Natural Resources Canada / Ressources naturelles Canada

# Height Reference System Modernization

Natural Resources Canada (NRCan) has released the Canadian Geodetic Vertical Datum of 2013 (CGVD2013), which is now the new reference standard for heights across Canada. This height reference system replaced the Canadian Geodetic Vertical Datum of 1928 (CGVD28).

CGVD2013 is defined by the equipotential surface ($W_0$=62,636,856.0 $m^2s^{-2}$), which represents by convention the coastal mean sea level for North America. This definition comes from an agreement between the United States of America and Canada. This new vertical datum is realized currently by the geoid model CGG2013a, which provides the separation between the GRS80 ellipsoid and the above described surface in the NAD83(CSRS) reference frame, making it compatible with Global Navigation Satellite Systems (GNSS) such as GPS.

Heights on the traditional benchmarks are also available in CGVD2013. These heights come from a readjustment of the entire federal first-order levelling network. However, CGVD2013 heights obtained from GNSS and geoid model CGG2013a prevail over the published elevations because NRCan cannot confirm the accuracy of the heights and stability of the benchmarks derived from the aging levelling network.

NRCan is continuing the publication of heights at benchmarks in CGVD28 and hybrid geoid model HTv2.0 to assure a smooth and gradual transition period to the new height reference system.

**NEW:** In 2022, the US National Geodetic Survey (NGS) will replace the North American Vertical Datum of 1988 (NAVD 88) with a geoid-based height reference system called the North American-Pacific Geopotential Datum of 2022 (NAPGD2022). This future US datum has the same definition as CGVD2013 and at the time of release will enable a unified continental height system.

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## Information about the Canadian Geodetic Vertical Datum of 2013 (CGVD2013)

In November 2013, Natural Resources Canada (NRCan) released the **Canadian Geodetic Vertical Datum of 2013** (CGVD2013), which is now the new standard for heights across Canada. This new height reference system replaced the Canadian Geodetic Vertical Datum of 1928 (CGVD28), which was adopted formally by an Order in Council in 1935.

CGVD2013 is defined by the equipotential surface $W_0$ = 62,636,856.0 $m^2s^{-2}$, which represents by convention the coastal mean sea level for North America. This definition comes from an agreement between the United States of America and Canada. This new vertical datum is currently realized by the **Canadian Gravimetric Geoid model of 2013 – Version A** (CGG2013a). It provides the separation between the GRS80 ellipsoid and the above described equipotential surface in NAD83(CSRS), making it compatible with Global Navigation Satellite Systems (GNSS) such as GPS. CGG2013a is also available in ITRF2008.

- CGG2013a (model and accuracy) can be downloaded through the Geoid Models page.
- CGG2013a (model and accuracy) is also available with the GPS·H v3.4 package through the Desktop Applications page.

Heights on the traditional benchmarks are also available in CGVD2013. These heights come from a readjustment of the entire federal first-order levelling network. In order to conform the orthometric heights to CGVD2013, the levelling network is constrained to geopotential numbers (C) determined from accurate ellipsoidal heights (h), CGG2013 geoid heights (N) and interpolated gravity (g) at benchmarks: $C = (h – N)*g_m$, where $g_m$ is the mean gravity along the plumbline between the geoid and benchmark. The selected benchmarks belong to the Canadian Active Control System (CACS), Canadian Base Network (CBN) and “GPS on Benchmarks” project.

- The continental levelling network has 32 constraints.
- The levelling network for Newfoundland has four constraints.
- A single constraint is required for the levelling network on Prince Edward Island.
- The levelling network for Vancouver Island includes two constraints, one at each end of the island.
- Minimum constraint adjustments are done for the following regional levelling networks: Anticosti Island, Iles de la Madeleine, Kuujjuarapik, and tide gauges in Nain, Iqaluit, Resolute, Baker Lake, Holman, Alert, Kugluktuk, Igloolik, and Sorel.

Heights of benchmarks in CGVD2013 are available through the Passive Control Networks page.

Even though each benchmark has a new elevation in CGVD2013, the heights obtained from precise GNSS observations and geoid model CGG2013a prevail over the published elevations because NRCan cannot confirm the accuracy of the heights and stability of the benchmarks derived from the aging levelling network.

NRCan is continuing the publication of heights at benchmarks in CGVD28 and hybrid geoid model HTv2.0 to assure a smooth and gradual transition period to the new height reference system CGVD2013.

Some important information:

- Stakeholders should make use of the **CGG2013a NAD83(CSRS)** version for their regular activities as it is recognized as the “fundamental” geoid model by NRCan. The ITRF2008 version can be used for scientific applications. The NAD83(CSRS) version is a direct transformation from the geocentric solution (ITRF2008 version) by applying these seven parameters for epoch 2011.0:
    - Tx = 1.0045 m Rx = -26.8481 mas
    - Ty = -1.9117 m Ry = 1.1777 mas
    - Tz = -0.5453 m Rz = -10.8807 mas
    - Scale = 0.2872 ppb
- Even though the geoid model is associated to an epoch (2011.0), NRCan considered currently the geoid model as **static**, i.e., the geoid heights do not change in time. The epoch is required for the transformation from ITRF2008 to NAD83(CSRS) due to the drift between the ITRF realizations. The epoch of 2011.0 is selected as it represents approximately the middle of the GOCE (satellite gravity mission) measurements time span used in CGG2013a.
- Stakeholders may not necessarily measure by GNSS the same height at benchmarks as the CGVD2013 published elevations once corrected by CGG2013a because NRCan is adjusting an aging first-order levelling network, which includes systematic and random errors. Generally, the absolute height difference is less than 5 cm, but it can also reach more than 20 cm especially in the Yukon Territory where levelling loops do not close properly and where several benchmarks are 5-foot rods in the permafrost (very unstable). On the other hand, the relative differences should be within 1 to 3 cm ($2\sigma$) for regional surveys.
- The formal height of a benchmark (or any points) is determined by GNSS measurements and corrected with CGG2013a. From such a point, it is then possible to resume the survey with levelling procedure and still be well integrated within CGVD2013. By initiating a survey from a benchmark with a published elevation adjusted from legacy levelling data, the survey may be offset with respect to CGVD2013.

- Prior to implementing CGVD2013, it is important that stakeholders conduct studies of the new vertical datum in order to understand clearly the possible impact on their activities and products. In some cases, the analysis could be simple if, for example, the objective is to integrate 10-cm precision heights within CGVD2013. On the other hand, it can be challenging when investigating centimetre precision over a large sector and understanding the root of the differences with the older height system. The current relative and absolute precision of CGG2013a can support most of our national referencing requirements.
- Finally, the geoid model is certainly not errorless and NRCan will continue to enhance the geoid model over the years. The next release was scheduled in 2018 to resume the five-year cycle. However, the Canadian Geodetic Reference System Committee, which includes federal and provincial members, recommended delaying the update of CGG2013a. In the meantime, NRCan is resuming enhancement of the geoid model until the next release, which will be at the latest in 2022 when US NGS adopts NAPGD2022.

## What is Height Modernization?

Height Reference System Modernization is a project at Natural Resources Canada (NRCan) for the development, implementation and promotion of a gravity-based height reference system for Canada. In other words, it is the redefinition of the vertical reference system and the realization of a new vertical reference frame by **geoid modelling**, rather than by **geodetic levelling**. It enables measurements of elevations with respect to a consistent vertical datum everywhere across the country using Global Navigation Satellite System (GNSS) and emerging GNSS technologies. This new approach allows reduction dependency on monumented networks for height determination. It reduces the physical maintenance from some 90,000 federal benchmarks to some 250 stations making the Canadian Active Control System (CACS) and Canadian Base Network (CBN). These networks are augmented by the provincial High Precision 3D Geodetic Networks (HPN). The project remains in place until stakeholders are well integrated to CGVD2013.

The project includes two main components:

1. Strategic planning and implementation; and
2. Improvement of the geoid model.

The **Strategic planning and implementation** component is accomplished in collaboration with provincial and territorial geodetic agencies. Its activities include a consultation with our stakeholders; the development of an implementation plan and a communication plan; preparation of educational materials; and promotion of the new vertical datum through the internet, conferences and workshops.

The **Improvement of the geoid model** component is the technical aspect of the project. It includes the enhancement of the geoid model and its error model based on the latest theory; the collection of new gravity data (terrestrial and spatial) and digital elevation models; the validation of the geoid model by conducting GNSS and levelling surveys; and development of tools to make use of the new vertical datum. This component also includes contribution from academic institutions and international agencies. This is an on-going activity.

## Why a new vertical datum?

Even though the Canadian Geodetic Vertical Datum of 1928 (CGVD28) remains overall very precise locally, it does not represent today's required national accuracy. Furthermore, the maintenance and expansion of the vertical network by spirit levelling is costly, time consuming and laborious. A readjustment of the levelling networks, similar to the North American Vertical Datum of 1988 (NAVD 88) project, would only be a temporary solution, albeit more accurate than CGVD28, and would not solve the problem of its limited coverage and cost of maintenance.

On the other hand, geoid modelling is a viable alternative for the realization of a long-term vertical datum for Canada. The geoid is a stable surface that can be determined accurately all across the Canadian territory. It is realized in relation to a reference ellipsoid (geoid height), making it compatible with space-based positioning technologies (e.g., GNSS, satellite radar altimetry).

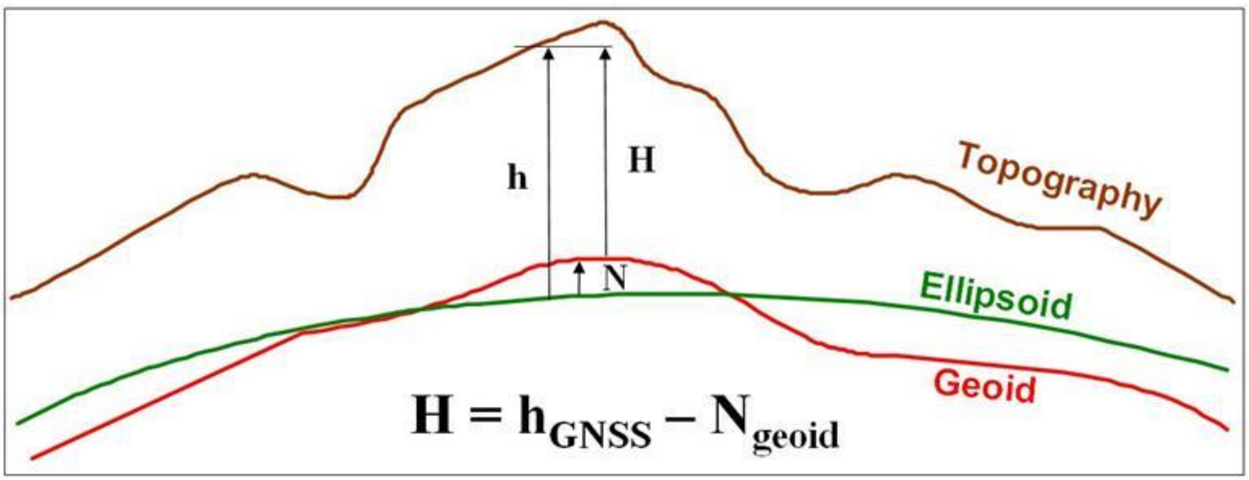


Figure 1: The ellipsoidal height (h), orthometric height (H) and geoid height (N)

Orthometric height (H), often referred as Mean Sea Level Height, can be obtained by subtracting the geoid height (N) from the GNSS ellipsoidal height (h): $H = h - N$. A geoid height (N) is positive (+) when the geoid is above the ellipsoid and negative (-) when it is below.

## What will be the impact on my activities?

The implementation of CGVD2013 corrects for the distortions in CGVD28 that ranges from -65 cm to +55 cm, nationally. The largest absolute changes will be in the Maritimes where the new datum will be higher by 65 cm, meaning lower elevations for the region. In the Rocky Mountains, the datum will be lower by 50 cm, meaning higher elevations.

The impact of these differences on users will depend on the required accuracy, location and size of their project. There are three main categories of users.

- The first category comprises those who require CGVD28 heights with a few metres of accuracy (e.g. digital elevation model). In this case, the difference between CGVD28 and CGVD2013 can be neglected.

- Those who require precision of less than 20 centimetres along corridors of tens of kilometres (e.g. LiDAR survey) make up the second category. For these users the difference between CGVD28 and CGVD2013 must be considered.
- Lastly, the third category represents those who transfer heights with precision of less than 2 cm over small regions (e.g. municipal infrastructure). For these users the difference between CGVD28 and CGVD2013 should be considered, but generally applying a constant offset will suffice.

For the short term, NRCan is resuming the publication of benchmarks in CGVD28 in order to ease the transition to the new height reference system.

The long-term impact will be the disappearance or reliability of benchmarks across the country. This will require stakeholders to install and maintain their own vertical control stations. This can be accomplished by preserving existing benchmarks or by establishing new benchmarks at more secure locations by spirit levelling procedure from the existing ones before their disappearances. On the other hand, it can also be done more efficiently by establishing on-the-fly new benchmarks in the area of interest by conducting RTK surveys, differential GNSS surveys with respect to CACS, CBN or HPN stations or Precise Point Positioning (PPP). The local height survey can be resumed either by GNSS or spirit levelling procedure.

## Vertical Reference Systems

### Canadian Geodetic Vertical Datum of 2013 (CGVD2013)

The Canadian Geodetic Vertical Datum of 2013 (CGVD2013) was officially released in November 2013. It replaces the Canadian Geodetic Vertical Datum of 1928 (CGVD28).

CGVD2013 is a gravimetric datum defined by the equipotential surface $W_0$=62,636,856.0 $m^2s^{-2}$, representing by convention the coastal mean sea level for North America. The definition and geopotential value comes from an agreement between Canada and USA. The Canadian Gravimetric Geoid model of 2013 – Version A (CGG2013a) is the current realization of the vertical datum. CGG2013a is available in NAD83(CSRS) and ITRF2008 for the GRS80 ellipsoid, making it compatible with space-based positioning technique. Heights in terms of CGVD2013 are orthometric (H).

The levelling networks (continental, Prince Edward Island, Newfoundland, Vancouver Island and other islands) are readjusted in conformity with CGVD2013 by constraining the levelling measurements to stations with precise ellipsoidal heights in NAD83(CSRS). The CGVD2013 heights at the benchmarks will not be considered official because they will be coming from an adjustment of legacy data. NRCan is not in a position to be able to confirm stability of the benchmarks. The formal height of a benchmark is determined by GNSS technique and the latest geoid model realizing CGVD2013.

### Canadian Geodetic Vertical Datum of 1928 (CGVD28)

The Canadian Geodetic Vertical Datum of 1928 (CGVD28) is the former vertical datum for Canada. It was adopted by an Order in Council in 1935 and repealed on February 5, 2015. CGVD28 is a tidal datum defined by the mean water level at five tide gauges: Yarmouth and Halifax on the Atlantic Ocean, Pointe-au-Père on the St-Lawrence River, and Vancouver and Prince-Rupert on the Pacific Ocean. In addition, the definition includes an elevation at a benchmark in Rouses Point, NY (next to Lake Champlain) accepted as fixed by the United States and Canada in 1925. The datum is propagated in land using geodetic levelling measurements. The vertical datum is accessible through some 94,000 benchmarks anchored to the ground and stable structures. The heights in terms of CGVD28 are normal-orthometric ($H^{no}$).

### North American Vertical Datum of 1988 (NAVD 88)

The North American Vertical Datum of 1988 (NAVD 88) is the vertical datum for the USA. It was affirmed as the official vertical datum in the National Spatial Reference System (NSRS) for the Conterminous United States and Alaska in 1993. NAVD 88 is a tidal datum defined by the mean water level at the tide gauge in Rimouski, Québec. The datum is propagated in land using geodetic levelling measurements. The vertical datum is accessible through benchmarks anchored to the ground and stable structures. The heights in terms of NAVD 88 are Helmert orthometric ($H^H$). Canada did not adopt NAVD 88; however, NAVD 88 heights are available on a subset of the Canadian levelling network.

**NEW:** USA is scheduled to replace NAVD 88 by NAPGD2022 in 2022.

### International Great Lakes Datum of 1985 (IGLD85)

The International Great Lakes Datum of 1985 (IGLD85) comes from the same adjustment as NAVD 88 except that IGLD85 is in the dynamic height system ($H^d$). IGLD85 heights at benchmarks are available on-line at the Geodetic Reference Systems web site.

**NEW:** IGLD85 will be replaced by IGLD2020 in 2025. It will use the same datum definition as NAPGD2022 (being the same as CGVD2013), but the heights will be dynamic ($H^d$).

**Table 1: Specifications of the three main vertical reference systems**

| | **Canadian Geodetic Vertical Datum of 2013** | **Canadian Geodetic Vertical Datum of 1928** | **North American Vertical Datum of 1988** |
|---|---|---|---|
| **Abbreviation** | CGVD2013 | CGVD28 | NAVD 88 |
| **Type of datum** | Gravimetric (geoid model) | Tidal (levelling) | Tidal (levelling) |
| **Vertical Datum** | $W_0$=62,636,856.0 $m^2s^{-2}$ | Mean water level at tide gauges in Yarmouth, Halifax, Pointe-au-Père, Vancouver and Prince-Rupert, and a height in Rouses Point, NY | Mean water level at the tide gauge in Rimouski, Québec |
| **Realization** | CGG2013 (NAD83(CSRS) and ITRF2008) | Multiple regional adjustments of the network over the | Continental adjustment in 1991 |

| | | | |
|---|---|---|---|
| | | years; original national adjustment in 1928 | |
| **Height System** | Orthometric | Normal-orthometric | Helmert orthometric |

## Mean Sea Level (MSL)

Conventionally, the mean sea level has been used as the reference surface for topographic elevations for generations. Regional, national and continental vertical datums were realized using geodetic levelling observations that were constrained to mean sea level as determined by tide gauge measurements. Nowadays, GNSS (e.g., GPS, GLONASS, and eventually Galileo) offer an alternative technique to determine elevations. However, these elevations are measured with respect to a reference ellipsoid, which does not have any physical meaning, i.e., water could flow from a lower ellipsoidal height to a higher ellipsoidal height. This is why ellipsoidal heights (h) must be converted to orthometric heights (H) using geoid heights (N): H = h - N. Unfortunately, the geoid does not coincide exactly with the mean sea level because the latter is not an equipotential surface (a level surface). The mean ocean surface has slight hills and valleys similar to land topography, but much smoother. Globally, these hills and valleys range from -2.0 m to +2.0 m with respect to the geoid.

This separation between the geoid and the sea surface is the Sea Surface Topography (SST) or Dynamic Ocean Topography (DOT).

This agreed potential surface ($W_0$ = 62,636,856.0 $m^2s^{-2}$) between USA and Canada lays approximately below the coastal Pacific sea level by 17 cm and above the coastal Atlantic sea level by 39 cm. This means that the coastline in the area of Halifax would has a negative elevation (H= -0.39 m) while the coastline for the area of Vancouver has a positive elevation (H = 0.17 m).

## Conversion: CGVD28 and CGVD2013

The release of CGVD2013 requires the development of procedures for the conversion of heights back and forth between CGVD28 and CGVD2013.

Officially, the height of a point in CGVD2013 ($H_{CGVD2013}$) is determined as:

$$H_{CGVD2013}=h_{NAD83(CSRS)}-N_{NAD83(CSRS),\ CGG2013a}$$

where $h_{NAD83(CSRS)}$ is the ellipsoidal height and $N_{NAD83(CSRS),\ CGG2013a}$ is the geoid height.

### GNSS Surveys on Benchmarks

Stakeholders can determine their own conversion by conducting precise GNSS surveys on benchmarks in the area of interest. It is important that the ellipsoidal heights and the geoid heights be in the same reference frame (RF). The reference frame can be either NAD83(CSRS) or ITRF. WGS84 is aligned with ITRF.

The conversion (β) can be determined as followed:

$\beta = (h_{RF} - N_{RF}) - H_{\text{Old Datum}}$

where $h_{RF}$ is the ellipsoidal height observed by GNSS and $N_{RF}$ is the geoid height interpolated from the model. The *Old Datum* can be CGVD28 or any local datums.

The disadvantage of this approach is the necessity to collect data in the field. On the other hand, it allows the most accurate conversion of any datums to CGVD2013. NRCan recommends conducting GNSS surveys at a minimum of three benchmarks to assure local stability.

### National Conversion Model

A second procedure is to make use of the difference between gravimetric geoid model CGG2013a and hybrid geoid model HTv2.0, which are realizations of CGVD2013 and CGVD28, respectively. This is the most efficient approach because it does not require field operations or downloading a series of benchmarks in the region of interest. However, the precision of the transformation may not be accurate, especially in remote regions or where levelling lines are sparse.

Orthometric height in the new vertical datum (CGVD2013) can be determined as followed:

$H_{CGVD2013} = H_{CGVD28} + N_{HTv2.0} - N_{CGG2013a}$

This conversion can be done through software GPS·H (desktop and on-line versions). The conversion is available for epochs 1997.0, 2002.0 and 2010.0, which are the most common epochs adopted by federal and provincial geodetic agencies.

### Benchmarks Information

NRCan disseminates heights of benchmarks in CGVD28 and CGVD2013. This allows stakeholders to estimate the separation between the two datums in their area of interest. This procedure does not require the needs to conduct GNSS surveys to determine the local conversion. However, the new orthometric heights may not reflect the actual heights of the benchmarks if these benchmarks are unstable. This is the least accurate procedure for the conversion between CGVD28 and CGVD2013.

Thus, the conversion can be expressed as:

$\beta = H_{CGVD2013} - H_{CGVD28}$

Stakeholders should download height information from a series of benchmarks to assure that the local conversion corresponds approximately to a bias. If the area is larger, it might require a planar conversion (bias and tilt).

## Geoid Modelling

### The Public Geoid Models for Canada

The actual shape of the Earth is neither a sphere nor an ellipsoid; it is a geoid. The geoid is the equipotential (level) surface that represents best, in a least square sense, the global mean sea level. However, the geoid does not coincide exactly with mean sea level because, just like land, oceans have a permanent topography albeit ranging from -2 m to 2 m globally. The geoid is expressed in potential unit of $m^2 s^{-2}$. Thus, two equipotential surfaces which differ by 1 $m^2 s^{-2}$ have a geometric separation of about 0.1 m because gravity is approximately 9.8 $m/s^2$ (0.1 m = 1.0 $m^2 s^{-2}$ / 9.8 m $s^{-2}$).

The geoid does not only represent the actual physical shape of the Earth, but it is also a reference surface for elevations. An elevation above the geoid is referred to as an orthometric height. The geoid cannot be access physically because it is potential afterward. However, it can be represented geometrically by a model that gives the separation between the geoid and a reference ellipsoid. This separation is referred as the geoid height (N). It is positive when the geoid is above the ellipsoid and is negative when the geoid is below the ellipsoid.

Naturally, the importance of determining the geoid accurately increased with the advance in space-based positioning (e.g., GNSS) where heights are given with respect to a reference ellipsoid. The geoid model allows the conversion of ellipsoidal heights (h) to orthometric heights (H): H = h - N.

Over the last 30 years, Natural Resources Canada (NRCan) has published six (6) geoid models (see Geoid Models). These geoid models have improved over the years by implementing better theory; by conducting gravity surveys to fill large areas void of data; by collecting more precise Digital Elevation Models (DEM), and by embedding more accurate global gravity models derived from satellite observations and dedicated satellite gravity missions, such as GOCE and GRACE. These enhancements brought significant changes to each published model. Table 2 shows the changes between the sequential models and their convergence over the years.

The long wavelength components of CGG2013a up to degree 120 (~350 km) are defined entirely by the Gravity Recovery and Climate Experiment (GRACE) and the Gravity field and steady-state Ocean Circulation Explorer (GOCE) satellite data, which are part of the EIGEN-6C3stat model (provided by GeoForschungsZentrum (GFZ), Germany). GRACE and GOCE are dedicated satellite gravity missions. The terrestrial gravity data are smoothly introduced into the geoid model in combination with satellite data between degree 120 and 180 (~225 km), and contribute entirely afterward.

**Table 2: Comparison of recent published geoid models in Canada**

| **Models** | | **Nodes** | **Min (m)** | **Max (m)** | **Mean (m)** | **St. Dev. (m)** |
|---|---|---|---|---|---|---|
| **GSD95-GSD91** | | 428544 | -9.230 | 10.740 | 0.048 | 0.706 |
| **CGG2000-GSD95** | | 419616 | -6.450 | 3.160 | -0.408 | 0.456 |
| **CGG2005-CGG2000** | **Canada** | 3637800 | -1.663 | 1.814 | -0.276 | 0.312 |
| | **North America** | 9216000 | -2.918 | 2.528 | -0.226 | 0.378 |
| **CGG2010-CGG2005** | **Canada** | 3637800 | -1.014 | 1.462 | 0.088 | 0.088 |
| | **North America** | 9216000 | -1.818 | 4.284 | 0.092 | 0.124 |
| **CGG2013-CGG2010** | **Canada** | 2892270 | -0.636 | 0.140 | -0.037 | 0.026 |
| | **North America** | 9216000 | -1.191 | 0.221 | -0.036 | 0.028 |

## Validation of Geoid Models

The most common technique to validate geoid models is by comparing them to geoid heights derived from GNSS measurements and levelling observations. The former gives the ellipsoid height (h) while the latter gives the orthometric height (H). The difference between the two heights is the geoid height (N). The discrepancy ε (= h – H – N) would be equal to zero if the three datasets (GNSS, levelling and geoid model) would be errorless. Furthermore, the levelling data and geoid model are required to be in the same vertical reference system while the GNSS data and geoid model must also be in the same geometric reference system.

For the validation of the geoid models, the orthometric heights are derived from the Sep12 adjustment, a minimum constraint adjustment of the federal first-order levelling network. The only fixed station is located in Halifax, NS. The reference system is the equipotential surface $W_0$=62,636,856.0 $m^2s^{-2}$ (same as CGVD2013). Overall, Sep12 should be very precise locally (unless of benchmarks instability), but it includes systematic errors of unknown origin that accumulate over long distances. These systematic errors represent a standard deviation of approximately 10 cm.

Since 1986, NRCan has conducted GPS surveys on benchmarks across the country for the purpose of validating geoid models in Canada. All these "GPS on BMs" surveys are put together in an adjustment to create the SuperNet. The accuracy of the ellipsoidal heights varies with the epoch of observations. Surveys prior to 1994 might have accuracy at the decimetre level while the most recent surveys have accuracy better than 2 cm.

The complexity in using this validation approach is that the discrepancy ε does not separate the errors from the geoid model, GNSS measurements and levelling observations. Furthermore, the discrepancy might be caused by the instability of the benchmarks, i.e., markers may move between the epochs of levelling and GNSS observations. It is not uncommon that the GNSS measurements were conducted some 30 years after the levelling survey.

Table 3 shows the comparison of the six latest published geoid models at NRCan to a common "GPS on BMs" dataset in Canada. The comparison includes only the benchmarks located on the mainland because the levelling networks for Newfoundland, Prince Edward Island and Vancouver Island are independent.

**Table 3: Comparison of geoid models to GNSS on BMs; where the levelled orthometric heights are from the Sep12 adjustment and the ellipsoidal heights are from SuperNet v3.3n**

| Model | No | Min (m) | Max (m) | Mean (m) | St. Dev. (m) |
|---|---|---|---|---|---|
| GSD91 | 2445 | -3.486 | 4.479 | -0.794 | 0.790 (0.695*) |
| GSD95 | 2445 | -1.524 | 0.730 | -0.693 | 0.413 (0.144*) |
| CGG2000 | 2449 | -1.069 | 0.474 | -0.361 | 0.225 (0.087*) |
| CGG2005 | 2449 | -0.654 | 0.420 | -0.107 | 0.140 (0.084*) |
| CGG2010 | 2449 | -0.737 | 0.324 | -0.193 | 0.135 (0.074*) |
| CGG2013 | 2449 | -0.678 | 0.349 | -0.157 | 0.131 (0.073*) |

*: Standard deviation after filtering out systematic errors

For the public geoid models, the comparison could be at best a constant because the reference system of these models is not the same as Sep12 (with the exception of CGG2013). On one hand, we can observe that the standard deviation of the discrepancies has decreased significantly since the realization of GSD91. It went down from 79.0 cm to 13.1 cm (66.7% confidence level). On the other hand, it will be challenging to reduce further the standard deviation because of systematic errors in the levelling network (about 10 cm).

## Documents

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### Rational

- CGRSC (2004) Report to the Canadian Council on Geomatics (CCOG) on the Modernization of the Canadian Height Reference System
    - Canadian Height Modernization: The rationale
    - Height Modernization - Background and Summary of Suggested Responsibilities
    - CGRSC Position Paper on the Modernization of the Canadian Geodetic Vertical Datum
- Véronneau M., R. Duval, and J. Huang (2006) A Gravimetric Geoid Model as a Vertical Datum in Canada, GEOMATICA, Vol. 60, No. 2, pp. 165-172.

### Stakeholder Consultation

- Stakeholder Consultation for the Development of the Canadian Height Reference System Modernization Implementation Plan
- CGRSC (2006) Report to the Canadian Council on Geomatics (CCOG) on the Height Modernization Consultation Results (preliminary)

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### US national height modernization discussions

The NGS 10-year plan 2013-2023

Gravity for the Redefinition of the American Vertical Datum (GRAV-D)

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## Glossary

**Equipotential Surface (*W*)**: It is a surface having a constant potential and being everywhere perpendicular to the direction of gravity. The equipotential surface is level, i.e., the water is at rest. It exists an infinity of equipotential surfaces. These surfaces do not intersect each other, but they converge towards the poles. Thus, the geometric distance between two equipotential surfaces is less at the poles than at the equator. Note: The mean sea level is not an equipotential surface because oceans have a permanent topography that is caused by temperature, salinity, currents, etc. (Unit: $m^2s^{-2}$)

**Geopotential number (*C*)**: It is the potential difference between an equipotential surface ($W_i$) and a reference equipotential surface ($W_0$) along a plumb line. The reference geopotential surface is usually the geoid or the vertical datum. (Unit: $m^2s^{-2}$)

**Geopotential number difference (*ΔC*)**: It is the potential difference between two equipotential surfaces at two distinct locations at the earth surface ($W_j(\Phi_2\lambda_2h_2 - Wi(\Phi_1\lambda_1h_1))$ . The geopotential number difference can be determined from levelling:

$$\Delta C_{ij}=(\Delta H_{ij}+\varepsilon)(g_i+g_j)/2$$

where $\Delta H_{ij}$ is the instrumental height difference between points *j* and *i*, *g* is the gravity and ε are the systematic corrections applied to the levelling measurement. (Unit: $m^2s^{-2}$)

**Geoid ($W_0$)**: Specific equipotential (level) surface, which defines best, in a least-square sense, the global mean sea level. It is the true zero surface to measure elevations. For practical purpose, the geoid can also be defined as the equipotential surface representing a national vertical datum. For example, NRCan is using the equipotential surface (62,636,856.0 $m^2s^{-2}$) representing best the coastal mean water level for North America as the new vertical reference system for Canada. (Unit: $m^2/s^2$)

**Telluroid**: Surface whose normal potential *U* is equal to the actual potential *W* at the Earth's surface along the ellipsoidal normal. The telluroid is not an equipotential surface. The telluroid was proposed by Molodenskii to avoid the complex determination of the topographical density and vertical gradient of gravity, which are necessary components in geoid modelling. (Unit: $m^2/s^2$)

**Quasi-geoid**: Surface parallel to the telluroid that is transferred to the mean sea level. The geoid and quasi-geoid are approximately the same surface over the oceans. However, the separation between the quasi-geoid and geoid can reach close to the metre level in the Canadian Rockies. (Unit: $m^2/s^2$)

**Mean Sea Level (*MSL*)**: It is the arithmetic mean height of the sea in reference to a surface such as a chart datum, ellipsoid or geoid. It is determined from hourly observations over an 18.6 year cycle to average out the tidal lows and highs caused principally by the gravitational forces from the moon and sun. The mean sea level has small hills and valleys with respect to the geoid. It is the traditional zero elevation.

**Vertical Datum**: It is the reference surface for a height system, i.e., it is the zero elevation. The vertical datum is not necessarily an equipotential surface (e.g., CGVD28, ellipsoid and telluroid). A vertical datum is made of two components: a reference system and a reference frame. The former is its definition while the latter is its realization.

**Reference ellipsoid**: Mathematical representation of the Earth (e.g., GRS80). Its surface is defined as equipotential. An equipotential ellipsoid of revolution is defined by four constants:

- a: Semi major axis (m)
- GM: Geocentric gravitational constant ($m^3s^{-2}$)
- $J_2$: Dynamical form factor (it is related to the ellipsoid eccentricity)
- ω: Angular velocity (rad $s^{-1}$)

**Geoid height (*N*)**: It is the separation between the reference ellipsoid (e.g., GRS80) and the geoid. The distance is measured along the ellipsoidal normal. Geoid heights are tied to a 3-D reference frame such as NAD83(CSRS) or ITRF. Geoid heights allow the conversion of ellipsoidal heights (*h*) to orthometric heights (*H*): $H = h - N$. The geoid height is also called the geoid undulation. (Unit: m)

**Height anomaly (*ζ*)**: It is the separation between the ellipsoid and the quasi-geoid. Height anomalies allow the conversion of ellipsoidal heights (h) to normal heights ($H^n$): $H^n = h - \zeta$ .(Unit: m)

**Orthometric height (*H*)**: It is the elevation of a point above the geoid. It is measured along the plumb line, which is perpendicular to the equipotential surfaces. (Unit: m)

**Normal Height ($H^n$)**: It is the elevation of a point above the quasi-geoid or elevation of the telluroid above the ellipsoid. The difference between normal and orthometric heights is more significant at high elevations. (Unit: m)

**Dynamic height ($H^d$)**: It is the potential difference between two equipotential surfaces along a plumb line scaled by a constant gravity value. For Canada and USA, the constant value is the normal gravity on the ellipsoid at latitude 45° ($\gamma_{45°}$). Dynamic heights have no geometric meanings. They are mainly used for the management of large water basins (e.g., Great Lakes). The surface of a lake has a constant dynamic height because it is an equipotential surface. Because the equipotential surfaces converge towards the poles, the surface of the lake closer to a pole will have a lower orthometric height than the opposite end of the lake. (Unit: m)

**Normal Orthometric height ($H^{no}$)**: This terminology is not proper, but it is used to define the type of heights associated with CGVD28. These heights are neither orthometric nor normal, i.e., they are not compatible with the geoid or quasi-geoid. They are determined using normal gravity, but they are based on the formulation of orthometric heights. Normal orthometric heights were used in Canada because no actual gravity measurements were available at the time of the realization of CGVD28. The objective of the 1928 adjustment was the determination of the most accurate orthometric heights, which explains why they are commonly referred as orthometric heights. (Unit: m)

**Geodetic or ellipsoidal height (*h*)**: Elevation of a point above the reference ellipsoid. The distance is measured along the ellipsoidal normal. (Unit: m)

**Sea Surface Height (*SSH*)**: It is the distance measured along the ellipsoidal normal between the ellipsoid and ocean surface. It is equivalent to the ellipsoidal height of the ocean surface. Instantaneous SSH can be observed by satellite radar altimetry (e.g., Topex/Poseidon, ERS-1, Jason, etc). (Unit: m)

**Sea Surface Topography (*SST*)**: It is the separation between the geoid and ocean surface. SST can be determined from Sea Surface Height (SSH) measured from satellite radar altimetry and a geoid height (N): SST = SSH - N. SST is positive if the ocean surface is above the geoid. It is equivalent to the orthometric height of the ocean surface. (Unit: m)

**Gravity (*g*)**: It is the combination of the gravitational (mass) and centrifugal (rotation) forces. Overall, gravity increases from ~9.78 m/$s^2$ at the equator to ~9.83 m/$s^2$ at the poles. The elevation and mass density are components that influenced the local gravity value. (Unit: $m/s^2$ or Gal; 1 $m/s^2$ = 100 Gal = 0.1 kiloGals = $1 \times 10^5$ milliGals)

**Normal gravity (*γ*)**: It is an approximate gravity value determined from the parameters defining an equipotential ellipsoid of revolution, e.g., GRS67, GRS80. (Unit: $m/s^2$ or Gal; 1 $m/s^2$ = 100 Gal = 0.1 kiloGals = $1 \times 10^5$ milliGals)

**Deflection of the vertical (*ξ, η*)**: It is the angle between the directions of the plumb line and ellipsoidal normal. It has two components: a north-south component ($\xi$) and an east-west component ($\eta$). (Unit: arcsec)

## Frequently Asked Questions

### User Concerns

1. Why do we need a geoid-based datum?
2. Who really need a new vertical datum?
3. Why NRCan did not delay the adoption of a new vertical datum?
4. Do the elevations of benchmarks have to change?
5. How can the confusion of having two vertical datums be minimized?
6. Does the geoid-based datum represent mean sea level better than the levelling-based datum CGVD28?
7. How do heights estimated by GNSS and corrected using a geoid model agree with CGVD28 heights?
8. How will I validate the precision/accuracy of my heights when I use a GNSS/geoid approach?
9. Can I still do surveys with spirit levelling and integrate them into the new vertical datum?
10. Will I have to update elevations in my database or my topographic maps?
11. How will I maintain compatibility between historical and new height surveys?
12. What will be the name of the new vertical datum?
13. Why a new name for the vertical datum?
14. Will NAVD 88 and the new datum in Canada coincide along the border?

### Geoid Modelling / Transformation

1. How Precise is the geoid-based vertical datum?
2. How can the geoid model be further improved?
3. How much will an orthometric height measured with GNSS and corrected with a geoid model vary in time (h-dot and N-dot)?
4. How is the geoid model validated?
5. Without new levelling lines, how will it be validated in the future?
6. How often will a new geoid model be published?
7. To what 3D reference frame realization is the geoid based vertical datum referred to?
8. What method can I use to convert my old CGVD28 elevations to the new datum (or the opposite)?

9. I am confused with all these acronyms: NAD83, NAD83(CSRS), ITRF, CGVD28, NAVD 88, NGVD29, IGLD85, GSD95, CGG2000, HTv2.0, GEOID03, etc. What is the difference?
10. Why the height of benchmarks changes?

## User Concerns

1. Why do we need a geoid-based datum?

   Even though CGVD28 is very precise over short distances (e.g., 30 km), it includes significant distortions at the national scale. Its access is only available at benchmarks, which are mostly located in southern Canada. Furthermore, the maintenance of a levelling network is very expensive. Thus, the best alternative to levelling is geoid modelling. A geoid-based datum is accessible by Global Navigation Satellite Systems (e.g., GPS) at any location across the Canadian territory.

2. Who really needs a new vertical datum?

   Already, a large number of stakeholders rely on GNSS as their tool of choice for accurate positioning and require a geoid model to convert their ellipsoidal heights to orthometric heights. In addition, an increasing number of stakeholders are conducting surveys in remote regions where the vertical datum is not accessible through traditional benchmarks.

3. Why NRCan did not delay the adoption of a new vertical datum?

   NRCan has stopped maintaining the levelling network since 1996. Thus, it was important that NRCan implements a new vertical datum before CGVD28 deteriorates to such a level that it might be difficult to have a smooth transition period between the old and new datums. Furthermore, it exists already a large community of GNSS users, who require an accurate geoid-based vertical datum across the country.

4. Do the elevations of benchmarks have to change?

   Unfortunately, CGVD28 includes significant distortions across the country. These distortions are corrected in the new datum meaning that absolute heights change by almost one metre in certain regions. For several regions, the change in heights will be less than a few cm. The local height differences will remain the same in the two datums.

5. How can the confusion of having two vertical datums be minimized?

   Having two vertical datums during the transition period may bring confusion to some stakeholders. NRCan and the provincial agencies will indicate clearly the datum of the data when disseminating heights. In addition, it is important for stakeholders to identify properly the datum used in their documents. Proper identification will remove many confusions.

6. Does the geoid-based datum represent mean sea level better than the levelling-based datum CGVD28?

First, let us mention that the mean sea level (MSL) is not a level surface. Just like land, oceans have permanent topography, albeit ranging from -2.0 to 2.0 m worldwide. CGVD28, which is constrained to a series of tide gauges across the country, represents well the MSL at these specific locations. However, these same constrains are also responsible in part for systematic errors in CGVD28. On the other hand, the geoid is a level surface, but it does not coincide with MSL along the coast. However, the geoid-datum is near the MSL because it was selected such as it represents the average of the coastal MSL for North America. The geoid-based datum will be about 38 cm above the MSL near Halifax while it will be about 17 cm below MSL near Vancouver. NRCan will make available a model showing the separation between the geoid and MSL along the Canadian coast.

7. How do heights estimated by GNSS and corrected using a geoid model agree with CGVD28 heights?

   CGVD28 contains systematic errors, which can reach close to one metre in an absolute sense. However, local GNSS-corrected height differences will agree well with CGVD28.

8. How will I validate the precision/accuracy of my heights when I use a GNSS/geoid approach?

   The stations from the federal Canadian Base Network (CBN) and provincial High Precision Network (HPN) can be used by stakeholders to validate GNSS/geoid procedure for the determination of accurate 3D positions. In addition, several benchmarks have 3D positions; however, the quality of these 3D positions may vary depending on the GNSS epoch of observations. In addition, one has to be careful about the stability of the benchmarks.

9. Can I still do surveys with spirit levelling and integrate them into the new vertical datum?

   Yes, most benchmarks will have an elevation in the new datum. If there are no benchmarks within a reasonable distance from your project, you can install your own control stations by GNSS in the project area and resume the work locally by levelling technique.

10. Will I have to update elevations in my database or my topographic maps?

    It will depend on the accuracy of your datasets. It might not be necessary if the changes are smaller than the error associated to your datasets. A conversion tool will be made available in order to convert heights between the two datums. If your datasets are local, the conversion can be as simple as adding a constant.

11. How will I maintain compatibility between historical and new height surveys?

    The compatibility between historical and new height survey can be maintained by conducting the first new survey in the two datums. This will allow you to determinate the relation between historical and new data. If the project is local, the conversion should be as simple as adding a bias to the old or new datasets.

12. What is the name of the new vertical datum?

The name of the new vertical reference system is the Canadian Geodetic Vertical Datum of 2013 (CGVD2013). The new vertical datum should be identified as follows: CGVD2013(CGG2013a), where the name between parenthesis is the geoid model realizing the vertical reference system. If NRCan updates the geoid model in 2020, the vertical datum would be identified as CGVD2013(CGG2020).

13. Why a new name for the vertical datum?

    The new vertical datum must be identified by a different acronym because CGVD28 and CGVD2013 are not in the same reference system, i.e., they do not have the same definition. In this case, we are not talking about levelling versus geoid modelling because these are only techniques to realize the vertical datum. Rather that CGVD28 is defined by MSL at five tide gauges across Canada while the new datum is defined by the equipotential surface ($W_0$=62,636,856.0 $m^2s^{-2}$), which represents conventionally the mean potential of the coastal MSL for North America.

14. Will NAVD 88 and the new datum in Canada coincide along the border?

    NAVD 88 and CGVD2013 will not coincide along the Canada/US border. NAVD 88 has a significant east-west systematic error, which indicates that MSL next to Vancouver is higher than MSL next to Halifax by 1.5 m. On the other hand, CGG2010 indicates a difference of about 0.55 m.

## Geoid Modelling / Transformation

1. How Precise is the geoid-based vertical datum?

   The geoid-based datum will have a better absolute accuracy than CGVD28 across the country. Still, the geoid model will not be errorless, but no systematic errors should be larger than the decimeter (95% confidence) across the country. CGVD28 have systematic errors reaching close to the metre level. Overall, the accuracy of the geoid model will be approximately 3 to 5 cm. On the other hand, the relative precision of the geoid model will be comparable to spirit levelling. Naturally, the relative precision of the GNSS-derived orthometric heights will also depend on the precision of your ellipsoidal heights.

2. How can the geoid model be further improved?

   Between the late 1980s and today, geoid models have improved quite significantly. We saw changes at a level of a few metres. Today, the theory takes care of many terms that were formally omitted or neglected; more gravity data are available from terrestrial and spatial techniques; and better Digital Elevation Models (DEM) are available. This new information is currently stabilizing the realization of the new geoid models. Furthermore, geoid modeling is gaining global acceptance as the future technique to realize national or continental vertical datum. Thus, national and international academic institutions and governmental agencies are developing new techniques to achieve higher accuracy in geoid modelling. NRCan is keeping abreast with all new developments.

3. How much will an orthometric height measured with GNSS and corrected with a geoid model vary in time (h-dot and N-dot)?

   The Earth is a dynamic planet; it is always changing. Some changes can be quite drastic (e.g., landslide, earthquake) while others are can be more subtle (e.g., post-glacial rebound). When you have drastic events, the benchmarks can move significantly or be destroyed completely. In this case, you lose access to the vertical datum. On the other hand, the impact of a drastic event on the geoid is very small; thus, it is possible to take new GNSS measurements and install new control stations immediately. Subtle changes are difficult to detect because they expend over a very large regions. These changes are usually not detected when conducting local relative surveys (e.g., levelling or differential GNSS). However, GNSS technique such as Precise Point Positioning (PPP) will show that the terrain can move by as much as 1 cm per year. This dynamic change of the topography will also bring a 10% change to the geoid. Thus, the long wavelength components of the geoid can change by approximately 1 cm every ten years.

4. How is the geoid model validated?

   A geoid model can be validated in two ways: error propagation and independent datasets. For the former, the challenge is to associate a realistic error model to the input data required in the determination of a geoid model. This internal accuracy can be too optimistic because it will not consider systematic errors and omissions. For the latter, GNSS on BMs is the most common approach. It consists of comparing the geoid models (N) to geoid heights determine from GNSS ellipsoidal heights (h) and spirit leveled orthometric height (H): $h - H - N = \varepsilon$. The discrepancies $\varepsilon$ should be zero (or a constant) if each height would be errorless. The problem with this technique is the difficulty to disassociate errors from the geoid model, levelling data, GNSS measurements and stability of the BMs. Other independent techniques for validation could be satellite radar altimetry and astro-geodetic deflections of the vertical.

5. Without new levelling lines, how will it be validated in the future?

   Existing benchmarks (BMs) are here to stay for many more years and most of these BMs are fairly stable. Even if we do not conduct new levelling surveys, we still have a lot of levelling lines to validate geoid models for many more years. In addition, we can also validate the geoid model at tide gauges. By the time that most BMs will disappear, validation of geoid models by "GNSS on BMs" will not be a priority.

6. How often will a new geoid model be published?

   We know that it is impossible to realize an errorless geoid model. The model will always be as good as the theory and input data. Certainly, these two elements will improve with time. It is hard to say at this time how often a new model will be published; however, we do not expect that the changes in geoid models will not be larger than what we saw with CGVD28 over the last 75 years. Furthermore, models will not be published at a higher rate than currently, which is approximately every five years.

7. To what 3D reference frame realization is the geoid based vertical datum referred to?

A geoid model is determined from gravity measurements. Knowing that gravity points towards the center of mass, we assume that the reference frame is ITRF. Usually, we associate it to the latest ITRF realization (e.g., ITRF2014). The geoid model is converted to NAD83(CSRS) using a seven-parameter transformation (rotations, translations and scale). The epoch of the geoid model is determined from the observations period of the satellite data.

8. What method can I use to convert my old CGVD28 elevations to the new datum (or the opposite)?

   There are three approaches. First, you can conduct your own GNSS surveys on a series on BMs in your area of interest and determine the separation between the two datums ($\varepsilon = (h\text{-}N)_{new}\ H_{old}$). The advantage is that it will convert any local datums to the new datum. The disadvantage is that you must be able to determine accurate ellipsoidal heights in the proper reference frame. A second approach is to use a grid shift file. This file is produced by differencing geoid model CGG2013a and hybrid geoid model HTv2.0. HTV2.0 is a realization of CGVD28. The transformation is fairly precise in regions with dense levelling lines, but the precision deteriorates in regions with sparse or no levelling lines. Finally, a third approach is to download benchmarks information in your area. Most BMs will have published heights in the two datums (CGVD28 and CGVD2013).

9. I am confused with all these acronyms: NAD83, NAD83(CSRS), ITRF, CGVD28, NAVD 88, NGVD29, IGLD85, GSD95, CGG2000, HTv2.0, GEOID12, etc. What is the difference?

   Traditionally, geodesy consists of two types of reference frames: a 2D horizontal network (latitude and longitude) and a 1D vertical network (height above mean sea level). Today, with the immersion of satellite positioning, we are now taking about 3D networks (latitude, longitude and ellipsoidal height).

   - NAD27 and NAD83 are traditional horizontal networks while NAD83(CSRS) and ITRF are modern 3D networks. The horizontal components of NAD83(CSRS) are more precise than those of NAD83. NAD83, who was thought to be at the Earth center of mass at the time, is actually off by approximately two metres. ITRF is a global reference frame with its origin is at the center of mass (±2 cm). There are several realizations of ITRF (e.g., ITRF97, ITRF00). These are new versions, which are more precise than the previous ones. Coordinates in ITRF can be converted to NAD83(CSRS), or the opposite, using a seven-parameter transformation for a specific epoch. WGS84 is an ITRF reference frame.
   - CGVD28, NGVD29, NAVD 88 and IGLD85 are traditional vertical networks. These networks are realized by spirit levelling. CGVD28 is the former vertical datum for Canada, replaced by CGVD2013. NGVD29 is the former vertical datum for the USA. That datum was replaced in 1993 by NAVD 88, which is a minimum constrain adjustment of the levelling data in North America. IGLD85 is a special vertical datum for the St-Lawrence Seaway and Great Lakes.
   - GSD91, GSD95, CGG2000, CGG2005, CGG2010, CGG2013, HTV2.0 and GEOID12 are geoid models. A geoid model is an integral part to a 3D network to convert ellipsoidal heights to orthometric heights (heights above a vertical datum). GSD91, GSD95,CGG2000, CGG2005, CGG2010, and CCG2013 are pure gravimetric geoid models. Each new model is a better representation of the geoid. CGG2013 is the realization of

vertical datum CGVD2013. HTv2.0 and GEOID12 are hybrid geoid models, i.e., they are distorted geoid models to represent a spirit-levelled datum. HTv2.0 is a representation of CGVD28. HT stands for Height Transformation. GEOID12, developed by the US National Geodetic Survey, is a representation of NAVD 88 in the USA. In Canada, we opted not to name our hybrid models geoid because these are distorted to represent a vertical datum, which includes systematic errors.

10. Why do the heights of benchmarks change?

    There are basically three reasons: 1) new reference system; 2) new realization of the reference system; and 3) the Earth is a dynamic planet.

    - Changes due to a new reference system are rare because we rarely adopt a new reference system. For example, 3D coordinates are different between NAD83(CSRS) and ITRF because these two reference frames do not have the same origin (about 2 m apart).
    - Changes due to a new realization of the reference system are more common because all new observations will modify the reference frame. For example, control stations will have new updated coordinates based on more precise observations.
    - Finally, the Earth is not static. There are earthquakes, landslide and post-glacial rebound to name a few natural changes to the planet. There are also some changes due to human intervention. For example, there is subsidence due to mining and oil exploration or construction of major hydro projects.

# Agreement

## The U.S. National Geodetic Survey and The Canadian Geodetic Survey

**March 14, 2012**

The U.S. National Geodetic Survey and Natural Resources Canada's Geodetic Survey Division, via conference call held 2012/02/17, **agree**:

- To ***define*** the common (a unique) vertical datum for the United States of America (USA) and Canada (CA) through use of an equipotential surface, realized through one commonly (jointly) computed geoid model, corresponding to the mean coastal sea level for North America by 2022. Adoption is subject to National decisions;
- To ***compute*** the potential $W_0$ of this equipotential surface using Global Positioning System (GPS) data on tidal benchmarks, by April 1, 2012 and to ***use*** this value, for the realization of geoid models in the USA and CA until 2022;
- To ***maintain*** this equipotential surface as one option to adopt as the vertical datum even if this surface diverges (departs) from the true mean coastal sea level for (around) North America over time;
- To ***monitor*** differences between the above-mentioned equipotential surface and the mean sea level via Global Navigation Satellite Systems (GNSS) on tidal benchmarks, altimetry or other means as required;
- To ***provide*** to the public, deformational velocities (*N-dot*) of the equipotential surface $W_0$;
- To ***collaborate*** in the realization of geoid models, through the sharing of data and related information:
- To ***compute*** updated geoid models and geoid deformation models with improved realizations as needed;
- To ***inform*** each other when large discrepancies (outside 95% confidence region) are found in overlapping regions; and
- To ***choose*** a threshold value (in alignment with both stakeholder needs and scientific integrity) in 2022, between predicted (modeled) geoid change and true geoid change (including deformation and sea level change) which will warrant new realization of the vertical datum.

## The geopotential for the North American height reference system

**April 16, 2012**

Canada and the United States are both working towards modernizing their national height reference systems to replace CGVD 28 and NAVD 88, respectively with the objective to create a seamless height reference system across North America. As the new vertical datum will be realized by a geoid model, it is essential that Canada and USA select a common equipotential surface. Both parties have agreed that this surface should be the best fit, in a least squares sense, of the coastal mean sea level around North America.

In order to compute the mean geopotential, GPS heights and water levels at coastal tide gauges were combined with various geoid models. Given the variability of the mean sea level due to Sea Surface Topography (SST), the analysis was affected by tide gauge location and distribution, and geoid model precision and resolution. Based on comparisons at tide gauges around Canada and the United States where SST models were available, the best fit is 62,636,856.0 $m^2s^{-2}$. By averaging the Arctic gauges that were outside the coverage of the SST models, the geopotential would have been higher, approaching 62,636,858.0 $m^2s^{-2}$. Although very little data were available around Mexico and in the Caribbean region, including more tropical data would have likely lowered the geopotential to 62,636,854.0 $m^2s^{-2}$. Thus, the lack of tide gauges in Arctic and tropical regions somewhat compensates itself. Estimates of the North American mean obtained with different datasets, station combinations and weighting scenarios remained within 1 $m^2s^{-2}$ of each other depending on the particular tide gauge distribution and geoid models selected.

Understanding the importance of selecting a conventional value without delay for CGVD2013 realisation, the decision was made to select:

$$\mathbf{W_0 = 62{,}636{,}856.0\ m^2s^{-2}}$$

as the geopotential value for all geoid models in North-America until 2022. This agreed upon value of $W_0$ was found to be within the uncertainty of the mean estimate that best fits with mean sea level around North America. Although sea level is known to be changing, this $W_0$ value will be adopted as a fixed reference value until at least 2022 in order to enable consistent height determinations over the coming decade. This value could also be suitable for Mexico, the Caribbean region and Greenland. It also corresponds to the current convention adopted by the International Astronomical Union (IAU) and International Earth Rotation and Reference Systems Service (IERS).