EOS Volcanology Team
Data Product Document
MOU81-3292

Thermal Anomaly - Low Spatial Resolution

(Third Draft: 1/5/96)

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Thermal Anomaly - Low Spatial Resolution: DATA PRODUCT DOCUMENT

TABLE OF CONTENTS

0. PREFACE

This document describes plans to produce a chronological image record which will show the large scale (1 km) thermal evolution of eruptive areas and provide a catalog of data for active periods of some volcanoes. A single band composite temperature map using channels 21 and 22 (both covering 3.959 μm) will be created which emphasizes hot spot development. To aid with orientation of the temperature map, a 3-band color composite image of the area will highlight vegetation, geologic features, and high-temperature hot spots. Volcano temperature maps from the currently "active listing" will be accessed through the EOS Volcanology IDS web site. Degree of on-line access to the map archive is unknown at this time and depends on whether or not these data will be stored at the EDC DAAC.

1. INTRODUCTION

Current and future (e.g., EOS) non-military satellite technologies do not include a means to image the world's volcanoes at less than 100 m resolution on a daily or even weekly basis. The primary reasons for this are a combination of the narrow swath width high resolution detectors, the data volume which would have to be downloaded and processed, and ultimately, the number of satellites which would be required to cover the globe on a daily basis. Resources, in terms of money, manpower, and electronic storage capacity are not available for this type of effort in the civilian sector. The AVHRR (1 km resolution) has been a stand-in instrument for this type of capability. The AVHRR network of satellites offers views of all parts of the world at least four times per day. However, for thermal anomalies, it has been shown (Mouginis-Mark et al., 1994; Harris et al., 1994) that the AVHRR sensors saturate at relatively low surface radiance values. The saturation problem combined with a lack of channels for radiative temperature calculations makes working with AVHRR data difficult. In contrast, MODIS of the EOS AM-1 and PM-1 platforms will offer 36 channels in the visible to infrared spectrum. The MODIS bands are much narrower and more numerous than the AVHRR bands, allowing for more accurate temperature determinations.

The Thermal Anomaly - Low Spatial Resolution product will show the large scale (1 km) thermal evolution of eruptive areas and provide a catalog of data for active periods of some volcanoes. These data can also be used to provide a temporal context for EOS Volcanology Team product MOU81-3291, Thermal Anomaly - High Spatial Resolution. Product MOU81-3291 will use Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data of volcanoes to show thermal anomalies, but data acquisitions will be restricted to once every 16 days. For the Thermal Anomaly - Low Spatial Resolution product, about 5 scenes per month from 6 volcanoes will be chosen, either in response to requests from the EOS Volcanology Team or from particularly active eruptions signaled by the Surface Thermal Alert

Data Product (MOU81-3290). Current plans will be to archive the data in the form of a GIF image and an associated temperature map which will be produced from 2 channels of MODIS Level 1B data. Possible users of this product include volcanologists and volcanic hazard assessment personnel (State, Federal, and Foreign agencies) who may be interested in changes in activity on lava flow fields or gross changes in thermal radiation from lava domes and associated lava flows. The data product algorithm could easily be used to process data of other types of natural disasters such as large forest fires; perhaps as an effort to study the development of fires on a daily basis over submonthly time periods.

1.1 Algorithm and Product Identification

The EOS product number is MOU81-3292, and the label is "Thermal Anomaly - Low Spatial Resolution". It consists of a MODIS channel 21 - 22 brightness temperature algorithm, and the products created from the results of that algorithm which are regional temperature maps for targeted volcanic areas. Also, a GIF image will be created using 3 MODIS channels (7, 6, and 1) for each acquisition. This product belongs to the EOS IDS (Interdisciplinary Science) Volcanology Team, led by Peter Mouginis-Mark.

1.2 Algorithm Review

The Thermal Anomaly - Low Spatial Resolution algorithm will use MODIS channels 1, 5, 6, 7, 21, 22, 29, and 31 (The latter channel will include data from the high-gain mode if available). Most of these channels will only be required for special circumstances. The main channels used in the algorithm will be channels 21/22 covering the 3.95 μm region of the spectrum for brightness temperature calculations, and channels 1, 6, and 7 for the GIF image of the eruptive area. It is estimated that 5 acquisitions will be obtained for 6 volcanoes per month and that the output of this effort will be 2 images per acquisition: one GIF image of the eruptive area in the near-infrared (channels 1, 6, and 7 for example) to locate high-temperature hot spots, and the associated 3.95 μm brightness temperature map.

1.3 Document Scope

This document describes the physical basis for the algorithm, implementation plan, required input, and output products.

1.4 Applicable Documents and Publications

Other applicable documents:

Flynn, LP, Mouginis-Mark, PJ, Horton KA (1994) Distribution of thermal areas on an active lava flow field: Landsat observations of Kilauea, Hawaii, July 1991. *Bull. Volcanol:56* , p. 284 -

296.
Flynn, L., EOS IDS Volcanology Data Product Document for product MOU81-3290: "Surface Thermal Alert." This data product will be used to identify active eruptions.
Realmuto, V., EOS IDS Volcanology Data Product Document for product MOU81-3291: "Thermal Anomaly: High Spatial Resolution." This product will provide higher spatial resolution data sets of active eruptions.
Realmuto, V., EOS IDS Volcanology Data Product Document for product MOU81-3296: "Volcano Temperature Change." This product will provide higher spatial resolution data sets of active eruptions.

2. OVERVIEW AND BACKGROUND INFORMATION

2.1 Experimental Objective

The overall objective of this data product is to provide a record of the large-scale thermal characteristics of the most interesting volcanic eruptions on a monthly timescale. Interest will be determined either by the result of an alert using the surface thermal alert system (EOS Product MOU81-3290), by requests from interested EOS Volcanology Team members (especially Vincent Realmuto, who will be responsible for the High Resolution Data Product (Product MOU81-3291)), or by information gained through other reliable sources (such as postings on the Volcano List Serve administered by Dr. Jonathan Fink). The most important goal of this product is to provide a large number of users with active volcanic eruption data. In order to deliver sufficient quality and quantity (both number of monitored volcanoes and number of images from those volcanoes per month) of information, a nearly fully automated algorithm has to be developed to produce output thermal maps. This method will be described below. The EOS Volcanology IDS Team recognizes that more rigorous (i.e., multi-band) data analyses are possible, but those methods would be highly interactive, and require much larger supporting meta-data sets. Thus, the number of targeted volcanoes and the number of acquisitions per site would be severely limited.

2.2 Historical Perspective

The use of satellites in the role of detecting and monitoring eruptions has been amply shown in recent years. Most notably, Landsat Thematic Mapper (TM) has been used to study the lava flows on Mt. Etna (Pieri et al., 1990), Volcan Lonquimay (Oppenheimer, 1991), and Kilauea (Flynn et al., 1994). Further interesting studies have used Landsat data to study lava domes such as Volcan Lascar, Chile (Rothery et al., 1988; Glaze et al., 1989; Oppenheimer et al., 1993) and Santiaguito, Guatemala (Andres and Rose, 1992). While TM data offers excellent spatial resolution (30m for the visible to near-infrared Bands 1 - 5 and 7; 120m for the infrared Band 6) for mapping volcanic anomalies, the main drawback of using the TM to study volcanoes is that the satellites can only obtain images of volcanic features once every 16 days. For future high-resolution satellite coverage, EOS will provide ASTER on the Earth Observation System (EOS) AM-1 platform. ASTER is currently scheduled for launch in 1998, and like TM, has the capability of imaging (by selected targeting) any point on the globe every 16 days (more toward the poles).

Currently there are no operating satellite systems which can provide both the frequency of coverage (i.e. a few passes per week), the spectral resolution, and the dynamic range necessary to discern small hot targets such as volcanic domes and fumaroles from larger targets such as lava flows. While AVHRR instruments offer the frequency and the scale of coverage necessary, they do not have the dynamic range or narrow spectral bands necessary to be truly effective. A combination of a large dynamic range per band, frequently referred to as the quantization of data, and adequate spectral coverage in numerous well-placed narrow bands are necessary for identifying changes in subpixel-sized high-temperature sources. The Moderate Resolution Imaging Spectrometer (MODIS) instrument scheduled for launch on the upcoming EOS AM-1 and PM-1 platforms offers the temporal coverage described to provide effective mapping of volcanoes on a regional scale.

2.3 Instrument Characteristics

MODIS is the instrument providing the primary source of input for this data product. The first MODIS is scheduled for launch in 1998 on board the AM-1 platform. In its current configuration as a nadir viewing instrument, MODIS will have a 1780 km total swath width and will provide 36 channels at variable spectral and spatial resolution as shown in Table 1 (W. Barnes, personal communication, 1993). As the overall purpose of the EOS mission is to study the effects of global change, several of the MODIS channels were selected to provide vital information about the dynamic processes of the Earth's atmosphere. For studying thermal anomalies on the ground, these particular channels are not useful to our study because it would be difficult to separate radiative changes due to thermal sources from those due to varying amounts of constituents in the atmosphere. MODTRAN was used to determine which channel positions do not suffer from atmospheric absorptions. Only ten channels (boldface in Table 1) fall within atmospheric windows (Channels 21 and 22 are both at 3.959 μm.), wavelength ranges where the absorption of radiation due to atmospheric constituents is minimal, and could easily be used for surface thermal calculations. The next step is to determine which of the 10 channels would be most suitable for thermal calculations.

Table 2 gives a summary of the important parameters which must be considered in choosing channels for the MODIS thermal calculations. One is that the minimum detectable radiance must be low, meaning that the instrument must be sensitive enough to detect small hot objects. This is especially important for MODIS, which has large 1 km pixels. If this quantity were large, then subpixel "activity" would be undetectable - lost in the instrument noise. Another characteristic which is important is that the detector must be sensitive enough and there must be sufficient dynamic range to allow for the accurate quantization of small changes in the radiance of target pixels. Fortunately, the 12-bit MODIS data offer better dynamic range than previous sensors such as Landsat TM (8-bit data).

3. ALGORITHM DESCRIPTION

3.1 Theoretical Description

Flynn et al. (1994) and Flynn and Mouginis-Mark (1995) have shown that qualitative information about the nature of active basalt lava flows (and forest fires) may be gained from the infrared channels of Landsat TM. In the following sections, we intend to show the rationale behind the choice of MODIS channels for this study and why certain channels will be used as an assessment of volcanic activity. Since the conversion from raw radiance (DN) to temperature is fairly simple and we will not attempt complex corrections for the atmosphere, an automated IDL code will be developed which will process 30 MODIS volcano acquisitions per month in an effective and consistent manner.

3.1.1 Physics of the Problem

The sensitivity of the MODIS instrument to detect volcanic features has been investigated by analyzing a number of examples derived from hyperpsectral data sets of volcanic anomalies. We have chosen 4 types of volcanic activity to determine the effective limits of the MODIS sensors in the wavelength regions of interest for the thermal study. For pairs of bands located at the same wavelength range (Table 2), 21 and 22, 31 and 31hi, 32 and 32hi, we have chosen the optimal configuration for detecting high temperature, small thermal anomalies as representatives in future discussions below. Naturally, the upper end-member condition for this study would be the temperature of magma, since that would be the highest possible temperature to observe on a volcano from MODIS. To represent this end-member, we have chosen a channeled basaltic lava flow (Flynn and Mouginis-Mark, 1994). The three other examples are derived from two-component models applied to radiances measured in the field of an active lava lake (Flynn et al., 1993), an active lava flow (Flynn and Mouginis-Mark, 1992), and cooling lava flows (Flynn et al., 1994). It may be noted that examples of hyperspectrally derived temperatures from silicic volcanoes are absent, but would be extremely important as test data for sensitivity studies. Figure 1 shows that although the spatial resolution of the MODIS instrument is low (1 km), it is possible to find extremely small thermal anomalies because the sensitivity of the detectors is favorable. Note that although the near -IR channels (5-7) have pixels which are one quarter the size of those in the mid-IR, channel 20 (3.750 μm) has a greater sensitivity to high temperature sources; hence, a smaller hot spot is capable of generating a 5 DN anomaly. Looking at Tables 1 and 2, the detractions of using channel 20 are its low saturation radiance and broad bandwidth. A comparable, but much more versatile pair of channels (21 and 22) cover the 3.95 μm region of the spectrum at a small radiance increment per DN for radiances just above background levels (channel 22), and at large radiance per DN increments for stronger signals (channel 21).

Figure 2 presents a range of "typical" background temperatures which may be found within a given target pixel. In addition, the contribution of reflected sunlight to the daytime target pixel is also given. Temperatures of the thermal background may vary widely with latitude, altitude and season. Ground temperatures may be 50°C in the tropics during the summer to subzero Celsius in the winter at high altitude or high latitude locations. Notice how the radiant flux from the background blackbodies increases dramatically in the 4 - 8 μm range. Channels 31 or 32 for non-anomalous pixels may be used to estimate the effects of the thermal background. Channel 6 can be used to estimate the amount of reflected sunlight in target pixels. Channels 21 and 22 are the logical choice for the Thermal Anomaly - Low Spatial Resolution product because of the minimum contamination due to reflected sunlight and the thermal background, and the extended dynamic range offered by using both channels. Also, the choice of channels in the near-infrared (such as channel 22 at 3.959 μm) rather than further into the infrared eliminates to some extent confusion with mid-temperature range sources (i.e. those less than 200°C [peak emission at ~6 μm]). Examples of the sensitivity of MODIS to the 4 types of volcanic features described previously are shown in Figure 3. Figure 3 shows how sensitive the <4 μm region of the spectrum will be to volcanic sources (the size of which, in square meters, is listed at the right of the graph) compared to longer wavelengths which will be used to monitor the background temperature of the pixel.

3.1.2 Mathematical Aspects of the Algorithm

The mathematical problems associated with this algorithm can be summarized in four steps: 1) Conversion of the MODIS channel 21 Digital Numbers (DN) to channel 22 equivalent DN, 2) Conversion from raw DN to radiance, 3) Correction for the small reflected solar component, and 4) Conversion from corrected radiance to surface temperature.

1) The conversion of MODIS channel 21 data into channel 22 is necessary to account for especially strong signals which may saturate channel 22. Using the numbers provided in Table 2, the planned dynamic range for channel 21 is 0.15 - 86.0 W/m^2/μm/sr, while that of channel 22 is 0.00190 - 1.89 W/m^2/μm/sr. If the entire dynamic range of channel 21 is linear, then the conversion would be:

$EquivalentDN_{22} = (20.0+(45.4691*DN_{21}))$

This conversion should also take into account the effects of the instrument response, as the dynamic range is linked to the performance of the instrument. This is the reason why a Landsat TM band 7 measurement of 1 DN results in a negative number in terms of radiance. The temperature map accuracy of this product will depend on the calibration of the 3.95 µm channels.

2) The conversion from raw DN to radiance is then given by:

$Radiance_{22} = 0.00190 + ((1.89 - 0.00190)/4096)*DN_{22}$

3) A small but non-negligible contribution of radiance at 3.95 microns is due to reflected sunlight. A correction for this component will be made with MODIS channel 6 data (1.65 µm). At 1.65 µm virtually all of the detected radiance in non-anomalous pixels is reflected sunlight. Based on the solar curve, ~4.26% of the solar flux measured at 1.65 µm should be detected at 3.95 µm. The correction becomes:

$\text{Corrected radiance}_{22} = Radiance_{22} - (0.0426*Radiance_6)$

4) The conversion from corrected radiance to surface temperature is:

$Temperature_{22} = c_1*(\ln[(c_2/CR_{22}) +1])^{-1}$

where $c_1 = 2EThc^2\lambda^{-5}$, $c_2 = hc\lambda^{-1}k^{-1}$, and CR_{22} is the corrected radiance calculated above. For c_1, parameter values used are E (surface emissivity) = 0.95, T (atmospheric transmissivity) = 0.95 using MODTRAN, h (Planck's constant) = 6.63×10^{-34} J s, c (speed of light) = 3.00×10^8 m/s, and λ (wavelength) = 3.959×10^{-6} m. For c_2, k is Boltzmann's constant of 1.38×10^{-23} J/K. Thus, the surface temperature equation reduces to

$Temperature_{22} = 3640.6*(\ln[(1.107E11/CR_{22}) +1])^{-1}$

3.1.3 Variance/ Uncertainty Estimate

Currently the MODIS SCF is trying to obtain a geolocation accuracy of 0.5 pixels or 0.5 km for 1-km data sets.

There are a host of assumptions which must be made in order to facilitate the automation of this product. The most important are that emissivity and atmospheric transmissivity must be fairly constant between anomalous and non-anomalous pixels within the same 128 x 128 pixel study area.

There are no estimates of uncertainties in temperature mapping of thermal anomalies. However, pseudo-MODIS data are being created using Landsat TM data of Kilauea. A comparison of the total emitted energy from 1-km square areas will be compared to results obtained with the MODIS converted data. This will provide an estimate on uncertainty.

3.2 Practical Considerations

At this point in the Low Resolution Data Product (MOU81-3292) development, it is not envisioned that an IDL user-interactive package will be available for investigators to process their own scenes. The major obstacles to a fully automated package or even a user-interactive package are the unavoidable variabilities including volcano target types (effusive vs. explosive eruptions), and the complex radiative mixing due to the number, size and temperature of thermal anomalies in 1 km pixels. Considerable experience is necessary to process the 1-km MODIS data which will not be available to most independent investigators. The volume of potential procedural queries which would result from such a system rules out a user-interactive package.

Lastly, if it seems that all results vary around a given number, then a section of the algorithm can be devoted to administering a given stretch on the temperature data. For instance, if the data values always seem to be 42 - 50°C with occasional active pixels at 65°C then the entire stretch of the temperature map can be inclusive of this range, but also designed to show the greatest possible contrast in this range.

The algorithm is expected to be operational at the start of the EOS mission in 1998.

3.2.1 Programming/ Procedural Considerations

Input data will be obtained from the Goddard DAAC. Product generation will occur at the Hawaii SCF. There will be no guarantee that data products will be made available in a specified time interval, but it is hoped that the products will be generated no more than 3 days after data arrives from the DAAC.

Variaibilities in target scenes due to seasonal changes (snow cover, vegetation changes), will be incorporated into the product-generating algorithm but is expected to be semi-automatic (requiring some interaction) for at least 1 year after launch.

The EOS Volcanology Team will choose which volcanoes will have Low Resolution Thermal Anomaly products generated during a given month. It is expected that the Team will be open to user requests. However, priority will be given to obtaining coincident images to support EOS Volcanology Team product #3291 (High Resolution Thermal Anomaly). There will be no supported user-interactive algorithm distributed by the Hawaii SCF as it is projected that it would require manpower resources which are not available to the EOS Volcanology Team.

The algorithm is expected to be fully operational (although, it will require user input) at the start of the EOS mission, in 1998.

3.2.2 Calibration Validation

Results for the Low Resolution Product will be compared with those obtained for the High Resolution Product (MOU81-3291) for coincident images.

The ongoing volcanic activity at Kilauea will figure prominently in the validation effort for this product. Numerous relevant data sets collected by other satellite instruments which can be downloaded to the Hawaii Receiving Station may also be used to supplement the Hawaii Volcano Observatory's excellent record of observations of developments and changes in activity at Kilauea. These data sets may include ADEOS, HSI (Hyperspectral Imager), and Landsat 7 ETM+ data sets. In addition, the University of Hawaii maintains an AVHRR receiving station, so numerous AVHRR instruments could also provide daily 1-km data sets. Other sources of data will include University of Hawaii field campaigns to collect spectral measurements of active lava flows.

3.2.3 Quality Control and Diagnosis

Quality Control will be monitored using the EOS Volcanology Team MOU81-3291 product for eruptions coincidentally viewed.

3.2.4 Exception Handling

Missing or bad data sets (including data sets in which thermal anomalies are obscured by clouds) will not be considered or processed. The Thermal Anomaly - Low Spatial Resolution products will be generated from only complete data sets.

3.2.5 Data Dependencies (Input Data)

The Low Resolution Thermal Anomaly Map Data Product would require MODIS Level 1B geometrically located radiance data at both $< 3\ \mu m$ (SPSO No. 2338) and $> 3\ \mu m$ (SPSO No. 2340). Within two weeks of their acquisition, a total of 8 channels would be required for each image (granule) as follows: 250m resolution MODIS channel 1; 500 m resolution MODIS channels 5, 6, and 7; 1 km resolution MODIS channels 21, 22, 29, and 31 (the latter two either in the high or low gain mode depending on their configuration). 5 scenes/volcano/month x 6 volcanoes x 150 Mb/acquisition = 4.5 Gb/month of input data. This input will be sent from the Goddard DAAC to the Hawaii SCF.

3.2.6 Output Product

The output data product will be two 128 x 128 pixel images per data acquisition. Both will be 8-bit GIF files. One image (MODIS channels 7, 6, and 1 as red, green, and blue) will provide the orientation of the data set acquired. Figure 4a shows an example of what this channel combination will provide for a 100 x 85 km area covering the east flank of Mauna Loa and Kilauea on the Big Island of Hawaii. Note that the MODIS images will be somewhat larger, but these pseudo-MODIS data were derived from a TM quarter scene. The GIF image clearly shows hot spots associated with the active lava flow field, as well as vegetation and areas covered by older flows. The other product will be the composite MODIS channel 21 and 22 temperature map. A black and white version of the temperature map is shown in Figure 4b (for the area covered in Figure 4a). Future versions of the DPD will include a color scale to emphasize temperature differences.

The 128 km x 128 km areas covering certain volcanic areas will be standardized to facilitate processing. In this way, the user can easily orient himself to successive images of the same eruption. The intent is to ensure that the overall image is sufficiently large that associated activity from one eruptive center is not beyond the bounds of the chosen image area. Larger image coverage has been rejected because, in addition to the increased storage load, it is extremely difficult to pick out hotspots on a larger regional scale (i.e. 512 x 512 pixels).

The output product will be stored at the Hawaii SCF. At the time of this draft, it is not clear whether any of the DAAC's will support the output products of any of the EOS IDS Teams. Not all 5 acquisitions per month for a given volcano may result in a pair of output images, but in the most extreme case, the expected data output will be 6 volcanoes x 5 acquisitions/volcano x 2 GIF images/acquisition x 128 pixels x 128 pixels ~ 1 Mb/month.

4. CONSTRAINTS, LIMITATIONS, ASSUMPTIONS

There are no constraints on the Thermal Anomaly - Low Spatial Resolution product or algorithm at this time. The algorithm uses a number of assumptions including atmospheric transmission and homogeneity of surface emissivity, which will have to be tested for accuracy.

5. REFERENCES

Dozier J (1981) A method for satellite identification of surface temperature fields of subpixel resolution. Remote Sensing Environ 11:221-229

Flynn LP, Mouginis-Mark PJ (1992) Cooling rate of an active Hawaiian lava flow from nighttime spectroradiometer measurements. Geophys Res Lett 19:1783-1786

Flynn LP, Mouginis-Mark PJ (1994) Temperature of an active lava channel from spectral measurements, Kilauea Volcano, Hawaii. Bull Volcanol 56:297-301.

Flynn LP, Mouginis-Mark PJ (1995) A comparison of the thermal characteristics of active lava flows and forest fires. Geophys Res Lett 22:2577-2580

Flynn LP, Mouginis-Mark PJ, and Horton KA, Distribution of thermal areas on an active lava flow field: Landsat observations of Kilauea, Hawaii, July 1991. Bull. Volcanol. 56:284-296

Flynn LP, Mouginis-Mark PJ, Gradie JC, Lucey PG (1993) Radiative temperature measurements at Kupaianaha lava lake, Kilauea volcano, Hawaii. J Geophys Res 98:6461-6476

Glaze LS, Francis PW, Self S, Rothery DA (1989) The 16 September 1986 eruption of Lascar volcano, north Chile: satellite investigations. Bull Volcanol 51:149-160

Harris AJL, Vaughan RA, Rothery DA (1994) Volcano detection and monitoring using AVHRR data: the Krafla eruption, 1984. Submitted to Int J Remote Sens

Mouginis-Mark PJ, Garbeil H, Flament P (1994) Effects of viewing geometry on AVHRR observations of volcanic thermal anomalies. Rem Sen Environ 48:51-60

Oppenheimer C (1991) Lava flow cooling estimated from Landsat Thematic Mapper infrared data: the Lonquimay eruption (Chile, 1989). J Geophys Res 96:21865-21878

Oppenheimer C, Francis PW, Rothery DA, Carlton RWT, Glaze LS, Infrared Image Analysis of Volcanic Thermal Features: Lascar Volcano, Chile, 1984-1992. J. Geophys. Res., 98, 4,269-4,286, 1993

Pieri DC, Glaze LS, Abrams MJ (1990) Thermal radiance observations of an active lava flow during the June 1984 eruption of Mount Etna. Geology 18:1018-1022

Rothery DA, Francis, PW, Wood CA (1988) Volcano monitoring using short wavelength infrared data from satellites. J Geophys Res 93:7993-8008

Table 1: Summary of MODIS Spectral Bands

Band	Center Wavelength (nm)	Bandwidth(nm)	IFOV
1	645	50	250
2	858	35	250
3	469	20	500
4	555	20	500
5*	**1240**	**20**	**500**
6*	**1640**	**24.6**	**500**
7*	**2130**	**50**	**500**
8	412	15	1000
9	443	10	1000
10	488	10	1000
11	531	10	1000
12	551	10	1000
13	667	10	1000
14	678	10	1000
15	748	10	1000
16	869	15	1000
17	905	30	1000
18	936	10	1000
19	940	50	1000
20*	**3750**	**180**	**1000**
21*	**3959**	**59.4**	**1000**
22*	**3959**	**59.4**	**1000**
23*	**4050**	**60.8**	**1000**
24	4465	65	1000
25	4515	67	1000
26	1375	30	1000
27	6715	360	1000
28	7325	300	1000
29*	**8550**	**300**	**1000**
30	9730	300	1000
31*	**11030**	**500**	**1000**
32*	**12020**	**500**	**1000**
33	13335	300	1000
34	13635	300	1000
35	13935	300	1000
36	14235	300	1000

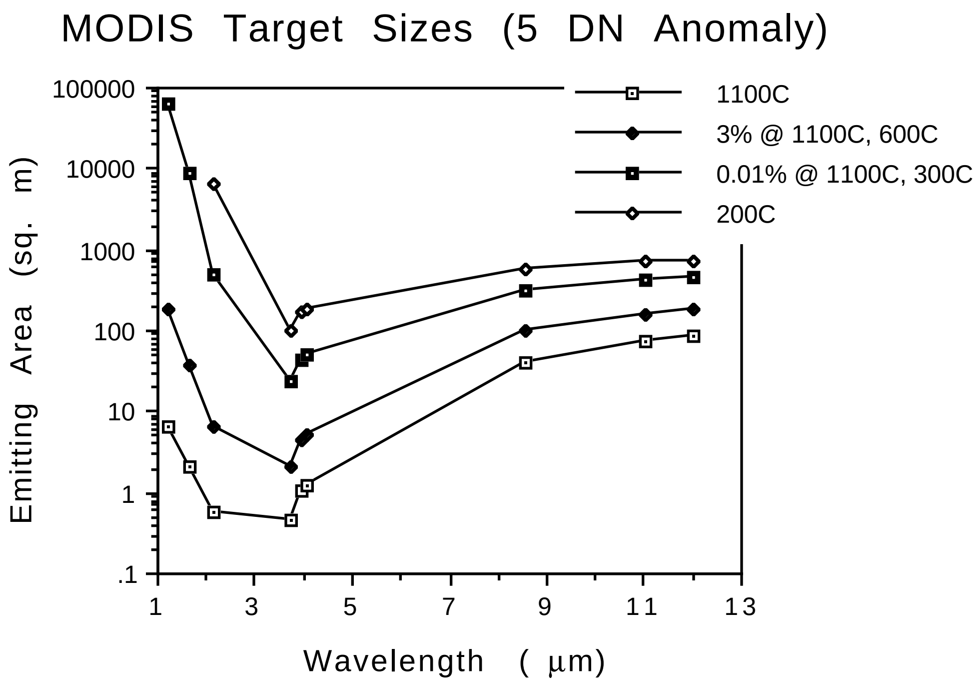
*** Denotes channel that could be used for thermal calculations.**

Table 2: Selection of MODIS Thermal Bands

Band	Center Wavelength (nm)	Required NEdL*	Max Radiance*
5	1240	0.045	138.0
6	1640	0.027	70.0
7	2130	0.009	27.0
20	3750	0.000957	1.71
21	3959	0.15	86.0
22	3959	0.00190	1.89
23	4050	0.00217	2.16
29	8550	0.00899	14.54
31	11030	0.00701	13.25
31hi	11030	0.247	29.08
32	12020	0.00606	12.10
32hi	12020	0.198	25.07

***** Watts/m^2/μm/sr

Figure 1:



Case 1: 1100°C - Fresh lava, high temperature fumaroles

Case 2: 3% @ 1100°C, 97% @ 600°C - Initial lava flow emplacement temperatures

Case 3: 0.01% @ 1100°C, 99.99% @ 300°C - Lava lake surface with some perimeter activity or cooling lava flow (hours after emplacement)

Case 4: 200°C - Cooling lava flow (days after emplacement)

Figure 2:

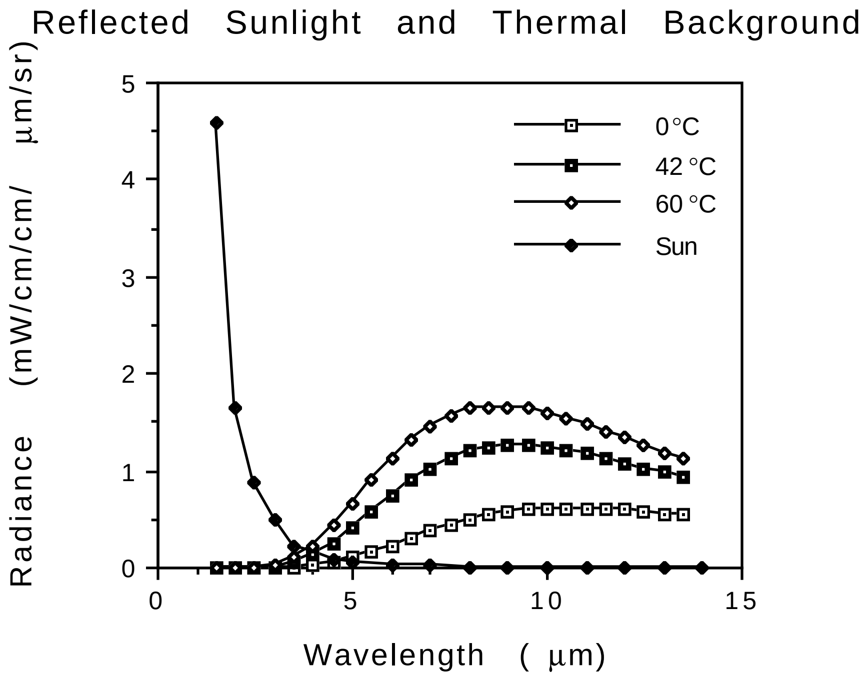
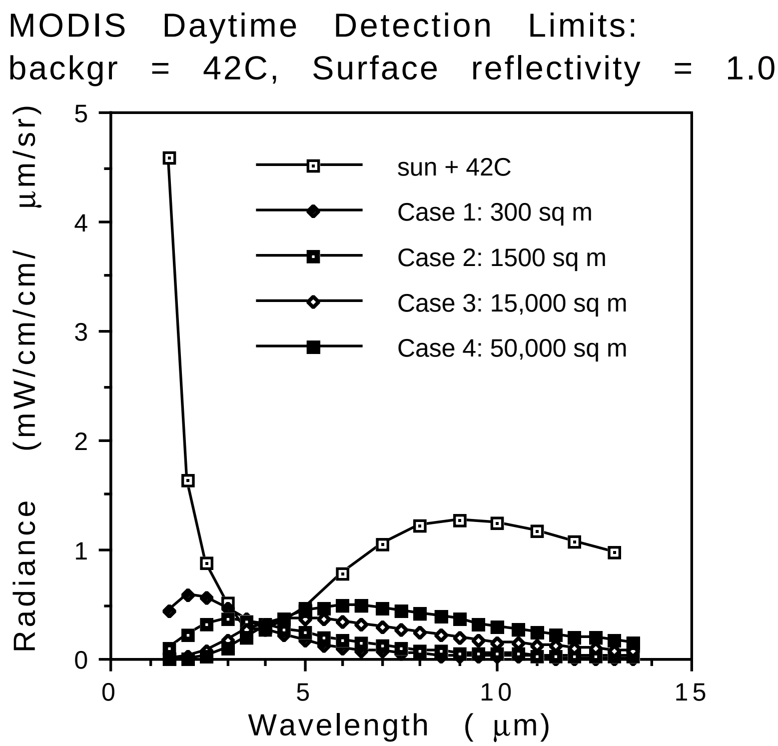

Reflected Sunlight and Thermal Background
Radiance (mW/cm/cm/ µm/sr)
5
4
3
2
1
0
0
5
10
15
Wavelength (µm)
0 °C
42 °C
60 °C
Sun

Figure 3:



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