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Monitoring ground displacement of Warri metropolis using persistent scatterer interferometry (PSI) and small baseline subset (SBAS) time series

Oluibukun Gbenga Ajayi*[1,2], Bilyaminu Yusuf [2], Yusuf Drisu Opaluwa[2]

[1]Namibia University of Science and Technology, Faculty of Engineering and the Built Environment, Department of Land and Spatial Sciences, Windhoek, Namibia
[2]Federal University of Technology, Minna, School of Environmental Technology, Department of Surveying and Geoinformatics, Minna, Nigeria

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Abstract
Ground subsidence is a major challenge faced by many cities worldwide, with infrastructure damage costing billions annually. This study aims to retrieve the subsidence of Warri, a coastal city in Southern Nigeria, using interferometry synthetic aperture radar (InSAR). Persistent Scatterer Interferometry (PSI) and Small Baseline Subset (SBAS) methods were used for the retrieval of the subsidence in the city. Results obtained show that Warri experiences subsidence, with PSI revealing a displacement of -0.5 to 1.5 mm/year, and SBAS showing 0.33 to 0.65 cm/year. The standard deviation for PSI ranges between 0.7 and 7.8 mm/year, and 0.2 to 1 cm/year for SBAS. Our study highlights the exceptional capabilities of InSAR in effectively and precisely monitoring subsidence across extensive urban regions, achieving remarkable accuracy down to millimetre scale.

1. Introduction

Urban growth often leads to increased infrastructure development, such as roads, highways, bridges, railways, buildings, and groundwater extraction. However, these developments can also lead to ground subsidence, which is a phenomenon that affects many cities around the world. Ground subsidence can be caused by a variety of factors, including earthquakes, landslides (Abraham, 2021), excessive groundwater extraction (Muhammad et al., 2016b), mining and construction, volcanic activity, and oil and gas exploration (Muhammad et al., 2016b).

Subsidence has the potential to cause damages to infrastructure, such as roads, highways, buildings, railways, and communication masts. It can also be a threat to human existence and lead to economic loss with high maintenance costs (Chen et al., 2012). Therefore, it is important for city planners to measure and monitor ground displacement.

Conventionally, geodetic surveying, levelling measurement, and Global Navigation Satellite System (GNSS) were used to measure displacement at very precise accuracy up to millimetre level but only small area can be covered in a short time. For large areas, the method is costly and time consuming (Chen et al., 2020; Nam et al., 2020), hence the need to explore other alternative approaches. Interferometry Synthetic Aperture Radar (InSAR) is a remote sensing method that is used in the monitoring of ground displacement. It involves the use of Synthetic Aperture Radar (SAR) images obtained through satellite at different time over the same area to study the ground deformation and displacement taking place (Abraham, 2021) over regions of interest. InSAR have demonstrated over time to be an efficient and valuable geohazard risk analysis method that is based on multiple radar images and has played an important role in recent years as a cost-effective and alternative method to geological and geotechnical investigations (Alesssandro et al., 2017).

Persistent Scatterer Interferometry (PSI) and Small Baseline Subset (SBAS) are powerful remote sensing techniques based on multi-temporal images and time series used to study the displacement of the ground surface. PSI as the name implies, is based on Permanent Scatterer (PS) while Small BAseline Subset is based on Distributed Scatterer (DS). They were developed to solve the problem of geometric decorrelation, temporal deorrelation and atmospheric delay encountered by Differential Interferometry Synthetic Aperture Radar (DInSAR).

In this study, we aimed at depicting the ground displacement of Warri, Delta State, Nigeria using PSI and SBAS.

* Corresponding Author

*(ogbajayi@gmail.com) ORCID ID 0000-0002-9467-3569
(yusufbilyaminu72@gmail.com) ORCID ID 0009-0003-9345-7658
(opaluwayd@futminna.edu.ng) ORCID ID 0000-0002-6897-1714

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2. Method

This study used 17 Sentinel-1A images acquired in IW mode over a period of 13 months from 15 May 2019 to 31 July 2020. A time series analysis was performed using interferograms generated from co-registered stack images. The phase difference of each interferogram reflected the influence of various factors such as topography, atmospheric phase, displacement phase, orbital and noise phase. To eliminate the topography artefact, a digital elevation model (DEM) was used.

Two methods were used to build the stack of interferograms: single master used by PSI and multiple master was used for SBAS. Various techniques have been used to perform the analysis of small base line (SBAS) and PSI. PSI determines phase changes by examining permanent and dominant scatterer (persistent scatterer) while the SBAS approach measures surface displacement associated with homogenously distributed scatterers which results in improved spatial coverage (Fabio et al., 2020; Osmanoglu et al., 2016).

2.1. Persistent scatterer interferometry (PSI)

The Stanford Method for Persistent Scatterer (StaMPS) was used in this study. The preprocessing was done using snap to stamps developed by Jose et al. (2019) which can be retrieved on the GitHub repository (https://github.com/mdelgadoblasco/snap2stamps).

The processing framework is subdivided into two main steps: preprocessing and postprocessing, and the summary of the processing steps are as follows;

Preprocessing

i. Master selection and splitting: The InSAR overview stack feature within SNAP was used to choose the primary (master) image. After the selection, TopSAR split was used for the subsetting.
ii. Slave splitting: Here, the specific subswath and burst that covered the desired region of interest were selected while also applying the precise orbit file. The precise orbit is automatically downloaded approximately 20 days after acquisition.
iii. Coregistration and interferogram generation: The auxiliary file (Digital Elevation Model) was subset using a bounding box to extract the desired area of interest while also saving the amplitude coregistered master, the slaves stack, and the interferograms with autorectified coordinate (latitude and longitude) and elevation as output.
iv. Export: This include the export of master-slave pair that is coregistered, along with its corresponding interferograms incorporating elevation and autorectified coordinate band.

Postprocessing

i. Data loading: The data was converted to a format compatible with PSI and saved in MATLAB workplace.
ii. Estimate phase noise: Here, the phase noise in each pixel candidate in every interferograms was estimated.
iii. PS selection: The PS were selected considering their noise properties while also estimating the proportion of random element (non-PS).
iv. PS weeding: Noisy PS selected in step 3 were eliminated and discarded and those that resulted from signals contributed by nearby ground resolution elements were removed.
v. Phase correction: In this step, the correction for wrapped phase due to DEM error was performed.
vi. Phase unwrapping: Phase unwrapping has the ability to resolve the ambiguity of modulus of 2π and obtain the absolute change of phase. It is always recommended to re-run steps 6 and 7 in order to determine the spatially correlated look angle and master atmosphere while compensating for the orbit error prior to the unwrapping process.
vii. Spatially correlated look angle error estimation: This error arises from spatially correlated DEM (this includes error within the DEM and incorrect mapping of the DEM into radar coordinate). Also, the estimation of both master atmosphere and orbit error phase occurs simultaneously.
viii. Atmospheric filtering: After the StaMPS processing in MATLAB, the linear-based correction in TRAIN is applied. At this stage, a specific reference area is chosen and an average velocity usually derive from GNSS data is introduced. By default, StaMPS utilizes the entire extent as the referenced area. In this study, we opted for the default mode due to lack of GNSS data at the time of processing.

2.2. Small baseline subset (SBAS)

This study used Mintpy incorporated in OpenSARLap, a cloud-based system for processing of synthetic aperture radar (SAR) workflows. First, interferograms of the imagery were generated using the OnDemand platform on the Alaska Satellite Facility (ASF) website.

To prepare the data, the HyP3 InSAR Stack for Mintpy was used. In this phase, the data were added and checked for the presence of DEM, incident angle map, and azimuth angle map. The area of interest was also subset and areas of no interest were removed. Finally, post-processing using Mintpy Time-series for processing of small baseline subset was carried out.

Interferometry Synthetic Aperture Radar (InSAR) time series analysis using Mintpy and HpP3 products based on the Losangeles_timeseies notebook by Yunjun et al. (2019) was used for the processing of small baseline subset.

3. Results

The PSI displacement map is presented in Figure 1 while the PSI time series of Warri metropolis is presented in Figure 3. An average subsidence of -13.9 to 13.4 mm/year and standard deviation of 0.7 to 7.8 mm/year was observed for the period of observation for

PSI, with the riverine and rural areas having the highest standard deviation which can be attributed to insignificant or complete absence of PS.

For SBAS (see Figure 2), an average of -6 to 2 cm/year was observed having a standard deviation of 0.2 to 1 cm/year.

In the metropolis, a subsidence of -0.5 to 1.5 mm/year for PSI and 0.65 to 0.33 cm/year for SBAS was obtained. In both PSI and SBAS, we observed a negative deformation in the metropolis which suggests the presence of subsidence.

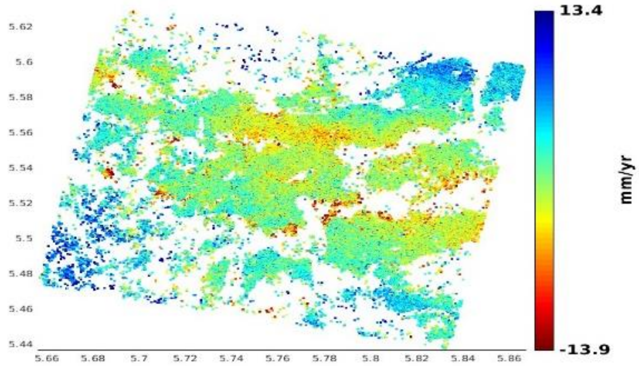

Figure 1. PSI Displacement map. Northing represent y-axis and Easting x-axis

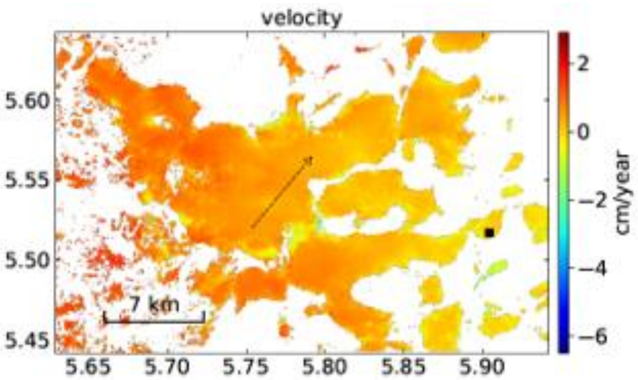

Figure 2. SBAS Displacement map overlayed on google earth image. Northing represent y-axis and Easting x-axis

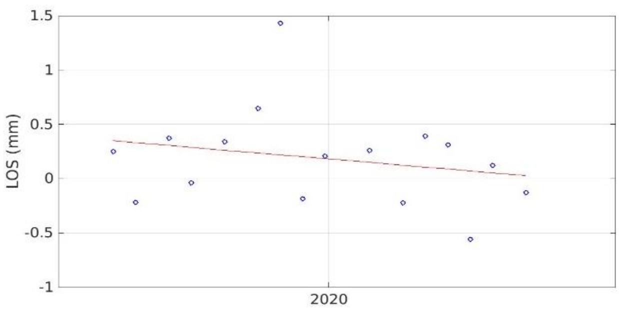

Figure 3. PSI Time series of the metropolis

4. Discussion

The ground displacement of Warri has been analysed using two different methods; Persistent Scatterer Interferometry (PSI) and Small Baseline Subset (SBAS). Results obtained from both methods showed negative deformation in the metropolis. Figure 1 shows PSI average annual displacement. From the Figure 4, it was observed that the average annual velocity obtained for the PSI method was between -13.9 mm/year to 13.4 mm/year. Also, some positive deformation (uplift) upward toward North east of Warri and downside of the area was observed. Figure 3 shows the deformation pattern in the urban centre which suggests that a deformation of -1 to 1.5 is inherent in the metropolis.

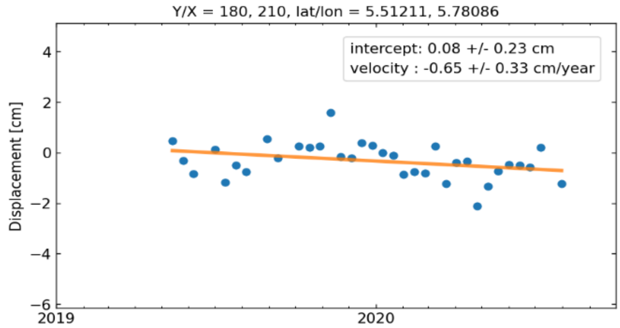

Figure 4. SBAS Time series of the metropolis

Figure 2 presents the displacement map of SBAS. On the map, an annual displacement of -6 cm/year to 2 cm/year can be observed. In the metropolis, SBAS subsidence of between 0.33 to 0.65 cm/year was obtained. Unlike the PSI where the upward and the downward show uplift, here, uplift is observed only in the western part of the study area. The time series of the SBAS in the metropolis (Figure 4) also shows a negative deformation at the rate of -0.65 cm/year to 0.33 cm/ year.

This implies that despite the differences in the rate of deformation, both methods confirmed that the urban centre is subsiding, and both methods detect an uplift on the Warri seaport which consequentially can result in increase in flooding and sea level rise due to climate change. The difference in the number of images used for both methods may be the main reason for the large differences in the average velocity between the two methods. The observed deformations may be caused by a combination of ground water withdrawal and excessive flooding.

The findings of this study are consistent with findings of Muhammad et al. (2016a) which also reported active subsidence in Warri. Their study specifically showed a deformation of -5 mm/year to 5 mm/year in the metropolis of Warri.

However, it is important to validate the results using other methods such as Global Navigation Satellite System (GNSS) in the future work to further confirm the findings of this study which are very important for city planning and policy developments by city planners and government authorities as it will aid in mitigating the urban risk of subsidence, and developing effective early-warning systems.

5. Conclusion

This study utilized remote sensing techniques, particularly the Interferometry Synthetic Aperture Radar (InSAR) with emphasis on persistent scatterer interferometry (PSI) and Small Baseline Subset (SBAS), to detect ground deformation in Warri, a coastal city in southern Nigeria. The results revealed several degrees of deformation in Warri metropolis, with subsidence ranging from -0.5 to 1.5 mm/year using PSI, and -0.65 to 0.33 cm/year using SBAS in different areas of the study area. The findings of this study can offer significant insight to city planners and government authorities to develop effective mitigation strategies and to design better drainage systems and overall city development plans. Further work will consider the validation of the results using global navigation satellite system (GNSS).

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