Journal of Environment, 1, (2014), 1–9

Original Paper

Monitoring of Merapi Volcano Deformation Using Interferometry Synthetic Aperture Radar (InSAR) Technique

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Received: 04 March 2014 / Accepted: 01 October 2014 / Published: 03 October 2014

***Abstract*:** The Merapi volcano is the most active volcano in Indonesia until now, because of eruption occur every two or five years. To minimize the impact of volcanic eruptions need to monitor the volcanic activity, one effort in monitoring is to monitor the surface changes (deformation) around the volcano. These surface changes can be monitored with InSAR technique. In this study monitoring by analyzing the Digital Elevation Model (DEM) and displacement map from result processing using InSAR technique. The accuracy of DEM compare with Shuttle Radar Topography Mission (SRTM) DEM. These results showed that after the eruption in 2006 led to the deflation that occurred in 2007. In 2010 after the eruption led to deflation in some areas of Merapi volcano. Whereas in 2008 due to the absence of volcanic activity that occurred then the deformation is not so large changing. Test on the DEM from the process of InSAR compare with SRTM DEM produced an accuracy of 96%.

***Keywords*:** deformation; InSAR; DEM

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1. Introduction

Indonesia is flanked by 5 plate tectonics, the Asian plate, India plate, Australian plate, Pacific plate, and plates of the Indian Ocean. This condition caused Indonesia has many volcanoes and make the dynamic parts of Indonesia. Indonesia has many volcanoes are still active until now.

Volcanology and Geological Hazard Mitigation, Ministry of Energy and Mineral Resources of Indonesia recorded 129 volcanoes about 13% of all volcanoes in the world are in Indonesia. Until recently there were 80 active volcanoes are categorized with the potential to erupt. Volcanoes in Indonesia spread over two main lines Ring of Fire is the circumference of the Mediterranean and the Pacific rim. Distribution of volcanoes in Indonesia include the west coast of Sumatra, Java, Nusa Tenggara, Maluku, Sulawesi and the northern part (Agustan, 2010).

In the top ten list of the world's largest volcanic eruption in history, nearly half are caused by a volcano in Indonesia. Merapi even listed as the most active volcano in the world until now. Merapi attract world scientists to do research because of high levels of activity and relative continue. Merapi volcano is in the middle island of Java. This volcano is located in a subduction zone, where the Indo-Australian plate continues to move down the Eurasian Plate. This leads to Merapi volcano is extremely dangerous because of an eruption every two or five years.

To minimize the impact of volcanic eruptions, especially the death toll from volcanic eruptions, there are four major activities carried out in Indonesia, namely: research on volcanoes, mapping of disaster prone areas and the eruption, monitoring, and early warning of volcanic eruptions. Ideal system of volcano observation system was able to observe the physical aspects (earthquakes, deformation, avalanches) and chemical (gas jets, temperature, and hot water). One effort in monitoring the volcanic activity is to monitor the surface deformation around the volcano. The volcano deformation can be caused by changes in pressure or movement of magma deep within the earth. These surface changes can be monitored with Interferometric Synthetic Aperture Radar technique. This geodetic method uses two Synthetic Aperture Radar (SAR) images to generate maps of surface deformation and Digital Elevation Model (DEM).

It is desirable to monitor subtle changes at volcanoes, especially surface deformation, in order to determine whether magma is moving at depth. Therefore a history of deformation and eruption must be established for each volcano (Pritchard and Simons, 2004).

These techniques have documented patterns of deformation before, during, and after eruptions of volcanoes (Lu et al., 2005). By observing the surface deformation (inflation-deflation cycle) using InSAR technique then the action of a volcano to volcano disaster mitigation can be more accurate and scalable.

The aims of the research are (1) To create a Digital Elevation model (DEM) and the displacement map of Merapi volcano area by InSAR techniques and to estimate the accuracy of DEM result from ALOS PALSAR. (2) To monitor the deformation (inflation and deflation cycles) occurring at Merapi volcano before and after eruption using InSAR technique.

2. Research Methods

2.1. Research location

The research location is surrounding in Merapi volcano area. Geographically, Merapi volcano area located in 7o32'30" S~110o26'30" E. Magelang city and Yogyakarta city are the nearest large town, is under 30 km from the summit (Voight et al, 2010).

Figure 1. Research Location

2.2. Methods

Materials used in this research are ALOS PALSAR fine-beam dual polarization (FBD) level 1.0 data Yogyakarta area taken on six different acquisition dates (8 June 2007, 8 September 2007, 25 April 2008, 10 September 2008, 16 June 2010, 01 November 2010). Shuttle Radar Topography Mission (SRTM) DEM Yogyakarta on 2006 with grid resolution 90 m.

This research conducted to process from raw data of ALOS PALSAR level 1.0 to make deformation map and DEM of Merapi volcano using InSAR technique. Analysis InSAR results compare with point reference generate from contours in topographical map.

At each image pixel has a value of SLC produced in the complex numbers. Real and imaginary parts of the form of complex numbers in each pixel is composed of information about the amplitude (A) and phase (reserve signal derived from signals emitted sensor. In the SLC form data of phase and the amplitude is still in one file (Kusman, 2008).

By using two SAR data with the same scene, but with the acquisition of different positions (different from the angle of the data), allowing to calculate the phase difference between two images and display the differences as the interferogram.

The phase data of SAR images are analyzed to derived the local topography (original InSAR) or detect and quantity the ground displacement that has occurred in the slant-range direction between the two acquisitions (Bayuaji et al., 2010). The phase difference between an InSAR data pair can be expressed as follows:

$$\phi_p = \frac{4\pi}{\lambda}\left(B\sin\left(\theta_p^o - \alpha\right) - D_p - \frac{B_{\perp p}^o}{R_1 \sin\theta^o} H_p\right) \quad (1)$$

Interferogram is an image of the phase difference between master and slave images, where the information is directly related to topographic relief. This information is limited between 0 and 2π, the phase is called the relative phase in two-dimensional shapes (Faculty of Engineering Diponegoro University, 2010).

The flattened interferogram provides an ambiguous measurement of the relative terrain altitude due to the 2π cyclic nature of the interferometric phase. The phase variation between two points on the flattened interferogram provides a measurement of the actual altitude variation, after deleting any integer number of altitudes of ambiguity (equivalent to an integer number of 2π phase cycles). The process of adding the correct integer multiple of 2π to the interferometric fringes is called phase unwrapping (Ferretti et al., 2007).

After unwrapping processing phase value obtained at each pixel, which the phase have lowest value to highest value, unlike the interferogram have value is limited only every 2π. Then the value obtained from the phase unwrapping process is processed into high. The absolute calibrated and unwrapped phase values are converted to displacement and directly geocoded into a map projection.

From there results be obtained how much deformation occurs and the deformation pattern of Mount Merapi before eruption and after eruption. The phenomenon of inflation and deflation, or can also be referred to as the deformation, the pattern can be seen from the resulting Digital Elevation Model and the value deformation obtained from the color combination of the Displacement Map.

3. Results and Discussion

The master and slave images should overlap to achieve sub-pixel accuracy in the slant range geometry. When the perpendicular component of the baseline increase beyond a limit known as the critical baseline, no phase information is preserved, coherence is lost, and interferometry is not possible (SAR map, 2008). Therefore, the baseline estimation are of vital importance for interferometric processing. ALOS PALSAR pair and baseline information shown in Table 1.

Interferometry mapping is to generate a Digital Elevation Model (DEM) data from radar Interferometry. The height information is obtained by combining two SAR images. The absolute calibrated and unwrapped phase values are converted to height and directly geocoded into a map projection. On this research produced three DEM images from the three pair data. The DEM from the processing using

Interferometry technique is shown in Figure 2 to Figure 4.

Table 1. ALOS PALSAR Pair and baseline information

Pair	Date 1 (Master)	Date 2 (Slave)	Interval Observation time (weeks)	Perpendicular baseline (m)
2007	20070608	20070908	14	340
2008	20080425	20080910	19	996
2010	20100616	20101101	20	419

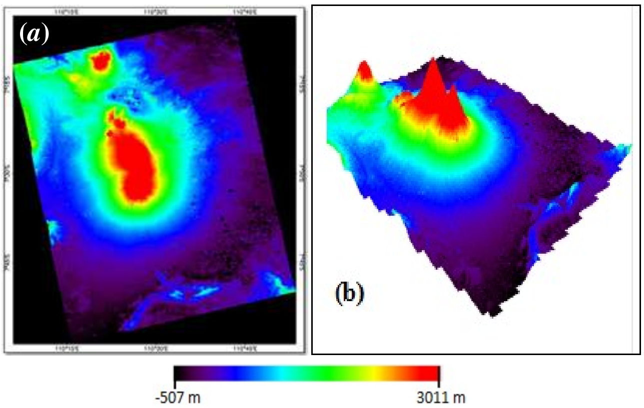

Figure 2. (a) The DEM from Pair 2007; and (b) DEM in a 3D view

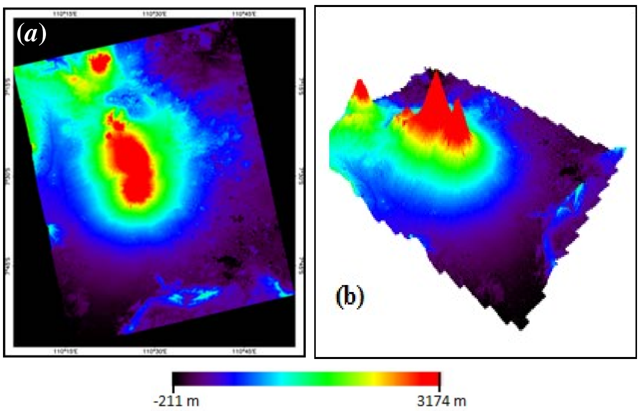

Figure 3. (a) The DEM from Pair 2008; and (b) DEM in a 3D view

To find out the error (the difference elevation) of the results DEM is done by cross section for each image. The cross section is the intersection of a figure in 2-dimensional space with a line. The cross sections for each image are shown in Figure 5. The cross section generated elevation values on each line for every image. Figure 6 shows comparison elevation value for each DEM images from 2007 until 2010.

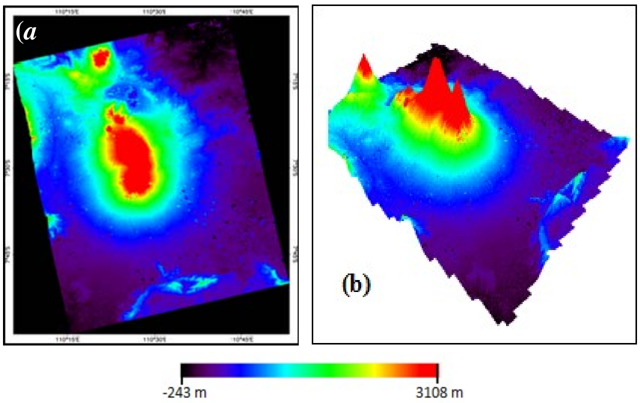

Figure 4. (a) The DEM from Pair 2009; and (b) DEM in a 3D view

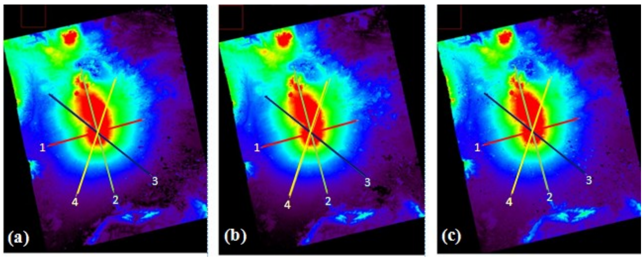

Figure 5. Cross section of image (a) Pair 2007; (b) Pair 2008; and (c) Pair 2010.

Table 2. ALOS PALSAR Pair and baseline information

DEM images	Mean bias error (m)			
	Line 1	Line 2	Line 3	Line 4
2007 - 2008	24	59	35	30
2008 - 2010	-24	-37	-31	-21

Deformation process in pair 2007 happen is the deflation that occurred during an interval 14 weeks of observation. Decrease in surface soil occurs in the peak area or around the crater, this happens because of a reduced of magma activity after the eruption on may 2006. The pattern of the decrease in surface soil (deflation) from the Merapi volcano can be seen in Figure 6(b). In this graph also show the graph elevation from Mount Merbabu. Can be seen in Mount Merbabu no changes in the surface soil because of there is no volcanic activity in this Mountain.

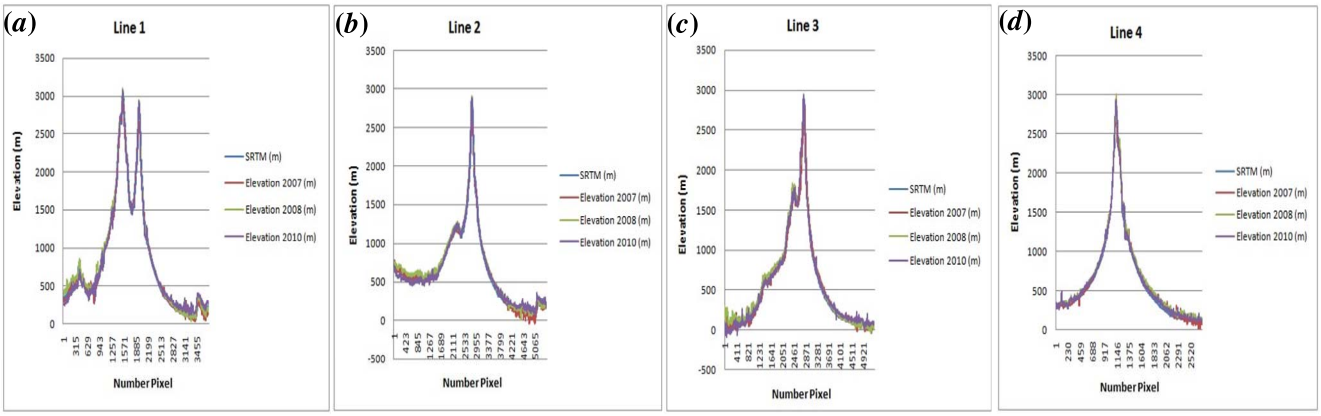

Figure 6. The graph elevation (a) Line 1; (b) Line 2; (c) Line 3; and Line 4.

The phenomenon of deformation or shape changes that occur after the eruption is subsidence or deflation, because of decrease of the volcanic activity. As happened in 2007 and 2010 due to decline of the eruption in May 2006 and October 2010. While the deformation that occurred in 2008 was an increase in soil due to the volcanic activity. The average value of difference elevation (mean bias error) between image 2007 with image 2008 and image 2008 with image 2010 are shown in Table 2.

Comparison elevations from DEM on 2007 with DEM on 2008 produce positive value in all lines. This illustrates that during the time interval there is inflation in Merapi volcano area. While comparison elevation between DEM on 2008 with DEM on 2010 produce negative values in all lines. This illustrates that during the time interval there is deflation in Merapi volcano area.

The accuracy of a DEM can be assessed by various procedures. One of the most common procedures is the comparison with a reference DEM (Sefercik and Dana, 2011). This is one of the powerful ways to understand the quality of a DEM and it has been applied in this research. For this research the reference DEM was obtained from the Shuttle Radar Topography Mission (SRTM) with a grid resolution of 90 m and Topographic Map Bakosurtanal data. To find out the accuracy of the results DEM is done by cross section for each image and compared with SRTM data. Cross section for each image can be seen in Figure 7.

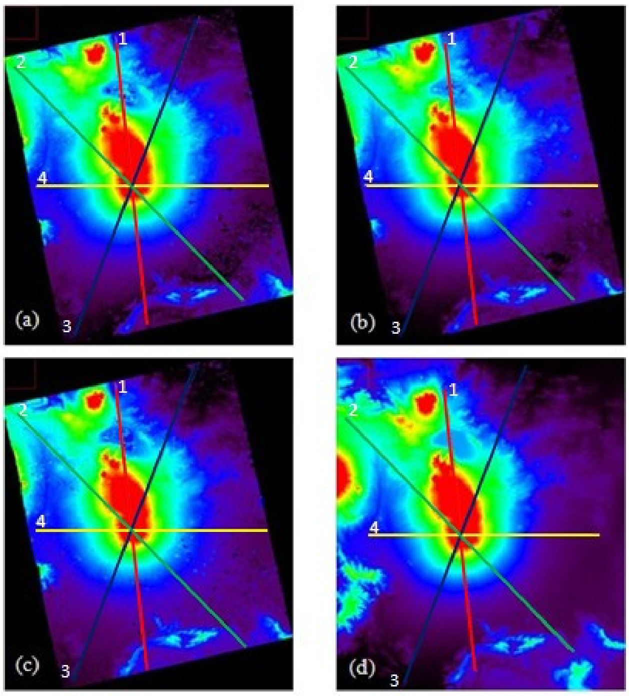

Figure 7. Cross section of image (a) Pair 2007; (b) Pair 2008; (c) Pair 2010; and (d) SRTM DEM.

Figure 8 shows comparison elevation value for each DEM images with SRTM data. The average value of difference elevation (mean bias error) between DEM images with SRTM data is shown in Table 3 and the percentage accuracy in Table 4.

Comparison between the DEM result from InSAR processing and SRTM DEM have a good accuracy. The value elevation from DEM InSAR more closed the value with SRTM DEM in every line. The

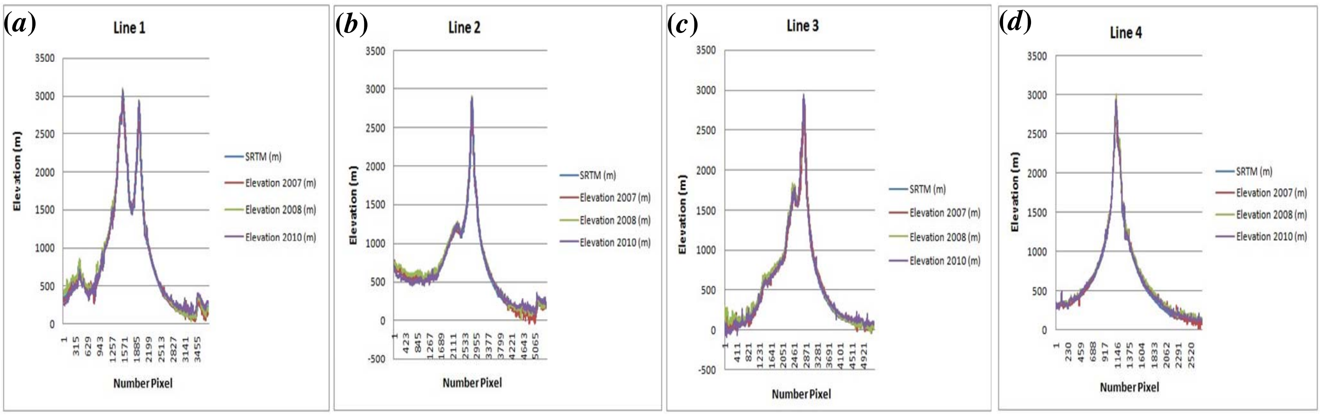

Figure 8. The graph elevation (a) Line 1; (b) Line 2; (c) Line 3; and Line 4.

everage elevation in line 1 is about -9.6 m, line 2 is about -7.3 m, line 3 is about 8.62 m and line 4 is about 27.71 m. The highest different is in the DEM on 2008, line 2 is about 37.93 m, line 2 is about 36.83 m, line 3 37.63 m, and line 4 is about 57.08 m.

Table 3. Value Mean Bias Error

DEM images	Mean bias error (m)			
	Line 1	Line 2	Line 3	Line 4
2007	-9.6	-7.3	8.62	27.71
2008	37.93	36.83	37.63	57.08
2010	12.44	3.66	11.81	31.5

Table 4. The accuracy DEM by InSAR

DEM images	Average Elevation DEM (m)	Average Elevation SRTM (m)	Accuracy (%)
2007	672.76	667.9	98
2008	710.27		93
2010	682.76		97
Average			96

The largest baseline value contained in the pair 2008 that is equal to 996 m (Table 1), it is very influential on the resulting DEM. So the DEM from pair 2008 has a highest errors in all lines compared with the other data pairs. Baseline parameters play very important role in flat earth effect removal and geometric transformation from phase to elevation. The larger critical baseline for a PALSAR interferogram causes it to be very sensitive to topographic relief (Lu and Kwoun, 2008). For the image pairs with inappropriate baseline the error introduced to the topographic maps is almost 100 m (Tarikhi, 2010).

Another source of error is interferometry affected by the atmospheric effects. According to Jonsson et al. (2002), variations in atmospheric refractivity that causes spatially variable delay of the radar signal. Relative delay within an interferogram is measure of the difference between the integrated refractivity structures at the two acquisition times, and can be as large as several centimeters (range change equivalent).

One of the main problems occurred during the InSAR processing was that for large areas no interferometric fringes and thus no height information could be calculated due to lack of coherence (Slob et al, 2000). Figure 9 there is no fringe in some areas of Mount Merapi on a pair of 2010. This due to an eruption that caused the large difference between the two sets of data. So that the value of coherence image is also very low, it can be seen from the results of coherence image pair 2010 in Figure 10.

The coherence is the key product of InSAR process. The area with high coherence obtains a good estimation of height. The magnitude of coherence can be used to determine the quality of height information in DEM (Lau, 2005).

Coherence value is the lowest seen in the Table 5 in pairs 2008 and 2010. This is because the coherence would be decreased indirectly by the increase of moisture content of object that attenuates the backscatter. On the other hand, the coherence would become lower when the behavior of volume scattering is different between two acquisitions as a result of the change of wind conditions (Lau, 2005).

Table 5. Values of the coherence image

Pair	Interval Observation time (weeks)	Value
2007	14	0.318
2008	19	0.296
2010	20	0.293

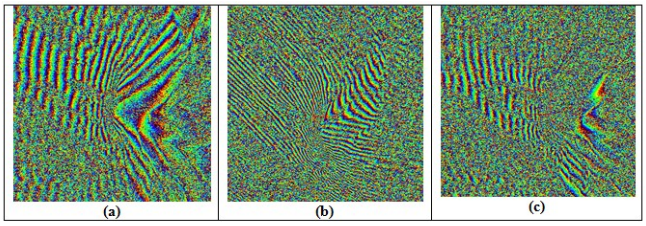

Figure 9. Interferogram of Merapi volcano area (a) pair 2007; (b) pair 2008 (b); and (c) pair 2010.

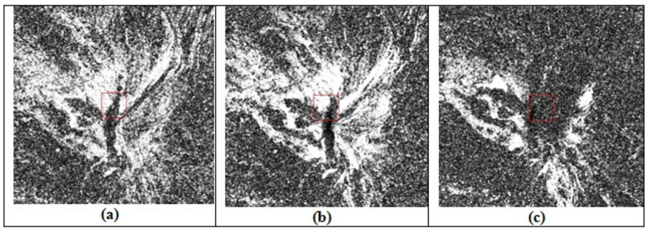

Figure 10. Coherence Merapi area (a) Pair 2007; (b) Pair 2008; and (c) Pair 2010.

The estimated coherence generally the value is between 0 until 1. These values of average coherence image are shown in Table 5. If the coherence value is 1, it can be concluded that the image master and slave is completely identical.

Almost in all of data pair in some parts of it have coherence values below 0.1. Changes in terrain surface during the two image acquisitions can cause low coherence in the interferomatric pair, low coherence (e.g. less than 0.1) means bad phase quality and can engender many problems for the phase unwrapping. In such areas the DEM quality is degraded (Crosetto et al, 1998).

The temporal separation in repeat-pass interferometry of days or even months can be used to advantage for long term monitoring of geodynamic phenomena, in which the target changes position at a relatively slow pace as in the case of lava-flow movements or surface changes of volcano. By utilizing the radar wave coherence properties, geometry changes can be monitored. The deformation maps of Merapi volcano is shown in Figure 11 and focus on several areas of deformation.

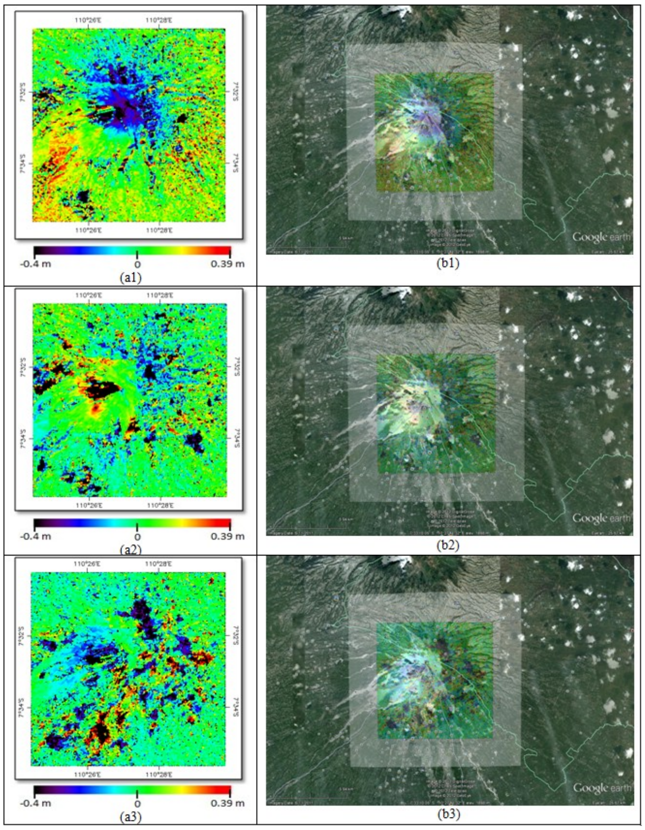

Figure 11. The deformation map of Merapi volcano (a1) Pair 2007; (a2) Pair 2008; and (a3) Pair 2010. Overlay the deformation map with Google Earth (b1) Pair 2007; (b2) Pair 2008; and (b3) Pair 2010.

Figure 11 shows displacement magnitude in meters. Green until red tones has positive values correspond to movement towards the sensor (slave respect to master acquisition). Red and blue tones of Figure 12 represent the areas of largest deformation (in opposite direction), while green areas correspond to smaller deformation zones.

Figure 12(A) is the deformation map of Merapi volcano on 2007, the blue tones has a negative value and the average changes in blue area is about -0.023 meters. There are two focuses area for observation in pair 2008 shown in Figure 5.10 point B and C, the peak area (point B) occur increase the land about 0,018 meters. And the other side (point C) occur decrease the land but the decrease very small indicated by the blue tones is about -0.0076 meters. In pair 2010 point D indicated blue tones occur deflation with value about -0.01 meters and point E indicated yellow area shows an increase about 0.026 meters.

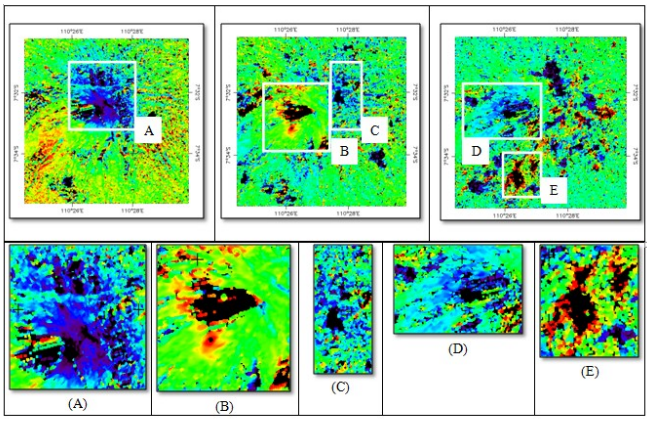

Figure 12. Focus on these areas, which are indicated by points A-E.

Pair 2008 shows smaller deformation during an interval 19 weeks of observation. There are two focuses area for observation in pair 2008 shown in Figure 12(A) and (B), the peak area occur increase the land. This increase can be interpreted uplift deformed area closer to the magma activity. And the other side occur decrease the land but the decrease very small indicated by the blue tones.

Eruption occurred in October 2010 caused large changes in soil surface and some areas have been damaged by lava. In the two observation areas shows a process of deflation indicated blue tones and the yellow area shows an increase because the area is a lava flow area so that the land be increased.

The lower coherence has meaning very big changes during the time observation. This is make the dark tones in pair 2010 image which was completely destroyed by the volcano eruption.

4. Conclusions

The conclusions of this research are; (1) InSAR technology can potentially be used to get a DEM and deformation map from active volcano. The results of processing are affected by coherence and baseline. It will get good result when coherence and baseline are balanced optimally. Average accuracy results DEM InSAR is about 96%, (2) InSAR technique capable to determining the value of deformation in the level a few centimeters and can see the deformation pattern is formed before and after eruption. The deformation occur in 2007 occur is the deflation about 0.023 m and in 2010 is about 0.01 m. In 2008 only have smaller deformation about 0.018 m the land increase (inflation).

The suggestion of this research is to obtain high precision, formation of the interferogram, phase unwrapping and other crucial steps must be further studied to eliminate errors and improve accuracy. Using the other software to processing InSAR technique so it can be known the good software to processing.

Acknowledgments

This work was supported by CReSOS and JAXA mini-ocean projects in Indonesia. We gratefully acknowledge data received from the following organizations: ALOS PALSAR data from the Japan Aerospace Exploration Agency (JAXA); and the Shuttle Radar Topography Mission (SRTM) 30 Plus from Scripps Institution of Oceanography, University of California San Diego.

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