SHAPE MODELING VALIDATION FOR THE DOUBLE ASTEROID REDIRECTION TEST (DART).
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Introduction: The Double Asteroid Redirection Test (DART) mission is the kinetic impactor experiment to demonstrate asteroid impact hazard mitigation. The DART mission is targeting the near-Earth binary asteroid system 65803 Didymos. The spacecraft will collide with the moon in the system, Didymos B. One of the mission requirements is to determine the momentum imparted to Didymos B by the impact. Target porosity can affect momentum transfer, the orbital velocity change that results from the impact, and resulting crater morphology [1]. The coupling of an impactor's energy and momentum to the target can be affected by local topography(e.g., slopes) [2] and geology [3].

An accurate shape model can provide both the global volume of Didymos B and the local tilts and topography of the impact site, thereby providing critical constraints to post-impact estimates of the momentum enhancement factor, β, and aiding the interpretation of all aspects of the deflection test. Here we assess how accurately we will be able to model the shape of Didymos B during the proximity operations undertaken by the DART spacecraft, primarily using imaging data from the Didymos Reconnaissance and Asteroid Camera for OpNav (DRACO) instrument.

Imaging timeline: The DRACO imaging campaign can be split into three phases:

(1) *Long-range phase*: This phase provides lightcurves at viewing geometries complementary to those obtainable by ground-based telescopes. It begins when the Didymos system is first detected by DRACO, about 30 days before impact. The Didymos system will not be resolved during most of this phase. Using approaches employed in previous efforts [4–6], these lightcurves will be used to tighten constraints on the rotation rate and shape of Didymos A and the orbital period and shape of Didymos B. The long-range images also will be used to search for additional satellites.

(2) *Terminal phase*: The terminal phase begins when the spacecraft initiates autonomous navigation a few hours prior to impact. During this phase, Didymos A and B can be separately resolved and DRACO images support both autonomous navigation and asteroid characterization. By the end of this phase, images of Didymos B will have a pixel scale of ~3.5 m.

(3) *Final phase*: The final phase comprises the last ~4 minutes of the DART mission. In the current operational plans, at ~17 s prior to impact, DRACO will image with a pixel scale ≤50 cm. Higher-spatial-resolution data will continue to be acquired in the final seconds of the mission. Planned real-time DSN coverage enables downlink of the images acquired up to 5 seconds before impact (which will have as good as ~15 cm pixel scale), and possibly including even higher-resolution images acquired during the final 5 seconds prior to impact.

Methods: Figure 1 summarizes the currently planned shape modeling workflow for the DART mission. It is based on the general approach used to model the shape of the asteroid Lutetia [7], which was observed during a flyby of the Rosetta spacecraft. We will use light curve data from Earth and the last stages of the long-range phase to develop an initial model of Didymos B. This model will be used as the starting point to develop a final shape model that makes use of resolved images. Images where Didymos B is more than ~50–100 pixels across images will be used to provide limb points and to create a model using stereophotoclinometry (SPC). SPC combines traditional geometric stereogrammetry with photoclinometry to achieve a level of precision unobtainable with either method alone [8].

SPC has been used successfully to develop high-resolution shape models of a variety of small bodies, including Eros [9], Itokawa [10], Phobos [11], Phoebe [12], Lutetia [13], and comet 67/P Churyumov-Gerasimenko [14], among others. The method is also integral to the altimetry and shape modeling efforts for the OSIRIS-REx [15] and Hayabusa2 missions [16]. Comparisons between the SPC shape model of Bennu and lidar scans from the OSIRIS-REx laser altimeter demonstrate that SPC can generate precise, accurate shape models [17].

However, the DART mission poses significant challenges for SPC shape modeling that typical flyby missions do not. Because the DART spacecraft is on a collision course with Didymos B, the DRACO images in which Didymos B is sufficiently resolved for use in SPC will have effectively no stereo or illumination variation. We have begun to test how accurately SPC alone can be used to develop a shape model of Didymos B given these constrains. To do so, we used a scaled-down shape and albedo model of Itokawa and a realistic trajectory to simulate DRACO images of Didymos B. We chose a challenging scenario: we view the elongated part of Itokawa, including the concavity at its neck. We also used a triaxial ellipsoid, rather than a lightcurve-based shape, as a starting point. For this first test, we assumed no uncertainties in the spacecraft trajectory and pointing. This study provides a limiting worst-case for the shape and volume estimates.

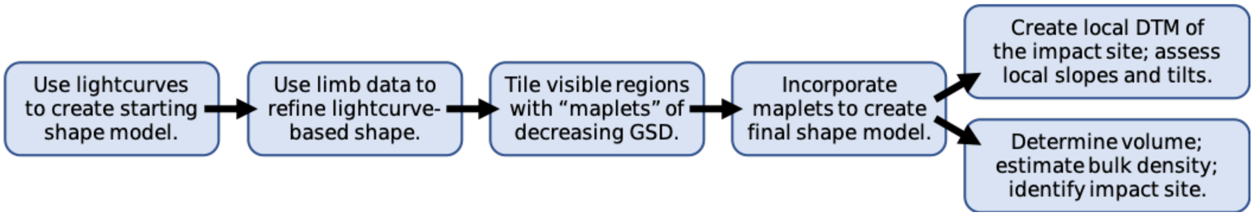

Figure 1. Preliminary DART shape modeling strategy. First, ground and spacecraft-based lightcurves will be used to create a preliminary shape model. Next, limb points identified in DRACO images will be used to further refine the lightcurve-derived shape. SPC will then be used to tile the limb+lightcurve-based shape model with DRACO-image-based "maplets" of progressively finer spatial resolution to model the topography and albedo of landmarks on the surface. A global shape model will then be created by incorporating the information in all of the maplets. This global model will provide the estimated volume of Didymos B. We will create a higher-resolution, localized digital terrain model (DTM) of the impact point to characterize the the tilts, slopes, and elevation of the impact site.

Initial Results. Preliminary results (Figure 2) show that we can estimate the simulated Didymos B shape to 35% volume error and 11% surface area error. The largest contributor to this uncertainty comes from the shape of the unseen side of the body. It is important to note that these values overestimate the uncertainty we will actually achieve: this test case did not include lightcurve information; the starting triaxial ellipsoid was too large; and this initial estimate does not include any attempt to mirror the asteroid. Improvements to each of these factors would further reduce the volume error by improving the shape of the unseen side. Additional processing will further improve the Didymos B model. Indeed, if we mirror the preliminary SPCv1 model of the visible part of the body onto the unseen side, the volume error is <25%. In a flyby mission (as opposed to an impact mission like DART), SPC will produce ever better volume estimates because of the added additional stereo and increased surface coverage of the images.

Future work: Once the current test case is completed, we will introduce errors into the spacecraft and pointing knowledge and repeat the test, and will perform tests using different truth shape models (e.g., non-elongate Bennu). We will also use lightcurve- or radar-based shapes as starting models. Based on these tests, we will formalize our procedure for the DART mission.

We will also evaluate the extent to which images from the LICIA CubeSat provided by the Italian Space Agency will improve the shape model. The LICIA CubeSat will be deployed from the DART spacecraft prior to impact and provide additional images. We expect the LICIA images to add significant stereo, thereby improving the quality of the Didymos B shape model.

References: [1] Stickle, A.M. et al. (2017) *Proc. Eng.,* 204, 116 – 123. [2] Aschauer and Kenkmann (2017) *Icarus*, 89 – 95. [3] Susorney, H.C.M. et al., 2017. *Procedia Engineering*, 204, pp.421–428. [4] Pravec, P. et al. (2006). *Icarus*, 181:63–93. [5] Viikinkoski, M., Kaasalainen, M., and Ďurech, J. (2015). *Astro. & Astrophys.*, 576, A8–11. [6] Weaver, H.A. et al., 2016. *Science*, 351(6), aae0030. [7] Sierks, H. et al. (2011). *Science*, 334, 487–490. [8] Gaskell, R.W. et al. *MAPS* 43:1049-1061. [9] Gaskell (2008) Gaskell Eros Shape Model V1.0, PDS. [10] Gaskell et al. (2008) Gaskell Itokawa Shape Model V1.0, PDS. [11] Gaskell (2011) Phobos Shape Model V1.0, PDS. [12] Gaskell (2011) Phoebe Shape Model V1.0, PDS. [13] Farnham (2013) Shape Model of Asteroid 21 Lutetia V1.0, PDS. [14] Jorda et al. (2015) SPC SHAP2 Cartesian plate model for comet 67P/C V1.0, PDS. [15] Weirich et al. (2017) *LPS48,* abs. 1700. [16] Hirata, N. et al. (2018) *AGU*, abs. P22A-06. [17] Barnouin, O.S. et al. (this meeting).

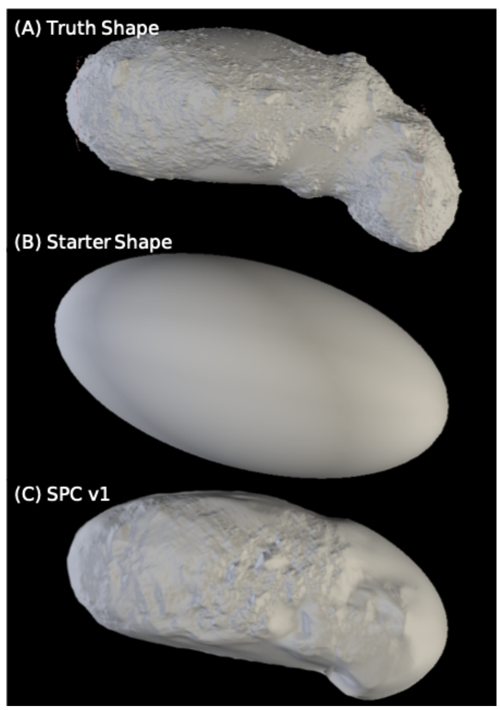

Figure 2. Preliminary results. All shapes are oriented as viewed by the simulated DART spacecraft. (A) The truth shape model that was used to simulate DRACO images. (B) The initial starting triaxial ellipsoid. (C) The preliminary SPC-based shape model.