GNSS at tide gauges for Mean Dynamic Topography:

Conventional measurements and Multipath Reflectometry

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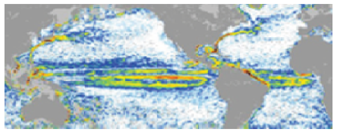
Mean dynamic topography at tide gauges… why?

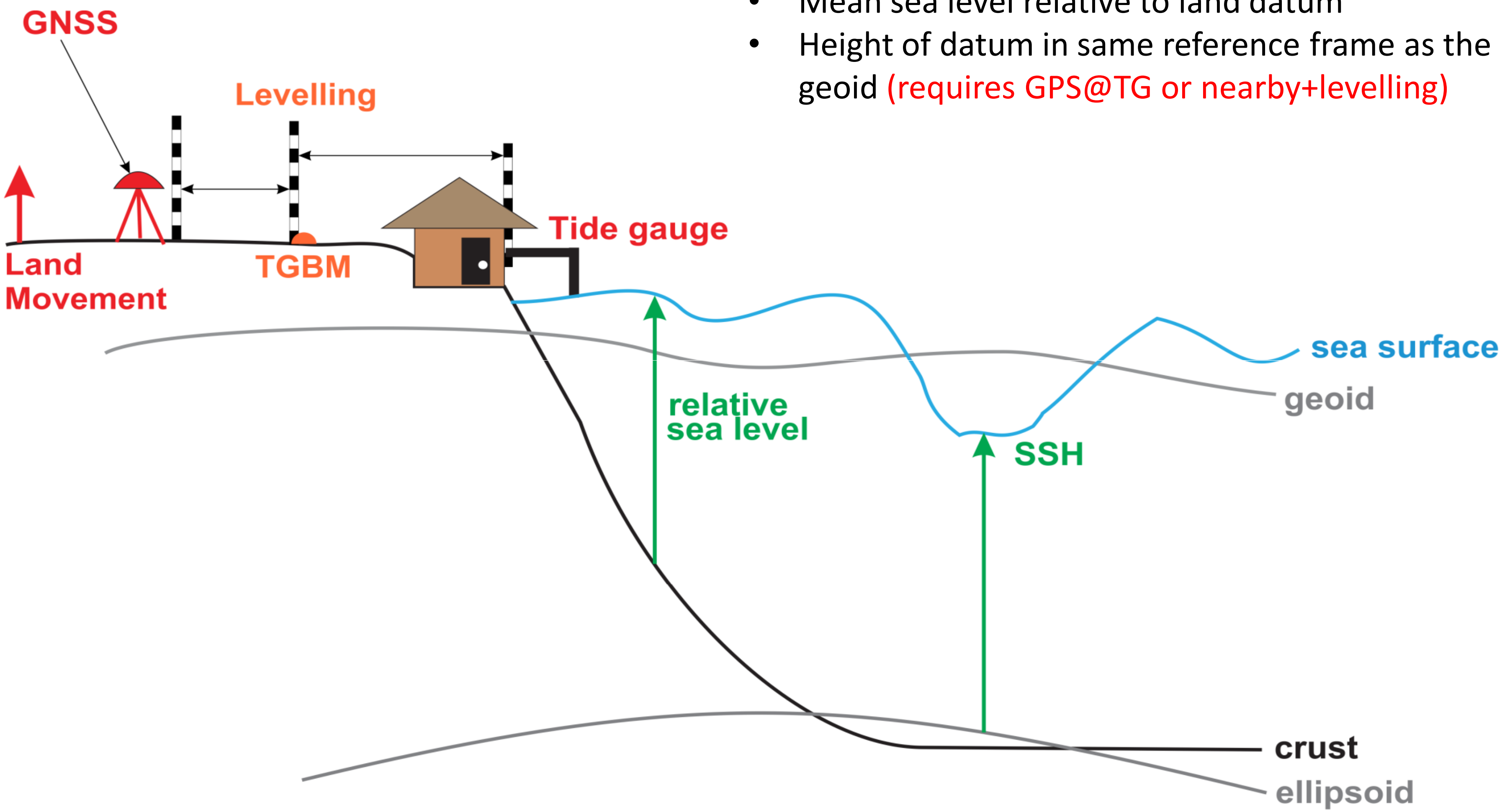
- Flooding results from sea level at the coast. Only tide gauges measure sea level precisely at the coast.
- We want to know whether local dynamics affects sea level significantly, and for long-term prediction (centuries) we want to know whether models can get this right.
- The only way to assess the long term is to look at the mean – time series aren't long enough.

GOCE++Dycot



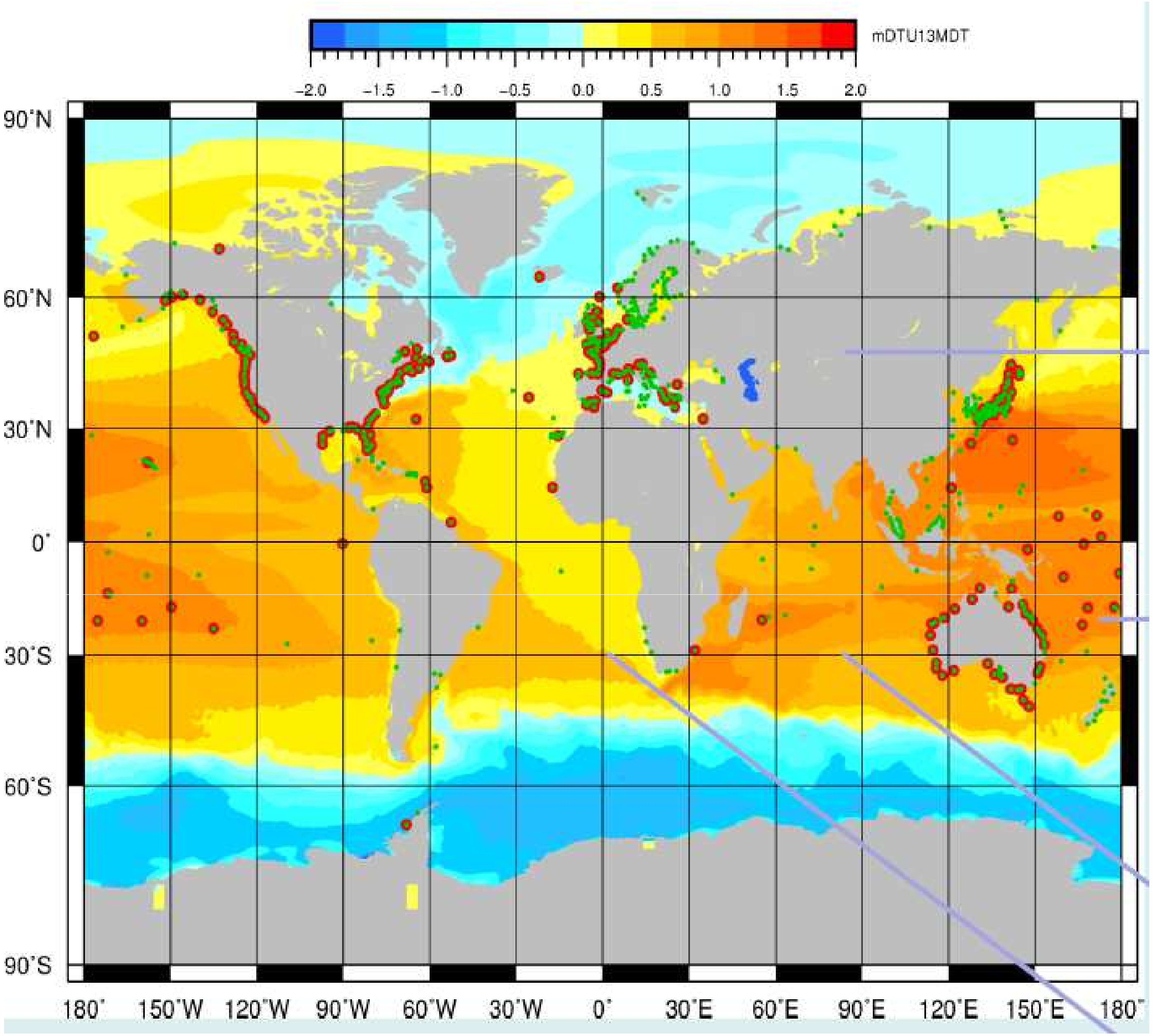
Denmark (DTU), France (La Rochelle)
Germany (Uni Bonn), UK (Liverpool and Bristol)

Traditional Implementation of a GLOSS CORE Network Site



Mean dynamic topography requires:

- Geoid (GOCE+GRACE+local)
- Mean sea level relative to land datum
- Height of datum in same reference frame as the geoid (requires GPS@TG or nearby+levelling)

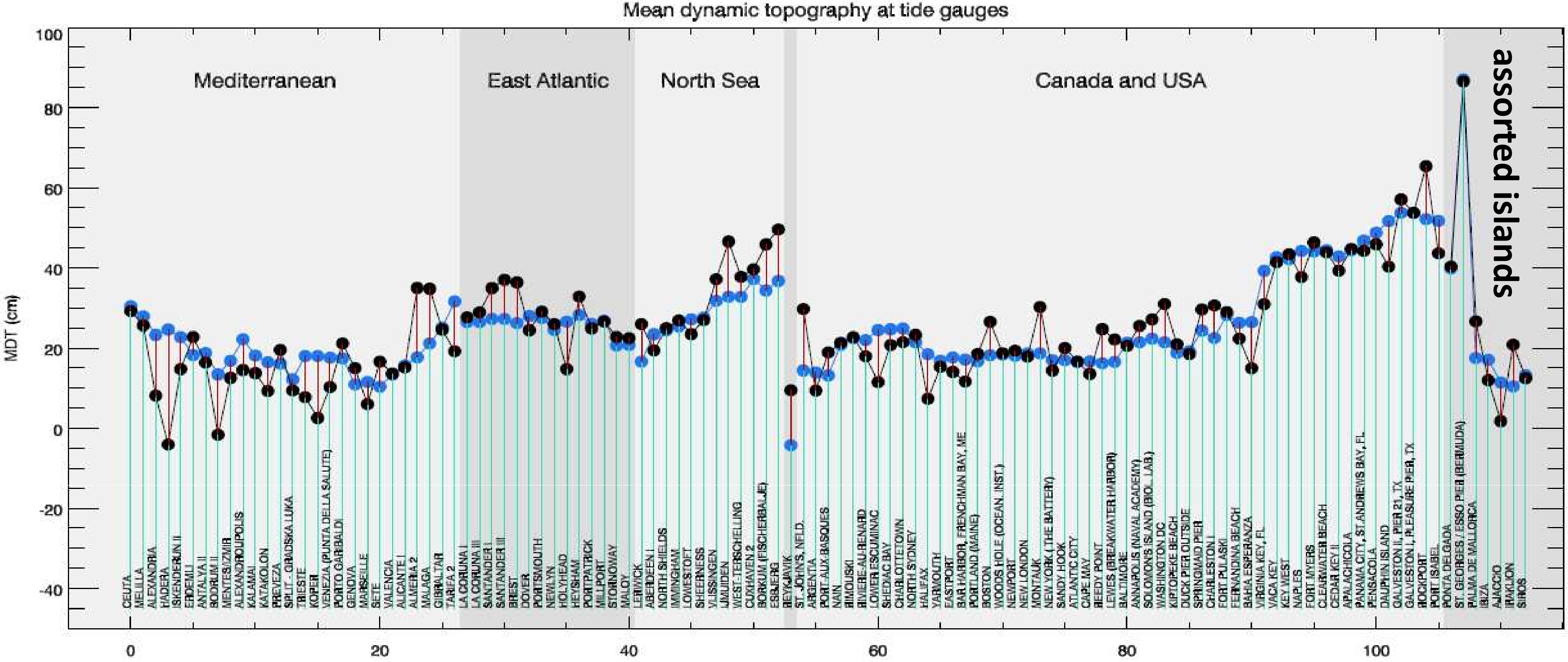


Most
tide gauges
do not have
GPS ties

So far about 280 identified

Some have GPS time series, some have only short measurements, for some, the measurement epoch is not known.

Comparing MDT in the N Atlantic and Mediterranean: 113 Tide gauges



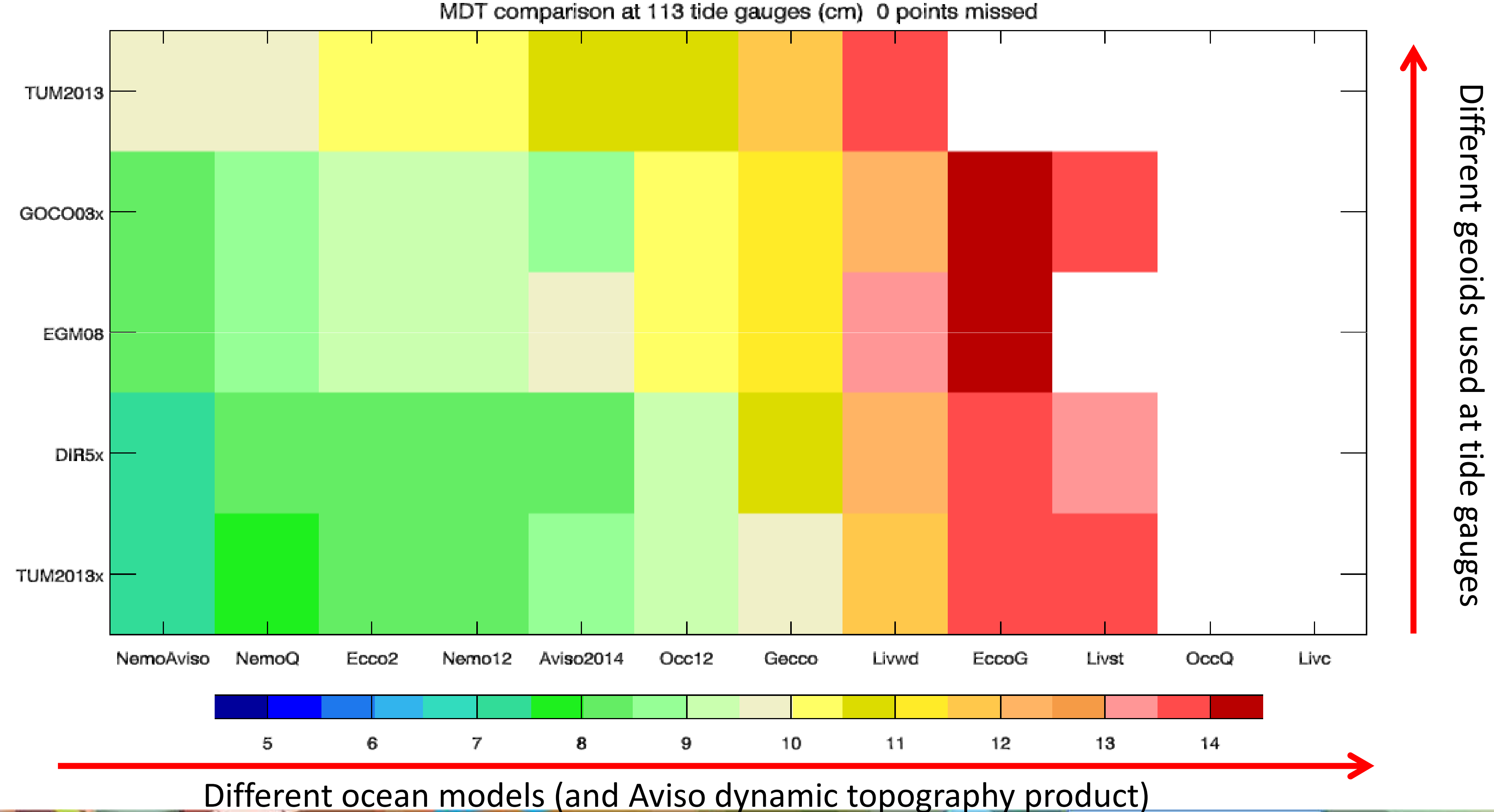
Tide gauge data + GPS position + TUM2013x geoid

(i.e. TUM 2013 extended beyond degree 720 using EGM08)

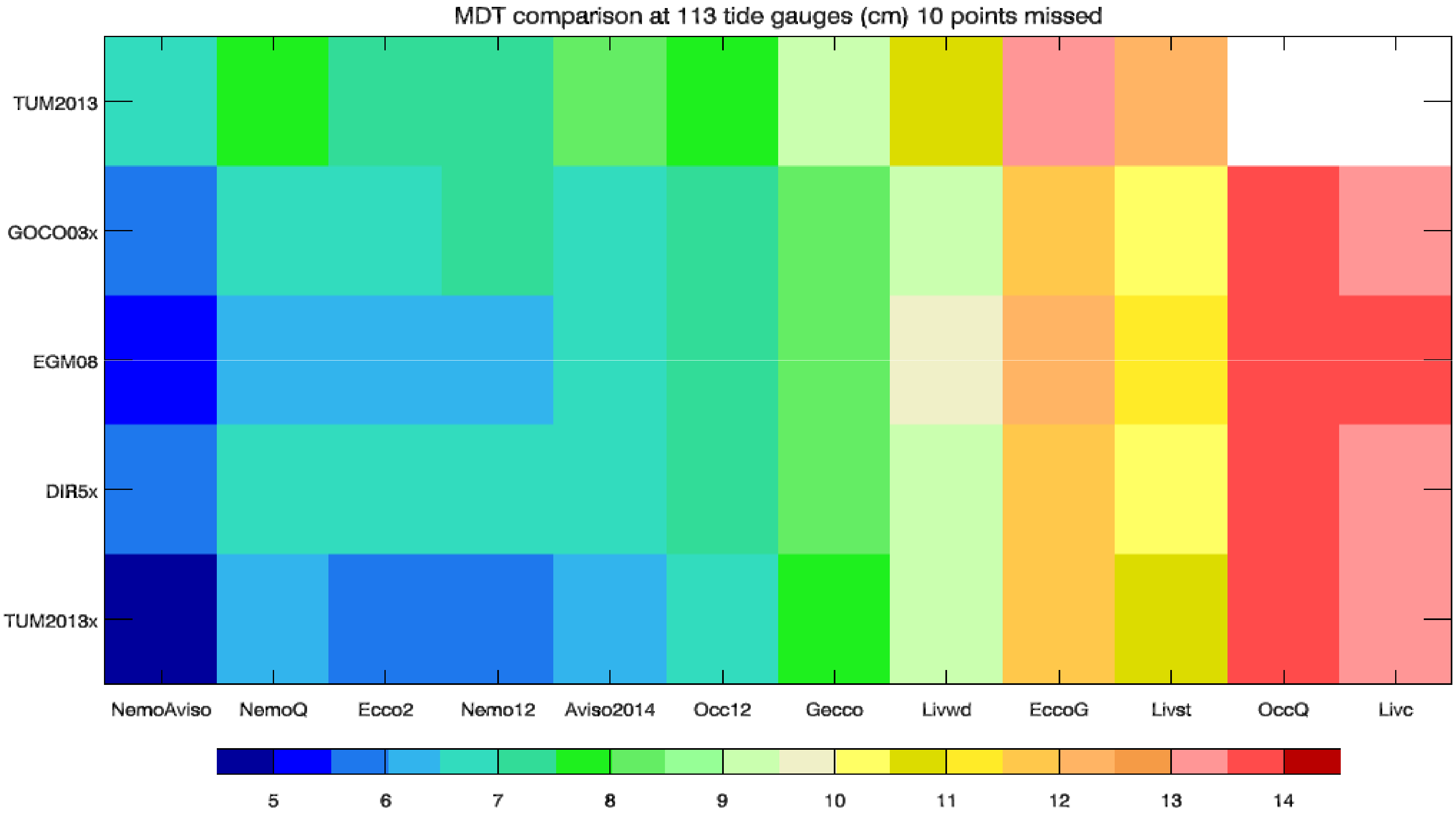
Average of NemoQ, Nemo12, and Aviso 2014 MDTs

Hughes, C. W., R. J. Bingham, V. Roussenov, Joanne Williams and P. L. Woodworth, 2015: The effect of Mediterranean exchange flow on European time mean sea level. *Geophys. Res. Lett.* **42**(2), 466-474. doi: 10.1002/2014GL062654.

Root mean square error, as a function of geoid used and model/MDT product. All tide gauges included.

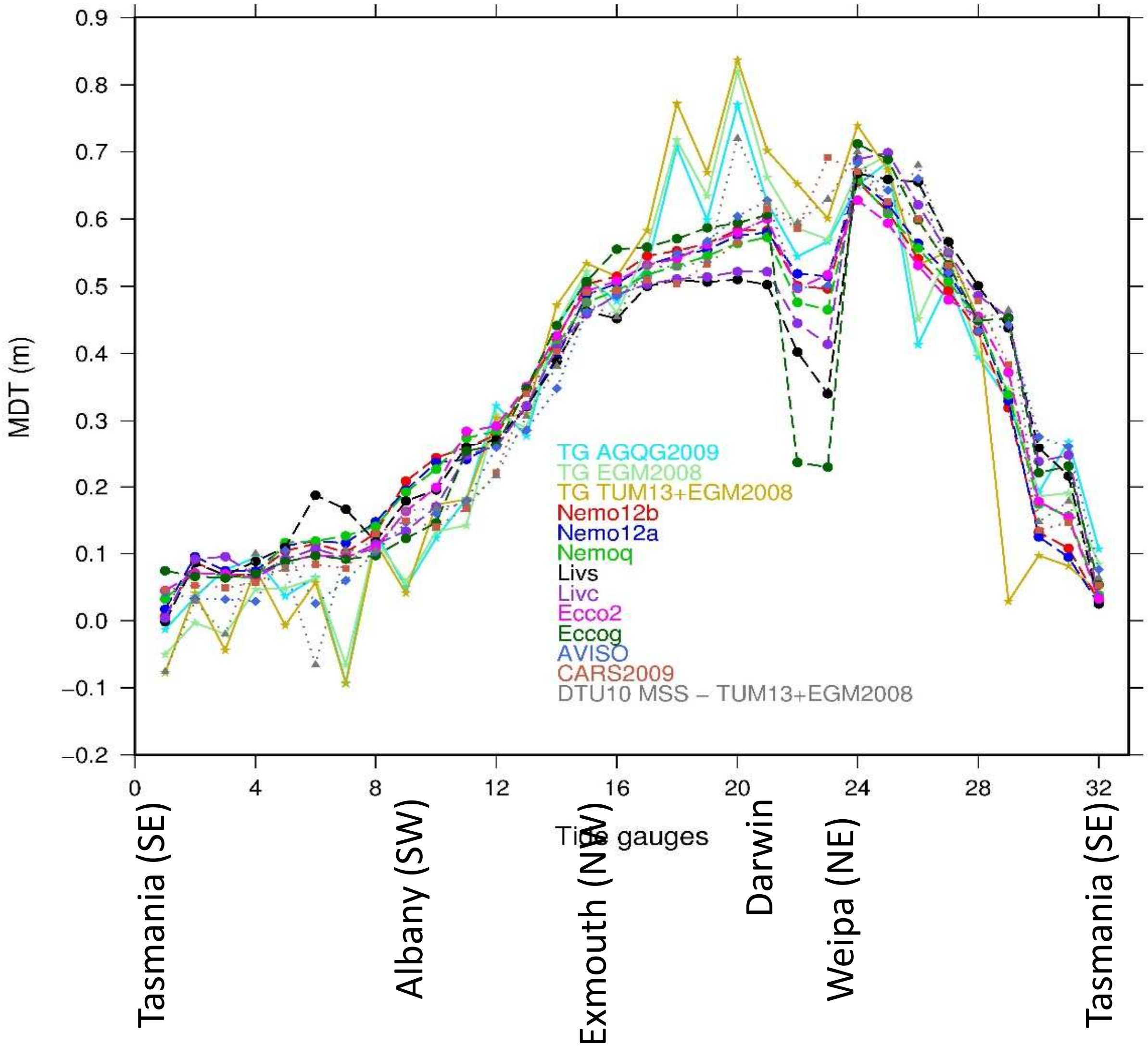


Root mean square error, as a function of geoid used and model/MDT product. “Worst” 10 tide gauges missed out.



Down to 5-6 cm RMS error (combined error of tide gauges and models)

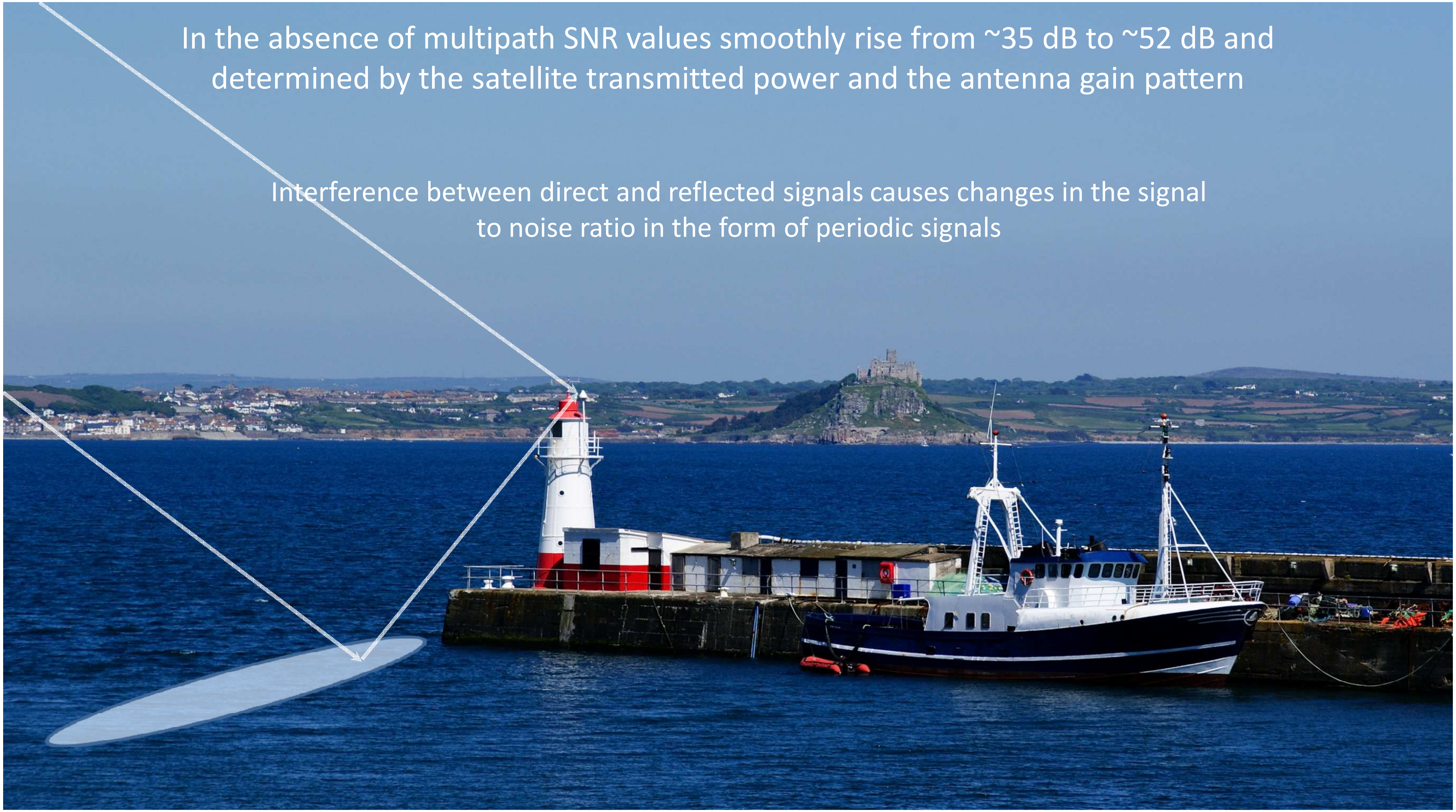
Preliminary results round Australia
(with Mick Filmer, Will Featherstone, Philip Woodworth)

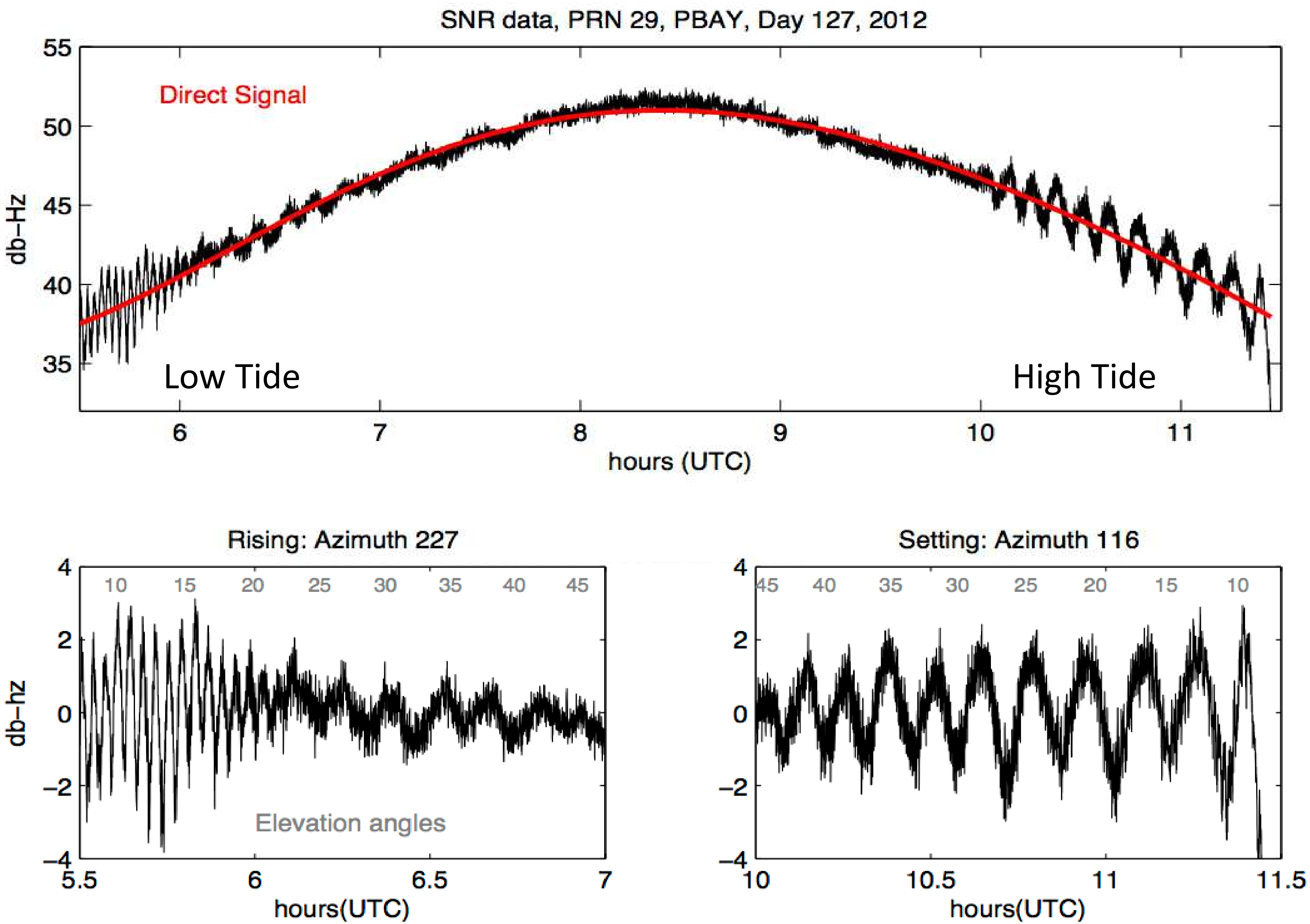


So far so good, but this is a long, slow, messy and complicated process.

What if we could find a way to shortcut all this combining of information using just GPS, or GPS near TG, without needing a tie?

GNSS Multipath Reflectometry





elevation angle

Larson, K. M., R. D. Ray, F. G. Nievinski, and J. T. Freymueller (2013), The Accidental Tide Gauge: A GPS Reflection Case Study From Kachemak Bay, Alaska, *IEEE Geoscience and Remote Sensing Letters, 10(5), 1200-1204.*

Oscillations in Signal to Noise have a frequency which tells you height above sea level: GPS=TG

Complications

- The measurement is a rate of change with satellite elevation angle.
- If sea level is changing during that period, that also has an effect.
- Anything else which varies with elevation angle can have a bigger effect than might be expected – including tropospheric delay.

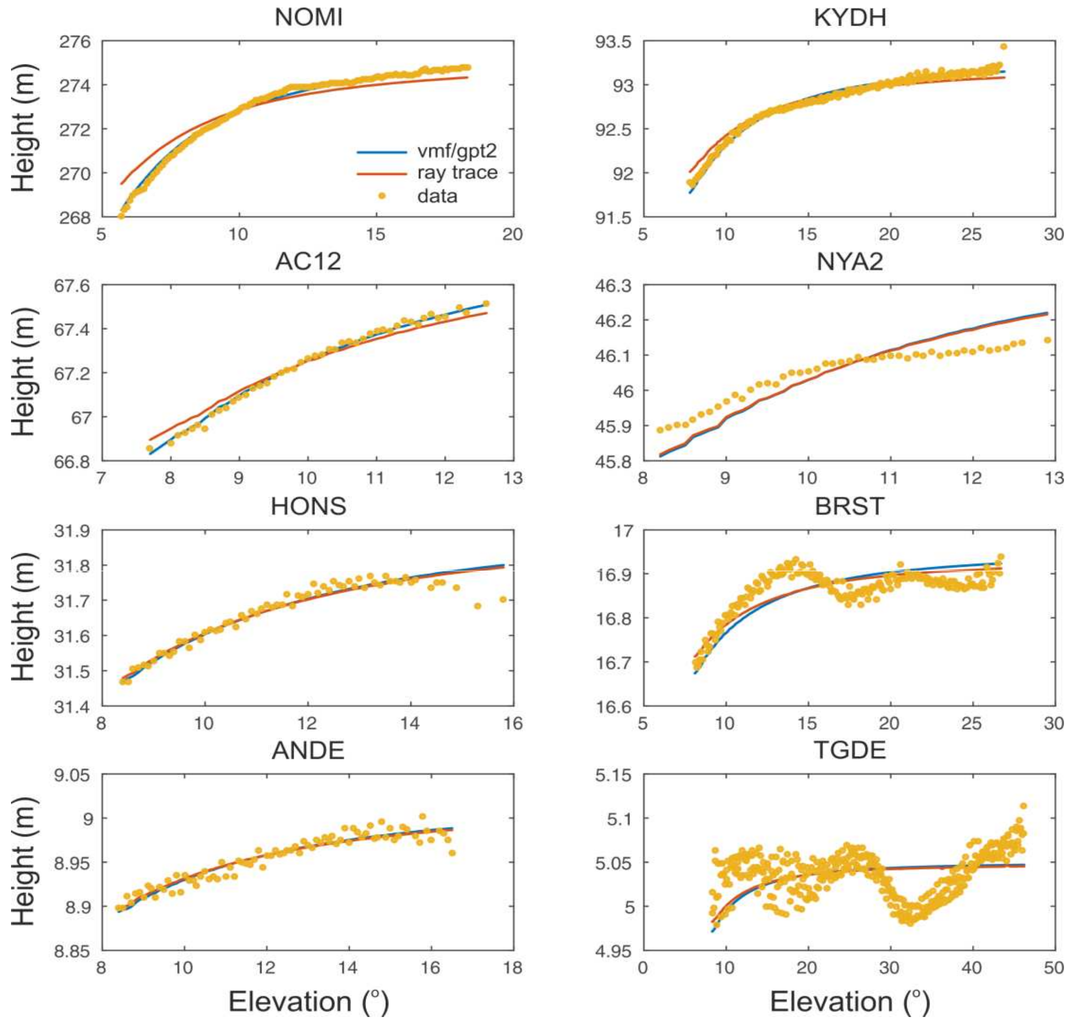
Tropo delay effect can be cm or metres depending on the height above sea level (~ 1%), but can usually be well modelled (these are not the best places, just a variety)

Santorini | Kentucky (lake)

Alaska (Aleutians) | Ny-Ålesund

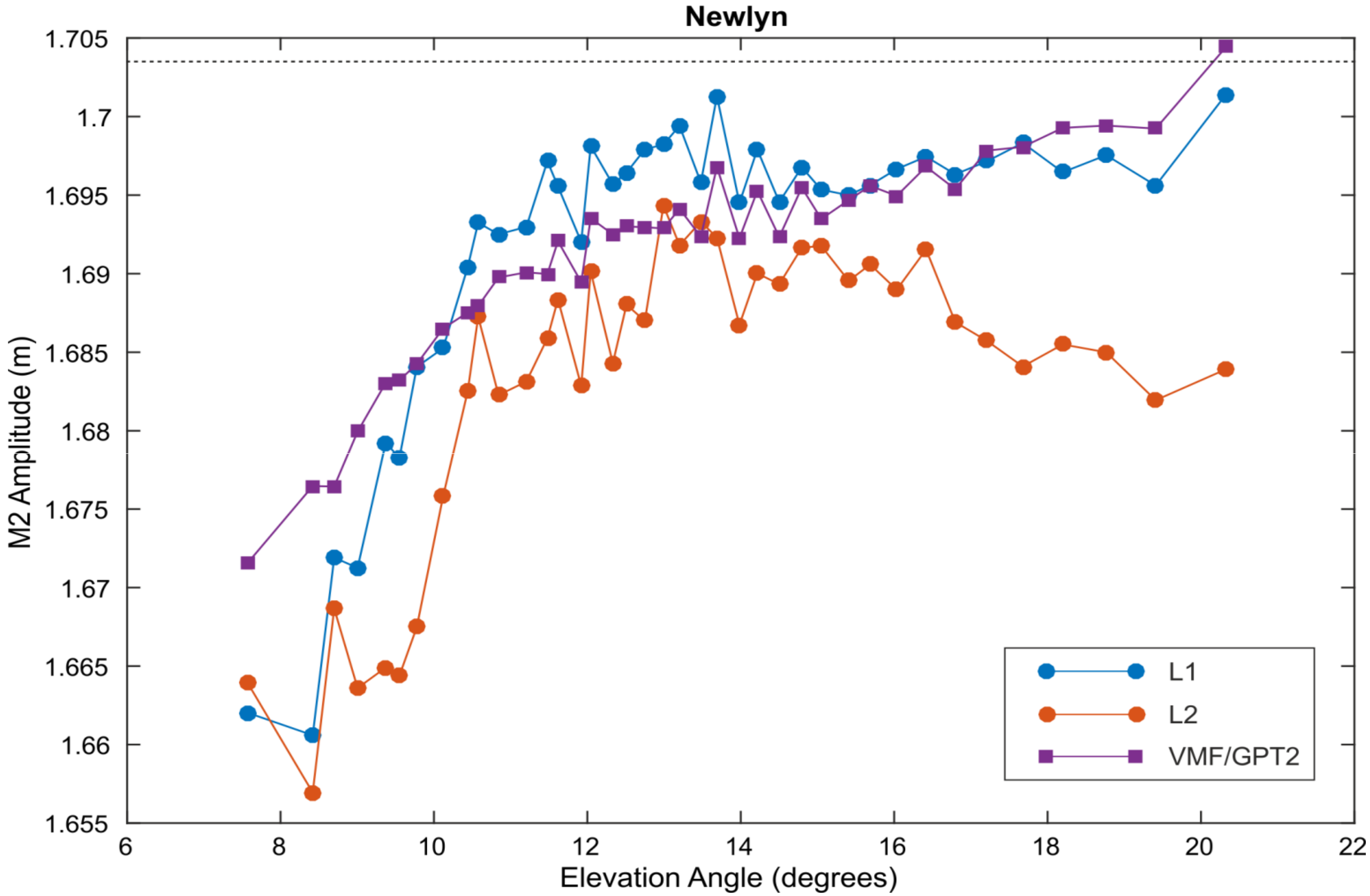
Norway (far north) | Brest

Norway (near Tromsø) | Norway (southern tip)



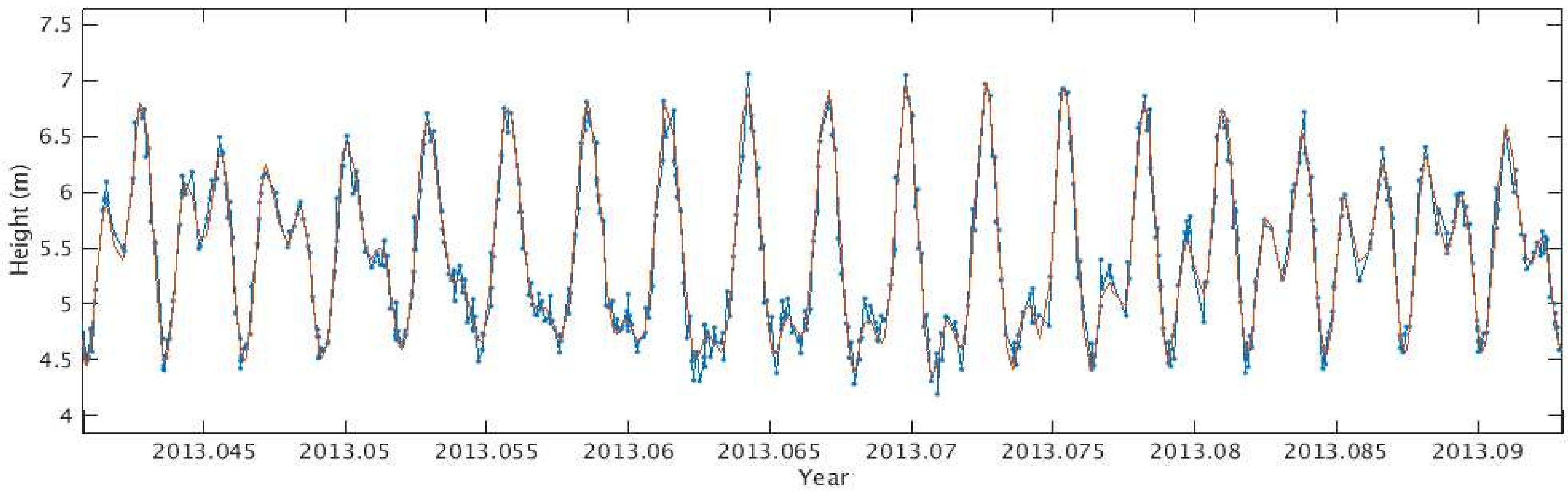
Williams, S. D. P. and Nievinski, F. G (2016 submitted) Tropospheric delays in ground-based GNSS Multipath Reflectometry – Experimental evidence from coastal sites, Journal of Geophysical Research – Solid earth

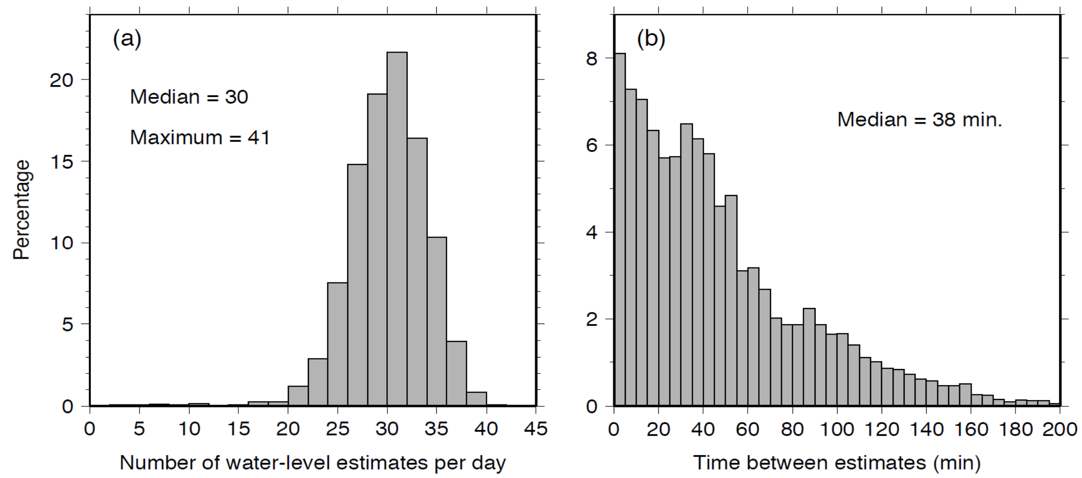
Newlyn M2 Amplitude vs Average Elevation Angle



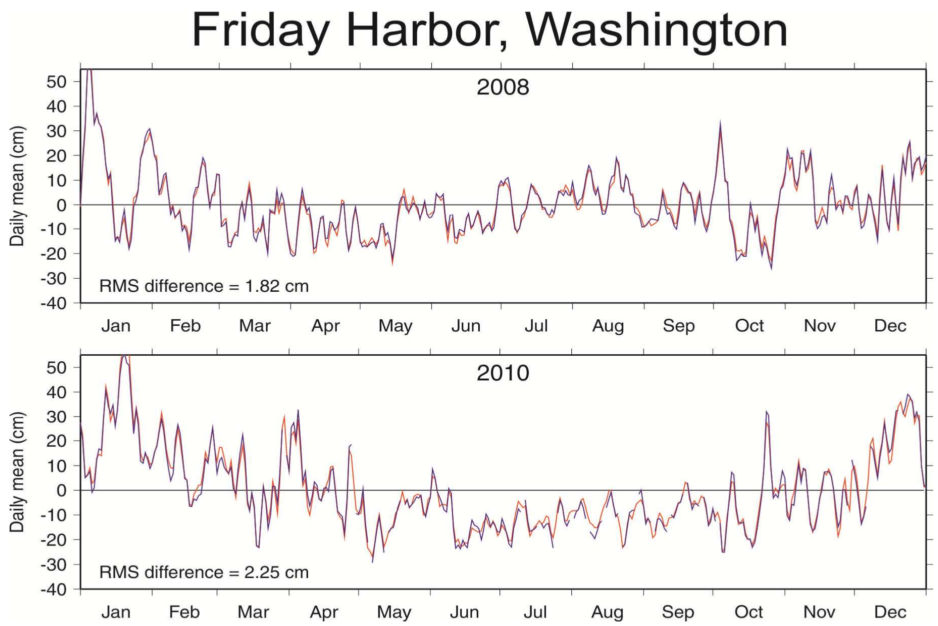
The tropo effect is not just an offset – it is also a scaling of sea level variations

Friday Harbour (near Seattle) Tide gauge and GPS sea level about 30 times per day

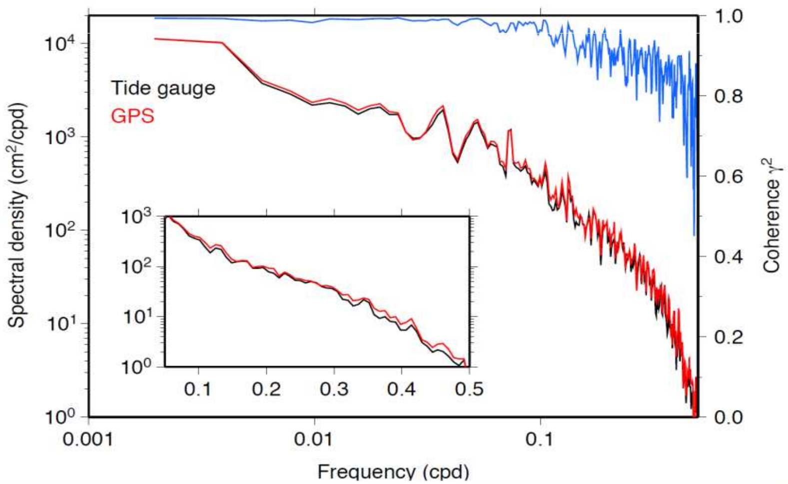




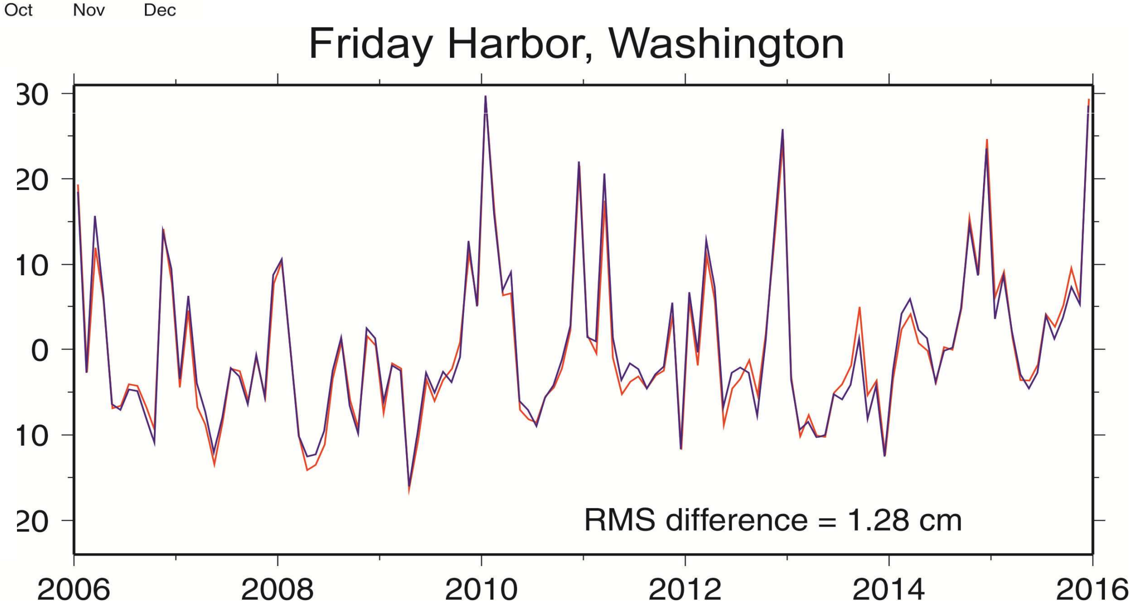
Larson, K. M., R. D. Ray, and S. D. P. Williams (2016 submitted):
A ten-year comparison of water levels measured with a geodetic GPS receiver versus a conventional tide gauge, *Journal of Atmospheric and Oceanic Technology*.



Daily means
RMS difference about 2 cm

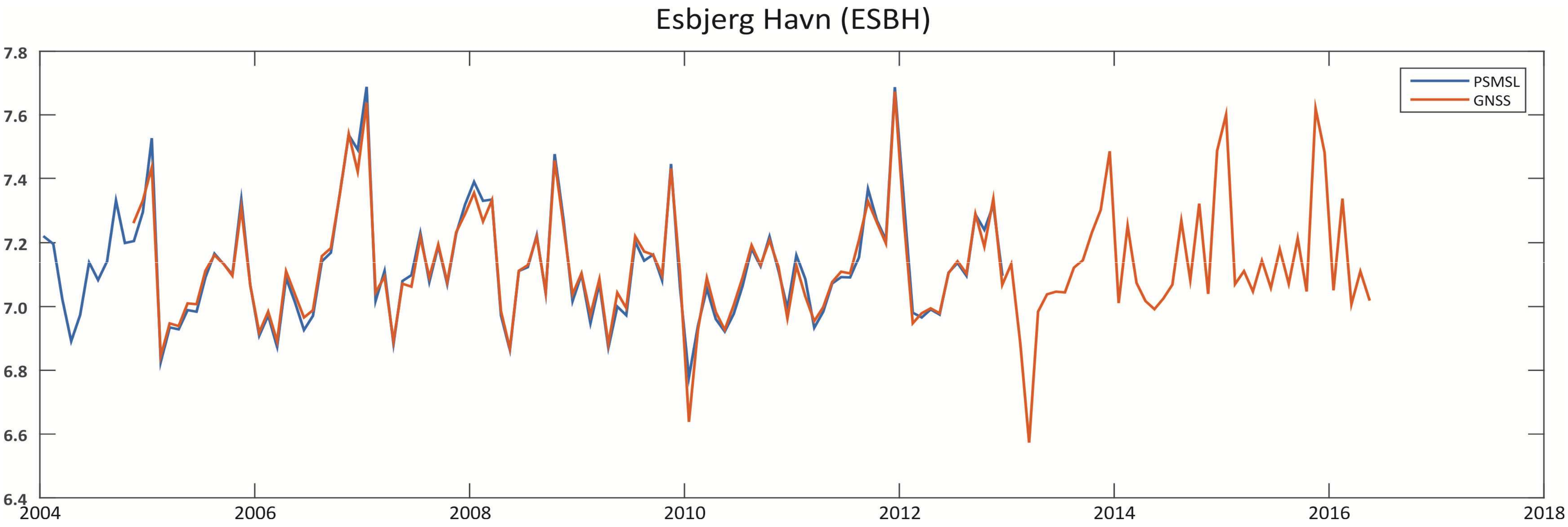


Spectrum shows very small low frequency errors

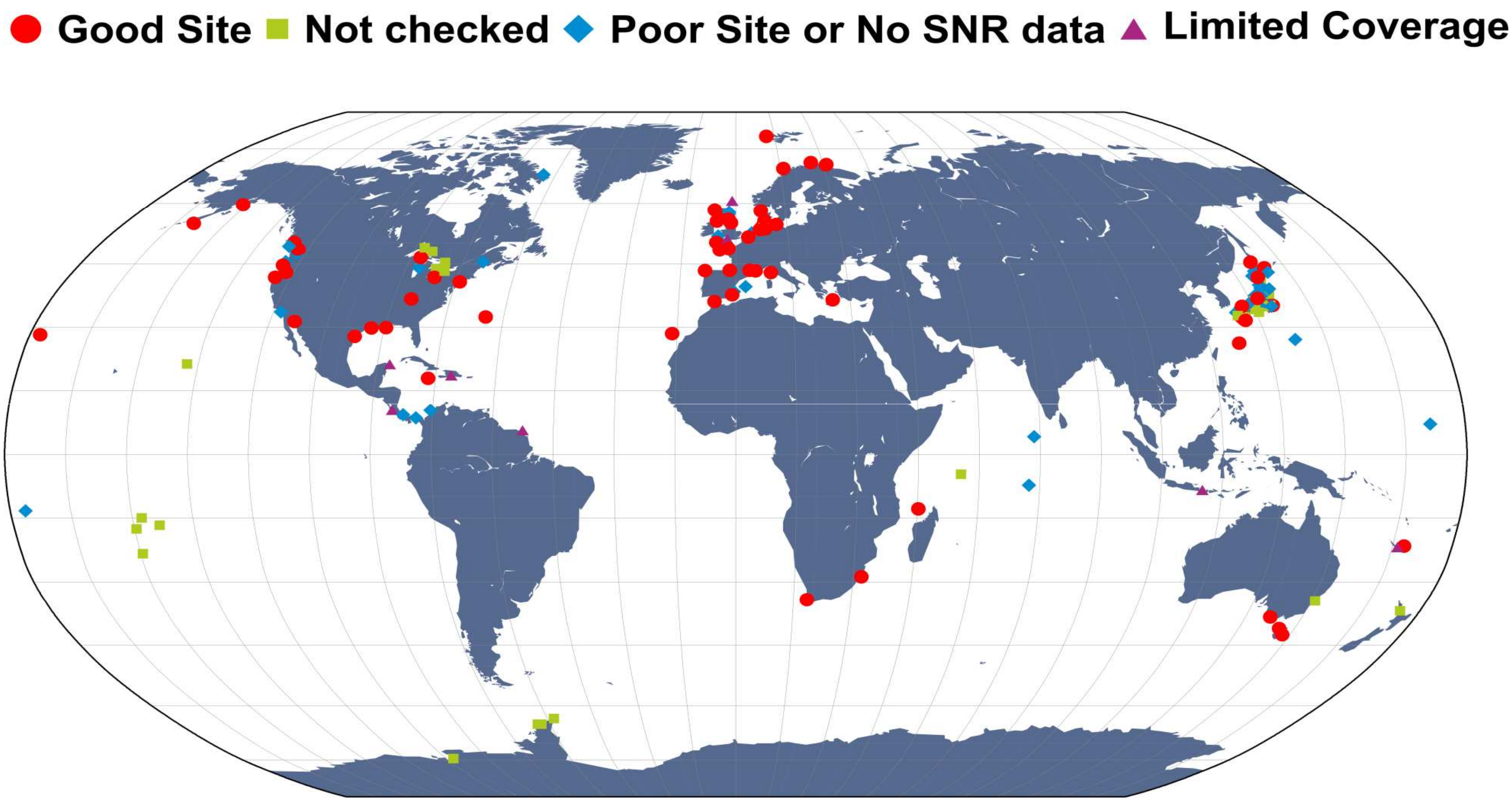


10 years of monthly means
RMS difference close to 1 cm

Esbjerg, Denmark – more than 12 years of data



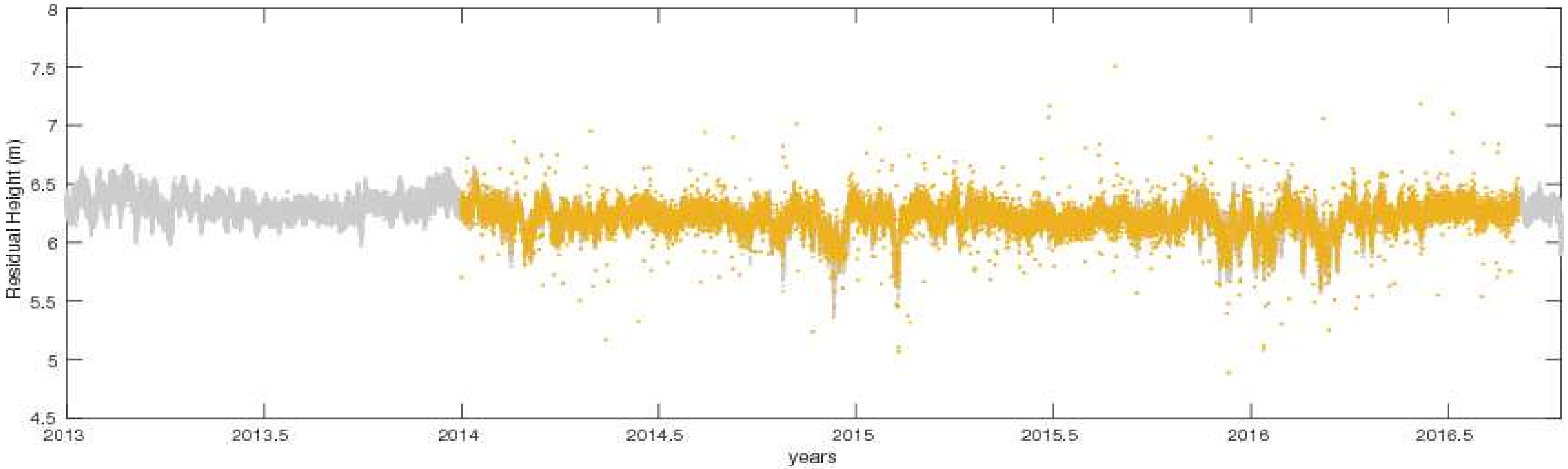
Current known GNSS water level sites



~60 – 70 good sites identified so far (only a few processed)

CACC
Crescent City, California
Testing new methods

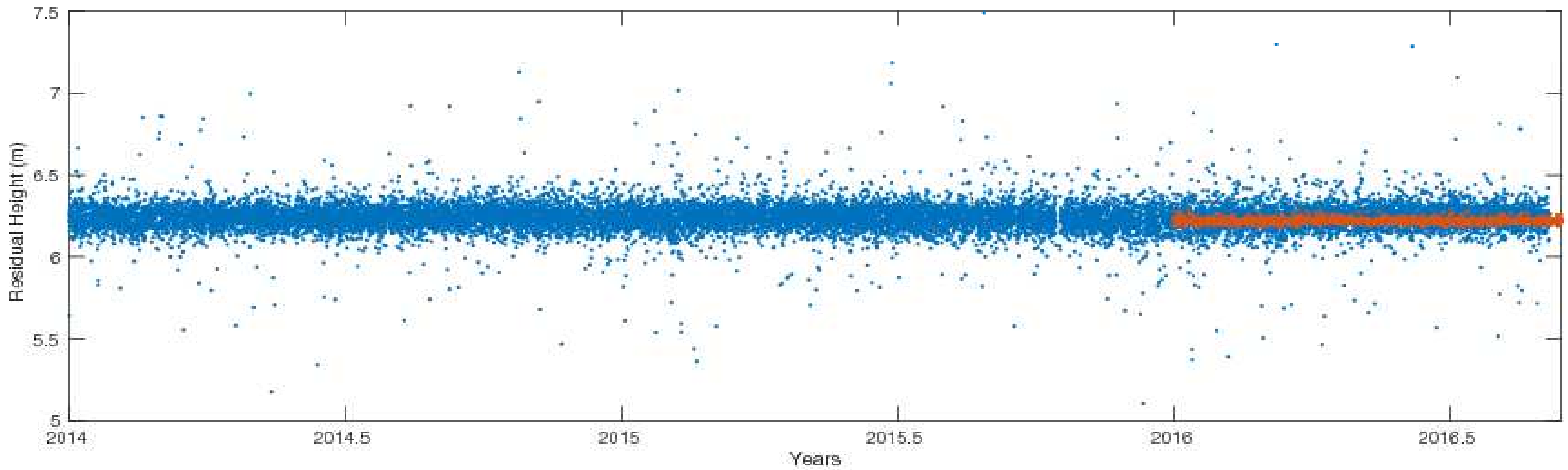
Tide gauge
GPS interferometry



Both detided, and using a power spectrum method
to identify the frequency of S/N oscillations.

CACC
Crescent City, California
Testing new methods (L5 signal)

Residual (= error on estimation of tide gauge height from each satellite pass).
RMS = 8.6 cm



New residual, using nonlinear least squares and known rate of change of sea level from tide gauge, and switching to L5 instead of L1 and L2
RMS = 1.5 cm

Summary

- Mean dynamic topography from tide gauges is consistent with ocean models/open ocean MDT at the 5-8 cm RMS level. We suspect that most of this is point geoid error, but some will also be local dynamics.
- Collating GPS ties to tide gauges is a slow, tedious process fraught with possible slips.
- GPS reflectometry offers a way to sidestep much of this, and to use GPS receivers as tide gauges.
- Correcting for tropospheric delay is very important, and can be done accurately.
- New analysis techniques offer significant improvements. 1-2 cm RMS is certainly possible, and below 1 cm may be attainable with averaging.