Validation of Stereophotoclinometric Shape Models of Asteroid (101955) Bennu during the OSIRIS-REx Mission

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Received 2020 December 11; revised 2021 February 3; accepted 2021 February 4; published 2021 April 29

Abstract

NASA’s OSIRIS-REx mission to asteroid (101955) Bennu relied on the production of real-time shape models for both spacecraft navigation and scientific analysis. The primary method of constructing shape models during the early phases of the mission was image-based stereophotoclinometry (SPC). The SPC shape models were used for operational planning, navigation, sample site selection, and initial scientific investigations. To this end, detailed analyses of the quality of each shape model and a thorough documentation of all sources of error were vital to ensure proper considerations of the limitations of each model. In this paper, we present methods used during the OSIRIS-REx mission to validate the SPC shape models and construct the associated quality reports. Although developed for the OSIRIS-REx mission, these validation techniques can be applied to SPC-derived shape models of other planetary bodies.

Unified Astronomy Thesaurus concepts: Asteroids (72); Small Solar System bodies (1469); Near-Earth objects (1092)

1. Introduction

NASA’s Origins, Spectral Interpretation, Resource Identification, and Security-Regolith Explorer (OSIRIS-REx) spacecraft launched on 2016 September 8 with the goal of delivering a sample to Earth from asteroid (101955) Bennu (Lauretta et al. 2017). The spacecraft’s approach to, and initial survey of, the asteroid in late 2018–early 2019 showed that Bennu has a spinning-top shape with a mean radius of 244 m (Barnouin et al. 2019) and that its surface is low albedo, rough, and covered with boulders ranging in size from centimeters to tens of meters (DellaGiustina et al. 2019; Lauretta et al. 2019).

A major effort of the OSIRIS-REx Team has been the generation of shape models of the asteroid (Barnouin et al. 2020). Such models are needed for operational decisions (e.g., the selection and characterization of candidate sample collection sites) and spacecraft navigation in the low-gravity environment of such a small asteroid (Antreasian et al. 2016). They are also fundamental scientific data products that provide the framework for the interpretation of scientific data returned by onboard cameras and spectrometers (Lauretta et al. 2017) during the asteroid encounter. One method of generating global and local digital terrain models (DTMs) of Bennu throughout the OSIRIS-REx mission is the technique of stereophotoclinometry (SPC). The technique combines the methods of stereo imaging and photoclinometry to produce DTMs of planetary bodies; it is described in detail in Gaskell (2005) and Gaskell et al. (2008).

Stereo imaging is the process of reconstructing a 3D shape from a pair of images taken at differing but close angles. The images are required to have a similar illumination geometry and pixel scale, as well as significant overlap. Photoclinometry (sometimes referred to as “shape from shading”) is based on the concept that the apparent brightness of a surface in a 2D image depends on the albedo and other surface reflectance properties (e.g., particle size and surface roughness), as well as the angle between the light source and that surface, such that surfaces sloping toward the light source appear brighter than those sloping away. Therefore, photoclinometry requires images taken under different illumination conditions and can be used to reconstruct surface slopes and albedo. The combination of the stereo and photoclinometry techniques removes the limitations on usable images imposed by either technique alone. It enables the use of images with varying illumination conditions, observation geometries, and pixel scales to produce a DTM with a ground sample distance (GSD) close to the inherent spatial resolution of the images. The SPC technique has been used to create global DTMs of various solar system bodies, including the asteroids Eros (Gaskell et al. 2008), Ceres (Park et al. 2019), Vesta (Jaumann et al. 2012), Iokawa (Kawaguchi 2006), and Ryugu (Watanabe et al. 2019); Saturnian satellites Mimas (Gaskell 2013a) and Phoebe (Gaskell 2013b); Galilean moon Io (Gaskell 1988); and Martian satellites Phobos and Deimos (Gaskell 2011; Ernst et al. 2021) and aided in the creation of shape models of Pluto and its moon Charon (Moore et al. 2016) along with stereophotogrammetry.

Alternatively, data collected by the OSIRIS-REx Laser Altimeter (OLA; Daly et al. 2017), which provided direct lidar measurements of Bennu’s surface, was used to create global and local DTMs of Bennu independently of and in concert with...
SPC (Seabrook et al. 2019; Daly et al. 2020). A global set of OLA data became available in 2019 August and enabled the creation of a high-fidelity 20 cm shape model (Daly et al. 2020). The OLA data collected before then were primarily used to validate the SPC-derived shape models of Bennu. The relatively small number of images required and the ability to iterate on the solution whenever more images became available made SPC the appropriate method for creating shape models early in the mission. Indeed, the first shape models were generated before the rendezvous with Bennu, during the Approach phase, using just under 300 images (∼2 m pixel$^{-1}$). Since then, SPC has been used to generate a series of products with increasing fidelity and decreasing GSD as more image data were acquired at successively closer distances (Figure 1), so that the latest official model (v42, with a maplet pixel scale of 0.12 m pixel$^{-1}$) used more than 10,000 images, the majority with a pixel scale of ∼4 cm pixel$^{-1}$. Furthermore, SPC’s ability to solve for the surface albedo along with position makes it a powerful tool for operational uses that require the direct comparison of images and DTMs, including orbit determination (Williams et al. 2018; Antreasian et al. 2019), optical navigation, and natural feature tracking (NFT) for sample collection (Olds et al. 2015).

Prior to flight, tests using images of a physical wall (Craft et al. 2020) and the simulated shape model of Bennu (Barnouin et al. 2020) demonstrated the efficacy of SPC for the uses intended by the OSIRIS-REx mission, as long as the imaging conditions (Section 2) are met. Therefore, imaging campaigns were planned to meet these requirements, and we developed a methodology that could be consistently applied to evaluate the models’ quality soon after their generation. Our methods involve tracking qualitative and quantitative measures that reflect the models’ accuracy, precision, and achievement of mission requirements. Some of the tools we developed are also applicable to SPC shape models of

![Figure 1. Global SPC models produced by the OSIRIS-REx mission to date. These are the official SPC products delivered to the PDS and/or used by the OSIRIS-REx team to perform scientific analysis or make operational decisions; interim products are not shown. Snapshots of the 80 cm GSD models are shown to illustrate their evolution over time; for example, note in particular the increased resolution of the large boulders on the limb profile. Models are labeled with their version number, creation date, and global pixel scale.](image-url)
other planetary bodies, allowing for intercomparison with and adaptation to other planetary missions.

For OSIRIS-REx science and operations, validating each SPC shape model and estimating its accuracy, shape uncertainty, and lateral feature positions were critical assessments because of the mission’s reliance on real-time production of shape models. On a global scale, uncertainties in the scale of the model have implications for navigation and orbit determination. On a local scale, errors in the relative distances between boulders can affect the optical navigation efforts (Olds et al. 2015), as well as projection and scientific interpretation of data acquired by spectrometers and the OSIRIS-REx Camera Suite (OCAMS) images. At least one model was produced during each phase of the OSIRIS-REx mission (Lauretta et al. 2017). Some updates were motivated by additional data, others resulted from further processing of an earlier SPC solution, and some were generated in parallel by independent efforts within the team. This required prompt comparisons and evaluations of each model to evaluate the suitability of each for the intended uses.

In this paper, we summarize the products required by the mission to achieve its science objectives (Lauretta et al. 2017) and the imaging criteria developed so that the resulting products would meet the requirements (Section 2). We also describe the methods used to validate the SPC shape models generated during the OSIRIS-REx mission and how these were used qualitatively and quantitatively to evaluate different aspects of each model (Section 3). We review SPC models that were used internally for operational decision-making and/or as science products that will be archived in the Planetary Data System (PDS) for the scientific community, and we discuss the fidelity of these products in the context of our evaluation metrics (Section 4).

2. Requirements

The main data products produced by SPC for the OSIRIS-REx mission are a 75 cm shape model after the Preliminary Survey (PS) phase of the mission, a 35 cm shape model after the Detailed Survey (DS) phase, and a set of local combined topography and albedo maps for NFT purposes after the second Reconnaissance (Recon B) phase (Lauretta et al. 2017; Crombie & Selznick 2019). Each of the global shape models to be used for the navigation purposes of the OSIRIS-REx mission is required to have agreement with images at a half-pixel scale (38 cm residuals for the 75 cm model and 18 cm for the 35 cm model). Furthermore, the 3D accuracy required for the 75 cm model is 1 m, and that for the 35 cm model is 75 cm (both 1σ level). Other important quantities that we have tracked throughout the mission are the model volume, which has a mission-level requirement to be accurate to within 0.9%, and the center-of-mass, center-of-figure offset, accurate to 1 m. In this paper, we focus on evaluation of the global shape models. Local DTMs, required for NFT as markers used by the spacecraft for autonomous navigation, were evaluated iteratively between the navigation and altimetry teams and are not discussed here.

Prior to flight, a set of imaging criteria were established to guarantee the satisfaction of mission-level requirements. An inability to meet these criteria in the actual imaging campaigns could be compensated for by additional decisions during the processing (e.g., increasing the number of control points, using limb information, and integrating OLA data in the SPC process), but such compensations do not guarantee meeting the shape model requirements. The details of these imaging criteria and how they were reached can be found in Barnouin et al. (2020), and we summarize them here for their importance in driving the evaluation techniques that we use. These criteria are as follows. (1) There are at least four images with four different observer viewing geometries, separated by a convergence angle of about 90°. The observer should be in opposite spatial quadrants centered on the region (e.g., N–S, E–W; NE–SW, NW–SE). These four images should have (2) varying incidence angles to minimize shadows. (3) There is a fifth image near 0° emission and ~10° incidence, which is necessary to obtain relative albedo solutions. Finally, (4) all of the images (four cardinal directions and one albedo) should have comparable pixel scales, with a minimum of one or two images at or below the GSD needed by the topographic model and none of the images exceeding 5 × the model GSD.

The imaging criteria were used to plan observations for different mission phases (Crombie & Selznick 2019). The SPC shape models with this fidelity are not achievable unless the imaging campaigns are specifically planned for their creation, and this may be a limiting factor for some planetary missions.

3. Methods

In the following sections, we describe the analyses performed to determine the reliability of each global shape model. We first review the steps, concepts, and products of the SPC technique (Section 3.1) to motivate the different evaluation approaches taken. For a more detailed SPC methodology, the reader is referred to Barnouin et al. (2020) for OSIRIS-REx–specific modeling and Gaskell et al. (2008) for the general SPC formulation. We then describe our evaluation approaches (Section 3.2). These include qualitative and quantitative evaluations of the SPC models based on multiple types of data, including (1) model input data, specifically, the images obtained by the OCAMS (Rizk et al. 2018; Golish et al. 2020); (2) diagnostic information produced during the SPC process; and (3) independent data obtained by the OLA instrument. Other analyses, not discussed here, were also performed to validate the shape and topography for use in specific image processing (Edmundson et al. 2020) and navigation applications (Leonard et al. 2020).

During the OSIRIS-REx mission, two teams simultaneously produced SPC-derived shape models (Figure 1 and Table 1). The Palmer/Weirich (P/W) models (named for their primary creators) used the validated and sanctioned version of the SPC code that was tested before the spacecraft’s arrival at Bennu. The Gaskell (G) models used an experimental version of the code in which certain parameters were changed in response to Bennu’s unexpected surface roughness, data restrictions (e.g., missed observations and changes in plans), and data availability. This flexibility allowed the resulting models to better resolve small (compared to the model’s GSD) boulders and sharp edges of boulders on Bennu but also introduced artifacts and roughness not observed in the images.

3.1. SPC Process: Steps and Quality Metrics

The first step in creating an SPC model is to generate a low-resolution model that serves as the basis for improved models that use additional images. In order to do this, the SPC team first needs to determine the pole position and rotational rate. For Bennu, the SPC team tested different planetary constant
Table 1
Evaluation Statistics Associated with the SPC Models Shown in Figure 1

| Model Date   | Model Version | Creators | Model GSD (m) | Number of Images | Perimeter Normalized Difference (rms) (m) | Keypoint Difference (rms) (m) | rms Residuals (m) | sigma (m) | OLA Residuals (m) |
|--------------|---------------|----------|---------------|------------------|------------------------------------------|-------------------------------|-------------------|-----------|-------------------|
| 2018 Nov 23  | v07           | P/W      | 1.2           | 294              | 1.97                                     | N/A                          | 1.44              | 0.10      | 2.07*             |
| 2018 Dec 6   | v10           | P/W      | 0.75          | 649              | 2.19                                     | N/A                          | 2.09              | 0.09      | 1.76*             |
| 2018 Dec 27  | v14           | P/W      | 0.35          | 1560             | 1.75                                     | N/A                          | 0.81              | 0.13      | 1.02*             |
| 2019 Jan 17  | v19           | G        | 0.35          | 4240             | N/A                                      | N/A                          | 0.53              | 0.21      | 0.83*             |
| 2019 Jan 21  | v20           | P/W      | 0.35          | 1560             | 0.96                                     | 1.06                         | 0.46              | 0.13      | 0.95*             |
| 2019 Apr 14  | v28           | G        | 0.35          | 16,161           | 0.65                                     | 0.52                         | 0.10              | 0.12      | 0.59*             |
| 2019 Jun 3   | v32           | P/W      | 0.35          | 10,088           | 0.82                                     | 0.60                         | 0.38              | 0.12      | 0.79*             |
| 2019 Aug 28  | v42           | P/W      | 0.14          | 10,722           | 0.60                                     | 0.45                         | 0.15              | 0.09      | 0.68*             |

Note. The SPC team member(s) who created each model are indicated. Some parameterizations, number of iterations, and input data differ between the P/W and G models. Model GSD refers to the GSD of the maplets that cover the surface globally. The rms residuals and sigma are defined in Figure 2. The perimeter normalized difference, keypoint difference, and OLA residuals are defined in the text. For the comparisons with OLA data, only data available at the time of the model creation were used, and they were collected during the #PS, SDS, and *OB phases. Keypoint analysis began only with model v20. Model v19 did not go through an extensive validation process, and no image comparisons were applied.
were easily identifiable and thus known as landmarks. Today, landmarks can be any point on the body being studied. The 3D position of each of these landmarks is determined based on its 2D pixel position in the images combined with knowledge of the spacecraft position, pointing, and camera parameters. Therefore, it estimates a least-squares solution for each landmark position and corrects the spacecraft position and attitude to match this solution. The modelers iterate this process until the rms residuals of the landmark position solutions are minimized. The final rms residuals (illustrated in Figure 2(a)) are one of the diagnostics for the internal agreement of the stereo solutions we use to evaluate the quality of the model. We discuss their use in our analysis in Section 3.2.3.

The SPC process uses each landmark position as a center for a local DTM with albedo solutions, or a maplet. For the OSIRIS-REx mission, maplets are 99 × 99 pixels each. The 3D positions within the maplet are calculated using the photoclinometry method, augmented by a random subset of available stereo points. The pixel scale (m pixel\(^{-1}\)) is constant within a maplet but dependent on the image coverage and the pixel scale of the images and thus can vary among maplets. When combined, the maplets generated for OSIRIS-REx fully cover Bennu’s surface with substantial overlap. Because each maplet is created using the images that cover it, there can be disagreements between point position solutions where maplets overlap. The final position for each point is the least-squares solution of all overlaps, and the standard deviation between the overlaps (sigma, illustrated in Figure 2(b)) is another diagnostic in the evaluation process. A global model is created at multiple GSDs from 12 to 0.8 m, as well as a globally tiled set of 0.3 m local DTMs. In this paper, for the general model descriptions (volume, mean radius, and best-fit ellipsoid), as well as for the comparison with OLA, we use the 80 cm GSD global models of Bennu.

3.2. Evaluation Approaches

3.2.1. Input Data

The first step in evaluating the model is the examination of the input data. The model GSD is limited by the pixel scale of the images used to create it; hence, an assessment of the image coverage provides information on the regions most and least well-captured by the models. For example, some early (Approach phase) SPC models of Bennu did not include SPC solutions of high-latitude regions (>45°) due to imaging

Figure 2. Illustrative sketch of SPC metrics. (a) Every pair of stereo images (t1, t2), (t2, t3), and (t1, t3) gives a different solution to the 3D position of a landmark owing to uncertainties in spacecraft position and pointing. The positions of the landmarks in the images are denoted by stars, the solved positions from the image pairs are shown by rectangles, and the least-squares solutions, derived from the image pair solutions, are given by boxed crosses. The rms residual is the rms of the difference between image pair solutions and the least-squares solution. (b) Different maplets overlapping the same region have different solutions to the position of each point on the grid, as seen in the seams and the cross section, in which different-colored lines represent the positions from different maplets. Sigma is the standard deviation of the different heights (given by different colors in this example) from each maplet solution where they overlap.
constraints (Figure 3 in Barnouin et al. 2020) and relied instead on limb images to capture the topography of those regions.

We examined the coverage of the images and the fraction of the surface of Bennu that met the imaging criteria listed in Section 2. We used the list of images that went into making the SPC shape models and the adjustments made by SPC for the spacecraft position and attitude to determine, for $2^\circ \times 2^\circ$ bins across Bennu’s surface, how many images of a given pixel scale satisfy the viewing geometry (Figures 3(a) and (b)) and albedo (Figure 3(c)) requirements. The map (Figure 3(a)) of the number of cardinal images with a scale $\leq 2.5 \times$ the model GSD (14 cm) shows that the cardinal image criteria are not met over the majority of Bennu’s surface. However, when the scale requirement is relaxed (slightly above the predetermined value of 5) to $\leq 5.7 \times$ the GSD, the majority of the surface is now covered by four cardinal images. Nonetheless, the SPC modeling team was able to produce a shape model given these input images that met the mission-level requirements, showing that the above-listed criteria represent sufficient but not necessary conditions for the creation of an adequate SPC model.

Another way of examining the input parameters and images and how they were used as input in the SPC model is to look at

![Figure 3](image-url)

**Figure 3.** Satisfaction of SPC imaging requirements for the v42 SPC model, including (a) the number of images <0.35 and (b) <0.8 m pixel$^{-1}$ that satisfy all of the cardinal directions required by SPC and (c) the number of albedo images with <0.8 m pixel$^{-1}$, emission near 0°, and incidence of $\sim 10^\circ$. Note that although there were images of the south pole captured by OCAMS, these images did not satisfy the small incidence angle requirements by the SPC, resulting in a “white” region in the map projections in panel (a).
Figure 4. Number of images per maplet for the (a) v20 and (b) v42 SPC models and maplet GSD for the (c) v20 and (d) v42 models. The maplets that are in v20 are also present in v42 but are obscured in this visualization by the higher-resolution maplets. In v42, the small regions (purple) with decreased maplet GSD (<\sim 0.1 \text{ m pixel}^{-1}) are areas that the team considered as candidate sample collection sites and thus were studied in greater detail.

3.2.2. Additional Image Data

Preflight testing of the SPC method indicated that increasing the iterations of SPC solutions (landmark position estimation and maplet construction) may result in an artificial reduction in the size of Bennu. The limb profiles, on the other hand, and the 3D positions estimated from them are not affected by iterations and enable us to detect artificial reductions in the size of the shape model. The images used for the limb comparison were primarily those in which either all of Bennu was captured within a single OCAMS image field of view or a large portion of the limb was visible in the field of view to capture the long-wavelength topography. Such images require a large field of view and thus were taken when the spacecraft was far from the asteroid; they are therefore limited in resolution. For the OSIRIS-REx mission, the highest pixel scale of the images that could be used to determine limb points is 32 cm pixel\(^{-1}\). This means that limb comparisons can, at best, be used to detect size and height errors of \~50 cm (1–2\times the image pixel scale), therefore providing limited information for models with a lower GSD.

A similar method to compare the images to the model is to apply the inverse of the process described above. Rather than using the SPC-provided limb position, we independently rendered synthetic images of the SPC model (using the navigation team’s orbit solutions) to mimic OCAMS images taken at the same time. We compared the rendered images to the reference OCAMS images in two ways: threshold limb comparison (for images in which the limbs of Bennu are resolved) and keypoint assessment (for limb-resolved images and those in which Bennu covers the entire field of view), described below. These analyses were implemented via an image processing toolkit in Python called scikit-image (van der Walt et al. 2014). For the model-rendering assessments, we used images with the best reconstructed navigation solutions, usually available some weeks after the imaging data were initially acquired. This approach assumes that the uncertainties in the location of the spacecraft and viewing geometry provided by the OSIRIS-REx navigation team contribute smaller effects than the uncertainty in the shape model, which may not always be true. This assessment was only helpful, therefore, for verifying that all uncertainty assessments of the shape model were in agreement.

For each of the images, the location of the limb and terminator was estimated by a thresholding algorithm in which the background and foreground of the image are separated, followed by identifying the limb by the longest continuous contour in the thresholded image. The thresholding algorithm was developed specifically for this investigation based on testing and differs between the OCAMS imagers PolyCam and MapCam (Rizk et al. 2018). For PolyCam images, the threshold was chosen to be two-thirds of the mean brightness value (Otsu 1979). In the case of MapCam, we first upscaled the image by a factor of 4 through a spline interpolant to avoid
edge detection degradation owing to smoothing. After that, we used the approach described in Glasbey (1993), in which the histogram of the pixel digital number is plotted and iteratively smoothed to remove local extrema until (in the case of MapCam images) two peaks are left. The threshold was then defined at the global minimum in the smoothed histogram. This algorithm was also used on the rendered images, simulating the view seen by either one of the cameras. The threshold value provides the limb and terminator outline of the asteroid in both the OCAMS and rendered images (Figure 5(a)). When Bennu was in the full field of view of the images, we fitted a circle to the edge detected using the threshold method in both the rendered and actual (reference) image in the image pixel/line frame, then transformed it to the physical distance frame by multiplying by the pixel scale (meters per pixel) of the central pixel. The differences in the radius of the circle fit provided one estimate in the size uncertainty of the shape model. We compared the rendered SPC v42 model with more than 300 images, and the results are shown in Figure 5(c). The median difference between the best-fit circles of ~40 cm radius implies that the model has a 1.6% smaller mean radius than what is observed in images.

We obtained another estimate of the limb agreement by summing the number of nonzero pixels in the difference map (Figure 5(a), right panel) and dividing it by the number of pixels in the perimeter of the truth image. We then converted this to physical units by multiplying by the pixel scale of the central pixel. This quantity (the perimeter normalized difference) is a measure of the limb mismatch (normal to the limb) per unit length along the limb. It is an overestimate of the mismatch because (1) it does not take into account the sign of the difference, and (2) it is sensitive to the local effects. We also report these differences when quantifying the uncertainty in the limb of the modeled shape.

Our second method of comparing the OCAMS images to the rendered images, keypoint matching, is a commonly used method in computer vision and image processing (Haralick 1983). In this assessment, matching keypoints are identified in both a reference OCAMS image and a rendered image obtained from the SPC shape model (Figure 5(b)) using the speeded-up robust features-based feature matching implemented in OpenCV (Bay et al. 2008). The rendered image is then rotated, translated, and scaled to reduce the difference in the keypoint positions between the truth and the rendered image. After the transformation, we compute the Euclidean distance (L2-norm) between the keypoints identified in the image and rendered shape model. When the distance between a pair of keypoints in an image is different from the distance between the equivalent pair in a rendered model, it is indicative of a local scaling error in the shape model. We report both the scale required to match the rendered model to the truth image (Figure 5(d)) and the difference between equivalent keypoints (Figure 5(e)). The median scale difference estimated using the keypoint analysis of v42 is 1.0008, equivalent to an ~20 cm difference in the best-fit circle radius. In this case, both the image differencing and keypoint analysis indicate that the model is smaller than it appears in the images, although the scale of the size reduction varies between the techniques.

We used a minimum of 30 OCAMS images at a range of spatial scales for this assessment. The original and rendered images used have GSDs that span the range of imaging data available, with the caveat that we never compare our model renderings to images where the GSDs are less than the GSD that went into constructing the SPC shape model.

3.2.3. SPC-derived Metrics

The SPC-derived rms residuals and sigma are two different measures of uncertainty in the shape model that provide
complementary information about the knowledge of local and global topography. The rms residuals represent the dispersion among a landmark’s stereo solution and the pixel position observed in the images, as illustrated in Figure 2(a). Therefore, they are a measure of the agreement between the images and the model solution and can be used to satisfy mission-level navigation requirements. The flight navigation team used this information to determine the suitability of each shape model for navigation. An example of the rms residual map for model v42 is shown in Figure 6(a). For this class of models (expected GSD of 35 cm), the mission required at least 80% of the maplets at or below 35 cm GSD to have rms residuals <18 cm, and model v42 meets this requirement (Figure 6(b)).

Sigma reflects the vertical disagreement in a vertex’s estimated position derived from different but overlapping maplets (Figure 2(b)). The distribution of sigma values across the model’s surface (Figure 6(c)) is another measure of positional uncertainty, evaluated at each vertex (point) in the model rather than only in maplet centers. Qualitatively, there is agreement between the rms residual and sigma; e.g., both maps show higher uncertainties associated with large boulders and boulder fields.

Figure 6. Vertex sigma and rms residuals and vertex sigma for the v42 SPC model: (a) rms residuals per maplet, (b) rms residuals histogram and empirical cumulative distribution function, and (c) vertex sigma per maplet. High sigma values generally correlate with high surface roughness (equatorial region) and large boulders (e.g., a boulder at ~−45° and 120°).
3.2.4. Adjustment to Spacecraft Position and Attitude

As mentioned in Section 3.1, modifying the spacecraft position and attitude to allow for better image registration is an integral part of the SPC process. Once the SPC team creates a final model after multiple iterations, we commonly compare the final spacecraft parameters with those delivered by the navigation team in the form of predicted or reconstructed solutions. During the construction of the SPC solution for the OSIRIS-REx mission, the SPC model creators preassign parameters that set the allowable change in the spacecraft position and attitude from those delivered in the navigation kernels, which are determined based on preflight testing and navigation team–recommended uncertainties (Barnouin et al. 2020). These values tether the spacecraft adjustment to that delivered by the navigation team such that exceeding these values is possible when multiple landmark solutions require it. Both the P/W and G teams set the spacecraft position to change the weight to 1 km in body-fixed coordinates, whereas the spacecraft attitude weight is 1 mrad for the P/W team and 0.1 mrad for the G team. The SPC team delivers the applied changes to the spacecraft ephemeris data to the navigation team, who validate this against their own evaluation of the SPC model, which is beyond the scope of the present paper. Examples of the corrections applied to the spacecraft solutions by SPC for v20 and v42 are presented in Figure 7.

3.2.5. Comparisons with OLA Data

The OLA instrument acquired lidar returns from Bennu’s surface at distances ranging from ∼7 km to a few hundred meters. When the spacecraft was between 7 and 1 km from the surface of Bennu, the High Energy Laser Transmitter (HELT) was used, whereas at distances less than 1 km, the Low Energy Laser Transmitter (LELT) was used. For more information on the instrument, observation plans, and mapping technique, the reader is referred to Barnouin et al. (2020) and Daly et al. (2017, 2020). For our purposes, the main differences between the two lasers are their footprint sizes (HELT, 200 μrad; LELT, 100 μrad one e-fold) and measurement uncertainties (HELT, 0.5 m; LELT, 0.3 m range accuracy). The HELT measurements were primarily used to validate the SPC shape models until LELT was deployed to produce a global OLA-based shape model. The LELT data were directly compared with the SPC model. In this study, we report statistics based on recalibrated OLA returns, which reflect an improved calibration over that available for use at the time of the SPC postproduction evaluation reports. Furthermore, we used OLA data from three mission phases to compare to the various SPC models based on data available at the time of the model production. In the following, we describe each data set and how we used them to evaluate the SPC shape models.
Data were acquired during the PS phase in 2018 December at an altitude of ~7 km from Bennu using HELT (Daly et al. 2019). Because the spacecraft was close to the range limit of the instrument, fewer than 0.1% of the laser returns were detected, and the coverage was sparse. Eight scans with ~3200 data points were collected during this phase. The footprint size of these returns was ~1.5 m. Because of the sparseness of the data, we did not divide each scan into 5 minute sections as we did for the DS phase data described below.

The OLA data acquired during the DS phase in spring 2019 consisted of scans that were hours in duration from distances of ~1.4 and ~4.6 km, resulting in footprint sizes of 0.3 and 0.9 m (Daly et al. 2019). In some cases, due to the long duration of the scan, a single scan covered (over a limited latitude band) a full rotation of Bennu and overlapped itself. Because of the long duration of the scans and the decreased knowledge of the spacecraft position and pointing with time, these scans did not agree where they overlapped and contained non-Gaussian noise that distorted the dimensions of the asteroid. As a result, before comparison with the SPC models, the data were divided into smaller, 5 minute duration strips of approximately constant uncertainty. Additionally, we removed off-body returns and those for which the spacecraft position and pointing had large uncertainties (e.g., data acquired when the spacecraft was performing a fast slew). Finally, we registered each of the strips to the SPC shape model to remove any rotations or translations between the two data sets that may arise owing to imprecise knowledge of the instrument (OLA or OCAMS) pointing in the spacecraft frame. The registration was done using the iterative closest-point method (Besl & McKay 1992), which involves finding the best rigid transformation (translation and rotation) that minimizes the mean-square distance between the data sets. After alignment is achieved, the residuals between the data sets provide information on areas in which we can have a high degree of confidence (in which the two data sets agree and the residuals are close to zero).

The Orbital B (OB) phase in summer 2019 provided a complete LE1T global data set (0.7 km range, 7 cm footprint) with substantial overlaps (Daly et al. 2017). This made it possible to create an independent global shape model based on OLA data alone (Daly et al. 2020), using the method described in Seabrook et al. (2019). During this process, the OLA scans were globally registered to each other so that the OLA models could use the same coordinate system as the SPC models. The self-consistency of this data set set allowed us to compare it to the SPC model without registering the individual scans to the SPC model, thereby enabling us to additionally evaluate the uncertainty in the size and shape of the model, as well as the long-wavelength topography. We calculated the distances between the closest points in the data sets, inspected their spatial distribution, looked for signs of long-wavelength trends in the difference map, and determined the mean and median differences across the surface.

Figure 8 shows the results of comparing SPC model v42 to the OLA data. In Figures 8(a) and (b), the model is compared to OLA data collected before OB, and the scan strips were registered individually to the shape model. As expected, the mean value of the differences (binned in 0.5° × 0.5° bins) is zero because of the registration, and the map only shows differences in the short-wavelength topography. However, as shown in Figures 8(c) and (d), comparing OLA OB points to the shape model without registration captures long-wavelength topographic features (e.g., negative anomalies in polar regions and, to a lesser extent, in the equatorial region). The median difference between the model and the OLA points is ~28 cm, which indicates, contrary to the image-based analysis, that the SPC model is too large. These results are discussed further in Section 4.2.2 below.

4. SPC Models for Bennu: Resolution and Fidelity

In this section, we summarize the main uses and characteristics of each shape model in this study, as well as the results of our analyses. The SPC model v20 is considered the official 75 cm shape model for the mission-level navigation requirements (<75 cm GSD for 80% of the maplets, <38 cm rms residuals for 80% of the maplets, and <1 m 3D accuracy for 80% of the surface), whereas the SPC model v42 is considered the official 35 cm shape model for mission-level navigation requirements (<35 cm GSD for 80% of the maplets, <18 cm rms residuals for 80% of the maplets, and <0.75 m 3D accuracy for 80% of the surface). Both were created using the preflight sanctioned version of the SPC software. Other models were either used to check the progress toward meeting these requirements, made using modified versions of the SPC software, or used to aid in the interpretation of scientific data.

We begin by summarizing the results of the global shape properties (Section 4.1), followed by the results of our analyses for the official navigation models (v20 and v42) in Section 4.2; finally, we discuss the rest of the models in Section 4.3. A summary of the quantitative assessment metrics for all models is shown in Table 1. As mentioned earlier, the lowest GSD version of the SPC models that can be combined into a single file is 80 cm, and the analysis applies to these files.

4.1. Global Properties

The first iterations of the shape model were focused on finding the best description of the global properties of Bennu, such as the rotation pole, wobble, rotational period, and center-of-mass, center-of-figure offset. Although the rotation parameters can be solved for using SPC, they do not directly relate to the actual shape (topography) and are not discussed here. In the discussion below, we use a body-fixed coordinate system, where +x points in the direction of the predefined prime meridian rock (Barnoun et al. 2019), +z is aligned with the rotation axis, and +y completes the right-hand system.

The model volumes converged on a solution after SPC model v10 (75 cm; Figure 9(a)), and subsequent SPC model volumes were all within 0.08% of the mean volume (0.061610 km³), thereby satisfying the mission volume uncertainty requirements (0.9% uncertainty). Furthermore, Daly et al. (2020) reported that the OLA-based shape model of Bennu has a volume of 0.061354 km³, within 0.4% of the mean value estimated from SPC models v10 (75 cm) and later, thereby confirming our early assessment of the stabilization of the shape volume solution.

The x- and y-components of the center-of-mass, center-of-figure offset solution similarly stabilized after the SPC v14 (35 cm) model at 1.38 ± 0.04 m and −0.40 ± 0.04 m, respectively, and the dispersion among all subsequent models was within the 1 m requirement (Figure 9(b)). The z-component offset, however, fluctuated with a larger amplitude between successive models with a post-v10 average of ~0.02 ± 0.28 m (1σ). The uncertainty in the z-component is likely due to the
inherently poor imaging conditions of the polar regions due to shadowing effects. The OLA shape model (Daly et al. 2020) has an offset of \((1.31 \pm 0.03, -0.46 \pm 0.04, 0.22 \pm 0.01)\) m, which agrees with the SPC models in the \(x\)-, \(y\)-, and \(z\)-directions (given the large uncertainty in the latter). Using the convergence of solutions as a measure of uncertainty, we conclude that, starting with SPC model v14 (35 cm), the global property requirements for the shape models were met.

4.2. Official Navigation Models

4.2.1. 75 cm Shape Model

The SPC model v20 represents the official 75 cm shape model for meeting the navigation requirements. It was created using 1560 images (from the Approach and PS phases), more than 65% of which have a pixel scale of \(<0.75\) cm pixel\(^{-1}\). It was globally tiled with 35 cm maplets, more than 80% of which had rms residuals \(<38\) cm, thereby meeting two of the navigation requirements. The comparison with images through limbs and keypoint assessment, as well as comparison with OLA PS data (Table 1), show an rms of differences of \(~1\) m, indicating that this shape has a 3D accuracy of \(~1\) m. This model was used for spacecraft navigation during the DS phase.

Qualitatively, we see that the 80 cm GSD (single-file) version of the model contains most (though not all) boulders \(>15\) m, but it tends to underestimate their height and overestimate their width. Furthermore, the comparison to OLA data shows that the extent of the shape model in the N–S direction is overestimated, with the poles modeled to be \(~60\) cm higher than indicated by OLA data.

4.2.2. 35 cm Shape Model

The SPC model version v42 was created using \(>10,000\) images, the majority of which (\(>50\%\)) have a pixel scale of \(<5\) cm pixel\(^{-1}\), and is globally tiled with 14 cm GSD maplets. Of these maplets, 81% have rms residuals \(<18\) cm. Thus, the GSD and rms residual requirements for the 35 cm shape model are satisfied by v42. As shown in Table 1, the assessments using different methods give results that vary from 9 to 68 cm. Limb comparison of the perimeter normalized difference and OLA OB data residuals shows similar results regarding the overall accuracy of the model (rms of 60 and 68, respectively). As mentioned earlier in the text (Section 3.2.2), the perimeter normalized

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**Figure 8.** (a) and (b) Comparison between OLA DS data and SPC model v42. The OLA data have been cleaned and registered to the SPC model. (a) The map of the residuals (0.5° × 0.5° bins) shows the short-wavelength topographic differences, primarily associated with boulder height (dark red) and extent (blue regions surrounding boulders). Also apparent are some E–W elongated wavelike structures (indicated by arrows, especially present near the equatorial region), which we interpret to be artifacts in the SPC model. (b) Histogram of the difference values, with mean and median differences of \(~0\) cm. (c) and (d) Comparison between OLA OB data and SPC model v42. No registration was applied to the data prior to differencing. (c) The map of the residuals (0.5° × 0.5° bins) shows both short- (bright red) and long- (blue/green near the poles and equator) wavelength topographic differences between the shape model and the OLA data. (d) Histogram of the binned residuals, showing a mean and median of \(~25\) and \(~28\) cm, respectively, indicating that the SPC model is larger than the OLA measurements.
difference is an overestimate of the topographic uncertainty. Similarly, because of the known effect of SPC smoothing of boulder tops, comparisons to OLA, which does not have such artifacts, results in high rms values. In the keypoint assessment, because we correct for scale variations, the rms residuals are slightly lower (45 cm). Sigma rms values are considerably lower (∼9 cm), and this difference can be explained by recalling that sigma is a measure of the disagreement between the maplets; therefore, it does not take into account any effect that is consistent across the maplets, such as a total reduction in the size of the shape. Furthermore, as noted earlier, image comparisons indicated that the SPC model is too small, whereas OLA comparison indicates that it is too big. In the absence of additional data, we consider the values estimated from these analyses to be the upper and lower uncertainties associated with the shape model, resulting in a mean radius (radius of the best-fit sphere) of 245.19\(\pm 0.60\) m. The 80 cm version of the SPC v42 model shows significant improvements in capturing the heights and widths of boulders, but the boulder heights remain underestimated in comparison to the OLA measurements (Figure 7).

4.3. Other Shape Models

The SPC models created prior to the v20 and v42 shape models are considered interim models. Their progress toward meeting the mission requirements was evaluated and informed the efforts to improve these models. As shown in Table 1, there is a general trend of decreased uncertainties in later versions of the global shape model using the different independent assessment techniques. Additionally, these models have served purposes other than navigation. For example, SPC model v28 (35 cm) included 50+ regions of interest as potential sample sites modeled at 5 cm GSD to help the OSIRIS-REx Team evaluate and characterize the best sites. As shown in Figure 8, their global properties (volume and center-of-mass, center-of-figure offset) do not differ statistically from the mean of the convergent models (v14 and later), but the details of some topographic
regions differ. Additionally, Table 1 and Figure 9(c) show that their evaluations (rms residuals, sigma, keypoint, perimeter normalized difference, and OLA comparisons) gradually improve and progressively result in higher-fidelity models.

5. Summary

We presented the evaluation techniques used to evaluate the SPC models of asteroid Bennu created during the OSIRIS-REx mission. The techniques fall into three main categories: (1) internal SPC metrics, (2) image comparisons, and (3) independent assessment (OLA). When these methods give similar results, we take that as indicative of known uncertainty in the model, and when they differ, we either seek further information or fold these assessments into the overall uncertainty in the shape.

The inclusion of a camera suite on planetary and small-body missions is standard practice, which makes SPC a valuable uncertainty in the shape model, and when they differ, we either seek further information that their evaluations are also available in SBMT.

This material is based upon work supported by NASA under Contract NNM10A111C issued through the New Frontiers Program. The OLA and funding for the Canadian authors were provided by the Canadian Space Agency. We are grateful to the entire OSIRIS-REx Team for making the encounter with Bennu possible.

Data Availability

The official models presented in this work (SPC v20 and SPC v42) are both available in the public release of the Small Body Mapping Tool (http://sbn.psi.edu//; Ernst et al. 2018). In addition, SPC v20 is available on the PDS in disk format (https://naif.jpl.nasa.gov/pub/naif/pds/pds4/orex/orex_spice/spice_kernels/dsk/). Some intermediary shape models (v13, v14, and v28) are also available in SBMT.

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