A HIGH-SPEED MULTISPECTRAL VNIR CAMERA CALIBRATED FOR REMOTELY RETRIEVING INCANDESCENT LAVA TEMPERATURES: IMPLICATIONS FOR STUDYING VOLCANISM ON EARTH AND IO.

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Introduction: Jupiter's innermost moon, Io, displays an impressive range of styles and magnitudes of volcanic activity. It is vital to accurately constrain eruption temperature to understand the composition and state of Io's interior, which control where tidal heat is dissipated, the magnitude and distribution of surface heat flow, and the position of Io in the evolving orbital resonance with Jupiter, Europa, and Ganymede [1, 2]. Remote sensing data of Io, from the *Voyager*, *Galileo*, *Cassini*, and *New Horizons* missions and Earth-based telescopic observatories [3] have been used to estimate the surface temperatures of lava-dominated thermal areas and provide insights into eruption mechanisms [4, 5, 6, 7, 8]. But one important question that remains, as described by [9], is whether Io's volcanism is dominantly basaltic or ultramafic in composition. One of the challenges of remotely sensing eruptions temperatures is that the outer surface of erupting lava cools quickly when it is first exposed – initially, by hundreds of degrees per second [10]. Hence, remotely measuring the eruption temperature is an attempt to record something that is visible for only a fraction of a second, and typically present in only a fraction of a pixel. To this end, we have been carrying out field investigations using a new imaging system.

Instrument and Calibration: The FD-1665 (by FluxData, Inc.) contains three 640x480 CCD cameras with Sony ICX-618 monochrome sensors. Wavelength separation is effected by a prism resulting in a 3-channel VNIR camera system with Green (~0.55 µm), Red (~0.66 µm), and NIR (~0.8 µm) channels. The prism, combined with 3 CCDs, allows for simultaneous multispectral image collection. The camera system has a 12-bit dynamic range and is capable of acquiring full-frame images at up to 120 frames per second (fps). Although, due to limitations in data streaming capacity to the laptop, a maximum of 50 fps was achieved in the field imaging experiments (described below).

The camera was calibrated by making a series of measurements, at 50-°C intervals, of a high-temperature blackbody calibration source with a 600-1500 °C temperature range. The camera driver software was used to systematically vary the gain, frame rate, and exposure time settings. For each CCD, the gain values could be varied from 150 to 400; the frame rate was set to 50 frames per second (the highest allowable by the data streaming capacity to the laptop); and the exposure time was varied from 0.1 to 20 milliseconds (the longest possible exposure time at 50 frames per second). One of the goals was to establish camera settings that would maximize the dynamic range of each channel, and avoid pixel saturation over active lava features with temperatures expected to be as high as 1150 °C.

A series of calibration equations was developed to (1) convert raw DN values measured by the camera to brightness temperature (T_B), using a single channel, assuming unity emissivity; and (2) relate measured DN ratios (e.g., DN_{NIR}/DN_{RED}) to a color temperature (T_C).

Field Imaging Experiments: Field imaging experiments were performed on Kīlauea volcano, HI, in November-December, 2016. We imaged an area of active breakouts of basaltic pahoehoe lava lobes along the 61g lava flow at night. We also collected high-speed image data of lava spatter in the Halemaʻumaʻu lava lake, which was visible from the Jaggar Museum overlook.

Custom IDL code was developed to spatially and temporally co-register concurrent image frames and process the data into T_B images for each channel, and into 2-channel-ratio T_C images, based on the derived calibration equations.

To test the temperature retrieval methods, T_B images of the laboratory calibration source were produced for comparison to its known temperature. Overall, the accuracy of the T_B retrievals from each of the channels was variable, depending on the exposure time and target temperature, but consistent from channel to channel. The range of actual blackbody temperatures in which T_B retrievals for each channel were accurate to within 5 °C are listed in Table 1. As expected, T_C, which depends on ratios, is more sensitive to random noise and has larger uncertainties (Table 1).

Table 1.	T_B within 5 °C	T_C within 25 °C
GRN	1000 - 1500 °C	
RED	750 - 1200 °C	
NIR	700 - 1150 °C	
DN_{NIR}/DN_{RED}		900 - 1350 °C

In the field, data were collected in all three channels simultaneously at 50 frames per second, with gain settings and exposure times optimized for each camera to observe flows and lava spatter without saturation, while maximizing the dynamic range of the instrument. An example of a retrieved temperature map from a lava flow sequence is shown in Figure 1a.

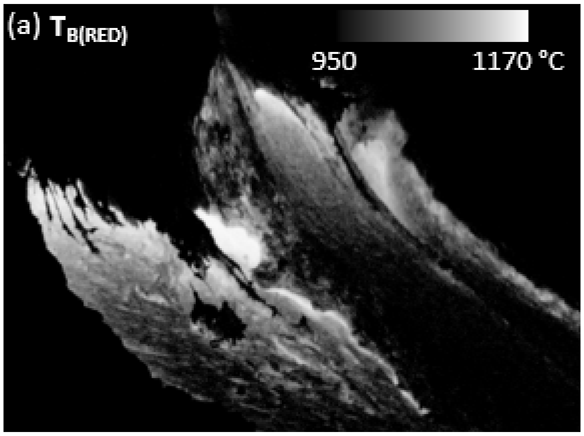
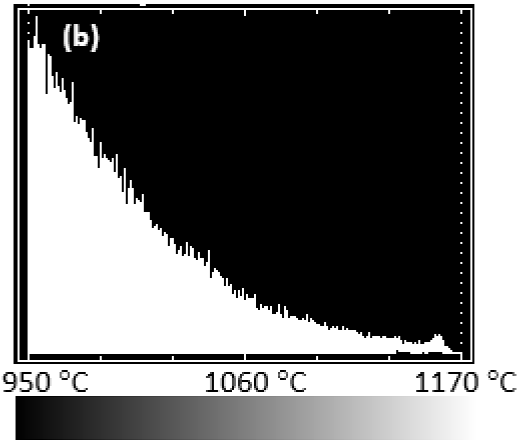


Figure 1. (a) RED Brightness Temperature (T_B) image of lava breakout from the 61g flow on Nov 30, 2016. Flow direction upper left to lower right. Distance to target ~12 m. Image ~0.5 m wide. Pixel size ~0.8 mm. Exposure time = 0.5 ms. Gain = 400. Temperature range 950-1170 °C. (b) (below) Histogram showing distribution of pixel temperature values for image in Figure 1a.



In the RED T_B image (Figure 1a) the highest single pixel temperature is 1168 °C, with a small clustering of hot pixels (histogram spike) around 1158 °C (Figure 1b). The method does not derive valid temperatures below ~930 °C, thus much of the scene is dark. Also, noise in the data are compounded by the ratio technique, resulting in a wide range of T_C values, from 0 to 2975 °C. In the T_C image, within just the active lava flow area (i.e., not including the background area) the highest single pixel temperature is 1601 °C, with a clustering of hot pixels (histogram spike) around 1060 °C. Lava eruption temperature was measured *in situ* with an Omega 1/16th inch stainless steel sheathed K-type thermocouple at 1136 °C.

Conclusions: The techniques, in general, worked well. Unsaturated data were acquired simultaneously at multiple wavelengths fast enough to capture radiances from surfaces that had suffered minimal cooling [10]. The resulting data could be converted into high spatial resolution temperature images of the emplacement of newly exposed basalt at very high temporal resolution. However, we were unable to derive reliable temperature estimates from these data because the data were heavily impacted by unstable patterned noise in the images. The noise most greatly impacted the derivation of temperatures from image ratios.

Although the overall trends seen in the data are correct where sufficient numbers of pixels can be averaged, we cannot derive reliable quantitative temepratures for the small populalion of hottest pixels. Further analysis of the noise may yield better constraints on derived temperature, but at present, these data are not adequate to provide quantitative requirements for a future imager designed to measure eruption temperatures at Io. Nevertheless, the experience has yielded a much better qualitative understanding of the necessary requirements of such a system, highlighting the importance of good spatio-tempral co-registration between multi-channel images, and good signal-to-noise ratios.

Acknowledgements: This project was funded by the NASA ROSES Outer Planets Research Program (GR14ZS00FNM0100). For their support of this project, we are grateful to: the staff at the USGS Hawaiian Volcano Observatory (Jim Kauahikaua, Steve Brantley, Tina Neal, Jeff Sutton, Matt Patrick, and Tim Orr); the State of Hawai'i Department of Land and Natural Resources, Division of Forestry and Wildlife (Nick Agorastos, Betsy Gagne, Steve Bergfeld, and Lyman Perry); the Office of Hawaiian Affairs (Pua Ishibashi); Volcopters pilot David Okita; Alicia Vaughan, Angie van Patten, Pano Spiliotis of FluxData, Inc.; Alfred McEwen, and the NASA Jet Propulsion Laboratory.

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