Gravity, Geoid and Heights

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OUTLINE OF TALK

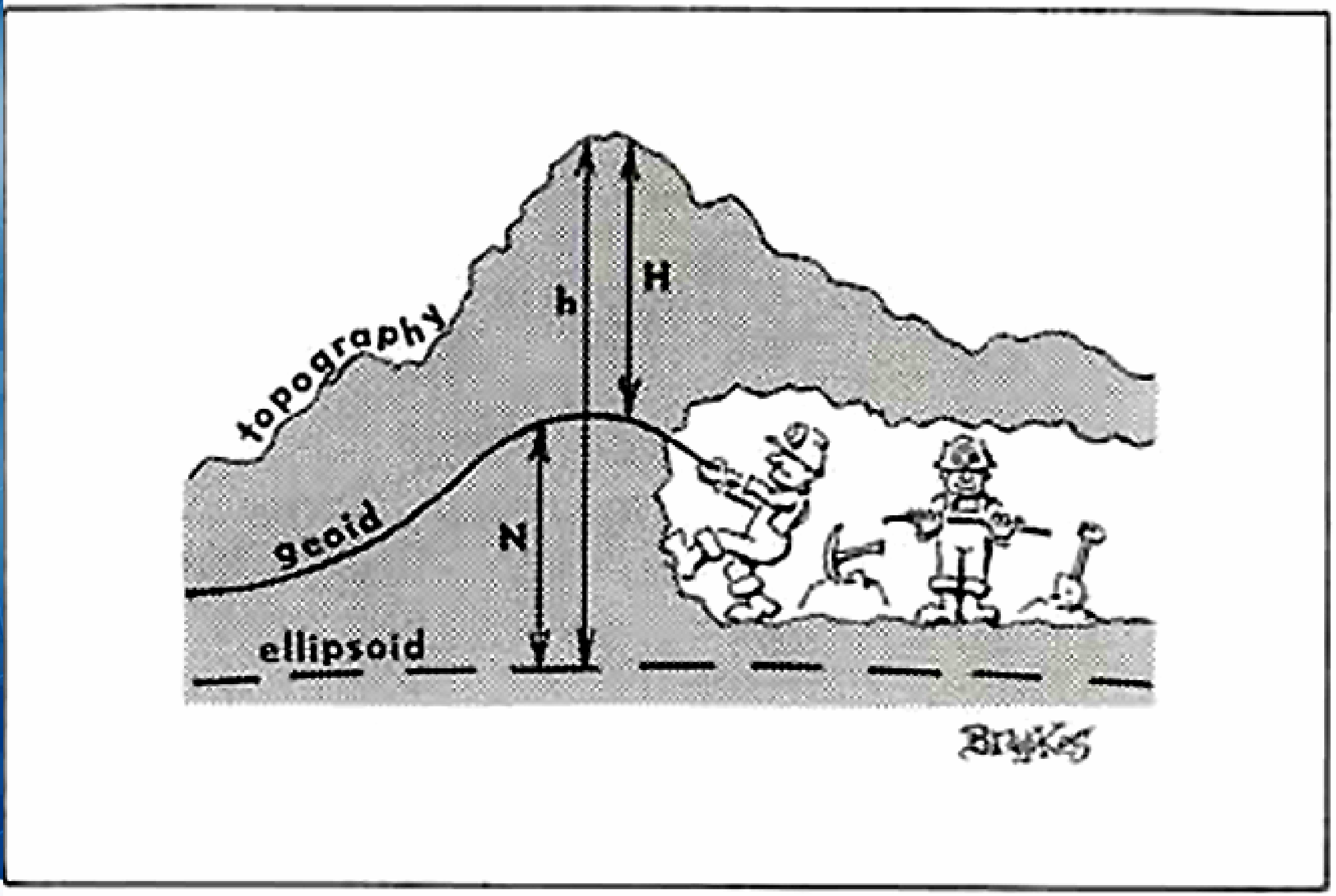
- Introduction
- Overview of current gravimetric geoid models
- Overview of current hybrid geoids
- Heights and the datasheet
- Plans for Geoid Modeling at NGS
- Ongoing research areas
- Of local interest
- Conclusions

GEOIDS versus GEOID *HEIGHTS*

- "The *equipotential surface* of the Earth's gravity field which best fits, in the least squares sense, (global) mean sea level."*
- Can't see the surface or measure it directly.
- Can be modeled from gravity data as they are mathematically related.
- Note that the geoid is a vertical *datum* surface.
- A geoid *height* is the ellipsoidal height from an ellipsoidal datum to a geoid.
- Hence, geoid height models are directly tied to the geoid and ellipsoid that define them (i.e., geoid height models are <u>not</u> interchangeable).

*Definition from the Geodetic Glossary, September 1986

In Search of the Geoid…



In Search of the Geoid

Courtesy of Natural Resources Canada www.geod.nrcan.gc.ca/index_e/geodesy_e/geoid03_e.html

High Resolution Geoid Models
G99SSS (Scientific Model)

- Earth Gravity Model of 1996 (EGM96)
- 2.6 million terrestrial, ship-borne, and altimetric gravity measurements
- 30 arc second Digital Elevation Data
- 3 arc second DEM for the Northwest USA
  - Decimated from 1 arc second NGSDEM99
- Computed on 1 x 1 arc minute grid spacing
- GRS-80 ellipsoid centered at ITRF97 origin

Long Wavelength - global

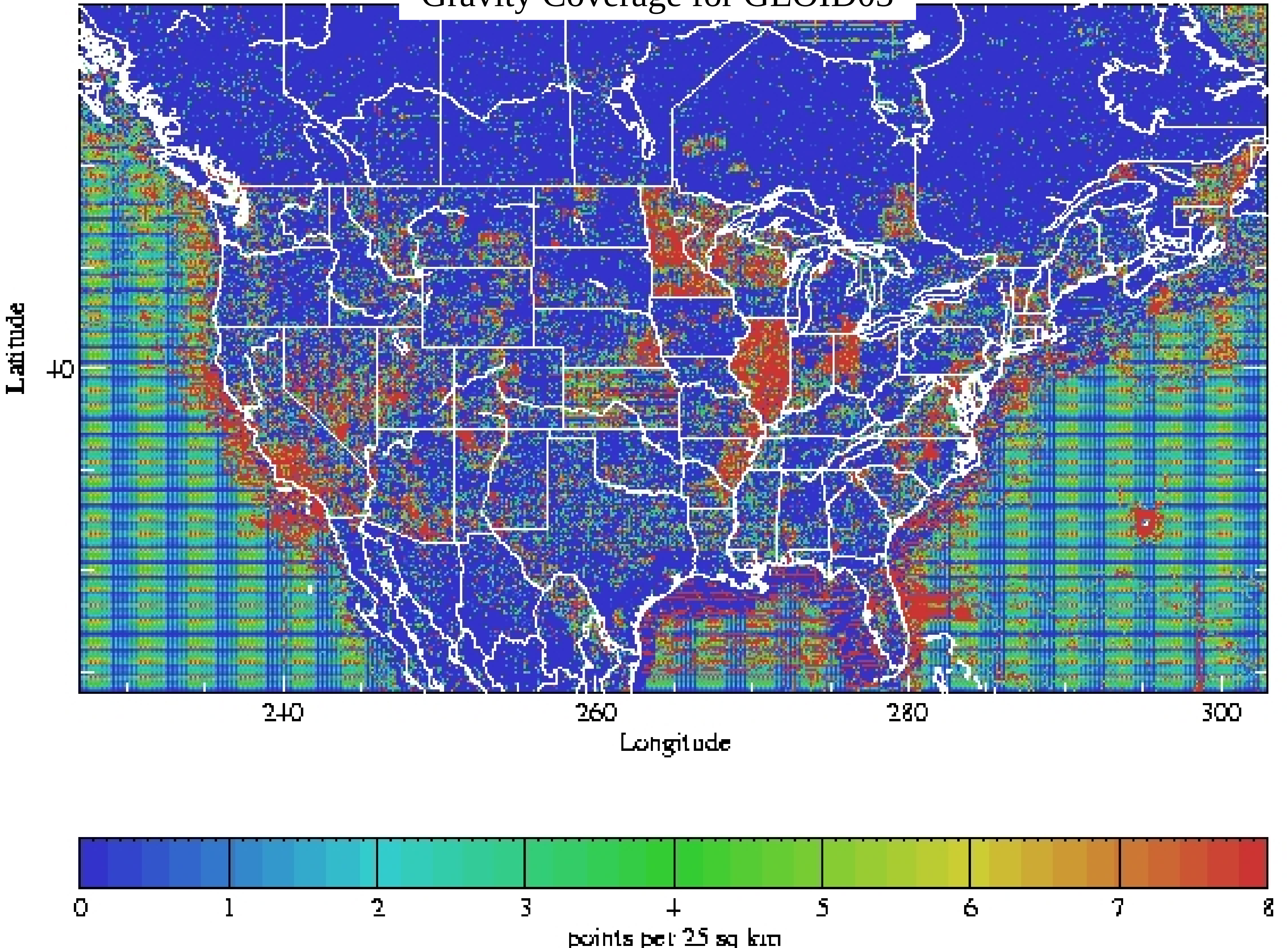
Medium Wavelength - regional

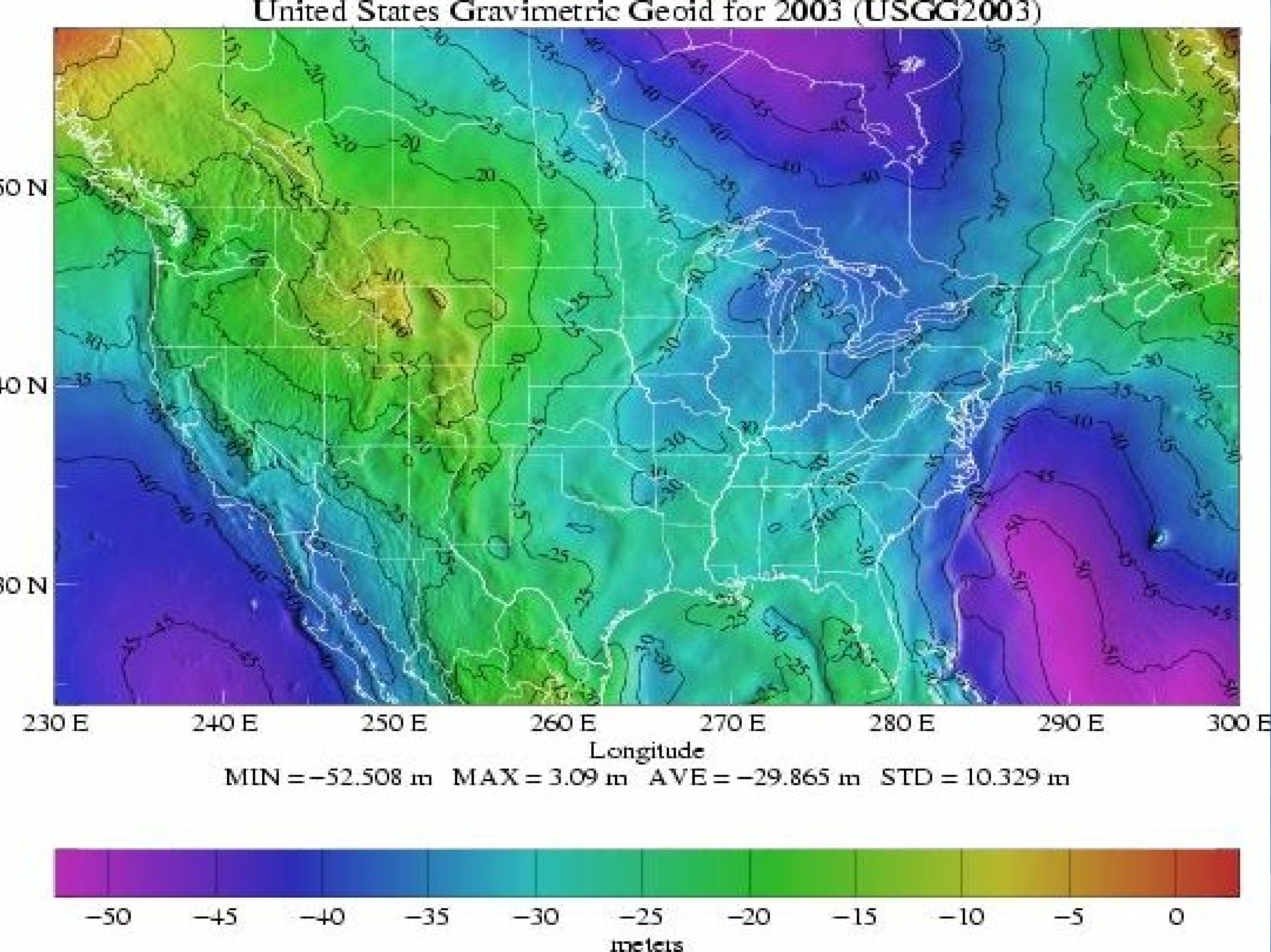
Short Wavelength - local

High Resolution Geoid Models
USGG2003 (Scientific Model)

- 2.6 million terrestrial, ship, and altimetric gravity measurements
  - offshore altimetry from GSFC.001 instead of KMS98
- 30 arc second Digital Elevation Data
- 3 arc second DEM for the Northwest USA
  - Decimated from 1 arc second NGSDEM99
- Earth Gravity Model of 1996 (EGM96)
- Computed on 1 x 1 arc minute grid spacing
- GRS-80 ellipsoid centered at ITRF00 origin

Gravity Coverage for GEOID03




United States Gravimetric Geoid for 2003 (USGG2003)
50 N
40 N
30 N
230 E
240 E
250 E
260 E
270 E
280 E
290 E
300 E
Longitude
MIN = −52.508 m MAX = 3.09 m AVE = −29.865 m STD = 10.329 m
−50
−45
−40
−35
−30
−25
−20
−15
−10
−5
0
meters

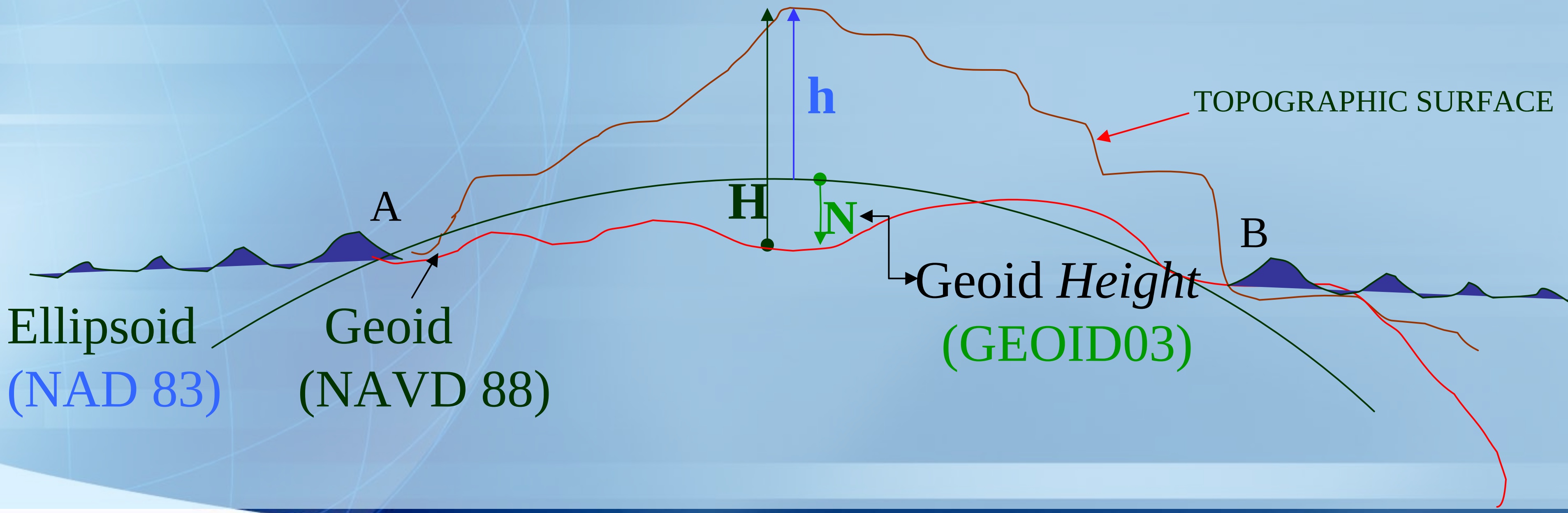
Ellipsoid, Geoid, and Orthometric Heights

H = Orthometric Height (NAVD 88)

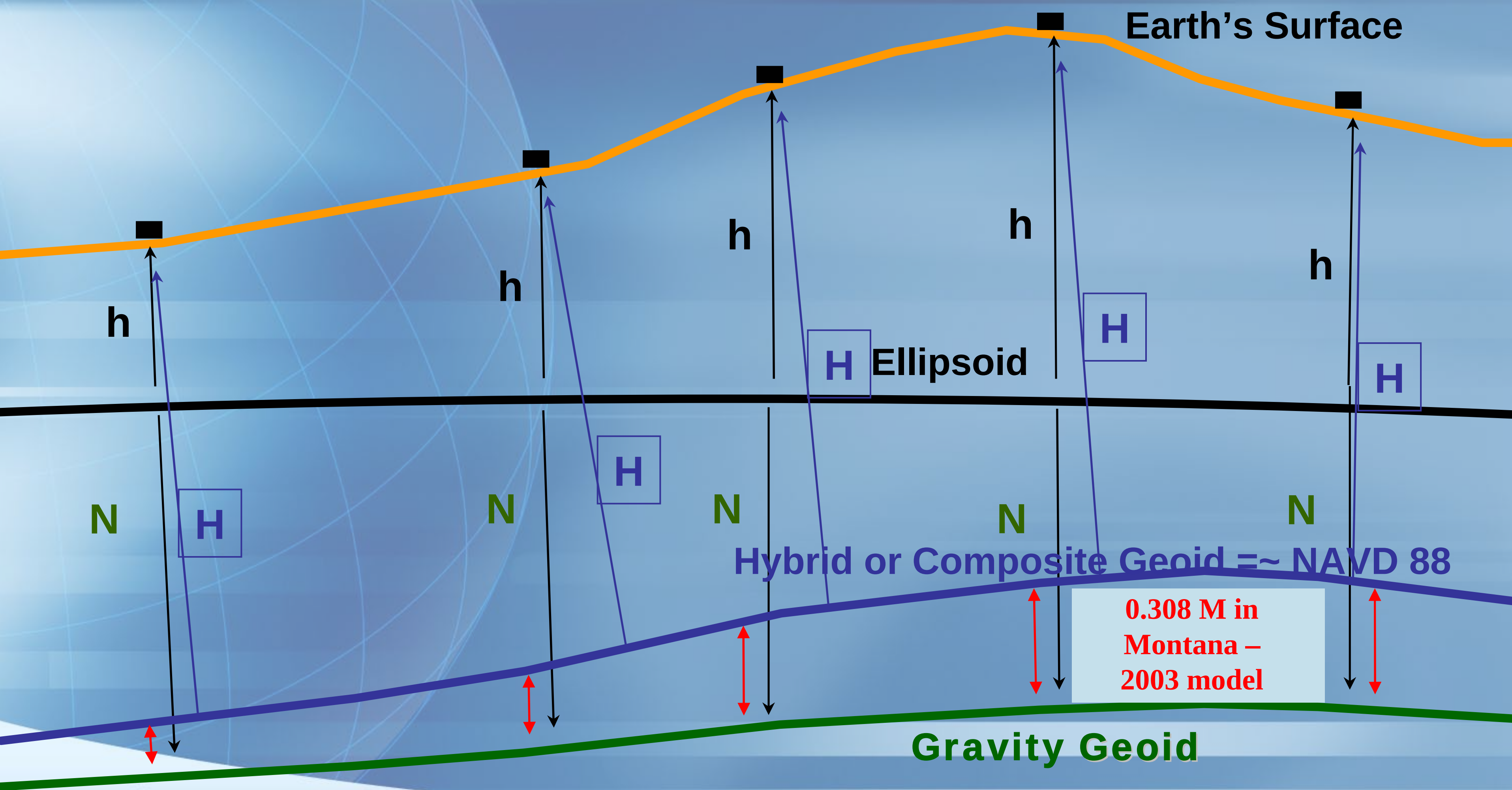
h = Ellipsoidal Height (NAD 83)

N = Geoid Height (GEOID 03)

$$H = h - N$$

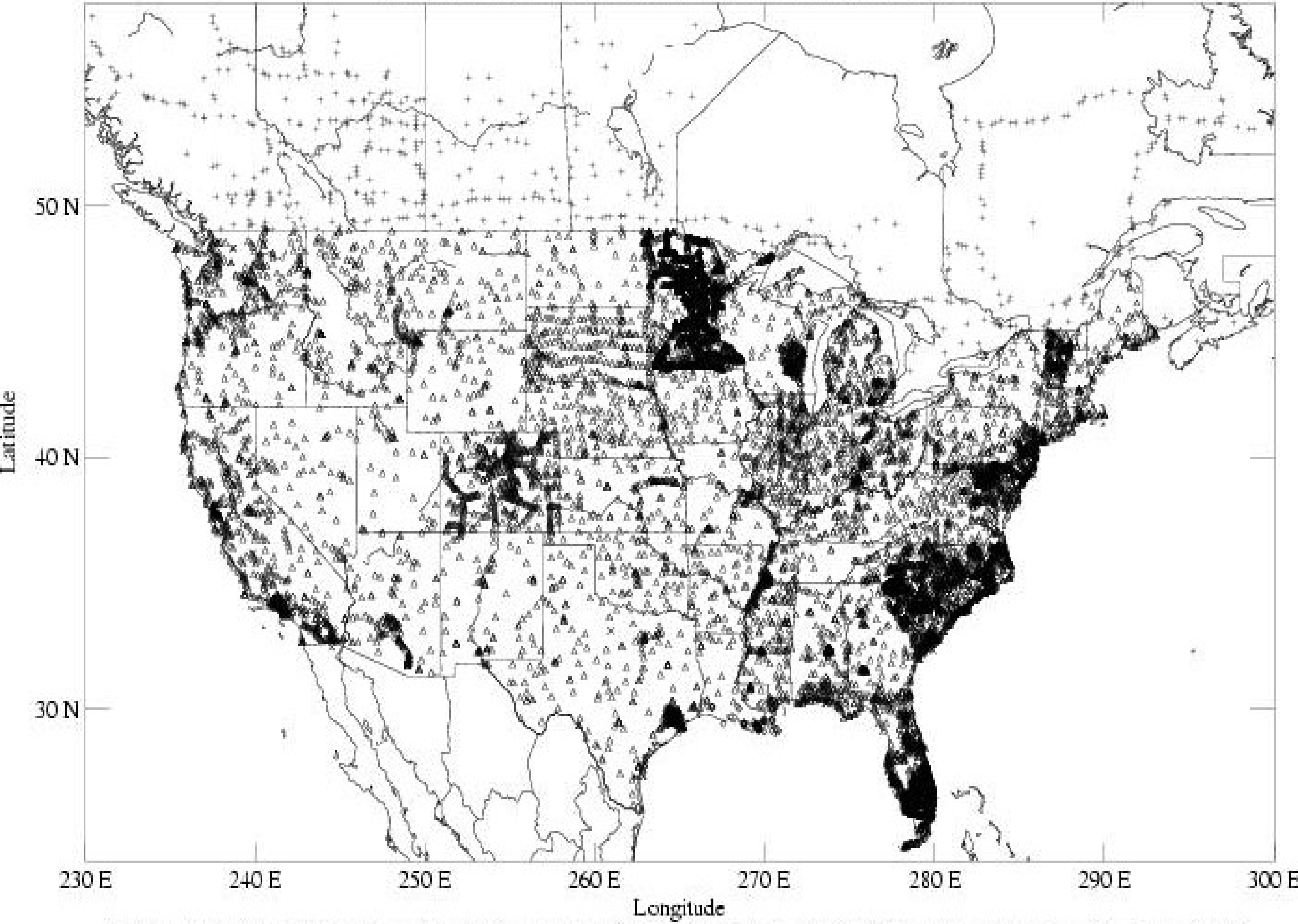


Composite Geoids



- Gravity Geoid systematic misfit with benchmarks
- Composite Geoid biased to fit local benchmarks
- e = h – H - N

2003 GPSBM Control Data Used to Create GEOID03



14308 total: 13554 NGS database (triangles) + 52 mod. S. Louisiana (diamonds) + 579 Canadian (plusses) + 123 rejected (X's)

High Resolution Geoid Models
GEOID03 (vs. Geoid99)

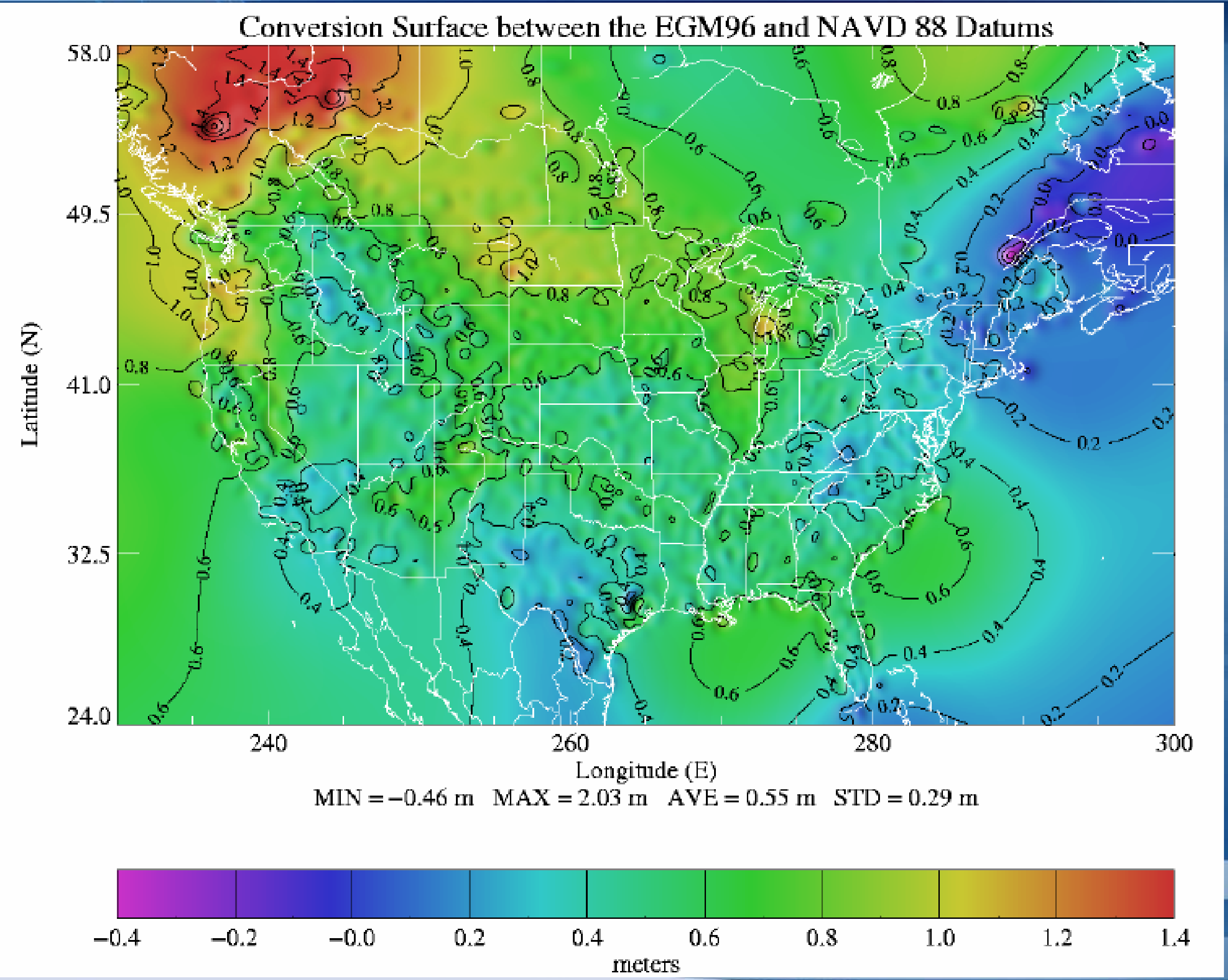
- Begin with USGG2003 model
  - 14,185 NAD83 GPS heights on NAVD88 leveled benchmarks (vs. 6169)
  - Determine national bias and trend relative to GPS/BMs
  - Create grid to model local (state-wide) remaining differences
  - ITRF00/NAD83 transformation (vs. ITRF97)
  - Compute and remove conversion surface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

High Resolution Geoid Models
GEOID03 (vs. Geoid99)

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

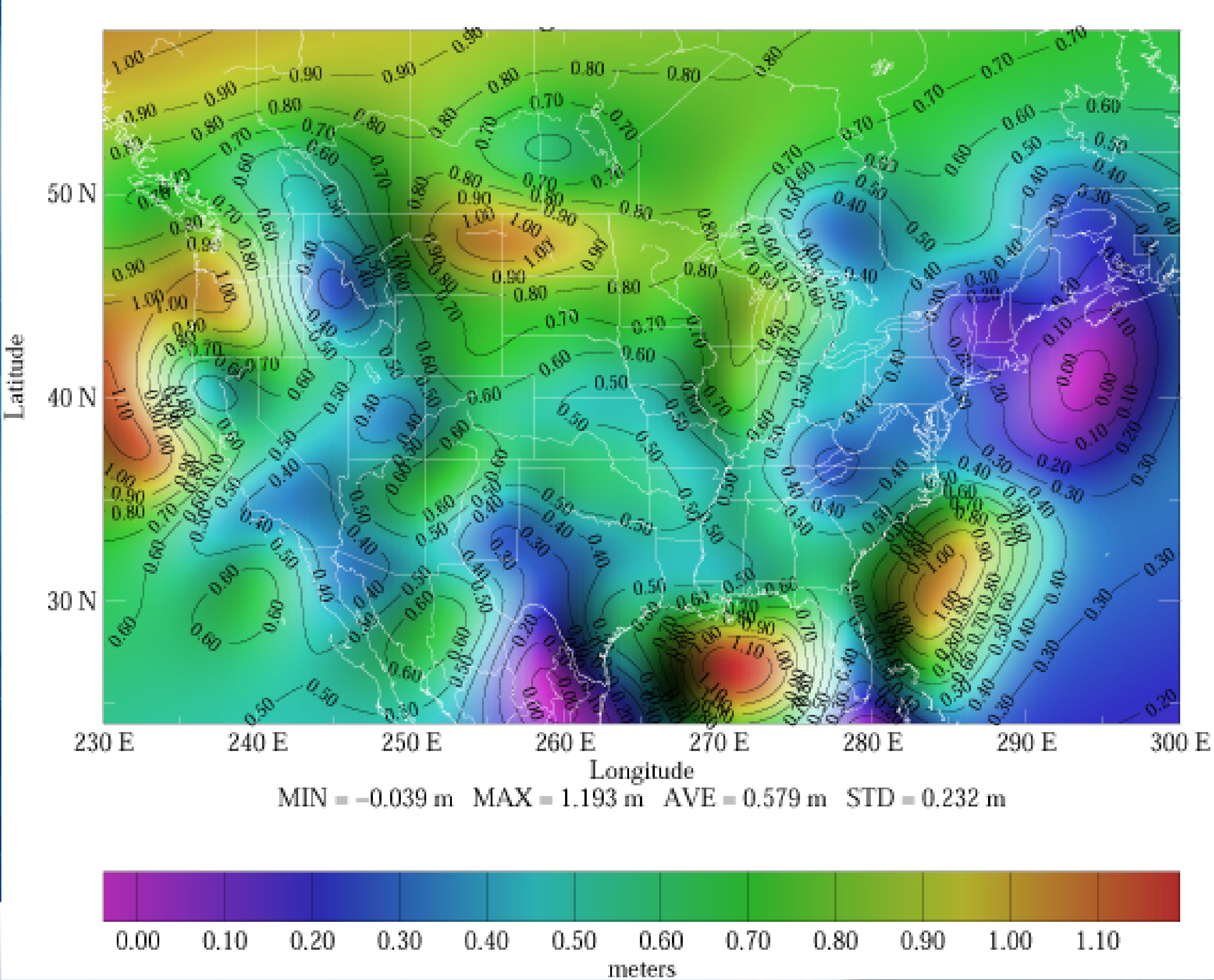
GEOID03 Conversion Surface

NATIONAL GEODETIC SURVEY



National Oceanic and Atmospheric Administration

GEOID99 Conversion Surface



Sample Datasheet


```
      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 (NAVD 88)

h (ELLIP HEIGHT)

N (GEOID HEIGHT)

Sample Datasheet

- 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

Sample Datasheet


```
PL0314
PL0314.The modeled gravity was interpolated from observed gravity values.
PL0314
PL0314;                   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;SPC MI C     -   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
```

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
- PL0314
- PL0314 STATION DESCRIPTION
- PL0314
- PL0314'DESCRIBED BY NATIONAL GEODETIC SURVEY 1951
- PL0314'IN INTERLOCHEN.
- PL0314'AT INTERLOCHEN, 131 FEET EAST OF THE JUNCTION OF THE ABANDONED
- PL0314'BRANCH OF THE MANISTEE AND NORTHEASTERN RAILROAD AND THE C AND

Sample Datasheet

NATIONAL GEODETIC SURVEY

```
        National Geodetic Survey,   Retrieval Date = DECEMBER 28, 2005
    PL0314 ***********************************************************************
    PL0314  DESIGNATION -  V 27
    PL0314  PID         -  PL0314
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    PL0314
    PL0314                         *CURRENT SURVEY CONTROL
    PL0314  ___________________________________________________________________
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    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 (NAVD 88 orthometric height) · **h** (ellipsoid height) · **N** (geoid height)

NAVD88 – Ellip Ht + Geoid Ht = …

257.838 – 223.17 – 34.953 = -0.285   USGG2003

257.838 – 223.17 – 34.68 = -0.012   GEOID03

Plans for Geoid Modeling at NGS

- 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 Wo value (geoid datum) and be based on GRACE-based global gravity models such as the forthcoming EGM06 from NGA
- Gravimetric geoids will be tested against tide gauges and lidar-observed sea surface heights to confirm choice of Wo.
- 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.

Plans for Geoid Modeling at NGS (cont.)

- 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

Ongoing research areas

- We must have a consistent and seamless gravity field at least along the shorelines if not across all the U.S.
  - Use GRACE data to test long wavelength accuracy.
  - Use aerogravity to locate and possibly clean systematic problems in terrestrial or shipborne surveys (biases, etc.).
  - Determine and remove any detected temporal trends in the nearly 60 years of gravity data held by NGS. Ensure consistency of datums, corrections and tide systems.
  - This solves problems of current remove-compute-restore approach, which honors terrestrial data over EGM's.
- Exploration of utility of coastal/littoral aerogravity
  - Need a consistent gravity field from onshore to offshore.
  - Aids in database cleansing; also fills in coastal gaps.
  - Ties to altimetric anomalies in deeper water.
  - In conjunction with tide gauges & dynamic ocean topography models, this will aid in determining the optimal geopotential surface for the U.S. (Wo).

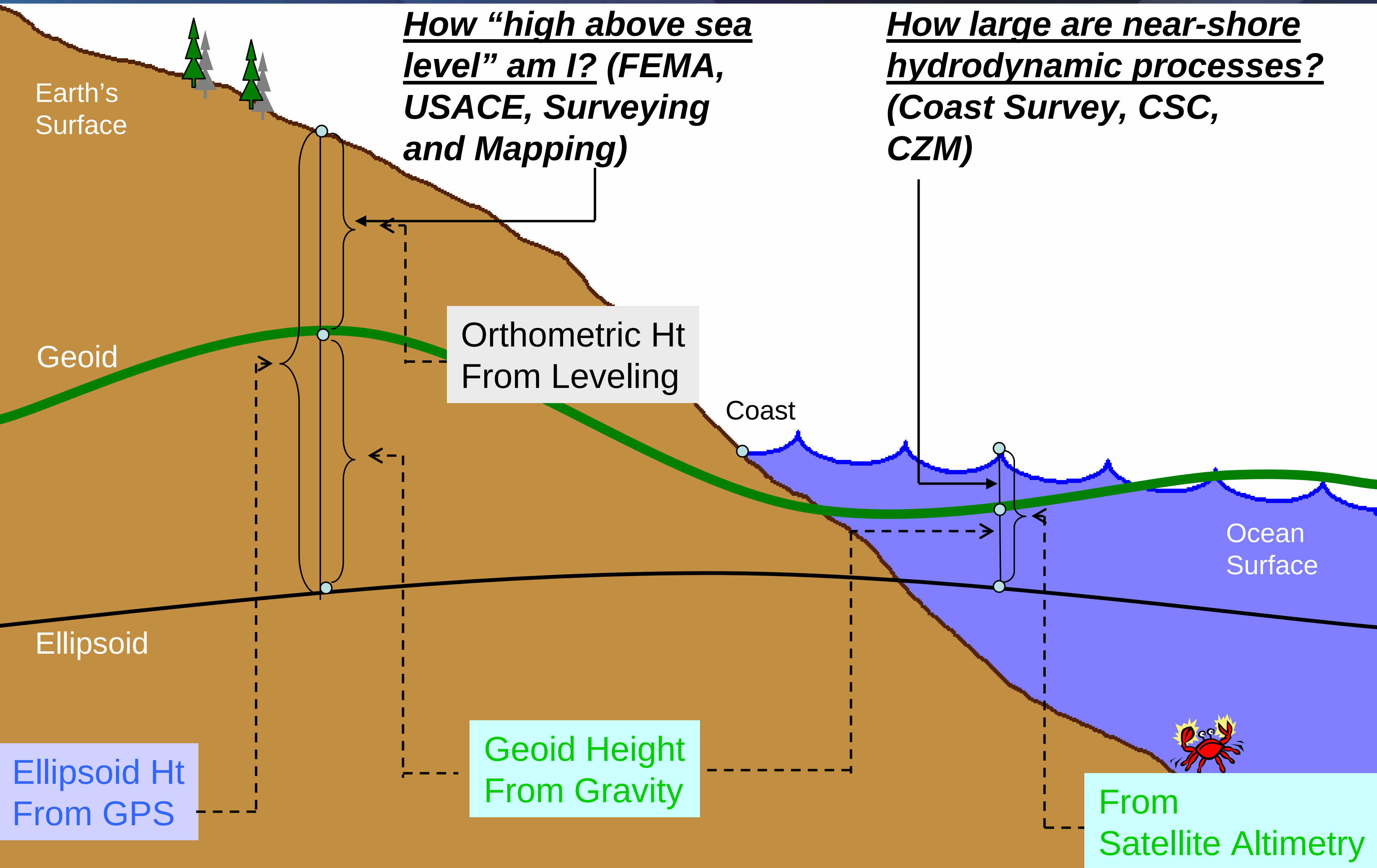
Ongoing research areas (cont.)

- Must acquire data and models for outlying regions.
  - Definitely need surface gravity (terrestrial and shipborne) and terrain models for Guam, CNMI, American Somoa.
  - Desire to get such for nearest neighbors including Mexico, Caribbean nations, Central American nations, etc.
  - Also need to get any available forward geophysical models for all regions (such as ICE-5G for modeling the Glacial Isostatic Adjustment).
- GPS/INS evaluation of the gravity field.
  - GPS & IMU information were also collected on flights.
  - This data can be used to derive gravity disturbances and to estimate gravity anomalies.
  - It may be useful in benign areas for determining the gravity field. Possibly cheaper and more cost-effective than aerogravity (run with other missions?).

Ongoing research areas (cont.)

- Geodetic theory improvements.
  - Downward continuation of high altitude gravity observations.
  - Merging of gravity field components.
    - Current approach is remove-compute-restore.
    - Spectral merging of EGM, gravity and terrain data.
    - Would honor long wavelength (GRACE).
    - Retain character of the terrain and observed data.
  - Determination of geoid height using ellipsoidal coordinates instead of the spherical approximation.
  - Resolution of inner and outer zone effects from terrain on gravity observations.

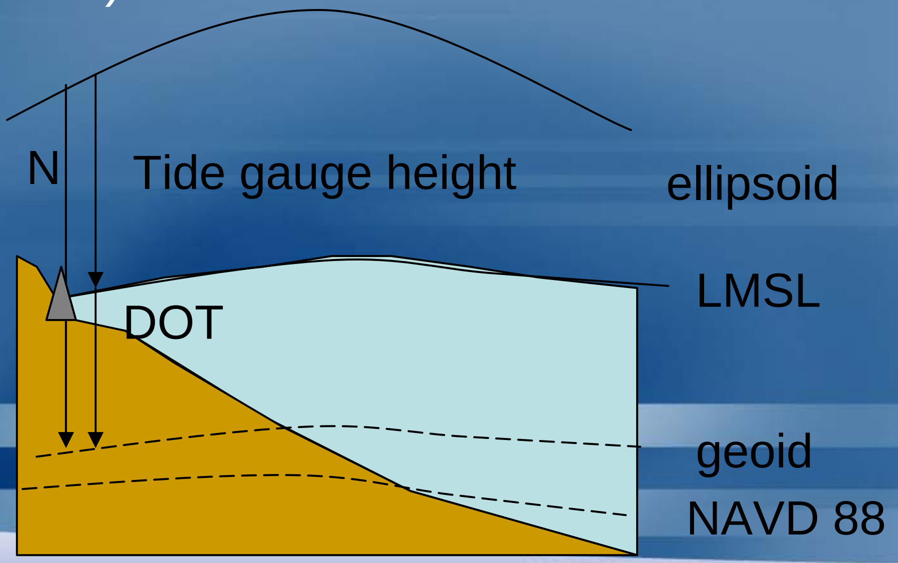
Gravity measurements help answer two big questions…

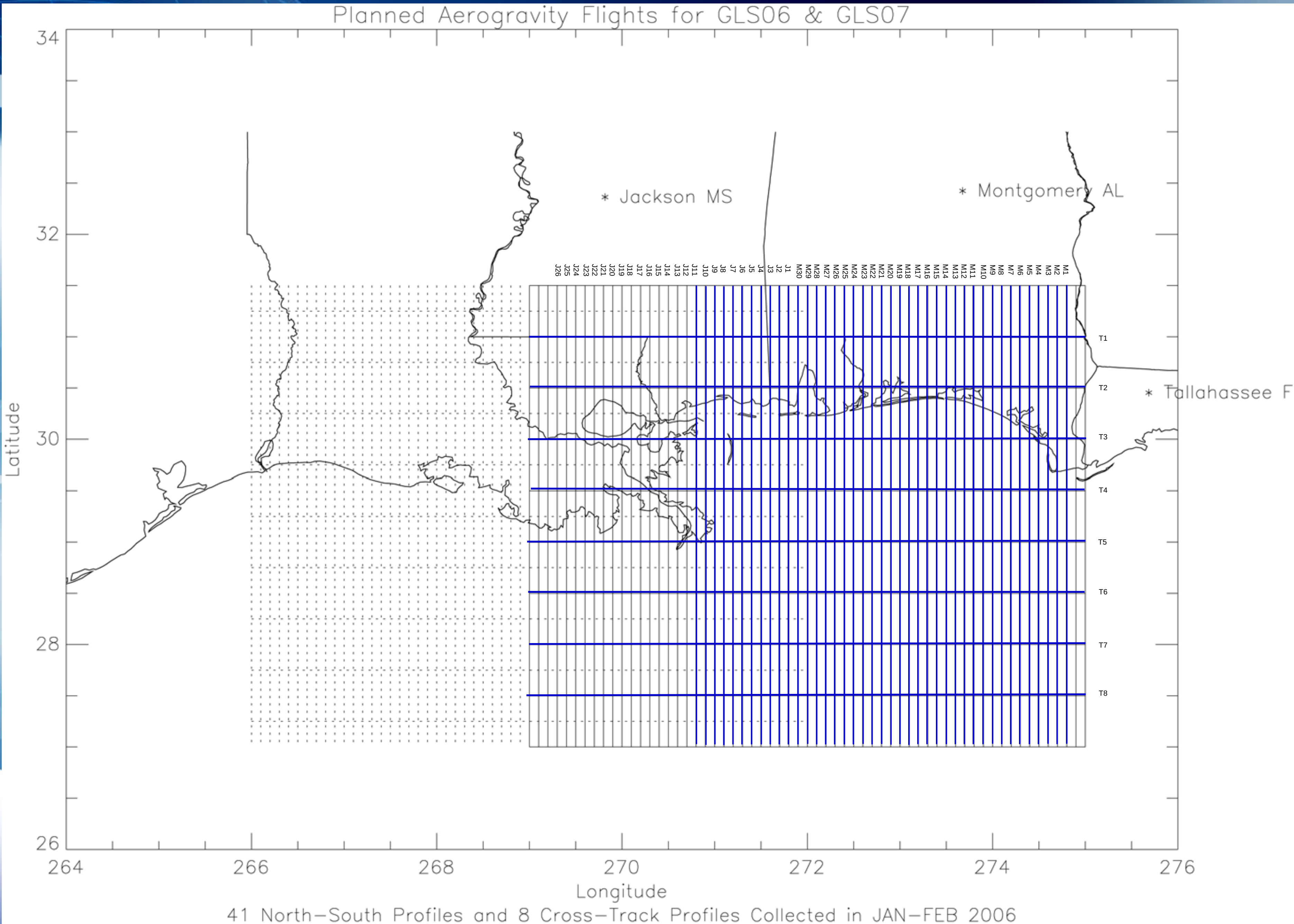


- **Geoid = global MSL**
  - Average height of ocean globally
  - Where it would be without any disturbing forces (wind, currents, etc.).
- Local MSL is where the average ocean surface is with the all the disturbing forces (i.e., what is seen at tide gauges).
- Dynamic ocean topography (DOT) is the difference between MSL and LMSL:

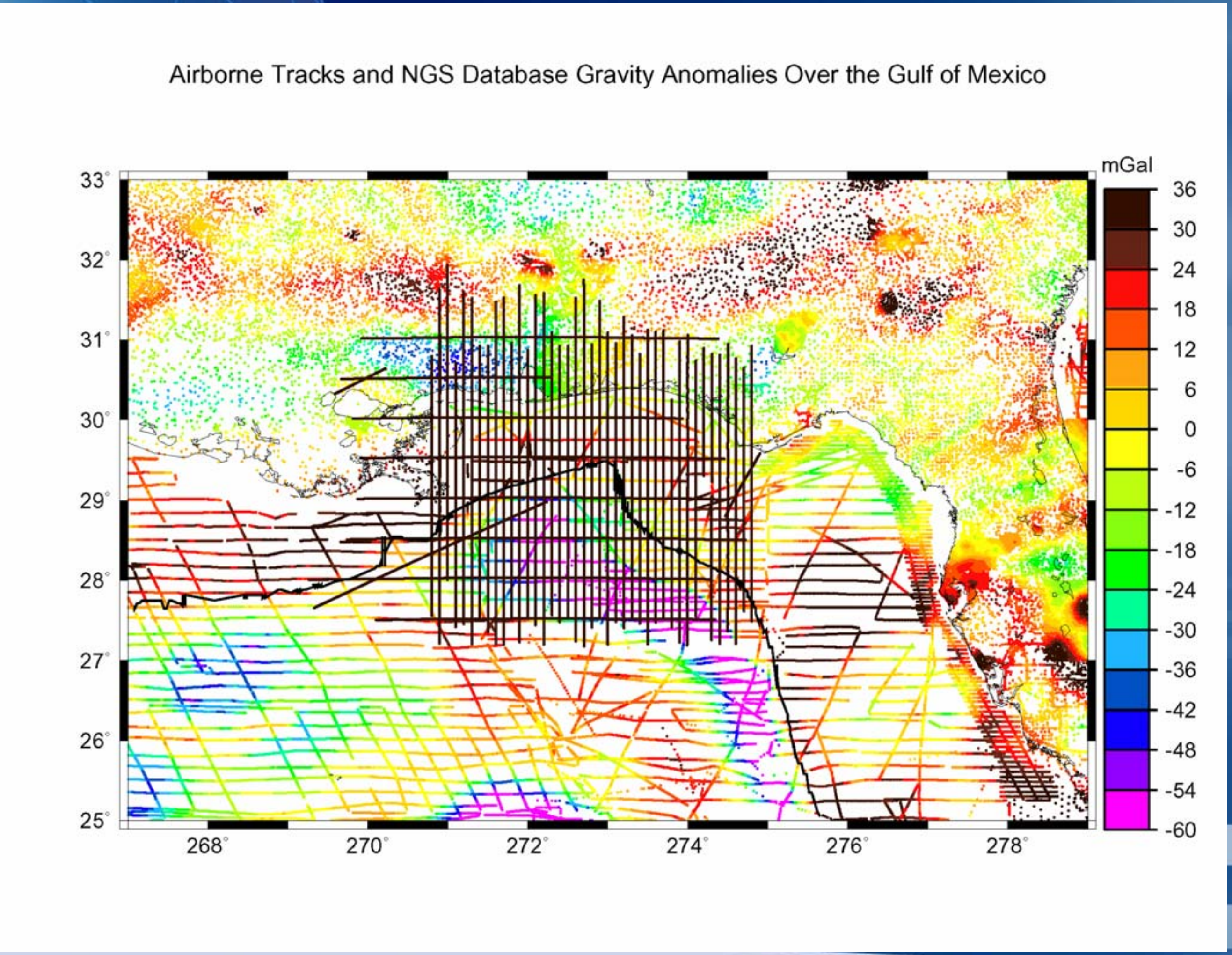
  LMSL = MSL + DOT
- Hence:

  error = TG – DOT - N

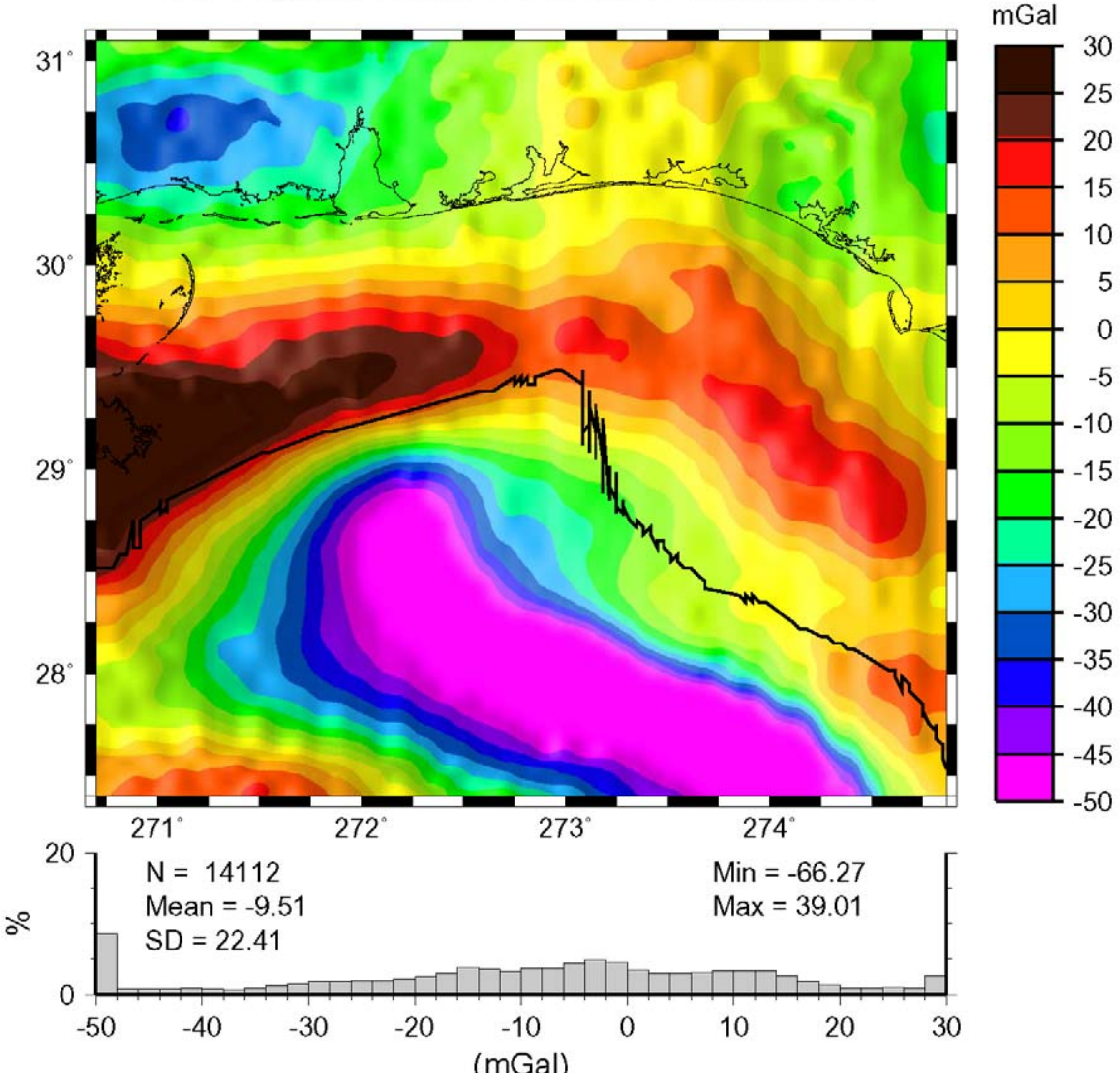



Planned Aerogravity Flights for GLS06 & GLS07
Latitude
34
32
30
28
26
Longitude
264
266
268
270
272
274
276
* Jackson MS
* Montgomery AL
* Tallahassee FL
J26 J25 J24 J23 J22 J21 J20 J19 J18 J17 J16 J15 J14 J13 J12 J11 J10 J9 J8 J7 J6 J5 J4 J3 J2 J1
M30 M29 M28 M27 M26 M25 M24 M23 M22 M21 M20 M19 M18 M17 M16 M15 M14 M13 M12 M11 M10 M9 M8 M7 M6 M5 M4 M3 M2 M1
T1
T2
T3
T4
T5
T6
T7
T8
41 North–South Profiles and 8 Cross–Track Profiles Collected in JAN–FEB 2006

Extent of Gravity and Data Collection Flights

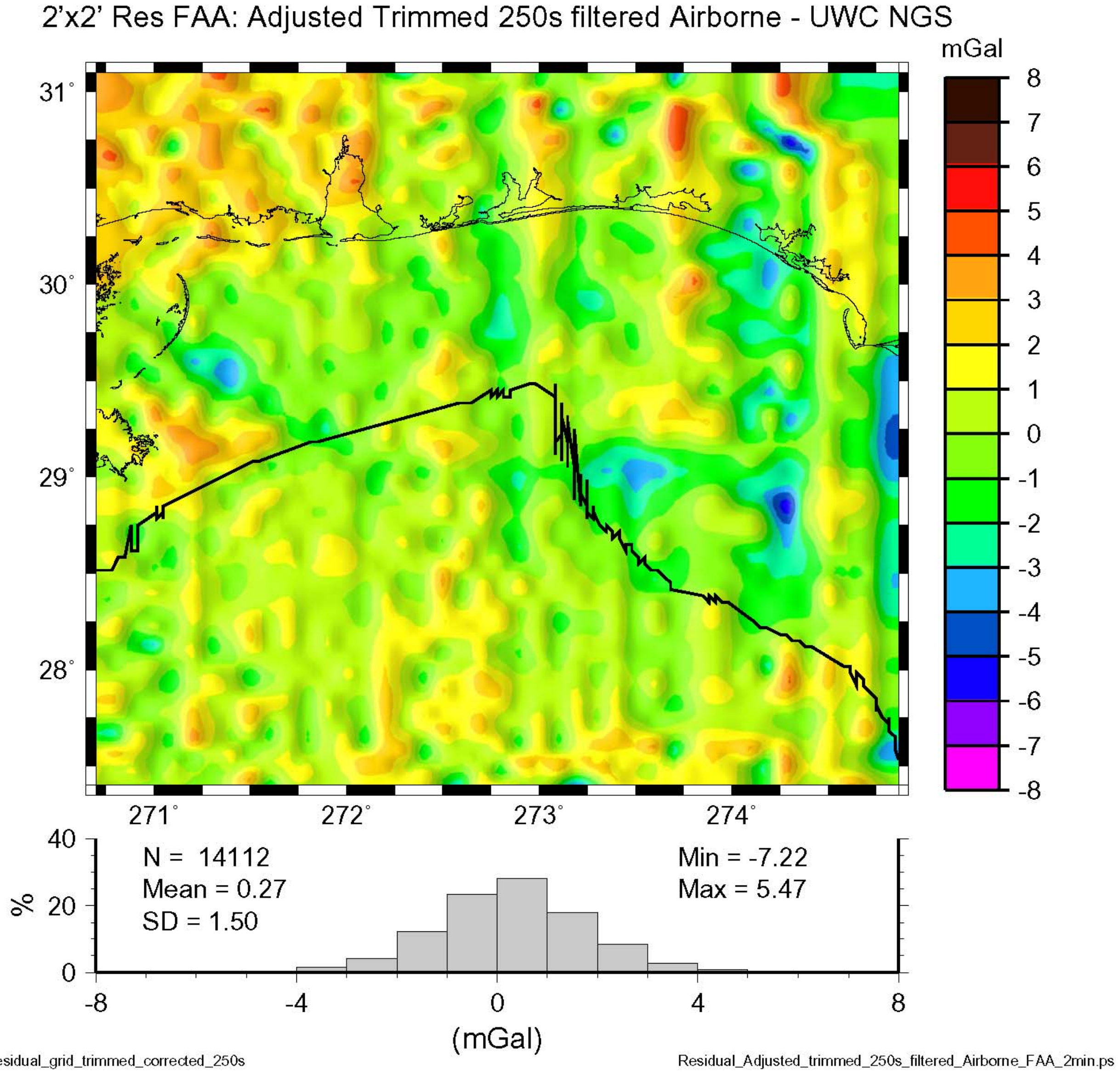


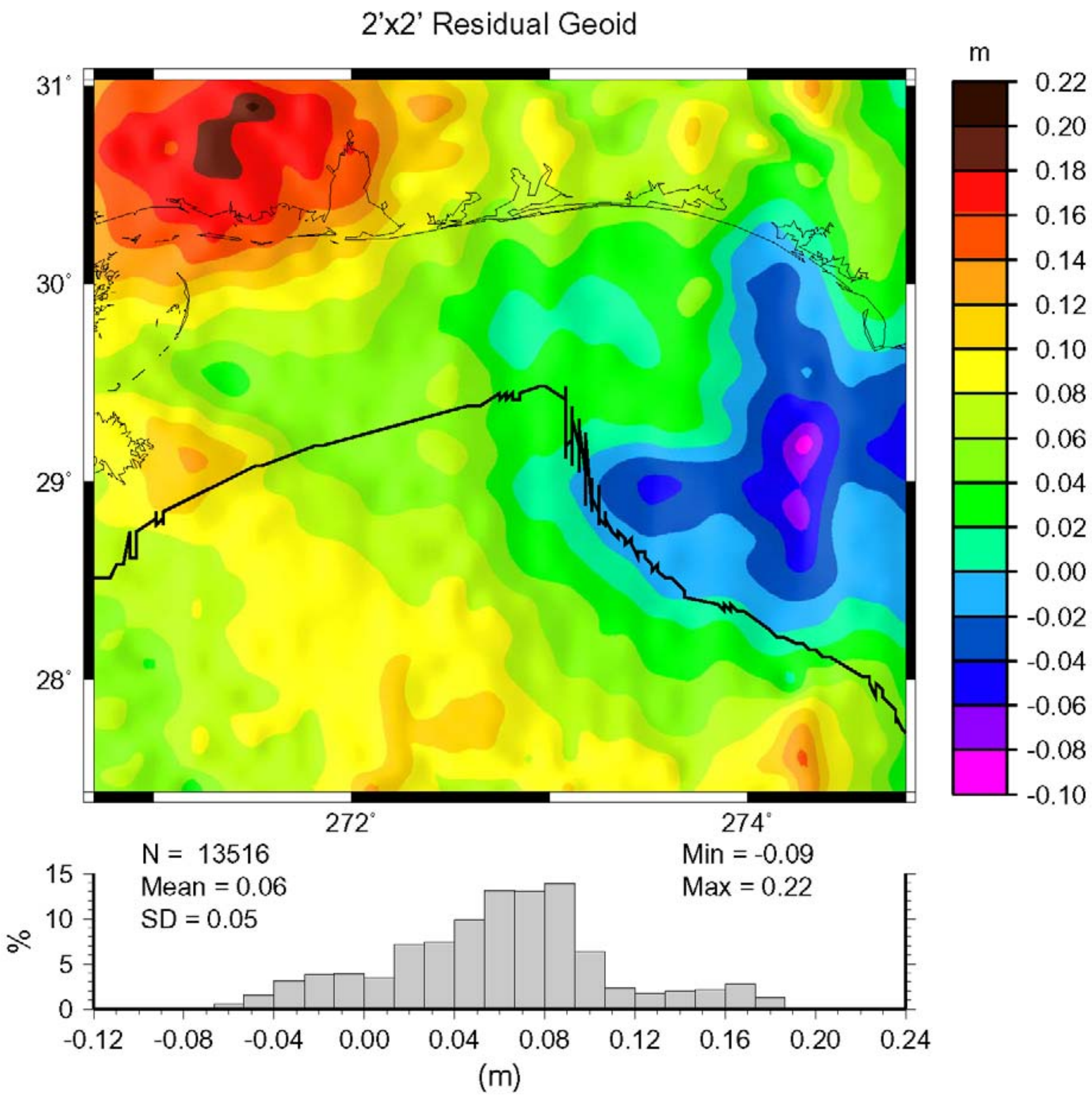
2'x2' Adjusted Trimmed 250s filtered Airborne FAA



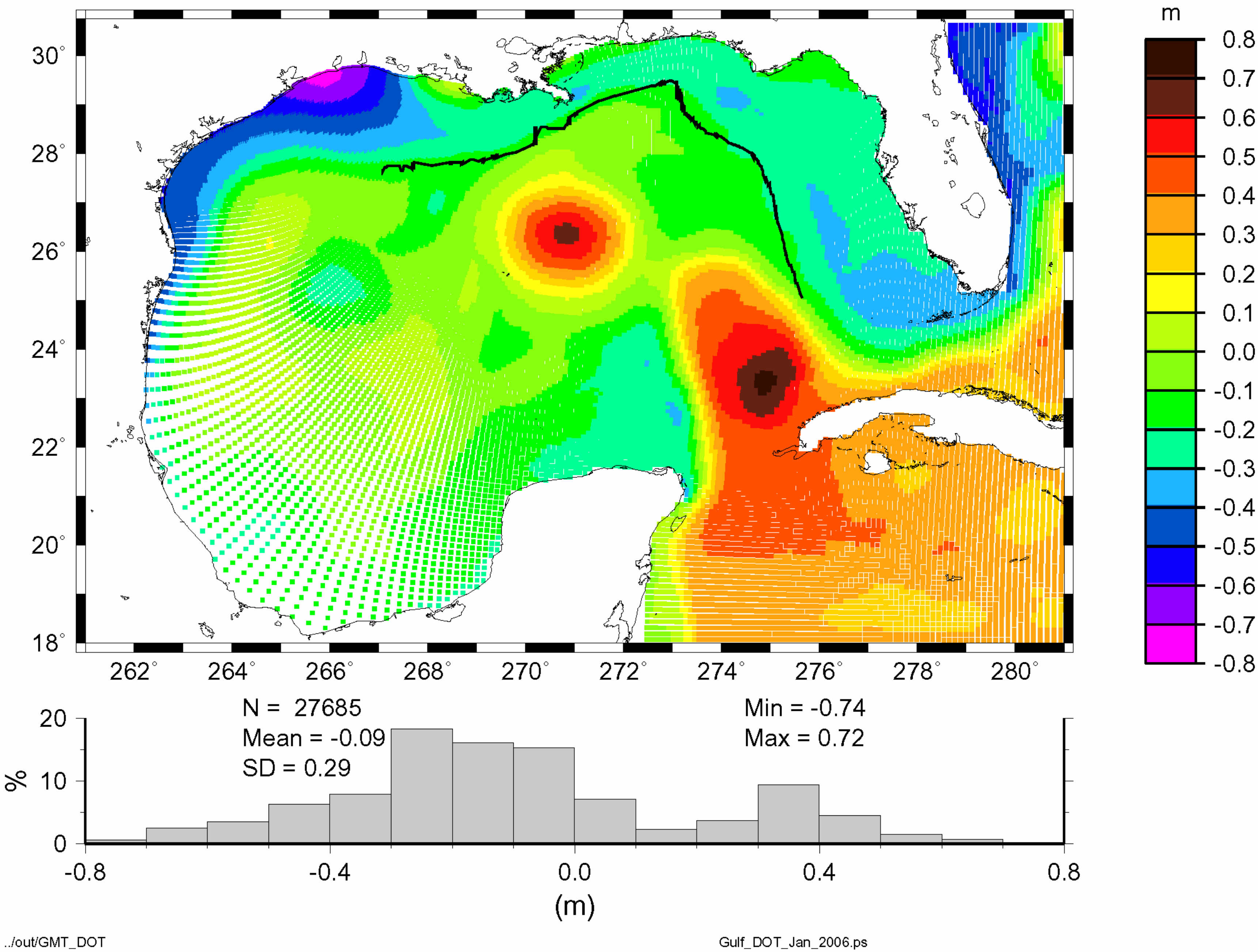
../out/NRL_Dg_grid_trimmed_corrected_250s

Adjusted_trimmed_250s_filtered_Airborne_FAA.ps


2'x2' Res FAA: Adjusted Trimmed 250s filtered Airborne - UWC NGS
mGal
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
31°
30°
29°
28°
271°
272°
273°
274°
40
20
0
%
N = 14112
Mean = 0.27
SD = 1.50
Min = -7.22
Max = 5.47
-8
-4
0
4
8
(mGal)
../out/NRL_residual_grid_trimmed_corrected_250s
Residual_Adjusted_trimmed_250s_filtered_Airborne_FAA_2min.ps


2'x2' Residual Geoid
m
0.22
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
-0.02
-0.04
-0.06
-0.08
-0.10
31°
30°
29°
28°
272°
274°
N = 13516
Mean = 0.06
SD = 0.05
Min = -0.09
Max = 0.22
%
15
10
5
0
-0.12
-0.08
-0.04
0.00
0.04
0.08
0.12
0.16
0.20
0.24
(m)

Dynamic Ocean Topography in Jan. 2006




tidal benchmarks with a NAVD88 tie
tidal benchmarks without a NAVD88 tie

Expected Results

- A Consistent vertical datum between all U.S. states and territories as well as our neighbors in the region.
  - Reduce confusion between neighboring jurisdictions.
  - Local accuracy but national consistency.
- This provides a consistent datum for disaster management.
  - Storm surge, tsunamis, & coastal storms.
  - Disasters aren't bound by political borders.
- Heights that can be directly related to oceanic and hydrologic models (coastal and inland flooding problems).
- The resulting improvements to flood maps will better enable decision making for who does & doesn't need flood insurance.
- Updates to the model can be made more easily, if needed, to reflect any temporal changes in the geoid/gravity.
- Finally, offshore models of ocean topography will be improved and validated. These models will provide better determination of offshore water flow (useful for evaluating the movement of an oil slick).

QUESTIONS?

Geoid Research Team:

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• Dr. Yan Ming Wang, research geodesist
yan.wang@noaa.gov
• Jarir Saleh, ERT contractor, gravity database analysis
• William Waickman, programming & database access

• Website: http://www.ngs.noaa.gov/GEOID/
• Phone: 301-713-3202