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The global topography of Bennu: altimetry, photoclinometry, and processing

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1. OSIRIS-REx

The Origins, Spectral Interpretation, Resource Identification, and Security–Regolith Explorer (OSIRIS-REx) mission will spend two years observing (101955) Bennu and will then return pristine samples of carbonaceous material from the asteroid [1]. Launched in September 2016, OSIRIS-REx arrives at Bennu in August 2018, acquires a sample in July 2020, and returns the sample to Earth in September 2023. The instruments onboard OSIRIS-REx will measure the physical and chemical properties of this B-class asteroid, a subclass within the larger group of C-complex asteroids that might be organic-rich. At approximately 500m in average diameter [2], Bennu is sufficiently large to retain substantial regolith and as an Apollo asteroid with a low inclination (6°), it is one of the most accessible primitive near-Earth asteroid.

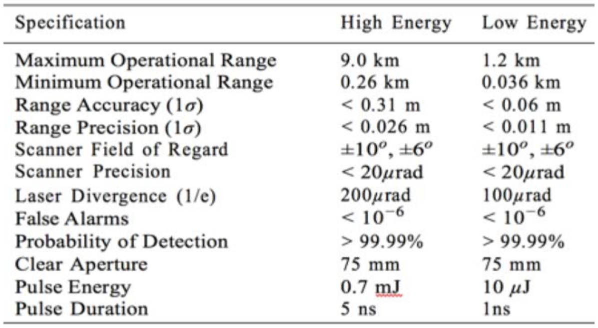
2. The AltWG

The Altimetry Working Group (AltWG) produces local and global topographic maps (digital terrain maps or DTMs) for science objectives [2] and for navigation, including Natural Feature Tracking (NFT) [3] used to autonomously guide OSIRIS-REx to the sample location on Bennu's surface. The AltWG generates the DTMs using two independent processes and datasets: stereo-photoclinometry (SPC) processing [4, 5] of images and analysis of range data obtained by the OSIRIS-REx Laser Altimeter (OLA [6]). The AltWG produces detailed data on the craters, surface topography, and data essential for interior-structure modeling. The DTMs are essential for characterizing the candidate sample sites, assessing their viability and value for sampling, and providing high-resolution feature for NFT. With each global DTM, the AltWG produces a suite of ancillary data that include gravitational potential, slope, and tilt maps. Combining OLA data with the SPC products generates the final, highest-fidelity version of these products [7]. The AltWG created a high-resolution (5cm) "truth" shape model of Bennu to develop and test processing and analysis tools.

3. OLA instrument

OLA is a dual-transmitter, high-rate scanning laser altimeter, built by MDA, and contributed by the Canadian Space Agency. During the Orbit-B phase of the mission, OLA will obtain global coverage in 6°x6° scans acquired every 2.5 minutes using the low-energy laser. Each scan covers a 80x80m section of the surface with 1.3×10^6 measurements with 7-cm spacing and spot size. During the Reconnaissance Phase, the spot size and spacing decrease to 2.5 cm.

Table 1: OLA performance and key characteristics for both the high- and low-energy modes.



Specification	High Energy	Low Energy
Maximum Operational Range	9.0 km	1.2 km
Minimum Operational Range	0.26 km	0.036 km
Range Accuracy (1σ)	< 0.31 m	< 0.06 m
Range Precision (1σ)	< 0.026 m	< 0.011 m
Scanner Field of Regard	$\pm 10^o, \pm 6^o$	$\pm 10^o, \pm 6^o$
Scanner Precision	$< 20\mu$rad	$< 20\mu$rad
Laser Divergence (1/e)	200μrad	100μrad
False Alarms	$< 10^{-6}$	$< 10^{-6}$
Probability of Detection	$> 99.99\%$	$> 99.99\%$
Clear Aperture	75 mm	75 mm
Pulse Energy	0.7 mJ	10 μJ
Pulse Duration	5 ns	1ns

4. OLA processing

Using the truth model of Bennu, we constructed an OLA test dataset that included statistical variations in range, trajectory, and pointing that were consistent with anticipated uncertainty in the reconstructed parameters. The simulations included the effects of laser beam divergence. The result is a set of 340 to 370 overlapping, ~80m x 80m raster scans or 3-D point clouds of the asteroid surface, each containing approximately 1.3 million laser range returns.

A keypoint-matching method reduces the data processing by registering hundreds of keypoints rather than the entire point cloud. Keypoints are features with distinctive characteristics that can be located and registered between scans. First, the ranges in each scan are converted to a 10-cm grid using the Generic Mapping Tools (GMT [8]). The 2-D Laplacian of these surfaces is then calculated to remove the curvature. VLFeat tools [9] locate keypoints and calculate keypoint descriptors, which are 128-bit representations of the local surface gradients. A VLFeat algorithm finds the matching keypoints between each pair of overlapping scans, and initial global registration is performed by sequentially registering each scan to the overlapping keypoints of the previous scans using an Iterative Closest Point (ICP) algorithm. All registration is by rigid rotation and translation.

During the sequential registration, alignment errors accumulate and propagate. An iterative Generalized Procrustes Analysis (GPA [10]) is used to globally distribute registration errors. The last step is to apply the final transform of the keypoints of each scan to all the ranges in each point cloud and to construct a gridded global shape model. Fig. 1 shows the result of one test of the process. Later, high-resolution OLA scans, with 2-3 cm ground sample distance (GSD), are individually registered to the global shape model.

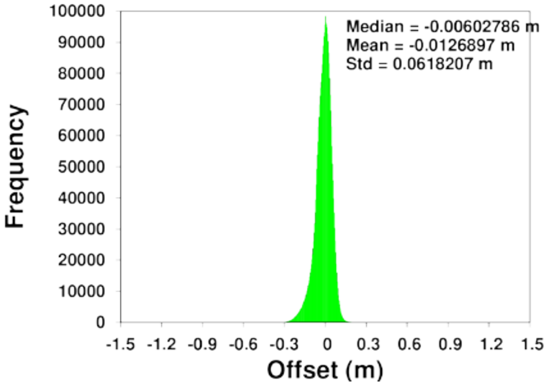


Figure 1: Difference histogram between the truth model and a DTM constructed from simulated OLA data. The requirement is 14-cm accuracy.

5. SPC processing

By analysing the brightness of pixels illuminated at different angles, the SPC process constructs slope and topography maps of the surface. The intermediate products are a set of landmark maps that can be used to build DTMs that match the best resolution of the source images. SPC has been used to produce accurate DTMs of Eros, Phobos, Mimas, Lutetia, Itokawa, Vesta, comet 67P, Mercury, and the Moon [c.f., 4, 5, 11]. To assess SPC performance at Bennu, we used the baseline observing plan to independently simulate 7,000 images of Bennu from the truth model, and then used SPC to generate a shape model using those images. The simulated images included trajectory and pointing errors. SPC will produce a 75-cm global model two weeks after the Preliminary Survey phase, and a 35-cm global model after the Detailed Survey phase. These DTMs will support optical navigation around Bennu.

SPC processing requires a range of incidence and emission angles, and the baseline mission [1] provides a data set that is sufficient for SPC to generate the required models. The height root mean squared (RMS) value between the truth and model shapes bettered the mission requirement of 75cm with a 51-cm RMS. For global models with 18-cm GSD, the RMS was 10cm. SPC will also produce local DTMs with smaller GSD. Fig. 2 shows a cross section of the truth and model over the sample site, and illustrates the excellent performance of the SPC-model. For smaller DTMs with GSD <35cm, we also use a cross-correlation technique to evaluate topography, the same technique to be used by the spacecraft to navigate to the sample site.

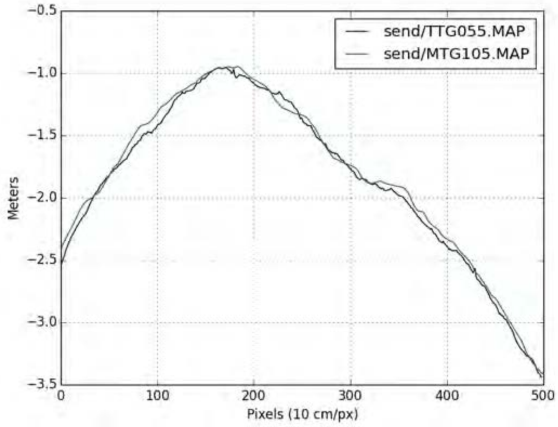


Figure 2: Cross-section of sample site showing model (green) and truth (black). The GSD is 10cm.

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