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# Determining shape of a seasonally shadowed asteroid using stellar occultation imaging

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ABSTRACT

A key objective in exploration of small, asteroidal bodies is to determine global shape and volume. The accuracy to which volume can be determined limits determination of bulk density, an important measurement for understanding internal structure. A special case for a rendezvous mission that uses stereo imaging to determine shape is a body with high obliquity encountered near solstice: half of the body is in shadow, and imaging of illuminated terrain alone under-constrains global shape. In this paper we demonstrate the use of stellar occultation imaging to place an upper bound on volume of such a shadowed hemisphere. Thirty-three sets of images of the night side limb of Mercury, acquired by the Mercury Dual Imaging System (MDIS) wide-angle camera (WAC) on MESSENGER, were used to bound the radius of that planet's night side. The maximum radius determined from this limited image set agrees with the actual radius to within ~0.1%. We show, by simulation, expected performance of a campaign of such night side limb images to bound the shape of an irregular, high-obliquity asteroid encountered at solstice. We assumed a body the size and shape of Deimos imaged from a 40-km radius orbit by an imager having specifications of the MDIS/WAC but an updated detector sensitive to mv ~ 10 stars, and a day-side stereo imaging campaign by a well-calibrated camera system. From an equatorial orbit, with one hemisphere in shadow, a campaign of ≥ 150 night side limb images determines volume of the shadowed hemisphere to ~4 to 6% accuracy. Increasing orbital inclination to improve sampling of high latitudes decreases residuals for the dark hemisphere by 2 to 3%, for the same number of images. A ~2 to 3% uncertainty in global volume – from stereo imaging of illuminated terrain and stellar occultation imaging of shadowed terrain – compares favorably to uncertainty of up to ±25% in the absence of direct measurements of the radius of the shadowed hemisphere.



## 1. Introduction

Shape is a fundamental measurement of small asteroidal bodies that provides insights into geologic evolution and interior structure. Most basically, it provides a measure of volume. Dividing mass, measured from radiometric tracking of the perturbation to spacecraft velocity during a flyby (e.g., Yeomans et al., 2000), from orbital period during a rendezvous accounting for higher-order gravitational terms (e.g., Greenberg, 1981; Miller et al., 2002), or from the orbital period of a natural satellite (e.g., Belton et al., 1995), by volume provides bulk density. A complementary physical measurement to bulk density, composition, can be ascertained by infrared spectroscopy (e.g., Izenberg et al., 2003; Abe et al., 2006) or elemental abundance measurements (e.g., McSween et al., 2013; Peplowski et al., 2015). Comparison of the density expected for the inferred composition (Consolmagno et al., 2008) with the measured bulk density yields an estimate of internal porosity. As porosity of an asteroidal body increases and its mechanical coherence decreases, internal structure transitions through four classes described by Wilkison et al. (2002) and Britt et al. (2002): coherent, with minimal macroporosity[1]; fractured but mechanically coherent, with up to 20% macroporosity; heavily fractured, with 20–30% macroporosity; and loosely consolidated or rubble pile, with ≥ 30% macroporosity.

Shape of a small body can also provide additional insights into geological and geophysical parameters. Combined with mass, a global shape model allows slopes relative to an equipotential surface to be determined, providing a framework for interpreting mass wasting processes (e.g., Thomas et al., 1996a, 1996b; 2002).

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[1] Porosity of a small asteroid can be separated into two types, microporosity between mineral grains that is not easily lost by compaction under very low gravity, and macroporosity due to large fractures and voids between pieces of loose rubble.

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Shape, combined with structural features, can be used to investigate whether an elongate body with protuberances may be a contact binary with the contact buried by regolith, a question pursued at Ida (Thomas et al., 1996b) and Itokawa (Fujiwara et al., 2006). Planar surfaces on faceted asteroids such as Gaspra can be compared with orientation of structural features such as grooves to search for internal structural fabric (e.g., Thomas et al., 1994).

For most asteroids encountered by spacecraft, shape has been determined by imaging, and accuracy of that determination depends on spatial resolution of coverage at different geometries, the availability of limb profiles (Thomas et al., 1994, 1996b), the fraction of the body in shadow (during a flyby, or seasonally during a rendezvous) (Thomas et al., 1999; Jaumann et al., 2014), and the accuracy of knowledge of the camera focal length, distortion, and pointing. Consider the effect of resolution, illustrated by the flybys of Gaspra and Ida by Galileo. Neither Gaspra nor Ida had a very large fraction of terrain in seasonal shadow. However compared to Ida, Gaspra is smaller (954 $km^3$) and has a longer rotational period (7.04 h), so that over the ~85% of a rotation that was observed, the small number of pixels subtended in the most distant views led to ~21% uncertainty in volume (Thomas et al., 1994). In contrast Ida is larger (16,100 $km^3$) and has a shorter rotational period (4.63 h), such that the more pixels subtended resulted in a much lower uncertainly (~12%) despite a more complex shape and smaller fraction of a rotation observed (~76%) (Thomas et al., 1996b). Consider also the example of the Near Earth Asteroid Rendezvous (NEAR) flyby of Mathilde and the Rosetta flyby of Lutetia. Mathilde has such a long rotational period (17.7 d) that less than half the surface was observed illuminated. *Ad hoc* estimates of hidden topography in Mathilde's shadowed hemisphere suggested to Thomas et al. (1999) a ~25% uncertainty in volume, which dominated the uncertainty in estimated bulk density. Lutetia has high obliquity and was near solstice during Rosetta's flyby, so one hemisphere remained in shadow. However the very large size of the asteroid (500,000 $km^3$) and its high albedo ($0.19 \pm 0.1$) facilitated light-curve analysis and ground-based imaging preceding the flyby that, together with spacecraft imaging, allowed construction of shape model with an estimated uncertainty of only ~8% (Sierks et al., 2011; Carry et al., 2012).

Even during a rendezvous mission, seasonal shadow and uncertainties in stereo methods (e.g., stereophotoclinometry and stereo photogrammetry) leave uncertainties. Uncertainties resulting from stereo methods are estimated at between <1% at Vesta (Ermakov et al., 2014) and ~5% at Itokawa (Fujiwara et al., 2006), dependent on accuracies in knowledge of camera focal length, distortion, and pointing. Active ranging decreases these errors, for example to ~1% at Eros using laser altimetry combined with accurate orbital reconstructions (Miller et al., 2002).

In this paper we consider a case analogous that of Lutetia, a body with near 90° obliquity observed at close to solstice, so that most of one hemisphere is in shadow. Unlike the case of Lutetia, we assume a low-albedo body so small and distant that ground-based measurements to augment spacecraft data would be much less effective. Such a case could be posed by a small (<25 km diameter), very low albedo (≤7%) Trojan asteroid observed during a Trojan Tour and Rendezvous mission as described in the Planetary Science Decadal Survey (Squyres et al., 2011). We demonstrate that imaging of stellar occultations by the night side limb is capable of constraining shape of the seasonally shadowed hemisphere, and of reducing uncertainty in shape by an order of magnitude compared with a case like Mathilde where shape of the shadowed terrain is unconstrained, without the need for instrumentation beyond the camera. This demonstration is accomplished in two parts: by demonstrating accurate measurement of the diameter of the night side of Mercury using stellar occultation images of Mercury's night side limb acquired by MESSENGER/MDIS, and then by simulating a campaign of night side stellar occultation limb imaging during a Trojan rendezvous mission, using a similar camera except with a modern, more sensitive detector capable of imaging fainter stars. We demonstrate effects of the number of images in such a survey, and of the inclination of the orbit in reducing residuals in the shape and volume estimate. Finally, we discuss advantages and disadvantages of this technique compared with other passive and active remote techniques.

## 2. Methods

### 2.1. Limb measurements of mercury

Limb images of the night side of Mercury were acquired by MDIS/WAC (Hawkins et al., 2007) as sets of 9 images, on 11 orbits between 5 November 2014 and 3 March 2015. In each case, the clear filter was used, 9989-ms exposures were acquired, and the 10.5° × 10.5° field-of view (FOV) was placed on the night side limb away from the illuminated part of Mercury to minimize scattered light. Onboard 2 × 2 pixel binning was applied, reducing the unbinned 1024 × 1024 pixel images to 512 × 512 pixels. On each orbit, three sets of three images were taken, one set each with the night side of Mercury filling ~25%, ~50%, and ~75% of the FOV. Fig. 1 shows a representative image that has been filtered to highlight detail: stars are detected above the nightside limb, and the limb itself is clearly delineated by its blockage of faint emissions by Mercury's exosphere.

A similar processing routine was applied to each image to reduce noise and subtract dark current. These steps yield lower residuals for long-exposure star images than does the calibration pipeline applied to much shorter-exposure images of Mercury (Murchie, 2016). First, the first pixel in each row of a binned image is behind an opaque mask and unexposed to light, thus providing an estimate of the dark current accumulation in that row of the CCD. This value is subtracted from the entire row. Second, the dark current subtracted image is processed through a high-pass filter, removing the low-frequency residuals in dark current or scattered

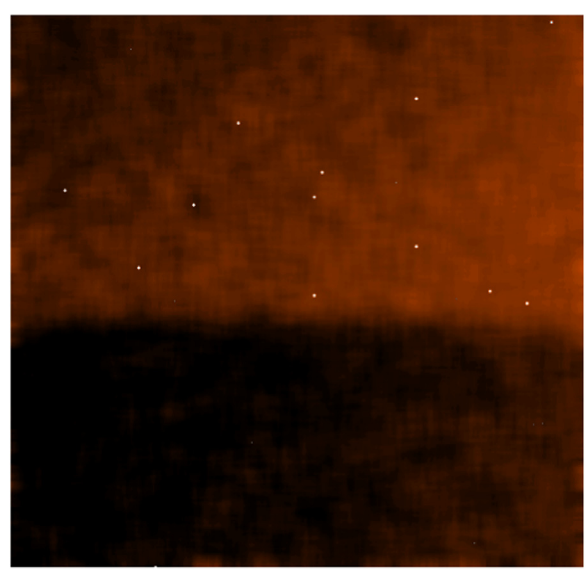

**Fig. 1.** Processed version of MDIS WAC image CW1057966058B, one of the 99 limb images acquired as part of the nightside limb imaging experiment. A despiking technique was used to enhance brighter stars, and the resulting image was overlain on a low-pass filtered image (false-colored orange). The low-pass filtered image highlights emissions from Mercury's exosphere, which indicate the position of the limb. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)