Constraining the inherent uncertainties in thermal infrared (TIR) measurements of active lava surfaces: The need for improved spatial and spectral resolution data

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Introduction

To understand the entire thermal regime of a volcanic system, a multi-instrument, multi-platform approach is ideal. For example, an orbiting instrument acquiring long-time duration but low spatial and spectral resolution data provides a synoptic overview of the volcanic system. However, detailed observations of specific thermal features and processes are missed. Higher spatial and spectral resolution airborne and ground instruments observe these features and details of the processes occurring within the system with high temporal frequency. These instruments are unable to provide repeat observations over longer time periods. Hence, there is a need for instrument and data synergy until orbital instruments are launched with the required spatial, spectral, and temporal resolutions. It is important to understand and quantify the accuracy and uncertainty within the current datasets to improve confidence in their analysis. This issue has been investigated in the past [1-2] but not for observations of active lava surfaces where rapid changes in thermal properties occur both spatially and temporally at very high temperatures (<1600 K). Furthermore, we propose that the results of this study will improve the accuracy of lava flow propagation modeling, which could reduce the risk to populations living near active volcanic systems.

Study Area

This study was conducted at Kīlauea Volcano in Hawai'i, USA, in January/February 2017 and 2018. The study focused on two volcanic features:

1. <u>Lava flows</u> – propagating lava flows from the Pu'u 'Ō'ō vent. (Fig. 1) [3].
2. <u>Lava Lake</u> – the <250 m diameter active lava lake within the Halema`uma`u crater (Fig. 1) [4-5].

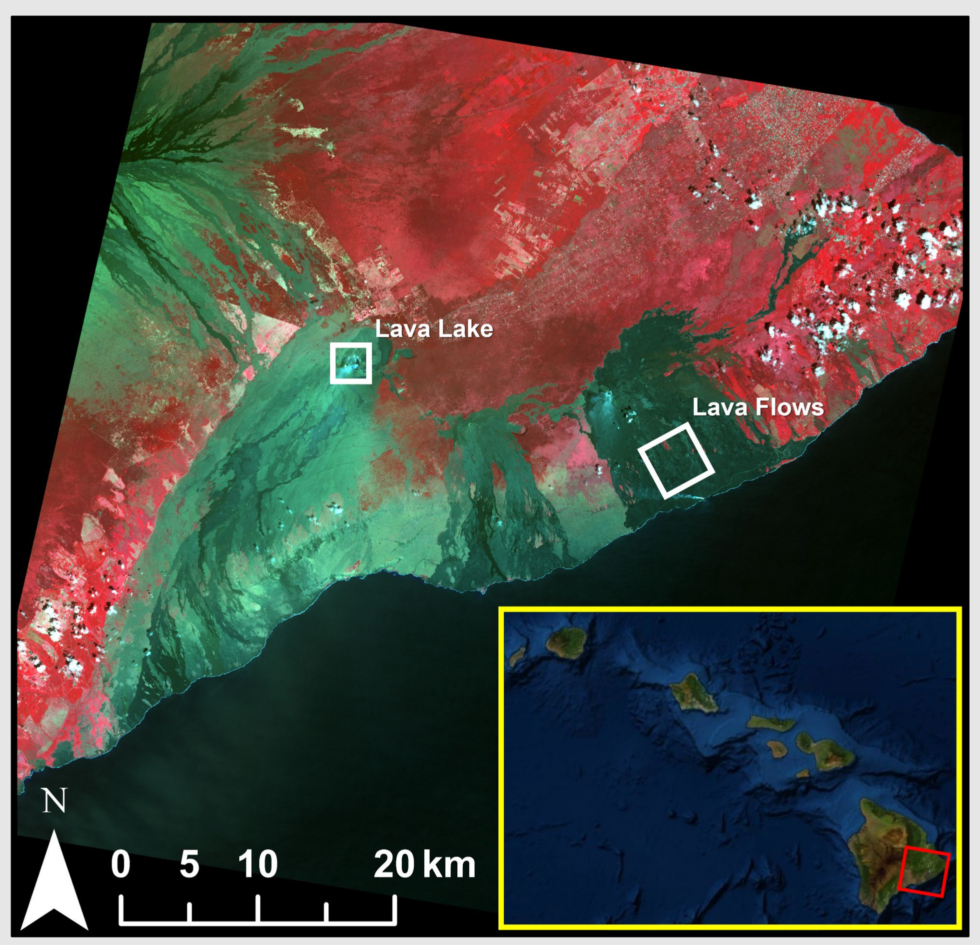


Figure 1: ASTER VNIR false color image (RBG: 3,2,1) of the southeastern region of the Island of Hawai'i, showing the location of the Halema'uma'u Crater lava lake and Pu'u 'Ō'ō lava flows at Kīlauea Volcano. Data were acquired on March 7, 2017 at 21:06:02 UTC. The white boxes mark the locations of the regions of interest. Insert map shows the location of the ASTER image (red box) within the state of Hawai'i in the central Pacific Ocean (ESRI).

Instrument Specifications

	MMT-Cam (ground)	MASTER TIR (airborne)	HyTES (airborne)	ASTER TIR (orbital)
Detector	VOX microbolometer	HgCdTe photoconductive	QWIP	HgCdTe photoconductive
Field of View	45° x 37°	85.92°	50°	
Spatial Resolution (m)	0.04 / 0.3	50	35	90
Spectral Resolution	6	9 (7)	186	5
Temporal Resolution	1 second	Daily during campaign	Daily during campaign	5-15 days
Radiometric Range (K)	233 to 832	245 to 480	240 to 455	200 to 370
Radiometric Accuracy	5%	<5%	<1%	<3%

Methods

Image Processing

- Data are first radiometrically and atmospherically calibrated to derive surface radiance using the instrument blackbody calibration data and radiative transfer modeling

Temperature and Emissivity Separation

- Calculated using the Temperature and Emissivity Separation (TES) algorithm [6]
- Derived from the mixed surface radiance

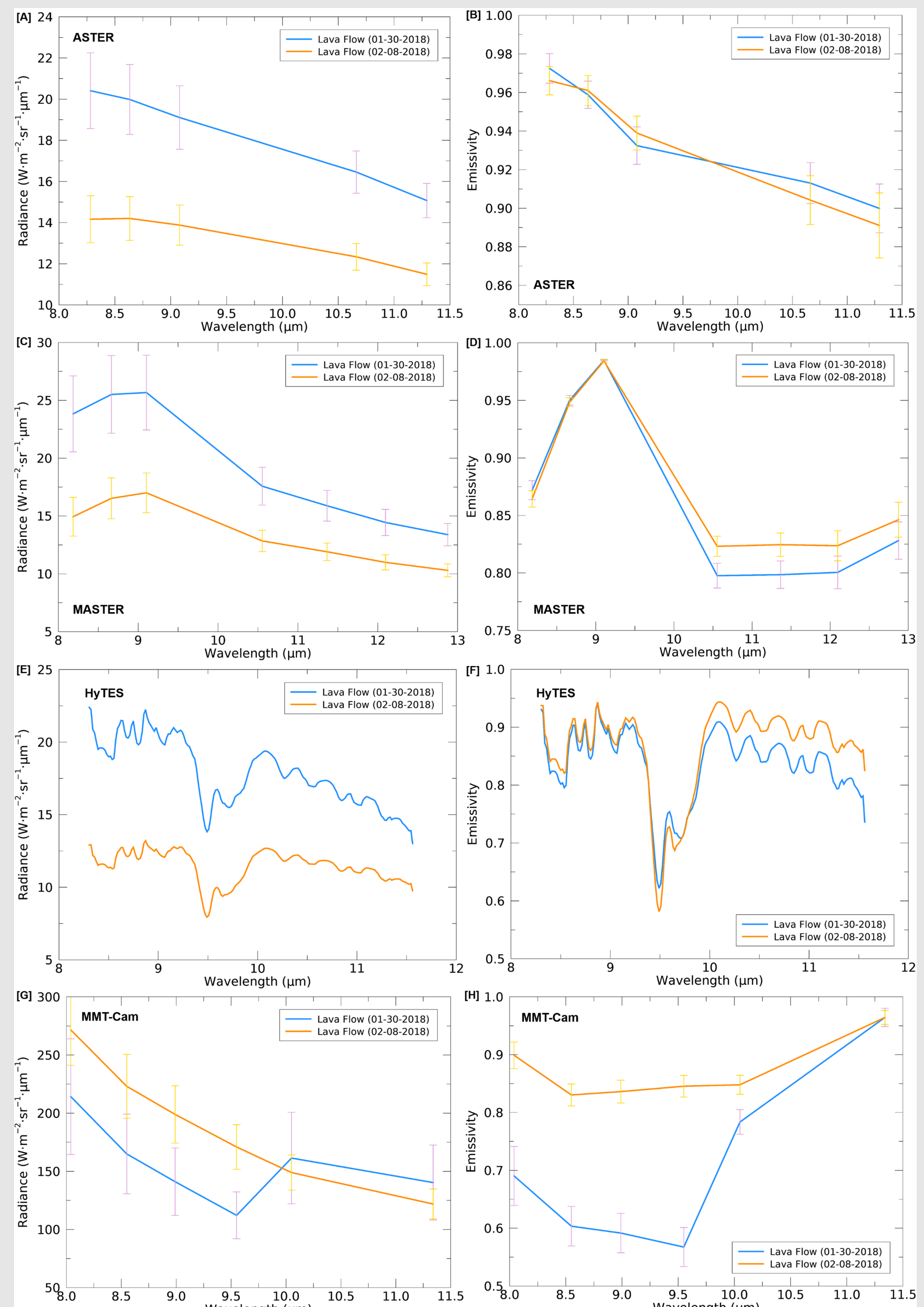
Thermal Mixed Pixel Analysis

- A thermally-mixed pixel (TMP) is composed of multiple temperature components
- The radiance of the highest temperature (molten) component within a given pixel is required
- Found using the dual-band mixed pixel solution [7], using the following equation:

$$M_{(\lambda_n, T_{int})} = p \cdot M_{(\lambda_n, T_1)} + (1 - p) \cdot M_{(\lambda_n, T_2)}$$

- Two TIR bands are used to derive the area and temperature of this molten component
- The radiance of this molten component serves as input into the TES algorithm

Results



Two regions of interest (ROI) were chosen from the each dataset to evaluate the retrieval of surface radiance, temperature, and emissivity of cooling lava surfaces. Pixels in these ROIs contain cool crustal and molten lava surface end-members as well as mixtures of both. Figure 2 and 3 show the average radiance and emissivity for only the lava flow data before (Fig. 2) and after (Fig. 3) the mixed pixel analysis.

Figure 2: Pixel integrated surface radiance (left column) and emissivity spectra (right column) acquired of the Pu'u 'Ō'ō lava flows derived from **[A and B]** ASTER TIR, **[C and D]** MASTER TIR, **[E and F]** HyTES, and **[G and H]** MMT-Cam data.

The average temperatures derived from the lava flow surfaces before (Fig. 2) and after (Fig. 3) the mixed pixel analysis:

- **ASTER:**
  - 354.1 K with a 23.8 K variability *(before)*
  - 1242.3 K with a 337.0 K variability *(after)*
- **MASTER:**
  - 425.2 K with a 64.3 K variability *(before)*
  - 1128.2 K with a 408.0 K variability *(after)*
- **HyTES:**
  - 407.8 K with a 32.5 K variability *(before)*
  - 1266.1 K with a 404.0 K variability *(after)*
- **MMT-Cam:**
  - 736.2 K with a 163.0 K variability *(before)*
  - 1225.9 K with a 329.6 K variability *(after)*

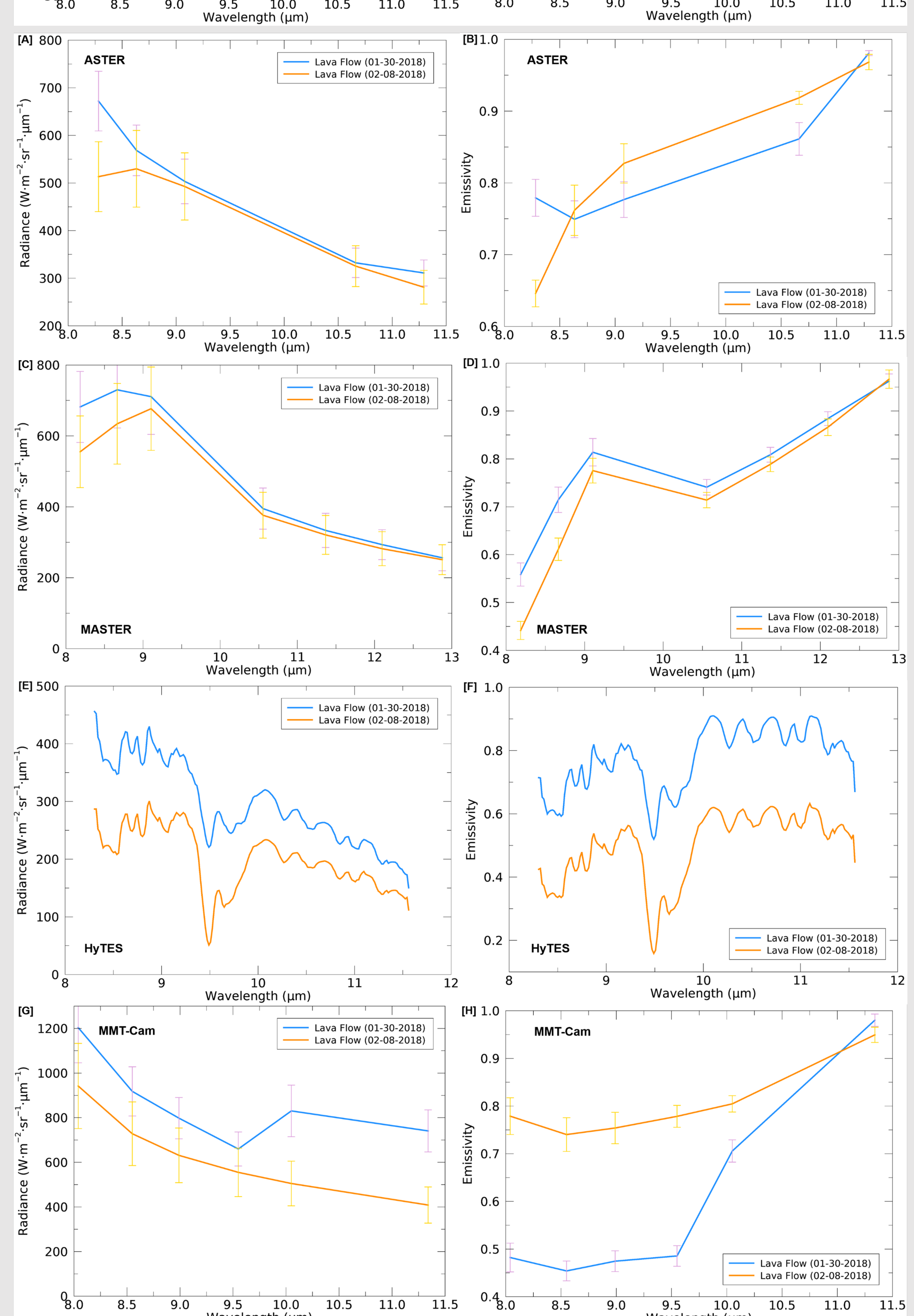


Figure 3: Surface radiance (left column) and emissivity spectra (right column) derived from the molten component within each pixel calculated using mixed pixel analysis. Data acquired of the Pu'u 'Ō'ō lava flows from the **[A and B]** ASTER TIR, **[C and D]** MASTER TIR, **[E and F]** HyTES, and **[G and H]** MMT-Cam data.

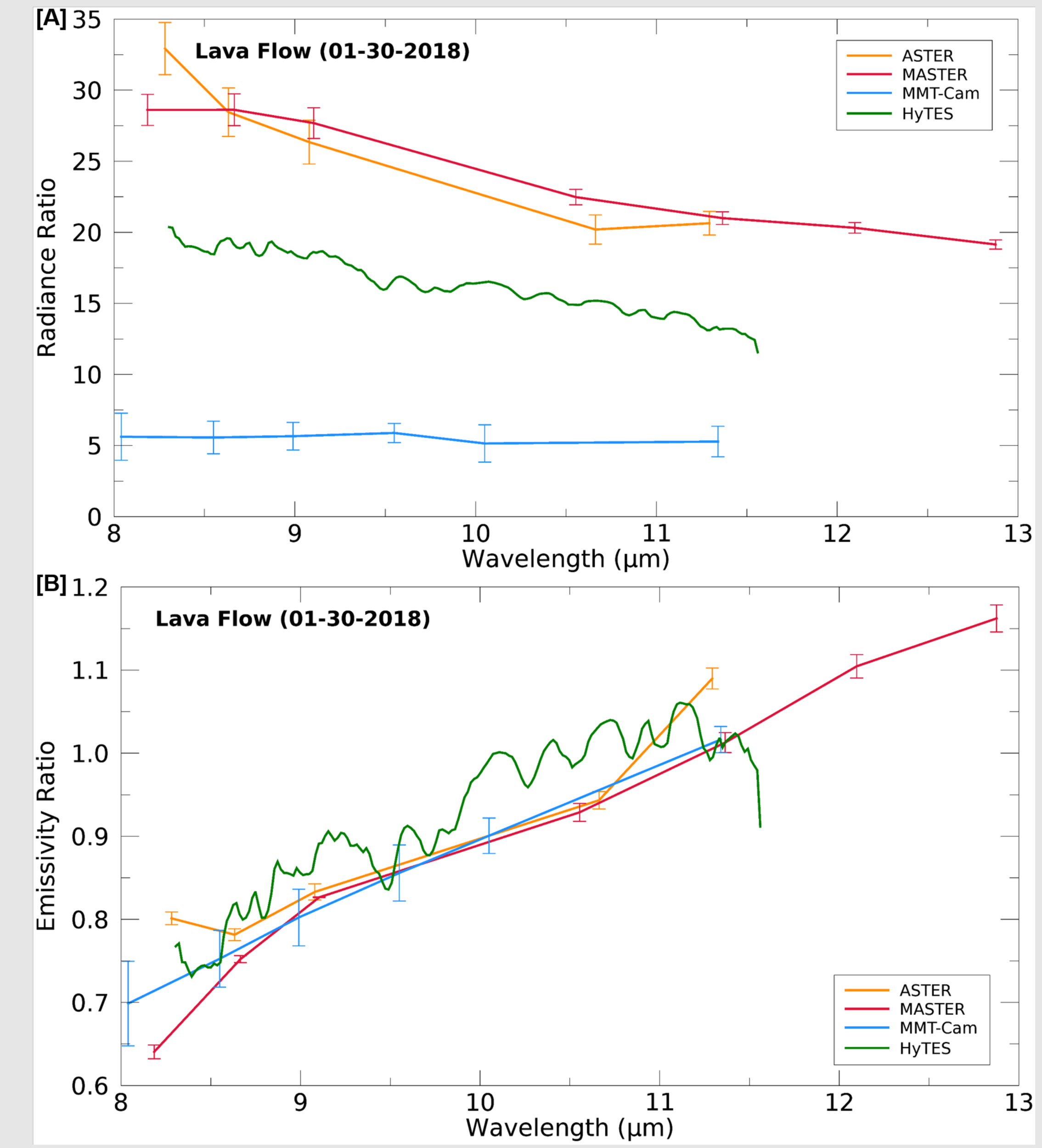


Figure 4: The divergence between **[A]** surface radiance and **[B]** emissivity before and after thermal-mixed pixel separation analysis derived from all the datasets acquired of the Pu'u 'Ō'ō lava flows on January 30, 2018. Values closer to 1.0 require less mixed pixel separation processing.

Figure 4 illustrates the influence of the mixed pixel analysis on the acquired and derived thermal measurements following the mixed pixel analysis from the different datasets.

- Surface radiance and temperature data are under-estimated by **>400%** and **80 – 120%**, respectively
- Emissivity data are offset (sloped) by **5 – 20%**

Conclusions and Future Work

- The ability to accurately measure thermal properties of active lava surface using TIR remote sensing data are limited by:
  - Spatial, spectral, and temporal resolutions of the current TIR instruments
  - Spatiotemporal variability of the ongoing volcanic processes
- The dual-band mixed pixel analysis is one solution to the spatial resolution constraint
  - Radiance values improve to **25%** of expected values for all data (**>300%** improvement)
  - Temperature and emissivity values are within **25%** and **10%** of expected values
- Mixed pixel analysis increases variability (**>200%**), decreasing precision
  - Minor change (**<10%**) observed in the MMT-Cam data with spatial resolution **<10** meters or molten pixel fractions of **~0.30** or greater
  - Increase in spectral resolution (multi- to hyper-spectral) decreases variability (**<40%**)
- Data and instrument synergies provide a useful tool for deriving more accurate thermal properties of active lava flow surfaces
  - Constraining uncertainties between these datasets will improve the collective potential
- Future orbital TIR instruments with improved spatial, spectral, and temporal resolutions are critical to improve our understanding of relationship between thermal emission and eruption dynamics
  - Requires accurate derivation of temperature and emissivity of active lava flows to improve radiant flux estimates and increase the accuracy and reliability of lava flow propagation models
    - Thus reducing the risk and uncertainty posed by lava flows on local populations
- **Future work**
  - Incorporate these results into lava flow propagation models to evaluate the influence on prediction results
  - Initial analysis estimates a potential **20%** underestimate

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