Review Appraisal of Synthetic Aperture Radar Technique for Earth Deformation Monitoring: Applications and Insights for Nigeria

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ABSTRACT: Interferometric Synthetic Aperture Radar (InSAR) is a geodetic remote sensing technique used to measure ground deformation with high precision and is widely applied in environmental monitoring and geodynamic studies. This review explored three main processing methods: Differential InSAR (D-InSAR), Persistent Scatterer Interferometry (PSI), and the Small Baseline Subset (SBAS) technique. D-InSAR estimates deformation by comparing phase differences between two co-registered SAR images, PSI focuses on stable reflectors called persistent scatterers, and SBAS uses multiple acquisitions with short temporal and spatial baselines to minimise decorrelation and atmospheric effects. SBAS performance is improved through singular value decomposition (SVD), which helps resolve rank-deficient problems in interferometric processing. In Nigeria, recent studies indicate emerging susceptibility to low-to-moderate seismic activity despite its historical classification as an aseismic region. The country's geology includes the Precambrian Basement Complex, Mesozoic-Cenozoic sedimentary basins, and minor volcanic zones, with ancient fault systems such as the Ifewara-Zungeru Shear Zone potentially reactivating due to natural and anthropogenic forces. InSAR can support monitoring of land subsidence, infrastructure instability, and seismic hazards in urban areas such as Lagos, Port Harcourt, and Abuja. However, its application is constrained by limited access to high-resolution satellite data, insufficient technical expertise, and signal decorrelation in vegetated regions. To fully realise InSAR's potential for sustainable development and disaster risk reduction in Nigeria, stronger capacity building, improved data access, and integration with GIS, GPS, and ground-based observations are required. Collaboration among national institutions and international partners is essential for effectively advancing geohazard monitoring and environmental management capabilities across Nigeria and beyond.

KEYWORDS: D-InSAR, PS-InSAR, SBAS, Environmental hazard, & Earth Deformation Monitoring

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I. INTRODUCTION

Earth displacement is a critical phenomenon that affects various aspects of our environment, including urban development, natural resource management, and disaster risk assessment (Huo and Peng, 2023; Liu *et al.,* 2020). Understanding the dynamics of earth deformation is essential for effective planning, infrastructure resilience, and environmental conservation (Kapucu *et al*., 2024; Sharifi and Yamagata, 2018). One of the most valuable and effective techniques for assessing earth deformation is the use of Interferometric Synthetic Aperture Radar (InSAR) (Lu *et al.,* 2007; Ferretti *et al.,* 2001). The large area coverage and high accuracy of InSAR make it more effective solution when compared to the classical method, which is confined to a narrow radius of just a few kilometres (Simons and Rosen, 2015; Macchiarulo *et al.,* 2021). This geodetic remote sensing approach leverages radar signals to measure ground displacement, making it valuable for monitoring the gradual movement of the Earth's surface (Rosen *et al.*, 2000). InSAR technology operates by comparing radar images of the same geographical space taken at different times and analysing the signal amplitude and the phase shift between these SAR images (Rao *et al.,* 2018; Bernardi *et al.,* 2021; Baba *et al.,* 2024).

This capability is particularly useful in regions prone to environmental hazards, such as subsidence, vertical and horizontal earth displacement (Galloway et al., 2008). Harnessing the potential of InSAR, researchers can analyse the impacts of human and natural phenomena on the environment (Wdowinski *et al*., 2015; Liu *et al.,* 2018; Zhong *et al*., 2024). Such analysis enables a comprehensive understanding of habitat loss, biodiversity, and ecosystem health (Aswathi *et al*., 2022). The insights gained are crucial for informing conservation strategies and policy decisions aimed at mitigating environmental challenges (Mashala *et al*., 2023; Machireddy, 2023). However, despite its benefits, the InSAR application also presents several challenges. The technique requires complex processing algorithms and interpretation skills (Jiang *et al*., 2024; Spans, and Hooper 2016). Moreover, factors such as atmospheric delay artefact, vegetation, and variations in the dielectric properties of urban infrastructure can complicate the analysis (Naserikia *et al*., 2023; Qamar *et al.,* 2022; Ferretti *et al.,* 2007). Furthermore, while InSAR

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provides a wealth of data coverage, the temporal resolution is a function of the satellite revisit times, which can limit the ability to monitor dynamic changes (Cheng *et al*., 2025; Coutinho *et al*., 2023). However, ongoing advancements in technology are continuously improving the temporal resolution by reducing repeated circles so that it can efficiently reduce the satellite revisit time to its barest minimum (Mondini *et al.,* 2021; Wdowinski *et al.,* 2020; Fiaschi *et al.,* 2019).

This review is restricted to three widely used InSAR techniques: Differential (D-InSAR), Persistent Scatterer Interferometry (PSI), and Short Baseline Subset (SBAS). Although numerous advanced techniques exist for processing InSAR data, these three methods have been selected for their prominence and effectiveness in various applications (Zhang and Lu 2022). The D-InSAR technique serves as a fundamental approach for other techniques relying on the differentiation of the phase components of two co-registered SAR images (Sarker *et al.,* 2024; Mourjane *et al.,* 2024). This process involves the removal of topographic artefacts and other contributing variables, allowing for an accurate measurement of surface displacement (Krishnakumar et al., 2021; Crosetto *et al.,* 2016). This approach is suitable for detecting land displacement over large areas and other geodynamic studies (Jia *et al*., 2022; Thapa *et al*., 2016). PSI is an advanced D-InSAR approach that relies on the retrieval of time-series SAR image datasets for deformation studies using the least-squares method (Osmanoglu *et al.,* 2015; Usai, 2003). It is easier to avoid the influence of spatio-temporal decorrelation on the resulting solution using PSI compared to D-InSAR; this edge is due to its stack of SAR images (Hopper *et al.,* 2004; Ferrati *et al.,* 2001). PSI may encounter a rank deficiency problem due to the presence of multiple baseline subsets Li et al., 2020; Wang e*t al*., (2024), However, the introduction Singular Value Decomposition (SVD) algorithm in the Small Baseline Subset (SBAS) method has greatly reduced these problems, making deformation measurements more flexible and efficient (Li *et al.,* 2022; Lanari *et al*., 2007).

Deformation studies are relevant and timely in Nigeria due to the country's ongoing urban expansion, infrastructure development, and exposure to environmental hazards (Daramola and Ibem, 2009; Abdulazeez, 2024). The rapidly growing states in Nigeria like Lagos, Abuja, and Port Harcourt experience significant land changes, leading to ground subsidence, structural instability, and heightened vulnerability to environmental disasters (Woillez *et al*., 2023; Akinyede *et al*., 2017). In coastal areas like the Niger Delta, land displacement is exacerbated by oil exploration, groundwater extraction, and erosion, threatening human settlements and ecosystems (Awoyemi *et al*., 2020; Isukuru *et al*., 2024; O'Farrell *et al*., 2025). Monitoring land deformation is vital for disaster risk reduction, sustainable development, and infrastructure resilience across Nigeria (Okem *et al*., 2024; Alabi, 2024). Deformation data provides early warning for geohazards such as landslides, flooding, and building collapse, allowing for timely intervention and planning (Nwagbara *et al*., 2020). It also supports smarter urban planning by guiding construction away from geologically unstable areas and informing engineering designs that withstand ground movement (Almulhim, 2025; Culshaw and Price, 2012). Addressing Nigeria's vulnerability as a function of natural and anthropogenic pressures, deformation studies will be a key role in achieving long-term socio-economic and environmental stability (Ojigi *et al.,* 2013; Adepoju and Adelabu, 2020).

The assessment of earth deformation using the InSAR technique represents significant advancement, as it initiates easy and comprehensive understanding of change dynamics in the environment (Hooper *et al*., 2012; Al-Zaidy and Al-Ali, 2023). As urbanisation and environmental challenges is at it rise, the need for reliable monitoring tools becomes increasingly important and timely (Furberg *et al*., 2019; Letsoalo *et al.,* 2024). The InSAR technique not only enhances our understanding of geodynamic activities around us but also empowers communities and decision-makers to take proactive measures in safeguarding lives, infrastructure and natural resources by disseminating updated information in regard environmental hazards (Jefriza *et al.,* 2020; Zheng *et al.,* 2020). This article provides an overview of the three key InSAR image processing techniques, discussing their principles and applications. It also explores Nigeria's geology and tectonics, the opportunities and challenges of InSAR technology, emerging trends in seismic exploration, challenges and opportunities of InSAR and future trends of InSAR in Nigeria.

II. THE GEOLOGICAL AND TECTONIC SETTING OF NIGERIA

The Nigerian geological features are classified into three parts: the Precambrian Basement Complex, Mesozoic-Cenozoic sedimentary basins, and some smaller volcanic areas (Tijanni, 2023; Ayodele, 2015). The Basement Complex, covering approximately 60% of the country, includes ancient rocks such as migmatites, schists, gneisses, and granites, which have been shaped by multiple structural and geological events, particularly the Pan-African orogeny which is about 600 million years ago (Rahaman, 1988; Okpoli, *et al*., 2022). Overlying these crystalline rocks in areas such as the Jos Plateau are Jurassic Younger Granites, which are associated with post-orogenic magmatism. The breakup of Gondwana and the expansion of the South Atlantic Ocean actively shaped Nigeria's sedimentary basins, including the Niger Delta, Benue Trough, Anambra, Chad, and Sokoto Basins, during the Mesozoic and Cenozoic eras. This process involved the stretching of the Earth's crust, resulting in the formation of these basins (Obaje *et al*., 2006; Okiwelu *et al*., 2014). These basins possess significant geological and economic importance, particularly the Niger Delta, which is a prominent hydrocarbon-producing region in Africa (Reijers, 2011; Akande and Erdtmann, 1998).

Nigeria is situated within the stable interior of the African Plate, distanced from active plate boundaries (Kadiri *et al*., 2011; Renato *et al.,* 2021). However, the Earth's crust shows signs of past mountain-building activities, which have created important faults and shear zones, like the Ifewara-Zungeru Shear Zone and the West African Rift System (Salawu *et al*., 2024; Oluseyi *et al*., 2017). Aged underground structures are

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influencing subsurface deformation, potentially acting as weak zones that may be reactivated under contemporary stress conditions (Kruszewski *et al*., 2022; Deangeli *et al*., 2024). Although the region exhibits relatively low seismic activity, there has been a significant increase in documented seismic events in recent decades (Oluwafemi *et al*., 2018; Zaka *et al*., 2024). Documented earthquakes with magnitudes between 2.5 and 4.0 have occurred in Ibadan, Ijebu-Ode, Saki, and Abuja, notably including the Mpape tremor near Abuja in the year 2018 (Adagunodo *et al*., 2020; Adepelumi *et al*., 2022). The recorded earthquakes, even though they are pocket-sized in magnitude, indicated there could be a chance of faults within the Earth's crust becoming active again, possibly due to distant tectonic pressures from the Mid-Atlantic Ridge or the East African Rift system, as well as anthropogenic activities like groundwater extraction and mining (Odukoya *et al*., 2020; McCalpin, 2013). Figure 1 illustrates the geological map of Nigeria, depicting the distribution of various rock types throughout the nation.

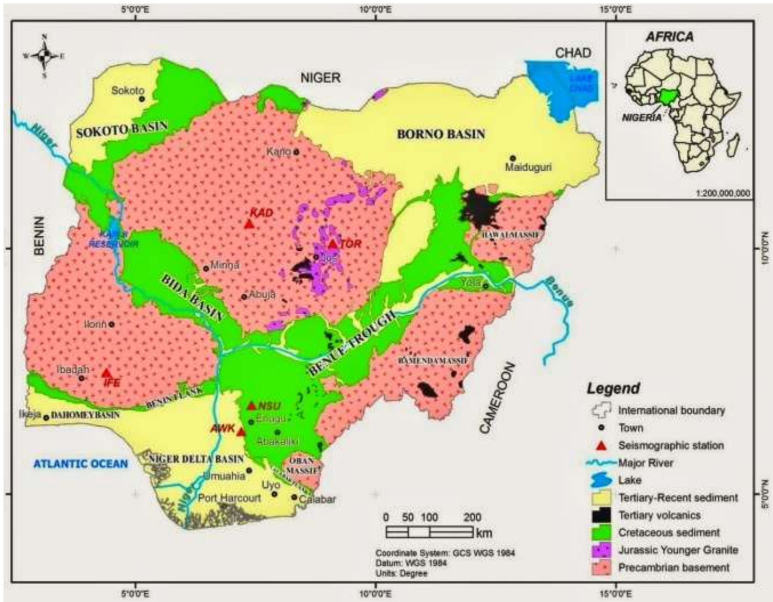

Figure 1. The Geological Map of Nigeria (Federal Ministry of Geological Survey, 2020).

The developing seismic trends in Nigeria, although still modest, highlight the necessity to re-evaluate Nigeria's historical designation as a low-risk seismic zone (Oluwafemi *et al*., 2018; UNDRR, 2018). The expansion of urban centres such as Abuja, Port Harcourt and Lagos, which are situated over ancient fault zones, raises significant concerns regarding the potential effects of even minor earthquakes on essential infrastructure and densely populated regions (Ikwuyatum, 2016). Therefore, it has become very important to include earthquake risk assessments in city planning, update national building rules, and improve the country's earthquake monitoring system to reduce risks (Sousa and Tsionis 2025).

The Nigerian Geological Survey Agency (NGSA), National Space Research and Development Agency (NASRDA) in partnership with academic institutions, has commenced efforts to map areas susceptible to seismic activity and enhance public awareness. Furthermore, investigations utilising geodetic techniques such as gravity modelling, hydrological models, microseismical monitoring, Geographical Information System (GIS) and remote sensing can deepen the understanding of Nigeria's tectonic dynamics and ultimately guide national development strategies and disaster mitigation initiatives (Tahir *et al.,* 2025; Yusuf *et al*., 2021).

III. PRINCIPLE OF InSAR OPERATION

The principle of InSAR operation is based on the use of radar phase differences to detect and measure small changes in the Earth's surface over time. This is best understood through its key processing techniques

A. DIFFERENTIAL InSAR

The principle of the D-InSAR process, an active remote sensing technique that detects ground deformation by analyzing amplitude and phase differences between two Synthetic Aperture Radar (SAR) images captured over the same area at different time (Uus, 2016) can be illustrated in figure 2 below.

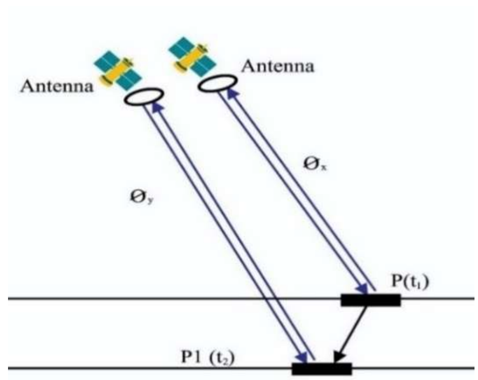

Figure 2 Basic Principle of Differential Synthetic Aperture Interferogram (D-InSAR).

The D-InSAR technique utilises the interferometric processing of SAR images, correlating the amplitude and phase differences between two radar signals to estimate the shift on the Earth's surface (Sabadini and Vermeersen, 2004; Lanari *et al*., 2020). Burgmann *et al*., 2000; Hrysiewicz et al., (2023), the objective of D-InSAR is to measure earth surface displacement by analyzing the differences in the phase of radar waves transmitted by the satellite sensor and reflected (Backscatters) from the Earth's surface. SAR imaging delivers amplitude and phase data for every pixel in the image files. The reflected signal depends on the amplitude intensity and the dielectric properties of the surface object (Burgmann *et al*., 2000; Zhou, *et al*., 2009). Lee *et al*., (2025); Burgmann *et al.,* (2000), The radar signal backscattered from the ground is recorded as a complex value, as illustrated in equation (1).

$$\left(m_{(Master)}, s_{(Slave)}\right) = A(m,s)e^{i\phi(m,s)} \quad (1)$$

Where:

$i\phi(m,s)$; Phase image at position, $A(m,s)$, the amplitude of the signal, $\phi(m,s)$, the phase of the signal as illustrated in figure 2. It demonstrates the fundamental principle of D-InSAR, where point P signifies the ground point imaged in two SAR images. The sensor captures the initial SAR image (master image) at time t_1, recording phase Φx, and acquires a secondary SAR image (slave image) at time t_2, recording phase Φy. Assuming surface displacement occurs between the two acquisitions, point p is presumed to have shifted to position p_1(Sheng *et al.,* 2012). However, the phase difference between the acquired image $\phi(m_{(Master)}, s_{(Slave)})$ can be estimated considering the following contributions from several variables as expressed in equation (2)

$$\phi\left(m_{(Master)}, s_{(Slave)}\right) = \phi_{topo(m,s)} + \phi_{Disp(m,s)} + \phi_{atm(m,s)} + \phi_{noise(m,s)} \quad (2)$$

Where:

$\phi_{topo(m,s)}$, is the phase parameter due to topography, $\phi_{Disp(m,s)}$, is the phase due to displacement (the deformation we aim to measure), $\phi_{atm(m,s)}$:is the phase contribution due to atmospheric delay, $\phi_{noise(m,s)}$, depicts the noise in the system.

The estimation of the ground displacement, D-InSAR generates an interferogram by computing the phase difference between the two co-registered SAR images taken at different times (i.e., master and slave images). The interferogram is given as expressed in equation (3)

$$\Delta\phi_{(m_{(Master)},s_{(Slave)})} = \phi_{2\,(m,s)} - \phi_{1(m,s)} \quad (3)$$

Where:

$\Delta\phi_{(m_{(Master)},s_{(Slave)})}$, is the interferogram of SAR images, $\phi_{2\,(m,s)}$, phase at t_2, $\phi_{1(m,s)}$, phase difference at t_1. However, it should be noted that the differential phase (deformation) $\Delta\phi_{displacement(m,s)}$ contains the phase shift caused by surface deformation between the two acquisitions. Since the satellite navigates along track. Hence, the displacement along the line-of-sight (LoS) direction of the radar can be expressed in equation (4) as:

$$d_{Los(m,s)} = \frac{\lambda}{4\pi} \Delta\phi_{disp(m,s)} \quad (4)$$

Where:

$d_{Los(m,s)}$ represents the displacement along the radar's line of sight, λ denotes the radar wavelength, and $\Delta\phi_{disp(m,s)}$ signifies the differential phase resulting from the displacement.

Consequently, to isolate the deformation signal, the contribution from the topographic phase ϕ_{topo} must be removed (Zebker and Goldstein 1986). This is accomplished by using an external Digital Elevation Model (DEM) or utilising a secondary interferogram that exclusively incorporates topographic data (Gao *et al.,* 2017; Tian *et al*., 2019). Upon eliminating the topography contribution and rectifying atmospheric noise artefact through a filtering technique algorithm, the resultant phase difference, which predominantly reflects surface displacement, can be articulated in equations (5) as follows:

$$\Delta\phi_{Disp(m,s)} = \phi_{2(m,s)} - \phi_{1(m,s)} - \phi_{topo(m,s)} \quad (5)$$

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IV. PERSISTENT SCATTERERED

PS-InSAR is an advanced method of D-InSAR that uses several InSAR images to accurately measure changes in the ground (Ghaderpour et *al*., 2024). Unlike regular D-InSAR, which sends radar signals across the entire area, PS-InSAR focusses on stable radar targets called persistent scatterers (PS) that reliably reflect radar signals over time (Raucoules *et al*., 2009). In contrast to traditional D-InSAR, which transmits radar signals throughout the whole scene, PSInSAR concentrates on stable radar targets referred to as persistent scatterers (PS), which consistently reflect radar signals over time (Raucoules *et al*., 2009; Oštir, and Marko, 2007). PS points are generally anthropogenic structures (such as buildings and bridges) or natural formations (like rock outcrops) that exhibit significant radar backscatter characteristics (Crosetto *et al*., 2016; Kampes, 2005). Figure 3 shows the satellite's signal streaming as it traverses the Earth's surface, as indicated in the SAR image files, while Figure 3.1 depicts the characteristics of the scatterers; the reflected signal is contingent upon the dielectric properties of the scatterers. However, Scatterers compensate for one another to minimize variations in signal changes, thereby reducing the likelihood of errors caused by the decorrelation effect (Kampes, 2006; Hooper *et al*., 2004).

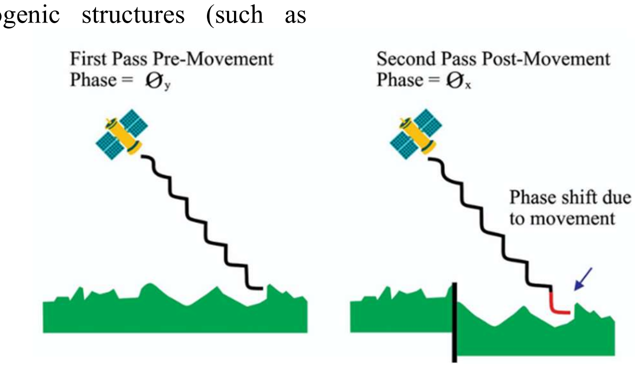

Figure 3. Streaming of signal from scatterers at the same area but at different time, the phase difference between to repeated pass is a function of displacement quantity after the removal of other contributing factors

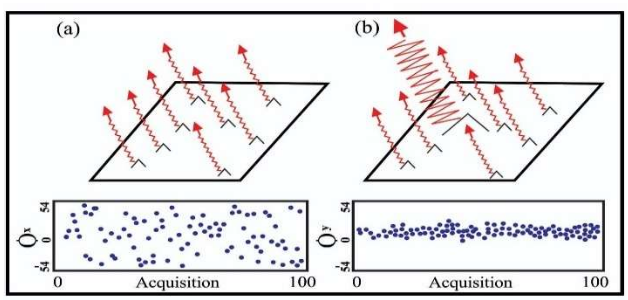

Figure 4. Concept of Distributed Scatterer (a) and Persistent Scatterer (b) distributed scatterer has a well-distributed signal density and hence, it will have good spatial coverage, while PS are mainly point-like target with stable phase (Hooper et al., 2007)

Thresholds are set in SAR image processing to balance the sensitivity to changes in backscatter signals from objects within a series of interferograms (Mastro *et al*., 2022). Subsequently, the phase displacement is isolated from other contributing ambiguities (Crosetto *et al.,* 2007). For an object to be an effective persistent scatterer, it must possess stable dielectric properties and maintain physical stability over the observation period (Wang *et al.,* 2011).

V. PRINCIPLE OF PS-INSAR OPERATION

The PS-InSAR technique relies on stacking many SAR images taken of the same area at different times to detect ground movement by analysing the phase changes at the PS locations (Shanker and Zebker 2007). The premise of PS-InSAR is that persistent scatterers maintain consistent radar backscatter characteristics across time (Njambi, 2022; Crosetto *et al.,* 2015). This technique facilitates the identification of PS points by the analysis of the temporal behaviour of the phase over multiple acquisitions (Wang *et al*., 2020). At PS sites, phase change depends on displacement. However atmospheric artefact, topographic contributions, and orbital effects must be effectively modelled and removed (Xu *et al*., 2019; Yu *et al.,* 2024). The main idea is to separate the unwanted phase contributors so that we can better understand the phase dynamics caused by displacement. The undesirable phase components encompass atmospheric errors, noise artefacts, and other phase contributions (Chen and Zebker, 2013). Equation (6) represents each pixel in a SAR image as a complex number, like the D-InSAR methodology:

$$(m_{master,} s_{slave,}) = A(m,s)e^{i\phi(m,s)} \quad (6)$$

Where:
$A(m, s)$ is the amplitude of the signal of both the master and slave SAR image, $\phi(m, s)$ is the phase of the signal, which contains several contributions. Equation (7) depicts total phase ϕ difference at a given PS point for SAR image acquired at time consists of several terms:

$$\phi(t_n) = \phi_{topo} + \phi_{disp}(t_n) + \phi_{atm}(t_n) + \phi_{noise}(t_n) \quad (7)$$

Where:
ϕ_{topo} is the phase contribution due to topography, $\phi_{disp}(t_n)$ is the phase due to surface displacement at time, $\phi_{atm}(t_n)$ is the phase contribution due to atmospheric delays at time, $\phi_{orb}(t_n)$ is the phase error due to orbital inaccuracies, $\phi_{noise}(t_n)$ is the phase noise. However, the interferometric phase difference between SAR images dataset acquired at times t_1 and t_n can be written as equation (8):

$$\Delta\phi(t_n\, t_1) = \phi_{topo} + \phi_{disp}(t_n) - \phi_{disp}(t_1) + \phi_{atm}(t_n) - \phi_{atm}(t_1) + \phi_{orb}(t_n) - \phi_{orb}(t_1) + \Delta\phi_{noise} \quad (8)$$

The term $\phi_{disp}(t_n) - \phi_{disp}(t_1)$ represents the surface displacement with relative to the master and the slaves image dataset at a given time, $\phi_{atm}(t_n) - \phi_{atm}(t_1)$ is the change in atmospheric delay between the SAR images data acquisition, $\phi_{orb}(t_n) - \phi_{orb}(t_1)$, accounts for errors in satellite orbit information, $\Delta\phi_{noise}$ is the noise contribution.

The displacement at a persistent scatterer can be derived from the interferometric phase over multiple acquisitions. Given a set of SAR images, the phase due to displacement at a PS point can be modeled as a linear function over time as depicted in equation (9):

$$\phi_{disp(t_n)} = \frac{4\pi}{\lambda} d_{LoS}(t_n) \quad (9)$$

Where:
λ is the radar wavelength, $d_{LoS}(t_n)$ is the cumulative displacement along the line of sight (LoS) direction at time t_n. Analyzing the phase evolution over time at the PS points, the line-of-sight displacement rates can be estimated using a linear regression model can be seen in equation (10):

$$d_{LoS}(t_n) = V_{LoS} \,.\, (t_n - t_1) \quad (10)$$

$$\Delta\phi_{disp}\,(t_n\, t_1) = \frac{4\pi}{\lambda}\; d_{LoS}(t_n) - d_{LoS}(t_1) \quad (11)$$

Where;

$d_{LoS}(t_n)$; The displacement along the satellite line-of-sight direction at time t_n , which is relative to a reference time t_1, λ; The wavelength of the radar signal; $\Delta\phi_{disp}\,(t_n\, t_1)$.The differential phase component attributed to displacement between two acquisition times depicts t_n and t_1.

the edge of PS-InSAR is its ability to correct for atmospheric phase delays and orbital inaccuracies effectively compared to D-InSAR (Liu *et al.,* 2024; Crosetto *et al.,* 2016; Wang *et al*., 2020). The introduction of large stack SAR images, atmospheric artifacts can be easily modeled and separated from the displacement phase by assuming that atmospheric effects are uncorrelated over time but correlated spatially (Zhewei *et al.,* 2022; Ding *et al*., 2008). The atmospheric phase at a given time t_n is typically estimated using a spatial filtering algorithm. Once the contributions from topography, atmosphere, and orbit errors are efficiently removed, the final phase difference primarily reflects surface deformation can be estimated as seen in equation (11). since the satellite navigates along tract direction, hence the displacement at such direction can be expressed in equation (12)

$$d_{LoS}(t_n) = \frac{\lambda}{4\pi}\; \Delta\phi_{disp}\,(t_n\, t_1) \quad (12)$$

VI. SMALL BASELINE SUBSET TECHNIQUE

SBAS is particularly useful for monitoring subtle and continuous ground deformation over large areas (Zhu *et al.,* 2024; Ashraf *et al.,* 2024). The technique is designed to minimize the spatial and temporal decorrelation effects by selecting pairs of SARS images with small baselines (both temporal and spatial resolution) (Gong *et al.,* 2016; Ma et al., 2021). Figure 5. Depict the position and the baseline plot of the dataset during processing.

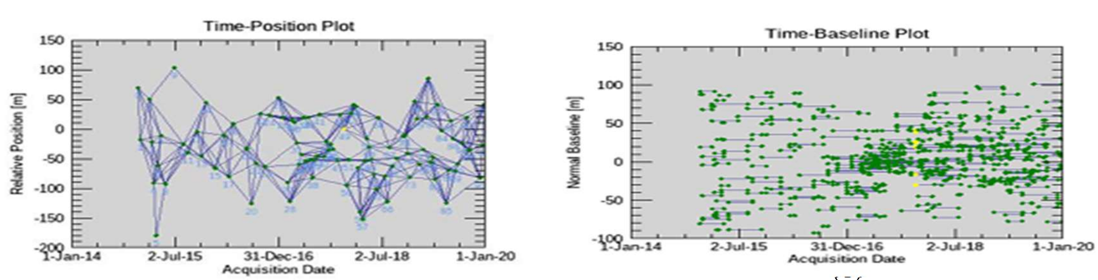

Figure 5 (a) SBAS position points graph help in visualizing whether it is connected relative to its defined threshold while (b) time baseline graph illustrates the interferogram coverage relative to its date of acquisition (Li et al., 2022)

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SBAS processing employs multi-master interferograms with minimal perpendicular baselines to reduce baseline decorrelation effects and utilise scattered pixels, referred to as Small Baseline (Berardino et al., 2002; Gong et al., 2016). To effectively address spatial decorrelation through the SBAS method, a minimal baseline threshold is set to encompass pixels that compensate for variations in scatterer signals (Schmidt and Bürgmann 2003). Spatial decorrelation transpires when radar signals from distinct pictures lose coherence because of alterations in the target's position or shape (Pepe and Calò 2017). Implementing this threshold will reduce effects due to tropospheric and ionospheric Zenith delays, which can compromise deformation estimate accuracy (Zhang et al., 2020; Doin et al., 2009; Rozsa et al., 2020). Notably, Atmospheric Phase (AP) errors are primarily a function of the heterogeneity of the medium through which the electromagnetic signal travels. Research indicates that AP artifacts exhibit spatial correlation but temporal uncorrelation (Emardson *et al.,* 2003). Furthermore, the dominant contributor to path delay-induced phase errors is the spatial heterogeneity of atmospheric refractivity's wet component (Yang *et al.,* 2023; Delacourt *et al*., 1998), which is largely governed by local climate parameters such as temperature, pressure, and humidity.

Moreover, ionospheric heterogeneities, which can significantly differ from tropospheric artefacts, influence the route delay (Pepe and Calo, 2017; Meyer et al., 2006). However, because there is a strong link between these factors affecting AP error and the landscape, they can be identified and modelled in a series of interferograms by finding leftover phases that closely match the height of the terrain. Again, by setting a threshold for SAR image during data processing, it discards the highly decorrelated data, also decreases the processing time and by extension, enhances computational efficiency by reducing the number of interferometric pairs that do not meet the threshold during processing (Casu et al., 2014; Lanari et al., 2004). Furthermore, the integration of the Single Value Decomposition (SVD) algorithm in Small Baseline (SBAS) processing tools has resolved the ranking deficit problem, leading to increased accuracy in displacement computation outcomes (Pepe *et al*., 2019).

VII. PRINCIPLE OF SBAS INSAR

The SBAS InSAR technique exploits a series of SAR images to create multiple interferograms. focusing on small baselines, SBAS minimizes the geometric, spatial and temporal decorrelation effect, allowing for more precise displacement measurements over time. The analysis is performed over a network of small baseline interferograms, from which the displacement time series is derived. According to (Casu *et al.,* 2011), each pixel in a SAR image is a function of a complex value with both amplitude and phase information displayed as expressed in equation (13)

$$I\left(m_{(Master)}, s_{(Slave)}, t\right) = A(m,s,t)e^{i\phi(m,s,t)} \quad (13)$$

Where;
$I\left(m_{(Master)}, s_{(Slave)}, t\right)$ is the complex SAR image at position $(m, s,)$ and at given time t, $A\left(m_{(Master)}, s_{(Slave)}, t\right)$ is the amplitude of the radar return signal, $\phi(x_{(Master)}, y_{(Slave)}, t)$.

Comparing the phase information from two SAR acquisitions, InSAR extracts meaningful surface deformation signals directly from observed phase differences. This relationship then forms the basis for deriving the interferometric phase, as expressed in Equation (14). The total interferometric phase difference is further decomposed into several contributing components, including topographic, deformation, atmospheric, orbital, and noise effects, as shown in equation (15)

$$\Delta\phi_{(m_{(Master)}, s_{(Slave)}, t_2, t_1)} = \phi_{(m,s,t_2)} - \phi_{(m,s,t_1)} \quad (14)$$

$$\Delta\phi_{(t_2, t_1)} = \Delta\phi_{topo} + \Delta\phi_{disp} + \Delta\phi_{atm} + \Delta\phi_{orb} + \Delta\phi_{noise} \quad (15)$$

Where:
$\Delta\phi_{topo}$ is the phase difference due to topography, $\Delta\phi_{disp}$ is the phase difference due to surface displacement (the deformation of interest), $\Delta\phi_{atm}$ is the phase contribution due to atmospheric delay, $\Delta\phi_{orb}$ is the phase contribution due to satellite orbit errors, $\Delta\phi_{noise}$ is the phase noise. SBAS selects pairs of SAR images that have both small spatial baselines and small temporal baselines.

The spatial baseline refers to the physical distance between the satellite positions during the two image acquisitions, while the temporal baseline refers to the time difference between acquisitions (Liu et al., 2025; Minotti *et al.,* 2021). ensuring high coherence between image pairs, SBAS imposes a threshold on both baselines. Only interferograms with small spatial baseline and small temporal baselines are used for deformation analysis (Yang *et al.,* 2023: Liu et al., 2020).

The displacement signal over time can be reconstructed by solving the phase difference equations for a set of small baseline interferograms, as SBAS involves creating multiple interferograms from different SAR image pairs (Gonzales and Fernandez, 2011). Also, compute the displacement phase, the topographic phase ϕ_{topo} must be removed (Zheng and Zebker 2017). This can be achieved using an external Digital Elevation Model (DEM). After correcting for topography, the remaining phase can be attributed to deformation and atmospheric noise. The atmospheric delay ϕ_{atm} can vary over time. However, it can be estimated and corrected through spatial and temporal filtering algorithms (Liang et al.,2023). SBAS uses multiple interferograms to distinguish between deformation and atmospheric effects, as atmospheric artifacts are typically uncorrelated in time but correlated in space (Berardino *et al.,* 2002). Once the interferograms are formed, and topographic, atmospheric, and orbital errors are removed effectively, the displacement time series $(d_{LoS}(t)$ can be retrieved by inverting the system of interferometric phase equations. The phase difference for each pair of images provides a measure of the cumulative displacement over the period between the acquisitions. This inversion step can be expressed as:

$$d_{LoS} = e^{\uparrow\uparrow}\Delta\phi_{disp} \qquad (16)$$

Where:

d_{LoS}: vector of line-of-sight displacements over time, $\Delta\phi_{disp}$: vector of interferometric phase differences for the different image pairs, $e^{\uparrow\uparrow}$: matrix that relates the interferometric phase to the displacement and is its pseudoinverse. However, equation (17) shows the final displacement along the radar's line of sight for each acquisition can be estimated as:

$$(d_{LoS}(t) = \frac{\lambda}{4\pi}\Delta\phi_{disp} \qquad (17)$$

VIII. SUMMARY OF APPLICATIONS OF D-INSAR, PSI AND SBAS TECHNIQUES

This section provides a concise overview of the major applications of D-InSAR, PSI, and SBAS techniques in monitoring Earth surface deformation. Table 1, highlights the principles of their operation and characteristics. The mode of detecting ground displacement related to tectonic activity, land subsidence, infrastructure stability, and environmental hazards.

Table 1. The Applications of all the Techniques in Review, their principle of operation, Area of Strength and Weakness

Criteria	D-InSAR Technique	PSI Technique	SBAS-Technique
Operational principle	Measurement of phase difference between two SAR acquisitions to detect surface deformation (Baba *et al.,* 2024)	Measurement is focused on stable, reflective permanent points (persistent scatterers) over a series of SAR images (Tofani *et al.,* 2013)	Measurement involves analyzing a series of SAR images with small temporal and spatial baselines to identify subtle deformation patterns (Luo et al., 2024)
Data collection mode	Utilize two SAR images (Master and Slave) acquired at different times	A minimum of 15 SAR images is required to form a robust dataset for reliable analysis of Persistent Scatterer (PS) points (Karamvasis and Karathanassi 2020).	Utilize multiple SAR acquisition to generate interferogram from image pairs with small spatial and temporal baseline (Wang *et al.,* 2019)
Number of SAR images	Typically, two images (master and slave)	Multiple SAR acquisitions should not be less than the (15-20) acquisitions (Ferreti *et al.,* 2011)	Multiple SAR acquisitions (typically at least 15-40) to create small baseline interferograms (Ferrati *et al.,* 2006)
Signal Target	It covers all the scenes of the study area (Tzouvaras et al., 2020)	It targets only the persistent scatterer in the study area (D'Aranno *et al.,* 2021)	It targets both persistent scatterers and distributed scatterers (Bouraoui, 2013; wang et al., 2023).
Target Areas	Suitable in areas with strong signal reflection and high coherence (Liu *et al.,* 2020; Zhang *et al.,* 2019)	Suitable in Urban or built-up areas with man-made structures or natural objects that has dielectric properties (Crosetto *et al.*, 2016)	suitable in urban and rural areas by analysing small baseline interferograms (Beradino et al.,2002; Lanari *et al.,* 2004)
Correction Errors	Contains topographic displacement, atmospheric delay and noise component. Requires correction of topographic phase using a DEM (Hanssen, 2001)	Displacement phase measurements are obtained by isolating atmospheric delays and noise artefact using PS points, which provide a stable reference over time. Ferrati *et al* 2001)	Multiple small baseline interferograms are generated to correct errors related to topography, atmospheric conditions, and orbital inaccuracies. (Berardina *et al.,* 2002; Lanari *et al.,* 2007)
Deformation sensitivity	Sensitive to large and sudden deformation event (Tong *et al.*, 2017).	Sensitive to slow, long-term deformation (Cascini et al., 2013)	Sensitive to both slow and moderate deformation, especially over a wide area (Pepe *et al.*, 2018).

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Merit	Simple to implement with two pair of SAR images. Useful for large, rapid deformation event (Baba *et al.,* 2024)	High precision on for detecting mm scale. Minimized atmospheric and noise effect by focusing on PS points	Suitable for large areas and slow deformation. Reduce decorrelation by small baseline pairs and SVD incorporated algorithm (Din *et al.,* 2015)
Decorrelation effect	Prone to spatial and temporal decorrelation in non-urban or vegetated areas (Wang *et al.,* 2019: Li *et al.,* 2018)	Minimum decorrelation since PS points have consistent back scatter characteristics over time (Ferretti *et al.,* 2011)	Reduces decorrelation by focusing on small baseline pairs with high coherence (Lanari *et al.,* 2014)
Disadvantage	Susceptible to atmospheric and temporal decorrelation; requires accurate DEM for topographic correction (Ducret et al.,2011)	Requires large stacks of SAR images. Which may not be available. Work best in built-up areas (Gernhardt and Bamler 2012).	Requires large stacks of SAR images. Spatial resolution depends on the number of SAR images and interferograms generated (cittaions)
Spatial Resolution	Varies based on radar wavelength and ground condition	High resolution data is required, since it focuses on specific stable scatterers	Moderate spatial resolution depending on the density of coherent pixels in the interferograms
Temporal Resolution	Dependent on the time interval between the two SAR acquisition	High temporal resolution, as it uses a long series of SAR images	Moderate temporal resolution, determined by the availability of small baseline image pairs.

IX. REVIEW OF LITERATURES ON EARTH DEFORMATION STUDIES IN NIGERIA

Earth deformation studies in Nigeria have been neglected for years, possibly due to the perception that it is not an aseismic region (Oyibo and Kadiri 2023). It has garnered significant attention in recent decades, mainly due to the geodynamic events (environmental hazards) affecting Nigeria (Onuoha et al., 2022). Recent earth tremors and frequent land subsidence have raised doubts about this idea, prompting detailed studies on the reasons behind and possible dangers related to these geo-tectonic activities. Nigeria has experienced a range of geodynamic activities, with many going unrecorded and only a handful documented (Zakka et al., 2024). Such activity has necessitated a comprehensive investigation into the potential causes and underlying reasons, as well as an examination of whether the concept of being an aseismic zone holds. Table 2 depicts a compilation of seismic events that occurred in Nigeria. This review summarises key studies on earth deformation in Nigeria, highlighting findings related to seismic events, fault line analyses, geophysical assessments, and the deformation monitoring methods employed in the region over time.

Studies generally agree that Nigeria is not strictly aseismic, as recurring tremors and land subsidence indicate ongoing deformation linked to fault reactivation, sediment compaction, and human activities. However, disagreement persists over whether tectonic or anthropogenic factors dominate, while sparse data, short monitoring periods, and limited instrumentation constrain robust hazard assessment.

Table 2. Seismic Event in Nigeria

`	Origin time	Felt Areas	Intensity	Magnitude (ML)	Probable epicenter
1933		Warri			
1939-06-22	19:19:26	Lagos, Ibadan and Ile-Ife	-	6.5	Akwapin fault in Ghana
1963-12-21	18:30	Ijebu-Ode	5	-	Near to Ijebu-Ode
1982-10-16	-	Jalingo and Gembu	3		Cameroun Volcanic line
1984-07-28	12:10	Ijebu-Ode, Ibadan, Shagamu and Abeokuta	6	-	Ijebu-Ode
1984-08-02	10:20	Ijebu-Ode, Ibadan, Shagamu and Abeokuta	5	-	Close to Ijebu-Ode
1984-12-08	-	Yola	-	-	Cameroun volcanic line
1985-06-18	21:00	Kombani Yaya	4	-	Kombani Yaya
1990-06-27	-	Ibadan	-	3.7	Ijebu-Ode
1994-11-07	05:07:51	-	-	4.2	Dan Gulbi

1997	-	Okitipupa	4	-	Okitipupa
2000-03-07	15:53:54	Ibadan, Akure, Abeokuta, IjebuOde and Oyo	-	4.5	Okitipupa
2000-05-07	11:00	Akure	4	-	Okitipupa
2005-03	-	Yola	3	-	-
2006-03-25	11:20	Lupma	3	-	Cameroun volcanic line
11/9/2009		Abomey-calavi	2		Benin
5/11/2011		Abeokuta		4.4	Abeokuta
10/7/2016		Saki	4		Oyo State
10/8/2016		Igbogene	3		Bayelsa
11/9/2016		Kwoi	3		Kaduna
12/9/2016		Sambang Da gi	3		Kaduna State
5/9/2018	2:30pm	Mpape/Maitama	3	3.0	Mpape district Abuja
13/9/2024	12:17	Katampe/Maitama	3		Mpape and Katampe district

Source (Tsalha et al., 2015)

X. SEISMIC OCCURRENCES IN NIGERIA

Nigeria was said to be seismically inactive (Onwuzuligbo and Ono 2022; Akpan and Yakubu 2010). However, Recent state-wide ground movement meanwhile, has altered this view. Significant ground motions in the years 1984, 1990, 2000, 2018, and 2024 affected different parts of the states, according to Abolarin and Adedeji (2016). On the modified Mercalli Intensity scale, these occurrences had magnitudes between 3.0 and 6.5 with intensities ranging from III and IV to VI, therefore indicating possible seismic dangers. Akpan and Yakubu's 2010 thorough assessment underlined the need of ongoing observation and study to better grasp the seismicity characteristic of Nigeria. The research emphasised the significance of seismic hazard evaluation and mitigation techniques to reduce the effects of forthcoming earthquakes (Ismail et al., 2023; Lim and Fang, 2022). The reassessment of Nigeria's seismic status is essential due to the nation's swift urbanisation and infrastructural advancement (Moluaa, et al., 2024). The government and stakeholders must prioritise the mitigation and management of seismic risk to maintain public safety and safeguard important infrastructure (Oyedele et al., 2020; World Bank, 2012). Chukwunweike et al. (2020) identified the epicentre, magnitude, and energy released during the January 10, 2020, earthquake in Abaji-Abuja, Nigeria.

The findings, suggest a likelihood of future earthquakes in the region, underscoring the necessity for preventative measures in geological and construction activities, especially considering the area's history of rock blasting and quarrying. According to Oluwafemi et al. (2018), Nigeria faces the potential threat of substantial earthquakes, with anticipated magnitudes varying from 6.0 to 7.1 during the period from the year 2020 to 2028. The research indicated that the Nigerian government ought to place a premium on preparedness for earthquakes and the development of effective mitigation strategies. Afegbuao et al. (2018) conducted a study examining the impact of tectonic activities along the Mid-Atlantic Ridge (MAR) on seismic events in West Africa. Techniques of statistical and probabilistic seismic hazard assessment were employed to scrutinise earthquake data spanning from the year 1963 to 2014. The results indicate a rising trend in seismic activity in the MAR region, characterised by a notable increase in both the frequency and magnitude of earthquakes. The study predicts that earthquakes with magnitudes of 6.0 and 7.0 will occur every 2 and 10 years, respectively, with elevated annual odds. The results underscore the necessity for additional research and heightened awareness of seismic risks in West Africa. Nigeria, although not classified as a high-seismic zone, has encountered tremors with magnitudes ranging from 4.3 to 4.5. Significant occurrences encompass the year 2000 earthquake (magnitude 4.4) and the 2009 Allada, Benin Republic earthquake (magnitude 4.4), both experienced in southern Nigeria (Shiwua, 2013). Most incidents transpired in proximity to the Ifewara-Zungeru fault. Notwithstanding these events, there is a deficiency of adequate monitoring (Oyibo and Kadiri 2023). The author examines the potential for comprehensive seismic hazard monitoring in Nigeria, highlighting proactive strategies utilising seismological and geodetic instruments to reduce seismic hazards. The implementation of early warning systems is essential for disaster preparedness (Afegbua et al., 2011).

There is broad agreement that Nigeria is not a high-seismicity region but cannot be regarded as seismically inactive. Multiple authors acknowledging recurrent low-to-moderate earthquakes and ground movements, particularly along fault zones such as the Ifewara–Zungeru system. observational and event-based studies (e.g., Abolarin & Adedeji, 2016; Chukwunweike et al., 2020) contradict earlier classifications of seismic stability (Akpan & Yakubu, 2010; Onwuzuligbo & Ono, 2022) by documenting measurable tremors, with intensities up to MMI VI, and localized fault reactivation, in some cases influenced by anthropogenic activities. Predictive and probabilistic assessments (Oluwafemi et al., 2018; Afegbua et al., 2018) further extend these findings by suggesting the possibility of moderate to strong future earthquakes, although their projections are more uncertain due to reliance on statistical extrapolation and regional tectonic assumptions such as Mid-Atlantic Ridge influence. A consistent limitation across nearly all studies is

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the scarcity of dense seismic and geodetic monitoring networks, which constrains event detection, magnitude accuracy, and hazard modelling, thereby introducing uncertainty into both historical interpretations and future seismic risk assessments.

XI. MAJOR FAULT LINES AND STRUCTURAL INVESTIGATIONS ACROSS NIGERIA

Researchers have actively recognized major fault lines to comprehend Nigeria's seismic activities (Onwuzuligbo and Ono, 2022). The Ifewara-Zungeru fault zone, a significant NNE-SSW oriented fracture, has undergone thorough examination. Adepelumi et al. (2008) employed a combination of remote sensing and geophysical methods to delineate this fault zone, revealing its connection to oceanic fracture systems and potential involvement in seismic occurrences. Subsequent research by Tsalha et al. (2015), Awoyemi et al. (2017), and Afegbua et al. (2011) has underscored the importance of this fault in understanding regional tectonics. The Zungeru-Kalangai fault zone has been studied using aeromagnetic and remote sensing data, highlighting its complex structural framework and implications for potential seismic hazards. The Pelusium Megashear system, stretching from Anatolia to the Gulf of Guinea, traverses Nigeria and has operated as a left-lateral megashear since the Precambrian age (Gamal, 2013).

This system is linked to clusters of lineaments identified in central and northeastern Africa (Eldosouky et al., 2022). Amponsah (2004) conducted a thorough seismic hazard assessment in West Africa, revealing the region's susceptibility to significant seismic activity and emphasizing the need for ongoing investigation. Figure 5, depicts the fault line areas in Nigeria that are prone to earthquake. The system's northeastward convergence pattern indicates anticlockwise rotation of the crust, caused by left-lateral shear movements in the asthenosphere (Neev and Hall, 1982). This has significant ramifications for Nigeria's seismic risk and tectonic development, highlighting the importance of continued research and monitoring to mitigate potential seismic hazards.

The studies acknowledge that major fault systems, especially the Ifewara–Zungeru and Zungeru–Kalangai zones, are fundamental to Nigeria's tectonic setting and possible seismicity. Nonetheless, uncertainty remains regarding their current level of activity and seismic significance, largely due to sparse seismic records, reliance on indirect remote-sensing evidence, and limited geodetic validation

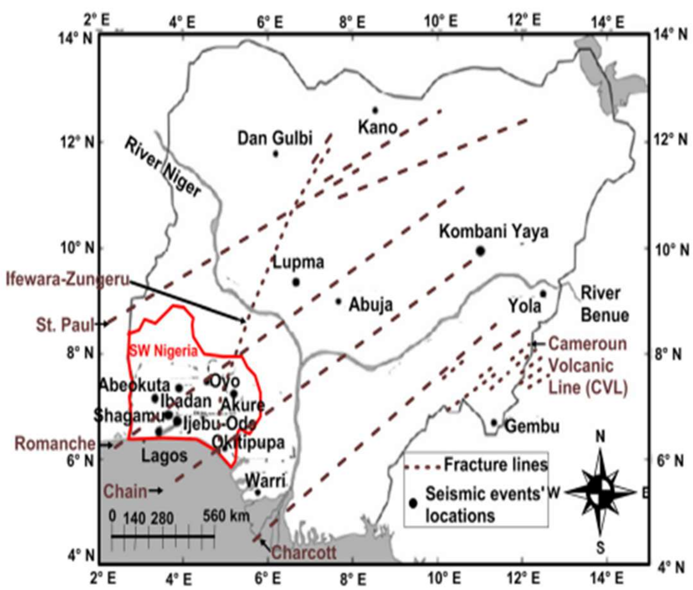

Figure 5. Map of Nigeria Showing Fault Lines, Areas and States That Are Prone to Seismic Activity, Highlighting Locations Where Earthquakes and Tremors Have Previously Occurred (Eluyemi et al., 2020; Oladejo et al., 2020).

XIII. GEOPHYSICAL EVALUATIONS OF EARTH TREMOR ACTIVITIES

Mostly, geophysical methods have been instrumental in evaluating earth deformation activities in Nigeria. David *et al*. (2022) conducted a geophysical evaluation of central Nigeria's earth tremor activities using high-resolution airborne magnetic data. Their analysis revealed dominant NE-SW and NW-SE trending structures, suggesting that areas prone to earth tremors are linked to the Romanche fault by numerous faults acting as conduits for seismic energy. Moustafa, et al., (2024); Ibrahim and Al-Bander (2024), underscores the importance of geophysical and geospatial techniques in identifying potential seismic hazards and understanding the structural controls of tremor activities. A recent study utilized aeromagnetic and gravity data to investigate the subsurface structure of Abuja's Mpape region, where earth tremors have occurred. The study revealed a more unstable subsurface structure, with deeper Moho depths (~34.1 km) and estimated depths to the magnetic crust's bottom ranging from 11.0-11.4 km (Osumje et al., 2023).

XIV. DEFORMATION AND SUBSIDENCE MONITORING

Researchers proactively assess structural stability and mitigate hazards by monitoring deformation and subsidence (Thomas et al., 2024). Alademomi et al. (2020) successfully established a robust deformation and subsidence monitoring system in Lagos, effectively protecting lives and properties. Their findings demonstrated the system's reliability for monitoring deformation and subsidence across the state. Ebere et al. (2024) conducted a thorough analysis of land subsidence in Awka South, Anambra State, Nigeria, utilizing Sentinel-1 data and InSAR techniques. The study uncovered alarming subsidence trends, with rates ranging from 2.33m to 9.76m in 2019 and 3.99m to 11.22m in 2020. The researchers strongly recommend leveraging these findings to inform decision support systems. Uncontrolled groundwater extraction and oil exploitation have triggered aquifer decline in Nigeria. Mahmud *et al*. (2016), discovered that Lagos state is experiencing subsidence at a rate of -7 mm/yr, with surrounding cities exhibiting even higher rates. Ikuemonisan *et al.,* (2020), investigated ground settlement in Lagos, revealing a maximum groundwater depletion rate of 11 mm/year and a maximum ground settlement rate of 94 mm/year. Isioye and Musa (2007) employed geodetic leveling to meticulously study crustal motion and deformation over three decades, examining benchmark stability on the main campus of Ahmadu Bello University, Zaria. Their study detected both downward and upward displacements, offering valuable insights into long-term crustal movements and structural stability.

XV. PROSPECTS AND OBSTACLES OF INSAR IN NIGERIA

InSAR delivers extensive, high-resolution data for monitoring surface deformation caused by earthquakes, volcanic activity, landslides, and land subsidence (Ferretti et al., 2007). Its ability to consistently observe large areas without relying on ground-based equipment makes it highly beneficial for countries with limited infrastructure like Nigeria (Ronczyk et al., 2022; Kumar et al., 2021). Countries such as Japan and Italy have successfully applied InSAR to monitor tectonic activity and reduce disaster risks (Hooper et al., 2012; Bakon et al., 2020; Fibbi et al., 2025). The availability of open-access satellite data from missions like Sentinel-1 has made InSAR a cost-effective tool for long-term monitoring of land and infrastructure. Despite its advantages, InSAR faces several technical and environmental challenges. Globally, factors such as signal decorrelation, atmospheric interference, and temporal coherence issues often reduce data accuracy, especially in humid or densely vegetated areas (Bürgmann et al., 2000; Yunjun et al., 2019; Wu et al., 2024).

Effective InSAR application demands advanced data processing skills, trained professionals, and access to robust computing infrastructure (Hoeser, 2018; Radman et al., 2021). Many developing nations, particularly across Africa, struggle to fully adopt InSAR due to limited technical infrastructure and expertise (Mbarika and Byrd, 2009; Gagliardi et al., 2021). Another limitation of InSAR is its exclusive focus on detecting surface deformation without revealing the underlying causes. This gap necessitates combining InSAR outputs with geological, hydrological, or engineering models for accurate interpretation (Zebker and Villasenor, 1992; Hoeser, 2018; Wang et al., 2025). For instance, Plate 1 illustrates an episode of earth tremor in Abuja, Nigeria's capital, highlighting the region's vulnerability.

In the African context, InSAR presents a powerful tool to address challenges such as urban subsidence, groundwater depletion, and infrastructure vulnerability. In fast-growing Nigerian cities like Lagos, Port Harcourt, and Abuja, InSAR proves useful in tracking ground deformation driven by groundwater extraction, urban construction, and climate change impacts. This technology enables proactive hazard management and mitigation (Ohenhen and Shirzaei, 2022; Orellana et al., 2023). Land subsidence in cities like Abuja threatens key infrastructure roads, bridges, and buildings and may trigger significant socioeconomic consequences over time (Josset et al., 2024; Gambolati and Teatini, 2021). By employing InSAR, urban planners and geotechnical engineers in Abuja can develop early warning systems and implement effective risk mitigation strategies (Reinders et al., 2022; Zheng et al., 2022). Additionally, Nigerian institutions like NASRDA have expanded their engagement with satellite technologies, paving the way for integrating InSAR into national development strategies.

However, several practical barriers still limit InSAR's application in Nigeria, especially in Lagos, Abuja, and Port Harcourt. These challenges include restricted access to high-resolution satellite data, limited training in synthetic aperture radar (SAR) data processing, and a general lack of awareness among policymakers regarding InSAR's role in urban planning and disaster risk reduction. Nevertheless, radar's ability to penetrate cloud cover gives it a clear advantage over optical remote sensing methods, particularly in Nigeria's cloud-prone, vegetation-dense regions (Hashemi et al., 2024; Uchegbulam and Ayolabi, 2013). To maximize InSAR's potential in Nigeria, stakeholders must prioritize capacity building, foster international partnerships, and invest in open-source platforms and education. Successfully integrating InSAR with GIS and ground-based validation will be vital for incorporating this technology into both national policies and local decision-making processes

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Plate I: Aftermath of the Earth Tremor in Part of Federal Capital Territory Abuja, Nigeria in the year 2018 (Daily Trust, newspapers, 2018)

XVI. THE FUTURE OF INSAR IN NIGERIA

Nigeria can unlock the vast potential of InSAR technology to drive environmental monitoring, urban planning, and risk management. By leveraging InSAR, Nigerian cities like Lagos, Abuja, and Port Harcourt can detect ground subsidence and infrastructure deformation, enabling more resilient urban development (Ojigi et al., 2013). InSAR can also provide critical insights into ground movement patterns in flood-prone and erosion-vulnerable regions, enhancing early warning systems and disaster preparedness efforts (Adepoju and Adelabu, 2020). To maximize the benefits of InSAR, Nigeria should prioritize integrating it with ground-based geospatial data and Geographic Information Systems (GIS) to facilitate more comprehensive analyses of geohazards (Bardi et al., 2014; Fadhillah et al., 2020). Combining InSAR data with GPS networks and hydrological models can improve understanding of the effects of groundwater extraction in northern Nigeria and regions of the Middle Belt (Abbas et al., 2018; Saber et al., 2018). InSAR can play a vital role in monitoring oil infrastructure in the Niger Delta, addressing issues of ground deformation tied to oil exploration and environmental degradation (Uchegbu and Chukwu, 2019). To fully harness InSAR technology, Nigeria must invest in local capacity development and access to high-resolution satellite datasets. While initiatives like Sentinel-1 by the European Space Agency have improved access to open-access SAR data, customized national platforms and specialized knowledge are necessary to efficiently process and interpret these datasets (Girei et al., 2021). Partnerships with global space agencies, academic institutions, and private enterprises will be crucial for integrating InSAR as a standard geospatial tool in Nigeria's environmental and infrastructure monitoring repertoire.

XIII. CONCLUSION

InSAR technology offers immense promise for monitoring and studying geohazards and earth surface deformation in Nigeria, especially in rapidly urbanizing areas with growing infrastructure and population density. Its applications in urban planning, disaster risk reduction, and environmental monitoring can aid in tracking infrastructure stability, subsidence, and ground displacement caused by natural and human-induced factors. the reviewed studies demonstrate a growing recognition that Nigeria cannot be simplistically classified as an aseismic region. Evidence from documented earth tremors, land subsidence, fault reactivation, and InSAR-derived deformation signals collectively points to subtle but significant geodynamic activity. Most studies agree that both natural tectonic processes and anthropogenic factors such as groundwater extraction, mining, and urban loading play interconnected roles in observed deformation patterns. However, contradictions remain across the literature, particularly regarding the origin, continuity, and seismic significance of identified fault structures. While some studies interpret observed deformations as indicators of tectonic reactivation, others attribute them mainly to surface or near-surface processes. These inconsistencies are largely driven by variations in data sources, temporal coverage, spatial resolution, and methodological approaches, highlighting the absence of a unified national framework for deformation monitoring and seismic assessment.

The major limitation of existing studies is their fragmented nature, with many analyses being event-specific, short-term, or spatially restricted. The limited integration of geodetic, geological, and geophysical datasets further constrains robust interpretation and hazard forecasting. Future research must therefore prioritize long-term, multi-sensor InSAR monitoring, improved ground validation, and interdisciplinary collaboration to strengthen understanding of Nigeria's geodynamic behaviour and to support evidence-based risk mitigation and planning strategies.

AUTHOR CONTRIBUTIONS

M. Baba conceived the study, designed the methodology and drafted the initial manuscript. Fadzli, Mohamed Nazri contributed to critically reviewed and revised the manuscript for intellectual content and provided technical and conceptual guidance throughout the study.

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