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Volumetric change quantification of the 2010 Merapi eruption using TanDEM-X InSAR

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ABSTRACT

Accurate and up-to-date information on the time-varying topography of active volcanoes is crucial for assessing material flows through these volcanic systems and along their surfaces. As dome -building volcanoes can change on meter scale within short time intervals in active phases, conventionally used repeat-pass SAR-interferometry (InSAR) often fails due to decorrelation effects, while other methods to measure topography like aerial photogrammetry or Lidar depend on the availability of the local infrastructure and on good weather conditions. Here, we show the potential of the spaceborne Earth observation mission TanDEM-X to monitor topographic changes at active dome-building volcanoes. In this innovative satellite mission, two nearly identical satellites fly in a close formation, taking radar images of the Earth's surface at the same time in bistatic mode. This opens the possibility to generate digital elevation models (DEMs) of volcanoes. Analyzing a series of repeated DEMs enables assessment of volume changes caused by lava dome activity. We apply this method to Merapi in Indonesia by analyzing the volume changes during the hazardous 2010 eruption. During this eruption, the old lava dome collapsed, and a new lava dome was extruded which collapsed again within twelve days. We show three DEMs derived from bistatic TanDEM-X InSAR in descending orbit taken before and after the eruption. We found a mean volume change of 19×10^6 m^3 in the summit area. The two estimates differ by 0.4×10^6 m^3 which is 2% of the average dome volume change. The TanDEM-X based results are about 25% lower than reference data, which can be explained by the shadow masks that were introduced to exclude geometrically decorrelated areas, resulting in conservative volume change estimates.

1. Introduction

Lava dome eruptions can last many years or even decades, in which phases of long-term effusive eruption are interrupted by dome collapses, commonly associated with pyroclastic flows and volcanic blasts. A quantitative knowledge of the mass transport through the volcanic system is essential to assess eruption dynamics as well as the hazard of pyroclastic flows and secondary phenomena such as lahars. Although crucial for eruption forecasting, quantitative data on mass transport is not easily determined. Ground-based methods may give direct information about magma ascent rates at vents as well as thickness, density and composition of flow deposits and volcanic tephra, but these observations may be spatially limited by obstructions that limit visibility, by cloud cover, or by limitations in access to proximal areas. In contrast, airborne and spaceborne methods have the ability to map the extent and volume of erupted material in a spatially continuous way. This is done by comparing topographic changes at different stages of an eruption cycle. Measuring the changing topography of a volcanic edifice enables quantification of mass flux and contributes to analyzing hazards in different ways: (1) frequent 3D views of a growing lava dome allow an estimation of magma ascent rates from vents that often are hidden by the erupting dome itself, and such rates may be important indicators of magmatic pressurization (Pallister et al., 2013); (2) before–after comparisons of negative topographic changes at the summit (formation of a crater) and positive changes along the flanks (deposition of volcanic debris) may help discriminate the amounts of juvenile and non-juvenile material erupted during an explosive event; (3) quantification of the amount of material deposited on upper parts of the volcano edifice is important to assess the hazard potential of lahars, and (4) exact determination of topographic changes is the basis for numerical models of total mass flow (including pyroclastic flows, lahars) on the flanks of the volcano.

The 2004–2008 activity of Mount St. Helens is an outstanding example in which periodic topographic measurements were successfully

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employed to observe the eruptive activity and especially the lava dome growth. The volcano was monitored over its 3-year-long activity, and three Lidar DEMs as well as more than 20 DEMs from vertical aerial photogrammetry were generated to analyze topographic changes of the growing volcano dome and deforming glacier. Lidar data acquired in 2003 provided initial datum control (Schilling, Thompson, Messerich, & Iwatsubo, 2008; Vallance, Schneider, & Schilling, 2008). Vertical aerial photographs and derived DEMs were used to determine extruded volumes and magmatic ascent rates. They served as a means to help assess volcanic hazards (Schilling et al., 2008).

The Mount St Helens example demonstrated that topographic information in the form of a time series of DEMs can be successfully employed to gain insight in eruption dynamics while observing topographic changes at dome-building volcanoes. However, high-precision data acquisition was only possible due to the fact that the topographic control had been in place before the eruption started. The high costs of the air photo and Lidar acquisitions and the time required for a photogrammetric data processing procedure that required manual identification of many control points limited the frequency of data acquisition and reporting. Although the rapid progress in automated image analysis and photogrammetry has significantly reduced the processing time recently (Diefenbach, Bull, Wessels, & McGimsey, 2013; Diefenbach, Crider, Schilling, & Dzurisin, 2012), the requirement of these techniques for good visibility of volcanic summits (especially during eruptions, when such areas are frequently obscured by clouds) remains a main disadvantage of these commonly used methods.

Spaceborne radar satellite missions, revisiting the volcano at regular intervals, have the potential to overcome this disadvantage, since the propagation of microwaves is much less affected by clouds or volcanic plumes (although the variable atmospheric water vapor content still is an issue for InSAR (e.g., Goldstein, 1995; Rao et al., 2006; Zebker, Rosen, & Hensley, 1997)). The interferometric analysis of two or more radar images from slightly different satellite positions allows the construction of a DEM or the measurement of subtle ground motions. The main advantages for using InSAR to derive DEMs are that no or only few ground control points are required, and images may be obtained during periods of cloud cover and during night. In addition, the technique can generate near-real-time and reliable DEMs with global access (Bürgmann, Rosen, & Fielding, 2000).

Utilizing repeat-pass InSAR for DEM generation is mainly limited by the recurrence intervals of current satellite missions (e.g., 46 days for ALOS, 11 days for TerraSAR-X, and 1 day for COSMO-SkyMed) as the approach depends on the stability of the backscattering conditions on the ground between the radar acquisitions (Zebker & Villasenor, 1992), which is not guaranteed during eruptive activity (Stevens, Wadge, & Williams, 2001; Wadge, 2003). At active lava domes, several sources of instability (rockfall, emplacement of new lava, thermal contraction, (partial) dome collapse) may lead to severe decorrelation of radar images, even for short repeat intervals (Stevens et al., 2001; Wadge, 2003).

In this paper, we apply data of the German TanDEM-X (TerraSAR-X add-on for Digital Elevation Measurement) radar satellite mission to generate DEMs and to measure the topographic and volume change during the 2010 Merapi eruption. Flying in a close formation, the two SAR sensors acquire bistatic images simultaneously enabling the construction of DEMs independent of temporal stability between the repeated satellite passes (Section 2). We analyzed a time series of three DEMs generated using bistatic TanDEM-X data to estimate topographic changes of Merapi during the 2010 eruption (Section 4). As we are mainly interested in changes of the lava dome, our study concentrates on a small area around the volcano summit (Fig. 1). Our study of the 2010 Merapi eruption serves as a first test of the capability of TanDEM-X to quantify large topographic changes of up to 200 m through use of the interferometric phase.

2. Method: bistatic InSAR

The TanDEM-X mission aims to produce a global DEM with an unprecedented accuracy. It also enables for the first time repeated single-pass acquisitions and generation of dynamic DEMs of the Earth's surface with a recurrence interval of 11 days. It consists of the two nearly identical satellites, TerraSAR-X and TanDEM-X. Both satellites carry high performance SAR systems, operating in X-band (9.6 GHz). While flying in a close helical formation (Krieger et al., 2007), they constitute a large single-pass interferometer with adjustable across-track baselines (Huber, Younis, & Krieger, 2010). Compared to monostatic repeat-pass acquisitions, a TanDEM-X bistatic acquisition consists of two simultaneously recorded radar images which form a single-pass interferogram. Hence there is an obvious increase in coherence compared to repeat-pass studies. In Section 4 we discuss measured coherences for the analyzed Merapi data sets. We performed interferometric analysis using the Delft Object-Oriented Radar Interferometric Software (DORIS) (Kampes, Hanssen, & Perski, 2003). The complex-valued raw data of the TanDEM-X mission are provided as coregistered CoSSC files that are stored in half-precision format (Fritz, Bräutigam, Krieger, & Zink, 2012). Therefore we first had to convert the CoSSC files from half-precision to floating point precision using the Half Precision Floating Point Converter in Matlab developed by Tursa (2009). We then created interferograms from the TanDEM-X pairs using the DORIS software package (Kampes et al., 2003). Because the two radar images were already coregistered, we skipped the processing steps concerning coregistration and started processing with the computation of complex interferograms. We additionally neglect introduced orbit errors since the knowledge of the accuracy of TerraSAR-X science orbits is very high, at about 4–5 cm (Wermuth, Hauschild, Montenbruck, & Jäggi, 2009).

The commonly used formula for repeat-pass interferometry according to Hooper, Zebker, Segall, and Kampes (2004)

$$\phi_{InSAR} = \phi_{ref} + \phi_{topo} + \phi_{def} + \phi_{atm} + \phi_{orbit} + \phi_{bs} + \phi_{noise} \tag{1}$$

is simplified in the bistatic case to

$$\phi_{InSAR} = \phi_{ref} + \phi_{topo} + \phi_{noise}, \tag{2}$$

in which the phase of the interferogram ϕ_{InSAR} is the sum of the reference phase ϕ_{ref}, the topographic phase ϕ_{topo}, the phase change ϕ_{def} due to the displacement of the ground scatterer in the satellite line-of-sight (LOS), the phase contributions due to atmospheric effects ϕ_{atm}, orbit errors ϕ_{orbit}, backscattering conditions ϕ_{bs}, and ϕ_{noise} the portion of phase noise.

We used a Goldstein filter (Goldstein & Werner, 1998) prior to phase unwrapping and unwrapped the phase using the SNAPHU algorithm (Statistical-Cost, Network-Flow Algorithm for Phase Unwrapping (Chen & Zebker, 2001)). We converted the unwrapped phase to topographic heights and geocoded the heights using DORIS. The gridding was performed afterwards using the Generic Mapping Tool (GMT). We chose a grid spacing of 3 m for the DEM products. These were further processed using MATLAB to calculate the volumetric changes. Geographic coordinates (WGS84) were used to compare the different DEMs and to perform the time series analysis. Data from three permanent GPS stations at Merapi were used to validate the accuracy of the generated DEMs (Fig. 1).

The processing workflow of the bistatic TanDEM-X data is as follows: Two radar images are recorded simultaneously during every overflight. We take the phase information of both radar images to calculate the interferometric phase. The terrain height h of the area of investigation is calculated (Hanssen, 2001), including the