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Mercury's shape from radio occultations

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1. Introduction

To support studies of Mercury's internal structure, a MESSENGER mission goal is to measure the shape of the planet. Radio-frequency occultation observations contribute to this objective, particularly in most of the southern hemisphere where there are no altimeter data. We describe the techniques used to derive radius measurements from occultations and report results to date on the long-wavelength shape of Mercury.

Before the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) mission, Mercury's shape was poorly constrained, primarily by Earth-based radar observations at low Mercury latitudes. During MESSENGER's 12-month primary mission, the Mercury Laser Altimeter (MLA) acquired an extensive data set on the topography of Mercury's northern hemisphere [1]. However, most of the southern hemisphere is beyond MLA range because the periapsis of MESSENGER's highly inclined, eccentric orbit is at high northern latitudes. Along with limb measurements and global stereo mosaics, occultation-derived radius measurements are essential for understanding the shape of Mercury's southern hemisphere.

As viewed from Earth, the MESSENGER spacecraft passed behind Mercury every twelve hours for most of the primary mission. This geometry caused Mercury to occult the radio frequency (RF) transmissions, and we used an open-loop receiver to record RF power at the ingress and egress of each occultation. Incorporating the effects of diffraction, we extracted the time of occultation and used it to determine the RF path that grazed Mercury's surface. The point on that RF path that is tangent to the surface defines a unique latitude, longitude, and radius.

Since the highest point along the RF path provides the occultation edge, the radius measurements are biased high relative to the surrounding terrain. We corrected for this bias by evaluating topography local to the tangent point. Digital-elevation models (DEMs), derived from surface images acquired by MESSENGER's Mercury Dual Imaging System (MDIS), contain the necessary topographic data. We compared northern-hemisphere occultation results to MLA data to verify the analysis approach and quantify uncertainty.

2. Occultation data

Most occultation data have a low signal-to-noise ratio (SNR) because the spacecraft RF link was through MESSENGER's low-gain antennas. The ingress RF signal can be recorded with a narrower bandwidth, which reduces noise, and the best occultation data are during ingresses when Mercury was less than 0.9 AU from the Earth. There are approximately 100 occultation events with data of sufficient quality to measure radius to better than 1-km accuracy. A subset of those high-quality occultations has been analyzed, and Fig. 1 shows the latitudes and longitudes of their tangent points.

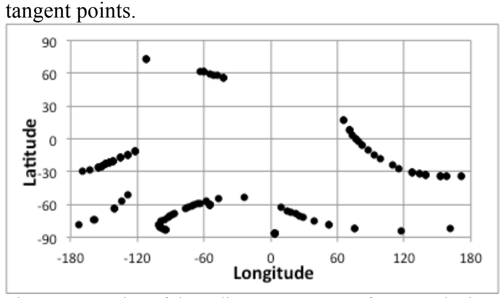

Figure 1. Location of the radius measurements from occultations that were analyzed before May 2012. Additional data are analyzed each month. Coverage in the southern hemisphere is sufficient for preliminary estimates of south polar flattening.

3. Deriving radius measurements

In addition to the height bias and low SNR described above, diffraction effects further complicate occultation analyses when using RF data to determine a planet's radius [2]. We account for these complications and produce radius measurements through the following process:

1) Extract power levels from the RF data. We have evaluated several methods. A Fast Fourier Transform algorithm is the most accurate, but it fails for lower-SNR observations. A software phase-locked loop algorithm is effective for the lower-SNR occultations.

2) On the basis of the geometry of the particular occultation, calculate the effects of diffraction on the RF signal and fit the resulting curve to the measured power history. From this fit, extract the time of geometric occultation, accurate to 0.05 to 0.25 s, depending on the SNR of the observation.

3) Use the known, time-based position of MESSENGER relative to Mercury to convert the time of the occultation to the latitude and longitude and the raw, measured radius at the point where the RF path is tangent to the surface of Mercury.

4) Using a DEM, extract the altitude profile along the RF path, correct for surface curvature, and locate the occulting edge, which is the highest point along the path (Figure 2).

5) Calculate the average height of surrounding terrain, and the difference in height between this average height and the height of the occulting edge.

6) Correct the raw, measured radius by the result in step 5. This final result is the average radius of the terrain surrounding the occultation point.

Detailed topographic information is necessary to adjust the height bias in the absolute measurement derived from the occultation. Image-based DEMs are locally accurate but may be subject to long-wavelength uncertainties that may introduce errors in absolute elevations. Many of these errors will be reduced following full global analysis that is not yet complete for the Mercury DEMs.

The uncertainty in the occultation-derived radius measurements is 100 to 500 m, depending on the SNR of the RF observations and the velocity of MESSENGER relative to Mercury's surface as viewed from Earth. Higher velocities increase the radius errors associated with timing accuracy.

4. Preliminary results

Although some verification tests remain, results to date indicate that Mercury's south polar region is flattened to a degree similar to that in the north. If correct, and if this flattening is a remnant of a shape established when Mercury was in hydrostatic equilibrium, then it corresponds to a rotation rate of 100 to 200 h, depending on the degree of relaxation since Mercury's rotation slowed to its current period. Coupled with the size of the core as revealed by gravity and libration analyses [4], the flattening provides insight into Mercury's rotational and thermal history. The hydrostatic shape indicates the historical rotation rate at the time when the lithosphere had cooled sufficiently to preserve the shape. This rotation rate can be used to constrain the despinning timescale, and thereby the historical tidal parameters (Love number, tidal dissipation function) [5], which in turn constrain the rheology (viscosity, rigidity) of the interior [6].

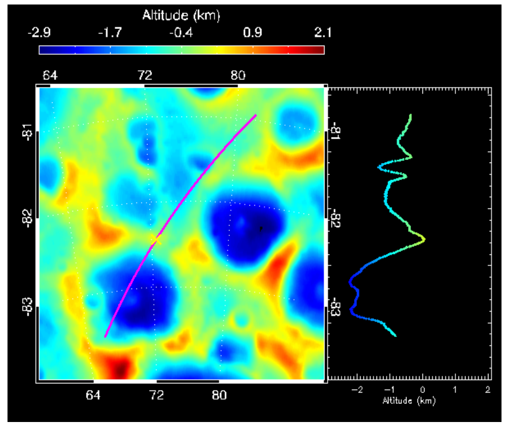

Figure 2. RF path (purple line) at the time of an occultation plotted over a map of topography specified by a DEM determined from MDIS images with stereo photoclinometry [3]. The altitude profile along the RF path is shown at right.

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