Thermal Infrared Imager Onboard Hayabusa2 Observes the Thermophysical Properties under the Surface Layer of the Asteroid Ryugu. T. Arai[1], S. Tanaka[2], T. Kouyama[3], H. Senshu[4], N. Sakatani[5], T. Okada[2], [1]National Institute for Environmental Studies (arai.takehiko@nies.go.jp), [2]Japan Aerospace Exploration Agency, [3]National Institute of Advanced Industrial Science and Technology, [4]Chiba Institute of Technology, [5]Meiji University

Introduction: The thermal infrared imager (TIR) is a thermal infrared camera onboard the Hayabusa2 spacecraft, which performs thermography of the asteroid 162173 Ryugu through in-situ observations in 2018 and 2019 [1]. The main purpose of TIR is to determine the thermophysical properties of asteroid surface materials and to reveal the asteroid's evolutional history such as physical properties of the originally coalesced bodies, orbital changes due to the Yarkovsky effects, and the thermal evolution.

The target asteroid, 162173 Ryugu (1999 JU_3), is a C-type, near-Earth asteroid which is considered to be a parent body of carbonaceous chondrites. Other asteroids ever explored are 433 Eros and 25143 Itokawa, for example. Eros is approximately 34x13x13 km in size [2], and its surface is entirely covered with fine regolith. Itokawa is approximately 0.5x0.3x0.2 km in size, and its surface is regolith and pebble rock mixtures. The explorations of these two progressed to knowing the origin of asteroids and rubble pile small bodies [3]. The size of Ryugu is approximately 0.8 km, and the surface is expected to be covered with regolith and rocks [4]. If under the regolith on the surface is observed, understandings of the originally coalesced bodies of Ryugu will progress.

This study examines observations of the interior of the asteroid Ryugu with TIR and discusses the estimation method for the physical properties of regolith-and-rocks multi-layer on the surface.

Observation: TIR observes the surface temperature of Ryugu. The band-pass filter of TIR limits the detection range of the thermal radiation emitted from the asteroid's surface to wavelengths of 8 to 12 μm and observed digital values are converted to temperatures using a calibration database [5]. TIR takes images of 328×248 pixels, and the spatial resolution is 0.051°/pixel with the field of view (FOV) of 16.7°×12.7°.

TIR nominally observes the asteroid at the altitude of 20 km (home position of the Hayabusa2 spacecraft). TIR will take global images of the sunlit area (above 50 images) during one asteroid day (rotation period of about 7.6 hours [6]) a few times a month. When the surface material samplings are performed [7], TIR will continuously take close-up images at low altitudes of about 5 m every 32 seconds. There, TIR will be expected to capture the spacecraft's shadow on the surface.

Simulation: TIR will make global maps of the thermophysical properties on the surface to observe a continuous profile of surface temperature. A thermal inertia Γ indicates for the thermophysical properties, which are written as the amount of the thermal conductivity κ, and the specific heat c_p, as follows:

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

where ρ is the bulk density. The thermal inertia depends on the physical and thermal properties of the targets and represents resistance to their temperature changes.

This study simulates powdered regolith on boulders as illustrated in Figure 1. The heat balance model ([8],[9]) of this configuration assumes to be written as a one-dimensional non-steady-state heat transfer equation 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 σ is the Stefan-Boltzmann constant. The upper boundary is the uppermost surface layer ($z = 0$), and the lower boundary is equivalent to the skin depth ($z \to \infty$). The heat balance equation can be approximately solved by using a numerical finite difference method [10].

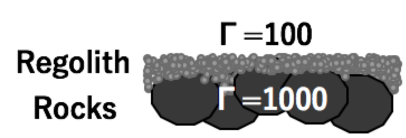

Figure 1: Illustration of regolith-and-rocks layer surface. We calculated the heat balance for the one-dimensional layers of 1 mm thick regolith on semi-infinite rocks. Thermal inertias of the regolith and rocks are 100 and 1000, respectively. There, thermal conducted resistance assumed to be negligible.

Results and Discussion: We estimated the surface temperatures for the regolith surface as well as the regolith-and-rocks layer. The assumed parameters of this model are shown in Table 1. The asteroid's shape was treated as a sphere.

Table 1: Parameters of the heat balance model

Parameter	Value
Thermal inertia of regolith (1mm)	Γ=100 $Jm^{-2}s^{0.5}K^{-1}$
Thermal inertia of rocks	Γ=1000 $Jm^{-2}s^{0.5}K^{-1}$
Specific heat	c_p=700 $Jkg^{-1}K^{-1}$
Bolometric albedo	A =0.05
Density	ρ =1600 kg m^{-3}
Emissivity	ε=1.0
Solar constant	S=1366 W m^{-2}
Asteroid rotation period	t =7.6 hours
Asteroid radius	r= 0.43 km
Asteroid-Sun distance	d=1.496x10^8 km

The calculated results indicate that the surface temperature of the regolith layer and the regolith-and-rocks layer will be different on the night side of the asteroid (Figure 2a) because their total thermal inertia is different. Also, this study assumed that the solar flux is half (Figure 2b). Such a configuration supposes that the solar flux incident to the asteroid is shaded with the shadow of the Hayabusa2 body (4.2 x 2.5 m) when the Hayabusa2 descends to the surface for the sampling of surface materials. There, the shadow will cause a decrease in the surface temperature, and the relatively the high thermal inertia surface will slowly decrease compared with the low thermal inertia surface. This difference is useful for finding out hidden rocks under thin regolith surface.

TIR nominally observes surface temperature on the day side of the asteroid. The observed temperature will depend on the thermophysical properties of the uppermost surface layer because solar insolation to the surface is dominant as a heat source. Thus, observed temperature of powered regolith covered with rocks will be same as regolith only layer. Therefore, temperature observations of the night side and shaded area are significant for the estimation under the surface.

If the surface of Rygu is similar to the Itokawa surface, surface regolith may be sorted by vibration of the asteroid [11]. Also, original coalesced rocks of parent body may be found on the surface sorted by Brasil nuts effects. However, the rocks may be covered with powdered regolith. TIR will find out invisible areas under surface layer and estimate their thermophysical properties.

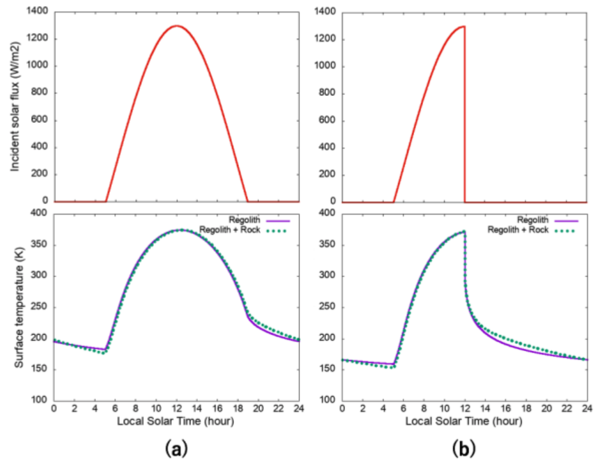

Figure 2: (a) The simulated solar flux incident to the asteroid surface and surface temperature of the asteroid (one asteroid day). The surface temperature will be different compared all regolith layer with the regolith-and-rocks layer on the night side of the asteroid. (b) The half solar flux incident to the asteroid surface, which supposes the spacecraft's shadow on the surface at the phase of surface material sampling. The shadow of the spacecraft will decrease the surface temperature. The surface temperate of the regolith-and-rocks layer varies slower than regolith only surface because the thermal inertia of rocks is relatively large.

References: [1] Okada T. et al. (2017) *Space Sci. Rev.* [2] Veverka J. et al. (2001) *Nature* **413**, 390–393. [3] Fujiwara A. et al. (2006) *Science* **312**, 5778, 1330–1334. [4] Hasegawa S. (2008) *Publ. Astron. Soc. Jpn.* **60**, 399–405. [5] Endo K. et al. (2017) *IEEE*. [6] Müller T.G. et al. (2011) *A&A* **525**, A145. [7] Sawada H. et al. (2017) *Space Sci. Rev.* [8] Lebofsky L.A. and Spencer, J.R. (1989) *in Asteroids II*, University of Arizona Press. [9] Takita J. *et al.*, (2017) *Space Sci. Rev.* [10] Crank and Nicolson (1947), *Proc. Camb. Phil. Soc.* **43** (1) 50–67. [11] Miyamoto H. et al. (2007) *Science*.