Investigation of Hayabusa-2/ONC sensitivity variation based on observed Moon images. T. Kouyama[1], Y. Yokota[2], Y. Ishihara[3], R. Nakamura[1], S. Yamamoto[4], T. Matsunaga[4], M. Yamada[5], S. Kameda[6], H. Sawada[3], H. Suzuki[7], R. Honda[8], T. Morota[9], C. Honda[10], K. Ogawa[11], E. Tatsumi[12], N. Sakatani[7], M. Hayakawa[3], and S. Sugita[12], [1]National Institute of Advanced Industrial Science and Technology (1-1-1 Umezono, Tsukuba, Ibaraki 305-8568, Japan, t.kouyama@aist.go.jp), [2]Tsukuba planetary science group, [3]Japan Aerospace Exploration Agency(Yoshinodai, Sagamihara, Kanagawa), [4]National Institute for Environmental Studies(Onogawa, Tsukuba, Ibaraki), [5]Chiba Inst. Tech. (Tsudanuma, Narashino, Chiba), [6]Rikkyo Univ. (Nishi-Ikebukuro,Toshima, Tokyo), [7]Meiji Univ. (Higashimita, Tama, Kawasaki, Kanagawa), [8]Kochi Univ. (Nangoku, Kochi), [9]Nagoya Univ. (Chikusa, Nagoya, Aichi), [10]Aizu Univ. (Aizu Wakamatsu, Fukushima). [11]Kobe Univ. [12]Univ. of Tokyo (Hongo, Bunkyo, Tokyo).

Introduction: Reliable and stable quality control of data products of planetary explorers is a key factor to obtain valuable scientific information from the data. Radiometric calibration in space is one of essential issues for image and spectroscopy data quality. Because the Moon has the long-term stable surface reflectance (less than 1% variation during 1 million years [1]) and no atmospheric absorption and scattering, it can be an ideal target for the radiometric calibration for spaceborne instrument, once we have a reliable lunar surface reflectance model.

A hyperspectral lunar surface reflectance and photometrical model which covers whole lunar surface has been proposed, based on hyperspectral observation data obtained by Spectral Profiler (SP) onboard SELENE, a Japanese Lunar orbiter [2]. This model (SP model) covers a wavelength range from 512 nm to 1600 nm with 6-8 nm spectral sampling interval [2, 6]. Since planetary explorers can observe not only the nearside but also the farside of the Moon, which cannot be observed from the Earth, with various sub-spacecraft latitudes depending on its trajectory, it is important that the reflectance models have global coverage for comparison between observed and simulated radiances under any observation condition. Therefore, the SP model is a suitable reflectance model for radiometric calibration of planetary explores.

Japanese planetary spacecraft, Hayabusa2, observed the Moon with its ultraviolet, visible and near infrared multi-band sensor when it approached the Earth for obtaining gravity assist to go to their targets in 2015 [3]. Observed and simulated Moon images were compaired, and variations in sensor sensitivities during launch and one-year cruise were investigated in this study.

Moon observations by Hayabusa2/ONC: Haybusa2 has a multi-spectral camera (Optical Navigation Camera Telescope (ONC-T)) with 2-dimensinal charge-coupled devices (CCD's) and filters for ultraviolet to near infrared wavelength bands for investigating surface condition of their target asteroid [4]. ONC-T has taken Moon images three times before and after the Earth swing-by operation with its 7 bands. Table 1 lists center wavelength for each band, and Table 2 summarizes ONC-T observations (date, sub observer latitudes and longitudes on the Moon). In Table 1, sub Earth latitudes and longitudes are also listed for emphasizing the difference of the observation geometries of ONC-T from the Earth position.

As described in previous section, considering above geometry information, we can simulate both Moon observations of ONC-T using SP model. Figure 1 shows examples of Moon observation simulation utilizing ray-tracing calculation [7]. The resolution of simulated image shown in Figure 1 is matched to be same as ONC-T observations, and Gaussian smoothing is performed with FWHM of 1.71 pixels to match the width of ONC-T's point spread function [4].

Table 1. Center wavlength for each ONC-T Band.

Band	ul	b	v	Na	w	x	p
WL (nm)	390	480	549	590	700	859	950

Table 2. Geometries of Moon observations by ONC-T. Moon positions in the image frame and Sub Earth points on the Moon are also listed.

Date	12/05 11:51	12/05 12:38
Distance (km)	764,658	775,112
Sub obs. lat.	-56.4°	-56.5°
Sub obs. lon.	-96.2°	-97.5°
Sub Earth lat.	-1.0°	-1.1°
Sub Earth lon.	1.2°	1.1°
Center X [pix]	485	82
Center Y [pix]	453	48

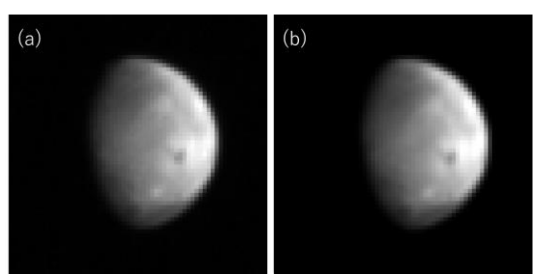

Figure 1. (a) An observed Moon image (band v: 550 nm) taken by Hayabusa2/ONC on December 5, 2015 and (b) its simulated image.

Comparison of irradiance between observed and simulated images: First, we focused on comparison of the disk integrated irradiance I (W m^{-2} μm^{-1}) between the observed and simulated Moon images, which is estimated from;

$$I = \sum_i r_i \omega_{\text{pixel}} \,,$$

where i indicates ith pixel included in Moon disk region in each Moon image, r_i is radiance at the ith pixel, and ω_{pixel} is the solid angle of a pixel. Since SP model covers wavelength range from 512 to 1600nm, we used Moon images observed by ONC-T with v, w, x, and p bands. The conversion factors from digital values to radiance are based on [4] for ONC-T. Sensor sensitivity correction based on CCD temperature [5] was performed to estimate r_i (approximately -29.5 °C during the Moon observation sequence).

It has been confirmed that the reflectance from SP model shows a darker trend in the short wavelength range (several tens %, [6] [7]), and thus a correction with another lunar reflectance model has been proposed [7]. In this study, the ROLO model was used for the correction, which is developed from ground-based multi-spectral lunar observations and whose absolute brightness has good consistency (up to 10% discrepancy) with many several satellite lunar observations in visible and near infrared wavelength range [8].

Irradiances (normalized at 550 nm) observed by ONC-T and simulation based on the SP model exhibit good agreement (Figure 2). The discrepancies were less than 1%, which indicates that the relative sensitivities among the ONC bands did not vary from pre-flight experiments [4]. With respect to the absolute irradiance comparisons, the observed irradiances were ~11% brighter than those from the simulated images. More thorough examinations are necessary for decisive conclusions due to the model uncertainty in absolute calibration [7].

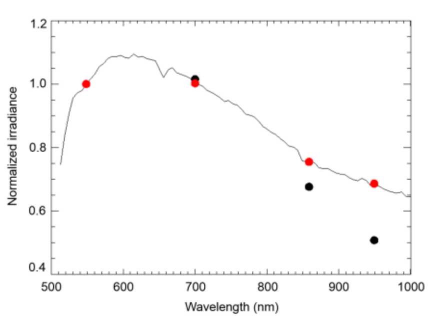

Figure 2. Comparison between normalized irradiance based on SP model corrected with ROLO model (solid line) and irradiances between observed lunar images taken at 11:58 Dec. 5 with (red dots) and without (black dots) CCD temperature correction.

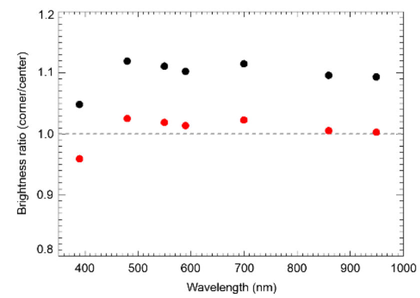

Figure 3. Moon brightness ratio of center and corner positions with (red dots) and without (black dots) additional flat correction.

Irradiance comparison among observed images: Since time difference between the first (Moon was center of the field of view (FOV)) and the second (in a corner of FOV) observations on December 5 was small and observation geometries were almost same, both Moon brightness should be almost same.

Figure 3 shows the comparisons of Moon brightness in all bands between the first and the second Moon observations with a distance correction. Though both brightness were expected to be almost same, we found ~10% differences. After performing additional flat field correction taking into account the slight change in the flatt pattern due to camera hood assembly [5], the differences were successfully reduced to less than 2% other than band ul.

Summary: Using the SP model, we have simulated Moon observations conducted by Hayabusa2/ONC-T. The observed irradiance (normalized) showed a good agreement with the simulation, indicating that relative sensitivity of ONC-T among bands has not changed significantly since the pre-flihgt experiment. In addition, comparing observed Moon brightness measured at different positions in FOV, we could detect a slight change in flat field property and found that error due to this change can be reduced by additional correction using data taken immediately before the launch.

These clearly demonstrate that the Moon is a useful calibration target for spacecraft that flies near the Earth and the Moon, and will help calibrate the radiometric accuracy of ONC-T for upcoming remote sensing observation of asteroid Ryugu in 2018.

References: [1] Kieffer (1997) *Icarus*, **130**, 327-323. [2] Yokota et al. (2011) *Icarus*, **215**, 639-660. [3] http://www.hayabusa2.jaxa.jp/topics/20151214_02_e/ [4] Kameda et al., (2016) SSR. [5] Suzuki et al., in prep. [6] Ohtake et al. (2013) *Icarus*, **226**, 364-374. [7] Kouyama et al., 2016, PSS. [8] Kiefer and Stone (2005) *Astronical J.*, **129**, 2887-2901.