (2006) "Attenuating Stereo Pixel Locking via Affine Window Adaptation", Proc. of IEEE International Conference on Robotics and Manipulation.

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