# POST-PROCESSED SPATIAL FILTERING TECHNIQUE FOR VOLCANO DEFORMATION BASED ON INSAR ESTIMATES

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**ABSTRACT:** Most of the filtering efforts in InSAR application are performed before unwrapping the interferogram to reduce noise and increase coherence. The phase noise is mainly caused by the thermal noise decorrelation, temporal decorrelation and geometrical decorrelation. Filtering methods that have been developed such as adaptive filtering algorithm, maximum likelihood estimation, and nonlinear filtering are proven to reduce noise and improve the coherence. However, the deformation signals as a final objective in ground deformation monitoring still contain noise related to the spatial resolution or pixel size factor. Since information obtained from differential InSAR data processing are still hard to interpret due to noise contained, further filtering process called post-processed filtering technique can be applied. This technique is based on the fact that noises which interfere with the deformation signals usually originates from different spatial locations. To suppress noise with this pattern, spatial filter can be applied. A filtered displacement map tends to appear flat unless strong frequency repeats patterns are brought out. This research focuses on the post-processed filtering of InSAR displacement estimates. As a case study, deformation of Anak Krakatau Volcano, Indonesia, is assessed using this technique. This study shows the limitation of InSAR to detect clear fringe visibility on the low coherence area covered by volcanic ash. However, after applying post-processed filtering technique of vertical displacement, a clear deformation pattern can be recovered and modeled to study the volcanic sources. By applying this method, it is possible to derive displacement contour map that is useful for monitoring ground deformation related to volcanic activity.

## 1. INTRODUCTION

Studies on ground deformation as one indicator of volcanic activity are still limited. To understand the status of a volcano, a complete volcano monitoring system comprising seismic observation, geodetic observation and geochemical observation (Dzurisin, 2007) is required. One technique in geodetic observation for volcano deformation detection is interferometric synthetic aperture radar (InSAR) that has been used since 1995 to monitor surface displacement related to volcanic activity (i.e. Massonet and Feigl, 1998; Stevens and Wadge, 2004). This technique has the potential to detect ground deformation without interference from clouds.

For ground deformation detection, the term differential InSAR (DInSAR) is introduced to subtract the topographic phase from the interferogram. The topographic phase can be derived from the following, i.e. a simulation of an existing DEM obtained from a topographic map; other survey techniques; or from the Shuttle Radar Topography Mission (SRTM). This kind of technique is known as 2-pass differential interferometry or simply DInSAR because it only needs two SAR images. The technique performs differentiation between real interferogram obtained from two SAR images and simulates interferogram derived from a DEM. The generation of full resolution interferogram and then deformation signals requires following steps: image registration and resampling, baseline estimation, range spectral shift and azimuth common bandwidth filtering, interferometric phase computation, generation of synthetic fringes (topographic phase), subtracting topographic phase from the interferometric phase, unwrap the differential phase, baseline refinement, mitigation of atmospheric phase, and deformation map generation.

After unwrapping the differential phase as a result of DInSAR data processing, line-of-sight (LOS) deformation can be decomposed to vertical and horizontal component along the LOS direction. Filtering method can also be applied to reduce noise and to improve homogeneity of pixel value on this stage. This is called post-processed filtering technique. This research focuses on the post-processed filtering of InSAR displacement estimates. As a case study, deformation of Anak Krakatau Volcano, Indonesia, is assessed using this technique based on Advanced Land Observing Satellite (ALOS) Phased Array type L-band Synthetic Aperture Radar (PALSAR) data.

## 2. ANAK KRAKATAU VOLCANO AND INSAR ESTIMATES

Anak Krakatau (Child of Krakatau Volcano) is an active volcanic cone located in Krakatau complex, Sunda Strait, Indonesia (Figure 1) with approximation coordinates 6$^{o}$06'05" S and 105$^{o}$25'22" E. This volcano was born in 1927 as a precedence of famous Krakatau after vulcanian eruption in 1883. After being calm since last eruption in 2001, Anak Krakatau Volcano started to erupt on October 2007 and ended on August 2008 with Strombolian activity. In this eruption period, a new crater was formed on the southwestern flank just below the main crater and produced ash plumes as well as lava flows.

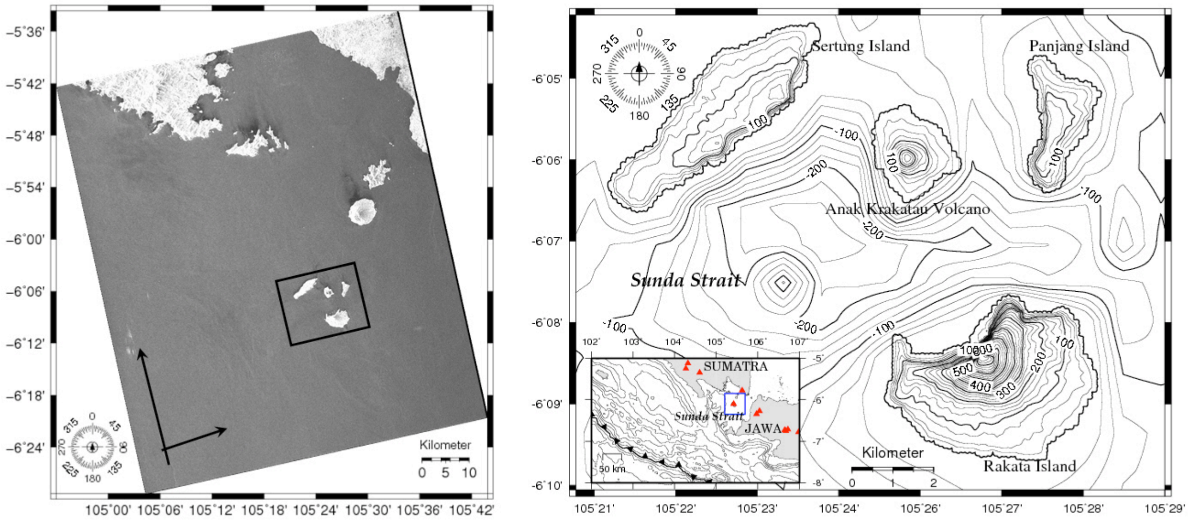


Figure 1. The PALSAR image of Anak Krakatau and its location in Sunda Straint, Indonesia

Ground deformation related to volcanic activity is usually indicated by inflation and deflation pattern that can be identified by concentric fringes in the interferogram. For example, the deflation induced by the activation of Etna Volcano, Italy, had been measured using InSAR technique by Massonnet et al. (1995); the deformation field detection associated to the 1997 eruption of Okmok Volcano in Alaska by Lu et al. (1998); and modeling magma intrusions and edifice radial spreading after eruption during magma recharging phase was conducted by Palano et al. (2008).

Five ascending Level 1.0 and 1.1 PALSAR data which are observed on June 2007, September 2007, February 2008, September 2008, and February 2009 (Table 1) are processed using GAMMA SAR Software (Wegmuller and Werner, 1997) to obtain SLC images and interferometric phase. Table 1 shows that the time difference for each observation ranging from 92 days to 598 days. To deal with different observation mode, oversampling method (Werner et al., 2007) is applied to Fine Beam Dual (FBD) polarization observation mode to obtain the same dimension with Fine Beam Single (FBS) polarization observation mode.

| $\Delta T$ / $B_{perp}$ | 2007-06-23 FBD 1.0 | 2007-09-03 FBD 1.0 | 2008-02-08 FBS 1.1 | 2008-09-25 FBD 1.1 | 2009-02-10 FBS 1.1 |
|---|---|---|---|---|---|
| 2007-06-23 | | 92 days | 230 days | 460 days | 598 days |
| 2007-09-03 | 344 m | | 138 days | 368 days | 506 days |
| 2008-02-08 | 262 m | 82 m | | 230 days | 368 days |
| 2008-09-25 | 750 m | 1093 m | 1010 m | | 138 days |
| 2009-02-10 | 489 m | 833 m | 751 m | 260 m | |

Table1. Perpendicular and temporal baseline of ALOS-PALSAR data set

Once the SLC images are generated, then the focus area is cropped out to derive the interferogram and deformation signals. This strategy is applied to minimize the co-registration error that might be occurred since the area is surrounded by open water. Open water is a specular reflector for radar signals that make the amplitude of each pixel almost zero (signal strength is low). This condition degrades the number of pixel offset when registering the slave image to master image to conform the geometry. Large number of pixel offset with high accuracy estimation ensures the visibility of interferogram generated.

Phase unwrapping is performed to retrieve the topographic height, displacement information by adding the correct integer multiple of to the interferometric fringes using minimum cost flow (MCF) algorithm (Costantini, 1998).

This technique is a global optimization technique to phase unwrapping problem that give the advantages in dealing with the gaps area caused by low coherence by considering their density in triangular network. In addition, by masking, adaptive thinning and patch processing steps in MCF allows the efficient and robust unwrapping for interferogram image in any dimension. To reduce the atmospheric phase, this study utilizes a linear phase trend with elevation model (Li et al., 2006). Series of interferogram can be seen in figures below.

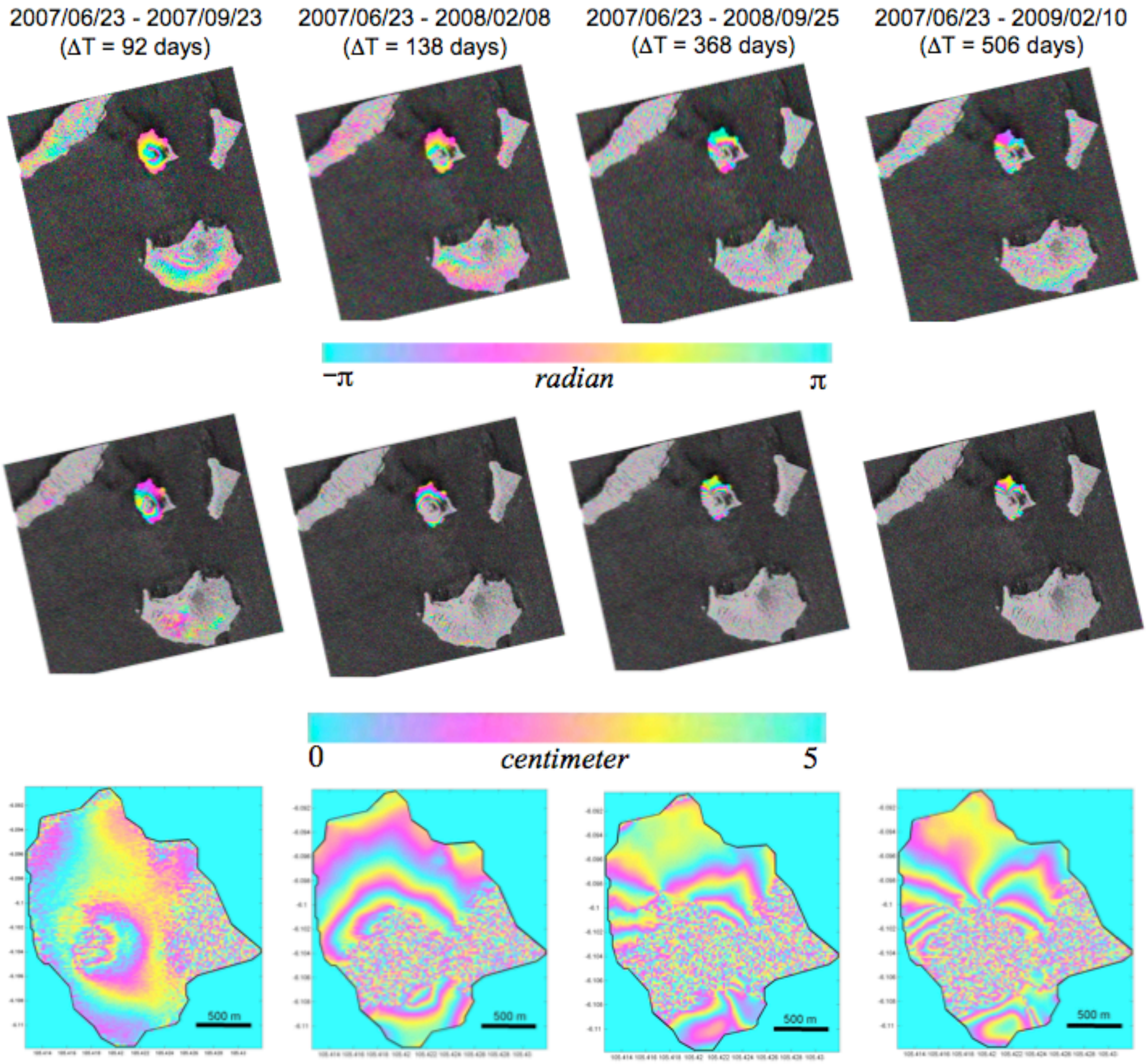


Figure 2. Series of Interferogram

Figure 2 illustrates series of interferogram: flattening interferogram images based on June 23rd 2007 observation epoch and vertical deformation after phase unwrapping in 5 cm color fringes.

## 3. POST-PROCESSED SPATIAL FILTERING TECHNIQUE

Since information obtained from DInSAR data processing still hard to interpret due to noise contained, further filtering process can be applied that called post-processed filtering technique. This technique based on the fact that noise that interfere the deformation signals usually originate from different spatial locations. To suppress noise with this pattern, spatial filter can be applied (Veen and Buckley, 1988).

Spatial filtering of digital images such as products of interferometry technique is accomplished by convolving an image (digital data) with a point-spread function (PSF) that is a two-dimensional data of point source (Schowengerdt, 1983). Carr (1990) showed that if $f(x, y)$ is the original digital data, $g(x, y)$ is the filtered data, a two-dimensional convolution of a PSF with a digital data can be expressed as Equation (1); and in practice, the PSF is a collection of weights and the convolution is approximated by a double summation as written in Equation (2).

$$g(x, y) = PSF(x, y) * f(x, y) \quad (1)$$

$$g(x_0, y_0) = \sum_i \sum_j PSF(x_0 - x_i, y_0 - y_j) * f(x_i, y_j) \quad (2)$$

Equation (2) shows that the PSF is a box filter that also known as sub-image or filter mask or filter window with column and row dimension and its values are referred as coefficients, rather than pixels. The process of spatial filtering consists simply of moving the filter mask from point to point in the digital data. At each point $(x, y)$ the response of the filter at that point is calculated using a predefined relationship such as linear convolution (weighted averaging) or non-linear convolution (i.e. statistical measure) relationship.

Median filter as a non-linear convolution method is applied to obtain a filtered vertical displacement. The Median filter process ranks the input values in determined window size and assigns the median value as the output which is not affected by the actual value of outlier cells within the filter window. A filtered displacement map tends to appear flat unless strong frequency repeats patterns are brought out. By applying this method, it is possible to derive displacement contour map that useful to study ground deformation. The processing chain is illustrated in Figure 3.

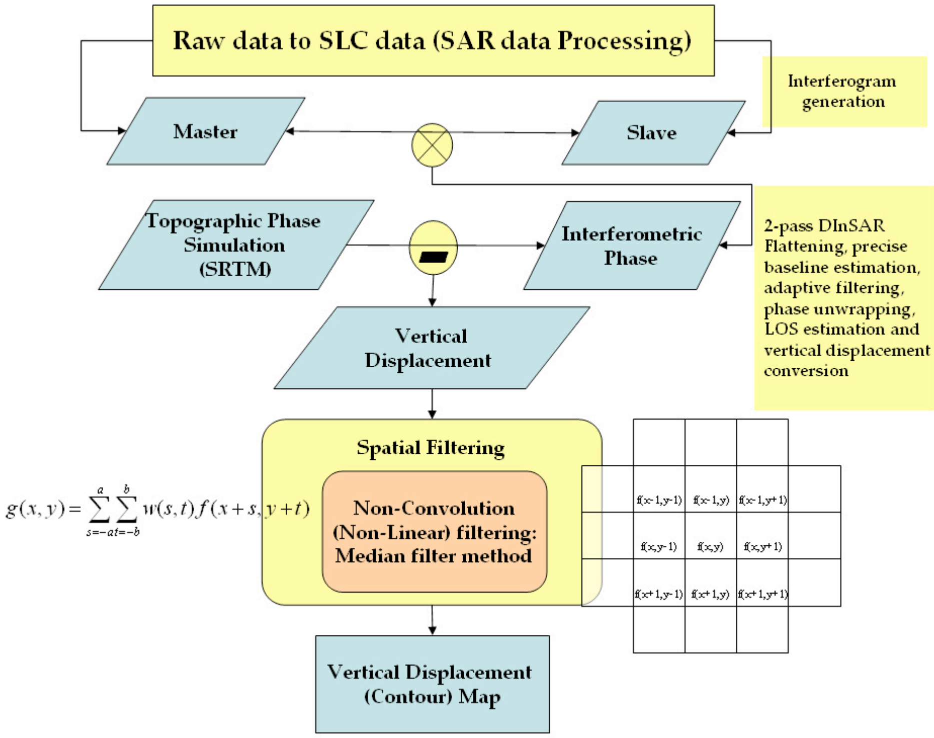


Figure 3. Processing flow of post-processed filtering technique

Figure 4 illustrates the vertical deformation before and after applying post-processed filtering technique. The smoothed grids that contain vertical deformation then can be used to model a volcano deformation.

## 4. DISCUSSION AND CONCLUSIONS

From InSAR data processing results, it is clear that during the observation periods, the deformation signals was only found in Anak Krakatau Volcano and was certainly related to the volcanic activity. Ground deformation pattern from June 2007 to September 2007 showed an inflation about 6 cm accompanied with subsidence pattern around the crater in 92. The ground deformation pattern changed to deflation from June 2007 to February 2008 for the whole area, especially around the crater with a maximum subsidence of 20 cm for 230 days. During this period, Anak Krakatau started to erupt on October 2007 with an average eruption of 160 times a day.

From early February 2008 to mid April 2008, no eruption was recorded. Starting April 14 2008, the volcanic activity increased significantly until September 2008. It is shown that the summit area was uplifted up to 26 cm whereas the southwestern flank was subsided 14 cm in 460 days, from June 2007 to September 2008. From June 2007 to February 2009, the southwestern area continued to subside with 22 cm whereas the northeastern area was uplifted with maximum 16 cm in 598 days.

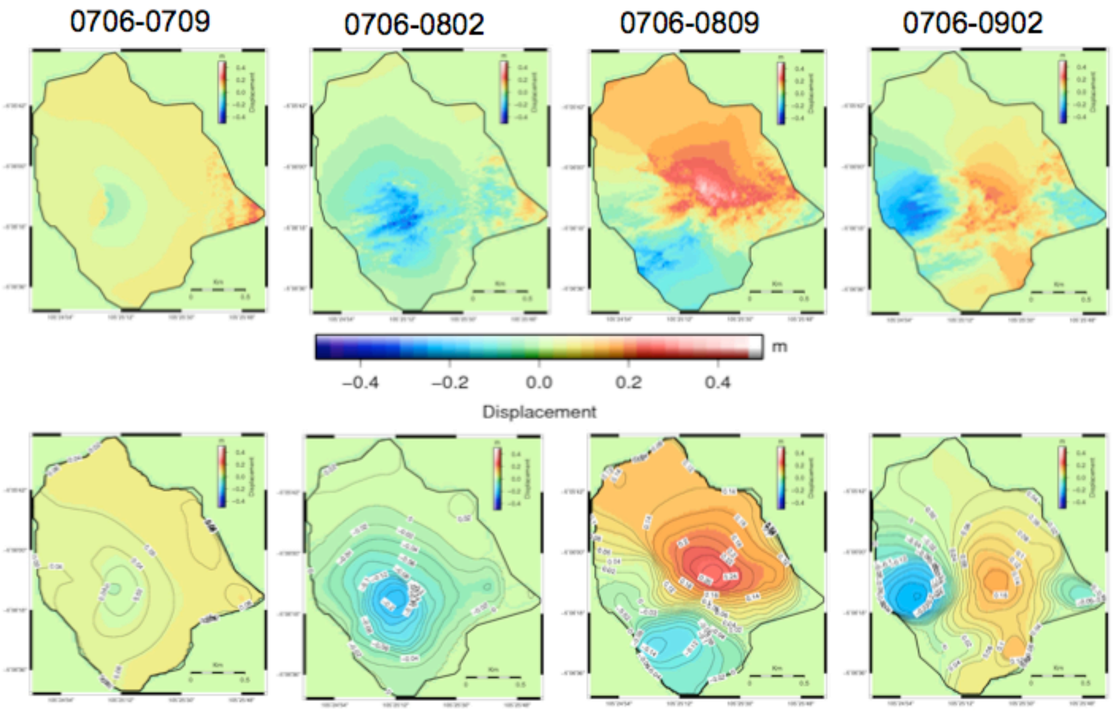

Figure 4. Deformation of InSAR estimates and the results of post-processed filtering technique

However, this study shows the limitation of InSAR to detect clear fringe visibility on the low coherence area covered by volcanic ash. In addition there is no ground truth data (i.e. GPS observation or leveling data) that can be used to validate the InSAR estimates. It is shown that after applying post-processed filtering technique of vertical displacement, the deformation pattern can be modeled to understand the volcanic sources. In conclusion, this study shows the ability of InSAR technique to detect ground deformation for Anak Krakatau Volcano.

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