SHAPE RECONSTRUCTION OF THE ASTEROID RYUGU WITH STRUCTURE-FROM-MOTION METHOD. Naru Hirata[1], T. Sugiyama[1], Naoyuki Hirata[2], S. Tanaka[2], N. Nishikawa[2], R. Noguchi[3], Y. Shimaki[3], R. Gaskell[4], E. Palmer[4], K. Matsumoto[5], H. Senshu[6], Y. Yamamoto[3], S. Murakami[3], Y. Ishihara[3, 7], S. Sugita[8], T. Morota[8], R. Honda[9], M. Arakawa[2], K. Ogawa[3], Y. Tsuda[3], S. Watanabe[10], [1]ARC-Space, the University of Aizu (Aizu-Wakamatsu, Fukushima, 965-8580, Japan, naru@u-aizu.ac.jp), [2]Kobe University, [3]ISAS/JAXA, [4]Planetary Science Institute, [5]NAOJ, [6]Chiba Institute of Technology, [7]NIES, [8]University of Tokyo, [9]Kochi University, [10]Nagoya University.

Introduction: The Hayabusa2 spacecraft has just finished its proximity observation operation at the asteroid Ryugu that continued from June 2018 to December 2019. During this period, the spacecraft made both global and regional observations to know the nature of Ryugu and to select sites for touchdown operations and the impactor experiment. The shape of the asteroid is one of the most critical information not only for landing site selection but also for scientific discussions. We adopted two different methods to model the global shape and local terrain models; one is stereophotoclinometry (SPC), and another is Structure-from-Motion (SfM).

SPC is a method combining stereophotogrammetry and photoclinometry and is widely adopted by many planetary missions, including Hayabusa, NEAR Shoemaker, Dawn, Rosetta, and OSIRIS-REx both for shape modeling of a target body and optical navigation of a spacecraft [1].

SfM is a method to be able to estimate the shape of the target object from multiple images by stereophotogrammetry. It can solve the shape from just the images themselves, without requiring information on the spacecraft positions and attitudes. The SfM technique is a popular shape modeling method in computer vision, and there are many open source and commercial implementations. We adopted Agisoft Metashape version 1.5 (formerly released as PhotoScan until version 1.4), one of the commercial implementations of SfM [2].

We successfully reconstructed the shape models of Ryugu with images taken by the optical navigation camera (ONC) onboard the spacecraft with these two methods [3] (Fig. 1). Because it is the first time to apply SfM to a space mission, we report detailed procedures for shape reconstruction and evaluation of our products.

Shape Reconstruction Procedure: Agisoft Metashape and other major SfM implementations reconstruct the shape of target object with the following procedure: 1) Loading images, 2) Image registration and building a sparse point cloud, 3) building a dense point cloud, 4) building a 3D polygon mesh model, and 5) Post-production processing. In a narrow sense, the second step is the Structure-from-Motion process, and the third one may refer to the Multi-View Stereo (MVS). We also employed other utility software, including MeshLab [4], OSIRIS-REx AltWG toolkit, and in-house developed scripts.

Loading Images: Because of a large number of images and high spatial resolutions, ONC-T [5] images are primary sources of shape modeling. Even though images with the v-band filter consist of the majority of the image set, other color data are also used. Sequential color observations obtained during decent operations are important, covering local regions with high spatial resolutions. Wide-angle images obtained by ONC-W1 and ONC-W2 are also incorporated. As Metashape accepts only images with the major image formats, all images are converted into an 8-bit gray-scale PNG format from the original multi-byte FITS images. Black-and-white binarized images are also produced to be used as mask images to exclude pixels seeing background deep space and shadows on the asteroid.

During the proximity operation, the spacecraft and Ryugu experienced a solar conjunction in December 2018. The illumination condition of the asteroid viewing from the spacecraft was reversed after the conjunction. Because SfM is based on image feature matching, it has difficulty handling an image set, including different illumination conditions. Thus, shape model production with SfM is separated into two parts; the pre- and post-solar conjunction periods. SPC is safe from this issue and is able to update the model with new images sequentially.

Image Registration and Building Sparse Point cloud: This step is a core process of shape modeling with SfM to register images each other based on image feature matching, and tries to solve camera position, attitude, and location of the feature points on the target surface in the 3D space. Feature points with the 3D coordinates are composed of a sparse point cloud briefly representing the target shape. Although image feature matching is automated in this step, manual try-and-error efforts are required to correct miss-aligned images.

Simultaneous with image registration, the camera internal parameters, including distortion coefficients are estimated. In our case, the pre-defined camera parameters by the ONC team are also available that estimated by in-flight operations [6]. The parameters automatically estimated during the image registration are consistent with those provided by the ONC team, but a more stable result is obtained when the pre-defined camera parameters are used as the initial values. However, a strict definition of the parameters may produce failures of several images taken at the extreme locations. It seems that there is a trade-off to be investigated between the looseness of pre-defined parameters and the success rate of image registration.

Building Dense Point Cloud: The sparse point cloud obtained in the previous step is too coarse to reconstruct the asteroid surface. Based on the estimated camera positions and the registered pairing of images, a dense point cloud representing the fine shape of the target at this step. Because the quality of the dense point cloud depends on the image resolution, careful selection of source images used in this step from the registered images is important to obtain the dense point cloud with homogeneous quality. By changing the image selection, we can obtain the global shape from the set of images with wide coverage, or regional but fine terrain models from the set of local close-up images.

Building a 3D Polygon Mesh Model: 3D polygon mesh models are reconstructed from a point cloud in this step. Small holes in the point cloud are filled by interpolation. Although this process is implemented in the Metashape package, remeshing may be done in the external software such as Meshlab to obtain a better result. The decimation of the polygons is used to produce low resolution models.

Post-production Processing: We do all SfM processes in a reference frame arbitrary defined by Metashape, then all products are transformed into the body-fixed frame of the asteroid. A transformation matrix is estimated by matching an SfM-based shape model to the SPC-based shape model in the body-fixed frame. The same matrix is used to transform the camera positions and attitudes estimated by the image registration.

Model Evaluation: Performance of the shape models was evaluated by several different ways: 1) errors or residuals computed during the shape reconstruction, 2) consistency among obtained shape models with different methods or different image data sets, 3) comparison between the camera (spacecraft) positions and attitudes estimated by different methods or different image data sets, 4) comparison between synthetic images from the shape models with ONC-T images, and 5) evaluation with LIDAR ranging data. Residuals of shape reconstruction give a quality of image matching and overall self-consistency of the model. Consistency among models with different methods shows a bottom-line of the model quality. A comparison between synthetic images and observed images evaluates the reproducibility of the models in small scales. A comparison with the individual LIDAR altitude profiles is another evaluation of small-scale topographic features [7]. Statistical analysis of the LIDAR data with the shape model gives a constraint on the asteroid size.

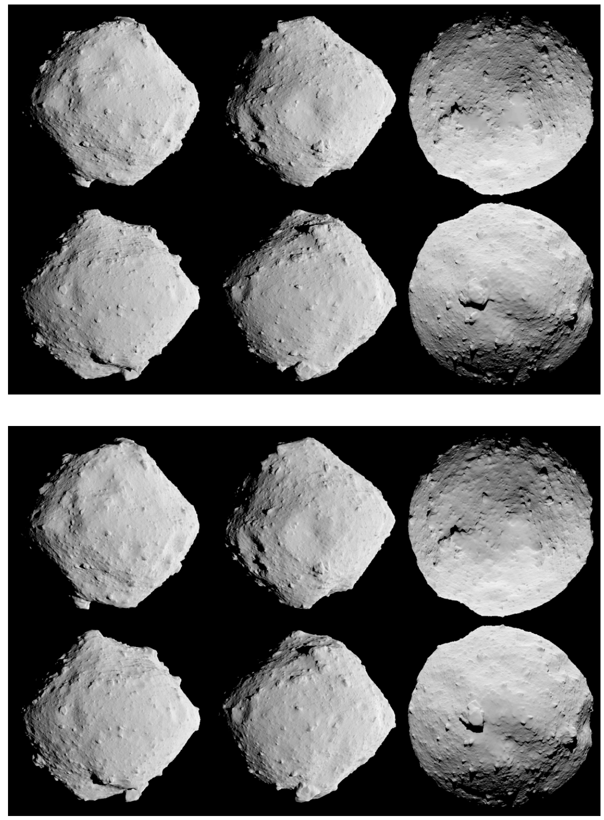

Figure 1. 6-sided views of the shape model reconstructed by SPC (top panel) and SfM (bottom panel).

Acknowledgement: This work is supported by KAKENHI from the Japanese Society for Promotion of Science (JSPS, Grant No. JP17K05639) and JSPS Core-to-Core Program "International Network of Planetary Sciences".

References: [1] Gaskell et al. (2008) *MAPS, 43*, 1049–1061. [2] https://www.agisoft.com [3] Watanabe et al. (2019) *Science*, 364, 268. [4] http://www.meshlab.net [5] Sugita et al. (2019) *Science*, 364, 252. [6] Suzuki et al. (2018) *Icarus* 300, 341. [7] Matsumoto et al. (2020) Icarus 338, 113574.