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Stereo topographic models of Mercury after three MESSENGER flybys

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ABSTRACT

From photogrammetric analysis of stereo images of Mercury obtained during three MESSENGER flybys, we have produced three digital terrain models (DTMs) that have a grid spacing of 1 km and together cover 30% of the planet's surface. The terrain models provide a rich source of information on the morphology of Mercury's surface, including details of tectonic scarp systems as well as impact craters and basins. More than 400 craters larger than 15 km in diameter are included in the models. Additionally, the models provide important test cases for the analysis of stereo image data to be collected during MESSENGER's orbital mission phase. Small lateral offsets and differences in trends between stereo DTMs and laser altimeter profiles may be due to remaining errors in spacecraft position, instrument pointing, or Mercury coordinate knowledge. Such errors should be resolved during the orbital mission phase, when more joint analyses of data and detailed orbit modeling will be possible.

1. Introduction

Mercury is the smallest and the least explored of all the terrestrial planets. Considerable information on a planet's history and on the processes that have acted on its surface can be obtained from the studies of the planet's surface morphology. Until recently, however, only limited information was available for Mercury. Stereo images collected by the Mariner 10 spacecraft during flybys of Mercury in 1974–1975 have been used to reconstruct maps of surface topography (Cook and Robinson, 2000; Watters et al., 2001). These maps, however, suffered from difficulties in the radiometric and geometric calibration of the Mariner 10 vidicon sensors. Moreover, stereo coverage was restricted to portions of the southern hemisphere (~20% of the planet's surface). Topographic data have also been obtained from Earth-based radar delay and Doppler data (Slade et al., 1997), but only along linear profiles in equatorial areas and with limited spatial resolution (approximately 5 km in longitude and 100 km in latitude).

The MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft is only the second probe to visit the innermost planet. The spacecraft is equipped with a well-calibrated imaging system (Hawkins et al., 2007, 2009), and data obtained during three Mercury flybys in 2008–2009 (Solomon et al., 2008) included images that allowed stereo topographic reconstructions for a substantial portion of the planet not covered by Mariner 10. The stereo analysis in this paper constitutes an important test case for MESSENGER's orbital mission phase, to begin in March 2011, when dedicated stereo mapping sequences will be obtained at near-global coverage.

2. Data

2.1. Camera system

MESSENGER's Mercury Dual Imaging System (MDIS) consists of two framing cameras, a wide-angle camera (WAC) and a narrow-angle camera (NAC), co-aligned on a pivot platform and equipped with identical 1024 × 1024-pixel charge-coupled device (CCD) sensors (Hawkins et al., 2007). NAC, the principal tool for stereo analysis in this paper, consists of a compact off-axis optical system that has been geometrically calibrated using laboratory as well as in-flight stellar observations (Hawkins et al., 2007, 2009). Image mosaics are obtained by a combination of pivot platform movement and spacecraft motion.

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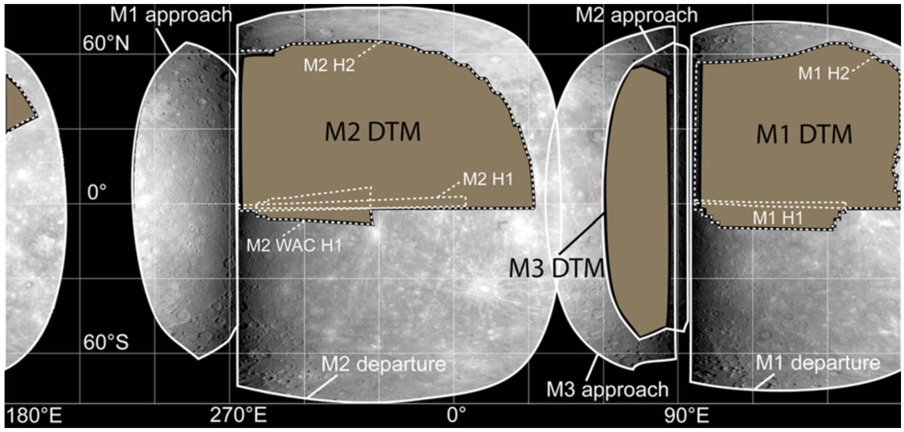

Fig. 1. Locations of MESSENGER image mosaics (Table 1) (outlined in white) and MESSENGER digital terrain models (brown shading) discussed in this paper, overlaid on a global MDIS image mosaic in cylindrical projection.

Table 1
Overview of digital terrain models.

DTM	Image mosaics	Image scale (m)	Image count	Object point count (1 0 ^{6})	3D point precision (m)
–	M1 approach	520–580	38	–	–
M1 DTM	M1 H1	120–180	68	150.0	250
	M1 H2	300–400	93		
	M1 departure	500–600	47		
M2 DTM	M2 WAC H1	250–750	5	220.0	290
	M2 H1	100–300	35		
	M2 H2	250–350	173		
	M2 departure	500–650	47		
M3 DTM	M2 approach	500–550	20	34.5	160
	M3 approach	450–500	28		

2.2. *Stereo image coverage*

The pivot-based scanning capability of MDIS allowed acquisition of several contiguous image mosaics (Fig. 1) during MESSENGER's three Mercury flybys on 14 January 2008 (M1), 6 October 2008 (M2), and 29 September 2009 (M3). These mosaics were constructed from a total of 2163 images, approximately 660 of which had a mean image resolution better than 550 m. The images were assembled into 10 individual sub-mosaics (Table 1). Five full-hemisphere sub-mosaics, M1 approach, M1 departure, M2 approach, M2 departure, and M3 approach, cover ~80% of Mercury's surface. In addition, MESSENGER acquired images from which five high-resolution local image mosaics were constructed: M1 H1, M1 H2, M2 H1, M2 H2, and M2 WAC H1 (Fig. 1).

From the images collected during the three flybys, there are three separate areas covered stereoscopically (Fig. 1) by a total of 516 images (Table 1). The stereo mosaics were taken under similar illumination conditions but variable viewing conditions (e.g., Fig. 2a). Apart from images viewed nearly at nadir, large areas in these mosaics were located near the planetary limbs, where emission angles (measured from the local vertical) were as great as 80° (Fig. 2a).

Stereo angle is an even more important parameter than emission angle for the generation of a high-fidelity digital terrain model (DTM). Stereo angles were appropriate for the M1 H1, M2 H1, M2 WAC H1, and M3 DTMs (up to 40° and 20–30°), but for the M1 H2 and M2 H2 mosaics stereo angles were often less than 14°, and the stereo angle was only 4° in the southwestern part of M1 H2, as may be seen in Fig. 2b. Maps of the relative three-dimensional (3D) precision achieved in the DTMs (Figs. 2c and 3) reflect a high sensitivity to stereo geometry. Even small residual errors within the radial distortion model are visible in the form of a decrease of the relative 3D precision toward the edges of the stereo models M1 H2 and M2 H2. In contrast, such effects are nearly unresolvable within the M1 H1, M2 H1, M2 WAC H1, and M3 DTMs. Visual inspection of the final DTMs indicates that with the additional redundancy provided by the typical multiple overlap (more than two images) at the image edges, an increase of the nominal 3D forward ray-intersection error does not necessarily lead to a marked decrease of the quality of the heights within these DTMs.

3. Photogrammetric stereo image analysis

The photogrammetric stereo analysis is based on algorithms and software realizations used extensively on previous planetary image data sets (Giese et al., 1998, 2006; Gwinner et al., 2009, 2010). The processing involves several stages and includes pointing corrections made with photogrammetric block-adjustment techniques, multi-image matching, and the generation of DTMs and orthoimage mosaics.

3.1. *Block adjustments*

Beginning with the nominal spacecraft position and camera pointing data provided by the MESSENGER project, image footprint information was generated to identify areas of stereo overlap between images. Next, multi-image matching was applied to all image data in overlapping areas to derive conjugate points (commonly termed tie points). A large matching grid size was used to avoid excessive numbers of points (Table 2).

The resulting image coordinates of the tie points and the nominal navigation data (pointing and position) for each image form the input (observations) to photogrammetric block adjustment. The ground coordinates and the orientation of each image were considered as unknowns. In contrast, the nominal spacecraft positions and camera pointing were assumed to be correct within the random errors assumed to be ± 50 m and ± 1.0 mrad, respectively (E.J. Finnegan and F.S. Turner, pers. comm., 2010). We expect that any systematic offsets of the spacecraft trajectory from nominal will not affect the characteristics of the terrain modeling beyond overall positioning. We estimate that the accuracy of the measured image coordinates was ± 0.3 pixel. Only tie points that concatenated at least three images were selected to minimize the total number of tie points and provide