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Surface Biology and Geology (SBG) Observing Terrestrial Thermal Emission Radiometer (OTTER)

Level 1 Radiometric Calibration Algorithm Theoretical Basis Document (ATBD)

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Veljko Jovanovic
Level 1 Algorithm Team
Jet Propulsion Laboratory
California Institute of Technology

Thomas L. Logan
Level 1 Algorithms Team
Jet Propulsion Laboratory
California Institute of Technology

William R. Johnson
Optics and Detector Team
Jet Propulsion Laboratory
California Institute of Technology

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, California 91109-8099
California Institute of Technology

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Change History Log

Revision	Effective Date	Prepared by	Description of Changes
Draft	07/26/2023	T. Logan; W. Johnson	SBG-TIR L1 Calibration ATBD first draft.
Draft	07/17/2025	V. Jovanovic, W. Johnson	Added accuracy requirements table. Several technical edits throughout the text.

Contacts

Readers seeking additional information about this study may contact the following:

Veljko M. Jovanovic
MS 168-420
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
Email: *Veljko.m.Jovanovic@jpl.nasa.gov*
Office: (818) 354-4032

William R. Johnson
MS 302-205
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
Email: *william.r.johnson@jpl.nasa.gov*
Office: (818) 393-5470

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Abstract / Background

In 2021, the NASA Earth System Observatory (ESO) identified the study of Surface Biology and Geology (SBG) as one of five science focus areas based on recommendations from the 2018 Decadal Survey. The concept's implementation has since evolved into two separate spacecraft platform systems: A VSWIR (Visible and Short Wave Infrared imaging spectrometer) for hyperspectral analysis, and dual VNIR (Visible and Near Infrared) and TIR (Thermal Infrared) instruments for focused thermal mapping science [1]. This document specifically addresses radiometric calibration of the SBG-TIR instrument abroad the second platform. Geometric calibration of the thermal imaging sensor is covered in a separate ATBD.

The SBG-TIR instrument, also known as "OTTER" (Orbiting Terrestrial Thermal Emission Radiometer), was designed and built by the Jet Propulsion Laboratory (JPL). It is mounted to a free-flyer satellite platform built and managed by the Italian Space Agency (ASI), who also manages the separate (co-boresighted) VNIR camera. The TIR instrument's focus is exploration of the Earth's surface temperature and emissivity, evapotranspiration, vegetative water stress, substrate composition, volcanic plumes, and other high-temperature features and their change over time. The instrument uses a continuously rotating scan mirror in a push-whisk configuration to direct light from the telescope through eight narrowband interference filters to the Focal Plane Array (FPA). The eight bands include two mid-infrared wavelengths (3-5μm) and six thermal wavelengths (8-12μm). (The VNIR camera provides three additional spectral bands managed by ASI.) The platform will have an operational altitude of ~693km providing an approximate ground sample distance (GSD) of 60m at nadir, and an image granule size of approximately 910x1060km with 3-day repeat visit time.

This algorithm theoretical basis document (ATBD) describes the Level 1 radiometric calibration of the SGB-TIR OTTER imagery. The calibration process involves correcting non-uniform light measurement (as needed) between individual pixel detectors on the focal plane array (FPA), and adjusting those values to represent radiometrically correct radiance values. Radiance is calculated from a two-point linear extrapolation between coincident measurements from on-board Hot and Cold Blackbodies for the thermal bands. An additional calibration may be required for the two mid-wave bands. Based on Laboratory experiments, the radiometric calibration measured as Brightness Temperature at the Sensor, is expected to have an accuracy of better than one degree Kelvin (1 sigma at 300° K).

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1 Introduction

The OTTER (Orbiting Terrestrial Thermal Emission Radiometer) is part of the NASA SBG (Surface Biology and Geology) mission that deploys an advanced imaging spectrometer on a "free-flyer" space platform managed by the Italian Space Agency (ASI) to monitor Earth environment temperatures using Thermal Infrared (TIR) wavelengths [1]. The planned science focus includes surface radiance, temperature, emissivity, evapotranspiration, volcanic plumes, water use efficiency, and related temperature manifestations. To measure radiance, the instrument uses a continuously rotating scan mirror in a push-whisk configuration to direct light from the telescope through eight narrowband interference filters to the Focal Plane Array (FPA). The focal plane consists of 8x16x256 arrays of Mercury Cadmium Telluride (MCT) detectors of CMOS (complementary metal oxide semiconductor) manufacture. The OTTER FPA design is an update of the "Prototype HyspIRI-TIR (PHyTIR)" instrument originally developed at JPL by Johnson, et al [2], and flown by the NASA ECOSTRESS Mission [7] aboard the ISS (International Space Station). Data are collected as 14-bit dynamic range pixels with a 60 m ground sampling distance (GSD) at nadir, and assembled into Earth coverage imagery measuring 910 km × 1060 km in size.

Level-1 (L1) "FPA Calibration" is the process of removing (correcting) non-uniform light measurement between individual pixel detectors on the focal plane array. L1 "Radiometric Calibration" is the process of relating the uniform values received from the focal plane detectors to a standard measurement. Laboratory testing of the OTTER instrument indicates that no special light correction steps (FPA calibration) are anticipated. For visual (VIS), near-infrared (NIR) and shortwave infrared wavelengths (SWIR), the conventional radiometric calibration approach is to apply Dark Current and Flat-Field procedures, then perform a separate vicarious ground calibration. Thermal Infrared (TIR) imaging systems (such as OTTER) typically have on-board "hot" and "cold" Blackbody temperature sources to directly calibrate the thermal bands in orbit. However, the two OTTER mid-infrared wavelengths, which provide a larger radiance measurement range than the thermal wavelengths, will require more extensive pre-launch blackbody calibration as well as on-orbit validation.

Detector	Channel	Bandwidth	Required Accuracy	Required NEdT	Required Sat.
Band Number	(microns)	(microns)	(K)	(K)	Temp. (K)
MIR-1	3.98	0.3	3 at 750K	0.300 at 750K	1200K
MIR-2	4.80	0.15	1 at 450K	0.200 at 450K	800K
TIR-1	8.32	0.3	0.5 at 275K	0.200 at 275K	500K
TIR-2	8.63	0.3	0.5 at 275K	0.200 at 275K	500K
TIR-3	9.07	0.3	0.5 at 275K	0.200 at 275K	500K
TIR-4	10.30	0.3	0.5 at 275K	0.200 at 275K	500K
TIR-5	11.35	0.5	0.5 at 275K	0.200 at 275K	500K
TIR-6	12.05	0.5	0.5 at 275K	0.200 at 275K	500K

Table 1: The OTTER Spectral Imaging Parameters and required accuracy specifications.

As designed, a combination of pre-flight and in-flight radiometric calibration activities, including on-orbit validations, will ensure data product quality that satisfies the radiometric accuracy requirements established in response to the overall science objectives. A summary of OTTER's spectral imaging parameters and associated accuracy requirements is provided in Table 1.

Over the lifetime of the instrument, subsequent FPA corrections may be necessary in the event of non-responsive pixels or Blackbody degradation. Note that preparations of Level-2 products (i.e., Land Surface Temperature and Emissivity) require the application of additional calibration algorithms as described by Hulley and Hook [3] and are outside the scope of this document.

2 Pixel Travel Path and FPA Reserves

Unlike the conventional Frame Camera in which the focal plane closely defines the size of the output image, the OTTER rotating scan mirror illuminates a relatively small focal plane (1x256 column of pixels) and combines multiple FPAs to produce a composite image. A single-band L1A image delivered to the ground is 17664 lines (Y-axis; across-track) by 15168 samples (X-axis; along-track), and is therefore a mosaic of 1,046,592 focal plane columns (15168 columns x 69 scans). The travel path of a pixel from photon to L1A radiance product is shown in Figure 1. Each Level-0 image is generated in approximately 2.4 minutes with eight bands, plus associated Blackbody calibration and related metadata.

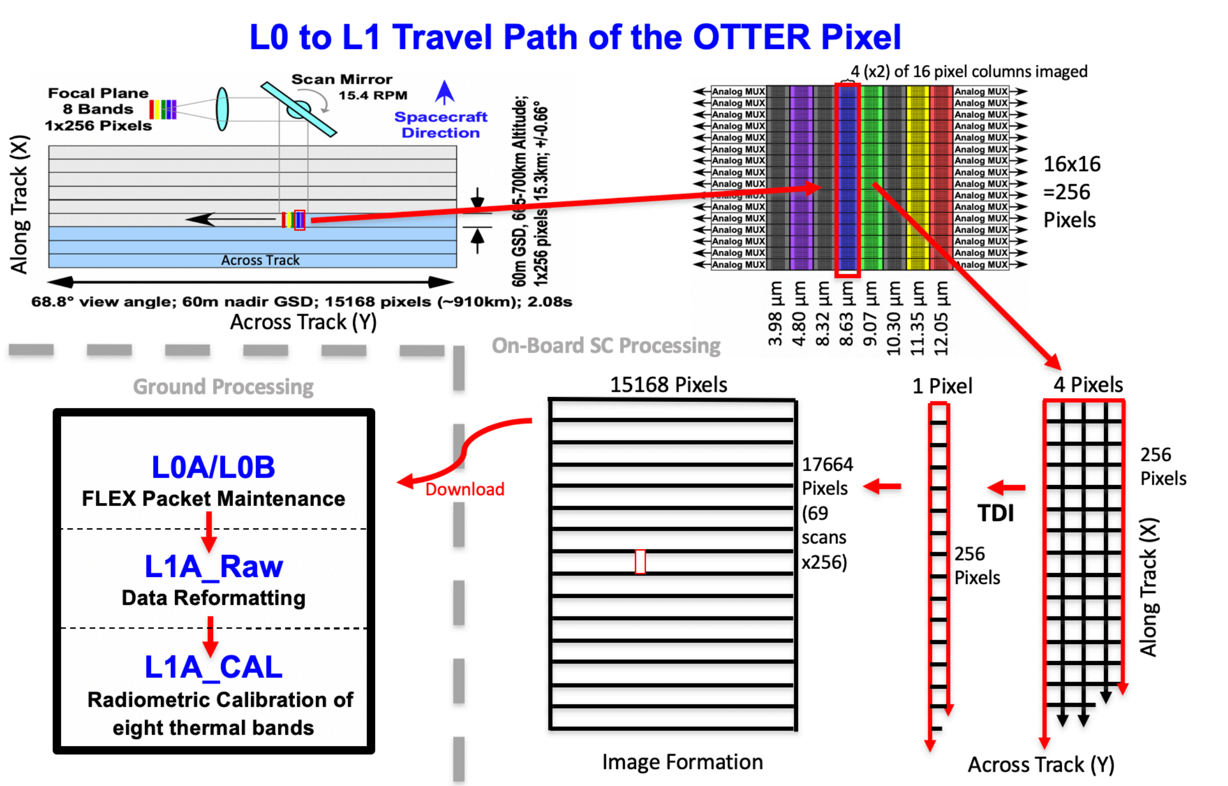

Figure 1: Simplified travel path of an OTTER pixel from photon to L1A CAL Radiometric Calibration PGE (Product Generation Executive). Only one band is shown for clarity (actual data flow includes eight bands plus Blackbody calibration metadata).

The FPA diagram in (the upper right corner of) Figure 1 shows the eight available focal plane band/columns. Each of the eight FPA band/columns is 16 by 256 pixels, with 4 of the 16 pixels columns readout. This means that only 4 of the 16-pixel columns in each FPA band are used for imaging. The remaining 12-pixel columns represent a reserve that could be configured for application should the need arise.

For each focal plane column set, a 4x256 14-bit integer "image" is readout and summed across-track (Time Delayed Integration; TDI) to a 1x256 pixel column image (Figure1; Bottom Right). Each collection of 15168 successive (1x256) pixel columns are concatenated across-track (one "mirror scan"), with 69 successive scans (along-track) completing one full image. The resultant image is 15168 samples by 17664 lines (by 8 bands) and is essentially a mosaic of 1,046,592 embedded focal plane images (per band). The data stream is downloaded to the Ground Data System (GDS) where the data are organized into Orbit and Scene files (L0A/L0B PGE) reformatted (L1A RAW PGE), and corrected for timing, missing, or invalid data. Radiometric calibration (L1A CAL PGE) begins once the "L1A Raw" process is complete and all the image data are properly formatted.

3 Algorithm Descriptions

The algorithmic processes typically involved with Level-1 optical satellite calibration include Dark Current (DC) removal and Flat-Field (FF) uniformity correction for focal plane repair, and some form of vicarious ground calibration [5] for radiometric calibration. For thermal imaging systems, the radiometric calibration algorithm typically uses two on-board Blackbodies of different (“hot” and “cold”) temperatures to interpolate radiance (directly from DNs) that inherently corrects (and removes the need) for a separate DC error correction. By performing the interpolation operation on every pixel independently, the data is automatically flat fielded. . The two mid-infrared bands will require additional laboratory measurements to manage their radiance linearity which extends beyond the range of the two instrument blackbodies. However, in the (unlikely) event of a blackbody failure, possible approaches for DC and FF correction are discussed.

3.1 Dark Current Correction

Dark Current (DC) is the sum total of all ambient energy sensed by the focal plane in the absence of incident light and is typically produced by electrical fields generated from the sensor’s operating electronics. DC noise tends to increase with increasing temperature and becomes significant above 72 degrees Kelvin. The FPA is therefore maintained at a constant 65K inside a Cryocooler that is further protected by a second enclosing 120K Cryocooler which combines to significantly reduce DC error. The error budget estimate has been released under the title, “SBG-TIR Radiometric Error Budget” and has a internal document number D-1002030. Goullioud [4] estimated the ECOSTRESS Dark Current at 270 electrons/read, which when combined with other noise errors (Read; Photon; Quantization; Optics thermal) amounted to less than 0.15K (at 275 Kelvin post TDI). Dark Current will be measured in the laboratory before launch, calibrated against the blackbodies after launch, and held in reserve until needed.

FP1 = FP0 – DC *Dark Current Formula*

Where:

FP0 = Raw Focal Plane image with Dark Current.

FP1 = Focal Plane image with Dark Current removed.

DC = Focal Plane image of Dark Current.

3.2 Flat-Field Uniformity Correction

The purpose of Flat-Fielding (FF) is to correct focal plane pixel artifacts and irregularities relative to a uniform "flat" field of pixels. For the OTTER thermal bands, this process is inherent in the radiometric calibration step (where individual pixels are adjusted to uniformity relative to the two Blackbodies), and is therefore replaced by that step. However, should it become necessary, the first step would be to create a Flat-Field calibration file. This is accomplished by dividing the focal plane's pixel measurement of a uniform brightness field by that field's pixel value (where the "uniform field" is the image collected in the field or laboratory of a scene at a fixed integration time or fixed image mean brightness value). The FF correction is performed on a per-pixel basis (after subtracting the Dark Current) by dividing the FPA image by the FF calibration file.

FFcal = (FF – DC) / UF

FP2 = FP1 / FFcal *Flat-Field Formula*

Where:

FFcal = Focal Plane Flat-Field Calibration File.

UF = Pixel value of the Laboratory-prepared Uniform Field.

FF = Focal Plane Image of the Laboratory-prepare Uniform Flat Field.

DC = Focal Plane image of Dark Current.

FP2 = Flat-Field (and Dark Current) corrected Focal Plane image.

FP1 = Focal Plane image with Dark Current removed (from DC Formula).

In the unlikely event of a degrading Blackbody necessitating a TIR Flat-Field, a stable thermal mass would be imaged as a replacement for the Uniform Field (UF), in conjunction with a ground campaign simultaneously measuring the temperature of that mass. Candidate ground sites include water bodies and JPL's vicarious calibration sites [6]. Note that the Flat-Field step only corrects FPA artifacts---a separate radiometric calibration process would still be required (possibly based on previous black body trending combined with vicarious ground calibration).

3.3 Blackbody Radiometric Calibration

For the TIR bands, Level-1 Radiometric Calibration is the process of converting incident thermal energy (in Digital Numbers; DN) on the Focal Plane to calibrated radiance values (at the sensor). For testing and evaluation purposes, the radiance values are also converted to temperature values (degrees Kelvin). This is accomplished through: 1) Pre-flight and in-flight on-board measurement of the cold (CBB) and hot blackbody (HBB) temperatures; 2) Conversion of the known blackbody temperatures to radiance using the Planck function; 3) Creation of hot and cold focal plane blackbody calibration and radiance files; 4) Conversion of each focal plane DN to radiance values using a two-point affine transformation; and 5) Use of the Inverse Planck function to convert each band's calculated pixel radiance to Brightness Temperature (K) for quality control and verification. Based on the ECOSTRESS experience, this radiometric calibration process should contribute less than 0.5 degree Kelvin error, and can be further reduced through corrections derived from validation (cal/val) ground calibration measurements.

3.3.1 Blackbody Temperature Measurement

Pre-flight blackbody calibration is performed in the laboratory on the flight hardware. This is particularly rigorous for OTTER because of previous experience with the similar PHyTIR [2] and ECOSTRESS instruments. The pre-flight process involves measuring the absolute skin temperature of each blackbody (BB) using a NIST-traceable radiometer (National Institute of Standards and Technology) to derive radiance versus temperature correction factors. A second thermal camera is used to map spatial gradients in the surface of each BB, although no gradients (+/- 0.01 degree) have yet to be measured. The final adjustments (if any) will be measured before flight and provided as part of the general metadata.

In-flight measurement and monitoring of the blackbodies is performed through the use of "platinum Resistance Temperature Detectors" (pt-RTDs) mounted on the backside of each blackbody. Five pt-RTDs are spatially distributed across each blackbody to accurately capture the temperatures, which are then downloaded as part of the spacecraft's State-Of-Health metadata. The ground calibration process updates the measured blackbody temperatures approximately once every minute.

Both of the spacecraft's blackbodies are electrically heated to maintain a stable temperature throughout the mission. The hot BB is planned for a constant 328 degrees Kelvin (131F; 55C), and the cold BB is planned to be a constant 278 degrees Kelvin (41F; 5C).

3.3.2 Blackbody Conversion to Radiance

The two calibrated Blackbody temperatures are converted to spectral radiance using the center wavelength of each TIR band in the Planck function. Figure 2 provides the spectral response functions (SRF) for the OTTER two mid-infrared and six thermal bands.

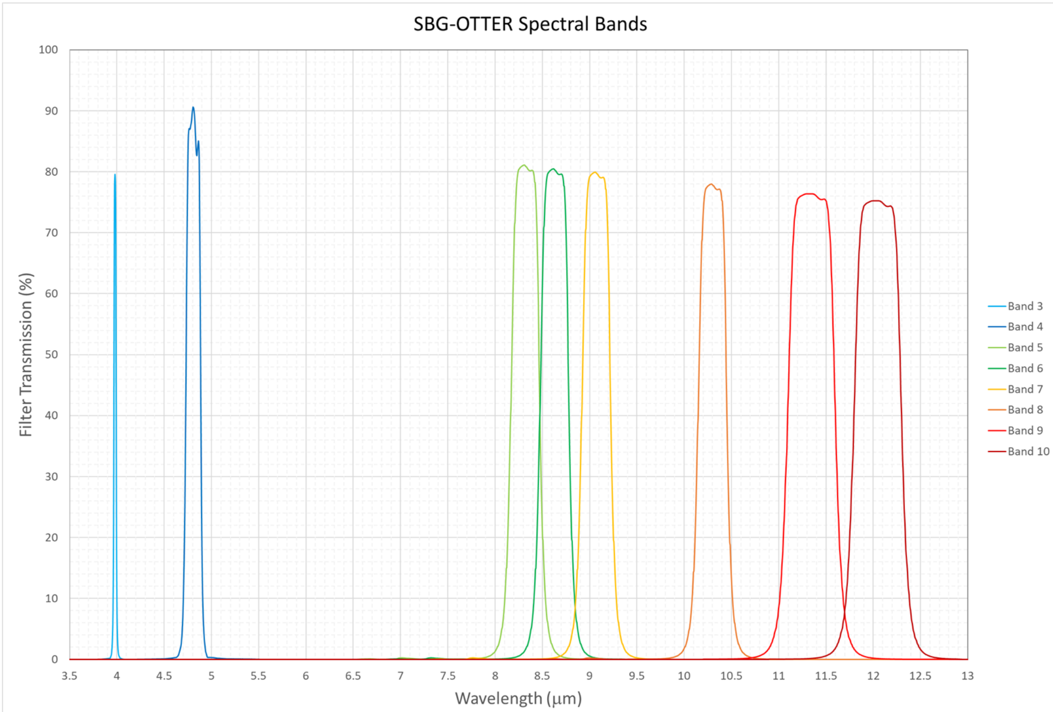

Figure 2: Spectral Response Function (SRF) for the eight OTTER Bands.

The Planck function converts blackbody temperatures (K) to spectral radiance. The standard algorithm is:

Planck (P) Function

$$L(\lambda,t)=\frac{c_1}{\lambda^5(e^{c_2/\lambda t}-1)}$$

Where:

$L(\lambda,t)$ = blackbody radiance (W/m^2-sr-um)

c_1 = 1.191042×10^8 (W/m^2-sr-um^{-4})

c_2=1.4387752×10^4 (K um)

λ = wavelength (um)

t = blackbody temperature (K)

(Source: WIKI/NOAA)

The Radiance of both the hot (R_h) and cold (R_c) blackbodies are calculated from the In-flight temperature metadata collected with each image set, which occurs approximately every 2.4 minutes.

Blackbody Radiance Formula

$$R_c = P(\lambda, Tc)$$

$$R_h = P(\lambda, Th)$$

Where:

R_c = *Radiance of the Cold Blackbody*

R_h = *Radiance of the Hot Blackbody*

P = *Planck Function (wavelength specific)*

T_c = *In-Flight collected Cold Blackbody Temperature (K)*

T_h = *In-Flight collected Hot Blackbody Temperature (K)*

3.3.3 Blackbody DN Calibration Files

With each half-rotation of the mirror scan, the focal plane (with 8 filters) collects the digital numbers (DNs) across the cold and hot blackbodies and the ground image. Sixty-four (64) focal planes are collected over each blackbody (64x256) and 15168 focal planes are collected over each Earth image (Figure 3).

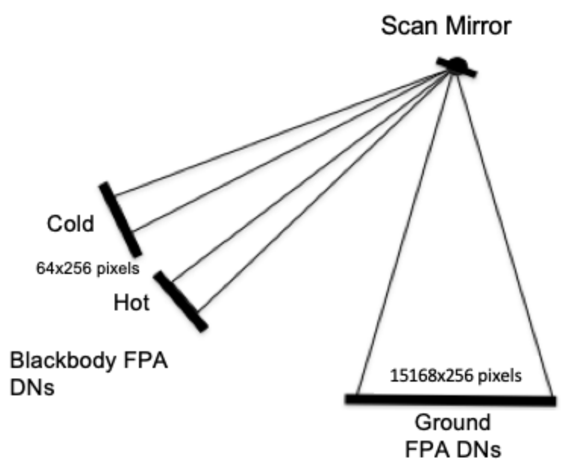

Figure 3: A Single Scan of the Mirror Images two Blackbodies and the Earth in each Wavelength.

The 64x256 pixel DN scans of the two blackbodies are appended to the L0 image data for download and later extraction, and 69 scans are combined to form full blackbody and ground images (69x256=17664 pixels). The 64 pixels in each blackbody DN file are averaged from 64x17664 to 1x17664 pixels to produce very precise DN focal plane measurements that can be aligned with the single pixel-width radiance images generated in Section 3.3.2.

3.3.4 DN to Radiance Two-Point Conversion

Given the FPA radiance values (Section 3.3.2) and the corresponding FPA DNs (Section 3.3.3) for both the cold (278K; 41F; 5C) and hot (328K; 131F; 55C) blackbodies, a two-point affine transformation is performed that converts each unique input pixel DN from the focal plane directly to radiance. Artifacts caused by detector non-uniformity implicitly corrected in the process. The linear fit between the two blackbodies for each pixel is very precise and will produce very accurate gain and offset terms. However, calculated radiance values above and below the two blackbody points will be extrapolations, with increasing error with increasing distance from the blackbodies. This will be of particular issue with the mid-IR bands (4 and 5), but will affect all bands to some degree, especially when imaging cold terrains and very hot events such as forest fires and lava exposures. Pre-flight calibrations and validation ground calibrations (Section 5) will be important for monitoring and adjusting TOA (Top Of Atmosphere) radiance values, with corrections applied to Level-2 products [6] as necessary.

Two-Point Calibration Formula

$$R_\lambda = a + bD_\lambda$$

$$a = \frac{R_h D_c - R_c D_h}{D_c - D_h} \qquad b = \frac{R_c - R_h}{D_c - D_h}$$

Where:

R = *Calculated Radiance of an input Digital Number (DN)*

a = *Offset Term*

b = *Gain Term*

D = *Input Earth Digital Number (DN)*

R_c = *Radiance of the Cold Blackbody (Section 3.3.2)*

R_h = *Radiance of the Hot Blackbody (Section 3.3.2)*

D_c = *Digital Number (DN) from the Cold Blackbody Calibration File (Section 3.3.3)*

D_h = *Digital Number (DN) from the Hot Blackbody Calibration File (Section 3.3.3)*

Each full blackbody and ground collection set of 69 scans by 15168 focal planes (by 8 bands) is imaged every 2.4 minutes. Gain and offset terms are uniquely calculated for each of the 69 scans and applied uniformly within each scan. The product of the L1A CAL calibration (Figure 1) are the Gain and Offset coefficients. In L1B production processing, Gain and Offset images are created to support the geolocation co-registration process with orthobase imagery.

3.3.5 Radiance to Temperature Conversion

For validation purposes, a number of pre-launch test images will be converted from DN to radiance and brightness temperature (Kelvin) to verify their accuracy is within 0.5 degree (at 275K). On-orbit TOA temperature testing will be performed as needed. The conversion from radiance to temperature is performed using the inverse Planck Function:

Inverse Planck Function

$$t(\lambda, L) = \frac{c_2}{\lambda \ln(c_1 / \lambda^5 L + 1)}$$

Where:

t = blackbody temperature (K)
L = blackbody radiance (W/m^2-sr-um)
c_1 = 1.191042×10^8 (W/m^2-sr-um^{-4})
c_2 =1.4387752×10^4 (K um)
λ = wavelength (um)

(Source: WIKI/NOAA)

The temperature validation approach will also be used for pre-launch Saturation Testing, which measures sensor response to the imaging of extreme heat sources. The TIR sensors will be exposed to a laboratory blackbody in the range of 500K, and mid-wave sensors will be exposed to temperatures around 1200K (Lava is typically 1100-1400K). The findings will provide important feedback to the calibration of Level 2 and 3 geologic products.

3.3.6 Mid-Infrared Calibration

The two mid-infrared bands are primarily intended for fire and volcanic heat monitoring that will significantly exceed the temperature range of the two on-board blackbodies (278-328K). Pre-launch Laboratory blackbody measurements will be performed to derive two-point Lookup Table (LUT) gain and offset coefficients that extrapolate beyond the standard blackbody ranges, and would be updated with blackbody calibrations obtained after reaching orbit. A similar calibration method for MODIS Band 21 (3.96μm) found that fixed linear radiance coefficients could be derived for accurate fire detection [8]. The plan is to acquire laboratory blackbodies with extended temperature endpoints in the range of 450K to 750K, and perform direct pre-launch calibration measurements. In-flight mid-wave calibration coefficients may be monitored and improved through feedback from on-going Level-2 atmospheric-corrected products (e.g., Land

Surface Temperature), vicarious ground validation data collection [9], and/or on-board (limited range) blackbody testing.

4 External Dependencies and Potential Issues

There are no external data dependencies for Level-1 Radiometric Calibration of the eight OTTER thermal bands. The joining of ASI's VNIR bands 1, 2, and 3 with the OTTER bands 4-11 occurs after both sensor bands have been independently and separately calibrated.

5 Validation

Radiometric thermal calibration techniques have been extensively tested and validated in the laboratory as part of the earlier PHyTIR instrument program [1] and in-flight by the ECOSTRESS mission [3]. For ECOSTRESS, this included extensive on-orbit skin temperature measurements of large stable lakes (i.e., Lake Tahoe; Salton Sea) compared with sensor radiance measurements [6]. Similar on-orbit tests will be performed as appropriate to validate OTTER mission sensors, as well as various integrated instrument and ground data processing activities performed by SBG/OTTER scientists.

6 References

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