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

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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
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

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)
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
IGSN71
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 Marianas Vertical Datum of 2003, 3 each
- GUVD04 Guam Vertical Datum of 2004
- VIVD09 Virgin Islands Vertical Datum of 2009, 3 each
- Hawaii ... Hawaiian Islands Vertical Datum (coming soon)
- various various datums, as national datum is inaccessible
- IGLD 85 International Great Lakes Datum of 1985
- IGSN71 gravity dataset
- GEOID12B geoid undulations
- DEFLEC12B deflection of the vertical

Why New Datum?

- cross-country build up of errors (“tilt” or “slope”) from geodetic leveling
- passive marks inconveniently located and vulnerable to disturbance and destruction
- 0.5 m bias in the NAVD 88 reference surface from the (best) geoid surface approximating global mean sea level
- subsidence, uplift, freeze/thaw, and other crustal motions invalidate heights of passive marks, and can make it difficult to detect such motions
- marks lacking adequate geophysical models - complicate sea level change detection
- changes to Earth's gravity field cause changes in orthometric heights, but NAVD 88 does not account for those changes (NAVD88 based on a static gravity model)
- gravity model and modeling techniques used to determine NAVD 88 are not consistent with those currently used for geoid modeling
Subsidence and Bench Mark Height

1954: Leveling Performed to bench mark
1954-1991: Subsidence
1991: Original 1954 leveling data is used to compute the NAVD 88 height which is then published for this BM

Obviously the true height relative to the NAVD 88 zero surface is not the published NAVD 88 height

Error in NAVD 88 Orthometric Height (H)
The distance along the plumb line from the geoid up to the point of interest

Errors in NAVD 88: ~50 cm average, 100 cm CONUS tilt, 1-2 meters average in Alaska
NO tracking
Approximate level of geoid mismatch known to exist in the NAVD 88 zero surface, which was an estimate of the geoid

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
Height-Mod means More Marks?

Height Modernization

- faster
- cheaper

Differential Leveling

GNSS + ...
1. Using GNSS is cheaper, easier than leveling
2. To use GNSS we need a good geoid model
The ellipsoid, the geoid, and you

You are here

Mean sea level

Ellipsoid height, $h$

Orthometric height, $H$

Geoid height, $N_G$

Deflection of the vertical

Earth surface

\[ h \approx H + N_G \]

Note: Geoid height is negative everywhere in the coterminous US (but it is positive in most of Alaska)

Gravity measurements help answer two big questions...

Earth's Surface

Geoid

Ellipsoid

Coast

Ocean Surface

How “high above ‘sea level’” am I? (FEMA, USACE, Surveying and Mapping)

How large are hydrodynamic processes? (Coast Survey, CSC, CZM)

From Gravity

From GPS

From Satellite Altimetry
Gravity Field Metaphor

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

Not detailed: Continental

Courtesy of NASA

Gravity Field Metaphor

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

Regional

Lake Tahoe (CA/NV)

Denali (Mt. McKinley), AK
Gravity Field Metaphor

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

**Local**

Acadia National Park, Maine

GRACE Gravity Model 01
- Released July 2003

Image credit: University of Texas Center for Space Research and NASA
Problems with Gravity Holdings

- Field is not sampled uniformly

Problems with Gravity Holdings

- Decades of gravity surveys are inconsistent with one another
- Airborne gravity will provide a baseline for removing these inconsistencies
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 wintery conditions and thunderstorms
- Aircraft Available
  - Differing Capabilities
- Funding
- Areas already completed
- GPRA  *GPRA = Government Performance and Results Act of 1993
Performance Metric
For Airborne Surveys

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- **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.

October 27, 2017

Airborne Gravity Current Coverage

Data Block Status

- Complete Processing
- Collecting
- Planned

As of Oct 27, 2017

http://www.ngs.noaa.gov/GRAV-D/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

- DOI Bureau of Land Management
  - Pilatus PC-12
- Fugro
  - King Air E-90A
- Naval Research Lab
  - King Air RC-12
- NOAA
  - Gulfstream Jet Prop
  - NOAA P-3 Hurricane Hunter

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

http://www.ngs.noaa.gov/GRAV-D/data_products.shtml

• 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

• 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 USGG 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...

Example of slopes over various distance scales:
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 ~1.5km
  - Leveling
  - Absolute/Relative Gravity
    - Vertical Gravity Gradient
  - Long-session GPS
  - Deflection of Vertical
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 FG5) at ~every 7th benchmark

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
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 CODIAC (C0mpact 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!

GSVS14 Iowa

- 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.

GSVS14 Line

Goal: Same as GSVS11
Region: Moderate terrain
       More complex gravity
Data: Same as GSVS11
Timeline: Fiscal year 2014 field season
IA (Cedar Rapids to Denison)
GSVS17 Colorado

- The third (and likely final) GSVS will take place along US160, from Durango to Walsenburg, in southern Colorado.
- 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 will be measured at all benchmarks.
- Topographic corrections are being developed to aid in field DoV quality control as well as post-survey geoid modeling.

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/GRAV-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
(Component)

- 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 $W_0$ 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 $W_0$ 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 xGG201? (annual experimental geoid)
  - to USGG2022 (the final geoid with GRAV-D)

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

- EGM08
  - 2008
- GRACE
- GOCO05S
- 2012
- USGG2012
- GEOID12A/B
- NGA
  - ArcticGP
- GRAV-D
- GOCO05S
- 2014
- 2015
- 2016
- xGeoid14B
- xGeoid15B
- xGeoid16B
- +
- NGA
- ArcticGP
- GRAV-D
- GOCO05S

xGeoid2017

- First experimental geoid model released June 30, 2014
- Online tools for accessing it (GRAV-D website)
The effect airborne gravity

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
  - USGG12 (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!!