CONTROLLING OBLIQUE APOLLO 15 METRIC CAMERA IMAGES: FINAL RESULTS. K.L. Edmundson[1], O. Alexandrov[2], B.A. Archinal[1], K.J. Becker[1], T.L. Becker[1], Z.M. Moratto[3], A.V. Nefian[2], J.O. Richie[1], and M.S. Robinson[4], [1]Astrogeology Science Center, United States Geological Survey, Flagstaff, AZ, USA, 86001 (kedmundson@usgs.gov), [2]NASA Ames Research Center, Mail Stop 245-3, Moffett Field, CA, USA, 94035, [3]Google, Inc., Mountain View, CA, USA, 94043, [4]Arizona State University, Tempe, AZ, USA, 85287

Introduction: The integrated photogrammetric mapping system flown on Apollo lunar missions AS15, AS16, and AS17 (AS refers to *Apollo-Saturn*, the Kennedy Space Center designation for manned Apollo flights) included a Metric (mapping) Camera (MC), a high-resolution Panoramic Camera (PC), and a star camera and laser altimeter to provide support data [1]. From the three missions, ~6,000 MC images are suitable for mapping. Of these, ~3/4 are nadir-pointed, covering ~16% of the lunar surface. The remainder are oblique, increasing surface coverage to ~25%.

The NASA Johnson Space Center and Arizona State University (ASU) have scanned the original MC and PC negatives at film-grain resolution and created a digital record of support data (ASU Apollo Image Archive; http://apollo.sese.asu.edu) [2,3]. The USGS Astrogeology Science Center (ASC), the Intelligent Robotics Group of the NASA Ames Research Center (ARC), and ASU are working together to develop Apollo mapping system data into versatile digital map products with a variety of scientific/engineering uses including mission planning, geologic mapping, geophysical process modeling, slope dependent correction of spectral data, and change detection.

The ARC previously completed our joint project to produce a controlled, orthorectified digital image mosaic (DIM) and terrain model (DTM) from AS15-17 nadir images [4]. These are tied to a reference frame based on Lunar Orbiter Laser Altimeter (LOLA) data [5]. This work was done with the Ames Stereo Pipeline software [6] and the Integrated Software for Imagers and Spectrometers (ISIS) planetary cartography package [7].

There are ~2,350 useful MC images from AS15 alone, ~475 of which are oblique. These were acquired in four orbits with the spacecraft oriented such that the camera was tilted either 25° forward or aft; or 40° north or south (orbits 23, 34, 35, and 71 respectively). Figure 1 exemplifies the extreme obliqueness of a 40°S image. In [8] we described our initial efforts to control the oblique AS15 MC images. Now we summarize our work and final results.

Work Highlights:

The Apollo Metric Camera Model. The initial geometric camera model was evidently sufficient in the ARC's control of the nadir images mentioned above. However, first attempts to control the AS15 oblique images exposed significant errors which were subsequently corrected. *A priori* NAIF format SPICE pointing (c) and position (sp) kernels [9] were created from original support data on microfilm from the National Space Science Data Center [10]. For ~150 otherwise useful AS15 MC images, no support data was available and *a priori* pointing and position were determined via either interpolation or photogrammetric resection [11].

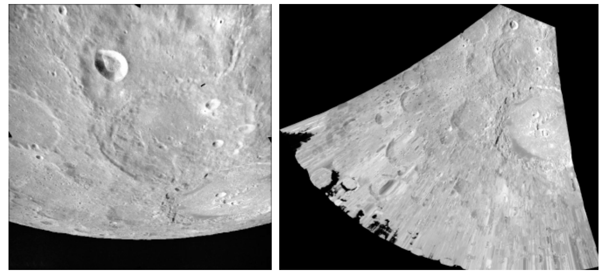

Figure 1: Image AS15-M-2515 from 40°S oblique orbit 71. Left: raw image. Right: projected image shows artifacts that may occur when projecting oblique data toward the limb.

Image Preprocessing. Scanned images were examined for usefulness and quality. Spacecraft hardware and blemishes in some images that could interfere with the control process were removed by masking when possible. The blemishes result in part from foreign debris on the film negatives during scanning.

Photogrammetric Control. This process serves to minimize misregistration between images and to place them in an absolute lunar reference frame so far as possible. At the simplest level it consists of image measurement followed by the least-squares bundle adjustment [12]. Overlapping images are connected by measuring common features (*tie points*). Images may be linked to the ground by measuring common features with known coordinates (*control points*). The Lunar Reconnaissance Orbiter Camera Wide Angle Camera mosaic [13] was used for absolute horizontal control. Radius values were obtained from a DTM combining data from LOLA and the SELENE (Kaguya) Terrain Camera [14].

Tie-point detection and the matching of tie-points between images are typically accomplished automatically with operator intervention when necessary. It is well-known that with high-oblique geometry (e.g. orbits 35 and 71), detection and matching are more difficult (for computers *and* humans) as camera-to-ground distance increases. Considerable operator intervention was required to tie the AS15 oblique images together and to the nadir images.

Table 1: Bundle adjustment statistics for AS15 MC. Statistics for 25° oblique orbits 23 (forward) and 34 (aft) are preliminary results reported in [8].

image set	# images	# tie points	# control points	# measures	rms residuals (pixels)
nadir only	1463	55692	222	506439	1.18
23 (25° fwd)	115	907	12	3902	1.54
34 (25° aft)	105	982	33	3350	1.51
35 (40° N)	128	551	4765	16175	1.75
71 (40° S)	127	1681	2673	17873	1.15

Bundle adjustments were performed with the ISIS program *jigsaw* [15] (Table 1). Nadir images were adjusted separately. Oblique orbits 35 and 71 were then individually adjusted against the updated nadir images, effectively holding the nadir fixed. The 25° orbits have been controlled individually and to LOLA. In the future we plan to control them to nadir as well.

Digital Image Mosaics. As part of the mosaic creation process, we applied cosmetic techniques to individual images and final mosaics to minimize variations in tone, brightness, and shadows (Figure 2). We have created controlled DIMs tied to the LOLA reference frame for 1) each individual nadir and oblique orbit; 2) the nadir orbits combined; and 3) the nadir orbits combined with oblique orbits 35 and 71 (Figure 3).

Final Products: The DIMs mentioned above and an expanded database of AS15 MC tie and control points will be made publically available via a USGS ASC website. Further, from our bundle adjustments we have generated updated SPICE kernels (c and sp) for the AS15 MC orbits. After validation, these will be available to the community via the ISIS public release.

Future Work: Under a separate LASER proposal we are currently controlling the AS15 PC images. Under future proposals we hope to ultimately control all MC and PC images from AS15, AS16, and AS17.

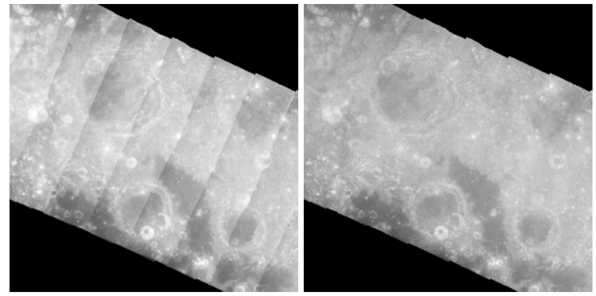

Figure 2: Example of improved mosaic appearance after image brightness adjustment. Area shown is part of nadir orbit 16 centered at ~10.8°N latitude, 71.3°E longitude. Left: Controlled raw image mosaic. Right: After adjustment, seams are notably less visible and tone more uniform.

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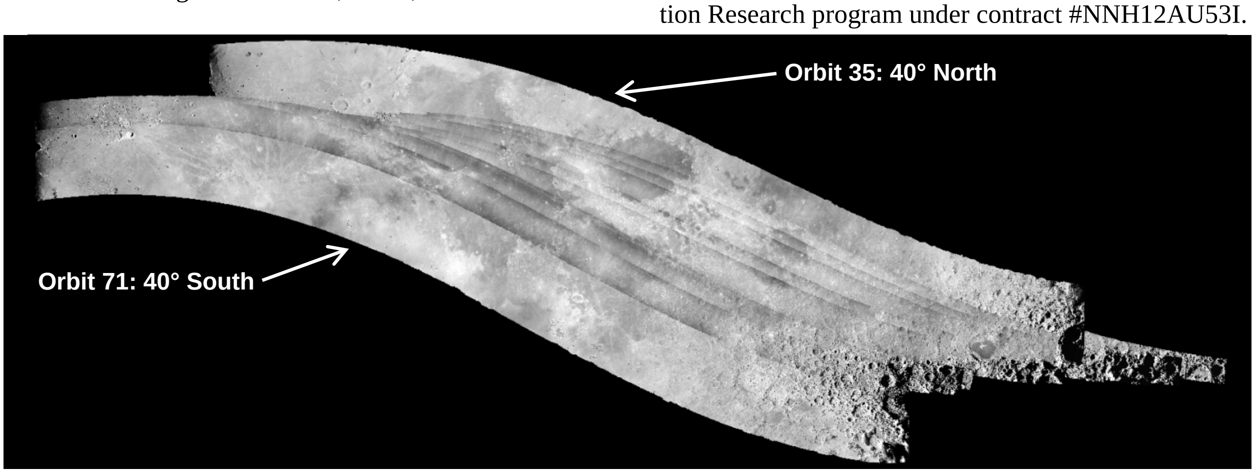

Figure 3: Controlled DIM of AS15 MC images including nadir orbits (04, 16, 22, 27, 28, 44, 60, 62, 63, 70) and oblique orbits 35 and 71. Orbits 35 and 71 are trimmed at an emission angle of 87.5°. Cosmetic methods to remove seams and match tone have been applied within each orbit. Latitude range: -46.4° to +45.4°; Longitude range: -76.7° to +160.8° east. Original image pixel scale: nadir images- ~7 m/pixel; 40° oblique images- from ~7 to 42 m/pixel. Projection is simple cylindrical.