The importance of multispectral thermal infrared (TIR) data for quantitative volcanic monitoring

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Introduction

Multispectral thermal infrared (TIR) data of active volcanic products (e.g., ash and lava) provides critical information such as temperature and emissivity as well as volcanological properties derived from it such as composition, particle size, thermal regime, and vesicularity [1]. Unsaturated, *in situ*, multispectral TIR data have been acquired from the ground, air, and space on numerous active volcanoes over the past two decades; however most has been saturated and thus, unusable. The unsaturated data reveal spectral changes with cooling lava flows and particle size/composition in ash plumes, relevant to several of the SGB science questions [2]. However, the limited spectral resolution constrains the science analysis, increasing uncertainty and decreasing accuracy. Development of inexpensive, near-hyperspectral TIR imaging systems/sensors are vital for improving our ability to map volcanic products, and in doing, improve eruption forecasting. For example, such data will improve ash cloud detection, provide compositional capabilities, and fully enable lava flow propagation modeling. This is an important objective highlighted in the 2018 Decadal Survey for Earth Science and Applications from Space [2]. We have developed tools that are now providing these data, useful for assessing possible future TIR configurations of the SBG missions. These data (e.g., MMT-Cam) provide valuable performance metrics for uncooled, inexpensive microbolometer instruments designed to detect changes in emissivity of active lavas and ash plumes.

Data

Specification	MMT-Cam	M-S40
Detector Type	Uncooled VOX microbolometer	Uncooled microbolometer
Spectral resolution	7.5 – 13 µm	7.5 – 13 µm
TIR Bands	6 + broadband	6 + broadband
Spatial resolution	Variable	Variable
Field of view (FOV)	45° x 37°	24° x 18°
Image frequency	500 msec	~1000 msec
Gain settings (saturation)	-25°C to 135°C / -40°C to 550°C	-40°C to 120°C / 0°C to 500°C / 350°C to 1500°C

Table 1. Ground based imaging systems used to quantitatively investigate volcanic activity and eruption products (e.g., ash and lava).

Volcanic Ash

New work on opaque ash plumes shows that treating the TIR data as a hypothetical solid emitting surface is valid [3]. By collecting laboratory emissivity spectra, and applying them to image data using a linear deconvolution model [4], it becomes possible to extract both particle size and composition. This method has thus far been used with ASTER TIR data but would improve markedly with future high spectral resolution TIR data.

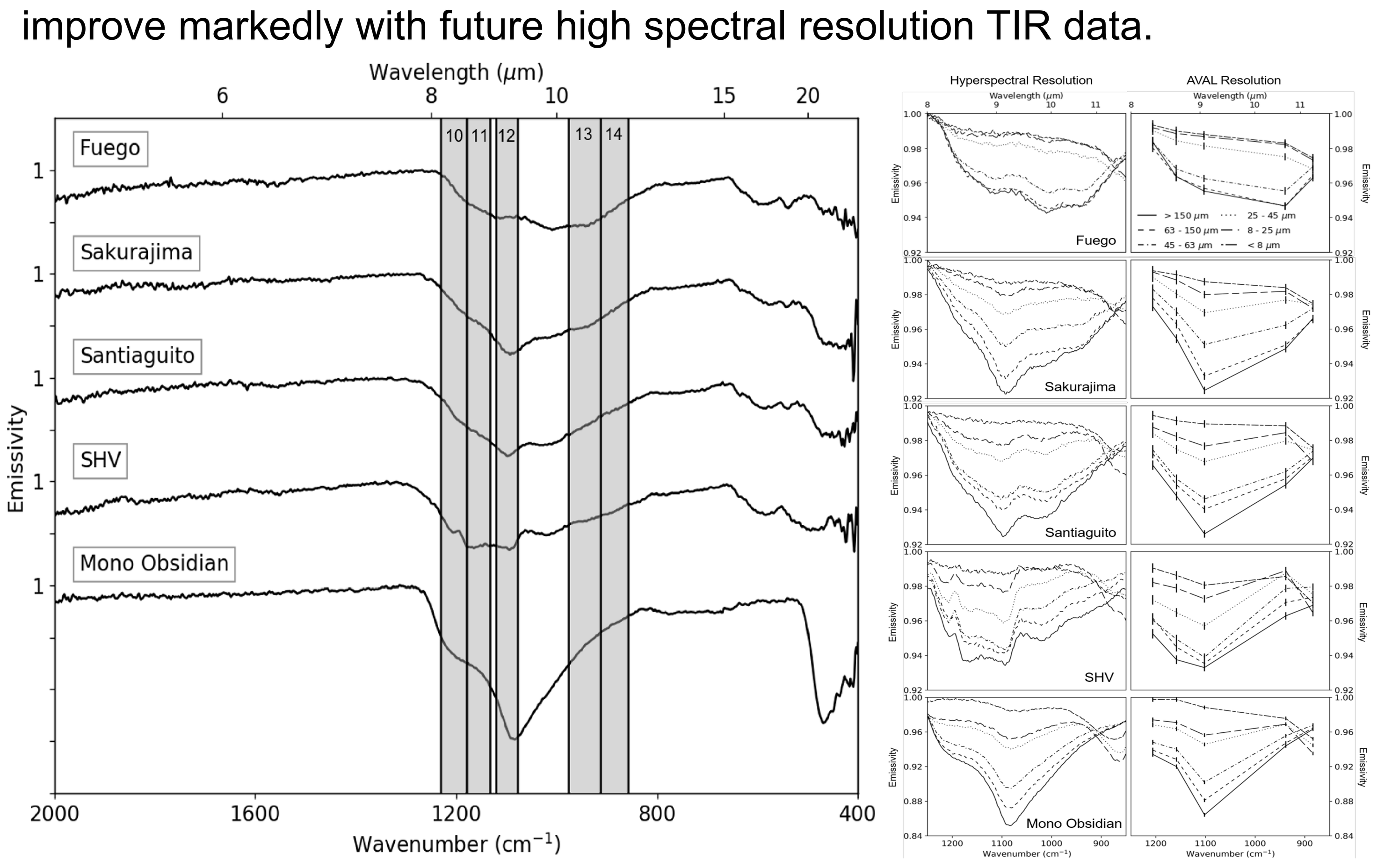


Figure 1. Laboratory FTIR spectra of the ASTER Volcanic Ash Library (AVAL). At this resolution, the diagnostic spectral features are clearly evident. **Left**; Largest particle size fraction of AVAL with the ASTER bands overlain. **Right**; Spectra subsampled to 8 – 12 µm and resampled to ASTER TIR bands (error bars denote NEΔε of the FTIR data for each band). Crushed Mono-Inyo Obsidian is used as a pure glass high SiO_2 end-member. Each sample is separated into six size fractions to account for spectral features that occur in particles < 63 µm.

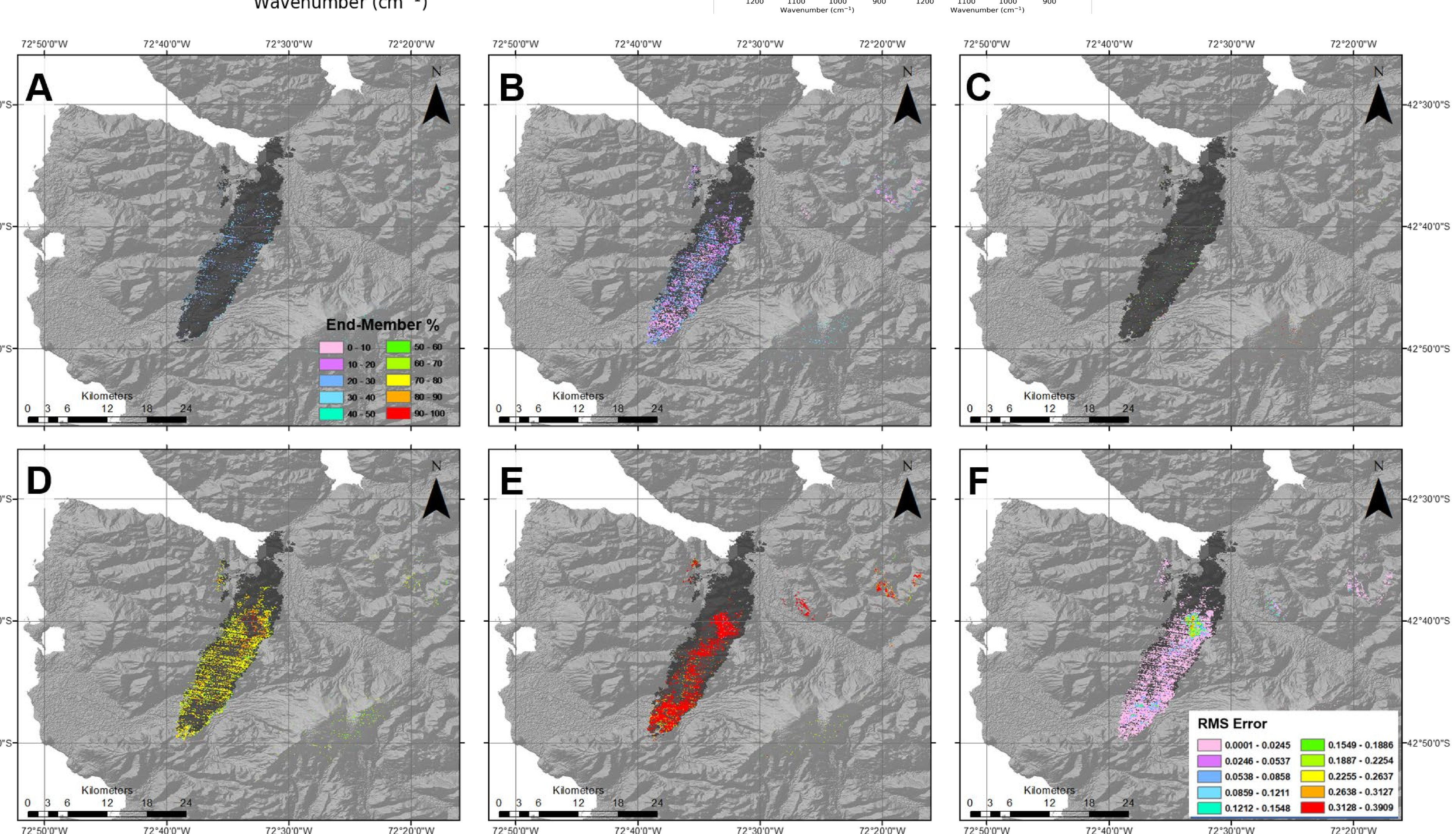


Figure 2. Results from the linear deconvolution model [4] tested on ASTER data of a volcanic plume from Chaitén, Chile on 19/01/2009. The model assumes that each image derived TIR spectrum is the sum of the areal percentage of each input end-member spectrum. The results produced here are obtained using the Mono-Inyo Obsidian end-member suite, given the highly-silicic nature of this eruption. Dark gray is the approximate area of the plume based on plume temperature. A) 63 – 150 µm; B) 45 – 63 µm; C) 25 - 45 µm; D) 8 - 25 µm; E) < 8 µm; F) RMS Error. Average error across the plume for this retrieval is 2.74%. This plume is dominated by finer size fractions. The largest size fraction (A) is commonly found around the plume edges, likely due to different layers within the plume being sampled as it becomes more diffuse. With improved spectral resolution of a future TIR sensor, both composition and particle size distribution could be simultaneously extracted.

Lava Flows

The ability to derive accurate, ***unsaturated*** TIR temperature and emissivity data *in situ* of molten lava surfaces is commonly hindered by spectroscopic assumptions and current instrument designs. Another focus of our work investigates emissivity change with temperature and lava crust formation to evaluate its influence on lava flow cooling. Changes in the temperature (and emissivity) with cooling creates the glassy crust, which then changes the TIR data analysis. To measure and quantify this spectral change and its impact on derived temperature, a new portable, ground-based multispectral imaging system (MMT-Cam) has been developed [5].

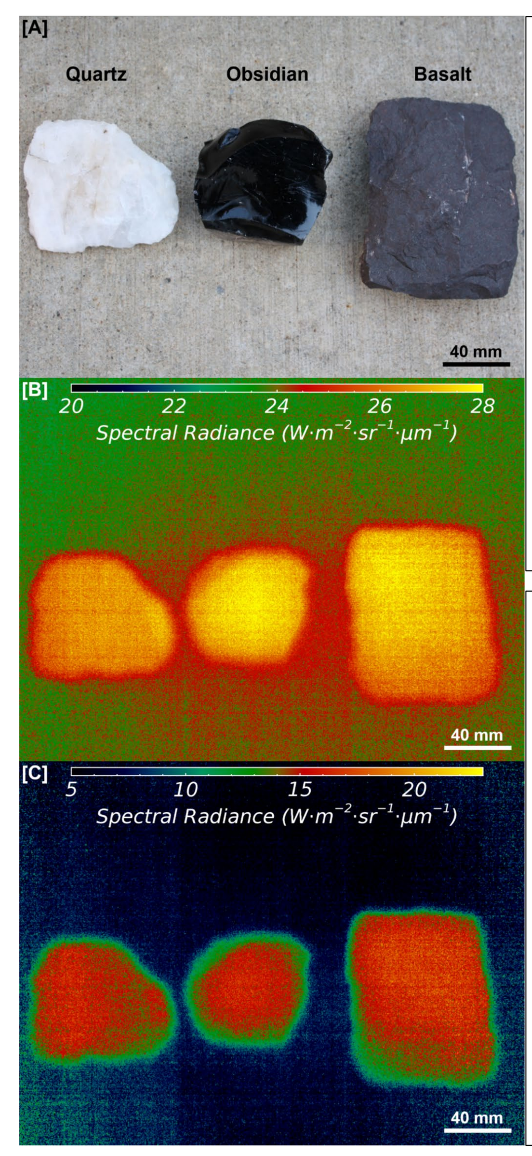
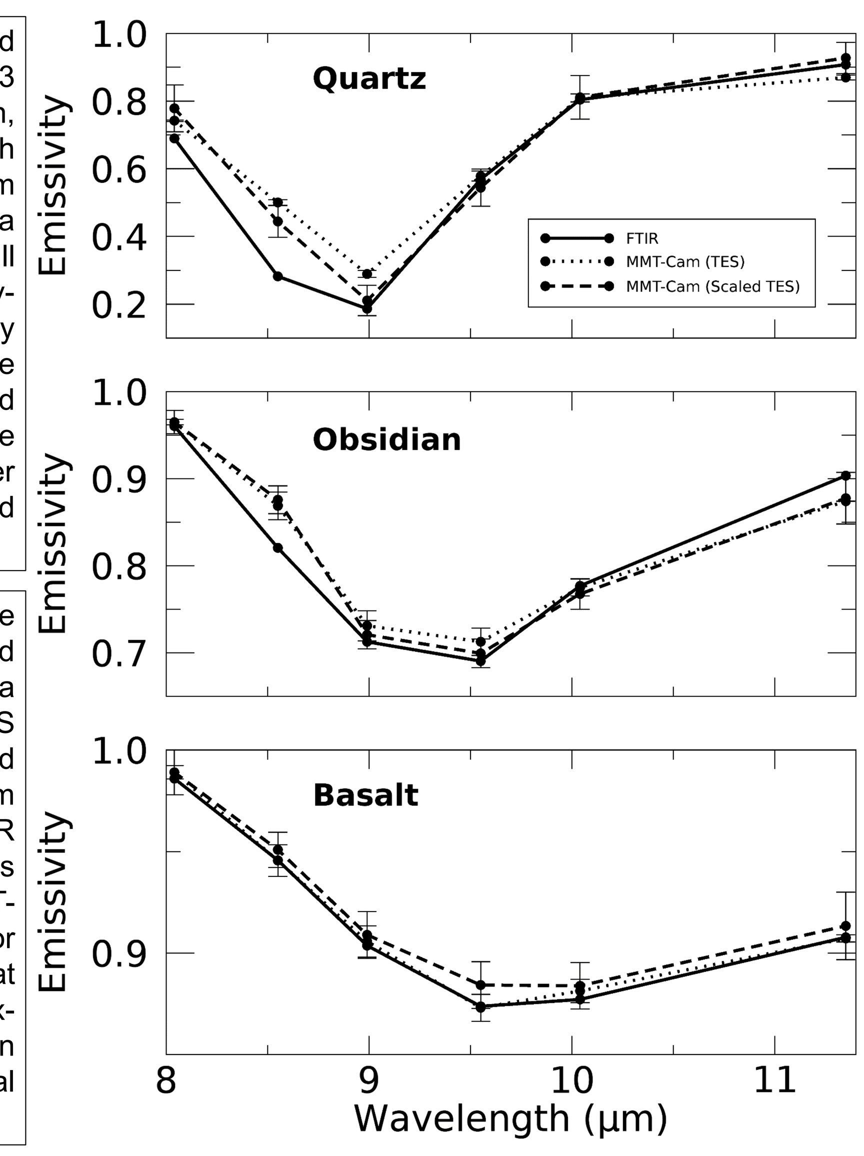


Figure 3 (left). The three hand samples heated to approximately 373 K (from left to right): quartz, obsidian, and basalt. **[A]** Visible image, with sample labels. **[B]** MMT-Cam uncalibrated spectral radiance data stretched to emphasize the full dynamic range. **[C]** MMT-Cam fully-calibrated and atmospherically corrected spectral radiance data. Note the improvement in errors associated with radiance (the overall lower scene radiance) and geometry (the lower radiance in the scene center) caused by the instrument design [5].

Figure 4 (right). Comparison of the MMT-Cam atmospherically corrected and TES derived emissivity spectra [dotted line], the MMT-Cam scaled TES derived emissivity spectrum [dashed line], and the pseudo-MMT-Cam spectra derived from FTIR spectrometer [solid line] of the samples shown in Fig. 3. The corrected MMT-Cam data are shown to be accurate for a variety of compositions acquired at lower temperatures. However, the six-point spectra reduce the certainty in accurate surface compositional analyses [5].



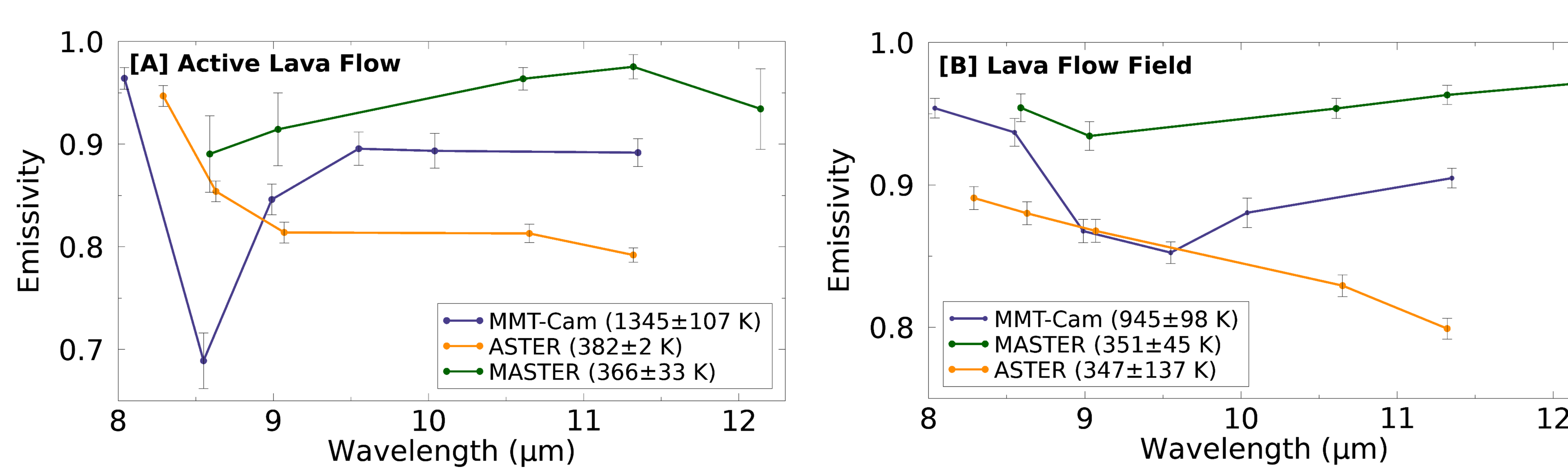


Figure 5 (above). Concurrent emissivity spectra derived from ground-based MMT-Cam (blue), airborne MASTER (green), and orbital ASTER (orange) data acquired from the Pu'u 'Ō'ō lava flow field on the coastal plain of Kīlauea Volcano, Hawaii. **[A]** The MMT-Cam acquired unsaturated multispectral data of actively propagating molten lava, whereas the MASTER data are saturated. The ASTER data produce a thermally-mixed spectrum due to pixel size. **[B]** Data from the entire lava flow field also produce thermally-mixed spectra, likely with a greater fraction of cooler basaltic crust (as shown my the MMT-Cam spectra). The six-point MMT-Cam spectra allow reasonable certainty in surface thermal analyses, including where acquiring measurements of mixed surfaces from fully molten to fully cooled. Furthermore, the temperatures derived from the MMT-Cam data are more accurate than those from the MASTER and ASTER data.

Conclusions

The volcanic ash mapping techniques present a clear opportunity to explore the composition and particle size of active opaque plumes as well as ash fall deposits. More importantly, these data over time provide the capability to monitor changes in the geochemistry of the magma erupted and assess the future eruptive activity potential. However, this ability is limited by the five ASTER TIR bands. Higher spectral resolution TIR data improves understanding of the relationship between the derived emissivity and acquired radiance. Furthermore, emissivity is used to determine the degree of glassiness, vesicularity, composition, viscosity, and cooling of a surface, which are parameters fundamental to lava propagation models. Our ground-based multispectral imaging systems can assess the spatial and spectral resolutions required for future satellite-based microbolometer TIR sensors to derive of these parameters.

However, in order to enable this and fully map volcanic plumes and assess ongoing eruptive potential, SBG must have increased spectral resolution in the TIR. Where applied to active lava surfaces, an improved spectral resolution coupled with ***unsaturated data*** will result in more accurate surface temperatures and therefore more accurate hazard assessments.

Recommendations

Possible recommendations for future TIR sensors to address the SBG Targeted Observable:

- **A spatial resolution of 30 – 40 meters to reduce spatial mixing.**
- **A spectral resolution of >12 bands (near-hyperspectral) [2] to improve spectral feature identification and improve derived temperature measurements.**
- **A high at-sensor saturation limit of 600 – 800K to prevent data saturation over very hot surfaces, where measureable spectral changes are occurring.**

These TIR datasets would significantly improve our ability to monitor and forecast volcanic activity and reduce risk to communities living near active volcanoes around the world.

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