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Mitigating the effects of third-party interference on crude oil pipeline network in South-South Nigeria using differential interferometric synthetic aperture radar (DInSAR) analysis

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Abstract: *This study explored mitigating third-party interference (TPI) on crude oil pipeline networks, in South-South Nigeria, as observed through Differential Interferometric Synthetic Aperture Radar (DInSAR) analysis. The research design used a dual-method approach, combining geospatial analysis through DInSAR technology with thematic analysis to identify, understand, and address the phenomenon of Third-Party Interference (TPI) in Nigeria's oil pipelines. The quantitative arm of the study employed DInSAR for mapping and detection of ground movement that could be pointers to unauthorized interference. The software used were the ESA'S SNAP (sentinel application platform) for processing Sentinel-1 specifically for: Coregistration, Interferogram Generation, Displacement Map Creation, Hot spot Analysis, Proximity Analysis, Temporal Analysis and curbing interference cases. The Python (ArcPy and Py SNAP) was used to automate data processing workflows and integrate SNAP and ArcGIS functionalities, including interferogram generation and displacement mapping. The semi-structured analysis revealed that difficult terrain (43%) accounted for most of the challenges of TPI mitigation. The results from the coregistered images reveal high-risk areas that proved to be potential TPI points of interest (POI) due to the uplifts. Risk areas showed uplift values of 0.87 meters or higher when these data were collected. The results demonstrated that an integrated approach using satellite and electronic surveillance offers a cost-effective and scalable alternative to traditional methods.*

Keywords: *Third-Party Interference, Pipeline Networks, Pipeline Security, Chi-Square, Global Positioning System.*

INTRODUCTION

The Nigerian oil and gas sector is one of the significant sectors in the development of the country and is also a major source of income and growth driver for the nation (Biose, 2020). However, the industry is plagued by many challenges, including the challenge of third-party interference on the oil and gas pipeline infrastructure. Third-party interference through malicious and criminal activities like vandalism, theft, and illegal tapping of pipelines has had adverse impacts on the efficiency and reliability of the pipeline system, leading to serious costs to the industry, environmental degradation, and massive disruption of the nation's energy supply, say Tahir and Udezi

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(2017). The chronic issue has placed the sector at a discounted level, reducing its capacity to meaningfully contribute to the economic development and growth of Nigeria. Nigeria has over the years, especially with the discovery of the black gold, largely depended on revenue from the oil and gas sector for the sustenance of her economy (Adenigbo *et al.,* 2017). The Nigerian economy is primarily driven by proceed from oil and gas and accounting for over 87% of the country's revenue, and with a cumulative annual contributory GDP growth of 9.61% (Okpi, 2018). Even with a drop in the annual contributory GDP of oil to 7.5% in the third quarter of 2021 due to the COVID-19 pandemic (Varella, 2021), any disruption in the transportation of the oil and gas through the network of pipelines, covering over 7,000 Km (Tade & Ayodele, 2019), will pose severe and adverse implication on the revenue accruing to the nation and by extension on the economy of Nigeria. Unfortunately, several factors are responsible for the disruption of crude oil and gas flow. Some of these factors range from terrorism, vandalism, sabotage and militancy. All of these aforementioned are termed Third- party Interference (TPI). TPI describes any activities of vandals / non-pipeline operators to deliberately tamper with the pipelines with the intention of stealing crude oil and associated petroleum products. Third-party interference also refers to unauthorized intrusion, interference, or damage to the pipeline infrastructure by unauthorized individuals or groups who are not licensed to do so. This may be sabotage, theft, or even terrorism and has resulted in enormous economic losses, environmental contamination, and loss of life (Biose, 2020; Ngonadi and Ajiroghene, 2021).

The risk posed by TPI can be measured in terms of the financial losses to the government (Umeje *et al.,* 2017), security implications (Okoli & Orinya , 2013), damage to the environment and its attendant health and safety implications (Albert *et al.,* 2019). The Nigerian National Petroleum Corporation (NNPC) reported that Nigeria annually loses over 200 bpd as a result of pipeline crude oil theft. The Corporation expended a total of ₦15 billion in the repair of pipelines and other facilities as a direct consequence of TPI over a 24month period spanning from January of 2019 to January 2021 while ₦59.1 billion was spent on repair and management of pipelines within the period of December 2019 and January of 2021 (Akinpelu, 2021). From the foregoing, the country spends on the average a total of ₦625 million monthly as a direct result of TPI. This, no doubt, is a very huge amount of money wasted in managing cases of oil theft in Nigeria. Sadly, TPI results in crude oil leakages of the pipeline at the exact location of the sabotage. These leakages, if not detected early, can lead to adverse economic and environmental consequences. Pipeline leaks may result, for example, from bad workmanship or from a destructive cause (TPI), due to sudden changes of pressure, corrosive action, cracks, defects in pipes or lack of proper adherence to maintenance program for the pipelines. In general, there are two major classes of leak detection. The first class includes methods that are mainly based on directly measurable quantities such as inflows, outflows, pressures and temperatures. The second class relies on non-measurable quantities such as internal state variables, parameters and characteristic quantities of the pipeline system (Emara-Shabaik *et al.,* 2013). Generally, pipeline systems are divided based on the type(s) of fluid it transports. As a result, pipeline systems are divided into six, that is, Oil and gas pipelines, Slurry pipelines, Water and sewer pipelines, Beer pipelines, Hydrogen pipeline and Pipelines for other liquids/solid particles using air (Nanzip, 2022). Pipeline transportation is one of the modes of transport that involves the use of hollow pipes in the transportation of water, crude oil, (petroleum), biofuels and gas. This mode of transportation is safer and cheaper than using barges, tankers or trailers in the transportation of these liquids. Furthermore, there are three major types of pipelines along the transportation route: the gathering system, the interstate pipeline system, and the distribution system (Natgas, 2022). Due to the strategic role pipelines play in the transportation of crude oil and associated products across various locations; and, giving the remoteness of the routes it often traverses and the consequent accessibility and security issues, it has become very necessary to develop an integrated system of monitoring our pipelines from human interference. The Trans-Ramos Pipeline (TRP) is a 24-inch Crude Oil Trunkline installed in 1995 to transport crude oil to the Forcados Terminal (FoT). The trunkline traverses' part of Bayelsa and Delta States, South-South Nigeria covering a distance of 54.4 Km ((SPDC), August 2019). Only recently, a major crude theft point was discovered on the TRP at Ogulagha Community. The Trans-Ramos Pipeline, supplies crude oil to the SPDC JV Forcados export terminal, with a capacity of around 100,000 barrels per day. The Shell Petroleum Development Company (SPDC) is the operator of the JV- in which the Nigerian National Petroleum Corporation, NNPC holds 55 percent; Shell, 30 percent; Total Exploration and Production Nigeria Limited, 10 percent; and NAOC, 5 percent. The Forcados Export terminal

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carries between 200,000 and 240,000 barrels of oil per day (Akintayo, 2019). From the foregoing, it is obvious that the Trans Ramos Pipeline is an important asset for national development and it holds the key to our economic growth.

In Nigeria, there are roughly 124 km lengths of pipelines used for the transportation of condensate; 4,045 km for gas; 164 km for liquid petroleum gas; 4,441 km for crude oil, and about 3,940 km lengths of pipes are used for refined petroleum product lines. Unfortunately, Nigeria has constantly been faced with increasing militants and vandals attack at a rate that is becoming alarming (Mmeje *et al.,* 2017). While a lot of research work has been done in the area of pipeline vandalism and sabotage most of the methods developed have been very expensive to procure. In addressing the challenge of vandalism and sabotage, the inside and outside sensor leak detection and monitoring technique can either be employed by researchers to solve the problem created by TPI (Rushikesh *et al.,* 2020). The inside pipeline sensor uses acoustic devices, mass balance methods and the transient-based method. On the other hand, the outside pipeline sensor employs the use of visual inspection such as ground penetrating radar (GPR), image/video cameras and soil property sensor. All of these techniques employ the Wireless Sensor Network technology which enables easy interpretation of results using the three major components, that is, microcontroller, sensing unit and then communication interface. This research work shall recommend best practice for an efficient and prudent pipeline leak detection system in order to reduce; and where practicable, eliminate the incidence of pipeline leaks. Hence, a system that employs an integrated approach comprising electronic surveillance of the pipelines, efficient ground truthing with limited accessibility time and prompt military response to any pipeline failure due to leakages shall be developed. The problem stems from the network of Nigerian oil and gas pipelines that are associated with a litany of problems, including third-party interference, which has been the main driver of the operations and profitability of the industry (Oyekan, 1991). In recent times there has been a phenomenal increase in the incidence of pipeline vandalisation and sabotage across the communities with pipeline oil and gas network. According to Akinpelu (2021) the country has within a twenty-one (21) month period, that is, January 2019 and September 2020, recorded the following pipeline incidences: the Port-Harcourt axis of the pipeline network experienced a total of 538 TPI incidences followed closely by the Mosimi-Ibadan axis with 535 points, Gombe-46, Kaduna-32 and Warri-River Niger-10. Unfortunately, the relative calm in the Oil rich Niger Delta region of Nigeria notwithstanding, the activities of vandals continue to soar with its attendant consequences on the environment and income profile of the country. A total of 2,787 pipeline vandalisations' were recorded between 2010 and 2012 and over 15,685 between 2002 and 2012 (Chukwuma, 2013). Also, from October 2018 to October 2019, a total of 2,181 pipeline points were vandalised as compared to 1,161 vandalised points between January 2019 to September 2020 (Akinpelu, 2021). The Nigerian National Corporation (NNPC) noted in one of her reports that "Product theft and vandalism have continued to destroy value and put NNPC at a disadvantaged competitive position," (Akinpelu, 2021). With such statistics, the problem of pipeline vandalism is no doubt a worrisome development for our country. A comparison of the figures shows that the incidence of leakages due to TPI is definitely on the rise in spite of the many efforts of government and relevant agencies to reduce it.

Furthermore, in Nigeria, as contained in the report of NNPC to the Revenue Mobilisation Allocation and Fiscal Commission (RMAFC) where it noted that Nigeria lost N898.93bn to crude oil theft and repairs of vandalised pipelines across the country between January and September 2021 (Nnodim, 2021). In view of the above, a number of researchers have sought to find a lasting solution to the problem of TPI. Some remarkable work done in pipeline monitoring is the use Magnetic Induction (MI) based sensors to detect leaks. Yuhana *et al.* (2017) employed an inside sensor at the upstream and downstream ends of a pipeline to measure variations in temperature, pressure and flowrate and thereafter sends the data generated to the control for interpretation. Also, in solving the challenge Zhi *et al.* (2011) employs the use of both the inside and outside sensors in designing an MI-based wireless sensor network for detecting interference on underground pipeline using the MISE-PIPE system. This design detects and localises leakage by a joint utilization of the measurements obtained from the different types of sensors that are located both around and inside the underground pipelines. The beauty of this technique is in employing both the inside and outside pipeline monitoring techniques. This in itself introduces high cost of surveillance. Another such work is the use of GSM module to track leakages as described by Rushikesh *et al*. (2020) who designed a magnetic induction (MI) based wireless sensor network which he located on the inside and outside of a pipeline. This design detects in real-time any leakage and localizes the leakage by joint utilization of the measurement of the magnetic induction-based sensor and thereafter sends the signal to a GSM module. This system was primarily designed for water pipelines. It is therefore evident that in spite of the enormous work done in remote pipeline surveillance by various researchers, not much has been done in the use of DInSAR technology as a veritable tool to track incidence of pipeline vandalism and sabotage. This research identifies a critical technological gap: the absence of proactive, wide-area surveillance tools capable of identifying subtle ground movements associated with interference. To address this critical challenge, this study explores the use of Differential Interferometric Synthetic Aperture Radar (DInSAR) technology as a viable remote sensing solution for early detection and mitigation of TPI. By capturing minute ground displacements associated with interference events, DInSAR enables wide-area surveillance with enhanced precision and timeliness. Differential Interferometric Synthetic Aperture Radar (DInSAR), a remote sensing technology with high spatial and temporal precision, presents a promising alternative. By leveraging satellite imagery to detect micro-deformations caused by tampering, DInSAR offers the potential to revolutionize pipeline security—moving from reactive damage control to predictive intervention. This study seeks to address the entrenched vulnerabilities in Nigeria's pipeline security framework by demonstrating the viability, cost-effectiveness, and precision of DInSAR as a strategic solution for mitigating TPI on critical infrastructure. It also seeks to demonstrate the feasibility of integrating DInSAR into Nigeria's pipeline monitoring framework, with particular attention to the TRP corridor. Ultimately, this study aims to provide a cost-effective, scalable, and data-driven approach that enhances pipeline security, reduces leak-related losses, and supports environmental preservation across South-South Nigeria. This is the gap that this work intends to address. This research work was limited to developing an integrated approach at early leak detection thereby mitigating the incidence of Third-Party Interference (TPI) across crude oil pipeline within the oil rich Niger delta region of Nigeria with particular reference to the 24inch Trans-Ramos Pipeline (TRP) which runs from Brass Creek Manifold in Bayelsa State to Forcados Terminal (FoT) in Delta State.

MATERIALS AND METHODS

The research design employed a mixed-method approach, combining geospatial analysis through DInSAR technology with thematic analysis to identify, understand, and address the phenomenon of TPI in Nigeria's oil pipelines. The quantitative arm of the study employed DInSAR for mapping and detection of ground movement that could be pointers to unauthorized interference. Qualitative thematic analysis was conducted simultaneously to extract stakeholders' views on the challenges, perceptions, and community impacts regarding pipeline security. The remote sensing technology applied is to locate and analyze TPI hotspots, monitor temporal trends in interference activities, and conduct proximity analysis to establish the relation between pipelines and nearby communities, roads, and other infrastructure. Thematic analysis was also conducted to investigate challenges and perceptions associated with pipeline security, technology adoption, and community dynamics. The research was centered on the principal oil and gas pipeline corridors within the Niger Delta area of Nigeria, that is, the regions with high third-party interference (TPI) levels. They were nodal points like Odimodi, Aghoro, Ogulagha, Agge, Ogbotobo, and the Brass Creek Manifold, which were part of Nigeria's oil-producing hub. The Trans-Ramos pipeline network flowed from Brass Creek, which was in the Peretorougbene community, through Ogbotobo, Aghoro, Agge, and Odimodi to Ogulagha, where the Forcados Terminal was situated. These regions were typified by coastal and swampy lands, making them strategic yet susceptible to vandalism, sabotage, and theft.

2.1 Research Design

The research design employed a dual-method approach, combining geospatial analysis through DInSAR technology with thematic analysis to identify, understand, and address the phenomenon of TPI in Nigeria's oil pipelines. The quantitative arm of the study employed DInSAR for mapping and detection of ground movement that could be pointers to unauthorized interference. Qualitative thematic analysis was conducted simultaneously for extracting stakeholders' views on the challenges, perceptions, and community impacts regarding pipeline security. Primary data collection in this study relied on semi-structured interviews and site visits, both selected for their ability to generate in-depth qualitative insights relevant to the socio-technical dimensions of TPI.

Questionnaires when administered or sent to the identified individuals or group of individuals, it usually creates many nonrespondents. Therefore, getting the right people to participate is important. The right sample space was selected for the survey from the population to represent the entire population. The options of using the either probability or nonprobability sampling techniques were considered. The Non-probability sampling is nonrandom, and includes systematic sampling, convenience sampling, quota sampling, and snowball sampling (Thomas, 2004). This questionnaire survey utilised the quota recruited nonprobability method of sampling in which samples was selected to meet specific representation. This method is similar to the stratified probability (random) sampling, where identified subgroups (*e.g*. stakeholders in the pipeline industry of the oil and gas sector, especially those familiar with the 24″ TRP section of the pipeline) are the sample frame. Non probability samples have the merit of the faster speed of data collection, lower survey cost, and easier accessibility to the potential respondents (Kyu-Seong, 2022). The non-probability sampling technique employed involves selecting participants without randomization, relying instead on accessibility, judgment, or predefined criteria e.g, familiarity with the study area. It is commonly used in qualitative research, pilot studies, or situations where the population is hard to define or access. The recruited sample identifies respondents enlisted from the subgroups via e-mail and are provided with the URL of a web-based questionnaire. The data collection instrument consisted of a self-administered web-based survey to assess respondents' demographic characteristics, opinions, management experience, and perception on pipeline third-party interference from 30 respondents. The Stakeholders that participated in the survey cuts across the Regulating agencies, the Operators, Security Agencies and the host Communities

The results from the data generated were analysed using Chi-Square. The Chi-Square analysis tool was selected because it has the advantages of robustness for distribution of the data, its ease of computation, the detailed information that can be derived from the test, its use in studies for which parametric assumptions cannot be met, and its flexibility in handling data from both two group and multiple group studies (Karlus *et al.,* 2012; Mary, 2013; Vernon *et al.,* 2018).

$$x^2 = \sum \frac{(O_{ij}-E_{ij})^2}{E_{ij}} \quad (1)$$

where,

O_{ij}= Observed frequency in cell (i, j).

E_{ij}= Expected frequency under independence:

$$E_{ij} = \frac{(Row\ Total_i)-(Column\ Total_j)}{Grand\ Total} \quad (2)$$

DInSAR measured the surface displacement by comparing SAR images taken at different times. This study used data from the Sentinel-1 satellite mission: C-band Sentinel-1 (SLC): Sentinel-1 which provided free, open-access SAR imagery with 6–12-day revisit times. The SLC (Single Look Complex) product was used, as it contained phase information necessary for interferometric analysis. DInSAR-compatible Sentinel-1 imagery was acquired to facilitate quantitative spatial analysis of surface displacement patterns. Sentinel-1, due to its high revisit frequency and open-access availability, served as the primary data source. The radar signals from successive passes are used to calculate changes in the distance between the radar sensor and the ground (Zhenqiang *et al.,* 2023). DInSAR relies on phase differences between two SAR images. The key mathematical model is:

$$\Delta\phi = \frac{4\pi}{\lambda}\Delta R \quad (3)$$

Where,

$\Delta\phi$ = phase difference between two SAR images

λ = radar wavelength

ΔR = change in the distance between the sensor and the ground (R′ – R)

The SAR model can also be expressed as follows (Colesanti *et al.,* 2003).

$$\Delta_{\varphi} = \varphi_{flat} + \varphi_{topo} + \varphi_{defo} + \varphi_{orbit} + \varphi_{atmo} + \varphi_{noise} \quad (4)$$

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Here,
$\Delta\varphi$ is the interferometric phase (i.e., the phase change between two acquisitions), where,
φ_{flat} = the horizon effect phase,
φ_{topo} = the terrain phase,
φ_{defo} = the phase component related to ground deformation,
φ_{orbit} = the phase error caused by the orbit information error,
φ_{atmo} = the atmospheric correlation phase, and
φ_{noise} = the combined noise term.

Fig. 1 summarizes the basic principle of DInSAR technique, when a single pixel point is considered. The first SAR image is acquired by the sensor at a given time, t_0, measuring the phase φ_M of the microwave. This first satellite and the corresponding image are referred to as the Master. Indicated by M. If the land is subject to a displacement D(t), the point P moves to P'. The sensors then acquire a second SAR image called the Slave, S at a time t, measuring the phase φ_S. The DINSAR technique exploits the phase difference $\varphi_{INT} = \varphi_M - \varphi_S$, called the interferometric phase, containing information on land displacement, thus finally retrieving the land displacement D(t).

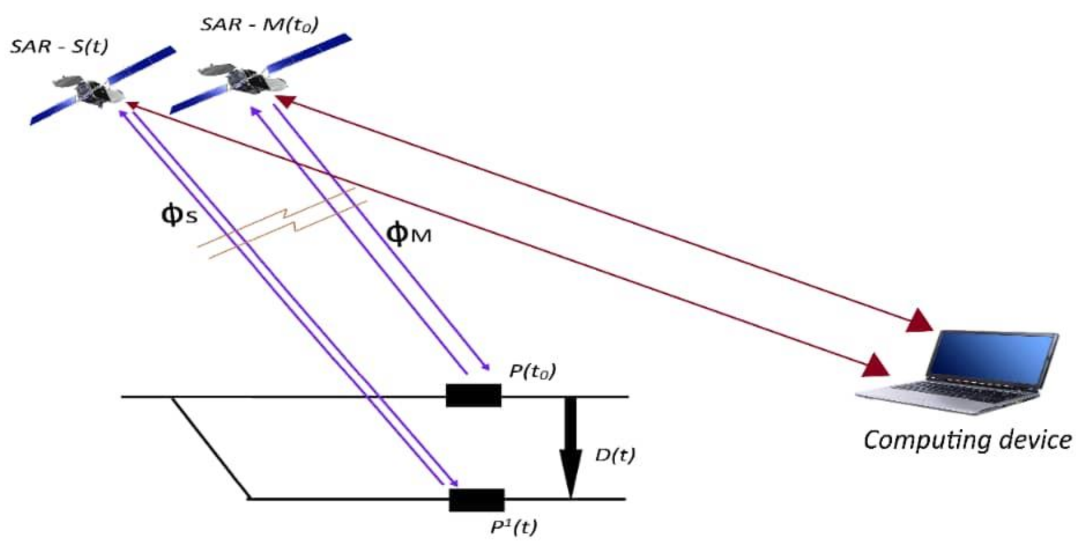

Fig. 1. Principle of DInSAR for measuring the D(t) displacement Adapted from (Sabadini, 2015)

2.2 Satellite Imagery and Sensor Data

DInSAR-compatible **Sentinel-1** imagery was acquired to facilitate quantitative spatial analysis of surface displacement patterns. Sentinel-1, due to its high revisit frequency and open-access availability, served as the primary data source. Alongside this source, historical sensor data, such as surveillance reports from pipeline operators, was incorporated to validate DInSAR findings

2.3 DInSAR Processing

The DInSAR methodology was used to detect ground deformation caused by TPI activities. The steps employed for processing SAR data using DInSAR include: Data Acquisition from Sentinel-1 SLC satellite. The data was downloaded from the Copernicus Open Access Hub. Data was obtained for different periods to allow for the temporal analysis of displacement patterns. Then was the preprocessing for Orbit Correction to remove inaccuracies aimed at ensuring accurate geolocation. Radiometric Calibration of the corrected image was normalized using radar backscatter values for better comparability between images. Coregistration of the images allowed for alignment of two or more SAR images acquired at different times for accurate interferometric comparison. Subset: Extracted the area of interest around the pipeline network for detailed analysis.

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Interferogram Generation

i. Interferometric Processing: Calculated the phase differences between the coregistered SAR images to generate an interferogram.
ii. Phase Unwrapping: Unwrapped the interferometric phase to create a continuous surface, allowing ground displacement to be calculated
iii. Displacement Map Creation: Converted the unwrapped phase into ground displacement measurements, identifying areas where ground movement indicated possible TPI activity.

Exporting Results: Displacement maps were exported as GeoTIFF files for integration into ArcGIS. The processed DInSAR data was imported into ArcGIS for further geospatial analysis. We applied the Hotspot Analysis (Getis-Ord Gi) tool to identify areas of significant TPI activity based on displacement data, pinpointing regions with frequent or severe interference. Then Buffer Analysis was used to assess the proximity of TPI hotspots to communities, roads, and water bodies, helping to determine whether closer proximity to infrastructure correlated with higher TPI activity. Temporal analysis integrated time-series displacement data into time-aware layers in ArcGIS. This allowed tracking of TPI activities over time and helped assess the effectiveness of security measures in reducing interference incidents. Mapping and Visualisation created high-quality maps using ArcGIS's Layout View to visualize displacement patterns, TPI hotspots, and proximity relationships. Finally, the TPI incident records obtained from the Document Control Centre of SPDC contributed an empirical dimension to the study. These records allowed for the cross-verification of geospatial findings and helped establish temporal patterns that contextualized recent interference incidents in the study area.

The integration of quantitative and qualitative techniques within this research design enabled a balanced approach, addressing both spatial patterns and social drivers of TPI. Primary data collection in this study relied on semi-structured interviews and site visits, both selected for their ability to generate in-depth qualitative insights relevant to the socio-technical dimensions of TPI. Direct observations conducted during field visits to key pipeline sites offered first-hand insights into the physical environment and security conditions. These site visits, particularly to locations like the Brass Creek Manifold and other high-risk areas in Odimodi, Aghoro, and Ogulagha, allowed for a closer inspection of the current security measures and their limitations. Observing these sites in person was invaluable for understanding the geographic and environmental factors—such as swampy terrain and proximity to human settlements—that may influence TPI vulnerability. The study utilized various secondary data sources to support and validate the primary data, including academic literature, satellite imagery, and government databases. The geography of the region, with hard-to-patrol coastal and marshy regions, presented an ideal challenge to pipeline security. The study location offered a varied set of conditions, allowing in-depth assessment of an integrated monitoring system in high-risk conditions.

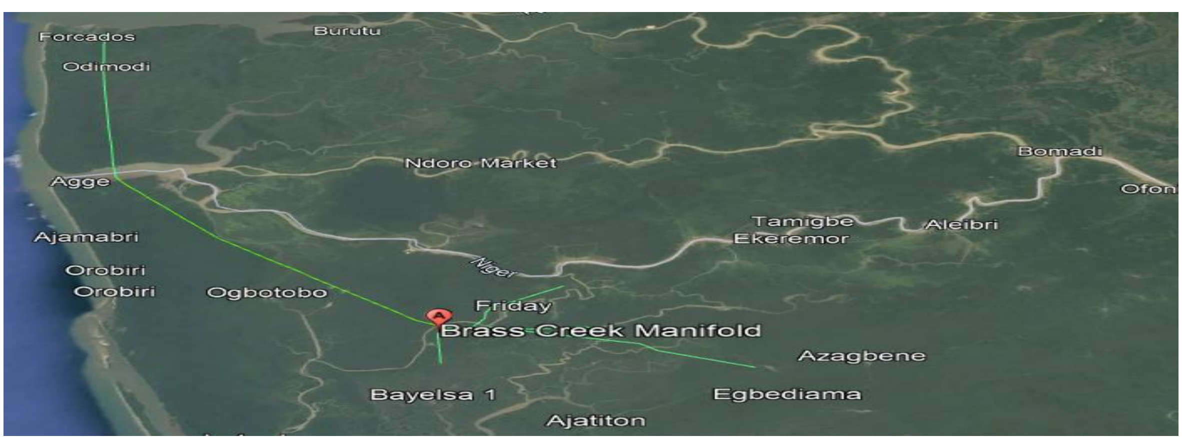

Fig. 2. Area of interest (Study area)

The marked locations Odimodi, Aghoro, Ogulagha, Agge, Ogbotobo, and Brass Creek Manifold are situated in the Niger Delta region of Nigeria, a key oil-producing zone characterized by its coastal and swampy terrain.

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These are situated along or close to the southern border of Nigeria, adjacent to the Niger Delta creeks and the Atlantic Ocean. The terrain is mostly swampy with numerous creeks, rivers, and mangroves characteristic of the deltaic ecosystem. The extremely dense network of water courses is fed by the distributaries of the Niger River on its way into the Atlantic. The area is biodiversity-rich, having mangroves and wetlands with diverse plant and animal species. The ecosystem has been affected in some areas by the presence of oil facilities and activities. The regions form Nigeria's oil production hub. The closeness to the oil fields and to infrastructure such as the Brass Creek Manifold indicates that they are significantly involved in oil production and transport. Due to the swampy land, the majority of access is limited to boats and helicopters, with minimal road systems. The terrain and waterways pose challenges to monitoring and building infrastructure. Geographically, they are situated southwest of Warri and southeast of Sapele, both of which are major urban cities in the Delta State. They fall within the general area between Bayelsa and Delta states. A zoomed in view of the area of interest is as shown in Fig. 3.

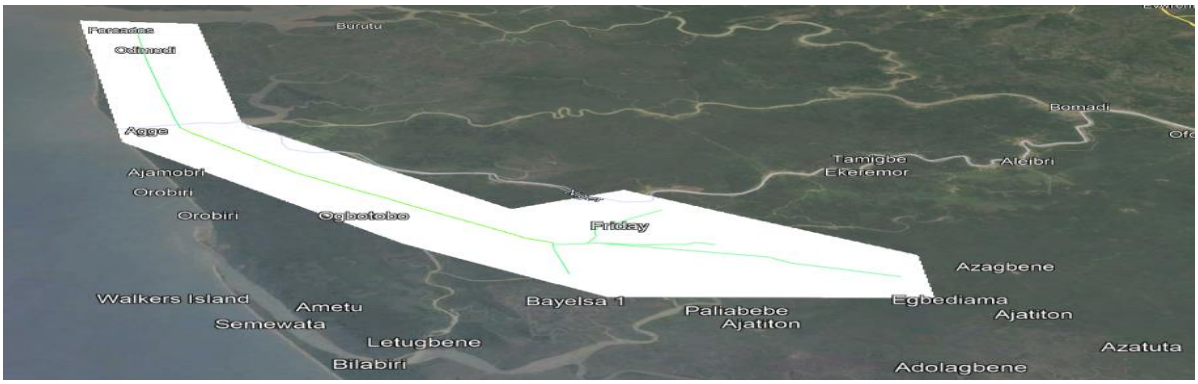

Fig. 3. Polygon around pipeline of interest

RESULTS AND DISCUSSION

This study analysed the results from thirty-two (32) respondents carefully selected from the research design. This number cuts across the different groups directly or indirectly involved with mitigating third-party interference (TPI). From the table 1 below, Forty-one percent (41%) of the respondents are oil company representative; thirty-four percent (34%) government/regulatory officials; thirteen percent (13%) security agent; Nine percent (9%) local security/vigilante; and one percent (1%) contractor staff.

Table-1 Respondents Demographic

Agency	No of Respondents	Percentage %
Government Regulators	11	34
Oil Company Representatives	13	41
Security Agencies	4	13
Local Security/Vigilante	3	9
Contractor	1	3

3.1 Challenges in Pipeline Security

Mitigating third-party Interference is compounded by quite some challenges. These challenges ranges from difficult terrain, corruption, poor/inadequate communication infrastructure, insufficient training/equipment, and involvement of GSA's in aiding illegal oil theft. The table below shows the result of the survey carried out on the challenges of pipeline security in the Niger Delta.

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Table-2. Pipeline Security Challenges

Pipeline Security Challenges	Count	Percentage %
Difficult Terrain	23	24
Corruption	25	26
Inadequate Communication Infrastructure	19	20
Lack of Coordination between Agencies	14	15
Insufficient Training & Equipment	12	13
Involvement of GSA's	2	2

Corruption in the system of pipeline security administration by government officials is cited as the most significant threat to mitigating third-party interference by 26% of the respondents. This is closely followed by difficult terrain, according to 24% of the respondents. A total of 20% of the respondents cited financial restrictions in procuring required technology and recruiting adequate manpower as a contributory factor to Third-Party Interference. Insufficient training of personnel and lack of equipment accounted for 13% of the challenges to pipeline security. The survey cited low involvement (2%) of Government Security Agencies (GSA's) in the challenges of pipeline security. This is a significant outcome as it suggests that the GSA's are not colluding with pipeline vandals to steal our natural resources.

3.2 Association between Role and Corruption as a Perceived Challenge

We set out to determine if there is a statistically significant association between respondent roles and the likelihood of citing corruption as a challenge in pipeline security through Chi-Square

Table-3 CHI-SQUARE setup

Role	Corruption		Total
	Cited	Not Cited	
Oil Company Representative	12	1	13
Government Officials / Regulators	7	4	11
Security/Local Groups	2	2	4
Vigilante	3	0	3
Contractor	1	0	1
Total	25	7	32

The computed χ^2 statistic (5.826) is less than the critical value (9.488) and has a p-value < 0.05. Therefore, it was concluded that there is no significant association between role and citing corruption as a challenge. This finding implies that stakeholders agree generally that corruption in the system of administration of Oil pipeline security is a major threat to Third-Party Interference in the Niger Delta region of Nigeria. This is the position also propounded by (Oshienemen, Amaratunga, & Haigh, 2019) when it stated that "The corrupt practice in the oil gas distribution sectors, the government sectors, and the security agencies are alarming, making it difficult to curtail the act of oil sabotage and the destruction of oil facilities".

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3.3 Interferometry Result of the Trans-Ramos Pipeline (TRP)

Two single-look complex (SLC) Sentinel-1 Level-1 SLC Products – the master (S1A_IW_SLC__1SDV_20231106T175335_20231106T175402_051100_062993_0588) and the slave (S1A_IW_SLC__1SDV_20242201T175333_20240504T175400_053725_0686E3_D31F) were acquired from the Sentinel-1 satellite. The properties of the acquired results are displayed in Table-4 below.

Table-4 Properties of SAR products

	Master	Slave
Sensing start time	06-NOV-2023 17:53:35.949235	04-MAY-2024 17:53:33.776547
Sensing stop time	06-NOV-2023 17:54:02.889356	04-MAY-2024 17:54:00.714612
Band grouping	IW1:IW2:IW3	IW1:IW2:IW3
Acquisition mode	Interferometric Wide (IW)	Interferometric Wide (IW)
Orbital pass	Ascending	Ascending
Track	103	103
Orbit	51100	53725

Both images like all Sentinel-1 SAR data contain complex (real + imaginary) values because they are stored as Single Look Complex (SLC) format, which preserves phase information. In SNAP software, the intensity bands of the images are computed using the expression

i_IW2_VV == 0.0 ? 0.0 : i_IW2_VV * i_IW2_VV + q_IW2_VV * q_IW2_VV

where **i_IW2_VV** represents the **real** (in-phase) component of the complex SAR signal for the IW2 VV (Vertical-Vertical) polarization and **q_IW2_VV** represents the **imaginary** (quadrature) component of the complex SAR signal for the IW2 VV polarization

i_IW2_VV == 0.0?0.0:... is a conditional (ternary) operator.

- If i_IW2_VV is exactly 0.0, then the intensity is set to 0.0.
- Otherwise, it proceeds to compute the intensity.

i_IW2_VV * i_IW2_VV + q_IW2_VV * q_IW2_VV

- This calculates the **intensity,** I of the SAR signal.
- It follows the formula for the magnitude squared of a complex number:

$$I = Re^2 + Im^2 \quad (5)$$

where **Re** is the real component (i_IW2_VV) and **Im** is the imaginary component (q_IW2_VV)

This expression is used in computing the intensity (power) from the complex SAR data. Intensity is important in SAR image processing because it represents the backscattered signal strength, which helps in analysing surface features and it is used in radiometric calibration, image interpretation, and classification tasks. Intensity images are commonly used for further processing like speckle filtering and coherence estimation in interferometry (Fig.4 & Fig.5).

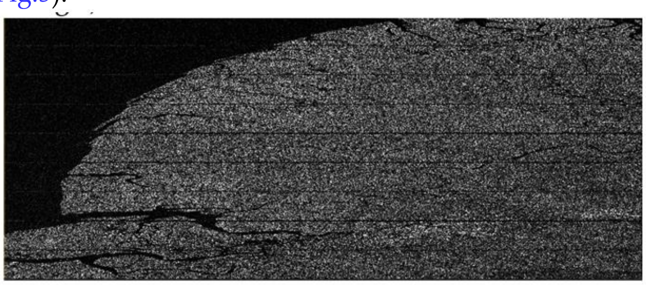

Fig 4. Intensity of master IW2_VV complex data (24797 x 13491 pixels)

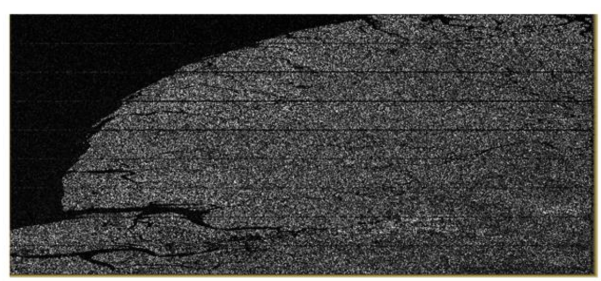

Fig 5. Intensity from slave IW2_VV complex data (24797 x 13491 pixels)

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The resultant intensity, phase and coherence bands of the coregistered images after applying orbital files are shown in Figs. 7 to 9.

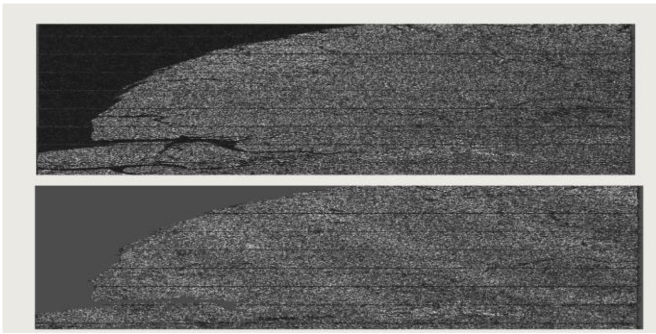

Fig 6 Co-registered images. The top shows the master image while the bottom image is the slave image

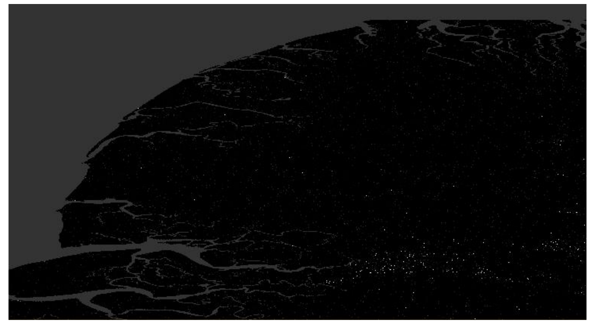

Fig. 7 Intensity band of co-registered images

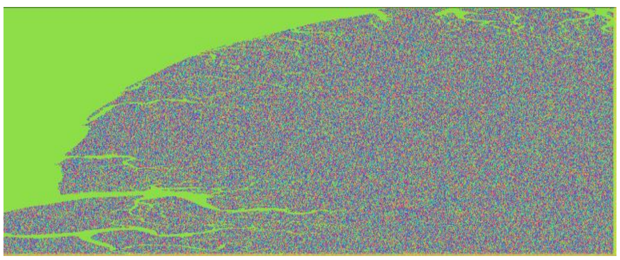

Fig.8 Phase band of co-registered images

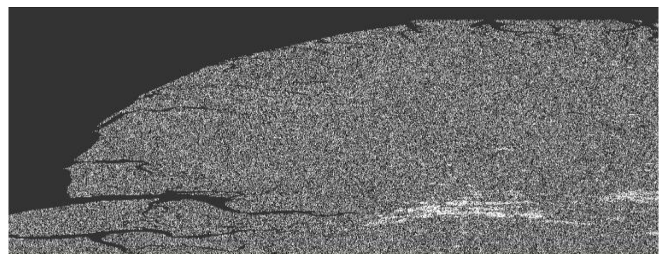

Fig.9 Coherence band of co-registered images

This step, that is, co-registration is crucial for ensuring accurate and reliable SAR interferometry results. Precise orbit data refines the satellite's recorded position and velocity, reducing geolocation errors that could compromise deformation mapping and DEM generation. By correcting baseline discrepancies, it enhances coregistration accuracy, leading to better alignment between master and slave images while improving coherence and minimizing phase decorrelation. Additionally, updated orbital files help mitigate residual errors in raw SAR data, preventing unwanted phase ramps that can distort phase stability in deformation analysis. They also correct geometric distortions such as azimuth shifts and range errors, ensuring more accurate interferometric phase computations. Moreover, since interferometric baselines are derived from orbit data, precise orbital corrections improve baseline estimation, reducing errors in ground displacement measurements

3.4 Phase to Displacement

The unwrapped phase was imported back into SNAP and "Phase to Displacement" algorithm was applied to convert the phase difference into displacements. The result is shown in Fig.10. Since SAR systems acquired the data in a side-looking geometry, the uncorrected displacement maps are generally plagued by geometric distortions of foreshortening, layover, and shadowing. Such distortions tend to misrepresent true displacement measurements across areas of variable topography. Thus, by applying terrain correction, displacement values are correctly georeferenced to ensure precise alignment with real-world coordinates. This is particularly crucial for GIS-based analysis, such as the monitoring of third-party interference (TPI) along oil and gas pipelines. Displacement anomalies will appear out of place if not duly corrected, leading to erroneous assessments of possible hazards. The result after applying Range-Doppler terrain correction is shown in Fig. 11. The displacement map was exported to ArcGIS Pro 3.1.0 as shown in Fig.12 and overlaid on the area of interest polygon (shape file)

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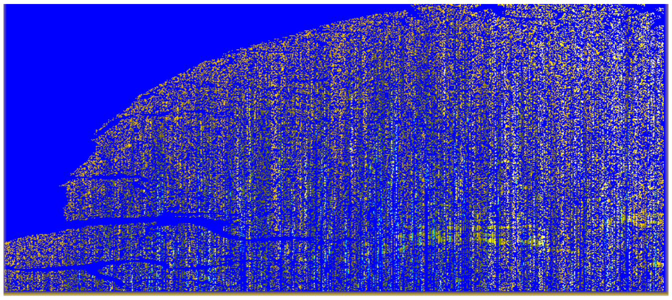

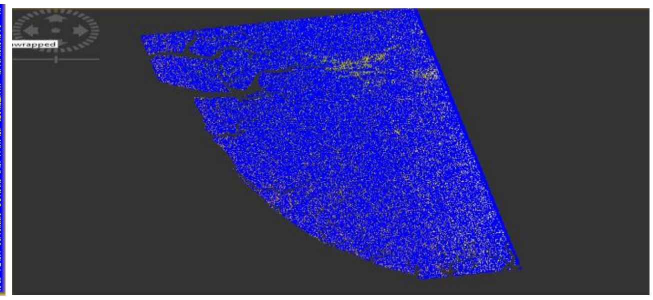

Fig. 10 Displacement map Fig.11 Terrain Corrected Displacement map

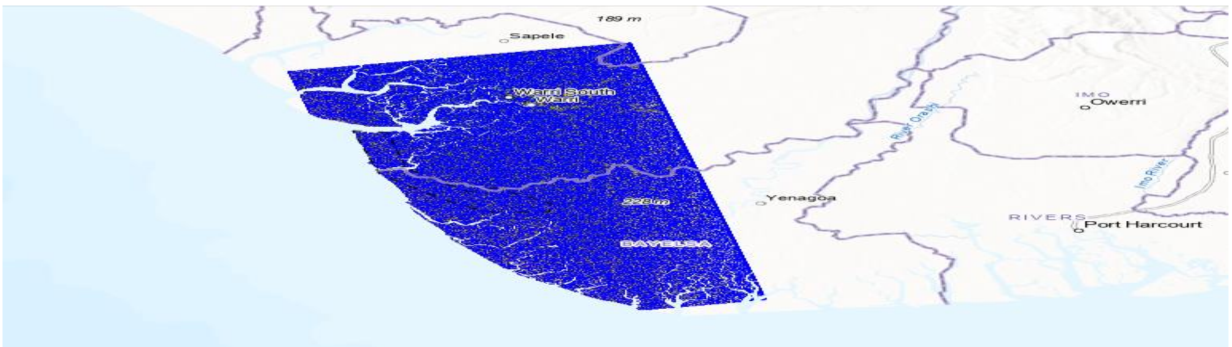

Fig 12. Area of interest polygon overlaid on Displacement map

The pipeline shape file was overlaid on the displacement map so that we can focus on displacements along or close to the pipeline infrastructure alone.

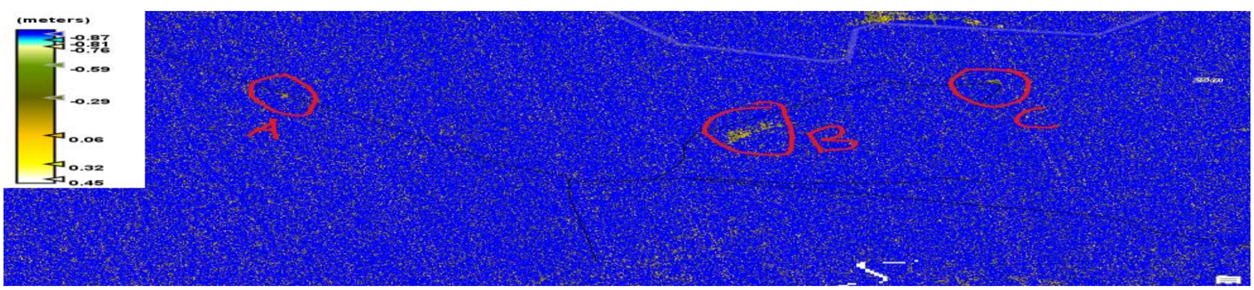

Fig 13. Zoomed-in section of the displacement map showing potential TPI points

Based on the color scale in the legend above, displacement values range from approximately -0.87 meters to 0.45 meters, with the following key observations: Blue Areas (-0.87 to -0.59 meters) indicate subsidence (negative displacement), which could result from soil compaction, illegal excavation, or pipeline leakage leading to ground instability, Large, localized clusters of deep blue values may be potential indicators of TPI activities like unauthorized digging or pipeline tapping, Yellow to Light Green Areas (-0.29 to 0.06 meters) represent minimal displacement and are generally within the normal range of ground stability. These areas are less likely to be associated with significant third-party interference. White to Light Brown Areas (0.32 to 0.45 meters) indicate uplift (positive displacement), possibly caused by underground pressure changes, soil expansion, or illicit construction activities. If detected along or around a pipeline corridor, uplift might be due to "spoil" or "excavated material", overburden, muck or stockpile which could be indicators of TPI activities. Both uplift and subsidence are indicators of third-party interference on pipelines. However, the displacement map shows an almost entire blue colour suggesting large-scale subsidence. Fig. 13 shows potential TPI areas (areas in red marker) that have uplift about 0.32m. Stress on uplift reduces the misinterpretation of atmospheric noise as actual subsidence, thus leading

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to a more regulated and uniform analysis with 0.81 and 0.87 meters. When the uplift points: A, B and C were checked it showed the folloeing coordinates (Table-5).

Table-5 Coordinates of Points of interest (POI)

Location	Easting	Northing
A	783,365.61	552,560.25
B	792,769.66	550,674.20
C	798,034.89	553,372.30

When these POI were verified against ground truth – TPI incidents record by the Operator (SPDC), it was found that there was a recorded pipeline leak incidence very close to location B coordinates on 4th of May, 2024. This location corresponds to Peretourugbene with coordinates 792,290.00E 550,836.00N. This result shows the application of DInSAR as a veritable tool in pipeline leak detection and prevention.

CONCLUSION

This work focused in verifying the application of Synthetic Aperture Radar (SAR) interferometry to detect potential areas of third-party interference (TPI) in oil and gas pipeline systems within Nigeria. The research used the detection of displacement maps from interferometric phase measurements to identify unauthorized activity anomalies along pipeline routes. This study has succeeded in verifying the application of Synthetic Aperture Radar (SAR) interferometry to detect potential areas of third-party interference (TPI) in oil and gas pipeline systems within Nigeria. The research used the detection of displacement maps from interferometric phase measurements to identify unauthorized activity anomalies along pipeline routes. The findings prove the applicability of remote sensing techniques in identifying minimal ground movements associated with tampering, vandalism, and unauthorized tapping on oil and gas pipelines. The study emphasizes the limitations of traditional monitoring systems that are mostly ground-based and sensor-based, typically being inadequate in terms of coverage and response times. Based on Interferometric SAR (DInSAR) technologies, the study demonstrates a low-cost, scalable approach to improved pipeline monitoring and risk management. The study sets forth that TPI events induce surface displacements that are detectable and measurable, which can be systematically detected and processed to facilitate preventive intervention.

CONFLICT OF INTEREST

There is no conflict of interest

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