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Satellite Radar Altimetry-based Significant Wave Heigh Monitoring of some proposed Jetties in Nigeria Coastal Waters

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Abstract: There are various methods and measuring devices for wave heights estimation, namely, radar altimeters, pitch and roll buoys, step gauges, capacity wires, pressure cells, amongst others. Satellite radar altimetry approach has the greater advantages of the capability of collecting wave information at single-multiple points and multi-temporal synoptic view of wave fields at relatively cheaper costs in comparison to the traditional in-situ point measurements. For the reason of guidance and safety of shipping traffic and stability of structures, jetty sites require sufficient predictable knowledge of in-situ significant wave heights (SWH). This study therefore attempts the near-real time (NRT) monitoring of the Significant Wave Height of selected proposed jetties in the Nigeria coastal waters from satellite radar altimetry. Six (6) proposed jetty sites were investigated; three exists in Lagos area (UWWS, NNS-B and TBC) and two in Delta State (FOB-E and Forcados), and one in Bayelsa State (Akassa-Bight of Bonny). The daily/monthly NRT significant wave heights datasets from the global 1/8o x 1/8o multi-mission satellite altimetry for the period of 14 September, 2009 to 10th October. 2017 were used. The datasets were processed through the LAS 7./Ferret 6.72 interactive software platform, and cloud computing facilities and visualisation. The average SWHs results showed that, FOB-E in Delta State had the highest mean SWH of 1.291067m, while ABB in Bayelsa State recorded the lowest average value of 1.24858m. Forcados in Delta State had a mean SWH of 1.255214m for the period of study. The NNS-B, TBC and UWWS stations in Lagos area recorded mean SWHs of 1.286403m, 1.286858m, and 1.287545m respectively. The 8-year analysis of the SWHs generally showed relative closeness and low SWHs across the stations. From these results, the SWHs estimated in this study are considered to be within a steady and safe threshold for relevant coastal structure installation and management in the study area. The study concluded that, the magnitude of SWHs estimated in this study does not constitute significant hazard and risk to the siting of jetties in the proposed locations.

***Keywords:** Satellite Radar Altimetry, Significant Wave Height, Jetties, Coastal Waters*

1. Introduction

Accurate Ocean wave information is important for guidance and safety of shipping traffic, establishment of design criteria for coastal engineering and defences, morphological investigations, weather forecasting, fishing and even tourism (Vogelzang, et al., 2000; ESA, 2011; Bonnet, 2015). Wave height and frequency are largely dependent on the speed and strength of the wind moving across ocean surface.

Waves are formed by wind blowing along the water's surface. Wave height is dependent on: (a) wind speed; (b) fetch length; and (c) duration of time the wind blows consistently over the fetch (Ainsworth, 2006). *Significant wave height (SWH) is an average measurement of the largest 33% of waves,* and it is more relevant than small waves in many applications of wave data, such as beach erosion, safety of coastal engineering infrastructure, navigation route planning, fishing, etc.

The wave spectrum is literally made up of thousands of interacting waves rolling on each other. Significant wave height (H_s) is defined as the average height of the *highest one-third waves* in a wave spectrum (Ainsworth, 2006; Zhang and Moore, 2015). The concept of *"highest one-third waves"* in a wave spectrum means that, in a wave water surface there are thousands of interacting waves that originated in different places and traveled in different directions at different speeds, whose filtered and averaged spectrum and distribution plot on a graph with different heights would result in a *"bell curve"* graph similar to figure 1.1. The highest one-third (33.3%) number of waves in this spectrum is the shaded portion on the right axis of the graph, and the average height of waves measured over a long time in th shaded group is the ***significant wave height (Hs)*** (*after* Bretschneider, 1964).

According to Bretschneider (1964), each of the dots in the figure 1.1 represents the number of waves (N) in the spectrum with a height of H. The graph shows there are relatively low number of small waves (left side of graph) and a low number of very large waves (right side of graph). The greatest number of waves (N) in this spectrum falls in the mid range of heights (centered under H_m).

Significant wave height measured by a wave buoy corresponds well to visual estimates of wave height. Most human observers tend to overestimate the real height of waves. As the significant wave height is an average of the largest waves over a recording period, some individual wave will be larger than this average. On average, about 15% of waves will equal or exceed the significant wave height, and the highest 10% of waves could be 25-30% higher than the significant wave height (https://www.weather.gov/mfl/waves)

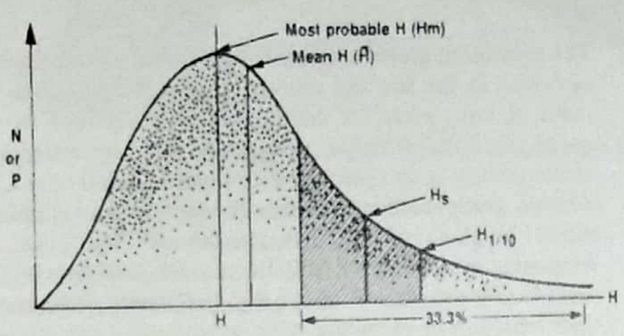


Figure 1.1: The statistical distribution of wave heights showing various parameters (Source: Bretschneider, 1964)

1.1 Statistical Wave Forecasting

The empirical relation for the fully formed waves height, which can serve as the upper limit of assessment of wave height for any wind speed has been derived (https://planetcalc.com/4442/)

$$H_f = \frac{\lambda_5 \upsilon^2}{g} \qquad 1.1$$

Where, H_f = height of the fully formed wave, λ_5 dimensionless coefficient approximately equal to 0.27, v = wind speed and g = acceleration of gravity. The magnitude of a wave is determined by three components: *height, length, and period* (or frequency). A fourth wave component is steepness. Wave height is the distance measured from the trough to the crest of the wave. Wave length is the distance between successive crests (or troughs) (Figure 1.2). Wave period is the time that elapses between the passing of successive crests (or troughs). Wind waves tend to have smaller heights and have shorter periods than swell. Wave steepness is the slope determined by the ratio between wave height and wave length. From figure 1.2, the typical ratio of wave height to wave length is about 1:7; giving a wave steepness angle of about 120°.

The extremes of a particular wave parameter represent the probability that its maximum value does not surpass a particular fixed value over return periods (González *et al.*, 2004). The most important environmental loading parameters for the design of Low Crested Coastal Structure (LCS) schemes are waves and water levels as they fully determine, together with tidal currents, the hydrodynamic load (Burcharth *et al.*, 2007).

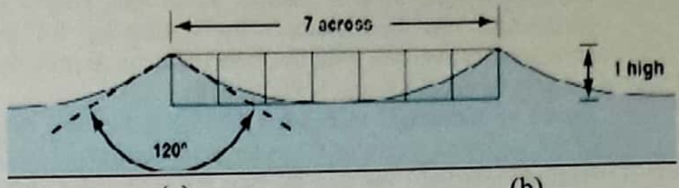


Figure 1.2: Relationship between Wave Height, Wavelength and Wave Steepness (Source: modified after Thomson Higher Education/www.slideplayer.com).

1.2 Significant Wave Height Measurement from Satellite Altimetry

The measuring and mapping of the ocean wave heights, SWH and velocity using wave echoes determined from satellite radar altimetry have become possible and convenient globally for nearly three decades. Satellite radar altimetry, is a crucial technique for observations of the ocean surface and of many aspects of land surfaces, and of paramount importance for climate and environmental studies (Stammer and Cazenave, 2017). The high level processed products, integrated data from several altimetry missions (validation, cross calibration, filtering, optimal interpolation on global grid) provides the most spatial, temporal, cost effective, accessible, timely, reliable, and robust ocean datasets and information for the understanding of the global geoid and ocean circulation, wave heights and associated dynamics compared to the traditional methods (Fu *et al.*, 1988; Ojigi *et al.*, 2016).

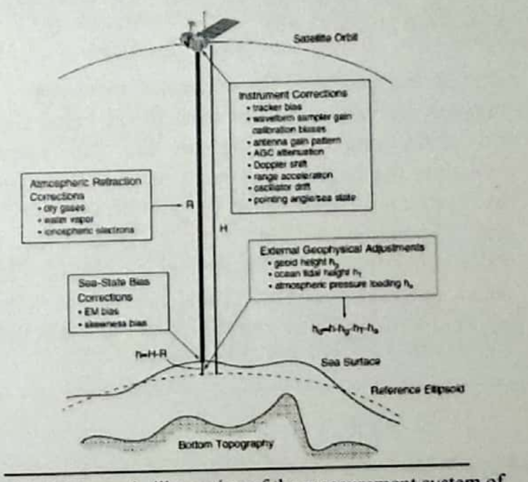


Figure 1.3: (a) Schematic illustration of the measurement system of satellite altimetry (Adapted from Chelton *et al.*, 2001)

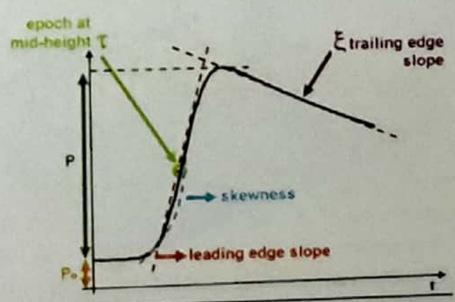


Figure 1.3: (b) Schematic illustration of Satellite Altimetry Waveform (ESA) (Adapted from Chelton et al., 2001)

Over an ocean surface, the echo waveform *(figure 1.3b)* has a characteristic shape that can be described analytically (the Brown model). From this shape, six parameters can be deduced, by comparing the real (averaged) waveform with the theoretical curve providing the best fitting (ESA and CNES (2018):

Epoch at mid-height in figure 1.3(b) gives the time delay of the expected return of the radar pulse (estimated by the tracker algorithm) and thus the time the radar pulse took to travel the satellite-surface range and back again.

P: the amplitude of the useful signal. This amplitude with respect to the emission amplitude gives the backscatter, sigma0.

P$_o$: thermal noise

leading edge slope: this can be related to the SWH

skewness: the leading edge curvature

Trailing edge slope: this is linked to any mispointing of the radar antenna (i.e. any deviation from nadir of the radar pointing). (ESA and CNES (2018)

SWH estimation is possible because the shape of an altimetric waveform, which usually presents a sharp leading edge and a slowly decaying trailing edge, depends on the sea state: in particular, the higher the sea state, the longer the rising time of the leading edge (Passaro *et al.*, 2016; ESA and CNES, 2018). The key challenges facing SWH detection from satellite altimetry are *coastal data* and *low sea states*. Traditionally, data in the coastal zone are flagged as bad or unreliable and left unused due to land and calm water interference in the altimeter footprint (Passaro *et al.*, 2016). Secondly, SWH are characterized by an extremely sharp leading edge that is consequently poorly sampled in the digitalized waveform. However, they observed that, taking a looking at the slope of the leading edge of the return pulse, the wave height can be measured (figure 1.4b).

Due to the potential for corrupted radar signal in coastal regions, the estimation of each SWH value are improved by performing retracking on the full waveform and calculate the root mean square error (rmse), and secondly by performing retracking on a subwaveform, increasing the estimation window by 1 gate each time, and calculating the rmse (Passaro *et al.*, 2016). On the other hand, relevant geophysical and instrument corrections are applied to mitigate systematic errors in SWH estimations.

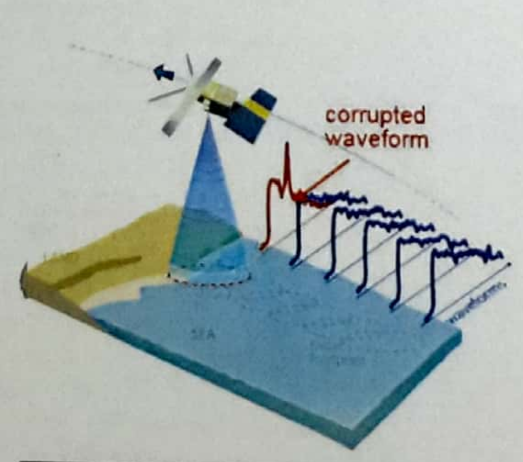


Figure 1.4: (a) Coastal Waveform (**http://www.coastalaltimetry.org/**; Passaro et al. 2016);

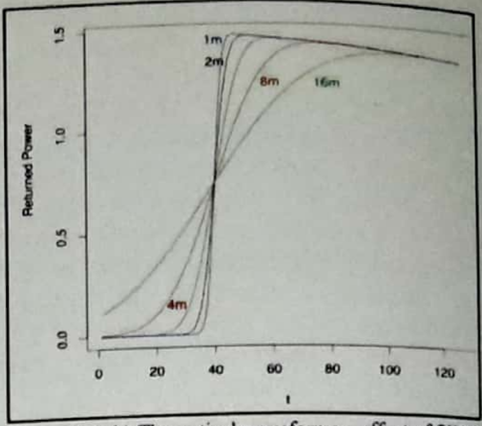


Figure 1.4: b) Theoretical waveforms – effect of SWH (modified after Passaro et al. 2016).

The prevailing global climate change-induced geodynamic activities in the sea and coastal regions of the earth, has made it imperative for continuous investigations of the geophysical variables for marine safety and environmental sustainability action plans in the Nigeria coastal area. One of such geodynamic activities is the time series significant wave heights, whose investigation is important for assessing the existence of a trend over a climatological time scale and safety of a jetty or coastal engineering infrastructure in particular. The mean values and samples of a time series significant wave heights are used to assess the existence of a trend over a climatological time interval and to determine the probability of extreme events to occur at fixed return periods (Martucci *et al.*, 2010). In determining the significant heights of the sea water, the measurement techniques and tools must be such that, does not further contributes to the sea wave motion at the point of measurements (Ojigi, 2017). Therefore, this study aims at the near-real time (NRT) monitoring of the Significant Wave Height of selected proposed jetties in the Nigeria coastal waters from satellite radar altimetry, and the objectives include:

i. Near-Real Time (NRT) Monitoring of the Significant Wave Height at some proposed jetties in the Nigeria coastal waters from the daily/monthly NRT global 1/8° x 1/8° Multi-Mission satellite altimetry data (2009-2017).

ii. Determine the extreme and average SWHs over the selected stations for the period of study.

iii. Assess the significance of the extreme and mean SWHs in the safety of coastal structure installation and management in the study area.

1.4 The Study Area

Dublin-Green *et al.*, (1999) described Nigeria's coastal region as *'low lying with heights of not more than 3.0 m above sea level'*, and generally covered by 'fresh water swamp, mangrove swamp, lagoon mashes, tidal channels, beach ridges and sand bars. The mean monthly temperature of the Nigeria coastal region varies between 24° C and 32° C throughout the year (Nwilo and Badejo, 2006). Between 1982 and 2010, the mean sea surface temperatures (SSTs) of the coastal waters of Nigeria (part of the Gulf of Guinea) for the month of January and September were about 26.654°C and 22.89

respectively, and with an annual increase rate of about 0.03°C/year (Ojigi, 2012).

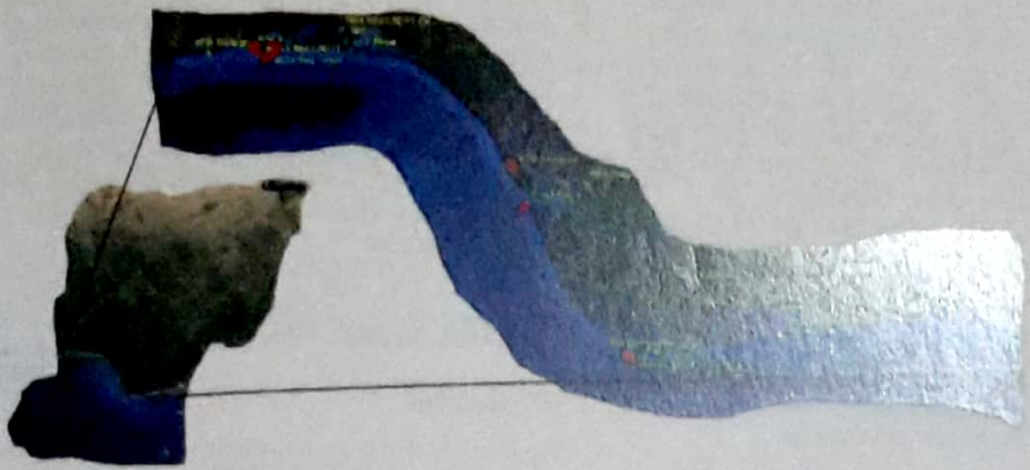


Figure 3: The Study Area (*along the Coastal Region of Nigeria*) (adapted from Ojigi, 2017)

The proposed Jetty sites (figure 3) in parts Nigeria coastal area comprised three in Lagos area [Under Water Warfare School (UWWS) *near Tin Can Island*, NNS-BEECROFT (NNS-B) at *NNS Ship Yard*, Apapa, and Takwa Bay Coast (TBC)] and Two in Delta State [FOB Escravos (FOB-E) Madangho, and Forcados Ughulagha] and one in Bayelsa State (Akassa-Bight of Bonny (ABB). The selected jetty stations are relatively of shallow water depths ranging between 5m and 10m, which may require dredging to accommodate deep draught vessels.

2.0 Materials and Methods

2.1 Datasets and Sources

The main secondary data used in this study is the multi-mission satellite altimetry Near Real Time daily/monthly 1/8° x 1/8° geostrophic velocity data provided by the French Archiving, Validation and Interpretation of the Satellite Oceanographic (AVISO) Data and the Copernicus Marine and Environment Monitoring Service (CMEMS). Table 2 shows the dataset used and their sources.

Table 2: Dataset and Sources

S/N	Data Name	Data Date	Format	Source(s)
1	Significant wave height merged (m) (SWH)	2009 - 2017	IGDR/NetCDF NRT SWH, 1/8° x 1/8° Global Merged The wave parameters were obtained by analyzing the shape and intensity of the altimeter radar beam reflected from the sea surface (radar echo).	http://marine.copernicus.eu http://las.aviso.altimetry.fr/las/getUI.do http://www.aviso.altimetry.fr/en/data.html http://ddo-aviso.vlandata.cls.fr:41080/thredds/dodsC/dataset-nrt-global-merged-mswh-latlon-switched

2.2 SWH Data Processing and Visualisation

The data sampling and processing was done interactively using the Live Access server (LAS) 7./FERRET 6.72 software platforms. Ferret is a product of NOAA's Pacific Marine Environmental Laboratory (PMEL), and an interactive computer visualization and analysis environment designed to meet the needs of oceanographers and meteorologists analyzing large and complex gridded data sets. It runs on recent Unix and Mac systems, using X windows for display (NOAA PMEL, 2015). Each station was process and visualized independently for the period of 2009-2017.

The SWH text data were exported from LAS7./Ferret 6.72 and edited to suit MS excel format. The missing data entries were identified, and removed before determining the means, and for the time series graphs, the missing entries were assign null value (zeros). The scattered plot and trend fitting were done using the MS excel sheet, plotted and mean values, and trends determined respectively.

2.3 SWH Trend Fitting

The process of fitting the data to predict the average trend of the SWH for each of the Jetty locations was achieved using a moving-average model. Moving Average (MA) is a statistical technique to get an overall idea of the trends in a data set; it is an average of any subset of numbers and it is extremely useful for forecasting long-term trends such as time series station SWH. The simple moving average (SMA) model assumes an average is a good estimator of future behavior of a phenomenon. The formula is given by (http://www.statisticshowto.com/moving-average/).

$$F_t = \frac{A_{t-1} + A_{t-2} + A_{t-3} + \ldots + A_{t-n}}{n} \qquad 2.1$$

Where F_t =Forecast for the coming period, n = number of period averaged, and A_{t-1} = actual values of the previous period for up to 'n' period. Moving average of 3 periods and 6 periods of consecutive estimates of SWH were adopted for fitting the trend line over the scattered plot of SWH of three (3) Jetty locations in the Delta and three (3) Lagos regions respectively.

The two basic and commonly used MAs are the simple moving average (SMA), which in this study is the simple average of sea surface heights over the time periods of 2009-2017. The exponential moving average (EMA), gives bigger weight to more recent values in the array of temporal data in an attempt to make it more responsive to new information.

2.4 Determining SWH Extreme Values and Threshold for Coastal Safety

The *extreme* and *mean* SWHs values at the proposed jetty locations are inherent in the sample data for the study. The extreme value theory provides analogues of the central limit theorem for the extreme values in a sample (Coles, 2001; Caires, 2011). The extreme value theory holds that, the extreme values in a large sample have an approximate distribution that is independent of the distribution of each variable, while the central limit theorem states that '*the mean* of a large number of random variables, irrespective of the distribution of each variable, is distributed approximately according to a Gaussian distribution (Caires, 2011). However, the extreme limit for safety of coastal engineering structures is a function of the purpose and design of the structure. The extreme values (upper and lower) for six (6) locations were extracted from the sample data using statistical queries.

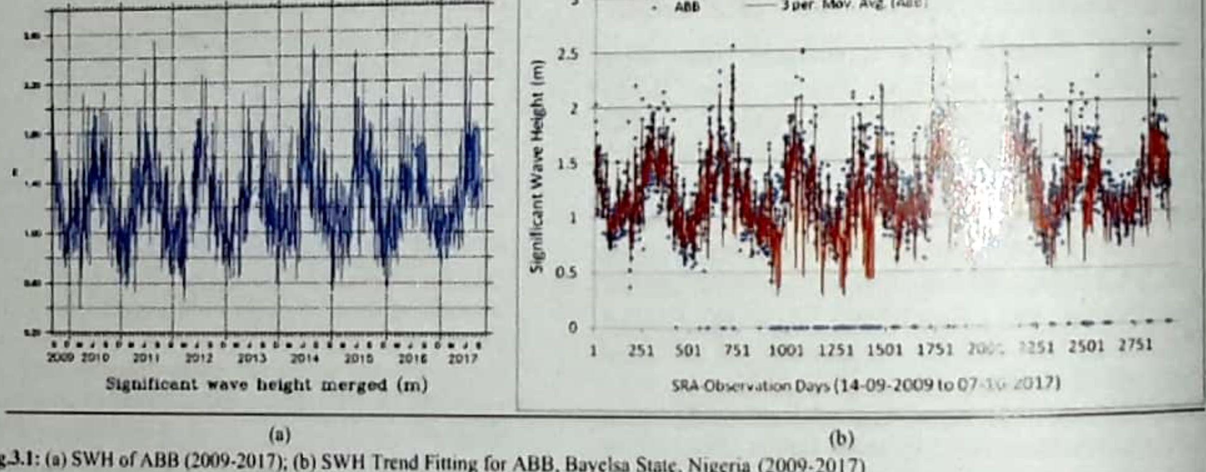
3.0 Results and Discussion

3.1 Results

Figures 3.1a and b show the time series plot of SWH for ABB (2009-2017) and the SWH moving average trend fitting for ABB, Bayelsa State, Nigeria (2009-2017) respectively. Figures 3.2a/b – Figures 3.6a/b show the respective time series plots of the SWH (2009-2017) and the corresponding SWH moving average trend fitting for other stations including *FOB-E, Forcados, NNS-B, TBC and UWWS* respectively. Table 3.1 shows the summary of the jetty locations and the significant wave height data statistics.

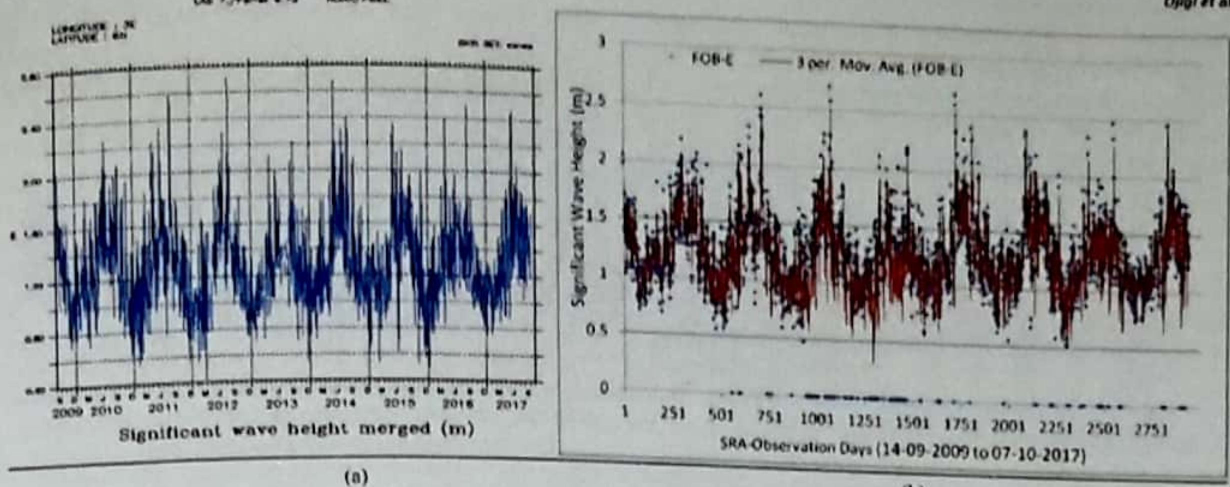
Table 3.1: Jetty Locations and SWH data Statistics

Station	Geog. Coordinates Lat.(dd)	Long.(dd)	No. of Missing Daily Data	No of Days of Daily Data	Mean SWH(m)	Extreme Values (m) upper	lower
ABB	4.247654	6.064725	153	2788	1.24858	2.742	0.37
FOB-E	5.599861	5.212889	113	2828	1.291067	2.704	0.478
Forcados	5.345702	5.301053	153	2788	1.255214	2.704	0.293
NNS-B	6.435048	3.395076	363	2578	1.286403	2.705	0.437
TBC	6.385567	3.373425	363	2578	1.286858	2.706	0.439
UWWS	6.438278	3.286250	363	2578	1.287545	2.707	0.435
			Out of Total of 2941 Days[14/09/0910/10/17				



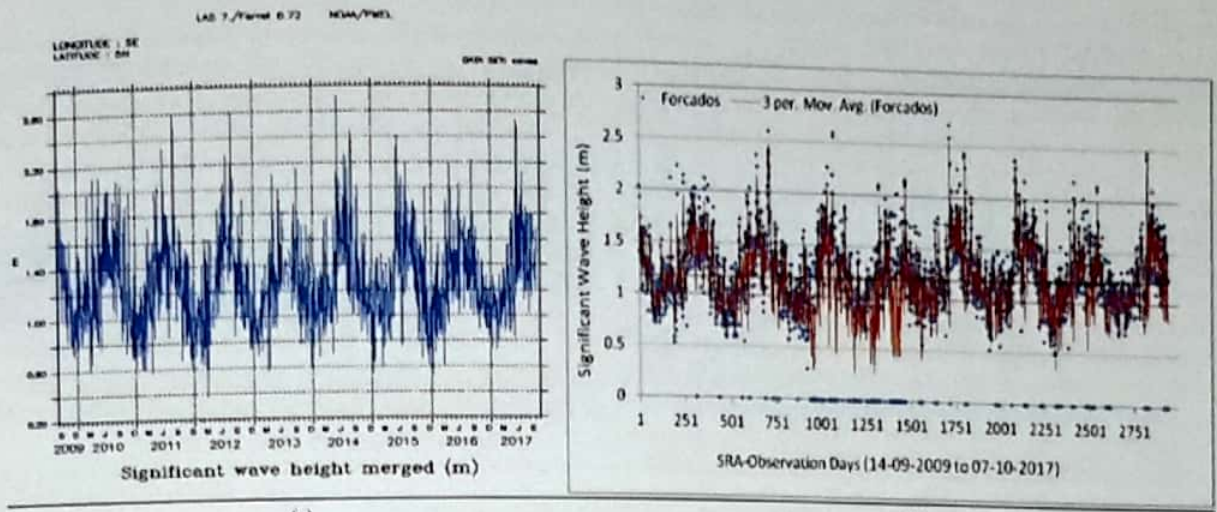
(a) (b)

Fig.3.1: (a) SWH of ABB (2009-2017); (b) SWH Trend Fitting for ABB, Bayelsa State, Nigeria (2009-2017)



(a) (b)

Fig.3. 2: (a) SWH of FOB-E (2009-2017); (b) SWH Trend Fitting for FOB-E, Delta State (2009-2017)



(a) (b)

Fig.3.3: (a) SWH of Forcados (2009-2017); (b) SWH Trend Fitting for Forcados, Delta State (2009-2017)

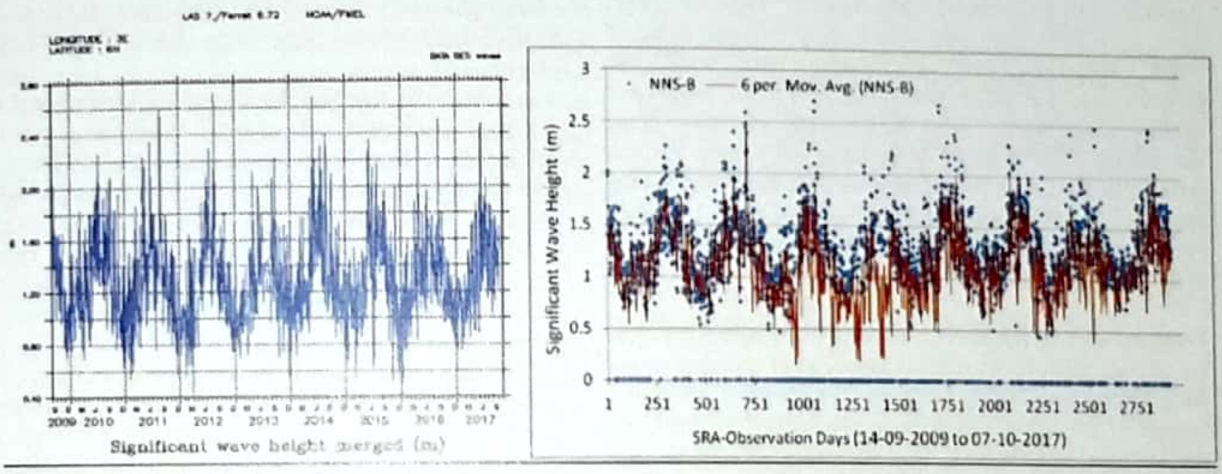
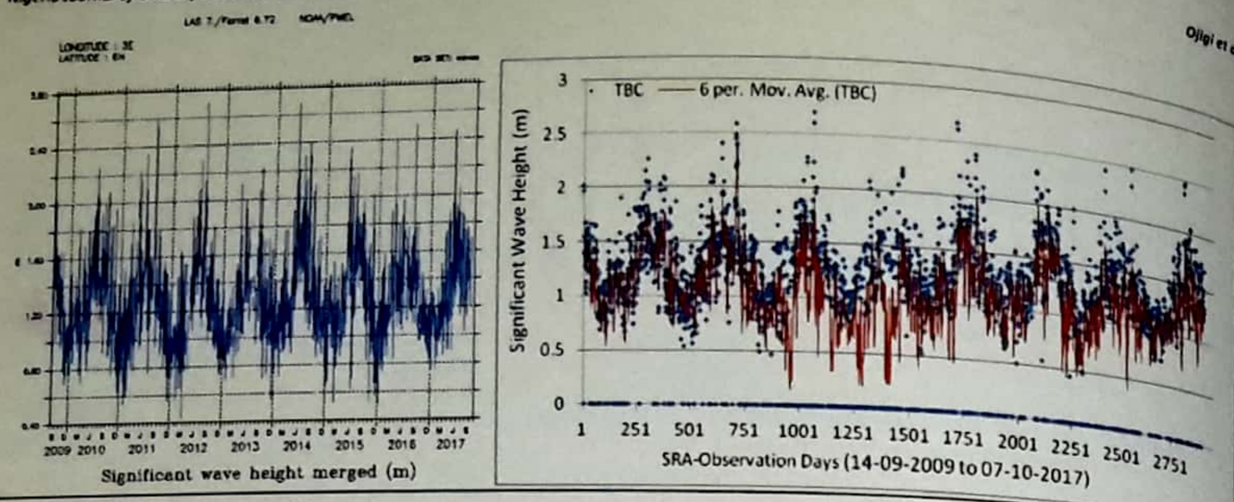
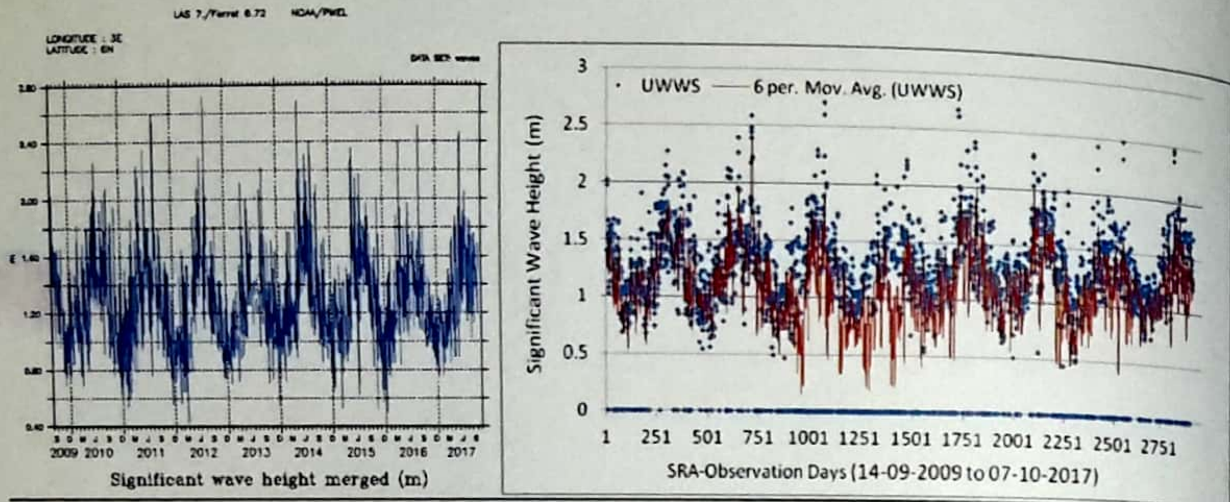


Fig. 3.4: SWH of NNS-B (2009-2017); (b) SWH Trend Fitting for NNS-B, Apapa Lagos (2009-2017)



(a) (b)

Fig.3.5: (a) SWH of TBC (2009-2017); (b) SWH Trend Fitting for TBC, Apapa Lagos (2009-2017)



(a) (b)

Fig.3.6: (a) SWH of UWWS (2009-2017); (b) SWH Trend Fitting for UWWS, Ojo-Lagos (2009-2017)

3.2 Discussion

Between 14th September, 2009 and 10th October, 2017, there were 2941 days, and with a daily average value of SWH. However, due to missing data from the observations, the daily data availability for respective stations varies slightly from the expected total 2941 in all the station. The number of missing daily data for the stations in the Lagos region was for 363, and this was the same for the three stations (NNS-B, TBC and UWWS). On the other hand, ABB and UWWS had 153 missing daily data, while TBC had 113.

From the time series plots of all the SWH (figures 3.1-3.6) for all the station, no critical absolute or extreme wave height was identified, as the annual or seasonal maximum returns of the SWH values does not exceed 2.75m in all the stations investigated. The maximum SWH for the stations was about an average of 2.7m (Table 3.1). From the time series graphs and the mean, all values were within *theoretical normal*. The suitable trend fitting model used for SWH in the six stations was the moving average model (MA). The trend predictor for the SWHs of the three (3) Jetty locations in Lagos area used 6per moving average best fit model, while 3per moving average provided the best fit model for ABB, FOB-E and Forcados. This implies that, the SWHs over NNS-B, TBC and UWWS in Lagos have less variable or differential values of consecutive observations, when compared with the SWHs at ABB, FOB-E and Forcados respectively (figures 3.1b-3.6b)

The time series mean of the datasets is most critical to the design, construction and safety of coastal structures in the selected locations. From Table 3.1, FOB-E in Delta State had the highest mean SWH of *[illegible]1067m*, while ABB in Bayelsa State recorded the lowest average value of *1.24858m*; showing differential in centimeters. Forcados in Delta State had a mean SWH of *1.255214m* for the period of study. The NNS-B, TBC and UWWS stations in Lagos area recorded mean SWHs of *1.286403m*, *1.286858m*, and *1.287545m* respectively. These values show relative closeness with differential in millimeters. From these results, the SWHs estimated in this study are considered to be within a steady and safe threshold for relevant coastal structure installation and management in the study area.

4.0 Conclusion

The study has used the daily/monthly near-real time (NRT) satellite altimetry for time series monitoring of the Significant Wave Height at selected proposed jetties in the Nigeria coastal waters from satellite radar altimetry. The six (6) proposed jetty sites were investigated; three exists in Lagos area (NNS-B and TBC and UWWS) and two in Delta State (FOB-E and Forcados), and one in Bayelsa State (Akassa-Bight of Bonny). The datasets were processed through the LAS 7./Ferret 6.72 interactive software platform, and cloud computing facilities and visualisation.

The 8-year results of the SWH generally showed relative closeness and low SWHs across the stations. From these results, the SWHs estimated in this study are considered to be within a steady and safe threshold for relevant coastal structure installation and management in the study area. The study hereby concludes that, the magnitude of SWHs estimated in this study does not constitute significant hazard and risk to the siting of jetties in the proposed locations.

This study is a valid proof that, SWH datasets is appropriate for understanding, visualizing and developing accurate ocean wave information for establishment of design criteria for coastal engineering and defences, in addition to guidance and safety of shipping traffic, morphological investigations, weather forecasting, fishing and even tourism, as observed by Vogelzang, et al., (2000); ESA, (2011) and Bonnet, (2015). However, it is hereby recommended that, the interested parties in the establishment of jetties to integrate some in-situ hydrographic investigations of the stations with the satellite altimetry-based data and results for validations prior and after the selection and installation of the Jetties.

Acknowledgements

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