

INFLIGHT SPECTROSCOPIC CALIBRATION OF HAYABUSA2 OPTICAL NAVIGATION CAMERAS (ONC) USING EARTH, MOON, MARS, AND STARS. ¹S. Sugita, ²H. Suzuki, ¹E. Tatsumi, ³M. Yamada, ⁴H. Sawada, ⁵S. Kameda, ⁶T. Kouyama, ⁷R. Honda, ⁸T. Morota, ⁹C. Honda, ¹⁰K. Ogawa, ³K. Shirai, ⁴M. Hayakawa, ⁴N. Ogawa, ³Y. Iijima, and ONC Team, ¹Univ. of Tokyo (sugita@eps.s.u-tokyo.ac.jp), ²Meiji Univ., ³Chiba Inst. Tech., ⁴JAXA/ISAS, ⁵Rikkyo Univ., ⁶AIST, ⁷Kochi Univ., ⁸Nagoya Univ., ⁹Aizu Univ., ¹⁰Kobe Univ.,

Introduction: The optical navigation cameras (ONC) consist of three visible framing cameras (a telescopic multiband camera (ONC-T), wide-angle panchromatic cameras (W1 and W2) on board JAXA's Hayabusa2, the first sample-return mission to a C-type asteroid [1,2]. In particular, observations of visible spectroscopic properties of possible hydrated minerals on Ryugu are of great importance for understanding the nature of this asteroid and for choosing sampling sites [3]. Our pre-flight validation experiments using the actual flight model of ONC-T and carbonaceous chondrites indicates that rather subtle $0.7\mu\text{m}$ absorption band, which are found in many C-type asteroids [e.g., 4] and may also be on Ryugu [5], can be observed with ONC-T [6].

However, change in environmental conditions and strong vibration during launch always poses concerns. Thus, we conducted inflight validation observations to verify such calibrations, including distortion, point-spreading function (PSF), spectral sensitivity for individual bands, and flat field using a variety of light sources since the launch in Dec. 2014 in this study. In particular, we had intensive observation campaign with our ONC system during the Earth-Moon swing-by in Dec. 2015 [7]. Subsequently, we observed Mars at its different rotational phases to examine the detectability of slight change in spectral properties of Mars. Furthermore, star fields were observed to verify both distortion and PSF of the cameras. More thorough discussions on the inflight calibration results will be given by [8], and this study provides highlights of these results.

Distortion and point-spread function (PSF): We conducted star measurements with T, W1, and W2. The distortion of W1 and W2 near the four corners of the field of view (FOV) is about 100 pixels. Correction using a degree 5 polynomial yields accuracy of distortion correction less than one pixel throughout the FOV.

The distortion of ONC-T is much less than that of W1 and W2. The maximum distortion at the four corners is about three pixels and that in the central part ($3^\circ \times 3^\circ$) of FOV ($6.35^\circ \times 6.35^\circ$) is less than one pixel. Thus, multi-band images of Ryugu (~ 0.85 km in diameter) from the home position, HP (~ 20 km), would be fit within the central area of the FOV and may not necessarily require distortion correction for co-registration of different bands for preliminary analysis.

Furthermore, no change in PSF was found for ONC-T (Fig. 1). The greater values of PSF at large

distance from the FOV center is due to mechanical vignetting (partial blockage of off-axis light) due to extended hood installed to prevent stray light through the lens tube [9]. However, because this increase in PSF is found only around the four corners of the FOV, this should not interfere with global observations of Ryugu from HP. Nevertheless, a care needs to be taken for PSF for full FOV images taken at lower altitudes.

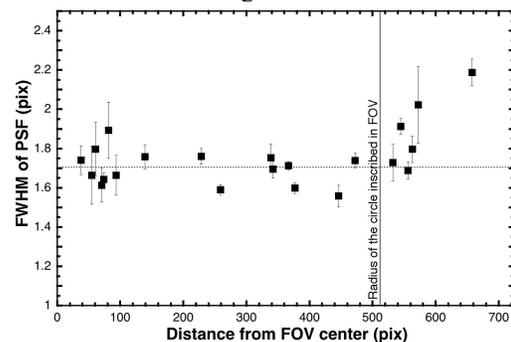


Figure 1. The full-width half maximum (FWHM) PSF of ONC-T measured with a star-field image as a function of the distance from the FOV center.

Sensitivity validation for ONC-W1/W2: Because W1 and W2 have wide-angle FOV, large light sources, such as Earth, are particularly useful for their validation. The results of the image analysis using pre-flight calibration reproduce brightness distribution expected for Earth very well (Fig. 2). Although comparison is qualitative, the consistency between pre-flight calibration data and actual inflight images strongly suggest that these two cameras are functioning well after the launch and one year of cruise to the Earth fly-by.

Relative spectral sensitivity for ONC-T: First, the accuracy of the relative spectral sensitivity normalized by the v -band (centered at $0.55\mu\text{m}$) is examined qualitatively with Mars and quantitatively with Moon.

Fig. 3 shows that the depth of the $1\text{-}\mu\text{m}$ silicate absorption band on Mars is significantly more pronounced for the image taken where Syrtis Major is near the disk center than other images, where more anhydrous nanophase ferric oxides are dominant. This consistency between observations and predictions suggest that ONC-T can detect such change in reflectance spectra accurately.

Furthermore, when 40×30 pixels of areas are binned together for the Moon, the spectrum based on preflight calibrations agree with that predicted from the spectral model based on JAXA's Kaguya measure-

ments [10, 11]. In particular, the discrepancy in the band ratios (w/v and x/v bands) used for quantifying the $0.7\mu\text{m}$ absorption for iron-rich serpentine is 0.4 and 0.8%, respectively (Fig. 4). If these values are good representatives for the error of our spectroscopic calibration of ONC-T, error propagation analysis indicates that 0.7% of error is expected for $0.7\mu\text{m}$ band depth ($A = (v + x - 2w)/2v$) measurements. This would be sufficient for detecting typical band depth (up to 3 – 5%) found for many CM chondrites [e.g., 12] and C-type asteroids [e.g., 4].

Absolute sensitivity and flat-field calibration:

These two quantities are necessary for obtaining the absolute brightness of individual pixel. The absolute sensitivity can be obtained with all the flux of light received in a FOV is summed together and is compared with the true value of the light flux. This comparison was made with the Kaguya model of the Moon, yielding about 10% of difference in absolute brightness of the Moon across all the seven filter bands on ONC-T [8,11]. This difference is probably on the same order of magnitude as the error of our spectral sensitivity calibration. However, because the absolute sensitivity of the Kaguya model may be improved in the future [11], the specific value may be subject to revision. Nonetheless, this order of error in absolute sensitivity is sufficient for most science observations of Ryugu.

Flat-field calibration was examined by comparing Moon images between near a corner and the center of FOV [8,11]. The ratio is within 2% after additional correction using a portable flat light source measurements immediately before the launch. This serves as a measure for brightness accuracy within one FOV of image. This error would lead to only one deg of error in slope for Lambert surfaces at 45° of slope of topography.

Summary: Inflight calibration observations of Haybusa2 indicate that the camera system is in a good condition without any noticeable damage or major change since the pre-flight calibrations. Result from our detailed analyses of the inflight spectral data strongly suggest that ONC-T can achieve visible spectroscopic observation of C-type asteroid Ryugu with high enough accuracy to detect signature of hydrated minerals, such as $0.7\mu\text{m}$ absorption, particularly when ~ a few tens by few tens of area is binned.

Acknowledgements: The research was supported by the Japan Society for the Promotion of Science KAKENHI (26247092, 15J06330, and 16H06719) and Core-to-Core program “International Network of Planetary Sciences”.

References: [1] Tsuda. et al. (2013), *Acta Astronaut.*, 91, 356 [2] Tachibana. et al. (2014), *Geochem. J.*, 48, 571. [3] Sugita et al., (2013) *LPSC #3026*. [4] Vilas & Gaffey (1989), *Science*, 246, 790. [5] Vilas (2008), *Astron. J.*, 135, 1101. [6] Kameda et al. (2015) *ASR*, 56, 1519. [7] Sugita, et al. (2016) *LPSC*, #2826. [8] Suzuki et al. (2017), in prep. [9] Kameda et

al. (2016), *SSR*, doi:10.1007/s11214-015-0227-y. [10] Kouyama et al. (2016), *PSS*, 124, 76. [11] Kouyama et al. (2017) *LPSC*, this issue, [12] Cloutis, et al. (2011) *Icarus*, 216, 309. [13] Singer et al. (1979), *JGR*, 84, 8415.

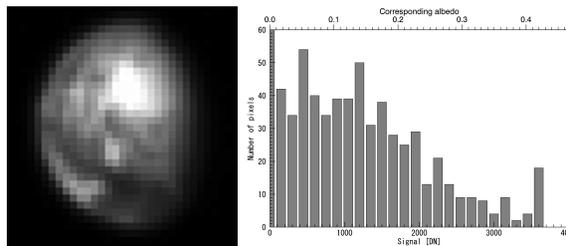


Figure 2. One of the Earth images obtained by the ONC-W1 on Dec. 4, 2015 and their brightness distributions.

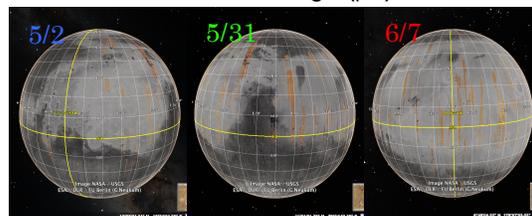
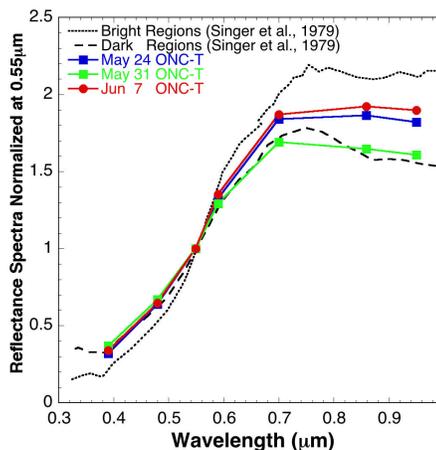


Figure 3. (Top) Reflectance spectra of Mars obtained by ONC-T different times. (Bottom) 1- μm albedo views of Mars (www.google.com/mars/) from Hayabusa2 at the time of observations. Note that Earth, Hayabusa2, and Mars were aligned approximately along a straight line during this period.

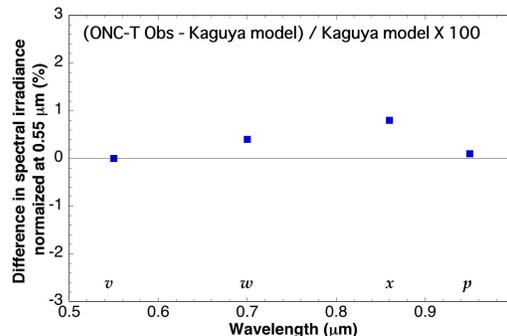


Figure 4. Difference in spectral irradiance of the Moon between ONC-T observation and Kaguya spectral model prediction. Note that both irradiance values are normalized at $0.55 \mu\text{m}$. Details of the comparison are given by [11].