**PHOTOGRAMMETRIC CONTROL OF CANDIDATE SAMPLE SITES ON (101995) BENNU.** K. J. Becker[1], T. L. Becker[1], K. L. Edmundson[1], D. R. Golish[1], C. A. Bennett[1], N. A. Porter[1], D. N. DellaGiustina[1], M. G. Daly[2], E. Palmer[3], J. Weirich[3], O. S. Barnouin[4], L. Philpott[5], M. M. Al Asad[5], J. A. Seabrook[2], C. L. Johnson[5], B. Rizk[1], and D. S. Lauretta[1]. [1]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, [2]The Centre for Research in Earth and Space Science, York University, Toronto, Ontario, Canada, [3]Planetary Science Institute, Tucson, AZ, [4]The Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA, [5]Department of Earth, Ocean, and Atmospheric Sciences, University of British Columbia, Vancouver, BC, Canada. Email: kbecker@orex.lpl.arizona.edu

**Introduction:** High-resolution (< 2 cm/pixel) images of asteroid Bennu acquired in the Reconnaissance A phase of the OSIRIS-REx mission were critical to the selection of the primary and backup sample sites [1]. In late 2019, the OSIRIS-REx Camera Suite (OCAMS) [2] captured images of four candidate sites: Sandpiper, Osprey, Kingfisher, and Nightingale. The sites were evaluated primarily for safety and sampleability.

OCAMS images were used to assess the presence of hazards (large boulders) and evaluate the relative sampleability of each site. Sampleable material includes particles < 2 cm that can be ingested by the OSIRIS-REx sampling mechanism; terrain absent resolvable boulders or cobbles was assumed to contain sampleable fines. Approximately 50 OCAMS PolyCam images were acquired in an “along- and across- track” mosaic pattern at each site. A subset of overlapping PolyCam images (3 to 6 images per site) was selected based on coverage. The precise measurement of features, such as cobbles, is dependent on the accurate alignment between images and the shape model. Selected images were processed through photogrammetric control to register the images to one another and to a terrain model of Bennu generated from OSIRIS-REx Laser Altimeter (OLA) [3] data.

Here we describe aspects of the photogrammetric control process including shape models and their use in establishing ground control, challenges encountered and results.

**Photogrammetric Control of Sample Sites:** Initial values for spacecraft position and camera pointing parameters were obtained from reconstructed NAIF kernels [4]. Uncertainty in these parameters lead to errors in image-to-image and image-to-ground registration. Photogrammetric control improves these parameters and in turn the quality of registration. In this process, image-to-image and image-to-ground measurements of tie-point features were input to a least-squares process known as the bundle adjustment [5]. The bundle adjustment produces updated 3D coordinates of the tie-point features in addition to improved position and pointing parameters.

**Bennu Shape Models:** The shape model provides a representation of terrain and encapsulates the geodetic coordinates necessary for navigation and the production of accurate cartographic products. A global shape model has been produced from OCAMS and NavCam [6] images via stereophotoclinometry (SPC) [7]. We used a global shape model (v42) [8] with a facet size of ~14 cm globally and a ground sampling distance (GSD) of 80 cm. Local shape models were also created for each of the four sample sites at ~5 cm GSD and global sets of tiles at 35 cm and 15 cm GSD.

OLA data collected at each candidate sample site were registered [9] to the v42 global shape model. Local shape models of 5 cm resolution for each site were created.

*Shape Model Accuracy:* The prime meridian in the global model is measured to within 1 cm longitude. There is a latitudinal shift at the equator between v42 and earlier shape model versions. This is due to differences in the location of the center of figure (up to 22 cm in Z direction) and in pole orientation. The residuals of the model are less than 70 cm when compared with OLA data collected from Orbital A and Detailed Survey OSIRIS-REx mission phases.

The planetary constants kernel (PCK) bennu_v15.tpc was used to establish the coordinate system for this shape model and all derived products.

**Establishing Ground Control:** The 5-cm OLA site shape models were used to establish latitude, longitude and radius ground control as they contained the highest quality terrain definition. The shape model serves as the basis to compute emission, incidence and phase angles from local surface topology at every pixel in the PolyCam images. Backplane images were subsequently created from these values using a priori SPICE data. From these backplane images, a Lommel-Seeliger model for Bennu’s reflectance was applied to create photometrically accurate, simulated images [10] that provide reference images for ground truth. A sun illumination mask, which represents true shadows of foreground surface topology, was computed and applied using the observation geometry, illumination source (Sun) and shape model. This mask product requires high fidelity shape models and precise ray tracing. A custom version of the Integrated Software for Imagers and Spectrometers (ISIS) system [11] developed and maintained by the OSIRIS-REx team provides this capability.

Ultimately, each simulated image is a representation of Bennu’s surface according to the shape model, a priori SPICE, and a photometric model of the surface. The pixel locations of observed features as seen within the FOV of the corresponding PolyCam image and the derived simulated image reveals offsets caused by geometric errors. A ground control point includes the sample, line pixel location of an identified feature in the PolyCam image and the latitude, longitude value reported for the same feature observed in the simulated image.

Figure 1 shows the result of a simulated image for one of the images obtained of the Nightingale site. The simulated image shows high quality rendering of surface features from the 5-cm OLA shape model at 1.4 cm/pixel resolution of the image.

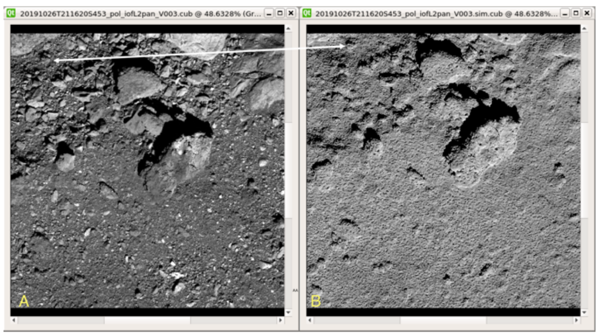


**Figure 1**: Image A (left) is the input OCAMS I/F image. Image B (right) is the simulated image using a priori SPICE, the OLA shape model, and a Lommel-Seeliger photometric model. The white arrows show the same feature in both images, which are spatially misaligned.

*Creation of Control Network:* The ISIS system was configured to recognize the simulated images as unique so that they could be incorporated into control networks seamlessly and processed along with the PolyCam images. This includes automatic determination of common surface areas, feature matching, and sub-pixel registration of control point measures. Due to the nature of the simulated images, automated feature matching did not always result in suitable networks for bundle adjustment. All networks required manual evaluation, corrections, and creation of ground control points measured on prominent features observed between the simulated ground images and original images.

**Photogrammetric Challenges Encountered:** Each site required iterative and customized parameterization of *jigsaw* [12] bundle adjustment options to converge and produce acceptable registration of all images to ground. The spacecraft acquired site-specific images at an average distance to Bennu's surface of 1.015 km. Image resolution was ~1.375 cm/pixel average with a desired bundle adjustment RMS residual error of less than 1 pixel. Accurate registration of images to the shape model was complicated for a number of reasons including (1) little to no variation in image acquisition geometry (i.e., spacecraft position and pointing attitude), (2) small, isolated regions of local shape model coverage, (3) varying quality of the shape model surface definition and (4) no single, optimal bundle adjustment parameterization was successful for all sites.

**Results:** Table 1 shows the different parameterization of bundle adjustment parameters used for each sample site. The best solutions numerically applied constraints for radius, spacecraft position and pointing attitude.

Validation was performed by re-producing local emission and incidence backplanes computed using the shape model for each image with updated position and pointing geometry to visually compare with the original image for feature alignment. The site mosaics were visually examined and check point analysis was also performed. All images were within a pixel when compared.

| Sample Site | Sandpiper | Nightingale | Osprey | Kingfisher |
|---|---|---|---|---|
| Solution | | | | |
| A priori S/C Sigma (m) | 5 | Fixed | Free | Free |
| A priori Pointing Sigma (°) | 0.25 | Free | 0.001 | Off |
| Control Point Radius Solved | Yes | No | No | No |
| Residual rms (pixels) | 0.12 | 1.31 | 0.25 | 0.35 |
| S/C Correction (m) | 3.62 | N/A | 4.83 | 5.3 |
| Pointing Correction(°) | 0.14 | 0.66 | 0 | N/A |
| Sigma0 | 0.16 | 0.89 | 0.63 | 0.88 |

**Table 1.** *jigsaw* bundle adjustment parameters and results for each sample site.

**Summary:** Photogrammetric control was used to ensure OCAMS PolyCam images were registered to the global shape model. Cartographic products derived from these images characterized the distribution/density, size and chemical composition of rocks in each of the candidate sites. These data were analyzed by the OSIRIS-REx science team and considered in the selection of Nightingale as the primary sampling site. The Osprey site was selected as the backup site.

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