Uplift of Kelud Volcano Prior to the November 2007 Eruption as Observed by L-Band Insar

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Abstract. Kelud volcano, a stratovolcano with summit elevation of 1731 m above sea level, is considered to be one of the most dangerous volcanoes in Java, Indonesia. Kelud volcano erupts frequently, with the most recent eruption occurred on November 3, 2007. Therefore, volcano monitoring, especially detecting precursory signals prior to an eruption, is important for hazard mitigation for Kelud volcano. Interferometric Synthetic Aperture Radar (InSAR) has been proven to bea powerful tool for investigating earth-surface deformation. Hence, we applied D-InSAR (differential InSAR) in an effort to identify pre-eruptive deformation of Kelud volcano before November 2007 eruption. SAR images, L band ALOS-PALSAR, were used to construct 3 coherent interferograms between January to May 2007. We used the D-InSAR technique to remove topographic effects from interferometry images. During the interval observation, we detected a continuous inflation with a maximum *line-of-sight* (LOS) displacement of 11cm. Uplift of Kelud volcano was also observed by the tiltmeter 1-2 months prior to the November 2007 eruption**.** We interpret this inflation as a manifestation of increased volume of magmatic material in the shallow reservoir and magmatic migration towards the surface, indicating an imminent eruption. This study confirms that InSAR technique is a valuable tool for monitoring volcano towards better hazard mitigations.

Keywords: *deformation; eruption; hazard; InSAR; Kelud; mitigation; volcano; tiltmeter.*

1 Introduction

Indonesia has 129 active volcanoes as a consequence of interactions and convergence among several tectonic plates [1]. One of the most active and explosive volcanoes in Indonesia is Kelud Volcano (Figure 1 and Figure 2), located in the East Java, Indonesia (7.65S; 112.19E; 1731 m a.s.l.) and part of the Sunda volcanic arc system that arises from the subduction of the Australian plate. Kelud is an andesitic stratovolcano with a complex structure, which principally includes two avalanche calderas; one is open to the south and one to the west; the latter is occupied by the active dome. Kelud volcano is considered to be one of the most dangerous volcanoes in Java because of its frequent eruptions [2].

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More than 30 eruptions have been recorded in historical times. The1000 AD eruption of Kelud is the oldest in the historical record of eruptions for the entire Indonesian archipelago. Since AD 1300, the periods of inactivity between eruptions range from 9 to 75 years [3,4]. One of the worst lahars in the historical record of volcanic eruptions, which took the lives of about 10,000 people, was in 1586. During the past century, eruptions occurred in 1901, 1919, 1951, 1966 and 1990. All these recent eruptions were very similar and were characterized by a very short duration (a few hours) and a small volume of eruptive products (0.1-0.2km^3) which are emitted as ash and pumice fallout of Plinian columns and "St. Vincent"-type nuéesardentes**.** Eruption on 1990, February l0, began at 11:41 local time with a series of phreatic explosions. In this eruption most of the damage and the 32 casualties were due to the weight of the tephra that caused houses to collapse [5].

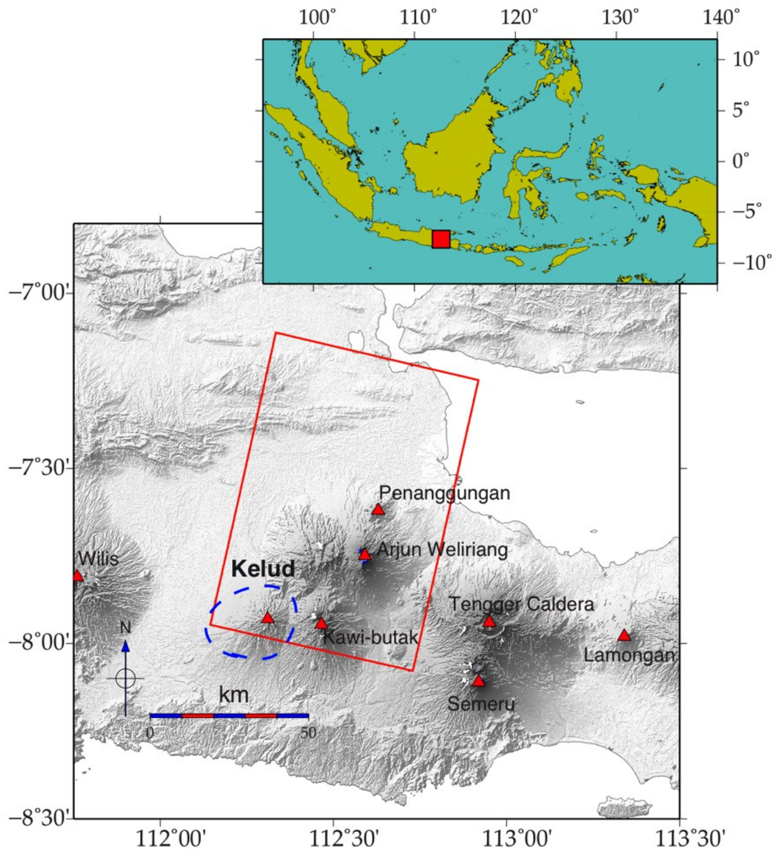

Figure 1 Location of Kelud volcano, rectangular box is target image of SAR. Dashedcircle is area of Kelud volcano.

The current state of the art in volcano hazard monitoring and mitigation is based on two techniques that provide information over very different time scales: (1) stratigraphic studies to elucidate a volcano's long-term eruptive history (typically 10^4-10^6 years) and (2) monitoring shallow-seated forms of unrest, such as seismicity, gravity, remote sensing and ground deformation, that are typically recognized a few days to months before an eruption [6].

Figure 2 Kelud volcano after November, 2007 eruption (source: http://www.ulb.ac.be/sciences/cvl/Kelud/cud_Kelut.HTM) [7].

The ground deformation is interpreted as are sult of inflation and deflation of the volcanic edifice in response to magma movement towards the Earth's surface before an eruption. After a volcanic eruption the ground moves downward, since the magma reservoir has been emptied. Detecting pre-eruption deformation signals would allow scientists to focus their monitoring of inflation-deflation cycles of a magma reservoir and would permit public officials to better mitigate volcano hazards.

Movements of deep magma reservoirs are difficult to detect beneath most volcanoes. This may be because: (1) deep magma accumulation occurs below the brittle/ductile transition and consequently is virtually a seismic and (2) any associated surface deformation is relatively subtle. InSAR could be an alternative tool for monitoring volcano deformation. InSAR has recently been used to study deformation at several volcanoes around the world [6,8-11] and has the capability of mapping centimeter-level deformation over a large area (hundreds of km^2). In other studies, scientists have been successfully using

InSAR for monitoring land subsidence due to intensive ground water extraction [12-14].

In this paper, we report pre-eruption deformation and describe the use of InSAR to image progressive inflation of Kelud volcano, observed between January to May 2007, about 7 months prior to the November 2007 eruption.

2 Basic Theory and Methodology

2.1 Theory of InSAR

InSAR data processing starts with generating an interferogram by differencing the phase values of two co-registered radar images acquired over the same scene. Several factors could possibly contribute to a measured phase difference (ϕ) [15]:

$$\phi = \phi_o + \phi_t + \phi_d + \phi_a + \phi_n \tag{1}$$

where $\phi_o$is orbital fringes and ϕ_t is the topographic contribution if the perpendicular baseline is not zero; ϕ_d comes from the sensor-scatterer range change that corresponds to coherent ground movement between the two SAR acquisitions; ϕ_a is due to the effects of atmospheric in homogeneity on both the temporal and spatial scales; ϕ_n is Gaussian random noise due mainly to temporal decorrelation of radar echoes backscattered from surface disturbances (*e.g*. vegetation growth, variation of ground moisture, *etc*.). Decorrelation and atmospheric effects are two main limiting factors in InSAR [16,17]. Since it is difficult to accurately quantify and correct for the effects, both ϕ_a and ϕ_n are usually assumed to be zero in data processing. It is clear that any deviation of the data from this assumption will result in errors in InSAR measurement results. If the imaged ground presents no motion (ϕ_d= 0), ϕ_t can be used to map the topography of the ground. Otherwise, when ϕ_d is not equal to 0 and needs to be determined, ϕ_t needs to be removed in a differential interferogram. The phase difference at each pixel in an interferogram is ambiguous since the integer multiple of 2π is unknown. The phase difference in an absolute sense can be determined through so-called phase unwrapping [18]. The suitability of an interferometric image pair for topographic mapping and surface deformation detection depends on the orbital separation, or more specifically, on the baseline component perpendicular to the radar *line-of-sight* (LOS) direction. Topographic mapping requires moderate perpendicular baseline length to balance between the sensitivity of ϕ_t to ground elevation variation and baseline decorrelation [8].

The longer the perpendicular baseline is, the smaller the elevation variation would be that is necessary to generate a 2π phase cycle (fringe) on the corresponding interferogram. On the other hand, deformation detection demands baseline to be as short as possible [19]. To extract surface deformations, a *digital elevation model* (DEM) can be used to remove the topographic contributions from an interferogram [20]. However, a DEM error of δh can cause the following residual phase error in the differential interferogram:

$$\delta\varphi = \frac{4\pi}{\lambda}\frac{B}{R\sin\theta}\delta h \qquad (2)$$

where λ is the wavelength; R is the slant range from satellite to ground; θ is the radar incidence angle and B is the length of the perpendicular baseline. Δh approaches 0 when B approaches 0. Therefore a short baseline can limit the propagation of DEM errors into a differential interferogram. The unwrapped differential interferogram with absolute phase values (ψ_m) is converted to the slant-range-change (ΔR) that reflects ground displacements:

$$\Delta R = \frac{\lambda}{4\pi}\psi_m. \qquad (3)$$

2.2 Data and Method

In this study, we use SAR data from two passes of ALOS-PALSAR (DAICHI) satellite, one of the largest satellites in the world, which was launched on January 24, 2006. The ALOS satellite has a mass of 4 tons and 7 kW electric powers generated by the 23 m solar array paddle. The PALSAR revolves in a circular orbit at 691.65km altitude; illuminating the Earth surface with L band radar with a microwave frequency of 1270MHz and inclination of 98.16 deg. ALOS (which carries PALSAR) is in a sun-synchronous orbit, in which it revolves around the earth every 100 minutes, or 14 times a day. ALOS returns to the original path every 46 days (repeat cycle), and the inter-orbit distance is approximately 59.7 km on the Equator. We use high-resolution observation data mode of Fine Beam Single (FBS) of 34.3° and horizontal-horizontal (HH) polarization. Figure 1 shows a location map of SAR data; the SAR image covers a larger area in rectangular box.

To process raw SAR data and generate intensity images of microwave backscatter intensity from the surface, we apply SIGMA_SAR software [21-22]. The deformation patterns are obtained by two-pass differential interferometry. In order to remove the fringes related to the topographic effect we use a 3-arcsecond SRTM digital elevation model (http://srtm.usgs.gov). A simulated SAR image from DEM SRTM 90m and a topography phase image can be seen in Figure 3. We improve the signal to noise ratio of each differential interferogram using a weighted power spectrum filter as discussed in Goldstein and Werner [23].

Table 1 SAR data for monitoring Kelud volcanodeformation.

Pair	Master (date)	Slave (date)	Path	Row	Off -nadir Angle	Polarization	Period (day)
a	2007/01/03	2007/02/18	89	3780	34.3^o	HH/HH	46
b	2007/01/03	2007/04/05	89	3780	34.3^o	HH/HH	92
c	2007/01/03	2007/05/21	89	3780	34.3^o	HH/HH	138

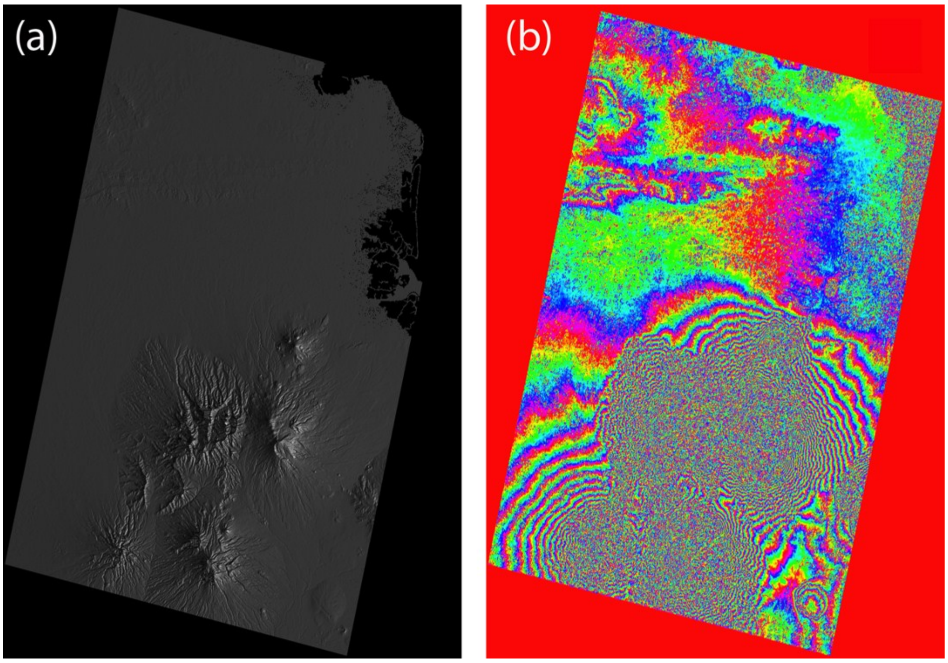

Figure 3 (a) Simulated SAR image from DEM, (b) Topography phase image.

3 Results and Discussion

We obtained four synthetic aperture radar (SAR) images suitable for measuring surface deformation at Kelud volcano from L-band satellite (PALSAR, wavelength=23.5 cm). We used the two-pass InSAR approach [8,24] to produce three deformation interferograms with reasonably good coherence that collectively span most of the January to May 2007 time interval. Image acquisition times and associated imaging parameters are given in Table 1.

We are able to detect ground surface deformation around Kelud volcano. Based on the D-InSAR LOS displacement maps (Figure 4), an average of 3 to 4 cm uplift was observed during the period of observation January to February 2007. Between period of January to April 2007, average of ground uplift of 7 to 8 cm in the slant range direction is detected. From January to May 2007, more than 11 cm uplift was captured. These results indicate deformation of Kelud volcano 5 to 10 months prior initial eruption that showing as a manifestation of magmatic processes underneath the volcano. This deformation signal is observable by InSAR technique. Such kind of ground uplift prior to avolcanic eruption has also been detected in Okmok volcano, Alaska [25].

Temporal variation of ground deformation observed around Kelud volcano (Figure 5) between January to May 2007, demonstrates that displacements are conserve well within the time span of observation. The uplift rate detected by InSAR images from January to May 2007 was almost constant.

As expected, the interferograms spanning the entire period January-February 2007 (pair a), January to April 2007 (pair b) and January to May 2007 (pair c) exhibit 1/4 fringe, 1/2 fringe and 1 fringe respectively on western part of Kelud volcano, where the uplift was up to 11.78 cm. We interpret the observations using the following conceptual model. Inflation begins as magma rises into the shallow reservoir. It pushes up through the crust and fractures and displaces the country rock. Magma migration towards the surface and increasing volume of accumulated magma in the shallow reservoir act as source of pressure along the crack and reservoir wall. This force causes displacement in the surrounding rocks, causing uplift of the surface of the Earth, which is detectable by deformation instruments/satellites. After the eruption, when magmatic material reached the surface in the form of dome extrusion, explosion, or gas burst, the ground surface around the volcano deflates or moves downward in response to lower subsurface pressure. Therefore, changes in the ground surface deformation are a reflection of changes in pressure within the volcano due to variations in magma location and volume [26].

Figure 4 (d)-4(f) shows InSAR coherence maps around Kelud volcano during the period of observation between January to May 2007. In general the correlation of our SAR analysis is good especially in the northeast part, even though some variation of coherences also observed for pairs a, b, and c. Observed correlations for the periods of January-February and January-April 2007 are better than during January-May 2007 (Figure 4(d)-4(f)).

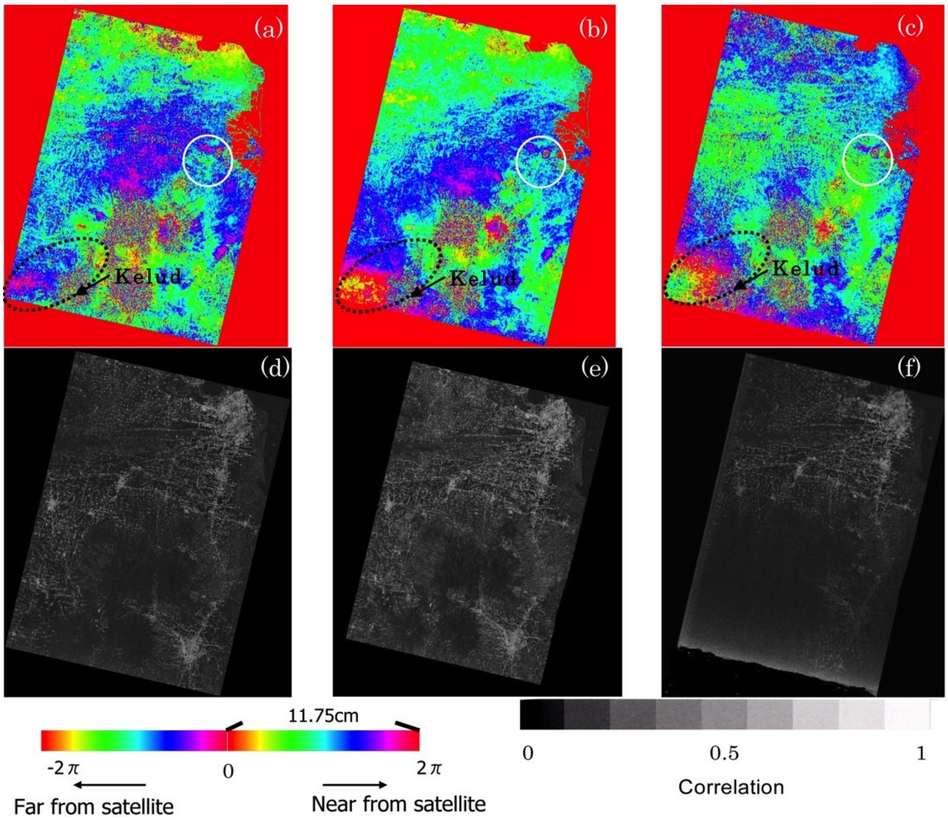

Figure 4 Temporal deformation of Kelud Volcano; a, b and c are displacement images that correspond to pair a, b and c in Table 1 and their correlation images d, e and f. Black dashed ellipse is the area of inflation.

Unfortunately we cannot directly compare our investigation with other observations such as GPS and tiltmeter methods for the same time span. However, tiltmeter signals continuously recorded at the observatory at Kelud volcano shows inflation during 1-2 months prior to the November 2007 eruption (Figure 6) [27]. Our InSAR results are consistent with deformation detected by the tilmeter. Even both measurements have different time span investigation, for instant, we can conclude that there was a signal of inflation of Kelud volcano prior to November 2007. Such kind behavior prevailing at volcano is very useful information for volcano hazard monitoring and mitigation in the future

In addition, we also detect ground surface subsidence associated with the Lusi mud volcano in the subdistrict of Porong-Sidoarjo, (white circle in Figure 4(a), 4(b) and 4(c)). The deformation is not due to the DEM error since the deformation was also detected by GPS measurements [28]. In addition, Fukushima, *et al.* [29] have also investigated the deformation associated with Lusi mud volcano from satellite images. Almost continuous eruption of mixed mud, water and gas started in May 2006 and has caused significant damage to livelihoods, the environment and infrastructure. In this study we are only able to observe the subsidence during period of January to May 2007.

To better understand precursory activity and to quantify the deformation signal prior to the eruption of Kelud in November 2007, future research should aim to incorporate a longer time span of SAR imagery.

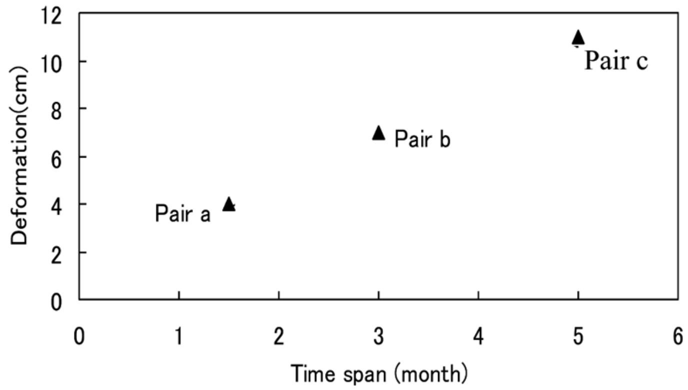

Figure 5 Temporal variation of Kelud volcano prior to November 2007 eruption obtained from Differential InSAR

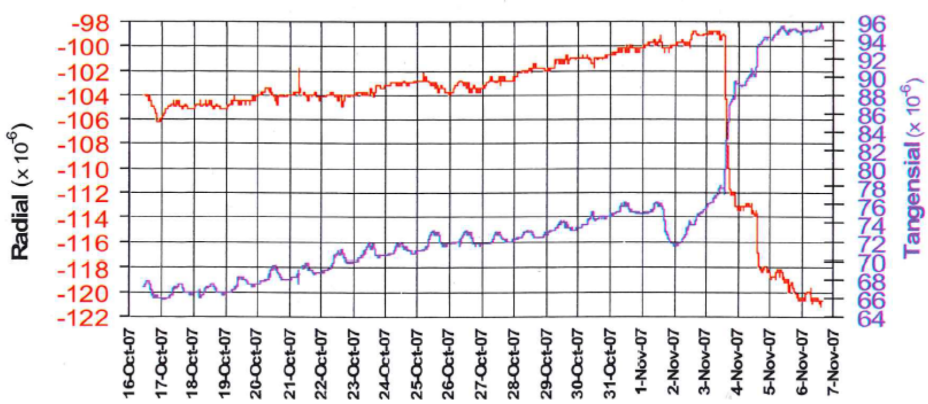

Figure 6 Temporal variation of uplift in Kelud volcano, 1-2 months prior to November 2007 eruption, as recorded by tiltmeter [26].

This study demonstrates that InSAR is capable on observing pre-eruptive deformation 5-10 months prior to initial eruption of Kelud volcano. Numerical modelling for a longer observation period leading up to the initial eruption would be necessary to be able to quantify magmatic volume and migration process, thus provide a better assessment on volcano hazard risk.

4 Conclusions

The earliest possible warning of the unrest of a volcano is a highly desirable goal in monitoring active volcanoes. Many such volcanoes are found in developing countries where real-time monitoring is non-existent or incomplete. InSAR provides a new tool in the remote sensing of volcanic activity that may give warnings appreciably before or simultaneously with other well-known monitoring methods. We are able to capture the pre-eruptive deformation signal of Kelud volcano using InSAR. Within 5-10 months prior to the November 2007 eruption of Kelud volcano, our analysis shows continuous uplift, with cumulative inflation of about 11 cm during January to May 2007, and the cumulative uplift increased prior to initial eruption. Based on De Bélizal et al. [30], this eruption ceased in May 2007 with extrusion of a lava dome with a volume of 3.5 x 10^7 m^3. We infer that the observed uplift displacement in this study was associated with increased volume of magmatic material in the shallow reservoir and magma migration towards the surface.

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