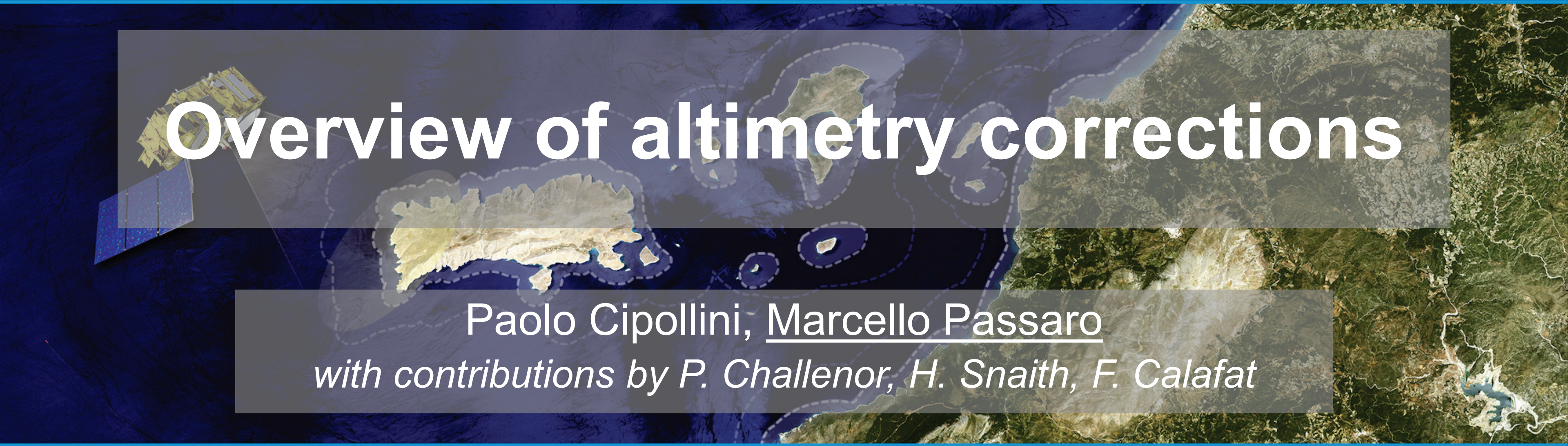
→ 10th COASTAL ALTIMETRY WORKSHOP

SAR Altimetry Training Course



Overview of altimetry corrections

Paolo Cipollini, Marcello Passaro

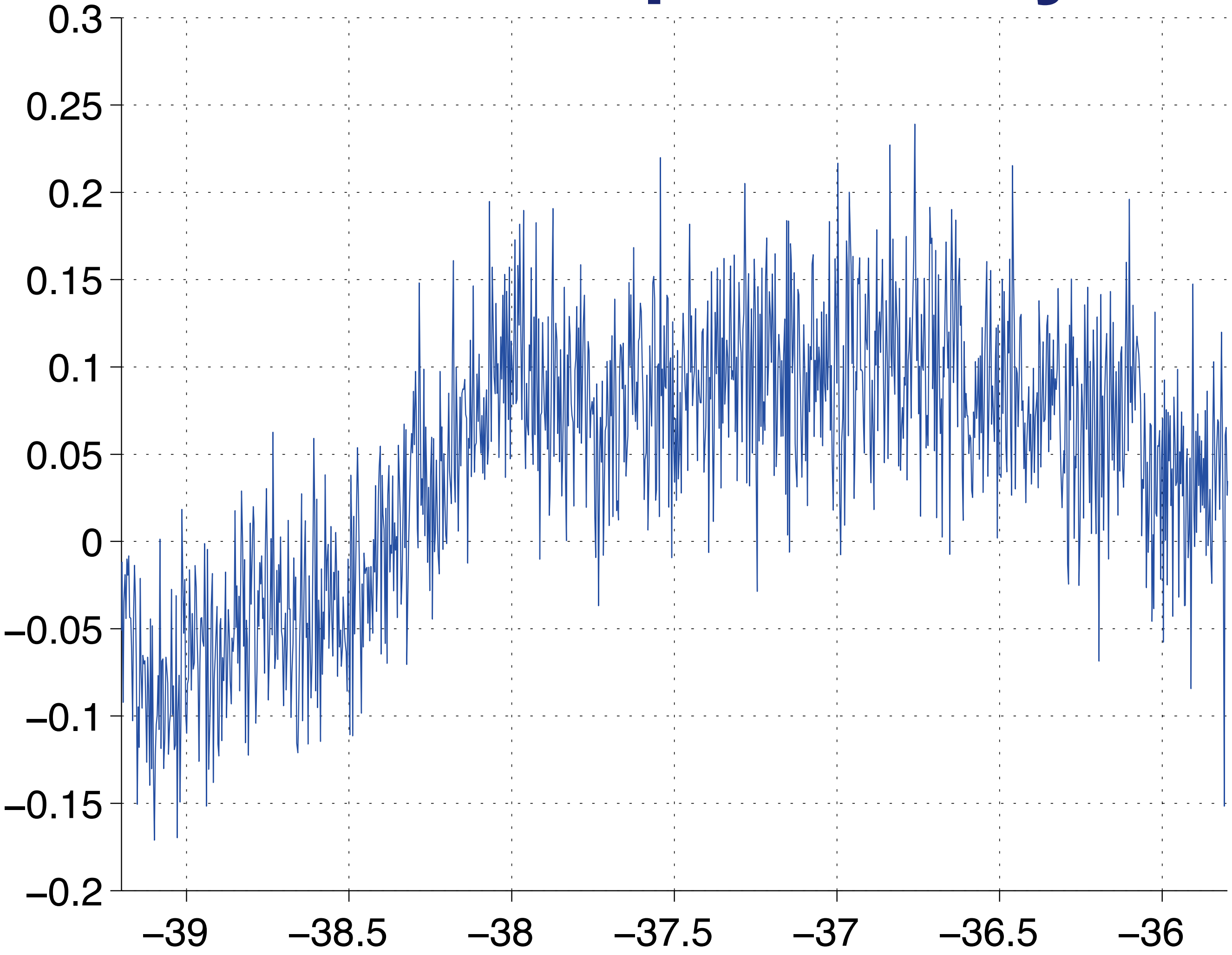
with contributions by P. Challenor, H. Snaith, F. Calafat

21–24 February 2017 | Florence, Italy

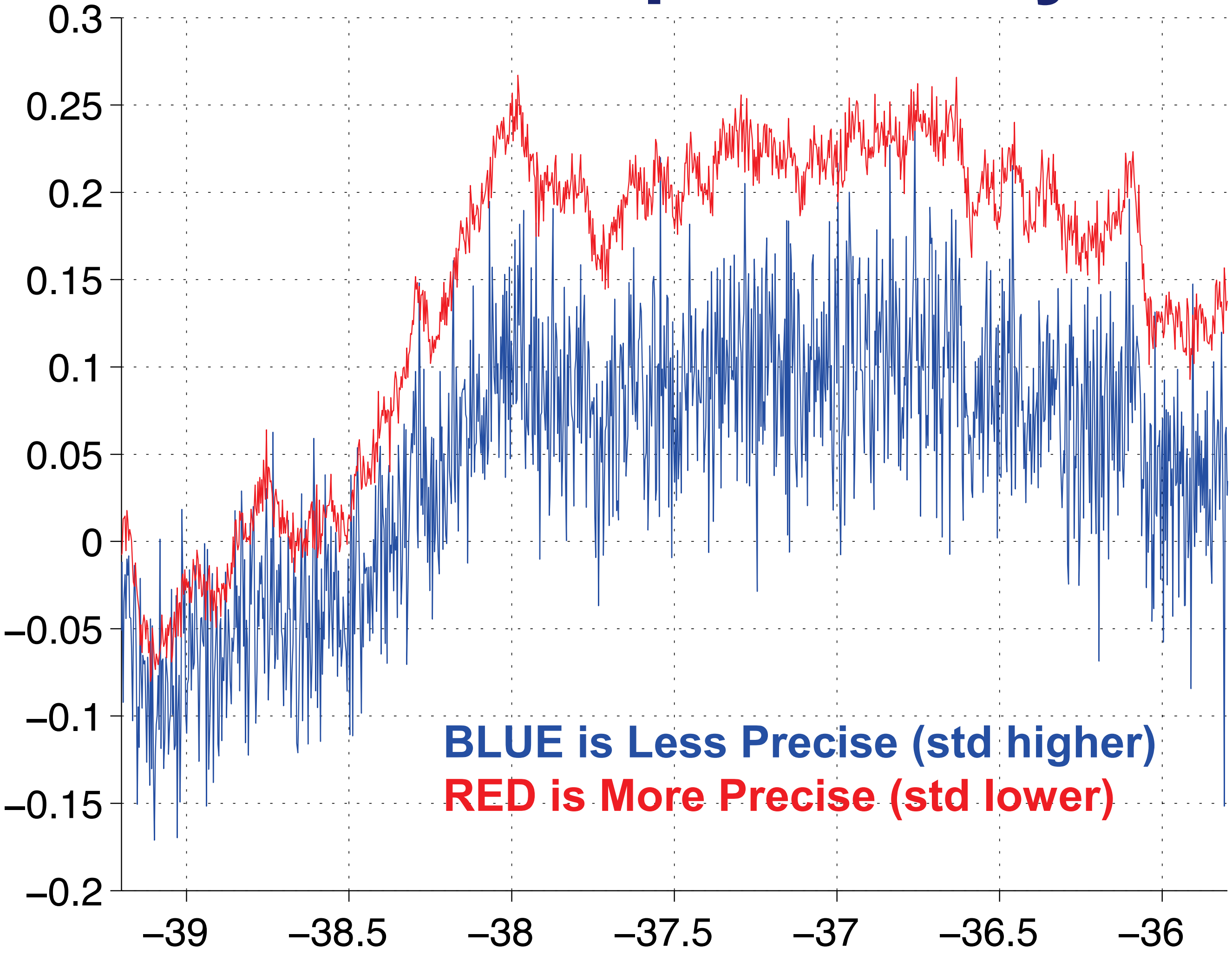
Motivation

- To be useful for oceanographic and climate applications, altimetry (and SAR mode altimetry) need to have:
  - **precision**
  - **accuracy**
  - **stability**

Precision: ‘repeatability’



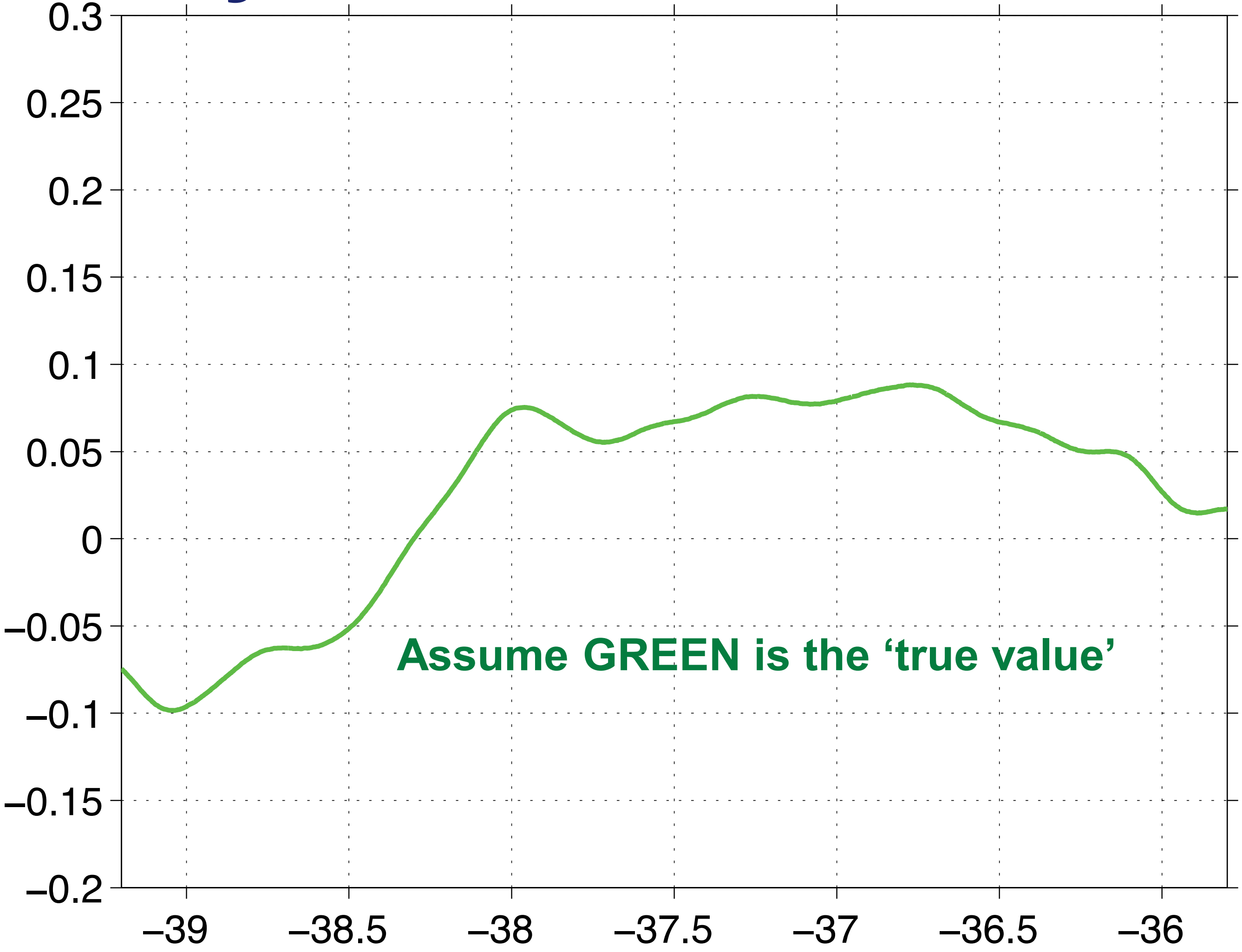
Precision: ‘repeatability’



BLUE is Less Precise (std higher)

RED is More Precise (std lower)

Accuracy: closeness to true value



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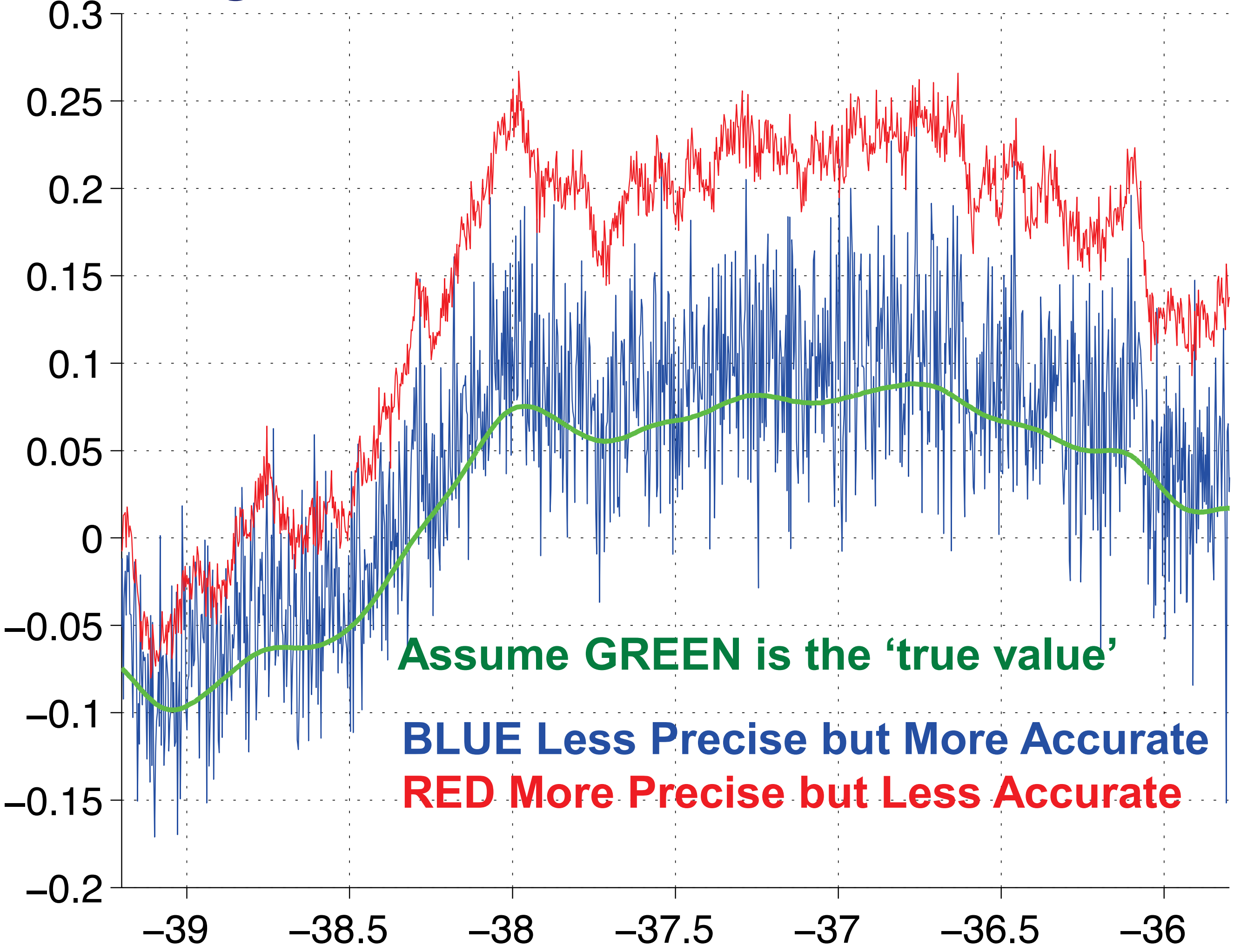


Assume GREEN is the 'true value'

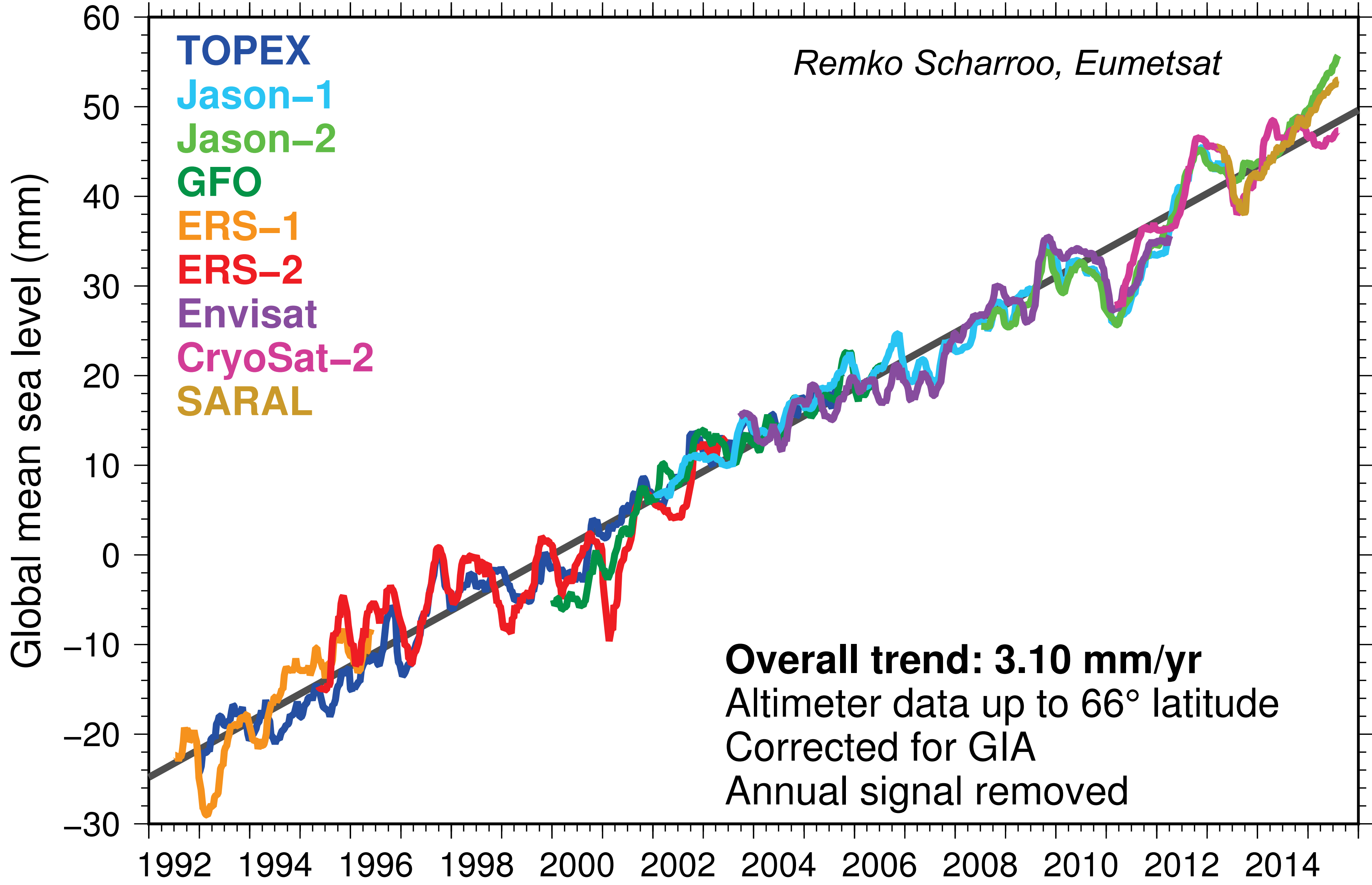
BLUE Less Precise but More Accurate

RED More Precise but Less Accurate

Stability: ‘keeps good long-term’

- the measurement system must not drift in time
- stability of altimeters (and inter-calibration) allows combining long-term measurements from different missions, such as in the Global Mean Sea Level curve (next slide)

SEA LEVEL RISE - global



Overall trend: 3.10 mm/yr

Altimeter data up to 66° latitude

Corrected for GIA

Annual signal removed

How do we achieve those?

- **Precision**: with **instrumental** and **processing** consideration to limit noise
  - with mode of operation: SAR is more precise (less noisy) than LRM
  - by averaging many waveforms. If we average N independent ones, noise is reduced by sqrt(N)
  - by good retracking practice (for instance, avoiding artefacts in the waveform tail in the coastal zone)

How do we achieve those?

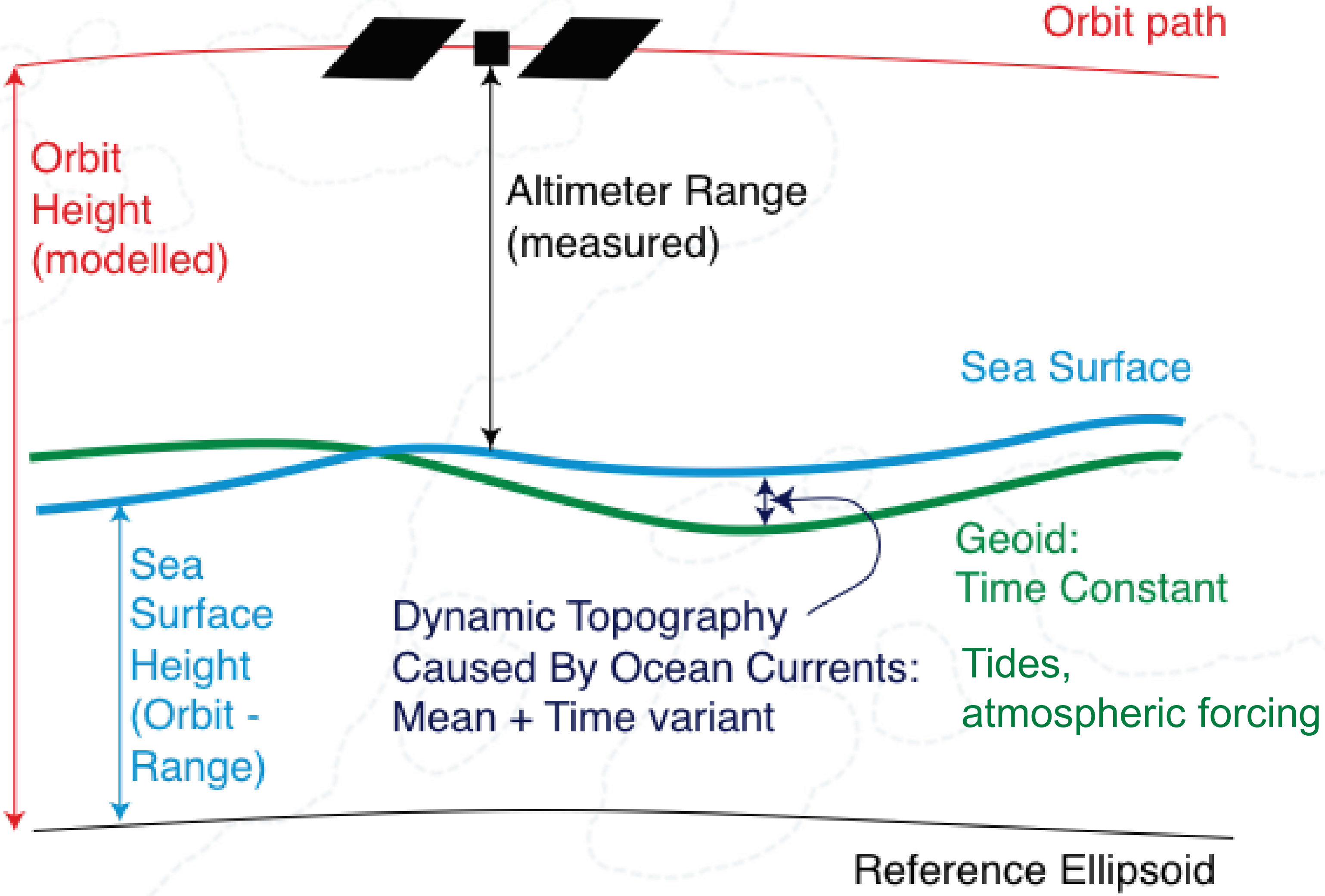
- **Accuracy**: with good **orbits** and **corrections**
  - – orbit errors must be < than desired accuracy
  - – by accounting for all factor (atmospheric, surface, geophysical) that introduce an error in the measurements

How do we achieve those?

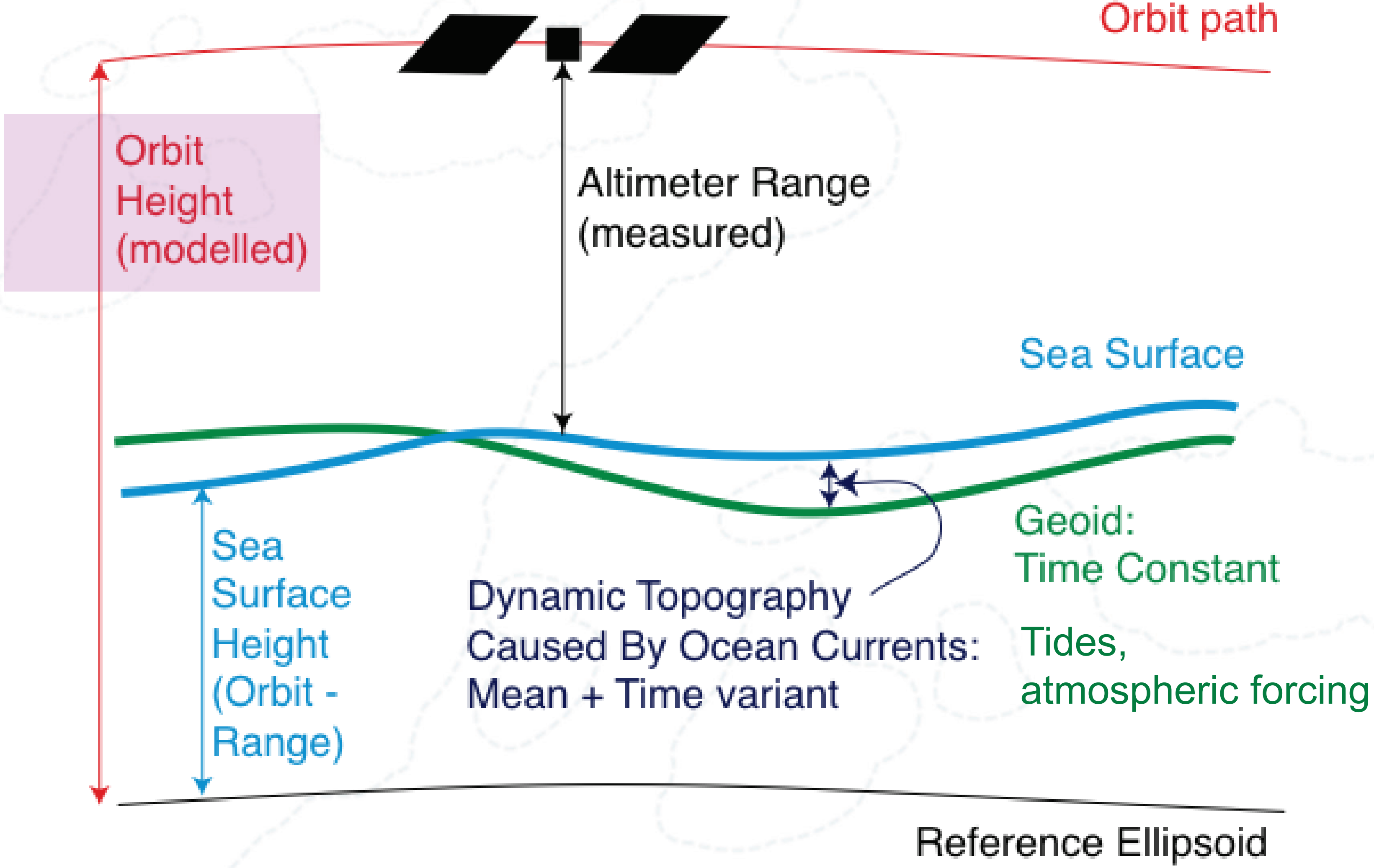
- **Stability**: instrument performance, corrections, etc must not **drift** (or if they drift, that must be corrected for)
- Example or required stability when measuring Global Mean Sea Level: **error in global rate should be < 0.5 mm/yr**
  - we are now approaching that low error level, thanks the ESA Sea Level Climate Change Initiative (SL-CCI)

An overview of altimetry corrections

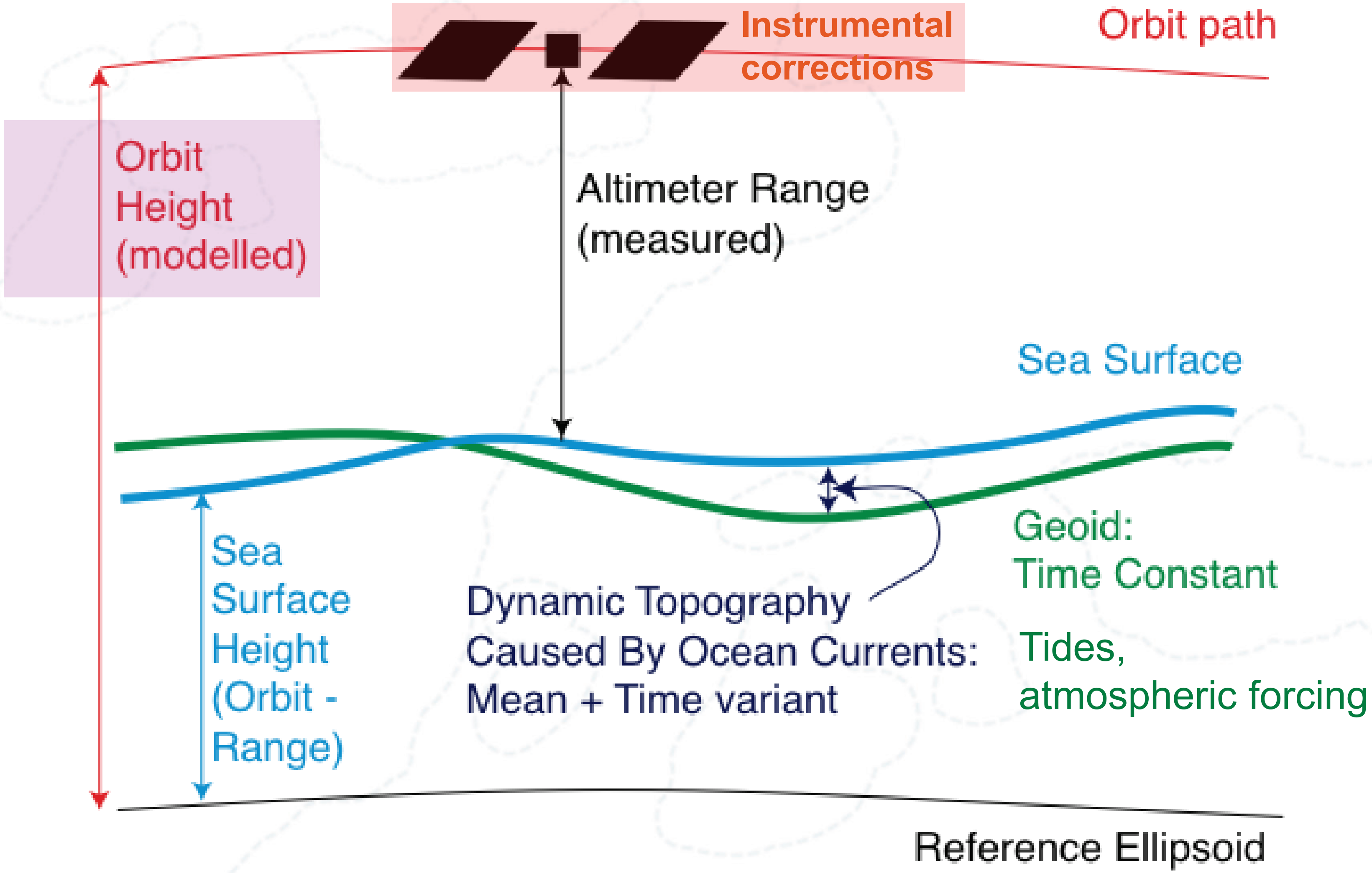
Orbits and corrections



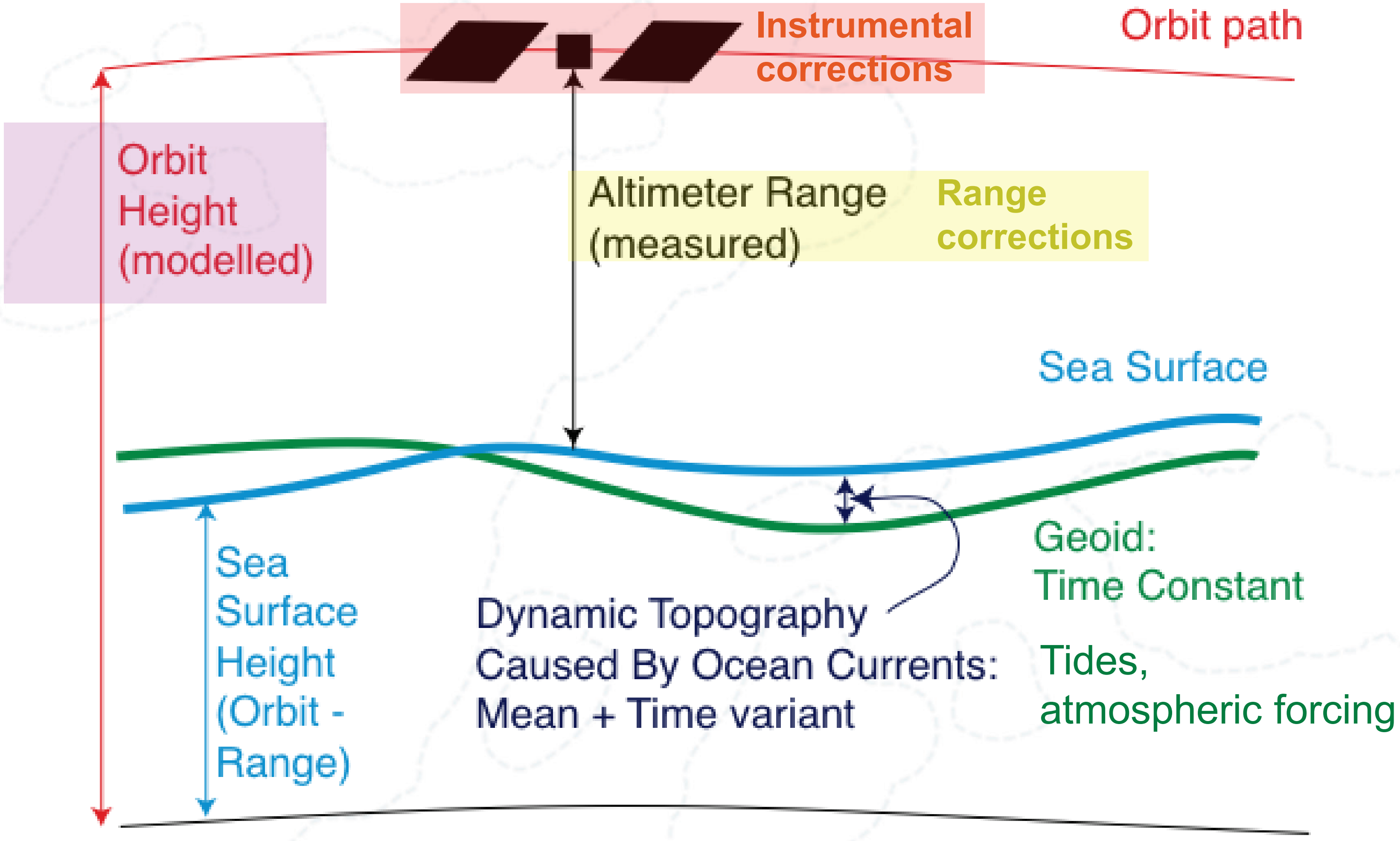
Orbits and corrections



Orbits and corrections



Orbits and corrections



Instrumental corrections

Orbit path

Orbit Height (modelled)

Altimeter Range (measured)

Range corrections

Sea Surface

Sea Surface Height (Orbit - Range)

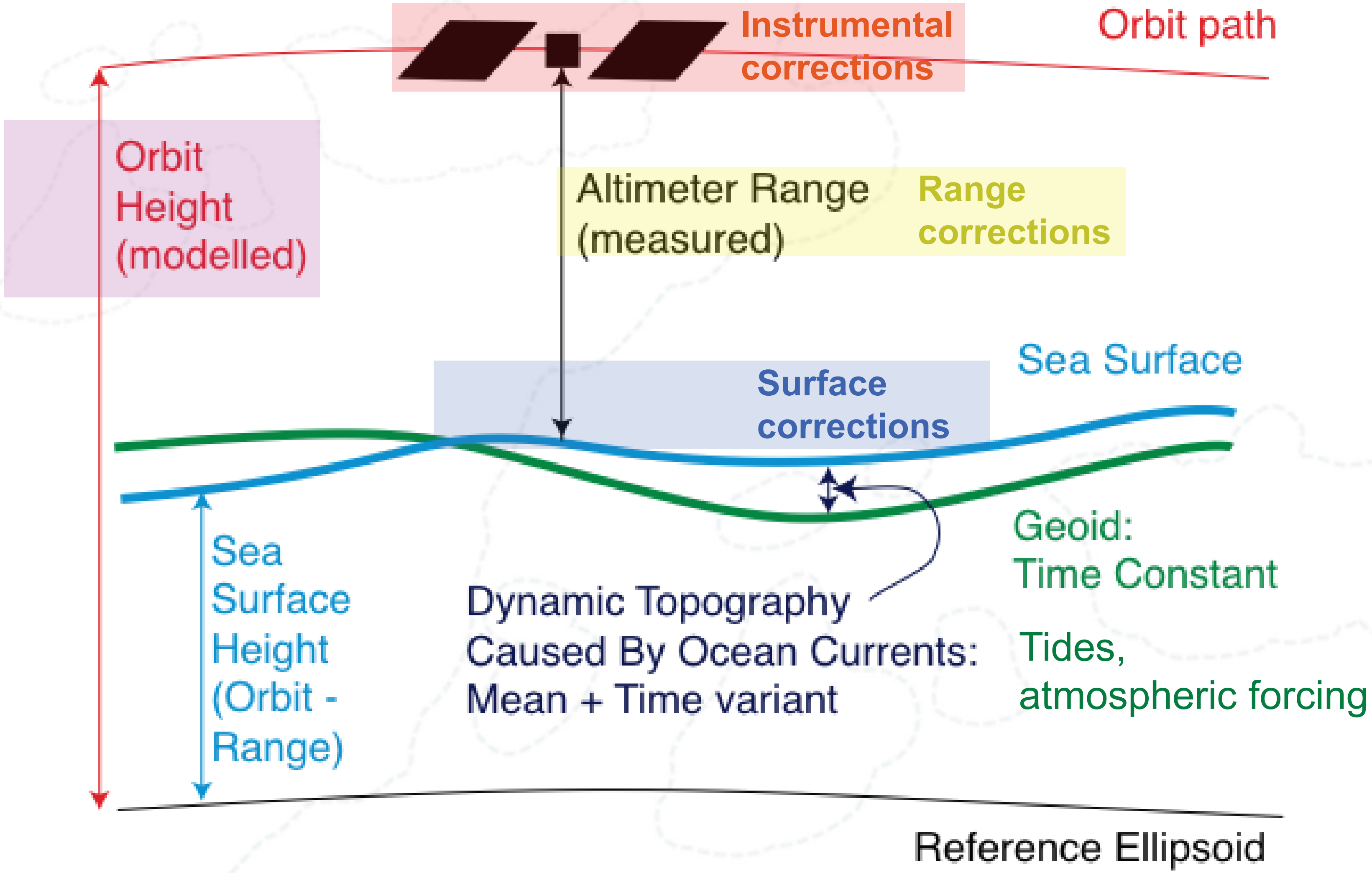
Dynamic Topography Caused By Ocean Currents: Mean + Time variant

Geoid: Time Constant

Tides, atmospheric forcing

Reference Ellipsoid

Orbits and corrections



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Surface corrections

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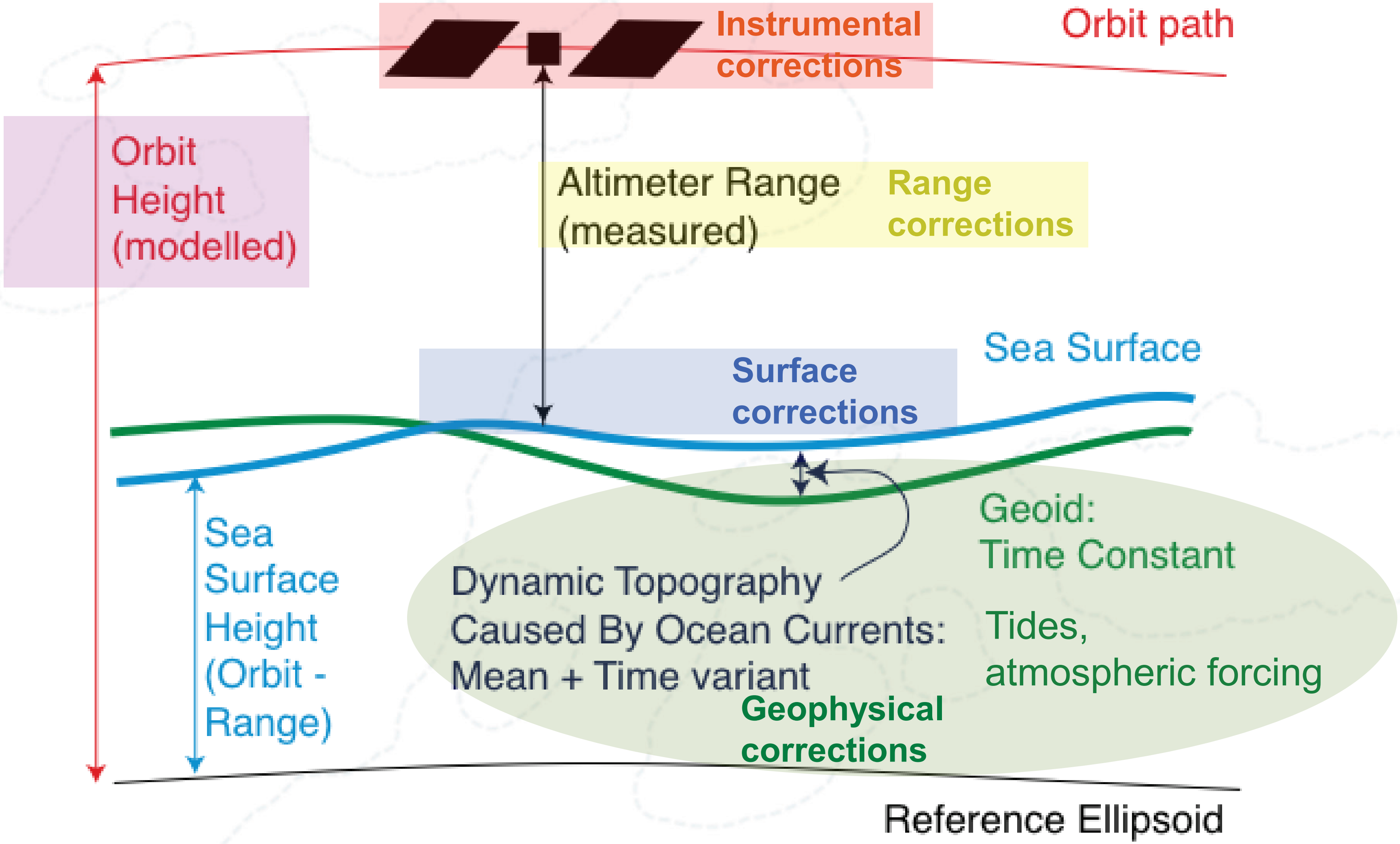
Orbits and corrections

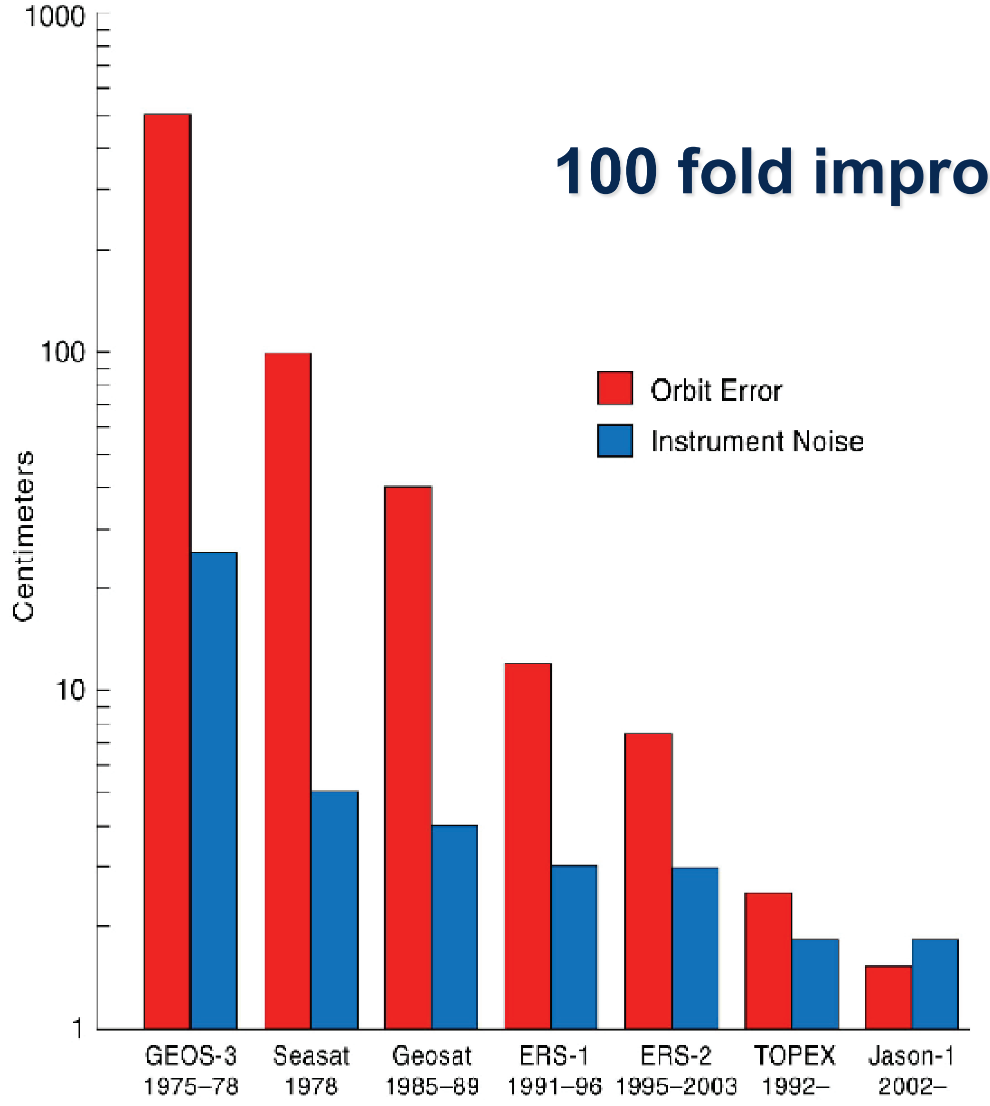


Orbits

- NOT a correction – but crucial for accuracy
  - success of altimetry is intimately linked to improvement in orbits
  - SSH = orbit-range, so accuracy of both orbit and range need to be better than the accuracy requirements for SSH!

- let's see how orbit (and range) accuracy and instrument noise have improved over the years

100 fold improvement in 25 years !



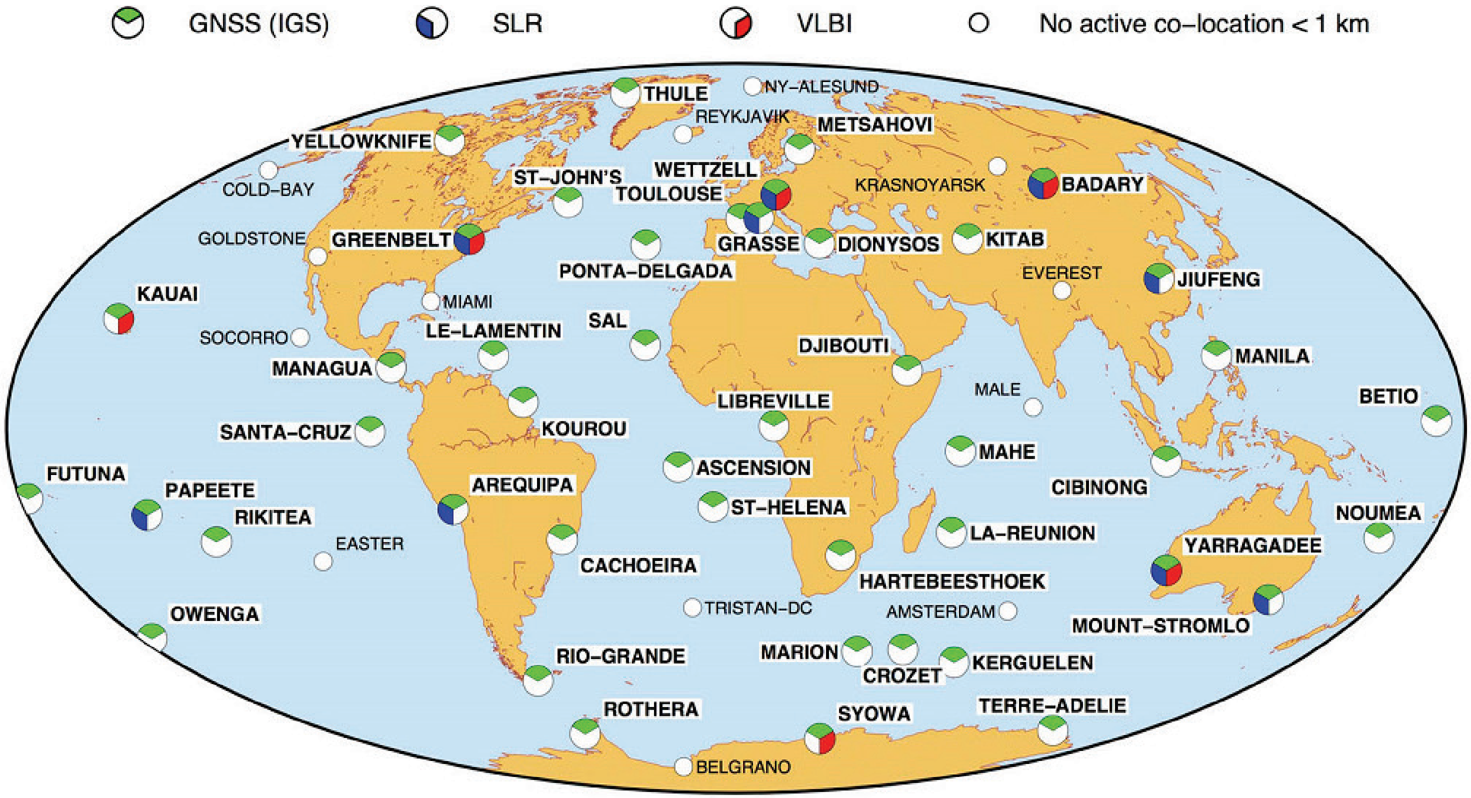
Now at 1-2 cm level!!

Courtesy of Lee-Lueng Fu., NASA

How we achieve great orbits

- satellite tracking: DORIS (microwave), SLR (Laser), GPS
- these are then fit into orbit models

DORIS stations and their colocation with other tracking techniques



Instrumental corrections

- account for:
    - radial motion of satellite relative to surface,
    - distance between the centre of gravity of the spacecraft and the altimeter antenna
    - other instrumental/platform effects
- normally already applied (so will not concern us)

Range (atmospheric) corrections

- 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

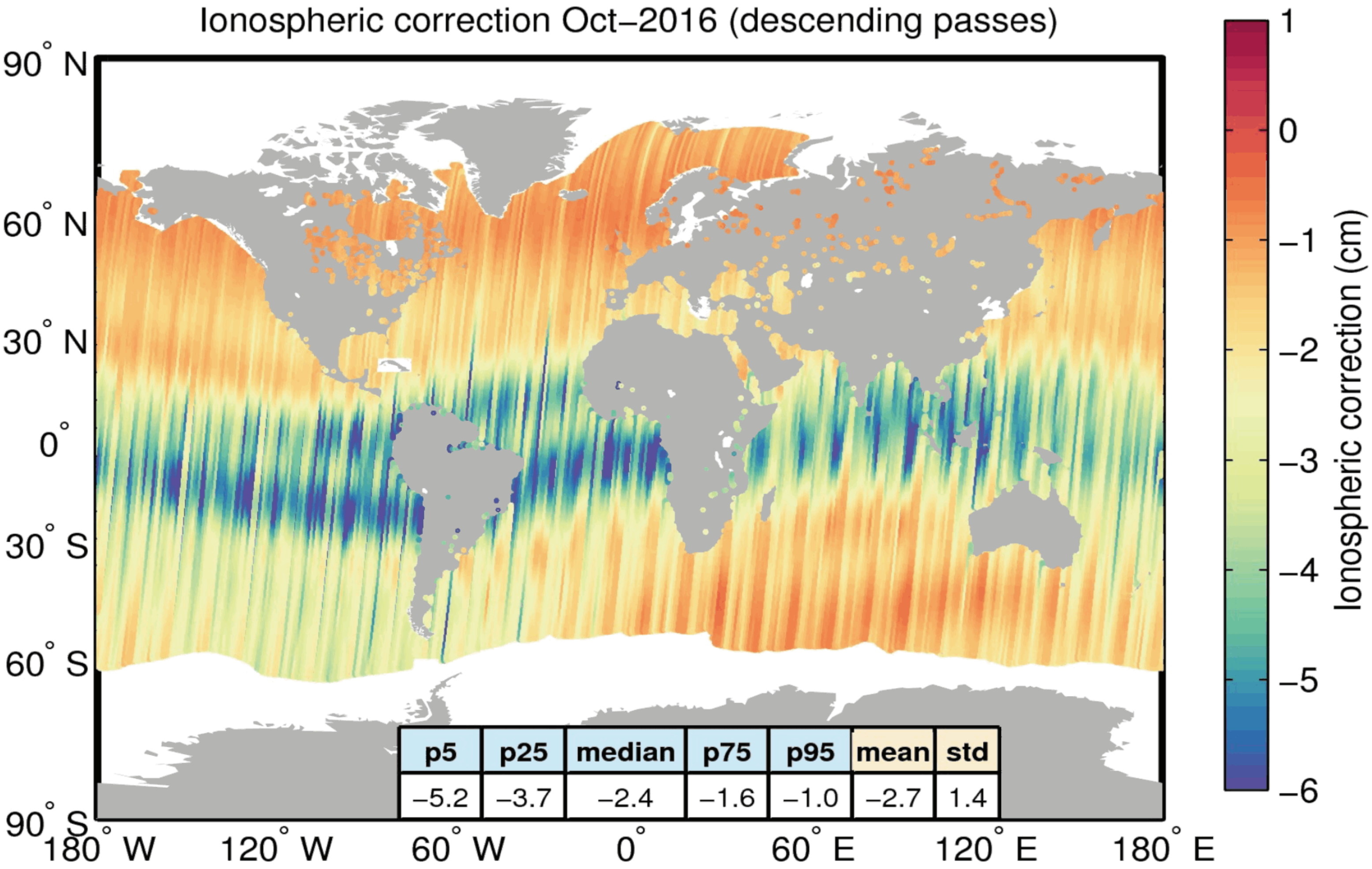
Ionospheric Correction

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

ERS-1/2 × Topex ✔ Jason-1/2/3 ✔ Envisat ✔(only up to 17/01/08) GFO × Cryosat × AltiKa × (Ka band almost unaffected by ionosphere) Sentinel-3 ✔

- Otherwise use a model (GIM) or other observations from another dual frequency radar system (GPS, DORIS

Example: ionospheric correction from GIM model for one month of CryoSat data. The “stripeness” is because different passes happen at different time of the day

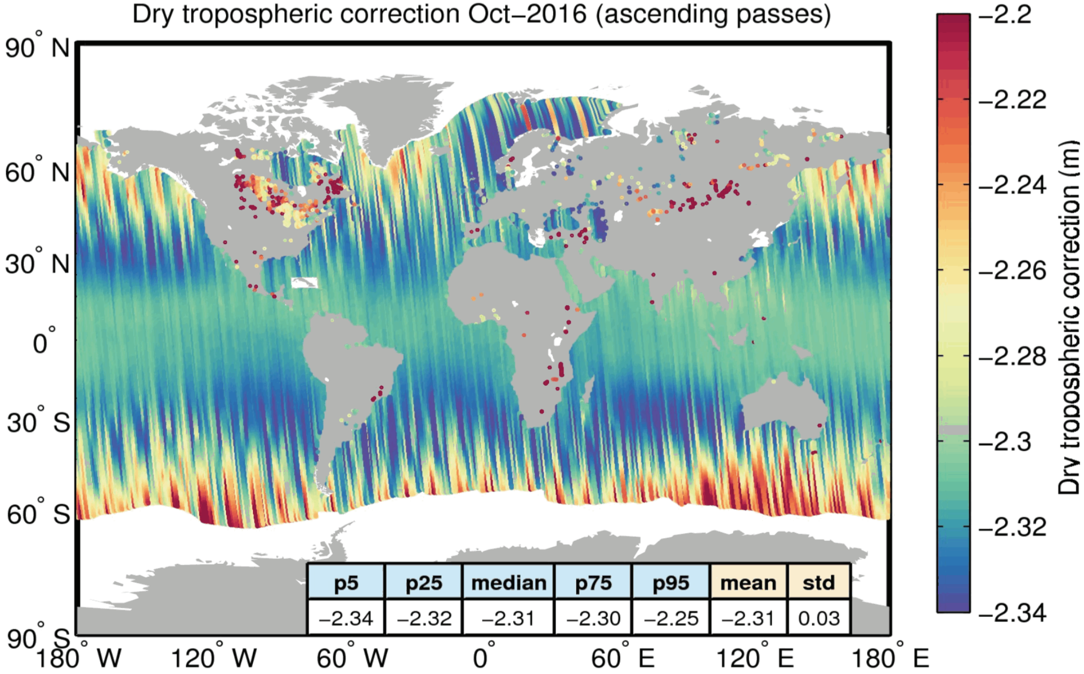


p5	p25	median	p75	p95	mean	std
–5.2	–3.7	–2.4	–1.6	–1.0	–2.7	1.4

Dry Tropospheric Correction

- Due to O_2 molecules in the atmosphere
- Large (~2.3 m) but with small variability (~3-5 cm), and can be computed very accurately based on surface pressure

Example: Dry Tropo correction from ECMWF pressure fields for one month of CryoSat data. The "stripeness" is because pressure varies from one pass to the next, but note that variability is minimal (except at high latitudes – probably due to storms)



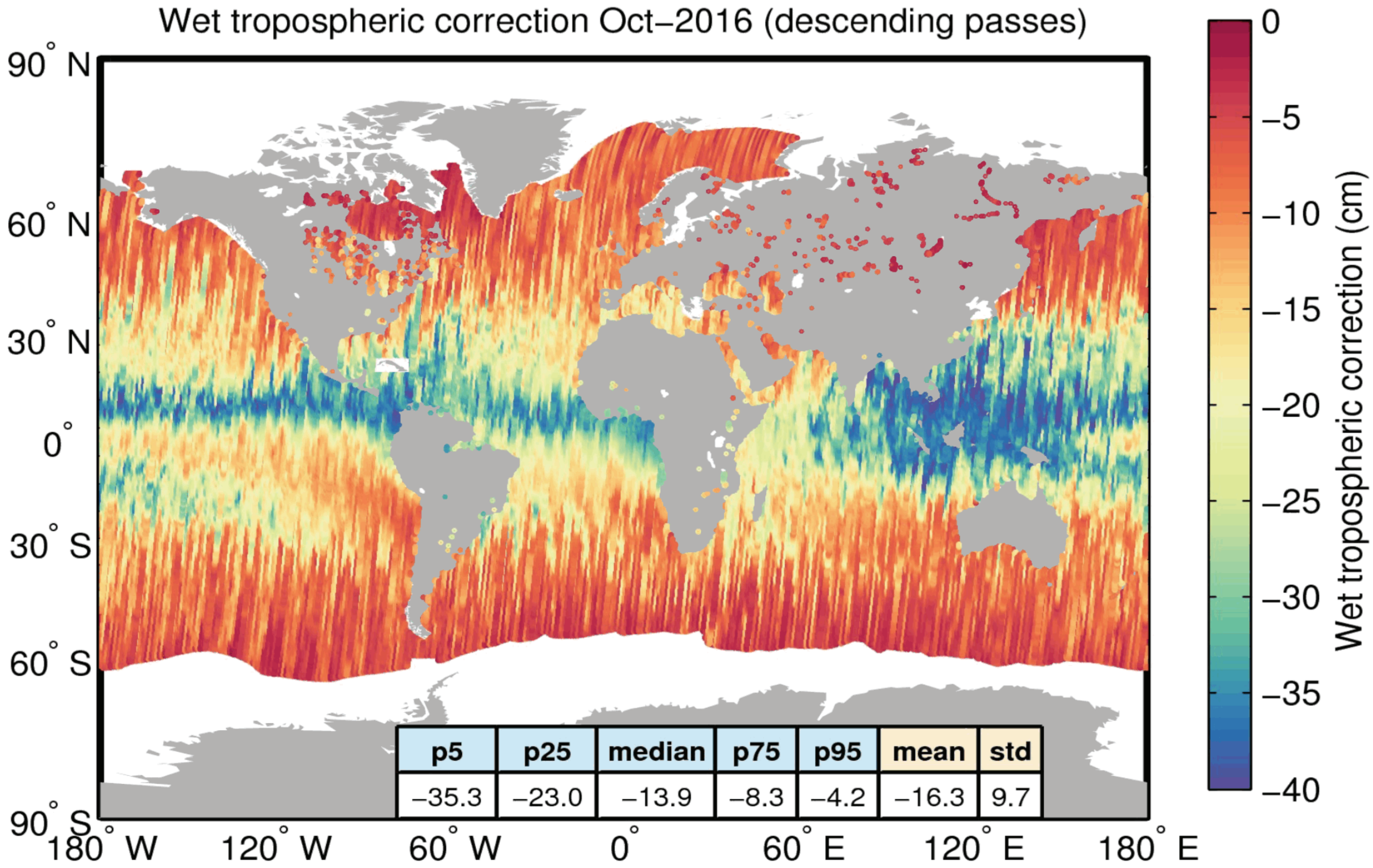
Dry tropospheric correction Oct–2016 (ascending passes)

p5	p25	median	p75	p95	mean	std
–2.34	–2.32	–2.31	–2.30	–2.25	–2.31	0.03

Wet Tropospheric Correction

- 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. a few cm, but can be very large in the tropics
- Obtained by dual- or triple-frequency microwave radiometer on satellite
  - but note this does not work in the coastal zone!
- Or from weather forecasting models (ECMWF)
- New approach: from GPS measurements and/or passive microwave radiometers on other satellites
  - GPD and GPD+ corrections by Univ. Porto, much better for the coastal zone!

Example: wet tropo correction from ECMWF model for one month of CryoSat data. Note higher spatial variability that the others



p5	p25	median	p75	p95	mean	std
−35.3	−23.0	−13.9	−8.3	−4.2	−16.3	9.7

Atmospheric corrections - summary

- Ionospheric correction: 2-20 cm [+/- 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 [+/- 1-2 cm]
  - Caused by oxygen molecules
  - Model the correction accurately using surface atmospheric pressure
- Wet tropospheric correction: 5-35 cm [+/- 3-6 cm]
  - Caused by clouds and rain (variable)
  - Measure H_2O with microwave radiometer
  - Or use weather model predictions
  - Or (more recent approaches): path delays from GPS stations; measurements from other satellite-borne passive radiometers, or combination of the two (GPD+ correction)

Surface effects (Sea State Bias)

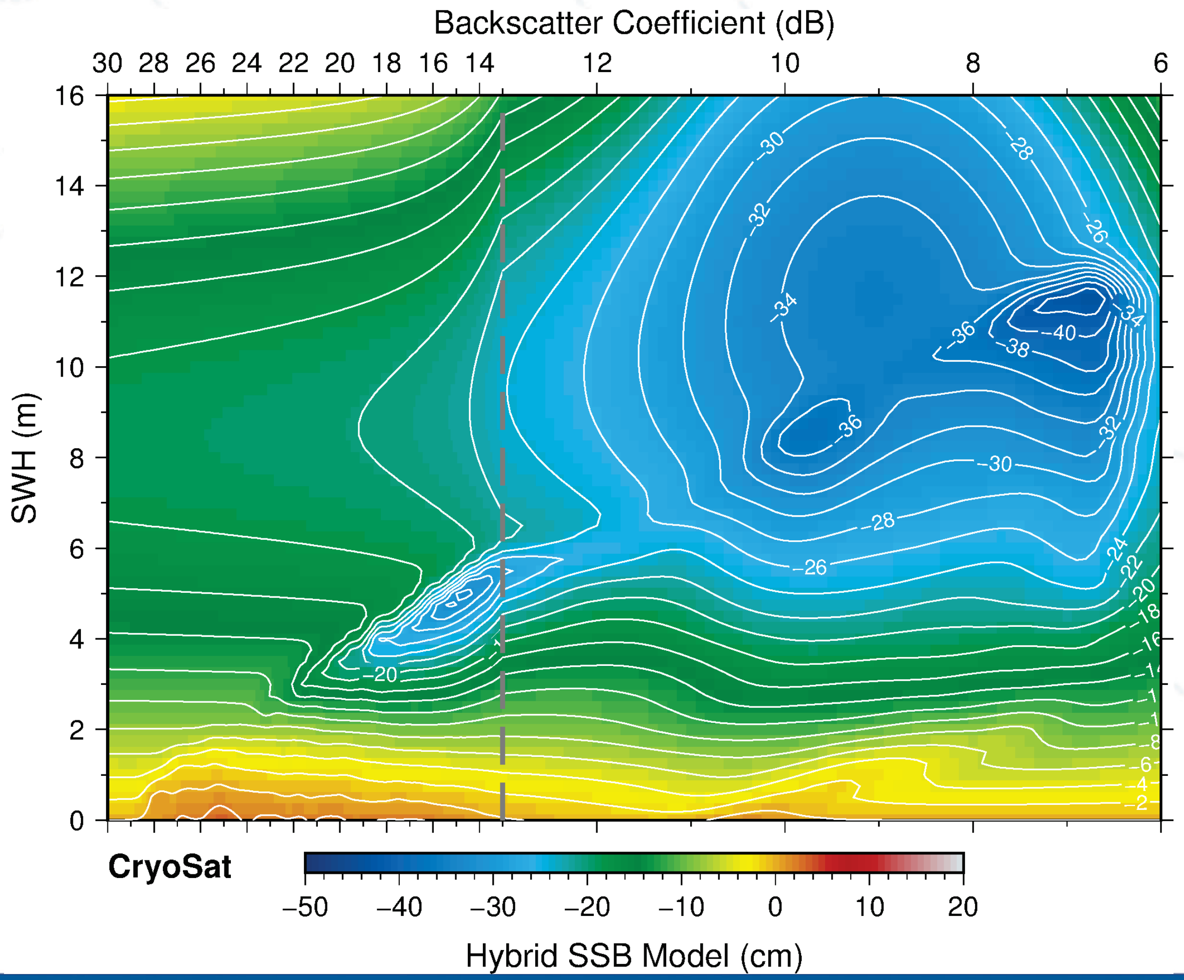
- Sea State Bias (SSB) is the sum of three sea-state dependent errors: skewness, electromagnetic bias, and tracker bias.
- In a nutshell, we get stronger radar returns from the (flatter) troughs than from the (peakier) crests, so altimetry tends to overestimate range
- This must be corrected
  - simplest approach: a % of the SWH. Simple but not very accurate!

State of the art in sea state bias

- 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 SWH (and sigma0, related to 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 – hopefully this will be possible soon, with >1 yr of Sentinel-3 SAR data

Example of SSB

- Hybrid SSB for CryoSat, by Scharroo et al



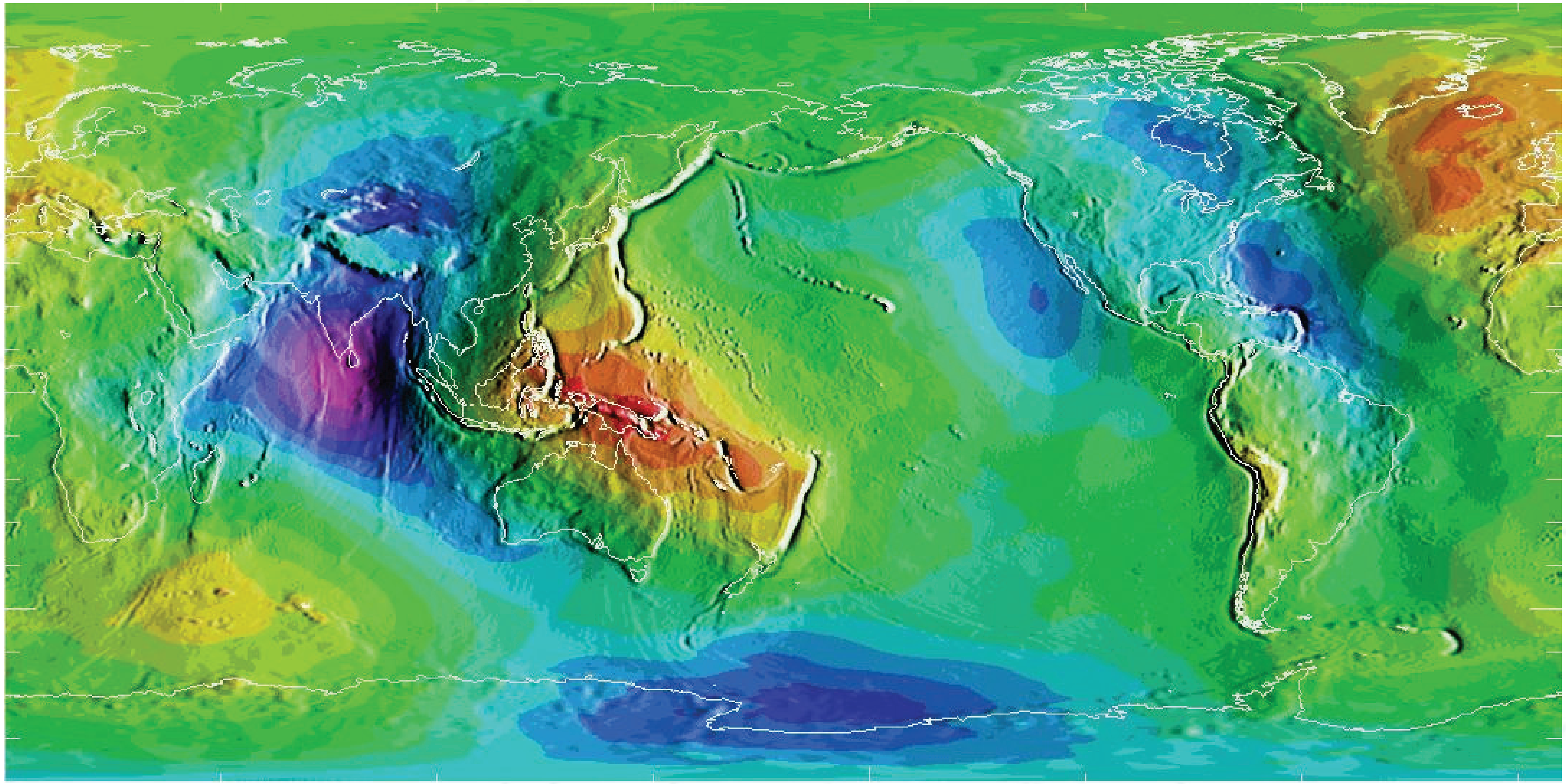
What is in the SSH?

- Once all the corrections seen above we are applied, we are left with a Sea Surface Height (SSH) w.r.t. a reference ellipsoid.
- The SSH is the results of several **geophysical contributions**:
  - the **geoid (±100m)**
  - the signal due to **currents (dynamic topography**) (±1-2m)
  - **the tides**
  - the signal due to the forcing of the **atmosphere** (pressure and wind) (normally <1m, but can be up to a few m when we have a **surge**!)
- **So any further ‘geophysical’ corrections depend on the application (i.e. on which of those signals we want to leave or remove)**

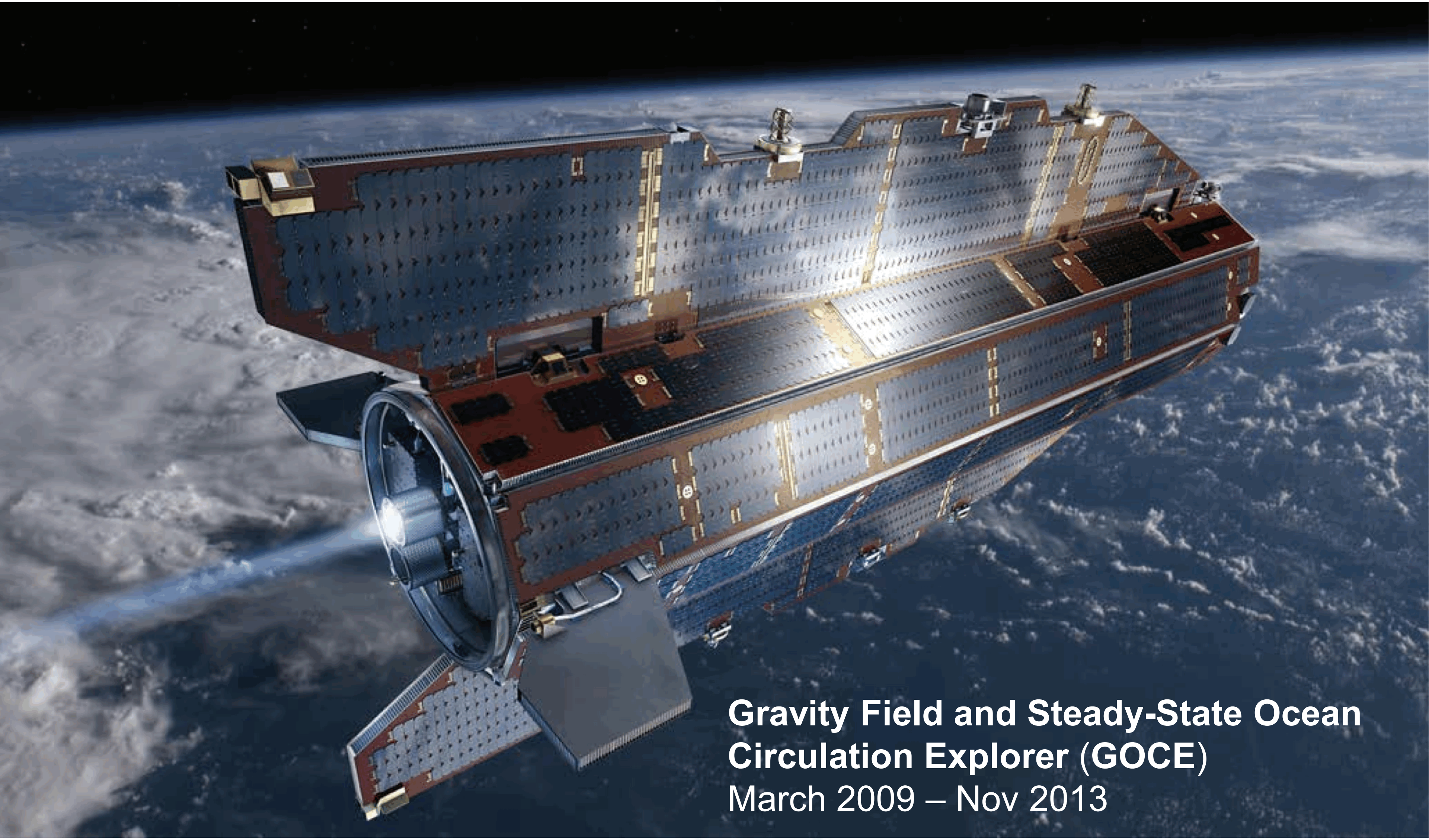
The Geoid

- The geoid is the surface of equal gravity potential on the Earth’s surface
- The signature of geostrophic currents (dynamic topography) is in terms of sea surface height relative to the geoid
- So ideally we should remove the geoid from the measurement, but existing geoid models may not be accurate enough for applications, especially at the short scales (<100 km)

The Geoid



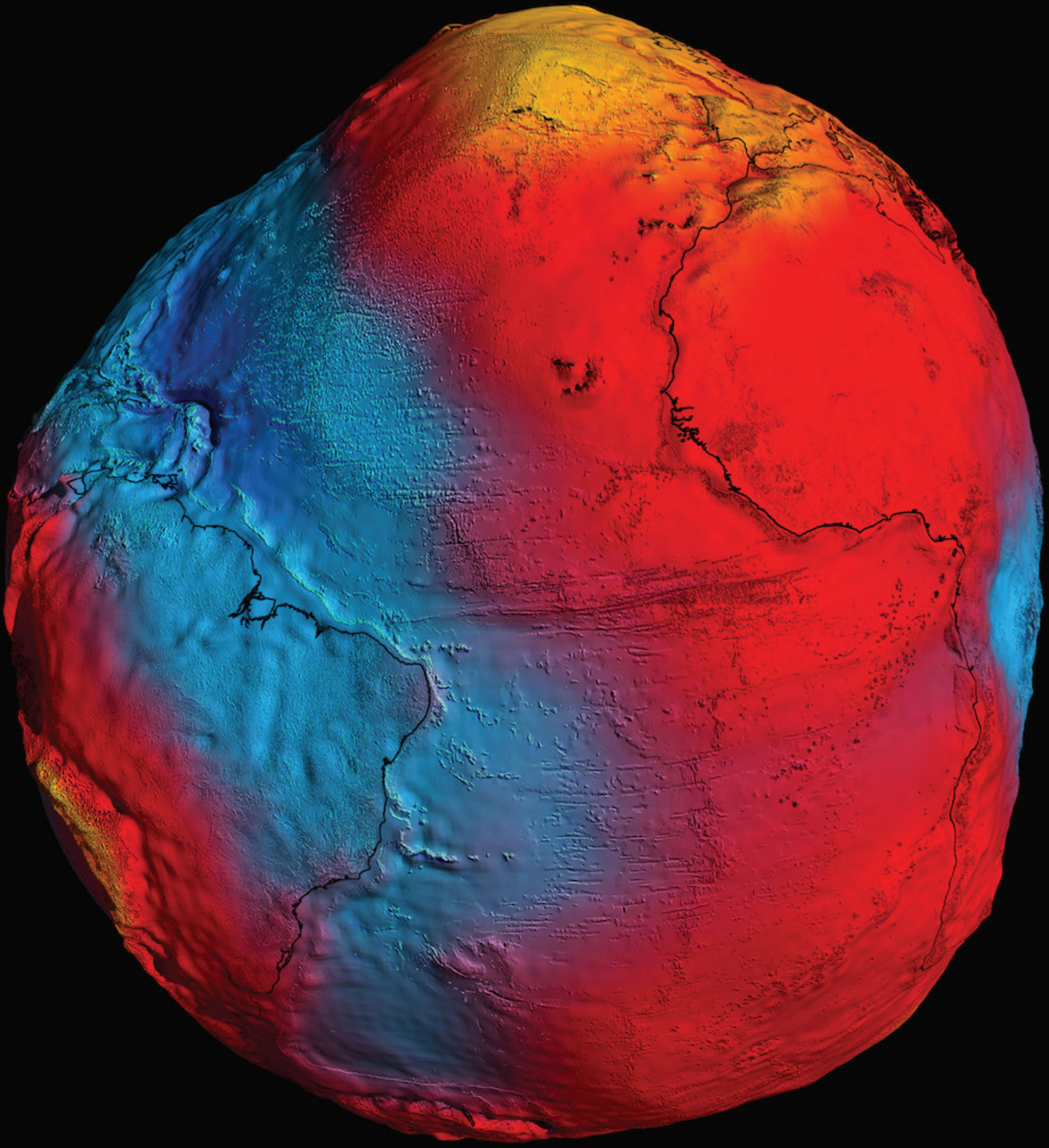
Scale: magenta (-107 m) to red (84.5 m)



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

March 2009 – Nov 2013

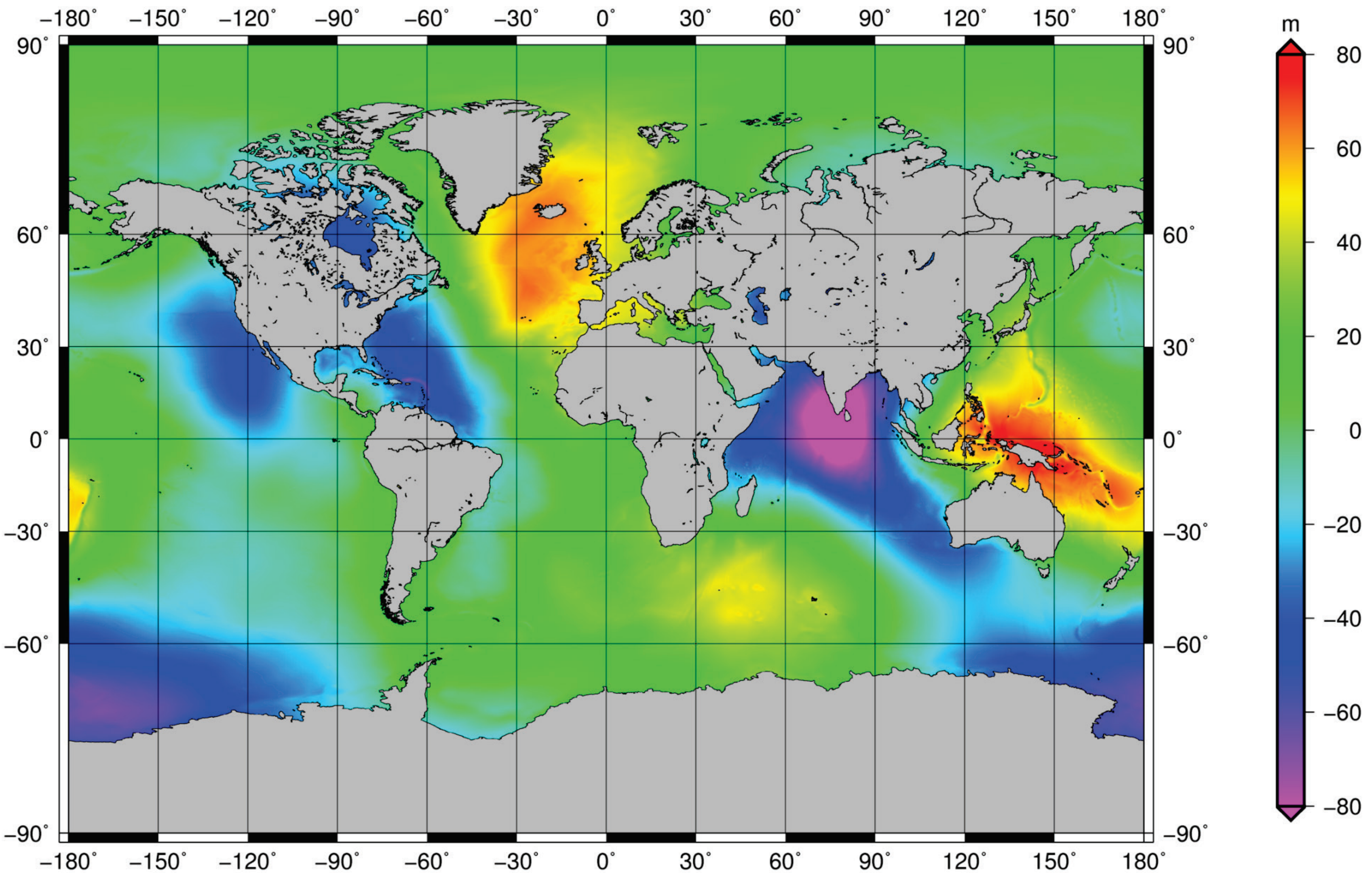
GOCE geoid



Removing the Geoid – an alternative

- The geoid is time invariant (approximately)
- So if we subtract a **Mean Sea Surface** we will remove the geoid
- (but we lose also the mean circulation, i.e the MDT)
- Mean Sea Surfaces are getting better and better, examples are the latest by CNES/CLES or by the Danish Technical University such as

DTU15MSS


−180˚
−150˚
−120˚
−90˚
−60˚
−30˚
0˚
30˚
60˚
90˚
120˚
150˚
180˚
90˚
60˚
30˚
0˚
−30˚
−60˚
−90˚
m
80
60
40
20
0
−20
−40
−60
−80

SSH residuals

- 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

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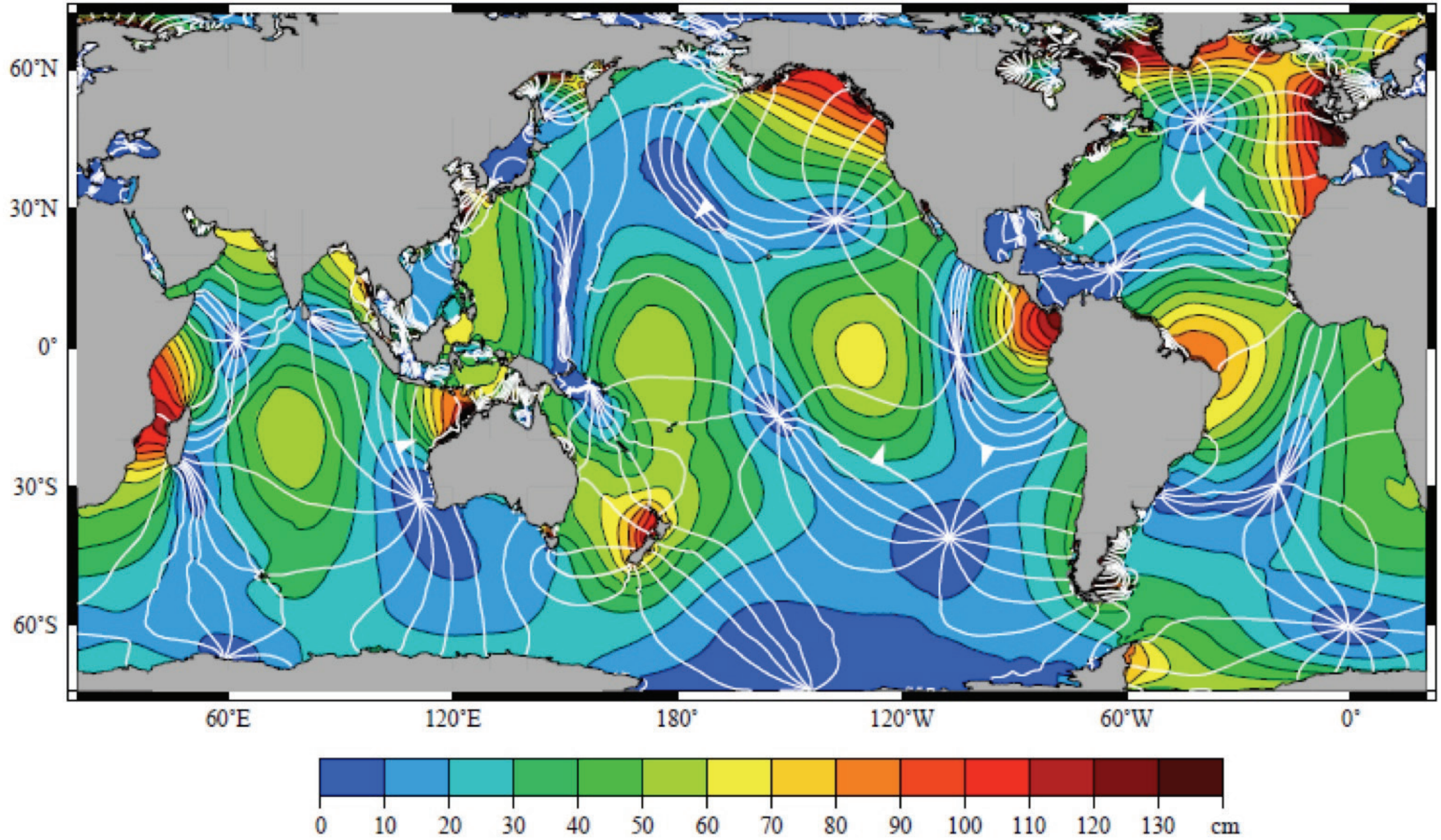
- May still contain time varying errors
  - Un-removed tidal or barometric signal
  - Orbit error
- With the recent independent accurate geoid models (from GRACE and ESA GOCE mission) we are getting closer to be able to subtract the geoid and work with **absolute dynamic topography** (much better for oceanographers!)

Tides

- 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

M_2



Map provided by Richard Ray (Goddard Space Flight Center) for Pugh and Woodworth (2014)

More tides!

- 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

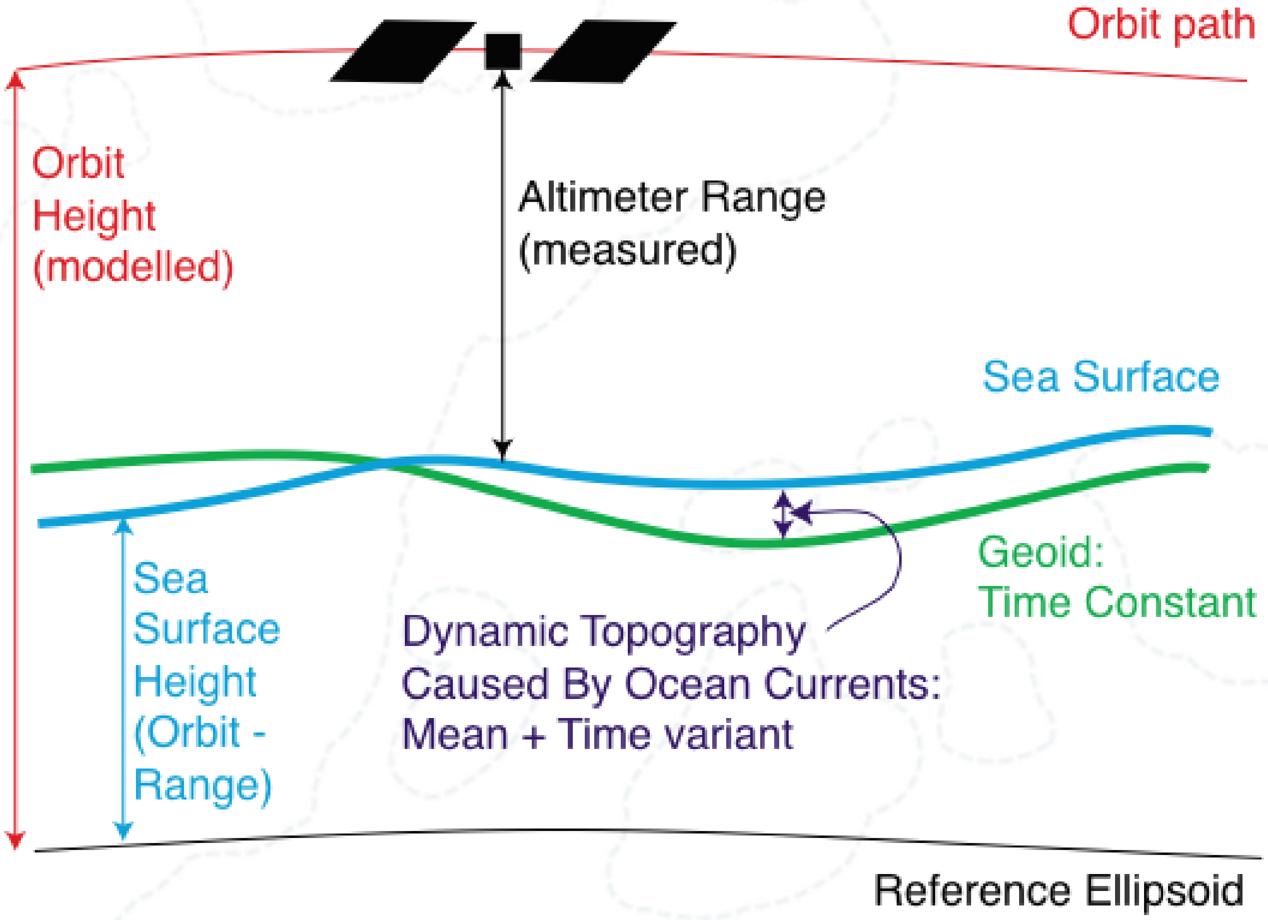
Dynamic Atmosphere correction

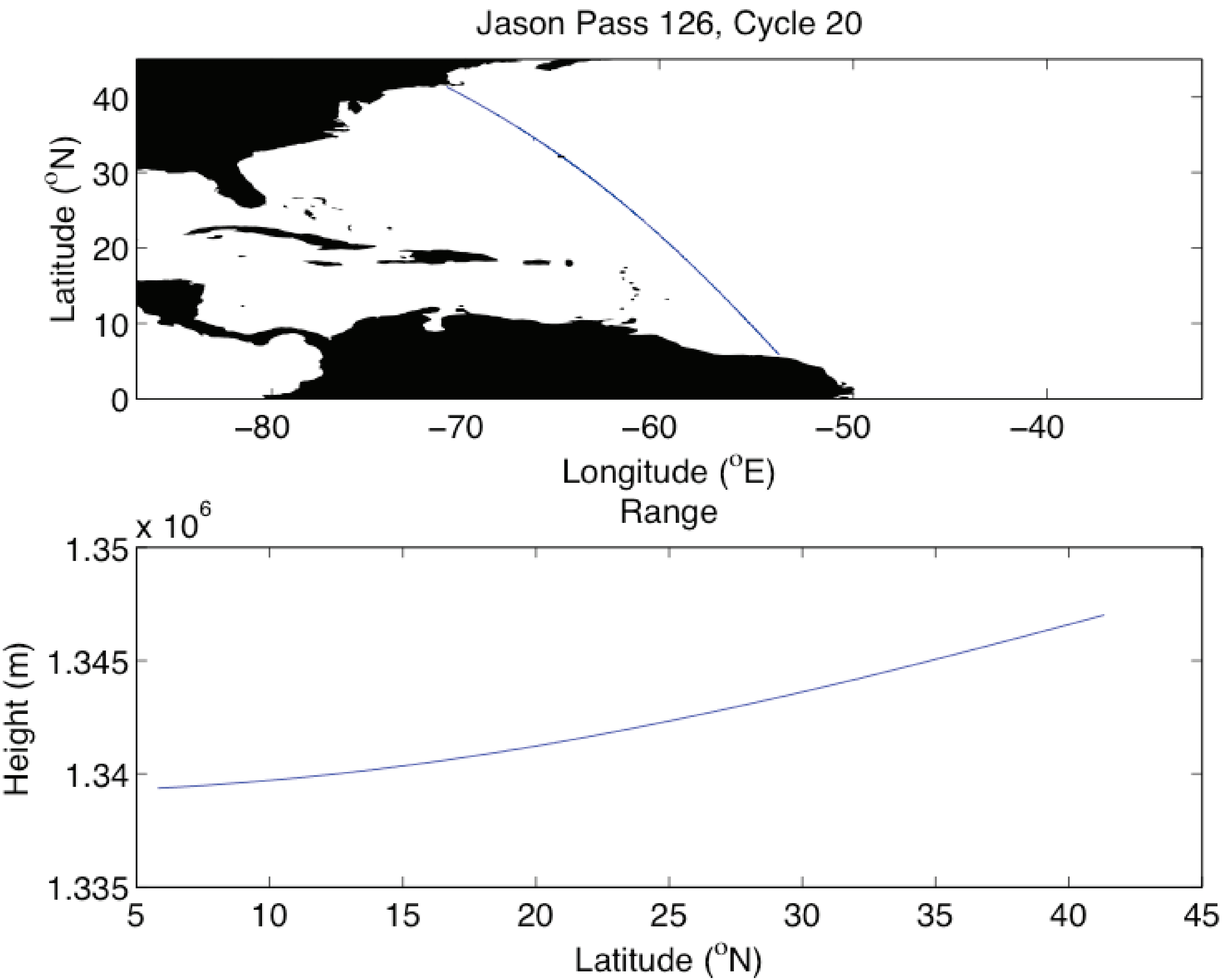
- The ocean responds to forcing by the atmosphere in two ways
  - changes in pressure: higher atmospheric pressure pushes down the water, lower atmospheric pressure sucks it up! this is called the ‘inverse barometer effect’ (1 millibar is equivalent to 1 cm)
  - effect of wind forcing ‘piling up’ water in places
- The combined effect can be dramatic especially at the coast – for instance in case of **surges**
- The correction for the atmosphere is very well estimated by barotropic models such as MOG2D, which is today of widespread use to correct altimetry.

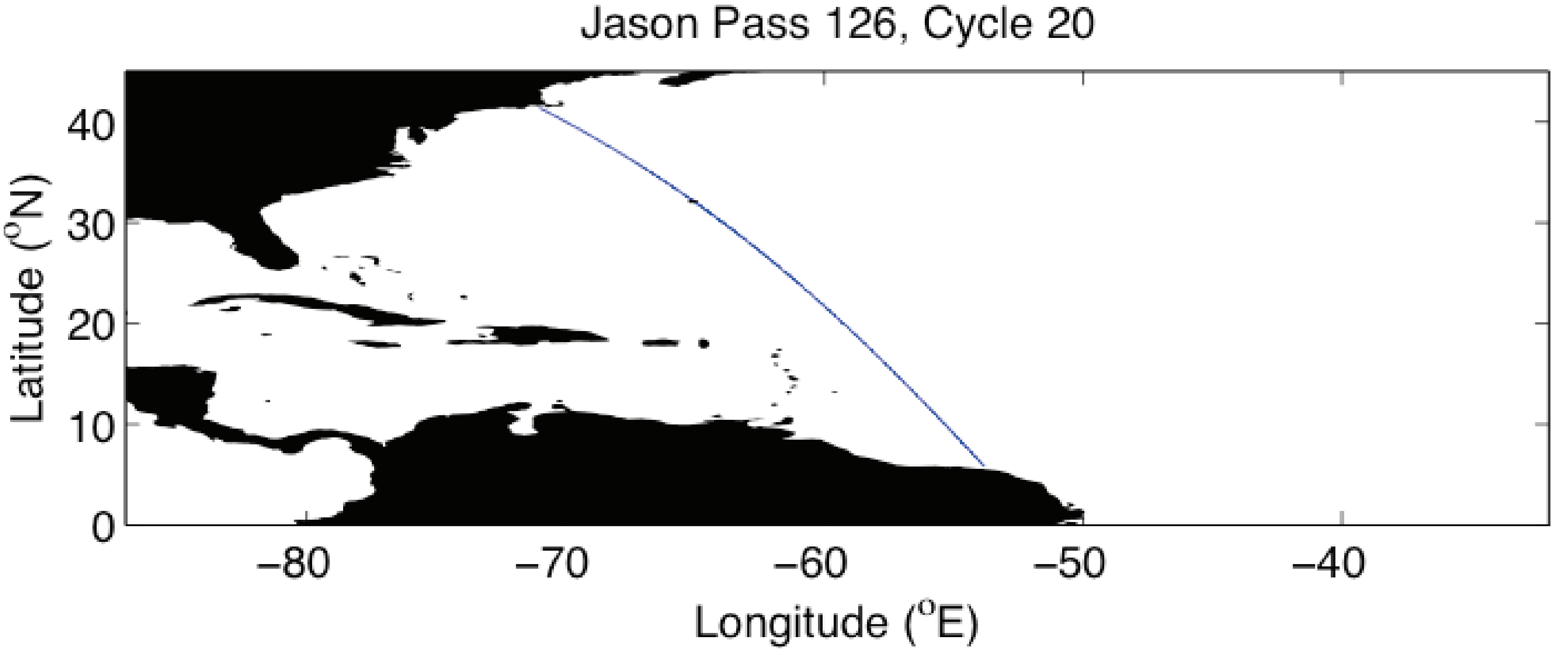
Example of applying corrections

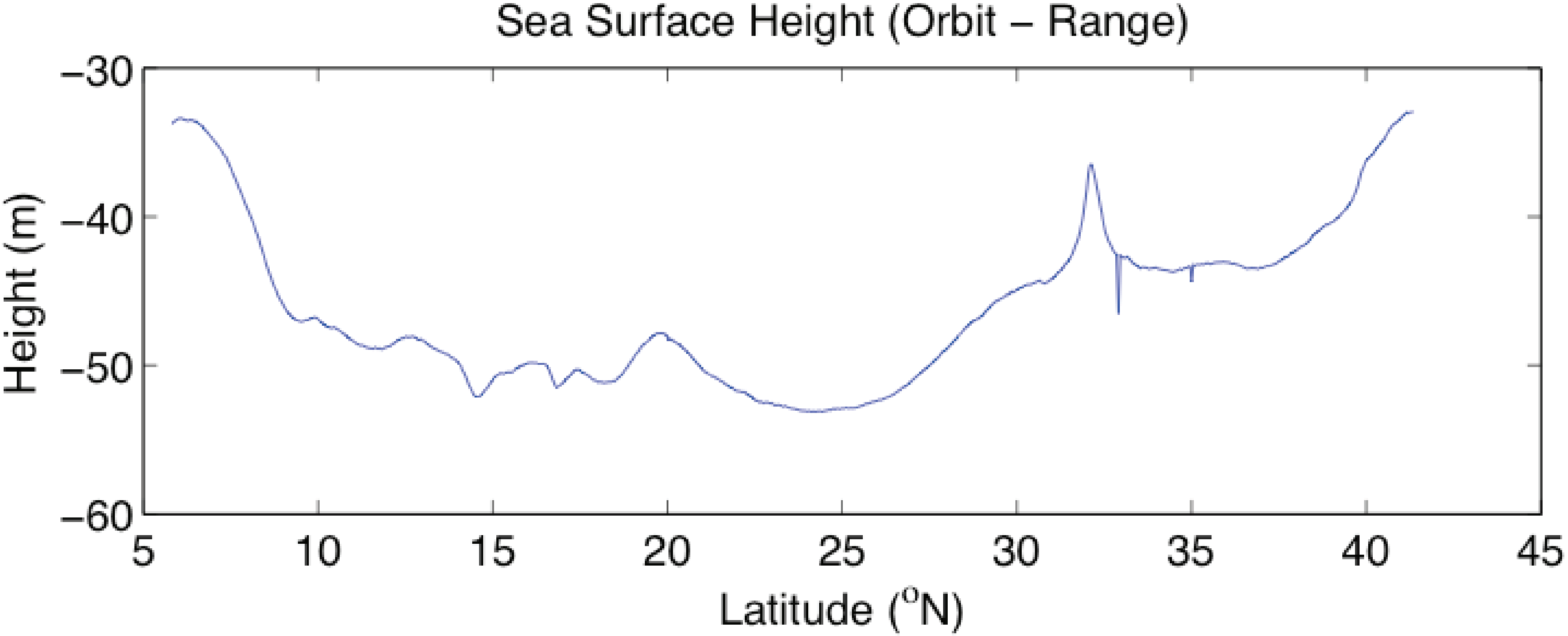
- Let’s see how things change when we do orbit-range and then apply all the corrections in sequence
- We use as example a Jason-1 (conventional altimeter) pass over the N Atlantic – but corrections would be the same for a SAR altimeter

Example over a pass

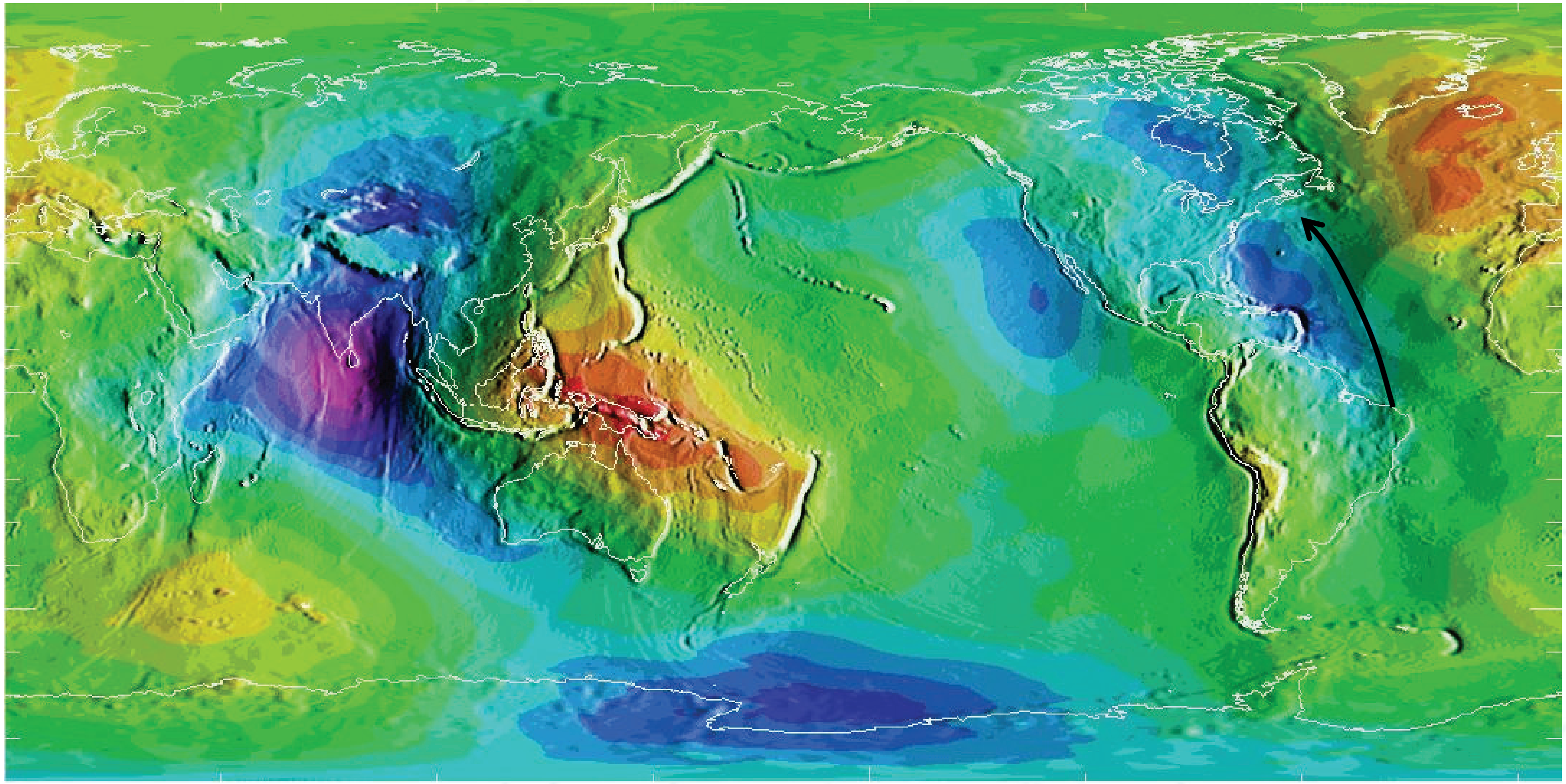



Jason Pass 126, Cycle 20
Latitude (°N)
40
30
20
10
0
−80
−70
−60
−50
−40
Longitude (°E)
Range
x 10^6
Height (m)
1.35
1.345
1.34
1.335
5
10
15
20
25
30
35
40
45
Latitude (°N)

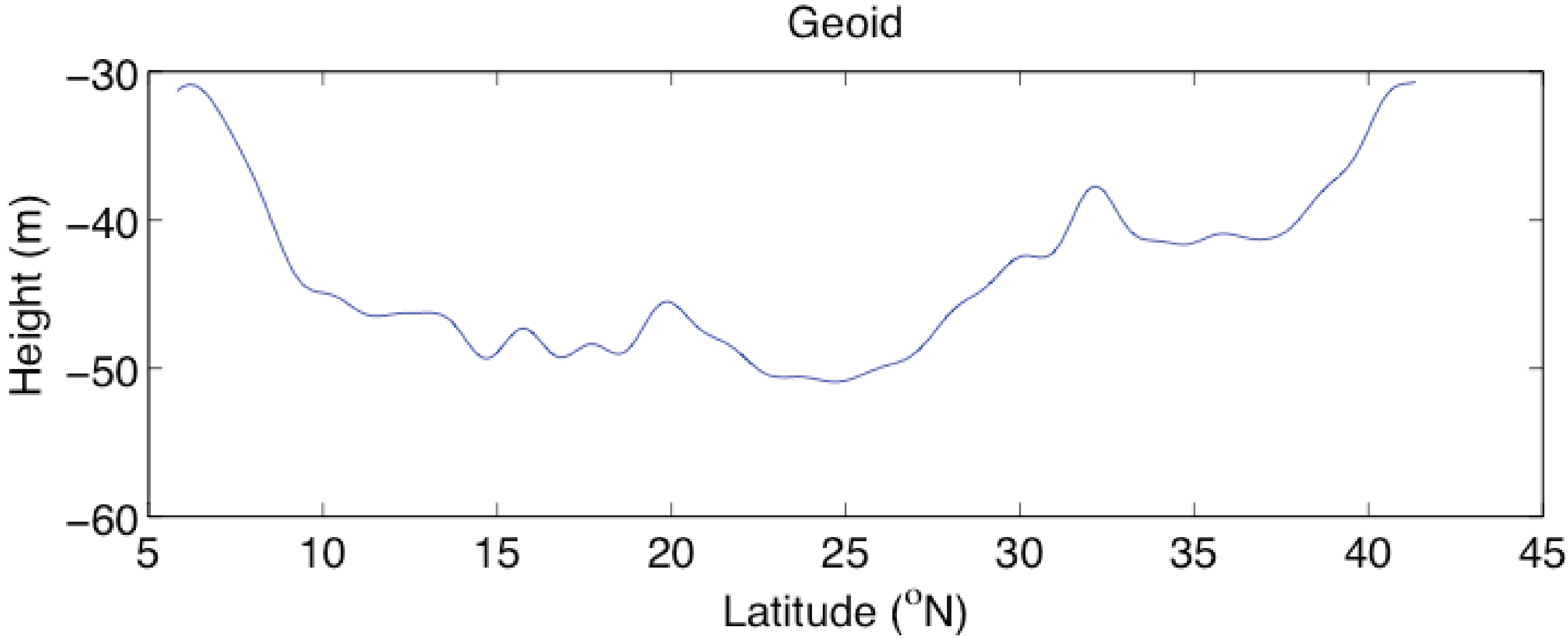

Jason Pass 126, Cycle 20
Latitude (°N)
0
10
20
30
40
−80
−70
−60
−50
−40
Longitude (°E)


Sea Surface Height (Orbit – Range)
Height (m)
−30
−40
−50
−60
5
10
15
20
25
30
35
40
45
Latitude (°N)

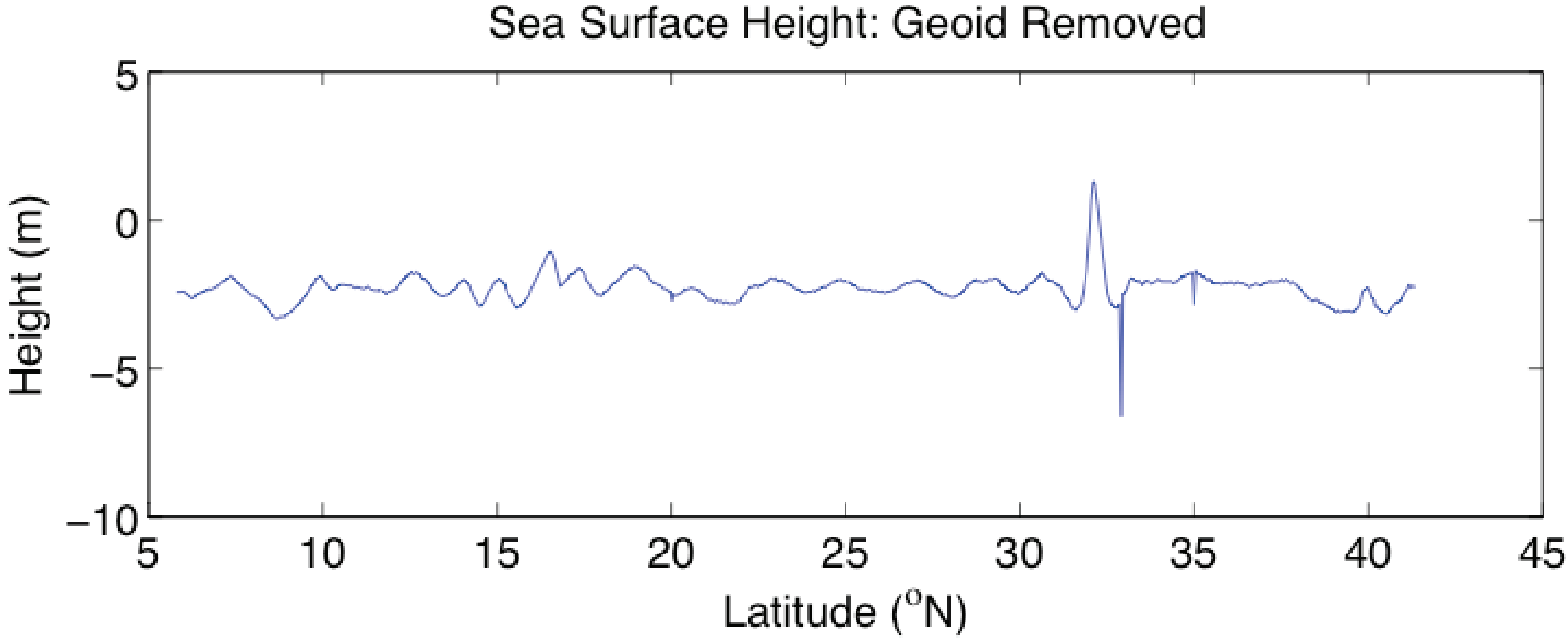
The Geoid



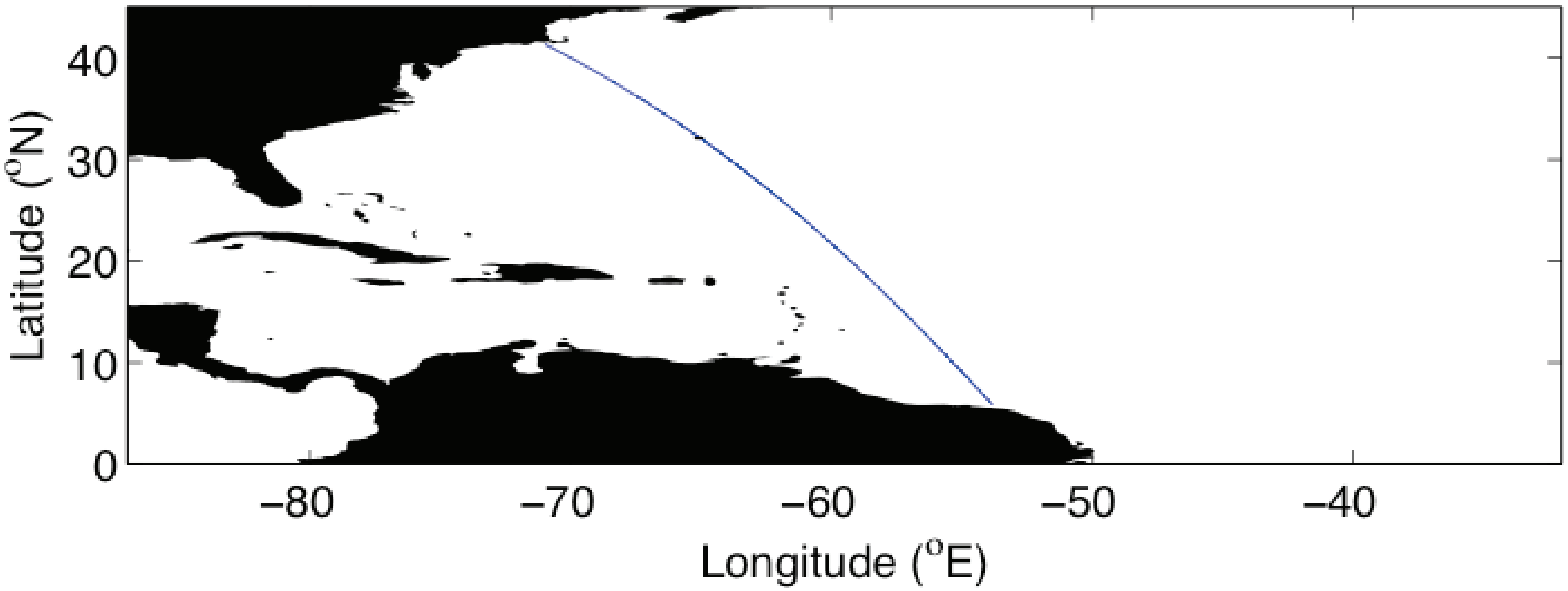
Scale: magenta (-107m) to red (84.5m)



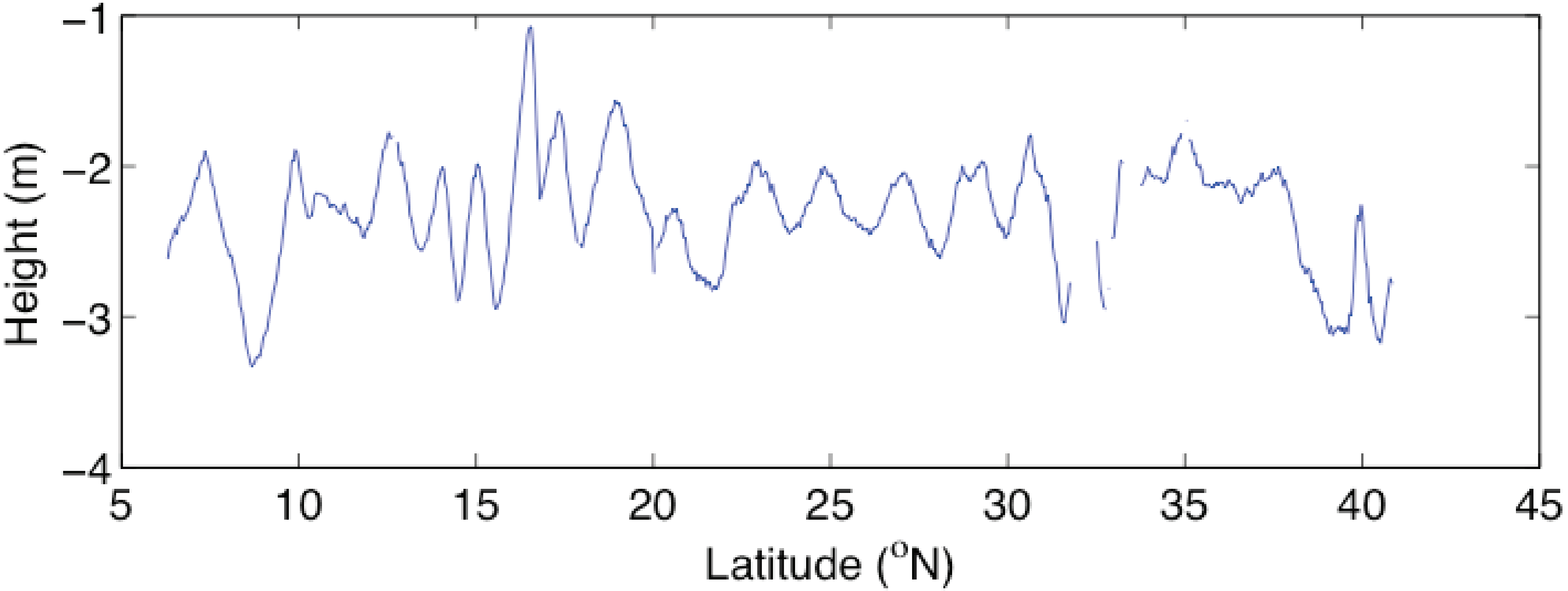
Geoid



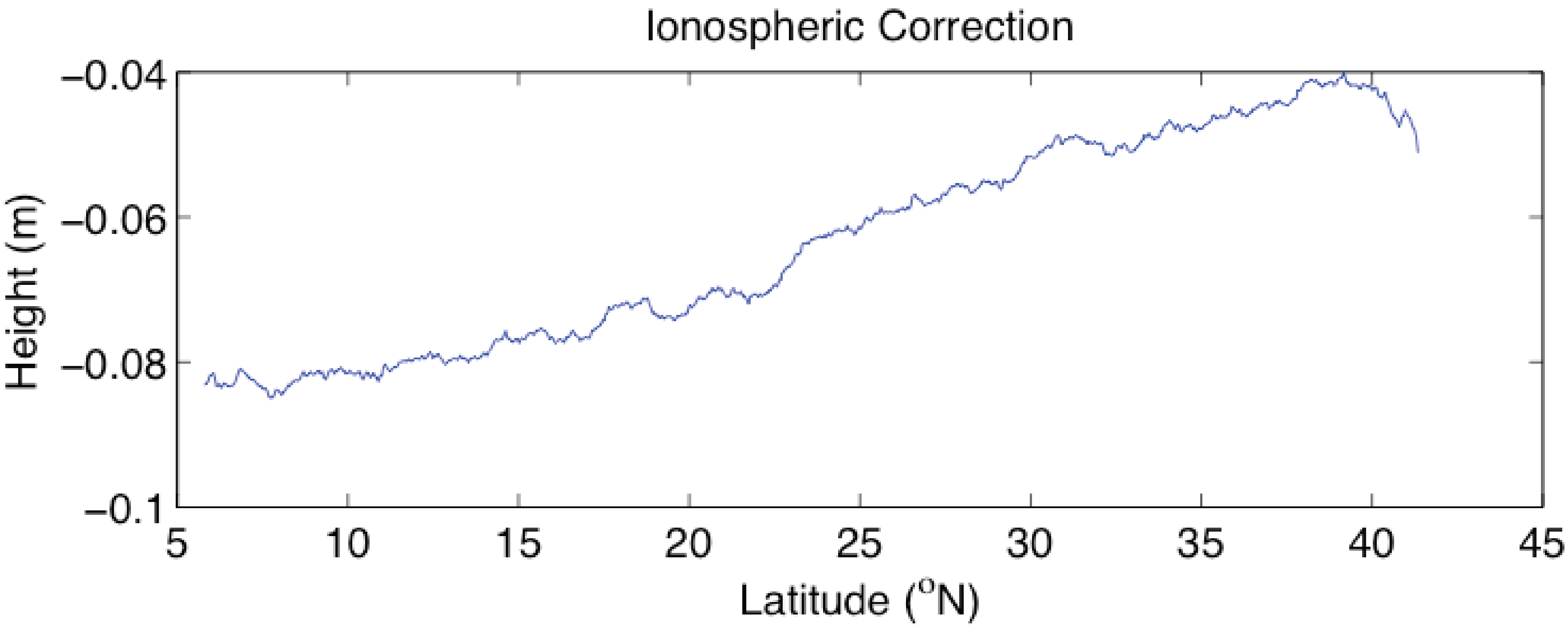
Sea Surface Height: Geoid Removed

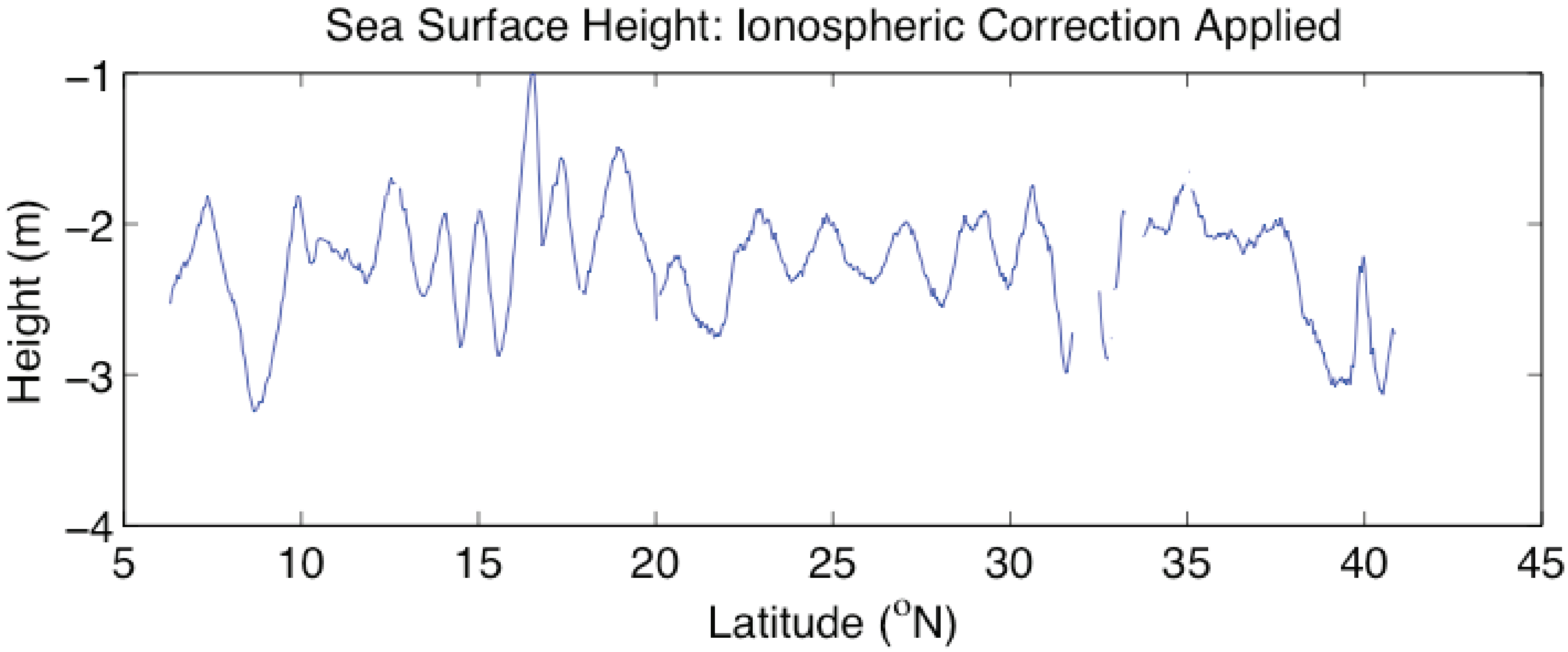


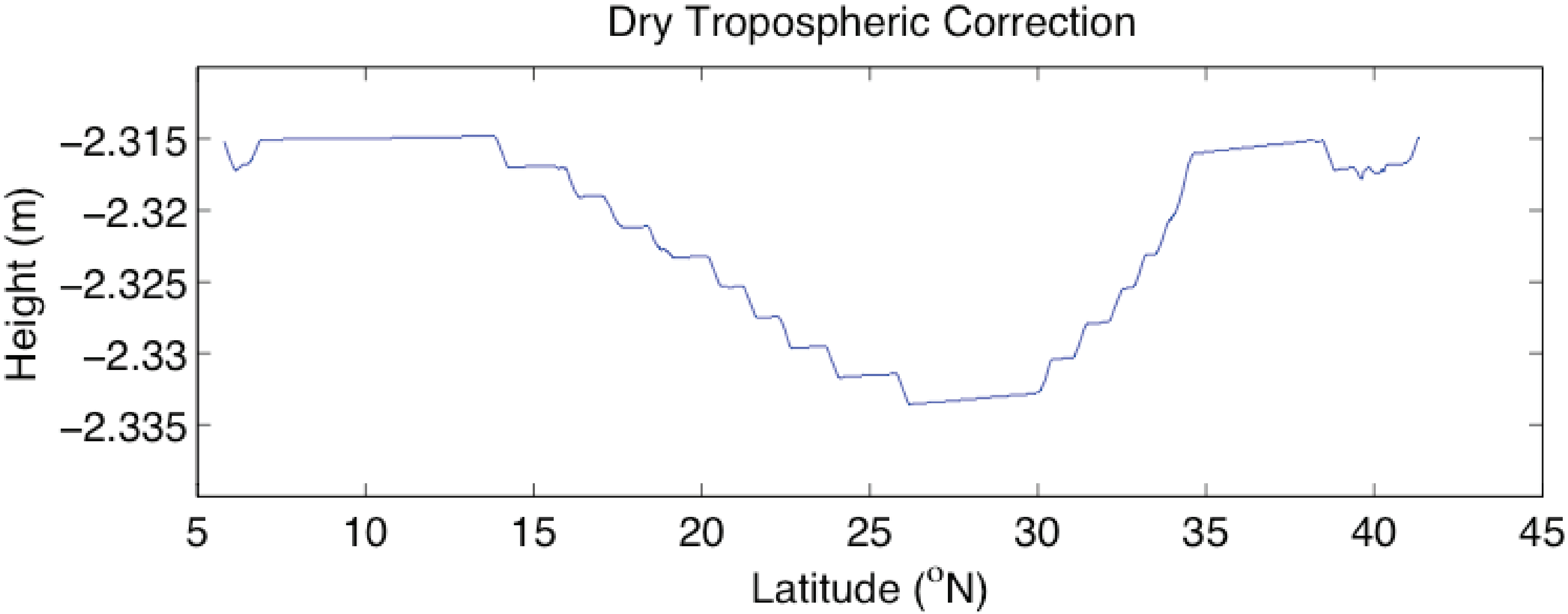
Jason Pass 126, Cycle 20

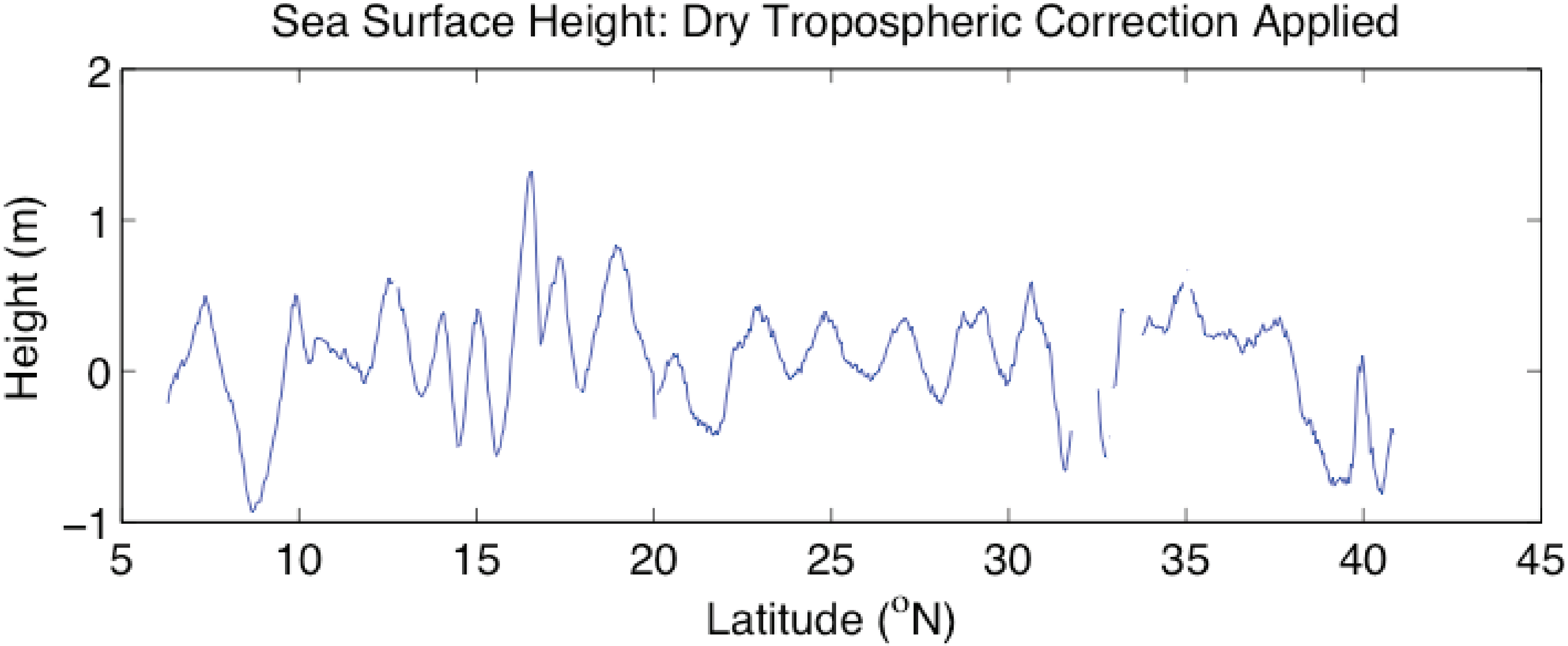


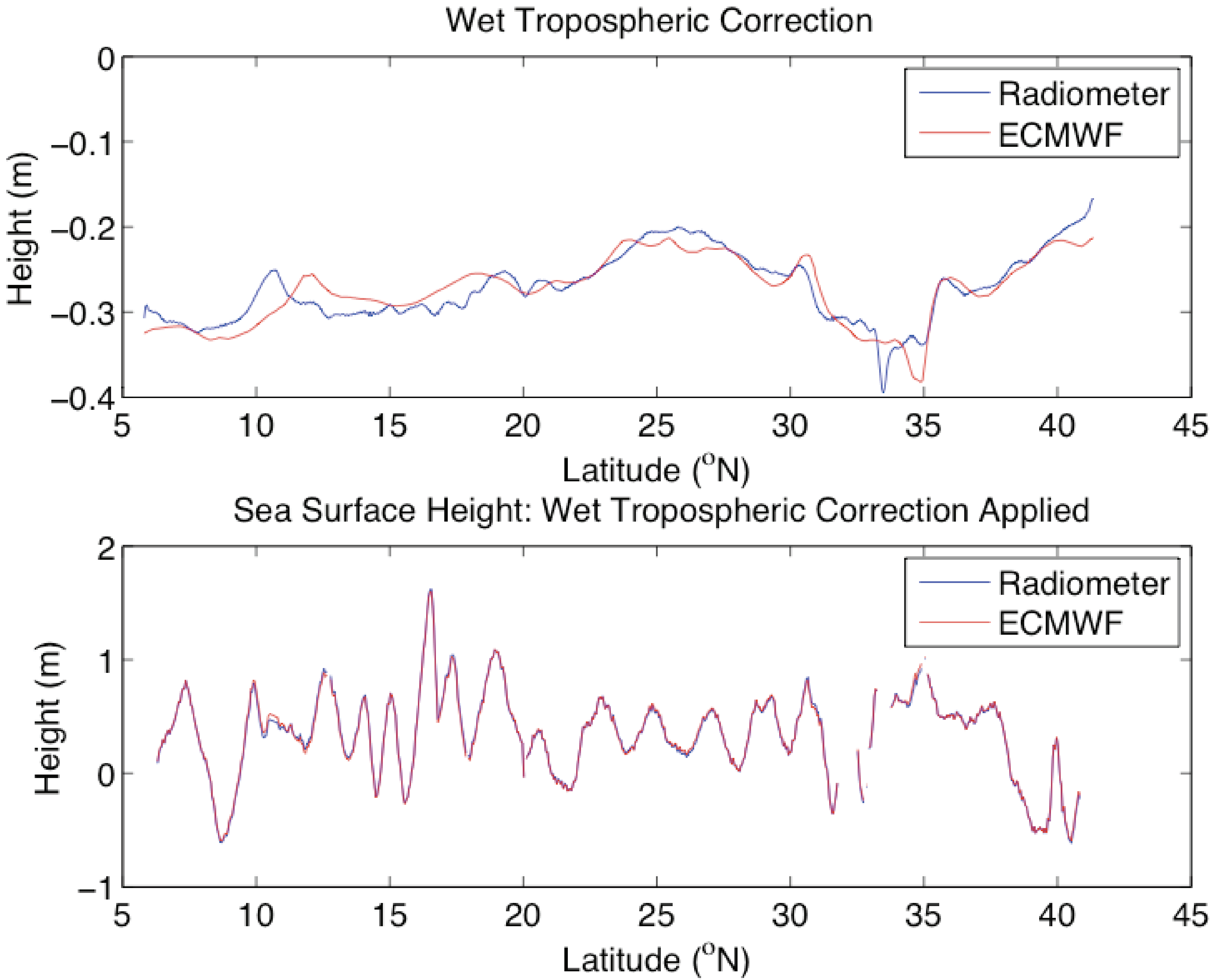
Sea Surface Height: Flagged Data Removed


Ionospheric Correction


Sea Surface Height: Ionospheric Correction Applied

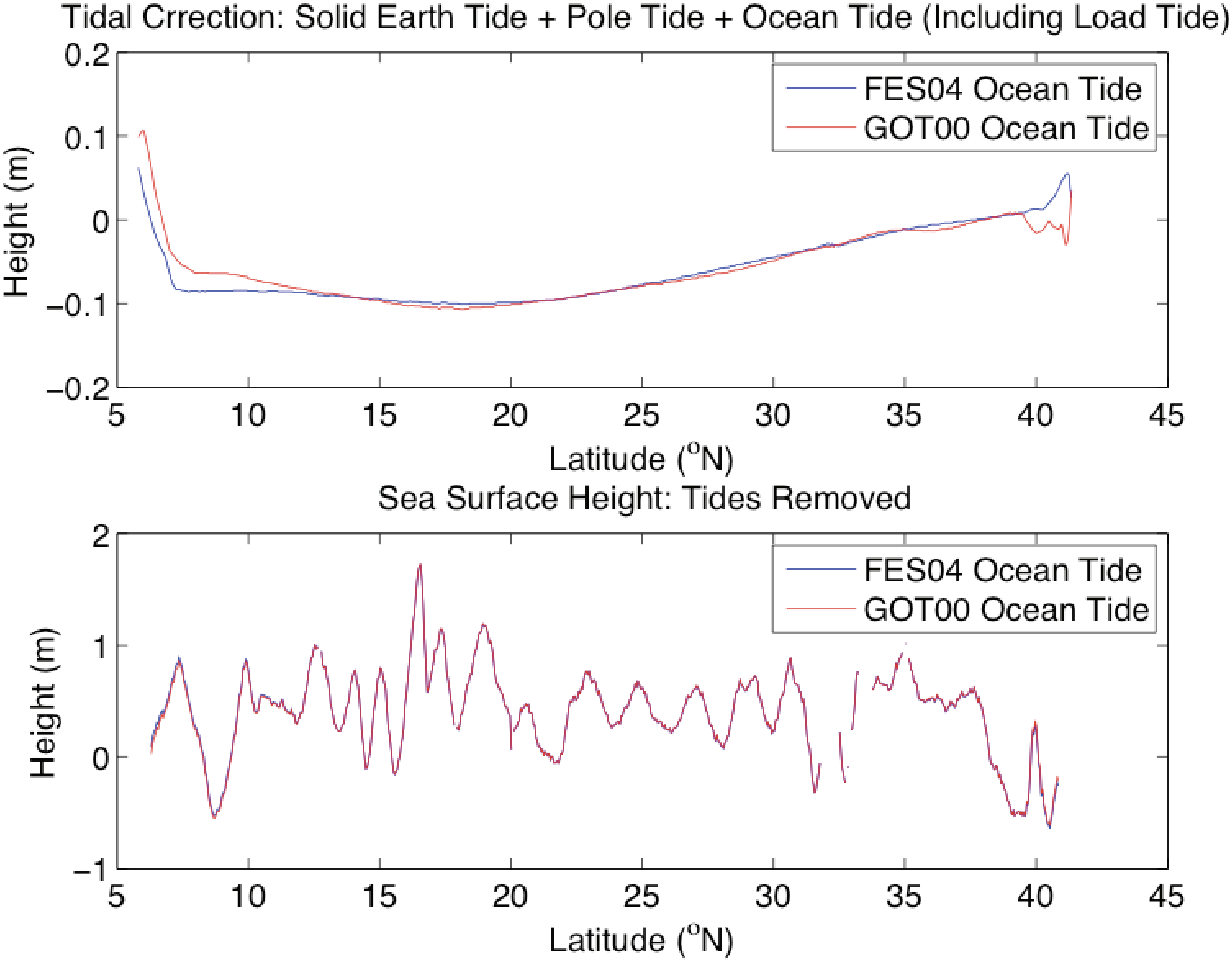

Dry Tropospheric Correction

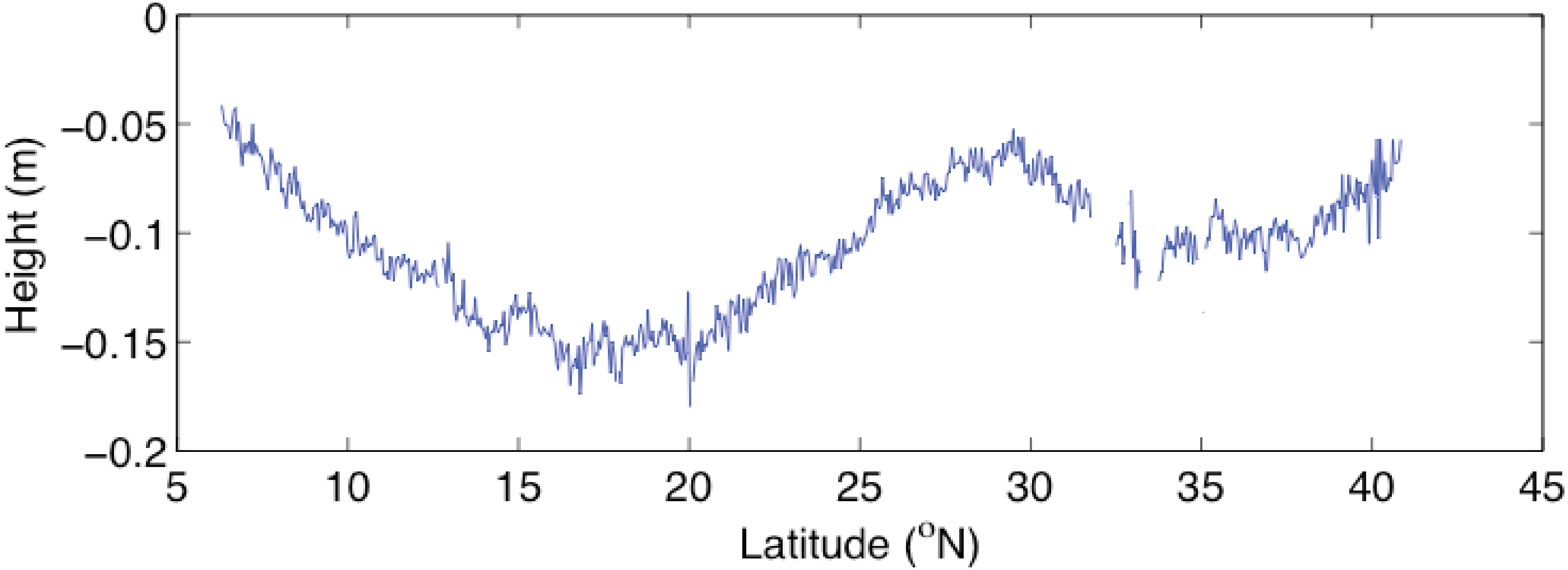

Sea Surface Height: Dry Tropospheric Correction Applied



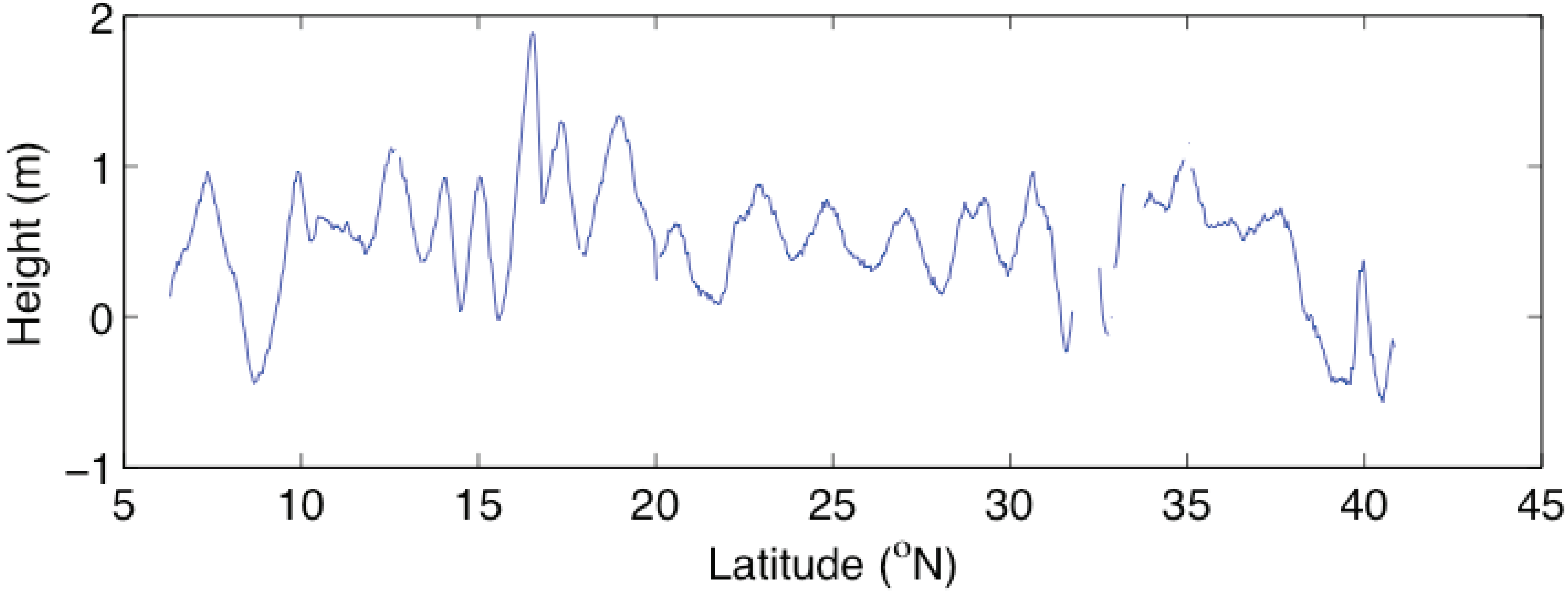
Wet Tropospheric Correction

Sea Surface Height: Wet Tropospheric Correction Applied

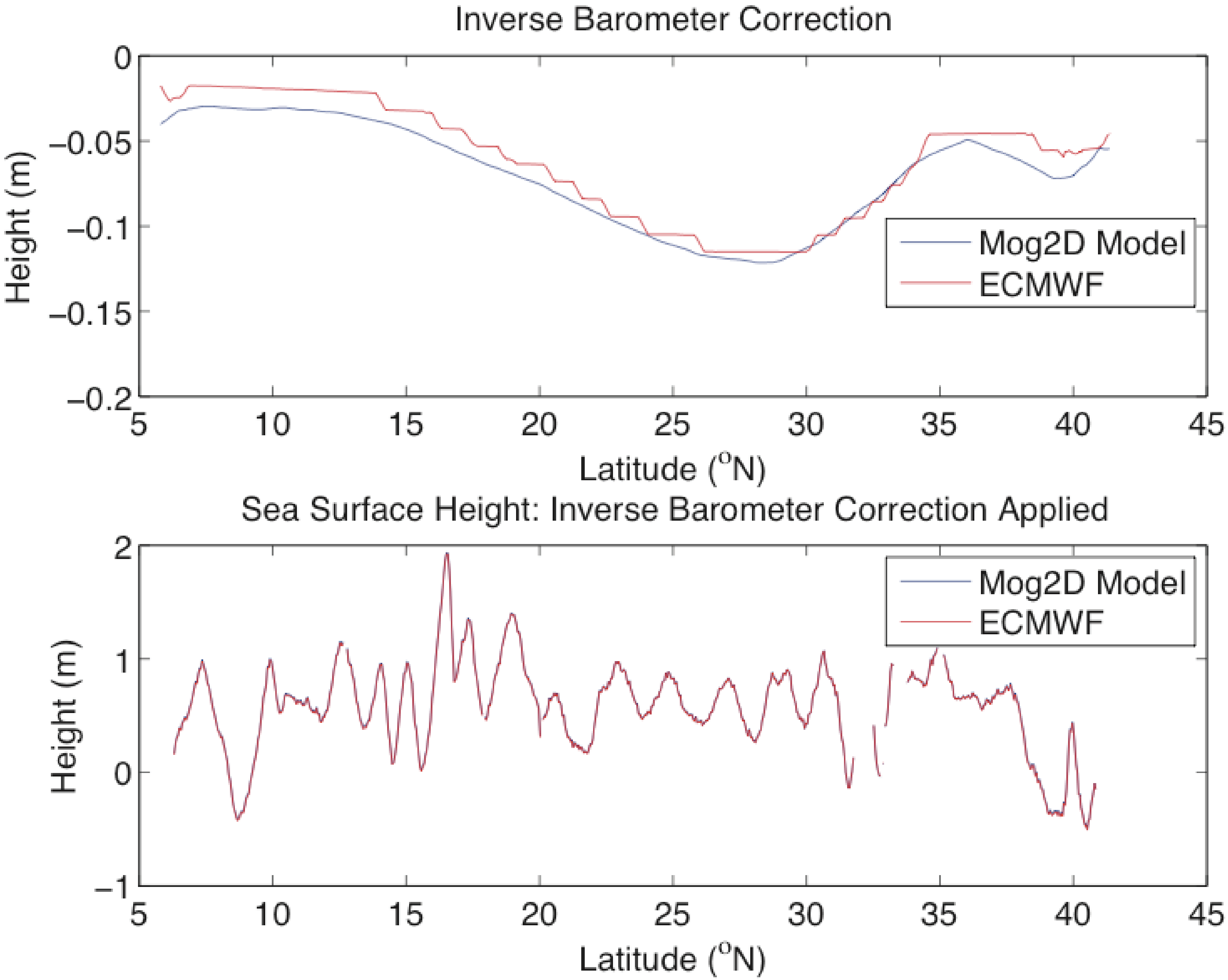

Tidal Crrection: Solid Earth Tide + Pole Tide + Ocean Tide (Including Load Tide)
FES04 Ocean Tide
GOT00 Ocean Tide
Height (m)
0.2
0.1
0
−0.1
−0.2
5
10
15
20
25
30
35
40
45
Latitude (°N)
Sea Surface Height: Tides Removed
FES04 Ocean Tide
GOT00 Ocean Tide
Height (m)
2
1
0
−1
5
10
15
20
25
30
35
40
45
Latitude (°N)

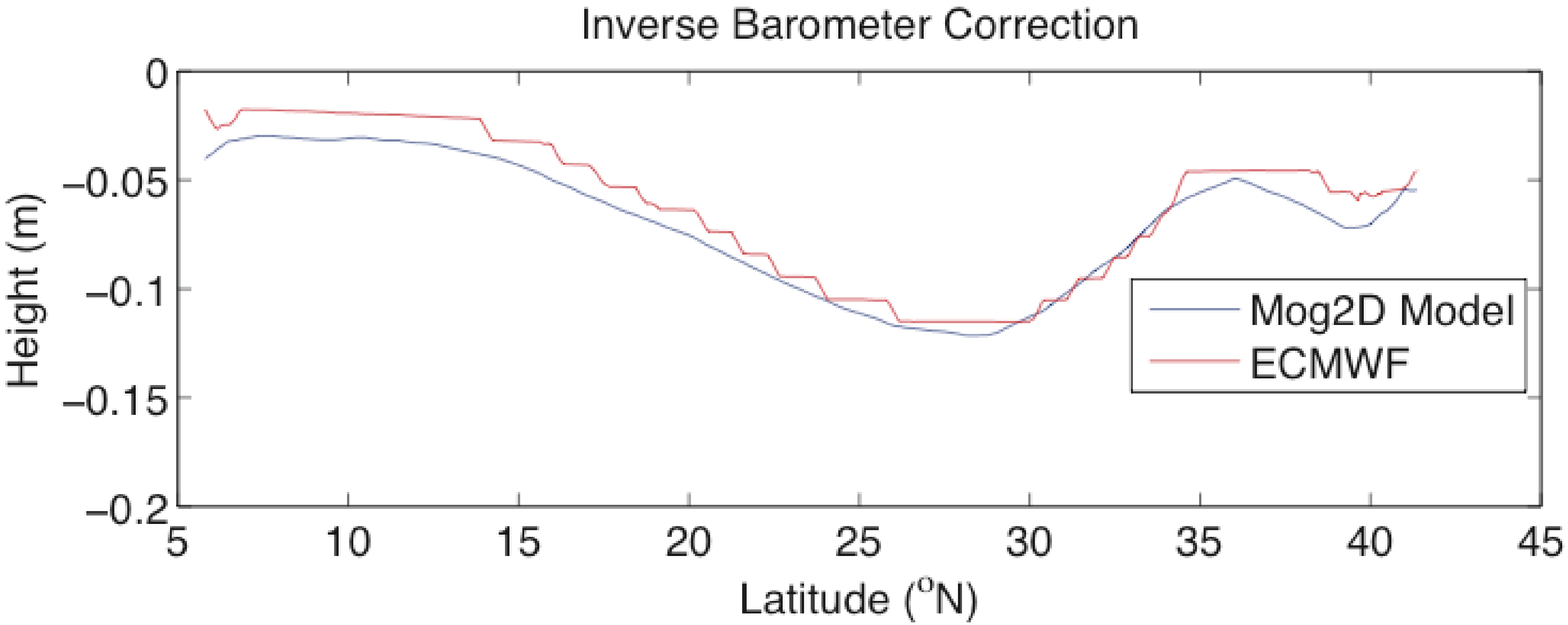


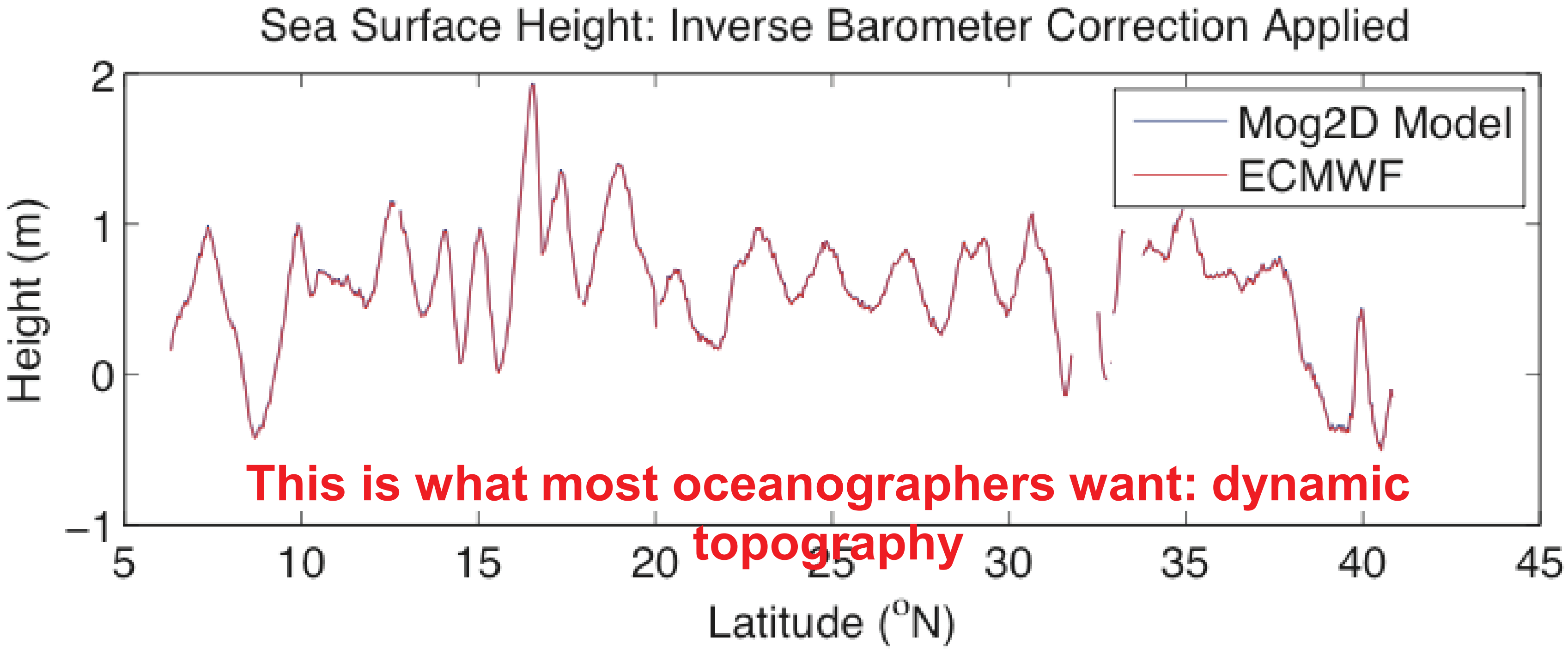
Sea State Bias Correction



Sea Surface Height: Sea State Bias Correction Applied


Inverse Barometer Correction
Height (m)
0
−0.05
−0.1
−0.15
−0.2
5
10
15
20
25
30
35
40
45
Latitude (°N)
Mog2D Model
ECMWF
Sea Surface Height: Inverse Barometer Correction Applied
Height (m)
2
1
0
−1
5
10
15
20
25
30
35
40
45
Latitude (°N)
Mog2D Model
ECMWF





This is what most oceanographers want: dynamic topography

Bottom line

- With the best **instrumental processing**, **orbits** and **corrections** altimetry achieves high **precision** and **accuracy** – at the ~2 cm level @ 1Hz with conventional altimetry, and even better for SAR altimetry (as the instrumental noise is better!)
- The measurements systems are also very **stable** (not shown today, but fully demonstrated by the ESA SL CCI project
- This allows lots of **applications** (dynamics, processes, events, long-term trends)
- A challenge is to extend this excellent performance to the **coastal zone** – challenge on-going, but already successful – see the Coastal Altimetry Workshop during this week!

→ 10th COASTAL ALTIMETRY WORKSHOP

SAR Altimetry Training Course

21–24 February 2017 | Florence, Italy

National Oceanography Centre
NATURAL ENVIRONMENT RESEARCH COUNCIL

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