Vertical Control Working Group
Issues and Status

Dru Smith
Topics

- Replacing NAVD 88
- NGS 58/59 update
- Passive Control as a monitoring tool
- Sea Level Rise
- Passive Control at NGS after 2022
Replacing NAVD 88
Terminology

• Horizontal Datum
  – Geometric Reference Frame
    • Geocentric X, Y, Z
    • Latitude, Longitude, Ellipsoid Height

• Vertical Datum
  – Geopotential Reference Frame
    • Geoid undulation
    • Orthometric height
    • Gravity
    • Deflection of the Vertical
Old vs New Datums

**The old way**

Text based datasheets

- NAD 83(2011) POSITION: 40 03 10.11468(N) 082 58 34.91800(W) ADJUSTED
- NAD 83(2011) ELLIP HT: 239.400 (meters) (06/27/12) ADJUSTED
- NAVD 88 ORINO HEIGHT: 273.3 (meters) 897. (feet) GPS OBS

Observed changes viewed as “corrections” not “movement”

Fragile, unchecked passive control

**The new way**

Modern datasheets

- CORS
- RTN

Geoid

Annual Geoid Change

Webinar for NGAC and FGDC on New Datums

January 16, 2015
Approximate extent of 2022 geoid model used for the “North American” part of the new geopotential reference frame.
Many US Pacific Territories (not Guam, CNMI nor American Samoa)
Canada Alaska, including entire Aleutian Island Chain

CONUS (USA)
GSVS11: Proving why we need GRAV-D

Geoids without new GRAV-D data: 1-3 cm differential accuracy over distances from 0.4 to 325 km

Geoids with new GRAV-D data: 1 cm differential accuracy over distances from 0.4 to 325 km
NGS 58/59

• NGS has been working with Ohio State to update the 58/59 guidelines

• Field data collected in 2013/2014 and report is in its initial stages

• Expect to finalize new guidelines in 2015
Passive Control as a Monitoring Tool

- Historically
  - “Supersede” coordinates
  - Change = Error or Correction

- Future
  - “Monitor motion”
  - Change = Movement
Assume “H” was determined four different times:

- 1990: 2.100
- 1994: 2.110
- 2002: 2.190
- 2009: 2.180
However, all measurements have error. Shown here are the same values of “H”, but with error bars representing their standard deviations.

1990: 2.100 +/- 0.0375 (3.75 cm)
1994: 2.110 +/- 0.0250 (2.50 cm)
2002: 2.190 +/- 0.0200 (2.00 cm)
2009: 2.180 +/- 0.0250 (2.50 cm)
If we presume the point has a constant velocity, we may fit a line, using appropriate weights to fit to the data.
We use $H = mt + b$, and:

$m = 0.00505 \text{ m/y} \ (5.05 \text{ cm uplift per year})$

$b(1970) = 2.004 \text{ m}$
Given $m$ and $b$, we can find $H$ at various time intervals.
And using the laws of error propagation through time we see that the error bars will depend on time removed from actual surveys.
As such, an NGS datasheet may have a graph like this for:

- $h_{\text{ITRF20xx}}(t)$
- $h_{\text{NAD2022}}(t)$
- $H_{\text{NAVD2022}}(t)$
Sea Level Rise

• Current definition:

  “The geoid is that equipotential surface which best fits global mean sea level in a least squares sense”
Issue

• If the geoid is related to sea level…

• And orthometric heights are measured “geoid up to surface”…

• And if sea level rises…

• Should your orthometric height drop?

• Should the geoid be “W=W0” forever or “fit sea level” forever?
  – Mutually exclusive definitions!

1/26/2015 FGCS VCWG meeting
Questions: What will be the H=0 surface at t1? Will it be A (W=non-constant), B (W=W0) or C (W=W1)? Which surface is “the geoid”? This answer must be defendable within the context of answering the question: “what is the definition of “the geoid?”"
Questions: What will be the H=0 surface at t1?
A) Will it be \( W=\?^* \) (“hold to the original surface size and shape at all costs”)
B) Will it be \( W=W_0 \) (“hold to the original W0 value at all costs”)
C) Will it be \( W=W_1 \) (“hold to the surface that best fits sea level at all costs”)

*no guarantee of being constant in the new mass re-alignment!

Which surface is “the geoid”?

This answer must be defendable within the context of answering the question: “what is the definition of “the geoid”?” Furthermore, it must also come with the answer to “is our chosen H=0 datum surface ‘the geoid’?”

NGS Policy is that the future vertical datum will use “the geoid” as its H=0 reference surface. As such, unless we change that policy, we need to pick A, B or C above in a way that also let’s us defend that choice as “the geoid”
Passive Control at NGS

- NGS has begun internal debates about every aspect of the NSRS after 2022

- One major issue: With active control as the primary access to the NSRS, does NGS have a continuing role in taking in passive control surveys from external users?
Passive Control: NGS Role

• Historically
  – 1,000,000 passive control marks
    • Horizontal & Vertical
    • Set and surveyed mostly by NGS
  – Only 80,000 have seen GPS
    • So only 80,000 have NAD 83(2011)
  – Motion unaccounted for
    • Supersede, rather than monitor
Passive Control: NGS Role

- Currently
  - GPS and/or leveling surveys from external users
    - Bluebooked = part of the NSRS
      - NGS decides on “the” coordinate (epoch fixed)
        » Continues the fallacy that Earth is not dynamic
    - OPUS-anything = not part of the NSRS
    - Few hundred surveys a year

- BB vs OPUS
  - Massive study and effort needed to reinvent BB
Passive Control: NGS Role

• Future
  – The NSRS will not be defined based on passive control
    • CORS and geoid only
  – Access will be primary through CORS and geoid
    • Passive = “secondary access”
Passive Control: NGS Role

• Question:

Should NGS continue to operate a passive control database, primarily populated with the surveys of external users of the NSRS?

• NGS seeks your answers to this question.
Extra Slides
Current Vertical Datums and Geoid Models used in North America

<table>
<thead>
<tr>
<th>USA (incl. Alaska)</th>
<th>Canada</th>
<th>Mexico</th>
<th>Puerto Rico (USA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAVD88</td>
<td>CGVD28</td>
<td>NAVD88</td>
<td>PRVD 02</td>
</tr>
<tr>
<td>IGLD85</td>
<td>IGLD85</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GEOID09 (USGG2009*)</td>
<td>HTv2.0 (CGG2010*)</td>
<td>GGM10*</td>
<td>GEOID09</td>
</tr>
</tbody>
</table>

* Gravimetric Geoid Models
<table>
<thead>
<tr>
<th>Hawaii (USA)</th>
<th>Virgin Islands (USA)</th>
<th>Caribbean Nations</th>
<th>Central American Nations</th>
</tr>
</thead>
<tbody>
<tr>
<td>None (HIVD15? pending)</td>
<td>None (VIVD09 pending)</td>
<td>Various</td>
<td>Various</td>
</tr>
<tr>
<td>GEOID09</td>
<td>GEOID03 (’09 pending)</td>
<td>CARIB97* / EGM08*</td>
<td>Various</td>
</tr>
</tbody>
</table>

* Gravimetric Geoid Models
Problems in NAVD 88

• A North American realization through spirit leveling networks

• Pre-satellite era product (625,000 km of leveling added to the NGVD29)

• Height information through passive bench marks whose positions change constantly in our changing world (e.g., PGR, subsidence, earthquakes, …)

• The geoid differences between NAVD 88 and GRACE are in meter range: compare to ±2-3 cm error in typical GPS ellipsoidal heights
Datum difference (GGM02S-NAVD88)

GRID STATS: MIN = 0.17 m  MAX = 1.88 m  AVE = 0.98 m  STD = 0.37
Problems in CGVD28

- Pre-satellite era product: Still based on the initial adjustment from 83 years ago

- Several local piecemeal adjustments since 1928

- Does not make use of any actual gravity (normal gravity only)

- Still neglects several systematic errors (Sea level rise, post-glacial rebound, systematic corrections to leveling measurements)

- Analysis indicates that the national distortion ranges from -65 cm (Halifax, NS) to 35 cm (Banff, AB), representing about a one-meter distortion nationally
Datum difference (CGG2010-CGVD28)

\[ W_{\text{CGG2010}} = 63636855.69 \text{ m}^2 \text{ s}^{-2} \]

Mean \[ W_{\text{CGVD28}} = 63636856.8 \text{ m}^2 \text{ s}^{-2} \]

GRID STATS: MIN = -0.824 m MAX = 0.680 m AVE = -0.114 m STD = 0.283 m
Datum difference (GGM10-NAVD88)

-0.9 m

0.6 m
Plans and suggested procedures for vertical datum unification
The GRAV-D Project

A US NGS lead gravity project for improving American geoid model

Redefinition of the vertical datum of the US by 2022

Airborne gravity “snapshot”

Geophysical modeling and in-situ based geoid change monitoring in out-years
Canada Height Modernization - 2013

The geoid model:
1. Entire coverage of the Canadian territory (land, lakes and oceans)
2. Compatible with space-based positioning (e.g., GNSS, altimetry)
3. Less expensive for maintenance
4. Fairly stable reference surface

Levelling Networks:
1. Established over the last 100 years
2. 120,000 km of levelling lines
3. Some 80,000 benchmarks
4. Time consuming
5. Expensive
6. Limited coverage
7. BMs are unstable
8. BMs disappear
9. Local networks

\[ H = h_{GNSS} - N_{Model} \]
Geoid model improvement in Mexico

Geoid and its relations to NAVD88 are modeled to make the link between GNSS technology and the official reference frame.

Improvements are sought now from building a new gravimetric network to mitigate all errors in data source for geoid modeling.

In Mexico, the geoid is regarded as a real alternative for referencing heights in the future.
Convergence of geoid theory and modeling
CGG2010 – USGG2009

St. Dev. for BC/AB (filter)
346 GPS on BM stations
CGG2010: 4.5 cm (4.4 cm)
USGG09: 6.7 cm (6.4 cm)
EGM08 : 6.5 cm (6.2 cm)

Errors come from levelling, GPS, geoid and marker stability.

St. Dev. for Rockies (filter)
102 GPS on BM stations
CGG2010: 5.3 cm (5.1 cm)
USGG09: 8.6 cm (8.3 cm)
EGM08 : 8.7 cm (8.5 cm)

CGG10 – USGG09
Min.: -0.771 m
Max.: 0.933 m
Mean: 0.002 m
StDev: 0.038 m

St. Dev. for Colorado
(filer)
602 GPS on BM stations
CGG2010: 7.4 cm (6.2 cm)
USGG09: 8.5 cm (7.5 cm)
EGM08 : 8.9 cm (7.8 cm)

St. Dev. for Florida
(filer)
2275 GPS on BM stations
CGG2010: 6.7 cm (3.1 cm)
USGG09: 7.2 cm (3.9 cm)
EGM08 : 7.3 cm (4.2 cm)
Repeatability of 20 different solutions
(common terrestrial dataset)

Five different global models
- EGM08 (GRACE + Terrestrial)
  + D360 and D2190
- GOCO1S (GRACE, GOCE)
  + D224 and ext. D360
- EGM08/GOCO01S
  + D2190

Statistics
Min.: 0.002 m
Max.: 1.288 m
Mean: 0.068 m
StDev: 0.066 m

Image depicts basically the gravity field difference between the GRACE/GOCE and Terrestrial data for the 60-140 frequency band.

Four degrees of modification
- 60 (335 km)
- 90 (220 km)
- 120 (165 km)
- 140 (140 km)
Comparison of N.A. plans

*(Geopotential Reference System)*

- Canada and USA agreed to move to a geoid-based datum
  - **USA:** Replace NAVD 88 (and VIVD09, PRVD02 and HIVDyy) with one geoid-based vertical datum at completion of GRAV-D *(2022)*. Similarly for Guam and American Samoa, but with special Pacific geoid models for them.
  - **Canada:** Replace CGVD28 with geoid-based vertical datum as early as 2013.

- USA and Canada will use a common geoid in 2022
  - Negotiations require agreement on $W_0$ value and other issues

- Mexico has no program in place to replace NAVD88, but engaging with USA and Canada in realizing a N.A. geoid model

- Other countries: No plans to participate or adopt a N.A. datum
Comparison of N.A. plans (Geometric Reference System)

- USA: Replacement of NAVD88 coincides with replacing NAD83 with a new “horizontal” (e.g. “geometric”) datum
  - Removes the non-geocentricity of NAD 83

- Canada: No plans to replace NAD 83(CSRS)

- Mexico: Already works in ITRF08 epoch 2010.0, alleviating the non-geocentricity issue
NAVRS: Fundamental concepts

- **NAVRS**: North American Vertical Reference System (singular vertical datum circa 2022)

- Defined according to international standards:
  - IAG ICP1.2 Conventions for the Definition and Realization of a CVRS

- An equipotential surface \( W_0, \ Unit: m^2 \ s^{-2} \)

- To be realized by a geoid model \( N, \ Unit: m \)

- A dynamic surface \( N^{\dot{}} , \ Unit: mm/yr \)
NAVRS: Requirements

• One geoid model for North America: Canada, United States (including Alaska and Hawaii), Mexico, Caribbean Islands and Central America (possible expansion to include Greenland … South America?)

• Accuracy
  – ±1 - 2 cm absolute accuracy in coastal and flat areas;
  – ±3 - 5 cm in mountainous regions

• A dynamic surface
  – Will be updated at certain time interval (time-tagged model)
  – Will realize a velocity model of the geoid
Required parameters for a geoid model

• Geoid model parameters
  • Potential (e.g., $W_0 = 62636855.69 \text{ m}^2/\text{s}^2$)
  • Reference ellipsoid (e.g., GRS80)
  • Geometric frame (e.g. NAD83(CSRS), ITRF2008)
  • Boundaries (North/South/West/East)
  • Grid Interval ($\Delta$Lat, $\Delta$Lon)
  • Geocentric gravitational constant (GM)
  • Epoch
  • Tidal System (Tide free, zero tide or mean tide)
  • Node: Point or mean values / Center or Corner

• Supplemental data
  • Error estimates for geoid heights ($\sigma_N$)
  • Geoid vertical velocity ($N^{\text{dot}}$)
  • Error estimates of velocities ($\sigma_{N^{\text{-dot}}}$)
Challenges in the 1-cm geoid realization

• Theories (more terms = more accurate?)

• All computation methods are theoretically equivalent, but not equal. Identical starting equations lead to different realizations and approximations.
  • Models computed from the same data sets using different methods may differ from cm to dm

• How to judge a geoid computation method is superior over others?

• How to quantify and verify geoid accuracy (relative and absolute)?
NAVRS: Realization

- Realization of the vertical reference system
  - Ellipsoidal harmonic approach (USA)
  - Stokes Integral; modified kernel (Canada)
  - Single datum origin point no longer needed
- Data
  - GRACE (long), GOCE (middle), airborne and ground gravity (short), DEM (very short)
- Validation
  - CORS, CACS, CBN, Benchmarks
    - No levelling surveys are conducted for the maintenance of the 1st-order network
  - Deflections of the vertical (astronomical and airborne)
  - Oceanographic SST models
    - Including GPS at water and tide gauges
NAVRS: Maintenance

• Three options

  – Define to the best potential value representing the geoid
    • Advantage: Datum always represent global MSL
    • Disadvantage: no consistency for heights as $W_0$ may change significantly

  – Define to a fixed potential value
    • Advantage: Possible height consistency if model is at correct surface
    • Disadvantage: Not necessary consistent with global MSL

  – Define by the same initial equipotential surface
    • Advantage: Height consistency; even correct for computational error
    • Disadvantage: Not consistent with global MSL
      – Geoid model parameters would allow advanced users to convert data to any datums
      – Not accounting for Sea Level Change
    • Favoured option in Canada
Geoid change monitoring

• Long wavelength changes can be monitored by satellite gravity missions
  – as long as a GRACE follow-up or equivalent mission is available
  – If not, national GNSS network (e.g., CORS, ACS, CBN) with absolute gravity measurements and a geophysical model (a challenging approach)

• Medium to short wavelength (e.g., 5-100km) changes may be monitored by combination of GNSS measurements, surface gravity measurements and Deflections of the Vertical for regions of high interest and rapid change

• Provide a velocity model of geoid variation
The “secular” geoid change from the monthly GRACE models (2002-2008).

The solution represents the effect due to total mass changes.

The solution uses a 400-km Gaussian filter.
Relationships between WHS, existing VDs and NAVRS

• The relationship is through conversion surfaces:
  – NAVRS ↔ WHS
    • Should be zero or a potential constant if WHS and NAVRS does not adopt the same equipotential surface
    • No WHS is established by IAG yet
  – NAVRS ↔ Levelling datums (NAVD88, CGVD28 and NGVD29)
    • Use of a hybrid geoid model to convert between geoid and levelling datum
  – NAVRS ↔ IGLD
    • Software to convert from orthometric heights to dynamic heights for proper water management of the Great Lakes and St-Lawrence Seaway or any drainage basins
Summary

• North America would benefit from a unified vertical datum

• NAVRS is to be realized through a geoid model with well established parameters

• The geoid model is required to have an absolute accuracy of ±1-2 cm in coastal and flat areas and ±3-5 cm in mountainous regions

• Challenges
  – Canada and USA do not have the same implementation date
  – Technical aspects
    • Data accuracy and coverage
    • Computation methods
    • Validation and verification
  – Long-term maintenance of the NAVD
  – No definition of a WHS yet