Bathymetry from Space

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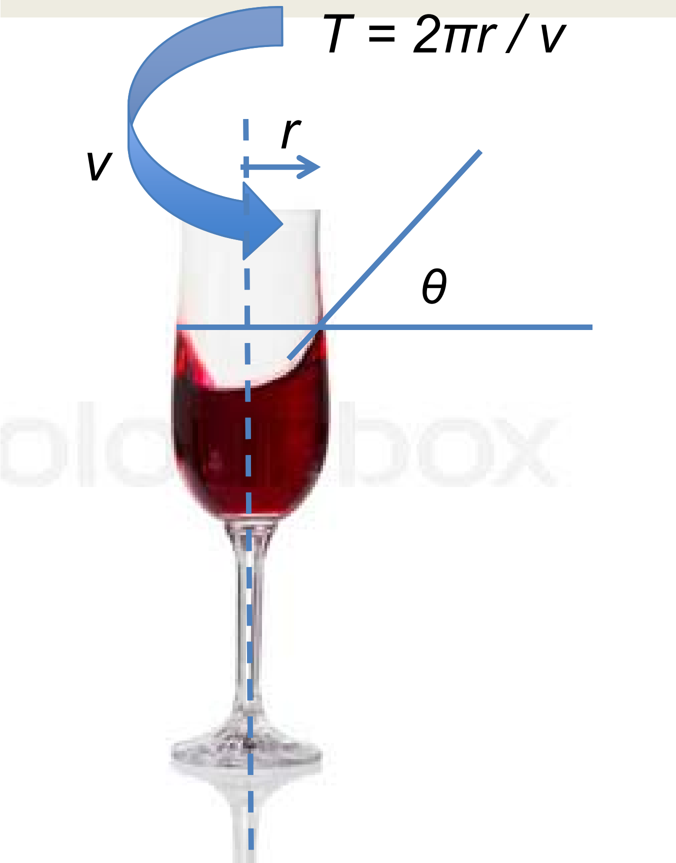
NOAA

Laboratory for Satellite Altimetry
NOAA-NESDIS-STAR

An Assignment To Keep You Awake :

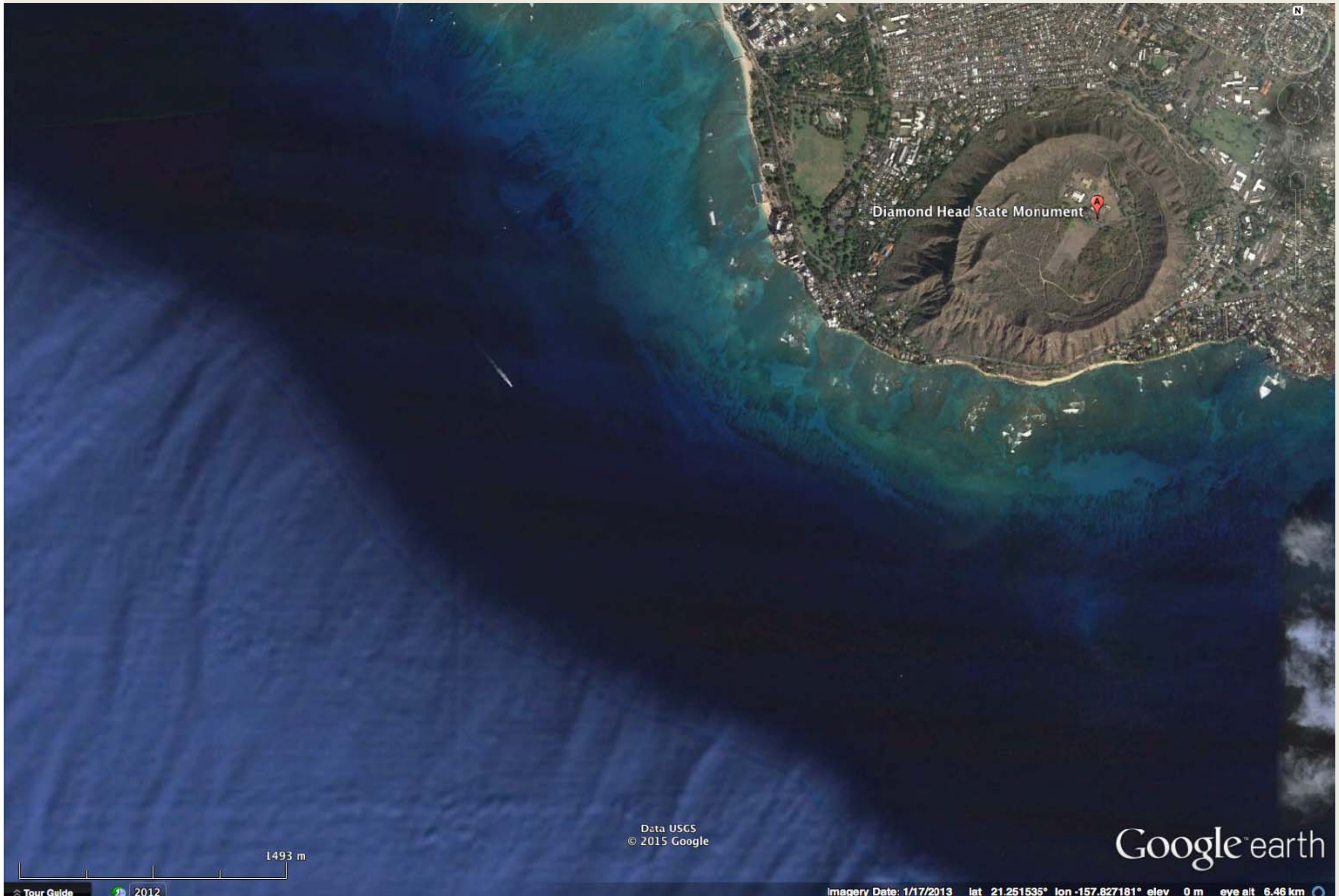


When wine swirls in a wine glass, how is the angle the wine surface makes with horizontal, θ, related to T, the time it takes a drop of wine to make one orbit of the glass, or to v, the wine drop's tangential velocity?

(Assume uniform circular motion and a radius, r, for the glass.)

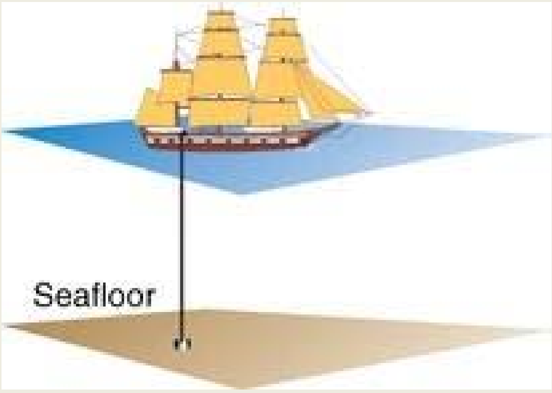
Your answer will be needed later.

Diamond Head as shown in Google Earth



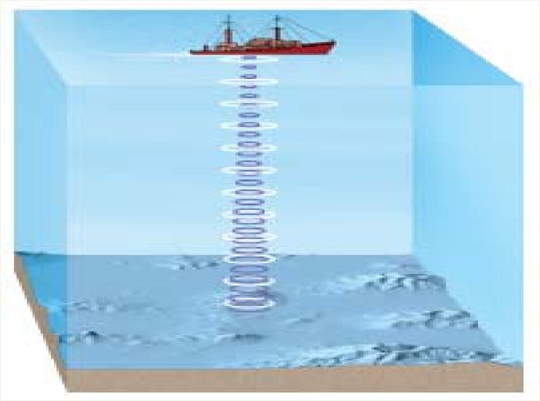
Google Earth has visual imagery over land and shallow water where the bottom is visible. [Here we see coral reefs around Oahu shallow enough to break waves. The bottom becomes invisible within ½ mile of the shore.] In deeper areas GE has a fuzzy blue visualization of sea floor topography. How we made that model is one of the themes of this talk.

Depth measurement requires "sounding"

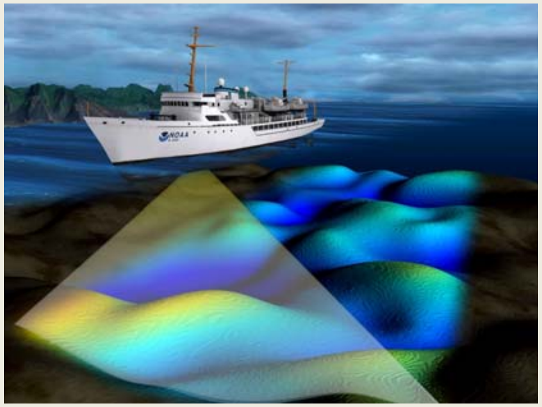


"Sounding" once meant probing for where things were "sound", i.e. firm. [Mark Twain]

In deep water it was a slow process. *Challenger* took 492 soundings during a 4-year expedition in 1872-6.

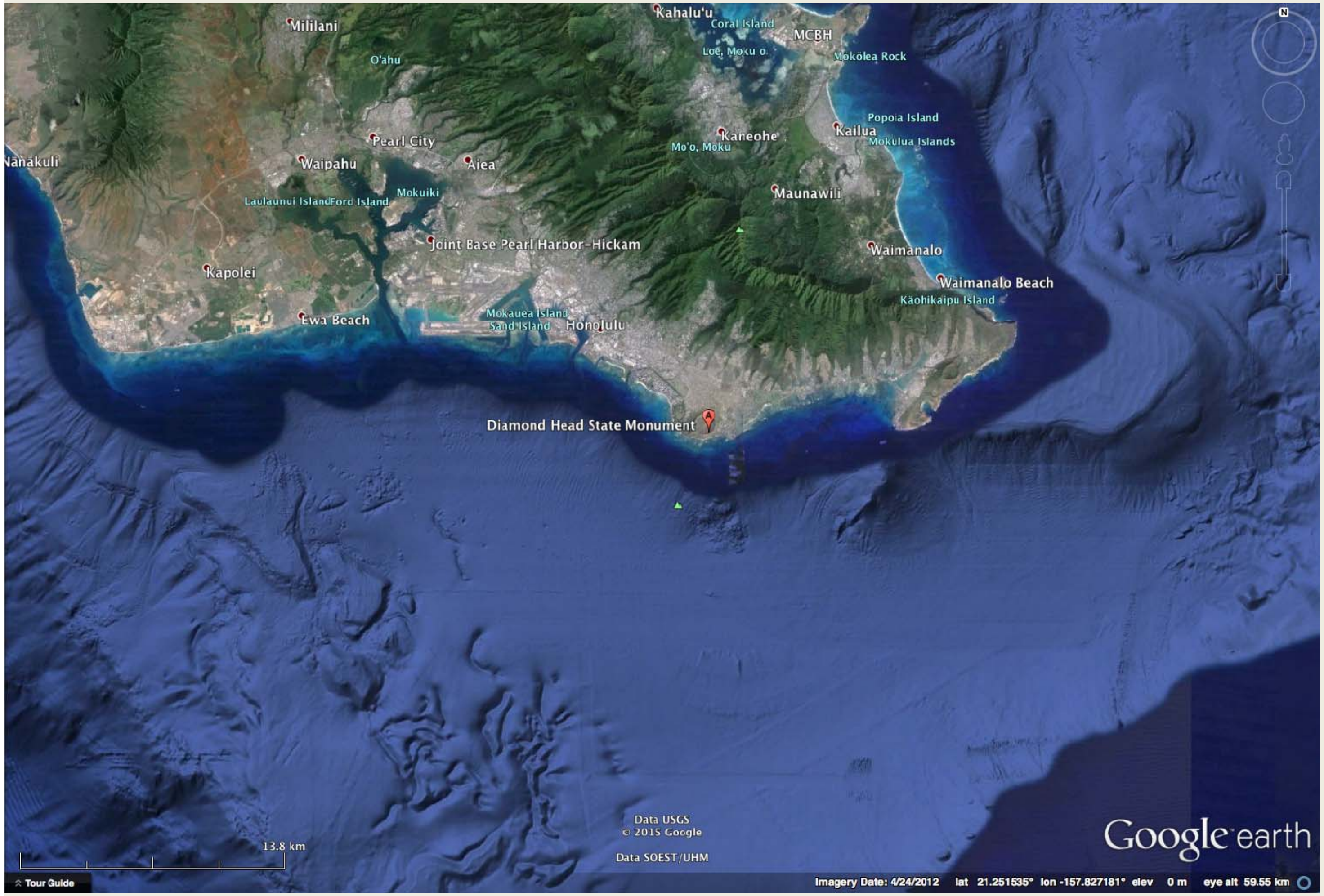


Since WW-II, single-beam echo-sounders record depth profiles on analog scrolls of paper, continuously along a ship's path. These are digitized and combined with (often poor) navigation to give us most of the data we have about the ocean floor.



Since the 1980s, some ships are equipped with multi-beam echo sounders. These measure a swath of data as the ship moves, and record it digitally. But in the deep ocean the vast majority of data are old & low-tech. [200 ship-years, Carron et al., Int'l Hydr. Rev., 2001.]

Farther off Diamond Head

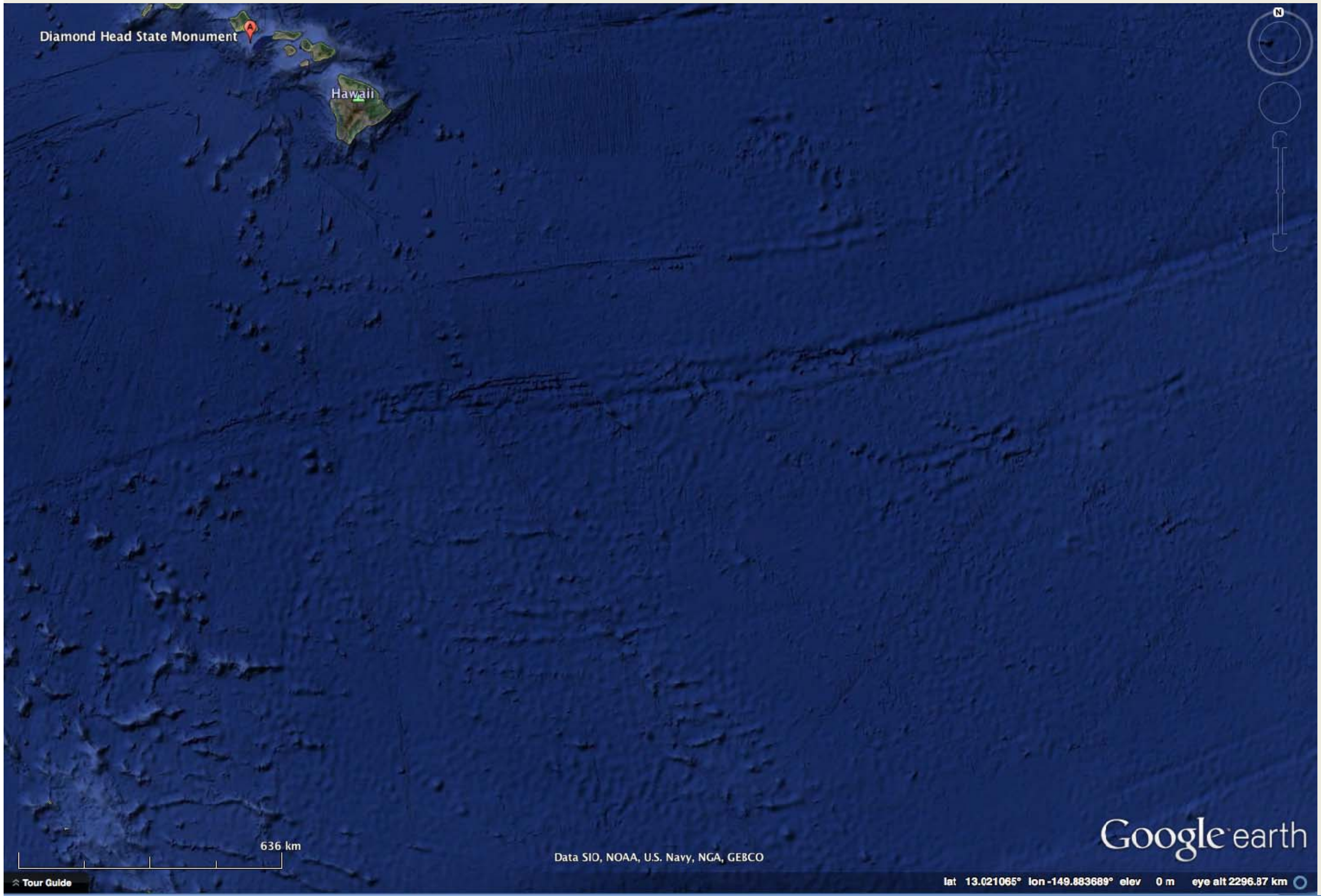


Zooming out, we see more of GE's visualization of the bottom topography.

Landslide slumps and submarine canyons appear.

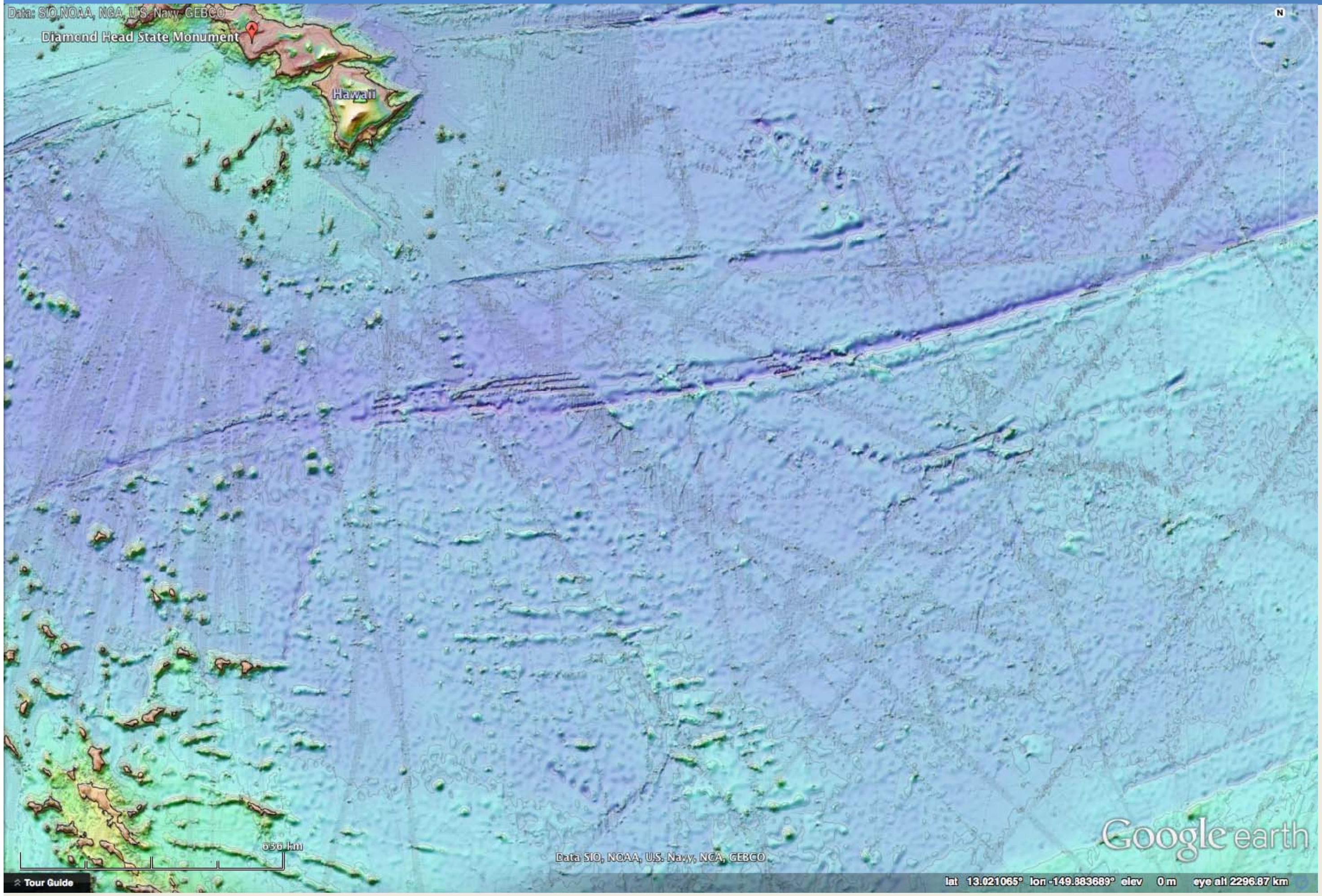
We also begin to see seams where swaths of echo sounding data do not quite match at their edges. These reveal ship "tracks".

Further South and East from Hawaii



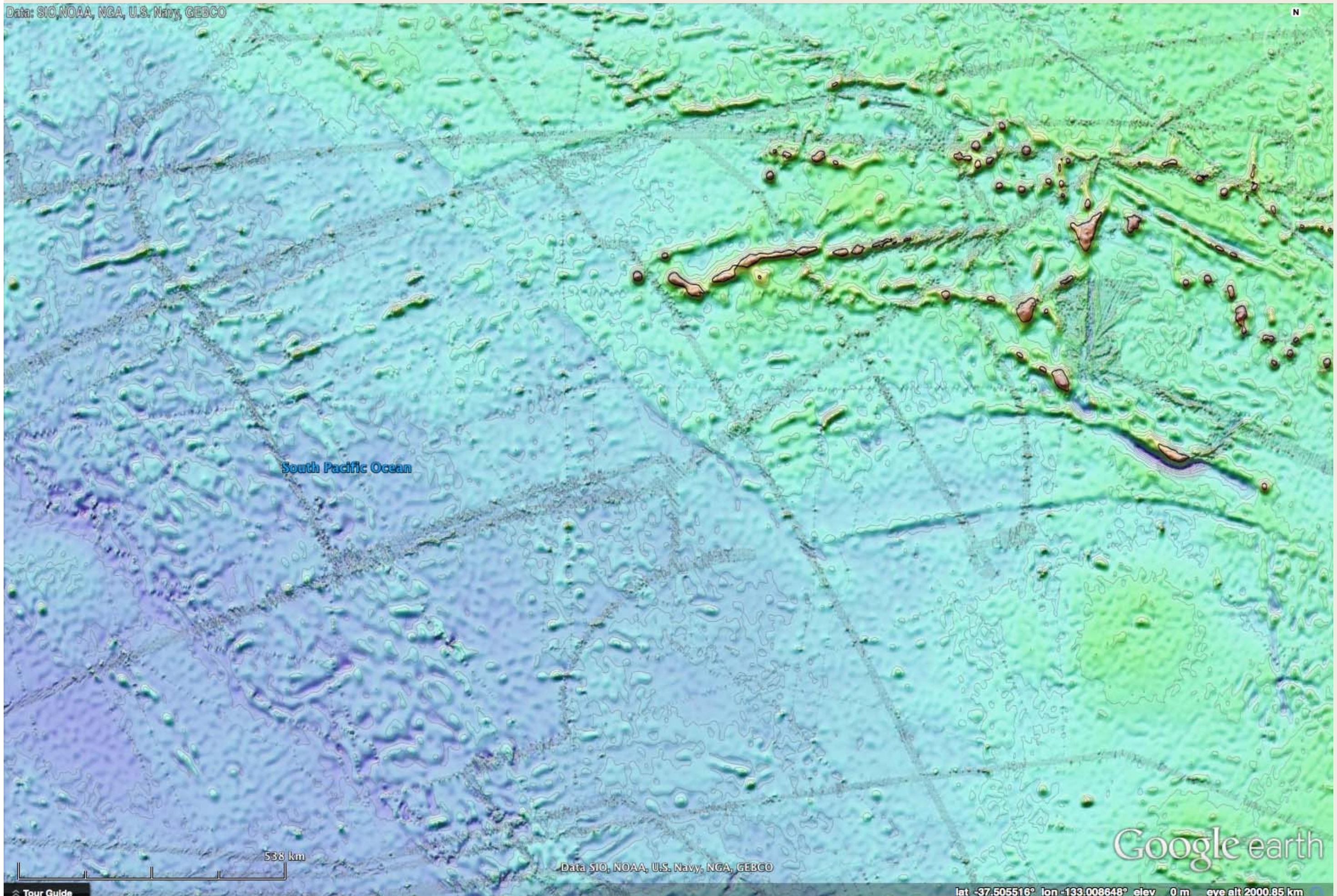
Zooming out more, if the room is dark and the display bright you can begin to see gaps between ship tracks.
I will color this differently in a later slide so you can see it more easily, but first **I must remember to tell the fake fractal topography story.**

Same Area, different colors



Soundings shown by gray dots.
Note high resolution in surveyed areas, lower where not surveyed.
Gaps between ship tracks can be as large as the Big Island of Hawaii.
But we are in the most densely mapped area of the central Pacific; every vessel in the area makes a port call in Honolulu.

Same size area, South Pacific



This area is equal in size to the one where we saw Hawaii in the upper left.

Notice how big the gaps between tracks are now, in comparison to the size of the volcanoes and mountain ranges.

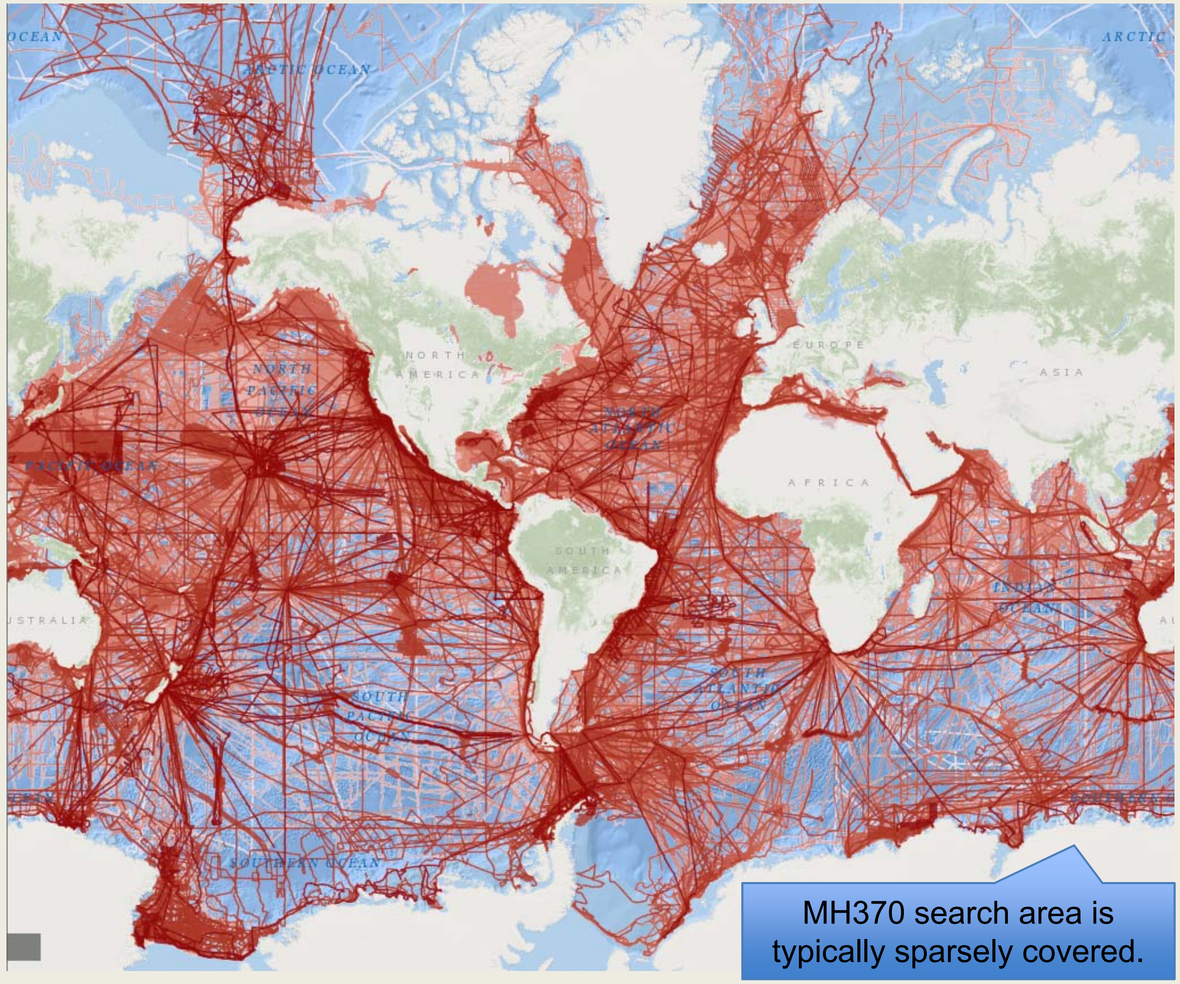
Global distribution of sounding data

The area around Hawaii is one of the most densely covered areas on Earth. Coverage is biased by ports, with most data in northern hemisphere, coastal areas, and some parts of mid-ocean ridges.

Worse than that, the majority of data in the remote southern basins is very old (celestially navigated, analog soundings).

NOAA's National Geophysical Data Center (Boulder, CO) is, by international agreement, World Data Center A for bathymetry, and the International Hydrographic Organization's Data Center for Digital Bathymetry. This is a map of their holdings.

Classified, international, or other data do not change this picture much.



MH370 search area

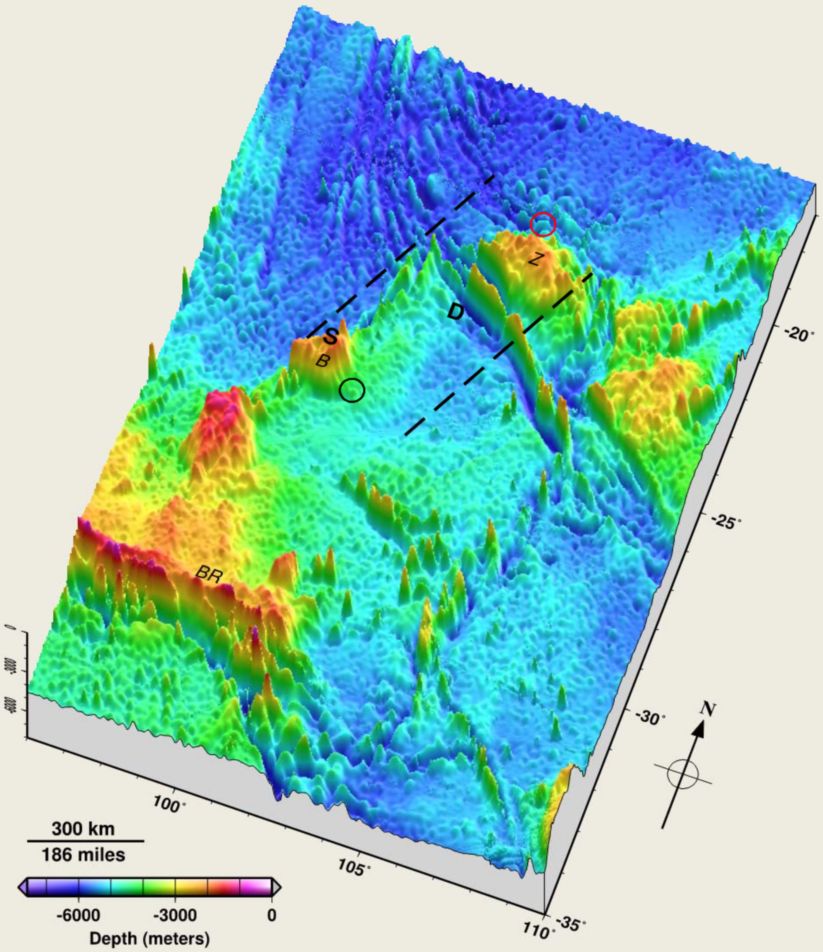
Eos, Vol. 95, No. 21, 27 May 2014

EOS

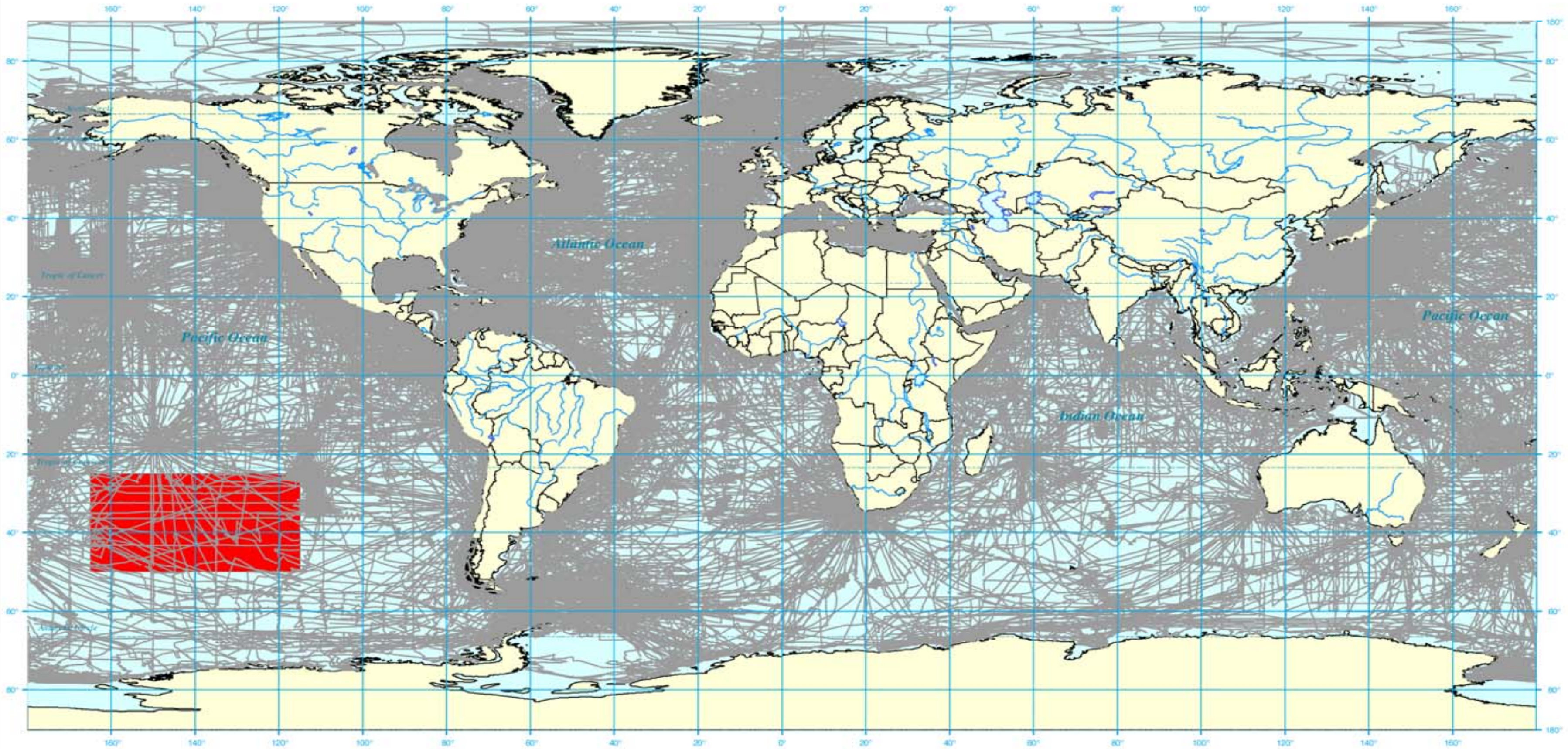
EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL UNION

Seafloor in the Malaysia Airlines Flight MH370 Search Area

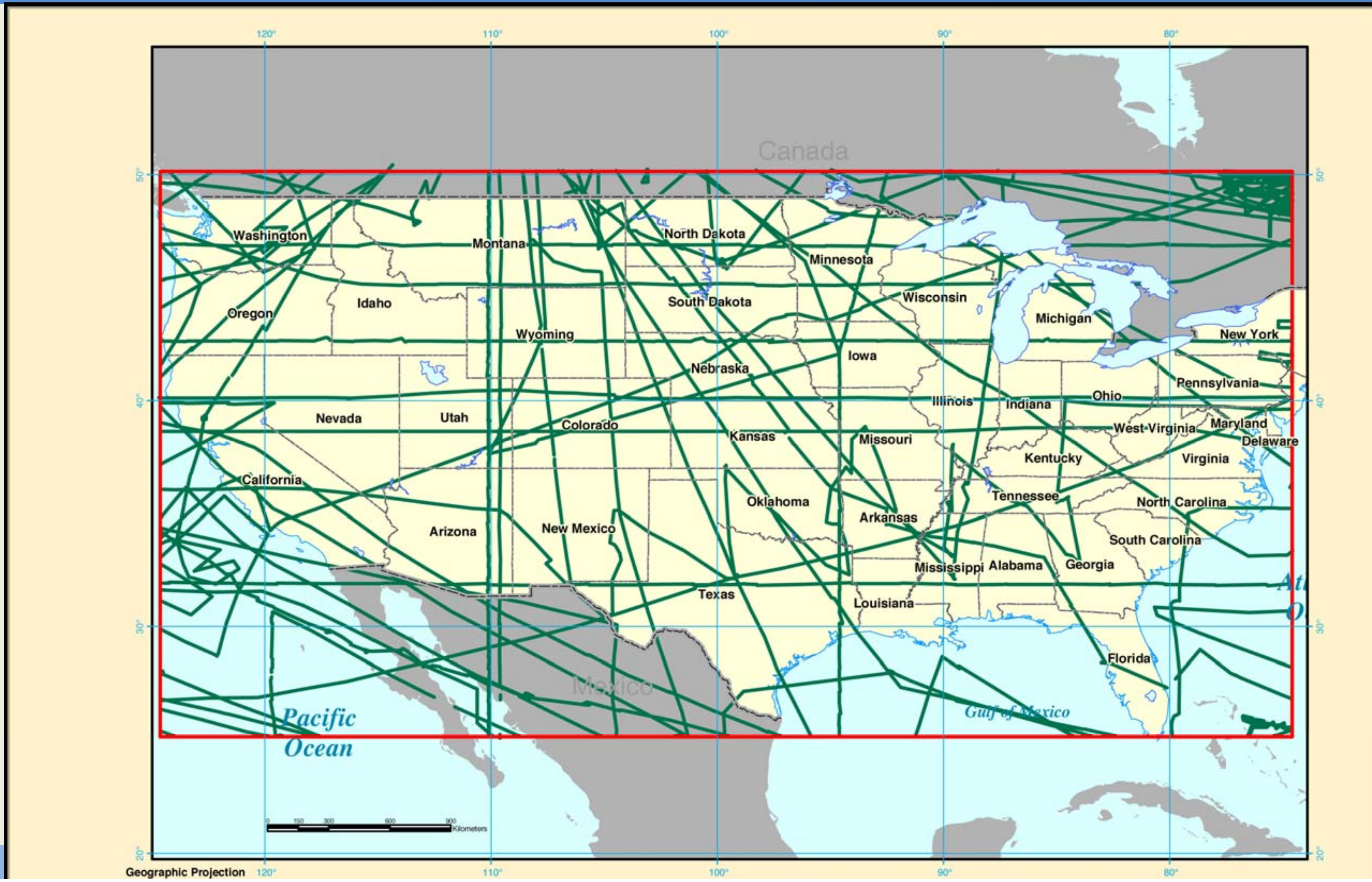
The south-east Indian Ocean west of Australia has a very typical distribution of echo-soundings: only 5% of the seafloor measured; almost all old, low-tech data. Two crossings of Batavia plateau, in 1962 and 1965; one crossing of Zenith plateau in 1967. Transit, the first global navigation system, became available in December 1965, so at least two of these profiles were celestially navigated. W H F Smith, doi:10.1002/2014EO210001



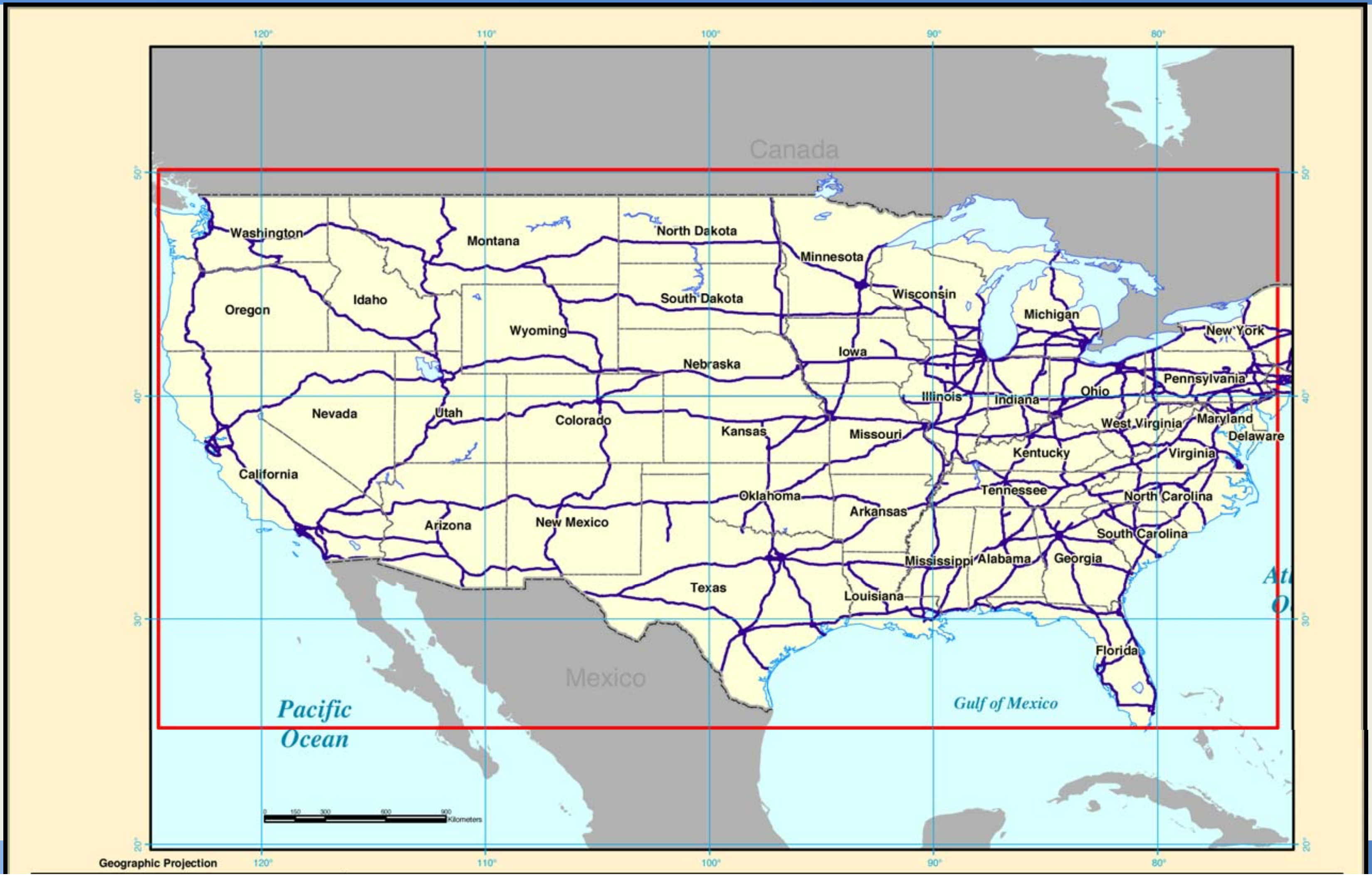
IHO DCDB Global Bathymetry



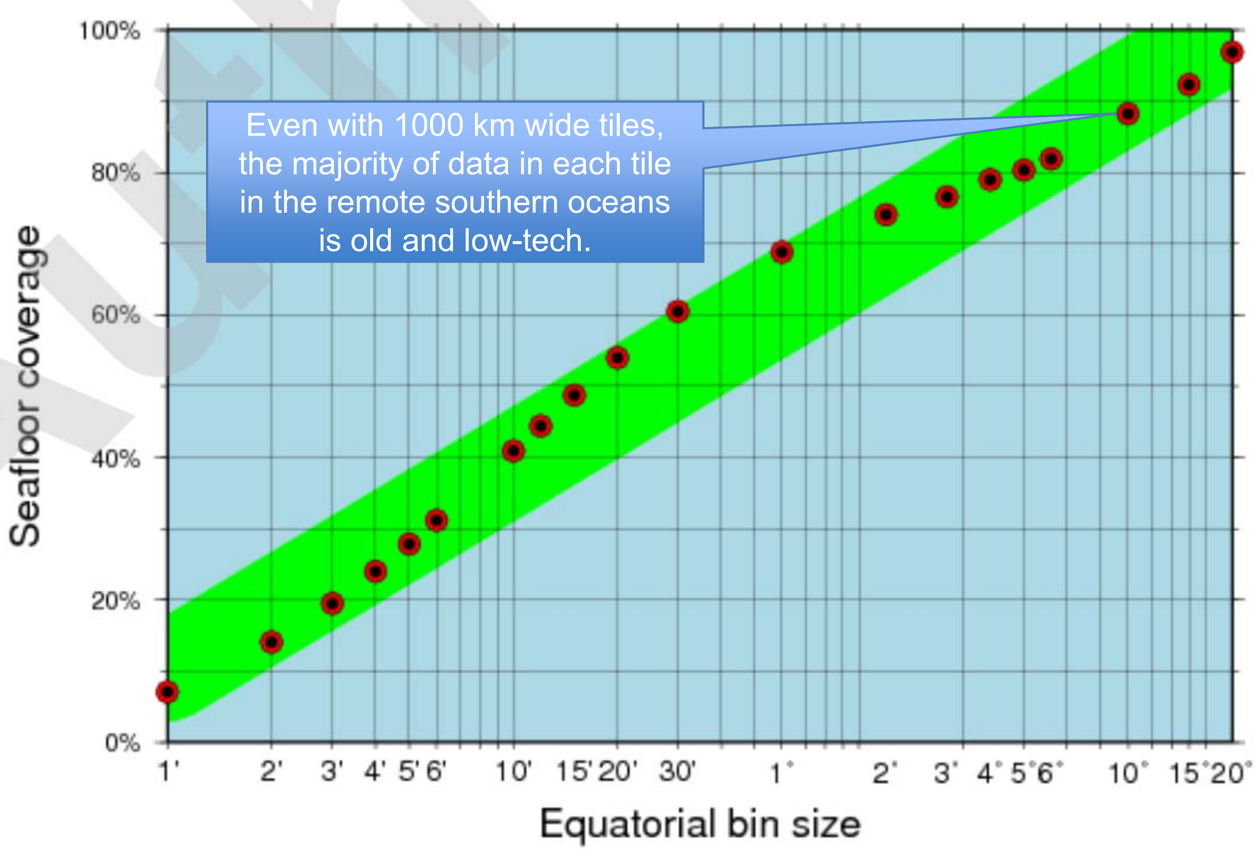
South Pacific ship tracks with depth data



U.S. Interstate Highway System



Why we say the ocean is only 10% mapped



If we "tile" the global seafloor with square tiles one n.m. (1.85 km) wide, more than 90% of the tiles have NO measurements of depth in them!

[2200 km is about the distance from Paris to Istanbul.]

Figure from Wessel & Chandler, 2011, doi:10.2478/s11600-010-0038-1

Even if we use tiles 2200 km by 2200 km, there are still some empty ones!

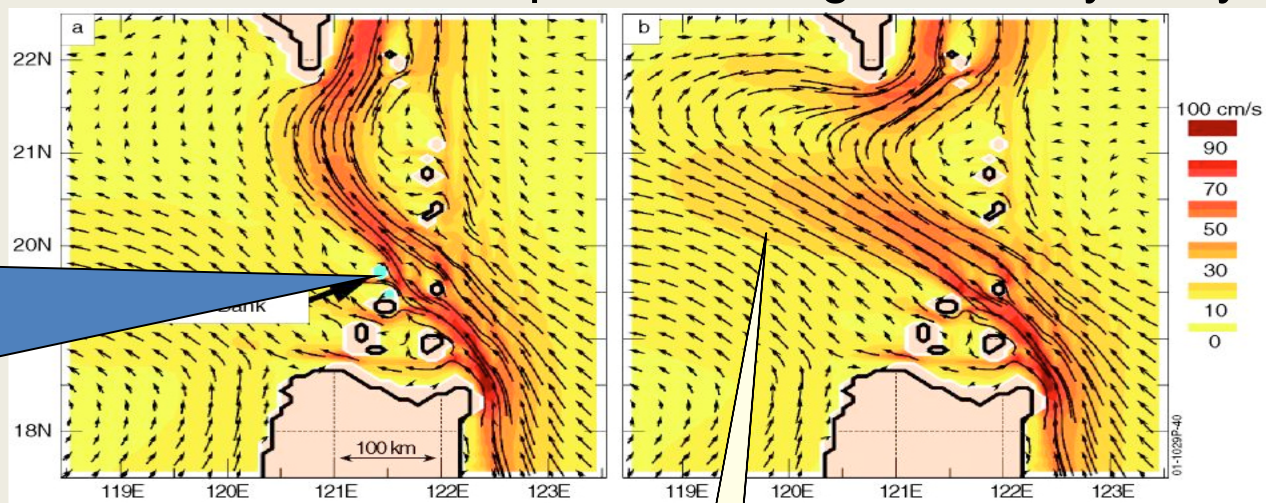
Consequences of not knowing ocean depths

Some people imagine that the world's major naval powers know everything but keep it secret.

When the *USS San Francisco* struck a seamount in 2005, the *New York Times* wrote that the US Navy had knowledge "gaps", according to RADM Andreasen, Chief Hydrographer.

Bathymetry steers currents

Forecast models require correct global bathymetry



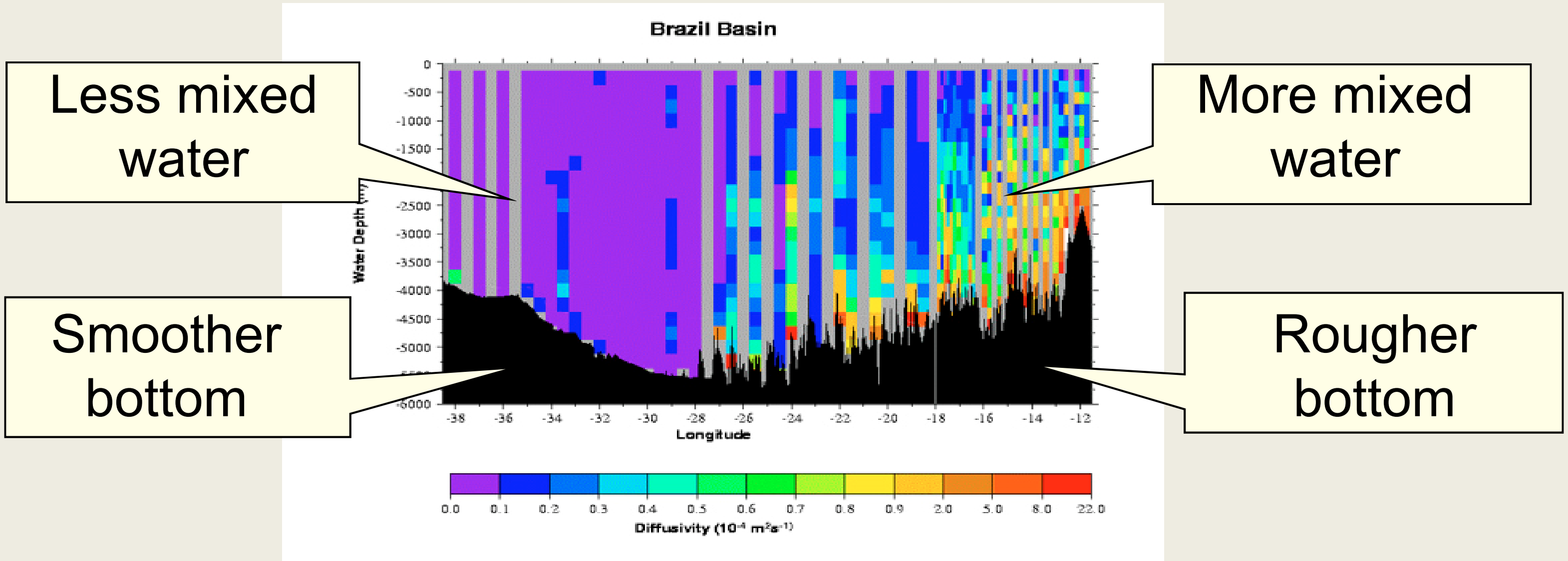
Model Bathymetry Changed Only Here

Approximates nature

Intrudes unnaturally

A single feature as small as 20 km across can steer a major current (Kuroshio mean flow in U.S. Navy model at 1/16°) [Metzger & Hurlburt, 2001]

Bottom Roughness Controls Mixing

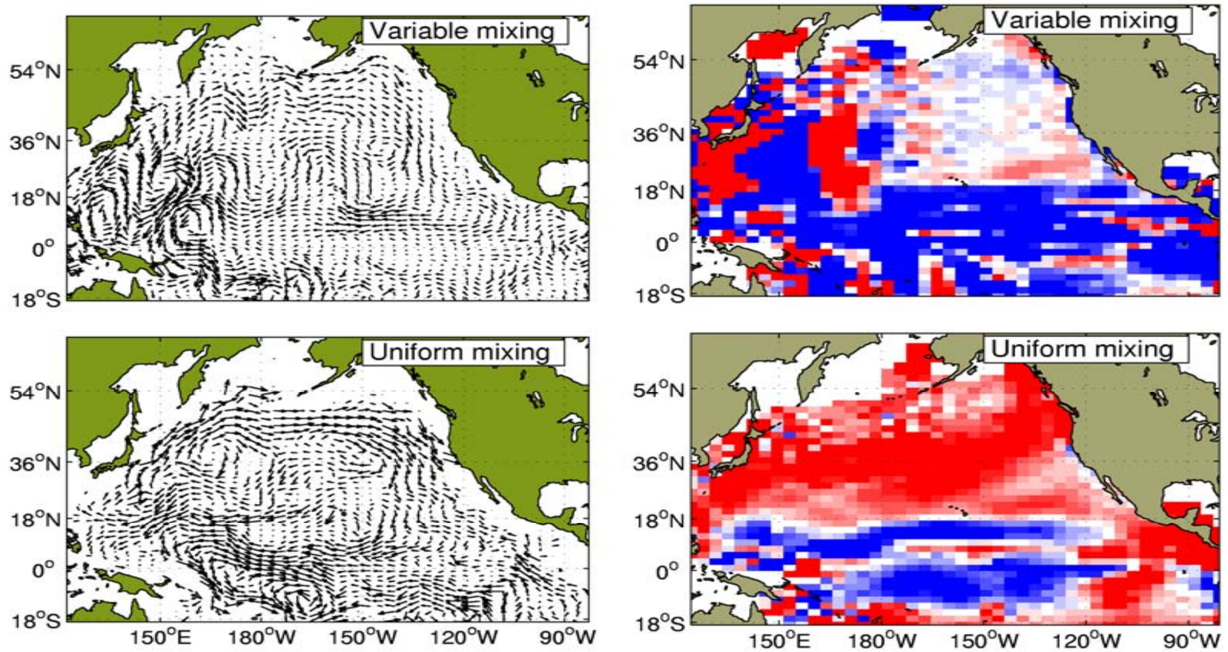


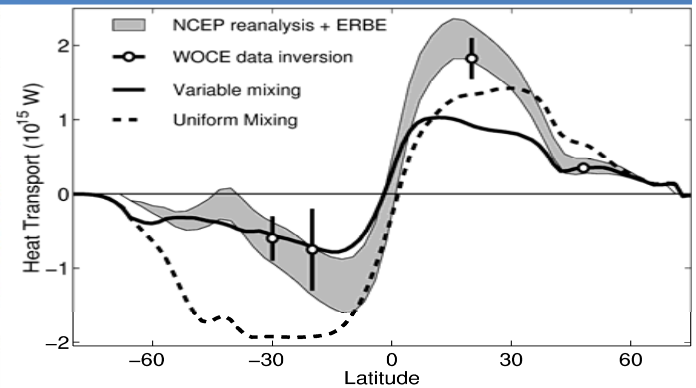
Spatial variations in bottom roughness change mixing rates by more than an order of magnitude (vertical diffusivity < 10^{-5} at left and > 10^{-4} at right; [Polzin et al., *Science*, 1997]).

λ< 100 km bathymetry controls mixing.

Seafloor spreading shapes bathymetry at these scales.

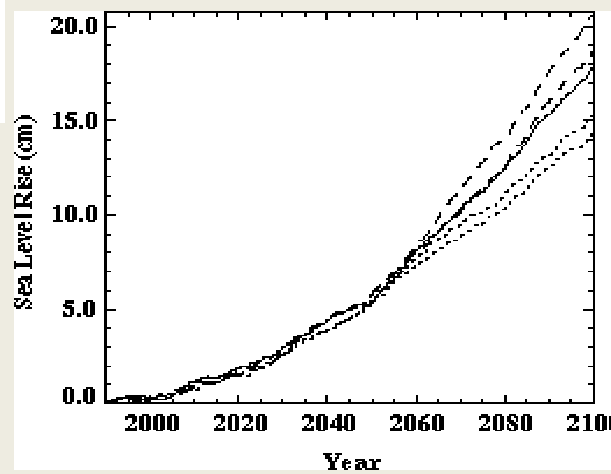
Spatially varying mixing changes everything





Including spatially variable deep mixing in an ocean model changes its circulation, upwelling, and climatic heat transport. It also changes forecasts of global sea level rise.

[Sokholov, 1997, 1998; Simmons et al., 2004]



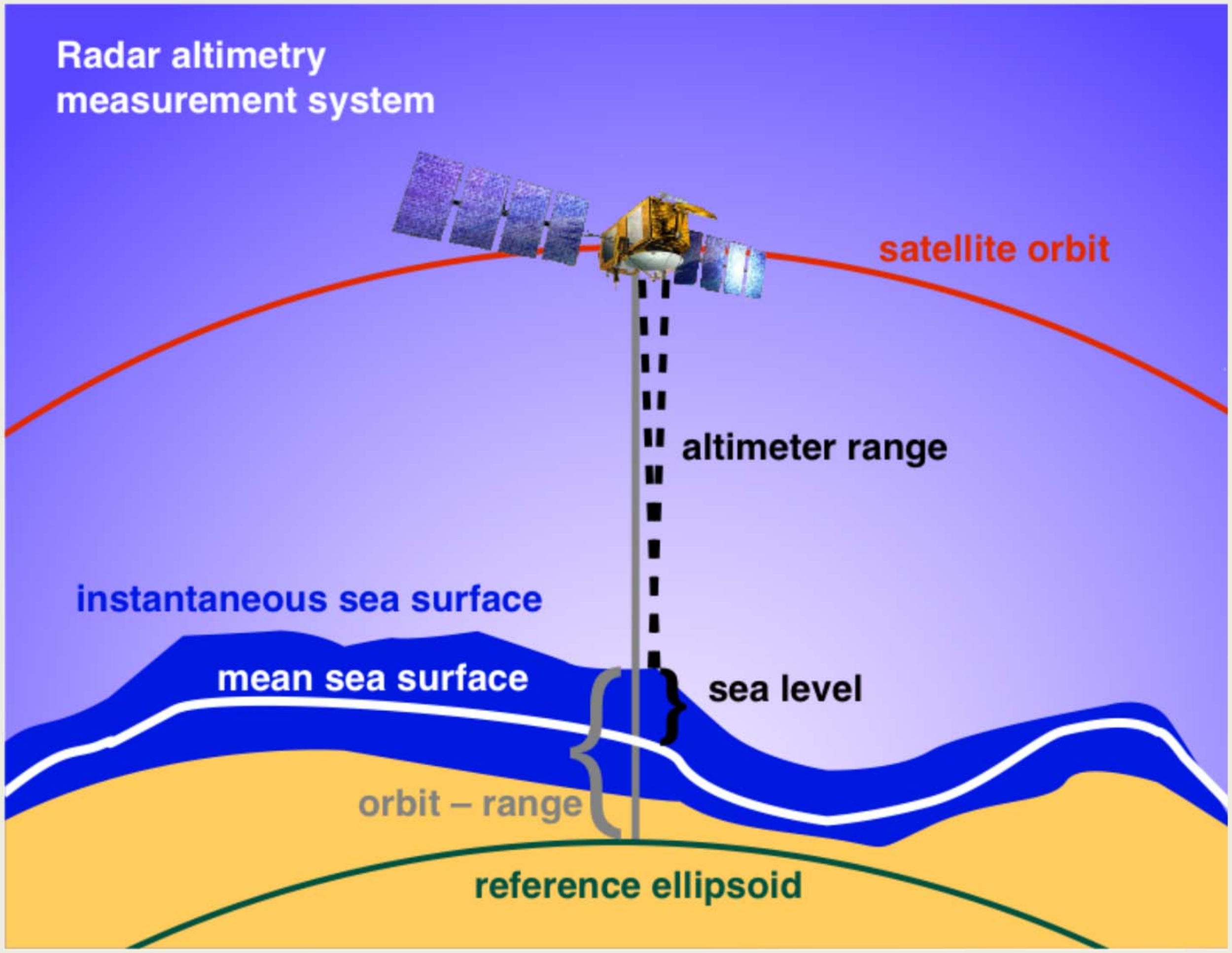
Satellite Radar Altimetry

The radar measures the satellite's height above the surface of the Earth.

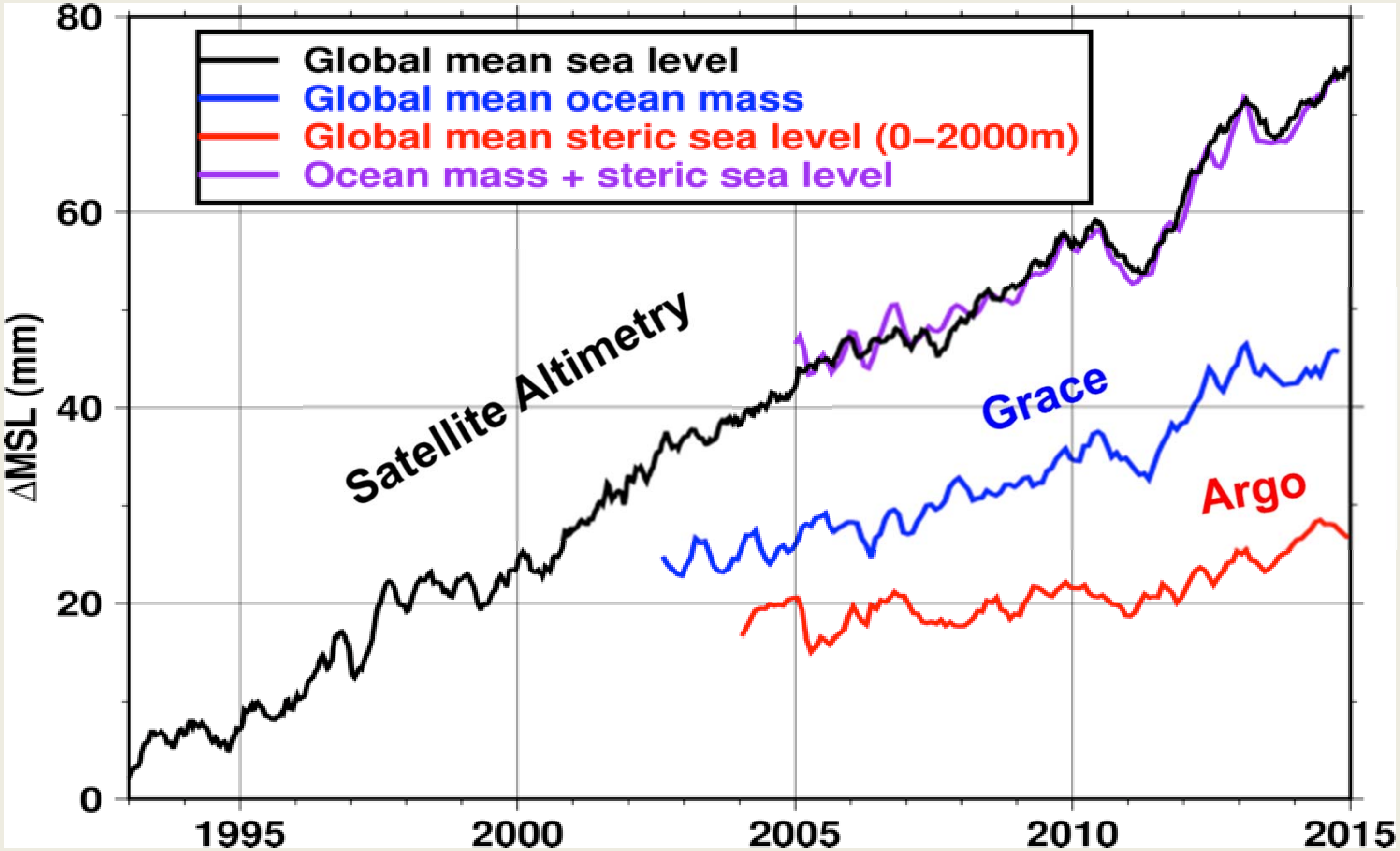
Orbit tracking and modeling locates the altimeter above a reference Earth ellipsoid.

Differencing the two yields the Earth surface height.

Sea surface height is the net result of dynamic heights (the ocean's response to tides and weather) plus the "geoid" height, the hydrostatic equilibrium level in the presence of gravity anomalies.



Global sea level rise and its sources



3.0 ± 0.2 mm/yr

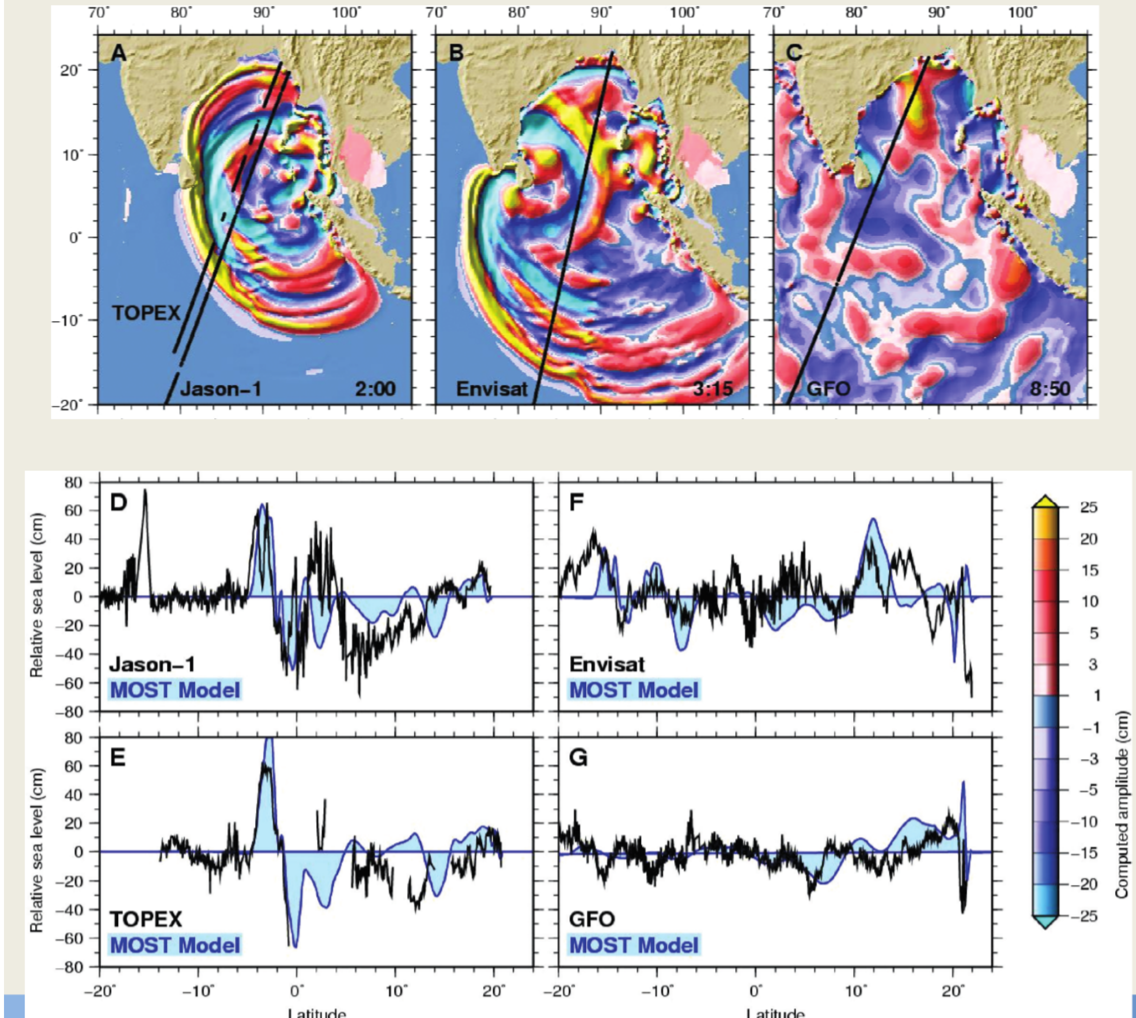
2.0 ± 0.1 mm/yr

0.8 to 1.1
± 0.3 mm/yr

Radar range
is order 10^9
mm.

The seasonal variation has been removed in this figure. A strong La Niña in 2010-2011 temporarily moved a lot of water to the continents. doi:10.1175/2015BAMSStateoftheClimate.1

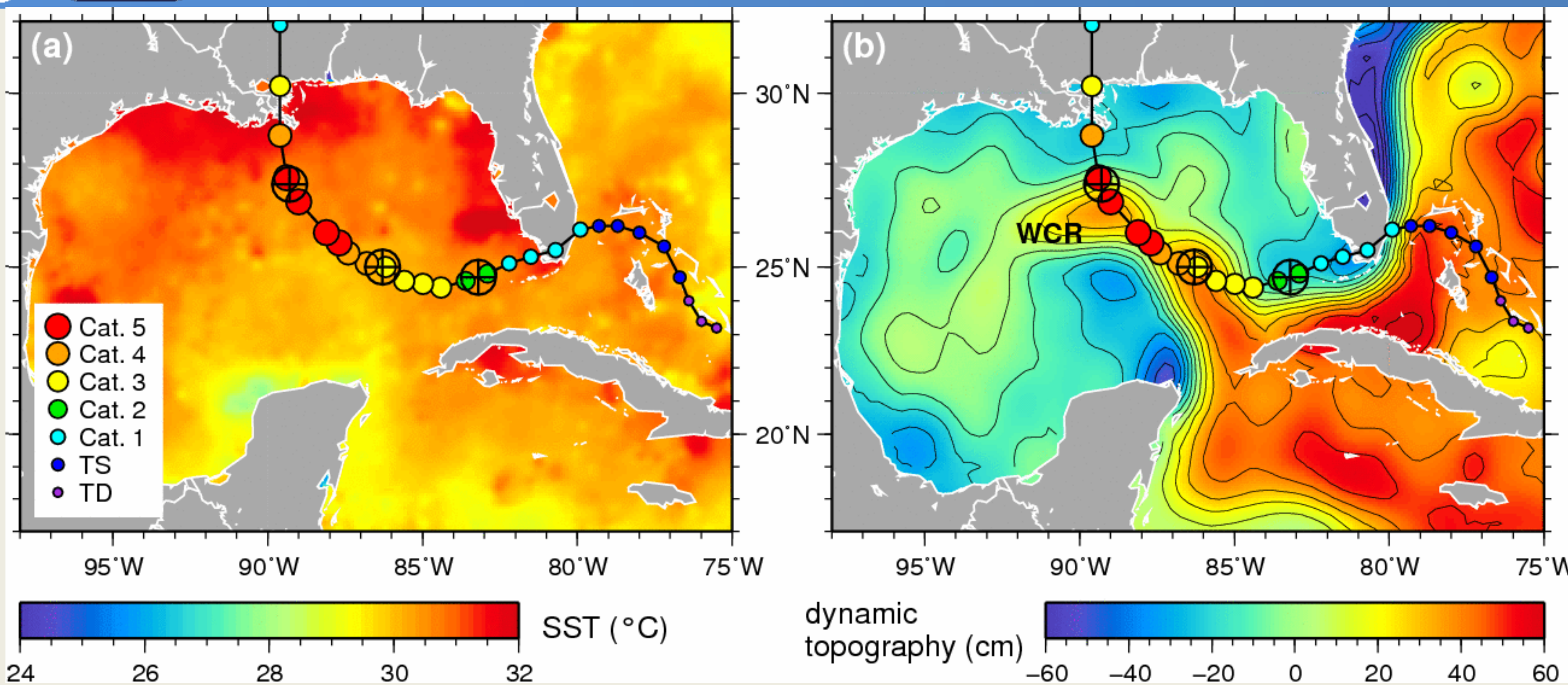
Tsunami height (2004 Dec 26 event)



Altimeters provided the only measurements of the open-ocean height of this tsunami, and contributed to a debate about the earthquake rupture mechanism.

doi:10.5670/oceanog.2005.62

The intensification of Hurricane Katrina



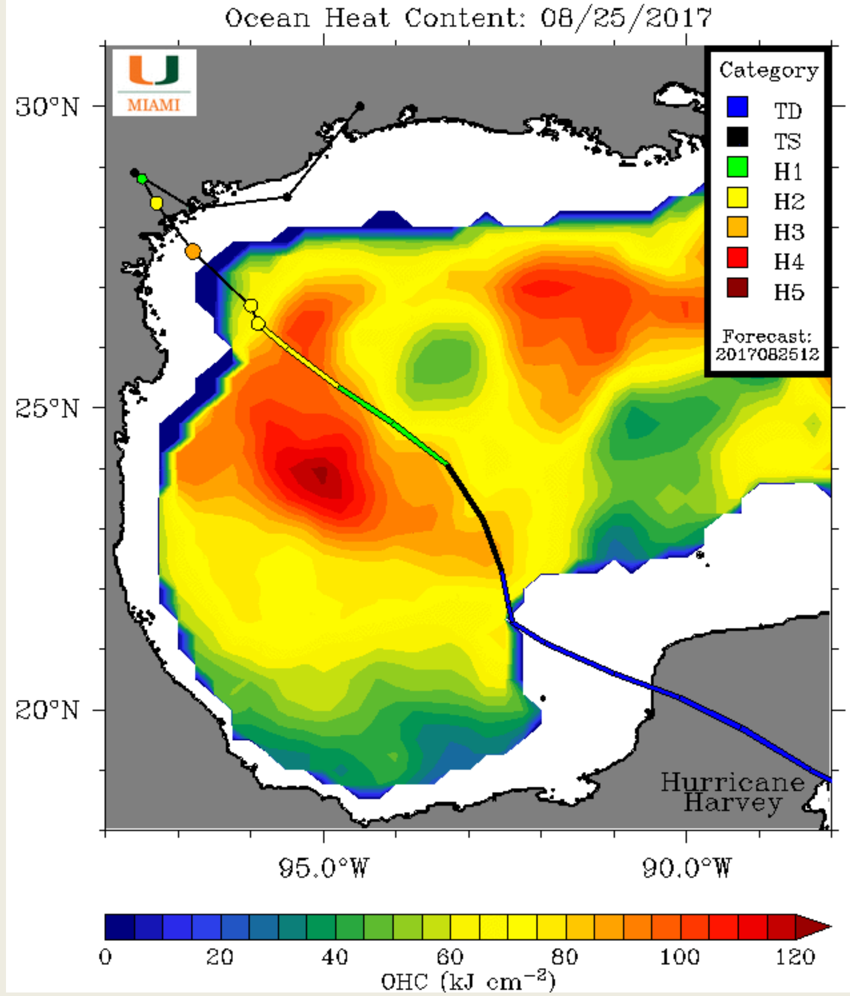
DOI 10.1029/2005EO400004

Intensification is not correlated with Sea Surface Temperature (SST), which was warm (~30˚C) everywhere along Katrina's path.

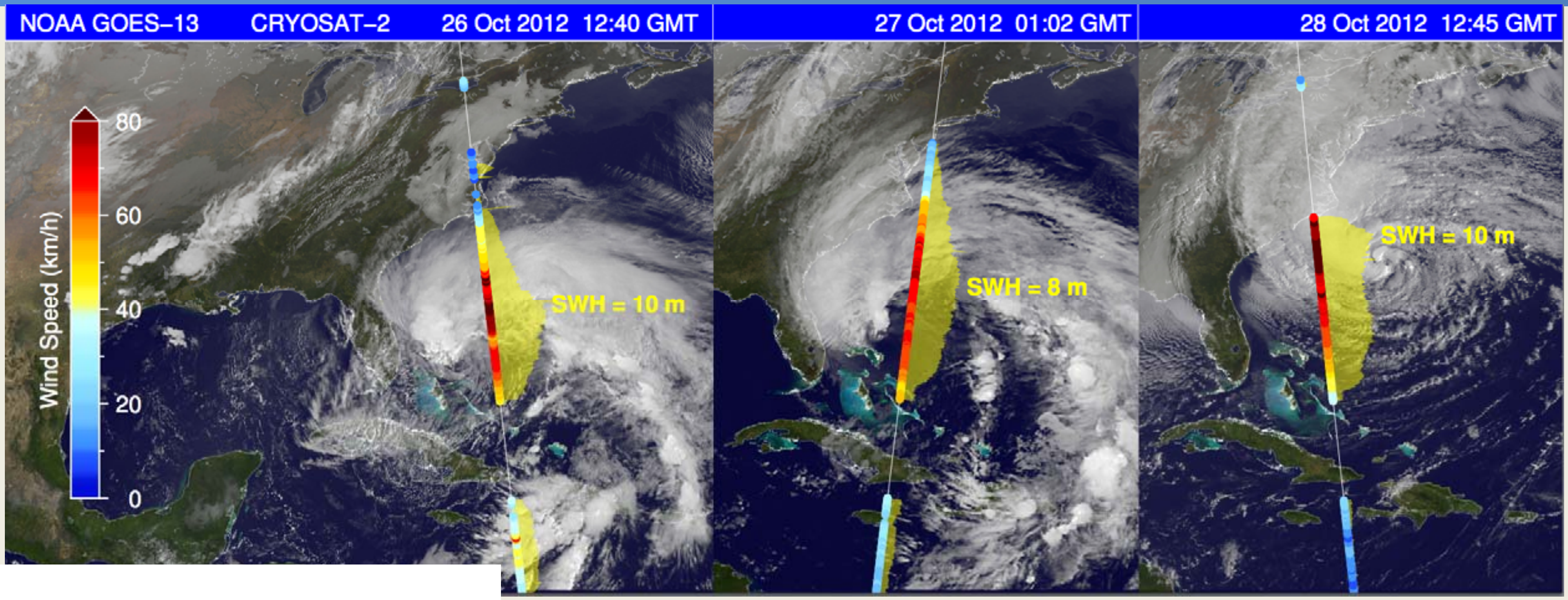
Intensification occurred when Katrina was over high "dynamic topography" (sea level anomaly) indicating warm water extending to greater depth.

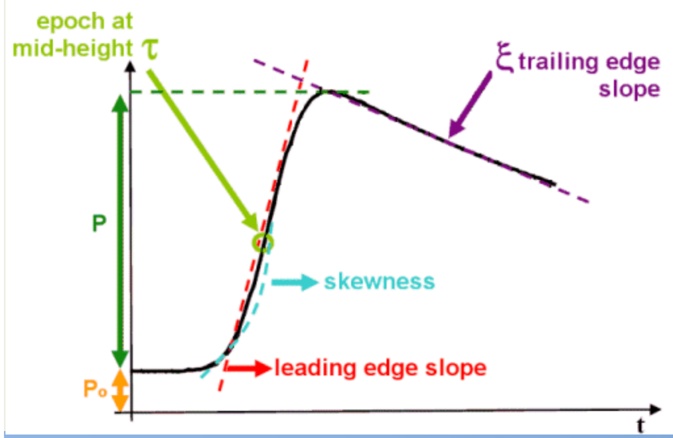
Forecasting Hurricane Harvey Intensification

- Here is the OHC forecast (Ocean Heat Content) on 25 August 2017 12h UTC, showing a deep warm pool.
- Hurricane Harvey was forecast to intensify (as it later did) because its track was forecast to pass over this high in OHC.
- OHC combines SST and altimetry: high sea level shows warmth extends deep, providing a reservoir of energy to fuel the storm.



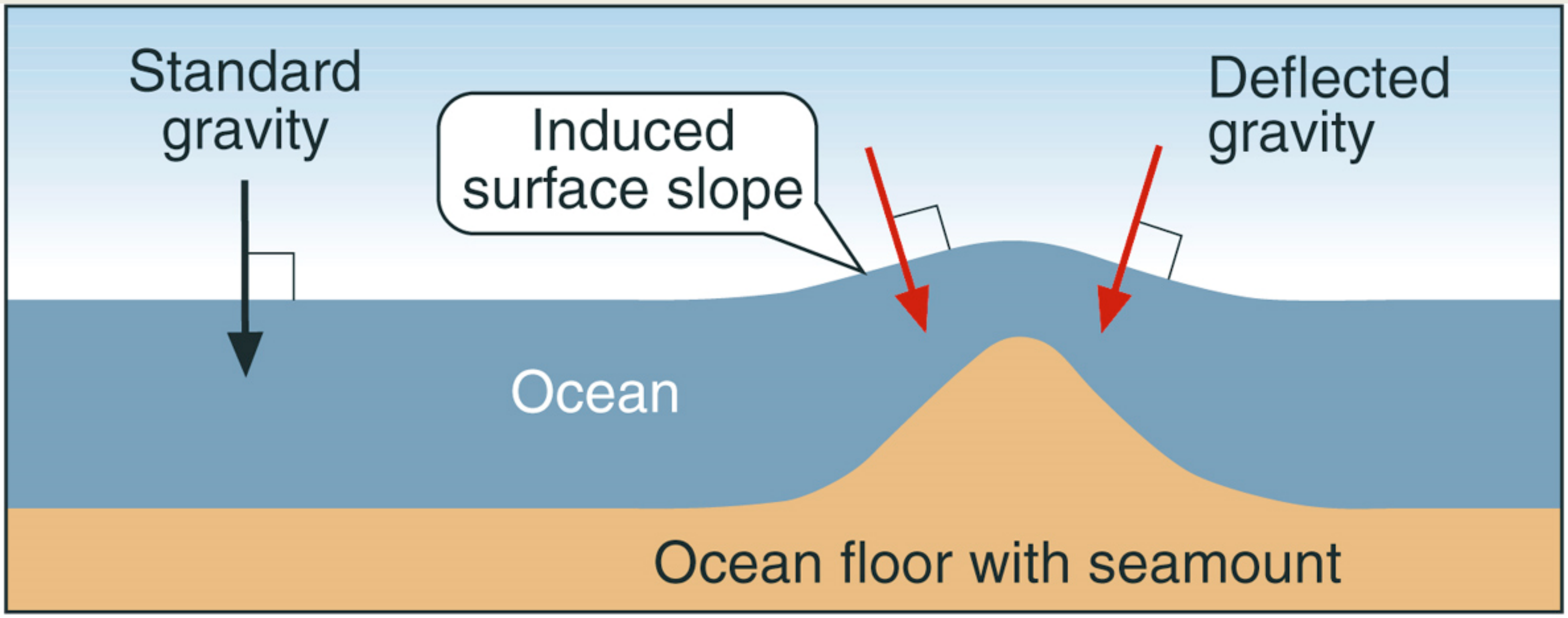
Hurricane Sandy Winds and Waves





The way that power varies with time in the echoes of altimeter pulses can be used to measure wave height and wind speed at the sea surface, as well as the distance to sea level. We feed altimeter wind and wave data to NOAA's marine forecasters in near-real time.

Inferring depth via sea surface altimetry



The gravitational attraction of seafloor geology distorts the hydrostatic equilibrium shape of the sea surface (the “geoid”, where sea level would rest if there were no winds, tides or currents). Sea floor topography induces geoid slopes of 1–700 µrad.

Hydrostatic equilibrium and level surfaces

A fluid surface at rest in a gravity field is a “level” surface.

The pull of gravity is perpendicular to the surface of the fluid.

Carpenters use a tool called a “level”, but one could also use a glass of wine.

Geoid versus sea surface: height & slope

$$\tan\theta = a_C / g = (2\pi)^2 r / (T^2 g) = v^2 / (g\, r)$$

$v = 0.01$ to $1\ m/s$

$r = 50$ to $3000\ km$

$\theta = 0.001$ to $2\ \mu rad$

Fluid at rest: level surface.

Fluid in motion: not level.

When wine orbits a glass at one revolution per second, the surface is far from level.

When sea water orbits an ocean basin, or even an eddy, the surface is almost level.

The departure from level is seldom more than 2 micro-radians (1/8 inch of sea level per mile.)

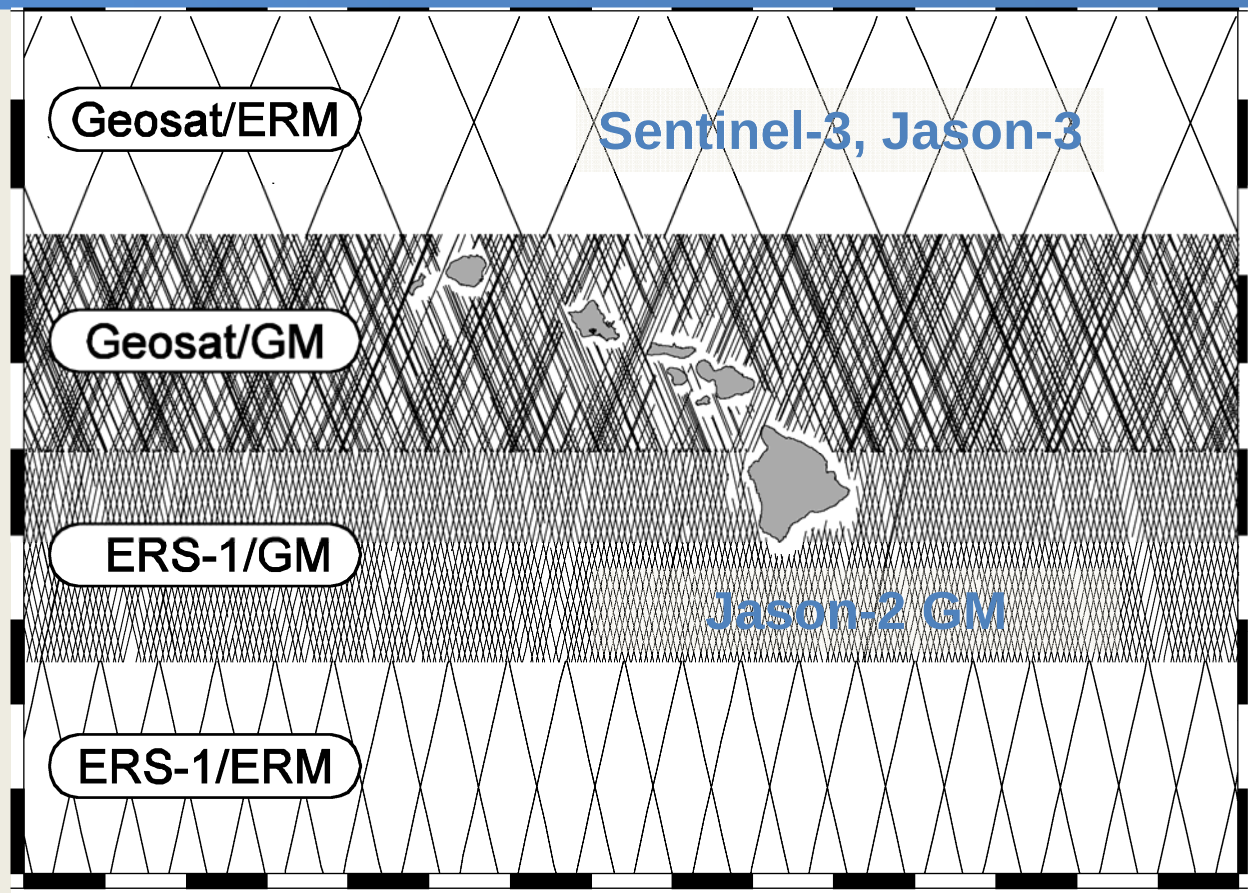
Ocean dynamic height can depart from the geoid height by up to 1 meter, but sea surface slope is almost always within 1-2 micro-radians of the geoid slope (gravity deflection angle).

We use sea surface slopes to infer gravity anomalies and thence bathymetry.

The ground track patterns of orbits

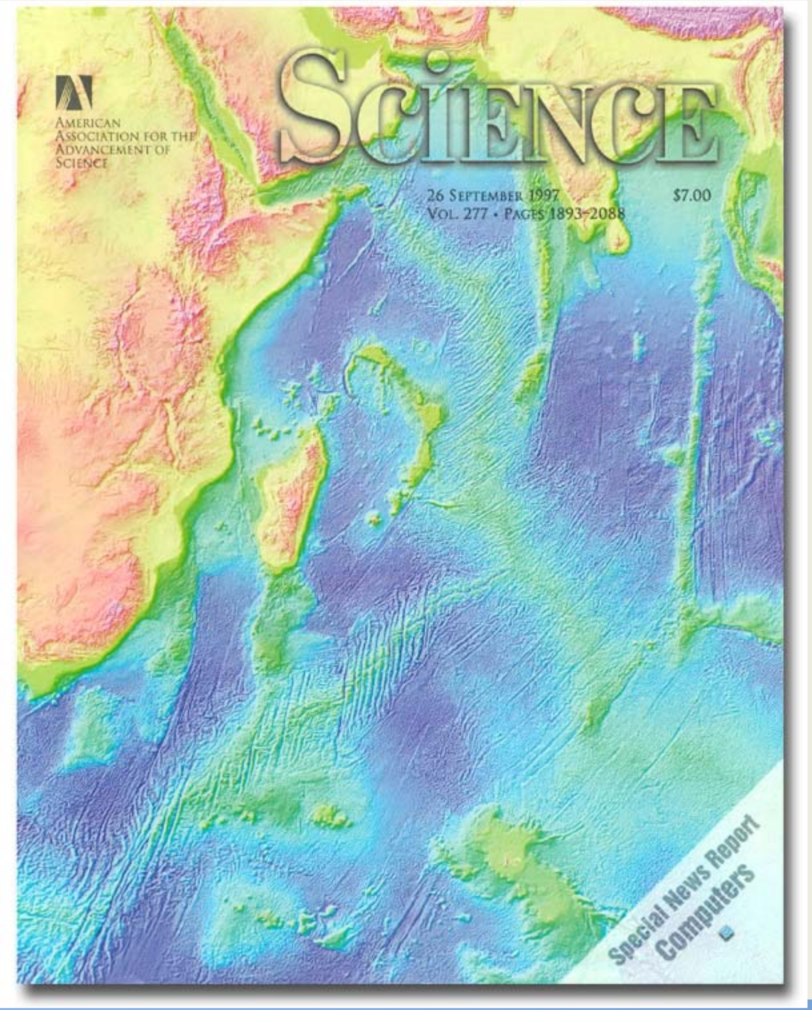
Since the geoid signal is steady and larger than the time-varying signal of ocean dynamics, oceanographers want altimeters to repeat the same set of tracks every few days to weeks. This allows them to observe temporal changes in ocean dynamics without needing to map the geoid, but it leaves big gaps unsurveyed. (“ERM”)

For ocean mapping we want a spatially dense set of tracks. Our signal is big and steady in time, so we need to collect each profile only once. (“GM”)

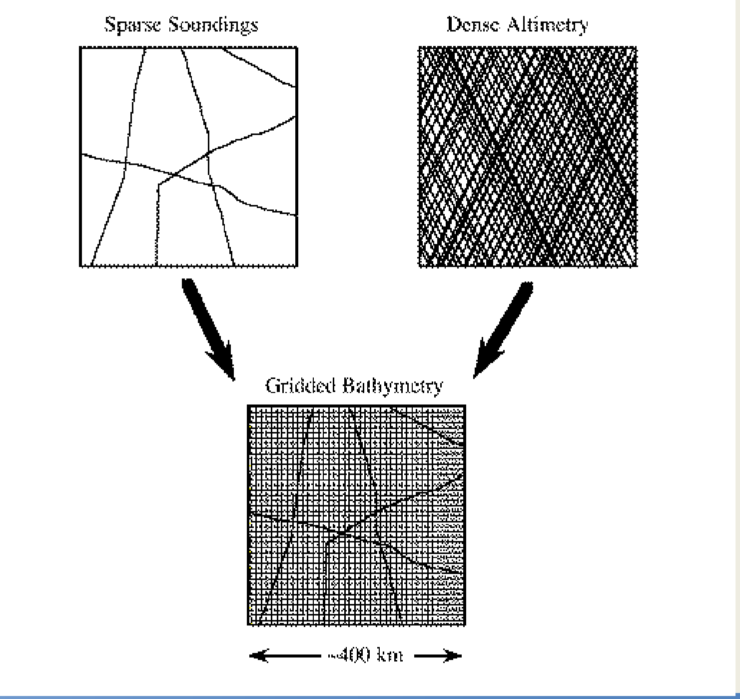


We got global GM data only in 1995, then waited until 2010 before we got more. We have proved that oceanographers can use a GM orbit, so now we may get more.

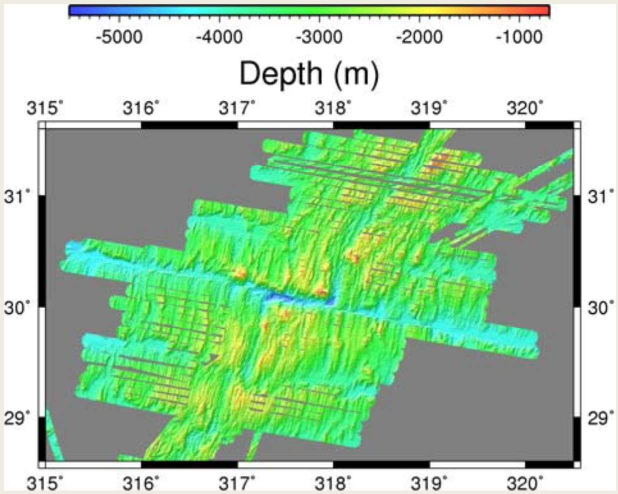
A simple notion, really

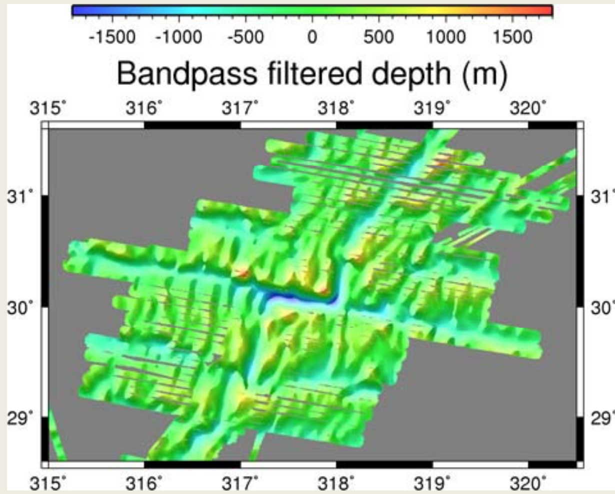


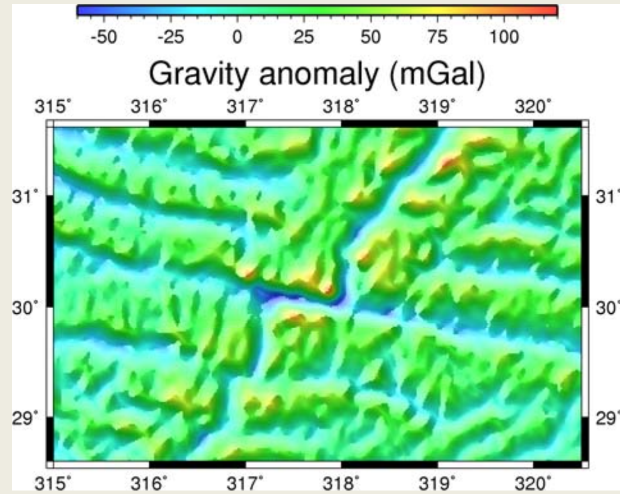
Use satellite altimetry to fill the gaps between ship surveys. Use depth soundings to calibrate the conversion of altimetric gravity to estimated depth.

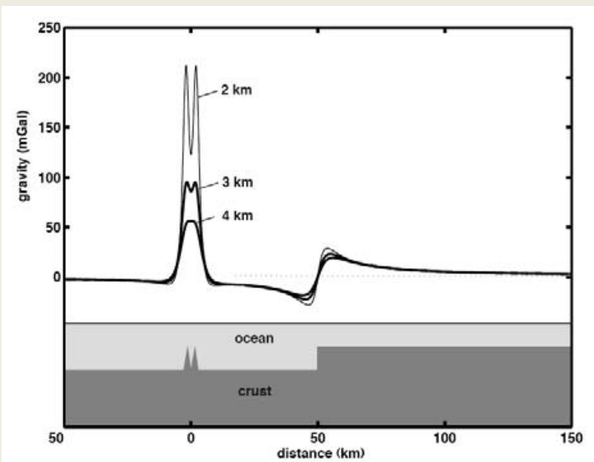


Gravity: an incomplete view of depth





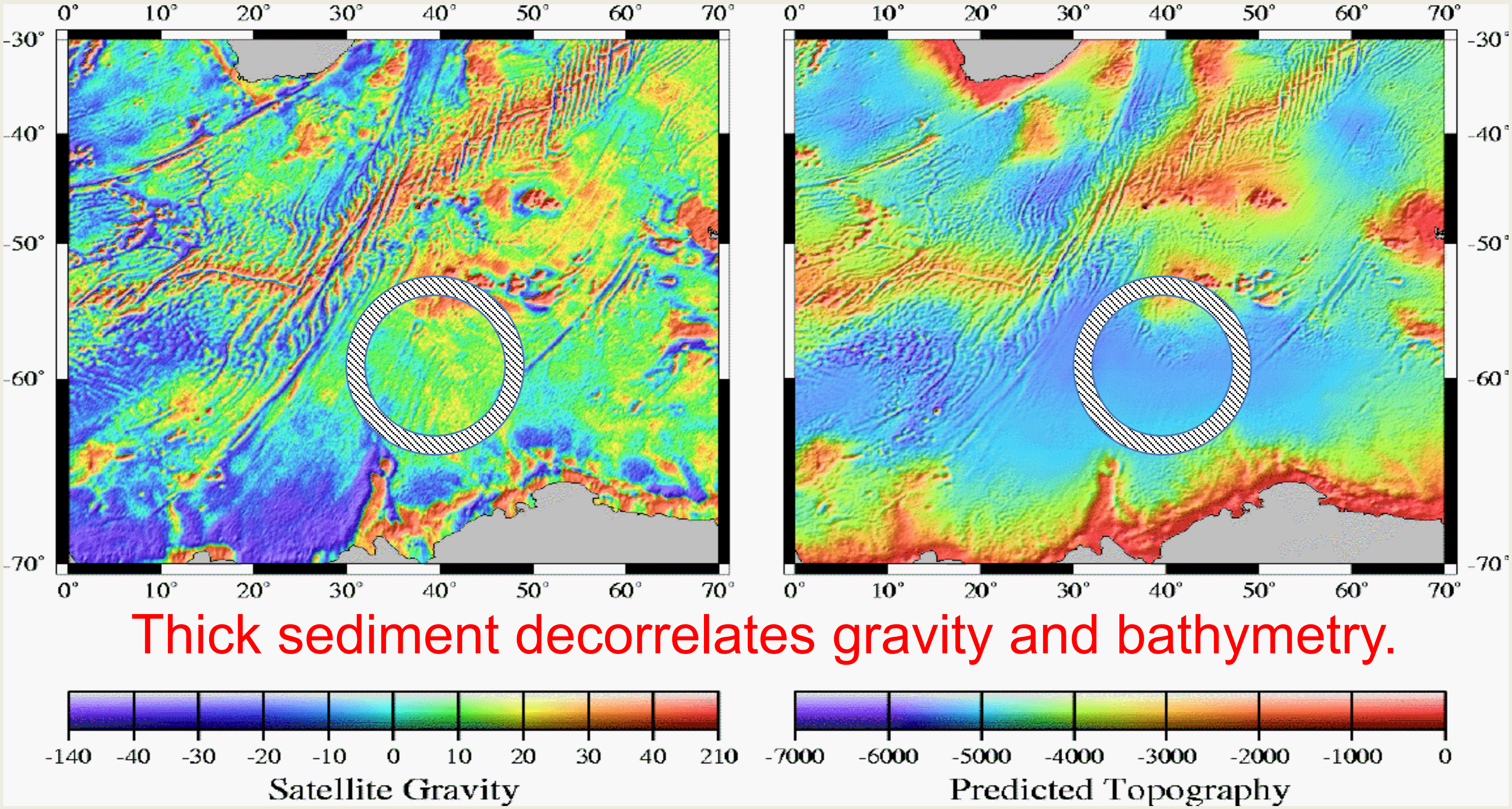




Horizontal resolution and signal amplitude (hence, sensitivity to noise) are a function of regional water depth, due to a phenomenon known in potential theory as “upward continuation”, a consequence of Newton’s law of gravity. This causes the texture mismatch you see in Google Earth where multi-beam echo sounding swaths cross the altimeter data.

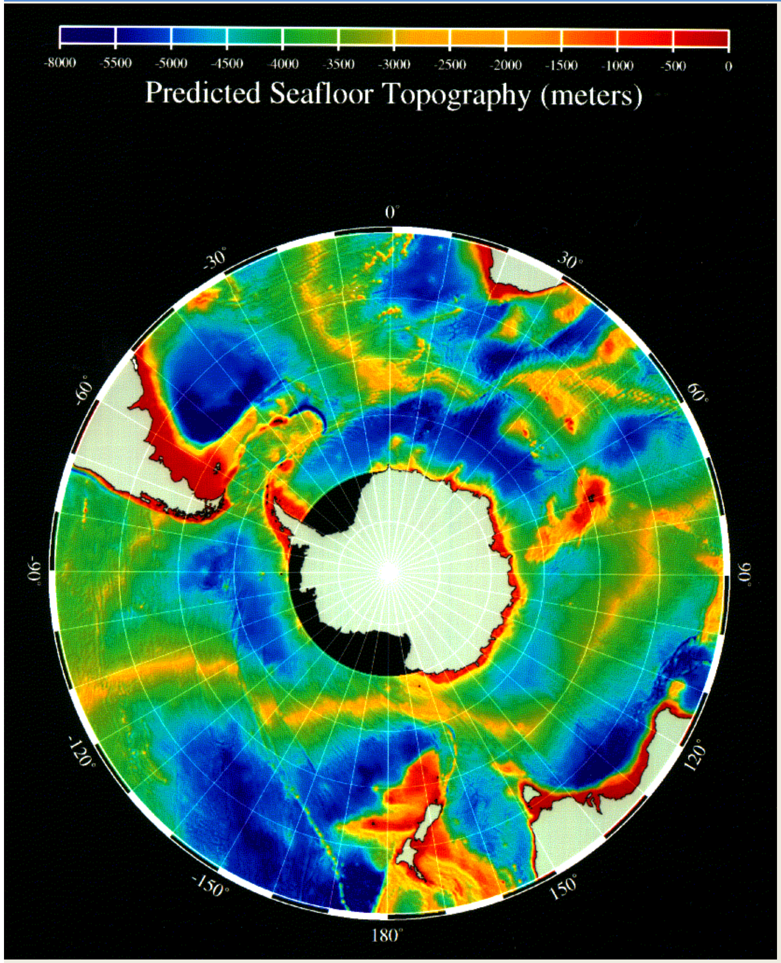
Absolute depth is not resolved; the step function response is a decaying dipole. This is due to the limited mechanical strength of the tectonic plates: large-scale topography is too massive for the plates to carry rigidly, and so it is held up buoyantly, which cancels the gravity anomaly at scales longer than the characteristic bending wavelength of the plate.

Example: SW Indian Ocean (*JGR*, 1994)



Thick sediment decorrelates gravity and bathymetry.

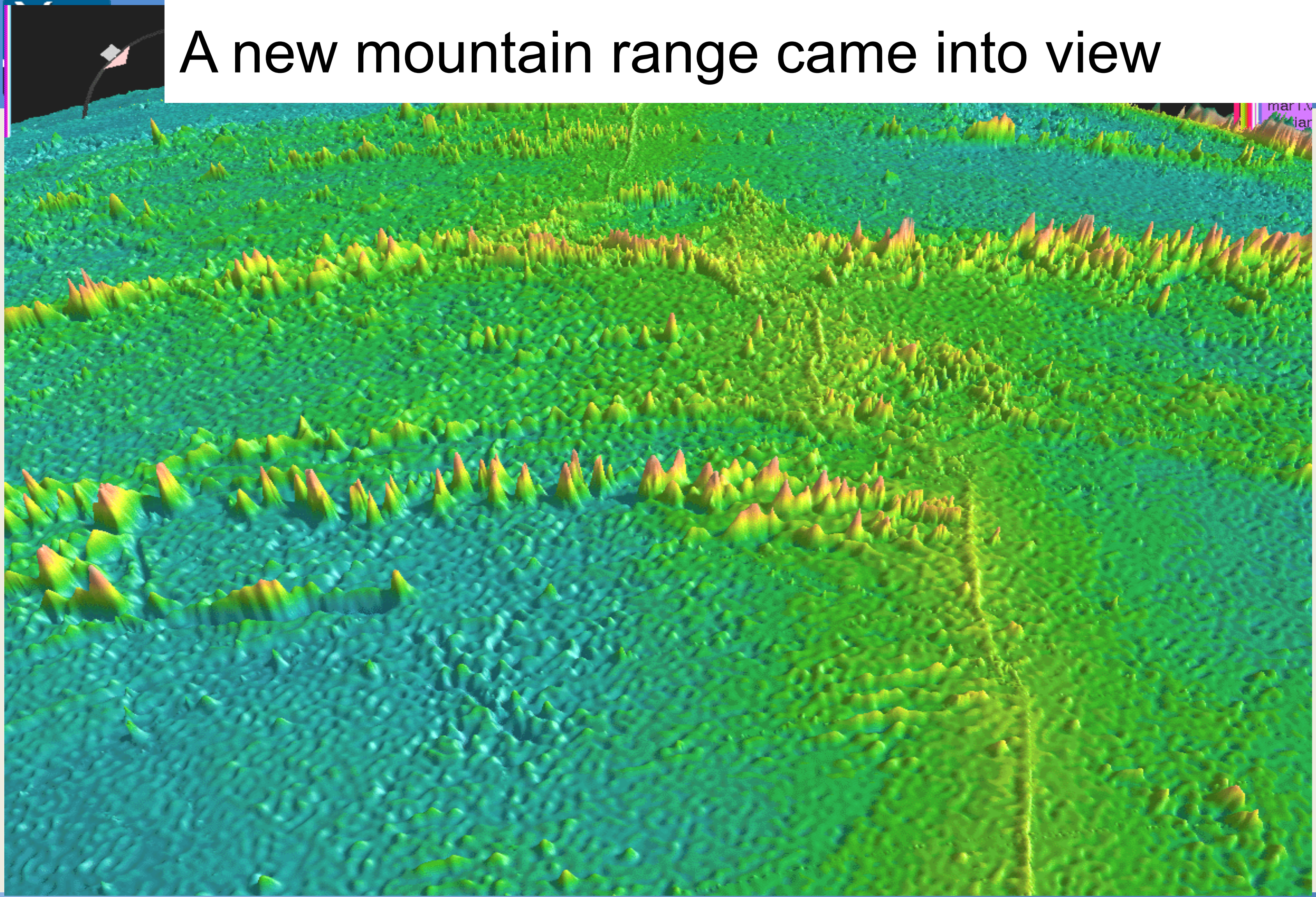
Estimated depth of the Southern Ocean



The first geodetic mission data (Geosat) were originally classified Secret and the first data released (1992) covered only the area south of 30˚S latitude.

Our first paper (1994) was limited to that area. doi:10.1029/94JB00988

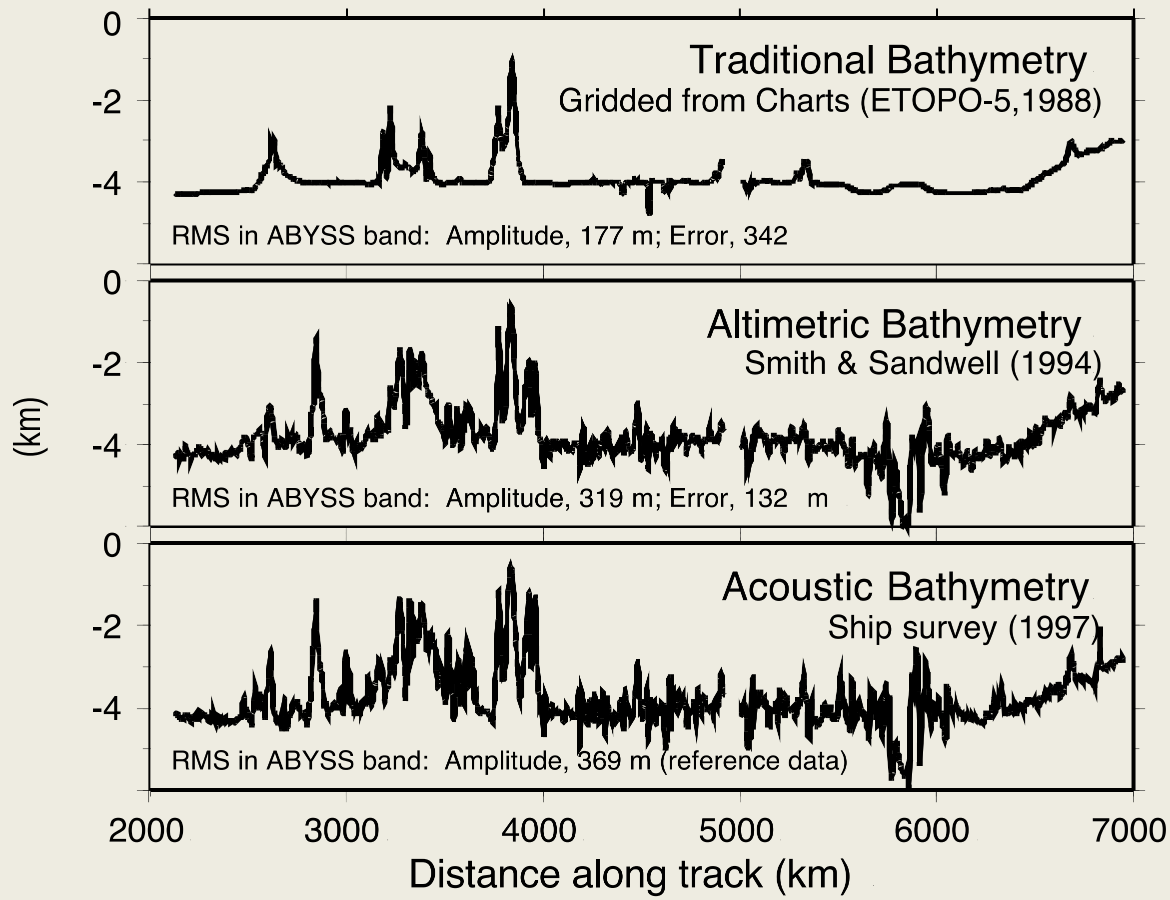
A new mountain range came into view



Bathymetry Profile from Southern Ocean

The mountain range was later verified by a ship survey.

The discovery of many new seamounts had unintended consequences.



The Orange Roughy Story

Scientists call for end to deep-sea fishing

(Claire Nouvian) - Orange roughy is one of the species mentioned in a new report this released this week by an international team of marine scientists that suggests industrial deep-sea fishing should be restricted.

Graphics at left and right from *The Washington Post*, 30 August 2011.

Deep-sea fish living on seamount flanks (orange roughy, oreos, …) soon became more than half the total fish catch landed in Australia and New Zealand [Sokolov, 1997].

They appeared in U.S. supermarkets and restaurants, and then just as quickly disappeared.

Early geodetic altimeter missions didn't find enough seamounts <2km tall (most of them)

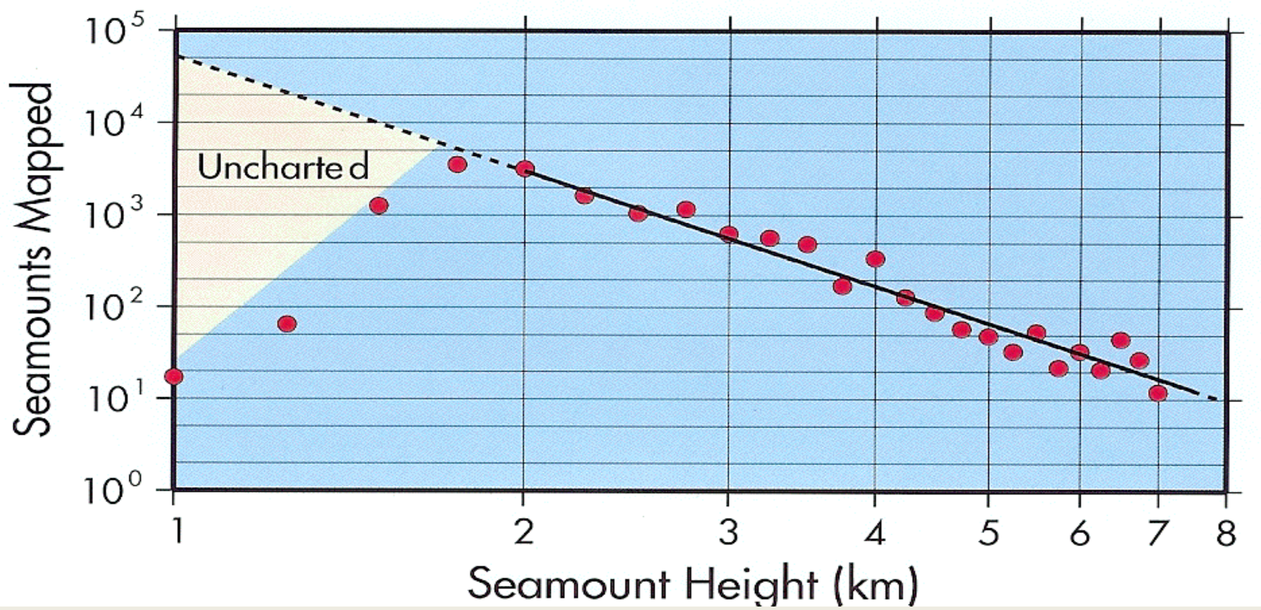
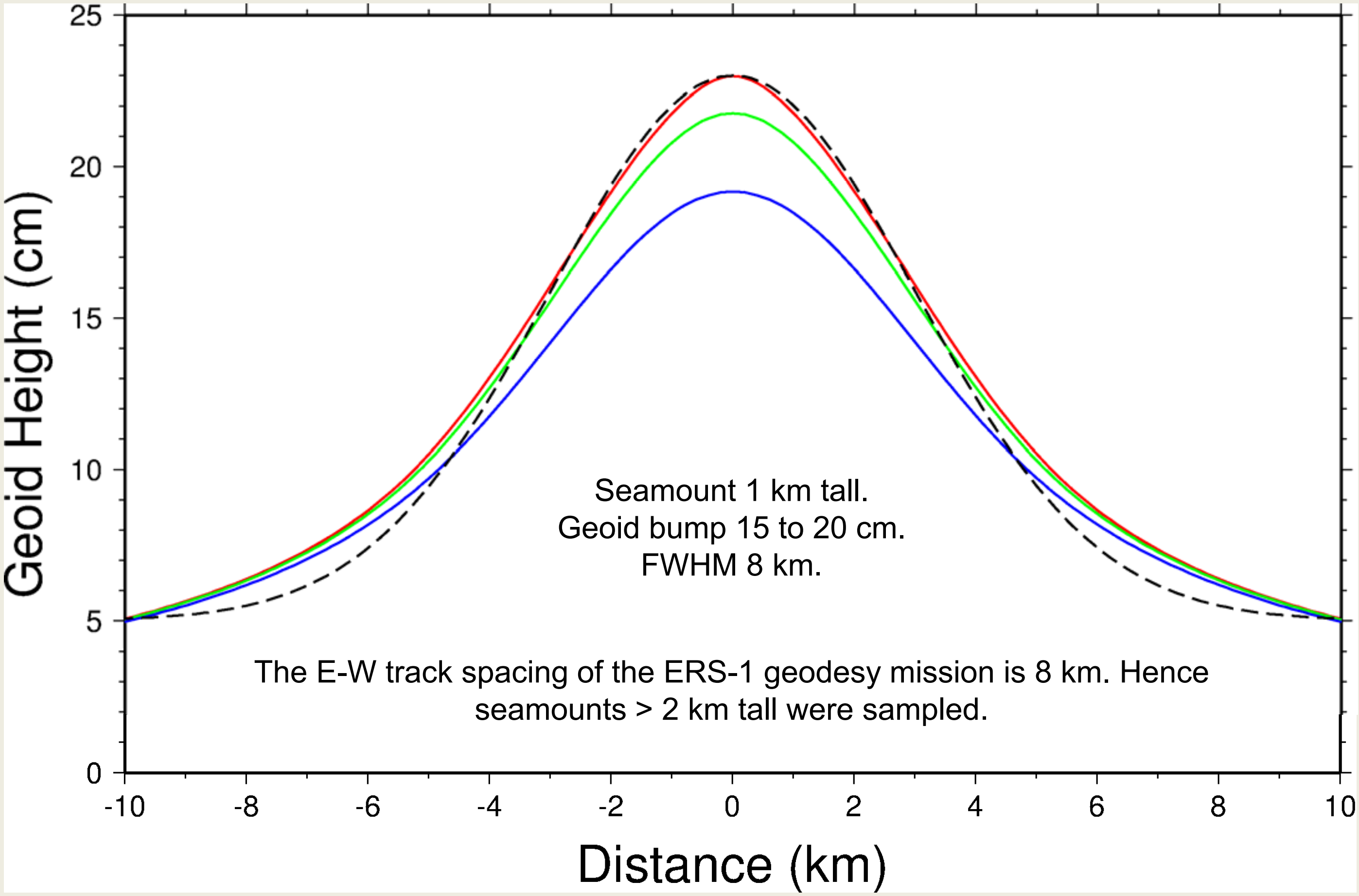


Figure here from a power-law ("fractal") model from Wessel [2001, doi:10.1029/2000JB000083]. One can also fit a Poisson model [Smith and Jordan, 1988, doi:10.1029/2000JB000083]. The models differ when extrapolated to extremes, but both models suggest that there are about 50,000 seamounts in the global ocean in the height range between 1 and 2 km tall.

We need more & better GM altimetry to find more seamounts and sea floor roughness.

Models of the abundance of seamounts versus their size suggests that there are 50k seamounts 1 – 2 km tall. Most of these were missed in early altimetric mapping by Geosat and ERS-1.

Small seamounts have narrow anomalies



Current state of the art altimeters can sense small seamounts.

Mapping them globally will require putting altimeters in geodetic orbits, to collect data on a set of closely spaced ground tracks.

New altimeter technologies since 2010

- Ku-band “SAR” altimetry
  - CryoSat SIRAL (since 2010; GM orbit since 2010)
  - Sentinel-3 SRAL (since 2016)
  - “Fully Focused SAR” (since 2016)
  - Sentinel-6/Jason-CS “interleaved SAR” (2020)
- Ka-band altimetry
  - Saral AltiKa (since 2013; GM orbit since 2016)
  - SWOT (2021)

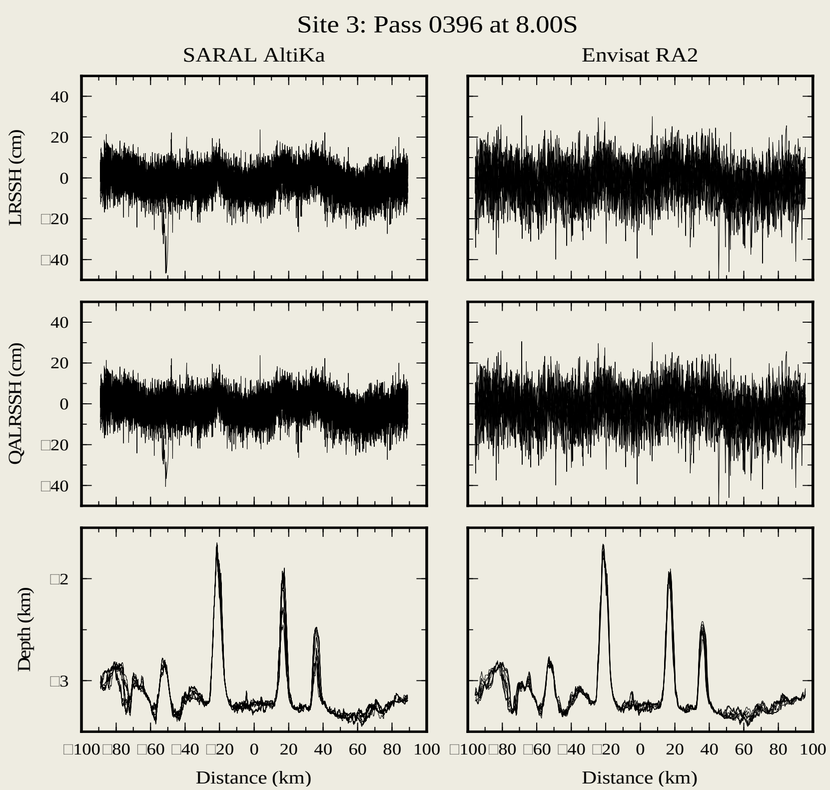
New Bathymetry resolution is a topic of research

Pass #0396 @8˚S: 3 small seamounts

Sea level (geoid) anomaly over Seamounts. 12 repeat tracks.

AltiKa samples @ 40 Hz rate

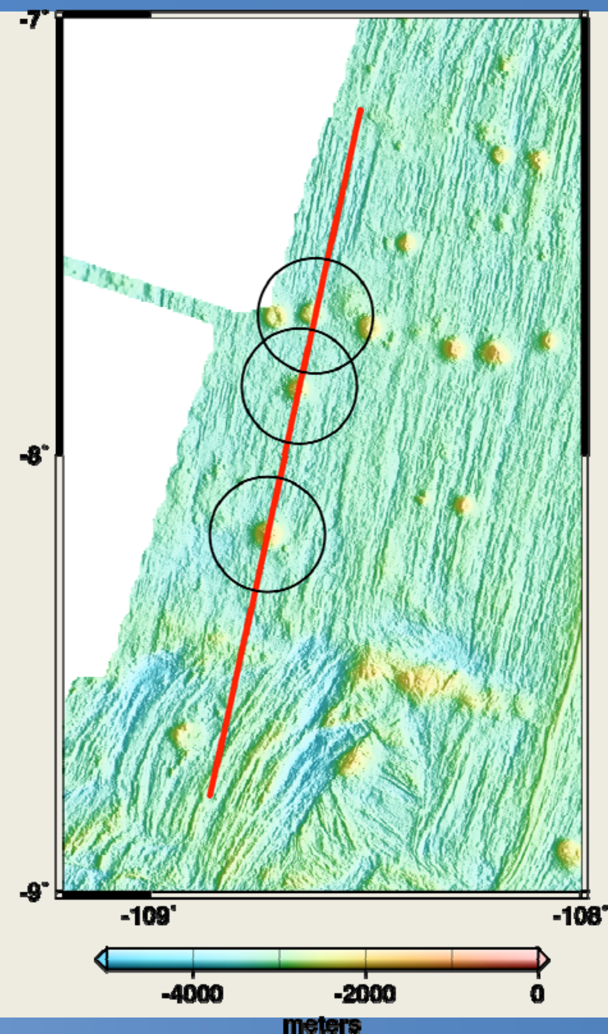
Ku samples @ 18 Hz rate



Left: Figure from Smith, doi:10.1080/01490419.2015.1014950.

Right: bathymetric survey by Cochran et al., image by Karen Marks.

1 km tall seamounts are resolvable. Mapping them requires new geodetic orbit data.

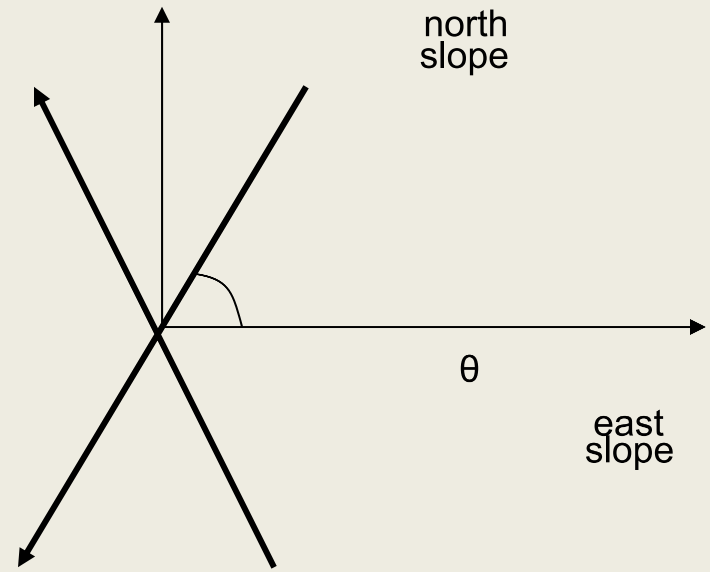


Orbit Inclination Controls Error Anisotropy: (north-south error versus east-west error)

- Error propagation
  - θ - local inclination of track
  - σ - error in along-track slope
  - σ_x - error in east slope
  - σ_y - error in north slope

$$\sigma_x = \frac{\sigma}{\sqrt{2}\cos\theta}$$

$$\sigma_y = \frac{\sigma}{\sqrt{2}\sin\theta}$$

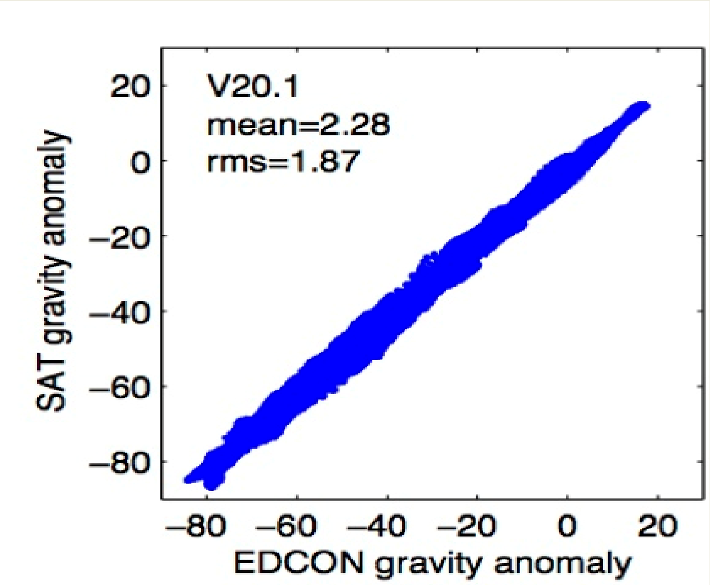


Because the required measurement is along-track sea surface slope, not sea surface height, the radiometer, C-band altimeter, and precise orbit are not required.
Ku altimetry and a crude orbit are enough to measure the slope.

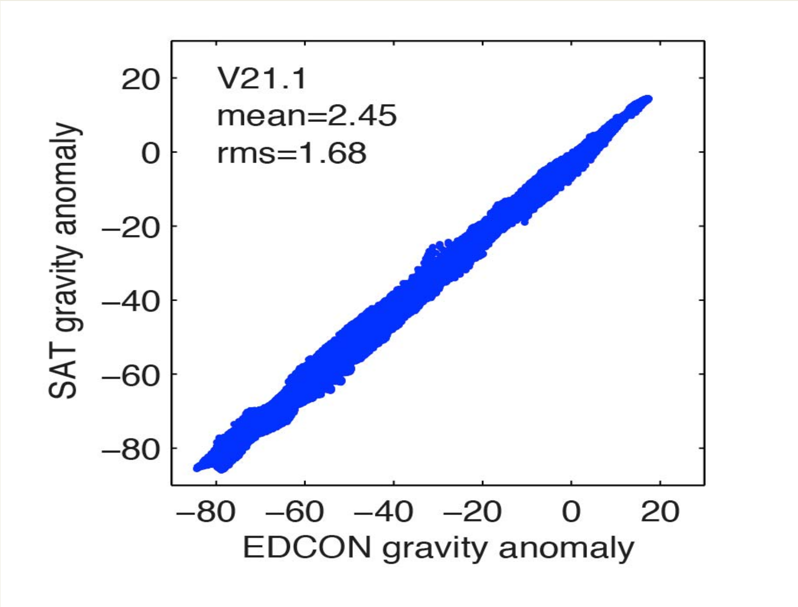
- Jason-1&2 GMs provide better east-west data than any other altimeter, due to lower orbital inclination.

Gravity improvement from Jason-1 GM

Before Jason-1 or -2 GM

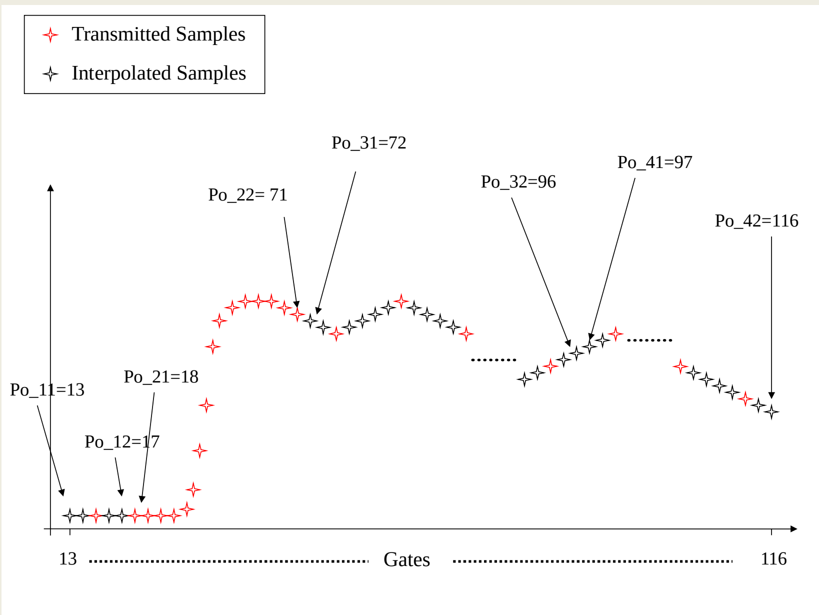


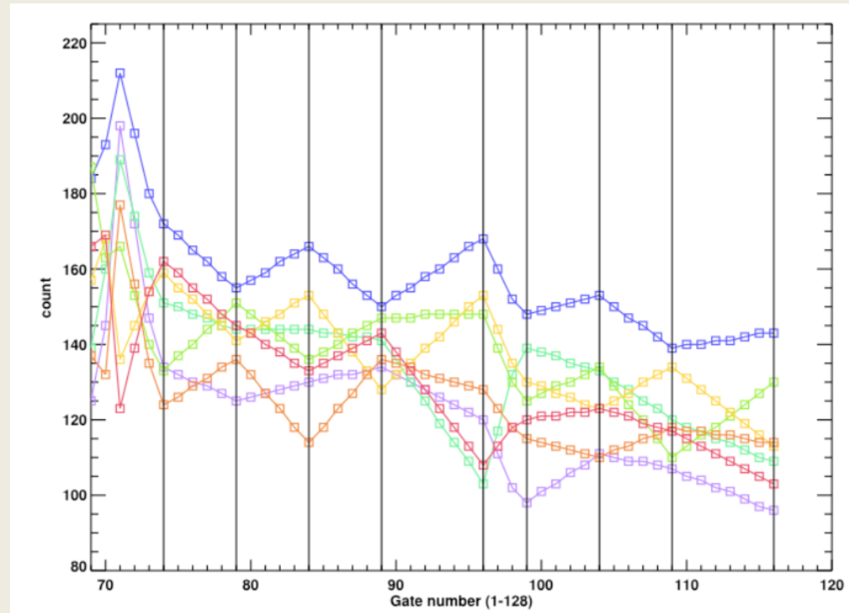
After ½ of Jason-1 GM



Geodetic Mission data in the Jason inclination are increasing the accuracy and resolution of the marine gravity field.

Why we need the Jason-2 Geodetic Mission





The Jason-1 Geodetic Mission proved the tremendous value of GM data in a Jason orbital inclination. However, J-1 had lossy compression and buggy decompression of waveforms, degrading the measurement; J-2 does not. Also, J-1 did not achieve the intended orbit and did not complete the mission. We hope J-2 may be able to do so (but there are gyro problems).

Summary / Conclusions

- We need to know the depth and roughness of the ocean bottom for meteo, climate, etc.
- Altimetry can probably find 50k more seamounts, with high-resolution altimetry in geodetic orbits and good inclinations.
- The Jason-2 geodetic mission is an important part of this ocean mapping process.

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