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Mercury's global shape and topography from MESSENGER limb images

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ABSTRACT

We derive models for the global shape and topography of Mercury from limb images obtained by the MESSENGER spacecraft during flybys and from orbit. Crossover heights of 225 individual limb profiles were adjusted by least-squares techniques to establish a rigid global topographic network. Mercury is confirmed to possess an equatorial ellipticity and a polar oblateness. Several large impact basins and craters can be identified in the topographic model, including one basin that was earlier proposed but unconfirmed. Comparisons with absolute height data from laser altimetry indicate that the limb model appears to overestimate planetary radius by ~900 m on average. Limb profiles and local digital terrain models derived from stereo-photogrammetry show good agreement.

1. Introduction

Size, shape, and topography constitute basic geodetic data for any planet. For the planet Mercury, ellipsoidal planetary shape models were obtained from observations as early as those made by the Mariner 10 spacecraft (Dunne, 1974). Subsequent radar observations from Earth (Harmon and Campbell, 1988; Anderson et al., 1996) yielded rotation parameters and topographic profiles of Mercury's equatorial regions. Since the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft (Solomon et al., 2001, 2007) was inserted into orbit about Mercury in March 2011, several complementary methods have been used to study Mercury's global shape and topography with MESSENGER observations. These include laser altimetry (Zuber et al., 2012), measurements of radio occultation times (Perry et al., 2013), stereo imaging (Preusker et al., 2011), and limb imaging (Oberst et al., 2011). A summary of estimates of the radius and shape of Mercury made with different techniques over time is given in Table 1.

Although the Mercury Laser Altimeter (MLA) on MESSENGER achieves high ranging accuracy (Cavanaugh et al., 2007), the coverage for Mercury is far from uniform. Because of MESSENGER's highly eccentric orbit and high northern periapsis, only areas north of approximately 10°S are within instrumental range. Moreover, the spacing between orbital ranging tracks increases toward the equator, decreasing the areal density of ranging measurements.

Topographic models can also be produced from stereo images, as has been demonstrated with MESSENGER data (Oberst et al., 2010; Preusker et al., 2011). Combining large numbers of local models to achieve hemispheric scale, however, requires substantial processing power and time. Further, stereo modeling is particularly sensitive to uncertainties in geometric calibration parameters for the imaging system, such as focal length and geometric distortion. Efforts have been undertaken to calibrate the camera system with the help of star images taken during the early mission stages. These calibration images yielded an accurate geometric distortion model with an average residual error for a single star of 0.1 pixels (Oberst et al., 2011).

Radio tracking of a spacecraft yields information on the local radius of the target body at the points where the spacecraft enters the radar shadow (ingress) or reappears (egress) (Kliore et al., 1972; Fjeldbo et al., 1976). Though the estimation of the instant of occultation can be highly accurate, the derivation of the body's radius is hampered by the grazing viewing geometry and local variations in topography near the grazing point. Also, coverage is limited, because each occultation event yields only one data point. For MESSENGER, radio occultation measurements have been used to complement MLA measurements in the southern

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Table 1
Previous estimates of the radius and shape of Mercury (modified from Oberst et al. (2011)).

Method	Value	Reference
Optical (mean radius)	2440.0 ± 7.5 km	de Vaucouleurs (1964)
Early radar (near-equatorial only)	2439.0 ± 1.0 km	Ash et al. (1971)
Mariner 10 occultations (local radius)		
Ingress (1.1°N, 67.4°E)	2439.5 ± 1.0 km	Fjeldbo et al. (1976)
Egress (67.6°N, 258.4°E)	2439.0 ± 1.0 km	
Radar (near-equatorial only)	2439.7 ± 1.0 km	Harmon and Campbell (1988)
(Currently IAU-recommended)		Davies et al. (1989)
		Archinal et al. (2010)
Radar		
a (Semi-major axis of equatorial shape)	2440.6 ± 0.1 km	Anderson et al. (1996)
b (Semi-minor axis of equatorial shape)	2439.3 ± 0.1 km	
c (Polar axis)	2432.9 ± 8.8 km km	
Longitude of equatorial major axis	−15.3°E ± 2.9°	
MESSENGER		
Laser altimetry of the northern hemisphere		Zuber et al. (2012)
North polar radius	2437.57 ± 0.05 km	
Equatorial mean radius	2439.83 ± 0.05 km	
Northern hemisphere mean radius	2439.59 ± 0.05 km	
Longitude of equatorial major axis	−18.6°E ± 4°	
Occultations (local radius)		
M1 ingress (25.54°S, 225.28°E)	2437.3 ± 0.35 km	Perry et al. (2011)
M1 egress (7.33°S, 41.83°E)	2439.9 ± 0.35 km	
M3 egress (36.06°N, 28.23°E)	2440.5 ± 0.35 km	
Stereo topographic models		
Mean radius	2440.3 km	Preusker et al. (2011)
Limb fits (flybys)		
Mean radius	2439.25 ± 0.69 km	Oberst et al. (2011)

hemisphere to produce a global model of planetary shape (Perry et al., 2011, 2013).

The use of limb imaging is an established method to determine the shape of celestial bodies (Dermott and Thomas, 1988; Thomas et al., 2007). The strong contrast between the bright limb and the dark space background provides a ready basis to extract local topographic profiles. By merging several intersecting profiles, a network of limb points can be created, to which model shape functions can be fit. In this work, we present an analysis of images of Mercury's limb obtained by MESSENGER for studies of the planet's global shape.

2. Image data

MESSENGER is equipped with the Mercury Dual Imaging System (MDIS) (Hawkins et al., 2007, 2009), which consists of a narrow-angle camera (NAC) and a wide-angle camera (WAC). The WAC features 11 narrow-band filters from visible to near-infrared wavelengths and a broadband clear filter.

During three flybys of Mercury in 2008 (Solomon et al., 2008; McNutt et al., 2010) and 2009 (Domingue et al., 2011), here labeled M1 through M3, and during its orbital mission (McAdams et al., 2012), MESSENGER obtained more than 3400 limb images (Fig. 1) through September 2013. From these we have chosen 225 images selected on the basis of coverage, image resolution, and lighting conditions. These images were used to construct a network of well-distributed limb profiles that crisscross the planet. Whereas limb profiles obtained during MESSENGER's flybys of Mercury extend from pole to pole, the profiles collected during MESSENGER's orbital phase (the majority of the profiles) typically extend in the east–west direction and cover areas between 60°S and 40°N. Because of MESSENGER's highly eccentric orbit and high northern periapsis, the spacecraft is too close to the planet for limb imaging of areas northward of 40°N.

We used images primarily from the WAC, supplemented with a few NAC images. To minimize systematic errors we included only those WAC images taken with the G filter (750.8 nm central wavelength). Because most WAC color images are acquired in sequences obtained within a time span of a few seconds, the analysis benefits little from the addition of images taken with other filters. NAC images obtained during the flybys at distances between ~15,000 km and 150,000 km were found to be useful for our analysis. Additional NAC limb images of the limb were acquired from close range, but unfortunately these images show only short limb arcs and therefore cannot be integrated readily into the network established from the other images.

3. Raw limb profiles

The image coordinates of limb point positions were found sequentially in a contrast-based search by applying a rectangular search window aligned with the limb and finding the maximum correlation between the gradient in the image data number (DN) of the actual limb and a step function pre-defined from the characteristic image point spread. The measured coordinates were corrected for geometric distortions in the images, following methods developed earlier (Oberst et al., 2011). Image coordinates also depend on the precise knowledge of the focal lengths of the camera systems. We used estimates of focal length derived from observed differences between MLA and image-based topographic models (Preusker et al., 2011).

Given the varying lighting conditions along the limb and the average residual image distortions from the geometric calibration, we assumed that the average uncertainty in the limb point