Software Interface Specification for the Hayabusa2 Thermal Infrared Imager (TIR) Data Products

Version 1.0

September 28, 2021

Prepared by

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Change Log

DATE	CHANGE	AFFECTED SECTIONS
2015-10-02	Initial Draft	All
2015-10-02	Second Draft	All
2020-03-21	Third Draft	All
2020-07-21	Forth Draft	All
2020-10-14	Fifth Draft	All
2021-05-02	Sixth Draft	All
2021-09-28	Version 1.0	All

Acronyms and Abbreviations

Acronym/Abbreviation	Definition
A/D	Analog to Digital
ASCII	American Standard Code for Information Interchange
BB	Black Body
CCSDS	Consultative Committee for Space Data System
CSV	Comma-Separated Values
C-SODA	Center for Science satellite Operation and Data Archive
DAC	Data Archive team
DE	Digital Electronics
DN	Digital Number
DSV	Delimiter-Separated Values
EDVEGA	Electric Delta-V Earth Gravity Assist
FITS	Flexible Image Transport System
FOV	Field Of View
HDU	Header Data Unit
IAU	International Astronomical Union
ID	Identifier
IFOV	Instantaneous Field Of View
IPDA	International Planetary Data Alliance
ISAS	Institute of Space and Astronautical Science
JAXA	Japan Aerospace Exploration Agency
LIR	Longwave Infrared Imager
LSK	Leapseconds kernel
LUT	Lookup Table
MTF	Modulation Transfer Function
NETD	Noise Equivalent Temperature Difference
OFPN	onboard flat pattern noise / on-chip fixed pattern noise
PDS	Planetary Data System
PNG	Portable Network Graphics
ROI	Region of Interest
SBN	Small Bodies Node
SCLK	Spacecraft Clock kernel
SIRIUS	Scientific Information Retrieval and Integrated Utilization System
SIS	Software Interface Specification
S/N	Signal-to-Noise
SPICE	Spacecraft, Planet, Instrument, C-matrix, Events
SQL	Structured Query Language
SSE	Size-of-Source Effect
TI	Time Indicator
TIR	Thermal Infrared Imager
tiu	thermal inertia unit, $J\ m^{-2}\ s^{-0.5}\ K^{-1}$
UTC	Coordinated Universal Time

Acronym/Abbreviation	Definition
XML	Extensible Markup Language

1 Purpose and Scope of Document

The purpose of this Data Product Software Interface Specification (SIS) is to provide users of the data products from the Hayabusa2 Thermal Infrared Imager, TIR, with a detailed description of the products and how each was generated, including data sources and destinations. The products defined in this document are raw, calibrated, and maps. The images are generally of (162173) Ryugu but may be of other targets of opportunity.

The SIS is intended to provide enough information to enable users to read and understand the TIR data products as stored in the PDS. The users for whom this SIS is intended are software developers of the programs used in generating the TIR products and scientists who will analyze the data, including those associated with the Hayabusa2 mission, TIR instrument and those in the general planetary science community.

2 Applicable Documents

This SIS is consistent with the following Planetary Data System Documents as adopted by the International Planetary Data Alliance (IPDA):

1. Planetary Data System Standards Reference, Version 1.14.0, May 22, 2020.
2. PDS4 Data Dictionary – Abridged – Version 1.14.0.0, March 23, 2020.
3. PDS4 Information Model Specification, Version 1.14.0.0, March 23, 2020.

This SIS is responsive to the following Hayabusa2 mission document(s):

4. Science Policy for Hayabusa2 Project, Version 3.0, May 14, 2018.

This SIS makes reference to the following documents:

5. Okada et al., Thermal Infrared Imaging Experiments of C-Type Asteroid 162173 Ryugu on Hayabusa2, *Space Science Reviews,* **208**, 255-286*,* https://doi.org/10.1007/s11214-016-0286-8, 2017.
6. Arai et al., Thermal Imaging Performance of TIR Onboard the Hayabusa2 Spacecraft, *Space Science Reviews*, **208**, 239-254, https://doi.org/10.1007/s11214-017-0353-9, 2017.
7. Endo et al., HEAT: Image and database browser for the thermal imager on Hayabusa2, *2017 IEEE Aerospace Conference, Big Sky, MT*, 1-10, https://doi.org/10.1109/AERO.2017.7943827, 2017.
8. Okada et al., Highly porous nature of a primitive asteroid revealed by thermal imaging, *Nature*, **579,** 518–522, https://doi.org/10.1038/s41586-020-2102-6, 2020.
9. Fukuhara et al., Absolute calibration of brightness temperature of the Venus disk observed by the Longwave Infrared Camera onboard Akatsuki, *Earth, Planets and Space*, **69**:141, https://doi.org/10.1186/s40623-017-0727-y, 2017.
10. Fukuhara et al, LIR: Longwave Infrared Camera onboard the Venus orbiter Akatsuki, *Earth, Planets and Space*, **63**, 1009-1018, https://doi.org/10.5047/eps.2011.06.019, 2011.
11. Pence et al., Definition of the Flexible Image Transport System (FITS), version 3.0, *A&A*, **524**, A42, https://doi.org/10.1051/0004-6361/201015362, 2010.

3 Configuration Management

The Hayabusa2 TIR team controls the data products described in this document, as well as the document itself. Requests for changes to the data products, or the scope and contents of the document are made to the PI of the Hayabusa2 TIR team, Satoshi Tanaka. An engineering change request will be evaluated against its impact on the TIR ground data processing system before acceptance. Once a change request has been approved, software and documentation are updated, version numbers incremented, tested, and finally released for production.

The data products and documentation described in this SIS as well as the SIS itself have completed a formal PDS peer review and lien resolution process. The peer review ensures that all data products described by this SIS comply with PDS4 standards as noted in Section 2 – Applicable Documents. The PDS peer review panel consisted of members of the PDS Small Bodies Node (SBN) and members of the planetary science community. Any changes to data products subsequent to the peer review will be reviewed internally by the PDS SBN to determine if an additional peer review is necessary.

4 Relationships with Other Interfaces

Changes to the data products described in this SIS affect the software, products, or document in Table 1:

Table 1 Interface relationships

Name of Interface	Type	Owner
TIR Database Schema	Product	TIR Team
TIR Raw Science Data	Product	TIR Team
TIR Raw Housekeeping Data	Product	TIR Team
Science Policy for Hayabusa2	Document	Project
TIR Ground Data Processing	Software	TIR Team
TIR Archive Software	Software	DAC Team

A systems engineering approach is used to evaluate how changes in any one of these interfaces affects the others. It is possible that changes to one of these items will not affect any other item.

5 Data Product Characteristics and Environment

5.1 Instrument Overview

Figure 1 shows the schematic view of TIR, and Table 2 shows the specification of TIR. TIR is a single band thermal infrared imager with the wavelength ranging from 8 to 12 μm and the field of view covering 16.7° × 12.7°. The detector is based on a two-dimensional uncooled microbolometer array (NEC 320A) with 344 × 260 pixels, a germanium detection window of anti-reflection coating, and the thermoelectric cooler module (Peltier module) to control the detector temperature at 40 °C within 0.1 °C stability. The 344 × 260 pixels data are arranged into image of 384 × 256 pixels to apply the image compression algorithm, StarPixel Lossless. The image includes 328 × 248 effective pixels, optical black pixels, reference level pixels, and dummy pixels (Figure 2). The spatial resolution is about 0.051° per pixel, which is corresponding to about 17 m per pixel when it observes the asteroid (162173) Ryugu from the Home Position at 20 km altitude. TIR has a shutter mechanism driven with a stepping motor and two positioning sensors. A pair of images are taken in turns with the shutter closed and open. The thermal images are derived from the subtraction of the two images.

The temperature of the shutter is monitored with 0.01 °C accuracy so that the bias of each pixel is canceled. The imager carried out well-calibrated in the laboratory within the temperature range from -40 to 150 °C, which covers the expected temperature of the sunlit surface of asteroid (162173) Ryugu. The detectable temperature range is wider than this, from -123 to 187 °C, which covers the whole asteroid even in the nighttime for the thermal inertia > 50 tiu.

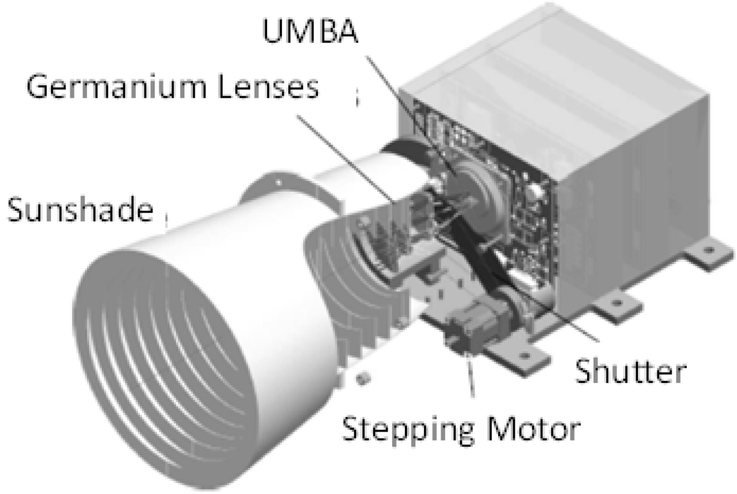

Figure 1 The characteristic of the sensor unit of TIR, TIR-S (modified from Fukuhara et al., 2011).

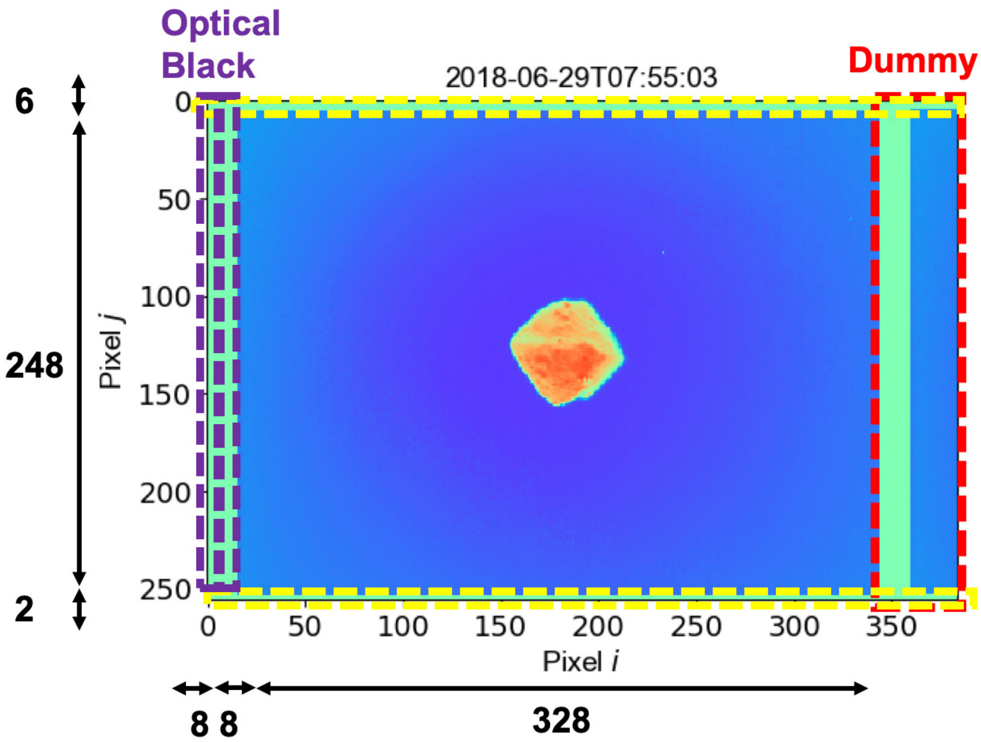

Figure 2 An example of the raw image of TIR. Out of 384 × 256 pixels, 328 × 248 pixels are effective, and the others are optical black pixels (purple), reference level pixels (yellow), and dummy pixels for making a compressed image (red).

Table 2 Performance of TIR

Mass	3.28 kg
Power	18 W (nominal)
Detector	Uncooled bolometer array NEC 320A (anti-reflection coating)
Pixels	344 × 260 (effective 328 × 248)
Field of View (FOV)	16.7° × 12.7°
IFOV	0.89 mrad (0.051°)
MTF (at Nyquist Frequency)	0.5
F-number	1.4
Temperature range	233 – 423 K (well calibrated), 150 – 460 K (detectable range)
NETD	< 0.3 K
Absolute Temperature accuracy	< 3 K
A/D Converter	12 bit (15 bit after summed)
Reference Temperature	Shutter temperature (monitored)
Frame Rate	1/60 s – 2.1 s (Accumulation for m = 1 to 128 images)

TIR has six operating modes, including Off, Standby, Protect, Idling, Parameter Setting, and Image modes. TIR can take an image only during the Idling mode. Before taking the image, the onboard flat noise pattern is prepared in the TIR memory. One method is to conduct onboard calibration. Another method is to upload the onboard flat pattern noise (OFPN) data from digital electronics (DE), which is constructed on the ground and uploaded beforehand.

Here, we introduce prelaunch images in calibration tests. Figure 3 shows examples of TIR images obtained in the pre-flight test.

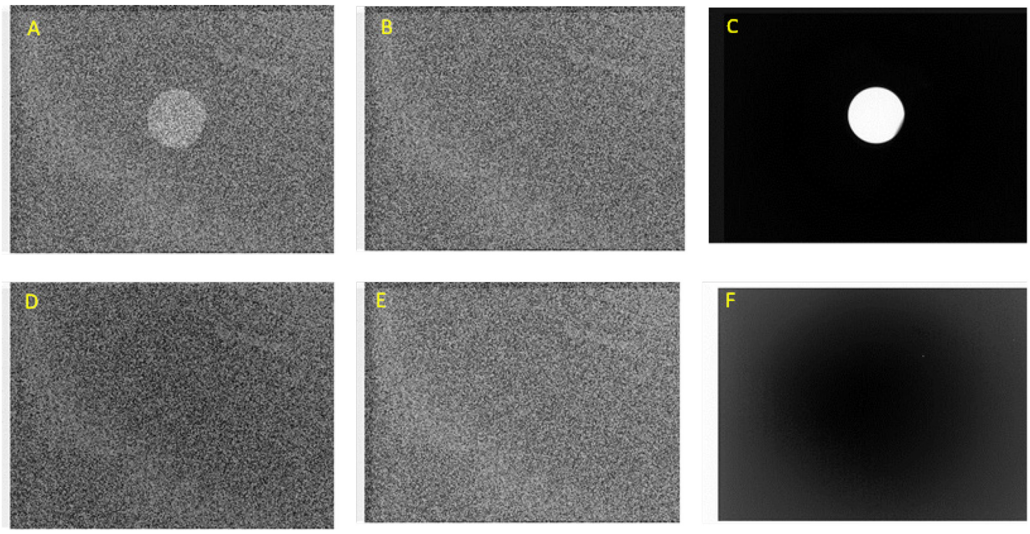

Figure 3 Examples of TIR images are shown. Images of 100°C blackbody target using a collimator in front of TIR were taken in a pre-flight laboratory test on 13 November 2013 with the shutter-open image (A), shutter-close image (B), and the subtracted image (C). The deep sky images were taken on 27 February 2015 during the in-flight TIR with the shutter-open image (D), shutter-close (E), and the subtracted image (F). The readout values have diverse biases in pixel to pixel, but shutter closes subtraction from the shutter-open images derives the low-noise thermal images (Okada et al., 2017).

The signal readout values from the two-dimensional bolometer array have a large diversity among pixels. Therefore, TIR always takes a pair of images when the shutter is closed and open, and then subtracts the closed image from the open one. The base position of the shutter is closed during the mission, and the first image is taken when the shutter is closed. Then the second image is taken when the shutter is open. The shutter has the quasi-black body surface painted in black by the anodic oxidation coatings with the emissivity ~ 0.89, and the shutter image can be used as the reference temperature for data processing.

After taking images, the analog electronics unit read the output signals from the detector at 60 frames per second and digitized them into 12-bit image data through the analog-to-digital converter. The readout data is compared with the OFPN for each pixel and is transferred from TIR to the DE. By subtracting the shutter-close data from shutter-open data, the bias-canceled image data is produced. The data are accumulated to improve S/N using the DE. Then, bit-shift procedure is applied to the generated images for converting to the nominal data format of TIR (15-bit). The number of the accumulated image is represented as the value of the IMGACCM keyword in the FITS (Flexible Image Transport System) header and the value of the hyb2:number_of_accumulated_images attribute in the hyb2:TIR_Instrument_Attributes class of the PDS4 label. The original bit data size is represented as the value of the BITDEPTH keyword in the FITS header and the value of the hyb2:number_of_bit_shift attribute of the hyb2:TIR_Instrument_Attributes class of the PDS4 label (Table 3).

Table 3 TIR accumulated frames and image bit depths.

IMGACCUM [frame]	BITDEPTH [bit]
1	12
16	16
32	17
64	18
128	19

To reduce the data amount, nominally, the DE makes telemetry packets of shutter-close images and subtracted images, such as B and C, or E and F of Figure 3. The IMGTYPE keyword in the FITS header and the hyb2:tir_image_type attribute of the hyb2:TIR_Instrument_Attributes class indicates the type of the TIR image, OPN for shutter-open image, SHT for shutter-close image, and PIC for shutter subtracted image. Only shutter-close images and subtracted images are included in the archive.

5.2 Data Product Overview

The TIR data products are composed of raw images, calibrated images, and calibration data. All TIR image data are formatted natively as FITS data, with images stored as arrays and metadata captured in the image headers. All metadata that are needed to use or interpret the images is duplicated in the PDS4 XML labels.

The Hayabusa2 TIR data products are:

1. **TIR Raw Image Data Product**: Image in FITS format that have been reassembled from downlinked telemetry with complete image metadata, including instrument settings and state.
2. **TIR Calibration Data Product**: Binary data arrays in FITS format and ASCII DSV table for conversion from raw image data to calibrated brightness temperature data.

3. **TIR Calibrated Brightness Temperature Image Data Product**: Image in FITS format that have been calibrated into brightness temperature with physical units in Kelvin (K), with complete image metadata including instrument settings and states.
4. **TIR Derived Temperature Map Data Product**: ASCII DSV table for temperature map data of the asteroid (162173) Ryugu (planned).
5. **TIR Derived Thermal Inertia Map Data Product**: ASCII DSV table for thermal inertia map data of the asteroid (162173) Ryugu (planned).
6. **TIR Browse Product**: Quick-look image in PNG format generated from other data product.

5.3 Data Processing

This section of the SIS provides general information about data product content, format, size, and production rate. The specifics of the data product formats are discussed in Section 6.

5.3.1 Data Processing Level

TIR will deliver raw and calibrated data to PDS. Table 4 describes the processing level of each product in both Hayabusa2 project terms and PDS4 terms.

Table 4 TIR data products and its processing levels

	Hayabusa2 TIR Product	PDS4 Processing Level	TIR Processing Level	Product Description
1	Raw Image Data Product	Raw	L1	This product contains raw digital number (DN) image. There are three kinds of images in this product. The raw shutter-closed image, the raw shutter-open (target) image, and the raw subtracted image, which is calculated by the subtraction of shutter-closed and shutter-open images. The size of the image is 384 × 256 pixels, including optical black areas.
2	Calibration Data Product	Derived	-	This product contains data used to convert from raw data into calibrated data. There are two kinds of products; one is table of black body temperature and radiance, and the other is LUT file for conversion between radiance and DN, which is obtained by the pre-launch data for all effective pixels (328 × 248).
3	Calibrated Brightness Temperature Image Data Product	Calibrated	L2	This product contains brightness temperature image which is converted from the raw subtracted image. The image is converted using a look up table (LUT) archived as calibration data product. The size of the image is 328 × 248 pixels for the effective pixels.
4	Derived Temperature Map Data Product	Derived	L3	This product contains temperature map data which are projected onto a shape model using SPICE kernels. This product is derived from calibrated brightness temperature image data product.
5	Derived Thermal Inertia Map Data Product	Derived	L4	This product contains calculated thermal inertia from the observed data which are projected onto a geographical

	Hayabusa2 TIR Product	PDS4 Processing Level	TIR Processing Level	Product Description
				map. This product is derived from derived temperature map data product.
6	Browse Product	Derived	-	This product contains quick-look image generated from other image data products.

5.3.2 Data Product Generation

5.3.2.1 Raw Image Data Product

The original image acquired by TIR onboard the Hayabusa2 spacecraft is processed at DE and is divided into six tiles where is stored to each tile consists of 128 × 128 pixels. Every tile is compressed by the StarPixel Lossless algorithm. The compressed tile was stored as telemetry data in CCSDS (Consultative Committee for Space Data System).

The telemetry data are downlinked from the Hayabusa2 spacecraft and are stored as sorted telemetry data in the telemetry database called SIRIUS, operated by C-SODA (Science Satellite Operation and Data Archive Unit) at ISAS, JAXA.

The tiles are extracted from the telemetry data, decompressed by the StarPixel Lossless algorithm, and are combined to reproduce the original image as shown in Figure 4. The original image is stored in FITS format by the TIR pipeline. Ancillary data for images are also stored in the FITS header of files. The FITS file containing the original image and ancillary data is provided as Raw Image Data Product.

Figure 4 Layout of tiles for raw and calibrated images. The square area enclosed by the blue dotted line is a tile of 128 × 128 pixels. The total area of six tiles has 384 × 256 pixels. The left grey rectangular area shows effective detector area with 328 × 248 pixels. Note that the right grey rectangular area is just a copy of a part of the left grey rectangular area.

There are corrupted pixels in some tiles only for a few images. These corrupted pixels are thought to be generated from decompression of a partially corrupted compressed image data which is usually occurred by packet loss of the telemetry. Because of the characteristics of the StarPixel Lossless compression algorithm, values at some pixels are not affected by the corruption of the compressed data, and the remaining pixels are corrupted which are polluted by corrupted data used to store data of predictive coding used in the compression algorithm. We could not determine which pixels of the decompressed image are corrupted. Therefore, we only describe the tile in the image which possibly has corrupted values of the pixels to warn it to users.

We used the IMGCRRPT of the FITS keyword and the img:segment_corrupted_flag attribute in the img:Image_Compression_Segment under the img:StarPixel_Lossless_Parameters class for the identification of the corrupted region. If there are no corrupted tile in the image, the value of the IMGCRRPT is OK in the FITS header, and there are no img:Image_Compression_Segment class(es) in the PDS4 label. If there are corrupted tiles, the tiles are identified by range along horizontal axis and range along vertical axis using the FITS header keyword IMGCRRPT. The value of IMGCRRPT has the format of [x0,x1]x[y0,y1] where x0 and x1 are the smallest and the largest indexes of the corrupted region in horizontal, respectively, and y0 and y1 are the smallest and the largest indexes of the corrupted region in vertical, respectively. The corrupted tile is also identified by the value of img:segment_corrupted_flag attribute which is set to true in the PDS4 label.

The Raw Image Data Product is not calibrated using temperatures of the instrument, e.g., shutter temperature. The calibration using temperatures is a part of the processing from raw data to calibrated data.

5.3.2.2 Calibrated Image Data Product and Calibration Data Product

TIR raw subtracted image data are calibrated and converted to a calibrated image using an image and database browser for the thermal imager on Hayabusa2, "HEAT" (Endo et al., 2017), as shown in Figure 5. The calibrated image has 328×248 effective pixels that are extracted from the raw image to remove optical black pixels, reference level pixels, and dummy pixels (Figure 2). The pixel coordinate conversion from the raw image (i', j') to the calibrated image (i, j) is written as follows:

$$i = i' - (8 + 8) \tag{1}$$

$$j = j' - 6 \tag{2}$$

where $i' = 1$ to 384, $j' = 1$ to 256 and $i = 1$ to 328, $j = 1$ to 248.

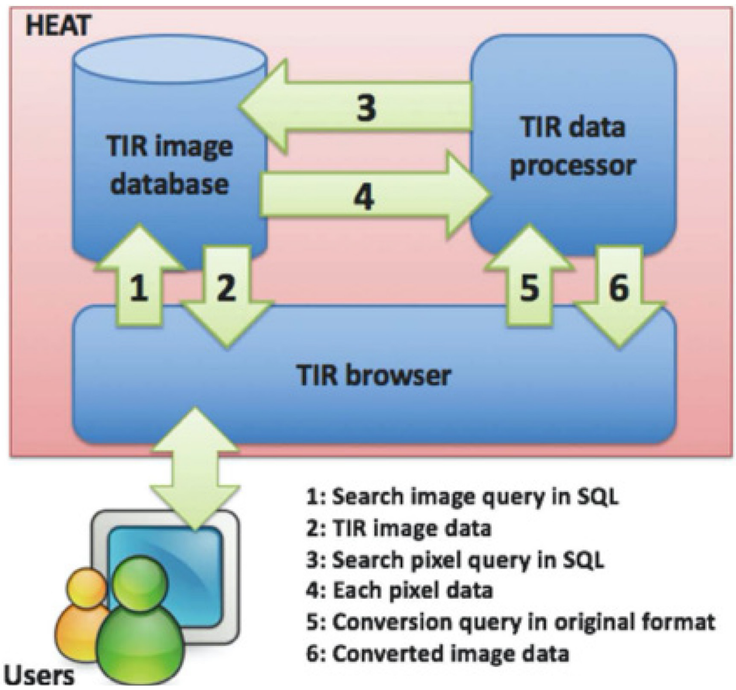

Figure 5 TIR calibration database "HEAT" (Endo et al., 2017). HEAT has three modules. The first module is the interface, which handles thermal models, calibrated data, and visualizing data. The

second module handles searching queries of the archived data and output results based on SQL. The third module handles data conversions for all pixels of the image and ancillary data.

The calibration data of TIR were derived from the pre-flight calibration tests. The tests were carried out using three types of calibrated targets: a collimator, a cavity blackbody source, and blackbody plates. We used the same apparatus prepared for the calibration of the Longwave Infrared Camera (LIR) onboard the Japanese Venus explorer Akatsuki. It allows us to control the temperature of a blackbody plate from −40 °C to +50 °C in a vacuum chamber. Temperatures at the asteroid surface in the daytime are estimated to be up to 100 °C. Therefore, we set up another experimental apparatus using an oil bath to control the temperature of the blackbody plate from +50 °C to +125 °C. These apparatuses enable us to investigate the response of all the pixels of TIR. The measured emissivity of the blackbody plates is 0.925.

The temperature inside the instrument affects the output of TIR. During the calibration test, we corrected the data using the four monitoring temperatures. We found that the shutter temperature is especially effective. Linear relations are seen for each temperature of the calibration target. We found that a better linear relationship appears after the package and case temperature correction:

$$D'_{i,j} = D_{i,j} - 6.125\left(T_{\text{case}} - T_{\text{pkg}}\right) \tag{3}$$

where $D_{i,j}$ and $D'_{i,j}$ are the original and calibrated digital numbers for pixel at (i, j), and T_{case} and T_{pkg} are found as the FITS header keywords, CAS_TEMP and PKG_TEMP, respectively, and the hyb2:case_temperature and the hyb2:package_temperature attributes of the hyb2:TIR_Instrument_Attributes class in the PDS4 label, respectively. This calibration corresponds to the temperature correction of the gain of the analog-to-digital converter. After the case and package temperature correction, we carried out shutter temperature correction by using the equation:

$$D''_{i,j} = D'_{i,j} - 6.158\,(T_0 - T_{\text{sht}}) \tag{4}$$

where $D'_{i,j}$ is the calibrated digital number, T_{sht} is the shutter temperature (SHT_TEMP in the FITS header and the hyb2:shutter_temperature attribute of the hyb2:TIR_Instrument_Attributes class in PDS4 label), and $T_0 = 28$ °C is the standard temperature, following the method in Fukuhara et al., 2017.

After the calibration using the instrument temperatures, we made a lookup table (LUT) to convert the digital number to the radiance of the target. The blackbody temperature is converted to radiance [W m^{-2} sr^{-1}],

$$I(T) = \pi \int_0^\infty \varepsilon B(\lambda, T)\, R(\lambda)\mathrm{d}\lambda \tag{5}$$

where ε is the emissivity (equal to 0.925 for the black body plate), λ is the wavelength, $R(\lambda)$ is the response function of TIR (Okada et al., 2017; Arai et al., 2017), and $B(\lambda, T)$ is the spectral radiance given by the Planck function. By linear least-squares fitting of output digital number and radiance, we defined the slope $a_{i,j}$ and intercept $b_{i,j}$ for all pixels (i, j) as:

$$D''_{i,j} = a_{i,j} I(T) + b_{i,j} \tag{6}$$

These conversion coefficients, the scaling factor $a_{i,j}$, and the offset $b_{i,j}$, are included in the LUT. The conversion from $I(T)$ to T is written in the table data that stores blackbody temperature [K] and radiance [W m^{-2} sr^{-1}] with the step of 1 K of blackbody temperature. A linear interpolation is applied to obtain desired temperature as follows:

$$T = \frac{\mathrm{temp}[n+1] - \mathrm{temp}[n]}{\mathrm{rad}[n+1] - \mathrm{rad}[n]} \times (I(T) - \mathrm{rad}[n]) + \mathrm{temp}[n] \tag{7}$$

where $\mathrm{temp}[n]$ and $\mathrm{rad}[n]$ are n-th record of blackbody temperature and radiance in the table, and n is chosen so that n satisfies the condition $\mathrm{rad}[n] \leq I(T) < \mathrm{rad}[n+1]$. The derived temperature T is set to be larger than 150 K, which is the lower limit of the TIR detection sensitivity (Okada et al., 2017). If the temperature is less than or equal to 150 K, i.e., $I(T)$ is less than or equal to $I(150\ \mathrm{K})$, the temperature T is set to 150 K which is usually for deep space pixel. On the other hand, if the temperature is larger than or equal to 500 K, i.e., $I(T)$ is larger than or equal to $I(500\ \mathrm{K})$, the temperature T is set to 500 K.

A critical problem for accurate calibration of infrared imagers and thermometers is the size-of-source effect (SSE). SSE occurs owing to the scattering and diffraction of thermal radiation within the optical component. We evaluate the SSE of TIR using a collimator and a cavity blackbody, whose temperatures were controlled from +20 °C to +125 °C. The emissivity of these targets is $\varepsilon = 0.97$. The measurements of these targets were carried out in the atmosphere owing to the constraints of the apparatus. We found SSE for TIR during the calibration (Figure 6); the output values become relatively low for the small image of the different calibration targets (collimator < cavity blackbody < blackbody plate). The position of the targets in the image was changed to check the SSE on the sensitivity of each pixel.

For the correction of SSE, we focused on the effective diameter of the targets, which is defined as $D_{\mathrm{eff}} = 2\sqrt{N/\pi}$, where N is the number of pixels of the observed target. The effective diameters of the collimator and cavity blackbody are about 60 and 125 pixels, respectively. In the flight phase, the pixels corresponding to the target are determined as the pixels where $D''_{i,j}$ is 50 digits higher than that of the deep sky image. The boundary pixels between the target and background deep sky are not counted into the target size. The effective diameters of asteroid Ryugu are around 55 and 180 pixels for the Box-A and Mid-altitude observations, respectively. A close-up image where the TIR image is fully covered with the asteroid surface combined with calibration data of the blackbody plate yielded effective diameter values of $D_{\mathrm{eff}} = 322$. The SSE for continuous observations during a descent operation for gravity measurement was determined on 6 and 7 August 2018. Averaged DN values of Ryugu increased linearly with increasing the effective diameter, but a rapid jump in DN value occurred with an effective diameter larger than 300 pixels. The LUT applied to the asteroid image is built based on the effective diameter D_{eff} of imaged Ryugu. In the range $D_{\mathrm{eff}} \leq 300$ pixels, LUT is created by linear interpolation and extrapolation of the LUTs for collimator and cavity blackbody. Note that the data for the blackbody plate is not fitted to this linear extrapolation owing to this higher effective diameter regime (300 pixels $< D_{\mathrm{eff}} \leq 322$ pixels). Therefore, we used another linear function derived from the LUT data for blackbody plate and extrapolated values at $D_{\mathrm{eff}} =$ 300 pixels from the lower effective diameter regime (Figure 7). Using the LUT derived from the effective diameter of the asteroid, the DN values are converted to the radiance values for each pixel using equation (6). The derived images of the radiance are converted to brightness temperature images from equation (5), assuming an emissivity of 1 at any wavelength. The SSE was corrected in the calibration data, and thus the conversion using Equations (1) to (7) can produce brightness temperature images from raw images.

The values for all pixels in the calibrated data product are rounded to the nearest value (round half away from zero) with a precision of two decimal digits.

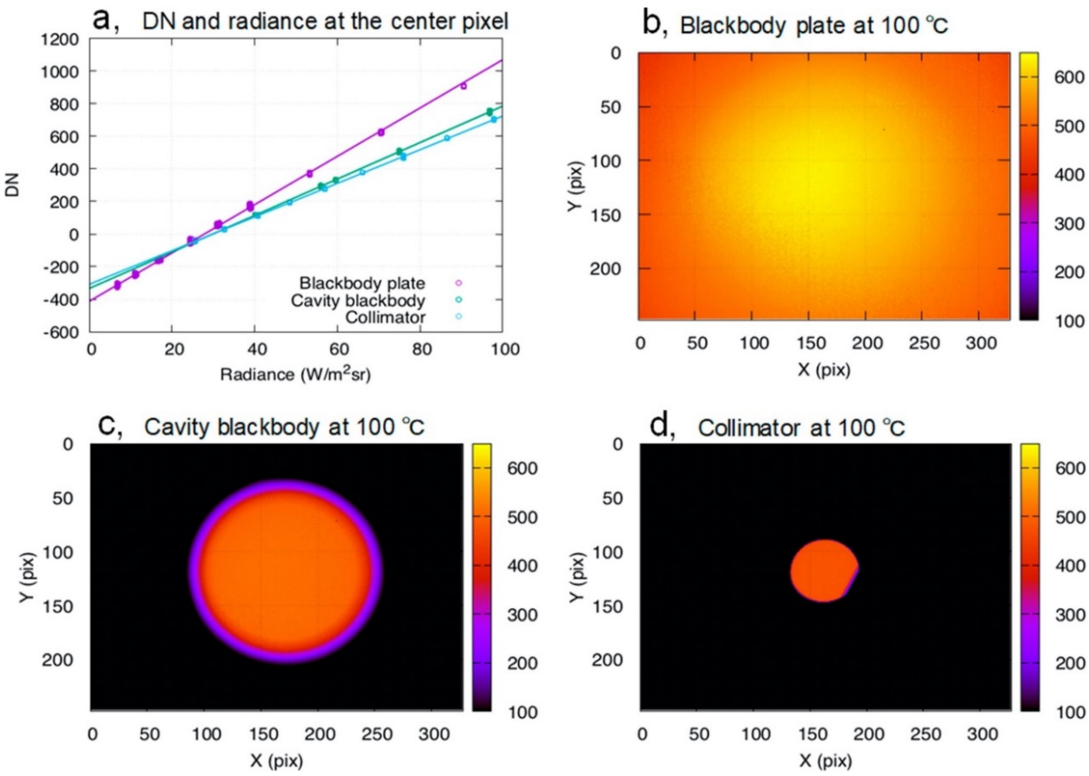

Figure 6 Temperature calibration of TIR using multiple apparatuses. a) An example of the TIR pixel response of a center pixel at (164, 124) obtained by the ground-based calibration tests. The vertical axis is measured value in DN, the digital number. The purple dots and line show the data for the blackbody plate and their linear regression. The blue and green dots show the data for the cavity blackbody and the collimator, respectively. b–d) Thermal images from TIR using the different apparatuses for the 100 °C target: b, the blackbody plate (total area coverage), c, the cavity blackbody (simulation to Mid-Altitude, 5 km), and d, the collimator (simulation to Home Position) (Okada et al., 2020).

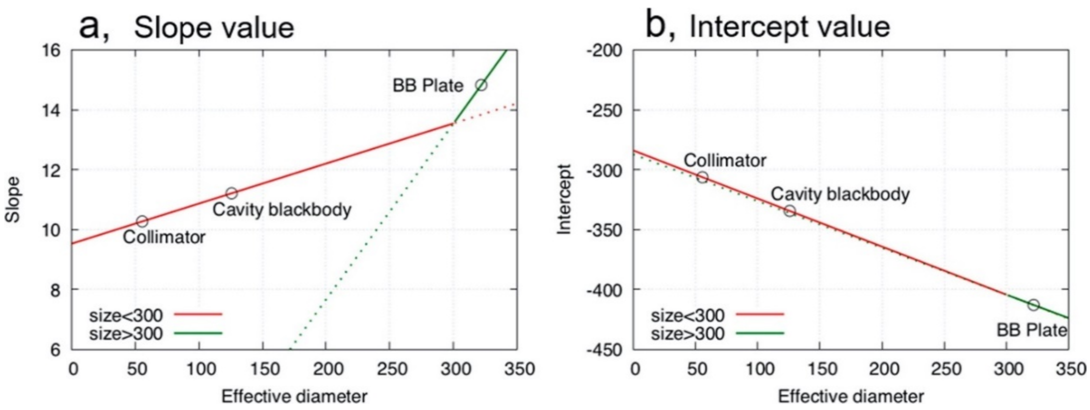

Figure 7 Effective diameter dependence of the LUT for TIR calibration. (a) shows the values of the slope (scaling factor) at the center pixel at (164, 124) in terms of the effective diameter D_{eff} of the target, and (b) shows the intercept (offset). The red lines are derived from the data of the collimator and the cavity blackbody sources for $D_{\text{eff}} \leq 300$ pixels. The green lines are derived from the blackbody (BB) plate source for 300 pixels $< D_{\text{eff}} \leq 322$ pixels (Okada et al., 2020).

5.3.2.3 Derived Temperature Map Data Product

Observed pixel coordinates connect to the planetocentric coordinates, calculated by the SPICE toolkit. The observed brightness temperature is projected onto the asteroid shape model. Generation of this data products will be described in detail in future revision of this document.

5.3.2.4 Derived Thermal Inertia Map Data Product

Thermal inertia is estimated for each polygon of the asteroid shape model from the latitude of the polygon and shift of the local time when the peak temperature is achieved. The "latitude" and "local time" is calibrated by using the local slope of the polygon. Generation of these data products will be described in detail in a future revision of this document.

5.3.2.5 Browse Product

Quick look image data in the PNG format are generated from other data products.

5.3.3 Data Flow

TIR raw, calibrated, and derived data products are built up in sequential data processing steps addressing specific corrections or calibrations. All data products are built from raw telemetry ingested into the SIRIUS database. The TIR data processing pipelines query the database directly for new raw science data. The TIR data files generated by the pipelines are stored in the storage system prepared by C-SODA. Figure 8 is a schematic that shows the TIR data flow from raw telemetry to derived data products.

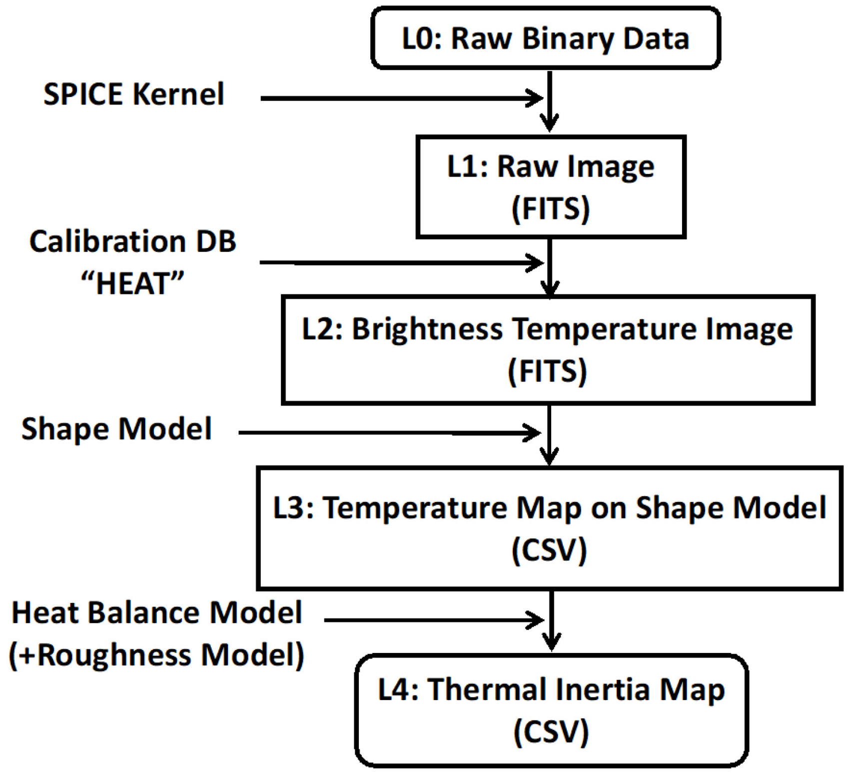

Figure 8 The schematic figure describing data flow.

The observation time in the Level 1 data (raw image data) and Level 2 data (calibrated brightness temperature data) is converted from TI (Time Indicator) to UTC by using the spacecraft time calibration library prepared by C-SODA. The spacecraft time calibration library uses the spacecraft time calibration table that is source information of SPICE SCLK in the Hayabusa2 SPICE bundle.

Table 5 shows the expected TIR science data volume by each mission phase.

Table 5 TIR Data Volume by Mission Phase

Mission phase/TIR Product	Commissioning	EDVEGA	Earth Swing-by	Transfer	Approach	Asteroid Proximity	Return	Reentry
Raw Image data	0	0	318 MiB	91 MiB	163 MiB	17 GiB	0	0
Calibration data	0	0	293 MiB	0	211 MiB	20 GiB	0	0
Calibrated Brightness Temperature Image data	0	0	104 MiB	0	75 MiB	6.9 GiB	0	0
Derived Temperature Map data	0	0	0	0	0	TBD	0	0
Derived Thermal Inertia Map data	0	0	0	0	0	TBD	0	0
Browse data for L1 (Raw Image data)	0	0	248 MiB	72 MiB	125 MiB	13 GiB	0	0
Browse data for L2 (Calibrated Brightness Temperature Image data)	0	0	21 MiB	0	15 MiB	2.2 GiB	0	0

5.3.4 Labeling and Identification

All TIR data products are labeled with PDS4 compliant detached XML labels. These labels describe the content and format of the associated data product. Labels and products are associated by file name with the label having the same name as the data product except that the label file has an .xml extension.

Labels are constructed with the PDS4 Product Class, Product_Observational sub-class. The Product_Observational sub-class describes a set of information objects produced by an observing system. A hierarchical description of the contents of Product_Observational products appears below:

Product_Observational
- Identification_Area – attributes that identify and name an object
  - logical_identifier – a unique identifier
    - urn:jaxa:darts:hyb2_tir:<collection>:<file_name_root>,
    - e.g., urn:jaxa:darts:hyb2_tir:data_raw:hyb2_tir_20180629_075503_l1
  - version_id – version of product
  - title – short description of product used as the PDS4 search return
  - information_model_version – version of PDS4 information model used to create product
  - product_class – attribute provides the name of the product class (Product_Observational)
- Observation_Area – attributes that provide information about the circumstances under which the data were collected.
  - Time_Coordinates – time attributes of data product
  - Primary_Results_Summary – high-level description of the types of products included in the collection or bundle
  - Investigation_Area – mission, observing campaign or other coordinated, large-scale data collection attributes
  - Observing_System – observing system (instrument) attributes
  - Target_Identification – observation target attributes

Mission_Area – mission specific attributes needed to describe data product
Discipline_Area – discipline specific attributes needed to describe data product
Reference_List – describes list of references associated with this product
File_Area_Observational – describes a file and one or more tagged_data_objects contained within.
File – identifies the file that contains one or more data objects
Header – defines a header for image array
Array_2D_Image – defines a 2D image array

Information in the preceding paragraphs was distilled from the PDS4 Information Model provided by PDS. Additional information on product labels can be found at https://pds.nasa.gov/datastandards/about/.

TIR data products are identified with file names that describe the following elements:

hyb2_tir_*YYYYMMDD_hhmmss_level.extension*

where

- date – date of observation
  - *YYYY* is year in 4 digits,
  - *MM* is zero-padded month in 2 digits,
  - *DD* is zero-padded day in 2 digits,
  - *hh* is zero-padded hour in 2 digits,
  - *mm* is zero-padded minute in 2 digits, and
  - *ss* is zero-padded second in 2 digits.
- *Level* – level of data product
  - l1 – Level 1 data product
  - l2 – Level 2 data product
  - lut – Lookup table
  - l3 – Level 3 data product
  - l4 – Level 4 data product
- *extension* – extension of the file
  - fit – FITS file for l1 image, l2 image, and LUT.
  - xml – XML file for PDS4 label
  - png – PNG file for quick look image
  - png.xml – XML file for PDS4 label associated with PNG file

Examples of filename are shown below:

1. hyb2_tir_20190630_005347_l1.fit
2. hyb2_tir_20190630_005347_lut.fit
3. hyb2_tir_20190630_005347_l2.fit
4. hyb2_tir_20190630_005347_l2.png

The filename of the table of blackbody temperature and radiance of the target is an exception of the above: the filename is temp_radiance_table.csv.

5.4 Standards Used in Generating Data Products

5.4.1 PDS Standards

All data products described in this SIS conform to PDS4 standards as described in the PDS Standards document noted in the Applicable Documents section of this SIS. Prior to public release, all data products will have passed a PDS peer review to ensure compliance with applicable standards.

In consultation with the PDS, the Hayabusa2 mission shall use the 1.14.0.0 version of the PDS4 information model. All Hayabusa2 products will conform to this standard, however products may have various versions of specific Discipline Dictionaries.

5.4.2 Time Standards

All Hayabusa2 data products contain a UTC time that has been derived from the Hayabusa2 spacecraft clock. The transformation table (spacecraft time calibration table) from the spacecraft clock to UTC is provided by SIRIUS and is converted to SPICE SCLK file by the Hayabusa2 DAC team. This transformation table itself is proprietary; however, the transformation can be achieved by SPICE routines with the SPICE SCLK and LSK files included in the Hayabusa2 SPICE bundle.

5.4.3 Coordinate Systems

All coordinate systems used by the Hayabusa2 mission conform to IAU standards. A complete discussion of the coordinate systems and how they are deployed in the mission can be found in the Ryugu Coordinate System Description prepared by the Hayabusa2 Shape Model team, included in the document collection of the Hayabusa2 mission bundle.

5.4.4 Data Storage Conventions

All TIR Level 1 and Level 2 data products and LUT files of calibration data product are stored natively as FITS files and conform to the FITS 3.0 standard (Pence et al., 2010). All TIR, Level 3 and Level 4 data products and blackbody temperature-radiance table of calibration data product are stored as ASCII delimiter separated variable tables. Comma has been chosen as the standard delimiter by the team.

5.5 Data Validation

The TIR team checks the validity of the data manually and visually.

In addition to software verification and validation, each data product has been peer reviewed for both PDS data format acceptability and scientific usefulness. No changes are expected to data formats after peer review. Should any changes be needed, the configuration control process will be followed and documented.

When data are prepared for submission to the PDS, the DAC team and the TIR team will use PDS / mission-provided validation tools for conformance to the PDS4 standards. TIR team members and DAC team members will validate the data contained within the TIR data products.

6 Detailed Data Product Specifications

The following sections provide detailed data product specifications for each TIR data product. These specifications will provide sufficient detail so that data product users can read and interpret the products.

6.1 Data Product Structure and Organization

The Hayabusa2 data archive is organized by instrument. The TIR bundle of the archive is organized by processing level, product type, and mission phase. Data products are stored under each mission phase directory which is just under the data collection directories. Which mission phase directory is selected to store data product is determined by the value of the start_date_time attribute of the Product_Observational/Observation_Area/Time_Coordinates class being in which mission phase period. The list of collections and products in each collection is summarized in Table 6. These collections are under the Hayabusa2 TIR bundle directory, *hyb2_tir*. Each name of collection is same as directory name in the bundle.

Table 6 List of collections and products in TIR bundle

Name of collection	Products in the collection
data_raw	TIR Raw Image Data Products
data_btemp	TIR Calibrated Brightness Temperature Image Data Products
data_temp_map	TIR Derived Temperature Map Data Products (planned)
data_tinertia_map	TIR Derived Thermal Inertia Map Data Products (planned)
document	SIS (This file) and instrument papers
calibration	TIR Calibration Data Products
browse	TIR Browse Products

The raw data products, calibrated data products, and a part of calibration data products are stored as FITS files with a detached PDS label, and the other part of calibration data product, the derived temperature map data, and derived thermal inertia map data are stored as ASCII delimiter separated variable table format with a detached PDS label. The detached PDS labels are PDS4 compliant XML labels that describe the contents of the file. The products are:

1. **TIR Raw Image Data Product** – These data are FITS format data with 384 x 256 data array of pixels. Data are in digital numbers (DN).
2. **TIR Calibration Data Product** – One is the FITS format data with two HDUs which contains lookup tables of scaling factor and offset from DN to radiance. The other is the ASCII DSV format data, which is a conversion table from the observed radiance to brightness temperature.
3. **TIR Calibrated Brightness Temperature Image Data Product** – These data are FITS format data with 328 x 248 pixels in absolute temperature (K).
4. **TIR Derived Temperature Map Data Product** – These data are ASCII DSV format data which includes polygon face ID, the normal vector of the polygon face, solar incident vector, solar emission vector, pixel x, pixel y, brightness temperature, and local solar time. (TBD)
5. **TIR Derived Thermal Inertia Map Data Product** – These data are ASCII DSV format data which includes estimated thermal inertia, etc. (TBD)
6. **TIR Browse Product** – These data are PNG format data created from other data products.

6.2 Data Format Descriptions

6.2.1 Raw Image Data

The values in each pixel are stored in a 16-bit signed integer. A list of metadata included in the FITS files is shown in Table 7. The data should be displayed left to right in horizontal and top to bottom in vertical.

Table 7 List of metadata for TIR image

PDS4 attribute	**FITS keyword**	**Description of the FITS keyword**
Array_2D_Image/Element_Array/data_type	BITPIX	number of bits per data pixel
Array_2D_Image/axes	NAXIS	number of data axes
Array_2D_Image/Axis_Array/elements	NAXIS1	length of data axis 1
Array_2D_Image/Axis_Array/elements	NAXIS2	length of data axis 2
Time_Coordinates/start_date_time	DATE-BEG	date of the start of observation in UTC
hyb2:Observation_Information/hyb2:observation_date_time	DATE-OBS	date of the middle of observation in UTC
Time_Coordinates/stop_date_time	DATE-END	date of the end of observation in UTC
Target_Identification/name	OBJECT	name of observed object
Array_2D_Image/Element_Array/unit	BUNIT	unit of pixel values
-	ROI_LLX	Horizontal index of lower left corner pixel of the image in detector coordinate
-	ROI_LLY	Vertical index y of lower left corner pixel of the image in detector coordinate
-	ROI_URX	Horizontal index x of upper right corner pixel of the image in detector coordinate
-	ROI_URY	Vertical index y of upper right corner pixel of the image in detector coordinate
used for hyb2:TIR_Instrument_Attributes/hyb2:number_of_bit_shift	BITDEPTH	bit depth of pixel value
hyb2:TIR_Instrument_Attributes/hyb2:bolometer_temperature	BOL_TEMP	bolometer temperature [degC]
hyb2:TIR_Instrument_Attributes/hyb2:package_temperature	PKG_TEMP	package temperature [degC]
hyb2:TIR_Instrument_Attributes/hyb2:case_temperature	CAS_TEMP	case temperature [degC]
hyb2:TIR_Instrument_Attributes/hyb2:shutter_temperature	SHT_TEMP	shutter temperature [degC]
hyb2:TIR_Instrument_Attributes/hyb2:lens_temperature	LEN_TEMP	lens temperature [degC]
hyb2:TIR_Instrument_Attributes/hyb2:number_of_accumulated_images	IMGACCM	number of accumulated images
hyb2:TIR_Instrument_Attributes/hyb2: coarse_grained_temperature_status	PLT_RDYC	Peltier temperature is roughly within PLT_TGTT ±10 degC
hyb2:TIR_Instrument_Attributes/hyb2: fine_grained_temperature_status	PLT_RDYF	Peltier temperature is roughly within PLT_TGTT ±0.1 degC
hyb2:TIR_Instrument_Attributes/hyb2: peltier_desired_temperature	PLT_TGTT	Target value of Peltier temperature control

PDS4 attribute	FITS keyword	Description of the FITS keyword
hyb2:TIR_Instrument_Attributes/hyb2:peltier_power_status	PLT_POW	Peltier cooler/heater power status: ON, OFF
hyb2:TIR_Instrument_Attributes/hyb2:tir_image_type	IMGTYPE	image type: PIC (subtracted image), SHT (shutter-closed image), OPN (shutter-open image)
img:Imaging/img:Onboard_Compression/img:onboard_compression_class	IMGCMPRV	type of image compression: N/A, LOSSLESS, LOSSY
img:Imaging/img:Onboard_Compression/img:onboard_compression_type	IMGCMPAL	name of algorithm for image compression: STAR_PIXEL for StarPixel Lossless
img:Imaging/img:Onboard_Compression/img:StarPixel_Lossless_Parameters/img:starpixel_initial_subsampling_interval	IMGCMPPR	parameter for image compression
hyb2:TIR_Instrument_Attributes/hyb2:number_of_accumulated_images	IMGACCM	Number of accumulated images
img:Imaging/img:Onboard_Compression/img:StarPixel_Lossless_Parameters/img:Image_Compression_Segment/img:segment_corrupted_flag	IMGCRRPT	Corrupted area of image: OK, corrupted area in the format of [x0,x1]x[y0,y1] where x0 and x1 are the smallest and the largest indexes of the region in horizontal, respectively, and y0 and y1 are the smallest and the largest indexes of the region in vertical, respectively.

6.2.2 Calibration Data

There are two kinds of calibration data: one is radiance acquired by observation of target by the TIR instrument as a function of black-body temperature and black-body temperature in ASCII DSV format, temp_radiance_table.csv, described in Table 8, and the other is lookup table for conversion from radiance to DN acquired by the TIR instrument in FITS format.

Table 8 Columns for black-body temperature and radiance table

	Name of column	Description
1	Black-body Temperature	Black-body Temperature.
2	Radiance	Observed radiance as a function of "Black-body Temperature" (field_number 1) which is calculated by convolution integral of emissivity, black-body spectral radiance, and the response function of TIR with wavelength.

The lookup table (LUT) is provided as FITS format with two HDUs; the primary HDU stores scaling factor for the conversion equation from radiance to digital number of each pixel, and the secondary HDU (first image extension of the file) stores offset for the conversion equation from radiance to digital number of each pixel.

6.2.3 Calibrated Brightness Temperature Image Data

The format of Level 2 is the same as that of Level 1, except that the image data is converted into 32-bit floating point number. A list of metadata included in the FITS files is same as Raw Image Data which is shown in Table 7. The data should be displayed left to right in horizontal and top to bottom in vertical.

6.2.4 Derived Temperature Map Data

The format of this product is the ASCII DSV table in physical unit (Table 9).

Table 9 Columns for Derived Temperature Map Data

	Name	Data Type	Unit	Description
1	TBD			
2	TBD			

6.2.5 Derived Thermal Inertia Map Data

The format of this product is the ASCII DSV table in physical unit (Table 10).

Table 10 Columns for Derived Thermal Inertia Map Data

	Name	Data Type	Unit	Description
1	TBD			
2	TBD			
3	TBD			

7 Applicable Software

7.1 Utility Programs

At the current time, the Hayabusa2 project team has no plans to release any mission specific utility programs.

7.2 Applicable PDS Software Tools

Data products found in the Hayabusa2 archive can be viewed with any PDS4 compatible software utility. A listing of these tools can be found at https://pds.nasa.gov/tools/about/.

7.3 Software Distribution and Update Procedures

As no Hayabusa2 specific software will be released to the public, this section is not applicable.

8 Appendices

8.1 Definitions of Data Processing Levels

PDS4 Data Processing Levels (From PDS Policy on Data Processing Levels (2013-03-11):

Telemetry: An encoded byte stream used to transfer data from one or more instruments to temporary storage where the raw instrument data will be extracted.

Raw: Original data from an instrument. If compression, reformatting, packetization, or other translation has been applied to facilitate data transmission or storage, those processes will be reversed so that the archived data are in a PDS approved archive format.

Partially Processed: Data that have been processed beyond the raw stage but which have not yet reached calibrated status.

Calibrated: Data converted to physical units, which makes values independent of the instrument.

Derived: Results that have been distilled from one or more calibrated data products (for example, maps, gravity or magnetic fields, or ring particle size distributions). Supplementary data, such as calibration tables or tables of viewing geometry, used to interpret observational data should also be classified as 'derived' data if not easily matched to one of the other three categories.