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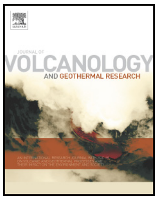

Integrated thermal infrared imaging and structure-from-motion photogrammetry to map apparent temperature and radiant hydrothermal heat flux at Mammoth Mountain, CA, USA

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ABSTRACT

This work presents a method to create high-resolution (cm-scale) orthorectified and georeferenced maps of apparent surface temperature and radiant hydrothermal heat flux and estimate the radiant hydrothermal heat emission rate from a study area. A ground-based thermal infrared (TIR) camera was used to collect (1) a set of overlapping and offset visible imagery around the study area during the daytime and (2) time series of co-located visible and TIR imagery at one or more sites within the study area from pre-dawn to daytime. Daytime visible imagery was processed using the structure-from-motion photogrammetric method to create a digital elevation model onto which pre-dawn TIR imagery was orthorectified and georeferenced. Three-dimensional maps of apparent surface temperature and radiant hydrothermal heat flux were then visualized and analyzed from various computer platforms (e.g., Google Earth, ArcGIS). We demonstrate this method at the Mammoth Mountain fumarole area on Mammoth Mountain, CA. Time-averaged apparent surface temperatures and radiant hydrothermal heat fluxes were observed up to 73.7 °C and 450 W m^{-2}, respectively, while the estimated radiant hydrothermal heat emission rate from the area was 1.54 kW. Results should provide a basis for monitoring potential volcanic unrest and mitigating hydrothermal heat-related hazards on the volcano.

1. Introduction

The measurement of surface temperatures and hydrothermal heat fluxes, their temporal variation, and spatial relationship to topography and geologic structures is important for understanding volcanic processes, monitoring volcanic activity and impacts of geothermal development, and geothermal exploration and resource assessment (e.g., Chiodini et al., 2001; Richter et al., 2004; Fridriksson et al., 2006; Bergfeld et al., 2006; Spampinato et al., 2011 and references therein; Vaughan et al., 2012; Hurwitz et al., 2012; Vaughan et al., 2014). The use of traditional ground-based methods (e.g., thermocouple) to measure temperatures and heat fluxes over large areas is laborious, time consuming, and sometimes hazardous. Thermal infrared (TIR) imaging from satellite and airborne platforms offers the ability to map thermal anomalies remotely and over large land areas that may be otherwise inaccessible. However, airborne imaging is relatively expensive, and the spatial resolution of acquired imagery from airborne and satellite platforms may be insufficient to map the spatial variability of thermal anomalies of interest. Handheld TIR cameras offer the benefits of ease of use, relatively low-cost surveys, high spatial resolution (to mm-scale) imagery, and high rate (to 60 Hz) of image acquisition (e.g., see review by Spampinato et al., 2011 and references therein; Schöpa et al., 2011; Patrick et al., 2014; Worden et al., 2014; Vilardo et al., 2015). However, the use of ground-based TIR cameras introduces the disadvantages of highly oblique and often unknown viewing orientation. Furthermore, TIR imagery should be collected before dawn in volcanic and geothermal systems to minimize the effects of solar heating and reflection (e.g., Spampinato et al., 2011 and references therein). In the absence of, for example, deploying numerous (typically four per TIR image) precisely located thermal targets and carrying out terrestrial laser scanning (ground-based LiDAR), these aspects create major challenges for orthorectification and quantitative analysis of the TIR imagery.

Structure from motion (SfM) is a relatively cost, time, and computationally efficient photogrammetric method used to map 3-D structures and create digital elevation models (DEMs) with a sequence of overlapping visible images (examples of geoscience applications include Westoby et al., 2012; James and Robson, 2012; Fonstad et al., 2013; Johnson et al., 2014). James et al. (2006) applied SfM to create a DEM from visible images of a lava flow on Mount Etna, Italy. Thermal targets contained within the visible and TIR imagery were used to estimate TIR camera orientation in the reference frame of the visible imagery, which

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allowed the TIR imagery to be orthorectified. The present study builds on this work by creating georeferenced joint topographic-thermal maps without the use of precisely located thermal targets. We do this by collecting time series (pre-dawn to daytime) of co-located visible and TIR images and integrating them with a sequence of overlapping visible images of a study area. This imagery was used to estimate apparent ground temperatures and radiant hydrothermal heat flux over the study area described below.

The study area used to develop this method was Mammoth Mountain, which is a dacite dome complex located on the southwestern rim of Long Valley caldera, eastern California (Fig. 1). Mammoth Mountain has undergone unrest over the past several decades, manifested as seismic swarms, ground deformation, and diffuse, non-thermal magmatic CO_2 emissions from five primary areas on the volcano flanks (e.g., Hill and Prejean, 2005 and references therein; Lewicki et al., 2014; Lewicki and Hilley, 2014). The Mammoth Mountain fumarole area (MMF) is located within one of the areas of diffuse, non-thermal CO_2 degassing (Fig. 1). Increases in $^3He/^4He$ ratios, flow rate, and temperature of gases at MMF were observed during an 11-month-long seismic swarm that occurred in 1989 and was ascribed to dike emplacement and/or migration of CO_2-rich magmatic fluids beneath the volcano (Sorey et al., 1998; Hill and Prejean, 2005). Mammoth Mountain is also host to one of the largest ski areas in the United States. In 2006, three ski patrollers died in an accident at MMF after exposure to toxic levels of volcanic gases that built up in a hydrothermal heat-produced snow cave at the site (Covarrubias, 2006). Mapping and monitoring change in surface temperature, and hydrothermal heat flux on Mammoth Mountain is therefore important for monitoring potential intrusive activity as well as for evaluating potential hazards to people working and recreating on the volcano.

2. Methods

Fig. 2 shows the workflow and associated technology we employed for data acquisition and processing. In the overall procedure, we (1) acquired pre-dawn to daytime time series of co-located visible and TIR imagery from two tripod locations; (2) collected a set of daytime overlapping visible imagery along a radial path around the study site and processed it, along with a daytime visible image from each of the two tripod locations using the SfM method to produce a DEM of the area; (3) applied an apparent surface temperature threshold (T_{min}) to pre-dawn TIR imagery and calculated time-averaged apparent surface temperatures for each of the scenes associated with the two tripod locations; (4) orthorectified and georeferenced time-averaged apparent surface temperatures to create a map of apparent surface temperature; (5) calculated radiant hydrothermal heat fluxes for each pre-dawn TIR image using the Stefan Boltzmann equation, applied a radiant hydrothermal heat flux threshold (T_{cut}) and time-averaged heat fluxes for each of the two scenes; (6) orthorectified and georeferenced time-averaged radiant hydrothermal heat fluxes to create a map of radiant hydrothermal heat flux; and (7) visualized joint thermal-topographic maps in ArcGIS and Google Earth. Details are given below.

2.1. Data acquisition

Co-located visible and thermal images were simultaneously acquired at the MMF site with a forward-looking infrared (FLIR) model T650sc thermal imaging camera mounted on a tripod. The resolution of visible digital photographs is 2560 × 1920 pixels. The TIR sensor is made of uncooled microbolometers, with a spectral range of 8–14 μm and a sensitivity and accuracy at around 30 °C of ± 0.02 and 1 °C,

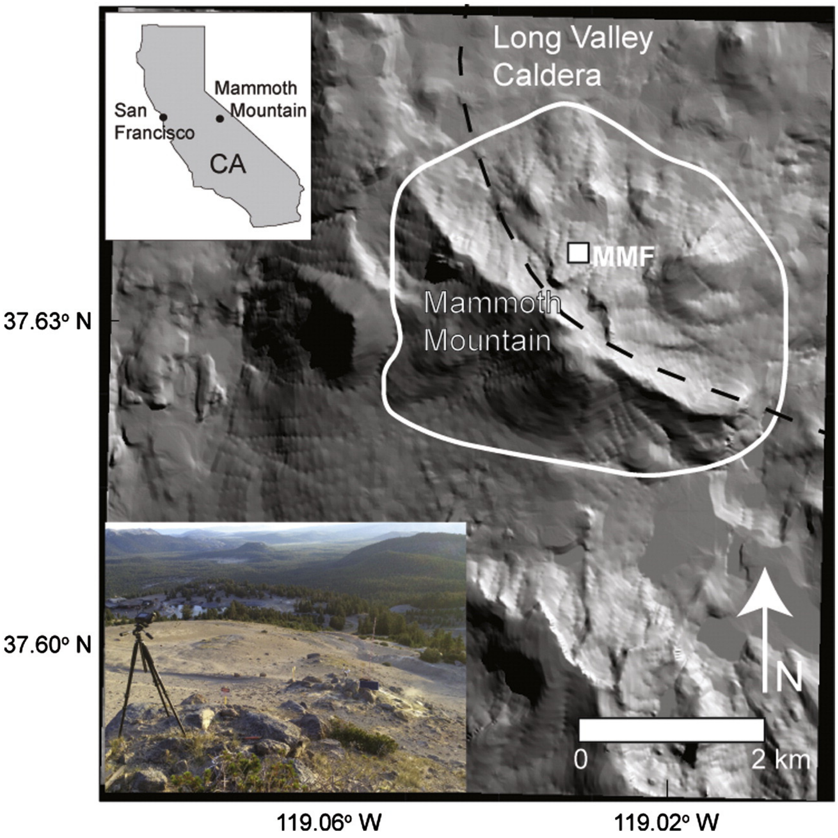

Fig. 1. Shaded relief map of Mammoth Mountain and surrounding area. Dashed black and solid white lines show approximate location of Long Valley caldera rim and extent of major Mammoth Mountain dacite flows, respectively. Square shows location of the Mammoth Mountain fumarole (MMF) area. Bottom left inset is photo of the FLIR T650sc thermal infrared camera mounted on tripod above the MMF area.