Mean Sea Level, Satellite Altimetry and Global Vertical Datum Realization

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Introduction

Over the past several decades, many different methods for defining a vertical reference system to be implemented all over the globe have been presented. The definition of such a global vertical reference system is complicated by accuracy and spatial coverage limitations of the traditional techniques, and the sea level variations affecting tide gauge and satellite altimetry measurements. This poster highlights the role of mean sea level and altimetric satellite measurements to the vertical datum definition issue. Since one of the major problems with the definition and subsequent acceptance or adoption of a globally defined datum is dealing with existing regional datums, the Canadian and North American (NA) situation are briefly presented first to illustrate some of the issues, and future plans, involved in vertical datum realizations. Then the most common approaches to vertical datum definition and realization are presented. Finally, details are given on the important role that mean sea level and satellite altimetry play in the realization of (i) regional vertical datums and (ii) the global vertical datum or World Height System.

The NA and Canadian Experience

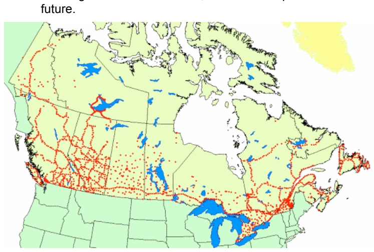
The North American vertical datum - NAVD88:

The current Height Reference System in the US is the North American Vertical Datum 1988 (NAVD88). The datum reference level was defined, through a minimally constrained adjustment of levelling observations in Canada, the United States and Mexico, with the tide gauge benchmark at Father Point/Rimouski, Quebec, held fixed at zero. There are still discrepancies between the east and west coasts, and Canada has not officially adopted NAVD88 as its vertical datum .

The current Canadian vertical datum - CGVD28:

The current Height Reference System in Canada is based on the Canadian Geodetic Vertical Datum 1928 (CGVD28), adopted in 1935. The datum reference level was defined, through an over-constrained adjustment, as the mean sea-level determined from data collected at 5 tide gauges on the east and west coasts. Over 80,000 precisely levelled benchmarks provide access to the datum; see picture below. CGVD28 has the following *problems*:

- The datum is only realized at benchmarks, located mostly in the south of the country, and some local datums have been developed, as well.
- The reference system has significant distortions and is not consistent with NAVD88.
- The physical network is very expensive to maintain because of the very large number of benchmarks.
- NRCan has performed no systematic maintenance of the levelling network since 1996, and none is planned for the future.

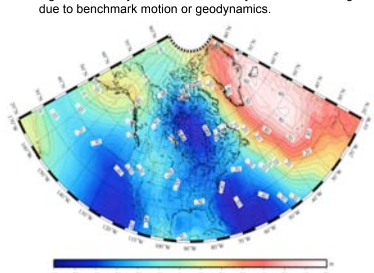


courtesy: GSD, NRCan

The planned (modern) Canadian vertical datum:

The new Height Reference System in Canada will be based on a geoid model, like the CGG2005 geoid shown below. This has several *advantages*:

- Much reduced costs as compared to spirit levelling and vertical network reobservation and readjustment.
- It would define the datum in relation to an ellipsoid, making it compatible with space-based techniques, such as GNSS and satellite radar altimetry.
- It will be easy to revise such a datum to accommodate new, more precise static geoid models and for any temporal variations of the geoid due to sea level change and post glacial rebound.
- It would allow easy access to heights above mean sea level throughout the Canadian territory.
- The new heights assigned to benchmarks will be of the highest accuracy, and could be easily revised for changes due to benchmark motion or geodynamics.



courtesy: GSD, NRCan

Vertical Datum Definition and Realization

Regional vertical datum - Five main approaches:

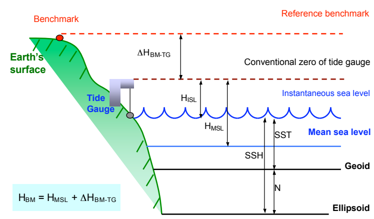
(i) Define the vertical datum by performing a free-network adjustment where only one point is held fixed. A correction factor is applied to the adjusted heights so that the mean height of all tide gauges equals zero. Relies on measurements from a single tide-gauge (see figure below); ignores mean sea level (MSL) observations made at other stations.

(ii) Define the geoid by MSL as measured by a network of reference tide gauges situated along the coastlines and fixing the datum to zero at these stations. Results in distorted heights; ignores movements of tide gauges; MSL is not an equipotential surface and geoid varies from it by a few metres (due to sea surface topography, SST).

(iii) Use the best model for the SST at the tide gauge stations and then adjust the network by holding MSL to zero for all tide gauges. SST models near the coast are not accurate enough; distortions are caused by poor models for MSL and SST in coastal areas.

(iv) Same as option (iii), but allow the reference tide gauges to 'float' in the adjustment by assigning them realistic a-priori weights. It will improve greatly with better models for SST and MSL, and their errors (from satellite altimetry).

(v) As in option (iv), but use estimates of orthometric heights derived from ellipsoidal heights and precise gravimetric geoidal heights. Relates the regional vertical datum to a global vertical reference surface (ellipsoid); aids in the realization of a World Height System (WHS).



Global vertical datum - Four main approaches:

(i) Pure oceanographic approach. Main problem with connecting regional vertical datums between continents separated by the ocean is the SST; models developed using geostrophic and steric levelling techniques; least reliable near coastal areas (where the 'datum connection' is).

(ii) Satellite altimetry combined with geostrophic levelling. Global geopotential model (GM), MSL and SST can be computed using altimetric data; Marine geoid; Geostrophic levelling used for extrapolation of SST at tide gauges.

(iii) The altimetry-gravimetry geodetic boundary-value problem (GBVP). Impractical due to data (GM, gravity, topography and altimetry) limitations.

(iv) Satellite positioning combined with gravimetry. Connection between GPS heights and levelled heights referred to a certain local vertical datum is utilized; combined adjustment of GPS/geoid/levelling data must be performed; limited by the achievable accuracy of ellipsoidal heights and the internal precision of the geoid model.

Global vertical datum realization:

Selecting a vertical datum based on a geoid model implies the acceptance of this geoid's (constant) gravity potential W_o as a fundamental parameter of the vertical datum. Also, $W_o = U_o$, where U_o is the gravity potential of the mean Earth ellipsoid. Then the height of any point P on the Earth's surface is defined by the potential difference between W at P and W_o, called the geopotential number $C_P = W_o - W_P$.

W_o is in a tide-free system and W_P is obtained by either

$W_P = U_P + T_P$ (from the solution of the geodetic BVP)

or

$W_P = W_o - C_P$ (from levelling plus gravity)

Datum realization is done by selecting a fundamental point (FP), usually at a tide gauge station, where C_{FP}=0, i.e., by selecting $W_{FP} = W_o = U_o$ = const., with U_o referring to, e.g., GRS80. W_{FP} can refer to either a single point or, preferably, be the average potential at many points. For example, a value that is averaged over the seas can be adopted. This value can be obtained from precise satellite altimetry measurements, such as, e.g., from TOPEX/POSEIDON observations, by satisfying

$$\Sigma(W - W_o)^2 = \text{minimum}$$

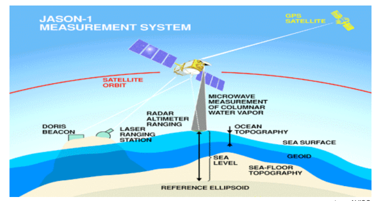
Frame realization is done through the (free) adjustment of all benchmark heights or geopotential numbers, reduced to a common epoch and zero-tide system. Result: normal heights H. From the geodetic BVP solution (or simply from a GRACE/CHAMP model) height anomalies ζ could be obtained at the same points. Then $h = H + \zeta$ and any discrepancies must be adjusted and distributed across the network. The procedure is the same if orthometric heights and geoid undulations N are used instead of normal heights and height anomalies, respectively. For sea surface heights (SSH), the relationship becomes SSH = SST + N.

Note: Over the oceans, and because the global SST average is not zero, $W_o \neq U_o$ and (SSH - SST) will not be identical to N obtained from the solution of the geodetic BVP; the difference is approximately $SST = (U_o - W_o)/\gamma$ and must be taken into account.

The Role of Satellite Altimetry

For a global vertical datum, or World Height System, the zero-level equipotential surface is the MSL. For the realization of such a WHS, we obviously need to combine

- best estimates of the MSL and other oceanographic models
- PSMSL tide gauge time series
- GPS/GNSS heights at tide gauges
- best gravimetric geoid models (from dedicated gravity satellite missions and other data).



courtesy: AVISO

Satellite altimetry can contribute directly to the following tasks:

- determination of MSL for the last two decades
- SSH/SST determination and removal from tide gauge and sea level data
- development of precise global geopotential models
- determination of marine geoid and gravity models for the solution of the geodetic BVP and improved GMs
- improved bathymetry determination, which in turn leads to better models of the marine geoid and gravity

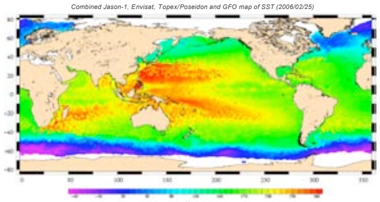
The most prevalent *advantages* that satellite altimetry offers in both the definition and realization phases, include:

- unprecedented near global coverage
- high spatial resolution
- consistent accuracy
- temporal continuity
- independent alternative to surface techniques
- measurements with respect to a geocentric reference frame
- indispensable for the ocean surface, sea level, ocean circulation and tides

There are some significant *shortcomings*, which prevent the exclusive use of altimetric data:

- limited temporal coverage. Only about 20 years of data currently available with all the missions combined - poor observability of long term trends
- poor performance in coastal areas
- observations on land - need a connection on boundary (coastlines) between land surface and ocean surface
- limited and uncertain polar coverage - what *exactly* is being recorded (depth of signal on snow, ice, glaciers)?

Combined Jason-1, Envisat, Topex/Poseidon and GFO map of SST (2006/02/25)



courtesy: AVISO

Concluding Remarks

Satellite altimetry offers high and consistent accuracy, coverage, and independent space-based measurements in a geocentric reference frame, all required for a practical realizable global vertical datum. In particular, precise determination of the SST is essential in establishing a WHS. With more missions planned for the future, the temporal resolution will improve and the altimetric database will increase.

The solution to the global vertical datum issue will involve a heterogeneous data set consisting of terrestrial measurements, satellite altimetry, global tracking networks, GNSS, dedicated gravity satellite missions, plus refined models and methodologies.

WHS must be established for a specific epoch and be accompanied by a temporal change model that accounts for the variations of the sea level and the Earth's surface and gravity field.

For the benefit of defining a global vertical datum, future altimetric missions should improve the large scale ocean variability observations, cover more of the polar regions, have more repeatability and improved across-track resolution. Multi-mission, simultaneous data processing will be essential to achieve these goals.

Nevertheless, tide gauges will remain necessary measurement tools and they must continue to be maintained, because they:

- are required in order to calibrate the satellite altimeters;
- have the capability of measuring more local variability in the oceans (higher frequency variations), which are needed for regional vertical datum definitions; and
- offer longer time series of data as there is more than 100 years of observations archived, whereas altimetry measurements have only been made for ~20 years. Therefore, it is impossible at this point in time to make long-term trend evaluations by strictly using altimetry data.

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