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The Development of Continuous Hydrographic Datum Using Geodetic Based Approaches: A Review

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Abstract. The development of a continuous hydrographic datum along the coastal region for a precise datum determination for any hydrographic survey works is very important. The development started in 2005 by France that developed the first phase of Bathymetry with reference to the Ellipsoid (BATHYELLI) and its second phase in 2011. Then in 2009, the United Kingdom with collaboration with Ireland developed the Vertical Offshore Reference Frame (VORF), followed by the Continuous Chart Datum for Canadian Water (CCDCW) in 2010 by the Canadian Hydrographic Services (CHS) and Canadian Geodetic Survey (CGS). Then in 2018, Netherlands and Belgium collaborate to develop Vertical Reference Frame for the Netherlands (NEVREF) that consist of two elements which are Netherlands Quasi-Geoid 2018 (NLGEO2018) model and also Netherlands Lowest Astronomical Tide 2018 (NLLAT2018) model. Finally, the latest development of continuous hydrographic datum was conducted by the Kingdom of Saudi Arabia (KSA) in 2019, a system known as Saudi Continuous Chart Datum (SCCD). Therefore, this paper provides a review of the approaches in creating a continuous hydrographic datum which encompasses the usage of tide gauge station, satellite altimetry, and interpolation algorithm, Global Navigation Satellite System (GNSS), Digital Elevation Model (DEM), Geoid Model and Hydrodynamic Ocean Tide Models. The findings show that the integration of tidal station, satellite altimetry, GNSS levelling and geoid model is the most appropriate solution for a continuous and accurate hydrographic datum along the coastal line. Finally, the future research direction is also discussed in this review paper.

1. Introduction

In the traditional methodology, data from the tidal station are used to reduce the bathymetry data (seafloor depth), to produce a discrete chart datum [1]. Nowadays, with the existence of global navigation satellite systems (GNSS), the depth reduction can be performed by the hydrographers precisely with an acceptable level of accuracy by referring the continuous reference system, for instance, the ellipsoid (WGS84) [2]. Nevertheless, the reduction of the bathymetry data will be executed according to the national chart datum (CD) that serve as the lowest astronomical tide (LAT) in Peninsular Malaysia after a period of observation for over than 18.6 years. Hence, the importance for establishing a continuous hydrographic datum with the objectives that it very well may be changed into a consistent tidal datum, for instance, the mean sea level (MSL) with another consistent reference model, the reference ellipsoid (WGS84) [3].

The continuous hydrographic datum is essential for several hydrographic works, for instance, surveying the route for mariners and as important assistance for real-time or post-processing kinematic to the bathymetry information to the hydrographic datum, if the clients have the height value from the GNSS [4]. With the advancement use of high accuracy vertical positioning derived from the GNSS by maritime agencies, errors associated with charts by the present usage of a conventional datum can contribute as a vital component for the overall vertical error in the measurement [5]. Therefore, a consistent and stable reference surface for vertical datum is best monitored by continuous hydrographic datum and also for datum transformation [6, 7].

2. Methodology

2.1 Bathymetry With Reference to the Ellipsoid (BATHYELLI)

The Bathymetry with reference to the Ellipsoid (BATHYELLI)'s first phase started in 2005 and 2011, the second phase begins. The objective of BATHYELLI is to establish vertical hydrographic datum on all metropolitan coastal area in a consistent, accurate and accessible benchmark, for example, GRS80 ellipsoid of RFG93 [8]. The vertical hydrographic reference surface that was used to estimate the following tidal datum with respect to GRS80 are as shown in Figure 1. The data sources for developing BATHYELLI include Hydrographic Mean Sea Surface (HMSS), European Quasi-Geoid Model 1997 (EG97), Lowest Astronomical Tide (LAT), and Vertical Datum IGN 1969 (IGN69) [9].

The data acquisition stage of BATHYELLI are divided into three categories which are for the offshore region, the data was acquired using satellite altimetry, while for the port and coastal area, tide gauge station was used, and finally, for the region in between the coastal area and offshore region, the data was obtained by conducting Global Positioning System (GPS) by Hydrographic and Oceanographic Services of the Marine (SHOM) in 2006 to 2008 and also during 2012 up to 2013 [9]. The accuracy of BATHYELLI is approximately 10 centimetres. The basic principles of BATHYELLI in measuring the bathymetry are as shown in Figure 1.

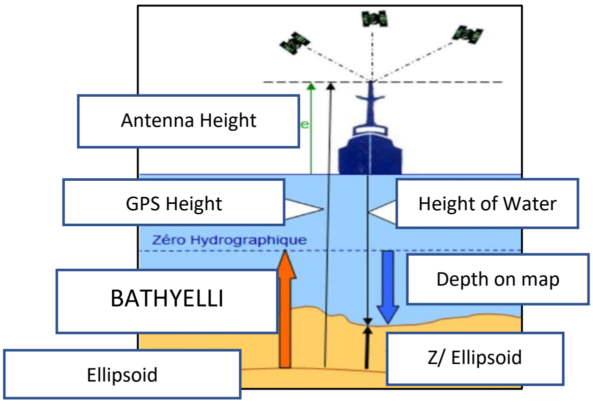

Figure 1. Basic principles of BATHYELLI [10]

Whereby,

$$Z/Ellipsoid = GPS\ Height - Antenna\ Height - Height\ of\ Water\ Level$$

Therefore, with the integration of BATHYELLI model of hydrographic zero with respect to the ellipsoid, for any hydrographic survey that was conducted on a ship or boat equipped with GNSS or GPS receivers, the tide and meteorological effects correction are no longer needed to acquire the final bathymetry of the surveyed area [10]. The second phase for BATHYELLI started in 2011 with three objectives which are:

a) Validation and improvement of vertical datum, taking also GPS measurement into account.
b) New processing and data collection strategy during any hydrography work with respect to the ellipsoid will be defined directly.
c) Development of software tools for vertical datum transformations.

Figure 2 illustrates the first version of SHOM BATHYELLI and the surveyed area around France during its data acquisition stages.

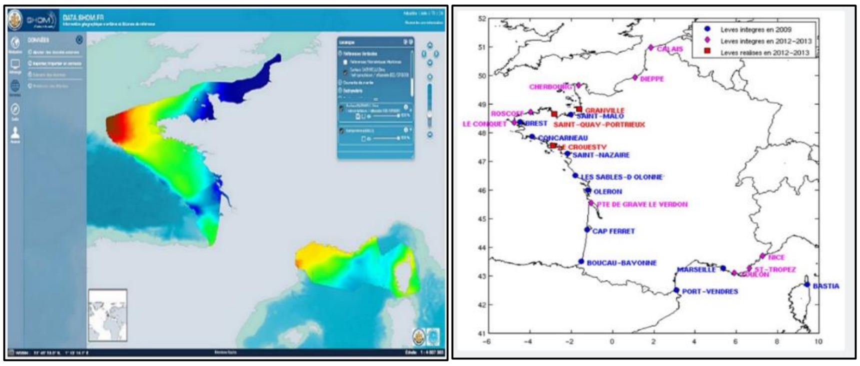

Figure 2. The interface of SHOM BATHYELLI product and the area surveyed by SHOM for data acquisition [10]

2.2 Vertical Offshore Reference Frame (VORF)

The Vertical Offshore Reference Frame (VORF) was developed in 2009 by the collaboration between the United Kingdom and Ireland [11]. The main objective of VORF is to establish a vertical tidal reference surface with respect to the World Geodetic System 1984 (WGS84) [12]. Other than that, VORF also serves as transformation tools for the vertical datum at the offshore region and coastal areas [13]. Among the importance of the establishment of VORF are as follows:

a) Continuing development in Global Navigation Satellite System (GNSS)
b) Multibeam and Light Detection and Ranging (LIDAR) technology
c) Datum transformation, unification and harmonization.
d) Data fusion

Among the hydrographic datum that can be derived from VORF are the Highest Astronomical Tide (HAT), Mean High Water Spring (MHWS), Mean Sea Level (MSL), Mean Low Water Spring (MLWS), Lowest Astronomical Tide (LAT) and Chart Datum (CD). The resolution of VORF is 0.008 degree (in terms of latitude and longitude, it is 900 metres and 500 metres respectively. The data acquisition for VORF is divided into four categories as shown in Table 1 [14].

Table 1. Data sources for developing VORF [15].

Permanent Service of Mean Sea Level (PSMSL)	Admiralty Tide Table (ATT)	Satellite Altimetry Data	Gravity Field Model
• High accuracy • Low density • Long time-series	• Low Accuracy • High Density • Short time-series	• Envisat • Topex • Jason • GFO • ERS 1 & 2	• United Kingdom OSGM05

Figure 3 shows the utilization of VORF and GPS in the bathymetry data processing. There are various problems in the current method in bathymetry data processing such as, in terms of complexity due to the onshore and offshore location, as well as the process is time-consuming. Furthermore, in terms of accuracy, since the co-tidal chart has limited resolution and area derived from limited data, it is not accurate. Besides, the data from seabed gauges are very expensive. Lastly, in terms of inconsistencies, the current practices by using chart datum that is poorly defined and thus can lead to discrepancies [15]. The benefit of VORF is that it can increase the rate of deployment for any hydrographic survey works. Furthermore, VORF can also be used reference for quality check and quality control in by hydrographers and mariners. Besides that, VORF also allows a quick response by the marine authorities in case of emergencies in the offshore or coastal region [10, 16].

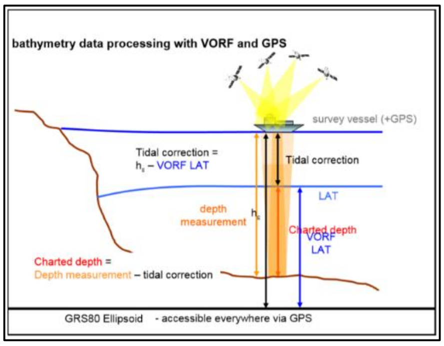

Figure 3. Utilization of VORF and GPS in bathymetry data processing [16]

2.3 *Continuous Vertical Datum for Canadian Water (CVDCW)*

The Continuous Vertical Datum for Canadian Water (CVDCW) was developed by Canadian Hydrographic Services (CHS) in collaboration with the Canadian Geodetic Survey (CGS) in 2010 [17]. The main objective of CVDCW is to establish a reference surface that interrelates the Chart Datum (CD) to the national geodetic reference frame. The data used to develop CVDCW are sea-level trends for 19 years, Global Ocean Model, satellite altimetry, Canadian Gravimetric Geoid Model 2013, and Global Navigation Satellite System (GNSS) [18]. The study area includes five regions which are the Pacific Coast, The Hudson Bay, Saint Lawrence Estuary, The Arctic and the Northwest Atlantic [19]. Among the hydrographic datum that can be derived from CVDCW are illustrated in Table 2.

Table 2. Tidal datum derivation from CDVCW [19]

No	Hydrographic Datum	Description
1	CD	Chart Datum
2	HHWLT	Higher High-Water Large Tide
3	MHHW	Mean Higher High Water
4	MHW	Mean High Water
5	MWL	Mean Water Level
6	MLLW	Mean Lower Low Water
7	MLW	Mean Low Water
8	LLWLT	Lower Low Water Large Tide

The tidal data interpolation from a total of 1266 tide gauge stations, which is a summation of 423 stations connected with GNSS, and 41 permanent stations, were conducted by using Lagrangian interpolation algorithm to cover the region between the coastal area and offshore region [20]. The tidal observation was recorded starting from 1960, where the tide gauge stations data varies from 10 days up to 100 years. Furthermore, there were a total of 10 up to 69 tidal constituents derived from each tide gauge stations. The modelling stages of CDVCW layers are as shown in Figure 4 [21].

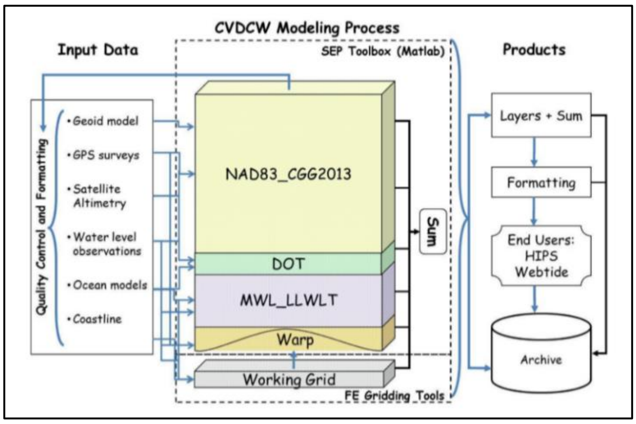

Figure 4. Process of modelling the CVDCW [21]

Figure 9 illustrates all the data individual layers for the development of CDVCW. The layer involves the Geoid height (N), Dynamic Ocean Topography (DOT), Tidal regime, and Warp (the difference layer). The purpose of each layer was described briefly before the combination of all layers to create CDVCW.

Table 3. All the layers in the processing stages in developing CVDCW [20, 21]

No	Layers	Description
1	Geoid Height (N)	• Represent the Mean Sea Level (MSL) • Canadian Gravimetric Geoid 2013 (CGG2013) was used. • CGG2013 define the Canadian Vertical Datum since 2013.
2	Dynamic Ocean Topography (DOT)	• DOT was obtained from the estimated ocean circulation models. • DOT was used to estimate the variation between Mean Water Level (MWL) and CGG2013.

		• Comparison between DOT from tide gauge and satellite altimetry. • When all DOT layer are c4ombined with Geoid layer, MWL with respect to Ellipsoid are obtained, aka Mean Sea Surface (MSS).
3	Tidal Regime	• Combination of MWL and LLWLT • Integration of water level from hydrodynamic ocean circulation model between the station and offshore.
4	Warp (The Difference Layer)	• Combination of all layers will produce the continuous model for Lower Low Water Level Tide (LLWLT) with respect to NAD83 (CSRS) reference surface also known as SEP_{LLWLT}. • SEP is necessary for the hydrographic survey from bathymetry reduction process on nautical charts and tide table. • The Warp layer will honour CD at coastal area, in the transition between SEPCD returning to SEP_{LLWLT} in a deeper water level.

The final summary after combining all the layers that correlating the Chart Datum (CD) to the North American Datum 1983 (NAD83), as the final CVDCW for all Canadian water (height in metres) with respect to the reference surface from GRS80 ellipsoid are illustrated in Figure 5 [21].

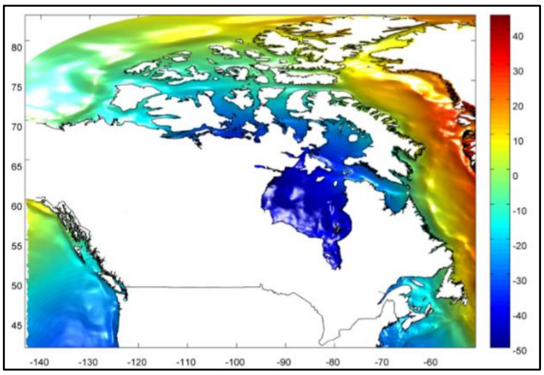

Figure 5. The final CVDCW for all Canadian water (height in metres) with respect to the NAD83 (CSRS) reference surface from GRS80 ellipsoid [21]

2.4 Vertical Reference Frame for Netherlands (NEVREF)

The Netherlands Vertical Reference Frame (NEVREF) was developed by the collaboration between the Netherlands and Belgium in 2018. The main objective of NEVREF is to acquire the high accuracy of quasi-geoid at centimetres level accuracy and Lowest Astronomical Tide (LAT) at a decimetres level accuracy respectively [22]. NEVREF also allows a precise vertical datum transformation for the land and sea area. NEVREF are divided into two categories which are Netherlands Quasi-Geoid 2018 (NLGEO2018) model and also Netherlands Lowest Astronomical Tide 2018 (NLLAT2018) model [22]. The data acquisition for NEVREF consists of satellite altimetry, tide gauge stations, Global Navigation Satellite System (GNSS), Hydrodynamic Tide Model and Gravimetric data [23]. The parameterization of the quasi-geoid is conducted by using spherical radial basis functions. And afterwards, all the parameters are estimated by using weighted least squares. The residual terrain modelling was performed by using Tesseroid (TS) software. As for the data acquisition for NLLAT2018, the tidal data was derived from 31 tide gauge stations. The approaches the data acquisition is as shown in Figure 6 [23].

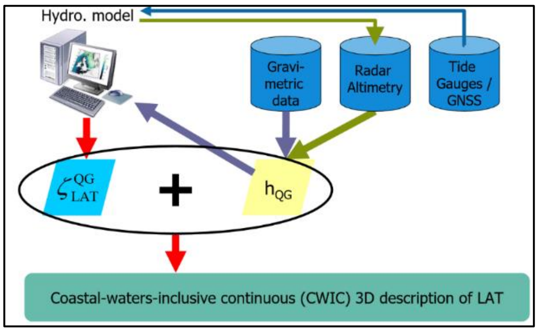

Figure 6. Data acquisition stages in developing NEVREF [23]

Hence, the final product of NLGEO2018 and NLLAT2018 are illustrated in Figure 7 below.

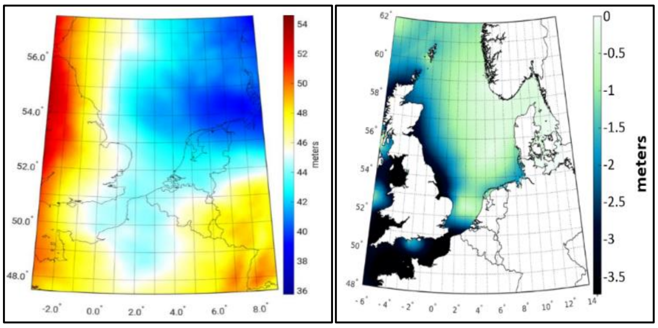

Figure 7. The final product of NLGEO2018 (left) and NLLAT2018 (right) [23]

2.5 Saudi Continuous Chart Datum (SCCD)

Saudi Continuous Chart Datum (SCCD) was developed by Hydrographic Surveying Department of King Abdul Aziz University, in collaboration with the Saudi Coastal Mapping and Monitoring Research Group (SCM2RG) in 2019 [24]. The main objective is to establish a consistent and continuous chart datum (CD) for the Kingdom of Saudi Arabia (KSA) by selecting the Arabian Gulf as a case study. The layer of separation model for SCCD is as shown in Table 4 [25].

Table 4. Separation models for SCCD development [25]

No	Separation Layer	Description
1	LAT to MSL	WebTide Based Triangulated Irregular Network (TIN) WebTide Tidal Analysis & Prediction software
2	LAT to WGS84	Use the Geoid model (EGM08) and Mean Dynamic Topography (DTU15)
3	CD to WGS84	Tidal data interpolation using a Kriging interpolation algorithm

The WebTide Prediction Tools, developed by Bedford Institute of Oceanography (BIO). It can perform data processing for Diurnal and Semi-Diurnal tide, producing various tidal constituent such as M2, K1, M3, M4, M6, MS4, N2, O1 and S2 for tidal prediction [24, 25]. The Kriging interpolation technique fits a mathematical function to a specific number of known control points to calculate the estimated interpolated value for each coordinate on the grid models. The accuracy of SCCD is approximately 0.13 metres [25]. Figure 8 shows the overall bathymetry for Saudi Arabia covered by SCCD.

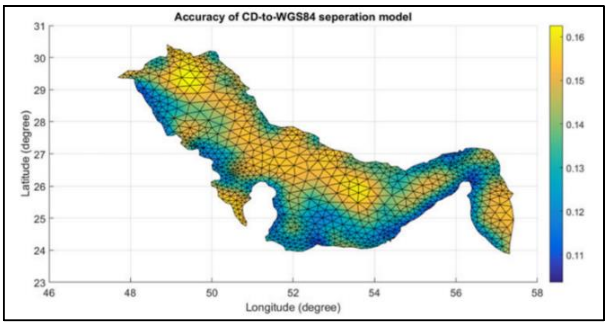

Figure 8. Overall bathymetry for Saudi Arabia using SCCD [25]

3. Results and Discussion

The comparison between all previous continuous hydrographic datum in terms of their accuracy, data sources, interpolation technique, data sources, and products are as shown in Table 5.

Table 5. Comparison of previous continuous hydrographic datum

	BATHYELLI	VORF	CVDCW	NEVREF	SCCD
Year	2005	2009	2010	2018	2019
Accuracy (cm)	± 10	± 10	± 10	± 10	± 13
Data Sources	Hydrographic Mean Sea Surface LAT Vertical Datum IGN69 European Quasi-Geoid Model EG97	Permanent Service of Mean Sea Level (PSMSL) Satellite Altimetry ATT Gravity Field Model (OSGM05)	Ocean Model Sea Level GNSS Satellite Altimetry Canadian Gravimetric Geoid Model 2013	Gravimetric Data Tide Gauge & GNSS Hydrodynamic Tide Model Radar Altimeter	Tide Gauge Geoid Model (EG08) Hydrodynamic Tide Model
Data Interpolation	None	None	Lagrangian	None	Kriging
Satellite Altimeter	Yes	Yes	Yes	Yes	None
DEM	None	None	None	None	None
Geoid Model	European Quasi Geoid Model 1997	UK Geoid Model 2005 (OSGM05)	Canadian Gravimetric Geoid Model 2013 (CGGM2013)	Gravity Observation Combination 2005 (GOCO05S)	Earth Gravitational Model (EGM08)
Products	CD	HAT MHWS MSL MLWS LAT CD	CD HHWLT MHHW MHW MWL MLLW MLW LLWLT	Quasi-Geoid LAT	CD

As shown in Table 5, the accuracy of all continuous hydrographic datum ranges from ±10 to ±13 centimetres, therefore it can be stated that there are still improvement that can be made to enhance the accuracy up to millimetres level. Furthermore, with the advancement in high frequency coastal altimetry currently, that is capable of capturing geophysical parameters near the coast accurately, will definitely provide a more reliable and precise derivation of hydrographic datum rather than only using conventional satellite altimetry.

4. Conclusion

In conclusion, the development of an accurate and continuous hydrographic datum of the coastal area is necessarily essential as it will result in an accurate and precise hydrographic datum determination for any hydrographic survey works. With the development of BATHYELLI, VORF, CVDCW, NEVREF and SCCD, the establishment of hydrographic datum for their respective region yields a very reliable and precise result. All in all, the future significance of the integration of tide gauge station, coastal altimetry technique, GNSS Levelling, and DEM Model can also become another precise method in developing a continuous hydrographic datum along the coastal area. The final goal is to develop a surface connecting hydrographic datum to the national geodetic reference frame which captures the relevant spatial variability which is applicable along the coast of Malaysia for any hydrography survey, permit the definition of coastline and intertidal zone on a national scale, help define maritime boundaries, marine cadaster and claims to sovereignty, serve as a baseline for sea-level rise and related climatic change adaptation strategies and will also act as a key for coastal infrastructure maintenance and development.

Acknowledgement

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