Towards the Development of a Vertical Offshore Reference Surface (VORS) for Seamless Bathymetry in Nigeria

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Abstract

A vertical offshore reference surface is a unified reference surface that is able to transform different datasets from the ellipsoidal to tidal datums such as (MSL, SST, MHWS, MLWS, LAT, HAT, etc.) and bring these to a common epoch, ellipsoid (GRS 1980) and ITRF reference frame. By unifying surfaces, heights (depths) can be converted from one vertical datum to another. This research discusses the impact of developing a methodology that will enable the transformation amongst the various vertical reference surfaces to support the modelling of data across the land-sea interface in the coastal waters (12nmi) of West Africa particularly, Nigeria. A methodology for use in the Nigeria is proposed after a review of common applied models. The principal challenge to the achievement of such a separation model is the difficulty in modelling and integrating datasets across the land-sea interface. This is prominent, where a homogenous and consistent vertical datum does not exist (absence of a geoid model), lack of tide gauges data along the coastline, hydrodynamic tide model and offshore Permanent Service for Mean Sea Level (PSMSL) tide stations. This research will therefore evaluate the impact of developing a vertical offshore reference surface and proffer solution towards mitigating the inherent challenges.

(Key words: Separation model, ITRF, Vertical datum, Coastal waters and Common epoch)

1.0 Introduction

The development of separation models for vertical reference surfaces is an increasingly interesting area of research in hydrography both in the developed and third world nations. Though previous efforts in countries such as Canada, Australia, USA and the UK have set the pace for the development of operational separation models, there is the need to also create such a model in developing countries such as Nigeria and subsequent application in research. The International Federation of Surveyors (FIG) has emphasised the need for the creation of vertical reference surfaces for hydrographic surveying (FIG, 2006) that are referred to the International Terrestrial Reference Frame (ITRF) using the GRS80 ellipsoid (Altamimi, et al., 2008). The implication of this is that it will reduce cost and give high efficiency in bathymetry surveying and set the pace for the combination of data obtained over the land and sea interface.

A vertical separation model can be used to define the relationship between a chosen vertical reference surface and other existing vertical datums (FIG, 2006). The model can be used as transformation tool that simulates a seamless vertical reference surface and the differences between this surface and all other vertical datums. A seamless vertical reference surface is one that is homogenous and consistent, does not vary over time and space. The development of this homogenous surface is a vital step in the creation of a separation model (FIG, 2006). This surface, when used in the separation model, will act as a medium to facilitate the transformation from one vertical datum to another. Theoretically, vertical reference surface must be defined continuously across and throughout the land-sea interface. As such chart datums are not ideal for use as they can vary significantly in time and space. An equipotential surface would be more appropriate (Miller, et al., 2005).

2.0 Adoption of a Vertical Datum

The geoid can be considered to be a seamless reference surface that could be used worldwide. At present, accuracy in determining geoidal characteristics varies from one location to another with the poorest accuracies in the mountainous areas and open seas. As a result geoids tailor-made to fit respective countries and regions have been used as the seamless vertical reference surface for the separation model (EL-Rabbany & Adams, 2004). FIG 2006 suggests that the GRS80 ellipsoid; oriented and fixed at a particular epoch in terms of the ITRF is a seemly vertical reference surface.

In the past, bathymetric and topographic data have been collected independently for different applications and purposes. Depths are referred to chart datum while heights are referenced to land datum both of which encompasses what is now termed a vertical datum. In hydrography, vertical datum is usually referenced to a physical surface, for example Lowest Astronomical Tide (LAT) and such a surface can be realised at a specific point (e.g. at a tide gauge station) but the physical surface (i.e. LAT) varies significantly over time and over a large expanse of area. It is therefore not a favourable tool for defining the relationship between various vertical datum surfaces (FIG, 2006).

Alternatively, chart datum may be chosen such that the tide will rarely fall below it and not so low as to be unrealistic and slowly varying between adjacent datum (Iliffe & Roger, 2008).

In practice, vertical datum have been developed using different approaches depending on hydrographic capability, availability of resources, prevailing data and area of coverage of that country or region. Chart datum is not a continuous or homogeneous reference surface as it changes from place to place.

Vertical datums suffer inconsistencies when interconversions are required across the land-sea interface, particularly when smooth transitions are required (Iliffe, et al., 2007a). Besides, it is also difficult to easily analyse the processes that happen across the land-sea interface. These challenges of overcoming the varying nature of chart datums and adopting a seamless model give rise to definition and implementation of a vertical separation model.

The campaign for the unification of both land and chart datum began in Canada and they have been a lead nation in the evolution of various separation models. In other countries, this unified model has evolved and are still emerging using different nomenclature such as (AUSHYDROID) in Australia, (VDatum) in United States of America, BLAST in the North Sea and in the United Kingdom (VORF) (Martin & Broadbent, 2004; Myers, et al., 2005; Slobbe, et al., 2012; Iliffe, et al., 2007a).

3.0 Statement of the Problem

The land-sea interface in the coastal zone is a function of water levels and land elevations, both of which are varying in space and time. To combine or relate coastal elevations (land heights and water depths) from different datasets, they must be referenced to the same vertical datum say (GRS 1980 ellipsoid and the ITRF). Using inconsistent datums can cause discontinuities that become problematic when generating charts at the accuracy needed to make informed geospatial decisions on a large scale. The challenges of overcoming the varying nature of chart datums gave rise to definition and implementation of a vertical separation model.

For Nigeria and the adjoining coastal nations, there are enormous challenges for the creation of this unified vertical offshore reference surface such as lack of and relation of a local geoid model to the global ellipsoid, lack of tide gauges data both from coastal tide stations that are analogous to Admiralty Tide Table Stations (ATT) in the United Kingdom and Permanent Service for Mean Sea Level (PSMSL), lack of hydrodynamic tide models for the definition of the Mean Sea Level at the various tide stations and the connection of some of these tides gauge stations to existing fundamental benchmarks in Nigeria. This research is therefore intended to discuss the methodology required, the inherent challenges towards the implementation of such a reference surface and how these challenges can be overcome.

4.0 Aim of the Research

This work focuses on the need for developing and implementing a homogenous and consistent vertical offshore reference surface for seamless bathymetry along the Nigerian territorial waters (12nmi) and to evaluate the inherent challenges that may arise for its implementation and applicability. The work also, intends to create the awareness amongst the various stakeholders in Nigeria that such a separation model (vertical surface) can be established and the benefits of creating such a surface for seamless bathymetry will be invaluable.

5.0 The Proposed Study Area

The area of study encompasses the Nigerian territorial waters through the contiguous zone and further into the Exclusive Economic Zone (EEZ) (Fig.1). Nigeria has a coastline of about 853km along the Atlantic Ocean (Ayeni, et al., 2004). This coastline is adjacent to the Gulf of Guinea and bounded between latitudes 04° 10' and 06° 20' North and Longitude 02° 43' and 08° 32' east. Figure 1 is a screenshot depicting the proposed domain of applicability.

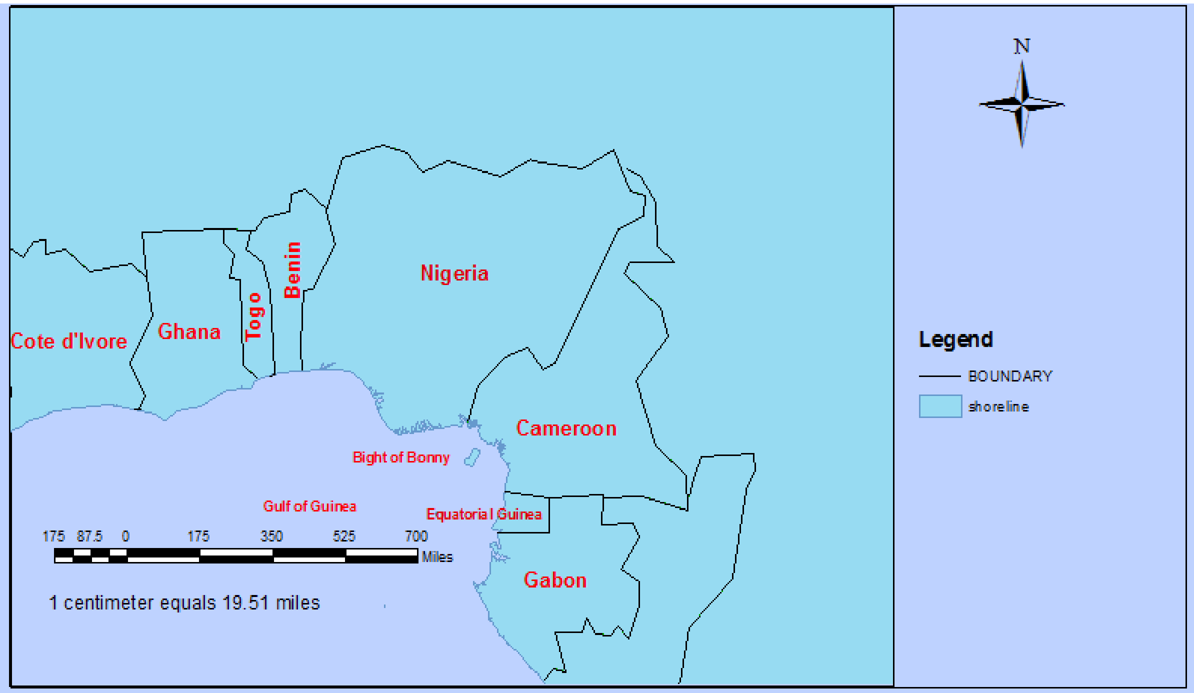

Fig. 1: A Map of the Study Area

6.0 Data Requirement

Different datasets are required for the successful implementation of a unified vertical offshore reference surface such as gravity data both from land and offshore, Digital Elevation Model (DEM), GPS/Levelling data and other related tidal data for the definition of the local geoid characteristics. Although different methods of geoid computation exist, the gravimetric method shall be explained briefly here since geoid computation methods and theories are beyond the scope of this study. (Forsberg, et al., 2002), gave a description of the computation of the geoid by gravimetric method using the remove-compute-restore techniques. In this method, the anomalous gravity potential T is separated into three components:-

$$\mathrm{T} = T_{EGM\,2008} + T_{RTM} + T_{RES} ------------------ Eq.1$$

Where,

$T_{EGM\,2008}$ – Anomalous gravity potential of the EGM2008 global field

T_{RTM} – Anomalous gravity potential generated by the residual topography

T_{RES} – Anomalous gravity potential residual

The quasi-geoid can be modelled via the Brun's equation using relationship below:

$$\zeta = \frac{T(\phi,\lambda,\mathrm{H})}{\gamma(\phi,\mathrm{H})} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots eq.2$$

Where,

γ is normal gravity on the ellipsoid,

ϕ and λ are the geographical latitude and longitude,

H is the Helmert orthometric height.

From Eq. (1), the height anomaly ζ, i.e. the quasi-geoid, can also be split into three parts:

$$\zeta = \zeta_{EGM\,2008} + \zeta_{RTM} + \zeta_{RES} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots eq.3$$

Nevertheless, the overall goal is to model the classical geoid heights *N*, i.e. the geoid. The relation between *N* and ζ is given approximately by

$$\zeta - \mathrm{N} = \frac{\Delta gB}{\gamma}\mathrm{H} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots eq.4$$

Where,

Δg_B is the Bouguer anomaly

N is the classical geoid

The definition of a local geoid for Nigeria can be achieved by establishing a relationship between the geoid and the global ellipsoid (GRS 1980 ellipsoid), as specified by (FIG, 2006). The other datasets required are satellite altimetry data, tide gauge data either along the coastline that are analogous to Admiralty Tide Table gauge stations (ATT) and/or Permanent Service for Mean Sea Level (PSMSL) offshore.The satellite altimetry data is the most important source of data for the definition of Mean Sea Level (Iliffe, et al., 2007a).

The satellite altimetry data should be of different epoch and missions (e.g. TOPEX POSEIDON and JASON-1/2) of cross-over variance of 6.5-7mm as specified by (Iliffe, et al., 2007a; Anderson, et al., 2002; Vincent, et al., 2003).The use of the altimeter in the "ocean mode" close to the coast (i.e. around land objects) can cause the signals to be noisier (Deng, et al., 2002). (Deng, et al., 2002; Illiffe, et al., 2007b), recommend rejection criteria of 10-14km radius from the shoreline so as to remove the contaminated altimeter foot-print. However, the accuracies derived when the observational noise have been removed and elimination of the contaminated signals vary from 0.02m-0.05m (1 sigma) (Hwang, et al., 2004; Yi, et al., 2006)

Besides, the low precision of the coastline tide gauges may also be attributed to spatial location (i.e. if they are located in subduction zone) and the satellite altimetry data has a very good spatial resolution in the open sea especially when observation of different missions is combined. However, degradation occurs when close to the shore due to the contamination of the altimeter foot-print (Vincent, et al., 2003; Illiffe, et al., 2007b).GPS developed ellipsoidal heights at some tide gauge locations are also required for the purposes of creating a link between the reference ellipsoid and the geoid and also GPS/levelling data are necessary to create a link between land-sea interfaces.

GPS buoys could also be used for data collection for the definition of MSL but due to its high cost, risk of loss and accuracy (10cm) (Jones, 2010), the other methods or sources of data collection are preferred. However, GPS buoys are usually deployed during the validation process. In summary, the data required for the Vertical Offshore Reference Surface (VORS) are:

i. Tide Gauge data

ii. Satellite Altimetry

iii. Gravity Field Models

iv. GPS data

v. Tidal Modelling

The data sets mentioned so far discussed have their strength and limitations; the coastline tide gauge data are said to have high spatial density but of weak precision due to the short term period of observation which are subject to or influenced by meteorological effect such as pressure variations, winds, currents, etc.

7.0 Methodology

The required methodology for the creation of a separation model can be summarized as illustrated in Fig. 2

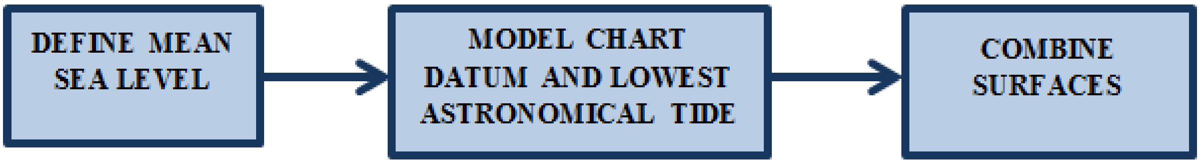

Fig. 2: The Overall Approach of the VORS

The overall approach of the VORS is to model mean sea level (MSL), the lowest astronomical tide (LAT), the Mean Low Water Springs (MLWS), the Mean High Water Springs (MHWS) etc. all above the reference ellipsoid (GRS 1980) and reconcile all these on a common reference epoch. High premium is placed on deriving the Chart Datum in ITRF; this would permit the combination of GPS height observations into the hydrographic data reduction process and decrease the dependence on coastal and tidal models (Ziebart, et al., 2007; Iliffe, et al., 2006). The major purpose for defining these surfaces is to generate a MSL model and then evaluate the difference in sea level from MSL to the other surfaces employing high resolution tidal models.

These tidal models are developed based on the topography of the sea bed (from bathymetry), the influencing forces being that of the moon, sun and other effects such as tidal friction as well as the topography of the land masses. Harmonic analysis is usually conducted on the tide gauge observations; besides, the chart datum (CD) is derived by transferring datum from established tide location using co-tidal chart and harmonic constituents to compute Lowest Astronomical Tide (LAT) using a Mean Sea Level value, (Iliffe, et al., 2006).

The derivation of the chart datum (CD) begins by first determining lowest astronomical tide with respect to the reference ellipsoid (GRS 1980) and this in turn is divided into two successive phases of evaluating a model of mean sea level with reference to GRS80 ellipsoid and then generating the height below the LAT through tidal modelling (Iliffe, et al., 2007a). The mathematical relationship for computing lowest astronomical tide (LAT) in the International Terrestrial Reference Frame (ITRF) using the GRS80 ellipsoid is given by (Turner, et al., 2010):-

$$LAT^{MSL} = CD^{ITRF} - MSL^{ITRF} \quad \text{......} eq.2$$

Where;

LAT^{MSL} = Lowest astronomical tide (LAT) with respect to mean sea level in ITRF

CD^{ITRF} = Chart datum with respect to ITRF

MSL^{ITRF} = Mean sea level with respect to ITRF

However, the issue of estimating Mean Sea Level within the buffered zone where the altimeter signals are eliminated due to its contamination still exist. This can be overcome by use of Least Squares Collocation (an interpolation technique) (Iliffe, et al., 2007a;Turner, et al., 2010).

But rather than interpolate mean sea level which may not be predictable all within the study area, the Sea Surface Topography (SST) which is the difference between the geoid and mean sea level, which varies smoothly between the satellite altimetry and tide gauges can be interpolated. Thus, when the interpolated SST is added to the geoid height above the ellipsoid, the Mean Sea Level height is modelled.

Most probably, the most vital pair of surfaces in the VORS project is LAT and CD because, these are the navigable and safety critical. It should be noted however, that the model value of VORS (LAT) is the approximate value of the lowest astronomical tide at the epoch of computation. Since VORS (LAT) and every other surface has been modelled, the next step is to stitch all these surfaces so as to develop a software suite for the project. Figure 3 is a schematic diagram showing the overall concept of the proposed VORS project.

In summary, VORS derives continuous surfaces, with fixed reference to ITRF.It provides a consistent interpolation between Chart Datums, and methodology for extrapolation offshore. Besides, it eliminates some of the reliance on remote or expensive tidal observations and has the potential to be built in to real-time applications. It wholly exploits current and future GPS technology, and is the foundation for future accuracy enhancements.

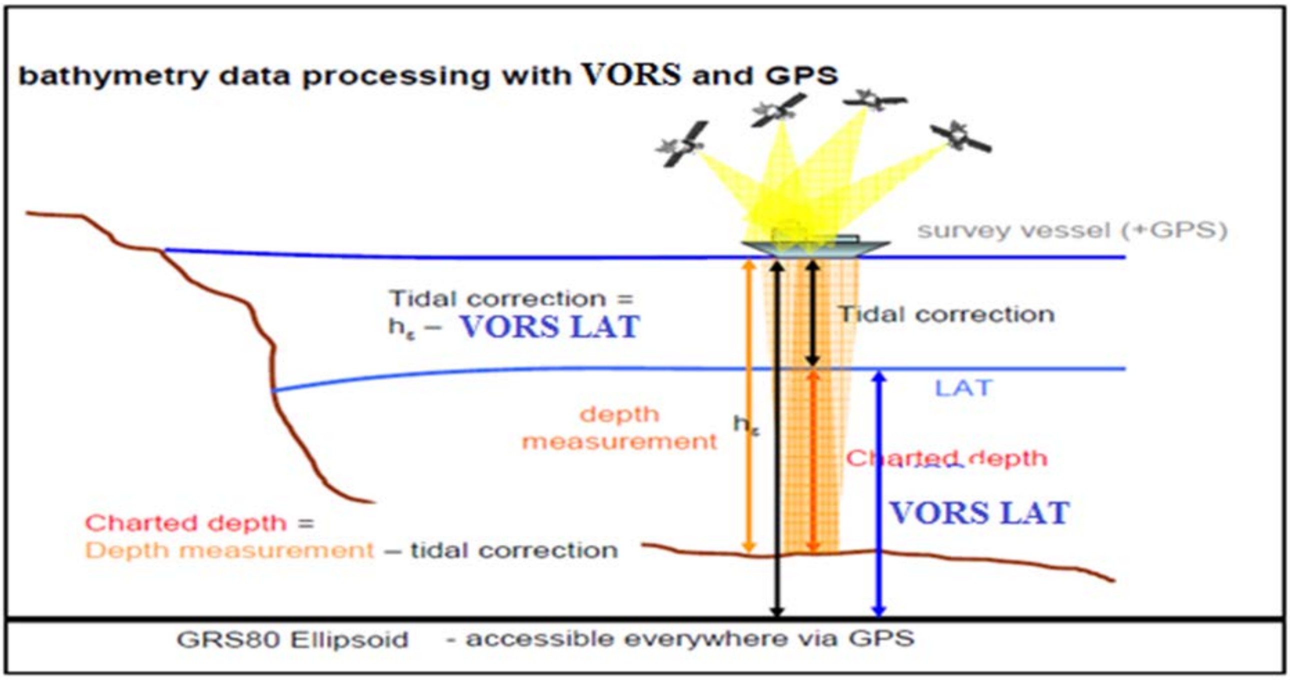

Fig. 3: Relationship between VORS LAT and GPS for Bathymetry Data Processing (after Iliffe et al 2007b)

8.0 Challenges towards the Implementation of the Vertical Offshore Reference Surface in Nigeria

The effective implementation of the VORS unified surface in Nigeria though achievable may be plagued by obvious challenges. In Nigeria, the lack of an acceptable geoid model remains a *lacuna* that will make it difficult to develop the necessary relationship with the global ellipsoidal surface (GRS 80). This is an underlying principle in the application of VORS.

In addition, it has been observed that the geodetic levelling data adjusted for the country by Ebong in 1981 when published was termed “provisional”. This was assumed to be orthometric but are actually based on an arbitrary chosen datum known as the Lagos Survey Datum that has been found not to be coincident with the Mean Sea Level (Fajemirokun, 2011 & 2013). It therefore means that our mean sea level is not yet properly defined.

Also, the paucity of tide gauges along the coastline of our study area and consequently the insufficiency of tide gauge data which is a basic input for defining Mean Sea Level (vertical datum) remains an issue to be addressed.

There is the need to increase GPS campaign and deployment of Continuously Operating Reference System (CORS) facilities to provide GNSS reference stations that facilitate and allows accurate , repeatable and cost effective ellipsoidal heights which, can be geo-collocated to existing tide gauges and bench marks.

This notwithstanding, VORS involves more than simply combining various digital datasets to achieve the seamless reference surface. It also requires an accurate application and knowledge of geodetic datum types, projection systems, temporal changes and geodynamical phenomena. This underscore the need for human capacity development in this emerging area of Space and Marine Geodesy, Hydrographic Science, Navigation etc.

It may be argued that the absence of synergy by the relevant stakeholders to increase research activities and develop this vertical reference surface may be due to lack of knowledge of this concept and/or appreciation of the enormous benefits.

Further to this, the absence of enabling laws in the marine sector for the implementation of geodata infrastructure for the purpose of its coordination and control for safety and security undermines the quick implementation of this noble venture.

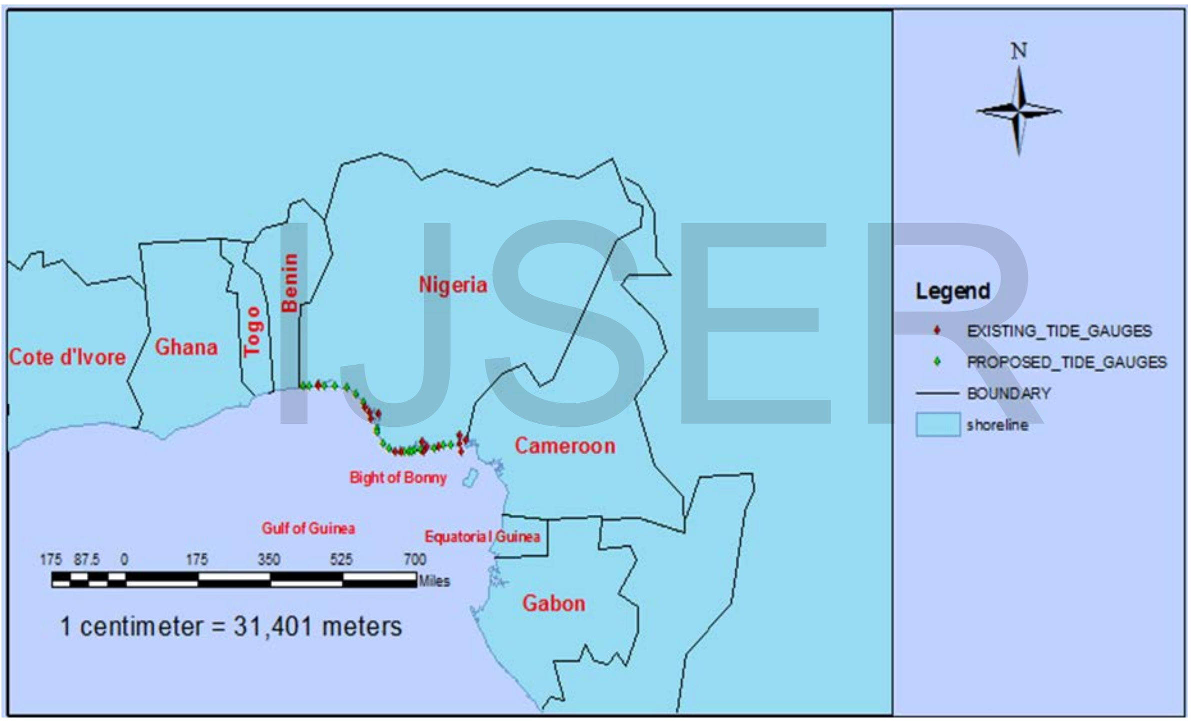

Fig. 4: A Map of the Study Area showing the Existing/Proposed Tide Gauges (Source: Nigerian Navy, 2002)

9.0 Conclusion and Recommendations

The land and sea interface is combination of two different environments, in spite of this, people are keen in understanding how these interact, and the VORS concept is the veritable link between the two. A vertical offshore reference surface is a veritable mathematical tool for relating different vertical datum. These datums are brought to a common epoch, datum and reference frame via an appropriate model.

VORS is a supporting technology which enables bathymetric surveying without tide gauges; it is cheaper, faster, and more accurate than the classical methods of obtaining bathymetric information. It is said to be a new navigation and space management concepts that provides improved navigation in critical areas as provided by Safety of Life at Sea (SOLAS). VORS will support the proposed Nigerian Hydrographic Office (NHO) in its development of marine charting and navigation products.

The said vertical offshore reference surface shall provide cost-effective means of obtaining bathymetric information on a large scale provided there is GPS coverage. Also, VORF will enable satellite-based observations on sea faring vessels in terms of position and heights to be used directly in hydrographic surveying without recourse to shore-based observations of the tide. This reference surface provides an increasing number of applications: in sea port operations, coastal zone management, territorial security and marine boundary delimitation. In view of the foregoing, the following recommendations are made:

i. There should be densification of tide gauges along the shoreline of Nigeria as specified in figure 4. This will enable the proper definition of the mean sea level which takes into account all the meteorological and other factors.
ii. Some of the existing and proposed tide gauges should contribute to the Permanent Service for Mean Sea Level (PSMSL). Besides, data from such tide gauges can also be put into other global studies such as sea level dynamics etc.
iii. A National Hydrographic office should be established herein named Nigerian Hydrographic Office (NHO) which is analogous to the United Kingdom Hydrographic Office (UKHO). This office shall be a depository of all hydrographic geo-spatial information.
iv. The establishment of a Vertical Offshore Reference Surface (VORS) for Nigeria is quite an enormous project in terms of human capacity, data availability and finance. We therefore emphasise the need for all stakeholders in geospatial usage such as Surveyors Council of Nigeria (SURCON), Office of the Surveyor of the Federation (OSGOF), Nigerian Institution of Surveyors (NIS), Nigerian Maritime Administration and Safety Agency (NIMASA), Nigerian Ports Authority (NPA), the Nigerian Navy and the academia) to give their support towards the realisation of this project.

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