**Observed data products and Asteroid Mappings of Thermal Infrared Imager onboard Hayabusa2.** T. Arai[1], H. Demura, T[2]. Kouyama[3], H. Senshu[4], Y. Ogawa[2], T. Fukuhara[5], T. Okada[6], S. Tanaka[6], T. Matsunaga[1], [1]National Institute for Environmental Studies (arai.takehiko@nies.go.jp), [2]The University of Aizu, [3]National Institute of Advanced Industrial Science and Technology, [4]Chiba Institute of Technology, [5]Rikkyo University, [6]Japan Aerospace Exploration Agency

**Introduction:** The thermal infrared imager (TIR) is a thermal infrared camera onboard the Hayabusa2 spacecraft, which performs thermography of the asteroid 162173 Ryugu (formerly 1999 JU3). It will estimate the thermophysical properties of the asteroid surface materials through in-situ observations in 2018 and 2019 [1]. The TIR takes images of 328×248 pixels, and the spatial resolution is ca. 0.05°/pixel with the field of view (FOV) of 16°×12°. The band-pass filter of the TIR limits the detection range of the thermal radiation emitted from targets to wavelengths of 8 to 12 $\mu$m.

To make global maps of the surface's physical properties for the asteroid is a primary goal of the TIR. In particular, a thermal inertia $\Gamma$ is the main target, which is written as the thermophysical amount of the thermal conductivity $\kappa$, and the specific heat $c_p$, as follows:

$$\Gamma = \sqrt{\rho c_p \kappa},$$

where $\rho$ is the bulk density. The thermal inertia depends on the physical and thermal properties of the targets and represents resistance to their temperature changes. It will affect peak shifts of diurnal time at the maximum temperature of the asteroid surface and cause orbital changes of the asteroid as studied in the Yarkovsky effect. Also, a surface thermal emissivity $\varepsilon$ will apparently change observed temperatures. In particular, a surface roughness, caused by surface shadows of light and multiple radiations, will apparently change the local emissivities and their temperatures. The effects will be changed by observed phase angles of the TIR-Asteroid-Sun, which are known as beaming effects, e.g., [2]. Therefore, the estimation of the $\Gamma$ and $\varepsilon$ is significant for the temperature determinations of the asteroid.

In the asteroid Ryugu, observation from the Hayabusa2 by the TIR will produce several data products about physical properties of the asteroid surface. This study introduces the observation data products of TIR, the prepared analysis tools, and the asteroid global mapping procedure.

**Data Products:** The TIR nominally observes at the altitude of 20 km from the asteroid (home position of the Hayabusa2 spacecraft). The TIR will take global images at the sunlit area (above 50 images) during one asteroid day (rotation period of about 7.6 hours [3]) for a week. When the surface material samplings are performed, the TIR will take close-up images at low altitudes of about 5 m. The observed data will be automatically converted from raw digital images to temperature images using a UNIX-based computer at ISAS/JAXA and the University of Aizu. Level-0 and Level-1 data are currently available on JAXA's website [4], including the Earth and the Moon images taken with the TIR on 2015 (Figure 1).

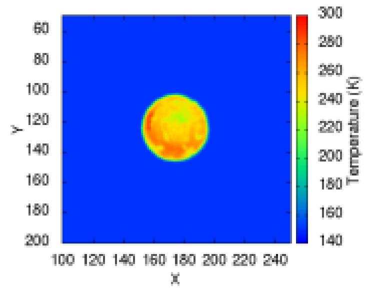


**Figure 1:** An example of the brightness temperature image (Level-1a). Observed data during the Earth swingby is currently available on JAXA's website (DARTS/ISAS) [4].

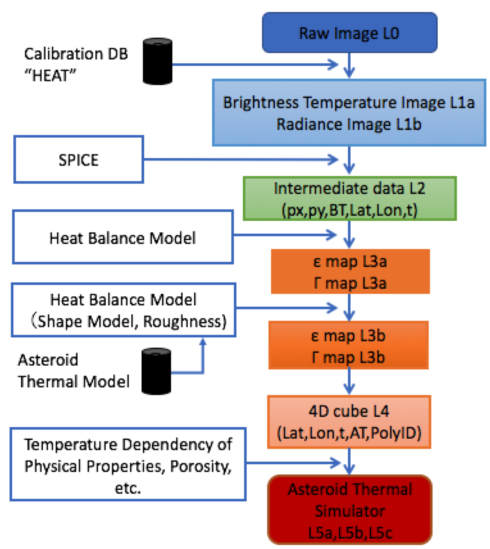


Figure 2: Observed data product generation flow of the TIR. The products are automatically generated by using a UNIX-based computer called a "reformatter" at ISAS/JAXA. These analysis algorithms have been developed at the University of Aizu, Chiba Institute of Technology, and National Institute for Environmental Studies.

The data generation flow is schematically shown in Figure 2. These details are mentioned below.

*Level-0. Law images:* Analog-to-digital value (DN) images are not converted to temperature or radiance. The TIR performs "chopping" to reduce its inner radiative backgrounds. It performs subtracting from shutter-opened images and transmits it to shutter-closed ones. The data products include pixel coordinates and raw observed values of shutter-closed images and shutter-opened ones (px, py, closed DN, px, py, opened DN).

*Level-1. Brightness temperature and radiance:* The level 1 data are converted from DN images to temperatures and radiances. A calibration DB "HEAT," powered by the University of Aizu [5], selects most suitable calibration tables from the pre-launch calibration database. It searches most near data at a temperature condition of the TIR when the TIR observes targets in the space because the observed data of the TIR varies with the temperature of the TIR itself. The brightness temperature (Level-1a) and radiance (Level-1b) images are constructed in 32 bit FITS format [6]. PDS4 metadata [7] are also available.

*Level-2. Intermediate data:* The observed pixel coordinates connect to the asteroid coordinates, generated by the SPICE kernels [8]. The file format is CSV tables (px, px, brightness temperature, latitude, longitude, time).

*Level-3. Thermal inertia and Thermal emissivity map:* Global maps of the thermal inertia and the thermal emissivity are generated in the file formats CSV, VTK, and KML. These are derived by a least-squares fitting for the observed temperatures with specific models using the fitting parameters $\kappa$ (or $\Gamma$) and $\varepsilon$. Level-3a is derived from a simple model for one facet of the asteroid shape model. There heat flows of the surface layer are modeled by using a one-dimensional non-steady-state heat transfer equation, e.g., [2] as follows:

$$\rho c_p \frac{\partial T(z,t)}{\partial t} = \kappa \frac{\partial^2 T(z,t)}{\partial z^2},$$

where $T(z,t)$ is the temperature at the depth $z$ and the time $t$. This boundary condition is expressed as using the Fourier equation and the Stefan-Boltzmann law as written as follows:

$$-\kappa \frac{\partial T(z,t)}{\partial z}\bigg|_{z=0} = (1-A)S - \varepsilon\sigma T(z,t)^4,$$

$$-\kappa \frac{\partial T(z,t)}{\partial z}\bigg|_{z\to\infty} = 0,$$

where $S$ is the heat flux supplied from the solar insolation, $A$ is the bolometric bond albedo, and $\sigma$ is the Stefan-Boltzmann constant. The upper boundary is an uppermost surface layer ( $z = 0$ ), and the lower boundary is equivalent to a skin depth ($z \to \infty$). The heat balance equation can be approximately solved by using a numerical finite difference method (implicit method) [10]. More detail analytic thermal models for multiple facets of the asteroid shape model have been developed at Chiba Institute of Technology and ISAS/JAXA [10]. These detail analysis products are more correct about surface roughness, multiple scattered radiations, and reabsorbed radiation (Level-3b).

*Level-4. 4D Cube:* The data are converted from brightness temperatures to absolute temperatures. Their radiometric and geometric corrections are completed, and thus these are the final data products (latitude, longitude, time, absolute temperature, polygon facet ID). The data provides net thermal emissivities and actual surface temperatures at local areas of the asteroid surface.

*Level-5. Asteroid Thermal Simulator:* This is the 4D surface temperature simulator (latitude, longitude, time, absolute temperature) for the asteroid Ryugu. It is corrected for the temperature dependency of the surface physical properties by using the results of the laboratory experiments [11]. In particular, surface particle size and porosity will be simulated.

**Future work:** The thermal inertia and thermal emissivity map of the asteroid Ryugu's surface will be provided. They are required to perform a huge number of model calculations about multiple scattered absorption, radiation, and least-squares fittings for each polygon facet of the asteroid shape model. Required spatial resolution of the maps is the one resolvable with local characteristic features of the surface, the same as the spatial resolution of the TIR (about 20 m @ 20 km home position). Therefore, high-speed analysis algorithms for the calculation for the asteroid thermal model have been developing. Also, data analysis tools have been automatized.

**References:** [1] Okada T. et al. (2016) *Space Sci. Rev*. [2] Lebofsky, L.A. and Spencer, J.R. (1989) *in Asteroids II*, University of Arizona Press. [3] Müller et al. (2011) *A&A* 525, A145. [4] DARTS/ISAS https://hayabusa2.darts.isas.jaxa.jp/ [5] Endo K. et al. (2017) *IEEE*. [6] FITS https://fits.gsfc.nasa.gov/ [7] PDS https://pds.jpl.nasa.gov/ [8] SPICE http://naif.jpl.nasa.gov/naif/ [9] Takita J. et al. (2017) *Space Sci. Rev*. [10] Crank and Nicolson (1947), *Proc. Camb. Phil. Soc.* 43 (1) 50–67. [11] Sakatani et al. (2012) *Icarus*, 221-2, 1180-1182.