

NATIONAL GEODETIC SURVEY

# Datum Shifts and Geoid Height Models

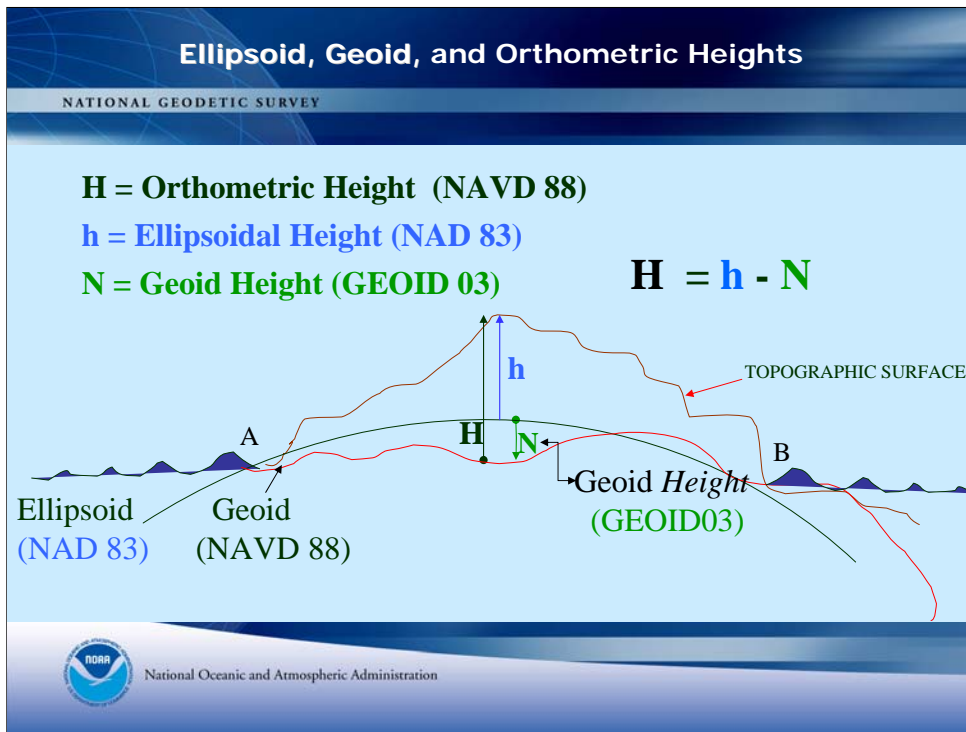
Session C of Datums, Heights and Geodesy

Presented by Daniel R. Roman, Ph.D.  
Of the National Geodetic Survey



National Oceanic and Atmospheric Administration

- add in noise element to show how data sigma must be accounted for
- show distribution of GPSBM's - discuss their impact
- show progression of LSC (99, 03, 06)
- discuss performance in extra points in MI
- lastly, discuss data sheets and why not exact fit.



- Mostly surveyors want their heights in NAVD 88 but get them in NAD 83. GEOID03 and other such models provide this transformation. But how is that accomplished? What if you have GPS coordinates in WGS-84 or in some ITRF model? How do you transform to NAD 83? What about if you have heights above NGVD 29 or EGM96? Are heights determined using older geoid height models still valid?
- Transforming between the various datums remains one of the commonest requests that I get at NGS. It can also be one of the most complicated to answer. I'll start with the easy one (ellipsoidal transformations) and then move onto the harder one (vertical datums).

# Transforming Between Ellipsoid Reference Frames

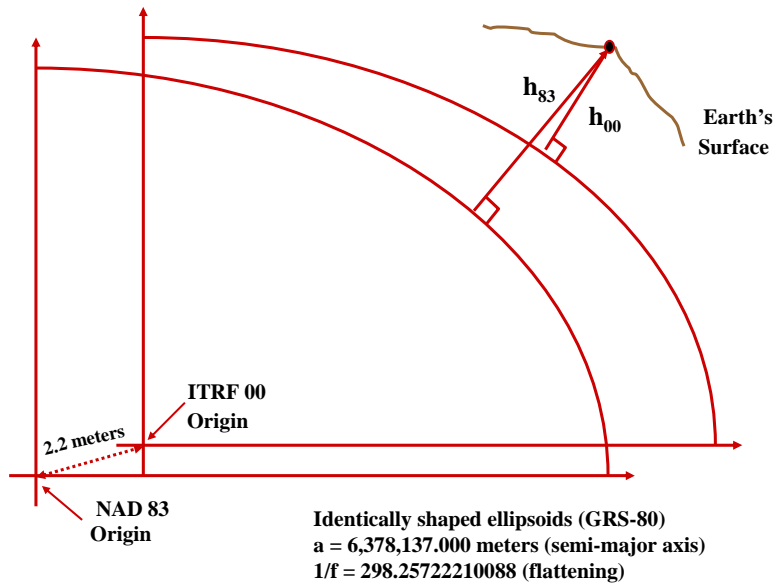
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- Most ellipsoids use the same shell (GRS-80)
- They mainly differ by the location of the center of the reference frame (geocenter)
- The geocenters are re-determined periodically in the International Terrestrial Reference Frame (ITRF)
- Successive ellipsoid datums can be related to earlier models
- Transforming ellipsoids is easy, because they are math constructs ( $a$ ,  $f$ ,  $GM$ ,  $\omega$ )
- "14-parameter transformation" sounds intimidating, but it's not: translation along X, Y, & Z (3), rotation around X, Y & Z (3) and scaling (1) plus velocities along all 7 of these.
- Horizontal Time Dependent Positioning (HTDP) enables this
- <http://www.ngs.noaa.gov/TOOLS/Htdp/Htdp.shtml>



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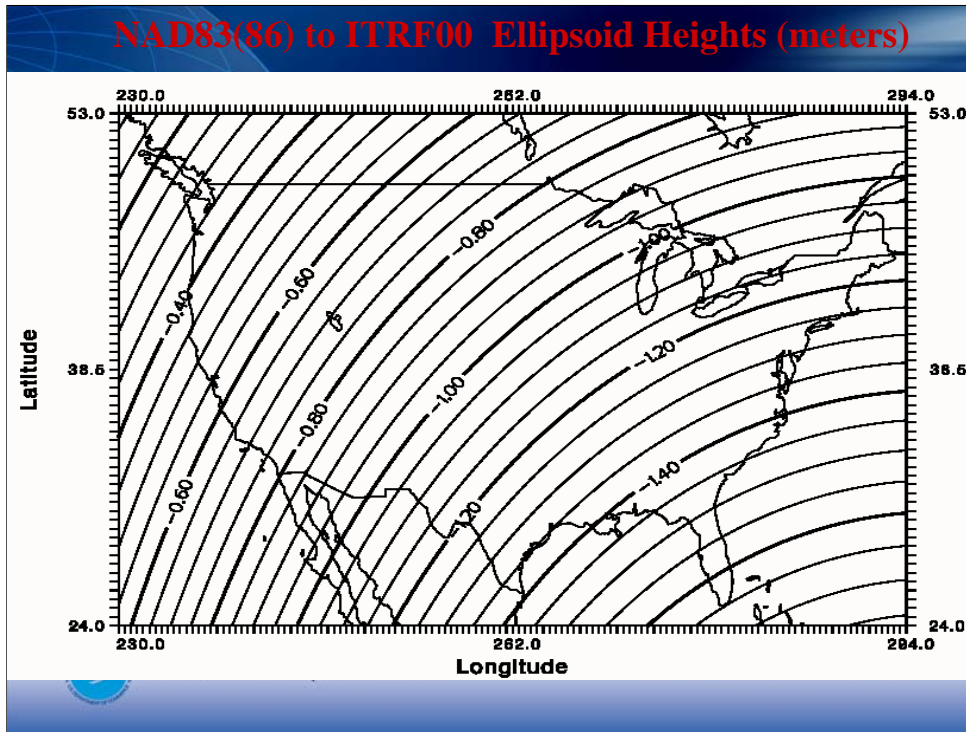
## Simplified Concept of ITRF 00 vs. NAD 83



**ITRF** (International Terrestrial Reference Frame) just has an origin; take NAD83 shaped ellipsoid centered at the ITRF origin to derive ITRF97 ellipsoid heights.

**Ellipsoid heights NAD83 vs. ITRF97** - Defined origins are best estimate of the center of mass; NAD83 is not geocentric. Move origin; move ellipsoid surface as illustrated.

**Ellipsoid height differences** reflect the non-geocentricity of NAD83.



Looking down on offset between ITRF00 and NAD83 ellipsoid heights. Note smooth curved contours as ellipsoidal surfaces move apart.

ITRF (International Terrestrial Reference Frame) just has an origin; take NAD83 shaped ellipsoid centered at the ITRF origin to derive ITRF00 ellipsoid heights.

**Ellipsoid heights NAD83 vs. ITRF00** - Defined origins are best estimate of the center of mass; NAD83 is not geocentric. Move origin; move ellipsoid surface as indicated by scale shown on map.

**Ellipsoid height differences** reflect the non-geocentricity of NAD83.

## Various NGS Geoid models

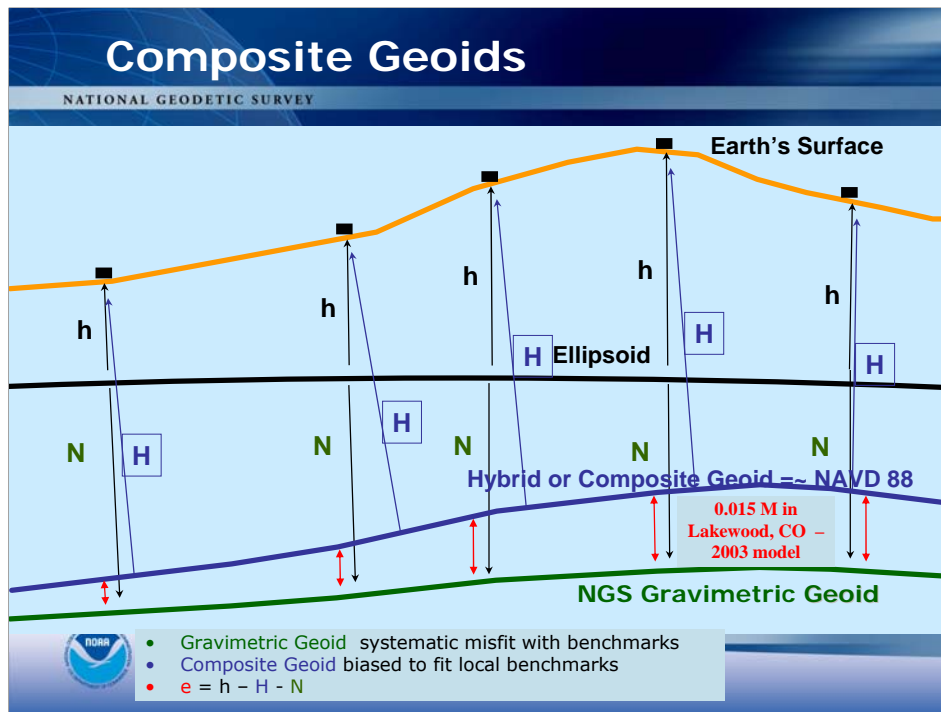
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- GEOID90
  - GEOID93
  - GEOID96
  - GEOID99
  - GEOID03
  - GEOID06
- Earliest model – gravimetric only
  - Another early gravimetric geoid
  - First hybrid geoid (2'x2') – CONUS only
  - Underlain by G96SSS gravimetric model
  - Still fairly heavily used (1'x1') - CONUS
  - Underlain by G99SSS gravimetric model
  - Models tie to NAD 83 everywhere – hybrid in CONUS
  - Underlain by the USGG2003 gravimetric model
  - Forthcoming this year. Available for Alaska already.
  - Will tie to NAD 83 and NAVD 88/PRVD02/etc.

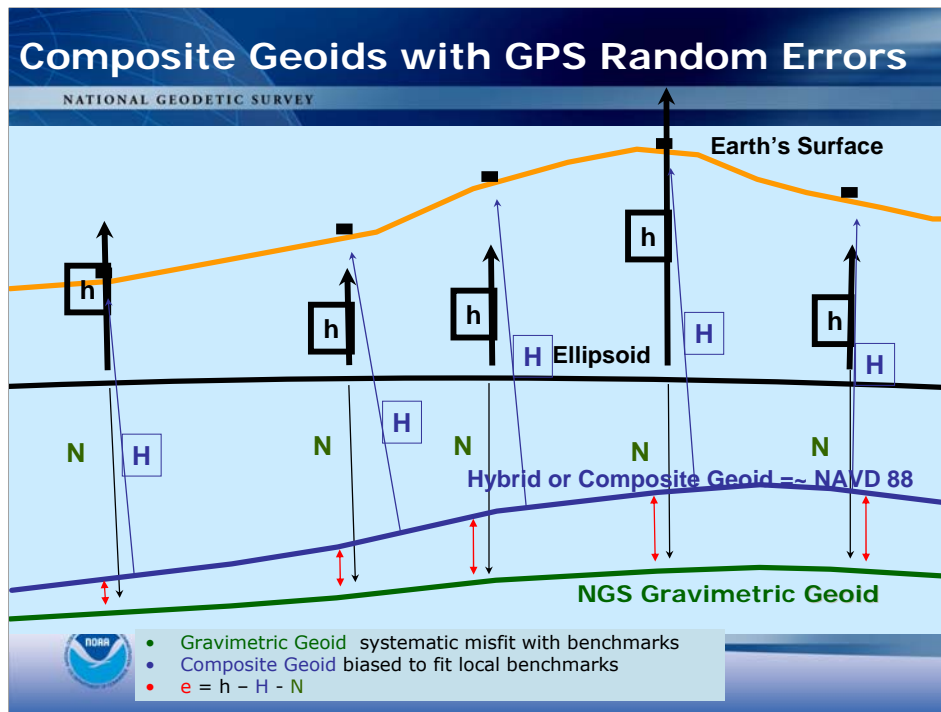


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Which model should you use? Usually, the most recent. They are better tied to NAD 83 and NAVD 88 and will provide geoid heights consistent with bench marks in the NGS database.



- to transform from the NGS gravimetric geoid to NAVD 88 is more complicated
  - Gravimetric geoid is from derived from gravity measurements
  - NAVD 88 bench marks are adjusted using a sea level height at Point au Pere
  - There is going to be a slight difference between the 2. If we want to use geoid to compute NAVD 88 heights, it must be consistent with the NAVD 88
- Therefore we “bias” the geoid to be consistent with the NAVD 88 using high accuracy GPS on NAVD 88 bench marks.
- Use Least Squares Collocation to determine the systematic components while allowing for random GPS observation errors (2-5 cm standard).
- Use the control points (GPSBM's) to define a surface that can be interpolated to make internally consistent predictions (precision versus accuracy).
- As you can easily see, the quality and distribution of the control, data will directly impact the quality of the predictions.
- also note that the error vector residual (e) is a function of **all** the errors sources: from the GPS observations (usually random, but each HARN could have systematic errors), the gravimetric geoid height model (errors in gravity & terrain data as well as theoretical/processing errors can contribute here) as well as any errors in the NAVD 88 network.



- When you allow for random GPS errors, you no longer will get an exact match at GPSBM locations.
- GPS observations include 2-5 cm of random error.
- Hence,  $h = H + N$  will not work exactly when you check the data sheets.
- This will be covered later. First the development of the hybrid geoid will be covered more fully.
- Obviously, selection of the GPSBM's is crucial to developing a good composite geoid height model.

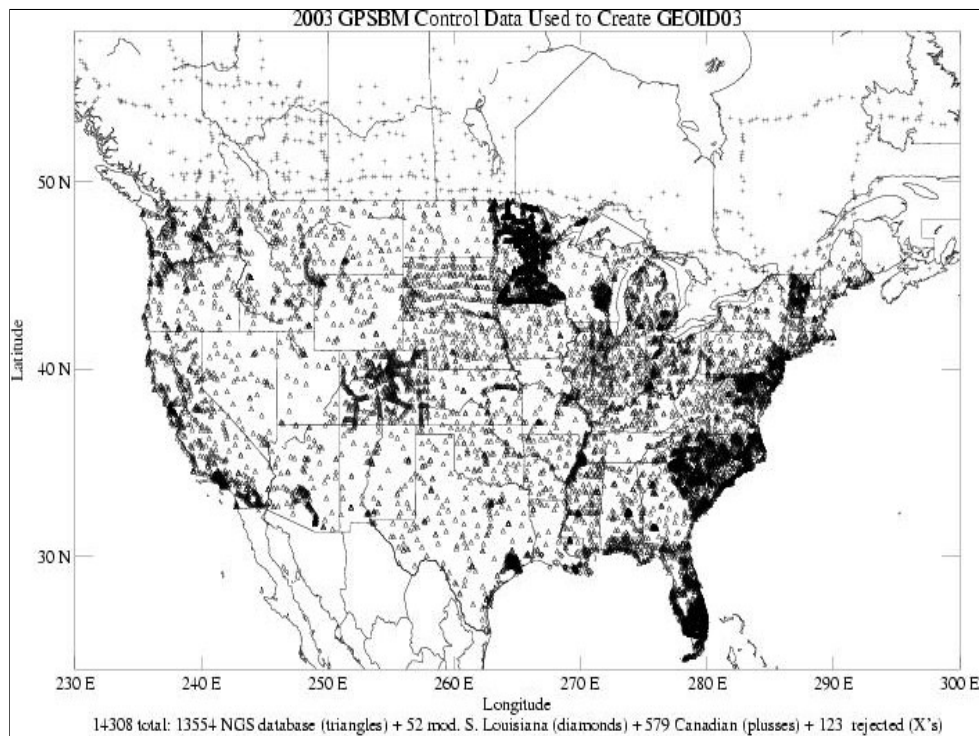


## GPSBM selection criteria

- A, B, and 1<sup>st</sup> order GPS only
- ABCRMH criteria for 1<sup>st</sup>, 2<sup>nd</sup>, and 3<sup>rd</sup> order leveling
  - A: Adjusted
  - B: Hand Keyed but not Verified
  - C: Computed from nearby Bench Marks
  - R: Reset
  - M: Readjusted due to earth movement
  - H: From Horizontal Branch. Based on quality and distribution
- Prefer only A & B order GPS on 1<sup>st</sup> order leveling



Bench mark heights were not used if they were posted, determined by a single spur, an unvalidated single spur, or from the horizontal branch but from another agency.



-These are the control data used to make GEOID03 (GPS on bench marks: GPSBM's).

-Note the inequitable distribution.

-You could practically grid the GPSBM's in South Carolina and get a good result.

-Other places are not so fortunate...

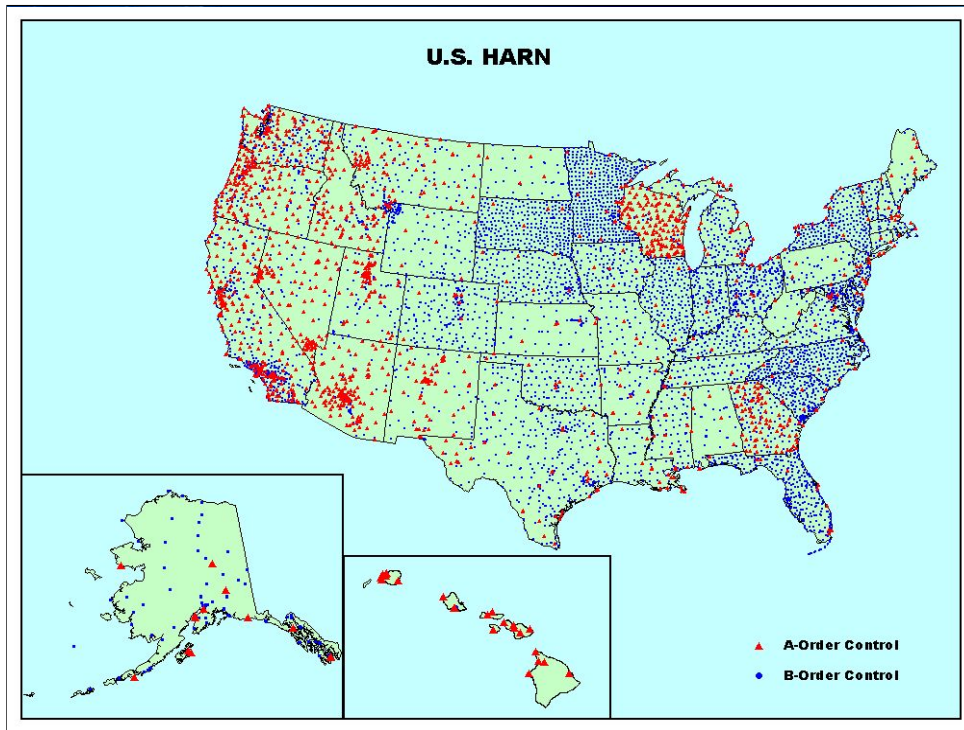
-Also note that this shows distribution but not quality of the points.

-Some regions (e.g., Texas) have systematic problems that impact the GPSBM's and the derived hybrid geoids.

-Current techniques rely on creating models of the systematic effects at multiple wavelengths. If the spatial density doesn't support the shorter wavelength models, then the quality of predictions will commensurately be reduced.

CO: # PTS = 514    Average = 0.0 cm    STD = 3.3 cm

This average is much worse than the national average of 2.4 cm and implies more significant problems exist either in the gravity data, leveling, or GPS observations.



Map of the National A and B Order, HPGN/HARN monumented station coverage as of 1999.

The distribution of the GPSBM's used to make the composite geoid height model is tied closely to this.

## High Resolution Geoid Models **GEOID03** (vs. Geoid99)

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- Begin with USGG2003 model
  - **14,185** NAD83 GPS heights on NAVD88 leveled benchmarks (vs. 6169)
  - Determine national bias and trend relative to GPS/BMs
  - Create grid to model local (state-wide) remaining differences
  - **ITRF00**/NAD83 transformation (vs. ITRF97)
  - Compute and remove conversion surface from USGG2003



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**GEOID03** - best model for North America; not a true interpretation of the geoid but includes bias to establish best orthometric heights relative to NAVD88.

**14,185 GPS/levels bench marks (NAD83/NAVD88)**; more to be included to further improve future models. GPS/BM constrained to help model reflect NAVD88 orthometric heights then unconstrained for final model.

**High Resolution Geoid Models**  
**GEOID03 (vs. Geoid99)**

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- Relative to non-geocentric GRS-80 ellipsoid
- **2.4 cm RMS** nationally when compared to BM data (vs. 4.6 cm)
- RMS  $\approx$  **50%** improvement over GEOID99 (Geoid96 to 99 was 16%)

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-**NAD83 non-COM** - model warped to reflect NAD83 (86) non-COM origin.

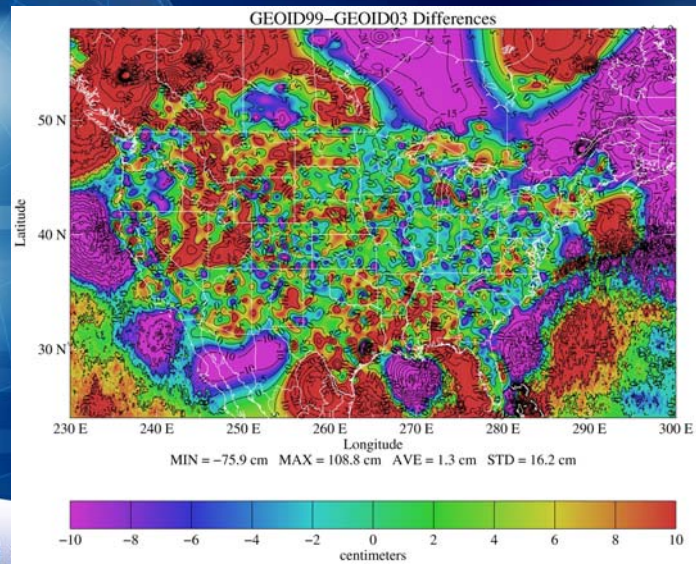
-**2.4 cm RMS** when comparing to bench mark data – includes 2 cm random error in GPS observations.

-The improvement largely resulted from the improved technique (multi-matrix), which is why we created it.

-Future models will adopt a similar modeling approach.

## Why did we go from GEOID99 to GEOID03?

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One of the chief complaints about GEOID03 was that derived heights were significantly different from GEOID99

What caused this? Why is GEOID03 better?

## More Fun with Formulas! Least Squares Collocation

$$\hat{s} = C_{sl} (C_{ll} + D_n)^{-1} l$$

where:  $\hat{s}$  = the solution vector for GPSBM locations and the grid nodes for the output file

$C_{sl}$  = the correlative relationships between all points and the GPSBM residual values

$C_{ll}$  = the correlative relationships between the GPSBM residual values

$D_n$  = the noise matrix for the observed data

$l$  = the observations (GPSBM residual values)

### Single Gaussian Function (GEOID99)

$$C_{ll} = A_0 e^{-\left(\frac{D_{ll}}{\kappa L}\right)^2}$$

where:  $C_{ll}$  = the correlation elements between two points

$A_0$  = the amplitude at auto-correlation

$D_{ll}$  = the distance between two points

$L$  = the correlation length (point where  $C_{ll} = \frac{1}{2} A_0$ )

$\kappa = \sqrt{\frac{1}{\ln 2}} \cong 1.2$

### Multiple Gaussian Functions (GEOID03)

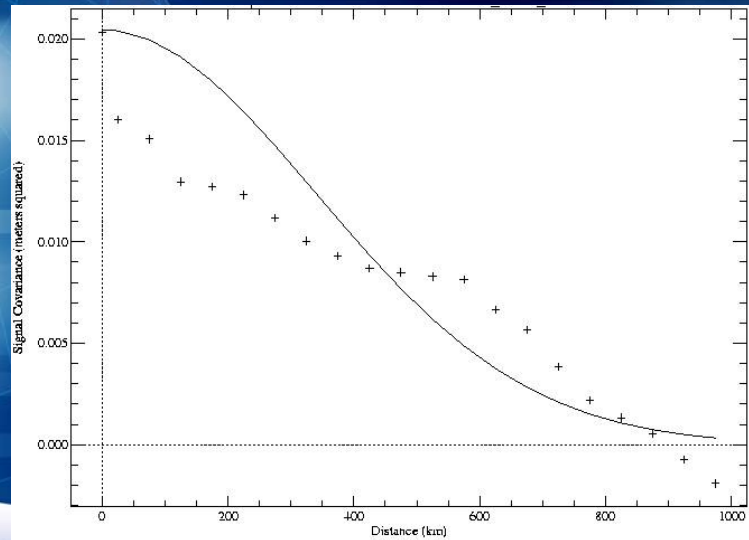
$$C_{ll} = C_{l_1 l_1} + C_{l_2 l_2}$$

where:  $C_{l_1 l_1} = A_0^1 e^{-\left(\frac{D_{ll}}{\kappa L_1}\right)^2}$

$C_{l_2 l_2} = A_0^2 e^{-\left(\frac{D_{ll}}{\kappa L_2}\right)^2}$

## Single Gaussian curve fit at 400 km for GEOID99

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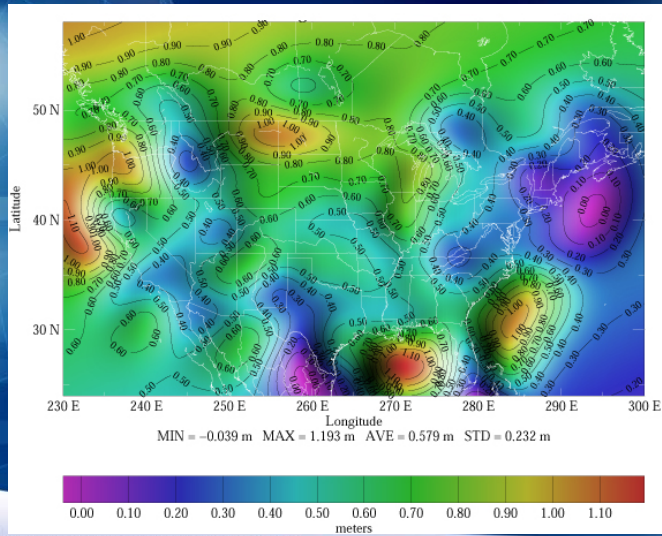
While there were fewer points in GEOID99 – the big difference is in how the data were modeled.

A single Gaussian function was fit at 400 km for the half amplitude. Any correlated signal shorter than that is treated as “noise”.



# GEOID99 Conversion Surface

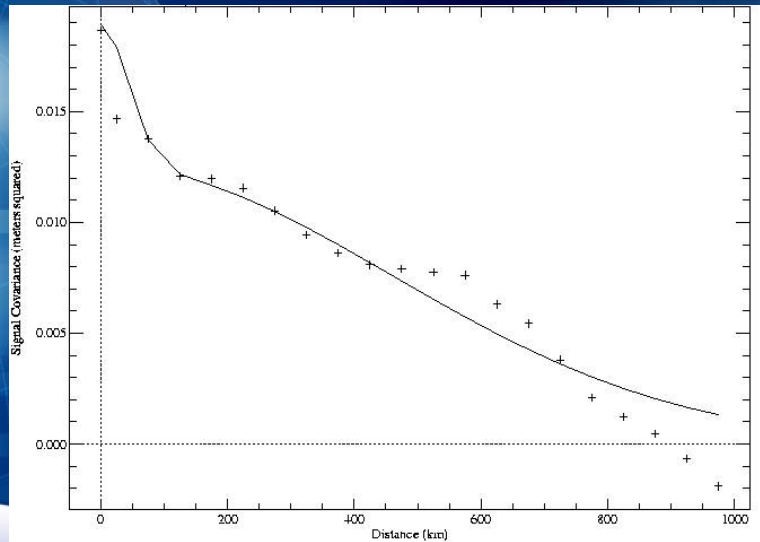
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## Single Gaussian curve fit at 400 km for GEOID03

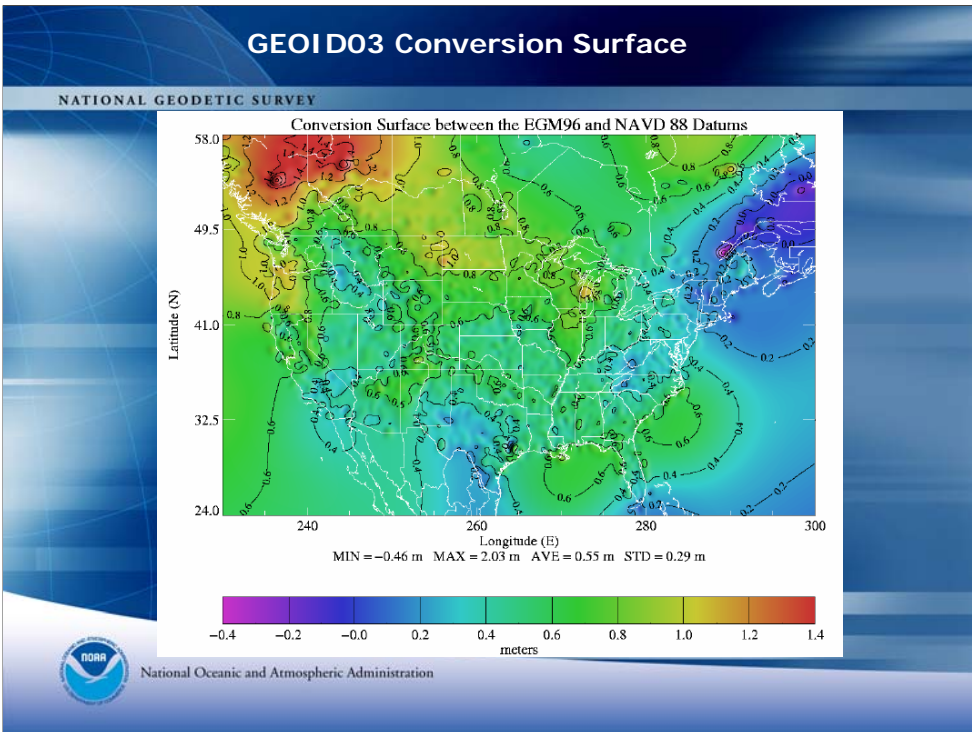
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While there were fewer points in GEOID99 – the big difference is in how the data were modeled.

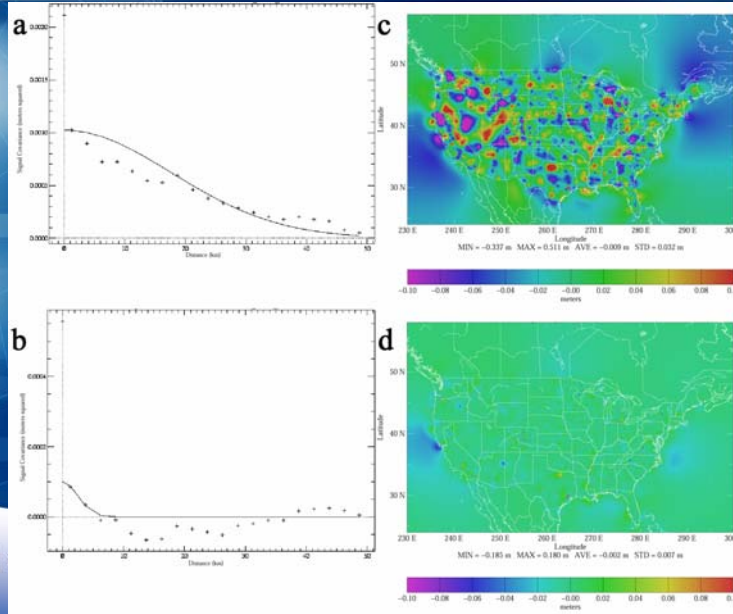
A single Gaussian function was fit at 400 km for the half amplitude. Any correlated signal shorter than that is treated as “noise”.



The differences shown here represent the systematic differences

# Residual Signal and Correlated Components

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Note that significant signal remains after GEOID99 that has significant spatial extents (county-level and broader)

For GEOID03, very little signal remains. Correlated signal falls off at only 5 km. Still have random component, but signals that correlate at about 60-120 km have now been accounted for.

## CO &amp; National Statistics for GEOID03

| State Code | No. of points | Ave.(cm) | St. Dev.(cm) |
|------------|---------------|----------|--------------|
| CO         | 514           | 0.0      | 3.3          |
| National   | 14185         | 0.0      | 2.4          |

For more details on the development of GEOID03, see:

Daniel R. Roman, Yan Ming Wang, William Henning, and John Hamilton  
Assessment of the New National Geoid Height Model—GEOID03, *Surveying  
and Land Information Science*, Vol. 64, No. 3, 2004, pp. 153-162



# Sample Datasheet

## NATIONAL GEODETIC SURVEY

```

National Geodetic Survey, Retrieval Date = DECEMBER 28, 2005
PL0314 *****
PL0314 DESIGNATION - V 27
PL0314 PID - PL0314
PL0314 STATE/COUNTY- MI/GRAND TRAVERSE
PL0314 USGS QUAD -
PL0314
PL0314 *CURRENT SURVEY CONTROL
PL0314
PL0314* NAD 83(1994)- 44 39 02.41202(N) 085 46 04.27942(W) ADJUSTED
PL0314* NAVD 88 - 257.838 (meters) 845.92 (feet) ADJUSTED
PL0314
PL0314 X - 335,419.145 (meters) COMP
PL0314 Y - -4,532,722.532 (meters) COMP
PL0314 Z - 4,459,971.520 (meters) COMP
PL0314 LAPLACE CORR- 5.18 (seconds) DEFLEC99
PL0314 ELLIP HEIGHT- 223.17 (meters) (07/17/02) GPS OBS*
PL0314 GEOID HEIGHT- -34.68 (meters) GEOID03
PL0314 DYNAMIC HT - 257.812 (meters) 845.84 (feet) COMP
PL0314 MODELED GRAV- 980,508.8 (mgal) NAVD 88
PL0314

```

H  
h  
N



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NGS datasheets show all heights where we have them.

## Sample Datasheet

### NATIONAL GEODETIC SURVEY

- PL0314
- PL0314 HORZ ORDER - FIRST
- PL0314 VERT ORDER - FIRST CLASS II
- PL0314 ELLP ORDER - FOURTH CLASS I
- PL0314
- PL0314.The horizontal coordinates were established by GPS observations
- PL0314.and adjusted by the National Geodetic Survey in February 1997.
- PL0314
- PL0314.The orthometric height was determined by differential leveling
- PL0314.and adjusted by the National Geodetic Survey in June 1991.
- PL0314
- PL0314.The X, Y, and Z were computed from the position and the ellipsoidal ht.
- PL0314
- PL0314.The Laplace correction was computed from DEFLEC99 derived deflections.
- PL0314
- PL0314.The ellipsoidal height was determined by GPS observations
- PL0314.and is referenced to NAD 83.
- PL0314
- PL0314.The geoid height was determined by GEOID03.
- PL0314
- PL0314.The dynamic height is computed by dividing the NAVD 88
- PL0314.geopotential number by the normal gravity value computed on the
- PL0314.Geodetic Reference System of 1980 (GRS 80) ellipsoid at 45
- PL0314.degrees latitude (g = 980.6199 gals.).
- PL0314
- PL0314.The modeled gravity was interpolated from observed gravity values.
- PL0314



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The source for each height is explained below the coordinates



## Sample Datasheet

### NATIONAL GEODETIC SURVEY

```
. PL0314
. PL0314.The modeled gravity was interpolated from observed gravity values.
. PL0314
. PL0314;
. PL0314;SPC MI C - North East Units Scale Factor Converg.
. PL0314;SPC MI C - 149,194.606 5,888,865.237 MT 0.99992569 -0 59 23.3
. PL0314;UTM 16 - 489,483.62 19,320,424.01 FT 0.99992569 -0 59 23.3
. PL0314;UTM 16 - 4,944,883.803 597,700.224 MT 0.99971738 +0 51 57.6
. PL0314
. PL0314! - Elev Factor x Scale Factor = Combined Factor
. PL0314!SPC MI C - 0.99996501 x 0.99992569 = 0.99989070
. PL0314!UTM 16 - 0.99996501 x 0.99971738 = 0.99968240
. PL0314
. PL0314 SUPERSEDED SURVEY CONTROL
. PL0314
. PL0314 ELLIP H (02/03/97) 223.19 (m) GP( ) 4 1
. PL0314 NAD 83(1986)- 44 39 02.41257(N) 085 46 04.28315(W) AD( ) 1
. PL0314 NAD 83(1986)- 44 39 02.38347(N) 085 46 04.27988(W) AD( ) 3
. PL0314 NAVD 88 (09/30/91) 257.84 (m) 845.9 (f) LEVELING 3
. PL0314 NGVD 29 (??/??/92) 257.915 (m) 846.18 (f) ADJ UNCH 1 2
. PL0314
. PL0314 Superseded values are not recommended for survey control.
. PL0314.NGS no longer adjusts projects to the NAD 27 or NGVD 29 datums.
. PL0314
```



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-Modeled gravity comes from the NAVD 88 gravity interpolation program  
NOT the Surface Gravity Interpolation tool

-The Surface tool draws from the existing database, while NAVD 88 tool  
draws from a database made static at the time of the national adjustment  
(1991) to make sure values are consistent.

-impact can be decimeter in high altitudes.



# Sample Datasheet

## NATIONAL GEODETIC SURVEY

. PL0314\_U.S. NATIONAL GRID SPATIAL ADDRESS: 16TEQ9770044884(NAD 83)  
. PL0314\_MARKER: DB = BENCH MARK DISK  
. PL0314\_SETTING: 7 = SET IN TOP OF CONCRETE MONUMENT  
. PL0314\_SP\_SET: CONCRETE POST  
. PL0314\_STAMPING: V 27 1930 846.176  
. PL0314\_MARK LOGO: CGS  
. PL0314\_MAGNETIC: N = NO MAGNETIC MATERIAL  
. PL0314\_STABILITY: B = PROBABLY HOLD POSITION/ELEVATION WELL  
. PL0314\_SATELLITE: THE SITE LOCATION WAS REPORTED AS SUITABLE FOR  
. PL0314+SATELLITE: SATELLITE OBSERVATIONS - October 24, 1992  
. PL0314  
. PL0314 HISTORY - Date Condition Report By  
. PL0314 HISTORY - 1930 MONUMENTED CGS  
. PL0314 HISTORY - 1951 GOOD NGS  
. PL0314 HISTORY - 1984 GOOD NGS  
. PL0314 HISTORY - 19890428 GOOD NGS  
. PL0314 HISTORY - 1990 GOOD USPSQD  
. PL0314 HISTORY - 19910701 GOOD NGS  
. PL0314 HISTORY - 19920824 GOOD MIDT  
. PL0314 HISTORY - 19921024 GOOD MIDT  
. PL0314 HISTORY - 19971029 GOOD USPSQD

### STATION DESCRIPTION

PL0314 DESCRIBED BY NATIONAL GEODETIC SURVEY 1951  
INTERLOCHEN.

PL0314 AT INTERLOCHEN, 111 FEET EAST OF THE JUNCTION OF THE ABANDONED  
NORTHERN AND SOUTHERN RAILROADS AND NORTHEASTERN RAILROAD AND THE C AND  
NATIONAL CENTER for Earth and Atmospheric Administration



# Sample Datasheet

## NATIONAL GEODETIC SURVEY

```

National Geodetic Survey, Retrieval Date = DECEMBER 28, 2005
PL0314 *****
PL0314 DESIGNATION - V 27
PL0314 PID - PL0314
PL0314 STATE/COUNTY- MI/GRAND TRAVERSE
PL0314 USGS QUAD -
PL0314
PL0314 *CURRENT SURVEY CONTROL
PL0314
PL0314* NAD 83(1994)- 44 39 02.41202(N) 085 46 04.27942(W) ADJUSTED
PL0314* NAVD 88 - 257.838 (meters) 845.92 (feet) ADJUSTED
PL0314
PL0314 X - 335,419.145 (meters) COMP
PL0314 Y - -4,532,722.532 (meters) COMP
PL0314 Z - 4,459,971.520 (meters) COMP
PL0314 LAPLACE CORR- 5.18 (seconds) DEFLEC99
PL0314 ELLIP HEIGHT- 223.17 (meters) (07/17/02) GPS OBS*
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PL0314 MODELED GRAV- 980,508.8 (mgal) NAVD 88
PL0314

```

H  
h  
N

NAVD88 – Ellip Ht + Geoid Ht = ...  
 257.838 – 223.17 – 34.953 = -0.285 USGG2003  
 257.838 – 223.17 – 34.68 = -0.012 GEOID03



-In a perfect world these heights would add up mathematically. But every height is derived in a way that includes some measure of error, whether it is from an observation and adjustment process or simply because it is derived from a model. The purpose of creating a version of the geoid model that is biased to fit the NAVD88 is to provide a means to compute that NAVD88 height from GPS and the model alone. You can see here how the change from the scientific model to the hybrid model provides a better fit between the 3 heights. And as the geoid model improves, along with our ability to measure and compute better ellipsoid heights, these differences will get smaller and smaller.

## Other Types of Transformations

- VERTCON: NGVD 29 to NAVD 88
- NADCON: NAD 27 to NAD 83
- VDATUM: Transforms between all surfaces using a lot of the tools and models you've seen here

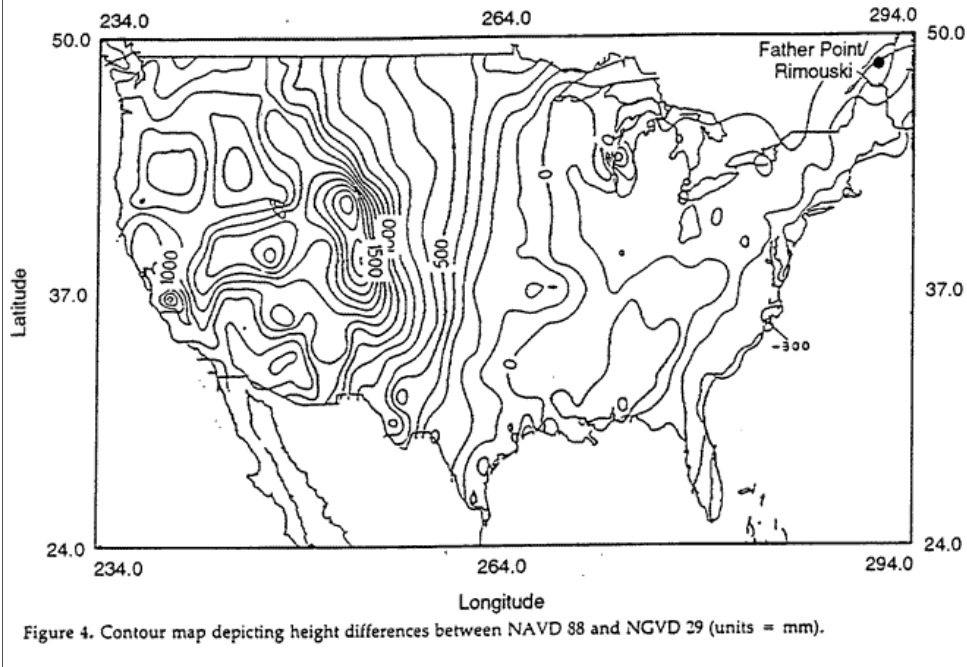


## VERTCON 2.0

- Used 381,833 points where both NAVD 88 and NGVD 29 were known
- Second version updated to incorporate a forward physical model => yielded better results
- Most recently, southern Florida region was remodeled to provide improved height changes
- While overall internal agreement is at the 2 cm level (one sigma) – reliability in sparser regions is probably closer to the dm-level or worse.



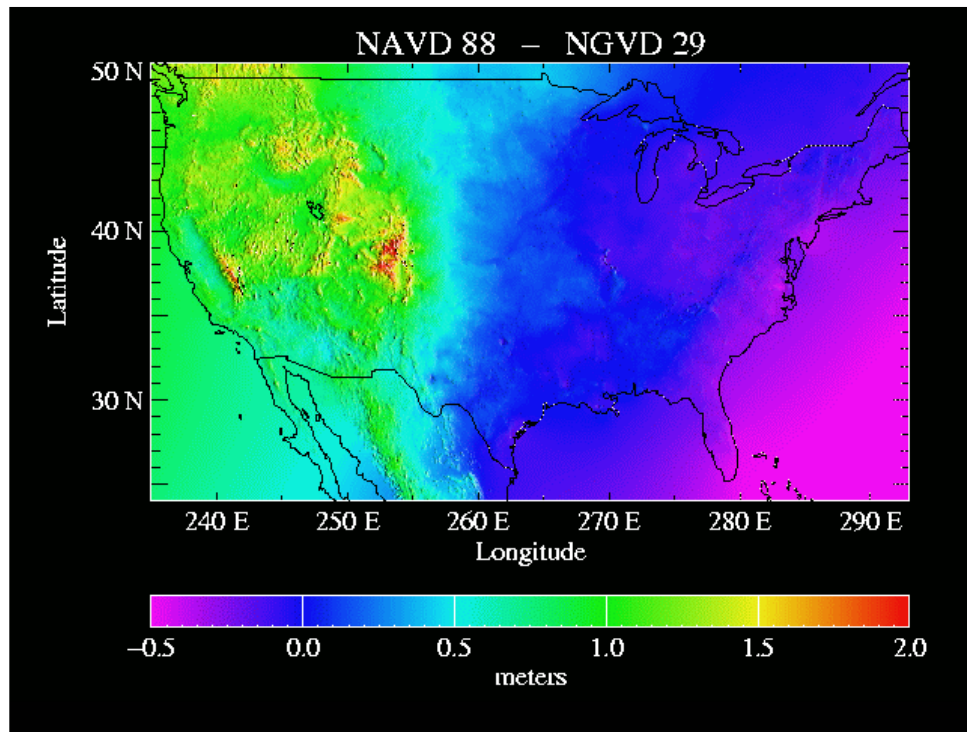
## Height Differences Between NAVD 88 and NGVD 29



**Area contour map** - note areas of extreme and moderate changes between datums.

If you check in to NGVD29 and not NAVD88 - need to apply orthometric correction to level heights in that area.

**LEVEL\_DH** program provides a means to remove orthometric corrections to level differences between adjacent bench marks. These corrections don't allow direct comparisons between optically derived differences and those published.



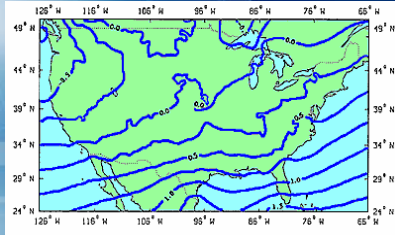
**National color map** - differences between NGVD29 and NAVD88 datums

Portrays general east - west tilt; rugged areas indicate major changes whereas smooth are minor changes. 2 & 3 cm level differences over steep gradients.

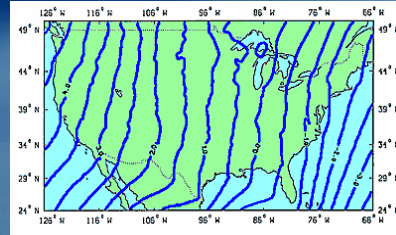
# NADCON

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Latitude



Longitude



- Used more than 150,000 horizontal control points
- The accuracy of transformations between NAD 27 and NAD 83 (1986) are typically 12-18 cm and 5-6 cm between NAD 83 (1986) and HPGN.
- NADCON is the Federal standard for NAD 27 to NAD 83 datum transformations.



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## Plans for Geoid Modeling at NGS

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- Near term plans are to define gravimetric geoids and hybrid geoids for all U.S. territories (USGG2006 & GEOID06).
- Gravimetric geoids would all have a common  $W_0$  value (geoid datum) and be based on GRACE-based global gravity models such as the forthcoming EGM07 from NGA
- Gravimetric geoids will be tested against tide gauges and lidar-observed sea surface heights to confirm choice of  $W_0$ .
- Hybrid geoids would be tied to NAD 83 & local vertical datums
  - NAVD 88 for Alaska and CONUS
  - PRVD02 for Puerto Rico
  - Etc.
- The quality of VDatum will be improved as the ties between the oceanic and terrestrial datums are better understood.
- Likewise, it would be very useful in providing decimeter or better *accurate* heights to estimate flooding potential.



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## Plans for Geoid Modeling at NGS (cont.)

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- Long term goals are to define a cm-level accurate geoid height model valid for all of North America
  - Work is ongoing with the Canadians
  - Other nations joining in (Mexico/INEGI, etc.)
  - We likely will also adopt a vertical datum based on a refined geoid height model – the ultimate in Height Mod!
  - Conversion surface will provide means of transforming between this new datum and NAVD 88 – much as VERTCON does now between NGVD 29 and NAVD 88.
  - This maintains compatibility with archival data.
- To do this, several major areas need work:
  - Gravity database cleansing/analysis/standardization
  - Acquisition of additional data sets
  - Refinement of geoid theory



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-Need seamless gravity data to reduce errors in gravity to geoid modeling

-Need additional gravity outside of U.S. areas – altimetric, neighboring countries

-Also need other data such as density anomalies and terrain data

-Current approach uses many simplifications – a more rigorous approach will reduce errors

-aerogravity fills in gaps and identifies systematic problems in gravity data (shipborne and terrestrial)

## QUESTIONS?

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