Surface Deformation Detection due to Mud Volcanoes Manifestation in East Java Basin Area using Permanent Scatterer InSAR

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Abstract. The manifestation of mud volcano changes the Earth's surface and can affect the objects above it. This research presents Permanent Scatterer InSAR (PS-InSAR) results for the analysis pattern and deformation value of the land surface due to the manifestation of mud volcanoes. This research was carried out in the mud volcanoes manifestation in East Java Province (at East Java Basin's coverage). Time-series data processing uses the SAR Image on Sentinel 1A. The PS-InSAR technique produces PSC to get deformation value based on coherence with a ± 4.5 km radius from the manifestation of mud volcanoes. The result showed that from 2015 to 2019, Lumpur Sidoarjo has a velocity rate with an average of -5.46 mm/yr, Mud Volcano in Gununganyar has a velocity rate with an average of +1.71 and -7.08 mm/yr, Mud Volcano in Kalanganyar has a velocity rate with an average of +0.99 mm/yr, Mud Volcano in Wringinanom has a velocity rate with an average of +3.36 mm/yr, and Bujhel Tasek Mud Volcano has velocity rate with an average of +2.88 mm/yr. The surface deformation's values and patterns on each mud volcano vary according to the morphology, geological conditions, and environmental condition around it.

1. Introduction
The study of mud volcanoes is essential for various activities, such as indicators of active oil systems, methane sources in the atmosphere and sea, and geohazards [1]. World cases present that diapirism and mud volcanism have a close relationship with petroleum. It is the same case of mud volcanoes phenomenon in Java and Madura Island. Oil, gas seepage, and drilling holes have been found and produced in the eastern part of Bogor Zone, North Serayu Zone, Rembang-Kendeng Zone. The Rembang-Kendeng Zone is part of the East Java Basin, the oldest and richest petroleum areas in Indonesia [2]. The mud volcano phenomenon can change the shape of the Earth's surface (ground deformation). Ground deformation affects the objects on it, such as building structures and utilities.
Therefore, it is crucial to be monitored. Ground or surface deformation is the situation when the land surface changes horizontally and vertically [3].

Observation methods to monitor deformation have been developed in the Geodesy field. Monitoring ground deformation can be performed using the Global Positioning System (GPS) and Interferometric Synthetic Aperture Radar (InSAR). The InSAR technique can detect changes in the Earth’s surface by utilizing different phase electromagnetic waves recorded at two other observation times. The selection of the PS-InSAR (Permanent Scatterer Interferometric SAR) method is the latest radar image processing method that provides the accuracy of up to millimeters and can minimize the effects of temporal decorrelation. This method can be used to measure small movements in time-series.

In this study, the PS-InSAR method's application is made using SarProZ software to determine the ground's deformation due to the manifestation of mud volcanoes in East Java Province in the East Java Basin region. The PS-InSAR method is used to measure deformation based on LOS (Line-of-Sight) from the SAR sensor to the Earth's surface. PS-InSAR can detect deformations as time series by estimating the PS point (Permanent Scatterer) on each SAR acquisition region, eliminating atmospheric, topographic, and signal noise effects [4].

This study aims to determine how the application of the PS-InSAR method using Sentinel 1A imagery for ground deformation due to the manifestation of mud volcanoes and to know the values and patterns obtained from processing using these methods along with the analysis of environmental conditions.

2. Study Area
The study area covered two different regions. The first area located in Madura Island, East Java Province with the longitudes 112°50′22.08″ - 113°18′4.17 ″ East and the latitudes 6°48′59.37″ - 7°17′2.7″ South. The other area is located at the longitude 112°27′16.7″ - 112°51′59.02″ East and the latitudes 7°13′7.21″ - 7°38′34.04″ South, which presents the scope of the study area in the Java Island, East Java Province.

![Figure 1. The location of study areas](image)

The mud volcano manifestation areas can be seen in Figure 1 and Table 1.
3. Dataset Description
The SAR data used in this study is Sentinel-1A acquired between 2015 and 2019. This data is freely available through the COPERNICUS website. Other Sentinel-1A advantages come from its wide range coverage (250 km in an interferometric wide swath mode) and sufficient spatial resolution (5 m × 20 m in range vs. azimuth) [5]. The pairs of images in the Single Look Complex (SLC) format were used. The PSI [6] (Permanent Scatterer InSAR) requires at least 20 SAR images to perform the analysis in C-Band data [7]. In this study, we used 20 SAR images to make a master and slave images. With flight mode in ascending pass and VV polarization, the process of selection data can handle it. The selection of the appropriate data pair is crucial because the method's success depends on coherence values. Therefore, attention to several parameters influencing coherence preservation, such as the perpendicular baseline between the satellite orbits, the temporal baseline between acquisition dates, and the overall coherence estimation is needed [6].

4. Methodology
The PS-InSAR technique applied in this research is following the workflow, as shown in Figure 2.

![Figure 2. The workflow of Permanent Scatterer InSAR](image-url)

| Mud Volcanoes Names | Coordinate Location                                      |
|---------------------|----------------------------------------------------------|
| Gununganyar         | Longitudes 7° 20′ 14.08″ South, Latitudes 112° 46′ 56.32″ East |
| Bujhel Tasek Bini   | Longitudes 6° 59′ 41.03″ South, Latitudes 112° 58′ 22.53″ East |
| Bujhel Tasek Laki   | Longitudes 6° 59′ 33.39″ South, Latitudes 112° 58′ 10.93″ East |
| Lumpur Sidoarjo     | Longitudes 7° 31′ 40.5″ South, Latitudes 112° 42′ 23.34″ East |
|                     | Longitudes 7° 31′ 32.22″ South, Latitudes 112° 42′ 28.08″ East |
|                     | Longitudes 7° 31′ 35.72″ South, Latitudes 112° 42′ 47.34″ East |
|                     | Longitudes 7° 31′ 28.92″ South, Latitudes 112° 42′ 55.74″ East |
| Kalanganyar         | Longitudes 7° 31′ 32.22″ South, Latitudes 112° 42′ 28.08″ East |
| Wringinanom         | Longitudes 7° 31′ 33.72″ South, Latitudes 112° 42′ 47.34″ East |
First, all the SLCs from the input dataset were converted into the format readable by SarProZ. Several tasks, such as computation of the dataset statistics, applying precise orbits, and selecting the subset of SLCs to cover the area of interest. At this stage, the selection of the optimal master image is carried out. Then the SAR image slave product selection is performed by the desired subswath and polarization and the updated orbit information. Master and slave images were extracted and co-registered. The offsets between the master and slave images are estimated by investigating the amplitude information’s correlation in the spatial and spectral domain. Each slave image is aligned to the master so that the portion of the imaged terrain of each pixel in the slave image is the same in the corresponding pixels of the master image. From the co-registered stack of images, the reflectivity map, as the temporal average of all images’ intensities in a dataset, was generated, and the amplitude stability index was computed. The preliminary geocoding could be done depending on the available data and the resolution; there are different strategies for selecting good tie points for geocoding. Next, the DEM in SAR coordinates was calculated to assist the PSI processing. Finally, the highway surface was large enough to be represented by tens of S-1 pixels; therefore, there were enough coherence PSI pixels [9]. The processing was carried out on a set of points exploiting a different characteristic related to the amplitude of the radar signal (reflectivity map and amplitude stability index), temporal and spatial coherence. For creating a network of PS candidates (PSC), a threshold on the amplitude stability index was applied to estimate preliminary parameters and Atmospheric Phase Screen (APS). This stage is done by entering the threshold value of the Amplitude Stability Index (ASI). The description of the formula proposed by Ferretti et al. [10] as follows:

$$ASI = 1 - D_A = 1 - \frac{\sigma_A}{\mu_A}$$

Where $\sigma_A$ is the standard deviation, $\mu_A$ is the average value, $D_A$ is the dispersion index, and then includes the values of the estimated height and linear trend parameters to select the reference point as a reference point PS in the next PS-InSAR processing. A larger set of points based on the reflectivity map and spatial coherence was used during APS’s compensation. Inverted residuals APS [11] were estimated using the stratification option to evaluate APS and elevation DEM correlation. After APS removal, the final estimates of height and velocity were computed [8].

5. Result and Discussion

5.1 Results of the Values and Deformation Patterns

5.1.1 Lumpur Sidoarjo

The deformation pattern of PS point in the Lumpur Sidoarjo area presents the estimated velocity rate is more significant when approaching the mud volcano manifestation area. This can be seen in Figure 2.
The results of the estimated deformation of the land surface due to the Sidoarjo mud volcano manifestation are presented in Table 2.

Table 2. Estimated Value of Land Deformation due to the manifestation of Lumpur Sidoarjo

| SAR Image Type | Total of PS Points within a radius of ± 4.5 km | Estimated of Mean LOS Velocity Rate (mm/yr) | Average Value of Standard Deviation (mm) |
|----------------|-----------------------------------------------|--------------------------------------------|----------------------------------------|
| Sentinel 1A     | 1,390                                         | Uplift : +2.62                             | 2.33                                   |
|                 |                                               | Subsidence : -5.46                         |                                        |

Table 2 illustrates the estimated value of the mean LOS velocity in the manifestation area of Lumpur Sidoarjo has an uplift in the southern and the southwestern regions of the study area in the amount of 2.62 mm/year. In contrast, most of the study area experienced subsidence with a rate of 5.46 mm/year.

5.1.2. Gununganyar mud volcano
The result of the deformation pattern from PS-InSAR processing illustrates that the area around the manifestation of Gununganyar is deformed in the southeastern part of the mud volcano. This is in line with the identification of the resistance value of the data processing by the geoelectric method, which presents that the direction of the distribution of mud is expanding towards the southeast and the area to watch out for mudflow disaster is the southeast direction of the center manifestation[12].
The results of the estimated value of land deformation due to the Gununganyar mud volcano manifestation are presented in Table 3.

Table 3. Estimated Value of Land Deformation due to the manifestation of Gununganyar Mud Volcano.

| SAR Image Type | Total of PS Points within a radius of ± 4.5 km | Estimated of Mean LOS Velocity Rate (mm / yr) | Average Value of Standard Deviation (mm) |
|----------------|-----------------------------------------------|---------------------------------------------|------------------------------------------|
| Sentinel 1A    | 6,704                                         | Uplift : +1.71                              | 1.66                                     |
|                |                                               | Subsidence : -7.08                          |                                          |

Table 3 illustrates that the estimated value of the mean LOS velocity in the manifestation area of Gununganyar Mud Volcano experienced an uplift in the north and northwest of the study area in the amount of 1.71 mm/year. While in other parts of the study area, subsidence decreased by 7.08 mm/year. Furthermore, based on its geological condition, Gununganyar is situated on the unconsolidated alluvium plains and still in the compaction process. The increasing loads due to the continuing development of infrastructure could worsen the subsidence. Since 2010, the reclamation project had been conducted in the East and North Coast of Surabaya, where Gununganyar mud volcano is located on the East Coast of Surabaya. Around 2500 hectares of the area are mangroves. However, 2300 hectares of the area has changed from fishponds and mangroves into settlements [3].

5.1.3. Kalanganyar mud volcano

The results of the estimated deformation of the land surface due to the manifestation of Kalanganyar Mud Volcano are as follows:
Table 4. Estimated Value of Land Deformation due to the manifestation of Kalanganyar Mud Volcano.

| SAR Image Type | Total of PS Points within a radius of ± 4.5 km | Estimated of Mean LOS Velocity Rate (mm / yr) | Average Value of Standard Deviation (mm) |
|---------------|-----------------------------------------------|---------------------------------------------|-----------------------------------------|
| Sentinel 1A   | 2,136                                         | Uplift: +0.99                               | 1.76                                    |
|               |                                               | Subsidence: -6.81                           |                                         |

Table 4 illustrates that the estimated value of the mean LOS velocity in the Kalanganyar mud volcano manifestation area has an uplift in the radius of ± 2 km in the amount of 0.99 mm/year. Simultaneously, the northwestern part of the study area experienced subsidence of 6.81 mm/year. PS points in the north dominate the study area to the west of the mud volcano manifestation area because the mud volcano area is located between vegetation areas, ponds, and settlement areas.

Figure 5. Plot results of estimated LOS velocity rate PS-InSAR in the area of Kalanganyar Mud Volcano

5.1.4. Wringinanom mud volcano

The results of the estimated value of land deformation due to the manifestation of Mount Wringinom are as follows:

Table 5. Estimated Value of Land Deformation due to the manifestation of Wringinanom Mud Volcano.

| SAR Image Type | Total of PS Points within a radius of ± 4.5 km | Estimated of Mean LOS Velocity Rate (mm / yr) | Average Value of Standard Deviation (mm) |
|---------------|-----------------------------------------------|---------------------------------------------|-----------------------------------------|
| Sentinel 1A   | 1,230                                         | Uplift: +3.37                               | 1.77                                    |
|               |                                               | Subsidence: -1.98                           |                                         |
Table 5 illustrates that the estimated value of the mean LOS velocity in the manifestation area of the Wringinanom mud volcano has experienced an uplift in the radius of ±1 km of 3.37 mm/year. While in other parts of the study area, subsidence decreased by 1.98 mm/year because the subsidence area is an area of settlements and highways.

![Plot results of estimated LOS velocity rate PS-InSAR in the area of Wringinanom Mud Volcano.](image)

**Figure 6.** Plot results of estimated LOS velocity rate PS-InSAR in the area of Wringinanom Mud Volcano.

5.1.5. **Bujhel Tasek Bini and Laki mud volcano**

The results of the estimated deformation due to the manifestation of the Bujhel Tasek mud volcano are as follows:

**Table 6.** Estimated Value of Land Deformation due to the manifestation of Bujhel Tasek Mud Volcano.

| SAR Image Type | Total of PS Points within a radius of ± 4.5 km | Estimated of Mean LOS Velocity Rate (mm/yr) | Average Value of Standard Deviation (mm) |
|---------------|-----------------------------------------------|--------------------------------------------|----------------------------------------|
| Sentinel 1A   | 201                                           | Uplift : +2.88                             | 1.66                                   |
|               |                                               | Subsidence : -0.83                         |                                        |

Table 6 presents the estimated value of the mean LOS velocity in the manifestation area of Mount Mud Bujhel Tasek has an uplift in almost all area of 2.88 mm/year. While there are only a few PS points that detect parts of the northwest area, occur the subsidence in the amount of 0.83 mm/year.
Figure 7. Plot results of estimated LOS velocity rate PS-InSAR in the area of Bujhel Tasek Mud Volcano.

5.2. Analysis of Deformation Identification Due to the Phenomenon of Mud Volcanoes Manifestation Based on Environmental Conditions

The phenomenon of mud volcanoes in East Java Province is due to the geographical condition of the mud volcano located in the East Java Basin, which is classified as an elastic basin that has several characteristics, including gas supply and high potential hydrocarbon, less dense sediment, and faults [2]. East Java was formed by the subduction of the Sundaland and Western Australia microcontinent, also influenced by Indian collision, which rotated the western part and formed the RMKS (Rembang-Madura-Kangean-Sakala fault) [13] and in additional, the East Java region traversed by several faults, namely the Kendeng Fault and the Watukosek Fault. Most of the faults in the study area are normal and most to be active or growing faults. The deformation of the land surface due to the manifestation of mud volcanoes can be influenced by the volume of mud eruption activity, such as the Sidoarjo Mudflow Manifestation, which releases around 7,000 - 150,000 m$^3$/day [14]. Its more dominant influence on land surface deformation compared to other mud volcano manifestations.

In addition to geography and geological factors, the deformation pattern is produced related to the study area's existing condition, located between the settlement and vegetation areas. The deformation value obtained is influenced by the growth of settlements and industrial activities around the mud volcano manifestation. This can be seen in the difference in values and deformation patterns between Bujhel Tasek and Kalanganyar Mud Volcano, in the manifestation area of Bujhel Tasek Volcano, which is located in the vegetation area which has a lower deformation value than the Mount Mud Kalanganyar manifestation area.

6. Conclusion

Based on the results of the analysis, it is known that Lumpur Sidoarjo in the majority has a velocity rate with an average of -5.46 mm/yr, Mud Volcano in Gununganyar has a velocity rate with an average of +1.71 and -7.08 mm/yr, Mud Volcano in Kalanganyar has a velocity rate of +0.99 mm/yr, Mud Volcano in Wringinanom has a velocity rate with an average of +3.36 mm/yr, and Bujhel Tasek Mud Volcano has a velocity rate with an average of +2.88 mm/yr. The value and pattern of land deformation
produced have varied following the morphology of the mud volcano manifestations, geological conditions, and its environment.

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