IAA-PDC-23-0X-XX

THERMAL INFRARED MULTIBAND IMAGER TIRI ONBOARD HERA TO INVESTIGATE S-TYPE BINARY ASTEROID DIDYMOS AND DIMORPHOS

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Keywords: *Thermography, thermal inertia, composition, porosity, roughness*

Abstract:

TIRI is a bolometer based thermal infrared imager with a multi-band filter wheel and being developed for the ESA Hera mission to explore S-type asteroid 65803 Didymos and its moon Dimorphos [1], for the purpose of planetary defense and planetary science. TIRI is used to investigate thermophysical properties and composition of the surface constituent materials of these asteroids, with a coordinated operations with other instruments on Hera. Here the specification of TIRI is introduced, and its mission objectives, the science cases, and the operation scenarios are discussed.

1. Introduction

Thermal imaging of an asteroid from spacecrafts is a useful method to investigate thermophysical properties of surface materials, as was proven during the JAXA Hayabusa2 mission [2-4]. The surfaces of asteroids smaller than 1 km in diameter so far explored at a close distance are always covered with pebbles or boulders but not by fine regolith like the Moon or Mars [5-8]. Surface temperature of rotating asteroids varies with the distance from the Sun, the local time of its rotation, geographic latitude, geologic features including local crops and small scale roughness at each site, as well as the surface thermophysical properties such as thermal inertia (the square root of the product of bulk density, heat capacity, and thermal conductivity of material). Thermal inertia is related to physical state like grain size, porosity made by inner pores and cracks.

Thermal inertia is derived when the asteroids are imaged from a near distance and other parameters above are known or observed by other methods. In Hayabsua2 mission, the thermal inertia of the C (carbonaceous) type asteroid 162173 Ryugu has been investigated with the thermal imager TIR and derived as 200-400 J kg^{-1} m^{-2} $s^{-0.5}$ (tiu, hereafter) in average [2], which is larger than the typical value of lunar fine regolith (~50 tiu) [9] and smaller than the typical value of most primitive carbonaceous meteorites (600-1000 tiu) [10]. There are also found such boulders with smaller thermal inertia [4] and those with higher thermal inertia [2] on Ryugu. Similarly low values of thermal inertia are also reported on the boulders of B-type asteroid Bennu by NASA OSIRIS-REx mission [11]. For the S-type asteroid, 25143 Itokawa explored by JAXA Hayabusa mission are covered with boulders for most of its surface and covered with pebbles at the flat area [12], but no thermophysical properties are observed. Up-close images of Dimorphos just before the impact of the NASA DART mission show that its surface is covered with boulders [8], and the thermophysical properties of these boulders will be investigated by thermal imaging during the Hera mission.

Multi-wavelength bands in thermal infrared range (7-14 µm) constrain composition of surface constituent materials, in comparison with meteorites and rocks. In the Hayabusa2 mission, the composition of a boulder on the surface of Ryugu was compared with meteorites and suggested that it is like aqueously altered carbonaceous chondrites using three bands of MARA radiometer on the MASCOT lander [13]. Similarly, the composition of lunar highlands was mapped with three bands in thermal infrared range of Diviner on the Lunar Reconnaissance Orbiter [14]. Here we describe about the TIRI instrument for the observations of asteroid Didymos and Dimorphos, the science cases, and the observation scenarios.

2. Hera mission and objectives

2.1. Hera mission and objectives

Hera is an asteroid rendezvous mission to explore S-type binary asteroid Didymos and Dimorphos, and jointly conducted with the NASA DART (Double-Asteroid Redirection Test) mission [15] to consist of the first planetary defense mission AIDA (Asteroid Impact and Deflection Assessment). The DART was launched on 24 Nov 2021 and performed a kinetic impact to the surface of Dimorphos on 26 Sep 2022. The Impact flash and dust ejection by DART impact were observed by ground and space observatories [16,17], as well as a decrease of rotation period around Didymos by 32 minutes from 11h55m to 11h23m was detected [18]. Effect of asteroid deflection by the DART impact was estimated [19] but needs to be investigated in more detail by Hera to determine the masses, densities, rotation states, physical properties including strength, porosity, and composition, as well as the dimension of the artificial crater formed by the DART impact.

Hera will be launched in Oct 2024 and rendezvous with the asteroid binary system in Jan 2027 to perform a half year long observations. The primary objective of Hera is planetary defense to validate the effect of asteroid deflection to avoid the disaster from the possible impact of asteroids to Earth. Hera will also play an important role for planetary science, especially for the understanding of the planetary formation processes.

2.2. Target asteroids

The binary system of Didymos and Dimorphos was observed from The DART and the LICIACube released from the DART [8,19]. Didymos is a spheroidal shaped S-type asteroid with the diameter of 851 x 849 x 620 m (errors of ± 15 m). Its surface is covered with large boulders while a smooth area was found at the equatorial region. Its density is estimated as ~2100 kg m^{-3}, similar to ~1900 kg m^{-3} of a rubble pile S-type asteroid 25143 Itokawa [20]. Its orbital period is 2.108 years, and the perihelion and aphelion are 1.0134 au and 2.2753 au, respectively. Didymos is one of a potentially hazardous asteroid with a minimum orbital intersection distance (MOID) is 0.04014 au (15.6 lunar distance) from the Earth. Since physical properties of S-type asteroids have never been directly measured, observations from Hera will be the first case.

Dimorphos is found a rubble-pile asteroid with boulders as was imaged from DART just before impact [8]. Its taxonomy is still unclassified. Its diameter is 177 x 174 x 116 m (errors of ± 2m) and its bulk density is 2400 (± 900) kg m^{-3} [19]. Before the DART impact, Dimorphos orbited in an almost circular orbit, with the eccentricity of <0.05, around Didymos in 11.921 hours at 1.19 km from the center of Didymos. The post-impact orbital period is 11.372 hours [19] and the detailed orbital state will be measured from Hera.

2.3. Hera instruments

Hera has five remote sensing instruments, two CubeSats, and the radio science [1]. TIRI is a thermal infrared imager developed by JAXA. AFC (Asteroid Flaming Camera) is a couple of visible imagers both for the scientific and navigational use to observe the size and shape, surface geology, and rotation state of asteroids. HyperScout is a hyperspectral imager with 5x5 mosaiced filters, covering 650 to 950 nm to inform the composition and space weathering effect of the asteroid surface. PALT (Planetary Altimeter) is a time-of-flight laser altimeter for measuring the distance from the asteroid and the surface shape. All these instruments are mounted on the top panel of the Hera spacecraft, able to point the target simultaneously. Milani is a 6U CubeSat to observe composition of asteroids using a set of visible to near infrared spectro-imagers and a thermogravimeter for duct detection. Juventas is another 6U CubeSat to measure physical properties of the asteroids using an HF radar, an accelerometer, a gravimeter, the guidance and navigation sensors, and a wide-angle camera for *in situ* surface measurement.

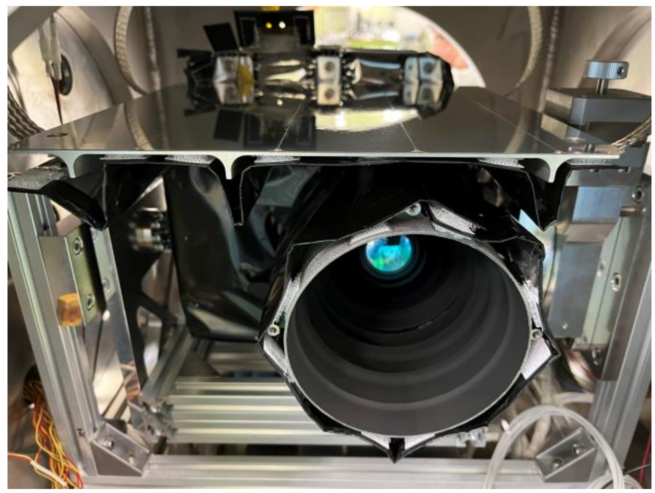

Fig.1 Photograph of TIRI EM in the calibration chamber.

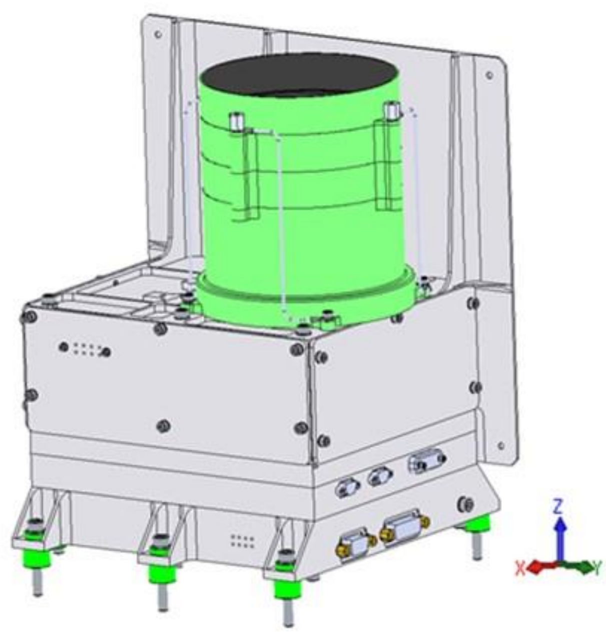

Fig.2 Outline of TIRI instrument.

3. TIRI instrument

3.1. Outline of TIRI

TIRI is a one-component remote sensing instrument onboard Hera, consisted of the sensor unit BOL and the electronics unit SHU. BOL are inherited from the thermal imager on an Earth-orbiting small satellite UNFORM2 [21], while the logics of SHU are inherited from the TIR on the asteroid explorer Hayabusa2 [22].

TIRI engineering model is now manufactured (see Figs. 1 and 2), and its total mass is 3.9 ± 0.1 kg, the power is 9 ± 1 W in the safety mode, 10 ± 1 W in the operational mode but the filter wheel is off, and 15 ± 1 W while the filter wheel is on. Additional power up to 8 W is used for the internal heaters. The envelope size is 190 (X) x 230 (Y) x 263 (Z) in mm, including the radiator and the six legs for fastening TIRI to the spacecraft. TIRI is supplied unregulated power of 28 V from the Hera power supply unit. TIRI has two channels of heaters and thermistors for temperature control by the Hera thermal control system. TIRI communicates with the Hera data handling unit via SpaceWire to receive commands and time information, and send telemetry of housekeeping, status, and image data. The specifications are shown in Table 1.

3.2. Sensor unit BOL

BOL is based on an uncooled bolometer array (Lynred PICO1024 Gen2) with 1024 x 768 pixels, with the anti-reflection coated Ge-based infrared lens (F/1, f = 75 mm), the sunshade baffle, the 8-point filter wheel, and the radiator. It takes images at the frame rate of 25 Hz, covers the wavelength range of 8 to 14 µm with a wide band filter, and has the FOV of 13.3° x 10.0°, with the IFOV of 0.013°/pixel (0.23 mrad/pixel). The instrument has proven to observe the black body targets controlled at 153 to 423 K (-120 to 150 °C) during the performance and calibration tests, meaning that TIRI can detect the asteroid surfaces both in the day and night sides. BOL is stabilized at 25-27 °C by the system heaters during the operation.

BOL has the 8-position filter wheel for thermal infrared multi band imaging. Three of the 8 positions are for the narrow band filters which cover the Christiansen Features (CF) at 7-10 µm (centered at 7.8, 8.6, and 9.6 µm), the other three of them are for the narrow band filters which cover the Reststrahlen Features (RF) at 10-13 µm (centered at 10.6, 11.6, and 13.0 µm), another one is a wide band filter at 8 to 14 µm for thermal imaging, and the rest is a closed plate to be used as a shutter to protect insolation and as a target for a reference temperature. The filter wheel moves to the next position in about 8.5 seconds, and the one set of all the 8-position images takes typically 85 sec.

3.3. Electronics unit SHU

SHU is the FPGA based electronics unit of TIRI. It performs the image data readout from BOL, the on-board image data processing, the house-keeping data collection, the CCSDS packetization, the control of telecommands and telemetry and the interface to the Hera data handling unit via SpaceWire, the electric power control for the 28V unregulated power supply, the fine control of BOL temperature, and the filter wheel control.

SHU captures raw thermal images of 1024 x 768 pixels at 14 bit depth from BOL at 25 Hz and stores them into the image buffer. Those images are integrated by the commanded numbers of 2^N, where N = 0 to 7, to improve its signal-to-noise ratio, and bit-shifted to form the 15-bit images. The dark frame images, typically the images of deep sky, are taken for all the 8-position filters and stored into each of the 8 slots in the BG (background) area of 1 GBytes size flash memory. The observed target images, such as the target asteroids, are taken and stored into IMG (image) area of the flash memory. The stored images are selectable as the raw images directly read from the image buffer or subtracted images with the corresponding dark frame image of the same filter stored in the BG area. In total, 2039 images can be stored in the IMG area at the same time. If necessary, the data in the flash memory can be erased by commands. The status of TIRI at the time of taking the image is also stored for each image.

Those images stored in the flash memory are output as the series of CCSDS packets. Before packetization, the images can be compressed by JPEG-LS or not, and selected the region of interest at the image size of 512 x 384 pixels, started at every 128 pixels in horizontal and vertical directions of image. The image data packets are transferred to Hera data handling system via SpaceWire when requested while the image packets remain in TIRI (the image flag is high in HK).

For the possible onboard use for the spacecraft guidance and navigation control, GNC images at 8 bit for each pixel can be constantly constructed as the CCSDS packet format and output via SpaceWire upon request.

TIRI has pre-defined automatic sequences for initial settings, calibration, thermal imaging, and multiband imaging. TIRI can run the macro sequences uploaded by commands to conduct the sequence commands with waiting times in a row, so that various combination of operations can be conducted.

Table 1. TIRI specifications

Items	Performance
Detector	Lynred PICO1024 Gen2
Pixels	1024 x 768 pixels
Wavelength	8 -14 µm (Wide band)
Filter bands	7.8, 8.6, 9.6, 10.6, 11.6, 13.0 µm
Frame rate	25 Hz
NETD	< 0.1 K @300K
Abs. Temp	< 3 K @300K
Optics	F/1.0, f=75mm, AR coating
FOV	13.3 x 10.0 deg (16.7°)
IFOV	0.23 mrad/pixel (0.013 deg/pixel)
Integration	2^N, N=0, 1, 2, …, 7
Total mass	3.9 ± 0.1 kg (max <5.5kg)
Envelope	230(X) x 190(Y) x 260 (Z) mm/mm
Total Power	15 ± 1 W (max: <30W)

4. Science cases for TIRI

4.1. Physical properties of S-type asteroid

Physical properties of S-type asteroids have never been measured directly from the spacecraft. TIRI will map the thermal inertia of Didymos through the one-rotation thermal images of asteroid observations of Didymos using the wide band, which is related to surface porosity, roughness, and grain size. TIRI will also map composition of Didymos through multiband imaging, together with visible to near infrared spectroscopy by HyperScout and from Milani CubeSat, to understand aqueous, thermal and chemical evolution on asteroid. Physical properties not only the average of the asteroid but also each of surface boulders could be compared with those of C-type Ryugu observed by Hayabusa2 [2-4] and B-type Bennu observed by OSIRIS-REx [11], both of them in sub-km diameter, to understand its dependency on taxonomic classes.

4.2. Smallest asteroid ever explored

Dimorphos is the smallest asteroid ever explored by spacecraft and the structure of such small asteroid, monolithic or rubble-pile, is an essential question to understand its formation process. Although it is observed as a rubble pile body from the up-close images taken by DART [8], it still remains unknow how dense or porous the surface boulders are and their variation. The composition of the boulders and the variation is also unknown. TIRI will map thermal inertia and composition of the surface average and each of the large boulders and compare them with those of larger asteroid Didymos to investigate the dependency on asteroid size.

4.3. Binary asteroid

Hera will observe a binary asteroid system for the first time from a proximity orbit, and it is interesting whether the thermophysical properties and composition are the same between Didymos and Dimorphos or not. Numerical simulation shows the possible formation of an asteroid binary from break-up of a rapidly rotating parent asteroid [1] but the capture of an asteroid coming from elsewhere cannot be ruled out to form a binary system, so that this could be the first case to validate the model.

4.4. Asteroid dynamics

The size, shape, rotation state, and the center of figure are essential to characterize the dynamic motion of the body, but a precise measurement of these values is difficult for such an irregular shaped asteroid not only by a visible camera and a LIDAR instrument. But it becomes much better with a thermal imager like TIRI, since the night side rim of the body can be imaged. Similarly, the co-rotation orbit and the center of gravity of an asteroid binary system could be well determined using the thermal imager covering the whole binary system within the FOV. Dynamical evolution of the binary could be investigated with such precise data, probably for understanding the binary formation process.

4.5. Non-gravitational acceleration

The long-term orbital evolution and rotation state is affected by non-gravitational acceleration, especially by thermal radiation, Yarkovsky and YORP effects for orbit and rotation, respectively. TIRI will construct the global asteroid thermophysical model, which consists of the thermal inertia, emissivity, roughness mapped on the asteroid shape model, and will strongly contribute to the orbital and rotational evolution of the binary system.

4.6. Impact phenomena

Hera is planned to observe the observations of the surface of Dimorphos from various distances, including the close flybys. If the artificial crater is formed by the kinetic impact of DART to the surface of Dimorphos, TIRI will observe the shape, dimension, and composition inside and outside the crater. If the surface is completely shattered by the DART impact, TIRI will observe the exposed surface at that time. TIRI will also observe the surface of Didymos in detail, where the ejected dust might be deposited. TIRI will observe these traces of DART impact to investigate the effect of impact to compare with the prediction [1], and construct a scaling law for the impact events for the purposes of planetary science and planetary defense.

4.7. Spaceweathering

Spaceweathering is the surface process which is altered by irradiation of solar winds or galactic rays as well as impacts by micrometeors, and observed as the change of spectral profile in visible to near infrared wavelength. The effect is more enhanced for fine grained surface compared to coarse grained or rocky surface [23]. The condition of asteroid surface such as grain size is informed as thermal inertia, which will be constrained by TIRI. Concurrent observations of thermal imaging by TIRI and near infrared spectroscopy by HyperScout are needed to understand the spaceweathering process.

5. TIRI operations

5.1. TIRI operations before arrival

TIRI will be powered on and perform its function check in the commissioning a few weeks after the launch of Hera in Oct 2024. During the cruise phase, dark sky images will be taken every three months for the purpose of health check, monitoring the degree of degradation, and adjusting the heater setpoints for the temperature control of TIRI. During the Mars flyby in March 2025, the thermal and multiband images of Mars and its moons, Phobos and Deimos, will be taken to be used for scientific research, especially about the thermophysical properties of Martian moons, and for the calibration of TIRI using the known targets.

During the approach phase in Jan 2027, the thermal and multiband images of the Didymos binary system will be taken at several distances from 2,000 to 30 km, from a point source to the disc-resolved target. Detectability of Didymos binary by TIRI is considered better than that of TIR on Hayabusa2 [24], so that the asteroid will be detected at the distance since the solar distance of Didymos is almost 1 au at that time. Its one-rotation light curve profile of thermal radiation from the asteroid will inform the asteroid shape before arrival. The variation of multiband color ratios indicates its longitudinal distribution of the target body. It is important for TIRI to observe the same target from various distance to investigate the size of source effect [2], the dependency of apparent radiance on the target size and necessary for calibration. TIRI will be kept turning on during the mission to stabilize its internal temperature.

5.2. TIRI operations at the proximity of asteroids

After arrival at the Didymos binary system, TIRI will perform observations of 1) a set of one-rotation thermal images of Didymos or Dimorphos by a step of 6° or 12° to investigate thermophysical properties, 2) a set of 8-band images by a step of 30° or 60° for mapping compositional distribution, 3) consecutive thermal images at a few second or a short time interval for the target tracking, rapid cooling at the eclipse, or observations during the fast flybys, 4) continual images from various solar phase angles and various solar distances, 5) dark sky images for each of 8 positions of filer wheel as the dark frame.

During the Early Characterization Phase (ECP, the observations at 20-30 km from Didymos), TIRI covers the entire binary system and observes those asteroids for the one-rotation periods of Didymos (2.26 hours) [1,18] and Dimorphos around Didymos (11.372 hours) [18,19]. Such observations will be done from the dawn, the dusk, the north, and the south directions, with the spatial resolution of 4.5-6.9 m/pixel (from 30 to 20 km distance). In the Hayabsua2 mission, similar one-rotation thermal imaging with the TIR instrument have been done at 4.5 m/pixel during the Mid-Altitude Observation Campaign (5 km altitude) of asteroid Ryugu and the thermal inertia and roughness of the asteroid surface were mapped. [2,3].

The DART impact of a 500 kg spacecraft at 6 km/s to the surface of Dimorphos may form an artificial crater much larger than the SCI crater of ~15 m diameter, which was formed by the impact of 2 kg copper liner at 2 km/s [25]. If the crater is formed, the crater should be identified by thermal imaging by TIRI, and the materials are compared between inside and outside the crater as well as between Didymos and Dimorphos with the multiband images of TIRI. Alternatively, the DART impact may completely shatter the surface of Dimorphos, in which case the thermophysical properties and composition could be observed at the newly exposed area.

During the Payload Deployment Phase (PDP, at 20-30km from Didymos), TIRI will take consecutive thermal images and track the CubeSats released from Hera, just as TIR tracked the SCI in Hayabusa2.

During the Detailed Characterization phase (DCP, at 8-20 km distance), TIRI will take one-rotation thermal images and 8-position multiband images of Didymos and Dimorphos from a nearer distance than ECP from the directions of dawn, dusk, north, south, and around noon, to map thermal inertia, roughness and composition of the binary asteroids at the spatial resolution of 1.8 m/pixel at best (from 8 km distance). Continual images from various solar phase angles will be taken to inform the angular dependency.

During the Close-up Operation Phase (COP, at 4-22 km from Didymos), TIRI will take one-rotation images and multiband images of Didymos and Dimorphos from north, south, and noon directions from much closer distances with the spatial resolutions of 1~1.5 m/pixel (from 4-6 km). In such cases, the DART crater, if it exists, will be imaged much more clearly.

During the Experiment Phase (EXP, close to 1 km from Didymos and Dimorphos), TIRI will take consecutive thermal images of local areas of Didymos and Dimorphos at <0.25 m/pixel at best, so that the dimension of crater will be determined with TIRI.

Table 2. TIRI operations and objectives

Phase	Operations	Objectives
Cruise	Commissioning	Function checks
	Dark sky imaging	Function check Health check Temperature adjusting
	Mars flyby	Calibration by known targets
Approach (8 weeks)	Detectability	Performance check
	Size of source effect	Calibration
	Light curves	Shape modeling
	Color variations	Composition mapping
ECP+PDP (30-20km) (6+2 weeks)	One-rotation thermal images	Thermophysical modeling
	Multi-band images	Composition mapping
	Consecutive thermal images	Rapid cooling at eclipse regions
	Tracking CubeSats	Checking the CubeSats
DCP (8-20km) (4 weeks)	One-rotation thermal images	Thermophysical modeling
	Multi-band images	Composition mapping
	Consecutive thermal images	Rapid cooling at eclipse regions
	Phase angle dependency, opposition effects	Photometry of thermal infrared, Phenomena at zero solar angles
COP (4-22km) (6 weeks)	One-rotation thermal images	Thermophysical modeling
	Multi-band images	Composition mapping
	Phase angle dependency, opposition	Photometry of thermal infrared, **Phenomena at zero solar angles**
EXT (<1~20km) (6 weeks)	Consecutive thermal images	Detailed imaging at DART crater
	Multi-band images	Compositional mapping, especially at DART crater

6. Summary

TIRI is a thermal imager with an 8-position filter wheel to investigate thermophysical properties and constituent materials of the surface of Didymos and Dimorphos. These data along with the data by other instruments will bring a new insight of planetary science and also planetary defense in Hera mission.

Acknowledgments:
TIRI is manufactured by Meisei Electric Co. Ltd. This work is supported by the ISAS/JAXA as a Strategic Overseas Joint Space Science Mission in collaboration with ESA.

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