MULTI- AND HYPERSPECTRAL COMPARITIVE STUDIES OF ACTIVE LAVA FLOWS

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ABSTRACT

Multispectral, high resolution, satellite data can be used in conjunction with ground-based hyperspectral data in order to provide a more accurate picture of thermal and visible characteristics of active lava flows. In this study, Landsat Enhanced Thematic Mapper bands 5 and 7 are used to determine active flow areas and discharge rates one a half hours prior to the image. Additionally, single channel and hyperspectral ground-based measurements were carried out on Kilauea to determine possible temperature relationships and emissivity differences. There was no correlation found between the temperatures recorded by a single channel radiometer (Raytek) versus those temperatures derived from the spectra using a two-component numerical model. Spectral reflectance measurements of s-type pahoehoe of known ages, with and without an intact glassy surface, show a wide range of reflectance, and hence, emissivity values ($emissivity_\lambda = 1 - reflectance_\lambda$). The wide disparity in reflectance spectra for pahoehoe flows raises an important question as to the appropriate choice of an emissivity value, which is important in calculations of total radiance.

INTRODUCTION

The field of satellite remote sensing has revolutionized the way we see our world. From military intelligence to agricultural practices, the use of satellites has become commonplace in today's dynamic world. The field of volcanology has benefited tremendously from the remote sensing capabilities of satellites. Satellite images combined with advanced ground based measurements work in conjunction to provide researchers with invaluable insights and information regarding volcanic characteristics and processes.

Multispectral, high spatial resolution imagery from Landsat 7 Enhanced Thematic Mapper has enabled scientists to map areas such as active lava flows. In this study, a temperature-threshold model is used to examine TM bands 5 (1.55 – 1.75 um), 7 (2.08 – 2.35 um), and 6 (10.42 – 12.42 um) in order to provide a brief history of active flow area and discharge rate. Band five can sense the hottest temperatures with values ranging from 220 to 430 degrees C. Band seven can detect those from 120 to 290, while the thermal infrared band six can see much lower temperatures in the -60 to 90 degrees C range [Flynn et al., 2000].

Hyperspectral data can provide a much higher spatial, temporal, and spectral resolution when compared to other remote sensing techniques. A spectroradiometer, collecting 1000 spectral measurements between .35 to 2.5 microns, was used to carry out measurements of active inflating pahoehoe lobes at the Kilauea flow field. These spectra were run through a two-component model, and with further calculations, corresponding integrated surface temperatures were derived. These temperatures were compared against those measured by a single channel radiometer. The final portion of my project entailed using a spectroradiometer to look at reflectance spectra of lava of distinct visible characteristics and known ages to determine if they can be used as an additional tool for dating flows.

METHODS

TM bands 5, 7, and 6 data can be used in a temperature-threshold model to map active flow units. By starting with the hottest band (band 5), and progressively stepping down the threshold input of digital number (DN) values, we can model the brief history of the flow field in terms of flow area over time. Using bands 5 and 7, we can model this history up to an hour and a half prior to the TM scene. Since band 6 is sensitive to much lower temperatures, it is sometimes difficult to determine whether an "active" area is due to an actual flow unit that is approximately 30 hours or so old, a lava tube, or sun-warmed flows. Additionally, the numerical model is unable to distinguish between lava tubes and day old flows, which may have similar temperature ranges.

For the second portion of my project, an Analytical Spectral Devices (ASD) spectroradiometer was used to carry out measurements of active inflating pahoehoe lobes at the Kilauea flow field. This device records over 1000 spectral measurements between the wavelengths of 0.35 to 2.5 microns with a spectral resolution of 1-5 nm [Flynn et al, 1993]. On April 25, 1999, 254 field spectra were collected at five second intervals over approximately a 20 minute period. These field spectra encompassed different types of activity ranging from hot red breakouts to stationary crust. During the collection of this hyperspectral data, Raytek was used to simultaneously collect integrated brightness temperature measurements (8-12 μm) over a similar area of interest. Due to the manual nature of recording the Raytek temperatures (i.e. pen and paper), measurements were made for every five spectra of ASD data.

Before any analyses could be done on the ASD data, each spectra had to be run through two programs (rcalc and portspec) to convert the raw digital numbers into units of radiance. After this procedure, a two-component numerical model [Flynn et al, 1992] was used to calculate a cool temperature, a hot temperature, and the percentage of hot area for each of the 254 spectra. This two-component numerical model assumes that there are two different temperatures, a cool crust component and a hot glowing component, at each input wavelength. The six input wavelengths of 1.2, 1.27, 1.53, 1.7, 2.08, and 2.23 μm were chosen within three atmospheric windows (1.2-1.3 μm, 1.52-1.79 μm, and 2.03-2.34 μm) for the first model run. Through an iterative process, the model attempts to separate the total radiance measured by the ASD spectroradiometer into its cool and hot radiative temperature components, while minimizing the deviation from a blackbody spectrum.

A majority of the 254 spectra collected exhibit a concave down shape in radiance between 1.79 μm and 2.3 μm which is indicative of sensor saturation (figure 1).

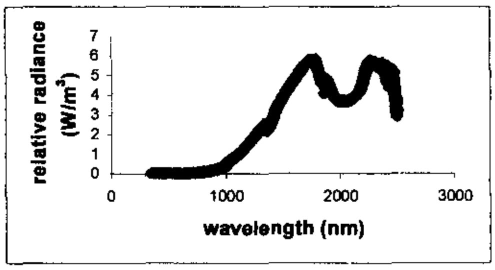

Figure 1: Example of lava spectra collected by ASD Spectroradiometer. Notice sensor saturation between 1.79 and 2.3 μm.

Therefore, six different input wavelengths (1.2, 1,27, 1.53, 1.59, 1.65, and 1.71 μm) prior to the saturation zone were chosen for the second model run. In order to compare the model results with the Raytek temperature measurements, a number of calculations must first be carried out. The outputs of the model include a cool temperature (T_c), a hot temperature (T_h), and the percentage of hot area (A_h). Using Planck's Law, we can calculate the amount of radiation $R(\lambda,T)$ at a given wavelength (λ) and temperature (T):

$$R(\lambda,T) = \tau_\lambda \varepsilon_\lambda (2hc^2/\lambda^5)*(e^{hc/\lambda kT}-1)^{-1} \qquad (1)$$

where τ_λ is the atmospheric transmissivity, ε_λ is the surface emissivity, h is Planck's constant (6.63×10^{-34} Js), c is the speed of light (3.00×10^{8} m/s), k is Boltzmann's constant (1.38×10^{-23} J/K), and T is temperature in Kelvin [Flynn et al., 2000]. Is given a value of 11 μm because that it is a good median for the wavelength range encompassed by the Raytek. The reflected radiance from the surface is negligible compared to the overall contribution from the emitted radiation, and thus omitted from the equation. Studies of recently formed basalt samples show reflectances (r) of less than 0.005 over the wavelength region between 0.4 to 2.25 μm [Flynn et al, 1993]. Therefore, this study assumes an ε value of .995 (Kirchoff's Law: $\varepsilon_\lambda = 1 - r_\lambda$) over the entire wavelength region. τ_λ is assumed to be one because all of the input wavelengths were chosen in atmospheric windows [Flynn et al, 1993]. Planck's Law is used to calculate the total radiance contribution of the hot lava component (T_h) and the cold crust component (T_c).

$$R_{total}(\lambda) = A_h R(\lambda,T_h) + A_c R(\lambda,T_c) \qquad (2)$$

where $A_c = 1 - A_h$. The total radiance can be converted back into a brightness temperature by rearranging equation (1):

$$T(\lambda) = (hc/\lambda k)(\ln[2hc^2)/(\lambda^5 F) + 1])^{-1} \qquad (3)$$

The resulting temperature can then be compared to the temperature recorded by the Raytek.

In our previous study, the ASD spectroradiometer was used to carry out radiance fluxes of active pahoehoe lobes in hopes of correlating the results with Raytek temperature measurements. On April 9, 2000, the ASD was used to carry out reflectance measurements of pahoehoe lobes. Data was collected on vesicle rich s-type (spongy) pahoehoe with their blue glassy surface intact and those without their glassy surface at a time period approximately one and 20 hours after emplacement. The ages of the units were determined by marking the designated area with a stick, and then returning one and 20 hours later to conduct the measurements. Furthermore, surface lava cooling rate equation: $T = -140 \log(t) + 303$, where T is temperature in degrees C and t is time in hours (Hon et al., 1994), was used to correlate the unit's temperature with its respective age.

RESULTS AND DISCUSSION

The temperature-threshold model was able to show the history of the flow field within one and half hours prior to the image acquisition time of 1030 HST on July 21, 1999. Figure 2 shows a cut-out of an active lava portion seen in bands five, seven, and six.

Figure 2: A portion of active lava flows on Kilauea from a July 21, 1999 Landsat Thematic Mapper image as seen by (a) band 5, (b) band 7, and (c) band 6. Bands 5 and 7 have 30 meter pixel resolutions, while the coarser band 6 has a 120 meter pixel resolution.

The saturated (completely white) pixels in band 5 (figure 2a) have a pixel-integrated temperature of 430 degrees C or higher. If we examine the band 7 image (figure 2b), we observe a greater number of saturated pixels because it has a lower temperature saturation threshold of 290 degrees C or higher. All of the saturated in pixels in band 6 (figure 2c) show temperatures that are 90 degrees C or higher. The two thin white lines in this image are likely lava tubes rather than day old active flows.

Using bands 5 and 7, we are able to model the active flow area and discharge rate up to one and a half hours prior to the TM image. Figure 3 shows the active flow area versus time since emplacent on the Kilauea flow field. Approximately 330,000 m^2 of lava was laid down over a period of one and a half hours. Kilauaea can have spurts of discharge within a matter of minutes. In fact, within less than half a minute it increased its discharge rate from approximately 20,000 m^2/minute to more than 90,000 m^2/minute (figure 4). I've experienced this fickle nature of Kilauea out in the field. There can be stagnant flows at one instance, and then suddenly there are breakouts everywhere.

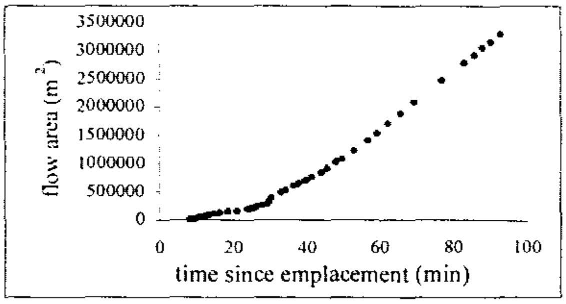

Figure 3: Active flow area vs. time since emplacement

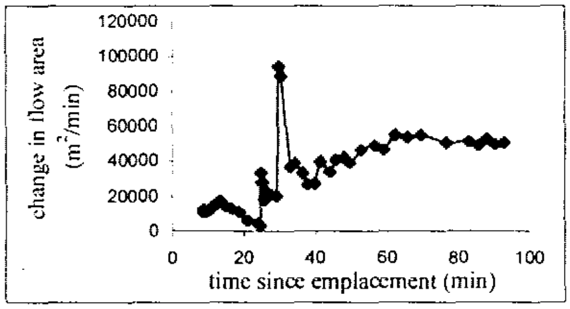

Figure 4: Change in active flow area vs. time since emplacement

In a separate study, a Raytek infrared thermometer is used in conjunction with a ASD spectroradiometer to determine if temperature outputs from the Raytek can be correlated with their corresponding spectra from the ASD. Using the calculations and parameters discussed in the methodology, there was no correlation found between the temperatures recorded by the Raytek versus those derived from the spectra using the two-component numerical model (figure 5).

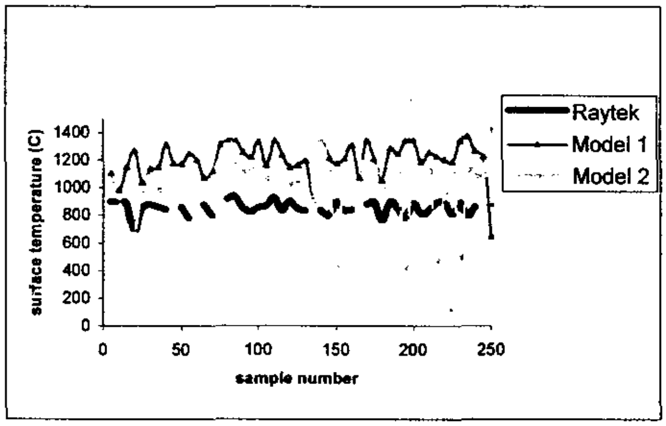

Figure 5: Measured Raytek temperatures vs. model derived temperatures from hyperspectral data

Differences could be due to incorrect assumptions made in the model inputs, different field of views encompassed by the ASD versus the Raytek, and inaccurate values chosen for emissivity.

In a third study, the ASD collected reflectance data for s-type pahoehoe with an intact and spalled off blue glassy surface at one hour and 20 hours after emplacement (figure 6).

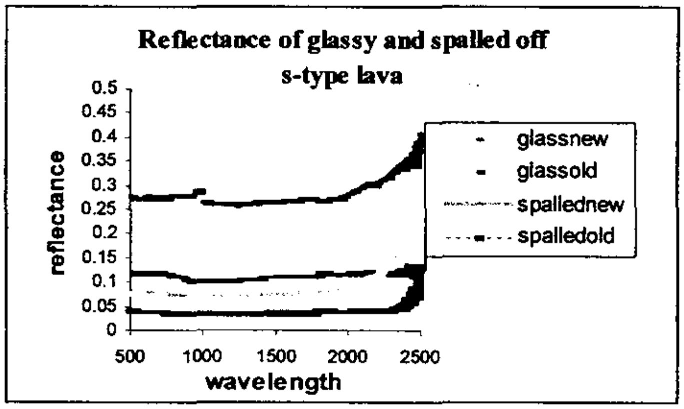

Figure 6: Spectral reflectance of s-type pahoehoe lava. The one hour unit with an intact glassy surface has the highest reflectance (glassnew) near 30%. The 20 hour old unit with an intact glassy surface has a reflectance over about 11% (spallednew). The one hour unit with the spalled off layer has a reflectance of 7-8%. The 20 hour old unit with the spalled off layer has a reflectance of 5% (spalledold)

The spalling effect that was observed on certain lava units was not temporally dependent, as there were units with their glassy surface spalled off after one hour and other units with their glassy layer intact after a 20 hour period. It is possible that the spalling effect is related to the vesicularity of the lava flow emplaced. Observations on the lava flow field show distinct examples of less vesicular p-type pahoehoe lava retaining its blue-glassy surface, despite being at least several days old. The more vesicular s-type lava more readily exhibits this spalling off effect. The higher vesicularity of the lava allows it to contract further thereby allowing an easier break-up of the glassy surface. So while we may be unable to estimate lava flow ages in the time frame of hours to days by measuring changes in visible reflectance, it may be possible to map units of different vesicularities with this technique. Studies have shown that emissivity varies as a function of wavelength, but it also dependent on the surface type [Flynn et al., 2000]. The wide disparity in reflectance spectra for basalt lava flows raises an important question as to the emissivity ($\varepsilon_\lambda = 1 - r_\lambda$) value, which is used in calculations of total radiance (see equation 1).

Reflectance values between 0.25 to 0.30 for the one hour old glassy pahoehoe and 0.10 to 0.12 for the day old glassy pahoehoe are considerably higher than previous measurements of fresh Kilauean basaltic pahoehoe of .005 [Flynn et al., 2000]. Previous calculations may have overestimated the total radiance if there was a significant portion of glassy surface pahoehoe in the image.

CONCLUSION

In this study, multispectral data from Landsat 7 Enhanced Thematic Mapper has enabled the mapping of active lava flows up to one and a half hours prior to the TM image. In a separate study, there was no correlation found between the temperatures recorded by the Raytek versus those derived from the spectra using the two-component numerical model. Differences could be due to incorrect assumptions made in the model inputs, different field of views encompassed by the ASD versus the Raytek, and inaccurate values chosen for emissivity.

Spectral reflectance measurements of s-type pahoehoe of known ages with and without an intact glassy surface show a wide range of reflectance, and hence, emissivity values ($\text{emissivity}_\lambda = 1 - \text{reflectance}_\lambda$). It seems that previous assumptions on appropriate emissivity values for pahoehoe flows should be under reconsideration. While there was no temporal relationship of the spalling effect, the wide disparity in reflectance spectra for pahoehoe flows raises an important question as to the choice of an emissivity value, which is an important term in calculations of total radiance.

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