Quantitative Analysis of Hot Spots Using EO-1 and Landsat 7
Luke Flynn

The objectives of this investigation were to compare the capabilities of the Earth Observing-1 (EO-1) Advanced Land Imager (ALI) and Hyperion instruments and the Landsat 7 Enhanced Thematic Mapper (ETM+) to monitor active volcanic eruptions and fires and to assess the merits of using spacecraft flying in formation over highly temporally variable targets. This capability would allow for (1) the evaluation of Hyperion and ALI spectral bands for incorporation into a Landsat-type follow-on instrument, (2) greatly improved maps of thermally emitted energy as a result of using improved EO-1 technology, and (3) the ability to study short-term changes associated with eruptions and forest fires.

EO-1 represents a unique opportunity to study the characteristics of high-temperature thermal anomalies including lava flows and forest fires. Previous attempts at measuring the thermal output of lava flows and forest fires at 30 meters resolution have been limited by instrument characteristics of the earlier Landsat 4 and 5 Thematic Mapper (TM). Frequent saturation problems with Landsat TM bands 5 and 7, which are sensitive to high temperatures, left the most interesting parts of the lava flows unstudied. While the qualitative aspects of these flow studies were tantalizing in that they showed that 30 m data can be used to assess geologic hazards from effusive eruptions, the limited number of relevant spectral channels of the TM precluded more quantitative assessments using more than pixel integrated temperatures. Similarly, a study of the differences in spatial temperature distribution between flows and fires demonstrated that both anomalies could have similar maximum temperatures while fires cool more rapidly than lava flows. However, TM data were insufficient to produce flux density maps of the fire data because of the inadequate dynamic range in the few relevant near-IR spectral channels.

In contrast, Hyperion and ALI represent a tremendous advance for high-temperature studies of volcanic eruptions and forest fires because:

- The number of spectral channels available with Hyperion (220 channels between 0.4µm – 2.5µm) is useful for solutions of multi-component models that would accurately determine the sub-pixel temperatures and spatial extent of anomalies.
- Comparisons of results derived from Hyperion, ALI (with its critical band 5p at 1.2µm - 1.3µm), and Landsat 7 ETM+ will allow an assessment of instrument capabilities from future Landsat-type sensors.
- Saturation at near-IR wavelengths is not as disastrous for Hyperion or ALI as it was with the TM, because channels at shorter wavelengths (i.e., 1.2µm - 1.3µm) can be used to make temperature and area calculations.
- Better sub-pixel solutions of hot spots will yield more accurate estimates of emitted energy for both lava flows and forest fires and also a basis for determining the requirements for future Landsat sensors.

This investigation examined the sensitivity of the EO-1 instruments to high-temperature thermal anomalies such as lava flows and forest fires focusing on Mt. Etna, Sicily, as the primary study site. Covering the same spectral region as the instruments aboard EO-1 (0.4µm - 2.5µm), the FieldSpec FR system developed by Analytical Spectral Devices was also used to provide simultaneous ground-truth. In addition, a FLIR (infrared) camera collected very high spatial resolution observations of active lava flows that were then used to model the number of thermal components present. The study showed that the number and placement of channels offered by Hyperion and ALI allowed investigators to assess more accurately the distribution of thermal radiators within a pixel than was available with Landsat ETM+.

It was expected that EO-1 data would yield much more detailed flux density maps and mass flux calculations than those derived from earlier Landsat TM data, which, nevertheless, have been particularly useful in assessing volcanic hazards. Further, assessment of ETM+, ALI, Hyperion, and ASTER data (flying on the TERRA satellite in formation with EO-1 and Landsat 7) would provide information about the short-term variability of eruptions and forest fires, which would be used to suggest constraints for the temporal distribution of successive measurements for future formation flying missions.

EO-1 was launched successfully in November 2000. By spring 2003, 10 volcanoes worldwide had been imaged with Hyperion and ALI. Images from Mt. Etna that showed a spectacular eruption during July 2001 were used most heavily in this investigation. Sixteen images were collected including two nighttime images. Of these, seven were good-quality images.

Volcanoes with lava flow activity
Lava flows that can easily travel tens of kilometers from their source vents in a matter of hours represent the most easily recognized volcanic activity from a satellite perspective. A February 14, 2000, Landsat 7 image acquired of Kilauea in Hawaii showed that lava flow fields and the underground tubes supplying them with lava can be mapped with ETM+. More importantly, the 15m/pixel ETM+ panchromatic band was used to map fresh (less than a few hours old) lava flows on the basis of their surface reflectance, not thermal radiance. However, ETM+ has suffered from the fact that usually only two bands detect emitted thermal radiance from the flows with the remainder of the bands suffering from saturation (due to higher thermal radiances that cannot be accommodated within the dynamic range of the detector) or a lack of anomalous radiance above the inactive background pixels. Both Hyperion and ALI provide more near-infrared bands that are necessary for accurate temperature and area determinations of active lava flows.

Hyperion observations of the Mt. Etna volcano collected on July 13, 2001, showed characteristic effusive lava flow activity typical of persistent effusion from the southeast cone (Figure 1). Lava flows and active vents containing molten lava with temperatures of up to 1080°C appear in the image as bright red and yellow colors. The inset to Figure 1 shows the four active craters that comprise the Mt. Etna summit complex. The red, green, and blue composite image was created using Hyperion bands 213, 152, and 32, respectively. In the west central portion of the inset, an active vent at the bottom of the Bocca Nuova crater is apparent. Approximately, 200 - 300 meters to the northeast is an active vent within La Voragine crater, while another 300 meters to the north, an active vent within the northeast crater is apparent. A large 300 m – 500 m-diameter anomaly about 700 meters southeast of La Voragine marks the location of the southeast cone of Mt. Etna. Lava flows issuing from fissures on the northeast side of the cone flowed to the northeast before turning east into the Valle del Bove. Lava flow appears to have been concentrated in a 600 m-long channel before flows bifurcated numerous times to form a compound flow field extending 1.5 km east in this image. A plume of ash and volcanic aerosol originates from the Bocca Nuova and disperses to the southeast.

Figure 1. Mt. Etna before the main eruption began, July 13, 2001.

Collected nine days later, on July 22, 2001, a second Hyperion image (Figure 2) revealed a much more active and potentially disastrous eruption of Mt. Etna. The pointing capability of the instrument allowed investigators to obtain multiple high-resolution images of this new flank eruption. On July 17, 2001, a much larger and more vigorous eruption had begun that involved lava flow activity on at least four separate active fissures. Again, in the west central portion of the July 22 image, a cluster of three yellow and red dots can be seen to mark the locations of active vents within the Bocca Nuova, La Voragine, and the southeast cone; however, at that time, the northeast crater was obscured by volcanic aerosols. The northernmost fissure had started to erupt on July 20, 2001, only two days before the Hyperion overpass. The July 22 image showed the 1.5 km-long lava flows from this fissure moving southeast at the base of the steep cliffs that mark the northern edge of the Valle del Bove. Approximately 360 meters to the southeast of the southeast cone a longer lava flow is apparent. These are flows from another fissure that had opened on July 17 to feed flows that first moved southeast before encountering the back wall of the Valle del Bove and being deflected in a more easterly direction. Two other fissures had also opened on July 17 to the south of the Etna summit complex and had fed lava flows that moved in a southerly direction. At the time the July 22 image was recorded, these two flows had advanced 2.7 km and 5.9 km, respectively, in the general direction of the town of Nicolosi. The end of the lava flow field is apparent as the more diffuse red and yellow anomaly south of a white cloud that obscures part of the flow. These fissures also erupted a large amount of ash and volcanic aerosols that are apparent in the image.

Figure 2. Mt. Etna eruption, July 22, 2001, acquired with Hyperion. The bands are equivalent to Landsat 7 ETM+ bands 7, 5, and 3 in red, green, and blue.

Vigorous, opening phases of flank eruptions on Mt. Etna were characterized by intensely hot molten lava flowing in open channels. It is certain that this vigorous eruption caused the infrared channels of Hyperion to malfunction, which is why the active lava flows were mirrored by a less intense radiance echo located roughly 300 meters to the west of the main lava flows. Discussions with researcher Pamela Barry led this investigative team to believe that it may be possible to reconstruct the original signal (above the saturation value for that spectral band) using the saturated pixel radiance and the radiance echo for that pixel. Essentially, the Hyperion data were collected in analog form. When they are converted to a digital signal, anything above a threshold value gets a saturation value. However, the remainder of the analog signal was recorded as a radiance echo 11 pixels west and one pixel south of the original saturated pixel. Thus, it may be possible to reconstruct the original analog signal using the radiance echo. This would enable calculation of higher temperatures and fractional areas for very high temperature lava channels and other areas prone to radiance saturation.

Spectra from this eruption are being evaluated. Obtaining spectra from Hyperion data was not too straightforward because of the data shifts required to align spectra. A shift of even one pixel will result in erroneous temperatures, as the pixels must be co-located in order for Planck curves to be fitted to the spectra. Spectra taken over active lava flows saturated in a number of areas. Temperatures were then modeled from those wavelengths that were not saturated. Investigators are developing an automated method to rapidly process large areas of the lava flow field at one time. If the attempt to reconstruct saturated pixel values is successful, this capability will greatly enhance the capacity to automate the creation of radiant energy maps using Hyperion data. Researchers can then compare these results with those obtained with Landsat 7 ETM+ and ALI.

ALI - Landsat 7 ETM+ comparison of temperature retrievals over active Etnean lava flows
Using near simultaneously acquired Landsat 7 ETM+ and EO-1 ALI data, investigators also assessed the relative radiant responses over active lava flows from the Mt. Etna July/August 2001 flank eruption. Investigators assessed the extent of saturation between the two instruments and by using the dual band method of extracting sub-pixel thermal information on the resulting lava flows. This dual band method simplifies lava flows as a two-component thermal surface: a hot incandescent core exposed through cracks in the crust and a cooler crust. Assessing the extent of saturation and use of the dual band method allowed the investigators to demonstrate that ALI represented an improvement over ETM+ in the current ability to assess temperatures of hot active lava flows. This was true because: (1) The extra spectral channels provided by ALI complemented the current shortwave infrared (SWIR) channels on ETM+ by providing a greater number of two-channel combinations for input into the dual band method. Thus, dual-band temperature solutions were available for a greater range of lava flow types than previously possible using the two channel combinations available on the ETM+. (2) The ALI instrument was less susceptible than ETM+ to saturation in the SWIR range, especially when using channels 5, 5p, and 4p. (3) The greater radiometric sensitivity of ALI's 12-bit electronics coupled with a significantly lower signal to noise ratio (SNR) aided in obtaining successful dual band solutions.

The investigators demonstrated the extensive application of the dual band method of extracting information on sub-pixel resolution hot spots in ETM+ and ALI data over active lava flows. The ability to obtain a successful solution requires the use of unsaturated instrument data within the SWIR range. The extensive saturation observed within ETM+ channels 7 and 5 have often precluded the use of this method. Similar levels of saturation were also found in ALI channel 7 that prevented the use of this channel in the dual band calculations. ALI channel 5 also displayed saturation over the most active flows and vents imaged within the study area. However, because ALI channel 5 can tolerate a higher level of thermal radiation before it saturates, it exhibited substantially less saturation than the equivalent ETM+ channel 5. The saturation of ALI data also was not readily apparent when using processed Level 1R data. Data based on Level 0 processing was used to identify areas where ALI was saturating. ALI channel 5p, placed in the SWIR range between ETM+ channels 4 and 5, saturated only over the most active regions within the study area. ALI channel 4p showed no saturation but was sensitive to the most active lava flows.

The ALI instrument demonstrated that it is possible to gain dual band estimates of sub-pixel detail over hot active lava flows that are not available or reliable when using ETM+ data because of the addition of the two extra SWIR channels, 5p and 4p. Different band combinations available using unsaturated ALI data are sensitive to differing P_H & T_C (basically area and temperature) combinations, providing coverage for a range of lava flows from cooling stagnating flows to flows close to the vent using channel combinations at progressively shorter wavelengths. This was not possible with ETM+ because the relevant channels do not exist. The ease with which ETM+ channels 7 and 5 saturate over such flows as those within the study area prevented successful dual band solutions.

Conclusions:

The increased SNR of the ALI and better radiometric sensitivity coupled with the extra SWIR channels has produced an instrument that is very capable in terms of remote sensing of active lava flows. If ALI technology is incorporated into a replacement Landsat instrument with a fully populated focal place, the resulting data should prove highly useful in the analysis of active lava flows to an extent not possible before. The study also showed that the number and placement of channels offered by Hyperion and ALI allow investigators to assess more accurately the distribution of thermal radiators within a pixel than was available with Landsat ETM+.