Detection of surface deformation in opak fault Yogyakarta using quasi persistent scatter interferometry synthetic aperture radar

M Yudinugroho¹ and C A Rokhmana²

¹Graduate School of Geomatics Engineering, Department of Geodetic Engineering, Universitas Gadjah Mada, Yogyakarta, Indonesia
²Department of Geodetic Engineering Universitas Gadjah Mada, Yogyakarta, Indonesia

E-mail: maulana.yudinugroho@gmail.com

Abstract. The Opak Fault is an active fault located in Yogyakarta. As an active fault, it leads to natural disasters, one of them being the Yogyakarta earthquake in 2006. Since then, Opak Fault surface deformation has not reoccurred; hence measurement to detect this movement is essential. A widely used method in surface deformation measurement is Persistent Scatter Interferometry Synthetic Aperture Radar. A refined version of the PSI technique, the QPSI method, allows identifying and estimating targets undergoing movement through the reflectivity and amplitude stability of SAR waves. This study analyzed multi temporal Sentinel-1 Ascending and Descending data to analyze the Quasi-PSI performance in detecting surface deformation surrounding the Opak Fault. Results showed subsidence of the Opak Fault with a displacement accumulation up to -50mm throughout a period of 6 years. A majority of the surface deformation occurring in the area of interest lies at the border between Bantul Graben and the highlands of Gunung Kidul. Some of the surface displacements implied the presence of ongoing slope activity. In the area with a velocity displacement of -7 to -10 mm/year, a cumulative displacement greater than -50 mm was found. Furthermore, areas with a -2.5 to -5.5 mm/year velocity displayed a cumulative displacement ranging from -30 mm to – 40 mm. Surface deformation in the study area expressed an adequate result with a few sparse zones. Nonetheless, results from the ascending and descending modes present dissimilarity between results from several locations.

1. Introduction
Indonesia is known to be a geographically disaster-prone country as it is a confluence of three major plates, them being the Eurasian and Indo-Australian plates. This condition subsequently allows for high-activity plate tectonics in several regions of Indonesia. One of the locations affected by earthquakes caused by plate tectonics lie in the Opak Fault. The Opak Fault is situated in Java island, which is juxtaposed with the Java Trench as one of the most tectonically active plate boundaries in the world, in consequence of being located in a subduction zone. Opak Fault (Figure 1), found in the Special Region of Yogyakarta, lies parallel along the Central Java Fault [1]. Consequently, data showed the occurrence of 7 major earthquakes spread in the year of 1867, 1943 and 2006 [2]. Following the wake of the aforementioned earthquake phenomena, several studies have since been conducted on the Opak Fault, in regards to plate tectonics as well as land deformations. Since then, the Opak Fault has been studied from the perspectives of various sciences, such as utilization of InSAR for remote sensing [3] which demonstrated the existence of a border, referred to as Bantul Graben, separating the uplift and subsidence of a region west of the Opak Fault, along with an amplified level...
of socio-economic vulnerability in several regions as a subsequent effect of the Fault [4]. Hence, an active fault that had not been mapped from the GNSS surveillance of deformation and plate movement had been speculated [5], [6].

![Figure 1](image-url). Earthquake history and fault lines in Java Island (a) and Opak River Fault and 2006 earthquake epicentrum [1], [3].

The measurement of surface deformation utilizing remote sensing offered an exceptional visualization for the medium scale analysis. A widely used method in measurement is InSAR, a traditional approach to measure surface deformation since 1980 [7]. Novel approaches more commonly applied recently were the Differential SAR Interferometry (DInSAR) and multi-interferograms, namely Persistent Scatter Interferometry (PSI). The PSI technique was established on the basis of multi-temporal remote sensing data computing the phase difference and observing plate tectonics throughout an extended period of time. PSI was initially introduced by Ferretti et al. (2001) in consideration of temporal and geometric decorrelation.

The PSI method has now been refined. Various PSI methods that have been used as of now are the PSInSAR [8], [9], SqueeSAR [10], Stanford Persistent Scatterers Interferometry (StaMPS) [11], [12], Interferometric Point Target Analysis (IPTA) [13], Small Baseline Subset (SBAS) [14], [15], Stable Point Network (SPN) [16], [17], Persistent Scatterer Pairs (PSP) [18], and Quasi Persistent Scatterer Interferometry (QPSI) SAR [19].

The QPSI method developed by Perissin & Wang (2012) elaborated on several methods such as SBAS and PS-StaMPS through function modifications. This method allowed the identification and estimation of targets undergoing movement through the reflectivity and amplitude stability of SAR waves on permanent and non-permanent objects. This study analyzed multi temporal Sentinel-1 Ascending and Descending data to analyze the performance of the Quasi-PSI method in detecting surface deformation surrounding the Opak Fault.

2. Methods

2.1. Area and Data Description

Opak Fault is located along the Opak River, eastward from the center of Yogyakarta city, approximately 15 – 20 km and borders Gunung Kidul - Baturaja Highland and Bantul Graben. Opak Fault is a phenomenon following a structural process consisting of hilly to steep morphology. The satellite dataset used for this analysis was Sentinel-1A ascending and descending, with SAR image type Interferometric Wide Swath (IW) mode in Level−1 Single Look Complex (SLC) format, and a spatial resolution of 5 m x 20 m (range x azimuth). The images below describe the study area (Figure 2).
Figure 2. Area of interest from ascending and descending orbit

Time series InSAR data processing required a minimum of 20 SAR images in order to obtain an adequate result [20]. This study made use of sentinel time series data with at least around 30 images with an incidence angle of 30 – 40 degrees, covering a total time period of 2014 to 2020 including both ascending and descending orbits (Table 1). Time series data processing demanded the consideration of perpendicular or temporal baseline, as a higher Bp value will impact geometric decorrelation. Sentinel data used in this study had a time-series perpendicular (Bp) less than 100 m, therefore, meeting the necessary requirements.

| Sensor   | Mode      | Inc. Angle | Head. Angle | Track | Polarization | Total Scene | Master       |
|----------|-----------|------------|-------------|-------|--------------|-------------|--------------|
| Sentinel-1A | Ascending | 33.6801    | -167.5330   | 127   | VV           | 33          | 20150717     |
|          | Descending| 39.1778    | -33.6801    | 76    | VV           | 32          | 20141209     |

2.2. **Quasi Persistent Scatter Interferometry (QPSI)**

QPSI refers to a more advanced version of data processing from persistent scatter interferometry (PSI). PSI utilizes data processing with two antennae installed separately, or better known as repeat pass. Analysis using PSI was developed in the premise of resolving problems commonly found in InSAR data processing through the utilization of multi-temporal analysis.

QPSI elaborated on several PSI techniques to extract information from partially coherent target and increased the spatial distribution of measured points or persistent scatter candidate (PSC). What differentiated QPSI from alternate methods was the minimum spanning tree (MST) algorithm to maximize coherency between interferograms, weighting to obtain displacement rate, and spatial filtering [20]. In this study, data processing was done with the software SARPROZ [21]. The study workflow is shown in the following Figure 3.
2.2.1. Data selection. The process of data selection consisted of determining the subswath, orbit settings, master determination, resample and coregistration. The subswath ascending mode used is IW1, whereas the descending is IW2. To shorten the process, the study area focused on the areas surrounding the Opak Fault (Figure 2). The coregistration step comprised of comparing orbital data and merging with digital elevation model (DEM) data with DEMNAS Indonesia to normalize regions without elevations. Furthermore, DEM data can be used for preliminary geocoding to synchronize reference point between SAR and DEM data coordinates.

2.2.2. Preliminary processing. Amplitude in SAR images described waves composed of complex signals, in which contained both magnitude and phase. With Sarproz, magnitude was deduced by calculating Amplitude Stability Index (ASI) (Figure 4). ASI played a significant role in regulating Persistent Scatter Candidate (PSC). In addition, ASI functioned in the correction phase of Atmospheric Phase Screen (APS) and geocoding processes. In consequence, during the preliminary processing phase, ASI was calculated with the following formula [20]:

\[
ASI = 1 - D_A = \left( \frac{\sigma}{m_A} \right)
\]
where $D_A$ represents the amplitude dispersion, $m_A$ is the mean deviation of amplitude in time, and $\sigma_A$ is the standard deviation of amplitude in time.

2.2.3. Preliminary geocoding. This was a three-step process in data processing with the intention of synchronizing the position of each pixel of the subset area using the orbit parameter and DEM data. DEM data in this study was collected from DEMNAS with a resolution of 0.27 arc-second (8.5 meter). Geocoding was executed manually by selecting ground control point. After selection of control point, DEM data and synthetic amplitude were processed into SAR coordinates.

2.2.4. InSAR processing. In this phase, image graph processing, InSAR processing, and coherence map generation were carried out. Image graph was performed to process configurations of multi temporal data. The image graph made use of minimum spanning tree (MST). The MST algorithm allowed maximization of association and coherence link between interferograms [19]. The result obtained from full graph coherence estimation is visualized in the following Figure 5.

![Figure 5. MST graph ascending image (left) and descending image (right)](image)

InSAR processing was conducted to obtain the difference between each phase recorded. A mathematical model to estimate interferometric phase via the pixel base value ($p$). The component that contributed the interferometric phase followed the equation [22]

$$\Delta \phi_{i,k}(p) = \Delta \phi_{i,k}^{\text{flat}}(p) + \Delta \phi_{i,k}^{\text{height}}(p) + \Delta \phi_{i,k}^{\text{disp}}(p) + \Delta \phi_{i,k}^{\text{atmo}}(p) + \Delta n_{i,k}(p)$$

In which $i$ refers to master image and $k$ signifies generic images in the dataset (slave). $\Delta \phi_{i,k}^{\text{flat}}$ illustrates flattening which estimates from orbital satellite data, $\Delta \phi_{i,k}^{\text{height}}$ refers to DEM reference or height, $\Delta \phi_{i,k}^{\text{disp}}(p)$ is the displacement in consideration to themovement speed relative from $p$ point and the temporal baseline distance from master and slave, $\Delta \phi_{i,k}^{\text{atmo}}(p)$ denoting atmospheric delay influenced by the size of study area and the type of wavelength used, whereas $\Delta n_{i,k}(p)$ depicts noise indicator measured using residual model.

2.2.5. Multi image insar processing. Multi-image InSAR processing was comprised of two pivotal phases, namely Atmospheric Phase Screen (APS) estimation and sparse point processing. Atmospheric phase screen component processing was carried out in regards to PSC pixels, in which PSC values derive from ASI with a threshold 0.8 or equal with dispersion amplitude ($D_A$) < 0.2 for both ascending and descending [23]. During the estimation process, the chosen mode of displacement was linear for all points. This process required a reference point, in particular a requisite temporal coherence value of
0.99, denoting a stable point. The result from APS processing is temporal coherence after graph inversion and APS remove shown in the following Figure 6 and Figure 7.

Multi temporal analysis phase was executed on data surface deformation time series from PSC, processed based on two parameters, ASI and temporal coherence. This study implemented pixels with ASI 0.7 and temporal coherence exceeding 0.7. In ascending mode with ASI 0.7, a PSC 28,253 was obtained, whereas in descending mode, a PSC 31,098 was acquired (Figure 8).

3. Results and Discussions
Following a thorough processing of ascending and descending data, a subsidence of the Opak Fault with a displacement accumulation of 50mm throughout a period of 6 years was ascertained. This was further substantiated by the visible boundary of the Bantul Graben (Figure 10). In contrast, the displacement rate in the LOS direction between ascending and descending descending analysis had a range between -10 mm/year and +5 mm/year (Figure 8). Certain displacements frequently occurring in
several zones surrounding the Opak Fault led to dividing the discussion section regarding surface deformation of the Opak Fault into three segmental zones, from zone A to C.

Zone A demonstrated an insignificant value in surface deformation. Ascending mode exhibited several deformations with values above -7 mm/year. In contrast, descending mode showed minor deformations within said region that were predominantly stable within -2.5 to -5.5 mm/year. Whereas Zone B showed a relatively similar subsidence between both ascending and descending modes. Ascending mode illustrated more sparse points in the fault scarp area with a value of -7 to -10 mm/year. This was due to the fact that the fault scarp faced west and directly facing the radar sensor transmitted at an incidence angle of 33.68. Zone C was situated opposing Zone B, in which there were more sparse points found with the descending mode, due to several slope aspects within said location facing S-SW, thus lying on opposition of the incidence angle from the ascending mode. Ascending and descending surface deformation had a similar value range of -5,5 to -10 mm/year, however they differ in scatter points of subsidence value. Difference between surface deformation values due to discrepancy in satellite orbits was also exhibited in the study [24].

Each end result scatter plot data was able to present time-series displacement of a certain point. This value exhibited the presence of cumulative displacement at each pixel. Visualization of time-series displacement was carried out on pixel sample from the three-analysis zone of each mode (Figure...
9). In the area with a velocity displacement of -7 to -10 mm/year, a cumulative displacement greater than -50 mm was found, visible at point 3887 (ASC B), 9144 (ASC A), and 260062 (DSC B). Furthermore, areas with a velocity of -2.5 to -5.5 mm/year displayed a cumulative displacement ranging from -30 mm to -40 mm on pixel points 486 (ASC C), 9341 (DSC A) and 30616 (DSC C).

A majority of the surface deformation occurring in the area of interest lied at the border situated between Bantul Graben and the highlands of Gunung Kidul. Some of the surface displacements implied the presence of ongoing slope activity. Study from (Widjajanti et al., 2020) elaborated on the existence of active tectonics to the east of Opak Fault scrap. This statement is further proven by the end result of the descending data by the abundance of scatter plot density located near Wonosari basin (Figure 11).

![Image of displacement velocity map in mm/years from 2014 – 2020 both ascending and descending orbit](image_url)

**Figure 11.** Average of displacement velocity map in mm/years from 2014 – 2020 both ascending and descending orbit

Multi-temporal analysis using QPSI on Sentinel data from the year of 2014 to 2020 was able to demonstrate the occurrence of surface deformation. Surface deformation in the study area expressed an adequate result with a few sparse zones. Nonetheless, results from the ascending and descending modes present a dissimilarity between results from several locations. Descending orbit had a more homogenous PSC distribution in contrast to ascending orbit (Image PSC). This event may have been probable due to the affect from the noise, specifically residual, atmospheric noise or orbital errors.
4. Conclusion

The presented research underlines that both C-band Sentinel-1 mission data and the QPS technique are highly effective, accurate and therefore play a pivotal role in detecting surface deformation zone, derived from processing 33 ascending and 32 descending SAR images by ESA within the period of 2014 – 2020 using SARPROZ. Information regarding temporal surface deformation such as velocity and total displacement value was able to be gathered through QPS-InSAR. A majority of surface displacements occur around the Opak Fault with varying values from -7 to -10 mm/year. Zones with a range of values between -2.5 mm to 2.5 mm can be considered a stable area, whereas zones with values of 2.5 – 5 mm were categorized as uplifting areas. However, there is a significant contrast between data processing using the ascending and descending method due to the noise during time-series data computing, such as atmospheric factor, orbital errors, and temporal and geometric errors are associated with spatial decorrelation. Therefore, to obtain a more accurate dataset, it is wise to obtain a sample from an in-situ measurement.

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