Towards the Development of a Methodology for Vertical Separation Models in the Caribbean

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SUMMARY

Coastal areas in the Caribbean have a high population density which is anticipated to increase in the future. For many of the islands, the coastal zone represents a high economic activity, as tourism based economies are predominant in the Caribbean. Historically and in recent times, coastal hazards such as hurricanes, tropical storms, tsunamis and landslides have had negative impacts on both coastal communities and national economies in the region. Additionally, the threat of coastal inundation as a result of sea level rise is becoming more of an issue for many of the islands. Coastal zone management, monitoring and defence mechanisms are being implemented to mitigate and adapt to these threats, and these initiatives can benefit from a seamless coastal spatial model that may be a crucial part of the decision support.

A major obstacle that presents itself is the difficulty in modelling and integrating datasets across the land-sea interface, where a consistent vertical datum does not exist. In this regard, the development of a separation model that simulates a vertical reference surface is applicable. While several projects of this nature have been carried out in countries such as the United Kingdom, the United States of America, Canada and Australia there is a growing need for this type of research in the Caribbean.

This paper discusses the significance of developing a methodology that will facilitate transformations among vertical reference frames to support the modelling of data across the land-sea interface in the Caribbean. An examination and assessment of the existing methodologies developed by the other nations will be made so as to ascertain their applicability in the Caribbean. A methodology for use in the Caribbean is also proposed.

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1. INTRODUCTION

The derivation of separation models for vertical reference surfaces is a growing area of research and developmental. While previous work in countries such as Canada, Australia, USA and the UK has set a solid foundation for the development of operational separation models, there is a need for further research and application in other regions, including the Caribbean.

The Caribbean, through its environmental, socio-economic and population density characteristics, presents a unique environment and specific needs and challenges to the development of a separation model. This study is aimed at developing a methodology for the creation of vertical separation models for the region. It considers the nature of vertical reference surfaces and assesses existing models and techniques, incorporating the distinctive factors of the Caribbean environment. A methodology is presented to be implemented using the west coast of Trinidad as a pilot area.

2. VERTICAL REFERENCE SURFACES

A vertical reference surface, as the name suggests, is essentially a surface to which the heights or depths of points are referred. The vertical reference surface is often selected to be the geoid for topographic applications, while Chart Datum is selected for hydrographic applications. There are approximately one hundred and fifty different physical height systems worldwide all related to different tide gauges. They can be placed into three main categories; tidal surfaces, ellipsoidal surfaces and equipotential surfaces. (Adams, 2003)

2.1 Tidal Surfaces

A tidal datum is essentially the average of all the water elevations (high, low or mean) over an 18.6 year period. This averages out most meteorological effects on water level. It is defined more simplistically as averaged stages of the tide such as MSL, MHW and MLLW. Tidal datum elevations vary significantly with geographic distance, especially in shallow waters. They are used as references to measure local water levels and should not be extended into areas having differing oceanographic characteristics without substantiating measurements. In order that they may be recovered when needed, such datums are referenced to bench marks. (FIG, 2006)

2.1.1 Chart Datum

Chart datum is the tidal datum to which levels on a nautical chart and tidal predictions are referred. It is a level so low that the tide will not frequently fall below it; which means that a chart datum is not a horizontal surface, but it may be considered so only over a limited local area. LAT and MLLW are two commonly used chart datums. (George, 1995)

2.2 Ellipsoidal Surfaces

Ellipsoidal datums are based on a geometric model, an ellipsoid that approximates the earth's surface without the topography. They are typically realised through observations from space based systems such as GPS. (FIG, 2006)

2.3 Equipotential Surfaces

Equipotential surfaces are surfaces of constant gravity potential. The gravitational potential of the earth depends on the distribution of mass density throughout the earth. Orthometric datums are essentially equipotential surfaces of the earth with one or more tide stations used as control points. They are based on a geoid or a form of MSL.

For all practical purposes, the equipotential surfaces can be considered invariant with respect to time. Equipotential surfaces are by definition seamless and smooth, the surface and its spatial derivatives are continuous. They are globally defined surfaces and can therefore be used both for height representation over land areas and for depth representation at sea and in inland waters. (Parker, et al. 2002).

2.3.1 The Geoid

The geoid is the equipotential surface of the Earth's gravity field which best fits mean sea level. (NGS, 1986) This surface includes topography and therefore differs from a geocentric ellipsoid, up to 100 metres, because of the earth's irregular mass distribution, being higher than the ellipsoid when there is a greater mass. (Parker, et al. 2002)

The practical representation of the geoid is not in terms of the numerical value of its gravity potential, but rather in terms of its separation from a reference ellipsoid. This separation is referred to as the geoid height N, also called the geoid undulation. On a global scale, the geoid heights remain in the range $-100 \text{ m} < N < +100 \text{ m}$. Such geoid approximations have been used in the past as the reference surface for the topography. The distance between the topography and the geoid, measured along the plumb line is the orthometric height, commonly called the height above sea level.

The accuracy of the geoid depends primarily on the correct knowledge of the gravity field of the earth. This gravity field is fairly well known in flat land areas and in continental shelf areas with extensive gravimetric measurements. It is known to a lesser accuracy in the open oceans, and in mountainous land areas. Correspondingly, the accuracy of the geoid varies between better than 10 cm and worse than one metre. A major portion of the geoid errors is of long wave length nature, it changes rather slowly with geographical position. As a consequence, the accuracy of the geoid height difference between two points will be generally better than the geoid height accuracy at a single point. (Canadian Hydrographic Service, 2003).

3. VERTICAL DATUM TRANSFORMATIONS

On land, a height datum is established by measurement of MSL at a particular point, usually a tide gauge, which is then carried through the country by precise levelling. It is therefore offset from the geoid and the differences are not constant due to accumulation of levelling errors. The datum so established can then modelled by development a geoidal model and fitting it to bench marks where GPS measurements have been made. This surface is sometimes termed GPS derived MSL.

Geoid modelling typically involves sophisticated mathematical techniques. A simplified explanation of the procedure is that gravity data from various sources are used to compute the shape of the geoid. The geoid shape is positioned above or below the reference ellipsoid according to more precisely known geoid heights at those stations having both accurate orthometric heights and ellipsoid heights. The results of the transformation are only as accurate as the model used.

For the coastal zone these problems are more significant as the vertical datums used in this area are quite dynamic. The discrepancy of particular interest is the difference between the geoid and tidally derived MSL due to permanent currents and mean meteorological effects. This separation is called the sea surface topography (SST) as shown in Figure 1. Additionally the definition of chart datum allows for a variety of realisations and while most countries have adopted the LAT as the standard chart datum, in practice there are often differences between them. (Iliffe, Ziebart and Turner 2007)

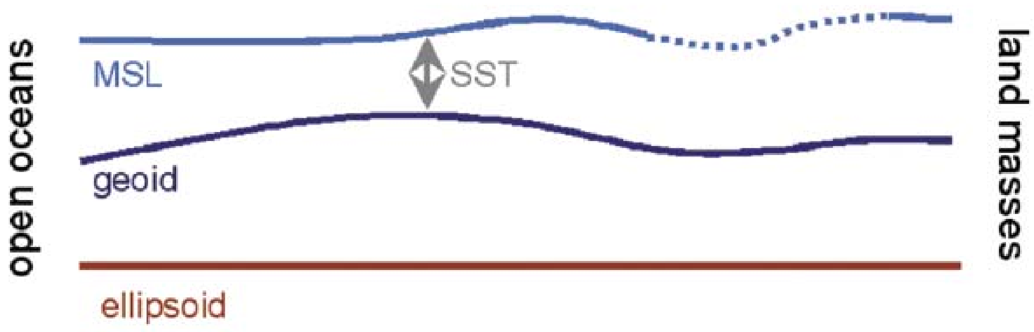

Figure 1 Vertical reference surfaces used in the Coastal Zone (after Ziebart et al 2007)

3.1 Vertical Separation Model

A vertical separation model defines the relationship between the chosen vertical reference surface and other extant vertical datums (FIG 2006). This model is essentially intended to be a transformation tool which 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 stable and does not vary over time and space. The development of this stable 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. The vertical reference surface must be defined continuously across and throughout the land-sea interface. As such tidal datums are not optimal for use as they can vary significantly in time and space. An equipotential surface would be more appropriate. (Miller, Hamilton and Neale, 2005)

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

4. CURRENT METHODOLOGIES

FIG 2006 collates and outlines general guidelines regarding the methodology to be followed when developing a vertical separation model. The first step is the selection of a vertical reference surface through which the transformations can be made. Following this, measurements are made onshore and offshore and modelling and interpolation techniques are implemented to relate the various vertical datums to this vertical reference surface.

The creation of separation models was pioneered by Canada in 1996. A GPS campaign was carried out by the Canadian Hydrographic Service, in selected areas to define the relationship between Chart Datum and WGS84 Datum. From this a separation surface was derived enabling the Canadian Hydrographic Service to handle data referred to a variety of vertical datums. Hydrodynamic modelling and satellite altimetry data was used to determine the separation offshore. (El Rabanny 2003). A similar project AUSHYDROID, was carried out in Australia in 2004. The AUSHYDROID is a vertical separation model developed for Queensland Australia. The height of chart datum was modelled with respect to the WGS84 ellipsoid via GPS measurements relative to ITRF. Zoning was used offshore while tide gauges was used on the coast. Two other major separation models, VDatum in the USA (Parker, Milbert, Hess, & Gill, 2002), and VORF in the UK (Iliffe, Ziebart and Turner 2007) are examined in more detail.

4.1 Vertical Offshore Reference Frame (VORF)

This project was commissioned by the UK Hydrographic Office in 2005 and carried out by the department of Geomatic Engineering at UCL. This scale of the project encompassed all the navigable waters of the UK and Eire out to the limits of the exclusive economic zone (EEZ), and also included estuaries and rivers. The aim of the project was to model chart datum and other tidal surfaces as a continuous surface with respect to ETRF89 and ITRF2000.

In determining the continuous surface for chart datum the mean sea surface was determined at reference epoch 2000 with respect to the ETRF89. This was done using tide gauges along the coasts and satellite altimetry data offshore. The tide gauge data was connected to the land datum and the ellipsoid using the accurate definition of the geoid via the OSGM02 model. The majority of the data used was from satellite altimetry, however its accuracy was compromised in the inshore areas (less than 14km from land), and so for this area tide gauge data was used. The mean sea level determined from the tide gauges on the coast and from the altimetry in the open seas were then interpolated and weighted.

Hydrodynamic modelling was used to determine the geographic distribution of the tidal surfaces such as LAT, MLWS, MHWS and HAT, above and below the mean sea surface. Interpolation between grid nodes and extrapolation up to the coastline was carried out. The tide gauge data had to be used as control points to correct the model.

The result was the height of LAT and the other tidal surfaces above the GRS80 ellipsoid in the ETRF89 datum. The overall accuracy was found to be 10cm in inshore areas and 15cm offshore. (Iliffe, Ziebart and Turner 2007)

4.2 VDatum

VDatum is a vertical datum transformation tool developed by the United States National Oceanic and Atmospheric Administration (NOAA) in 2002. It allows for the transformation of elevation data between any two vertical datums out of a choice of 28 tidal, orthometric and ellipsoidal vertical datums.

VDatum was first used in Tampa Bay to create a DEM by combining bathymetry and topography referenced to different vertical datums. The main focus of this project was to determine the relationship between the tidal datums and the seamless reference surface.

Hydrodynamic modelling was used to determine the geographic distribution of tidal datums. The model used was a three-dimensional, free-surface, sigma-coordinate baroclinic hydrodynamic model using a curvilinear grid with typical grid spacing from 1000 to 100 meters. The typical standard deviation of the differences between model predictions and data was approximately 2.7 cm.

For calibration purposes the model was forced with coastal water levels, inputs from seven rivers, winds and air temperature, and coastal salinity and temperature. For the purpose of determining the geographic distribution of tidal datums the model was forced at the Bay entrance with accepted tidal harmonic constants and run for one year, with the various stages of the tide picked off and averaged for every grid point of the model. The one-year averages were corrected for the 18.6-year lunar nodal cycle by comparison to the St. Petersburg water level station. The hydrodynamic model was used to generate a set of fields representing the difference between MLLW and: mean low water (MLW), diurnal tide level (DTL), mean tide level (MTL), mean sea level (MSL), mean high water (MHW), and mean higher high water (MHHW).

For bays or estuaries where a fully calibrated hydrodynamic model is not available, a technique for spatial interpolation among locations with water level station data has been developed (Hess, 2002). This method, the tidal constituent and residual interpolation (TCARI) method, uses a set of weighting functions (generated by solving numerically Laplace’s Equation) to quantify the local contributions from each of the water level stations.

When using a numerical hydrodynamic model (the preferred way to produce the distribution of tidal datums in a waterway), it is necessary that the model values at the locations of water level stations match exactly the values derived from the long time series of data at those water level stations. To assure this, TCARI is used to interpolate the errors for each tidal datum between the tide stations, and then the resulting error correction fields are used to correct the tidal datum fields. (Myers et al, 2005)

5. DEVELOPING A CARIBBEAN MODEL

Recent studies have shown that the overwhelming percentage of human settlement is concentrated along or near coasts on just ten percent of the earth's land surface. The population of the Caribbean is even more littoral. Sixty percent of the Caribbean population lives less than 100 kilometres from a coast. (Hinrichsen, Don, 2004)

For the Caribbean (see Figure 2), the ocean and coastal environment is of strategic importance and constitutes a valuable development resource. All capital cities in the insular Caribbean are on the coasts. Forty three percent of the combined gross domestic product of the Caribbean and one third of export revenues are generated in the coastal areas. Many Caribbean economies are tourism based and over one hundred million tourists visit annually. (UNEP, 2008)

Hazards and natural disasters such as hurricanes, tropical storms, tsunamis and landslides have had negative impacts on both coastal communities and national economies in the region. Additionally, the threat of coastal inundation as a result of sea level rise is becoming a concern for many of the islands. The issue is adequately summarised in the following:

"Coasts are the foundation for the well being and economic viability of present and future generations... There is increased pressure on coastal environments with the significant coastal population increase as well as rapid changes in the global climate. The fragility of eco systems existing in the coastal zones is now more than ever, evident and so is the need to manage marine spaces in a more structured and sustainable manner... Recent natural disasters have demonstrated an urgent need to increase our understanding of the natural processes that threaten our coastal communities." (Reeve, Chadwick and Flemming, 2004).

Figure 2 Map of the Caribbean region

Coastal zone management, monitoring and defence mechanisms are now being designed and implemented in the Caribbean to mitigate and adapt to these threats. Flood prevention schemes, coastal defence systems, land reclamation, pollution management, coastal resource and sea level monitoring are also being done to keep up with the growing population demands.

The execution of such projects requires the amalgamation of the datasets of both topographic and bathymetric surveys and in order to achieve this, seamless spatial data across the land-sea interface is necessary. Elevation data such as bathymetry and topography must be referenced to a vertical datum. These surveys, however, result in spatial data that cannot be compared far less seamlessly integrated once they are not referenced to the same vertical datum, and therein lays the challenge, as a consistent vertical datum does not exist across the land-sea interface. (Parker, Milbert, et al 2002)

The CARIB97 geoidal model is the main tool for determining orthometric heights in the Caribbean. There has been, in recent times, movement towards the use of the EGM 2008, which is a global model. In the case of the CARIB97 (2004) model, it is stated that systematic errors may appear as extreme (30+ ppm) tilts, over very short ranges, island by island, and this is likely to be true in the case of the Gulf of Paria off the west coast of Trinidad. Furthermore, the horizontal resolution of the grid on which CARIB97 is based is 2'x2', which provides insufficient detail at the island level. The EGM 2008 is a more recent model with a resolution of 1' x 1', however there is no evidence that suggests it is better suited for the Caribbean than the CARIB97 model. (Miller, Hamilton and Neale 2005)

Additionally, in most islands sea surface topography has not been measured and thus the difference between tidally derived MSL and GPS derived MSL (via the geoidal model) is still unknown. The lack of resources, data, tide gauges, gravity measurements and more accurate geoidal models are challenges faced by Caribbean hydrographic surveyors, land surveyors and coastal engineers, daily. They have each devised their own method of circumventing these obstacles such as, measuring tides for short periods and applying corrections to obtain MSL for each survey or deriving their own shifts for SST. Not only is this process expensive but highly ad-hoc and not standardised.

6. PROPOSED METHODOLOGY

The main consideration in developing a separation model is its purpose. The purpose or end use of the model will determine the resources needed, the accuracy required and consequently the approach adopted. Table 1 identifies other issues of consideration in the development of a vertical separation model.

Table 1 Issues for consideration in the development of a vertical separation model

DEVELOPMENT ISSUES	CONSIDERATION
Coverage	What is the scale of the project? How far inland and how far offshore does the model cover? What types of vertical surfaces are to be used?
Resources	Resource availability/constraints – data, time, money, equipment and labour.

Accuracy	The overall accuracy is dependent on the accuracy of all the datasets used (the total error budget)
Maintenance	The cost of maintaining and updating the model should be carefully considered. The updating regime should reflect the amount of expected change in the model over time and the accuracy needed by the user
Storage	The system should be sufficiently flexible to store and manipulate all of the vertical models relevant to the region, and the user should be able to use the model in their system.

The methodology employed in this study also has to take into consideration the major characteristics pertinent to Caribbean territories:

- Data availability,
- The absence of an accurate geoidal model, and
- The vertical movement of the land
- Institutional challenges.

6.1 Proposed Study Area

The proposed test site where the model is to be developed and tested is the West Coast of the island of Trinidad, shown in Figure 3. This site provides an ideal area to review the issue of vertical reference surfaces as the semi diurnal tidal regime is at the micro-tidal level and there is a change in chart datum along the coast. LAT was calculated to be 0.730m below MSL at Port of Spain in the north and 0.824m below MSL at Point Fortin in the south. There is a difference of approximately 3m in the geoid-spheroid separation, using the WGS84 spheroid, which gives an average deflection of the vertical of 11 seconds. (Miller, Hamilton and Neale 2005) It is envisioned that the methodology developed from this study will be useful for not only Trinidad but the entire Caribbean.

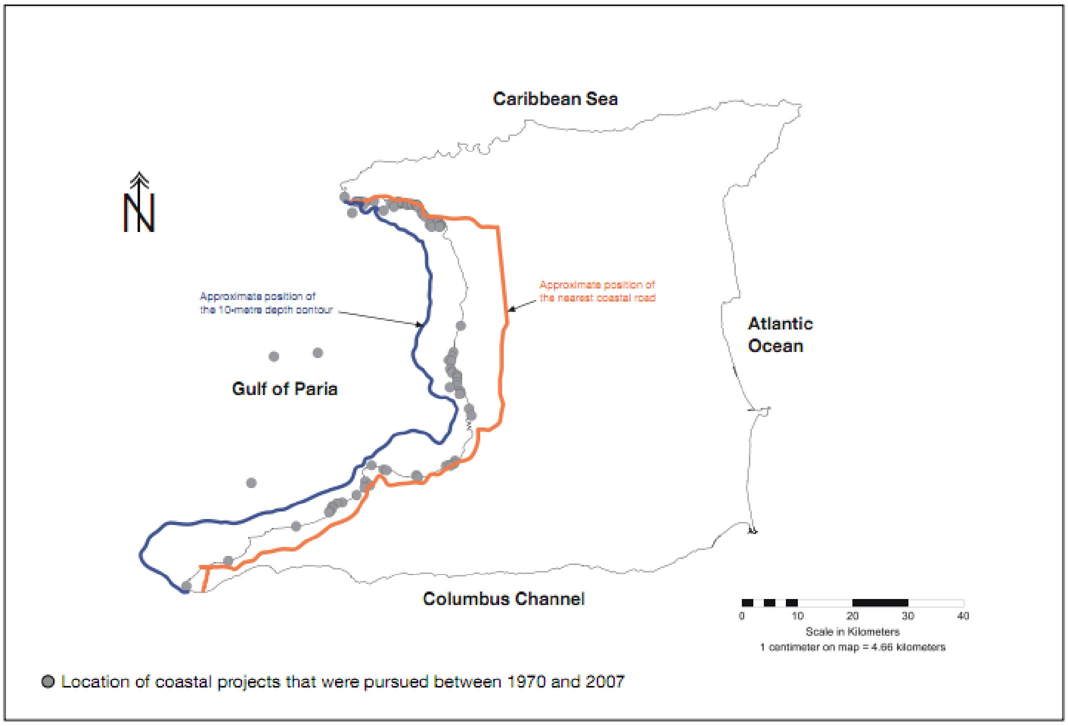

Figure 3 Map of Study Area (Neale and Mohammed 2010)

The aim of the research is to develop a separation model that allows for the seamless integration of marine and terrestrial data across the land-sea interface. In developing the model, the key objectives would be:

1. To quantify the separation between land-based vertical datums at discrete points in the study area.
2. To determine the geographic distribution of the various tidal datums used at sea.
3. To interpolate the separation values for the entire study area.

It therefore follows that the first phase of the study would be to define the most appropriate vertical reference surface and proceed to determine the separation at discrete points on land in the study area. The challenge with this task is the lack of available data. Extensive GPS surveying would be carried out to measure the height of the control points above the GSR80 ellipsoid. A levelling link from the tide gauges will establish the relationship of MSL to the reference surface. Additionally the geoidal elevations (both EGM2008 and CARIB97) will be deduced as well. To account for the lack of long term tidal observations, short term observations will be carried out and corrections applied.

The second phase of the project will be to determine the geographic distribution of the tidal datums offshore. The creation of a calibrated hydrodynamic model is envisioned however if the data is insufficient other spatial interpolation techniques will be employed. The model will include the two main tidal surfaces used in the Caribbean, MSL and LAT. SST will also be determined. This model is expected to be useful for the coastal zone and while in the future its development can be useful inland for rivers and estuaries or offshore in the high seas, the model will only cover up to the 20m contour.

Having determined the separation at discrete locations the next step is to apply interpolation and extrapolation techniques to determine the separation for the entire West Coast of Trinidad. The accuracy of the techniques used will be carefully considered as the desired accuracy for this model less than 5cm so that it has practical use for coastal engineering projects. The problem of extrapolation offshore is challenging. There is a paucity of tidal information out at sea and hence the nature of the tidal surfaces is less well known. The preparation of co-tidal charts will be considered. These define the behaviour of Chart Datum offshore with respect to a tidal station onshore. However, in many cases, these are not now thought to be the most accurate models of Chart Datum at sea. A more modern method for defining Chart Datum offshore is with the use of satellite altimetry and tidal models. (Adams 2003)

Any physical realisation of the vertical reference surface must accommodate vertical land movement. When considering CORS sites for GPS for example, velocity components are provided in addition to displacement at a particular epoch. Equivalent circumstances in the vertical component are documented for the region of the Great lakes, where the Canadian Hydrographic Service (2003) suggest a revision of the vertical reference system every 25- 30 years to accommodate differential movement of the earth's crust. Many of these requirements are understood and accommodated by existing standards. The difficulty lies in extending the function to include the capacity of modern technology and the dynamics of the environment, such as has been identified in this research. (Miller, Hamilton and Neale 2005)

7. CONCLUSION

Land surveyors, hydrographers, coastal engineers and anyone carrying out projects in the coastal zone in the Caribbean will benefit from the development of a vertical datum separation model. The lack of a consistent vertical datum across the land-sea interface has to be addressed in order to facilitate the seamless amalgamation of land and sea data. For the coastal zone and the Caribbean at large this could lead to better decision making and support better policies. With global climate change, increasing advances in surveying technology and the need for integration and amalgamation of survey data from across the land-sea interface and across regions, it is the opportune time for such a development.

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