Preliminary photogrammetric control of MESSENGER orbital images of Mercury

Kenneth L. Edmundson[1], Lynn A. Weller[1], Kris J. Becker[1], Tammy L. Becker[1], Mark R. Rosiek[1], Mark S. Robinson[2], Sean C. Solomon[3]

1-Astrogeology Science Center, U.S. Geological Survey, Flagstaff, AZ 86001, USA

2-School of Earth and Space Exploration, Arizona State University, Tempe, AZ 85281, USA

3-Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, DC 20015

INTRODUCTION

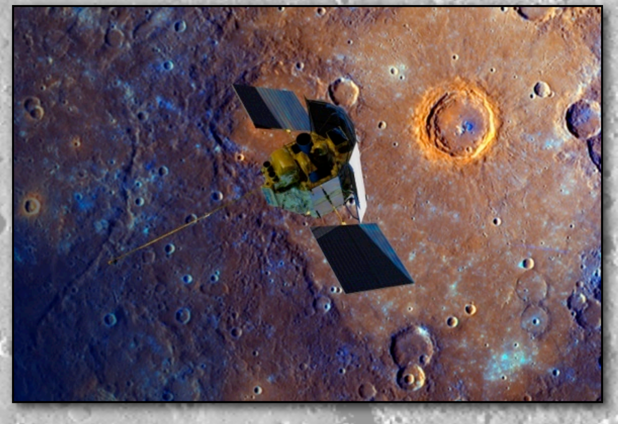

Figure 1. Artist's rendition of MESSENGER over Calvino Crater. Image courtesy NASA/Johns Hopkins University Applied Physics Laboratory/Carnegie Institution of Washington.

Key products to be generated from the Mercury Dual Imaging System (MDIS) on the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft [1] (Figure 1) include a global image base map and digital elevation model (DEM). MDIS consists of a monochrome, narrow-angle camera (NAC) and a multispectral, wide-angle camera (WAC) which are co-aligned and mounted together on a pivot [2] (Figure 2). The NAC has a 1.5° field-of-view (FOV) and a focal length of 550 mm. The WAC has a 10.5° FOV, a 78 mm focal length, and a 12-color filter wheel. MDIS acquired images through three flybys of Mercury [3] and has continued to do so since MESSENGER entered orbit around the planet in March 2011.

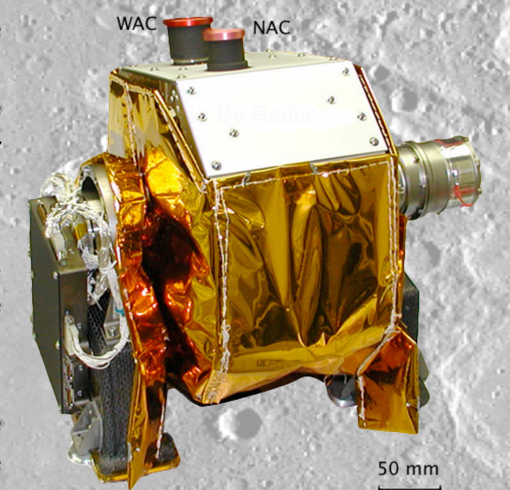

Figure 2. Mercury Dual Imaging System (MDIS) showing NAC and WAC camera positions (After [2]).

The Astrogeology Science Center (ASC) of the U.S. Geological Survey has produced global and near-global mosaics of Mercury from the MESSENGER flyby images [4,5]. In further support of the MESSENGER team, the ASC has been tasked with the creation of several mapping products from MDIS orbital images including mosaics, base maps, and DEMs. Image mosaics may be uncontrolled or controlled. Uncontrolled mosaics rely solely upon spacecraft navigation and attitude data for the registration of the underlying images. While the characterization of MESSENGER spacecraft navigation and attitude has proven to be very good to date, an element of uncertainty in these parameters is unavoidable. This may in turn lead to mis-registrations between mosaic images (Figure 3). To minimize registration errors, images are controlled photogrammetrically. In this process, images are registered to each other and the ground through the measurement of features common to overlapping images (tie points).

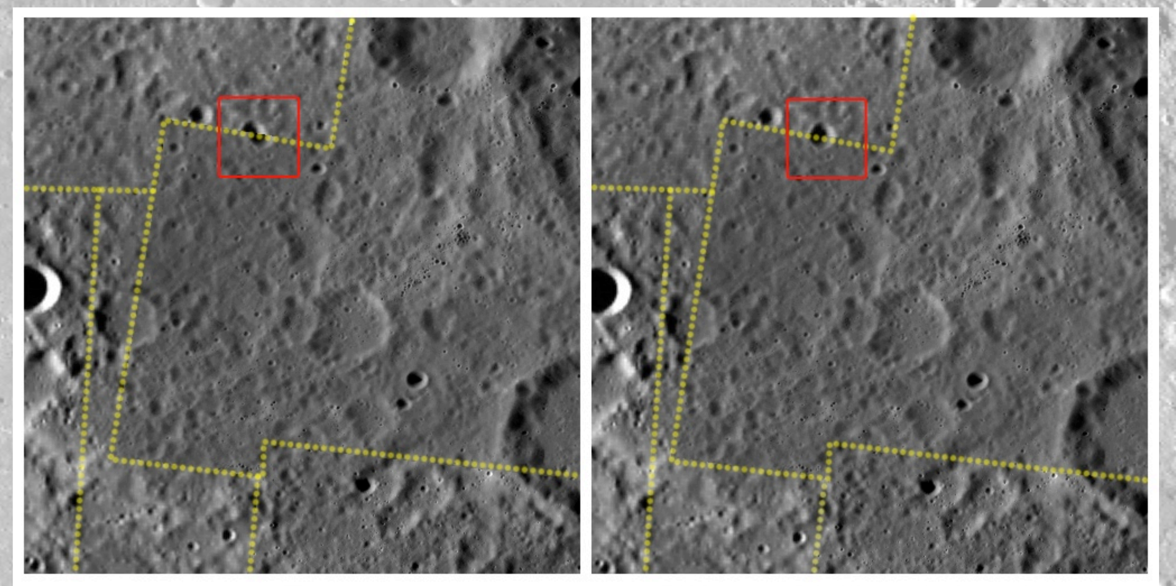

Figure 3. Portion of uncontrolled image mosaic (left) vs. photogrammetrically controlled (right). Approximate location of seams between images are indicated by the yellow dotted lines. The crater within the red box provides a clear example of improved registration after control.

Photogrammetry is a measurement technique in which the size, shape, and position of an object are determined from one or more images of that object. The primary objective is typically the three-dimensional reconstruction of the object in digital and/or graphical form. Application of photogrammetry is extensive, ranging from industrial, archaeological, and forensic measurement to the creation of traditional mapping products such as base maps, mosaics, and DEMs of the surface of the earth and extra-terrestrial bodies.

Specific products to be generated by the ASC include: (1) global, monochrome, NAC and WAC mosaics with 200 meter pixel scale (controlled and uncontrolled); (2) a global, controlled, color base map mosaic with 200 meters pixel scale from WAC G-filter images; and (3) a global DEM. In a preliminary effort toward this end, the ASC has processed a subset of images acquired with the NAC and WAC (G-filter) during a portion of the first solar day (5 April - 10 May 2011). Covering more than a third of the surface of Mercury with a mean pixel scale of 180 meters, 4542 images (2781 NAC, 1761 WAC) were photogrammetrically controlled using the Integrated Software for Imagers and Spectrometers (ISIS3) system developed by the ASC [6]. From these images (all with a pixel scale of 100 meters or greater) a controlled mosaic and DEM were created. Color images will be processed in the future as a separate effort.

In the following, we describe the control of the MDIS images and the generation of the controlled mosaic and DEM. Our results are compared to a preliminary DEM derived from data generated by the Mercury Laser Altimeter (MLA), also onboard the MESSENGER spacecraft [7]. Future work by the ASC with images from the MESSENGER mission is summarized.

PHOTOGRAMMETRIC PROCESSING OF MDIS IMAGES

The photogrammetric process is broadly defined by the steps of image acquisition, image measurement, and object reconstruction. Here we the describe the process as applied to the control of MDIS images. Emphasis is placed on the results of the least-squares bundle adjustment [8] which serves to refine image attitude and/or position parameters (collectively referred to as image Exterior Orientation - EO). The bundle adjustment also generates triangulated ground coordinates (latitude, longitude, and radius) for all tie points.

The functional model for the bundle adjustment, the *collinearity condition*, defines the relationship between image and object space coordinate systems (Figure 4). The collinearity condition stipulates that the camera perspective center, a ground point, and its associated image point measurement are collinear. Systematic deviations from ideal collinearity such as camera lens distortions are incorporated into the functional model.

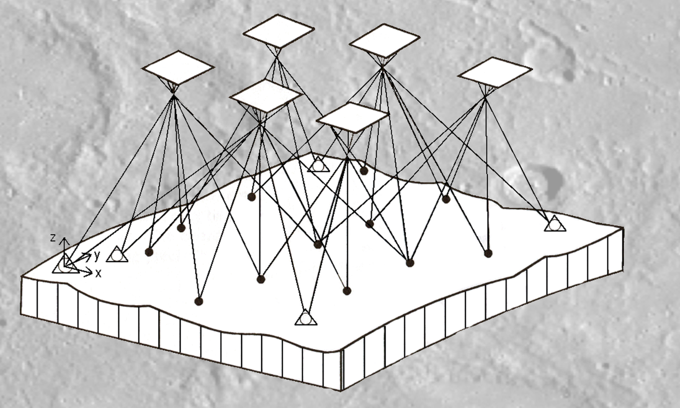

Figure 4. Illustration of the collinearity condition and bundle adjustment. All connections between object and image space points form a *bundle* of light rays, the origin of the term *bundle adjustment* (from [9]).

After ingestion into ISIS3, the images are radiometrically calibrated. Initial estimates of image EO parameters are from MESSENGER spacecraft navigation and attitude data. This data is available in ISIS3 in the form of SPICE (Spacecraft, Planet, Instrument, C-matrix (pointing), and Events) kernels consistent with the standards of NASA's Navigation and Ancillary Information Facility [10]. The measurement of tie points between overlapping images is accomplished in ISIS3 primarily through automated image matching techniques which utilize available EO parameters. Figure 5 shows the results of automated measurement in the ISIS3 *QNet* application. Operators have the ability to measure tie points manually, if necessary, and to manually correct errors occasionally produced by automated methods. For this MDIS dataset, nearly 200,000 sample/line tie point measurements were made for more than 52,000 ground points. It should be noted that this is significantly more measurements than are required for image orientation only. For this test, a high number of measurements were made to produce a set of ground points sufficiently dense for DEM generation.

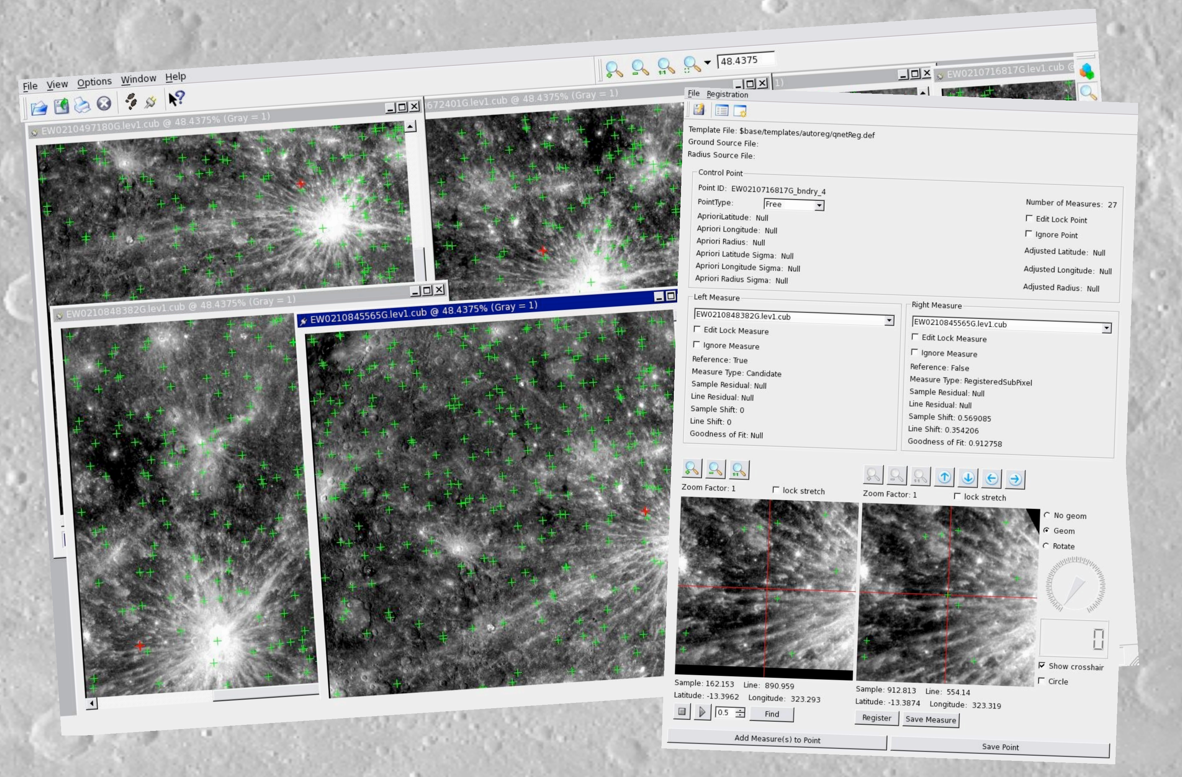

Figure 5. ISIS3 *QNet* application windows. The left window contains a number of images in which tie points between overlapping images (marked by green crosses) have been measured by automated image matching techniques. The right window shows part of the QNet interface allowing an operator to modify individual tie point measurements that may be in error or to make measurements manually.

Bundle Adjustment Results

After tie point measurement, the bundle adjustment was performed. In this adjustment, spacecraft position was rigidly constrained, attitude angles constrained to ±2°, and the radius coordinate of all ground points constrained to ±10 km in accordance with an estimated elevation range for Mercury. Parameters and constraints are summarized in Table 1. The adjustment converged in four iterations with a sample/line residual rms of 0.25 pixels in image space. The rms of adjusted uncertainties for the remaining ground points were 100, 145, and 310 m in latitude, longitude, and radius respectively. To expand upon Figure 3 and further illustrate the merits of photogrammetric control, the ground points were triangulated in an independent test by rigidly constraining both initial spacecraft position *and* attitude angles. The rms of all sample/line residuals from the bundle is better than that of triangulation by nearly a factor of four. The rms of adjusted ground point uncertainties is also significantly improved after the bundle. Results are summarized in Tables 2 and 3. The triangulated ground points range from 80°S to 86°N latitude and from 158°E to 358°E longitude (Figure 6).

Table 1. Bundle adjustment parameter numbers and constraints.

Bundle Adjustment	
images	4542
angle constraints	±2°
ground points	52464
all points constrained in radius	±10 km
sample/line measurements	198538

Table 2. Root mean squared error of sample/line residuals in pixels for bundle adjustment and triangulation only.

image space	root mean squared error of sample/line residuals (pixels)		
	sample	line	All residuals
Bundle adjustment	0.21	0.29	0.25
Triangulation only	1.03	0.78	0.92

Table 3. Root mean squared error of triangulated ground point coordinate uncertainties in meters for bundle adjustment and triangulation only.

object space	root mean squared error of triangulated ground point coordinate uncertainties (meters)		
	latitude	longitude	radius
Bundle adjustment	100	145	310
Triangulation only	128	328	945

IMAGE MOSAIC

After improving image EO parameters with the bundle adjustment, the image mosaic was produced (Figure 7). In a preliminary step, image normalization was accomplished by application of the Hapke-Henyey-Greenstein photometric model [11] to all images. Using an equirectangular projection, all images were projected to the sphere at a scale of 200 meters/pixel.

Figure 6. Triangulated ground points ranging from 80°S to 86°N latitude and from 158°E to 358°E longitude.

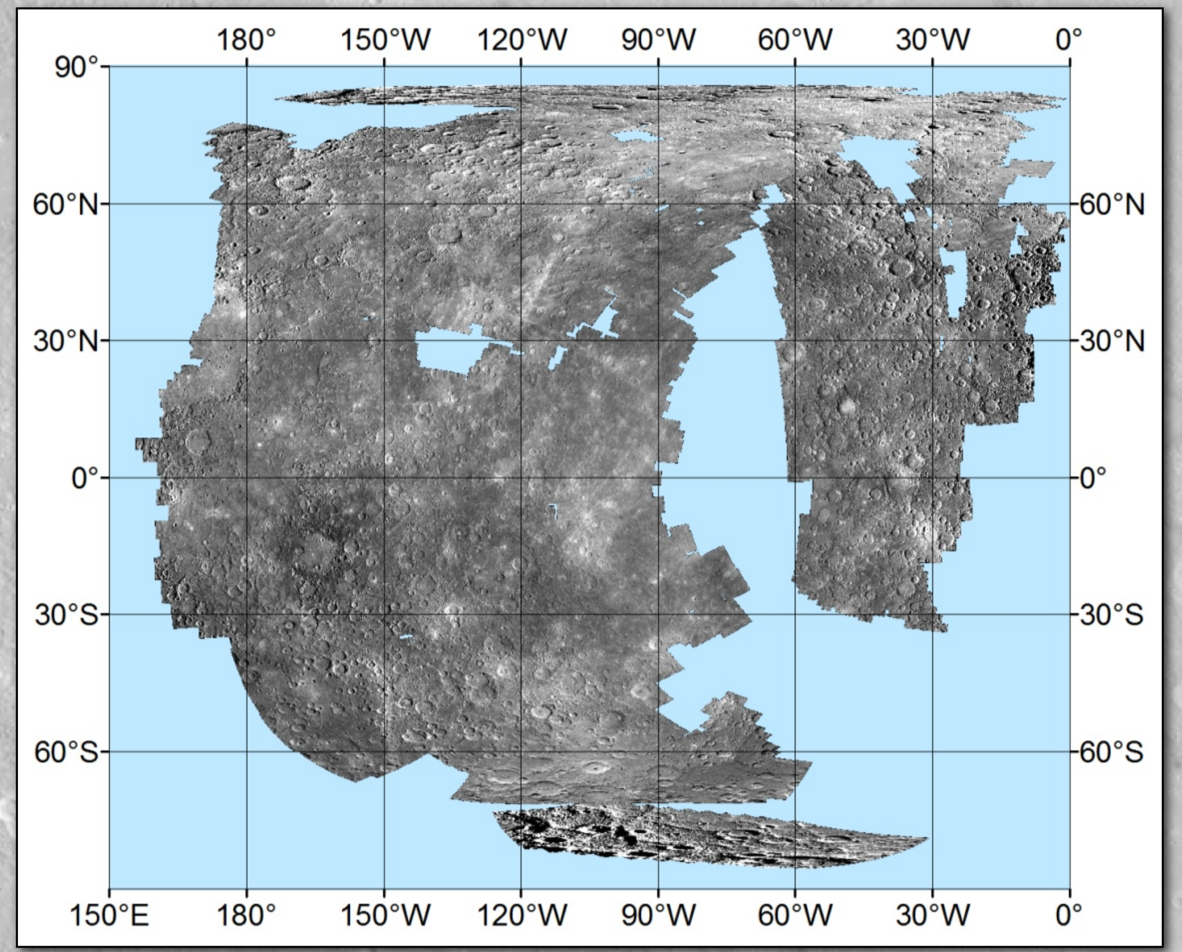

Figure 7. Photogrammetrically controlled MDIS mosaic. Projection is equirectangular with a scale of 200 meters/pixel.

DIGITAL ELEVATION MODEL

The DEM (Figure 8) was generated in the ArcMap software package (version 10) from the points triangulated in the bundle adjustment. Of these, nearly 5000 were rejected for the DEM due to high uncertainty in the radius coordinate (resulting from narrow intersection angles). A Triangular Irregular Network (TIN) was first created from the point data. From the TIN, the gridded DEM was produced using natural neighbor interpolation. Grid spacing is 2.7 x 2.7 km (16 elevation posts per degree). Hypsometry of the region is characterized by a symmetric, unimodal distribution. The dynamic range of the DEM is 9.5 km. Minimum, maximum, mean and median elevations are -4.9, 4.6, -0.24, and -0.23 km relative to the mean radius of Mercury (2440 km) adopted by the MESSENGER mission.

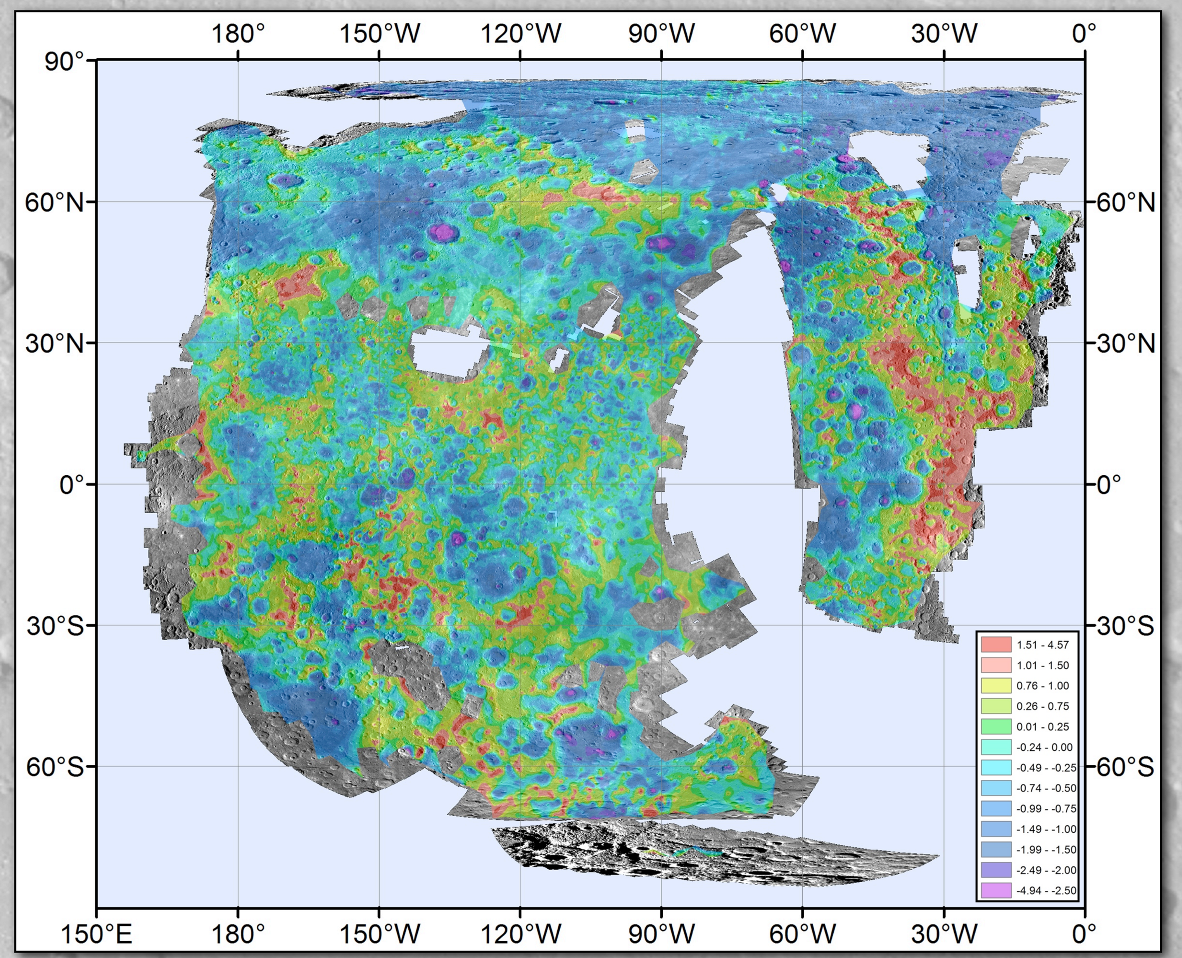

Figure 8. Gridded DEM generated from MDIS images. Grid spacing is 2.7 x 2.7 km (16 elevation posts per degree).

Comparison with the Mercury Laser Altimeter DEM

The MLA, a profiling laser altimeter onboard the MESSENGER spacecraft, is generating topographic measurements of Mercury, primarily in the northern hemisphere [12]. These data provide an early ground truth model against which to compare photogrammetric results. Comparisons have previously been made between topographic profiles from the MLA and from limb images obtained during the MESSENGER flybys [13]. Here, nearly 20,000 points triangulated in the bundle adjustment were projected to a DEM interpolated from MLA orbital test data. Visual inspection shows good horizontal alignment between the points and the DEM. The mean offset in elevation is approximately 470 meters.

CONCLUSIONS AND FUTURE WORK

With these MDIS images, we have clearly demonstrated the necessity for photogrammetric control in the making of accurate mapping products. Photogrammetry will be crucial for the characterization of topography in the southern hemisphere as MLA measurements are available primarily in the north. As new images are acquired, they too will be controlled and merged with those used here. The mosaics and DEM will be continuously refined until the final, global versions are created. Improved image position and attitude parameters will ultimately be provided to users in the form of new SPICE kernels. Increasing density of MLA topographic data will allow for more rigorous comparisons with that generated photogrammetrically. Figure 9 shows an example of the ongoing effort to create a global, controlled color base map mosaic. This preliminary mosaic was created from a single band of 1037 WAC (G-filter) images acquired from 5 April - 19 July 2011. It ranges from 0° to 65°N latitude and from 52°E to 358°E longitude. As in Figure 7, an equirectangular projection was used and images were projected to the sphere at a scale of 200 meters/pixel.

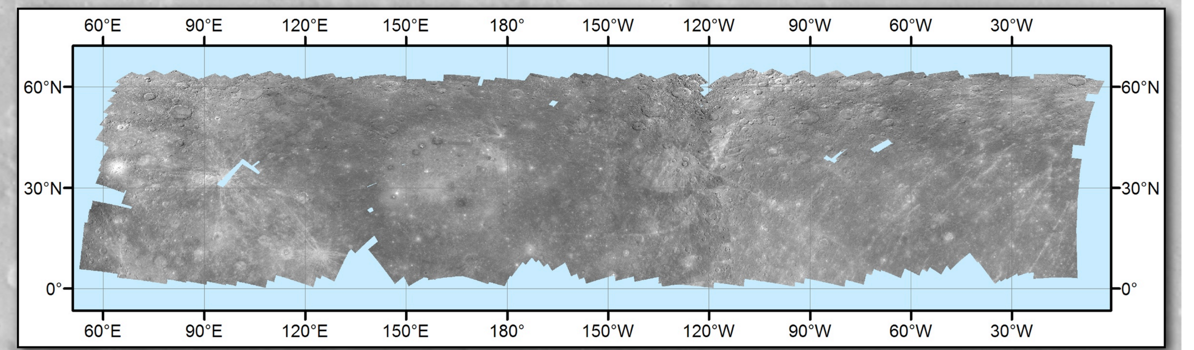

Figure 9. Portion of preliminary global, controlled color base map mosaic. Projection is equirectangular with a scale of 200 meters/pixel.

REFERENCES

[1] Solomon, S. C., et al., 2001. The MESSENGER mission to Mercury: Scientific objective and implementation. *Planet. Space Sci.*, 49, 1445–1465.

[2] Hawkins, S. E., III, et al., 2007. The Mercury Dual Imaging System on the MESSENGER Spacecraft. *Space Sci. Rev.*, 131, 247–338.

[3] Solomon, S. C., et al., 2008. Return to Mercury: a global perspective on MESSENGER's first Mercury flyby. *Science*, 321, 59–62.

[4] Becker, K. J., et al., 2008. A New Global Mosaic of Mercury. *Eos Trans. AGU*, 89(53), Fall Meet. Suppl., Abstract U21A-0015.

[5] Becker, K. J., et al., 2009. Near Global Mosaic of Mercury. *Eos Trans. AGU*, 90(52), Fall Meet. Suppl., Abstract P21A-1189.

[6] Anderson, J. A., et al., 2004. Modernization of the Integrated Software for Imagers and Spectrometers. *Lunar and Planetary Science*, XXXV, Abstract 2039.

[7] Cavenaugh, J. F., et al., 2007. The Mercury Laser Altimeter instrument for the Messenger mission. *Space Sci. Rev.*, 131, 451-480.

[8] Brown, D. C., 1976. Evolution and Future of Analytical Photogrammetry. Paper to the *International Symposium on "The Changing World of Geodetic Science," Columbus, Ohio 6-8 October 1976*, The Ohio State University.

[9] Kraus, K., 1993. *Photogrammetry. Volume 1: Fundamentals and Standard Processes.* 4th ed. Bonn: Ferd. Dümmlers Verlag.

[10] Acton, C. H., 1996. Ancillary Data Services of NASA's Navigation and Ancillary Information Facility. *Planetary and Space Science*, Vol. 44, No. 1, 65-70.

[11] Hapke, B., 1993. *Theory of Reflectance and Emittance Spectroscopy*. Cambridge University Press.

[12] Zuber, M. T., et al., 2011. Orbital Observations of Mercury with the Mercury Laser Altimeter. *EPSC-DPS Joint Meeting*, Vol. 6, EPSC-DPS2011-278.

[13] Oberst, J., et al., 2011. Radius and limb topography of Mercury obtained from images acquired during the MESSENGER flybys. *Planet. Space Sci., doi:10.1016/j.pss.2011.07.003.*

A note on the background image: This is a portion of an uncontrolled, global morphology mosaic of Mercury generated by the ASC from 10,062 MDIS NAC and WAC (G-filter) images acquired from 5 April to 23 August, 2011.