THE SHAPES OF SIMPLE CRATERS IN THE OUTER SOLAR SYSTEM DETERMINED WITH AN ENHANCED SHADOW MEASUREMENT TECHNIQUE. R. R. Herrick, Geophysical Institute, University of Alaska Fairbanks, Fairbanks, AK 99775-7320 (rherrick@gi.alaska.edu)

Introduction: Chappelow [1,2] developed an "enhanced" shadow measurement technique that allows determination of crater shape (parabolic, hemispheric, etc.) and rim-floor depth *d* for any crater whose shape is a conic section of revolution; simple craters on the planets are generally well described by this shape. A key advantage of the enhanced shadow measurement method is that the shadow front does not need to pass through the crater center (i.e., the deepest point in the crater) in order to accurately determine depth. The methodology involves fitting an ellipse to the shadow front (Figure 1), and the shape and position of the ellipse uniquely determine the shape of the conic section and the crater depth. The method originally was restricted to nadir-pointing images, but subsequently a method was developed to account for the parallax of the shadow tip with non-zero emission angles [3]. Here I further test and calibrate the enhanced shadow measurement (ESM) method, and then I use it to survey the simple crater populations on the outer-planet satellites Rhea, Miranda, Phoebe, and Hyperion.

Figure 1. Simple crater shadow front traces part of an ellipse.

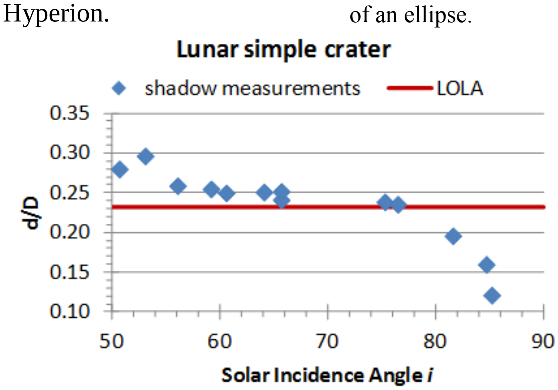

Figure 2. Variation of *d/D* with *i* for test lunar crater (*D* = 3.8 km, at 1.83 S, 351.81 E). Solid line is LOLA data.

Calibration and Variation with Incidence Angle: In Barnouin et al. [3] ESMs were found to produce results consistent with MESSENGER altimetry, but there was some question as to whether the method produced a systematic variation in depth/Diameter (*d/D*) ratio with solar incidence angle *i* (the angle of the sun relative to surface normal). To further evaluate the methodology I examined a simple lunar mare crater (*D* = 3.8 at 1.83 S, 351.81E) that has good LOLA coverage and was imaged by LROC over a wide range of incidence angles. WAC images were used at 60-150 m/pixel, so that the crater is ~25-60 pixels across, and formal error for *d* is ~15-40 m. For each LROC image I made three ESMs of the crater. The resulting values of *d/D* were always within 20% of the median in each image, and for *i* < 80 they were within 10%. In Figure 2 I show the median value of *d/D* for each image vs. *i* along with a horizontal line for *d/D* from the gridded LOLA data (*d* = 870, *d/D* = 0.23). For 55° < *i* < 77° (corresponding to shadow lengths of ~0.3-0.75 *D*) there is a small, but systematic decrease in *d* from a median of 990 to 900 m (10%), with lower and higher values of *i* showing unrealistic values. The LOLA-derived depth is a few tens of meters less than the ESMs, and I attribute this to the LOLA altimeter not quite sampling the rim crest and that there is a small amount of floor debris that makes the crater not quite parabolic. Based on these initial tests, to avoid major errors I recommend limiting ESMs to shadows that extend from the rim to ~0.3-0.75 *D*. Within this range of shadow lengths one could choose to detrend with respect to *i* empirically or assume a ±5% variation about the value of *d/D* where the shadow crosses crater center. I also found that parallax correction was important even for seemingly modest emission angles of 10°-20°. Finally, I note that depths derived from shadow measurements should be deeper than altimetry- and stereo-derived sources, and more accurate, if those other methods do not sample fine enough to capture both the narrow rim and the floor center. My experience is that reasonable depths from ESMs can be obtained for craters with *D* ~10x image resolution, but good stereo-derived depths can only be obtained for *D* > 30x the lowest resolution image of the stereo pair.

Results for Icy Satellites: Using the ESM method, I have begun a survey of craters on outer planet satellites. These are objects for which no altimetry exists and stereo-derived topography is generally limited in resolution. I began the survey by looking at four bodies: Rhea, a largely inactive moon of Saturn that should provide a baseline for "typical" icy satellite depths; the Uranian moon Miranda, whose initial *d/D* values [4] now seem at odds with Galileo-era measurements [5] of other moons; and Hyperion and Phoebe, two small, irregularly shaped moons of Saturn, the latter thought to be a captured body [6].

For Rhea, I made measurements from an initial set of three Cassini ISS images, one at a resolution of 40 m/pixel and two at 260 m/pixel. For 62° < *i* < 78°, I saw no correlation of *d/D* with *i*, and Figure 3 shows *d/D* versus *D* for this range of incidence angles. The data span 300 m < *D* < 12 km and show no obvious trend of *d/D* with *D*. The mean value of *d/D* is 0.197±0.032. This is consistent with stereo-derived depths for Rhea in [7] and simple craters on the Galilean satellites in [5], but higher than those for Rhea in [8]. I also do not see the drop in *d/D* for *D* < 1 km that is described in [8].

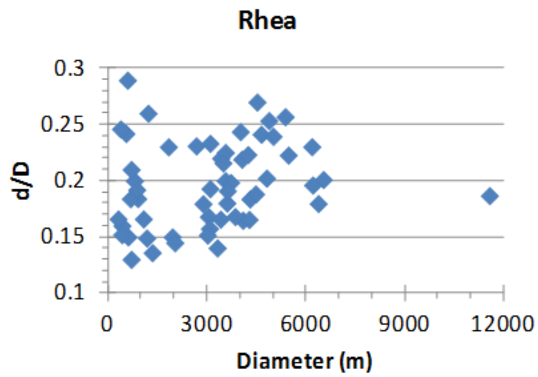

Figure 3. *d/D* versus *D* for simple craters on Rhea.

Two Voyager frames with resolutions of 240 and 270 m/pixel were used for Miranda. Once again, for 62° < *i* < 78°, I saw no correlation of *d/D* with *i*. Figure 4 shows *d/D* versus *D* for this range of incidence angles. For 2 km < D < 13 km, I see no dependence of *d/D* with *D*. The mean value of *d/D* is 0.195±0.016. These *d/D* values are consistent with other "typical" icy satellites, but higher than the initial post-Voyager Miranda measurements of [4], which were primarily based on photoclinometry.

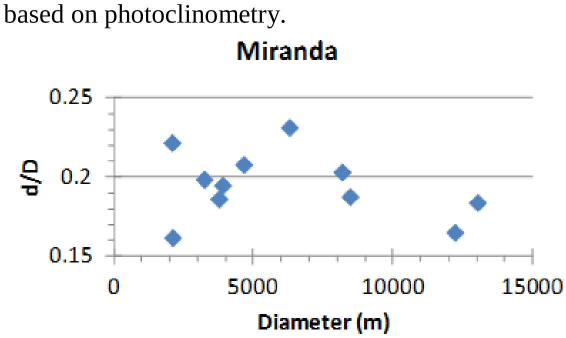

Figure 4. *d/D* versus *D* for simple craters on Miranda.

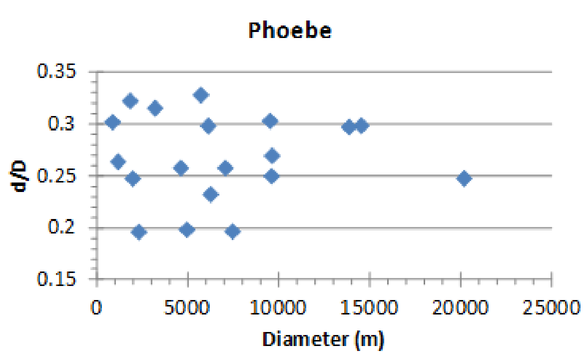

Figure 5. *d/D* versus *D* for simple craters on Phoebe.

Two Cassini images with resolutions of 89 and 194 m/pixel were used to examine Phoebe's craters. For 56° < *i* < 78° there was no correlation of *d/D* with *i*. Figure 5 shows *d/D* versus *D* for this range of incidence angles. For 850 m < *D* < 20 km, I see no trend of *d/D* with *D*. The mean value of *d/D* is 0.268±0.035, consistent with stereo-derived profiles in [9].

Incidence angles for many of the shadows on Hyperion cannot be reliably estimated because the moon's highly irregular shape makes local slopes deviate from the spheroidal model assumed in the ISIS software. I found one image where the spacecraft facing surface was relatively well-behaved with good shadows, and I was able to determine a handful of *d/D* values (Figure 6). For 68° < *i* < 79° and 1.8 < *D* < 10.6 km, no dependence of *d/D* on *D* is observed, and the mean *d/D* is .253±0.051.

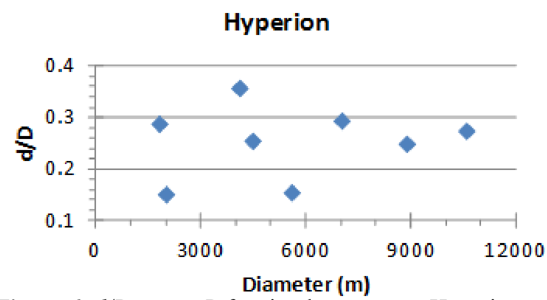

Figure 6. *d/D* versus *D* for simple craters on Hyperion

Analysis of the shape information is very preliminary, but generally craters on Rhea and Miranda are roughly parabolic (and lunar-like) in cross-section, while Phoebe craters are more hyperbolic (conical) and Hyperion's craters are elliptical (bowl-shaped).

Discussion and Future Work: The enhanced shadow measurement method produces reliable results and should prove particularly valuable for studying icy moons and asteroids. Rhea and Miranda generally have "typical" simple craters with *d/D* similar to the Galilean satellites and the terrestrial planets. Phoebe and Hyperion both seem to have unusually deep craters, although probably from different causes. Craters may be strength-controlled on Phoebe, while Hyperion is an exceptionally porous target.

References: [1] Chappelow J. E. and Sharpton V. L. (2002) *MAPS, 37*, 479-486. [2] Chappelow J. E. (2008) *LPSC 38*, #1441. [3] Barnouin O. S. (2012) *Icarus, 219*, 414-427. [4] Schenk P. M. (1989) *JGR, 94*, 3813-3832. [5] Schenk P. M. (2002) *Nature, 417*, 419-421. [6] Johnson T. V. and Lunine J. I. (2005) *Nature*, *435*, 69-71. [7] White O. L. and P. M. Schenk (2011) *LPSC 42*, #2283. [8] Rivera-Valentin E. G. et al. (2012) *LPSC 43*, #2042. [9] Giese B. et al. (2006) *PSS*, *54*, 1156-1166.

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