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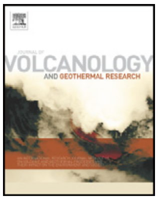

Thermal photogrammetric imaging: A new technique for monitoring dome eruptions

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ABSTRACT

Structure-from-motion (SfM) algorithms greatly facilitate the generation of 3-D topographic models from photographs and can form a valuable component of hazard monitoring at active volcanic domes. However, model generation from visible imagery can be prevented due to poor lighting conditions or surface obscuration by degassing. Here, we show that thermal images can be used in a SfM workflow to mitigate these issues and provide more continuous time-series data than visible-light equivalents. We demonstrate our methodology by producing georeferenced photogrammetric models from 30 near-monthly overflights of the lava dome that formed at Volcán de Colima (Mexico) between 2013 and 2015. Comparison of thermal models with equivalents generated from visible-light photographs from a consumer digital single lens reflex (DSLR) camera suggests that, despite being less detailed than their DSLR counterparts, the thermal models are more than adequate reconstructions of dome geometry, giving volume estimates within 10% of those derived using the DSLR.

Significantly, we were able to construct thermal models in situations where degassing and poor lighting prevented the construction of models from DSLR imagery, providing substantially better data continuity than would have otherwise been possible. We conclude that thermal photogrammetry provides a useful new tool for monitoring effusive volcanic activity and assessing associated volcanic risks.

1. Introduction

Lava domes are known to pose significant volcanic hazards, due to their tendency to generate collapse related pyroclastic flows and their association with explosive eruptions (Fink and Anderson, 2000). For example, successive dome collapses at Soufrière Hills on the island of Montserrat, starting in 1995, caused the evacuation and eventual abandonment of the capital Plymouth and surrounding areas (Wadge et al., 2014), while the 1994 collapse of Mount Merapi (Indonesia) resulted in 95 deaths and damage to several villages (Abdurachman et al., 2000). A similar event at Volcán de Colima in 2015 generated pyroclastic flows that travelled ~10 km, fortunately causing only minor damage.

Monitoring of dome geometry (e.g. volume and height), growth rate and deformation is key to forecasting such dome collapse events (Voight, 2000), and photogrammetry and structure from motion (SfM) are increasingly being used for this purpose (e.g. Herd et al., 2005; Ryan et al., 2010; Diefenbach et al., 2012; James and Varley, 2012; Diefenbach et al., 2013). Using these techniques, morphological and geometric data can be safely and inexpensively acquired, and used to track eruption progress, identify signs of instability or changes in effusion rate, and forecast changes in volcanic risk. These methods, however, rely on clear viewing conditions and so are highly sensitive to degassing, cloud and poor lighting conditions.

Thermal imaging techniques are also widely used for monitoring purposes (Spampinato et al., 2011), as they allow quantitative evaluation of heat flux from volcanic vents (e.g. Harris and Stevenson, 1997; Sahetapy-Engel et al., 2008), domes (e.g. Hutchison et al., 2013; Pallister et al., 2013), flows (e.g. Calvari et al., 2003; James et al., 2006) and fumaroles (e.g. Stevenson and Varley, 2008; Harris et al., 2009). Importantly, the spatial distribution of heat flux can reveal features that are difficult to detect using reflected visible light, such as fumaroles, fractures and rock fall traces (Hutchison et al., 2013; Mueller et al., 2013).

Changes in the distribution and intensity of thermal anomalies can also precede volcanic eruptions or changes in eruptive style (Spampinato et al., 2011) and thus have potential for hazard forecasting. However, to facilitate inter-survey comparisons, thermal data need to be spatially referenced, and producing orthorectified thermal maps

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usually requires additional topographic data, knowledge of the camera location and viewing direction (e.g. James et al., 2006; James et al., 2009; Lewis et al., 2015).

This study demonstrates a method for deriving topographic data and georeferenced thermal maps directly from oblique thermal imagery using SfM techniques and imagery captured during an episode of dome growth at Volcán de Colima (Mexico) between 2013 and 2015. We suggest that the resulting three-dimensional thermal models provide intuitive and georeferenced representations of dome surface temperature and valuable measurements of dome geometry. Furthermore, we demonstrate that despite the lower spatial resolution of thermal images, dome volume estimates are comparable to those estimated using SfM reconstructions deriving from visible-light digital single lens reflex (DSLR) photographs, and that unlike the DSLR models, the thermal models can be constructed during periods of poor lighting and extensive degassing.

Volcán de Colima is an andesitic and frequently erupting stratovolcano, located at the western limit of the Trans-Mexican Volcanic Belt. During the most recent eruptive periods, six episodes of dome growth have been observed at the volcano (1998–1999, 2001–2003, 2004, 2007–2011, 2013–2015 and an ongoing episode initiated in February 2016). This represents the most active period at the volcano since its last catastrophic eruption in 1913. A range of effusion rates have been estimated, with the longer-lived eruptions associated with rates as low as 0.01 $m^3 s^{-1}$. During the current eruption the volcano has exhibited the continuous generation of small Vulcanian explosions with a frequency of the order of hours. Larger magnitude explosions usually follow periods of dome emplacement, which re-excavate the summit crater.

The episode of dome growth investigated in this study began in January 2013 when lava erupted into the base of a ~150 m wide and ~50 m deep crater formed (by several large explosions that same month) on top of a previous (2007 to 2011) lava dome. The new dome proceeded to fill this crater and by April 2013 overflowed to form several lava flows and eventually fill the entire summit crater (~300 m across). Several partial collapses (accompanied by increased volcanic activity) resulted in dome destruction on 10–11 July 2015; pyroclastic density currents generated by these collapses travelled up to ~10.6 km along the ravine of Montegrande, threatening several ranches and the town of Quesaría (pop. 8611 in 2010). This eruption was the largest (by volume) at Volcán de Colima since 1913.

2. Methods

2.1. Image capture and pre-processing

Images (Fig. 1) were acquired using a consumer DSLR (Nikon D90) and a thermal camera (Jenoptik VarioCAM HiRes) from a light aircraft during 30 observation flights, conducted at intervals of approximately one month. The DSLR had an 18–105 mm zoom lens (most images were captured using the 105 mm setting), while the thermal camera used a 75 mm fixed-focal lens. Thermal images had an order of magnitude lower resolution than the DSLR images (640 × 480 pixels and 4288 × 2848 pixels respectively).

Observational flights involved 2–3 circuits around the crater at a slightly higher elevation than the summit. Typical viewing distances varied between ~1–3 km, corresponding to ground sampling distances of ~5–15 cm/pixel for the DSLR camera (at full zoom) and ~25–75 cm/-pixel for the thermal camera. Both cameras were operated by hand, with DSLR photographs captured every ~5–10 s and the thermal camera programmed to take an image every 3.5 s.

Blurry and poorly exposed images were manually removed from the resulting image sets (of ~100 DSLR images and ~200–400 thermal images) prior to photogrammetric processing. Normally, ~50–75 DSLR images and ~100–200 thermal images were considered usable, though this varied substantially with viewing conditions.

The thermal images were converted from Jenoptik's proprietary IRB format to JPEG (using a colour scale selected to maximise the amount of detail visible on the dome and volcanic flanks) before photogrammetric processing. A second set of JPEG images were additionally created from the thermal images using a fixed colour scale, and later projected onto

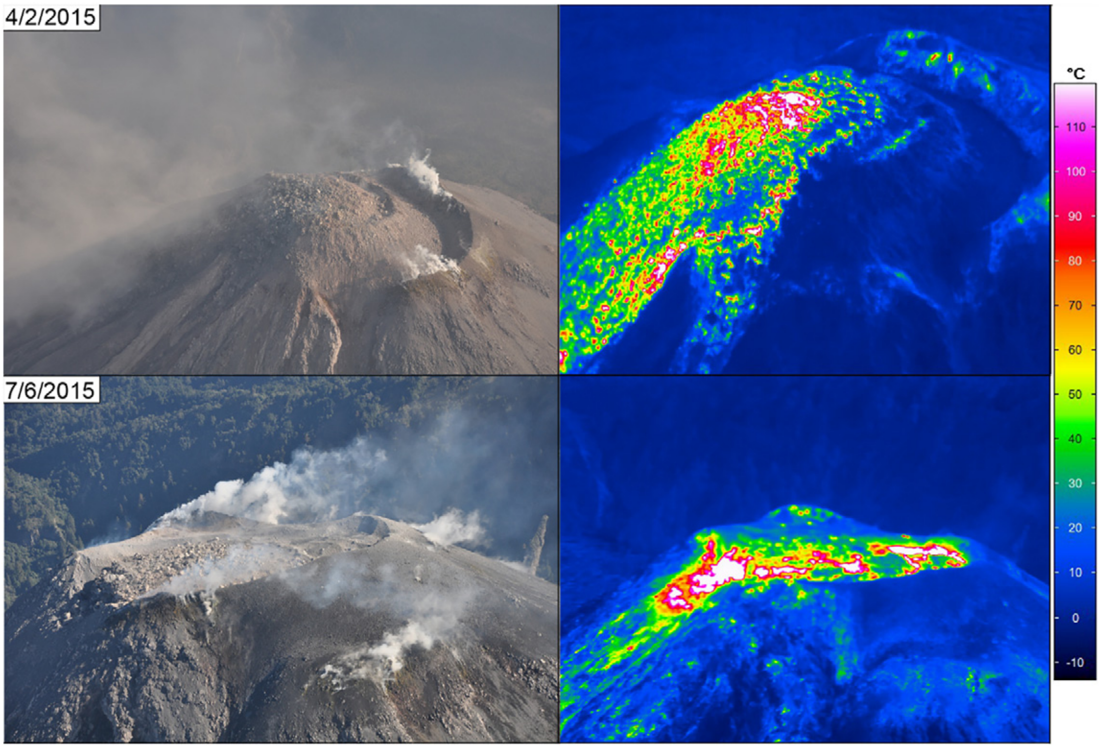

Fig. 1. Examples of typical DSLR (left) and thermal (right) images from two different observation flights. Both views are looking to the north-west, and the summit region is ~300 m across.