Digital Terrain Models of Mercury from MESSENGER Stereo Images. Frank Preusker[1], Jürgen Oberst[1], Roger J. Phillips[2], Thomas R. Watters[3], James W. Head[4], Maria T. Zuber[5], F. Scott Turner[6], Sean C. Solomon[7], [1]German Aerospace Center, Institute of Planetary Research, D-12489 Berlin, Germany, [2]Planetary Science Directorate, Southwest Research Institute, Boulder, CO 80302, USA, [3]Center for Earth and Planetary Studies, National Air and Space Museum, Smithsonian Institution, Washington, DC 20560, USA, [4]Department of Geological Sciences, Brown University, Providence, RI 02912 USA, [5]Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139-4307, USA, [6]The Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, USA, [7]Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, DC 20015, USA

Introduction: Procedures have been developed to derive three separate digital terrain models (DTMs) from stereo images obtained by the MESSENGER narrow-angle camera (NAC) during the spacecraft's three Mercury flybys of 2008 and 2009.

Initial data: The Mercury Dual Imaging System (MDIS) [1,2] consists of wide- and narrow-angle cameras, coaligned on a pivot platform. Both cameras are equipped with identical 1024x1024-pixel charge-coupled devices. The NAC, the principal tool for stereo data analysis to date, consists of a compact off-axis optical system that has been geometrically calibrated with laboratory as well as in-flight stellar observations. Image mosaics are obtained by scanning the pivot platform in combination with turning the spacecraft. This powerful capability was used to acquire several contiguous image mosaics during MESSENGER's three Mercury flybys on 14 Jan. 2008, 6 Oct. 2008, and 29 Sep. 2009 [3,4].

Data processing: The stereo processing for the three DTMs followed algorithms and software realizations used extensively on previous planetary image data sets [4,5]. The processing involves several stages, sophisticated pointing correction, digital image matching and DTM interpolation. At first, available stereo pairs were identified using footprint and pointing data for all images. The resulting lists of image combinations were used for the following processing steps. Next, corrections for spacecraft position and camera pointing data were carried out using bundle-block adjustment techniques on the basis of large numbers of tie-point measurements. For tie-point collecting, automatic image matching was applied. Only tie-points that spanned at least three images were selected. Using the improved navigation data, automatic image matching was applied on large scale again to determine large numbers of match points for the purpose of DTM generation. We applied an area-based matching strategy, where we compare and correlate pixel patterns within small windows in a reference image with those in the stereo partner images. Forward ray intersections of all matched points were computed to derive surface coordinates of object points using co-linearity equations. Finally all object points were interpolated to form a contiguous DTM grid with 1-km spacing. The DTMs are computed purely on the basis of image disparity effects and do not rely on assumptions regarding surface photometric properties. No adjustments for absolute height or trend and no lateral shifts were applied.

DTM	NAC mosaics	scale [m]	image count
M1DTM	M1-H1	120-180	68
	M1-H2	300-400	93
	M1-D1	500-600	47
M2DTM	M2-H2	250-350	108
	M2-D1	500-650	47
M3DTM	M2-APP	500-550	20
	M3-APP	450-500	28

Table 1: DTM overview

Results: *M1DTM* is derived from 208 stereo images acquired during the first flyby, which were obtained as three individual sub-mosaics (Table 1). Approximately 22,000 tie-points (line/sample coordinates), representing ~6,500 ground control points, were collected for navigation correction. Residual mean errors of ground-point coordinates were reduced from ±10 km to ±220 m. A total of 241 individual matching runs were carried out on double- or triple-overlapping images to yield 150 million object points with a mean intersection error of ±250 m. *M1DTM* covers 17% (12.8×10^6 km²) of Mercury's surface. One highlight of the model is the prominent large Caloris basin [6]. *M2DTM* is derived from 155 stereo images acquired during the second flyby and includes two sub-mosaics (Table 1). About 24,000 tie-points, representing ~6,500 ground points, were collected for navigation correction. The residual mean errors were reduced from ±4 km to ±320 m. 79 million object points with a mean intersection error of ± 340 m were computed from 92 individual matching runs. *M2DTM* covers 13% of Mercury's surface. Finally, *M3DTM* is the result of combining the two approach mosaics acquired during the second and third flybys. A total of 48 stereo images were used (Table 1). In all, 22.5 million object points were computed with a mean intersection error of ±150 m and interpolated to a continuous

DTM. *M3DTM* covers 3% of Mercury's surface. Fortuitously, M3DTM covers the MLA Laser altimeter track obtained during MESSENGER's first Mercury flyby, giving us the opportunity to study the DTM effective resolution and to verify the long-wavelength topography (Fig. 1). All DTM heights are given with respect to a Mercury standard sphere of 2440 km radius. The total height range is about 8-km.The three DTMs cover 33% of Mercury's surface (Fig. 2).
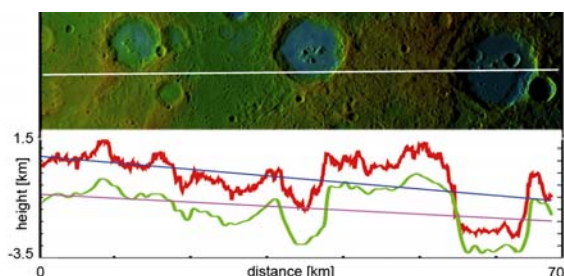

Fig 1: Height-color-coded M3 NAC Mosaic, MLA profile (red) and M3DTM profile (green). Mosaic is centered at ~4.8°S, 76.6°E.

Discussion: Because the flybys permitted only oblique viewing and (for the most part) small stereo angles, image data were not optimal for stereo analysis. In particular, small errors in image matching introduced large height errors and noise in the terrain model. On the other hand, the illumination conditions were uniform, so image matching performance was excellent and the number of blunders was small. Given some remaining errors in spacecraft navigation or geometric calibration, we cannot rule out small offsets in absolute height or errors in long-wavelength model trends. Indeed, height offset between the stereo model and the MLA track in M3DTM range from 0.8 km to 1.4 km, with a trend from east to west. However, owing to the large number of interlinked images and the wide range of involved stereo and viewing angles, we expect that the relative orientation of images within the block is stable. The analysis of residuals of control point coordinates does not show evidence of "stresses" in the image block, i.e. displacements or vertical offsets of the individual DTM segments.

Conclusion: During the orbital mission phase, MESSENGER will obtain global stereo data for topographic models that exceed the spatial resolution of the current models by a factor of four. With a more favorable viewing geometry, the noise in the terrain models will be reduced. Laser altimeter profiles with a superior height precision will be used to provide "ground truth" to remove ambiguities regarding absolute elevations and trends in long-wavelength topography. The models represent important tools for a variety of geological studies and will shed new light on the Mercury's surface morphology and tectonics.

References: [1] Hawkins III, S.E., et al., Space Science Reviews, 131, 1-4, 247-338, 2007. [2] Hawkins III, S.E., et al., paper 74410Z, 12 pp., SPIE Proceedings, vol. 7441, SPIE, Bellingham, WA, 2009. [3] Solomon, S.C., et al., Science, 321, 59-62, 2008. [4] Gwinner, K., et al., Photogrammetric Engineering Remote Sensing, 75(9), pp. 1127-1142., 2009. [5] Gwinner K., et al., Earth Planetary Science Letter, submitted, 2009b. [6] Oberst, J., et al., Icarus, submitted, 2009.
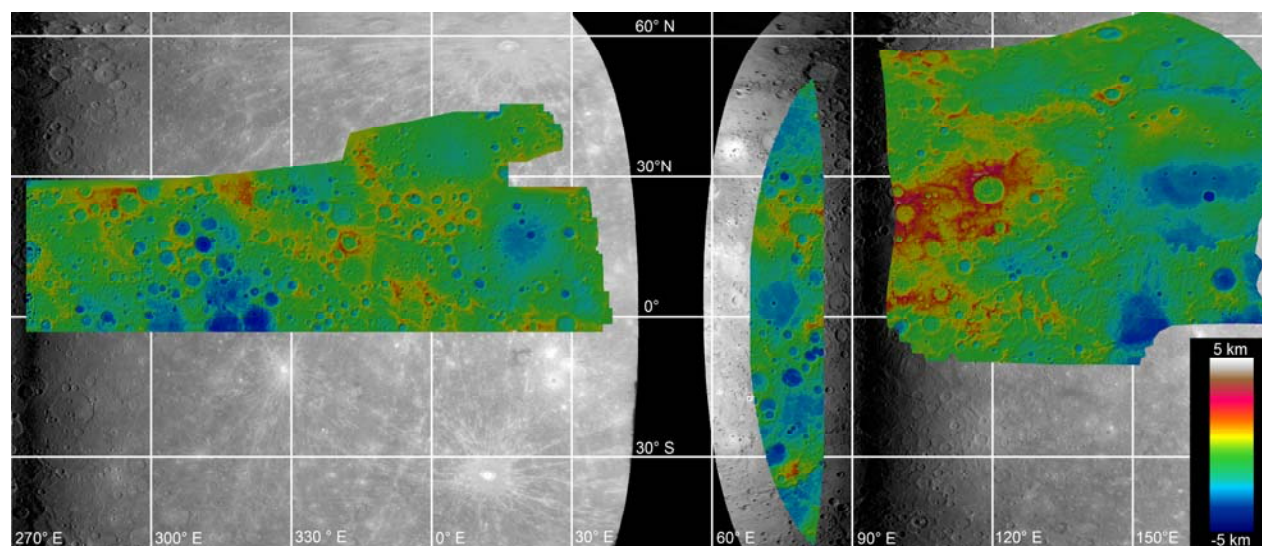

Fig. 2: Overview of DTMs produced from stereo images obtained during MESSENGER's Mercury flybys (left: M2DTM, center: M3DTM, and right: M1DTM).