CROSS CALIBRATION BETWEEN HAYABUSA2 ONC-T AND OSIRIS-REX MAPCAM FOR COMPARATIVE ANALYSES OF ASTEROIDS RYUGU AND BENNU.

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Introduction: The telescopic Optical Navigation Camera (ONC-T) onboard Hayabusa2 [1] and the MapCam medium-field imager onboard OSIRIS-REx [2] acquired multispectral images of the Cb-type rubble-pile asteroid (162173) Ryugu and the B-type rubble-pile asteroid (101955) Bennu, respectively. The two imagers share four band-pass filters at similar wavelengths — 480, 550, 700, 860 nm for ONC-T, and 480, 550, 700, 850 nm for MapCam — which allows a direct comparison of the UV-to-VIS spectra of the two asteroids. Such comparative study has the potential to provide insights into the differences between the parent bodies of Ryugu and Bennu. A preliminary comparison on a global scale found that the mean reflectance of the two asteroids only differs by ~6% (0.0241 for Bennu and 0.0227 for Ryugu at 18º phase angle), with a slightly higher value for Bennu [3]. The 850/480 nm reflectance ratio also has a small difference of ~10% with a higher value for Ryugu. Detailed analyses including a comparison between geologic units have captured attention recently due to the findings of inconsistent space weathering trends between the two bodies [3,4].

However, while the current radiometric calibration coefficients (RCCs) were derived with an uncertainty of ~2% for ONC-T from inflight observations of stars [5], MapCam used the Moon [6], getting uncertainties of ~5%. Thus, the current calibration uncertainties are too large to conclude whether Bennu has a significantly higher reflectance than Ryugu, even on a global scale. Since the systematic uncertainties in spectral measurements of calibration targets are the main contributor of the errors in RCCs, the recalibration of the two imagers using the same target (for cross calibration) should greatly reduce errors and allow an accurate comparison. In this study, we aim to reduce the errors in the relative reflectance measurements of Ryugu and Bennu by conducting a cross calibration based on observations of the Moon.

Method: Multispectral observation of the Moon was performed during Earth fly-bys: 2 image sets on Dec 5, 2015, for ONC-T, and 12 image sets on Sep 25, 2017, for MapCam. The diameter of the lunar disk spanned 42 pix in the images from both cameras. We compared the observed lunar images with a shared lunar photometric model, which was used to correct for differences in the observation/illumination geometries and to account for differences in the observed faces of the Moon. Because both imagers observed the far side of the Moon, orbit camera-based models were used. Two models were selected to cover the entire wavelength range of ONC-T and MapCam: the LRO/WAC model [7] for 480 to 550 nm and the Kaguya/SP model [8,9] for 550 to 850 nm (hereafter, WAC and SP). RCCs of WAC and SP were updated inflight based on the ROLO model [10] in [9] and [11]. Thus, reflectance derived by the two models agrees within <3% (Fig. 1). Based on these photometric models, the observed lunar images were simulated following the procedures developed in [9] and [12].

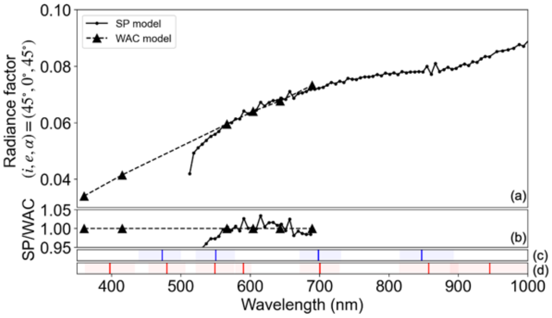

Fig. 1. a) Spectra from the two lunar photometric models: SP and WAC. b) SP spectrum normalized with WAC. Band centers and FWHMs of c) MapCam filters [6] and d) ONC-T filters [5].

Results: Figure 2 shows the observed-to-simulated ratio for one ONC-T image. In this case, the reflectance derived from the current calibration overestimates the simulated reflectance by ~10% and shows that RCC should be upscaled by 1.1. The rescaling factors for all bands are shown in Fig. 3. WAC underestimates the rescaling factor relative to SP images at 550 nm due to the fall-off of SP model reflectance at shorter wavelengths (Fig. 1). Nonetheless, dividing the rescaling factor of ONC-T by that of MapCam cancels this inconsistency. The residual inconsistency between

WAC and SP at 550 nm and the 1σ error among images, which are <±~2%, determines the uncertainties in our calibration method; the error obtained from our cross calibration is <1/3 of that from the current independent calibration. Figure 3 shows that RCCs of ONC-T should be upscaled by ~10% (or downscale the same amount for RCCs of MapCam) to derive the relative spectra of Ryugu and Bennu with low error. Namely, the reflectance of Ryugu should be relatively darkened by ~10±2% with respect to that of Bennu (or vice versa).

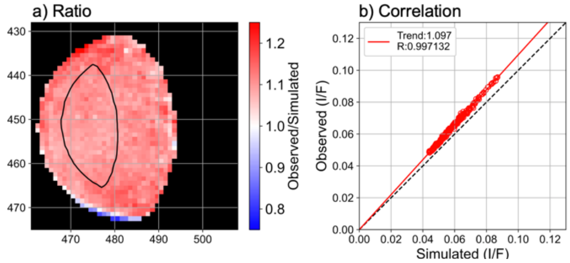

Fig. 2. a) An example of the observed-to-simulated ratio for ONC-T. The simulated image was created using the SP model [8,9]. The black line indicates the region where i, e <50º, which was used for updating the RCCs. d) The observed-to-simulated correlation.

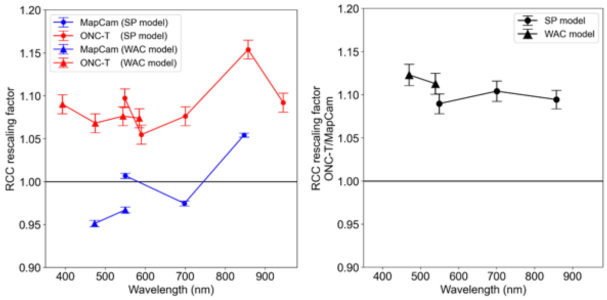

Fig. 3. *Left*: The rescaling factors for the current RCCs derived from cross-calibration. *Right*: The ONC-T/MapCam ratio of the rescaling factors. The error bars are derived from the 1σ variation among all processed images.

Discussion: We applied our results to ~0.3 m/pix images of Ryugu and Bennu. Because the RCC errors are larger for MapCam than for ONC-T, the rescaling factors were applied to the images of Bennu for simplicity. The phase angles during Ryugu and Bennu observations were 13º and 9º, respectively. The images were corrected to an intermediate condition of (i, e, α)=(10º,0º,10º) using the photometric models of the two asteroids [13,14] (Figs. 4 and 5). We conclude that Bennu is brighter by 12±2% at 550 nm and bluer by 10±3% in 850/480 nm reflectance ratio than Ryugu. The bluer slope found for Bennu may be attributed to the abundance of phyllosilicate material on this asteroid [15]. Also, we confirm that spectral heterogeneity is dominated by boulders for Bennu, whereas surface migration patterns dominate the heterogeneity on Ryugu [3,4]. Such substantial differences could have been inherited from parent body materials and/or caused by space weathering maturity differences between the two asteroids. However, some anomalously bright boulders and small craters on the two bodies appear to have similar spectra. Comparative analyses of these geological units based on the cross-calibration results obtained in this study will aid in understanding the similarities and differences between the underlying materials.

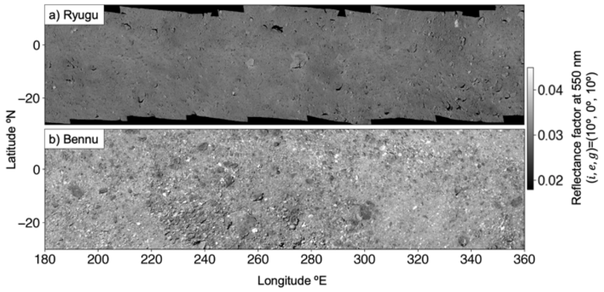

Fig. 4. Reflectance at 550 nm after cross calibration.

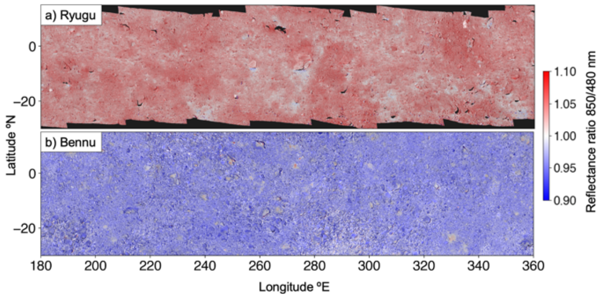

Fig. 5. 850/480 nm reflectance ratio after cross calibration.

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References: [1]Kameda et al., 2017, *Space Sci. Rev.*, *208*(1-4), 17-31. [2]Rizk et al., 2018, *Space Sci. Rev.*, *214*(1), 26. [3]DellaGiustina et al., 2020, *Science, 370*(6517). [4]Morota et al., 2020, *Science, 368*(6491), 654-659. [5]Tatsumi et al., 2019, *Icarus*, *325*, 153-195. [6]Golish et al., 2020, *Space Sci. Rev.*, *216*(1), 12. [7]Sato et al., 2014, *JGR*, *119*(8), 1775-1805. [8]Yokota et al., 2011, *Icarus*, *215*(2), 639-660. [9] Kouyama et al., 2016, *PSS*, *124*, 76-83. [10]Kieffer & Stone, 2005, *AJ*, *129*(6), 2887. [11]Mahanti et al., 2016, *Space Sci. Rev.*, *200*(1-4), 393-430. [12]Ogohara et al., 2012, *Icarus, 217*(2), 661-668. [13]Tatsumi et al., 2020, *A&A*. [14]Golish et al., 2020, *Icarus*, 113724. [15] Hamilton et al., 2019, *Nat. Astron*, *3*(4), 332-340.