EOS IDS Volcanology Team
Data Product Document
Product # 3291

Thermal Anomaly - High Spatial Resolution

Version 3

November 4, 1995

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1. INTRODUCTION

1.1 Algorithm and Product Identification

This document describes an algorithm for mapping the surface temperature of volcanic features using data acquired by the Advanced Spaceborne Thermal Emission and Reflectance Radiometer (ASTER). ASTER is currently scheduled for a 1998 launch on the AM-1 Earth Observing System (EOS) platform. This data product is number 3291, Thermal Anomaly-High Spatial Resolution, of the Global Assessment of Active Volcanism Interdisciplinary Science (IDS) Team. This team is led by Dr. Peter J. Mouginis-Mark of the University of Hawaii at Manoa.

1.2 Document Scope

The following sections of this document contain an overview of the remote sensing of surface temperatures at volcanoes, and a discussion of a procedure designed to map surface temperature. The Thermal Anomaly data product described in this document has a great deal of overlap with ASTER product AST08 (parameter # 3803): Surface Kinetic Temperature. This document will focus on the differences between the two data products. Those seeking more information on AST08 are referred to the corresponding Algorithm Theoretical Basis Document (ATBD-AST-04, see below).

1.3 Relevant EOS Documents

Gillespie et al., Temperature Emissivity Separation Algorithm Theoretical Basis Document (ATBD-AST-03)

Guenther et al., MODIS Level 1B Algorithm Theoretical Basis Document (ATBD-MOD-01)

Menzel WP and Gumley LE, MODIS Atmospheric Profile Retrieval Algorithm Theoretical Basis Document (ATBD-MOD-07)

Palluconi et al, Atmospheric Correction Methods for ASTER Radiometry (ATBD-AST-04)

Watanabe et al., Algorithm Theoretical Basis Document for ASTER Level 1 Data Processing (ATBD-AST-01)

2. OVERVIEW AND BACKGROUND INFORMATION

2.1 Experiment Objective

The objective of the experiment described in this document is to use satellite-based sensors to map the surface temperature of volcanic features. The ability to map surface temperatures from space will be a valuable asset to volcano monitoring programs, since such measurements are often impractical or even dangerous to obtain. Satellite-based remote sensing is the only mapping technique that can produce a virtually instantaneous image, or map, of surface temperature distributions over large areas (3600 km^2 per scene in the case of ASTER). In addition, the repetitive coverage provided by satellite-based sensors will facilitate the separation of temporal temperature changes due to volcanic or geothermal activity from those due to normal diurnal and seasonal variations in insolation, ground cover, and local weather conditions. A time-history of temperature maps is required to characterize the non-geothermal variations in surface temperature.

2.2 Historical Perspective

The direct measurement of the surface temperature of volcanic features is not practical or safe in many field settings. Infrared (0.9 - 13 µm) remote sensing of surface temperatures offers an alternative to direct measurements, and this mapping technique has been applied to a variety of volcanoes since the early 1960's. Most of these surveys have utilized single channel thermal infrared (TIR, 8 - 13 µm) sensors.

Airborne remote sensing surveys of volcanic and geothermal regions have been conducted in Hawaii [Fischer et al., 1964; Realmuto et al., 1992], Iceland [Friedman and Williams, 1970; Palmason et al., 1970], various Cascade volcanoes [Moxham, 1970; Friedman and Frank, 1980; Friedman et al., 1981 and 1982; Kieffer et al., 1981], Italy [Friedman and Williams, 1968; Bianchi et al., 1990, Abrams et al., 1994], Costa Rica, Antarctica, and the Philippines [Friedman and Williams, 1968].

Current satellite-based TIR sensors provide repetitive coverage, but the spatial resolution of these data is coarse relative to airborne data. TIR image data collected with the Landsat Thematic Mapper (TM) and Advanced Very High Resolution Radiometer (AVHRR) have spatial resolutions (at nadir) of 120 m and 1 km, respectively. Recent examples of the use of TM and AVHRR thermal imagery to map volcanic features can be found in Bonneville and Gouze [1992], Flynn et al. [1994], Gaonac'h et al. [1994], and Mouginis-Mark et al. [1994].

TIR radiance is a function of emissivity as well as surface temperature, and therefore multispectral imaging systems are needed to separate the effects of temperature and emissivity. Realmuto et al. [1992] demonstrated the separation of temperature and emissivity effects in the mapping of an active Hawaiian lava flow field. The launch of ASTER in 1998 [Kahle et al., 1991] will permit the collection of multispectral TIR image data on a global, rather than local, scale.

Virtually all airborne and spaceborne TIR imaging sensors were designed to observe the ground surface at ambient temperatures near 20 °C. Consequently, the TIR sensors saturate when the surface temperature is in excess of 50 - 75 °C and the surface fills the field-of-view of the sensor. This temperature range is too low for the mapping of active volcanic features.

The surface area of hot volcanic features is typically less than the instantaneous field-of-view (IFOV), or footprint, of the sensor. In such cases, the radiance observed by the sensor is a mixture of the radiance emitted by the hot feature with that emitted by the cooler region surrounding the feature, and the sensor is not saturated. Dozier [1981] and Matson and Dozier [1981] were the first to exploit this "radiance mixing" to estimate the temperature of hot features. These investigators discussed the use of data from two TIR channels (3.55 - 3.93 and 10.5 - 11.5 µm) of the Advanced Very High Resolution Radiometer (AVHRR).

Planck's Law dictates that the peak of the radiance spectrum emitted by a surface shifts to shorter wavelengths as the temperature of the surface increases. This shift in peak radiance permits high-temperature features to be mapped with short-wave infrared (SWIR, 0.8 - 2.5 µm) image data. Francis and Rothery [1987] and Rothery et al. [1988] were the first to adapt the Matson-Dozier "mixed pixel" procedure to Landsat Thematic Mapper (TM) SWIR data acquired over volcanic targets. TM SWIR data has since been used to survey a number of volcanoes [e.g. Glaze et al., 1989a and b; Pieri et al., 1990; Abrams et al., 1991; Oppenheimer 1993, Oppenheimer et al., 1993a, Flynn et al., 1994].

The investigators referenced above employed two TM (or AVHRR) channels to estimate the elevated temperatures of volcanic features. The two-channel approach has recently been extending to 3 or more channels using data acquired with ground-based spectroradiometers [Flynn and Mouginis-Mark, 1992; Flynn et al., 1993], AVHRR [Mouginis-Mark et al., 1994], and NASA's Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) [Oppenheimer et al., 1993b].

The ASTER instrument [Kahle et al., 1991] will provide multispectral imagery in the SWIR and the TIR, and will therefore be a powerful tool in the study of geothermal phenomena. The TIR data will be used to map ambient temperatures, while the SWIR data will be used to map elevated temperatures. ASTER data will allow investigators to accommodate variations in ground emissivity, perform detailed atmosphere corrections, and improve the accuracy of "mixed-pixel" temperature estimation techniques.

2.3 Instrument Characteristics

As indicated by Table 1, the ASTER instrument is actually a collection of three separate imaging sub-systems, each operating in a separate spectral region. The visible and near-infrared (VNIR) subsystem features nadir and forward-looking telescopes to provide panchromatic stereographic coverage in ASTER Channel 3.

The AM-1 platform will orbit the Earth 15 times per day, repeating the ground track every 16 days. ASTER will have a 8 - 9% duty cycle, meaning that the instrument will be acquiring data for roughly 9 minutes out of each 100 minute orbit. All three of the ASTER imaging subsystems will have crosstrack pointing capability of at least ± 8°. The crosstrack pointing will enable ASTER to image virtually any point on Earth. However, ASTER will probably acquire fewer than 50 volcano images per year due to operational constraints.

3. ALGORITHM DESCRIPTION

3.1 Theoretical Description

The radiance of an isothermal, homogeneous ground target, as measured by a satellite sensor, may be expressed as

$$L_s(\lambda) = \tau(\lambda)\ \{\varepsilon(\lambda)\ B(\lambda,T)\ + [1 - \varepsilon(\lambda)]\ L_d(\lambda)\} + L_u(\lambda) \qquad (1)$$

where $\tau(\lambda)$ is the transmission of the atmosphere, $L_d(\lambda)$ is the downwelling atmospheric radiance,and $L_u(\lambda)$ is the upwelling, or path, radiance. The dependance of these terms on the pathlength through the atmosphere has been omitted to simplify notation. $B(\lambda,T)$ is the Planck Function, (Planck's Law) which describes the radiant exittance of a surface as a nonlinear function of temperature (T) and wavelength. The symbol $\varepsilon(\lambda)$ denotes the emissivity of the surface.

The radiance of a homogeneous ground target with two thermal components may be expressed as

$$L_s(\lambda) = \tau(\lambda)\ \{\varepsilon(\lambda)\ [xB(\lambda,T_1) + (1\text{-}x)B(\lambda,T_2)] + [1 - \varepsilon(\lambda)]\ L_d(\lambda)\} + L_u(\lambda) \qquad (2)$$

where x denotes the area fraction of the high-temperature component of the pixel, and T_1 and T_2 are the temperatures of the high and low (ambient) components, respectively. The radiance expression can be generalized to heterogenous surfaces with more than two thermal components, but the addition of more model parameters (degrees of freedom) prohibits the recovery of unique temperature estimates from radiance measurements.

The atmospheric radiance terms $\tau(\lambda)$, $L_u(\lambda)$, and $L_d(\lambda)$ are typically removed by subtracting the sensor-perceived radiance of a non-geothermal ground target adjacent to the geothermal target from that of the target [cf. Rothery et al., 1988; Oppenheimer et al., 1993b]. Alternatively, the atmospheric transmission term can be calculated using a radiative transfer model such as MODTRAN [cf. Oppenheimer et al., 1993b] or one can assume that the atmospheric absorption is negligible [Rothery et al., 1988]. Surface emissivity can be measured with laboratory or field instruments.

Once the atmospheric and emissivity terms are accommodated, we are left with an expression for radiance that is a function of the area fraction (x) and temperature of the geothermal feature (T_1) and the temperature of the non-geothermal portion of the pixel (T_2). Given the radiance of the same pixel in a second (and typically adjacent) channel, we obtain a set of two nonlinear equations with three unknowns. $B(\lambda, T_2)$ may be neglected if T_2 is low, or T_2 may be assigned a value based on field observations or other ancillary information [Glaze et al., 1989b]. Alternatively, T_1 maybe assigned a value [Oppenheimer, 1991; Oppenheimer et al., 1993a]. Either approach leaves a system of two nonlinear equations with two unknowns (*x* and the remaining temperature term), which may have a unique solution.

3.2 Practical Considerations

3.2.1 Operation of Procedure

The majority of the ground temperatures in an ASTER scene will be estimated from the TIR channels, since there will be relatively few high-temperature volcanic features depicted in the scene. The ambient ground temperatures will be calculated using the isothermal radiance model (Eq. 1); the estimation of temperatures of hot volcanic or geothermal features will require the use of two-component radiance model (Eq. 2), together with data from the SWIR ASTER channels.

As illustrated in Table 1, the radiance data from the TIR and SWIR ASTER subsystems will have different spatial resolutions. The dimensions of the TIR product will be 700 pixels X 830 lines while the dimensions of the SWIR data product will be 2100 pixels X 2490 lines. We will produce temperature maps with the same dimensions as the TIR imagery. The positions on the map where high-temperature volcanic features forced the use of the two-component radiance model will be flagged, directing the user to a text file containing the temperatures and area fractions of the thermal components. In an interactive analysis mode, the text files will "pop up" when the analyst clicks on a flagged pixel.

The disparities between the spatial resolutions of the ASTER TIR and SWIR channels has an analogue in the Landsat TM. The TM thermal channel (Band 6) has a resolution of 120 m while the remaining channels have a resolution of 30 m. Flynn et al. [1994] discussed the combined use of the TM channels to study the active Kupaianaha flow field of Kilauea Volcano, and we propose to use similar algorithms to process the ASTER data.

We would prefer to use night-time data in the surveillence of volcanoes to minimize the effects of solar heating and reflection in the IR measurements. Since ASTER will not routinely collect night-time data, some form of threshold strategy will be required. Flynn et al. found that most anomalous TM pixels were at least five digital numbers (DN, the quantization increment resulting from the conversion of radiance measurements from analog to digital format) higher than the average DN in the neighborhood of the anomaly. We will apply the change-detection algorithm (Volcanology Team Product # 3296) to find anomalous ASTER pixels.

Once anomalous pixels were identified, Flynn et al. applied a convergence test to each anomaly to determine the validity of the two-component radiance model. The convergence test was based on a requirement that the radiance contributed by the low temperature component of the surface be greater than zero. We anticipate that the high spectral resolution of ASTER in the SWIR (Table 1) will allow us to refine the convergence test. The two-component radiance model will be applied to those pixels that pass the convergence test.

3.2.2 Input Data Requirements

The primary data set for the temperature-mapping procedure will be AST03 (parameter # 2452), which is the registered version of the radiance data from all three ASTER subsystems. The size of AST03 is 243 Mbytes per 60 X 60 km ASTER scene.

The preparation of a temperature map from AST03 requires that (1) the radiance data be corrected for atmospheric effects, and (2) we recover a estimate of surface temperature from the ASTER radiance measurements. Prior to the launch of the EOS PM-1 platform in 2001, the primary source of profiles of atmospheric temperature and water vapor will be MODIS data product MOD30 atmospheric temperature (parameter # 3726) and moisture (parameter # 3727) profiles. This products will be available at a spatial resolution of 5 km X 5 km, and 12 MODIS temperature and humidity profiles will be used to cover an 60 km X 60 km ASTER scene. The MOD30 profiles are stored in a data record containing 237 bytes; approximately 3 kbytes of MODIS product will be required per ASTER scene.

Following the launch of the EOS PM-1 platform in 2001, data collected with the Atmospheric Infrared Sounder (AIRS)/Advanced Microwave Sounding Unit (AMSU) experiment will be incorporated into the temperature mapping procedure. These relevant AIRS data products are the atmospheric temperature (AIR07, parameter # 1588) and humidity profiles (AIR05, parameter # 1828). The size of the AIRS data products has yet to be determined, but the profile data should be on the orderof 1500 bytes. In addition to MODIS and AIRS/AMSU data products, atmospheric profile data will be obtained from a variety of ancillary sources, such as radiosoundings, climatologic models, and assimilation models.

We note again that ASTER will offer a surface (kinetic) temperature product, AST08 (parameter # 3803). The Volcanology Team data product 3291 will differ from AST08 by the application of more localized atmospheric corrections and the incorporation of data from the VNIR and SWIR channels over high-temperature ground targets. If the differences between the AST08 and Volcanology Team temperature maps are negligible for ground targets with no (significant) geothermal components, our "custom" atmosphere corrections will not be necessary. In this event, we will use AST09 (parameters # 2378 and 3817), surface radiance, as the input to our temperature maps.

The substitution of AST09 for AST03 will have little effect on the volume of input data as both products are approximately 245 Mb/scene. Adding in the MODIS and AIRS profile data brings this total to no more than 250 Mb/scene.

3.2.3 Output Data Characteristics

Our experiment plan is to produce approximately 22 temperature maps per year. This total includes bi-monthly maps for three select volcanoes with a contingency of four extra maps to document unexpected eruptions.

Output data volume will be considerably less than the input data volume. Producing the final maps in an 8-bit color graphics format such as GIF or HDF will reduce the data volume to approximately 0.44 Mb/map. HDF is the preferrable format, since it will allow text files to be merged with image data. As discussed above, the text files will contain the temperature and area fraction of the two components making up the non-isothermal, high temperature surfaces. Our total output data volume will be approximately 10 Mb/year for GIF or HDF.

4. CONSTRAINTS, LIMITATIONS, AND ASSUMPTIONS

The descriptions of the mathematics involved in creating the temperature maps are deceptively simple. Fortunately, the mixed-pixel temperature-estimation procedure will only have to be applied relatively few pixels in a given scene. The software written to perform the temperaturemapping will be written in IDL to give the analyst a graphic user interface into the mapping procedure. We assume that the Land Processes Distributed Active Archive Center (LP-DAAC) at the USGS EROS Data Center (EDC) will accept procedures written in IDL and that any users requesting copies of the procedure will have their own copies of IDL. We further assume that there will be no violation of copyright or distribution agreements if the EDC or any member of the Volcanology IDS team distributes software written in IDL.

Table 1. Characteristics of the ASTER Channels

Specifications for ASTER Channels			
Subsystem	Band Number	Bandpass (μm)	Spatial Resolution (m)
VNIR	1	0.52 - 0.60	15
VNIR	2	0.63 - 0.69	15
VNIR	3	0.76 - 0.86	15
SWIR	4	1.600 - 1.700	30
SWIR	5	2.145 - 2.185	30
SWIR	6	2.185 - 2.225	30
SWIR	7	2.235 - 2.285	30
SWIR	8	2.295 - 2.365	30
SWIR	9	2.360 - 2.430	30
TIR	10	8.125 - 8.475	90
TIR	11	8.475 - 8.825	90
TIR	12	8.925 - 9.275	90
TIR	13	10.25 - 10.95	90
TIR	14	10.95 - 11.65	90

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