THERMAL INFRARED IMAGER TIR ON HAYABUSA2 AND ITS PREPARATION FOR ASTEROID PROXIMITY PHASE OPERATIONS AROUND 162173 RYUGU.

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Introduction: TIR [1] is a two-dimensional thermal infrared imager on Hayabusa2 [2], the second asteroid mission organized by JAXA, to explore C-type near-earth asteroid 162173 Ryugu (formerly 1999 JU$_3$). During the cruise phase, TIR observed the deep sky with setting the instrument at various temperatures, and also observed the Earth and the Moon before and after the Earth swing-by. Asteroid proximity phase operations are planned for TIR. The exercise for the landing site selection (LSS) and the real-time integrated operations (RIO) have been done in 2017 for the preparation of asteroid proximity phase operations. The status of TIR observations of asteroid Ryugu is presented.

Hayabusa2 and Ryugu: Hayabusa2 was launched on 3 Dec 2014 by the 26th H-2A launch vehicle, and accelerated by a gravity assist of Earth on 3 Dec 2015. It will arrive at, observe, and collect sample from Ryugu in 2018, and return them back to Earth in 2020 [3]. Ryugu is a C-type near-earth asteroid, with ca. 0.9 km in diameter, 7.63 hours in rotation. Its geometric albedo is estimated about 0.05, and the thermal inertia is 250 ± 50 [tiu = $\mathrm{J\ m^{-2}\ s^{-0.5}\ K^{-1}}$] [4]. After arrival, a series of global mapping of Ryugu will be carried out to investigate its shape, rotation state, geologic features, mineralogy, thermal inertia, density (or bulk porosity). A small lander MASCOT will observe the surface physical state, mineralogy, degree of hydration, thermal inertia and magnetic field. Analysis of returned samples is also planned. Origin and evolution of the asteroid as well as the surface processing, with multi-scale science by remote, surface, and sample analysis.

TIR performances: TIR is basically the same as the LIR on Akatsuki Venus climate orbiter [5], based on a two-dimensional uncooled micro-bolometer array with 328 x 248 effective pixels, and covers 8 to 12 am range. TIR has been proven during the pre-flight tests and in-flight operations to confirm the temperature range from 150 to 460 K [1]. This implies that not only the sunlit areas of Ryugu but even the nighttime areas could be observed if the thermal inertia is larger than 50 tiu. Field of view of TIR covers 16.7° x 12.7° in horizontal and vertical directions with IFOV is 0.051° per pixel. This corresponds to ca. 17 m per pixel from the Home Position (20 km altitude from asteroid) and to ca. 85 cm per pixel from 1 km altitude. Closest views of asteroid surface by TIR will be ca. 1 cm per pixel from 10 m altitude just before the final free fall to the surface for touchdown.

TIR Observation Plan during Proximity Phase: TIR observation plan is prepared for asteroid proximity phase as shown in Table 1. During the approach phase, TIR will observe Ryugu for light-curve measurements and search for the moons orbiting the asteroid at 2000 km, 200 km, and 20 km, along with the alignment and health checks. TIR will take 30 images per asteroid rotation. After the checkout is completed, TIR will conduct global mapping of the asteroid by more than 60 images for one rotation at 20 km (Box-A), at 5~7 km (Box-C), and at 5 km (Mid-Altitude). These data will be used for the landing site selection (LSS) for the sample collection and the release of small deployable robots (MASCOT, Minerva).

Close-up images at lower altitudes (~1 km) will be taken during the descent for gravity measurements, taking almost 100 images at lower than 5 km. Most of TIR observations will be conducted from the Earth direction, but the dawn/dusk regions can be observed from the oblique view (Box-B). Higher resolution local images will be taken during TD1 and its rehearsals, at 40 to 10 m altitude around the TD1, 2, and 3 sites.

During MASCOT operations, TIR observations at 3 km altitude will be done for 24 hours. For the Small Carry-on Impactor (SCI) separation, TIR will track the SCI for one minute (30 images), and during the escape of spacecraft, TIR will take four long-exposure images for dust cloud observations. TIR will be used to search for the crater excavated by SCI at Mid-Altitude (5km) and Low-Altitude (1km).

In-Flight Operations of TIR: In-flight health and performance checks have been continually conducted almost monthly except for Ion Engine periods. So far, no substantial problems were found for TIR health and performances. Before launch, it was reported that dark patched region was found in TIR images if the sensor was operated at lower than 26 °C. During the cruise, the performance of TIR has been investigated for various temperature at 26 to 34 °C, and only to find no patches. Thermal calculations show that, during the touchdown operations, TIR will be heated by thermal radiation from the asteroid surface to become up to 30 °C. Now it has proven no problem for TIR to take images at 40m or lower altitude during the touchdown operations.

Before and after the Earth swing-by on 3 Dec 2015, TIR has taken images of the Earth and the Moon from 14 Oct 2015 to 21 Dec 2015. It was used to update the alignment of TIR relative to the coordination of Hayabusa2 spacecraft (update of SPICE Kernels) [6]. The Earth and the Moon are the only targets that can be used as the calibrants of TIR before arrival. We have already reported the thermal radiation from the Earth and the Moon relative to the distance [7]. The results show that the thermal radiation intensities are inversely proportional to the square of distance even if they occupy only 3 % of the pixel area. Therefore, the detectability of Ryugu is estimated at 1.5 x 10^4 km for 3-σ accuracy. The distance to Ryugu at the beginning of Approach phase is less than 3000 km, so that TIR will detect Ryugu at the beginning. And the detectability of the orbiting moons is also estimated. If the moons are C-type, 10 m sized moons will be detected at 200 km (the second timing for light curve observations), and 1 m sized moons are detected from 20km (after arrival, and the third timing for light curve observations).

Preparation for LSS Process & RIO Exercises: TIR is responsible for the landing site selection process with the products as shown in Table 2. For this exercise, and asteroid model "Ryugoid" was constructed and the corresponding thermal images were produced with some errors. TIR will convert the raw thermal images (L-1) to the brightness temperature images (L-2a) using the HEAT database [8] that includes the preflight calibration data and converts the DN to brightness temperature for each pixel. The exercise started with the brightness temperature but we confirmed that the HEAT is now in work. Due to the limitation of TIR spatial resolution and the precision of errors, thermal inertia map of plains or geologic features more than 100 m in size will be properly realized, but the thermal inertia of smaller size such as the boulders or small craters cannot be properly realized. This is due to the inaccuracy of positioning and the variation of temperature within a pixel of TIR images which makes the thermal inertia of small features difficult to determine. Temperature prediction map is strongly requested for the operational purpose of MASCOT and Hayabusa2 thermal calculations beforehand.

RIO trainings have been conducted using the hardware in the loop (HIL) simulator. All the TIR functions have worked well so far during the specific operations as planned.

Table 1: Plan of TIR Observations:

Timing	Altitude [km]	Contents of TIR Observations
2018/06	2000	Light curves & search for moons (1)
2018/06	200	Light curves & search for moons (2)
2018/07	20	Light curves & search for moons (3)
2018/07	20	Global mapping (1): Box-A
2018/07	5~7	Global mapping (2): Box-C
2018/08	5	Global mapping (3): Mid-Altitude
2018/08	1	Close-up images during gravity measurements
2018/08	20	Global mapping (4): Box-B (dawn/dusk view)
2018/09	0.01	Global to local images: TD1-rehearsal1, MNRV
2018/10	3	Low altitude mapping: Hovering for MASCOT
2018/10	0.01	Global to local images: TD1, TD1-rehearsal2
2018/11	20	Global mapping (5): Box-A
2019/01	5	Global mapping (6): Mid-Altitude
2019/02	0.01	Global to local images: TD2, TD2-rehearsal2
2019/03	0.5	Tracking of SCI impactor and dust cloud images
2019/04	5	Global mapping (7): Mid-Altitude
2019/04	1	Close-up images for crater search
2019/05	0.01	Global to local images: TD3, TD3-rehearsals

Table 2: TIR Products for LSS

Level	Contents	Remarks
L-1	Raw thermal images	
L-2a	Brightness temperature images	Using HEAT
L-2b	Radiance Images	Using HEAT
L-3a	Intermediate Geo-Map data (lat-long)	SPICE, Shape
L-3b	Intermediate Shape-Map data (polygon)	SPICE, Shape
L-4a	Thermal maps at specific local time	
L-4b	Thermal inertia map	[9]
L-4c	Grain size map with a specific conversion	[10]
L-4d	Temperature prediction at specific timings	[9]

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