Update on GRAV-D and Progress toward a new vertical Datum

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What is a Vertical Datum?

• Strictly speaking, a vertical datum is a surface representing zero elevation
• Traditionally, a vertical datum is a system for the determination of heights above a zero elevation surface
• Vertical datum comprised of:
  – Its definition: Parameters and other descriptors
  – Its realization: Its physical method of accessibility

U.S. Department of Commerce
National Oceanic & Atmospheric Administration
National Geodetic Survey

Mission: To define, maintain & provide access to the National Spatial Reference System (NSRS) to meet our Nation’s economic, social & environmental needs

National Spatial Reference System

• Latitude
• Longitude
• Height
• Scale
• Gravity
• Orientation

& their time variations

History of vertical datums in the USA

• **NGVD 29**
  – National Geodetic Vertical Datum of 1929
  – Original name: "Sea Level Datum of 1929"
  – "Zero height" held fixed at 26 tide gauges
    • Not all on the same tidal datum epoch (~ 19 yrs)
  – Did not account for Local Mean Sea Level variations from the geoid
    • Thus, not truly a "geoid based" datum

The National Geodetic Vertical Datum of 1929 is referenced to 26 tide gauges in the US and Canada

Current Vertical Datum in the USA

• **NAVD 88**: North American Vertical Datum of 1988
  - **Definition**: The surface of equal gravity potential to which orthometric heights shall refer in North America*, and which is 6.271 meters (along the plumb line) below the geodetic mark at “Father Point/Rimouski” (NGSDB PID TY5255).
  - **Realization**: Over 500,000 geodetic marks across North America with published Helmert orthometric heights, most of which were originally computed from a minimally constrained adjustment of leveling and gravity data, holding the geopotential value at “Father Point/Rimouski” fixed.

*Not adopted in Canada
History of vertical datums in the USA

• NAVD 88
  – North American Vertical Datum of 1988
  – One height held fixed at “Father Point” (Rimouski, Canada)
  – ...height chosen was to minimize 1929/1988 differences on USGS topo maps in the eastern U.S.
  – Thus, the “zero height surface” of NAVD 88 wasn’t chosen for its closeness to the geoid (but it was close...few decimeters)

History of vertical datums in the USA

• NAVD 88 (continued)
  – Use of one fixed height removed local sea level variation problem of NGVD 29
  – Use of one fixed height did open the possibility of unconstrained cross-continent error build up
  – But the H=0 surface of NAVD 88 was supposed to be parallel to the geoid...(close again)

Types Uses and History of Geoid Height Models

• Gravimetric (or Gravity) Geoid Height Models
  – Defined by gravity data crossing the geoid
  – Refined by terrain models (DEM’s)
  – Scientific and engineering applications

• Composite (or Hybrid) Geoid Height Models
  – Gravimetric geoid defines most regions
  – Warped to fit available GPSBM control data
  – Defined by legislated ellipsoid (NAD 83) and local vertical datum (NAVD 88, PRVD02, etc.)
  – May be statutory for some surveying & mapping applications
Errors in NAVD 88: ~50 cm average, 100 cm CONUS tilt, 1-2 meters average in Alaska. No tracking.

Why isn’t NAVD 88 good enough anymore

• NAVD 88 suffers from use of bench marks that:
  – Are almost never re-checked for movement
  – Disappear by the thousands every year
  – Are not funded for replacement
  – Are not necessarily in convenient places
  – Don’t exist in most of Alaska
  – Weren’t adopted in Canada
  – Were determined by leveling from a single point, allowing cross-country error build up
The National Geodetic Survey 10 year plan
Mission, Vision and Strategy
2008 – 2018
http://www.ngs.noaa.gov/INFO/NGS10yearplan.pdf

- Official NGS policy as of Jan 9, 2008
  - Modernized agency
  - Attention to accuracy
  - Attention to time-changes
  - Improved products and services
  - Integration with other fed missions

2022 Targets:
- NAD 83 and NAVD 88 re-defined
- Cm-accuracy access to all coordinates
- Customer-focused agency
- Global scientific leadership

Names

The Old:
NAVD 88
PRVD 02
VIVD09
ASVD02
NMVD03
GUVD04
IGLD 85
IGN71
GEOID12B
DEFLEC12B

The New:
The North American-Pacific Geopotential Datum of 2022 (NAPGD2022)
- Will include GEOID2022

NAVD 88 is not alone
- NAVD 88 North American Vertical Datum of 1988
- PRVD02 Puerto Rico Vertical Datum of 2002
- ASVD02 American Samoa Vertical Datum of 2002
- NMVD03 Northern Mariana Vertical Datum of 2003
- GUVD04 Guam Vertical Datum of 2004
- VIVD09 Virgin Islands Vertical Datum of 2009, 3 each
- various Hawaiian Vertical Datasets, coming soon
- IGLD 85 International Great Lakes Datum 1985
- IGN71 International Geoid
- GEOID12B Geoid undulations
- DEFLEC12B deflection of the vertical
1. Using GNSS is cheaper, easier than leveling
2. To use GNSS we need a good geoid model
Gravity Field Metaphor

Orbit View
- Mountain Ranges
- Deserts
- Large Rivers
- Coastlines
- Large Islands

Not detailed; Continental

Gravity Field Metaphor

Airplane View
- Individual Peaks
- Large Lakes
- Human Activity
- Mountain Ranges

Regional
- Lake Tahoe (CA/NV)

Gravity Field Metaphor

Ground View
- Rocks/Boulders
- Plants
- Mountains, Valleys, Lakes, etc

Local
- Rocky Mountain National Park, Colorado
- Acadia National Park, Maine

Courtesy of NASA
Image credit: University of Texas Center for Space Research and NASA

GRACE Gravity Model 01
- Released July 2003

Problems with Gravity Holdings

- Decades of gravity surveys are inconsistent with one another
- Airborne gravity will provide a baseline for removing these inconsistencies

Problems with Gravity Holdings

- Field is not sampled uniformly
GRAV-D Project Overview

• Overall Target: 2 cm accuracy orthometric heights from GNSS and a geoid model
• GRAV-D Goal: Create gravimetric geoid accurate to 1 cm where possible using airborne gravity data
• GRAV-D: Two thrusts of the project
  – Airborne gravity survey of entire country and its holdings
  – Long-term monitoring of geoid change
• Leveraging partnerships to improve and validate gravity data

Data Collection Scope

• Entire U.S. and territories
  – Total Square Kilometers: 15.6 million
  – Initial target area for 2022 deadline
  – ~200 km buffer around territory or shelf break if possible

Gravity Survey Plan

• National Scale Part 1
  – Predominantly through airborne gravity
  – With Absolute Gravity for ties and checks
  – Relative Gravity for expanding local regions where airborne shows significant mismatch with existing terrestrial
GRAV-D Expected Coverage

Puerto Rico
US Virgin Is.

Priority - Greatest Datum Need

• Alaska
• Puerto Rico/US Virgin Islands (PRVI)
• Coastal US and Great Lakes
  • Great Lakes
  • Gulf of Mexico & FL
  • Eastern Seaboard
  • Western Seaboard
• Hawaii and Pacific Islands
• Aleutian Islands
• Interior CONUS
  • Mountainous areas first

Other Variables to Consider

• Time of Year, Need Smooth Air
  – Likelihood of Turbulence: Hurricanes, Tornados
  – Prevailing winds and weather patterns, especially wintry conditions and thunderstorms
• Aircraft Available
  – Differing Capabilities
• Funding
• Areas already completed
• GPRA *GPRA = Government Performance and Results Act of 1993

NOAA TurboCommander at Denver Rocky Mountain Airport
September 2012
### Performance Metric for Airborne Surveys

<table>
<thead>
<tr>
<th>FY</th>
<th>FY9</th>
<th>FY10</th>
<th>FY11</th>
<th>FY12</th>
<th>FY13</th>
<th>FY14</th>
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<th>FY18</th>
<th>FY19</th>
<th>FY20</th>
<th>FY21</th>
<th>FY22</th>
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<tr>
<td>%</td>
<td>6.14%</td>
<td>7.5%</td>
<td>12%</td>
<td>20%</td>
<td>28%</td>
<td>40%</td>
<td>51%</td>
<td>62%</td>
<td>70%</td>
<td>79%</td>
<td>87%</td>
<td>96%</td>
<td>100% and beyond</td>
<td></td>
</tr>
</tbody>
</table>

*Measure: Percentage of the U.S. and its territories with GRAV-D data available to support a 1 cm geoid supporting 2 cm orthometric heights.*

As of Oct 27, 2017

### Airborne Gravity Current Coverage

Data Block Status

As of Oct 27, 2017

http://www.ngs.noaa.gov/GRAD/Data PRODUCTS.shtml

### Survey and Block Plans

- Layout rectangular survey 400 x 500 km
- Extends beyond the shelf break
- Block size will reflect the endurance of the aircraft
Survey and Block Plans

- Data lines spaced 10 km apart
- Cross lines spaced 60-80 km apart
- Flight altitude 20,000 ft
- Nominal speed 220-250 kts

GRAV-D Aircraft

- Bureau of Land Management Pilatus PC-12
- National Research Laboratory King Air RC-12
- NOAA P-3 (background)
- Fugro King Air B-400B

Requirements

- Geodetic quality results require accurate aircraft positions, velocities, and accelerations
- High-altitude, high-speed, long baseline flights for gravimetry
GRAV-D Instrumentation

- Micro-g LaCoste TAGS Gravimeter
- NovAtel SPAN-SE w/ Honeywell µIRS IMU

- Both instruments include GNSS receivers
- SPAN system allows for tightly coupled GPS/IMU solutions

From Measurement to Product

- Airborne Gravity Collection
- GPS and Gravity Data Processing
  - Kinematic positioning is critical
  - NGS-developed software

- Gravity Data Release to Public
- Inclusion in Yearly Experimental Gravimetric Geoid Models

Online Data Portal

- Interactive Google Map:
  - Up-to-date info on all blocks
  - 20 blocks released (as of Jan. 2014)
  - Clicking a block pops up basic info and a link to the block's page if data is available

Online Data Portal
Example Block Site: http://www.ngs.noaa.gov/GRAV-D/data_as01.shtml

• Data Available Now:
  - Airborne gravity at altitude
  - GIS Images
  - .kmls of block extent and data lines
  - Two user manuals (one general, one specific to block)
  - FGDC metadata

• Future Data:
  - Experimental geoid products, similar to USGS official products
  - WILL incorporate GRAV-D data

Validating Geoid Accuracy

“...the gravimetric geoid used in defining the future vertical datum of the United States should have an absolute accuracy of 1 centimeter at any place and at any time.”

-- The NGS 10 year plan (2008-2018)

Admirable!...Achievable?

Validating Geoid Accuracy

• NGS planned 3 surveys to validate the accuracy of the gravimetric geoid model
  - GSVS11
    • 2011; Low/Flat/Simple: Texas; Done; Success!
  - GSVS14
    • 2014; High/Flat/Complicated: Iowa; Field work Complete
  - GSVS17
    • 2016 - 2017; High/Rugged/Complicated: Colorado
Objective of the GSVSs

• How do we know that GRAV-D is working?
• The Geoid Slope Validation Surveys (GSVSs) use high precision, high resolution (~1.5km spacing), ground-based survey techniques to determine the shape of the geoid consistently along a large (~300km) distance.
• This allows for the direct comparison of the geoid shape predicted by various, gravity-based geoid models.
• This also allows for a quantification of the airborne gravity’s contribution to the improvement of these models.

Objective of the GSVSs (cont.)

Why compare the shape of the models?

Rather than using “absolute” values of the geoid at specific locations to compare models, it is actually more useful to look at the changes in the shape of the geoid over various distance scales (i.e. looking at the slope between various pairs of survey points separated by 1, 2, 5, 10, 20, 50, 100, 200 km, etc.). Hence the name...

Choosing the Place and Time for a New Survey

• Criteria:
  – Significantly exceed 100 km
  – Under existing GRAV-D data
  – Avoid trees and woods
  – Along major roads
  – Cloud-free nights
  – No major bridges along the route
  – Low elevations
  – Significant geoid slope
  – Inexpensive travel costs
GSVS Survey Techniques

- Survey techniques employed:
  - Benchmarks installed ~1.5 km
  - Leveling
  - Absolute/Relative Gravity
    - Vertical Gravity Gradient
  - Long-session GPS
  - Deflection of Vertical

The Chosen Line in 2011

- 325 km
- 218 points
- 1.5 km spacing

South Texas
July-October, 2011
Hot…Hot…HOT!

Leveling and Gravity

- The entire line was leveled (double-run). Geodetic heights provided at each benchmark.
- Leveling and gravity are both needed for orthometric height determination.
  - Usually gravity is modeled, but in this case was actually measured at every point.
    - Relative gravity and vertical gravity gradient at every benchmark
    - Absolute gravity (A10 and/or F65) at “every 7th” benchmark
Geodetic Leveling

Gravity Observations
Long Period GPS

- Calibrated, fixed-height antennas, all identical models
- In Texas 2011:
  - 20 complete sets of equipment (2 parties, 10 sets each)
  - Each party observed 10 new stations each day
  - 20 hours of observation each day
- Project processed with OPUS Projects

Campaign GPS

- Full antenna recalibration check before survey
- Each fixed height tripod height measured before and after
- 20 complete sets of equipment
  - 2 parties (10 sets each)
- Each party observe 5 new and 5 repeat stations each day
- 30 observation days
- Project processed with OP

The “Dimple-ometer”
Deflection of the Vertical (DoV)

- Measure the slope of the geoid directly!
- Precision tilt meters provide alignment “level” to the geoid.
- Celestial almanacs provide predicted alignment with star field (relative to ellipsoid).
- The difference between the two vectors (broken into orthogonal components) are the Deflections of the Vertical (or “slopes”).
- In Iowa 2014:
  - 228 stations (204 official points, 11 redundant observations, 3 reobservations)
  - 31 nights
  - 7 stations/night
  - Observing with Swiss CODAC (COMPact Digital Astrometric Camera)
GSVS11, South Texas

- The first survey was performed in south Texas in 2011
- Low (close to the geoid) and flat.

Results were excellent!

After the success of GSVS11, Iowa was chosen for the next test in 2014. Higher elevation and geologically interesting terrain (traversing the Midcontinent Rift System). (Very) similar survey techniques were employed. Preliminary results again show excellent (<2 cm geoid discrepancy) agreement and noticeable improvement when airborne data are included. March 2017: Accepted for publication in Journal of Geodesy.

Central Iowa
330 km
205 points

Two crews of 4-5 people/crew
1st order Class II
749 km
105 crew days
7.1 km/day/crew
Gravity Observations

- 3 1st-order Class II stations
  - Dennison, Ames, Cedar Rapids
- A-10 Absolute stations (every 7th station)
- Gravity Gradients (every 7th station)
  - 2 stations per day, 31 days to observe
- Relative Gravity (205 stations)
  - 10 per day, 23 days to observe

DoV

- 228 stations (204 official points, 11 redundant observations, 3 reobservations)
- 31 nights
- 7 stations/night
- Observing with Swiss CODIAC COmpact DIgital Astrometric Camera

GSVS17 Colorado

- The third (and likely final) GSVS will take place along US160, from Durango to Walsenburg, in southern Colorado.
- High elevation and rugged topography, “Worst case” for geoid modeling.
- Variation from 6,000’ (MSL) to 11,000’, over two passes.
GSVS17 Colorado (cont.)

• 220 benchmark locations (approximately 1 per mile) have been installed
• The survey will take place in overlapping phases beginning May 2017 and is expected to continue through September.

Differences with GSVS17

• Numerous “extra” bench marks had to be installed for leveling accuracy purposes (very steep terrain in some sections).
• Absolute gravity (A10) and quadratic (3 tier) gravity gradients measured at all benchmarks.
• Topographic corrections are being developed to aid in field DoV quality control as well as post-survey geoid modeling.

Conclusions – Problems (IA)

• Flooding (access to marks) in June
• One damaged fixed-height tripod
• Tall grass, ticks, mosquitoes
• Trains, Trains, Trains on Western 1/3rd of line
Conclusions-Successes (IA)

- Over a year of planning and preparation
- Two Co-Project Managers (Scientific/Admin)
- Single Team-Lead for each activity
- Frequent Team meetings (pre-deployment)
- Team-Leads wrote the project instructions
- Field work was successfully completed on time and was of high quality

NEW VERTICAL DATUM (Rationale)

- A move away from differentially leveled passive control as the defining mechanism of the reference surface
- To be consistent with the shift in the geometric reference frame/ellipsoid (2022)
- Improvement in our technical abilities in reference surface realization (geopotential gravimetric reference surface - 1cm accuracy of geoid (GNSS/GRV-D))
- The new geopotential reference surface will be aligned with the geometric reference frame/ellipsoid (i.e., no hybrid geoid)

NEW VERTICAL DATUM (Rationale)

- The technology to make accurate vertical heights measurements with GNSS technology
- To provide vertical access to formerly prohibitive places
- To allow monitoring of physical or geophysical datum deformation
NEW VERTICAL DATUM
(Components)

- Design and adopt new geometric reference frame (Geometric Datum Project)
- Realize new geometric datum with existing passive/active control, i.e., a horizontal (geometric) adjustment
- Definition of the W₀ surface as the new datum reference surface
- Build a gravimetric geoid with an overall accuracy of 1 cm (GRAV-D Project)
- Make orthometric heights easily available

Agreement on W₀ Value

Experimental Models

Annually update an experimental gravimetric geoid with GRAV-D data
- Evolution as we move
  - from USGG2012 (last non-GRAV-D gravimetric geoid)
  - through xGG2017 (annual experimental geoid)
  - to USGG2022 (the final geoid with GRAV-D)

- Starting 2014: National Ocean Service Requirement
Evolution of the Geoid

- EGM08
- GRACE
- GOCE
- USGG2012 GEOID12A/B
- 2008
- 2012
- 2014
- 2015
- 2016
- xGeoid14B
- xGeoid15B
- xGeoid16B

First experimental geoid model released June 30, 2014

- Online tools for accessing it (GRAV-D website)

The effect airborne gravity
How much will heights change?

• How much will NSRS ellipsoid height change?
  – Geometric Datum will be aligned to ITRF
  – Approx -1.9 m (Puerto Rico) to +2.0 m (Guam)

• How much will NSRS CONUS orthometric height change?
  – Approx +0.1 m (Florida) to -1.3 m (Washington)
  – More than 2 meters of change in Alaska

Metadata is Critical

• Your positional metadata should include:
  – datum
  – epoch
  – source
• These will facilitate transforming from current to new datum
• Maintaining your original survey data will provide more accurate results

How to Plan for the Future

• Move to newest realizations
  – NAD 83(2011) epoch 2010.00
  – USGS12 (gravimetric geoid) / GEOID12A (hybrid geoid)
• Obtain precise ellipsoid heights on NAVD 88 bench marks
  – OPUS-DB, contact NGS Geodetic Advisor
  – Improves hybrid geoid models and provides "hard points" in new vertical datum
  – Follow new NGS Guidelines when released
• Move off of NGVD 29 to NAVD 88
  – Understand the accuracy of VERTCON in your area
• Move away from passive marks to GNSS
  – Especially move off of classical passive control
• Require/provide complete metadata for all mapping contracts
  – How did they get the positions/heights? Document it!!
Monitoring Geoid Change: Static vs. Dynamic
From Damiani, 2017 Geospatial Summit

Static, except for model updates
Deforms, subsides, uplifts at all length scales
Changes along with large-scale gravity change (caused by mass movement)

\[ H = -N + \bar{N} \]

Option 1: Provide a series of static geoids, updated whenever change somewhere in the U.S. reaches 0.5 cm. [Not NGS' choice]
Option 2: Provide a static geoid (N0) and geoid change over time (\( \bar{N} \)) so that orthometric heights remain accurate to 1 cm at all times. \[ H_t = h_t - (N_0 + \bar{N} \times t) \] [NGS' choice]

In a static world, \( H \approx h - N \)

2022 aim is to achieve 1 cm geoid height accuracy (wherever possible) and 1 cm ellipsoidal height accuracy.

Components of a Long-Term Monitoring Plan

1. What and Where to Monitor
   - For all gravity change signals, need to know:
     - How big (magnitude)?
     - How big (spatial)?
     - Other characteristics (constant change, sudden change, etc.)
   - Which signals do we monitor to maintain geoid accuracy at the 1 cm level over the next 100 years?

2. How to Monitor in the Near-Term (next 1 to 3 decades)
   - Which monitoring methods are available?
   - Are they reliable, replaceable (if there's a failure), and cost effective?
   - How much do the signals vary (e.g. seasonally) and how accurately can they be measured, to estimate accumulation of error over time?

3. Which Products Need to be Available
   - How do we integrate geoid/vertical datum maintenance for NSRS users?

4. Long-Term Program Adaptation
   - What future technologies may become available for use in monitoring later this decade & this century?

1. What to Monitor?

Question: What changes affect the geoid in North America?

<table>
<thead>
<tr>
<th>Timescales of Geoid Change</th>
<th>...</th>
<th>...</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous, Multi-Decadal</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Complex, Multi-Decadal</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Continuous, Sub-Decadal</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Episodic, Cataclysms</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

| Time span for signal occurrence, | | |
| Variable | ... | ... |
| Continuous, multi-decadal | ... | ... |
| Continuous, sub-decadal | ... | ... |
| Complex, multi-decadal | ... | ... |
| Episodic, Cataclysms | ... | ... |

...
1. Where: Cataclysms

All Recorded Magnitude 8+ Earthquakes, Last 110 Years

[Map of earthquake locations]

1. What is Glacial Isostatic Adjustment?

In North America, the ground (and geoid) are adjusting after the melting of the Laurentide Ice Sheet, which was largest at the Last Glacial Maximum ~21,000 years ago.

[Diagram of Glacial Isostatic Adjustment]

Explosive eruptions occur at volcanoes along plate boundaries when gas (often water vapor) is trapped in the magma.

[Image of volcanic eruption]

Wouters, et al., 2014

Image courtesy of Byrd Polar Research Center, The Ohio State University
1. Where: Glacial Isostatic Adjustment

Geoid Height Trend (from GIA only)

From the ICE-5G GIA Model Created by Dr. Peltier at the Univ. Toronto
Jacob, et al., 2012

1. Where: Present Day Ice Mass Loss

*If these computed geoid trends remain more or less constant into the future, one might expect a geoid change of 10 mm every 3.5–6.5 years immediately over the glaciated regions of North America.*

Jacob, et al., 2012

Canadian

SE Alaska 3 cm/decade

Greenland 3.5 cm/decade

1. What to Monitor?

- Jacob, et al. 2012 considered the next 100 years of change.

- To maintain 1 cm accuracy:
  - For the next 30 years, only glacial isostatic adjustment and present-day ice mass loss continuously affect the geoid.
  - For the next 30 years, local, episodic adjustments will be needed after cataclysmic disasters, likely only affecting Alaska and the volcanic portions of the Western US.
  - From 30-100 years, we must also account for: hydrology and climate-related change, the slow eruptions of Hawaiian volcanos, and global sea level rise.
2. How to Monitor?

**Possibility 1: Combined Models + Data**

1. Identify each significant gravity change source.
2. Use specialized models to estimate mass change, then predict gravity and geoid change over time from each source.
3. Add results together to get total geoid change over time.
4. Validate with terrestrial gravity data, to be sure the models are correct.

<table>
<thead>
<tr>
<th>Can we do it?</th>
<th>Should we do it?</th>
</tr>
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<tbody>
<tr>
<td>Yes.</td>
<td>Maybe.</td>
</tr>
<tr>
<td>- 6 significant sources already identified from Jacob, et al., 2012.</td>
<td>- Relies on models created and maintained by others.</td>
</tr>
<tr>
<td>- Models exist for 2 near-term sources (GIA and glacier melting) and can be used to predict geoid change.</td>
<td>- Could be expensive to set up and maintain a terrestrial gravity network, depending on the size of the network.</td>
</tr>
<tr>
<td>- A validation network for terrestrial gravity can be created with existing technology.</td>
<td>- This is how Canada already monitors geoid change, to upkeep their geoid-based vertical datum.</td>
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**How Accurate are Glacial Isostatic Adjustment Models?**

GRACE and GIA Models are very similar in error. Using current GIA models (not GRACE) would introduce a 10 mm geoid offset over 18 years, centered mostly in N. Canada.

**Canadian Geodetic Survey LTM Program**

CACS is the Canadian GNSS Active Control System similar to NGS' Continuously Operating Reference Stations (CORS). CACS is the Canadian GNSS Active Control System similar to NGS' Continuously Operating Reference Stations (CORS).

All Primary CGSN Stations

All CACS, National (green), Regional (yellow), and Local Arrays (red and blue).

New website to access data and time series in the Canadian Gravity System Network.

Enter "CGSN map" into Google.

Canada's Natural Resources – Now and for the Future.
2. How to Monitor?

Possibility 2: Direct Measurement

1. Estimate most of the geoid change from satellite gravity measurements, which measures total change regardless of the source.
2. Add in "small" gravity signals that the satellites can't detect but do affect the geoid, from models or data.
3. Create a combined gravity model of change over time and estimate the geoid change over time from that.

Can we do it?
Yes.
• Satellite gravity from GRACE exists from 2008 – present, but it is at end-of-life.
• Satellite gravity will be provided by GRACE Follow-On starting in early 2019, if all goes well.
• We can research which "small" signals are needed; data and models mostly exist.
• NGS has experts at merging gravity data and making geoid models.

Should we do it?
Very likely.
• Relies on satellite gravity data that is either freely available or highly-likely to be available soon.
• Requires building some in-house expertise but mostly relies on existing expertise.
• Only a small portion of the monitoring relies on models or data created outside NGS.

Geoid Change Based on Monthly GRACE Solutions 2002-2014

Annual Change Amplitude in mm

Trend in cm

Accumulated Change Over 1 Decade

Trend in cm

Images courtesy of Ryan A. Hardy, pers. comm.

2. Mascons: Detailed GRACE Change over Time

• Mascon: "Mass Concentration"
• A different way of displaying local gravity changes from GRACE data; gives better local results, especially for magnitude and extent of change.

• EXAMPLE: http://ccar.colorado.edu/grace/gsfc.html
• This online model removes GIA and other "non-water" related signals, since the primary product is focused on the gravity change due to water storage.

• For monitoring, NGS will need custom GRACE mascon models that include all gravity signals.
GRACE (2002-present) Mascons, Goddard SFC

Trend in Water Equivalent Change

GIA signal is removed. Mostly reflects changes in groundwater, seasonal snowpack, drought, and glacial melting.

Mascon Time Series: Trend and Seasonal Signals

Alaska

- For all locations within this mascon, total loss of ~80 inches of water from glacial ice melting from 2002-2016.
- Seasonal cycle: ~20-40 inches accumulated and lost each year.

Mascon Time Series: Trend and Seasonal Signals

SW US Drought

- Plot settings units:
Future Satellite Gravity Missions

GRACE Follow-On Mission to launch 12/2017 – 2/2018
- 1 satellite built and tested, other very near completion.
- Mostly the same mission as GRACE
- New: Test a laser ranger; possible 20 – 25x improvement in intersatellite ranging.
- 5-year mission length ends 2023*

(*GRACE was planned for 5 years and is finally near end of life after 14 years)

Pail et al., 2015

Plans for GRACE-2 and beyond:

| Table 1. Performance number of GRACE-FO compared to the previous generation of gravity missions. |
|---|---|---|---|---|---|
| satellite-limited | geographic-limited | mission-limited | mission-limited | mission-limited | mission-limited |
| Improvement | Improvement | Improvement | Improvement | Improvement |
| ~factor of 5 better than GRACE | ~factor of 10 better than GRACE | Leap Forward | Leap Forward | Leap Forward |
| Table 2. Performance number of GRACE-FO compared to the previous generation of gravity missions. |
|---|---|---|---|---|---|
| satellite-limited | geographic-limited | mission-limited | mission-limited | mission-limited | mission-limited |
| Improvement | Improvement | Improvement | Improvement | Improvement |
| ~factor of 5 better than GRACE | ~factor of 10 better than GRACE | Leap Forward | Leap Forward | Leap Forward |

Possible Monitoring Scenarios

Primary Operations (Proposal 2):
- For next 30 years: Estimate geoid change rate from GRACE/GRACE-FO.
- Add in “small” signals from surface gravity and models.
  - (85% modeling, 15% new campaigns)

Emergency Response Operations:
- For cataclysmic events, measure with satellite gravity, surface gravity, and GNSS instruments.
  - (100% new campaigns)

Backup Operations (Proposal 1, if failure of gravity satellites):
- Estimate gravity change from 1. mass change models and 2. co-located vertical velocity measurements (GNSS) and surface gravity measurements.
  - (33% existing data, 33% modeling, 33% new campaigns)

3. Vision for Vertical Datum Products, 2022 +
- In 2022, will release an “S” and “D” geoid models: static and dynamic.
  - The “S” static will be a typical geoid model, aimed to capture the 1 cm-accurate model at a TBD epoch.
  - The “D” dynamic will capture the rate of change of the geoid at all places. In 2022, it will capture at least the continuous, permanent change signals such as GIA.
  - Both models will be integrated into OPUS, mostly invisible to users. Orthometric heights provided by OPUS will be time-sensitive, so that they are the combination of the static geoid model plus the geoid rate of change indicated by the dynamic model.
  - H = h – (N + Np)

* We’ll provide separate tools to directly access both the “S” and “D” models.
4. Future of Monitoring, 2052 and beyond

- NGS plans to re-evaluate our “S” and “D” models periodically to see if they are meeting our constituents’ needs and maintaining accuracy.

- Future advances in satellite gravimetry, quantum gravimetry, airborne gravimetry/IfSAR, and unmanned vehicles will eventually replace current monitoring technology, necessitating a flexible monitoring plan.

- Monitoring will likely evolve, as understanding of gravity changes and technology also improves.

Conclusions

- The Geoid Monitoring Service is a new project since January 2017, planned to be operational and produce NGS’ first “D” dynamic geoid by 2022.

- NGS will likely work with satellite gravity experts to build on in-house NGS expertise and to create the geoid change model.

- We are currently doing research to determine which signals need to be added to the satellite gravity models and how best to estimate/measure those (models or data).

- NGS acknowledges the need to create a realistic plan for geoid emergency response, for response to cataclysmic earthquakes and explosive volcanic eruptions.

- Although all of North America will be monitored, most change occurs in: Alaska, volcanic areas of the Western US, and Canada.