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Measurement of the radius of Mercury by radio occultation during the MESSENGER flybys

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ABSTRACT

The MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft completed three flybys of Mercury in 2008–2009. During the first and third of those flybys, MESSENGER passed behind the planet from the perspective of Earth, occulting the radio-frequency (RF) transmissions. The occultation start and end times, recovered with 0.1 s accuracy or better by fitting edge-diffraction patterns to the RF power history, are used to estimate Mercury's radius at the tangent point of the RF path. To relate the measured radius to the planet shape, we evaluate local topography using images to identify the high-elevation feature that defines the RF path or using altimeter data to quantify surface roughness. Radius measurements are accurate to 150 m, and uncertainty in the average radius of the surrounding terrain, after adjustments are made from the local high at the tangent point of the RF path, is 350 m. The results are consistent with Mercury's equatorial shape as inferred from observations by the Mercury Laser Altimeter and ground-based radar. The three independent estimates of radius from occultation events collectively yield a mean radius for Mercury of 2439.2 ± 0.5 km.

1. Introduction

The shape of a differentiated planetary body provides constraints on its internal structure, its thermal and rotational evolution, the degree of compensation of large-scale topography, and other physical properties. Planet-shape data are of particular interest in studies of Mercury's interior structure because of the planet's large core and the indications that at least the outer core is molten (Margot et al., 2007; Hauck et al., 2007). Before 2008, the best shape information for Mercury came from Earth-based radar data, which were confined to within 10° of latitude of the equator (Harmon et al., 1986; Anderson et al., 1996). Since 2008, the MErcury Surface, Space ENvironment, GEochemistry, and Ranging (MESSENGER) spacecraft has flown by Mercury three times (Solomon et al., 2008), providing new data on the planet's equatorial shape and radius (Zuber et al., 2008; Smith et al., 2010; Oberst et al., 2010).

This paper reports on the three radio-frequency (RF) occultation events that occurred during MESSENGER's flybys. We derive radius measurements from observations of the occultations, estimate uncertainties, and relate the results to current knowledge of Mercury's shape. The three occultation events are the ingress and egress during the first flyby of Mercury (M1) and egress during the third flyby of Mercury (M3). Mercury did not occult the spacecraft during the second flyby (M2), and a spacecraft anomaly prevented observation of the ingress during the third flyby.

During the start and the end of an occultation, the RF signal amplitude displays a diffraction pattern that contains information needed to extract the time of occultation. Combined with accurate position data, the time of occultation defines the path of the RF transmission that just grazes the surface, a line that is tangent to the outer surface of the planet (Fjeldbo et al., 1976; Smith and Zuber, 1996; Asmar et al., 1999). The grazing RF path provides the radius of the planet at the point where the grazing path intersects the surface.

High-standing topographic relief on the surface can intercept the RF signal and define a grazing RF path that is 1 km or more above the average height of the surrounding terrain and 50 km

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or more from a tangent point calculated on the basis of a smooth sphere. To relate an occultation-derived radius measurement to the general shape of the planet at the point of measurement, we must understand the topography where the grazing path is tangent to the surface. The grazing RF path can be well defined, but the relationship of the grazing path to the long-wavelength planet shape may be poorly determined. To find the intersecting feature, we examine images. If a clear intersecting edge is not found, we use surface roughness characteristics as revealed by MESSENGER's Mercury Laser Altimeter (MLA) data to relate statistically the radius measurement to the broad-scale planet shape and quantify the uncertainty in that relationship.

Our understanding of Mercury's shape comes from MLA (Cavanaugh et al., 2007; Zuber et al., 2008), images of Mercury's limb (Oberst et al., this issue), and Earth-based radar data. RF occultation measurements make two primary contributions to these other data sets: (1) absolutely calibrated estimates of radius with a set of error sources that are largely independent of the other planet-shape data; and (2) near-global, albeit sparse, coverage. Of particular importance will be measurements of Mercury's radius from occultation events in the southern hemisphere, which is beyond MLA's range due to MESSENGER's elliptical orbit and its periapsis at 60–70°N.

2. Data analysis

There are three steps to the use of RF occultations to derive knowledge of Mercury's shape:

1. Obtain the time of occultation ingress and egress by extracting power levels from the RF data, and then compare the levels to the calculated diffraction pattern.
2. Use the known position of MESSENGER relative to Mercury to convert the time of each occultation event to the radius at the point where the RF path grazes the surface.
3. Use all available information on local topography to relate the calculated radius to the large-scale shape of the planet.

2.1. Diffraction and the time of occultation

Mercury's surface does not cause an instantaneous transition in MESSENGER's RF transmissions as observed from Earth. The transmissions diffract around Mercury's surface, displaying a classical edge-diffraction pattern as recorded at the ground antennas of NASA's Deep Space Network (DSN). To locate the point of geometric occultation, where the spacecraft, Mercury's surface, and the DSN antenna all lie along a single straight line, we must fit a diffraction pattern to the time history of the RF power. Mercury's surface-bounded exosphere is too tenuous to affect radio-wave propagation or the diffraction pattern.

For each occultation event, we recorded the RF transmissions using the Radio Science Receiver (RSR), an open-loop receiver (Kwok, 2010). The RSRs are installed at the DSN antennas and operated by the Jet Propulsion Laboratory (JPL) Radio Science Systems Group. RSR data are recorded at a rate between 16 kb/s and 32 Mb/s. Depending on the signal strength and on the analysis requirements, the data are integrated to a time resolution that provides the needed signal-to-noise ratio for the intended analyses. For the flyby occultations, the data were collected by the RSR at 16 bits per sample at four bandwidths: 1, 16, 50, and 100 kHz. We used the 1 kHz data, where available. For M1 egress, we used the 50 kHz data because the 1 kHz bandwidth did not contain the MESSENGER signal. Communications were coherent entering the M1 occultation, and they remained coherent through the period covered by the measurements analyzed in this paper. For M1 egress, communications were non-coherent during the analyzed period. For M3 egress, the MESSENGER transponder locked onto the diffracted uplink approximately 0.3 s before the time of geometric occultation, and the analyzed data are all coherent.

The quality of the extracted RF power history, as measured by time resolution and noise, degrades for low levels of RF signal power. Operational constraints require that MESSENGER use its low-gain antennas (LGAs) during the periods when most occultations occur (Srinivasan et al., 2007). The low power delivered by the LGAs at the ground tracking stations causes low signal-to-noise ratios and obscures the diffraction patterns. LGA power is further reduced if the LGA boresight is not pointed toward Earth. For the occultation ingress and egress times during M1, the angle between the spacecraft-Earth line and the LGA boresight was within 60°. With a 70 m ground-station antenna, the signal-to-noise spectral density ratio, P_c/N_o, where P_c is carrier power (W) and N_o is the noise spectral density in W/Hz, was 23 dB Hz during M1. Power was higher for M3 egress. The spacecraft anomaly, noted above, triggered a reconfiguration of the RF system onto the medium-gain fan-beam antenna, increasing the unocculted RF power from 23 dB Hz to 35 dB Hz.

We used both the lower-power M1 occultation data and the higher-power M3 egress data to evaluate several software techniques for extracting the carrier-frequency power levels from the RSR data: fast Fourier transform (FFT), total power in the in-phase (I) and (out-of-phase) quadrature (Q) components, and a software phase-locked loop (PLL). None of these techniques is ideal. The FFT routine has good accuracy when power exceeds 30 dB Hz, but noise spikes of 20 dB Hz prevent monitoring the RF diffraction pattern at the lower power levels typical of the LGA. Similarly, the I/Q-power technique provides excellent time resolution at the higher power levels and minimal information at low power. Summing the squares of the I and Q components produces the total power in the bandpass, which puts all noise within the bandpass into the result, interfering with tracking of the diffraction pattern to low power levels. Results from the FFT technique and I/Q-power agree for M3 egress, the occultation event with highest RF power. For the lower-power M1 events, both techniques have noise floors that are within 5 or 6 dB of the unocculted power level, particularly when using the wider bandpass.

The PLL technique can track the RF signal to low power levels using a narrow tracking bandwidth of 5–10 Hz. By tracking the frequency, the PLL routine captures the power in the RF transmissions without including other noise in the bandpass. Unfortunately, the RF signal is broader than 10 Hz, and a narrow bandwidth distorts the RF power history because it captures only a portion of the signal power. We evaluated several bandwidths and found that 25–50 Hz provides a good compromise between accurate capture of the total power and tracking to low power levels. The PLL technique enabled the extraction of additional details of the diffraction pattern for the low-power M1 events.

The diffraction pattern of an occultation event is set by the specific geometry and velocities of that occultation. For a planetary body occulting RF radiation, the observed power levels follow the predictions of edge diffraction theory. The diffraction pattern at the observer – the DSN station – can be parameterized with a scale length, u, which depends on the wavelength of the radiation and on the geometry of the source, edge, and observer. For the MESSENGER flybys, where the distance to Earth is much greater than the distance between MESSENGER and Mercury, the appropriate parameterization of the standard Fresnel diffraction result is

$$u = \sqrt{\frac{d_E^2 \lambda}{2 d_S}} \quad \text{for } d_E \gg d_S \tag{1}$$