THERMAL-INFRARED IMAGER TIR ON HAYABUSA2 AND ITS IN-FLIGHT PERFORMANCE AND CALIBRATION USING EARTH AND MOON THERMAL IMAGES. T. Okada[1,9], T. Fukuhara[2], S. Tanaka[1,9], M. Taguchi[3], T. Imamura[1,9], T. Arai[1], H. Senshu[4], Y. Ogawa[5], H. Demura[5], K. Kitazato[5], R. Nakamura[6], T. Kouyama[6], T. Sekiguchi[7], S. Hasegawa[1,2], T. Matsunaga[8], T. Wada[1], J. Takita[1,9], N. Sakatani[1], Y. Horikawa[1,10], K. Endo[5], J. Helbert[11], T. Mueller[12], A. Hagermann[13], and Hayabusa2 Thermal-Infrared Imager (TIR) Team[2], [1]Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency (ISAS/JAXA), 3-1-1 Yoshinodai, Chuo-Ku, Sagamihara 252-5210, Japan, okada@planeta.sci.isas.jaxa.jp, [2]National Institute of Information and Communications Technology (NICT), Koganei, Japan, [3]Rikkyo University, Tokyo, Japan, [4]PERC, Chiba Institute of Technology, Japan, [5]University of Aizu, Japan, [6]National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, Japan, [7]Hokkaido University of Education, Asahikawa, Japan, [8]National Institute of Environmental Studies (NIES), Tsukuba, Japan, [9]University of Tokyo, Japan, [10]Graduate University for Advanced Studies (Sokendai), Sagamihara, Japan, [11]Institute of Planetary Research, German Space Research Center (DLR), Berlin, Germany, [12]Max-Planck Institute for Extraterrestrial Physics, Garching, Germany, [13]The Open University, Milton Keynes, UK.

Introduction: Thermal infrared imager TIR is one of remote instruments on Hayabusa2 asteroid explorer, which is based on the uncooled micro-bolometer array inherited from the Longwave Infrared Camera LIR on Akatsuki [1], the Venus climate orbiter now circling the planet. TIR will observe thermal emission off the surface of asteroid (162173) Ryugu, the target body of Hayabusa2, and investigate thermo-physical properties of the asteroid surface. Performance and calibration of this instrument has been carried out before launch and also continued during cruise. We report the results of in-flight performance and calibration of TIR.

Hayabusa2: Hayabusa2 is the second sample return mission from a near-Earth asteroid organized by Japan Aerospace Exploration Agency (JAXA) [2-4]. The target asteroid (162173) Ryugu (former code name is 1999 JU_3), C-type in taxonomy, 0.9 km in diameter, 7.63 hours in rotation. Hayabusa2 was launched on 3 Dec. 2014, and passed by the Earth on 3 Dec. 2015 for using the gravity assist of Earth's mass to change its trajectory to the asteroid. It will arrive the asteroid in July 2018 and stay around there about 1.5 years, and return to the Earth for sample recovery in 2020.

TIR Instrument: TIR is a thermal infrared imager on Hayabusa2 to investigate the physical conditions and their regional distribution of the asteroid surface. TIR is based on a commercial based thermal infrared (thermographic) camera, and slightly redesigned for space use.

TIR consists of the sensor unit (TIR-S) and the power supply unit (TIR-AE), along with the digital electronics (DE) for processing of image data as well as the telemetry and command interface. The bias level of raw image data is so dispersive pixel to pixel, so that a couple of images are taken with its shutter open and close, and an effective thermal image is consequently derived by subtraction of these two images [5].

It covers the wide temperature range from 150 to 460 K, so that all the sunlit areas of Ryugu, and even the shadowed areas in case of thermal inertia > 50 [tiu = J m^{-2} $s^{-0.5}$ K^{-1}]), are measurable during the 1.5 year-long rendezvous phase. Field of view of TIR covers 16.7° x 12.7° in horizontal and vertical directions with 328 x 248 effective pixels, so IFOV is 0.051° per pixel. This corresponds to about 17 m per pixel from the Home Position, 20 km altitude from asteroid surface, and about 85 cm from the low altitude at 1 km from the surface. The closest view by TIR will be about 1 to 2 cm from the 10 to 20 m altitude during the final approach to touchdown [5].

In-Flight Performance of TIR:

Functionality and Heater Setting Points: We have confirmed that all the functions of TIR work well during the first test after launch. Performance of TIR has been checked monthly. We have found during the preflight test that temperatures of the filter and the shutter of TIR should be kept higher than 27.0 °C and 26.5 °C, respectively, to reduce noise level of spotty abnormal region within 1 digit. We controlled the temperatures by adjusting the setting points of the Heater Control Electronics HCE of Hayabusa2 to investigate what the spotty region looks like below and beyond the critical temperatures. We found the spotty region in the same way before and after launch, so that we selected the setting points of HCE to become 29.5 °C at the filter and 28.0 °C at the shutter.

Deep Sky View and Peripheral Brightening: TIR observed the deep sky during the monthly performance check. TIR images have peripheral brightening due to thermal radiation from the hood and optics of TIR, which are warmer than the deep sky. The lower limit of detection temperature by TIR is also determined as about -123 °C (or 150 K).

The peripheral brightening occurs just the same way every time, provided that the temperature settings are the same. The effect is cancelled from TIR images within 1 digit or so for the whole region of TIR image by subtracting a deep sky image of same temperature settings. This subtraction also cancels the dead pixels and the unbalanced biases of odd and even lines.

Alignment Check: TIR was mounted on the +Y panel of Hayabusa2 spacecraft and pointed to –Z axis, but no special treatment was taken for its alignment adjustment because there is no place to mount an alignment cube on TIR-S. Then the alignment of TIR in –Z axis was surveyed using the images of the Earth and the Moon taken before and after the Earth swing-by from October to December 2015. The alignment is checked relative to the –Z axis of spacecraft attitude and orbit control system AOCS (and the SPICE Kernel derived from it). The alignment was proven only 1 or 2 pixels (0.05° or 0.10°) shifted both in horizontal and vertical directions [6].

Thermal Emission from the Earth and the Moon: Performances and characteristics of TIR have been well studied and calibrated on ground, but it was the only opportunity that TIR observed the Earth and the Moon, the bodies with known thermo-physical properties and able to be used as calibrants, after launch and before arrival at Ryugu. TIR images were taken a few minutes before the optical images with the telescopic Optical Navigation Camera (ONC-T) so that TIR and ONC-T images could be compared. Figure 1 shows a thermal image by TIR, a pseudo-color image by ONC-T, and the computer graphic image at the time, 04:06 UTC on 4 December 2015. In this figure, you can find Australian Continent is hotter and Antarctica is colder than the surrounding ocean area, as well as the cloud vortices are colder. Preliminary estimates show that Australian Continent is the desert in the daytime and 10 to 20 °C, the Antarctica is covered with ice sheet and -45 to -40 °C, the southern Indian Ocean is about 0 °C, and the clouds are -45 to -30 °C, although we have not taken account of atmospheric absorption yet.

Even the highest resolved image of the Moon has only 5 pixels in diameter, but the highest temperature can be estimated as 60 to 70 °C for the area at medium latitude. This is consistent with the estimated value for the area.

Summary: Thermal Infrared Imager TIR onboard Hayabusa2 has been developed to investigate thermo-physical properties of C-type asteroid Ryugu, and has been checked for its functionality and performances during the cruise phase. So far we confirmed that TIR works well and observed the deep sky, the Earth, and the Moon. The alignment of TIR pointing direction has been determined relative to –Z axis of spacecraft. The observations of the Earth and the Moon by TIR show that the surface temperatures are consistent with the estimated values. Thus we believe that thermal images by TIR are expected to make an essential contribution as planned for the exploration of asteroid Ryugu.

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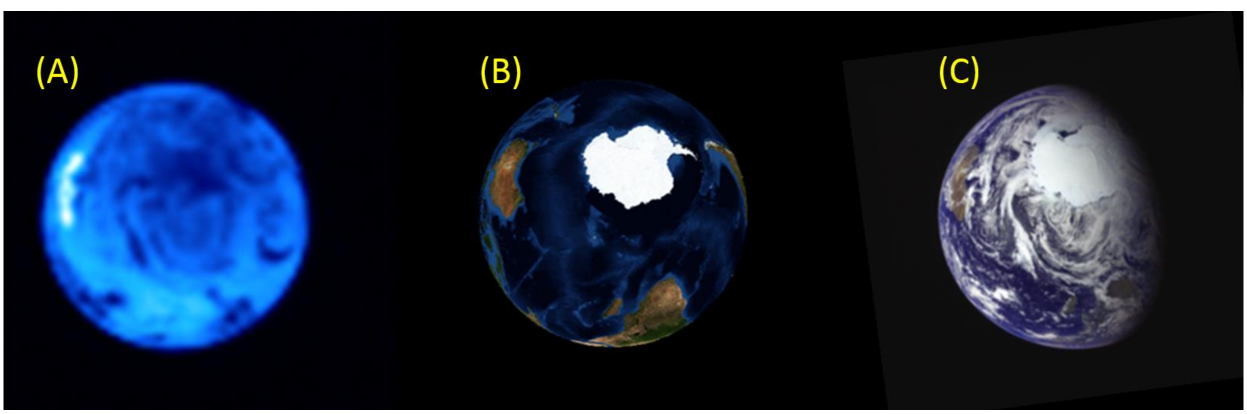

Figure 1: The image A is a thermal emission image of the Earth taken with TIR at 04:06 UT, on 4 December 2015, which is compared with the computer graphic image of the southern hemisphere of the Earth viewed from the direction of Hayabusa2 (FLOW/DARTS, ISAS/JAXA) (B), and with the pseudo-color image of the Earth taken just after the TIR image with the telescopic optical navigation camera (ONC-T) on Hayabusa2 (C). Australian Continent is hotter (brighter in image A) than the surrounding ocean area, while the Antarctica is colder. You can find the huge cloud vortices in image C are also detected in image A as the colder regions, even in the night side.