Investigation of Ground Deformation Caused by Volcanic Eruptions in 2010 and 2015 at Mt. Bromo-Indonesia Observed by PALSAR and PALSAR-2

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ABSTRACT : One of the most active volcanoes in Indonesia is Mt. Bromo, located in East Java Province. Volcanic activities at Mt. Bromo has been recorded in 1775 which characterized by small eruptions with cycles ranging from one to five years. The two last eruptions occurred on 2011 and the end of 2015 activities of Mt. Bromo has increased and still continuing. Based on the eruption evidences Mt. Bromo is Strombolian Volcano, relatively mildly explosive at discrete but fairly regular intervals of seconds to minutes. Tectonic/quake activity dominated by continuing tremor vibration with maksimum amplitude which tend to fluctuate reported by PVMBG. According to the eruption, we investigated ground deformation by interferometric SAR method related to ground structure before and after eruption, in this study we compared two events of eruption, using PALSAR imagery to investigate 2010 eruption and using PALSAR-2 imagery to investigate 2015 eruption. We expect the InSAR deformation field to infer volume changes, geometries and locations of sources of deformation involved in the eruption. Ground displacement in the radar line-of-sight (LOS) direction is obtained from the phase difference of synthetic aperture radar (SAR) pairs of the same area acquired at different times (interferograms) then be flattened by removing the topographic phase an inflating volcano (or any other landform) produces a pattern of concentric fringes in a radar interferogram from which the effects of viewing geometry and topography have been removed. Pre-study in this research showed the RGB color identified the change detection during 2015 eruption. Finally, we inspect the surface changes induced by the modeled of deformation on Mt. Bromo rift zones and provide insights about the relationships between recent eruptions and changes in eruption behavior based on deformation. Further study, the results could be used for human assessment.

KEYWORDS : Mt. Bromo, Volcano, Deformation, InSAR, ALOS/PALSAR.

1. INTRODUCTION

Volcanic eruptions produce disaster materials such as the lava, pyroclastic fall, pyroclastic flows, pyroclastic surges, lateral blast, debris avalanche, volcanic tsunamis, mud, flooding and harmful gases (Tilling, 1989). A large number of volcanoes are situated in the (so-called) ring of fire area. Analysis from geographic and topographic data suggests that Indonesia is the most volcanically active in the world, with numerous eruptions each year and millions of people living on the flanks of the volcanoes (Loughlin *et al*., 2015). About 13 % of the world's active volcanoes are located in Indonesia. Tectonically, the active volcanoes are the result of a collision between Indian-Australian, Eurasian, and Philippine Plates (Zaennudin, 2010). On the other hand, large number of people (choose to) live close to volcanoes because these areas usually contain some of the most mineral rich soils, which provide perfect conditions for farming. Lava and material from pyroclastic flows are weathered to form nutrient rich soils which can be cultivated to produce healthy crops and prosperous harvests.

The objective of this study is to investigate ground deformations episode caused eruptions in 2010 and 2015 eruption by using InSAR (interferometric SAR) to find evidences in 5year cycles of mount Bromo. To identify the characteristics and status of volcano, the most commonly technique is used remote sensing method (Lu *et al*, 2007), remote sensing has been largely implemented to characterize of volcano eruptions, both of optical remote sensing and SAR (Synthetic Aparture Radar), SAR data involve the reflection and radiation of electromagnetic waves. In this research, we propose to use the InSAR analysis method to process SAR images taken from ALOS/PALSAR data. Characteristic of SAR image is an inherent characteristic of coherent imaging, including SAR imaging is the presence of speckle noise which is random, deterministic, interference pattern in an image formed with coherent radiation of a medium containing many sub-resolution scatterers. Mapping active volcano using SAR (e.g Solikhin *et al*, 2015b) in Merapi to classify and map the pyroclastic deposits has applied to observe active volcano.

2. METHODOLOGY

2.1 Mount Bromo-Indonesia

Mount Bromo is located in East Java Province, one of the most active volcanoes in Indonesia which short eruptions cycle among 1 year to 5 years. The Bromo-Tengger volcanic massif is located in a cluster of Tengger-calderas and strato-cones including, from north to south: the Bromo-Tengger (7.942°S, 112.95°E), Jambangan (8.065°S, 112.92°E) and Ajek-Ajek (8.042°S, 112.92°E) calderas; the Mount Kepolo (8.077°S, 112.92°E) lava cone; and the composite cone of Mount Mahameru-Semeru (Solikhin *et al*, 2012a). Recently, mount Bromo activity increased on 1 November 2015, and started erupting with lava on Tuesday morning, 26 January 2016 which characterize continuing tremors, the terrain slope and surface roughness are dominant for creating new surface structure. PVMBG (Centre of Volcanology and Geological Hazard Mitigation) reported activities of Mount Bromo, their recorded tectonic activity dominated by continuing tremor vibration with maksimum amplitude which tend to fluctuate. Mount Bromo status is now *siaga* (level 3 of 4). Potential to evoke freatik eruptions and magmatic materials, distribution materials such as ash plumes and pyroclastis fall will occur around the volcano.

2.2 Data Processing

For analyzing the eruption events in 2010 and 2015 we used SAR data derived from PALSAR and PALSAR-2 Images which L-band frequency characteristic onboard from Advanced Land Observing Satellite (ALOS) with active microwave sensor. Table below show detalis data are used for this study.

Table 1. Data information

Date	Sensor/ Satellite Name	Processing Type	B_{perp}[m]	Stack	Polarization	Orbit
25 Mar 2015	ALOS/PALSAR	L.1.1	0.0	Master	HH	Descending
04 May 2016	ALOS/PALSAR	L.1.1	-0.3	Slave	HH	Descending
01 Apr 2010	ALOS2/PALSAR-2	L.1.1	0.0	Master	HH	Descending
04 Apr 2011	ALOS2/PALSAR-2	L.1.1	-677.5	Slave	HH	Descending

2010 and 2011 scenes are ALOS/PALSAR, 2015 and 2016 scenes are ALOS2/PALSAR-2 are L-band frequency (active microwave remote sensing) which characterize enable to penetrate cloud (cloud-free) and day and night observation. The synthetic aperture radar signal processing could be implemented simply as follow below.

2.3 Method

In this study we proposed InSAR method in the conventional single-interferogram approach, exploits two radar images of the same area acquired at different times to measure ground displacement. The technique uses the phase difference of backscattered signals from the two acquisitions to measure differential motion in the Line of Sight (LOS) direction include vertical and horizontal components. The InSAR deformation image produced from two SAR images that associated the 2010 and 2015 eruptions.

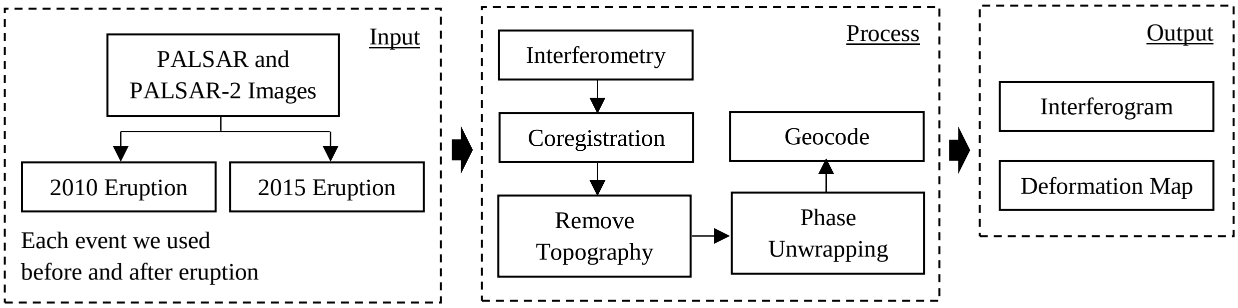

Figure 1. Flowchart study

To measure ground deformation with high spatial resolution and accuracy on the large ares observation we used differential synthetic aperture radar interferometry (Massonet 2008; Gabriel A K *et al*, 1989) which phase can be substracted from the SAR interferogram to remove topography. DInSAR used to analysis the line of sight displacement for monitoring and detecting change volcano in long-term and short-term (Papageorgiou, E *et al*, 2012) and also for studying fault mechanism (Currenti G *et al*, 2010). We presented the interferometric analysis using snap software, a common architecture for all Sentinel Toolboxes is being jointly developed by Brockmann Consult, Array Systems computing and C-S called Sentinel Application Platform by ESA, (2016) to get interferogram and line of sight displacements, the interferometric phase was unwrapped with the SNAPHU program.

3. RESULTS AND DISCUSSION

InSAR is a remote sensing technique using two or more SAR phase images acquired at different times to generate displacement maps to detect surface changes over a specific area in Bromo volcano. Figure below as a pre-study of mount Bromo in East Java Province, Indonesia. To make the task of monitoring volcano deformation more manageable, we can approximate the complex shape of a volcano with a network of recoverable points on its surface, and then monitor the geometry of the network rather than the entire volcano.

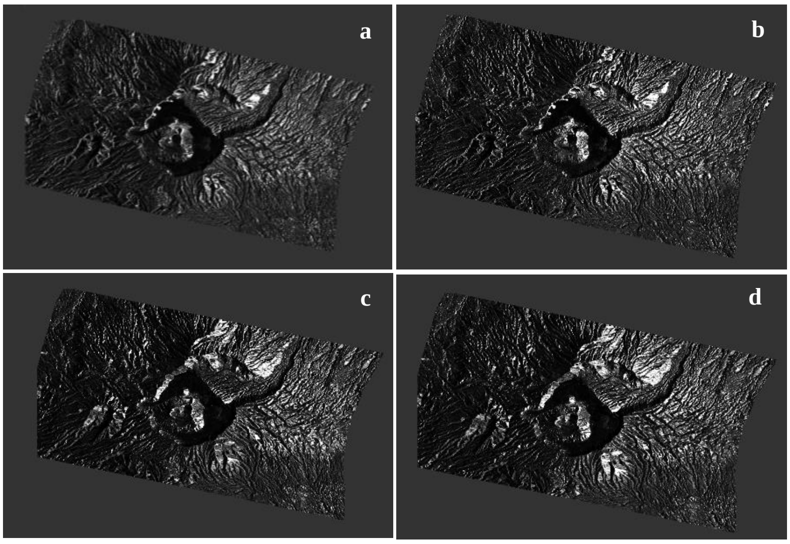

Figure 2. SLC Product of PALSAR and PALSAR-2 Images from the shape of Area taken in 4 different time pre-eruptive and post-eruptive in 2010 Eruption (Figure a taken in 2010 and b taken in 2011) and 2015 Eruption (Figure c taken in 2015 and d taken in 2016).

Those images (Figure **2a,c**) are indicated for pre-eruptive where the shape of mount Bromo be assumed not changes, following eruption in the end of 2010 (figure **2b**) show some changes area in northern of mount Bromo. In the other hand, eruption 2015 showed in the (figure **2d**) north-east part of mount Bromo indicated changes. Four scenes could be allowed us to see changes in Bromo calderas. We can confirm by coregistered images into each euption period, detail coregistration images are shown below.

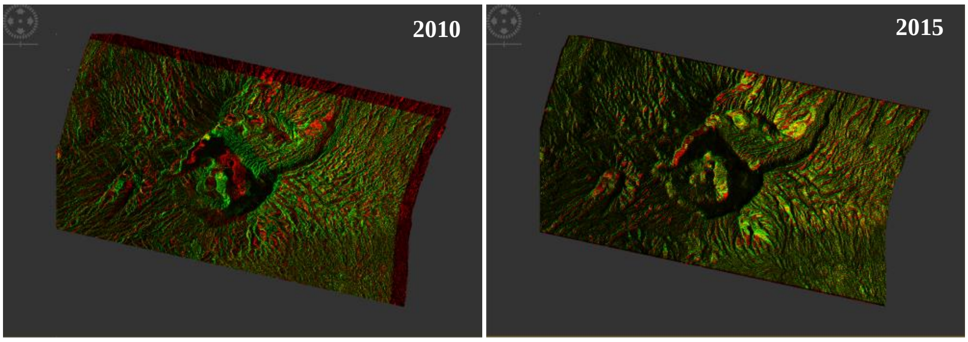

Figure 3. SLC Product of PALSAR and PALSAR-2 Images from the shape of Area taken in 4 different time pre-eruptive in 2010 Eruption and and post-eruptive in 2015 Eruption

For The RGB View can be useful for amplitude change detection. Regarding to ESA SNAP (2016) those images, we will see things that have changed in red or green and things that have not changed in yellow. It is also a visual indication that the coregistration has properly aligned both images. The resulting of RGB view should look mostly yellow. Poor registrations will have badly lined up terrain. The first result of interferograms as RGB could be allowed us to study interferometric SAR in volcano disaster in particular landslide case.

3.1 Deformation Analysis

We processed SAR images from four different datasets from PALSAR and PALSAR-2 (Table 1.) by using the SNAP procedure to generate LOS deformation rate maps of the mount Bromo region for the following observation periods: 2010.04.01–2011.04.05 (PALSAR track 91-3780; Figure **2a,b**), 2015.03.25–2016.05.04 (PALSAR-2 track 131-7030; Figure **2c** and **2d**). All four tracks proceed into SNAPHU developed at Stanford university, processing after removed topographic phase, phase unwrapping is a key step during the signal processing of interferometric synthetic aperture radar (InSAR) data. The precision and efficiency are two key problems of phase unwrapping. The path-following phase unwrapping algorithm usually has high computational efficiency, but low coherence areas are prone to have accumulated errors. The result indicate that mount Bromo started inflating soon after the end of 2010 eruption and 2015 eruption (Figure 4).

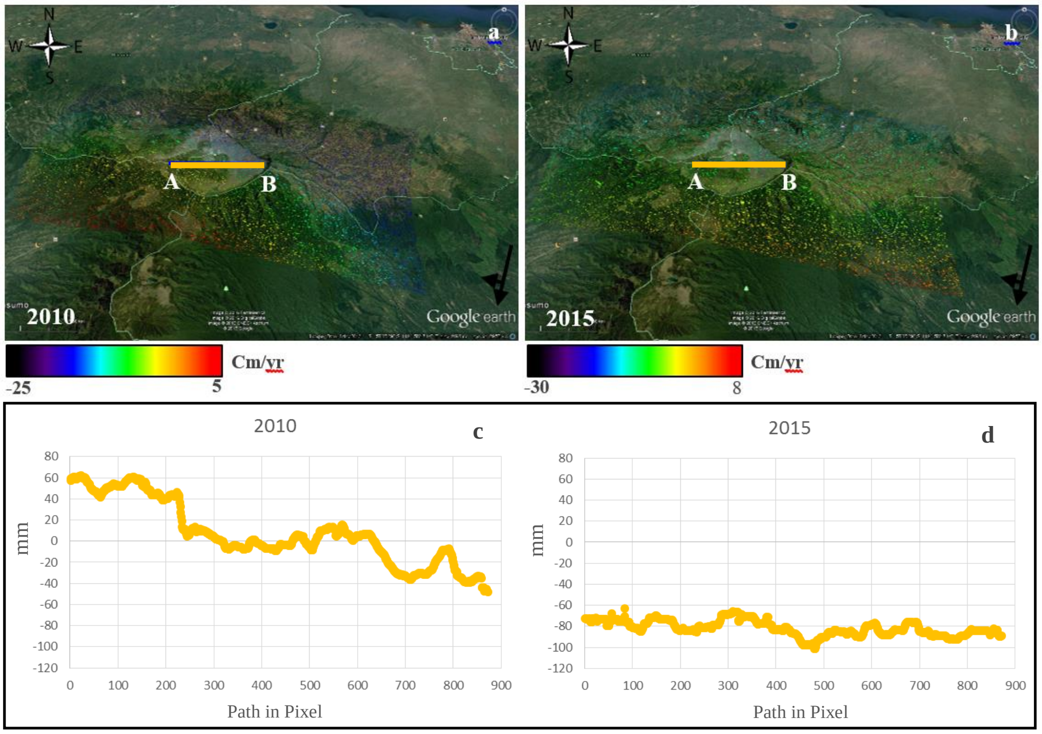

Figure 4. Line of sight displacements are used to highlight the deformation in interferograms of pre-eruptive in 2010 Eruption and and post-eruptive in 2015 Eruption.

Regarding the unwrapping result, the interferograms could give us some hints to interpretate land surface changes around the volcano. Slope deformation surrounding the end of 2010 eruptions, with the blue line marking the outline of the slope instability in graph (**4a,c**) representative from A to B where is deformation occurred until 5 cm inside the calderas. (**4b,d**) High subsidence of the centre caldera is seen prior to the eruption in 2015; Look at (**4b**) during the eruptions in the end of 2015 until beginning of 2016, ~8 cm of LOS slope displacement can be seen on the southwest sector of mount Bromo during the period in the end of 2015 until February 2016 atleast 6 quakes recorded as countinously tremors quake which maximum of dominant amplitude around 1-24 mm (PVMBG, 2016).

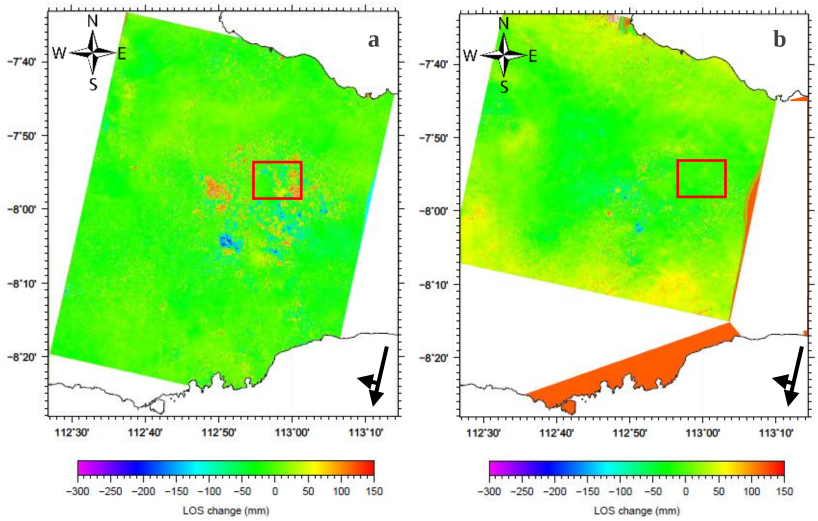

Figure 5. The complete scenes of Line of sight (LOS) displacements in interferograms of pre-eruptive in 2010 eruption show in **a** and and post-eruptive in 2015 eruption show in **b**, which the red line is surrounding of Mt. Bromo has overlayed with Java island boundary

(**4c**) The graph shows very fluctuating changes immediately after the eruption, subsidence cover a similar width of the southwest flank that moved during the slide, this land surface changes decreases in magnitude and spatial extent until late December, otherwise (**4d**) the graph shows stable deformed around 8 cm, supported by a report from

Centre of Volcanology and Geological Hazard Mitigation the zone has high degree susceptibility to landslide. In this zone, landslide occurred very frequently. Previous and new landslides still occurs induced by high rainfall or strong erosion process. Interval of the natural slope is moderate (30-50 %) to very steep (>70%), depending on the physical and engineering properties of rock and soil forming the slope. The slope is mostly poor coverage vegetation. Comparing the 2010 eruption and 2015 eruption (**4c,d**) relation among two graphs are shows very clear condition, where is every year the caldera surrounding the mount Bromo still deforming (subsidences). Complete area (**4c,d** and **5a,b**) show deformation map in whole scenes derived from PALSAR and PALSAR-2 look direction are labelled. The interferogram colors (magenta to red) represent subsidence the color scale is the same for those images, the hot-colored points show high-rate up of subsidences.

In the 2010 eruption, deformation occurred over the mount Bromo calderas and less of changed which easy to identify in green color range. On the other hand, in 2015 eruption, more changes and some areas are given the uplift representative with yellow color. Among 2010 and 2015 eruption, there was changes in the percentage areas much more in 2015 eruption, it will allow us to make a comparison study. Ground backscattering as generally depends on the local topography, soil roughness and surface moisture. However, ground backscattering is also a function of the radar wavelength and, for a given wavelength (i.e ALOS/PALSAR and ALOS2/PALSAR-2 which L-Band wavelength about 24 cm), it depends on the polarization of the radar emission and reception. Surfaces oriented towards the radar, rough at the scale of the radar wavelength and/or moist, will have stronger reflected returns than those that are not oriented towards the radar.

3.2 Validation Work Plan

The result given the new sight of volcanic activities monitoring and implementing of InSAR to observe volcano. Based on our study, we plan to check ground truth (field survey) analysis by surveying surrounding the volcano to understand of volcanic activities associated to the fault and vegetation surrounding the volcano (mount Bromo), and comparing with Modis dataset to obtain the hotspot area for future study.

4. CONCLUSIONS

Volcanic activities has produced hazards, including large scale land subsidence and small scale fault activity, which has caused serious infrastructure damages and property losses. As PALSAR and PALSAR-2 are good instruments, the present study showed as a demonstration of its potential in volcano research field. We have shown that the PALSAR and PALSAR-2 data can be used to assess subsidence and volumetric changes in the areas of volcanoes. By this study we claimed that using InSAR method it is possible to calculate large mass movements in the two observations during the different eruption to get clues for further study we can use same technique to quantify volumetric changes in the summit areas of volcanoes dome and the utility of InSAR for measuring the complex geophysical signals at mount Bromo is evident given the variety of deformation measurements revealing both eruptive and non-eruptive behaviour, following the interseismic deformation over the Java fault, our study could supports to understand the surface movements along the fault, which agrees well with previous geological studies. For future study we will do risk and vulnerability assessment including this study to create disaster prone-areas due to volcanic activities and InSAR time-series analysis for monitoring sense of motion in East Java volcanic system and fault along the South Semarang to East Java about 300 km. In this case, we evaluating the InSAR result and overlay with Indonesia earthquake map or fault zone map in particular East Java tectonic and volcanic system where is the fault slips with ~5 mm/year. Those evidences are good agreement with geological assessment for the human assessing in risk and vulnerability frame.

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