Geometric Correction for Thermal Imaging of Asteroid Ryugu Observed by TIR onboard Hayabusa2

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Abstract

The thermal infrared imager (TIR) onboard the Hayabusa2 spacecraft performed thermographic observations of the asteroid 162173 Ryugu (1999 JU3) from June 2018 to November 2019. In this study, we performed a geometric correction for TIR images by making a one-to-one correspondence between the observed areas and the surface coordinates derived from a shape model of Ryugu. The pointing direction, which is an alignment direction of TIR, was adjusted by rotating the TIR frame relative to the base of the Hayabusa2 frame using a least-squares fit. This geometric correction allows us to identify observed local areas within one pixel, which corresponds to 5 m error in a 5 km altitude observation. The corrected temperature images projected onto the shape model were constructed. Hot temperature regions were found at the base of Ejima Saxum and Otohime Saxum, for instance. A simulation result indicates that multiple radiations from the surrounding terrains generate hot regions. The estimated thermal inertia of the base of Ejima Saxum as characteristic shape area is approximately 300 Jm$^{-2}$s$^{-0.5}$K$^{-1}$ within the error bars of the observed temperature profile. This estimation is succeeded by performing the geometric correction in case that the surface topographic features are greater than the spatial resolution of the pixel. However, thermal inertia estimations of smooth terrains, such as the center of Urashima crater, were difficult probably because of surface roughness effects. Our results suggest the necessity to develop a hybrid thermophysical model that implements large- and small-scale surface roughness.

Keywords

Hayabusa2, Asteroid, Ryugu, Thermal Infrared Imager, TIR, Shape model, Thermal model, Surface roughness.

Introduction

Hayabusa2 is a Japanese asteroid sample return mission that rendezvoused with the asteroid 162173 Ryugu (previously known as 1999 JU3) from 2018 to 2019. The asteroid Ryugu is classified as a C-type asteroid (Binzel et al. 2004), which is considered to be parent bodies of carbonaceous chondrite meteorites. Watanabe et al. (2019) revealed that the asteroid Ryugu is shaped in tospin, whose rotation...
period is 7.63 hours. Kitazato et al. (2019) suggested that the surface materials of Ryugu, observed using the near-infrared spectrometer (NIRS3), are similar to thermally or shock-metamorphosed carbonaceous chondrites. The optical navigation camera (ONC) onboard Hayabusa2 found several characteristic features of the surface in the scale of centimeters to meters; they are large ridges, regolith deposits, and cracked rocks (Sugita et al. 2019). The gravitational observation indicated that the bulk density of Ryugu is $1.19 \pm 0.02 \text{ g cm}^{-3}$ (Watanabe et al. 2019). These results implied that the asteroid Ryugu has a porous, coalesced rubble piles internal structure.

The thermal infrared imager (TIR) onboard the Hayabusa2 is a thermographic camera of $328 \times 248$ pixels resolution (Okada et al. 2017). The sensor is an array of microbolometers, and one pixel has a size of 37 $\mu$m. The observation wavelength is integration energy ranges from 8 to 12 $\mu$m. The field of view is an angle of $12.66^\circ \times 16.74^\circ$, and the spatial resolution is $0.051^\circ$/pixel. The goal of TIR is to reveal the history of Ryugu, such as the thermal properties of coalesced parent bodies, orbital evolution due to radiation force (Yarkovsky effect, Bottke et al. 2006), and the thermal alteration in parent bodies. In particular, to obtain thermal inertia of the Ryugu surface is the primary purpose. The thermal inertia is written as $\Gamma = \sqrt{\rho c_p k}$, where $\rho$ is the bulk density, $k$ is the thermal conductivity, and $c_p$ is the specific heat.

The observed thermal images of TIR indicated that the distribution on the brightness temperature of the Ryugu surface is broadly homogeneous over the observed hemisphere. This phenomenon is considered to be caused by surface roughness due to a variety of surface angles within a pixel resolution (Groussin et al. 2007; Senshu et al. in preparation). By using a thermophysical model utilizing a shape model of Ryugu, TPM1 (Takita et al. 2017), the global thermal inertia of Ryugu was roughly estimated to be $300 \pm 100 \text{ Jm}^{-2}\text{s}^{-0.5}\text{K}^{-1}$ (Okada et al. 2020). Note that TPM1 cannot reproduce the observed temperature distribution of Ryugu because TPM1 does not implement the effect of surface roughness on the apparent brightness temperatures. By using a thermophysical model utilizing a shape model of local rough surface, TPM2 (Senshu et al. 2017), the global thermal inertia map of Ryugu was obtained, and its mean value was estimated to be $225 \pm 45 \text{ Jm}^{-2}\text{s}^{-0.5}\text{K}^{-1}$ (Shimaki et al. 2020). However, because TPM2 considers surface roughness within a TIR pixel, the thermal inertia of regions where topography changes drastically (e.g., bases of large boulders) was not determined.

The observed temperatures are affected by the surface terrain larger than a pixel resolution, such as bases of large boulders. Thus, the derivation for the accurate observation area of TIR is necessary to
determine actual surface temperature. The shape models of Ryugu were constructed by ONC observations (Watanabe et al. 2019). The position and attitude of Hayabusa2 were calculated and controlled by an attitude and orbit control system (AOCS) and controlled by a reaction control system (RCS) (Tsuda et al. 2013). After each observation and following data reduction, the data of ONC and the light detection and ranging (LIDAR) laser altimeter provided detailed trajectories that include relative attitude and position between Ryugu and Hayabusa2 after observation (Matsumoto et al. 2020). Since TIR and ONC nominally took images alternately, the observation coordinate for TIR can be calculated by complementing data of ONC and LIDAR observation. However, the pointing coordinate of TIR was uncertain when observations with ONC and LIDAR was not performed.

The pointing direction of TIR depends on its alignment, which is defined by the TIR frame relative to the Hayabusa2 frame. The alignment of TIR was determined in the Moon observation during the Earth swing-by sequence of Hayabusa2 (Okada et al. 2018). However, the observation distance was too far (>76,100 km) to obtain accurate alignment. The current alignment value includes offsets in images equivalent to a few pixels.

In this study, we performed a geometric correction with a one-to-one correspondence between the observed area and the surface coordinate addressed on the polygons of the shape model. The pointing direction of TIR was adjusted to rotate the frame of images from the Hayabusa2 frame using a least-squares fit. We update the alignment values of TIR and discuss the application for temperature estimation of the Ryugu surface using the geometric correction, comparing the observed data with the simulated data.

Data

The brightness temperatures of the Ryugu surface were obtained by observations at several altitudes and angles. The nominal observations of Hayabusa2 were called Box-A, -B, and -C (Watanabe et al. 2019, Figure S1). The Box-A (Home Position) was performed at an altitude of around 20 km at the sub-Earth point. The Box-B was performed at an altitude of 20 km, moving the horizontal direction within 9 km. The Box-C was performed at a low altitude below 20 km at the sub-Earth point. Besides the Box observations, several observations were carried out at low altitudes, such as Mid-Altitude operation at an altitude of 5 km, and the MASCOT deployment operation at an altitude of about 50 m (Jaumann et al. 2019).

The observed data of TIR were converted from digital data to brightness temperature using a calibration...
database “HEAT” (Endo et al. 2017). The calibration table was constructed in prelaunch experiments (Okada et al. 2020; Arai et al. 2017). The observed data are published in DARTS/ISAS (Yamamoto et al. 2016). They are the raw digital data (Level 1 product), the brightness temperature (Level 2 product), and the higher degree products.

The surface terrain of Ryugu has been modeled by numerical shape models constructed from ONC images (Watanabe et al. 2019). The shape models were derived by a structure from motion (SfM) method (Szeliski 2010) and a stereo photoclinometry (SPC) method (Gaskell et al. 2010). The 3M, 800k, and 200k shape models of Ryugu are composed of 3,145,728, 786,432, and 196,608 triangles, and sizes of the triangles are tens centimeters, about 1 meter, and a few meters, respectively.

NASA’s numerical toolkit for the geometry system of the space mission called SPICE kernels (NAIF/NASA) for the Hayabusa2 mission has been released on the website of DARTS/ISAS. The SPICE kernels include the spacecraft information on trajectories derived from data of AOCS and LIDAR, and that on attitudes based on the data of AOCS and the SPC shape models. In this study, using version 03 of the SPICE kernel, released in March 2020, we analyzed data of early major observations (Box-A on 2018-07-10, Box-C on 2018-07-20, Mid-Alt on 2018-08-01, and Box-B on 2018-08-31). Version 03 kernels contain the improved trajectory of Hayabusa2 derived from LIDAR (Matsumoto et al. 2020) but do not include the relative position and attitude between Ryugu and Hayabusa2 derived from the SPC shape model. The new version of the SPICE kernels for Hayabusa2 will be released in December 2020, which includes a precise attitude of Hayabusa2 derived from the SPC shape model, along with the results of this study.

**Geometric Correction**

To fit areas observed by TIR to the coordinates of a shape model, performed by rotating the TIR images frame using the SPICE toolkit (N0066) is geometric corrections for the TIR brightness temperature images (Level 2). The temperatures in the brightness temperature images are represented by \( T(i, j) \) in the image pixel coordinate, where \( i \) and \( j \) are the index of pixels \( (i = 1 \sim 328, j = 1 \sim 248) \), respectively. On the other hand, the observed brightness temperatures projected on facets of a shape model are represented by \( T(X, Y, Z) \) in the Cartesian coordinate of the Ryugu system (Figure 1), where, the positional vector of the facets are denoted by \( \mathbf{V}(X, Y, Z) \).
The brightness temperature projection from a TIR image to a shape model of Ryugu is expressed as a coordinate transformation from the pixel coordinate to the Ryugu coordinate. We consider that the observed brightness temperature in a pixel is the mean temperature of the region because the TIR pixel detects total radiation fluxes from a region of the Ryugu surface (e.g., 5m squares in Mid-Alt). Here, we assume that the observed fluxes are isotropic radiation fluxes from the Lambertian surface. The brightness temperature value in an image is directly converted to that in a shape model as $T(i,j) \rightarrow T(X,Y,Z)$. This transformation is represented by using the vector sum of positional vectors. A ray vector $\mathbf{V}_R$ from a polygon of the shape model of Ryugu to TIR is written as $\mathbf{V}_R = \mathbf{V}_T - \mathbf{V}_P$, where $\mathbf{V}_P$ and $\mathbf{V}_T$ are position vectors of the polygon and TIR, respectively (Figure 1). The ray vector in the coordinated system of Ryugu $\mathbf{V}_R$ is transformed into that in the coordinate system of Hayabusa2 $v_R$ using a coordinate conversion tool of the SPICE kernels, as $\mathbf{V}_R \rightarrow v_R$. A normalized boresight vector of TIR in the coordinated system of Hayabusa2 is $(x,y,z) = (0,0,1)$. This frame of TIR is the coordinate system of Hayabusa2 rotated $-180^\circ$ in the y-axis (Figure 1). The focal point length of the TIR is 42.2 mm, and thus the positional vector of the focal point is written as $v_F(x,y,z) = (0,0,0.0422)$. The incident rays from polygons of the shape model to TIR intersect the image plane of TIR at the positional vector $v_I$, where $v_I = \mathbf{V}_R + \mathbf{V}_F$. A pixel size of the TIR sensor is 37 $\mu$m squares, and thus the scalar value $|v_I(x,y,z)|$ normalized by the pixel size is converted to the pixel coordinate $(i,j)$.

The shape-to-image temperature conversion is written as well as the image-to-shape conversion to iterate the temperature projection. Note that we consider a blended brightness temperature of a pixel included rays from several polygons of the shape model. Thus, the reprojection is irreversible, i.e., $T(X,Y,Z) \not\rightarrow T(i,j)$. Here, the radiant flux $F$ from the polygons to a pixel of the image as the sum of their radiations using the Stefan-Boltzmann law and the scattering component of the solar radiation are calculated, as follows:

$$F = \frac{1}{\pi} \sum_k \epsilon_k \sigma T_k^4 s_k \cos \phi_k + \text{scattering},$$

where $\epsilon_k$ is the emissivity, $\sigma$ is the Boltzmann constant, $s_k$ is the area of the polygons, $\phi_k$ is the emission angle to TIR direction, and $k$ denotes the index of the polygon. The observation area for one pixel is
written as the sum of polygon areas, as follows:

\[ S = \sum_k s_k \cos \phi_k. \]  \hspace{1cm} (2)

We neglect the scattering component because the intensity of the radiation flux in the is 8 to 12 \( \mu m \) wavelengths is more than two orders of magnitude smaller than that of infrared radiation of a body with about 300 K. We assume a constant emissivity each facet, and thus the re-imaged temperature \( \tau \) for a pixel is rewritten using Equation (1) and (2), as follows:

\[ \tau \sim \left( \frac{\pi F}{\epsilon \sigma S} \right)^{\frac{1}{4}}. \]  \hspace{1cm} (3)

Frame Rotation

The frame of TIR \( v_T(x, y, z) \) is defined based on the frame of Hayabusa2 \( v_H(x_o, y_o, z_o) \). The frame transformation is described by using the Euler rotation, as follows:

\[ v_H = R_z R_y R_x v_T, \]  \hspace{1cm} (4)

where \( R_z, R_y, \) and \( R_x \) form the Euler rotation matrix in the right-handed coordinate system. The matrix \( R_z \) is the rotation of the TIR boresight vector, which has a bimodal path in the clockwise and the counterclockwise rotations. In this study, \( R_z \) is fixed as a unit matrix because TIR is a 2D imager, and this parameter is not effective in minimizing the converge value of the least-squares fitting by the geometric correction. Hence, Equation (4) is written, as follows:

\[
\begin{bmatrix}
  x_o \\
y_o \\
z_o
\end{bmatrix}
= 
\begin{bmatrix}
  \cos \theta_y & \sin \theta_y & \cos \theta_x & -\sin \theta_y & \cos \theta_x \\
0 & \sin \theta_x & \cos \theta_x & 0 & \sin \theta_x \\
-\sin \theta_y & \cos \theta_y & \cos \theta_x & \cos \theta_y & \sin \theta_x
\end{bmatrix}
\begin{bmatrix}
x \\
y \\
z
\end{bmatrix},
\]  \hspace{1cm} (5)

where \( \theta_x \) and \( \theta_y \) are the Euler angles.

The pointing direction (i.e., alignment) of TIR is fixed in the frame of Hayabusa2. The pointing area of TIR is varied with the spacecraft attitude. Therefore, the derivation of observation points is required by fitting the observation image with the coordinate of Ryugu. The geometric correction is carried out by minimizing the difference between the observed temperature \( T(i, j) \) and the re-projected on the Ryugu shape \( T'(i, j) \) in the image pixel coordinate using the least-squares fit, as follows:

\[ \text{RSS} = \sum_{i, j} [T(i, j) - T'(i, j)]^2, \]  \hspace{1cm} (6)
where RSS is a residual sum of squares in temperature. The free parameters of this fitting are the Euler angles of $\theta_y$ and $\theta_x$ in Equation (5). The fitting is performed by using the algorithms of the Levenberg-Marquardt and Simplex fitting method (Press et al. 2007). The fitting converged value of RSS is ideally zero. However, the observed temperature at the asteroid limb increases the RSS value because the pixel value at the limb includes temperatures of the Ryugu surface and space background.

Results

The geometric correction was performed for the observed TIR images in the early major observations. Figure 2 shows the best-fit Euler angles of $\theta_y$ and $\theta_x$ as a function of the observation time for each observation, along with the alignment values determined in the Moon observation during the Earth Swing-by in 2015. The geometrically corrected TIR boresight points in the Ryugu geographic coordinate system also shown.

On the results of the Box-A (2018-07-10), the best-fit Euler angle $\theta_y$ increased with time. The raw TIR images showed that Ryugu moved in a horizontal direction within the TIR image. We believe that the spacecraft trajectory information of the SPICE kernel is accurate. Therefore, we consider that the increase of the Euler angles is derived from a shift of the pointing direction due to the motion of Hayabusa2 in the $x_0$ direction during the parabolic hovering. On the results of the Box-C (2018-07-20), the mean with a standard deviation of $\theta_y$ during the observation was $-179.95 \pm 0.01$, and that of $\theta_x$ was $0.06 \pm 0.01$, showing that the pointing direction was stable. The Box-C observation was a scanning observation measuring the sensitivity of the angle of view for TIR. Hayabusa2 changed the attitude controlled by a reaction wheel (RW) every image shoot of TIR. Thus, we see a bimodal distribution of $\theta_y$. On the results of the Mid-Alt (2018-08-01), show that the pointing direction was varied due to low altitude observation affected by gravity. The attitude of Hayabusa2 was frequently controlled by the thruster of RCS and the AOCS to keep observation direction, but the ONC observation was not performed during the thruster injection. It caused an offset of the spacecraft trajectory that resulted in an offset of a projection of the TIR image onto the shape model. Thus, the geometric correction is necessary to reduce such offsets. On the results of the Box-B (2018-08-31), the mean with a standard deviation of $\theta_y$ during the observation was $-180.00 \pm 0.01$, and that of $\theta_x$ was $0.08 \pm 0.01$, showing that the pointing direction was stable. The attitude control was continuously performed in this observation positioned horizontally -9 km from the home position.
Table 1. Observation configuration and mean values of the best-fit Euler angles.

| Observation | Sun Distance | Phase Angle | SC Latitude | Altitude | Image | Euler $\theta_Y$ | Euler $\theta_X$ |
|-------------|--------------|-------------|-------------|----------|-------|----------------|----------------|
|             | (AU)         | (degree)    | (degree)    | (km)     | -     | (degree)        | (degree)       |
| Box-A       | 1.005        | 18.57       | -4.33       | 19.58    | 64    | -179.78        | 0.08           |
|             |              |             |             |          |       | ± 0.07         | ± 0.01         |
|             |              |             |             |          |       | ± 0.05         | ± 0.13         |
|             |              |             |             |          |       | ± 0.13         | ± 0.01         |
| (2018-07-10)|              |             |             |          |       |               |                |
| Box-C       | 1.028        | 18.45       | -4.93       | 6.59     | 96    | -179.95        | 0.06           |
|             |              |             |             |          |       | ± 0.07         | ± 0.01         |
|             |              |             |             |          |       | ± 0.08         | ± 0.01         |
|             |              |             |             |          |       | ± 0.01         | ± 0.01         |
| (2018-07-20)|              |             |             |          |       |               |                |
| Mid-Alt     | 1.060        | 18.98       | -5.37       | 5.28     | 120   | -179.93        | 0.09           |
|             |              |             |             |          |       | ± 0.07         | ± 0.01         |
|             |              |             |             |          |       | ± 0.08         | ± 0.01         |
|             |              |             |             |          |       | ± 0.13         | ± 0.07         |
| (2018-08-01)|              |             |             |          |       |               |                |
| Box-B       | 1.148        | 40.10       | -1.66       | 21.41    | 96    | -180.00        | 0.08           |
|             |              |             |             |          |       | ± 0.10         | ± 0.01         |
|             |              |             |             |          |       | ± 0.04         | ± 0.01         |
|             |              |             |             |          |       | ± 0.01         | ± 0.01         |
| (2018-08-31)|              |             |             |          |       |               |                |

Table 1 shows observation configuration for each observation, such as the solar distance, the solar phase angle, the sub-spacecraft latitude, the spacecraft altitude, and the number of observed images, along with the mean Euler angles. These errors in the Euler angles indicate the standard deviations of best-fitted Euler angles in each observation. The largest standard deviation of $\theta_y$ among the four observations was 0.13°, which is equivalent to positioning difference as two pixels of the image (0.051°/pixel). Note that the maximum deviation of $\theta_y$ was about 0.3 taken at 2018-08-01 23:07 (see also Figure 2). Since the error bars of the best-fit Euler angles in Figure 2 is less than equivalent to a pixel, the geometric correction could reduce the projection deviation. Therefore, TIR can identify observed local areas within positioning error as the one-pixel difference, which corresponds to 5 m error in a 5 km altitude observation. These mean values in $\theta_y$ and $\theta_x$ are about 0.1° different from the measured values determined during the Earth swing-by sequence. This difference is considered to come from that the observation distance of Moon was too far (>76,100 km) to recognize the center position of the Moon. The mean $\theta_y$ and $\theta_x$ values of Box-B and Box-C are stable, and thus these stable values are net frame angles of TIR without Hayabusa2 position and attitude fluctuations. The best-fit Euler angles derived from the Box-C and Box-B observations implement the frame kernel (FK) of the SPICE kernels for Hayabusa2 as alignment values of TIR, which will be released in December 2020. An example of an observed image and a temperature projection map onto the shape model is shown in Figure 3. Figure 3b shows the differential temperature image between the raw image and the corrected image.
image. The projected image was spread because the Ryugu position was shifted from the center of the
image. Although the correction amount of Figure 3b is over 20 pixels (1.02°), we confirmed that the
observed areas’ correspondence was achieved within one pixel corrected by using the best-fit Euler angles
of θ_y and θ_x, as shown in Figure 3c.

Discussions

We compared the observed brightness temperatures with the simulated kinetic temperatures using TPM1,
mapped on the shape model, as shown in Figure 4. As reported in previous studies (Okada et al. 2020;
Shimaki et al. 2020), the distribution of simulated temperatures in the sub-solar region is similar to that
of the observed temperatures. In contrast, the temperatures in the dawn and dusk regions are different
from the observed temperatures. From the results of TPM2, Shimaki et al. (2020) concluded that the
effect of surface roughness caused such differences.

Hot regions are found at the base of Ejima Saxum and Otohime Saxum (see 2018-08-01 16:05 UTC of
Figure 4). These temperature distributions are well reproduced in the simulated data when we consider
the effect of secondary radiation in the simulation (center row of Figure 4). This result implies that the
secondary and multiple radiations from surrounding terrains generate the hot regions.

The observed temperature profiles of the base of Ejima Saxum and the Urashima crater and the simulated
temperature profiles derived from Equation (3) are shown in Figure 5. As a characteristic area with large
topography change, the thermal inertia of the base of Ejima Saxum was estimated to be approximately
300 ± 100 Jm−2s−0.5K−1 from Figure 5. This estimation is succeeded by performing the geometric
correction when the surface shape is greater than the spatial resolution of TIR. On the other hand, the
thermal inertia of the Urashima crater was estimated to be 100 to 500 Jm−2s−0.5K−1 from dawn to dusk
(meridian passage at 15:48 UTC). These results indicate that the brightness temperatures of observed
areas larger than a TIR pixel are determined by large-scale surface topography that can be reproduced
by TPM1. In contrast, the brightness temperatures of observed areas smaller than a TIR pixel are
determined by small-scale roughness that can be reproduced by TPM2. Thus, we conclude that the
development of a hybrid thermophysical model that implements large- and small-scale surface roughness
is required.
Figure 1. Schematic view of Ryugu coordinate and TIR and Hayabusa2 frames relation. The TIR frame is rotated in the Euler angle $y$ of -180° relative to the Hayabusa2 frame. We consider that the rays from a polygon of a Ryugu shape model are incident to TIR.

Summaries

The geometric correction for TIR observations was performed for the individual observed images of TIR for the four observations, which improved the accuracy of the pointing area. The alignment of TIR was determined, and the positioning accuracy of the observed area was achieved within a one-pixel difference equivalent to 5 m in a 5 km altitude observation. TIR found several characteristic features of the surface, such as hot regions at the bases of large boulders. Comparing the observed temperature with the simulated temperature, the cause of the hot region at the base of Ejima Saxum can be explained by the effect caused by multiple radiations surrounding terrains. The thermal inertia estimation was succeeded by performing the geometric correction when the topographic variation of surface shape is greater than the spatial resolution of TIR. However, the effect of small-scale surface roughness generates complicated thermal profile areas. The new version of the SPICE kernels for Hayabusa2 will be released on the web site of DARTS/ISAS in December 2020, which includes the precise attitude and trajectory of Hayabusa2 derived from the SPC shape model and the results of this study. The higher degree products of TIR constructed by using the geometric correction are also published.
Figure 2. The best-fit Euler angles and the resulting the TIR boresight points for the early major observations of Box-A, Box-C, Mid-alt, and Box-B, along with the sub-spacecraft points (Latitude, Longitude) calculated using the SPICE kernel. Top two-rows: the Euler angles of $\theta_y$ and $\theta_x$ as a function of the observation time. These error bars on symbols show the variation of the best-fit parameters when the RSS in Equation (6) converged to a constant value. The asymptotic standard error derived from the Levenberg-Marquardt method was negligibly small. Dashed lines show the alignment values determined by the Moon observation during the Earth swing-by sequence of Hayabusa2. Bottom two-rows: the TIR boresight points on the Ryugu geographic coordinate corrected by using the best-fit Euler angles (Boresight New). The TIR boresight points on the Ryugu geographic coordinate obtained by using alignment determined by the Earth swing-by (Boresight Old) are also shown. Large fluctuation is shown at around 18:00 of Mid-Alt (2018-08-01), which was caused by the thruster control with RCS to keep the observed position of Hayabusa2 at low altitude observation affected by gravity.
Figure 3. An example of the observed image and the best-fitted projection figure using the geometric correction. (a) The observed image of TIR (hyb2_tir_20180801230744.fit). The observation configurations are the sub-spacecraft point (Lat:-5.21°, Lon:130.17°), and the sub-solar point (Lat:-8.37°, Lon:110.95°), corresponding to the local solar time of 13.28 hours. (b) The differential temperature image between the raw image with the Euler angles (0.00, -180.00, 0.00) and the corrected image with the Euler angles (0.00, -179.66, 0.23). It is the worst case for the projection onto the shape model (see the data at 2018-08-01 23:07 of Figure 2). (c) The corrected temperatures image projected onto the Ryugu shape model (SFM_800k_v20180804), where Urashima crater, Ejima Saxum, Kintaro crater, and Otohime Saxum are seen in this hemisphere.
Figure 4. Examples of the observed temperatures (Mid-Alt: 2018-08-01) and simulated temperatures (Takita et al. 2017) mapped on the shape model, changing by 30° rotation of Ryugu. The boresight points of TIR are shown in the bottom row. The arrows indicate typical hot regions, such as the center of Urashima Crater, the base of Ejima Saxum, and the base of Otohime Saxum (See Figure 3c). Top row: the observed temperatures are projected onto the shape model (SFM,200k,v20180804), and the Ejima Saxum and Otohime Saxum is shown in closed up in the detail shape model (SFM,800k,v20180804). Center row: the simulated temperatures with consideration of the effect of secondary radiations surrounding terrains. Bottom row: the same as the center figures except for neglection of the effect of secondary radiations. The parameters of these simulations were assumed to be the emissivity of 1.0, the albedo of 0.045 (Sugita et al. 2019), and the thermal inertia of 350 Jm$^{-2}$s$^{-0.5}$K$^{-1}$. 
Figure 5. Examples of the observed temperature profiles and the simulation temperature profiles in time series are shown for the base of Ejima Saxum and the Urashima crater. These points indicate the observed brightness temperature of TIR by the time interval of 76 seconds on 1 August 2018 (Mid-Alt). These blue points denote the corrected data using the geometric correction, and these orange stars denote uncorrected data. These uncorrected data of the Ejima Saxum appear mixed with other areas’ temperatures because the projection was out of position due to the characteristic shape before the correction. (a) The observed temperature profiles are composed of the maximum temperature areas at the base of Ejima Saxum at 16:05 (see Figure 4), where the temperature range is 354.2 to 365.3 K ((Lat:-28.1°, Lon:105.7°); polygon ID: 120,269∼120,274, 120,276, and 120,277). (b) The observed temperature profiles are composed of hot areas at the center of Urashima crater at 16:05, where the temperature range is 346.2 to 349.2 K ((Lat:-6.2°, Lon:97.2°); polygon ID: 117,138∼117,142 and 117,394∼117,396). These temperatures are equivalent to the mean temperature derived from the mean flux converted by the Stefan-Boltzmann law in Equation (3). These error bars are the observed temperature range of the minimum to maximum temperature. These lines indicate the simulated thermal inertia $\Gamma$ in steps of 100 Jm$^{-2}$s$^{-0.5}$K$^{-1}$ using the shape model of SFM 200k v20180804 and the thermal model of Ryugu (Takita et al. 2017).
List of abbreviations

AOCS: Attitude and Orbit Control System
DARTS: Data Archive and Transmission System
FK: Frame Kernel
ISAS: Institute of Space and Astronautical Science
JAXA: Japan Aerospace Exploration Agency
LIDAR: Light Detection and Ranging
MARA: Mobile Asteroid Surface Scout
MASCOT: Mobile Asteroid Surface Scout
Mid-Alt: Middle Altitude
NAIF: Navigation and Ancillary Information Facility
NASA: National Aeronautics and Space Administration
NIRS3: Near Infrared Spectrometer
ONC: Optical Navigation Camera
RCS: Reaction Control System
RSS: Residual Sum of Squares
RW: Reaction Wheel
SC: Spacecraft
SfM: Structure from Motion
SPC: Stereo Photoclinometry
SPICE: Spacecraft Planet Instrument C-matrix Events
TIR: Thermal Infrared Imager
TPM: Thermophysical Model
UTC: Coordinated Universal Time

Declarations

Availability of data and materials

The original data of this study are available and downloadable on the following web site:

TIR data: https://www.darts.isas.jaxa.jp/pub/hayabusa2/tir_bundle/browse/
SPICE kernels: https://www.darts.isas.jaxa.jp/pub/hayabusa2/spice_bundle/document/spiceds_v001.html
Competing interests

The authors declare that they have no competing interests.

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Authors’ contributions

TA: Preparation of the manuscript, Methodology, and Data analysis
TO: Methodology, and Administration of TIR science team
ST: Administration of TIR science team
TF: Administration of TIR science team
HD: Software development
TK: Methodology
NS: Data analysis
YS: Methodology
HS: Methodology
TS: Methodology
JT: Data analysis
NH: Software development
YY: Science operation of the spacecraft

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Yamamoto Y. et al. (2016) Scientific Data Archives in Hayabusa2 Mission. Trans. JSASS Aerospace Tech. Japan 14:151–154. https://doi.org/10.2322/tastj.14.Pk.151
The thermal infrared imager (TIR) onboard the Hayabusa2 spacecraft performed thermographic observations of the asteroid 162173 Ryugu (1999 JU3). In this study, we performed a geometric correction for TIR images by making a one-to-one correspondence between the observed areas and the surface coordinates derived from a shape model of Ryugu. This geometric correction allows us to identify observed local areas within one pixel, which corresponds to 5 m error in a 5 km altitude observation.