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Application of Interferometric Synthetic Aperture Radar (InSAR) Technique in Monitoring the Deformation of Large Oil Storage Tanks

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***Abstract* — This paper proposes an approach for monitoring the deformation of large oil storage tanks using Interferometric Synthetic Aperture Radar (InSAR) technique. The aim is to proffer a solution that tackles the challenge of oil spillage due to failure of oil storage tanks. Failure of large oil storage tanks could be fatal leading to loss of lives and property, pollution of aquatic lives, lawsuits amongst others. Periodic monitoring of these engineering structures is necessary to ascertain the health of these structures and to detect if there are any significant displacements from their insitu design. The study area is Forcados, Warri, Delta State, Nigeria. Satellite images used were acquired from the European Space Agency (ESA) Sentinel-1 Synthetic Aperture Radar (SAR) satellite hub between March 2016 and March 2017. Small Baseline Subset Differential Interferometric Synthetic Aperture Radar (SBAS-DInSAR) technique was combined with an Object-Based Image Analysis (OBIA) procedure to detect and validate deformation measurements on a crude oil storage tank. We illustrate the validation analysis using one (tank 7), out of ten tanks within the study area. The results show that the horizontal distortions of the circular cross-section of tank 7 is within a range of -3.131mm and -29.669mm. Our effort proffers a practical and economic solution to a major challenge of engineering geodesy and most important petroleum provinces in the world.**

***Index Terms* — Deformation, Distortion, Differential Synthetic Aperture Radar (DInSAR), Oil Storage Tanks.**

I. Introduction

The failure of large storage oil tanks is always fatal and as such, the safety of oil tanks and their contents are of concern to the petroleum refinery industries [1]. The integrity of these tanks could be compromised by any slight change in shape and area of these tanks. Large storage tanks in refineries and oil farms habour large volume of flammable and hazardous chemicals. Any failure usually leads to environmental degradation, economic loss, public health and safety jeopardy, law suits among others [2]. In Nigeria, cases of oil spills has been on the increase in ever since the discovery of crude oil in Oloibiri, Bayelsa State in 1956 [3]. It has been observed that there was a total number of 784 oil spill incidents between 1976 and 1980 which resulted in the loss of 1,336,875 barrels of oil [1]. Similarly, the oil disaster that occurred in 1970 in Rivers State was one of the worst environmental disasters on record [4]. The spillage involved Texaco Oil Company and over 40,000 barrels of oil spread through the Delta region polluting about 1,200km^2 in area. This covered a total of 321 villages with a population of 320,000 being affected by the oil spill. In this disaster, about 180 people died while 300 persons contacted various illnesses through drinking polluted water and eating contaminated food [1,2].

Previous studies undertaken on the causes of oil spill in Nigeria between 1970 and 1998 recorded that more oil spills have been caused by failure in storage facilities than by sabotage [2]. Steel oil storage tanks especially those that are 15 to 20 years old are at significant risk due to tank age, location, condition of storage, soil properties and other factors. In addition, non-uniform settlement of tanks foundations, loading and offloading of oil and temperature of the crude will cause stress for tanks membrane and settlement of sediments [1]. These tanks therefore tend to undergo radial deformation. Despite these risks, these oil storage tanks are continuously used to store crude oil, which is the major source of income to the Nigerian economy [1,4]. Due to global warming, and sea level rise, associated with storm surge, persistent concerns have been drawn to the structural deformation of these oil tanks [5]. In addition, due to poor monitoring, inspection and maintenance practices the possibilities of these tanks failing is very high [4]. To forestall the grave consequences of tank failure, early detection of possible structural damage is critical; hence, the need for a reliable methodology for routine structural deformation monitoring.

In the past, Geodetic Measurements, Photogrammetry and Laser Scanning (ALS) Techniques have all been employed [6]. However, these methods are costly, time consuming, rigorous and needs to be critically interpreted in order to achieve desired results [7]. Moreover, the formulation of the mathematical models (for geodetic technique), that will reveal the characteristics of the deformation is a major problem of engineering geodesy [3,4]. With recent incoming of satellite constellations, delivering high-resolution SAR images, (eg. Sentinel-1 satellite remote sensors), new possibilities for Differential Interferometric SAR (DInSAR) applications have become open to detect surface changes with

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fine spatial details and with a short revisiting time [8,9].

This research was therefore aimed at developing a reliable and robust, cost effective methodology for monitoring the radial displacements of large oil storage tanks using DInSAR technique and to ascertain their health status. Our approach leverages on the opportunity presented by Sentinel-1 SAR satellites to addresses the shortfalls of traditional geodetic methods. We proffer a solution that tackles the challenge of oil spillage in Nigeria due to failure of large oil storage tanks and other engineering facilities. The processing technologies applied was the Small BAseline Subset - Differential Interferometric Synthetic Aperture Radar (SBAS-DInSAR) and Geographic Object Based Image Analysis (GEOBIA) Techniques. Our efforts provides a sustainable solution which tackles a critical challenge in the Nigerian oil sector, by reducing the cost, rigors and time constraints of existing traditional techniques.

II. STUDY AREA

The study area is Forcados located in Warri South Local Government Area, Delta State, Nigeria. It lies between latitude 5˚ 20’ 56’’N, longitude 5˚ 20’ 32’’E and latitude 5˚ 20’ 01’’N, longitude 5˚ 21’ 30’’E. It is located at about 120km South East of Lagos Communities such as; Ugborodu, Ogidigben, Jala, Madagho and Ajidubu. Forcados is one of the most important petroleum provinces in the world and as a result, the area has been under intense study. It plays host to two major Trans National Companies; Shell and Chevron. Shell has three flow stations in Escravos namely; Sagara, Otumara and Ogidigben while Chevron has its flow Station offshore. The surrounding Escravos River is characterized by strong wave activity and tidal currents. Soil formation and plant growth on beach ridge is prevalent. The prevalent mangrove marshy swamp and criss-crossing creeks impose obvious difficulties in assessing the pipeline route.

A. Primary Data

The primary dataset used in this research is from the Copernicus Sentinel-1 Earth Observation Satellite SAR Data Archives. Terrain Observation with Progressive Scans SAR (TOPSAR), Single Look Complex (SLC) Sentinel 1 SAR images were acquired on the 11th of March 2016 and 6th of March 2017. The size of each image was about 4.6 GB, making a total of approximately 9.3 GB for both images used. (Fig 1B).

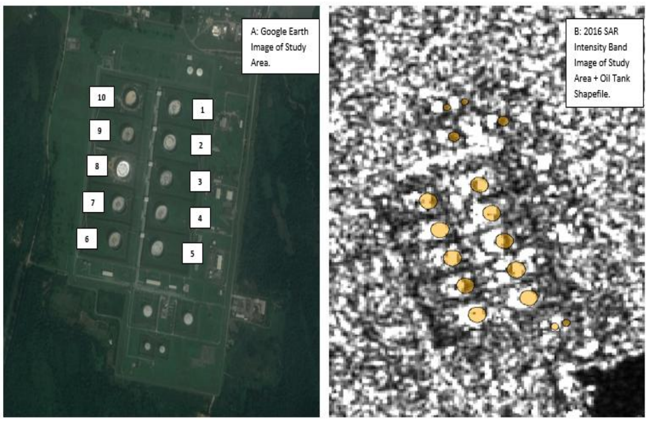

Figure 1: Showing (A) Study Area (source: Google Earth) and (B) Sentinel-1 SLC SAR data with reference shapefile of oil tanks.

B. Validation

Validation of the deformation velocity results was done using an Object-based Image Analysis (OBIA) approach to determine the existential accuracy assessment within the oil storage tanks. A secondary reference data is required to implement object based accuracy assessment and validation of the final deformation result based on our objectives. The reference data was acquired from (1) traditional geodetic (X,Y,Z) field measurements of STUD locations on the storage tanks using a reflectorless total station instrument and (2) vector shapefile derived from digitizing the oil storage tanks from 2m high-resolution Google Earth image of the study area.

The accuracy assessment measure applied in this research to validate the deformation results is ***existential accuracy assessment*** [11,12,13]. This is an *object level validation of the oil tank deformation, which* is of interest in our study. The existential accuracy helps to ascertain the presence of the deformation (if they exist or not) within the oil tanks. Two accuracy indicators were estimated that concerns the existence of deformation within the oil tanks;

i. **True positives (TP)** – This is where deformation exist in the polygon reference layer (*shapefile of oil tanks).*

ii. **False negatives (FN)** – This is where there is failure to identify deformation in the polygon reference layer (*shapefile of oil tanks).*

Note: False positives (this concerns improper detection of deformation which does not exist in the polygon reference layer), was ignored because our interest was on deformation within the tanks. Hence, we generated our reference from standalone tanks. Any attempt to compute the false positives will give a bias result (Figure 2).

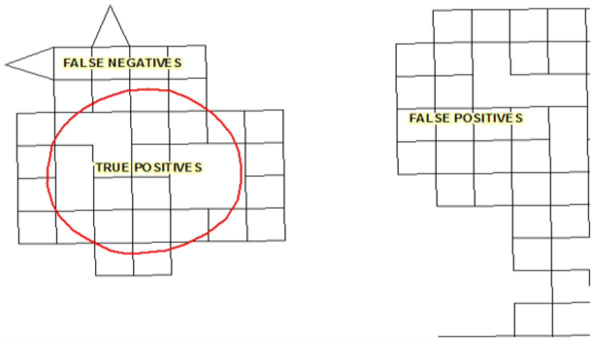

Figure 2: Example of OBIA existential accuracy measure to determine the existence of deformation within the oil tanks.

III. METHODOLOGY

The methodology for deriving deformation measurements on crude oil storage tanks was developed in six different phases as follows;

a) Download the Sentinel -1 SAR images of 11th March 2016 and 6th March 2017) of study area. One-year temporal variation.
b) Process the downloaded Sentinel-1 images using SBAS-DInSAR Technique.
c) Generation of horizontal deformation and time-series data based on the processed Sentinel-1 SAR images.
d) Create and import tank shapefile coordinate using 2m high-resolution Google Earth image (useful for validation).
e) Perform an Object Based Image Analysis (OBIA) for the validation and accuracy assessment of the radial deformation of circular cross-section of the tank.
f) Perform statistical regression analysis of the deformation result to identify any change in deformation pattern or trends.

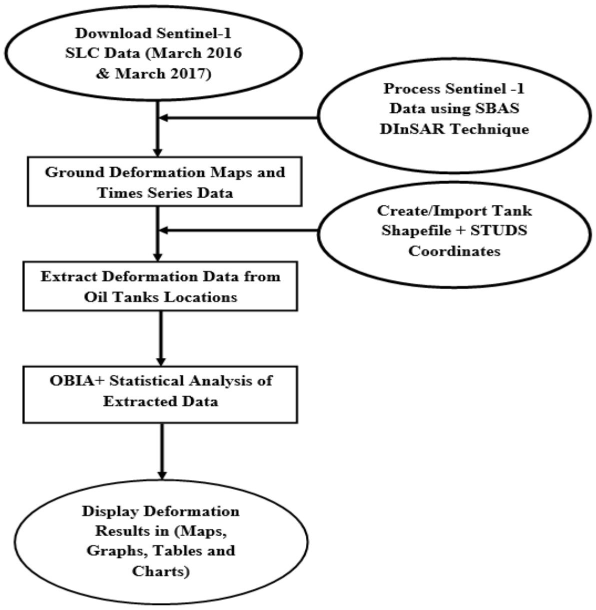

Figure 3: Showing workflow of the methodology.

C. Data Processing Using SBAS-DInSAR Technique

Among several DInSAR techniques, we adopted a parallel computing solution of [8], the Small-Baseline Subset (SBAS-DInSAR), for the processing of the Sentinel-1 SAR images.

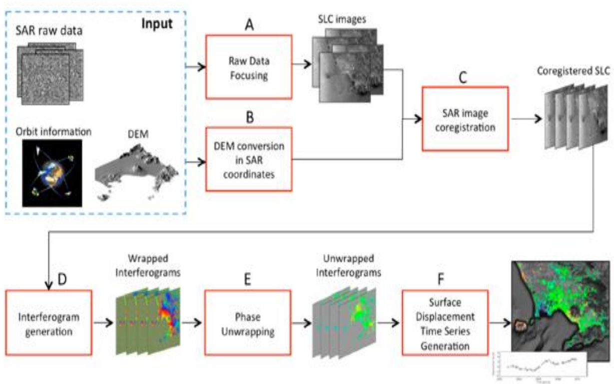

Figure 4: The supervised implementation of the SBAS-DInSAR processing chain (source: [8]).

The technique is an advanced DInSAR processing chain for the generation of Earth deformation time series (TS) along the satellite line of sight (LOS) and the estimation, with millimetric accuracy, of the mean yearly velocity maps (in mm/yr) [8].

According to [8], inputs of the SBAS-DInSAR workflow are the SAR raw data acquired by the satellite along time over the same region and from the same look angle (same acquisition geometry), together with the orbital information indicating the position of the satellite during the acquisition time, and the Digital Elevation Model (DEM) of the investigated area. The SAR raw data undergo (Block A of Figure 4) a specific processing (SAR focusing) to be converted in the corresponding radar image, referred to as Single Look Complex (SLC). As complex entities, SLCs are constituted by amplitude and phase, the latter being at the base of the SAR interferometric process. All the SLCs have to be referred to the same spatial grid (master) to allow the correct combination of the phase contributions associated to each pixel of every image. This operation, referred to as co-registration, is carried out through a geometric considerations based on the satellite orbital information and the topography of the area (DEM). Therefore, the DEM has to be properly converted into the SAR geometry (Block B of Figure 4) to be correctly exploited within the subsequent co-registration step (Block C). Once co-registered, the SLCs can be coupled in the so-called interferometric pairs, which are selected, among all the possible couples, according to a minimum baseline criterion (being the spatial and temporal baselines the orbital and time separations between two SAR images, respectively). From such image pairs, the differential interferometric phase (interferogram) is then extracted. It has been demonstrated that such phase difference is directly related to the ground displacement occurred in the time span between the two SAR images [13]. The phase difference known as (wrapped phase), needs to be unwrapped to retrieve its full evolution. Such operation, referred to as phase unwrapping, is carried out in block E by applying the Extended Minimum Cost Flow (EMCF) phase unwrapping algorithm [8,13]. On the unwrapped interferograms a procedure to estimate the residual topography phase component due to possible DEM errors is carried out. This operation is carried out through a least square approach [13]. The residual topography estimation step precedes the final retrieval of the displacement time series (Block F), which is carried out at a pixel level. Here, the number of SAR acquisition used for the interferometric analysis corresponds to phase velocities between time adjacent acquisitions. In general, DInSAR processing requires some skilled user interventions and evaluations to increase the quality and reliability of generated DInSAR results [8,13].

D. Geographic Object-Based Image Analysis (GEOBIA)

The concept of Geographic Object-Based Image Analysis (GEOBIA) has evolved and widely suggested as probably one of the ways to handle the limitations and challenges of pixel based image analysis [14]. GEOBIA builds on older techniques of remote sensing image analysis such as segmentation, feature extraction and edge detection. In this process, remote sensing imageries or thematic outputs are partitioned into regions or objects and subsequently their characteristics are analyzed at various scales [14]. This technique takes cognizance of the temporal, spectral and spatial characteristics of objects during processing while also providing the ability to query and link individual objects [15]. When applying object based image analysis, the image-object is the central methodological element and the object of investigation, therefore image context is well documented for object recognition [16]. This is very useful in overcoming ambiguities caused by limited evidence during classification. Where spectral properties are not unique, but shape and neighborhood relations are distinct, GEOBIA technique is very useful in capturing reliable information [17].

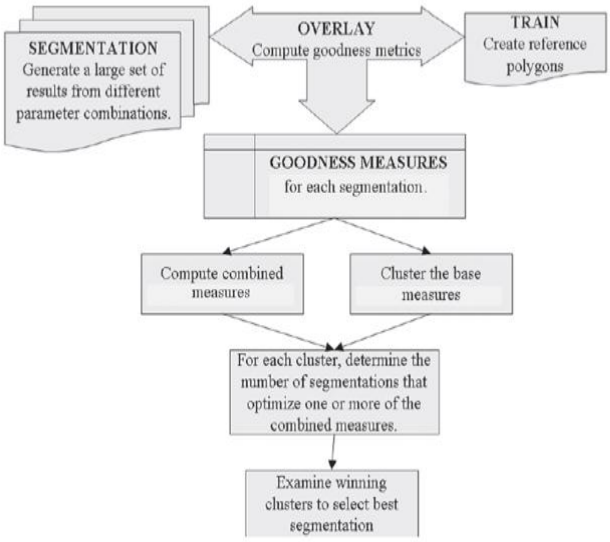

Figure 5: The supervised implementation of the GEOBIA technique (source: [14]).

The major aim of GEOBIA is to incorporate the concept of human visual interpretation of objects during or after classification to obtain more accurate representation that will result in increased repeatability, while reducing labour subjectivity and time cost [14]. Image segmentation plays an important role in GEOBIA where features are extracted with respect to their various characteristics to distinguish one region from another.

IV. RESULTS

Ten tanks (Figure 1A) were within the study area; however, we limited our validation analysis to just tank seven (7) for the purpose of this research. Results includes, horizontal deformation velocity map (millimeters), coherence image map, segmentation results and time series plot showing trend comparison between our deformation results using (DInSAR) with the traditional geodetic insitu measurements.

E. Horizontal Deformation Results

The horizontal deformation maps for every InSAR pair was derived after the conversion from the residual phase correction, phase to deformation (Figure 4), masking area of low coherence, and geo-coding the products to have absolute geographical coordinates.

Figure 6: The horizontal deformation map of displayed on Google Earth.

Figure 6 and 7, shows that some tanks have been affected by deformation, while some others may have not been affected. The range of deformation is between (-41.76 mm – 2.04 mm). According to the amount of deformation within each pair, the displacement is classified with three different colors (red, white, and blue), representing (high risk, medium risk, and low risk) deformations, respectively.

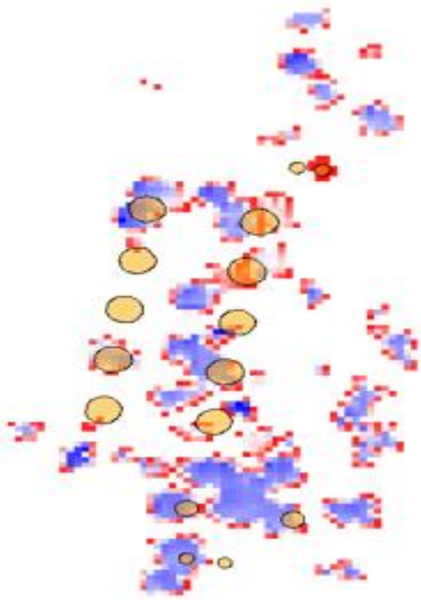

Figure 7: The horizontal deformation overlaid with shapefile of oil storage tanks.

F. Coherence Image Results

The accuracy of monitored ground subsidence values is directly related to the coherence of the subsidence zones [18]. Hence, the coherence between the reference and the secondary image is estimated as an indicator of the quality of the phase information [19]. If the images have strong similarities, they are therefore usable for interferometric processing.

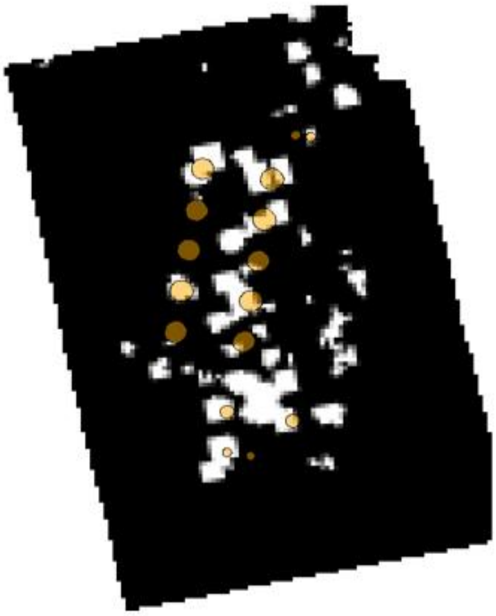

Figure 8: The coherence image of March 2016 – March 2017 overlaid with shapefile of oil storage tanks.

Figure 8, shows the coherence image of March 2016 – March 2017 ranging from 0 – 1 in intensity. The bright pixels show an intensity of 1 (deformation), while the black pixels show 0 (no deformation). About twelve tanks out of sixteen showed may have been affected by deformation.

G. Segmentation Results

Image segmentation plays an important role in GEOBIA where features are extracted with respect to their various characteristics to distinguish one region from another. In our method, the deformation map results, was partitioned into raster objects (segments) using region growing segmentation algorithm as a post classification procedure (Figure 9).

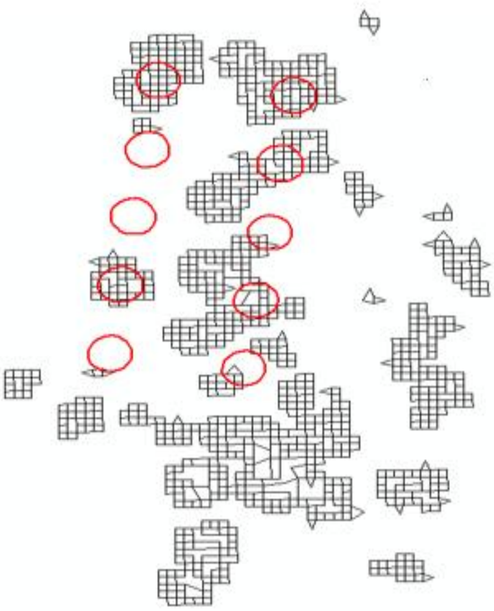

Figure 9: Segmented deformation image overlaid with shapefile of crude oil storage tanks.

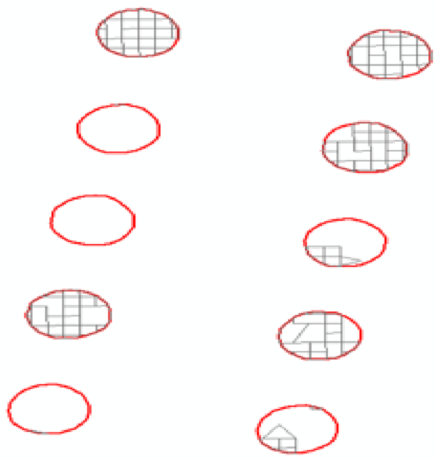

Figure 10: True positives segmented deformation image overlaid with shapefile of crude oil storage tanks

The segmented deformation image of the study area (Figure 9) was clipped to eliminate the false positives and retain the true positives (Figure 10). The resulting thematic object was analyzed for existential accuracy.

H. Extraction of Deformation Values

The XYZ survey points observed from STUD located on the oil storage tanks was imported and used to extract the deformation values from the DInSAR processed image. Thus verifying the observation points (STUD) along the monitoring results of the deformation image (Figure 11). These extracted deformation values was used for statistical analysis.

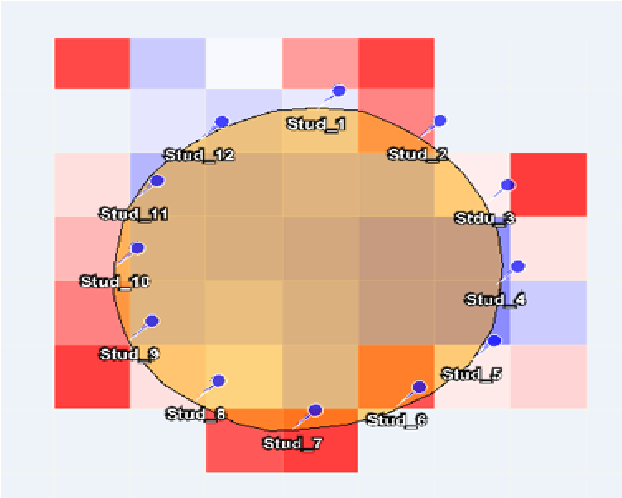

Figure 11: Deformation image of Tank 7 with STUD (12) around the crude oil storage tanks.

Figure 12 shows the bubble plot result of the extracted deformation values of Tank 7. The deformation values ranges from (-29.669mm to -3.131mm). The size of the bubble differentiates the level of deformation from one STUD to another. Figure 13 shows the deformation values of traditional geodetic X,Y,Z deformation measurements. Similarly, deformation values ranges from (-129.254mm to -122.6mm). Also, the size of the bubble differentiates the level of deformation from one STUD to another.

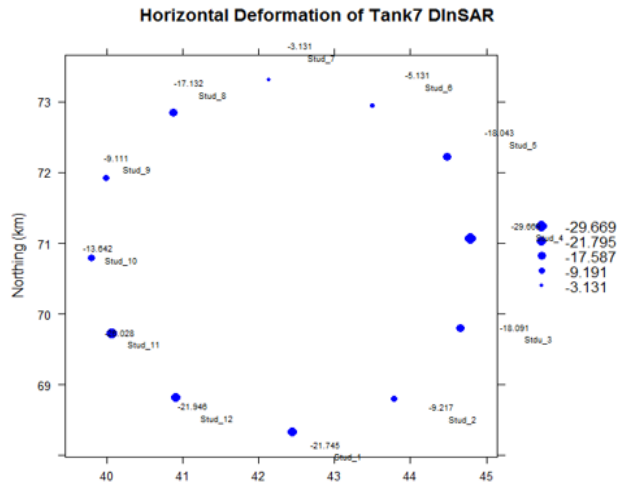

Figure 12: Bubble plot of extracted deformation values on STUD locations on Tank 7using DInSAR technique.

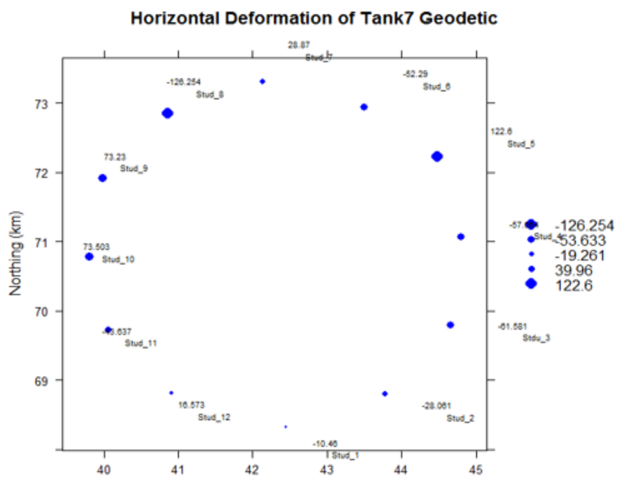

Figure 13: Bubble plot of extracted deformation values on STUD locations on Tank 7 using traditional geodetic technique.

Table1: Summary of accuracy assessment of the ten oil storage tanks within the study area.

Tanks	% True Positives	% False Positives	Tank Status
1	95.846	4.154	Deformed
2	86.155	13.845	Deformed
3	20.712	79.287	Deformed
4	88.521	11.479	Deformed
5	21.633	78.367	Deformed
6	0.513	99.487	Deformed
7	69.235	30.765	Deformed
8	0	100	Not Deformed
9	0.037	99.963	Deformed
10	95.433	4.566	Deformed

I. Statistical Analysis Results

Statistical analysis was performed using linear regression. Linear regression tests for the relationship between the extracted deformation results from DInSAR technique and the measures or computed deformation results from traditional geodetic technique.

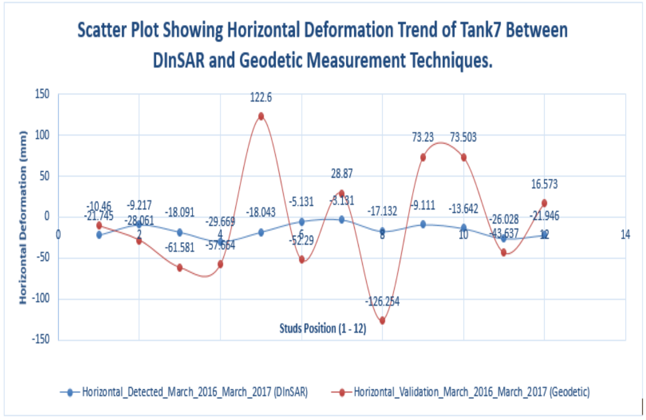

Figure 14: Statistical correlation plot of extracted deformation values on STUD locations using DInSAR and traditional geodetic technique.

V. DISCUSSION

The results presented in Figure 7, show that Tanks 1-7 and 10 experienced total deformation, Tank 9 experienced little deformation while Tanks 8 obviously did not experience any deformation. The reason for not experiencing deformation in tank 8 is that it was empty and not in use between the period of study. Furthermore, the coherence image shown in Figure 9 clearly supports this undergoing deformation. The bright pixels show an intensity of 1 and the black pixels show an intensity of 0. The bright pixels also show the areas of deformation while the black pixels show no deformation. Clearly, some tanks fall into the white pixels (showing deformation), while some tanks fall into the black pixels (showing no deformation). The summary of the accuracy assessment further confirms in Table 1, radial displacement throughout the observation period at varying rates and reveal a shift in the location of the maximum deformation magnitude. The observed subsidence is likely to be influenced by recent global warming, and sea level rise, associated with storm surge [4,18]. In addition, non-uniform settlement of tanks foundations, loading and offloading of oil and temperature of the crude will cause stress for tanks membrane [1]. Also due to poor monitoring, inspection and maintenance practices, the dissolution of the tank substrate by soluble sediments may likely lead to deformation [1,3]. Figure 11 shows the horizontal deformation map with STUDS (1 – 12) around the crude oil tank 7. This was used to extract values of deformation.

Fig 12 shows the horizontal deformation plot from Studs around Tank 7 using our method (DInSAR). The deformation values ranges from (-29.669mm - -3.131mm). The size of the bubbles differentiates the deformation on one Stud from another. Figure 13 shows the horizontal deformation plot from Studs around Tank 7 using geodetic methods. The deformation values ranges from -126.254mm to 122.6mm. Similarly, the size of the bubbles differentiates the deformation on one stud from another. However, though some of the tanks experienced deformation, none of the tanks should be put out of use because the deformation is still within safety limits according to American Petroleum Insitu (API) Standards.

Figure 14, shows a non-uniform correlation between the DInSAR and traditional geodetic measurement. Both estimated DInSAR deformation is in the LOS direction of the SAR satellite and the geodetic is in reference to the GPS position [20]. The fluctuation in vector direction (both DInSAR and geodetic) is as a result of changes in pressure due to the variation in oil level [4,21]. The DInSAR deformation trend is gradual which represents in reality the expected deformation pattern in oil storage tanks (except in extreme cases of external pressure). The geodetic deformation trend is irregular and doesn't represent in reality the expected deformation pattern in oil storage tanks (it shows extreme external pressure which is rare) [3,22]. The error in geodetic deformation trend may be due to complexities in mathematical model used to derive the results (this is still a huge challenge in engineering geodesy). The regression analysis suggests that the horizontal distortions of the circular cross-section of tank 7 is deforming at a maximum LOS range of -3.131mm and -29.669mm per year for DInSAR and -126.254mm to 122.6mm per year for traditional geodetic method [23,24].

VI. Conclusion

Failure of large oil storage tanks are usually fatal leading to loss of money, lives and property, pollution of aquatic lives, law suits amongst others. In this study, we demonstrated a methodology for periodic monitoring of these engineering structures and ascertain its health as well as the significant displacements from their insitu design. Our approach addresses the shortfalls of traditional geodetic methods for measuring oil storage tank deformations by reducing the cost, rigors and time constraints. It also proffers a solution that tackles the challenge of oil spillage in Nigeria due to failure of large oil storage tanks and other engineering facilities through systematic monitoring. Although a detailed structural deformation of the observed deformation is not the primary goal of this paper, the simplified approach (supplementary information) does show the ability of to observe the radial horizontal circular distortion in crude oil storage tanks. Thus, this cost effective solution, which show a great improvement than the traditional geodetic approach, will tackle a critical challenge in Nigeria oil sector and reduce global warming due to oil pollutions. It will also be effective and useful for safety management of these oil tanks especially in developing countries with fewer resources.

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