

-ellipsoid only loosely tied to the Earth -(4 parameters: a , f , GM , and ω)

-great for tracking satellites - but not flood plains

-mass variations cause gravity and geoid variations

-explain about geoid undulations/heights (+/- 100 m)

-cover reference feidl models, such as EGM96

Emphasize that geoid height models are transformation models between ellipsoids and vertical datums (geoids).

Definitions: GEOIDS versus GEOID HEIGHTS

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- "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 not interchangeable).

*Definition from the Geodetic Glossary, September 1986



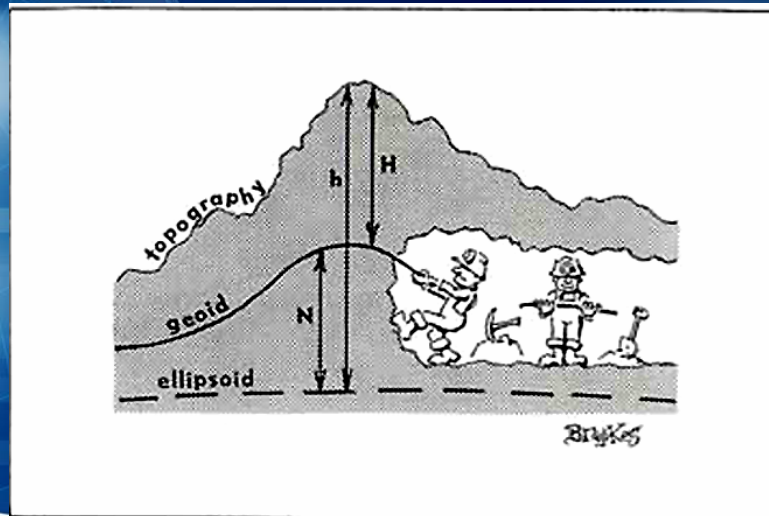
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-If you recall, this was shown previously to emphasize the nature of the geoid as a vertical datum

--now we'll focus on the geoid height model as a transformation between an ellipsoidal datum and a vertical datum

In Search of the Geoid...

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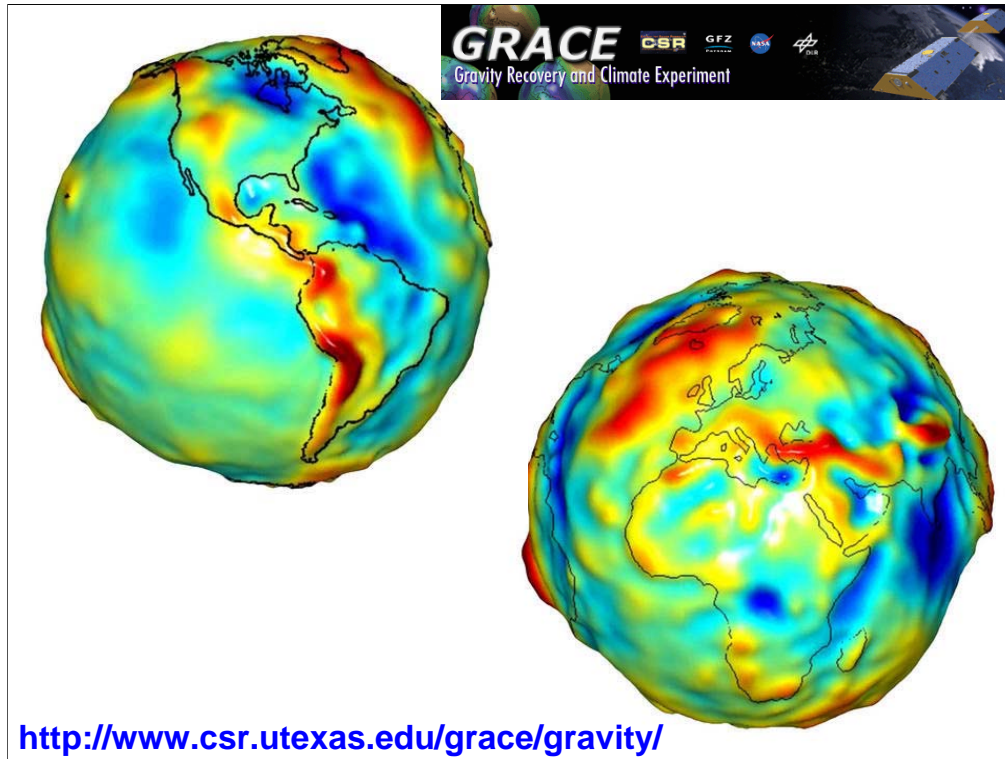


In Search of the Geoid



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

-The geoid extends everywhere and provides a common datum for all.
... but where is it and how do you find it ...



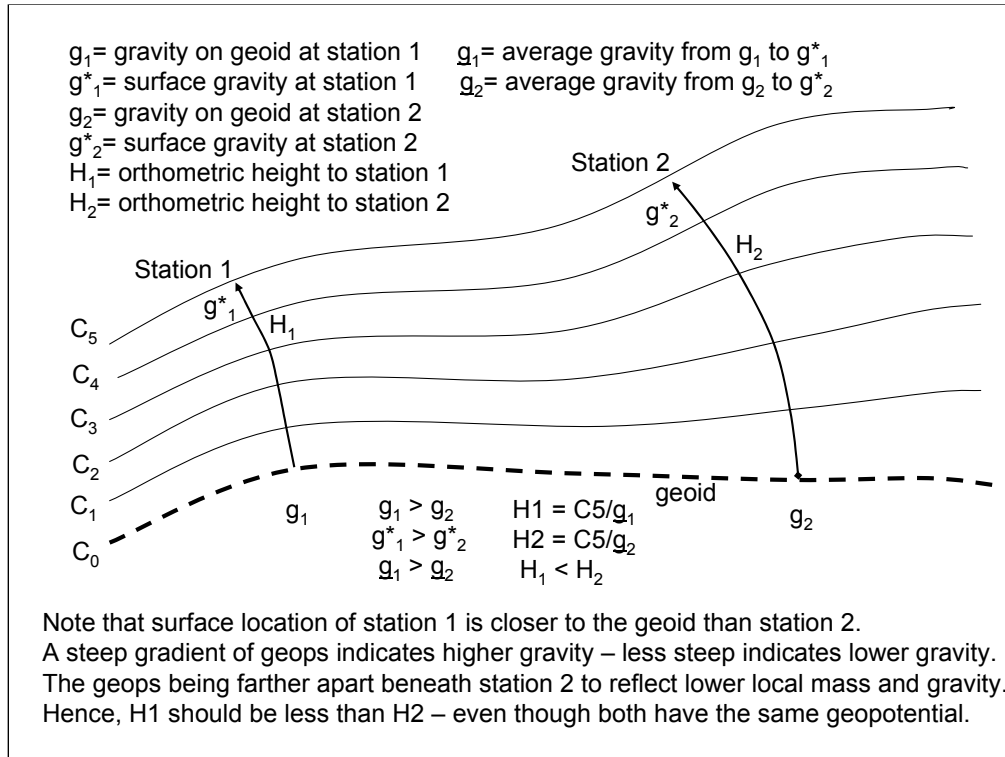
-The GRACE satellite mission determined a global gravity field model by circling the Earth and tracking the orbital perturbations of the satellite pair.

-This model is incomplete because significant short wavelength signal was omitted. Recall that the further above the Earth you are, the more the gravity field resembles an ellipsoid because all these humps and bumps attenuate.

-Hence, the GRACE model by itself can provide accurate estimates for the geoid and gravity field changes – but only sufficiently large regions – such as the entire Colorado Plateau.

-NGS models add back the missing shorter wavelengths to give a more complete model for surveying, engineering and scientific applications.

-This also brings up another point: that the variations in the mass of the Earth cause these features. This point will become clearer shortly.

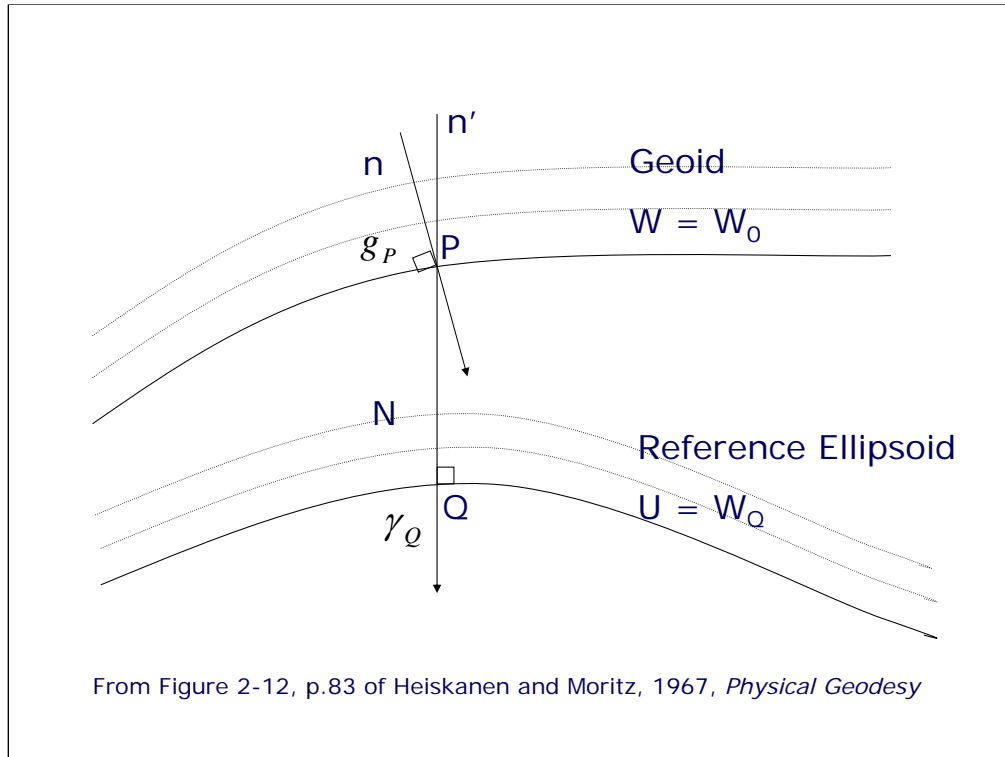


-Heights, gravity and the geoid are all related.

-As see here, both stations have different heights but the same geopotential. Since there is not geopotential difference, water will not flow even though one point is “higher” than the other. This is why dynamic heights are favored over orthometric heights in local areas dealing with hydrographic issues.

-However, you can’t see the geoid. The ocean surfaces are close, but ocean currents and weather disturb the ocean surface from what it would be ... and you definitely can’t “see” it under the land.

-Hence, another means must be found to define this surface – possibly in relation to one already established.



-As discussed earlier, the international ellipsoid (GRS-80) can be used to define most of the Earth's gravity field and geospatial information. The normal gravity (γ) from the GRS-80 model is even used to define some heights.

-The surface of the ellipsoid is not only a datum from which to measure heights – it also is a sphero-potential surface. The potential of normal gravity varies smoothly towards the poles but is constant along that datum surface (U). The geoid is also a constant potential of the real gravity field (W) and undulates about the ellipsoid. The separation can be +/- 100meters – and these differences are geoid heights that are a function of the difference in the potentials ($T = W - U$).


-Hence, the ellipsoid can be used to define most of the Earth's gravity signal as well as a coordinate system. Then geoid heights can be used to define the geoid surface away from the ellipsoid surface.

Well, OK, maybe a *few* formulas ...

NATIONAL GEODETIC SURVEY

Disturbing Potential:	$T = W_P - U_P$
Bruns Formula:	$N = \frac{T}{\gamma}$
Height Relationships:	$h = H + N$
Gravity Anomalies:	$\Delta g = g_P - \gamma_Q = -\frac{\partial T}{\partial r} - \frac{2T}{R}$
Stokes' Formula:	$N = \frac{R}{4\pi G} \iint_{\sigma} \Delta g S(\psi) d\sigma$

where: $S(\psi) = \frac{1}{\sin(\frac{\psi}{2})} - 6 \sin(\frac{\psi}{2}) + 1 - 5 \cos \psi - 3 \cos \psi \ln\left(\sin \frac{\psi}{2} + \sin^2 \frac{\psi}{2}\right)$



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-The undulations of the geoid surface reflect lateral and vertical variations in the mass of the Earth. These mass variations cause a disturbing potential (T). The actual geopotential (W) differs from that predicted by the ellipsoid model (U) by the disturbing potential (T).

-This disturbing potential can then be related to both geoid undulations and gravity anomalies, both of which represent deviations away from some standard. Hence all three are and can be mathematically related.

-While the geoid surface and the disturbing potential are very difficult to observe, gravity observations are fairly easy. Removing the normal gravity yields gravity anomalies that can be used to determine the geoid surface.

-That's the big takeaway from this slide. The reason we are trying to invigorate a gravity observation program is because the quality of the gravity data will directly relate to the quality of the geoid height models produced.


-Also note that the geoid height (N) is scaled by the normal gravity. This is appropriate because a geoid height is measured along the ellipsoidal normal (i.e., perpendicular to the ellipsoid – not the geoid). It measures the distance from the ellipsoid to the geoid. The “ $h = H + N$ ” formula is true only in so far that the DoV can be neglected. This has sub-cm impact for the most part.

-This all seems straight forward except that these formulas shown here are all *spherical* approximations. Ellipsoidal formulations are similar but more complicated to implement. These approximations represent one area where theoretical improvements should directly contribute to improved geoid height models.

High Resolution Geoid Models
G99SSS (Scientific Model)

NATIONAL GEODETTIC SURVEY

- Earth Gravity Model of 1996 (EGM96) ← Long Wavelength - global
- 2.6 million terrestrial, ship-borne, and altimetric gravity measurements ← Medium Wavelength - regional
- 30 arc second Digital Elevation Data
- 3 arc second DEM for the Northwest USA ← Short Wavelength - local
 - Decimated from 1 arc second NGSDDEM99
- Computed on 1 x 1 arc minute grid spacing
- GRS-80 ellipsoid centered at ITRF97 origin

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- **G99SSS** (scientific model) - determined from 2.6 million gravity measurements taken over the last century and stored in NGS database. Major improvements over previous models; more data.
- 30 arc second, 1 km x 1 km, grid of digital elevation data; with updated Canadian Rockies data from G96SSS.
- 3 arc second DEM - northwestern portion of U.S. which has history of poor geoid interpretation.
- EGM96 (Earth Gravity Model of 1996) developed by National Imaging and Mapping Agency (NIMA) - global model of gravity and geoid undulations; good in large areas but not as good for smaller areas.
- 1-D spherical Stokes' FFT (Fast Fourier Transformation) - "remove-compute-restore" (fix and put back into model - iterative process).

Final outcome - 1 x 1 arc minute spacing interpolation of the geoid model; 2' x 2' in Alaska. 1 arc minute equals about 1.8 km on ground.

ITRF97 (1997.0) COM (Center Of Mass) based origin for model.

High Resolution Geoid Models USGG2003 (Scientific Model)

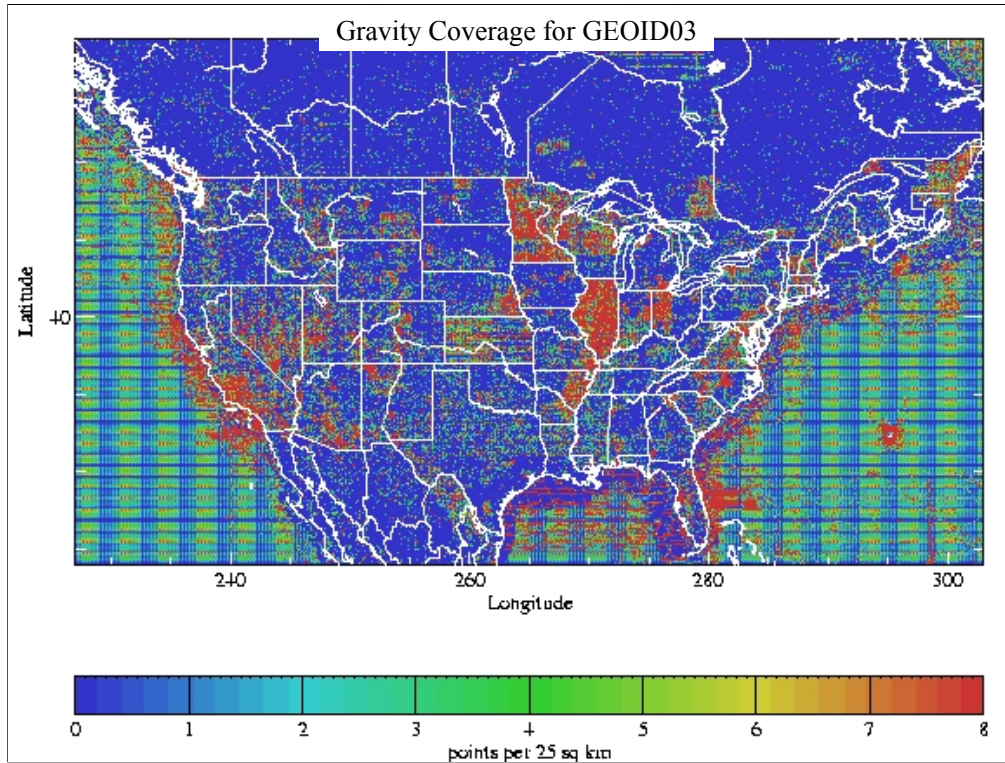
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- 2.6 million terrestrial, ship, and altimetric gravity measurements
 - offshore altimetry from GSFC.001 instead of KMS98
- 30 arc second Digital Elevation Data
- 3 arc second DEM for the Northwest USA
 - Decimated from 1 arc second NGSD99
- Earth Gravity Model of 1996 (EGM96)
- Computed on 1 x 1 arc minute grid spacing
- GRS-80 ellipsoid centered at ITRF00 origin



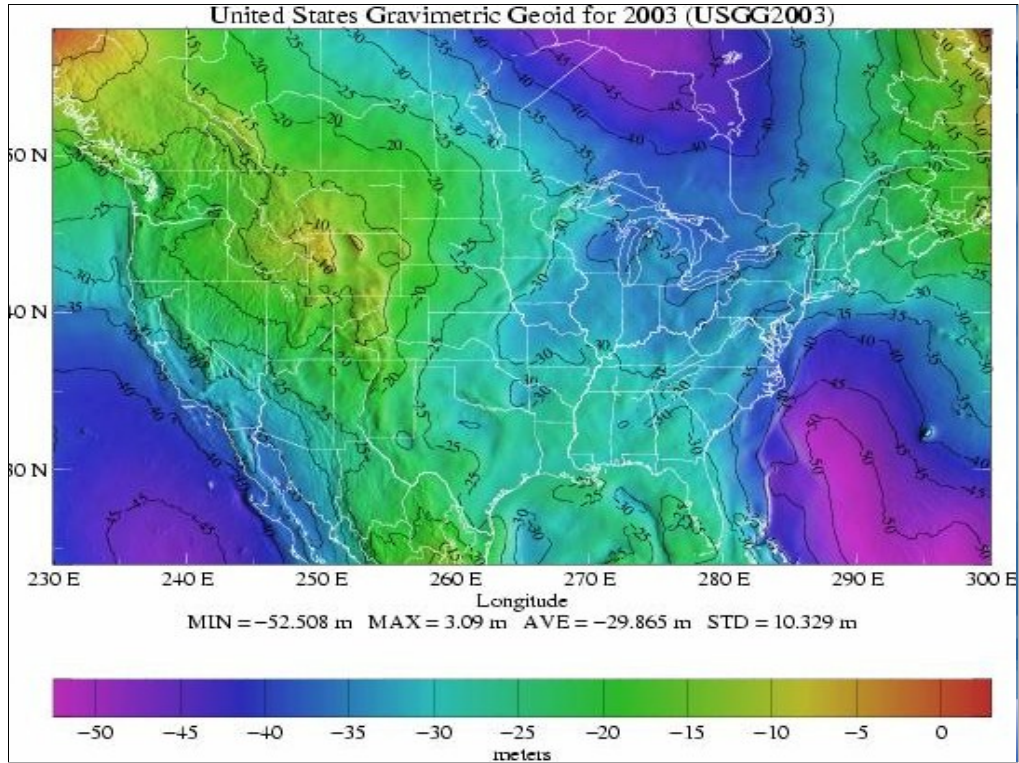
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Offshore altimetry from a different source => better defines ocean topography.
ITRF00 used instead of ITRF97.



This shows the extent of the gravity data that went into the USGG2003 geoid model.

Terrestrial data onshore; shipborne and altimetric data offshore.



-although GSFC00.1 created significant changes (50 cm or more in some regions when looking at the difference between G99SSS and USGG2003, the magnitude of those differences is dwarfed by the total signal

This model is tied to a GRS-80 ellipsoid centered at ITRF00 and the W_0 value of EGM96 ... but that isn't what we need to use it with level data.

Ongoing research areas

NATIONAL GEODETIC SURVEY

- 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).



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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)

Ongoing research areas (cont.)

NATIONAL GEODETIC SURVEY

- Must acquire data and models for outlying regions.
 - Definitely need surface gravity (terrestrial and shipborne) and terrain models for Guam, CNMI, American Samoa.
 - 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?)



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Ongoing research areas (cont.)

NATIONAL GEODETIC SURVEY

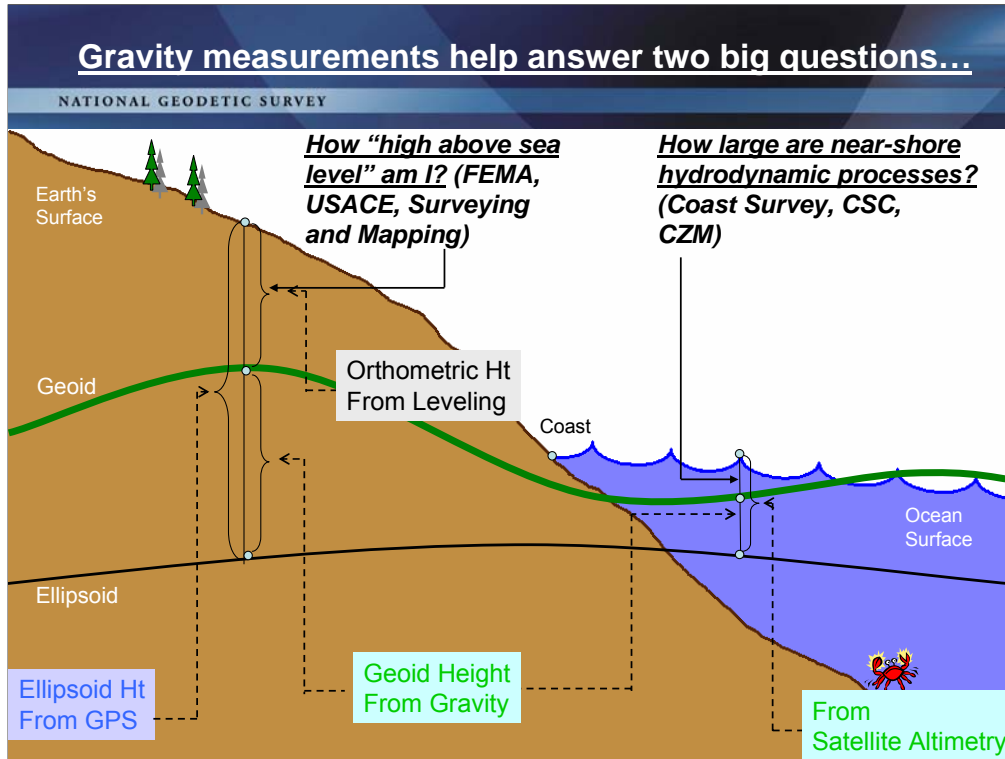
- Geodetic theory improvements.
 - Downward continuation of high altitude gravity observations.
 - Merging of gravity field components.
 - Current approach is remove-compute-restore.
 - Spectral merging of EGM, gravity and terrain data.
 - Would honor long wavelength (GRACE).
 - Retain character of the 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.



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This slide is an idealized situation demonstrating the usefulness of near-shore gravity, specifically the use of such gravity to accurately compute a gravimetric **geoid** model. (The geoid is the one unique equipotential surface of the Earth's gravity field which best fits, in a least-squares sense, global mean sea level).

On land, the use of the Global Positioning System (GPS) for fast, accurate surveying is well documented. However the height determined by GPS refers to a highly idealized, mathematically simple surface known as the ellipsoid. Thus GPS heights are "**ellipsoid heights**". Unfortunately, ellipsoid heights are non-intuitive in many ways. First, they can be dozens of meters different from heights above the geoid (known as **orthometric heights**, or more colloquially, but less correctly as "**heights above sea level**"). Secondly, ellipsoid heights do not give an accurate portrayal of how water will flow, due to their complete disconnect from the gravity field of the Earth. If one has an accurate model of **geoid undulations** (the separation between the geoid and ellipsoid), then one can take the GPS-derived ellipsoid heights, remove the geoid undulation, and arrive at your orthometric height (a.k.a. "height above sea level"). This is a significantly faster method of determining orthometric heights compared to traditional surveying methods of spirit leveling.

On the ocean, satellite altimetry is used to monitor sea level. However, because the satellite orbits are known relative to the ellipsoid, and the altimetric measurement is from satellite to sea surface, the resulting information is the height of the sea surface above the ellipsoid, often called the "**sea surface height**" or SSH. If one is interested, however, in the impact of winds, heating, currents and other phenomena on the ocean surface, then one must remove the gravitational impact on the ocean surface. That is, one must know the separation between the ellipsoid and the geoid over the ocean in order to remove this signal, and arrive at the residual value. This residual, the distance from the geoid up to the sea surface, is known by many names, the most common being "**sea surface topography**" (SST) or "**dynamic ocean topography**".

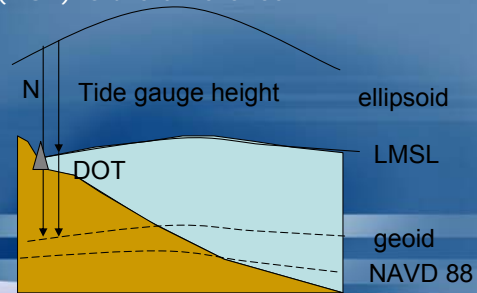
Coastal areas prone to flooding would benefit both by knowing accurate land elevations (to aid in construction planning, floodplain mapping, etc) as well as knowing accurately how the near shore ocean processes work (to better model responses to hurricanes and other dynamic ocean phenomena). It is an unfortunate fact that the largest areas missing accurate gravity measurements are those areas immediately offshore. This is because ships with gravimeters can not get into these shallows, altimetrically derived gravity models are unreliable due to the inability to accurately compute near-shore tides, and terrestrial gravimeters can not measure in the water. The only practical option to collecting the near-shore ocean gravity data is through airborne based technologies.

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Relationships

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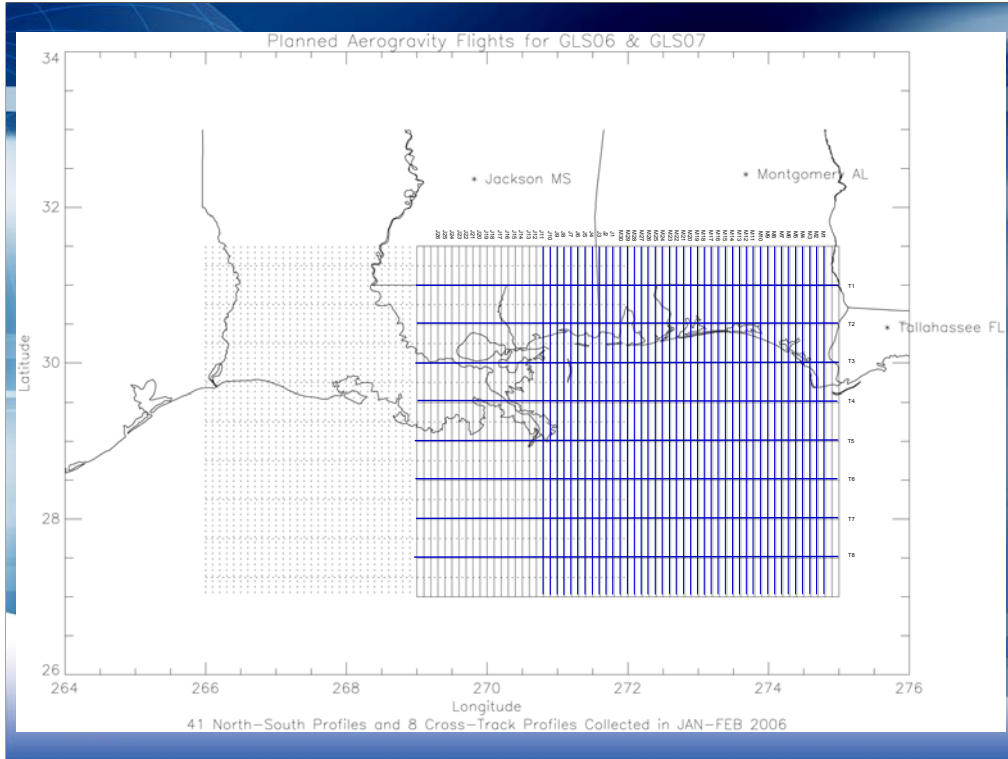
- **Geoid = global MSL**
 - Average height of ocean globally
 - Where it would be without any disturbing forces (wind, currents, etc.).
- Local MSL is where the average ocean surface is with the all the disturbing forces (i.e., what is seen at tide gauges).
- Dynamic ocean topography (DOT) is the difference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

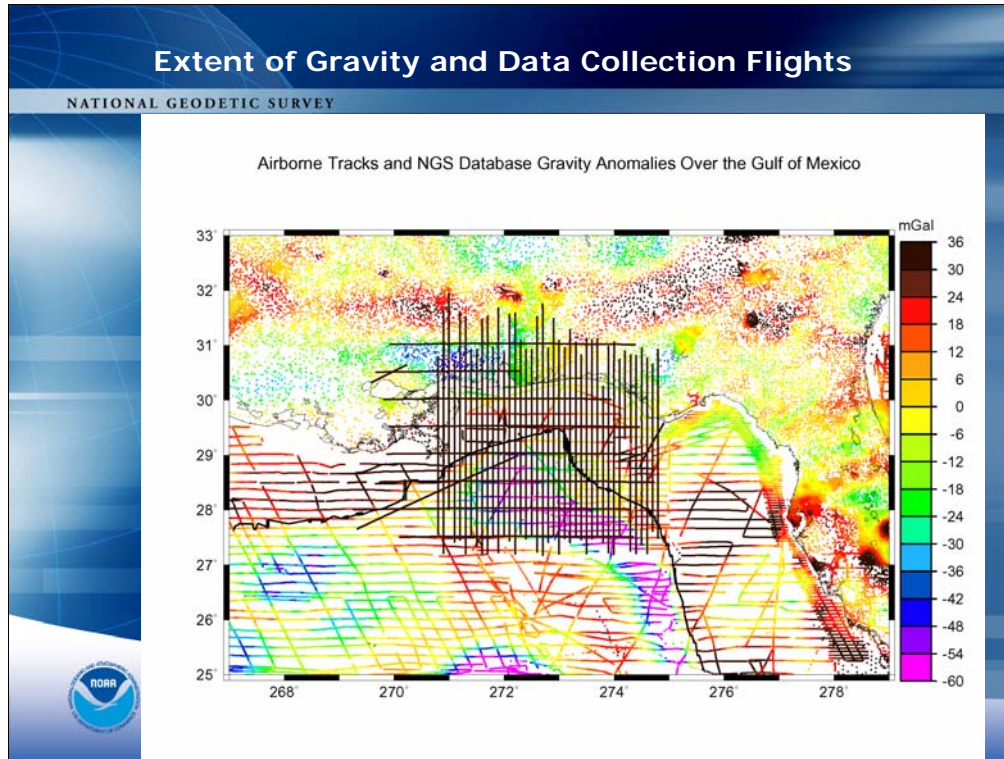


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-Additionally, lidar observations on the open ocean can be reduced as well in VDatum areas where the tides are known.

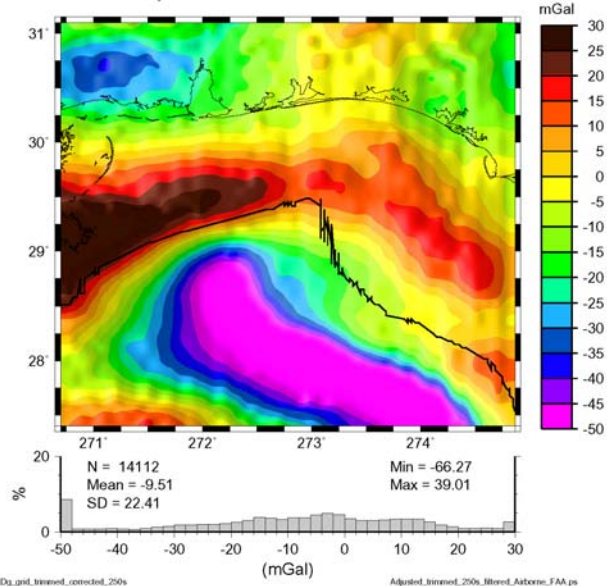
-Only temporal effects due transient weather will remain unmodeled – and generally you don't fly in adverse weather.

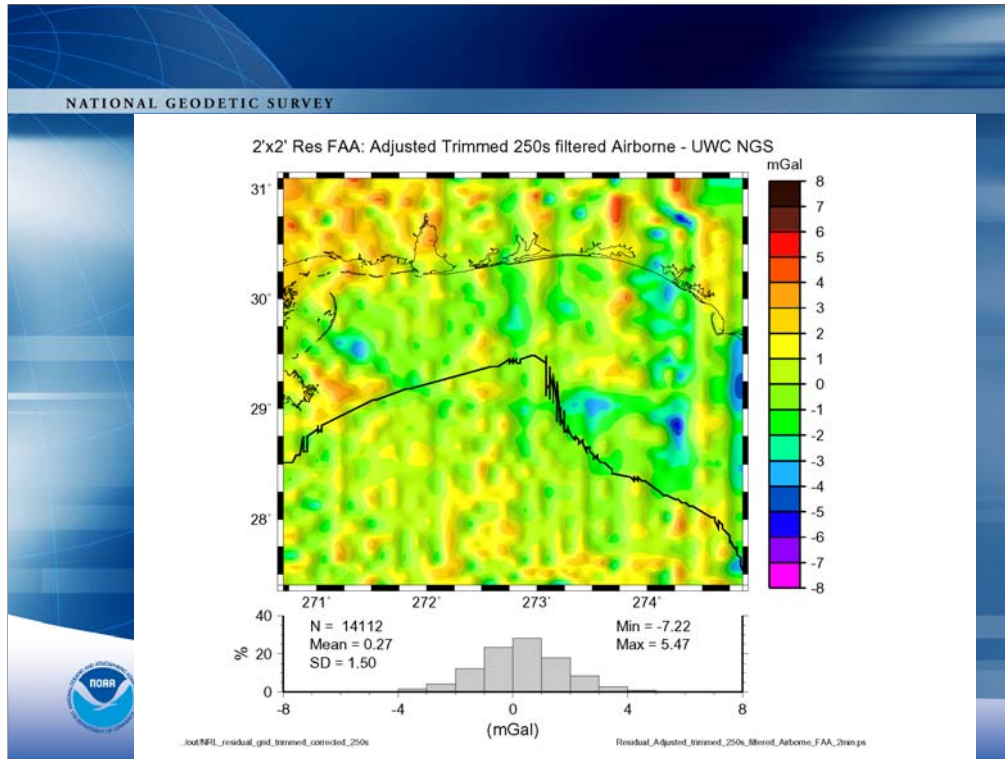




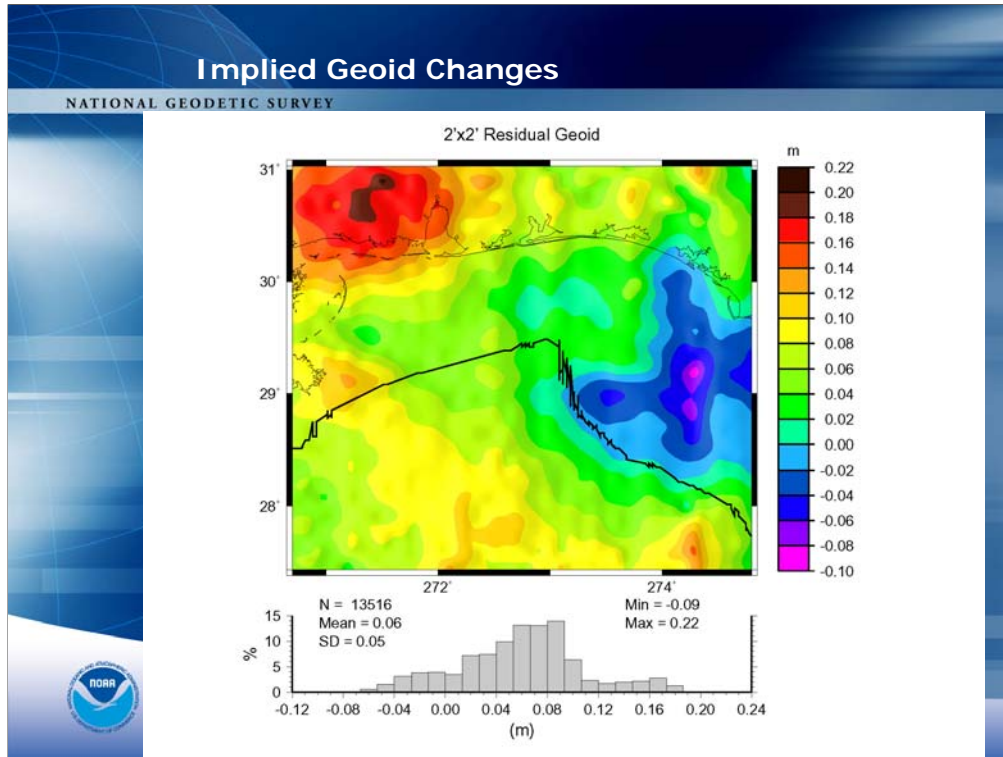
- Surface gravity data are from NGS database: terrestrial, shiptrack and altimetry farther offshore (500 m depths)
- Flights extend from 50-100 km onshore (to stable regions) to well offshore (trustworthy ocean models & altimetry)
- Note lack of crossovers and actual data in Northeast corner => this will affect results later on

2'x2' Adjusted Trimmed 250s filtered Airborne FAA

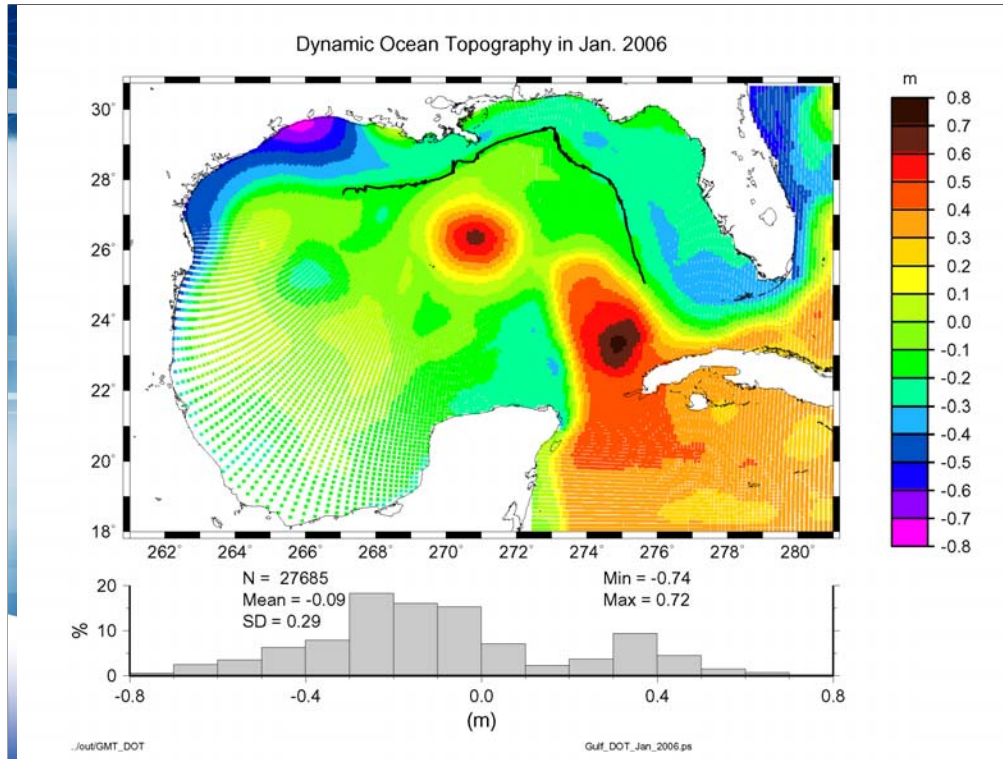




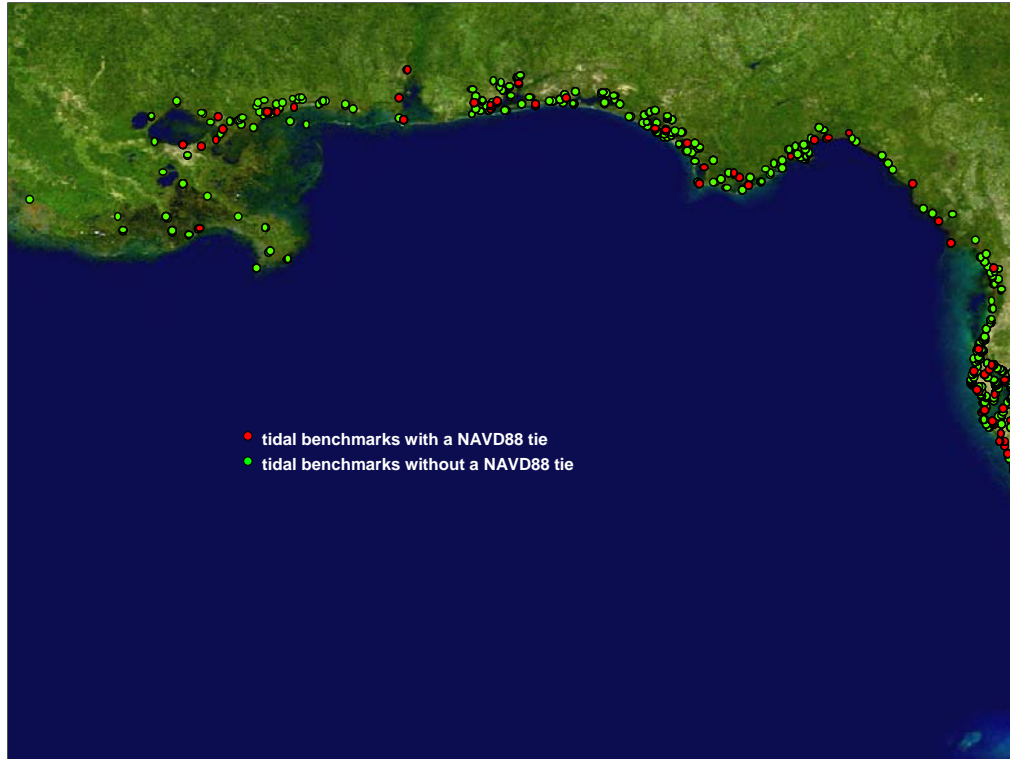
- Unresolved gravity signal differences between airborne and terrestrial data at elevation (10 km)
- Note the stripes – residual biases in aircraft lines
- Also note the features that have significant lateral extents between the lines – particularly in the NW corner.
- This implies a significant problem in our terrestrial data.
- Additional collections further North and West will be needed to verify and analyze this.
- These differences must be accounted for because they imply significant errors in a geoid model
- ...



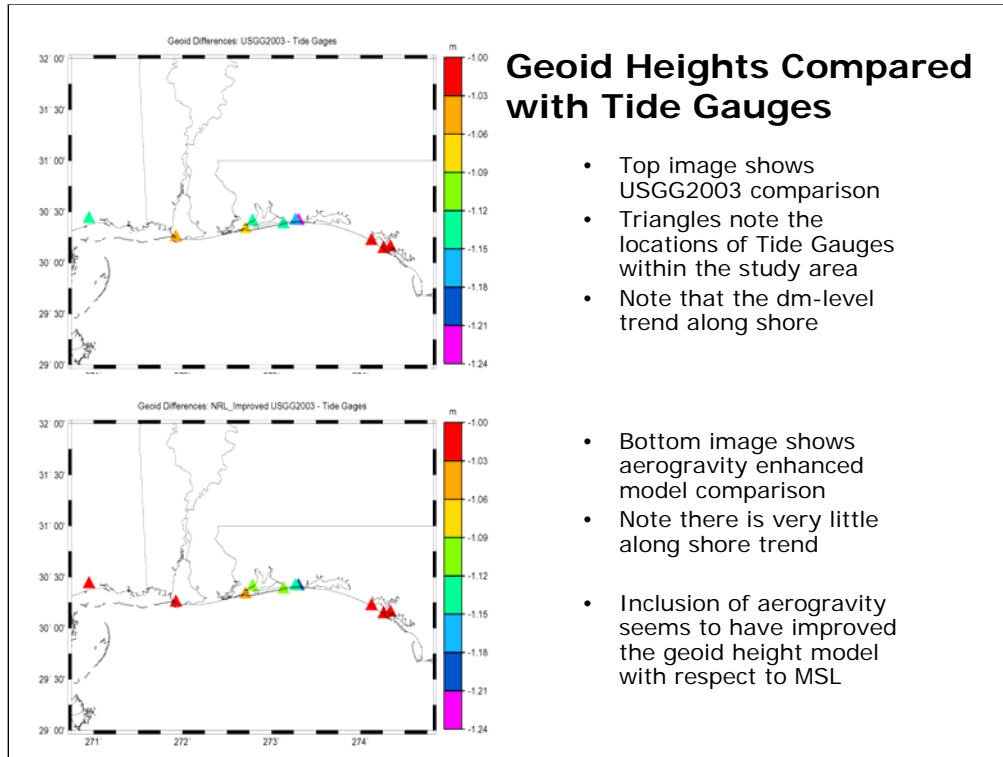
- Unresolved gravity signal differences between airborne and terrestrial data at elevation (10 km)
- Note the stripes – residual biases in aircraft lines
- Also note the features that have significant lateral extents between the lines – particularly in the NW corner.
- This implies a significant problem in our terrestrial data.
- Additional collections further North and West will be needed to verify and analyze this.
- These differences must be accounted for because they imply significant errors in a geoid model as can be seen here.
- Note the decimeter level feature in the NW corner 9in the eastern part of the Louisiana subsidence area.
- Note the range of values from +18 cm to -2 cm along the shoreline.
- The aerogravity are consistent (agreement was at the +/- 2 mgal level with no systematic effects accept biases).
- Hence, the differences seem valid and imply a significant error in the terrestrial data.
- These must be resolved before proceeding with geoid generation.



Once a satisfactory geoid has been made, it can be added to the DOT to simulate SSH's, which can be compared to TBM's.

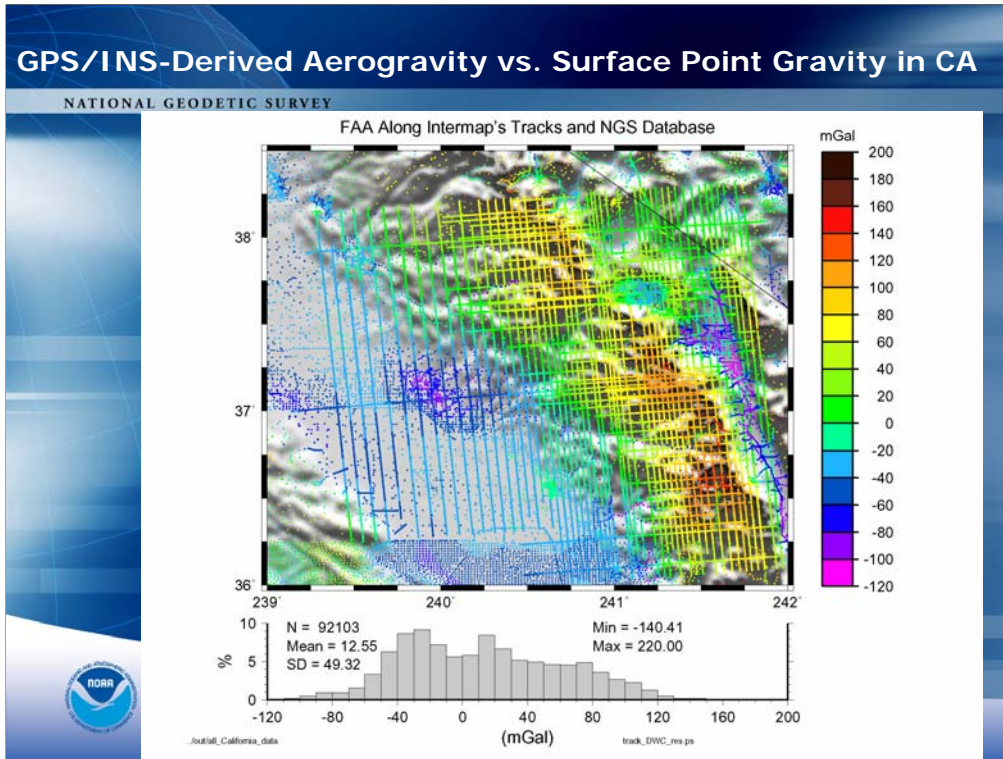


Numerous TBM's exist where the NAVD 88 value and ocean surface (MDT+geoid) are both known. These sites could suffice, providing that suitable gravimetric geoid and MDT models are generated.



The bias shown here is around -1.00 meters. Subsequently, a datum bias was determined that moved the offset to +0.35 m. This remaining bias is thought to relate to possible errors in the generation of the reference gravity & geoid fields.

Which proves exactly why we are performing these studies – to resolve such differences and better estimate the accuracy of geoid height models.



- Note the agreement between tracks at crossovers (internally consistency)
- Note the larger number of surface points in the flat plains and lack of points in mountains
- Note the increased disagreement of surface points in mountains WRT the aerogravity
- Given the reduced amount of data in the mountains and greater likelihood of error in it, the result is that geoid errors will be greater in and near the edges of the mountains – where flooding can more readily occur from runoff.

Expected Results

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- 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).



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QUESTIONS?

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