RADIO FREQUENCY OCCULTATIONS SHOW THAT MERCURY IS OBLATE. Mark E. Perry[1], Daniel S. Kahan[2], Olivier S. Barnouin[1], Carolyn M. Ernst[1], Sean C. Solomon[3], Maria T. Zuber[4], David E. Smith[4], Roger J. Phillips[5], Steven A. Hauck, II[6], Gregory A. Neumann[7], Stanton J. Peale[8], Jean-Luc Margot[9], Erwan Mazarico[7], Catherine L. Johnson[10,11], Robert W. Gaskell[11], James H. Roberts[1], Sami W. Asmar[2], Ralph L. McNutt, Jr.[1]. [1]The Johns Hopkins University Applied Physics Laboratory, Laurel, MD 20723, USA; [2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA; [3]Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY 10964, USA; [4]Department of Earth, Atmospheric and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139, USA; [5]Planetary Science Directorate, Southwest Research Institute, Boulder, CO 80302, USA; [6]Department of Earth, Environmental, and Planetary Sciences, Case Western Reserve University, Cleveland, OH 44106, USA; [7]NASA Goddard Space Flight Center, Greenbelt, MD, USA; [8]Department of Physics, University of California, Santa Barbara, CA 93106, USA; [9]Department of Earth and Space Sciences, University of California, Los Angeles, CA, USA; [10]Department of Earth, Ocean and Atmospheric Sciences, University of British Columbia, Vancouver, BC, V6T 1Z4, Canada; [11]Planetary Science Institute, Tucson, AZ 85712, USA.

Introduction: Measurement of the shape of Mercury, particularly when combined with the shape of its geoid, can provide clues to the planet's internal structure, thermal evolution, and rotational history [1]. The Mercury Laser Altimeter (MLA) provides accurate measurements of the northern hemisphere and shows that higher latitudes have elevations that are lower than in the equatorial regions [2]. Without measurements in the southern hemisphere, it was not clear whether these lower elevations were due to polar flattening or the result of regional processes. Recently analyzed observations of radio frequency (RF) occultations provide approximately 120 southern-hemisphere elevations (Fig. 1) that show a difference between the south-pole radius and the equatorial radius of 2.2 ± 0.1 km (on the basis of the $C_{2,0}$ term of the 24-degree spherical harmonic fit to the MLA and occultation data) that is nearly identical to that observed by MLA for the northern hemisphere (2.26 ± 0.05 km) [2]. We present the occultation data and discuss possible implications for Mercury's history and interior structure.

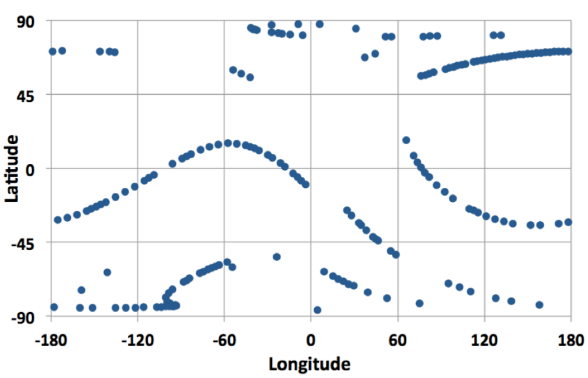

Fig. 1. Locations of the RF occultation measurements used with MLA data to determine Mercury's low-degree shape. A comparison of northern hemisphere occultation data with MLA data has provided a verification of the accuracy and uncertainty estimates of the occultation radii.

Data analysis: Measurements of Mercury's radius during occultations are from open-loop receiver data. The initial product is the time-dependent RF power as MESSENGER passes behind and past Mercury, as viewed from Earth [3]. Depending on the RF signal strength, the optimal algorithm for extracting the RF power histories is a fast Fourier transform or a software phase-locked loop. The time of occultation is then determined by fitting an edge-diffraction curve to the RF power history. By edge diffraction theory, the received RF power is 1/4 (-6 dB) of the unocculted power at apparent geometric occultation, the time when the source, edge, and observer are aligned along the RF path.

The positions of MESSENGER, Mercury, and the Deep Space Network antenna provide the radius of Mercury at the point where the RF path grazes a smooth sphere centered at Mercury's center of mass. Local topography determines the actual occulting edge, which

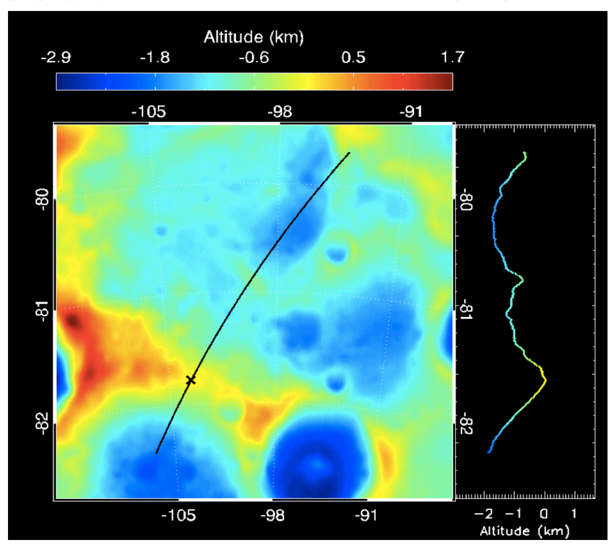

Fig. 2. The RF path (black line) at the time of an occultation is plotted over a DTM determined from stereo photoclinometric analysis of MESSENGER images [4]. The terrain model provides the location of the occulting edge and the adjustment required to associate the height of that edge with the elevation of the surrounding terrain. The **x** indicates the occulting edge. The altitude profile along the RF path is shown at the right.

may be displaced both radially and horizontally from the smooth-sphere location. We use digital terrain models (DTMs) derived from stereo photoclinometry [4] to identify the local occulting edge or feature and to measure the height of this feature above the average height of the surrounding terrain (Fig. 2). This height difference is applied to the raw occultation radius to produce the final result, the average elevation in the region surrounding the occultation edge. The occultation analyses produce accurate elevations by using precise relative data from the DTMs to adjust the absolute radii obtained from the raw occultation measurements.

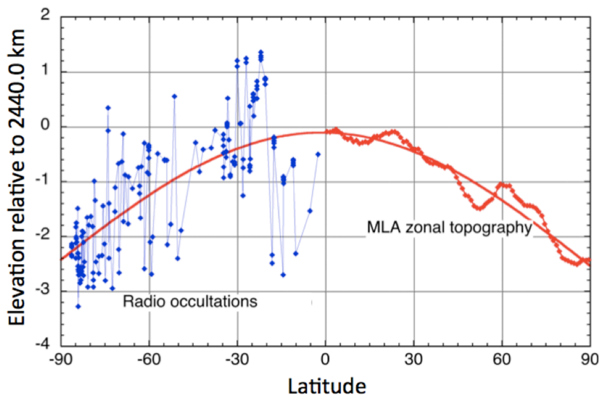

Fig. 3. The oblate shape of Mercury is apparent in this plot of southern hemisphere RF occultation elevations (adjusted for topography) relative to 2440 km and the longitudinally averaged MLA data in the northern hemisphere. The occultation data are individual measurements and show variations due to local topography. For example, the low-elevation occultation measurements between 5°S and 20°S are low, smooth plains north of the Rembrandt basin. The solid curve, the best-fit oblate shape to the MLA data, agrees well with the occultation data.

The unadjusted radius measurements from occultations with northern-hemisphere locations were compared with MLA data and found to be an average of 230 m higher than the MLA measurement closest to the occulting edge. We expect such a difference, since the separation between MLA measurements averages approximately 400 m and an MLA measurement is unlikely to occur at the occulting edge. (With an angle of repose of 30°, a 400-m offset corresponds to a height difference of 230 m.) The standard deviation of the occultation-to-MLA comparison is 210 m, in agreement with the average occultation uncertainty, which is derived from the time uncertainty determined by the quality of fit of the RF power histories to the diffraction pattern. The combination of the occultation and MLA data confirms the oblate shape of Mercury (Fig. 3).

Discussion: Coupled with the size of the core as revealed by gravity and libration/obliquity analyses [5], the flattening provides insight into Mercury's rotational and thermal history. If the observed shape indicates the hydrostatic shape of the historical rotation rate at a time when the lithosphere had cooled sufficiently to preserve this shape, the rate can, in principle, be used to constrain the despinning timescale, and thereby the historical tidal parameters (Love number, tidal dissipation function) [1,6]. Those parameters in turn constrain the rheology (viscosity, rigidity) of the interior [7].

We discuss two aspects of Mercury's oblate shape: its source and the implications of its difference from the geoid, which is nearly spherical. The current flattening, if a preserved hydrostatic shape, corresponds to a rotation rate of 100 to 200 h, depending on the degree of relaxation as rotation slowed. Both the formation and thickening of Mercury's lithosphere and despinning from an initial rapid rate such as a 10-h rotation period were likely complete before the end of late heavy bombardment [8,9]. The timescales for the two processes are comparable but may be too rapid and too dependent on stochastic events to establish a relationship. Mercury's geoid is a factor of 10 less oblate than Mercury's shape [5]. This difference requires compensation on a global scale. Because of the nearly spherical geoid, it is unlikely that the core-mantle boundary shows the same degree of oblateness as the surface.

If the compensation is confined to variations in crustal thickness, then a mantle/crust density ratio of 1.1 implies that pole-to-equator crustal thickness variations of 22 km are required to maintain the 2.4 km difference in polar and equatorial radii, a figure similar to the differences in crustal thickness reported by Smith et al. [5]. Alternatively, compensation could be achieved by latitudinal variations in the density of the crust or mantle. However, such observational evidence as the low surface concentration of iron [10] argues against differences in crustal density as an explanation for the difference in flattening between geoid and shape.

The northern hemisphere crustal thickness indeed displays a thinning toward the pole [5]. However, models of mantle convection [11,12] predict smaller-scale structure than would be consistent with either the hemispheric-scale crustal thickness pattern or the oblateness. Understanding the relationship between geophysical and geological observations and geodynamical evolution will be a high priority for further study.

References: [1] Matsuyama I. and Nimmo F (2009) *J. Geophys. Res. 114,* E010101, [2] Zuber M. T. et al. (2012) *Science 386*, 217-220. [3] Perry M. E. et al. (2011) *Planet. Space Sci., 59*, 1925-1931. [4] Gaskell R. W. et al. (2008) *Meteorit. Planet. Sci., 43,* 1049-1061. [5] Smith D. E. (2012) *Science*, *336*, 214-217. [6] Goldreich P. and Soter S. (1966) *Icarus 5*, 375-389. [7] Tobie G. et al. (2005) *Icarus 177*, 534-549. [8] Solomon S. C. (1977) *Phys. Earth Planet. Inter. 15,* 135-145. [9] Correia A. C. M. and Laskar J. (2009) *Icarus, 201*, 1–11. [10] Nittler L. R. et al. (2011) *Science 333*, 1847-1850. [11] Michel N. C. et al. (2012) *JGR,* in press. [12] Roberts J. H. and Barnouin O. S. (2012) *J. Geophys. Res. 117,* E02007.