SHAPE MODEL CONSTRUCTION OF BENNU USING THE OSIRIS-REX LASER ALTIMETER (OLA).
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Introduction: During a part of the OSIRIS-REx mission's proximity operations at asteroid 101955 Bennu, the OSIRIS-REx Laser Altimieter (OLA) will take high resolution (spot spacing of ~7cm) raster scans of the surface at a rate of 10 KHz using its two-axis scanning mirror . The orbits during this phase will allow OLA to obtain overlapping scans across the entire surface of Bennu. From this high spatial-resolution data set, a high fidelity shape model of Bennu will be generated. Here we present an one of our two approaches to minimize 3D offsets between overlapping scans (strip adjustment) due to spacecraft position and pointing uncertainties. This approach will be used to create a shape model of Bennu with low dependence on spacecraft position and pointing knowledge in contrast to the second method that has a greater dependence on spacecraft state.

Data: A high-resolution (5cm) "truth" shape model of Bennu (Figure 1) was used to simulate the performance of OLA. The OLA simulation used ray casting in order to determine ranges between the shape model and the outgoing laser pulses. The origin and direction of these pulses were determined from pre-calculated OSIRIS-REx orbit orientations, along with simulated OLA mirror scan patterns. The simulations incorporated instrumental uncertainties in ranging (±3cm, 1σ), along with a method for taking into account the effects of laser beam divergence. The result of these simulations is a data set containing 370 overlapping ~80m x 80m raster scans of the asteroid surface, each containing approximately 1.3 million laser range returns.

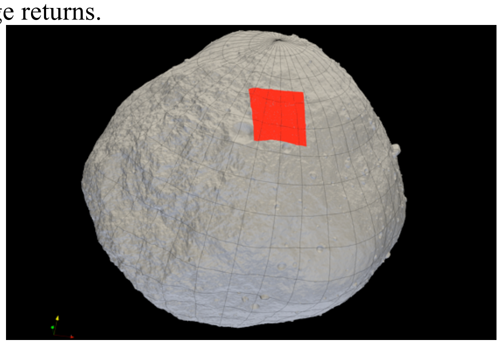

Figure 1: Bennu truth shape model overlayed with an OLA simulated raster scan in red.

Method: Due to the volume of data generated (over 400 million points), a fast data reduction method is required in order to perform strip adjustments in a reasonable amount of time (hours rather than days or weeks). A keypoint, i.e. a feature, matching method has been implemented to find common features, which vastly reduces the number of points that are considered during the point cloud registration process. As a rough first step, offsets between overlapping data are sequentially corrected by using rigid transformations (rotation and translation) on each of the raster scans. A Generalized Procrustes Analysis (GPA [1]) is performed in order to globally distribute alignment errors and to perform the final registration of each data set position. The result is a larger self-consistent data set that, through adding raster scans, can be built into a closed shape model.

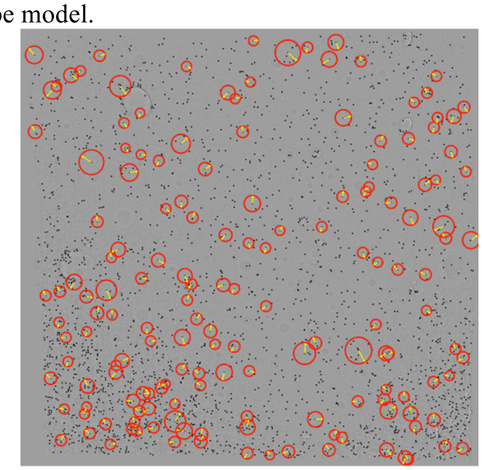

Figure 2: Laplacian surface with calculated keypoints (black). For select keypoints the associated scale and orientation (red and yellow) are shown.

Keypoint determination. After the filtering of invalid range returns, the point clouds (*x,y,z* Cartesian Coordinates) representing the surface of Bennu are processed using The Generic Mapping Tool (GMT [2]) to create gridded surfaces (10cm resolution) of each of the raster scans. The 2D Laplacian of these surfaces is then calculated in order to remove the curvature and generate a surface that represents the edges of features on the surface. These edge data is output as 8-bit grayscale images that are then processed using the VLFeat library [3] in order to calculate keypoints and keypoint descriptors for each of the raster scans (Figure 2).

For each keypoint, a 128-bit keypoint descriptor is calculated that describes the local surface gradients. A keypoint matching algorithm is run on these descriptors to find matching features between overlapping data sets. The keypoint correspondences are then used in place of the full data set, which dramatically reduces the time required to process the OLA data.

Strip adjustment. A two stage registration process begins once a list of feature correspondences has been determined. During the initial registration stage, one set of raster keypoints is chosen as the base set in which to sequentially build a keypoint shape one cloud at a time. The matching feature list is searched for the set of keypoints with the largest number of feature matches to the keypoint shape. A least-squares distance minimization (a variant of the Iterative Closest Point algorithm) between the current set of keypoints (from an unregistered raster scan), and keypoint shape is performed to transform rigidly the position of the raster (Figure 3). This process continues until no rasters with matching keypoints remain. During this sequential registration approach, alignment errors can accumulate and propagate. In order to minimize these errors a Generalized Procrustes Analysis is performed on the transformed keypoints. The GPA algorithm is an iterative process that uses the reduction in the sum of squared differences between the original and adjusted positions or a maximum number of iterations as termination criteria.

Results: The registered OLA data are ingested into the next step of the processing pipeline which uses GMT to construct a gridded shape model. The GMT output is then resampled to produce a shape model of Bennu containing triangular plates of roughly uniform area. This shape model is then directly compared to the truth model by finding the distance between the plate centroids of the reconstructed model, and the nearest point on the truth model. A histogram of the differences is shown in Figure 4. The standard deviation of the reconstruct is approximately 6cm globally, with a mean difference ~1cm and a median value of ~6mm. A direct comparison map of the plate to plate differences is shown in Figure 5. It is clear that a section of the shape model at 45°E is under-representing the surface by 10-20cm, and one patch near 135°E is under-representing the surface of Bennu by as much as 50cm. Determining the cause of these surface discrepancies will require further investigation. A probable cause is likely improperly filtered OLA data, which results in the creation of surface artifacts during the gridding process or poor filtering of keypoint matches that leads to the use of improperly matched features during the least-squares fitting process.

References: [1] Toldo R. et al. (2010) *3DPVT 2010 Conference*. [2] Wessel P. et al. (2013) *EOS Trans. AGU*, 94, 409–410. [3] Vedaldi A. and Fulkerson B. (2010) *MM '10. ACM*, 1496-1472.

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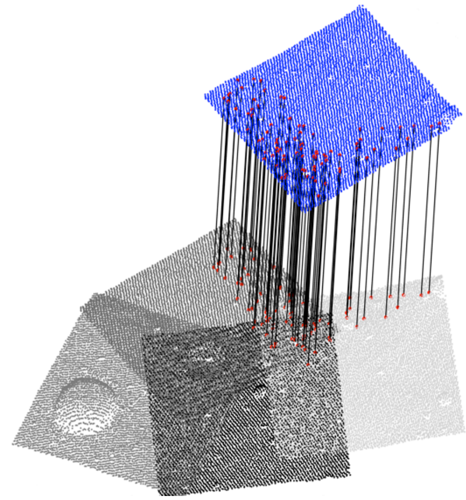

Figure 3: Rough OLA point cloud registration using sequential keypoint matching. Transformed keypoint clouds are added to the keypoint shape.

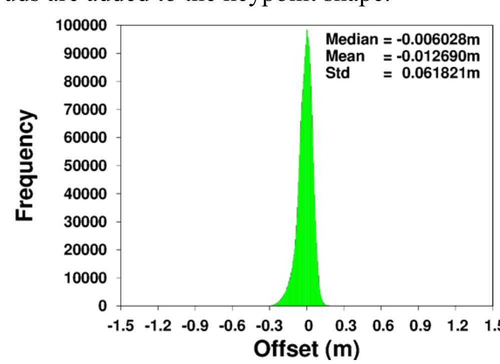

Figure 4: Difference histogram between reconstructed and truth models.

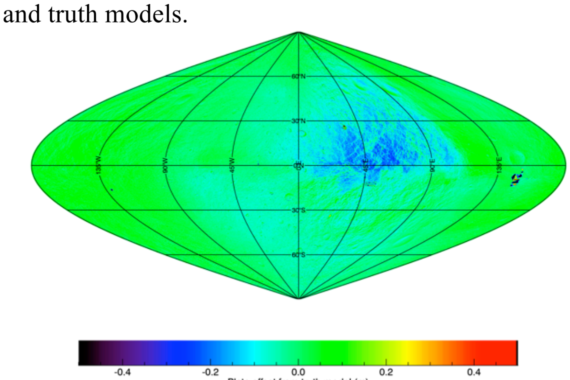

Figure 5: Difference between reconstructed and truth models.