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A low-cost method applicable worldwide for remotely mapping lava dome growth

Estelle Chaussard

Department of Geology, University at Buffalo, 126 Cooke Hall, Buffalo, NY 14260, United States

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ABSTRACT

Lava dome growth and collapse represents both a significant hazard, as it can trigger pyroclastic density currents, and a monitoring challenge, limiting monitoring to a few known active volcanoes. Here, I propose a new differencing technique based on Synthetic Aperture Radar (SAR) amplitude images to quantify the extent of lava dome growth. This differencing technique, which is both low cost and can be utilized worldwide, is applied to SAR amplitude images at Mount St. Helens and validated using 2004–2008 aerial photography observations. Difference of amplitude images accurately characterize the dome growth location. The low ground resolution of the 2004–2008 SAR data leads to underestimation by 10 to 15% of the dome extent, but the accuracy of this method will increase with the improved resolution of current and future SAR missions. Amplitude images are a low-level SAR product available from all SAR satellites, mostly freely, making the proposed method ideal for systematic, low-cost monitoring of lava dome growth worldwide with minimum processing required.

1. Introduction

Lava domes are formed by viscous magma erupting and pilling up near a volcanic vent. They are commonly found within the crater of composite volcanoes, such as Mount St. Helens, but also occur on the flanks of volcanoes. Lava domes can have various morphologies, which are mainly controlled by the slope of emplacement and the viscosity of the magma. Blake (1989) distinguished between circular and flat-topped dome (Tortas), circular and spiney domes (Pelean), piston shaped domes (Upheaved Plugs), and a hybrid form between a dome and a lava flow (Coulee). A lava dome can form as a distinct event or may grow from successive eruptions (Huppert et al., 1982). Growth rate can vary greatly through time at a single volcano. For example, the 1995–1997 Montserrat dome growth started slowly and accelerated (Sparks et al., 1998), while the 2004–2008 Mount St. Helens dome growth did the opposite (Major et al., 2008). Two main style of dome growth exist, growth by addition of material on top, common for Pelean domes, and growth by internal processes in which the lava fills in the center of the dome near the vent and pushes layers outward, forming an onion-like internal structure, common for Tortas. A dome may alternate between these processes, as observed at Unzen volcano (Nakada et al., 1995) with corresponding change in the dome morphology.

The danger associated with volcanic unrest in the form of lava dome growth can sometimes be overlooked. However, extreme hazards exist as the result of lava dome growth. When a dome grows rapidly it may become unstable and collapse, typically by reaching a crater rim, leading to the formation of pyroclastic density currents (PDCs). PDCs triggered by dome collapse have been responsible for many of the largest volcanic disasters in history, including the 1902 destruction of St. Pierre on the island of Martinique (Fink and Anderson, 2000). More recently, the "100 year" eruption of Merapi (Indonesia) in 2010 was triggered by collapse of the lava dome; timely evacuations were achieved relying on a combination of SAR amplitude images and ground-based monitoring of seismicity and deformation using Electronic Distance Measurements (EDM) (Surono et al., 2012; Pallister et al., 2013).

A large number of people remain at risk from lava-dome-collapse-spawned PDCs as well as scientists working near volcanoes for monitoring purposes. Traditional methods to quantify the extent of lava domes rely on ground-based measurements. Although such techniques are critical, they can be dangerous. In addition to the traditional seismic monitoring systems used universally by volcano observatories, deformation monitoring methods include EDM (Surono et al., 2012; Matsushima and Takagi, 2000), GPS (Dzurisin, 2006) terrestrial photography (Ryan et al., 2010; Major et al., 2009), ground-based LiDAR (Jones, 2006), and ground-based radar (Wadge et al., 2005, 2008). Recently, remote sensing techniques have been introduced to reduce the risk associated with monitoring with aerial photography (Schilling et al., 2008; Diefenbach et al., 2011) and the use of the German TanDEM-X radar satellite mission with a bistatic acquisition mode (Kubanek et al., 2016). However, these methods remain expensive due to plane flight time or data access, and are therefore limited to a few known active volcanoes.

E-mail address: estellec@buffalo.edu.

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To better understand lava dome dynamics and mitigate the risks posed by dome collapse, a systematic, low-cost method applicable worldwide for quantifying dome extent is necessary.

Here I propose a new differencing method relying on amplitude images from Synthetic Aperture Radar (SAR) satellites derived from the Single Look Complex (SLC) products to quantify lava dome spatial extent and growth. SLCs are a low-level product available from all SAR satellites. Amplitude images in low resolution can often be accessed freely from platforms distributing SAR data or high resolution amplitude images can be produced at low cost and with minimal processing. Therefore, the proposed method can be easily used by non-InSAR specialists and with the current and planned SAR missions, these products will soon be available globally every few days. Amplitude images have been used to qualitatively evaluate the locations of physical changes associated with volcanic domes (e.g. Wadge et al., 2002, 2011; Surono et al., 2012; Pallister et al., 2013) and to quantify extrusion rates (Pallister et al., 2013). Systematically tracking dome changes with SAR amplitude images has only be done on a short time span and with an offset tracking method, which requires heavy processing and expensive software (Wang et al., 2015). Here, I propose a simple greyscale differencing method to map the changes in lava dome extent from successive amplitude images and validate it by comparing the extent of the Mount St. Helens lava dome extracted from SLC amplitude difference images with aerial photography during the 2004–2008 unrest.

The proximity of a lava dome to the crater rim and its direction of growth are especially important for assessing the risk of pyroclastic density currents. The new differencing technique proposed here enables quantification of the dome extent, its distance to the crater rim, and its direction of growth, therefore providing a remote low-cost method for identifying potential for collapse and generation of extremely hazardous pyroclastic density currents and for guiding further monitoring. The volumetric or vertical growth of the dome are not directly addressed by this technique because of the limited viewing geometries of the satellites, but the volume change could be derived by assuming proportionality between the area and the volume of the dome. In this paper, I focus on validating the amplitude differencing technique for spatial characterization of lava dome change with the study of the 2004–2008 unrest at Mount St. Helens.

2. Mount St. Helens 2004–2008 unrest episode

The 1980 eruption of Mount St. Helens was a seminal event for the field of volcanology. It was the first explosive eruption to be closely monitored through all stages of activity and provided a lens through which we view both past and current volcanic activity around the world. However, not all periods of unrest at Mount St. Helens led to eruptions with a strong explosive component. Mount St. Helens' latest episode of unrest began in October 2004, and consisted of continuous lava-dome extrusion punctuated by only two minor explosive events (Sherrod et al., 2008; Dzurisin et al., 2015). During the ~40 months of unrest nearly 100 million m^3 of dacitic lava was extruded into the crater (Schilling et al., 2008; Gardner, 2008).

Seismic activity preceding the unrest began in late September 2004 after heavy rains and during a year of overall low seismicity and no anomalous trends in either deformation or volcanic gas emissions (Moran et al., 2008; Gerlach et al., 2008). Soon after the increased in seismicity, spatially limited deformation occurred on the south side of the 1980 lava dome, followed by an increase in gas release (Sherrod et al., 2008; Dzurisin et al., 2008; Lisowski et al., 2008). The Pelean lava dome extrusion began in mid-October 2004. During the first year, relatively high extrusion rates (2–10 m^3/s), lava spines, and an increase in seismicity were observed (Major et al., 2008). By 2006, extrusion rates were below 0.5 m^3/s and the eruption was nearly aseismic. Remote cameras, LiDAR, and aerial photography provided most of the details on the dome growth with images acquired every few days to weeks (Supplementary Material Fig. S1) (Schilling et al., 2008; Vallance et al., 2008; Poland et al., 2008). Volcanic gas emission rates remained low during the entire unrest period (Gerlach et al., 2008; Scott et al., 2008). Flank and far-field subsidence was detected starting in late September 2004 (after near-summit GPS stations were deployed) with continuously decreasing rates, suggesting deflation of the volcanic edifice (Dzurisin et al., 2008; Lisowski et al., 2008; Poland and Lu, 2008).

3. Method

3.1. SAR and single look complex images

A SAR system illuminates the ground both day and night and the microwave radiation penetrates through clouds and precipitation. The direction of motion of the platform carrying the radar system, the azimuth direction (along-track), and the direction of the radar illumination, the range (across-track) direction, are orthogonal. The radar illuminates the ground in the line of sight (LOS) direction, from the radar to the target, called the slant-range direction. The range resolution is based on the arrival time of the radar signal (echo), the timing precision, and the transmitted radar pulse width (narrow pulses produce finer resolution). The azimuth resolution depends on the position of the platform carrying the radar antenna (as the beam fans out, the resolution decreases) and the beam width of the radar.

SAR systems take advantage of the relative motion between the sensor and target (ground) to synthesize a very long effective antenna aperture and achieve a high azimuth resolution. The term “aperture” refers to the forward motion of the antenna over many radar pulses that are combined to create an image of a ground scatterer. Ground features in the range direction are resolved by timing the radar energy return (“range migration”) and features in the azimuth direction are resolved by tracking changes caused by the Doppler effect (“target Doppler history”). Because the signal energy from a point target is spread in range and azimuth, a focusing technique is used to collect this disperse energy into a single pixel in the output image, the Single Look Complex (SLC) image. The focusing procedure is composed of 1) a Doppler Centroid estimation of the center frequency of the Doppler spectrum of the data; 2) a Range Compression of the received echo to simulate a narrow transmitted pulse; 3) a Range migration procedure to correct for the changing range delay through the antenna beam; and 4) an Azimuth Compression procedure to compensate for the spread due to the synthesized antenna.

Each pixel in the SLC image is encoded as a complex number that carries the amplitude (intensity of the returned radar energy) and phase information (fraction of a complex wavelength). While SLCs are typically produced in slant range coordinates, they include the latitude and longitude positional information that can be used for geocoding. The amplitude (or brightness) depends on the incidence of the wave front at the surface, which is related to the surface roughness and slope. Rough terrain or terrain with a slope facing towards the radar are strong backscatterers (high amplitude signal is returned to the radar, bright pixels) whereas smooth flat surface are weak backscatterers (low amplitude). Amplitude images show recognizable ground features illuminated by the difference in intensity of the backscattered echoes (Fig. 1), while phase images look like random noise. Amplitude images are mostly used in SAR quality assessment, calibration, and application requiring the phase signal, such as Interferometric Synthetic Aperture Radar (InSAR) (Bürgmann et al., 2000), which requires considerable meta-data. Amplitude images are produced from the SLCs by removing the phase information.

Surono et al. (2012) and Pallister et al. (2013) showed that growth and destruction of a lava dome can be observed in SAR amplitude images. Detailed analysis of amplitude images at Mount St. Helens revealed that dome growth and retreat can be identified even if of smaller amplitude and not associated with dome destabilization (Fig. 1). I rely on the open source GMTSAR software to produce full resolution SLCs and the associated amplitude images (with the scripts pre_proc_batch.csh, align_batch.csh, and slc2amp.csh). Low resolution