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Volcanic Plume Elevation Model and its velocity derived from Landsat 8

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ABSTRACT

In this paper we present a method to restitute the volcanic gas/ash Plume Elevation Model (PEM) from optical satellite imagery. As the volcanic plume is moving rapidly, conventional satellite based photogrammetric height restitution methods do not apply as the epipolar offset due to plume motion adds up to the one generated by the stereoscopic view. This is because there are time-lags of tens of seconds between conventional satellite stereoscopic acquisitions, depending on the stereo acquisition mode. Our method is based on a single satellite pass. We exploit the short time lag and resulting baseline that exist between the multispectral (MS) and the panchromatic (PAN) bands to jointly measure the epipolar offsets and the perpendicular to the epipolar (P2E) offsets. The first are proportional to plume height plus the offsets due to plume velocity in the epipolar direction. The second, are proportional to plume velocity in the P2E direction only. The latter is used to compensate the effect of plume velocity in the stereoscopic offsets by projecting it on the epipolar direction assuming a known plume direction, thus improving the height measurement precision. We apply the method to Landsat 8 data taking into account the specificities of the focal plane modules. We focus on the Holuhraun 2014 fissure eruption (Iceland). We validate our measurements against ground based measurements. The method has potential for detailed high resolution routine measurements of volcanic plume height/velocity. The method can be applied both to other multifocal plane modules push broom sensors (such as the ESA Sentinel 2) and potentially to other push-broom systems such as the CNES SPOT family and Pléiades.

1. Introduction

1.1. Importance

The retrieval of both height and velocity of a plume is an important issue in volcanology. As an example, it is known that large volcanic eruptions can temporarily alter the climate, causing global cooling and shifting precipitation patterns (e.g. Robock, 2000); the ash/gas dispersion in the atmosphere, their impact and lifetime around the globe, greatly depends on the injection altitude. Plume height information is critical for ash dispersion modelling and air traffic security. Furthermore, plume height during explosive volcanism is the primary parameter for estimating mass eruption rate (e.g. Mastin et al., 2009). Knowing the plume altitude is also important to get the correct amount of SO_2 concentration from dedicated spaceborne spectrometers (e.g. Carboni, Grainger, Walker, Dudhia, & Siddans, 2012; Corradini, Merucci, Prata, & Piscini, 2010). Moreover, the distribution of ash deposits on ground greatly depends on the ash cloud altitude, which has an impact on risk assessment and crisis management. Furthermore, a spatially detailed plume height measure could be used as a hint for gas emission rate estimation and for ash plume volume researches, which both have an impact on climate research, air quality assessment for aviation and finally for the understanding of the volcanic system itself as ash/gas emission rates are related to the state of pressurization of the magmatic chamber (e.g. Hreinsdottir et al., 2014; Urai, 2004). Today, the community mainly relies on ground based measurements (e.g. Arason, Petersen, & Bjornsson, 2011; Petersen, Bjornsson, Arason, & von Löwis, 2012; Scollo et al., 2014) but often they can be difficult to collect as by definition volcanic areas are dangerous areas (presence of toxic gases) and can be remotely situated and difficult to access. Satellite remote sensing offers a comprehensive and safe way to estimate plume height. The various techniques that can be used today either estimate average volcanic plume heights indirectly, based on wind speed for instance (see Sparks et al., 1997 for a review) or plume shadowing (e. g. Simpson, McIntire, Jin, & Stitt, 2000; Spinetti et al., 2013), each of which do not aim at restituting a spatially detailed map of the plume heights. Conventional photogrammetric restitution based on satellite imagery fails in precisely retrieving a Plume Elevation Model as the plume own velocity induces an apparent parallax that adds up to the standard parallax given by the stereoscopic view. Therefore, measurements based on standard satellite photogrammeric restitution do not apply as there is an ambiguity in the measurement of the plume position. Standard spaceborne along-track stereo imagers (e.g. SPOT 5, ASTER or Quickbird among the others) present a long temporal lag between the two stereo image acquisitions. It can reach tens of seconds

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for baseline-to-height ratios (B/H) between 0.2 and 0.5, during which time the surface texture of the plume may have changed due to the plume fast displacement (i.e. velocities larger than 10 m/s) biasing automatic cross correlation offset measurements (Kääb & Leprince, 2014). Urai (2004) succeeded in retrieving the plume height on Miyakejima volcano using ASTER stereoscopic view, on 3 specific points manually chosen on the forward and backward images. However, for the purpose of PEM extraction, the ideal is as small as possible time lag, with still a B/H ratio large enough to provide a stereoscopic view for restituting the height.

1.2. Method

In this study we propose to use the physical distance that exists between the panchromatic band (PAN) and a multispectral band (MS) in push broom spaceborne sensors to jointly measure the plume velocity and its height, at a high spatial resolution. A number of push broom sensors present a physical distance between the PAN and MS bands. This is because the PAN and MS Charge Coupled Devices (CCDs) sensors cannot coexist in an identical position on the focal plane of the instrument. This physical offset between the CCDs yields a baseline (i.e. the distance between the sensor positions when it acquires two images) and a time lag between the PAN and the MS bands acquisitions. On the one hand, the small baseline has already been successfully exploited for retrieving Digital Elevation Models (DEMs) of still surfaces such as topography or building heights (e.g. Mai & Latry, 2009; Massonnet, Giros, & Breton, 1997; Vadon, 2003). On the other hand, the time lag has been successfully exploited to measure the velocity field of moving surfaces, such as ocean waves and artic river discharges (e. g. de Michele, Leprince, Thiébot, Raucoules, & Binet, 2012; Kääb, Lamare, & Abrams, 2013; Kääb & Leprince, 2014; Poupardin, Idier, de Michele, & Raucoules, 2015). The problem of extracting a spatially detailed elevation model of a moving surface such as a volcanic gas/ash plume has not yet been addressed by common photogrammetric methods. The aim of this paper is to propose a method to address this problem. We propose a method based on a single pass of Landsat 8. We focus on the 2014–2015 Holuhraun fissure eruption (Iceland) as a test case.

The 2014–2015 Holuhraun eruption in the Bárðarbunga volcanic system is the largest fissure eruption in Iceland since the 1783 Laki eruption (Sigmundsson et al., 2015). It started at the end of August 2014 and lasted six months, to late February 2015. It has been characterized by large degassing processes and emission of SO_2 into the atmosphere (Gettelman, Schmidt, & Kristjánsson, 2015; Haddadi, Moune, Sigmarsson, Gauthier, & Gouhier, 2015). The eruption steam and gas column was nicely captured by the Landsat 8 on 6 September 2014 at 12:25 UTC (Fig. 1). The reasons why we use Landsat 8 data are manyfold. Firstly, Landsat 8 captured the Holuhraun fissural eruption on a clear sky conditions. Secondly, raw Landsat 8 data are provided free of charge by the United States Geological Survey (USGS). Thirdly, Landsat 8 CCD sensors accommodation on the focal plane is somehow similar to the one employed by the ESA Sentinel-2, which is of high interest for the ash/gas plume research community as Sentinel-2 data will be free of charge and high revisit time. We chose the Holuhraun eruption as it represents a challenging test case for us as its plume was rapidly moving and reached low altitudes. Therefore, if our method works on the Holuhraun test case then it will apply to other types of volcanic plumes (higher and slower).

2. Data

The Landsat 8 Operational Land Imager (OLI) is a push-broom (linear array) imaging system that collects visible, Near-InfraRed (NIR), and Short-Wavelength InfraRed (SWIR) spectral band imagery at 30-m (15-m panchromatic) ground sample distance (Storey, Choate, & Lee, 2014). It collects a 190-km-wide image swath from a 705-km orbital altitude.

The OLI architecture is described as follows by Knight and Kvaran (2014) and Storey et al. (2014). The OLI detectors are distributed across 14 separate Focal Plane Modules (FPMs), each of which covers a portion of the 15-degree OLI cross-track field of view. Adjacent FPMs are offset in the along-track direction to allow for FPM-to-FPM overlap. This is to avoid any gaps in the cross-track coverage. The reader should refer to Fig. 1 in Storey et al. (2014) for the OLI layout image. The important point in this study is that the internal layout of all 14 FPMs is the same, but with alternate FPMs being rotated by 180° to keep the active detector areas as close together as possible. This has the effect of inverting the along-track order of the spectral bands in adjacent FPMs. Such an assembling of FPMs is rather frequent for multi-spectral sensors and is similar to the Sentinel-2 sensor. The OLI can be thought of as being composed of 14 individual sub-sensors, each of which covers approximately 1/14th of the cross-track field of view. Details of the OLI focal plane layout are presented by Knight and Kvaran (2014) and Storey et al. (2014). USGS provide orthorectified Landsat 8 data free of charge and raw data on demand. Our analysis is based on raw data.

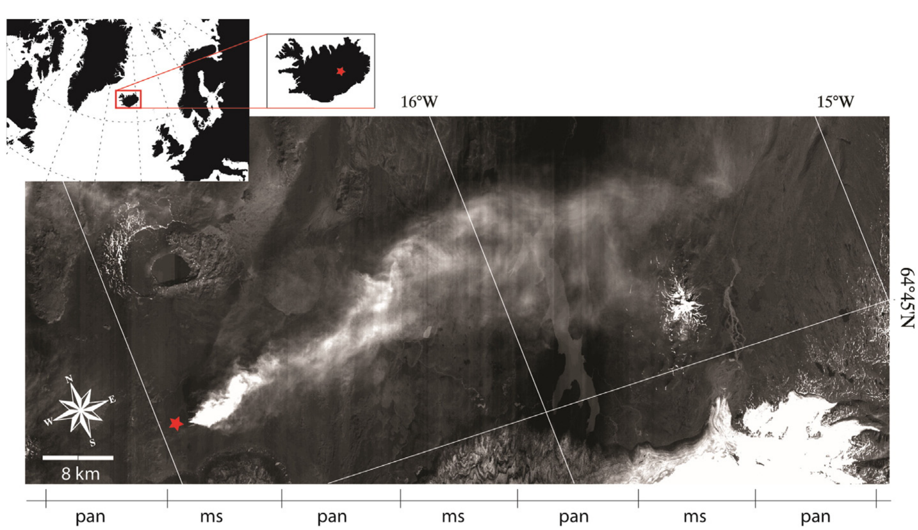

Fig. 1. The study area. Holuhraun (Iceland) eruption site (red star) and the volcanic plume from Landsat 8. The data were acquired on 6 September 2014. We reconstructed this image from raw Landsat data (courtesy of USGS). The image is made of alternate PAN–MS stripes from adjacent FPMs. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)