Remote Sensing of Environment xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Using picosatellites for 4-D imaging of volcanic clouds: Proof of concept using ISS photography of the 2009 Sarychev Peak eruption

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A R T I C L E I N F O

Keywords:
Volcanic ash clouds
Photogrammetry
Cloud top height
Sarychev Peak
International Space Station
Telematics Earth Observation Mission
Satellite formation
Picosatellites

A B S T R A C T

Volcanic ash clouds can present an aviation hazard over distances of thousands of kilometres and, to help to mitigate this hazard, advanced numerical models are used to forecast ash dispersion in the atmosphere. However, forecast accuracy is usually limited by uncertainties in initial conditions such as the eruption rate and the vertical distribution of ash injected above the volcano. Here, we demonstrate the potential of the Telematics Earth Observation Mission (TOM) picosatellite formation, due for launch in 2020, to provide valuable information for constraining ash cloud dispersion models through simultaneous image acquisition from three satellites. TOM will carry commercial frame cameras. Using photogrammetric simulations, we show that such data should enable ash cloud heights to be determined with a precision (~30–140 m depending on configuration) comparable to the vertical resolution of lidar observations (30–180 m depending on the cloud height). To support these estimates, we processed photographs taken from the International Space Station of the 2009 Sarychev Peak eruption, as a proxy for TOM imagery. Structure-from-motion photogrammetric software successfully reconstructed the 3-D form of the ascending ash cloud, as well as surrounding cloud layers. Direct estimates of the precision of the ash cloud height measurements, as well as comparisons between independently processed image sets, indicate that a vertical measurement precision of ~200 m was achieved. Image sets acquired at different times captured the plume dynamics and enabled a mean ascent velocity of 14 m s^{-1} to be estimated for regions above 7 km. In contrast, the uppermost regions of the column (at a measured cloud top height of ~11 km) were not ascending significantly, enabling us to constrain a 1-D plume ascent model, from which estimates for the vent size (50 m) and eruption mass flux (2.6 × 10^{6} kg s^{-1}) could be made. Thus, we demonstrate that nanosatellite imagery has the potential for substantially reducing uncertainties in ash dispersion models by providing valuable information on eruptive conditions.

1. Introduction

Volcanic ash clouds represent a serious hazard to aviation and can cause widespread disruption. Numerical models are used to forecast ash cloud dispersion away from volcanoes. However, forecast accuracies are limited by poor constraints on eruption source parameters, including how high the ash is emplaced at the source, the mass eruption rate and the near-source plume dynamics (Bonadonna et al., 2012; Zehner, 2010). Uncertainties in these parameters can lead to particularly different forecast results in areas of high wind shear, e.g. Heinold et al. (2012), which can occur across height intervals of < 500 m. Here, we show that pico- and nanosatellites can be used to provide valuable data to constrain ash cloud dispersion models by providing high quality estimates of ash cloud height and by constraining eruption models.

Ground-based measurements of ash cloud properties can be made by weather radar (Lacasse et al., 2004; Rose et al., 1995), specialised Doppler radar (Donnadieu, 2012; Hort and Scharff, 2016; Scharff et al., 2012) or lidar (Hervo et al., 2012; Mona et al., 2012). However, such observations are restricted by the spatial and temporal availability of instruments. Wider opportunities are provided by satellite remote sensing and a recent overview of satellite techniques for observations of volcanic Cloud Top Height (CTH) is given by Merucci et al. (2016).

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https://doi.org/10.1016/j.rse.2018.02.061
Received 18 October 2017; Received in revised form 6 January 2018; Accepted 22 February 2018
0034-4257/

Operationally used height estimates are based on satellite observations of brightness temperature in CO_2 absorption bands (Frey et al., 1999), but these estimates are of low accuracy, e.g. with biases of > 1 km and standard deviations of ~3 km (Holz et al., 2008). The most precise CTH measurements are achieved with satellite lidar such as the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) instrument on the CALIPSO satellite (NASA, 2014), with a horizontal resolution of 333–1667 m and vertical resolution of 30–180 m, depending on the distance to the ground. CALIOP has already been used successfully for volcanic ash cloud monitoring at Chaiten 2008 (Carn et al., 2009), Kasatochi 2008 (Karagulian et al., 2010), and Eyjafjallajökull 2010 (Stohl et al., 2011). However, by providing only nadir measurements over swath width of 1 km, the instrument has a revisit time of 16 days and so is unlikely to capture the earliest stages of eruptions, when estimation of initial eruption parameters is critical for timely and accurate ash dispersion modelling.

Future measurement opportunities will be offered by the continuously increasing capabilities of pico- and nanosatellites, e.g. CubeSats, with a mass between 1 and 10 kg, and a size approximately that of a toaster (Chin et al., 2008; Heidt et al., 2000; Puig-Suari et al., 2001; Schilling, 2006; Zurbuchen et al., 2016). Such platforms have many benefits over classic satellites including simpler and cheaper designs, faster build times and, consequently, many more units can be deployed. They can be applied to Earth surface monitoring (Selva and Krejci, 2012), and a constellation of > 150 CubeSats from the company Planet is already delivering almost daily global coverage with up to 3 m spatial resolution in the visible spectrum (Planet, 2017). CubeSats are also currently being used for atmospheric monitoring, e.g. Stratos satellites for atmospheric profiles retrieval (Spire, 2017). Recent advances are developing the capability for in-orbit cooperation, to form self-organizing picosatellite formations (Schilling et al., 2017) rather than constellations (in which each satellite is individually controlled from ground). Formations will offer further interesting potential for innovative approaches in Earth observation applications and, here, we consider the forthcoming Telematics Earth Observation Mission (TOM), which is specifically designed for retrieving accurate CTH measurements by simultaneous acquisition of visible imagery from three different nanosatellites. The TOM is part of the Telematics International Mission (TIM; Schilling et al., 2017), and we focus on application of the TOM system for retrieving the height of volcanic ash clouds.

In this work, we first review photogrammetric approaches to volcanic CTH measurements, then quantify CTH measurement precision for TOM and assess its sensitivity through processing simulated photogrammetric image networks. Finally, to test the use of structure-from-motion photogrammetric software on images of a real plume, and to demonstrate what eruptive parameters can be derived, we provide a case study in which images of the Sarychev 2009 eruption captured by astronauts on the International Space Station (ISS), are processed and used to constrain a 1-D eruption model.

2. Ash cloud photogrammetry using satellite data

The earliest use of satellite data to estimate ash cloud heights with photogrammetric methods relied on measuring the length of the shadow cast by the cloud under known illumination conditions (Glaze et al., 1989; Prata and Grant, 2001; Simpson et al., 2000; Spinetti et al., 2013). However, more recent approaches, based on photogrammetric analysis of image pairs, use the observation of parallax shifts (apparent movement in the projection plane). Photogrammetric methods can have a substantial advantage over other techniques for measuring cloud top heights due to requiring fewer metadata and assumptions about atmospheric conditions (Merucci et al., 2016). However, clouds can move very rapidly (e.g. > 50 m s^{-1}) and so, if images are not acquired simultaneously, additional estimates of cloud motion are also required (de Michele et al., 2016; Nelson et al., 2013; Urai, 2004). For a system to be fully independent of any additional atmospheric information, simultaneous observations of the same area must be available from two or more satellites (Zakšek et al., 2015).

2.1. Parallax observations from a single satellite

The most common approach to cloud photogrammetry is through instruments with multi-angle observation capabilities; for example, Prata and Turner (1997) used the forward and nadir views of the Along Track Scanning Radiometer (ATSR) to determine volcanic CTH for the 1996 Mt. Ruapehu eruption. ATSR was used also by Muller et al. (2007), who proposed that a combination of visible and thermal bands could yield information on multi-layer clouds. The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) is also equipped with two cameras, and derived stereo cloud top heights have shown values that were ~1000 m higher than Moderate-resolution Imaging Spectroradiometer (MODIS) brightness temperature heights (Genkova et al., 2007). The Multi-angle Imaging SpectroRadiometer (MISR) has been utilized to retrieve volcanic CTH, optical depth, type, and shape of the finest particles for several eruptions (Flower and Kahn, 2017; Kahn and Limbacher, 2012; Nelson et al., 2013; Scollo et al., 2010, 2012; Stohl et al., 2011). The stereo infrared spectral imaging radiometer flown on mission STS-85 of the space shuttle in 1997 has also been used to estimate CTH (Lancaster et al., 2003). Comparing the results with coincident direct laser ranging measurements from the shuttle laser altimeter showed that the radiometer mean heights were about 100 m greater, although this could be reduced if the data are segmented first (Manizade et al., 2006).

The most recent volcanic CTH estimation used high resolution imagery from the Operational Land Imager (OLI) on Landsat 8 (de Michele et al., 2016), which retrieves multispectral channels at 30 m resolution and a panchromatic channel at 15 m resolution. Due to the very short time lag between the retrievals of different channels (< 1 s), the baseline available to estimate CTH from a single satellite overpass (the distance between satellite positions at the time of retrieval for each spectral channel) is also relatively short (about 4 km from an orbit height of 705 km). Thus, a CTH accuracy better than ~500 m (de Michele et al., 2016) can only be achieved using high resolution imagery (~10 m) in which parallax can be resolved over such short baselines. If image resolution is coarser (e.g. 275 m for MISR), then a larger baseline is required.

2.2. Parallax observations from two different satellites

The use of two independent geostationary satellites for stereoscopic measurements of meteorological cloud-top heights was proposed several decades ago (Hasler, 1981; Hasler et al., 1983, 1991; Ondrejka and Conover, 1966; Wylie et al., 1998; Wylie and Menzel, 1989), with the results accurate to between 500 m (Hasler et al., 1983) and 1000 m (Seiz et al., 2007). For ash clouds, a combination of Meteosat-5/−8 TIR data has been used to monitor the eruption of Karthala in 2005 (Carboni et al., 2008) and Etna in 2013 (Merucci et al., 2016). A combination of satellites in low and geostationary orbits can also be used (Hasler et al., 1983) although this has only been applied so far to the 2010 Eyjafjallajökull (Zakšek et al., 2013) and 2013 Etna eruptions (Corradini et al., 2016) with MODIS and Spinning Enhanced Visible and InfraRed Imager (SEVIRI) images.

2.3. Telematics earth observation mission

The Telematics Earth Observation Mission (TOM) is a proposed satellite mission for photogrammetric observations of clouds (Zakšek et al., 2015) and will be realized as part of the international Telematics International Mission (TIM; Schilling et al., 2017), that is focused on the application of picosatellites (CubeSats) for Earth observation purposes. TOM is dedicated to observing cloud top heights and will be launched as a formation of three satellites in 2020. The satellites will be operated