ERTA'ALE (ETHIOPIA) LAVA LAKE THERMAL EMISSION VARIABILITY – WHAT WE NEED TO MEASURE TO ANSWER THE BIGGEST OPEN QUESTION ABOUT IO'S LAVAS. A. G. Davies[1], L. P. Keszthelyi[2] and A. S. McEwen[3], [1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA (email: Ashley.Davies@jpl.nasa.gov); [2]USGS Astrogeology Branch, Flagstaff, AZ, USA; [3]University of Arizona, Tucson, AZ, USA.

Summary: We report on the analysis of high-spatial resolution temperature measurements of the active lava lake at Erta'Ale volcano, Ethiopia, to derive requirements for spacecraft exploration to understand eruption temperatures at Io's volcanoes. These requirements have to be considered for instruments and design of future missions to the jovian system and to Io in particular, such as the proposed Discovery-class *Io Volcano Observer* (*IVO*) [1].

Introduction: Io is the only place in the Solar System (including Earth) where very large-scale silicate volcanic processes can be observed in action. Io, therefore, provides unique insights into high-temperature and high effusion-rate volcanic processes that were important in the early histories of the early Earth, Moon, and other terrestrial planets. It is particularly important to derive eruption temperatures of Io's lavas because this applies strong constraints not only on composition but on the state of Io's mantle. The mantle state, in turn, is a function of the degree of tidal heating caused by the evolving orbital resonance between Io, Europa and Ganymede. Understanding the interior conditions of Io, therefore, provides constraints on Europa's interior state and history. Io, as the most extreme example of tidal heating in the Solar System, is the best place to understand how this process works.

Basalt versus ultramafic lavas: In the wake of the *Galileo* mission, the biggest open question is that of the lava eruption temperature of Io's dominant lavas and if they are typically in the basaltic (1300-1500 K) or ultramafic (up to ~1900 K) ranges. The importances of eruption temperature, the implications for Io's interior, and limitations of *Galileo* datasets are described elsewhere [2].

It would be ideal to know Io's lava eruption temperature to within ≈50 K. However, determination of lava eruption temperature from remote-sensing data is very difficult, as the areas at the temperatures close to eruption temperatures are small: only certain types of volcanic processes reveal large enough areas at high enough temperatures to allow remote sensing of lava eruption temperature. For Io, these eruption styles include lava fountains [2], lava tube skylights [3] and lava lakes [4]. Of these processes, lava lakes are particularly attractive targets as they are often long-lived (years to decades, so we know where they are), and, on Io, very large. The Pele lava lake is some 10's of km across, and almost certainly contains persistent lava fountains [4, 5] where escaping gas disrupts the crust on the lava lake.

Data: Hand-held infrared imagers have been used to collect thermal emission data from the anorthoclase phonolite lava lake at Erebus volcano (Antarctica) [6] in December 2005 [7] and the basalt lava lake at Erta'Ale volcano (Ethiopia) in September 2009 [8]. These data have been analysed to establish surface temperature and area distributions, and from these, the integrated thermal emission spectra for each lava lake. This analysis concentrates on Erta'Ale as it is probably the closest terrestrial analog for Io's lava lakes. Figure 1 shows an example of data obtained at Erta'Ale. At the rime of the observations (1-2 September 2009) The lava lake was 55 m in diameter and was gently overturning. Small lava fountains (≈2-3 m high) were common.

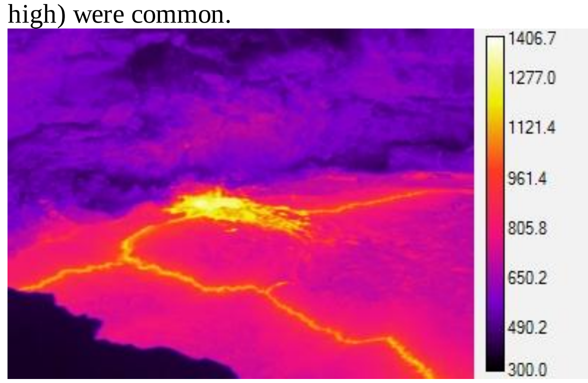

Figure 1. Part of the lava lake at Erta'Ale volcano, Ethiopia, 1 Sept 2009. The small lava fountain reveals temperatures in excess of 1400 K, close to the eruption temperature of the basaltic lava.

Using a FLIR Systems P65 thermal imager, data were obtained of the temperature distribution on the lava lake surface, and how this distribution changed as a result of styles of volcanic activity. The sequence analysed here (SEQ_0212) consists of 600 frames obtained at 25 frames/sec. This sequence was processed to generate integrated thermal emission spectra with very high spatial and spectral resolution. Having calculated the temperatuere of each active pixel, and having corrected the data for viewing angle and distance from vantage point to lake surface, the resulting data were used to examine the characteristics needed for a camera on a spacecraft to determine, or at least strongly constrain, eruption temperature.

Analysis: The data have been examined at different spatial resolutions, beginning with data deconvolved such that the entire lava lake is within one pixel, as would be seen by a distant spacecraft. We tested different pairs of observations at wavelengths from 0.4 to 1.0 µm to determine limitations of this technique and also how the variability affected 2-filter analysis. The following results come from an intermediate range observation where the lava fountain is just resolvable from the rest of the lava lake [Figure 2] – an analogous observation (heavily affected by saturation and other problems) was obtained by *Galileo* [5].

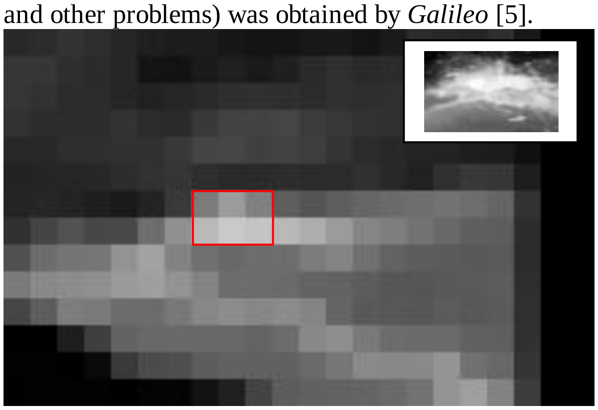

Figure 2: Deconvolved FLIR data to isolate the small lava fountain shown in the inset image.

Results: Temperatures incorporated into the integrated thermal emission spectra peaked at 1441 K, typical of basalt eruption temperatures [9]. A selection of temperatures generated from synthesized two-filter observations are shown in Table 1. Peak temperatures are typically 80 K to 100 K less than highest temperature incorporated into the derived spectra.

Table 1. Two-filter temperature derivations

	0.4/0.5 µm	0.7/0.8 µm	0.6/0.8 µm
	Temp. (K)	Temp. (K)	Temp. (K)
Maximum	1360	1324	1331
Minimum	1219	1180	1186
Average	1293	1255	1262
Stand. Dev.	31	32	32

Temporal variability and instrument operation: The determination of temporal variability of thermal emission as a function of wavelength allows the effect of the temporal aspect of camera operations to be quantified, as it may take a finite amount of time to switch camera filters. Figure 3 shows the effect of time delay on derivation of temperature from two-filter observations. A delay of 1 s causes large uncertainties, with a standard deviation of more than 140 K. This is not good enough to differentiate compositions by temperature. However, with a time delay of 0.12 s, the variation is much smaller and the standard deviation is 44 K.

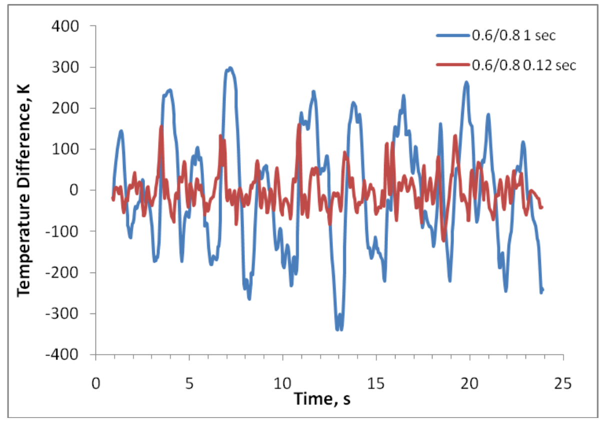

Fig. 3. Effect of time lag on 2-filter temperature derivation. Filters are centered at 0.6 and 0.8 µm.

Conclusions: To determine lava eruption temperatures from remote-sensing data, multi-wavelength observations in the visible and short-wavelength infrared have to be obtained no more than 0.1 s apart to overcome the effects of rapid cooling of lava at eruption temperatures. This constraint is met by the cameras on the proposed *Io Volcano Observer* [1]. Data at more than two visible wavelengths would further help constrain temperatures. Close-range observations, where lava fountains can be separated from the quiescent, but still hot, areas of the lava lake, are also highly desirable, unless activity is so violent that large areas at the highest temperatures are exposed which are detectable at great distances from Io. The lack of an atmosphere to inhibit gas expansion may enhance lava fountain activity in Io's active lava lakes.

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