Vertical Datum Separation Models for the British Columbia Coast

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SUMMARY

With the establishment of modern navigation and hydrographic surveying technologies, the Canadian Hydrographic Service (CHS) recognised the need to establish a continuous vertical datum for Canada's navigable waters. In 2009 the Continuous Vertical Datum Canadian Waters Project (CVDCW) project was initiated, building on earlier work. This paper describes the present status of the Pacific separation model component of the national CVDCW project. Work for the Pacific coast was initiated in 2010 with a proof of concept exercise followed by model versions based primarily on sparse, shore based tide gauges and offshore pressure gauges with spot enhancement using tidal model data. The most recent work is based primarily on the NEP28 tidal model of Foreman et al., (2000) and includes data from tidal stations. Limitations of the available tidal models meant that two tidal models are required to provide the desired coverage of the British Columbia coast. The process to create the models and the resulting models of the separation surfaces between present Chart Datum (CD) and the GRS80 ellipsoid in the NAD83 (CSRS) reference frame, as well as CD and CGVD28 are presented. The plan for ongoing work is to generate other separation surfaces such as for high water datum (HW), e.g. CD_{LAT} – NAD83 (CSRS), HW_{HAT} – NAD83 (CSRS), in addition to refining existing separation models as more data become available. These surfaces are intended to improve the efficiency of nautical surveys and other government operations, the maintenance of vertical datum for Canadian nautical charts, electronic navigation and the integration of terrestrial and marine data.

Key words: hydrography, chart datum, vertical datum, datum separation, datum surfaces

1. INTRODUCTION

With the establishment of modern navigation, hydrographic surveying and charting technologies, the Canadian Hydrographic Service (CHS) recognised the need to establish a continuous vertical datum for Canada's navigable waters as compared to the existing series of tidal station based, discontinuous vertical datum values. The enabling technology, Global Navigation Satellite System (GNSS) navigation and surveying and the enabling infrastructure, a stable, globally accessible reference frame, both reached maturity at the same time as the recognition of the need to better manage height datum issues in the coastal zone. Several national organizations, such as CHS (CHANNEL), NOAA (VDATUM), UKHO (VORF) and Australia (AUSHYDROID) have already developed operational, extensive and mature realizations of the necessary surfaces and transformations (FIG, 2006; Dodds et al., 2012).

In 2009 the Continuous Vertical Datum Canadian Waters Project (CVDCW) project was initiated by the CHS, building on earlier localised work in the various regions (Lefaivre et al., 2010). Robin et al. (2012) provide updated details on methods and accuracy. Separation models for Canada's Pacific coast were initiated in 2010 with a proof of concept followed by more detailed model versions based primarily on sparse shore based tide gauges, offshore pressure gauges plus localised enhancement with tidal model data to fill major gaps. Both chart datum (CD) to NAD83 (CSRS) separation and CD to CGVD28 (Canadian orthometric height datum) separation surfaces were modelled.

The results presented here summarise the present status of the CHS Pacific separation model component of the national CVDCW project. The CHS Pacific most recent work is based on the NEP28 tidal model of Foreman et al., (2000) and includes data from tidal stations. Limitations of the available tidal models mean that two tidal models will be required to provide the desired coverage of the British Columbia (BC) coast.

The immediate goal is to have a Pacific operational CD_{LLWLT} – NAD83 (CSRS) separation model for the 2012 survey season. Longer term, additional separation models will be created as part of the national project (e.g. CD_{LAT} – NAD83 (CSRS), HW_{HAT} – NAD83 (CSRS)) and existing separation models will be refined as additional data become available.

2. BACKGROUND

2.1 History

At the present time, the Canadian Hydrographic Service maintains a network of 1,656 tidal stations throughout the country. CD, the vertical reference for nautical charts has been established for each tidal station. However, our knowledge of CD is not well defined spatially because it is determined on a point basis and the stations are widely spaced. CD can be interpolated between sites using tidal propagation models or geostatistical techniques such as kriging, with an associated uncertainty that is sometimes difficult to assess. Of the tidal stations, only 88 of are equipped with active, permanent water level gauges. At the stations the physical integrity of benchmarks must be constantly monitored for local ground or infrastructure movement and new benchmarks must be installed to replace those that have disappeared or been damaged.

A GNSS positioning system can be used to link CD at tidal stations to a global reference system (e.g., WGS84), and spatial modeling techniques can interpolate CD continuously over a large area (e.g., the Gulf of St. Lawrence, the British Columbia coast). In addition, because global reference systems are commonly used by various countries, they can be relied upon as well defined, permanent references. In this way, improved seamless vertical accuracy between two national reference systems can be achieved.

Bathymetric surveys presently require the deployment of local water level gauges to provide the parameters to reduce bathymetric data for varying water levels. Such a local gauge network would not be required if vertical datum separation surfaces are available. Vertical reference surfaces and accurate GNSS positioning provide simple and accurate vertical survey control. The use of continuous vertical reference surfaces reduces the complexity and costs of bathymetric surveys, providing greater efficiencies and more accurate data, products and services for navigators and users in general.

A number of countries have already adopted this process, enabling them to rationalize the costs of operating a tidal station network and carrying out hydrographic surveys (FIG, 2006; Dodds et al., 2012). To date the Canadian Hydrographic Service has made progress in this field. Natural Resources Canada is also on the point of adopting a similar spatial reference system as a height reference for Canada, to replace the present CGVD28. The maritime vertical reference system can then be harmonized with the vertical land reference system permitting greater accuracy in shoreline engineering, navigation and the prediction and mitigation of marine natural hazards.

2.2 CHS Pacific Surveys

2.2.1 Hydrographic Surveys

Historically hydrographic surveys in marine waters have reduced the measured bathymetry to local CD using either directly or indirectly observed tides. In some cases, different surveys have used separate tidal stations for tidal reductions in the same general area. Both the desire to move to a seamless vertical datum and the desire to reduce the support activities required to install, remove and process tidal data, have driven the need for an ellipsoid referenced CD for CHS Pacific. Some testing with small, localised surveys on the BC coast has been encouraging.

2.2.2 GPS Tidal Surveys

A key element in validating the vertical datum model results is the availability of independent measurements of the CD elevation on a defined ellipsoid. GNSS based measurements of the elevation of tidal benchmarks provides such a measurement. In 2009 a more extensive observational program was started after an earlier limited CHS Pacific GPS observation campaign. As part of the national CVDCW project, the work is ongoing for the BC coast, with several more years of work yet to be done. As of March 2012, 87 sites have been occupied (Figure 1).

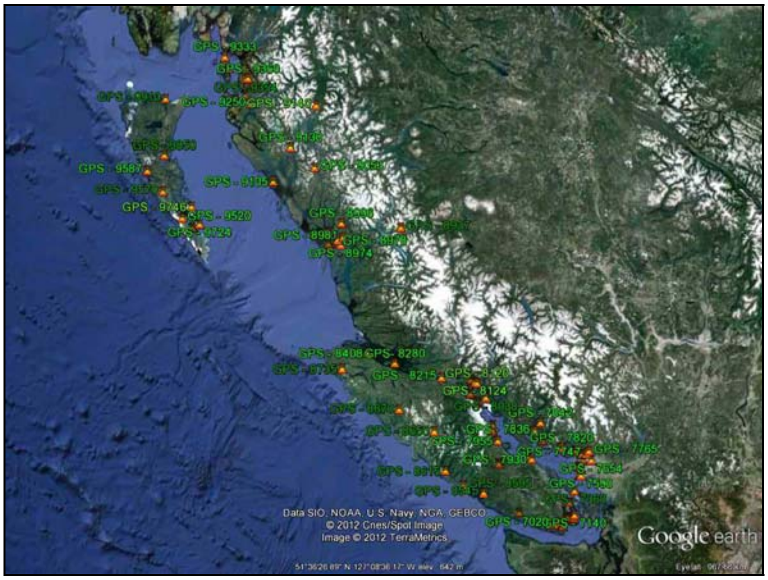

Figure 1. Completed GPS benchmark surveys at British Columbia tide stations.

2.3 CHS Pacific Concept/Approach

2.3.1 Tools

The overall approach is to use existing data and tools to expedite development and the creation of useable results. This is done to minimise development time and costs. Thus off-the-shelf software that is available in-house is utilised if it could accomplish the required tasks. The tools include commercial software (Caris BASE Manager/BDB, Microsoft Excel, TextPad); government developed software (NRCan GPS-H, DFO/CHS TCWL Tools); free software development tools (AWK, Perl).

2.3.2 Data

In keeping with the rapid development approach, we are fortunate to have access to previous tidal model results (Foreman et al., 2000) and dynamic ocean topography or sea surface topography (Foreman et al., 2008). Nearly all of the BC coast tidal constituents were immediately available although most of the submerged tide gauge data required further processing. Twenty-four hour GPS observations on tide station bench marks are used to ground truth the derived separation model results. Results available prior to March 2012 are incorporated.

2.4 Tidal Models and Ocean Dynamics

2.4.1 Overview

In Canadian marine water, vertical datums used in hydrography are based on tidal observations. In order to establish a continuous vertical datum surface between widely spaced tide gauge sites and particularly to extend the datum surface into the offshore, the use of hydrodynamic tidal models is necessary. For the BC coast, the results of many years of extensive tidal modelling are available, obviating the need to develop tidal models for this project. Two regional tidal models for the North-East Pacific have been used in the CVDCW project, referred to here as the NEP28 and the NEP35 models. The results of two models need to be blended to achieve full coverage because a single validated model for the complete BC coast is not available.

2.4.2 NEP28 Tidal Model

The primary tidal model we used (here referred to as NEP28) is described in detail by Foreman et al. (2000). This model is a spherical-polar coordinate version finite element model which has also been used by NOAA to drive more localised models for the development of the VDatum software (Dodds et al., 2012). NEP28 provided amplitude and phase values for the eight tidal constituents (M_2, S_2, N_2, K_2, K_1, O_1, P_1, and Q_1) at each model grid point. The model vertical reference is a geoid, hence at all grid points, $Z_0 = 0.0$ m. Figure 2, showing the 51,330 model grid points, illustrates the full extent of the NEP28 model with SW limit of 30° N, 180° W. In work described here, a subset of the model results is used, in the range of 45.5° N to 56.5° N and 122.4° W and 143.0° W, consisting of 30,335 grid points.

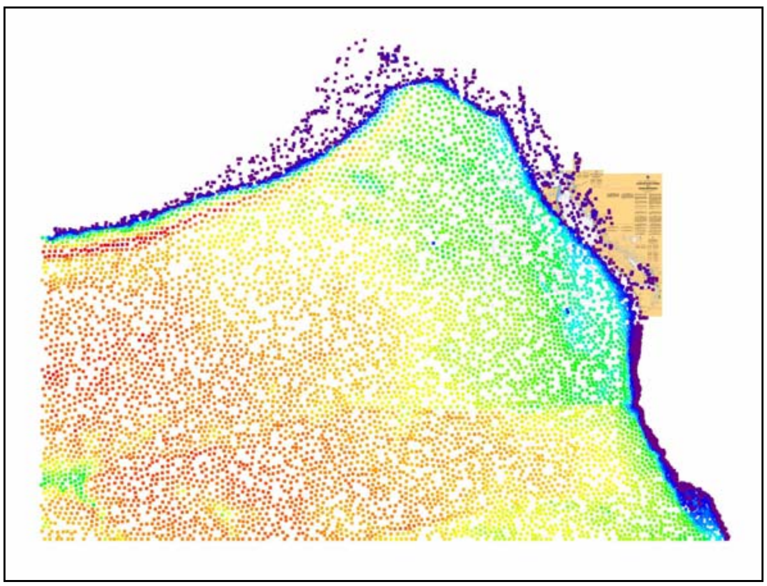

Figure 2. NEP28 full model domain, colour coded as depth from violet (0 m) to magenta (6910 m).

Although NEP28 had the advantage of having generally good agreement with observations, particularly on the open coast (Foreman et al., 2000), a disadvantage for our use is the incomplete coverage of the British Columbia (BC) coastal waters. A particularly large gap exists in the northern Strait of Georgia and many of the passages and inlets of the southern BC coast. See Figure 3 for example. This requires the use of another model to compensate for the gaps in the NEP28 coverage.

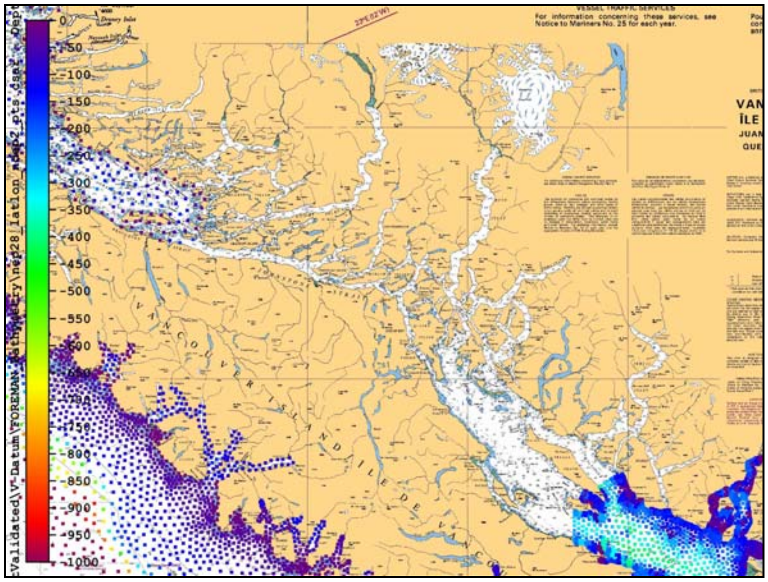

Figure 3. An example of NEP28 model coverage limit near southern Texada Island in the northern Strait of Georgia. Left hand scale refers to depths in metres.

2.4.3 NEP35 Tidal Model

The second tidal model we use (here referred to as NEP35) is described in detail by Foreman et al. (2008). This model is also a spherical-polar coordinate version finite element model. The full model consists of 97,959 grid points (Figure 4). With the greater number of grid points, NEP35 is more complete in its coverage of the BC coast in addition to better resolving areas of spatially variable bathymetry. Although NEP35 has more grid points than NEP28, many of the grid points are coincident. Given the coverage of NEP35, ideally it would be the sole model used in deriving the vertical datum separation surfaces. However, some initial comparison of model results with observations, indicated differences of ±0.5 m or more in the computed datum values. Although further work is planned, the NEP35 tidal constituents have not been optimised to date (Foreman, personal communication, 2011).

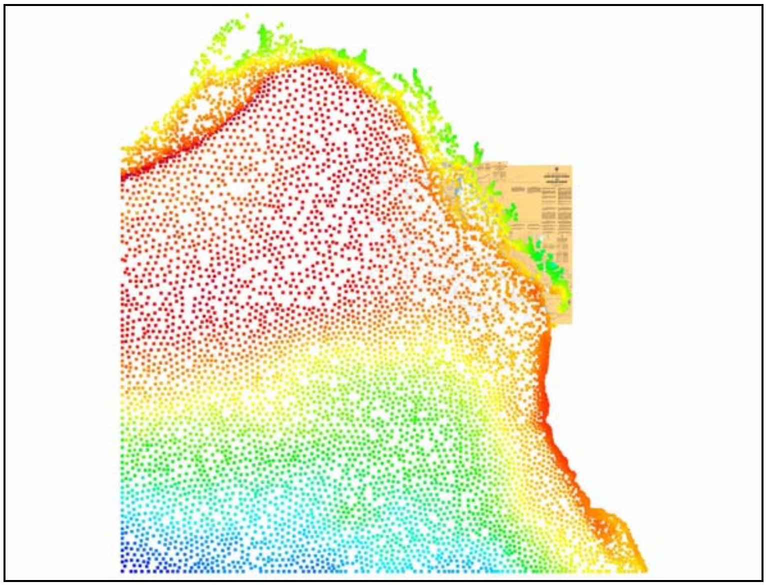

Figure 4. NEP35 model domain, colour coded as annual mean dynamic ocean topography (DOT) from violet (0.516 m in the southwest) to magenta (0.006 m in the north).

2.4.4 Dynamic Ocean Topography

As the NEP28 and NEP35 models do not include the dynamic ocean topography (DOT), also referred to as sea surface topography, it is necessary to include DOT as a separate parameter. The mean dynamic ocean topography used in the computations is that of Foreman et al. (2008). The DOT is available as gridded seasonal average values for summer and winter on the same grid as NEP35 tidal model (Figure 4). DOT values for autumn and spring are not available but are in process (Foreman, personal communication, 2011), hence summer and winter values are averaged to derive an estimate of the annual mean DOT at each grid point.

3. SEPARATION MODEL DEVELOPMENT

3.1 Background

3.1.1 Vertical Datums

In tidal water the target datum (TD) for CD is lower low water, large tides (LLWLT). At many tide stations on the Pacific coast LLWLT ≠ 0.0, i.e. TD ≠ CD. This became evident after CD was established and subsequent better or longer water level time series were obtained. Also at some sites CD has changed over time, hence to precisely reference CD, it needs to be referred to an epoch. For convenience, we will use the short form CD as denoting the present implementation of chart datum (CD2005). Also, the tidal model results are referenced to a geoid not to CD.

3.1.2 Notation

Following the convention used in geodesy (NRCan, 2012) and particularly by the CVDCW project, the notation used is as follows.

h is the elevation of a point or surface relative to an ellipsoidal reference frame; *H* is the elevation of a point or surface relative to a geoid (orthometric height), N is a geoid height. Using the convention of the CVDCW project, a superscript denotes the reference frame (reference datum) and a subscript denotes the target datum unless otherwise stated, e.g. $h_{CD}^{NAD\,83}$ refers to the elevation of CD relative to the NAD83 reference frame.

Present CD in tidal waters is generally established via observations of the tide and in turn determining a mean water level relative to CD, usually denoted as Z_0. Using the above notation we can write:

$$Z_0 \equiv Z_0^{CD} \equiv H_{MWL}^{CD} \tag{1}$$

where MWL is mean water level.

3.1.3 Equations and Relationships

See Figure 5 for a sketch of the various surfaces and datums under consideration. Using the notation from 3.1.2, the relationship between ellipsoidal height and orthometric height of point *P* can be stated as:

$$h_P^{NAD\,83} = H_P^{CGVD\,28} + N_{CGVD\,28}^{NAD\,83} \tag{2}$$

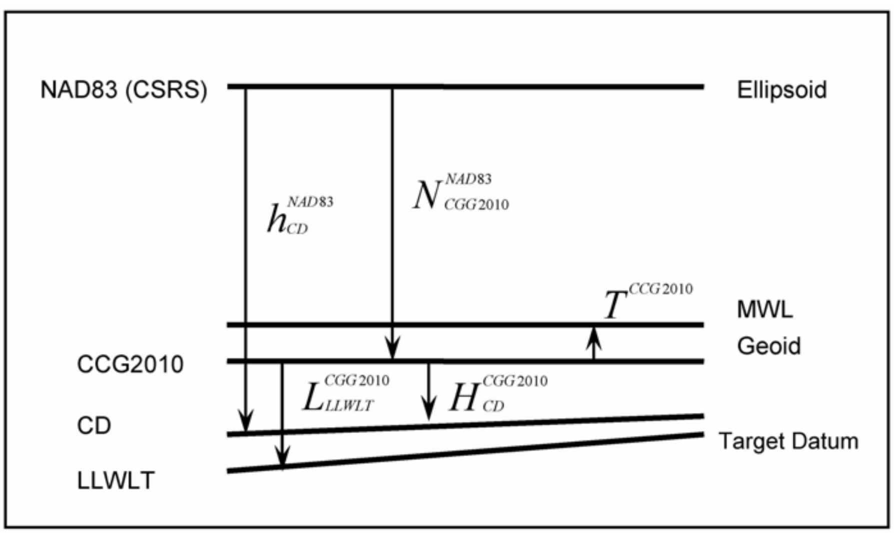

Figure 5. Vertical datum and reference surfaces.

Similarly for the CGG2010 geoid:

$$h_{P}^{NAD\,83} = H_{P}^{CGG\,2010} + N_{CGG\,2010}^{NAD\,83} \quad (3)$$

At tide stations the orthometric height of CD on CGG2010 can be expressed as:

$$H_{CD}^{CGG\,2010} = T_{MWL}^{CGG\,2010} - Z_{0}^{CD} \quad (4)$$

where $T_{MWL}^{CGG2010}$ is the dynamic ocean topography (DOT) relative to the CGG2010 geoid and the minus sign in the equation is to compensate for fact that Z_0 is referenced to CD. Away from tidal stations, the tidal model results are used to estimate CD values. Thus for the NEP28 model we have:

$$H_{CD}^{CGG\,2010} = T_{MWL}^{CGG\,2010} + D_{CD}^{CGG\,2010} \quad (5)$$

where $D_{CD}^{CGG2010} = L_{LLWLT}^{CGG2010}$ is the target datum (Figure 5) with LLWLT computed from the NEP28 constituents. Combining equations 3 and 4 for the case of CD at tide stations gives:

$$h_{CD}^{NAD\,83} = T_{MWL}^{CGG\,2010} - Z_{0}^{CD} + N_{CGG\,2010}^{NAD\,83} \quad (6)$$

and for the tidal model grid points combining equations 3 and 5 gives:

$$h_{CD}^{NAD\,83} = T_{MWL}^{CGG\,2010} + D_{CD}^{CGG\,2010} + N_{CGG\,2010}^{NAD\,83} \quad (7)$$

Then rewriting equation 2 gives:

$$H_{CD}^{CGVD\,28} = h_{CD}^{NAD\,83} - N_{CGVD\,28}^{NAD\,83} \quad (8)$$

where h_{CD}^{NAD83} is computed from equation 7.

Although CGVD28 is not an accurate geoid surface, at present it is the Canadian orthometric height datum.

3.2 Process Steps

3.2.1 NEP28 calculations

Several steps are required in order to use the NEP28 tidal model results. Existing in-house software tools (both CHS developed and commercial off-the-shelf) are used (as far as practical) to develop the separation models.

The NEP28 model amplitudes and phases are first extracted for the region of interest and reformatted for compatibility with the TCWL Tools suite. The tidal prediction tool in TCWL Tools is that of Foreman (1977). For each NEP28 grid point, 19 years of high and low water times and heights are predicted. From these predictions, various target datum values are computed for the model grid, including LLWLT (i.e. $D_{CD}^{CGG2010}$ in equation 7).

Although the NEP28 model individual constituents generally shows good agreement with measurements (Foreman et al., 2000), the eight constituents of the model underestimate the tidal range at a grid node. Comparison of computed large tide ranges at 93 tide gauge sites with adjacent NEP28 model points indicated that on average the range from the tide stations is 4.3% larger than the range computed from the model. Hence the computed target datum values from the model are scaled up using ratio of average range (tide station to model) prior to computing the separation surface.

3.2.2 DOT calculations

The DOT summer and winter values are averaged at each grid point to derive an estimate of the annual mean DOT at each grid point. A simple program is then used to extract the closest DOT value for each NEP28 model grid point. Interpolation is not used as adjacent DOT values typically differed by 0.002 m or less. As the DOT values are referenced to an arbitrary geoid (Foreman et al., 2008), a vertical shift is applied next. The DOT values for the BC coast are relative to a geoid such that the mean DOT is equal to 0.0 m at Station Papa (50 N, 145 W; Foreman et al., 2008). By comparing GPS derived h_{CD}^{NAD83} from tide stations with NEP28 derived values at the tide station locations, a mean shift value is calculated and applied to reference the DOT values to the CGG2010 geoid. This gives $T_{MWL}^{CGG2010}$ at the model grid points.

3.2.3 Geoid Height

The geoid heights are calculated for the model grid by using the NEP28 grid point latitude and longitude co-ordinates as input to the NRCan GPS-H (version 3.1) program (NRCan, 2011). The latest available geoid, CGG2010 (NRCan, 2012), is used as the reference geoid for computing the CD height in the NAD83 (CSRS) reference frame. This gives $N_{CGG2010}^{NAD83}$. Similarly, GPS-H is used to compute the geoid heights for CGVD28 in order to calculate the CD height on CGVD28, i.e. N_{CGVD28}^{NAD83}.

3.2.4 Ellipsoidal Height of Chart Datum

Using equation 7 and the values described in the preceding sections, the ellipsoidal heights are calculated for the model grid. This irregular grid is used to create a triangular irregular network (TIN) and using linear interpolation, a regular gridded surface of the ellipsoidal height of CD is created. Caris BASE Manager 4.0 is the tool used for this process.

3.2.5 CGVD28 Height of Chart Datum

Using equation 8 and the values described in the preceding sections, the orthometric heights of CD are calculated for the model grid points. Similarly to the ellipsoidal height of CD, a regular gridded surface is generated for the CD separation on CGVD28.

4. RESULTS

4.1 NAD83 to Chart Datum Separation

Figure 6 depicts the resulting h_{CD}^{NAD83} surface (Chart Datum relative to NAD83 (CSRS)). The results presented here do not include any from the NEP35 model. As may be expected, due to the large geoid undulation relative to changes in tidal range (i.e. CD variation relative to mean water level), the most noticeable feature is the geoid undulation. In the area depicted, h_{CD}^{NAD83} varies from +2.44 m in the northwest to -27.66 m in the southeast. In a more localised area, the direction of the maximum gradient can vary significantly. For example, in Saanich Inlet (south-eastern Vancouver Island) the maximum gradient is east-west whereas in English Bay (Vancouver, BC) the maximum gradient is north-south.

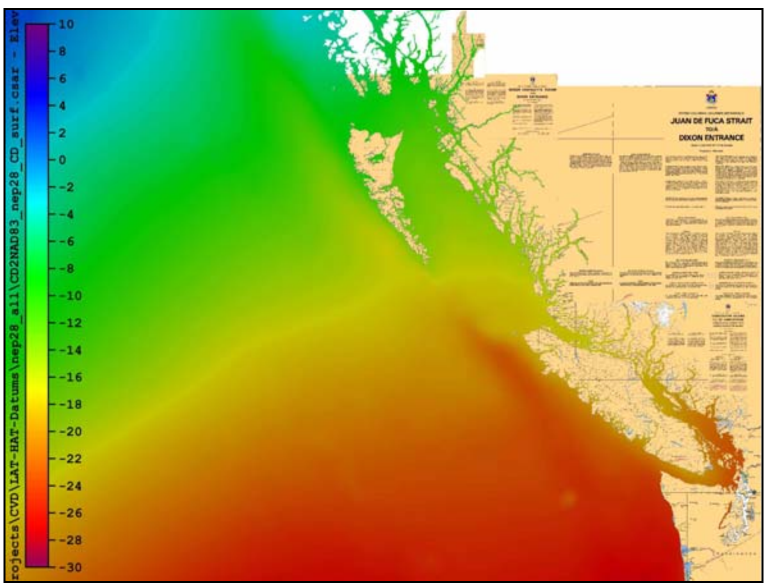

Figure 6. Elevation of Chart Datum (m) in NAD83 (CSRS) reference frame for the British Columbia coast. Negative values indicate CD falls below the ellipsoid.

4.2 CGVD28 to Chart Datum Separation

The H_{CD}^{CGVD28} surface (Chart Datum relative to CGVD28) is depicted in Figure 7. For this separation surface the dominant variation reflects changes in tidal range (i.e. CD variation relative to mean water level). In the area depicted, $H_{CD}^{CGVD\,28}$ varies from -1.62 m near Sooke in the Juan de Fuca Strait (in the southeast) to -4.15 m in Portland Canal near Stewart, BC (in the north, excluding Alaskan waters). In localised areas, the gradient can vary significantly. For example, between the east and west coast of Haida Gwaii, particularly through Skidegate Channel which separates Moresby and Graham Islands.

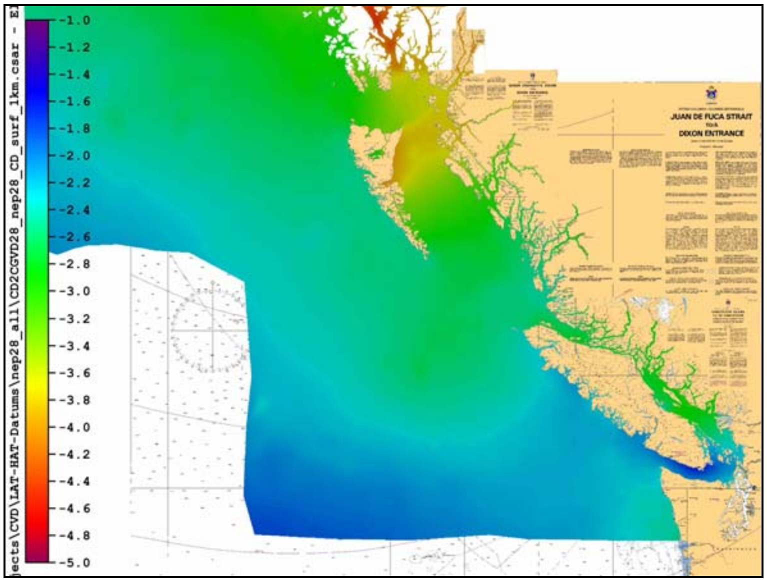

Figure 7. Chart Datum elevation (m) on CGVD28 for the British Columbia coast. Negative values indicate CD falls below CGVD28. The blank area in the southwest and south of the image coincides with the area where CGVD28 is not defined.

4.3 Accuracy

A preliminary comparison with observations indicates a bias in the derived $h_{CD}^{NAD\,83}$ surface. The comparison values are from the tide stations (either from GPS measurements or tide gauge measurements). Differences are computed between the tide station values and the co-incident $h_{CD}^{NAD\,83}$ surface. The initial 97 comparison values gives (mean ± standard deviation) 0.10 ± 0.27 m with a maximum of 1.79 m and a minimum of –0.27 m, i.e. the $h_{CD}^{NAD\,83}$ surface is biased to the low side. The differences are skewed to positive values with a few large values. Eliminating the outliers (more than three standard deviations from the mean) improved the results to 0.05 ± 0.16 m with a maximum 0.47 m and minimum –0.27 m. The largest deviation (1.79 m) is the result of the tidal model excluding a lagoon with a small tide range. Other significant contributions to the error budget are localised biases in the model. For example, on the south (USA) side of the Strait of Juan de Fuca, the NEP28 model appears to be over estimating the tidal range. Further analysis of errors, both bias and random, is presently underway.

5. SUMMARY AND FUTURE WORK

The project has successfully created a process for and produced CD_{LLWLT} – NAD83 (CSRS) and CD_{LLWLT} – CGVD28 separation models for the British Columbia coast. Further work is warranted to enhance and extend the results to date. These include:

- Undertaking a more detailed error analysis, removing systematic bias and minimising the remaining uncertainties.
- Improving CD_{LLWLT} – NAD83 (CSRS) separation model surface prior to the 2012 survey season by incorporating the results from the spring 2012 GPS campaign; incorporating additional results from good quality tide stations; enhancing the near-shore extent of the separation surface.
- Creating an improved CD_{LLWLT} – CGVD28 separation surface by incorporating results from the previous steps.
- Incorporating an associated uncertainty surface as part of each of the separation surface data sets.
- Creating high resolution, area specific separation surfaces for locations with large spatial gradients of the tides.
- Creating separation surfaces for other hydrographic datums, i.e. HW_{HHWLT} – NAD83 (CSRS), CD_{LAT} – NAD83 (CSRS), HW_{HAT} – NAD83 (CSRS), HW_{HHWLT} – CGVD28, CD_{LAT} – CGG2010, HW_{HAT} – CGG2010.
- Maintaining and enhancing the separation surfaces by regular updates of the surfaces through incorporating new data.

6. ACKNOWLEDGEMENTS

Thanks to Mike Foreman for generously providing the NEP28 and NEP35 model results and the dynamic ocean topography; the CVDCW project team for stimulating and fruitful discussions, in particular André Godin and Catherine Robin for ideas on techniques; Anne Ballantyne for quick implementation of enhancements to TCWL Tools and processing of submerged tide gauge data; the staff of the CHS Pacific Tides, Currents and Water Levels section for the acquisition and processing of GPS benchmark observations; David Lilly for the refinement of techniques for the initial separation models and processing of data from NOAA tide sites; Karen Cove of Caris for providing BDB 4.0 Beta. This work was funded in part by the Continuous Vertical Datum Canadian Waters Project.

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BIOGRAPHICAL NOTES

Bodo R. de Lange Boom obtained his M.Sc. (Univ. of British Columbia) in physics, specialising in oceanography. After undertaking oceanographic work on all three Canadian coasts in private industry, in 1989 he joined the Canadian Hydrographic Service in the Pacific Region, working first in the Tides and Currents section. He is presently an Engineering Project Supervisor of the Data Validation, Integration and Access unit of the Data Acquisition and Technical Support Division. His areas of interest include horizontal and vertical datum issues in tidal waters and integrating hydrographic and terrestrial data.

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