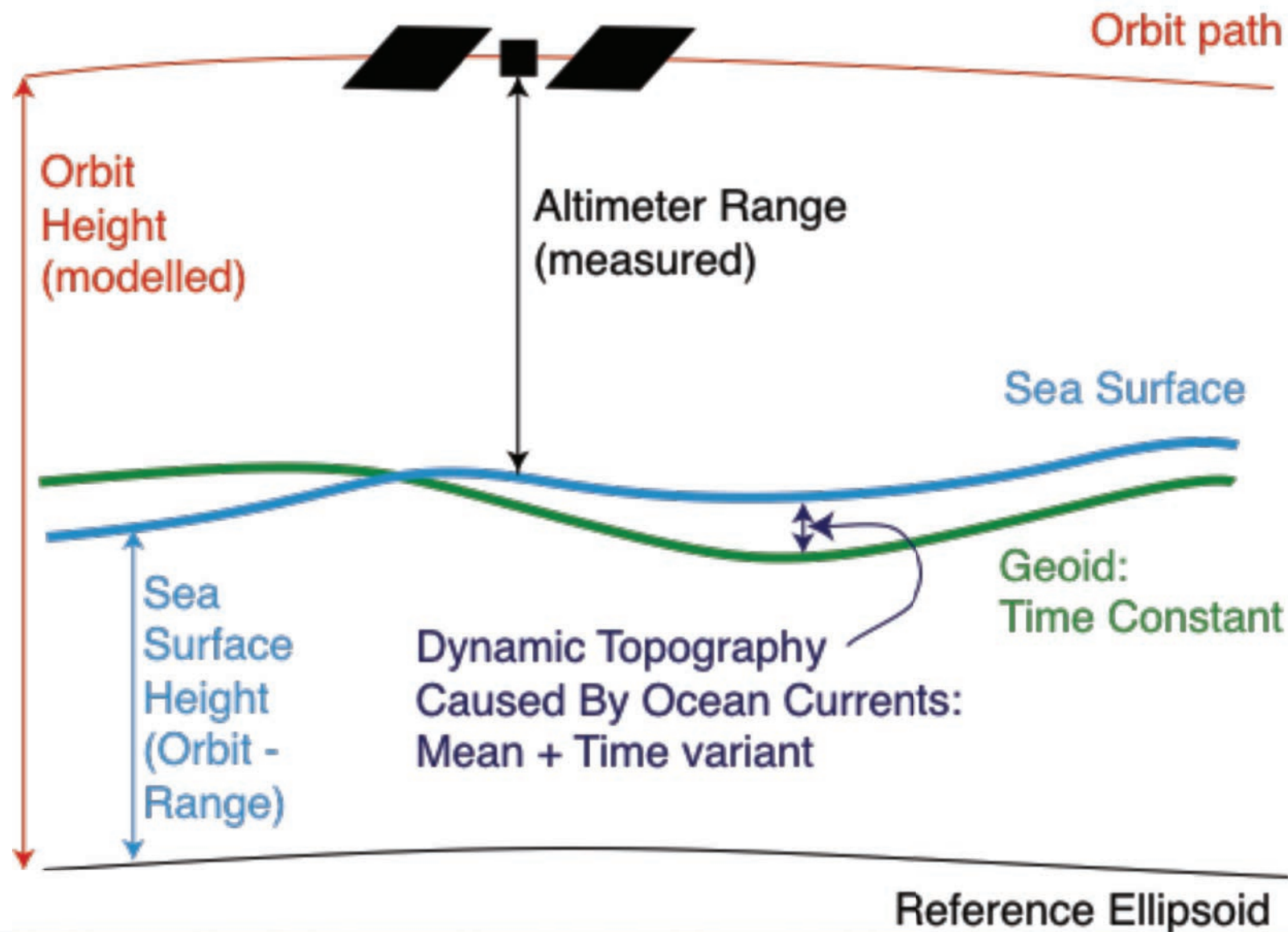


P. Cipollini, H. Snaith - A short course on Altimetry

# **Altimetry 2 – Altimeter data processing (from satellite height to sea surface height)**

- The altimeter measures the altitude of the satellite above the earth surface
- The oceanographer wants a measurement of sea level
- Steps that need to be taken
  - Instrument corrections
  - Platform corrections
  - Orbit determination
  - The effect of refraction: ionospheric, wet/dry tropospheric
  - Sea surface effects





- **Platform Corrections** - due to instrument geometry and other effects on the satellite
- **Orbits** - must be known as accurately as possible
- Correction for **atmospheric** delay effects
- Correction for **surface effects**
- Correction for **barometric effects**
- Estimating/Removing the **geoid**
- Estimating/Removing **tides**



- The Earth is not round.
  - The true shape of the earth is the geoid
  - As the satellite orbits the Earth it moves closer and further away responding to changes in gravity
- ⇒ Satellite is moving towards and away from the earth
- ⇒ A Doppler correction applied to range
- Other platform corrections are applied to range and need not worry the scientist...
  - Eg correction for the distance between the centre of gravity of the spacecraft and the altimeter antenna
- ...unless something goes wrong
  - eg the USO (Ultra Stable Oscillator) range correction for RA-2 on board Envisat

- From the altimeter measurement we know the height of the satellite above the sea surface
- We want to know the height of the sea surface above a reference (the geoid or an ellipsoid)
- Therefore we need to know the satellite orbit, to a few cm or less, relative to the same reference
- This is done through a combination of satellite tracking and dynamical modelling.
- A dynamical model is fitted through the tracking data. Solutions cover a few days at a time.
- The tracking information comes from DORIS, GPS and Satellite Laser ranging (SLR)



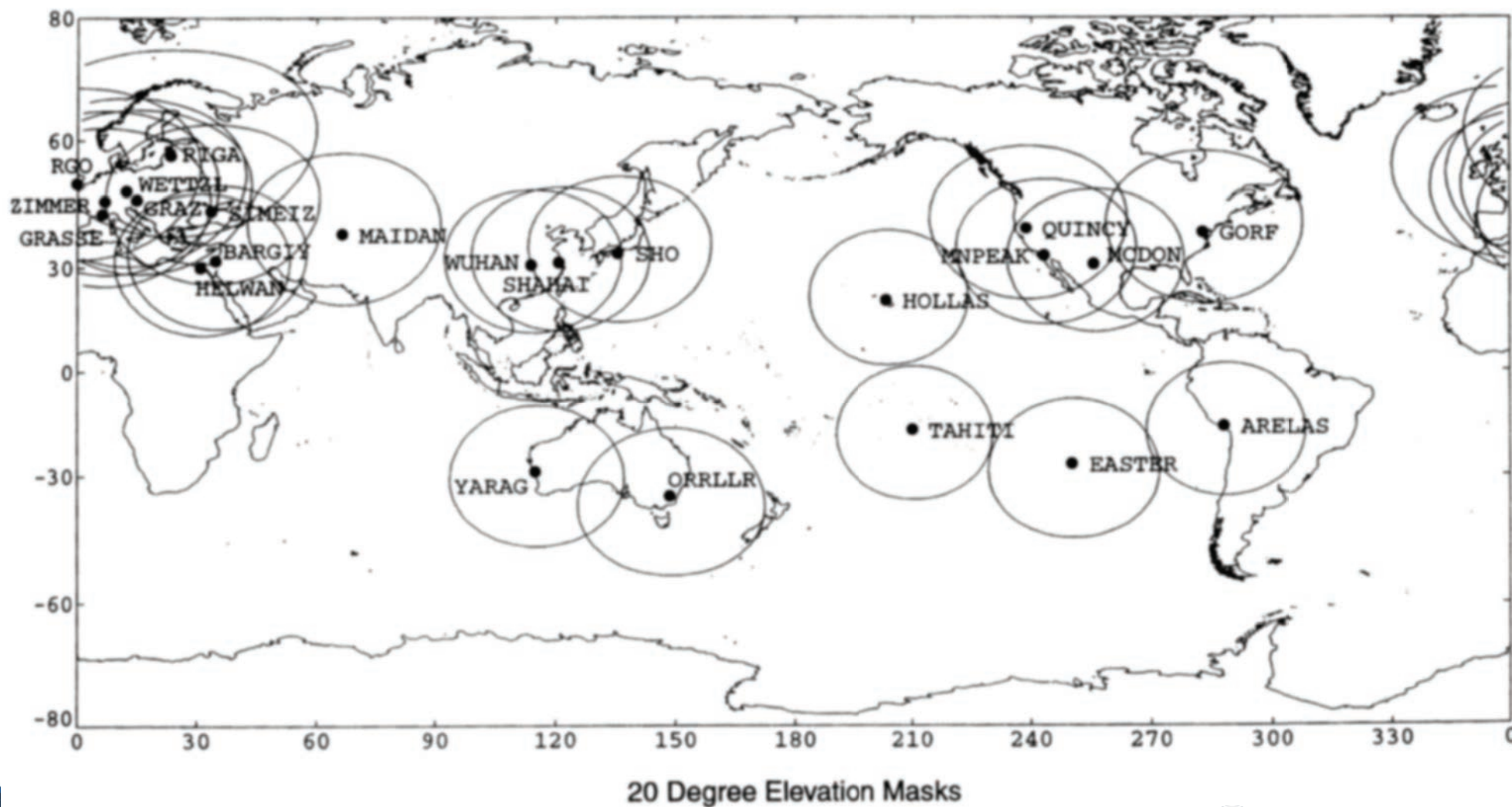


DORIS

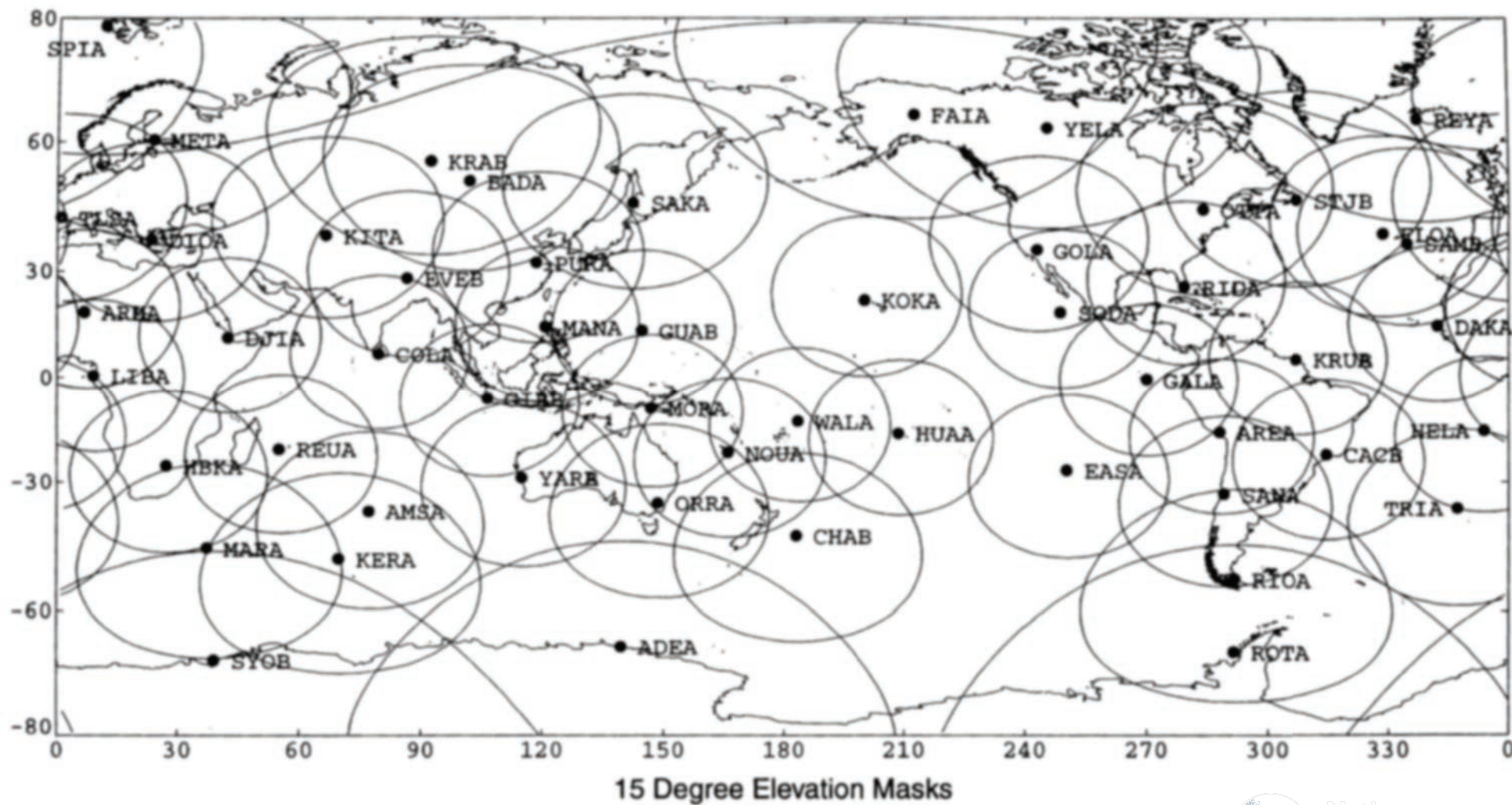
SLR













- The quality of orbits are measured by the reduction of crossover differences and by comparison to SLR stations
- TOPEX/Poseidon and Jason orbits are now good to the **~2-cm** level
- ERS-2 and ENVISAT: **~3 cm**
  - more affected by drag, as in lower orbit, and much larger, than T/P and Jason



- Size of observed error in orbit model, by parameter
  - Gravity, 2.0 cm
  - Radiation pressure, 2.0cm
  - Atmospheric drag, 1.0 cm
  - Geoid model, 1.0 cm
  - Solid earth and ocean tide, 1.0 cm
  - Troposphere, < 1 cm
  - Station location, 1.0 cm
- ⇒ **Total radial orbit error, 3.5 cm**
  - Mission design specification, 12.8 cm
- **With latest, state-of-art models, the above total orbit error decreases to ~2.0 cm**

- As the radar signal travels through the atmosphere it is slowed down w.r.t. speed of light in the vacuum
- Since we need speed to estimate range, we must correct for this effect.
- There are three parts of the atmosphere that must be taken into account
  - Ionosphere
  - Dry troposphere
  - Wet troposphere

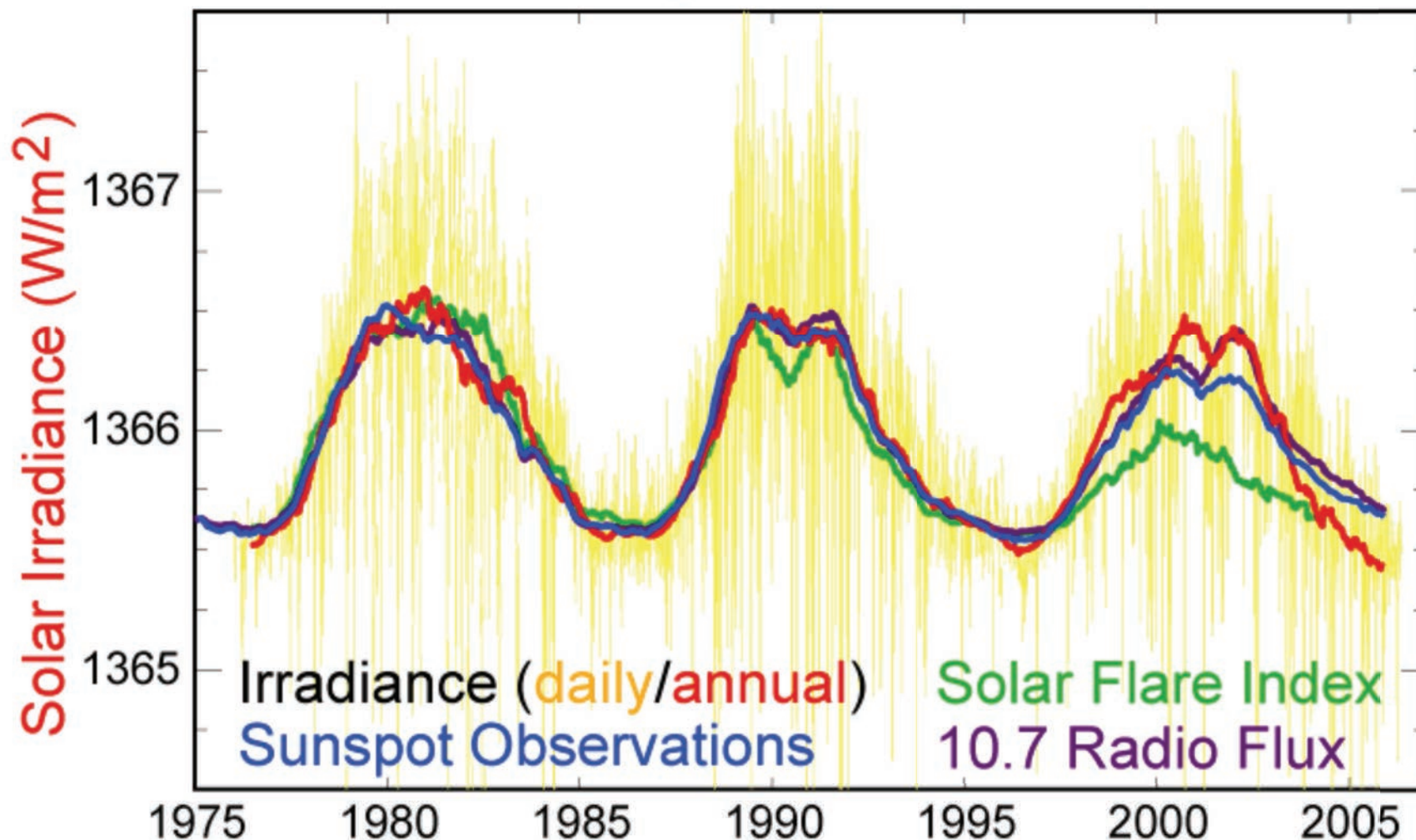


- Caused by free electrons in the ionosphere
- Frequency dependent so it can be measured with a dual frequency altimeter:

ERS-1/2 × Topex ✓ Jason-1/2 ✓ Envisat ✓ (only up to 17/01/08) GFO × Cryosat × AltiKa × (Ka band almost unaffected by ionosphere)

- Otherwise use a model or other observations from another dual frequency radar system (GPS, DORIS)
- Average value 45mm, s.d. 35mm
- Depends on solar cycle and time of day
- GIM (based on GPS, produced by JPL) is a good product to use for single-frequency altimeters

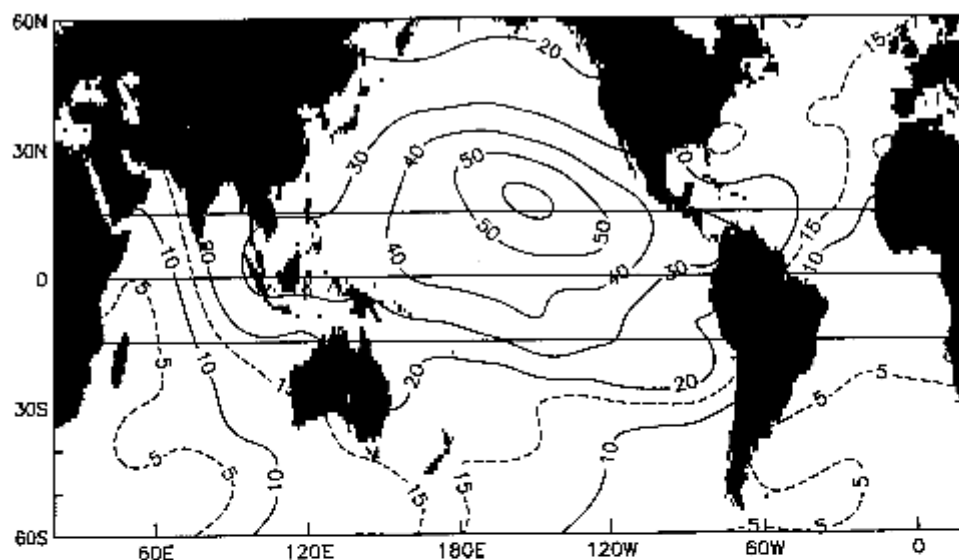
# Solar Cycle Variations



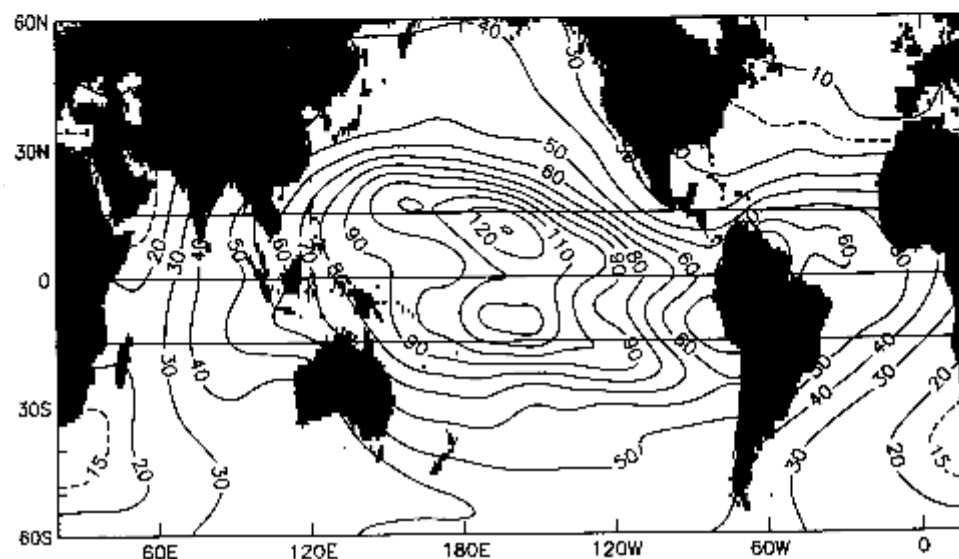
<http://spaceodyssey.dmns.org/media/13466/solar-cycle-data.png>



# Typical IonO correction values (mm)



Low solar activity



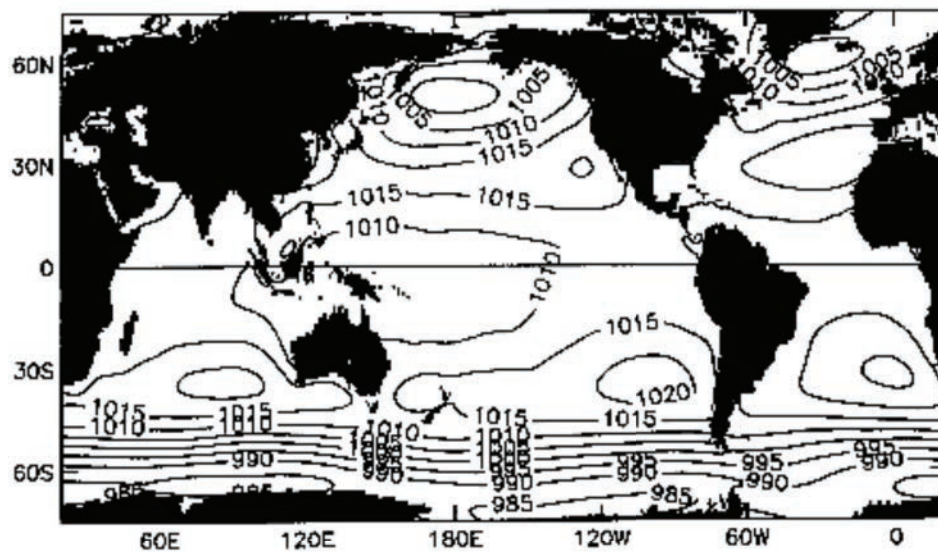
High solar activity

- Due to O<sub>2</sub> molecules in the atmosphere
- Derived from atmospheric pressure (from met models) by:

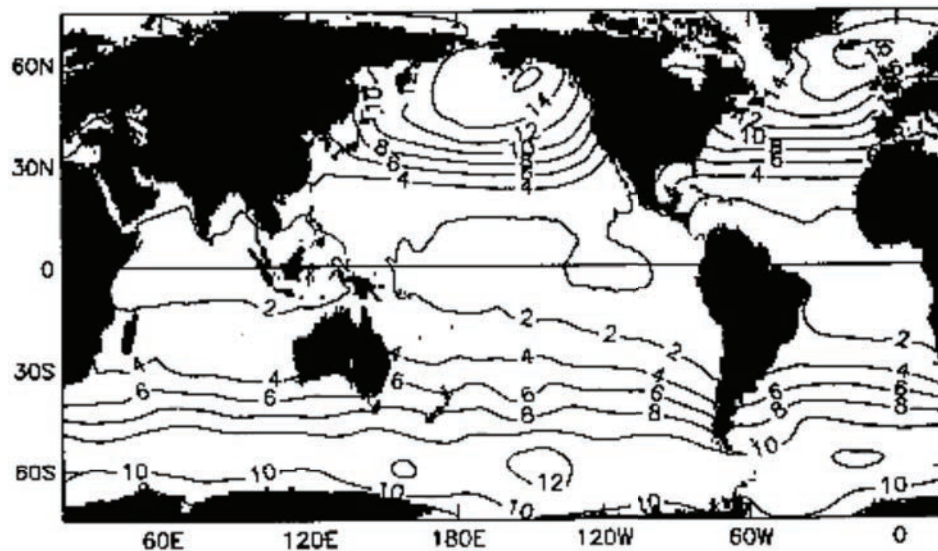
$$\text{Dry\_trop (mm)} = 2.277 \text{ p (hPa)} (1 + 0.0026 \cos(2 \times \text{latitude}))$$

- Average value 2300 mm, s.d. 30 mm





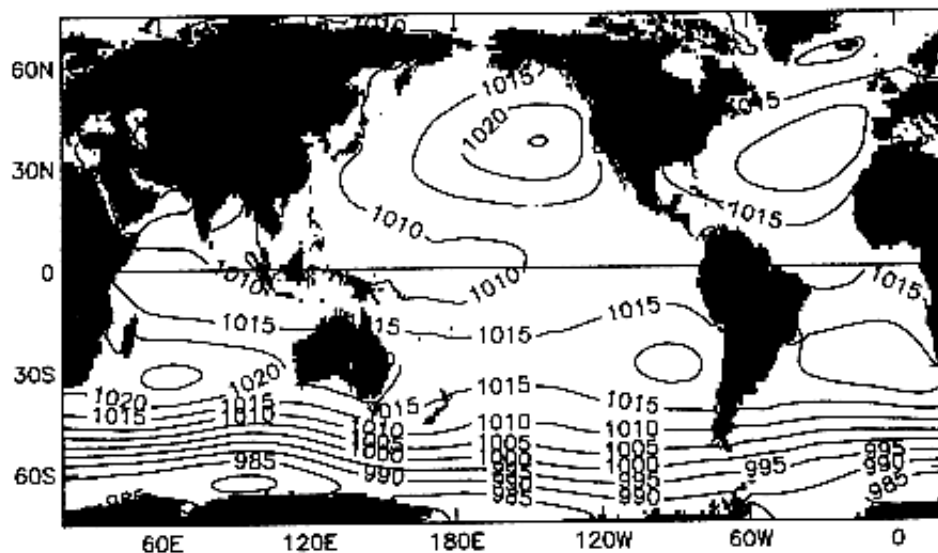
Winter DJF  
Air Pressure  
Mean (hPa)



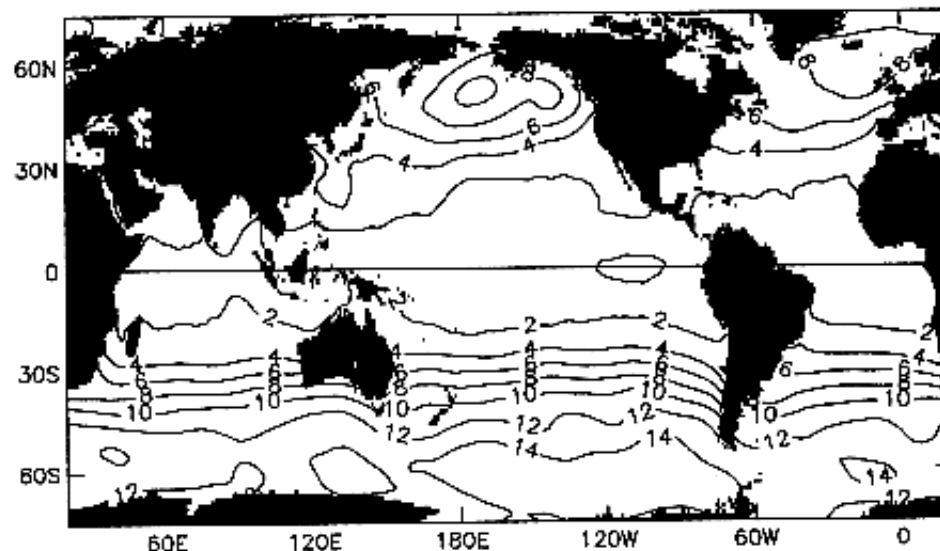
Standard  
deviation



# Summer JJA Atmospheric Pressure Mean (hPa)



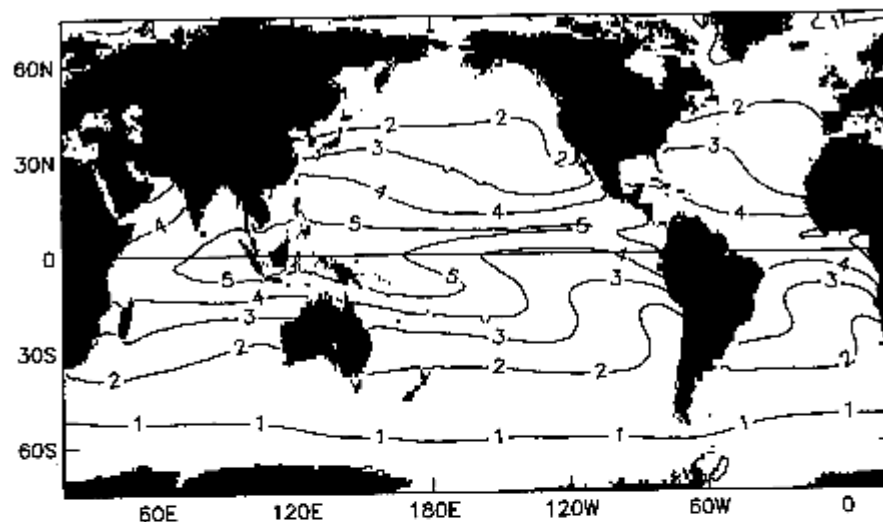
# Standard Deviation



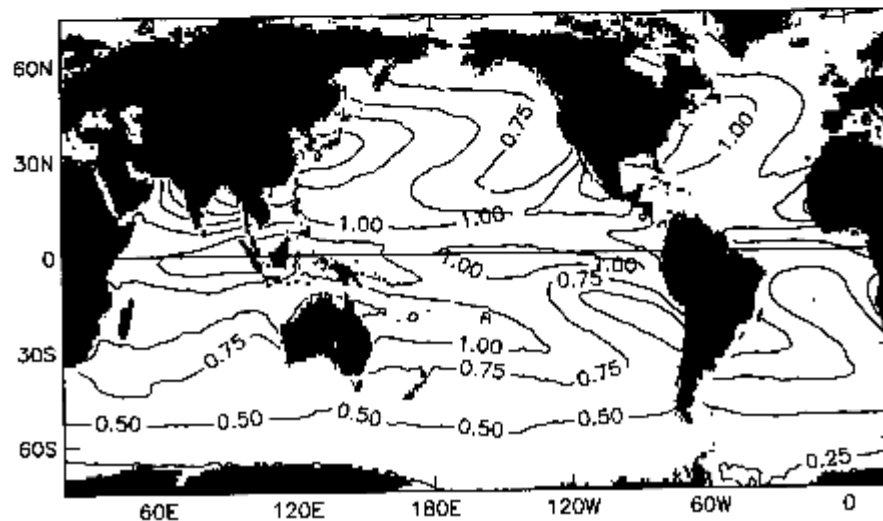


- Caused by water vapour in the atmosphere
- This is a difficult correction due to the high temporal and spatial variability of water vapour
- Average value 150 mm, s.d. ~50 mm
- Obtained by microwave radiometer on satellite
  - two frequency on ERS-1/2 and Envisat
  - three frequency on T/P and Jason-1/2
- Or from weather forecasting models (ECMWF)
- New approach: from GPS measurements and/or passive microwave radiometers on other satellites
  - GPD and DCOMB corrections by Univ. Porto

Tropospheric  
water vapour  
from SSM/I  
Mean ( $\text{g/m}^2$ )



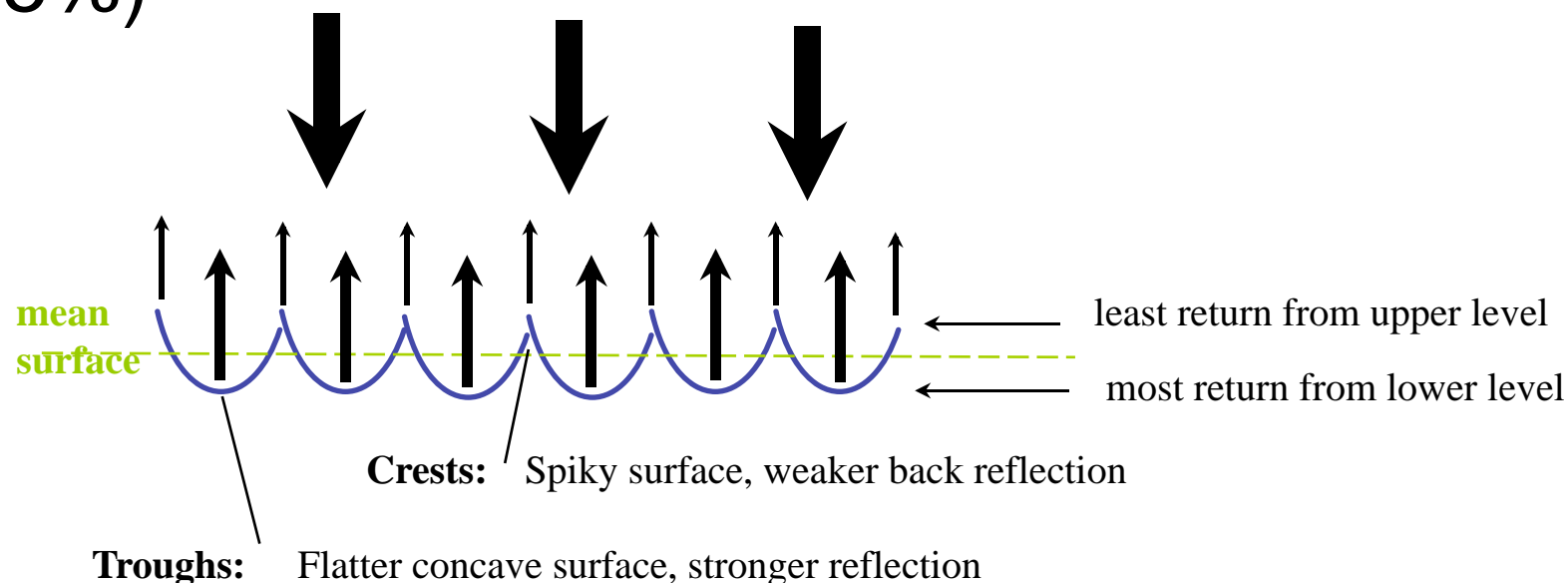
Standard  
deviation





- Ionospheric correction: 2-20 cm [ $\pm$  3 cm]
  - Caused by presence of free electrons in the ionosphere
  - Use model or measure using dual frequency altimeter
- Dry tropospheric correction: 2.3 m [ $\pm$  1-2 cm]
  - Caused by oxygen molecules
  - Model the correction accurately using surface atmospheric pressure
- Wet tropospheric correction: 5-35 cm [ $\pm$  3-6 cm]
  - Caused by clouds and rain (variable)
  - Measure H<sub>2</sub>O with microwave radiometer
  - Or use weather model predictions
  - Or (more recent approaches): path delays from GPS stations; measurements from other satellite-borne passive radiometers

- Tracker bias
  - Problem with “tracking” the pulse when the sea is rough
- Electromagnetic Bias
  - Radar return from the troughs is stronger than from the crests
- First approx: empirical correction based on  $H_s$  (~5%)

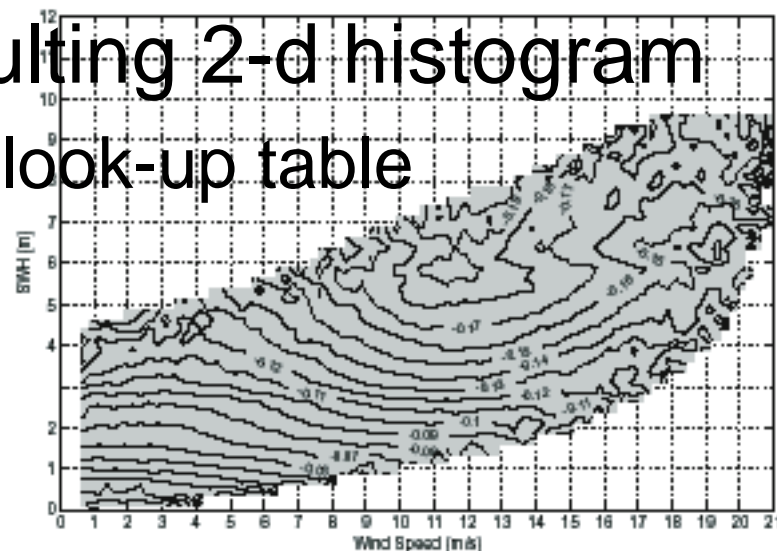




- There is as yet no **theoretical method** for estimating the sea state bias.
- We are therefore forced to use **empirical methods**
- We find the function of  $H_s$  (and  $U_{10}$  - that is wind) that minimises the altimeter crossover differences or the differences w.r.t in situ observation (from wave buoys)
- Sea State Bias is intimately linked to the retracking model adopted
- Sea State Bias for SAR altimetry, is particularly in need of better characterization.

- With parametric methods we have a specified function for the SSB and estimate the parameters of this function, e.g. the BM4 model used for TOPEX
  - Then we use the fitted function
- With non-parametric methods we compile statistics and smooth the resulting 2-d histogram
  - Then we use the histogram as look-up table

An example  
non-parametric  
SSB

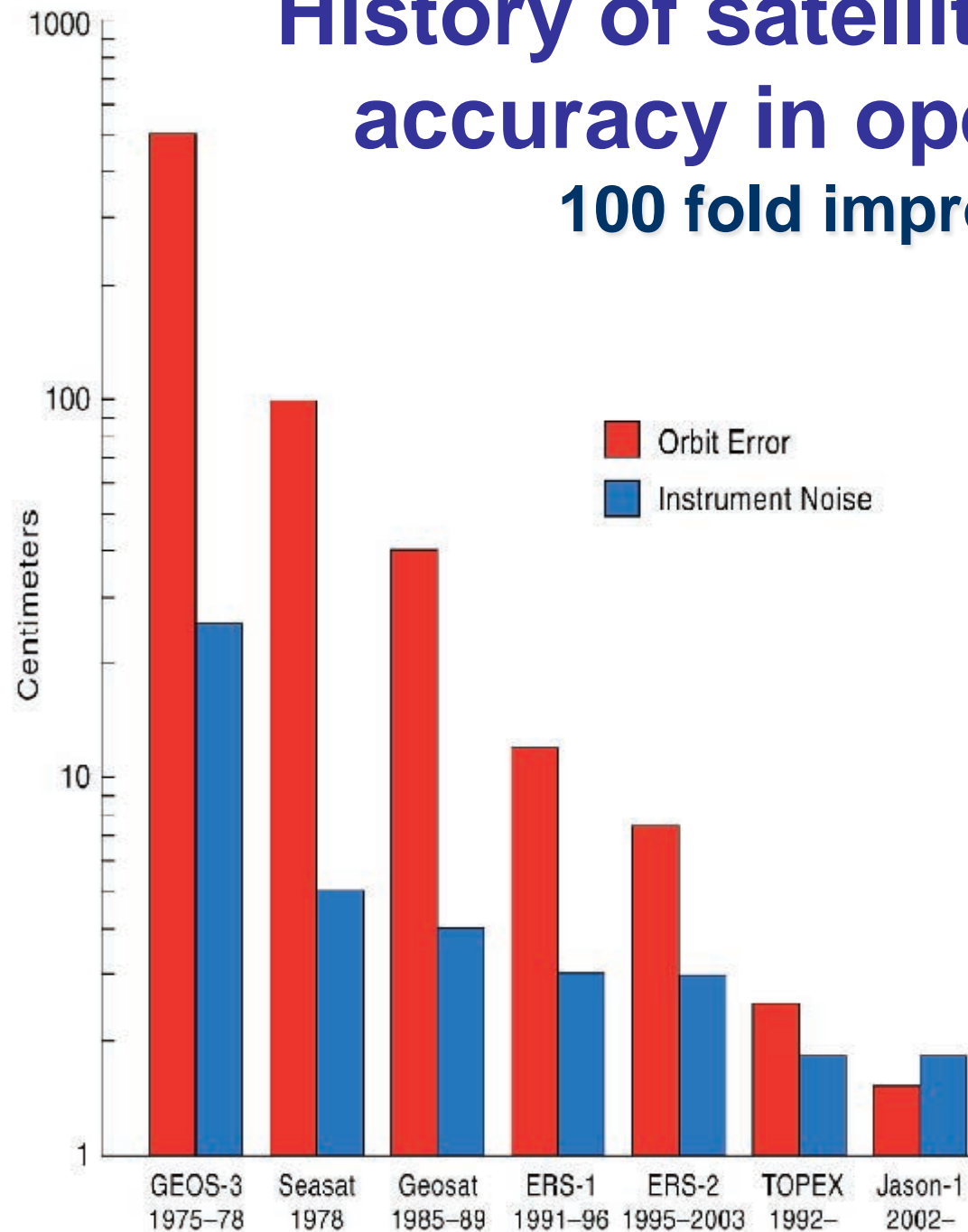




Source	Error
Instrument Noise	1.7cm
Ionosphere	0.5cm
EM Bias	2.0cm
Skewness	1.2cm
Dry Troposphere	0.7cm
Wet Troposphere	1.1cm
Orbit	2.5cm
<b>Total</b>	<b>4.1cm</b>

# History of satellite altimetry accuracy in open ocean

**100 fold improvement in 25 years !**



**Now at 1-2 cm level!!**

Courtesy of Lee-Lueng Fu.,  
NASA



**Table 7**

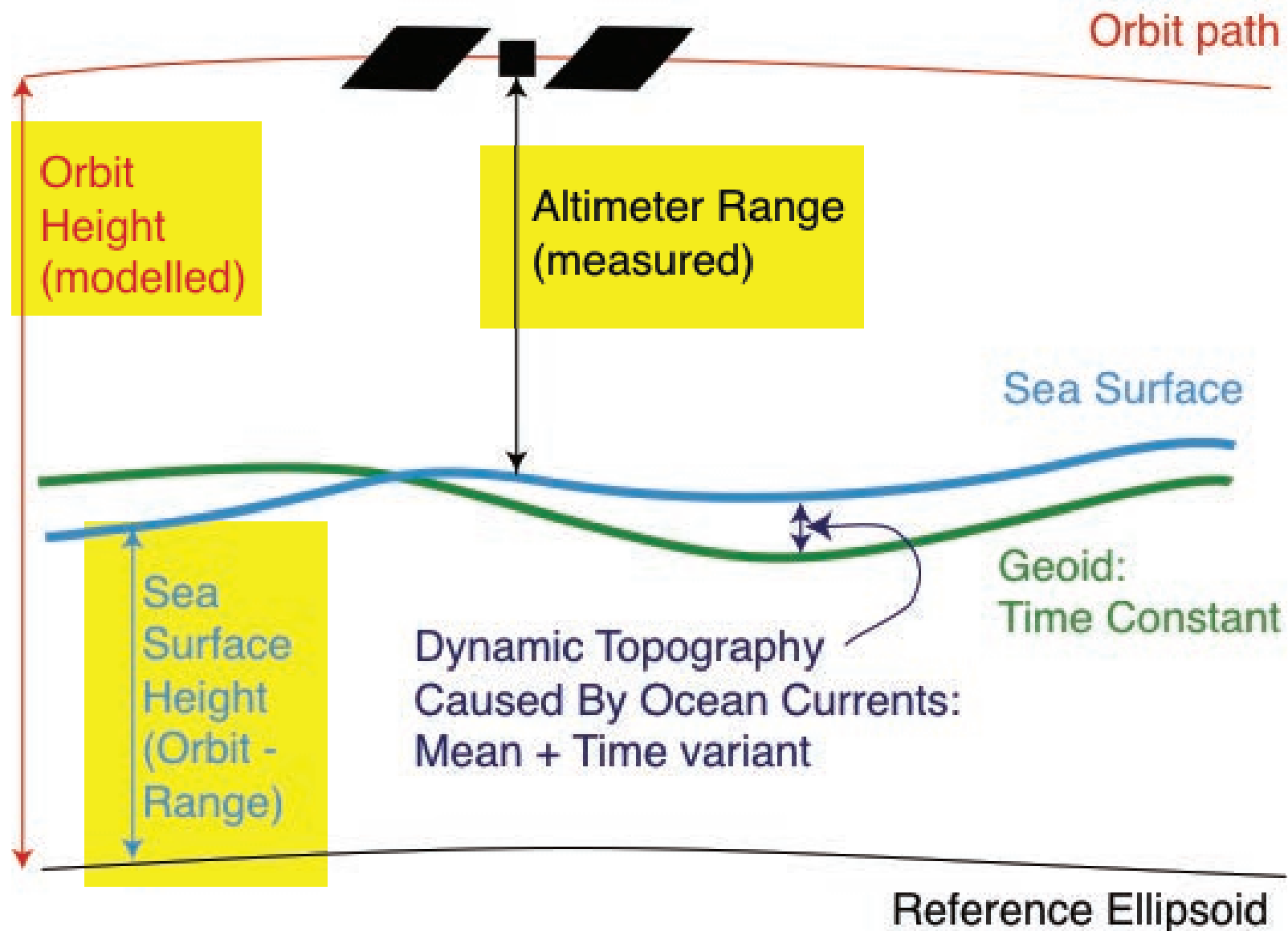
Estimated Sea Surface Height (SSH) error budget for the Sentinel-3 topography mission.

Source	ENVISAT error [cm]	S-3 error [cm]	Contributor
Altimeter noise	1.8	1.4 for LRM	SRAL
Sea state bias	2	2	SRAL
Ionosphere	0.5	0.5	SRAL
Dry troposphere	0.7	0.7	SRAL
Wet troposphere	1.4	1.4	MWR
Total range error	3.1	2.9	
Radial orbit error	1.9	1.9	POD
Sea Surface height error	3.6	3.4	

from Donlon et al., 2012

**Altimeter noise expected in SAR mode < 1 cm (@ 1 Hz, 2m SWH)**

All the processing seen so far is to get a good  
**SSH=orbit-range**



**Next: what is there in the SSH? ....**

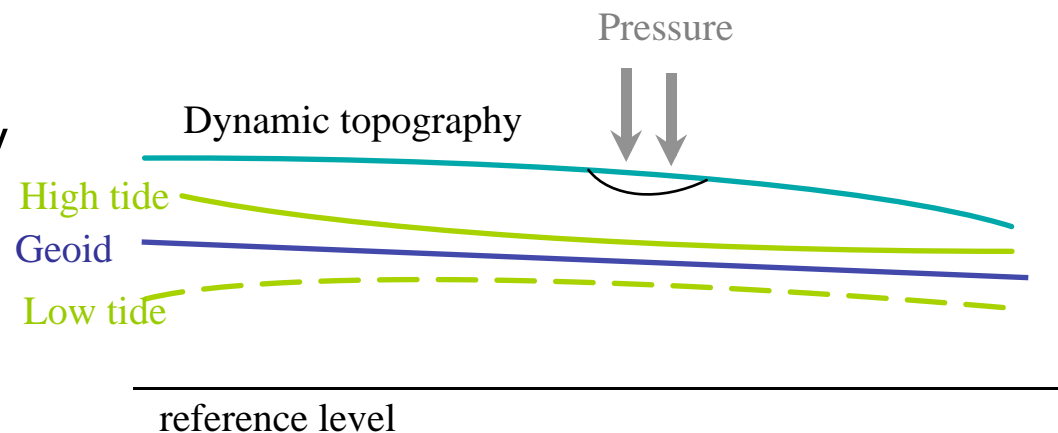


## Geoid (~100 m)

- Time invariant
- Not known to sufficient accuracy
- To be measured independently (gravity survey)

## Tides (~1-2 m)

- Apply a tidal prediction
- New tidal models derived from altimetry
- Choose orbit to avoid tidal aliasing



## Atmospheric pressure (~0.5 m)

- Apply inverse barometer correction (1mbar ~ 1 cm)

## Dynamic topography (~1 m)

- The intended measurement

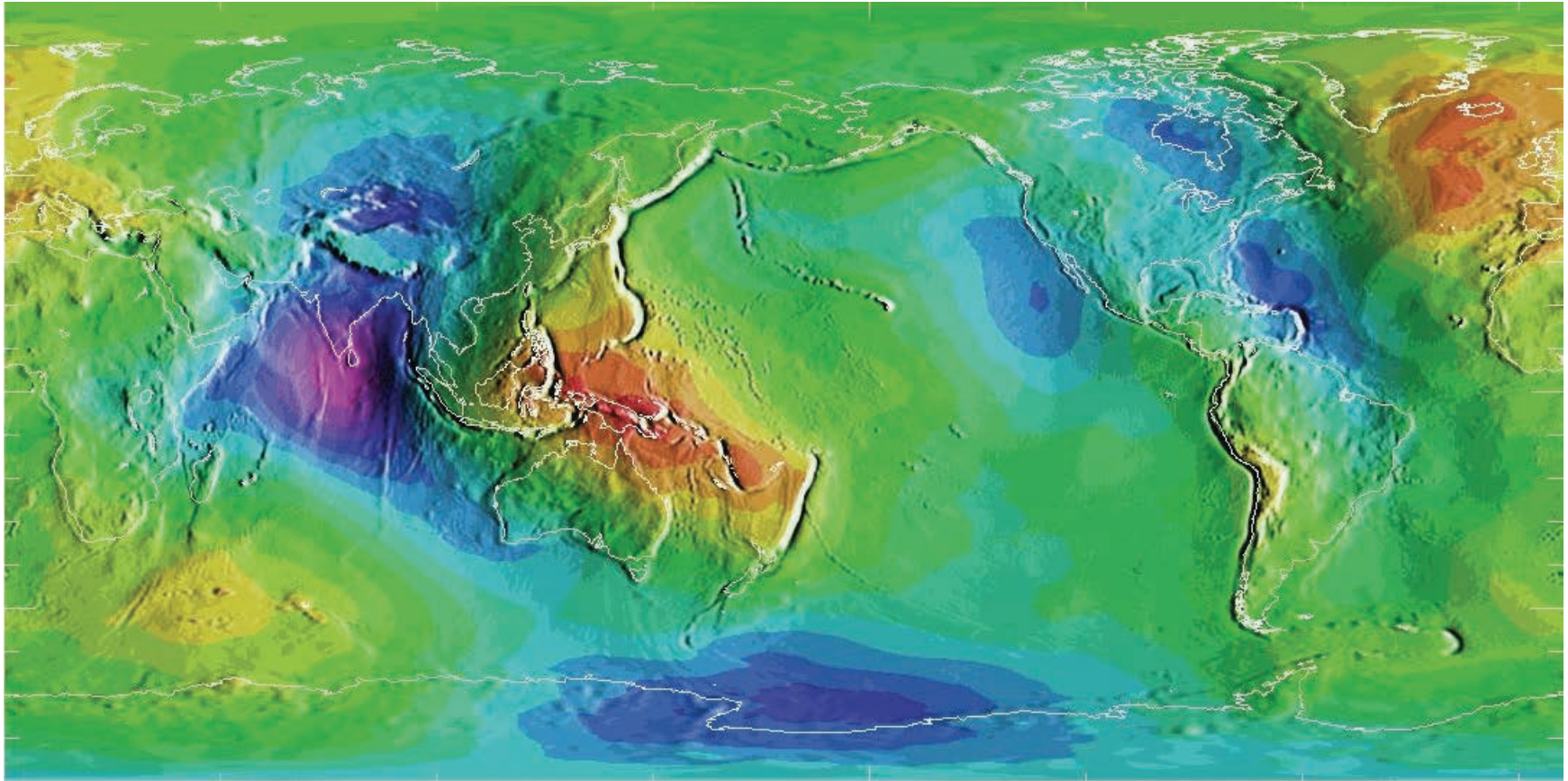
**Some of these we want to correct for  
– or not, depending on the application!!!**

- When air pressure changes the ocean acts like a barometer (in reverse). High air pressure depresses the sea surface, low air pressure raises it.
- 1 mbar (hPa) change in air pressure is approximately equal to a 1cm change in the sea surface
- Good in mid and high latitudes not in Tropics
- Also, not very accurate in enclosed basins (like the Mediterranean)
- and there are other-high frequency fluctuations of the ocean
- Latest high-resolution barotropic models (like MOG2D/T-UGO) allow a very accurate correction of the atmospheric forcing



- The geoid is the surface of equal gravity potential on the Earth's surface (the shape of the Earth)
- The ellipsoid is an approximation to the shape of the Earth
- We know the ellipsoid - we do not know the geoid with the accuracy we would like!!!

# The Geoid

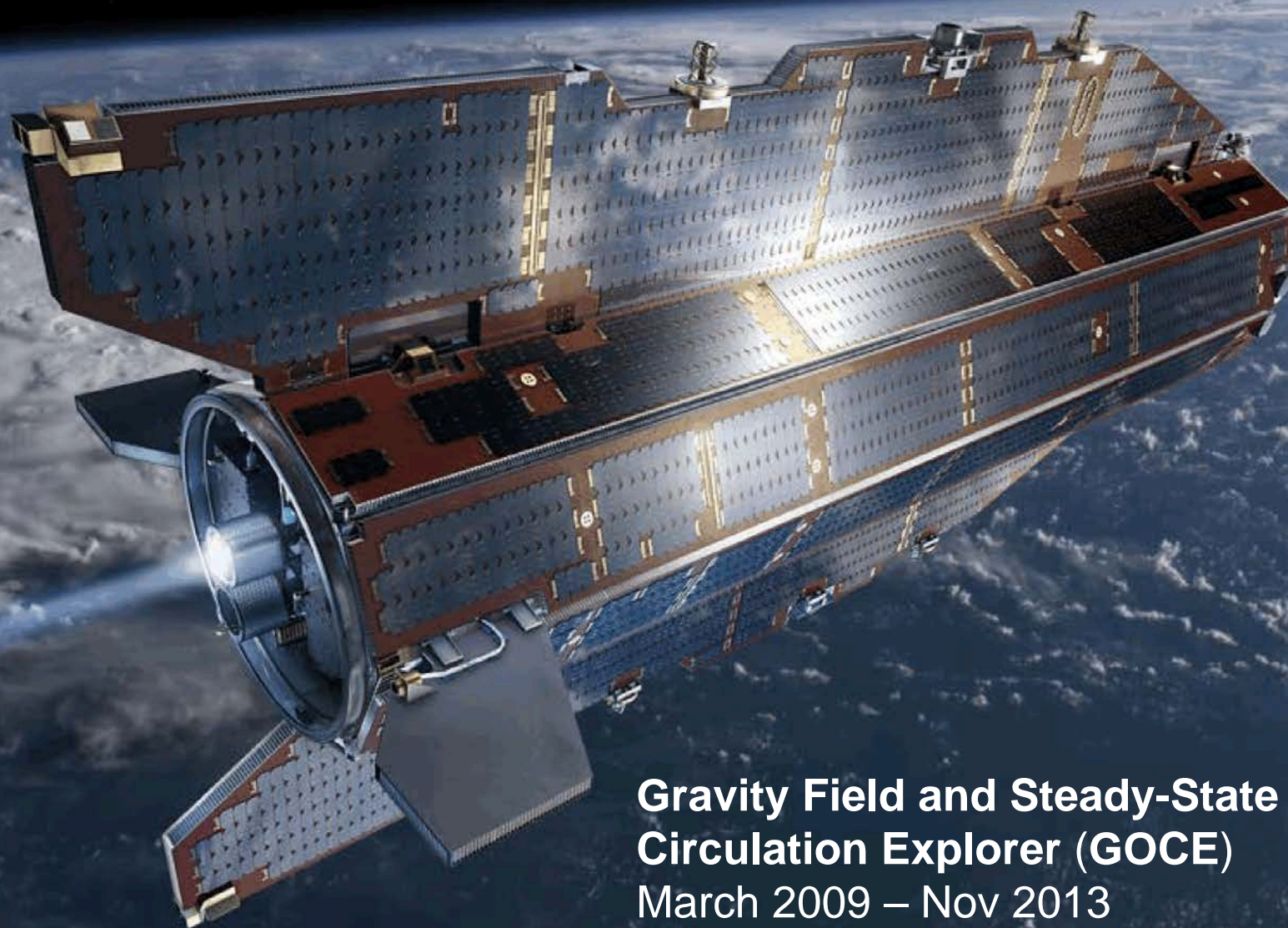


Scale: magenta (-107 m) to red (84.5 m)



- The geoid is usually expressed in terms of spherical harmonics (sine curves on the sphere). These have degree and order
  - Degree and order 360 is a resolution of approx.  $1^\circ$
- Sea surface pressure and hence geostrophic currents are in terms of sea surface height relative to the geoid
- We measure sea surface height (and hence slopes) relative to the ellipsoid.



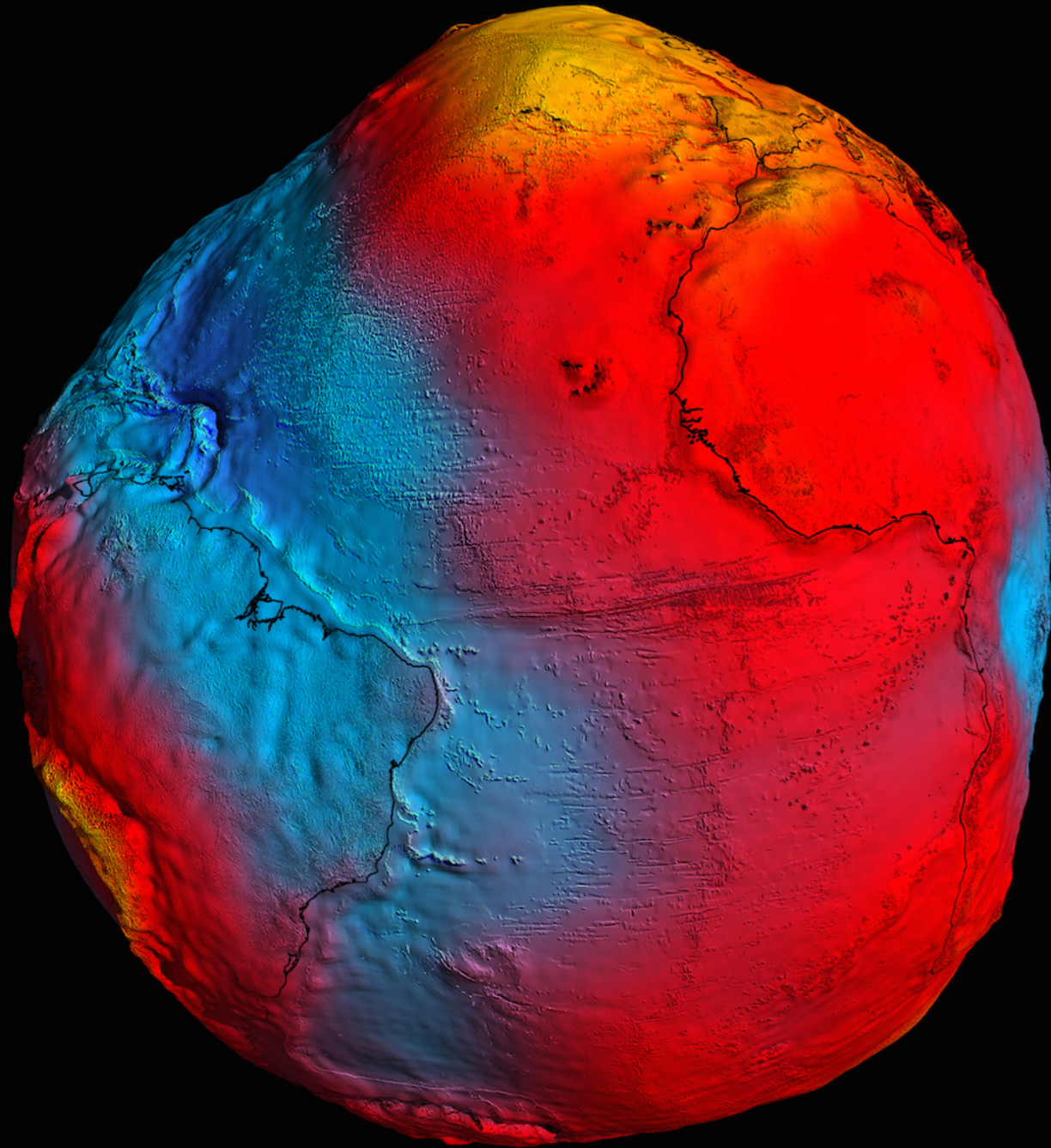


## Gravity Field and Steady-State Ocean Circulation Explorer (GOCE)

March 2009 – Nov 2013



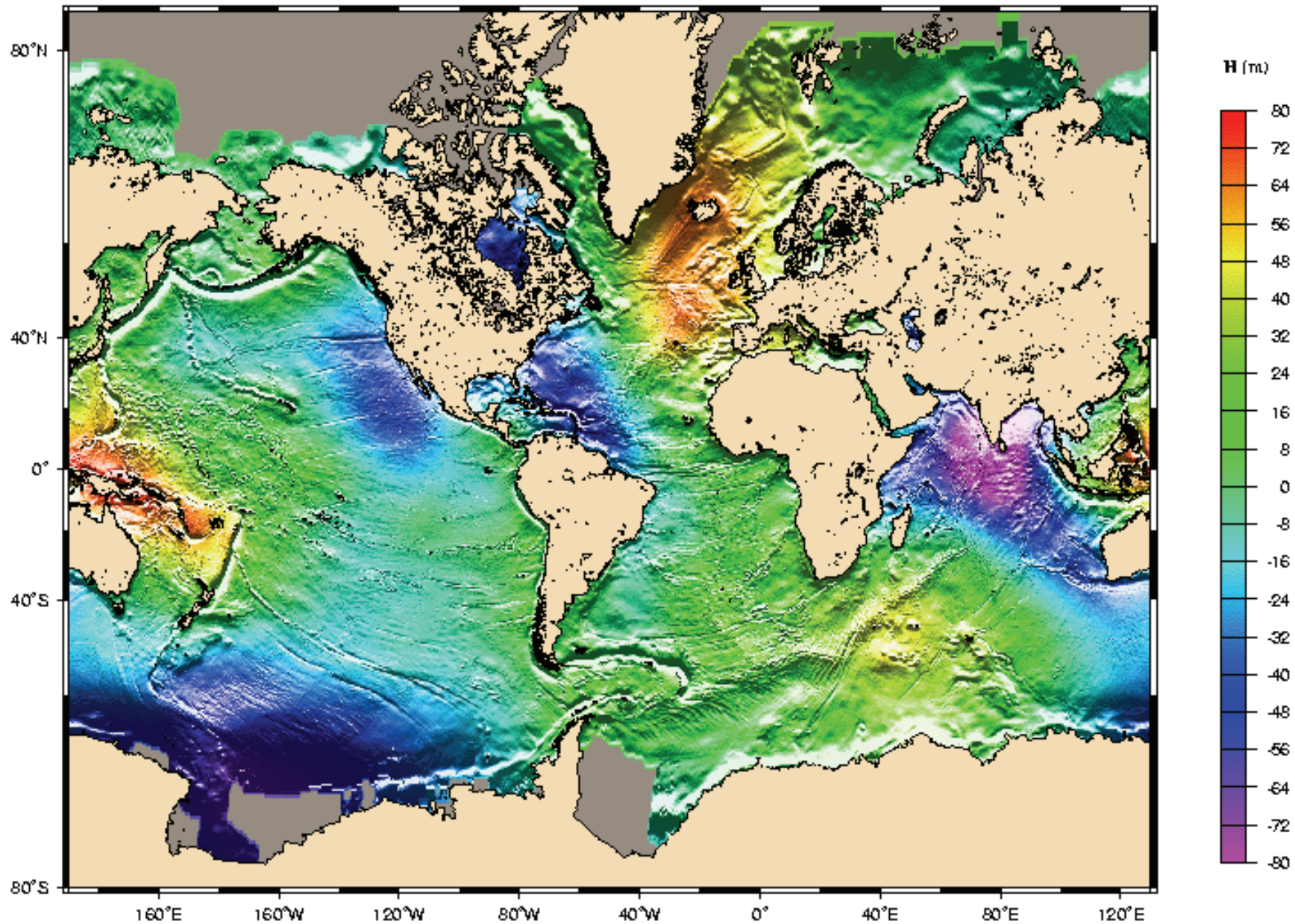
# GOCE geoid



- The geoid is time invariant (approximately)
- So if we subtract a mean sea surface we will remove the geoid
- But we lose ...  
... the mean circulation



# Mean sea surface

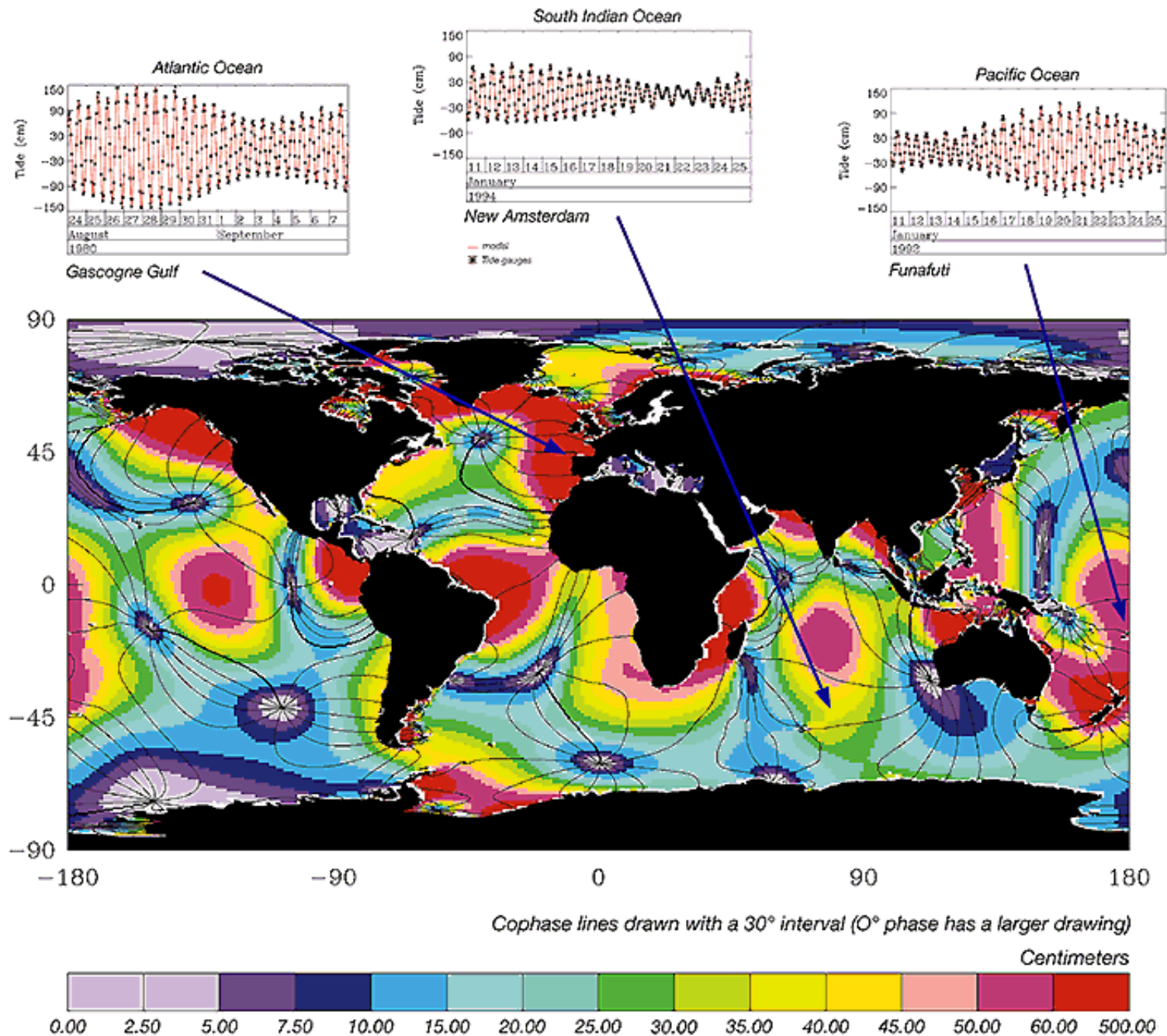


- The sea surface height residual (or Sea Surface Height Anomaly - SSHA) is what remains after removing the mean in each location (Mean Sea Surface)
- Any constant dynamic topography (from steady currents) will have been removed!
- Contains only the **time-varying** dynamic topography
- May still contain time varying errors
  - Un-removed tidal or barometric signal
  - Orbit error
- With the recent independent accurate geoid models (from GRACE and ESA GOCE mission) we are getting closer to be able to subtract the geoid and work with **absolute dynamic topography** (much better for oceanographers!)



- If we are going to use altimetry for oceanographic purposes we need to remove the effect of the tides
- Alternatively we could use the altimeter to estimate the tides - tidal models have improved dramatically since the advent of altimetry!
- In general we use global tidal models to make predictions and subtract them from the signal

# The up and down of the ocean tides



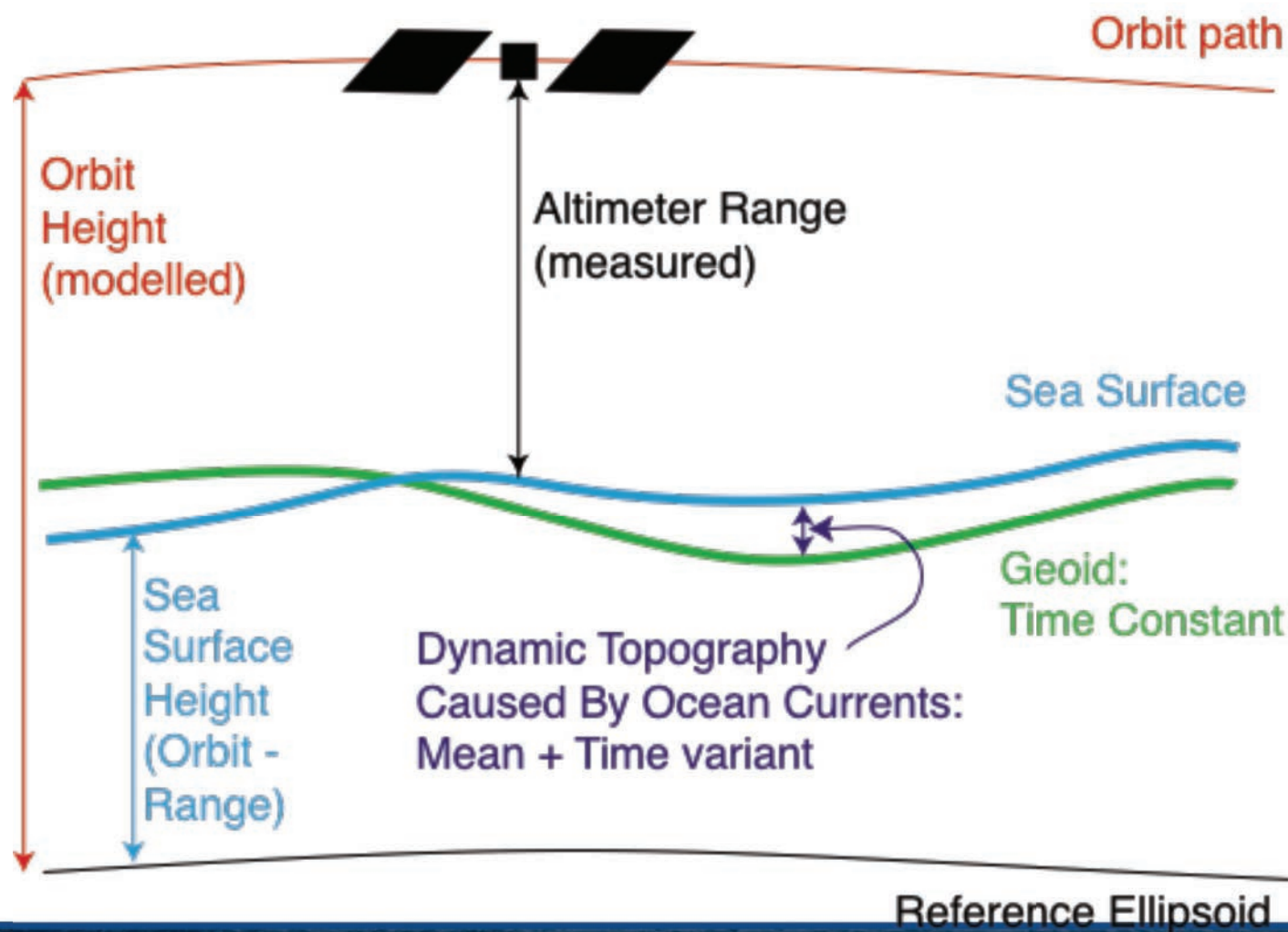
Source : IMG/LEGI, Grenoble 1995



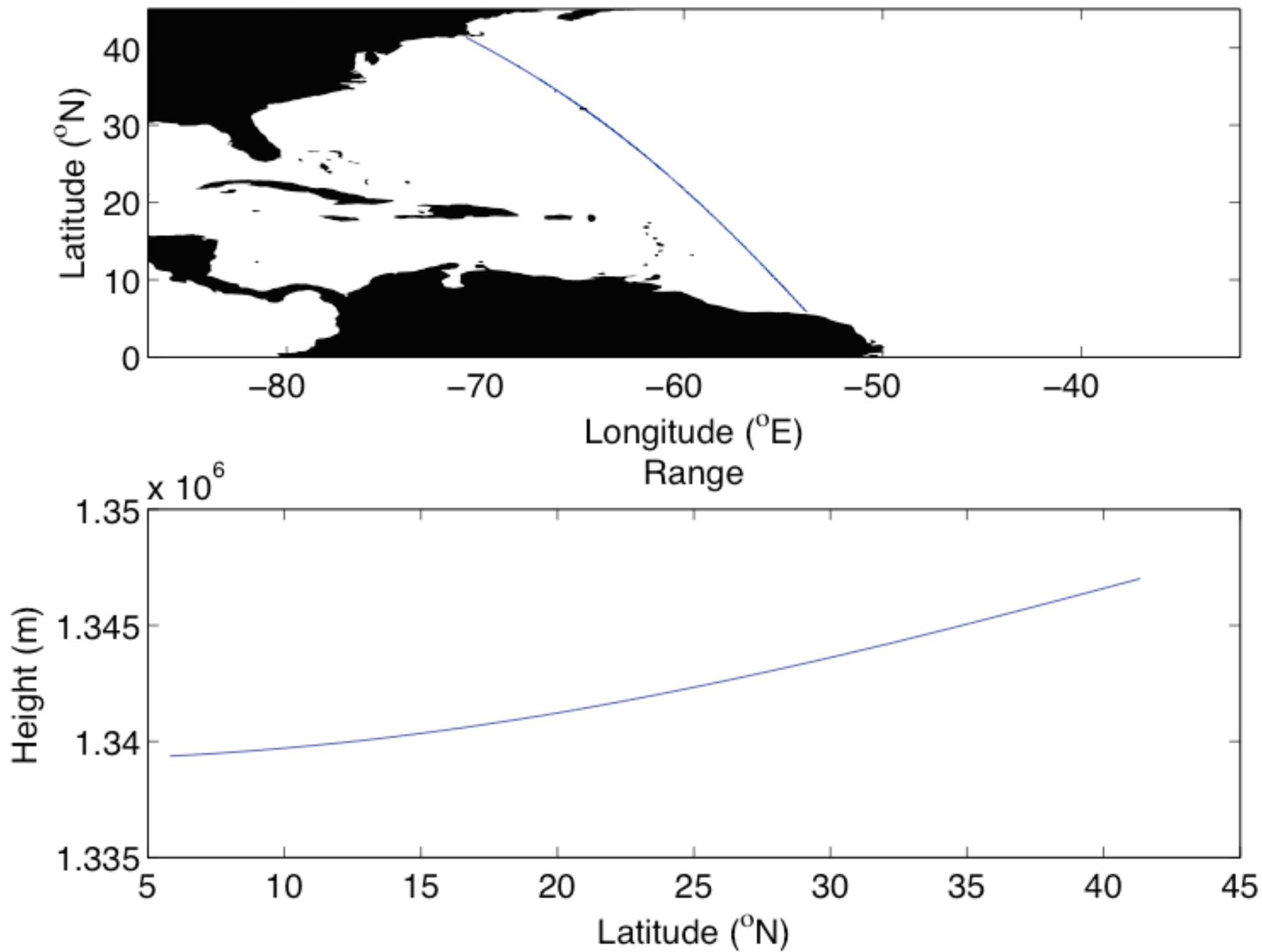
- As well as the ocean tide we have to consider
  - the loading tide (the effect of the weight of water). This is sometimes included in the ocean tide
  - the solid earth tide
  - the polar tide
- On continental shelves the global models are not very accurate and local models are needed
- Any residual tidal error is going to be aliased by the sampling pattern of the altimeter

Tide	Period (h)	T/P		ERS	
		Alias (days)	wave length (°)	Alias (days)	wave length (°)
M2	12.42	62	9E	95	9E
S2	12	59	180W	0	∞
N2	12.65	50	9W	97	4W
K1	23.93	173	360W	365	360E
O1	25.82	46	9.23E	75	9E
P1	24.07	89	360W	365	360W



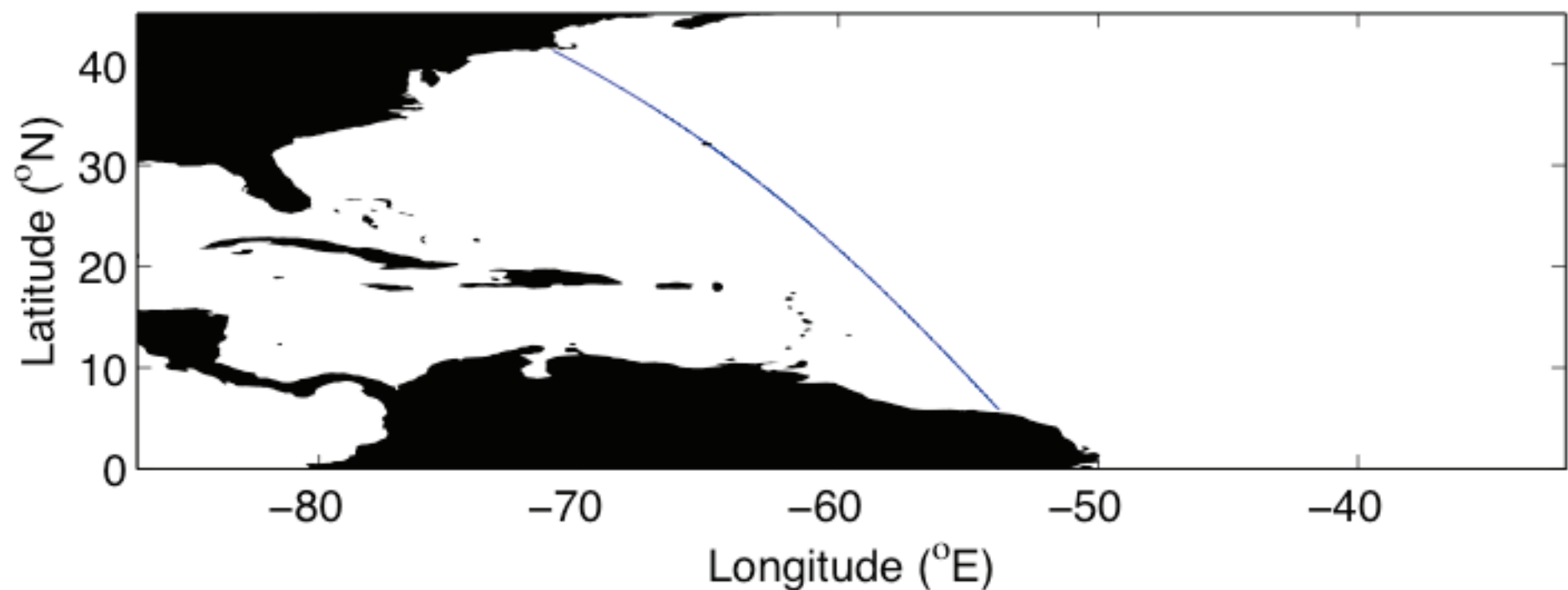


Jason Pass 126, Cycle 20

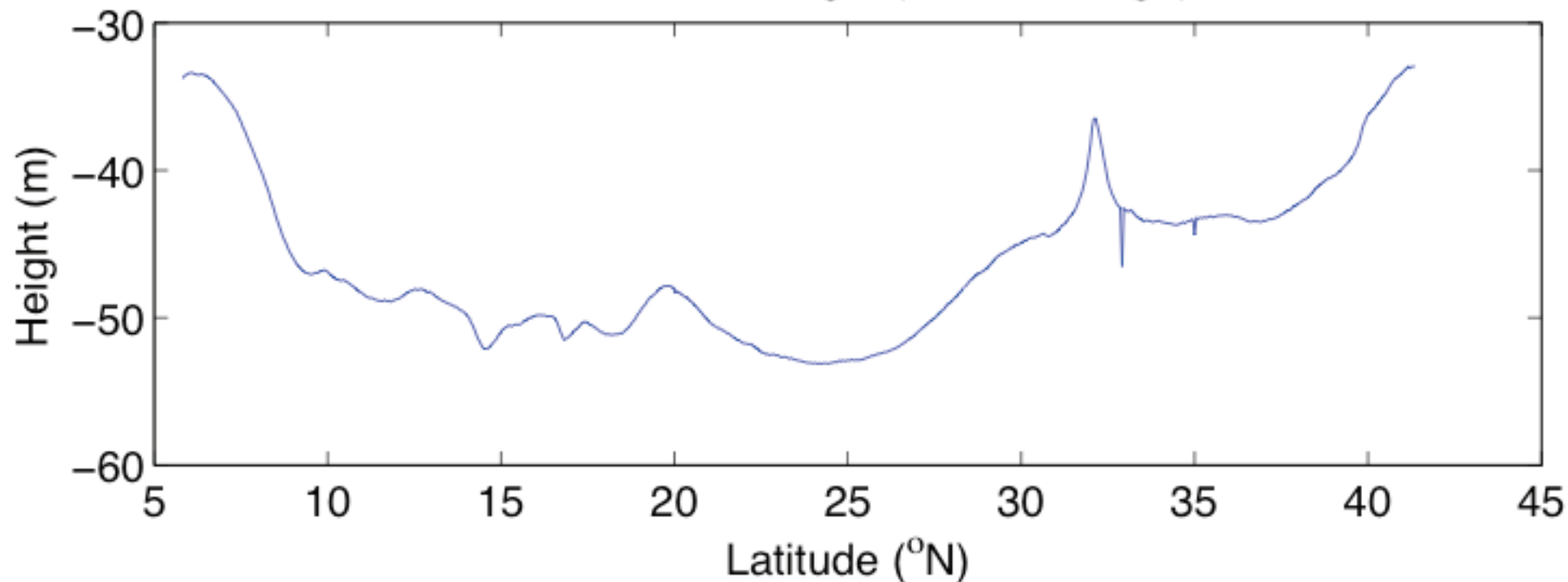




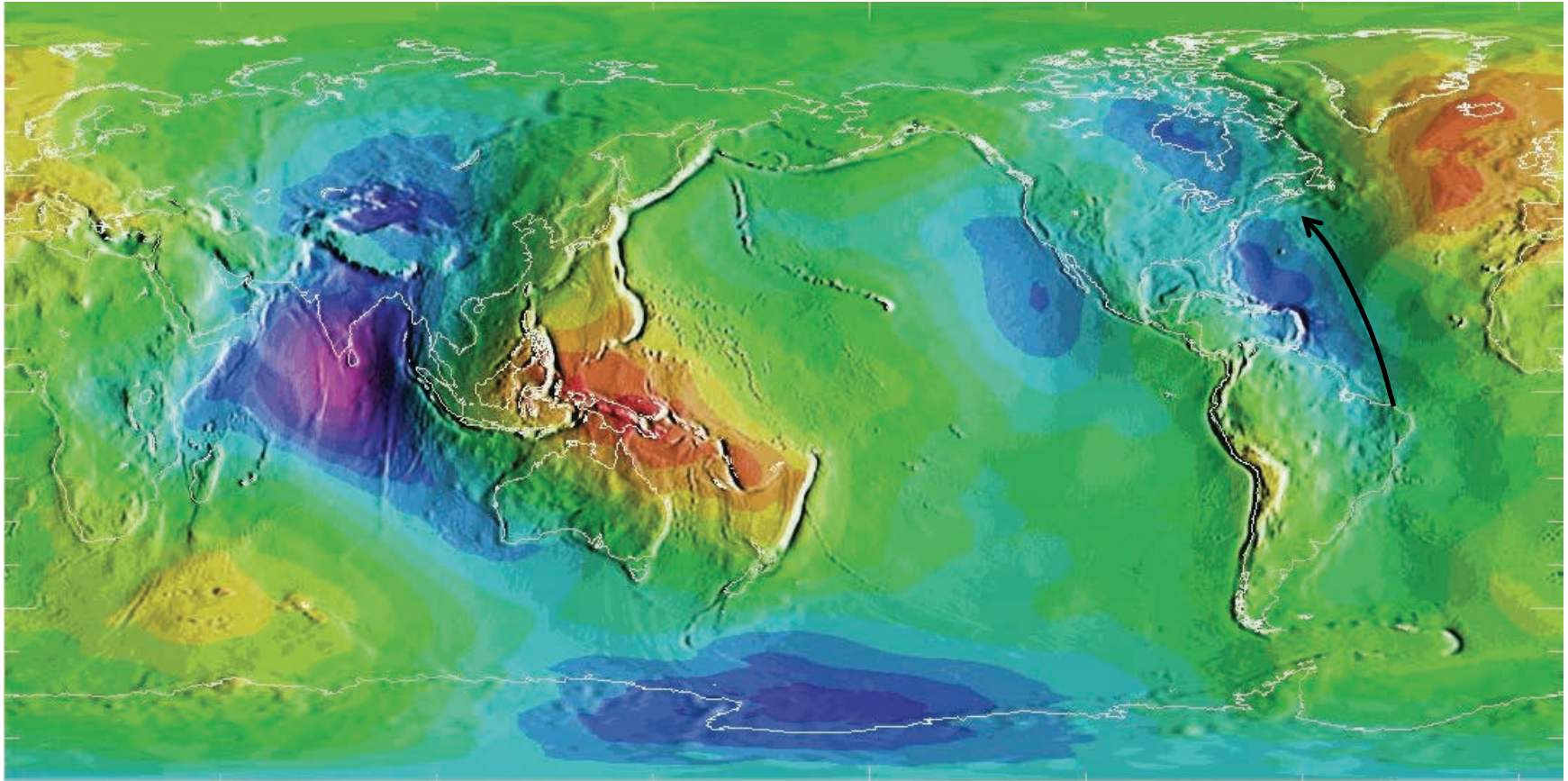
Jason Pass 126, Cycle 20



Sea Surface Height (Orbit - Range)



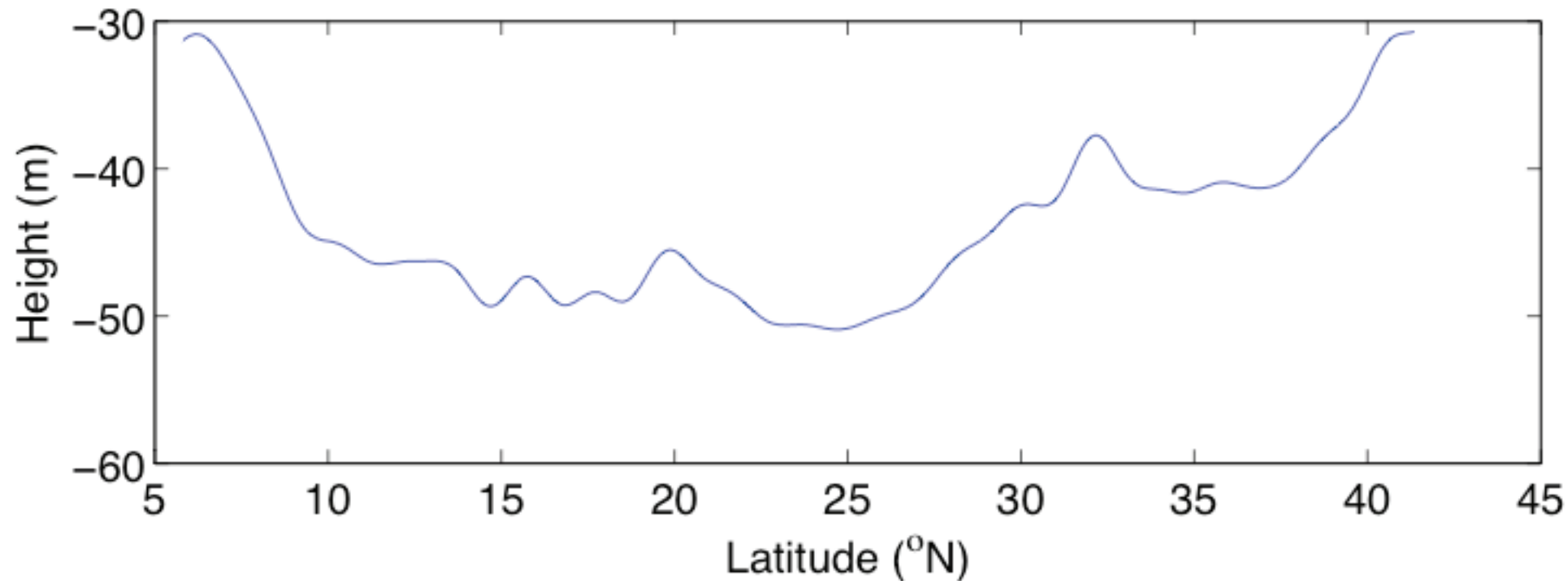
# The Geoid



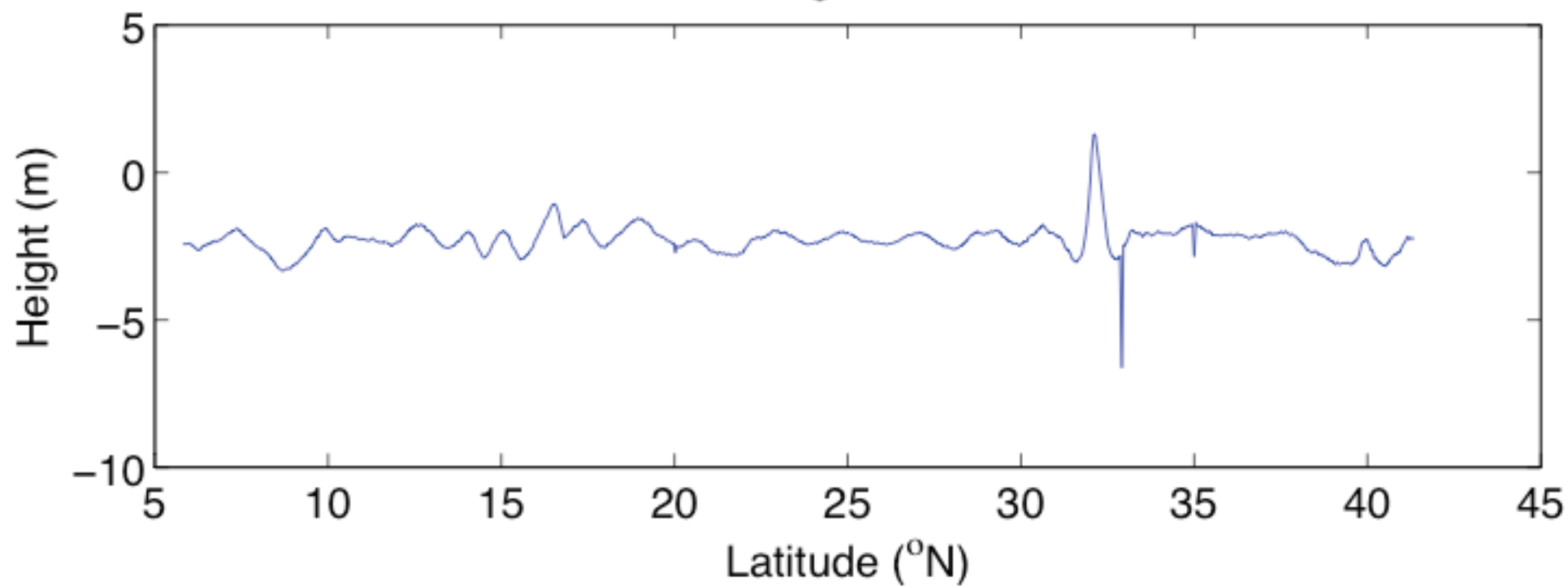
Scale: magenta (-107m) to red (84.5m)



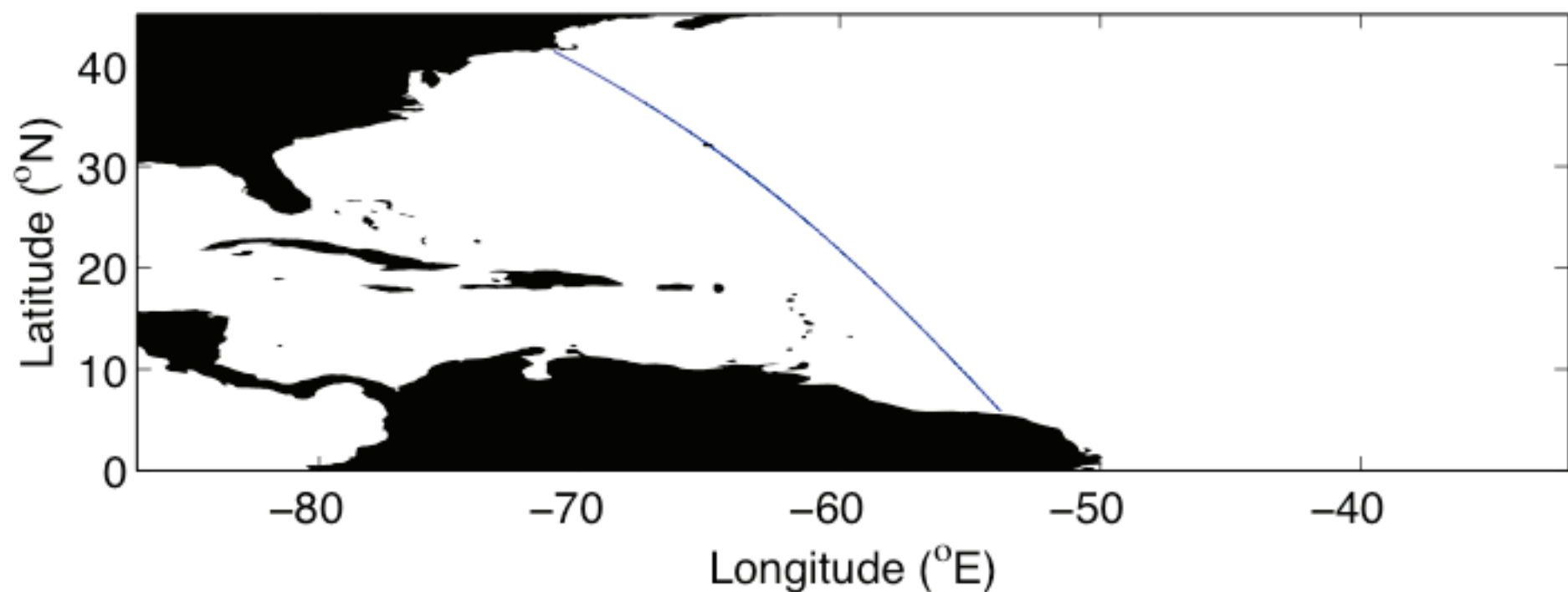
Geoid



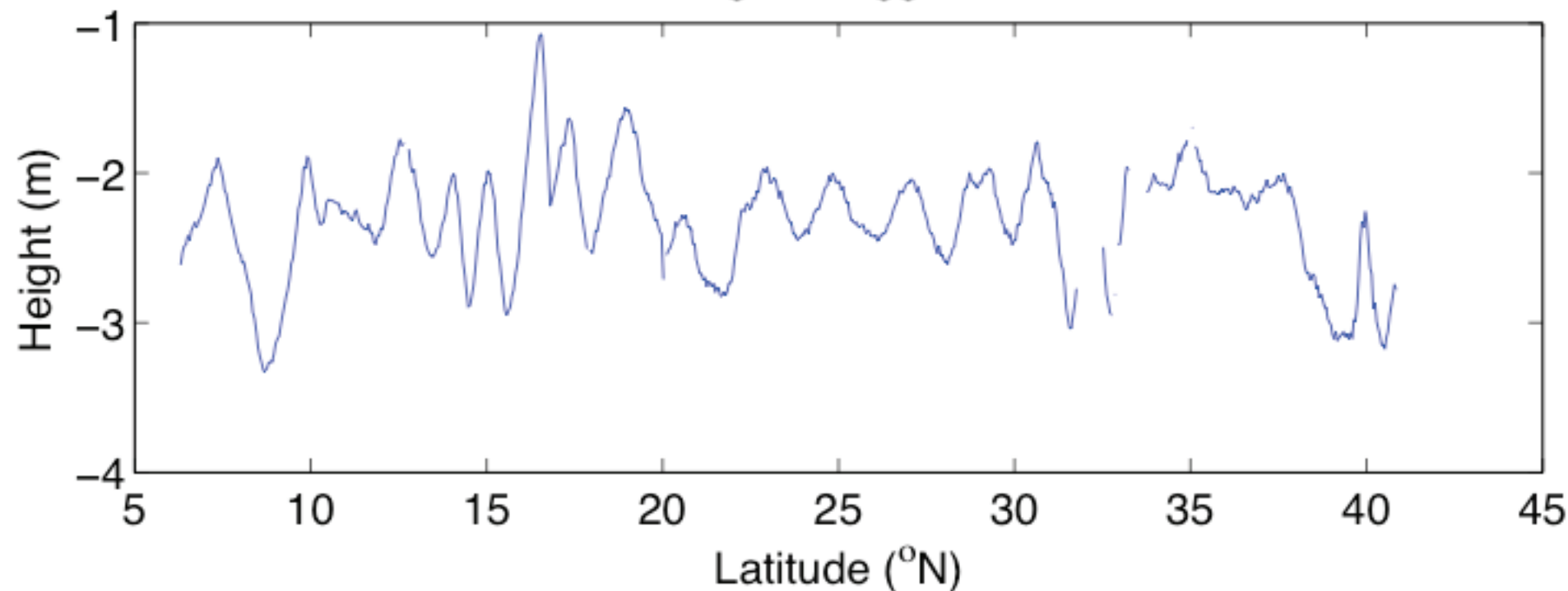
Sea Surface Height: Geoid Removed



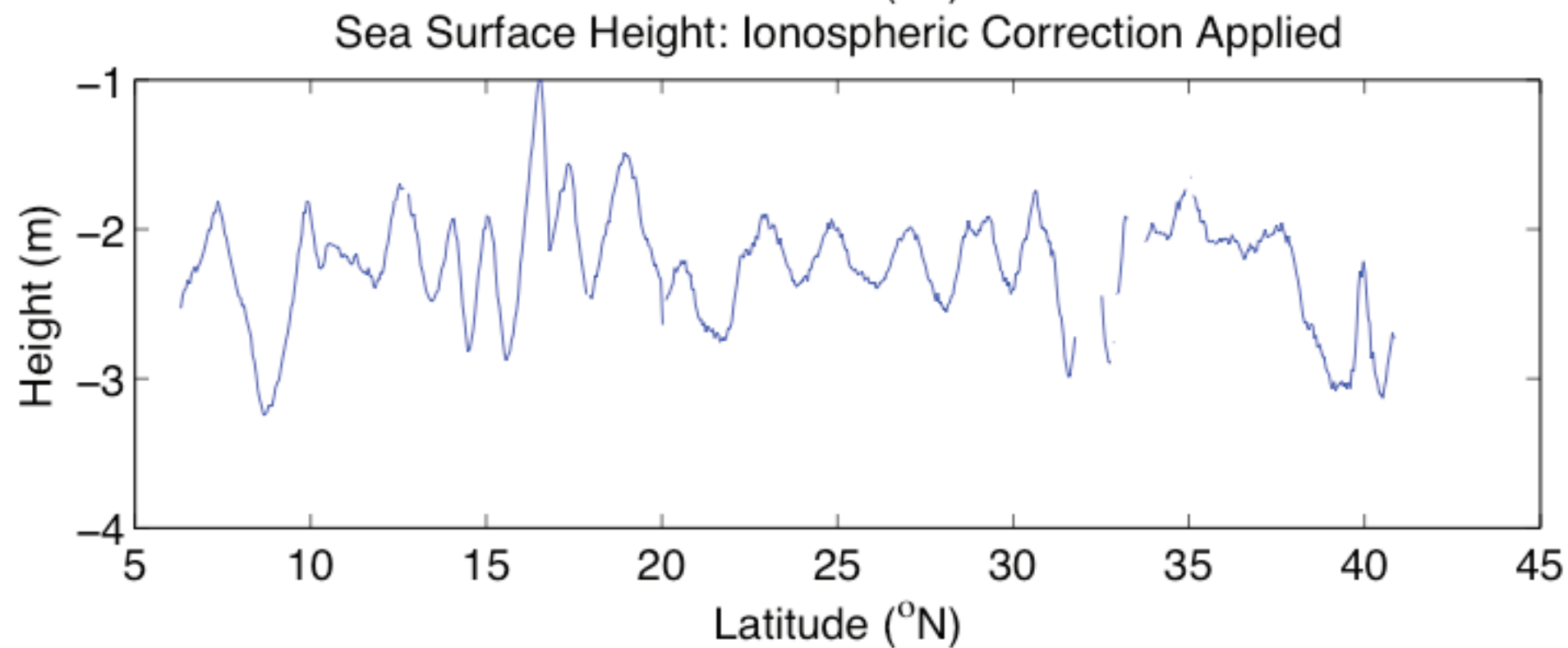
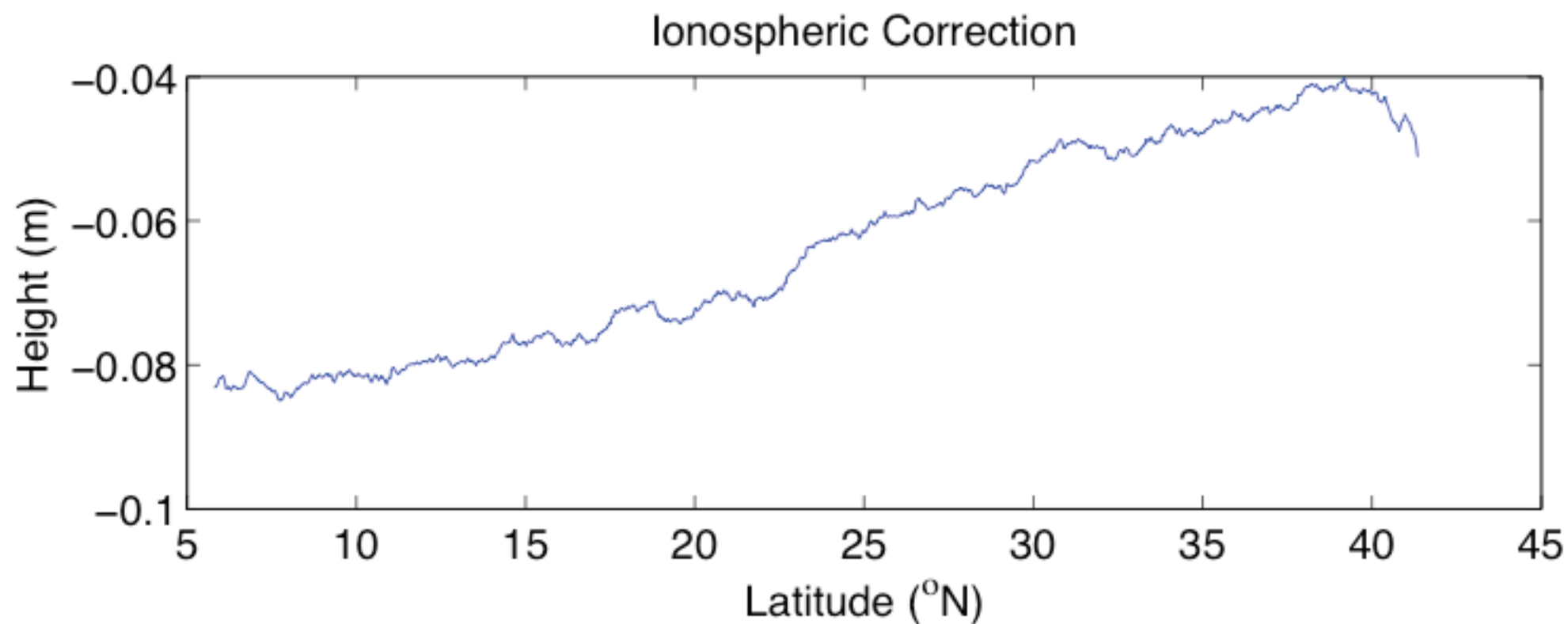
Jason Pass 126, Cycle 20



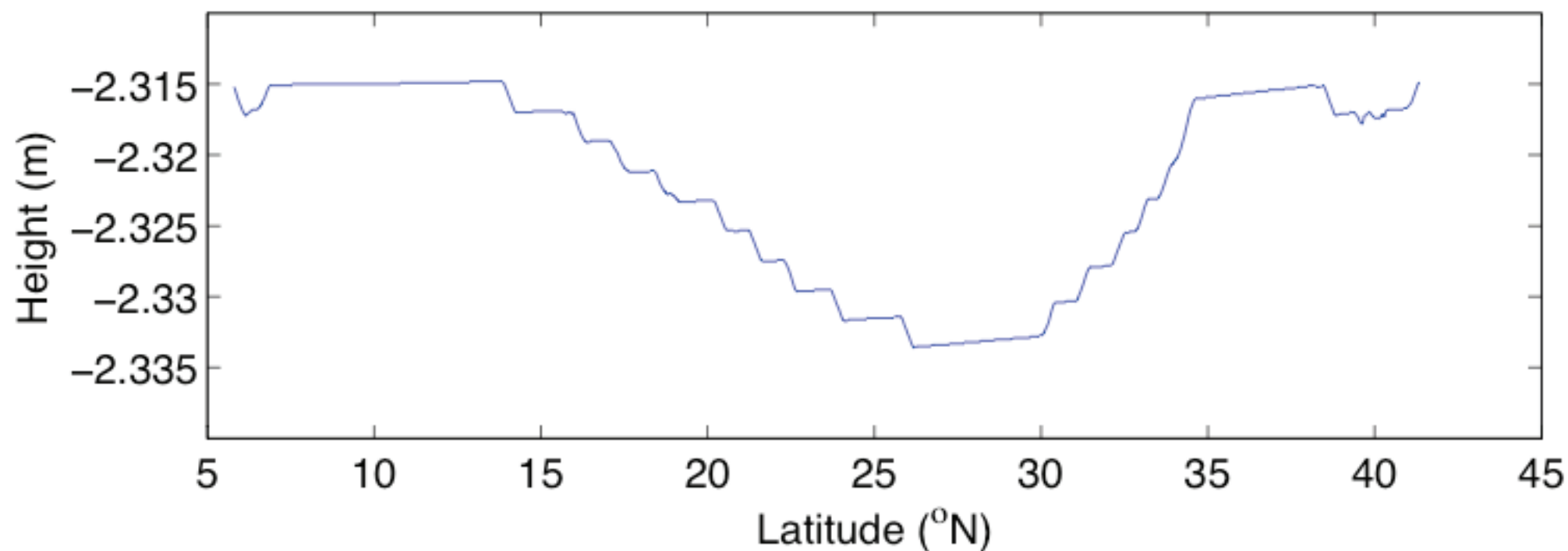
Sea Surface Height: Flagged Data Removed



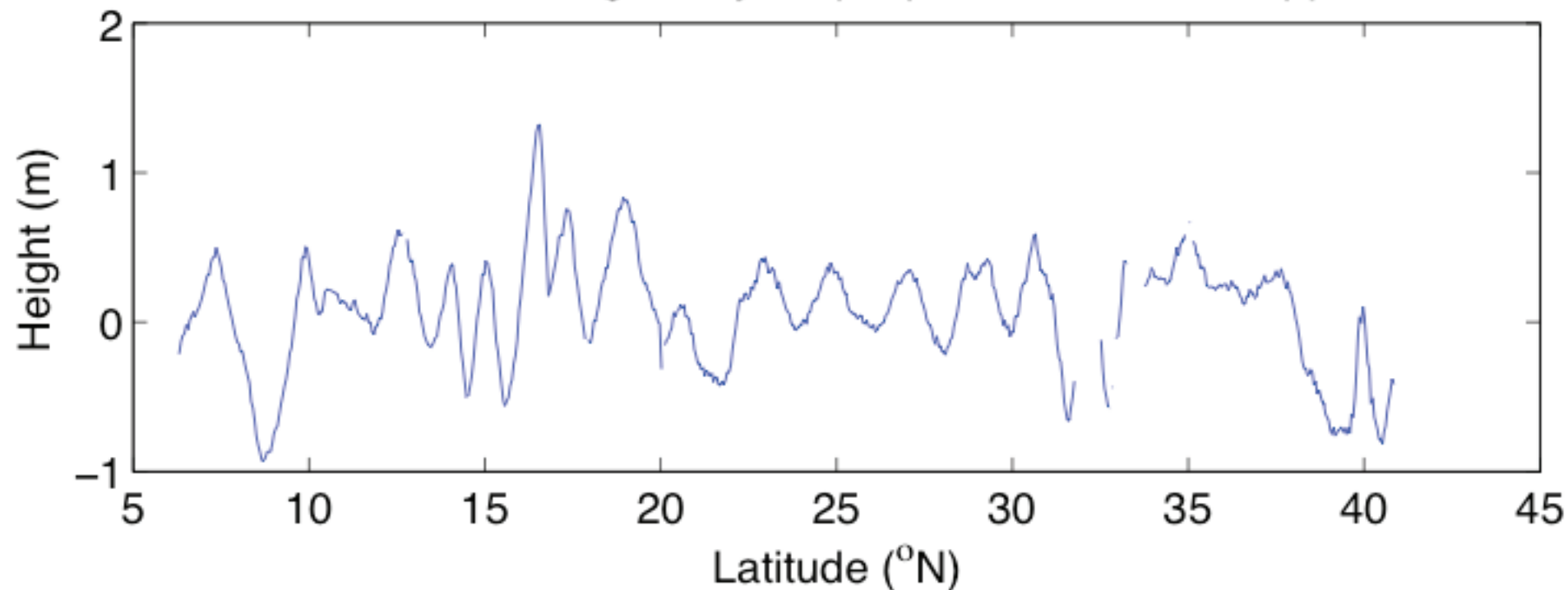




Dry Tropospheric Correction

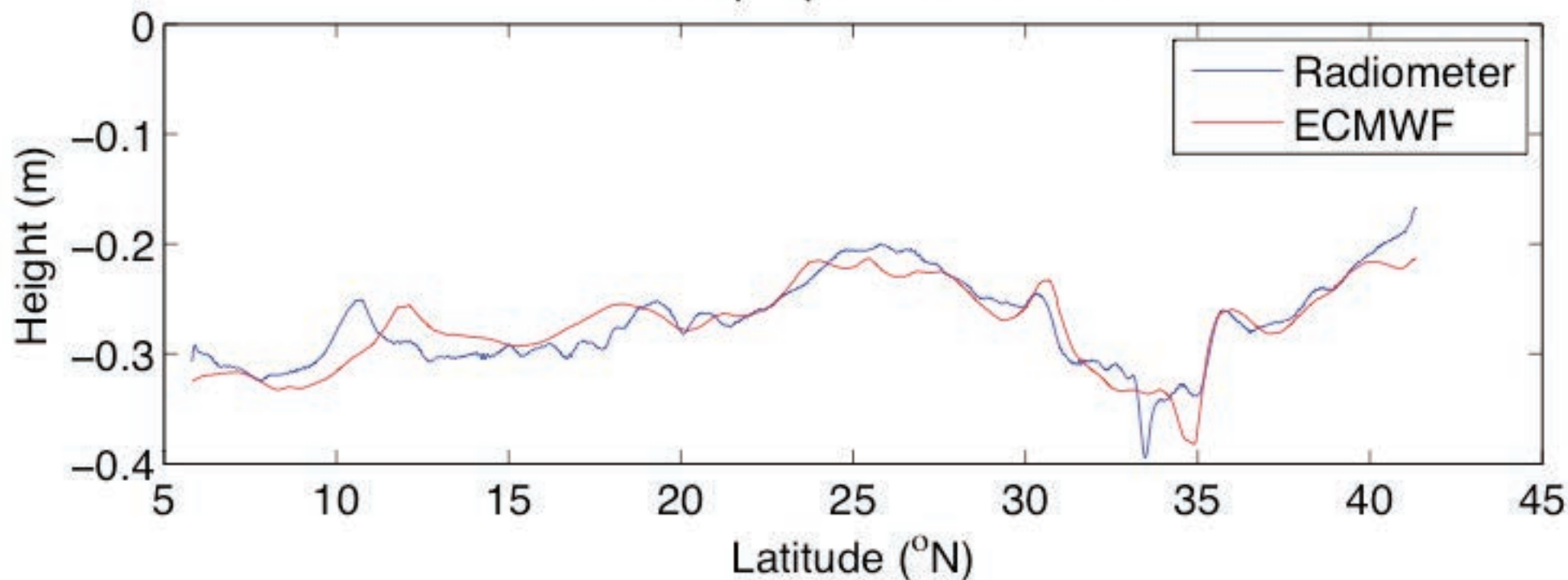


Sea Surface Height: Dry Tropospheric Correction Applied

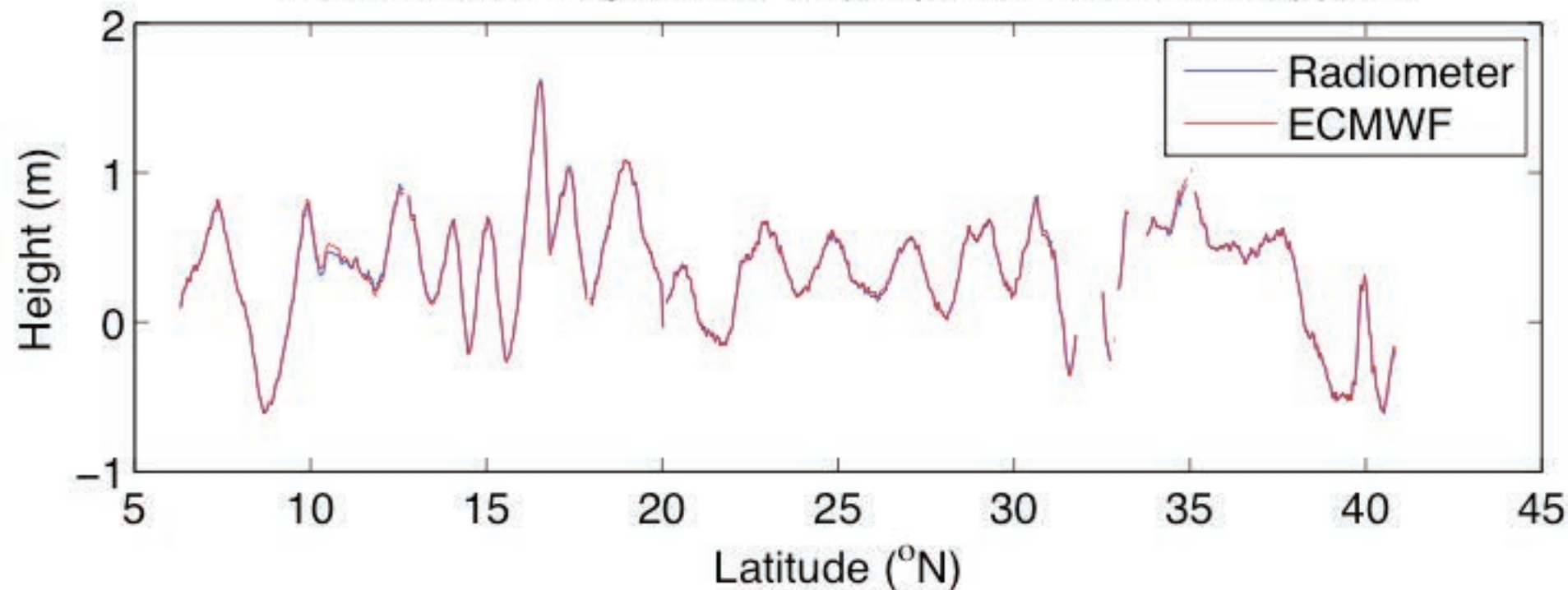




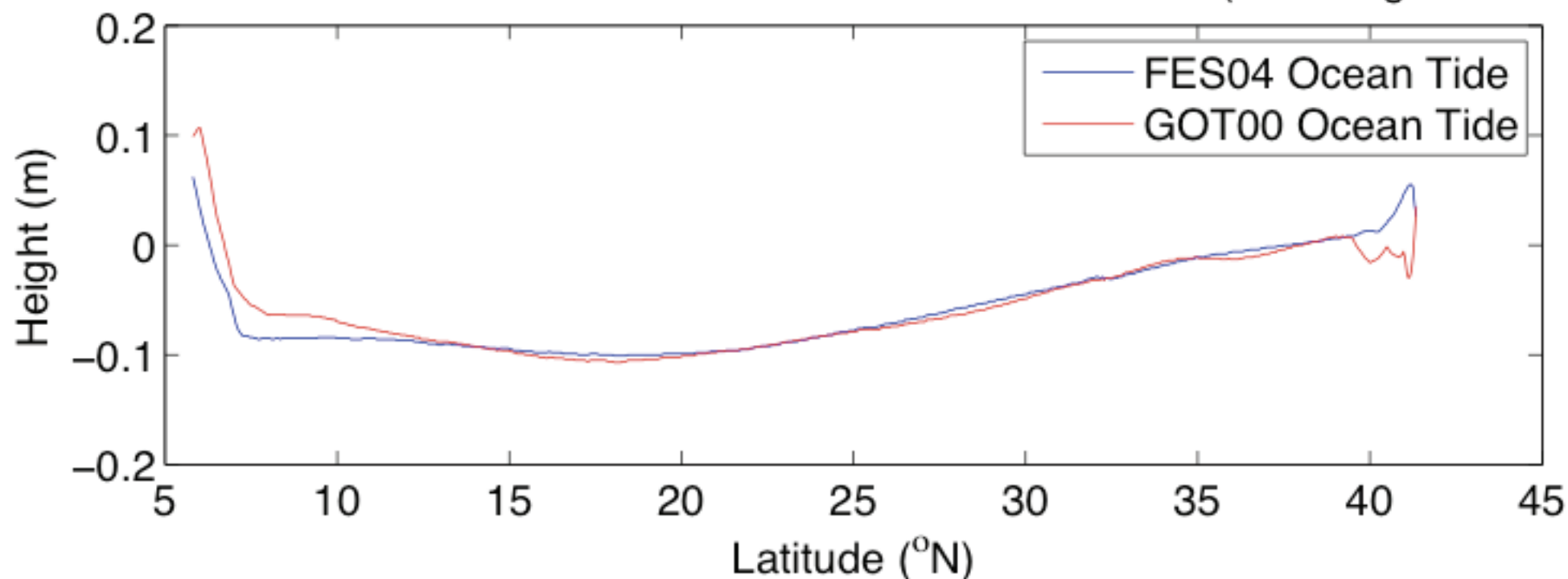
Wet Tropospheric Correction



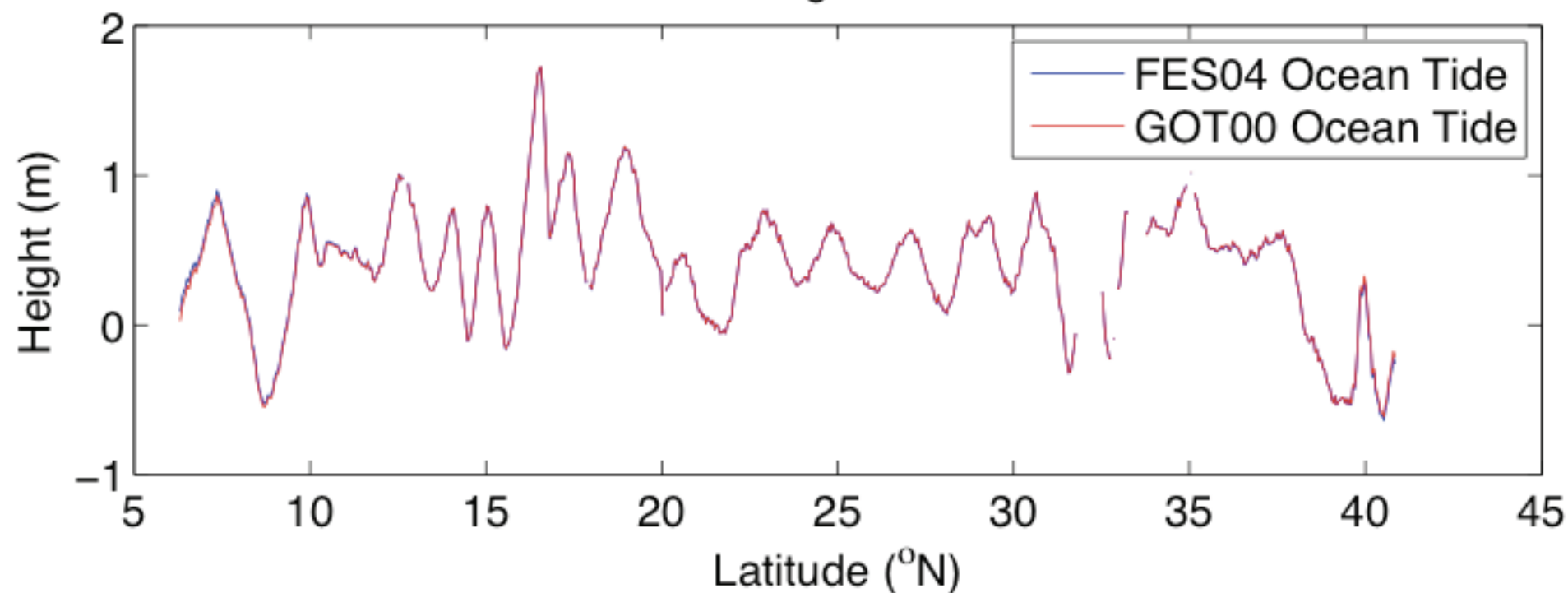
Sea Surface Height: Wet Tropospheric Correction Applied



Tidal Correction: Solid Earth Tide + Pole Tide + Ocean Tide (Including Load Tide)

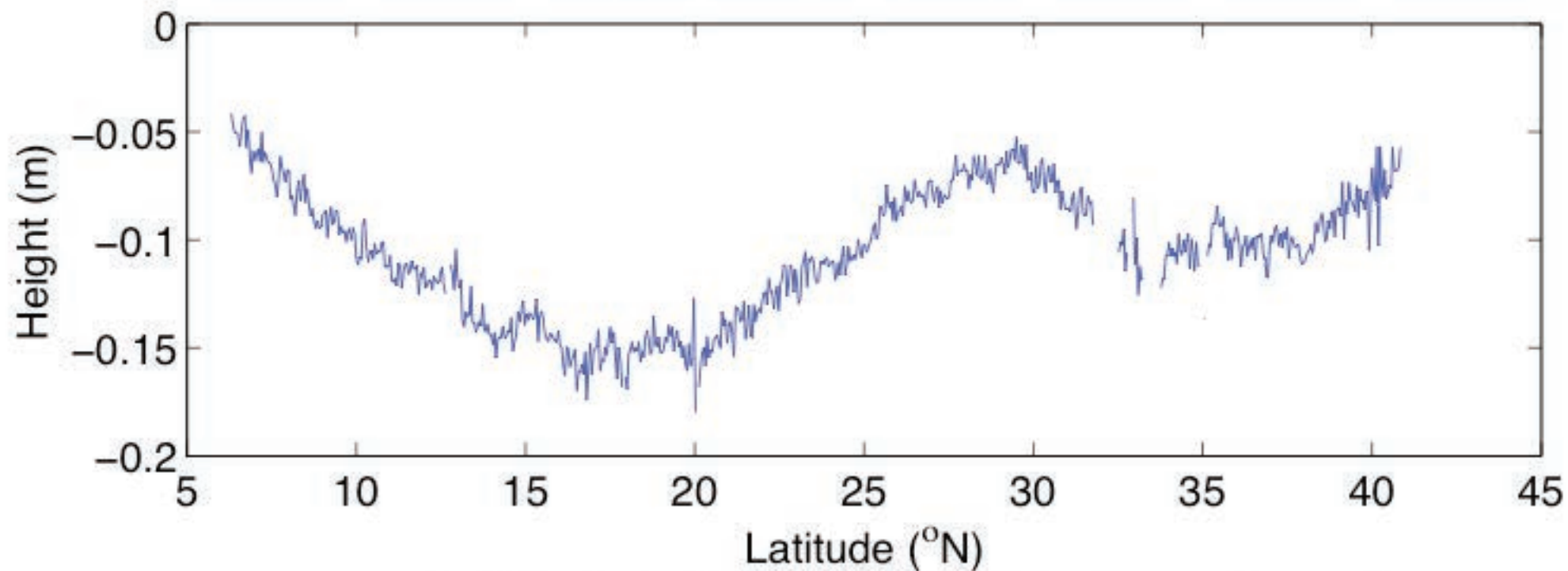


Sea Surface Height: Tides Removed

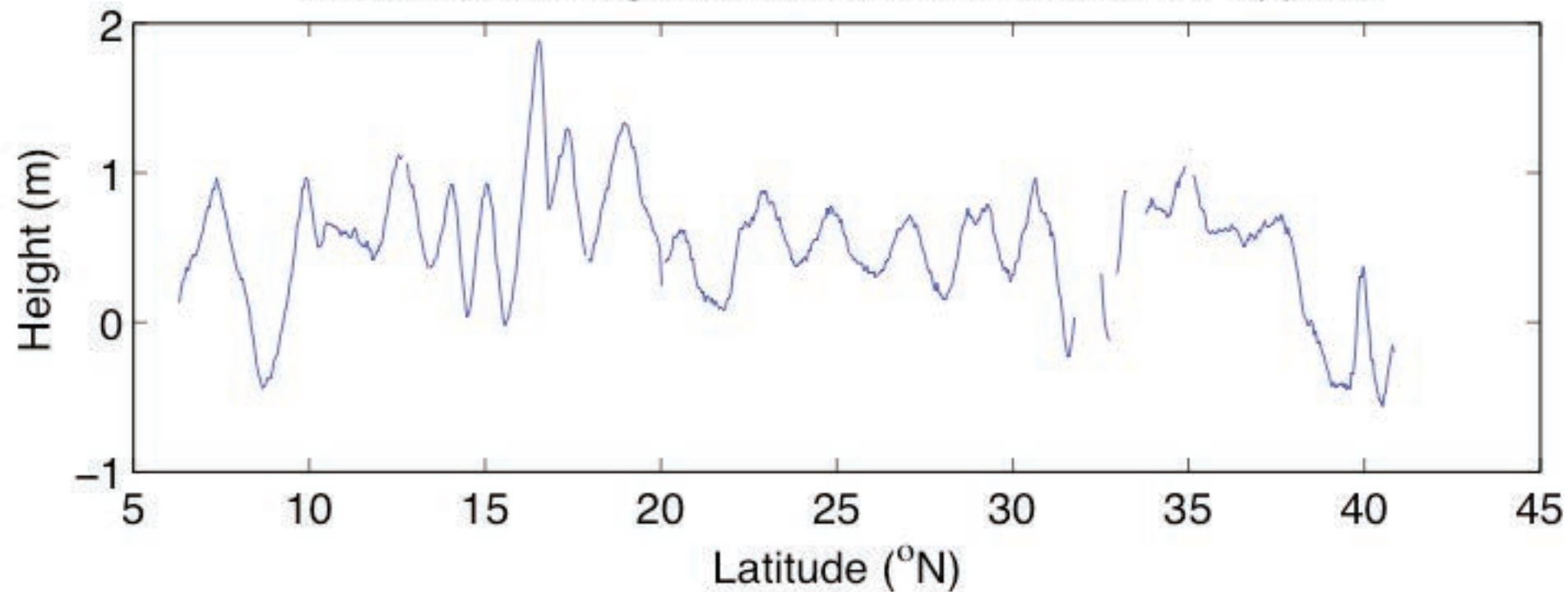




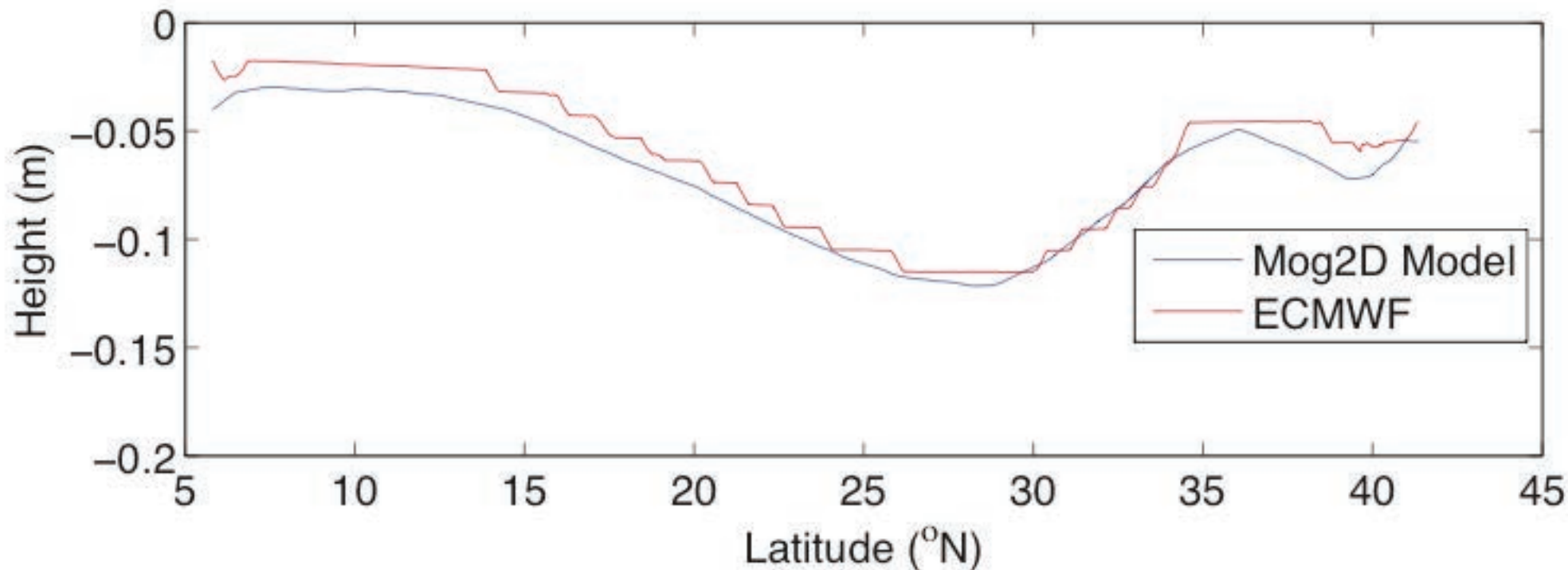
Sea State Bias Correction



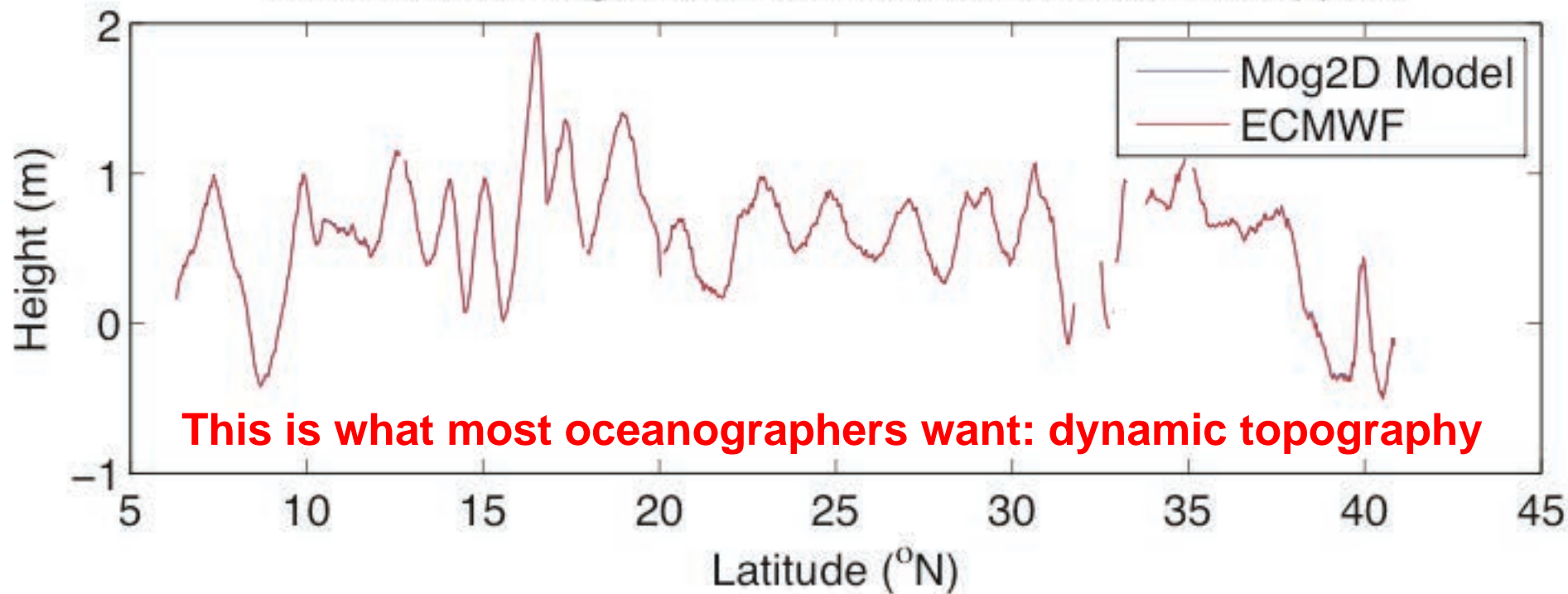
Sea Surface Height: Sea State Bias Correction Applied



### Inverse Barometer Correction



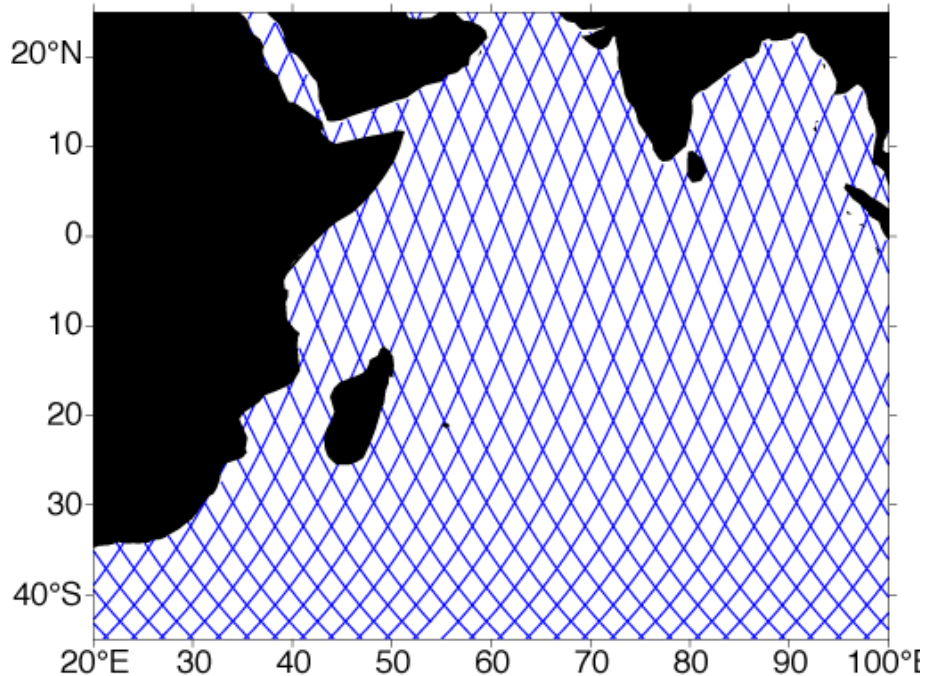
### Sea Surface Height: Inverse Barometer Correction Applied



**This is what most oceanographers want: dynamic topography**

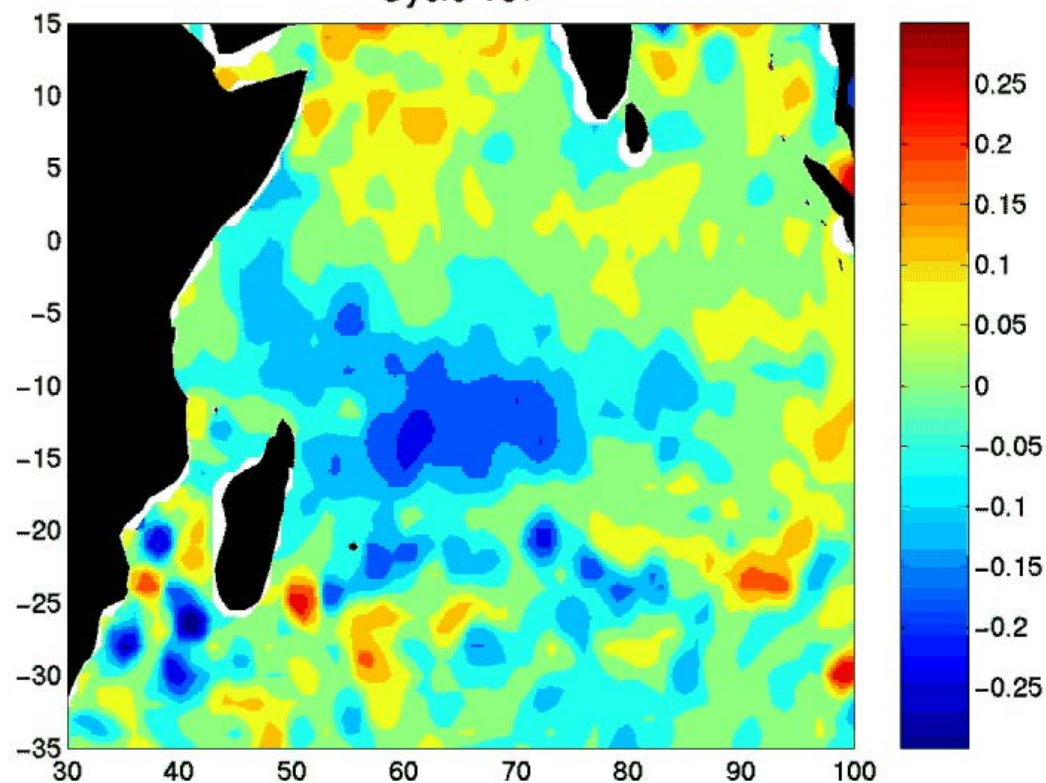


TOPEX/POSEIDON tracks in a 10-day cycle



“Interpolation”  
“Gridding”

Cycle 137



Example of interpolated data  
and data in space and time