Exploiting radar power to study oceans and climate: the rise and prospects of satellite altimetry

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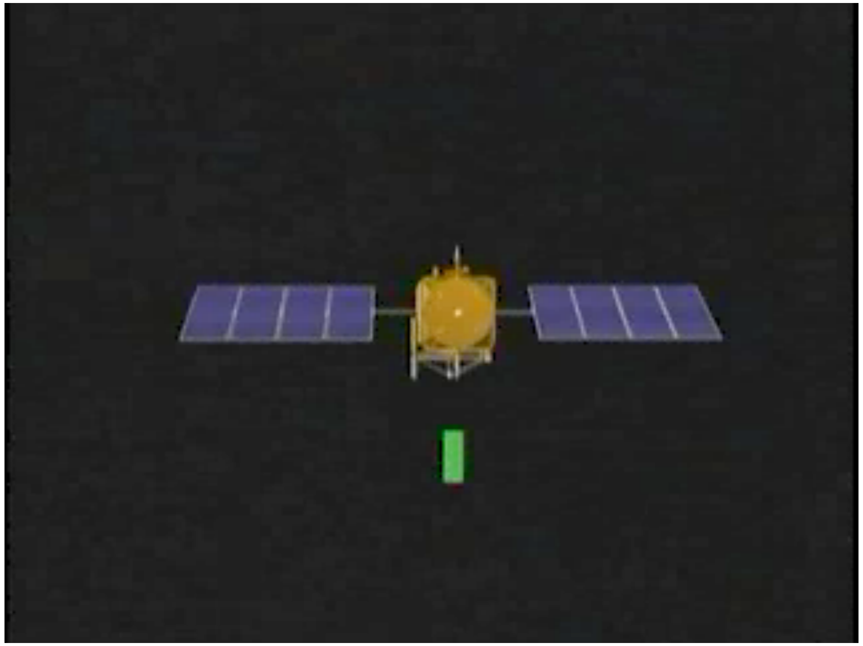
Outline

- Rationale
  - (why we need altimetry)
- Principles of altimetry
  - (how it works in principle)
- Corrections
  - (how it is made accurate)
- Geophysical parameters
  - (what quantities we measure)
- Examples of applications
  - (how we use it!)

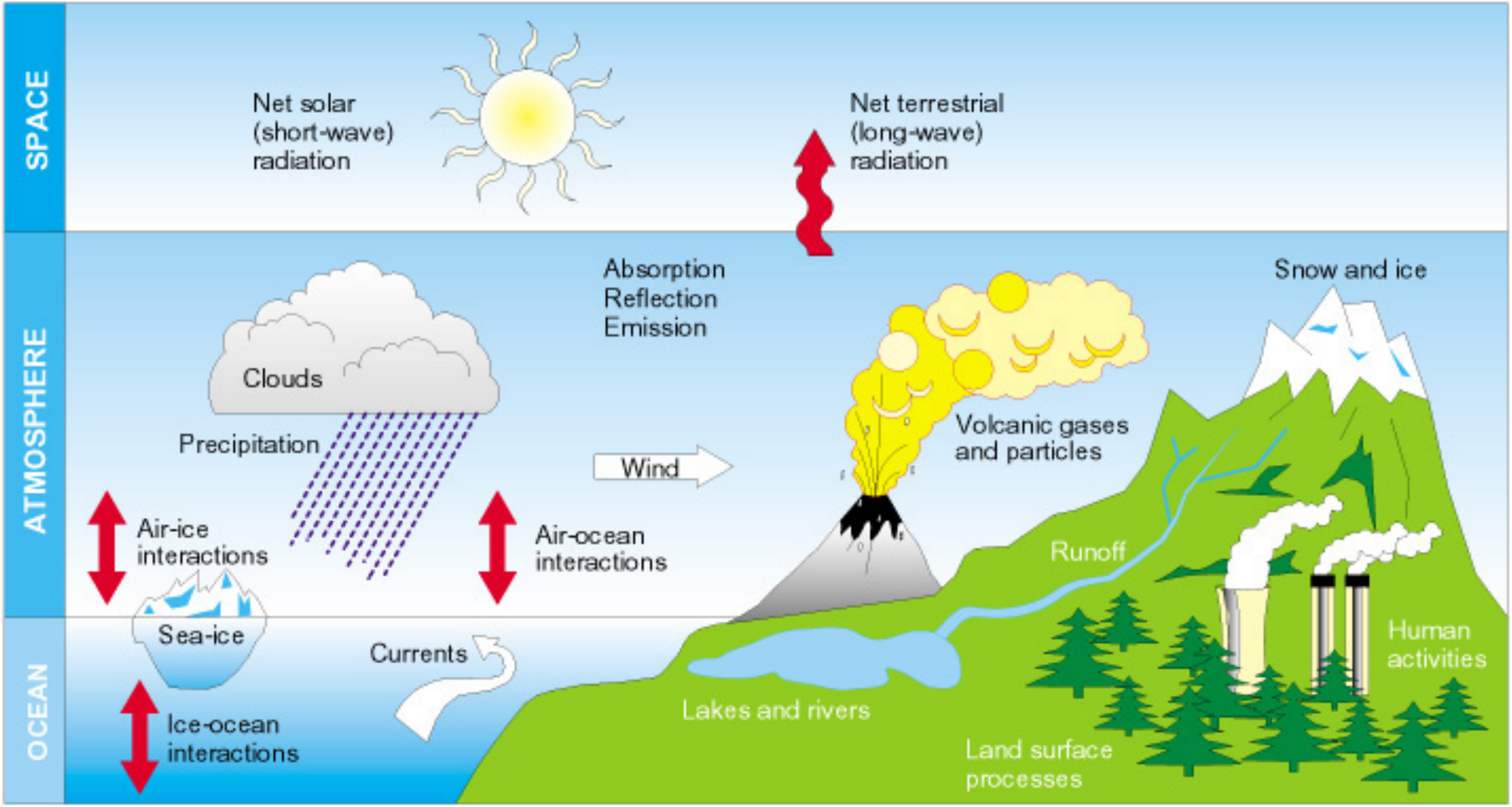
Rationale for Radar Altimetry

over the oceans

- Climate change
  - oceans are a very important component of climate system
- Altimeters monitor **currents / ocean circulation**…
- …that can be used to estimate **heat** storage and transport
- … and to assess the interaction between **ocean and atmosphere**
- We also get interesting by-products: **wind/waves**, **rain**, gas exchange



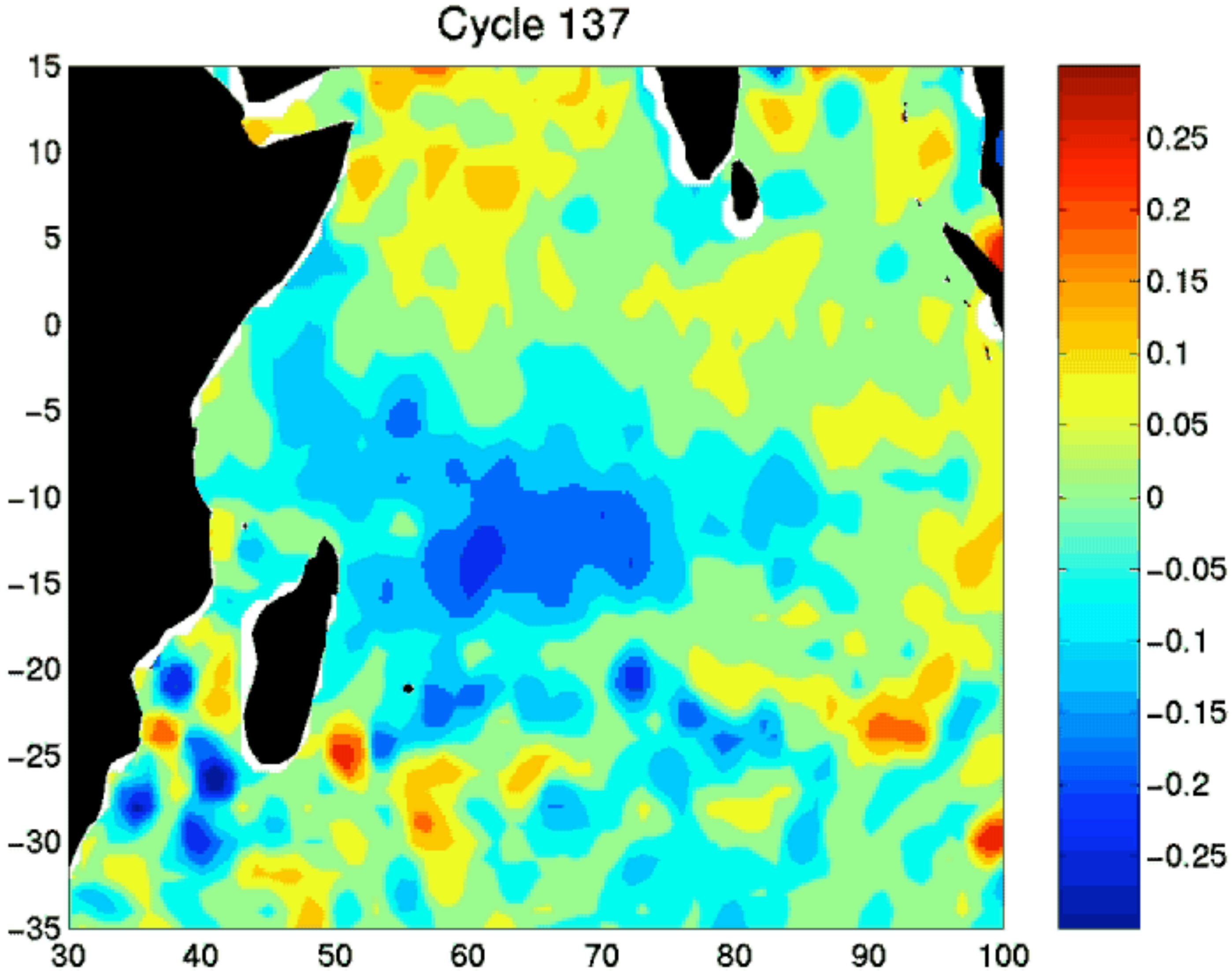
The Climate System



courtesy N. Noreiks, L. Bengtsson, MPI

AV/Global/0101

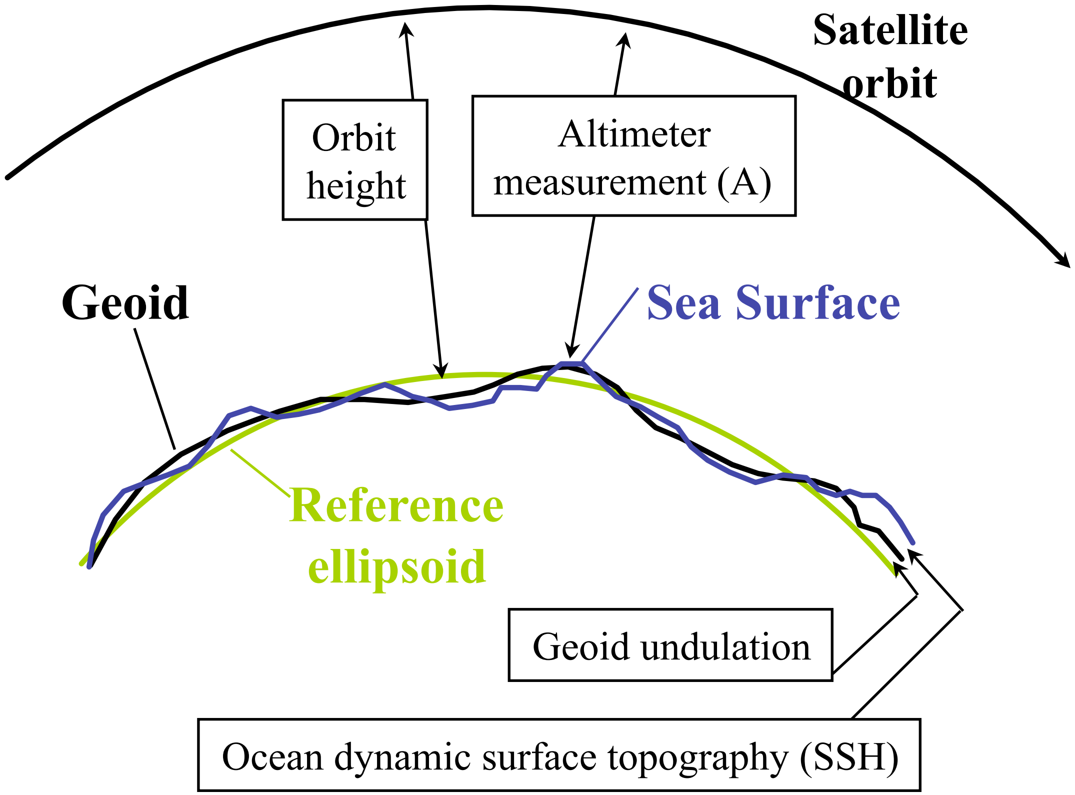
The sea is not flat….



Surface dynamical features of height **= tens of cm** over lengths = **hundreds of kms**

Altimetry I - principles & instruments

- The altimeter is a radar at vertical incidence
- The signal returning to the satellite is from quasi-specular reflection
- Measure distance between satellite and sea
- Determine position of satellite
- Hence determine height of sea surface
- Oceanographers require height relative to geoid



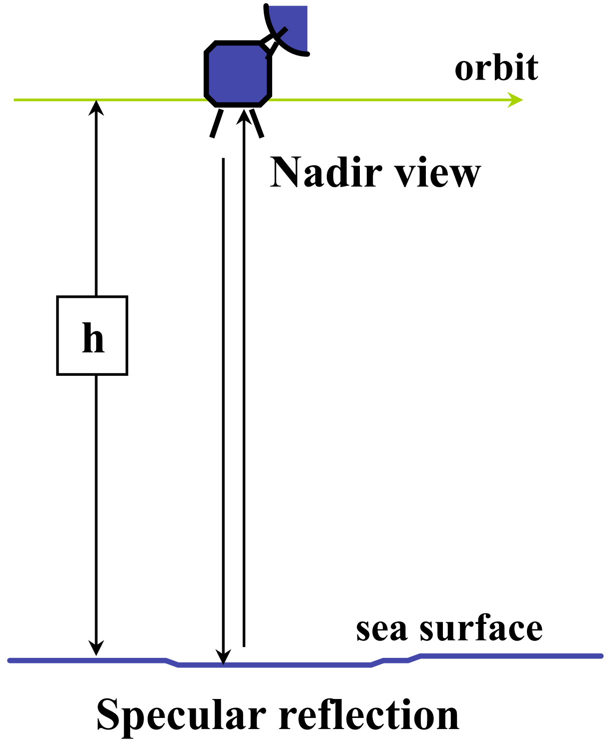
SSH = Orbit - A - Geoid

Measuring ocean topography with radar

– Measure travel time, 2T, from emit to return

– $h = T/c$ ($c = 3 \times 10^8$ m/s)

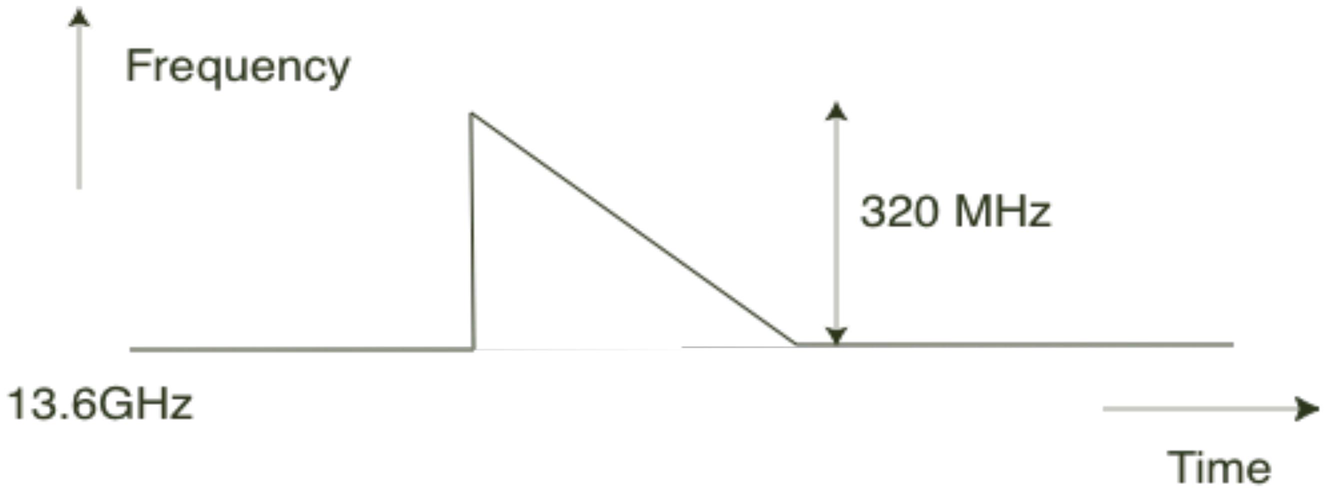
– **Resolution to ~cm** would need a precision of 3×10^{-10}s, that is 0.3 nanoseconds)



0.3ns…. That is a pulse bandwidth of >3 GHz…. ahem, wait a minute….

Chirp, chirp….

- So we have to use tricks: chirp pulse compression



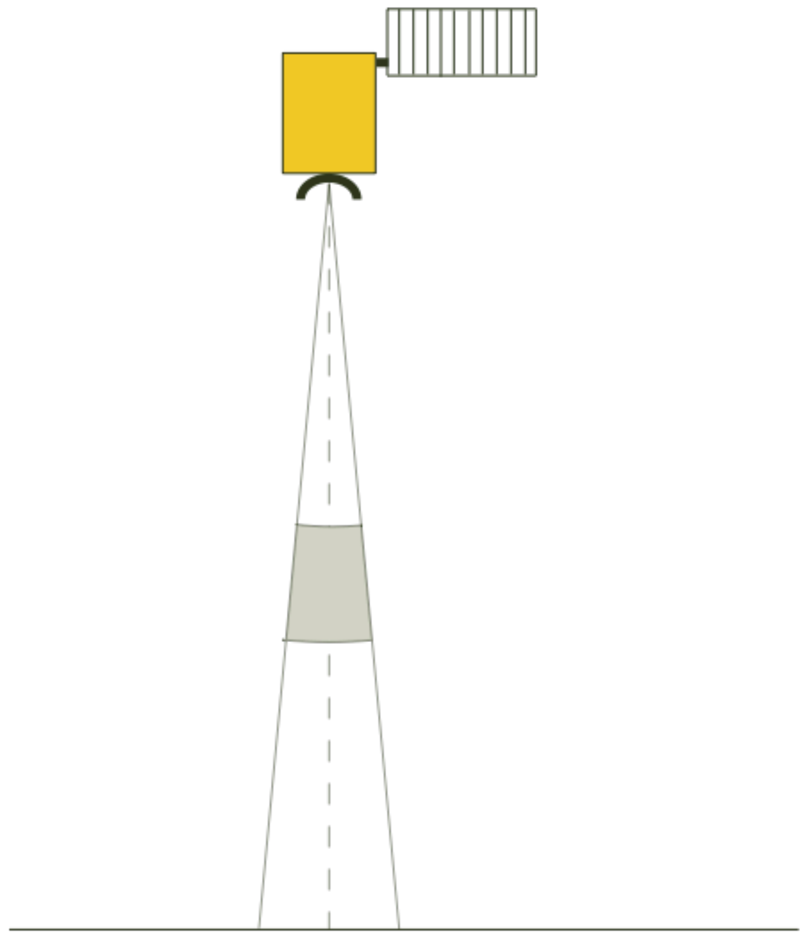
- …and average ~1000 pulses
- It is also necessary to apply a number of corrections for atmospheric and surface effects

Beam- and Pulse- Limited Altimeters

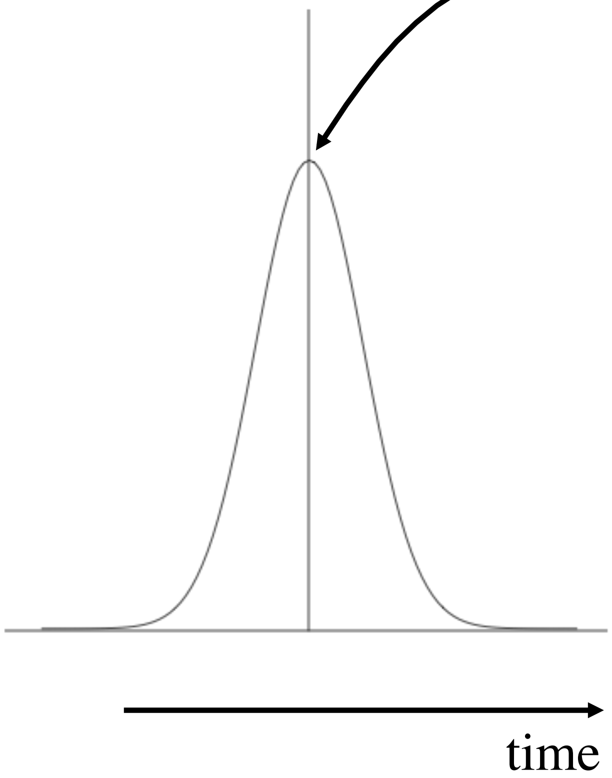
- In principle here are two types of altimeter:
- beam limited
- pulse limited

Beam Limited Altimeter

- In a beam limited altimeter the return pulse is dictated by the width of the beam



- A plot of return power versus time for a beam limited altimeter looks like the heights of the specular points, i.e. the probability density function (pdf) of the specular scatterers



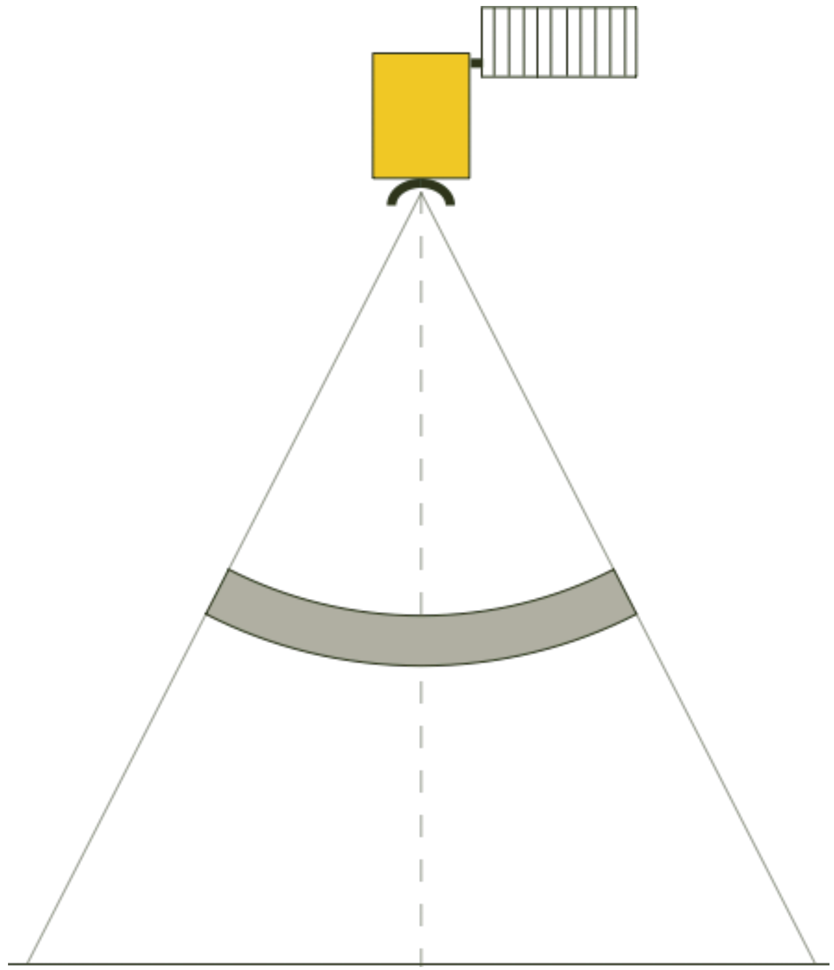
The **tracking point** (point taken for the range measurement) is the maximum of the curve

Beam-limited - technological problems

- Narrow beams require very large antennas and are impractical in space
  - For a 5 km footprint a beam width of about 0.3° is required. For a 13.6 GHz altimeter this would imply a 5m antenna.
- Even more important is the high sensitivity to mispointing, which affects both amplitude and measured range
- Forthcoming mission like ESA's CRYOSAT and Sentinel-3 will use synthetic aperture techniques (delay-Doppler Altimeter) that 'can be seen as' a beam-limited instrument in the along-track direction.

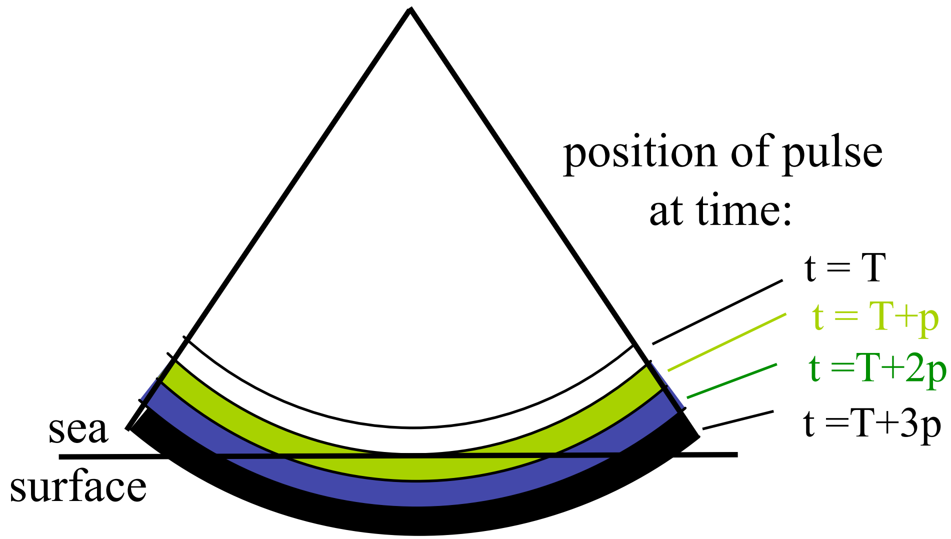
Pulse Limited Altimeter

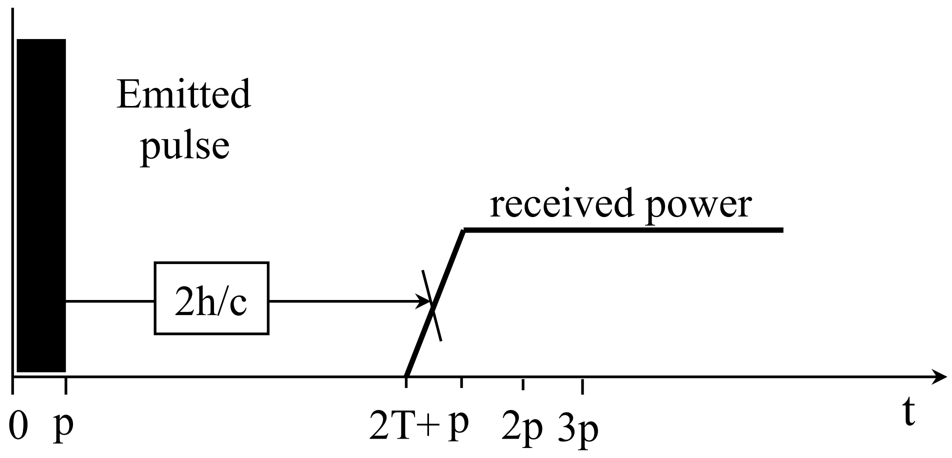
- In a pulse limited altimeter the shape of the return is dictated by the length (width) of the pulse

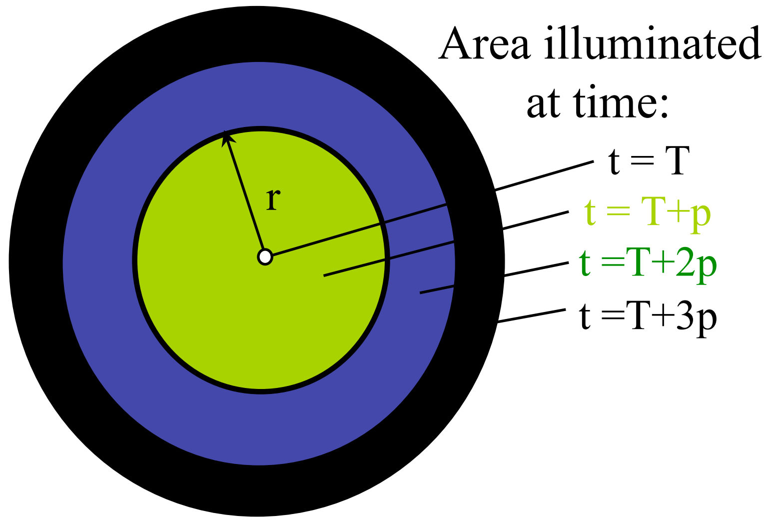


The "pulse-limited" footprint

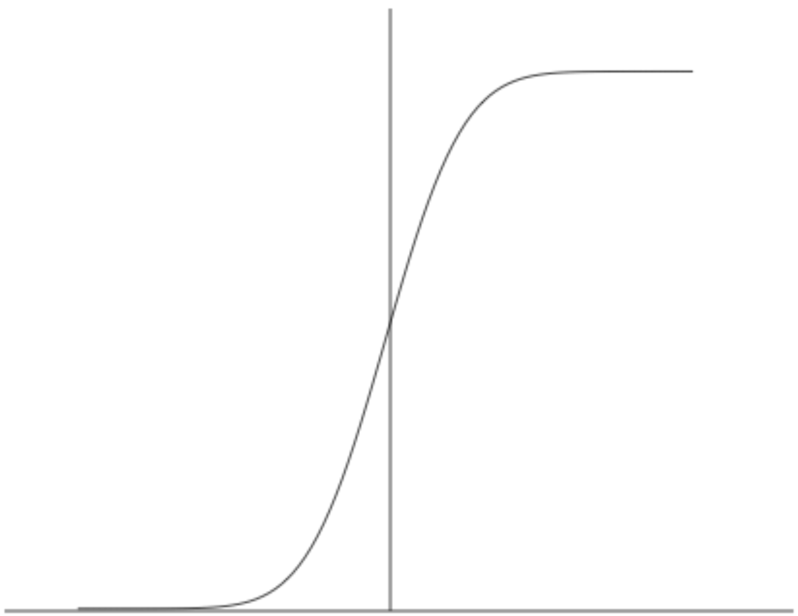
- Full illumination when rear of pulse reaches the sea – then area illuminated stays constant
- Area illuminated has radius
  $r = \sqrt{(2hcp)}$
- Measure interval between mid-pulse emission and time to reach half full height







- A plot of return power versus time for a pulse limited altimeter looks like the integral of the heights of the specular points, i.e. the cumulative distribution function (cdf) of the specular scatterers



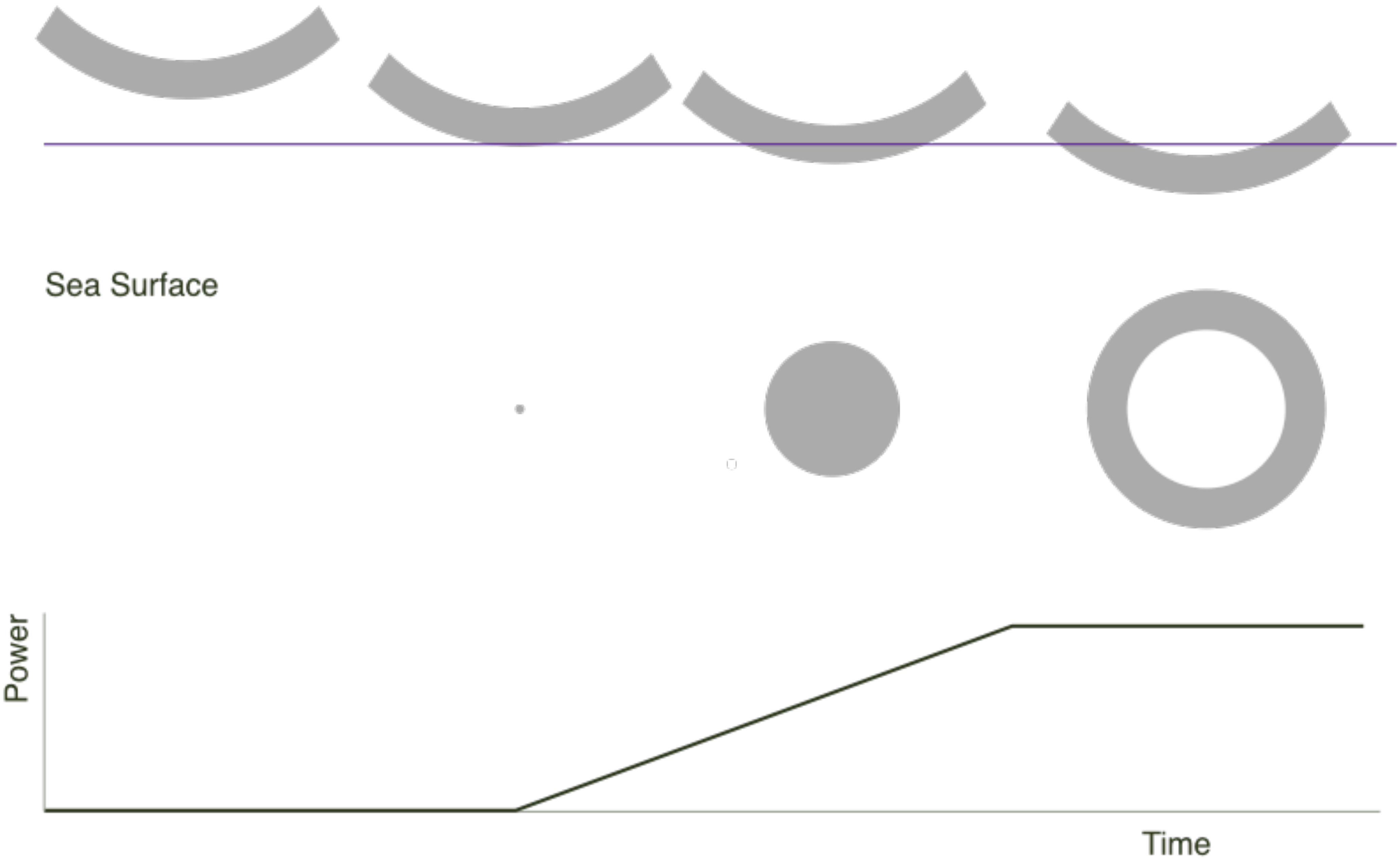
The tracking point is the half power point of the curve

Pulse- vs Beam-

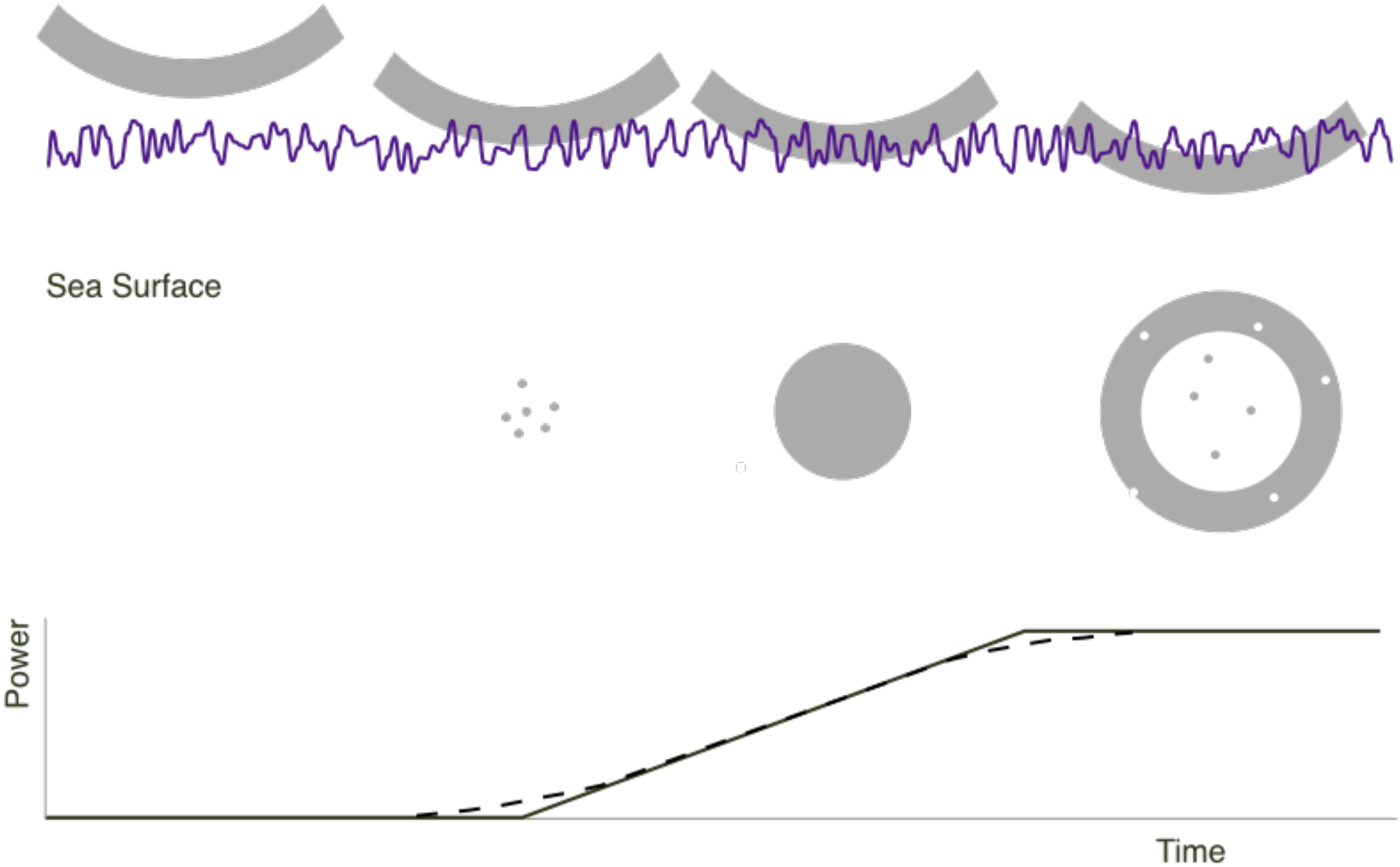
- All the microwave altimeters (including very successful TOPEX/Poseidon, ERS-1 RA and ERS-2 RA, Envisat RA-2) flown in space to date are pulse limited but….
- … laser altimeters (like GLAS on ICESAT) are beam-limited
- As said, delay-Dopper Altimeter can be seen as pulse-limited in the along-track direction
- But to understand the basis of altimetry we first consider the pulse limited design

Basics of pulse-limited Altimeter Theory

- We send out a thin shell of radar energy which is reflected back from the sea surface
- The power in the returned signal is detected by a number of **gates** (bins) each at a slightly different time


Sea Surface
Power
Time

If we add waves ...



The area illuminated

- The total area illuminated is related to the significant wave height
- The formula is
- $$\frac{\pi R_0(c\tau + 2H_s)}{1 + R_0/R_E}$$

where c is the speed of light, τ is the pulse length, H_s significant wave height, R_0 the altitude of the satellite and R_E the radius of the Earth

Hs (m)	Effective footprint (km) (800 km altitude)	Effective footprint (km) (1335 km altitude)
0	1.6	2.0
1	2.9	3.6
3	4.4	5.5
5	5.6	6.9
10	7.7	9.6
15	9.4	11.7
20	10.8	13.4

From Chelton et al (1989)

The Brown Model

- Assume that the sea surface is a perfectly conducting rough mirror which reflects only at specular points, i.e. those points where the radar beam is reflected directly back to the satellite

The Brown Model - II

- Under these assumptions the return power is given by a three fold convolution

$$P_r(t) = P_{FS}(t) * P_{PT}(t) * P_H(-z)$$

where

$P_r(t)$ is the returned power

$P_{FS}(t)$ is the flat surface response

$P_{PT}(t)$ is the point target response

$P_H(-z)$ is the pdf of specular points on the sea surfac

The Flat Surface Response Function

- The Flat surface response function is the response you would get from reflecting the radar pulse from a flat surface.
- It looks like

$$P_{FS}(t) = U(t - t_0).G(t)$$

- where U(t) is the Heaviside function
- U(t) = 0 t <0 =1 otherwise
- G(t) is the two way antenna gain pattern

The Point Target Response Function

- The point target response function is the shape of the transmitted pulse
- It’s true shape is given by

$$P_{PT}(t) = \left[\frac{sin(\pi t/\tau)}{\pi t/\tau}\right]^2$$

- For the Brown model we approximate this with a Gaussian.

The Brown Model - III

$$P_r(t) = P_{FS}(0)\eta P_T \sqrt{2\pi}\,\frac{\sigma_p}{2}\left[1 + erf\left\{\frac{(t - t_0)}{\sqrt{2}\sigma_c}\right\}\right] \qquad t < t_0$$

$$P_r(t) = P_{FS}(t - t_0)\eta P_T \sqrt{2\pi}\,\frac{\sigma_p}{2}\left[1 + erf\left\{\frac{(t - t_0)}{\sqrt{2}\sigma_c}\right\}\right] \qquad t > t_0$$

$$\sigma_c^2 = \sigma_p^2 + \frac{H_s^2}{4c^2}$$

$$P_{FS}(t) = \frac{G_0^2 \lambda_R^2 c \sigma^0}{4(4\pi)^2 L_p h^3} \exp\left\{-\frac{4}{\gamma}\sin^2\xi - \frac{4ct}{\gamma h}\cos 2\xi\right\} I_0\left(\frac{4}{\gamma}\sqrt{\frac{ct}{h}}\sin 2\xi\right)$$

where

$$erf(t) = \frac{2}{\sqrt{\pi}} \int_0^t e^{-x^2} dx$$

Compare with the Normal cumulative distribution function

$$\Phi(t) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^t e^{\frac{-x^2}{2}} dx$$

$$\Phi(x) = \frac{1}{2} \left[1 + erf\left(\frac{x}{\sqrt{2}} \right) \right]$$

$I_0()$ is a modified Bessel function of the first kind

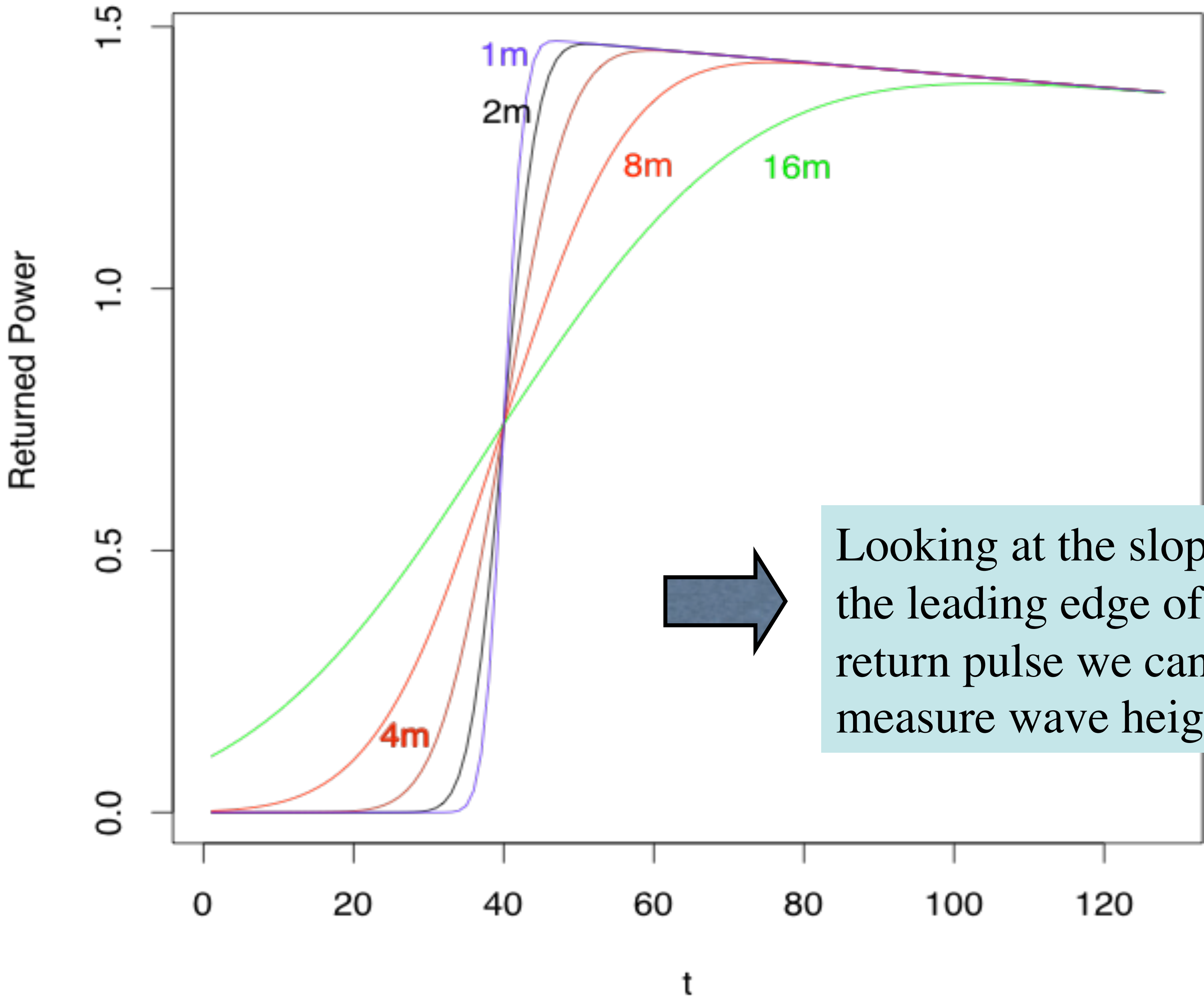
What are we measuring?

- Hs - **significant wave height**
- t_0 - the time for the radar signal to reach the Earth and return to the satellite (we then convert into **height** – see in the next slides)
- σ_0 - the radar **backscatter coefficient**, (somehow related to wind**)**

What are the other parameters?

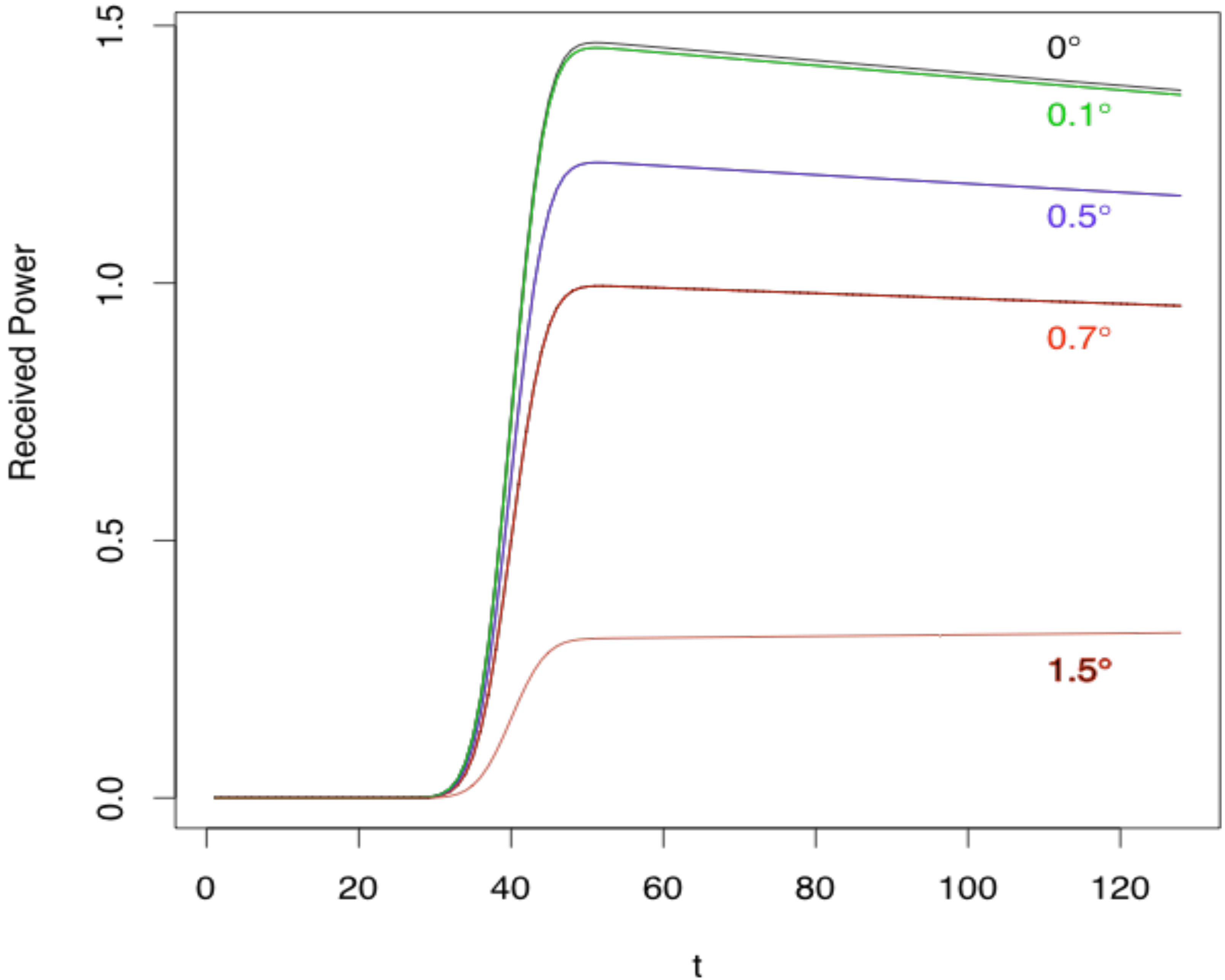
- λ_R is the radar wavelength
- L_p is the two way propagation loss
- h is the satellite altitude (nominal)
- G_0 is the antenna gain
- γ is the antenna beam width
- σ_p is the pulse width
- η is the pulse compression ratio
- PT is the peak power
- ξ is the mispointing angle

Some example waveforms



Looking at the slope of the leading edge of the return pulse we can measure wave height!

The effect of mispointing



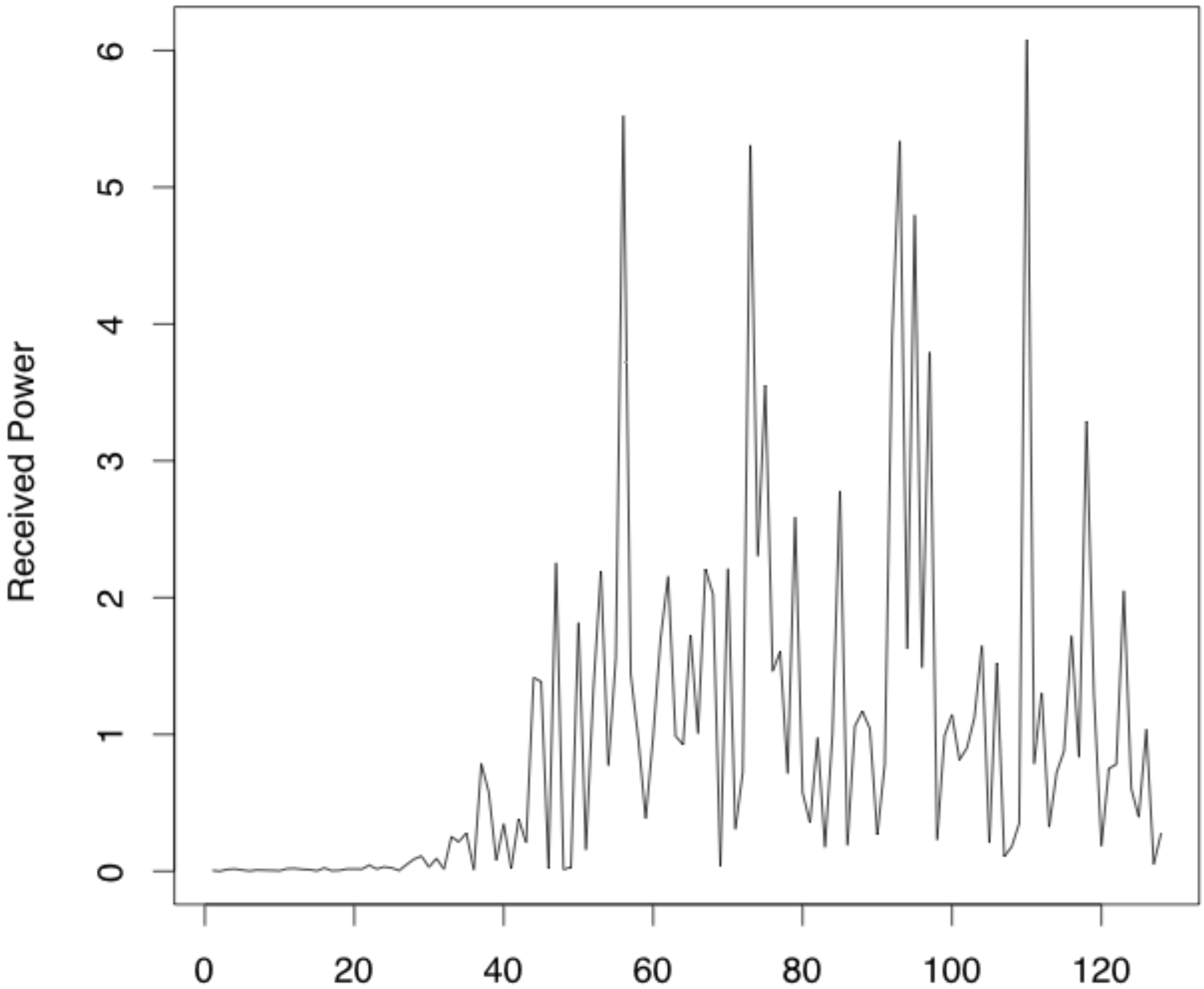
Noise on the altimeter

- If we simply use the altimeter as a detector we will still have a signal - known as the thermal noise.
- The noise on the signal is known as fading noise
- It is sometimes assumed to be constant, sometimes its mean is measured
- For most altimeters the noise on the signal is independent in each gate and has a negative exponential distribution.

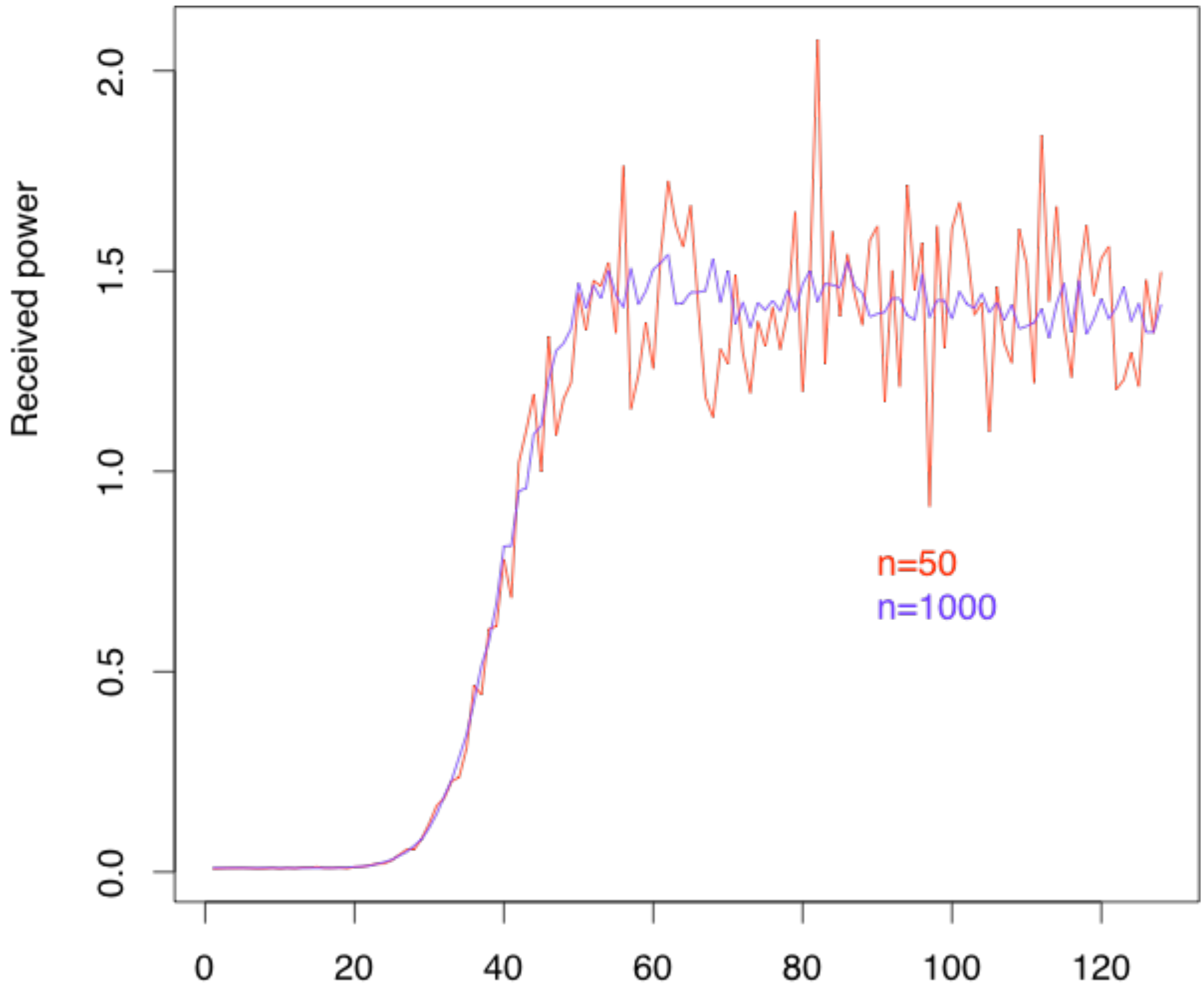
Averaging the noise

- For a negative exponential distribution the variance is equal to the mean. Thus the individual pulses are very noisy
- The pulse repetition frequency is usually about 1000 per second
- It is usual to transmit data to the ground at 20Hz and then average to 1 Hz

A single pulse



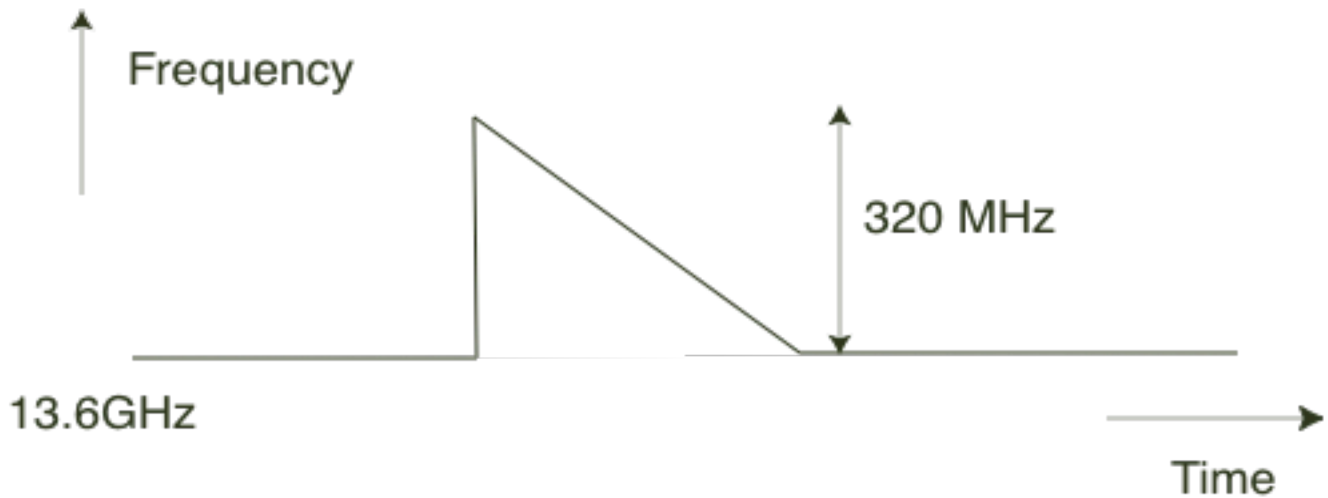
Time (gate number)



Time (gate number)

How altimeters really work

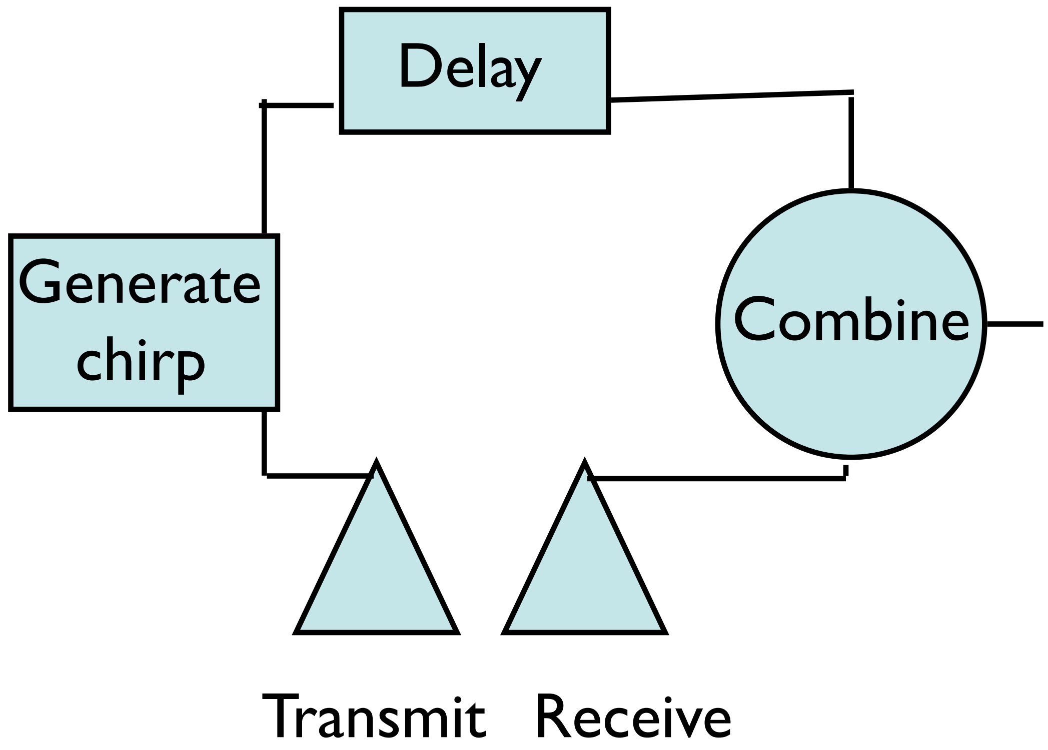
- It is very difficult (if not impossible) to generate a single-frequency pulse of length 3 ns
- However it is possible to do something very similar in the frequency domain using a chirp, that is modulating the frequency of the carrier wave in a linear way



The equivalent pulse width = 1/chirp bandwidth

Full chirp deramp - 1

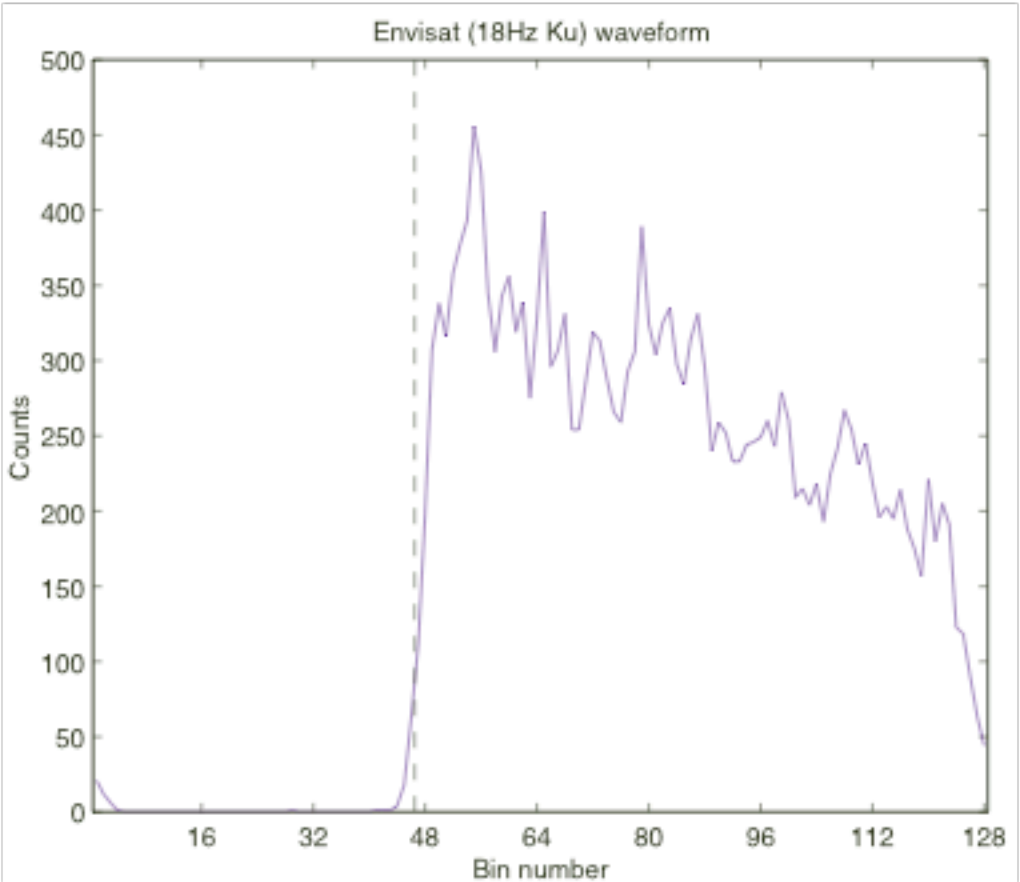
- A chirp is generated
- Two copies are taken
- The first is transmitted
- The second is delayed so it can be matched with the reflected pulse



Full Chirp Deramp - 2

- The two chirps are mixed.
- A point above the sea surface gives returns a frequency lower than would be expected and viceversa
- So a ‘Brown’ return is received but with frequency rather than time along the x axis

A real waveform - from the RA-2 altimeter on ESA's Envisat



Ku band, 13.5 Ghz, 2.1 cm

Altimeters - Some Instruments flown

- GEOS-3 (04/75 - 12/78)

  height 845 km, inclination 115 deg, accuracy 0.5 m, repeat period ??
- Seasat (06/78 - 09/78)

  800 km, 108 deg, 0.1 m, 3 days
- Geosat (03/85 - 09/89)

  785.5 km, 108.1 deg, 0.1 m 17.5 days
- ERS-1(07/91-2003); **ERS-2 (04/95 – present!)**

  785 km, 98.5 deg, 0.05 m 35 days
- **TOPEX/Poseidon (09/92 – 2006); Jason-1 (12/01-present); Jason-2 (06/08-present)**

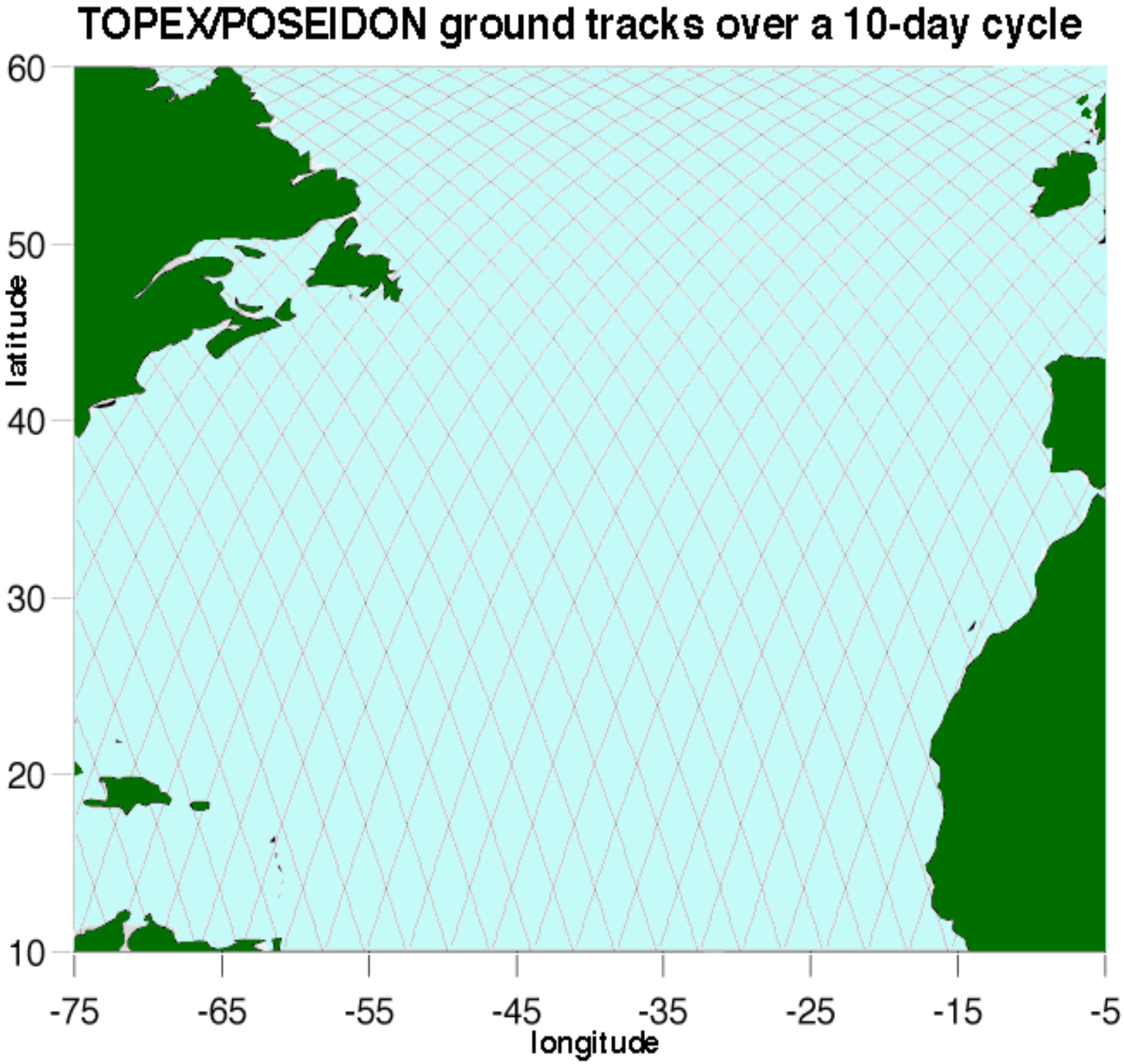
  1336 km, 66 deg, 0.03 m 9.92 days
- **Geosat follow-on (GFO) (02/98 - 2007)**

  800 km, 108 deg, 0.1 m 17.5 days
- **Envisat (03/02 - present)**

  785 km, 98.5 deg, 0.05 m 35 days

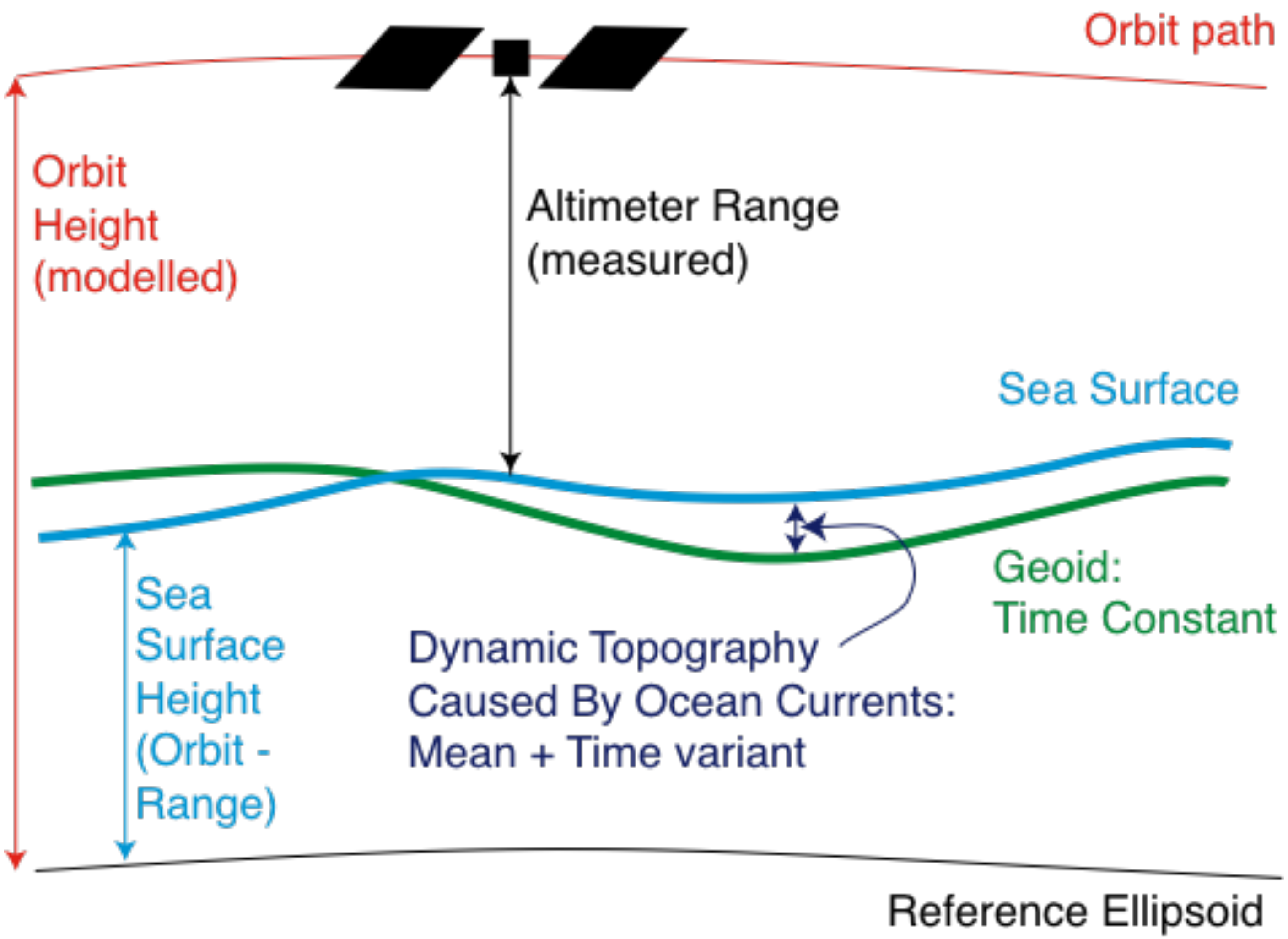
Altimeter missions to date

Mission, Sensor	Launch Date	Range Precision (cm)	Frequency (GHZ)	Uncompressed Pulse Width (µs)	Compressed Pulse Width (µs)	Peak Power (W)	Beam Limited Footprint (km)	Pulse Limited Footprint (km)	Orbit altitude, inclination (km/°)
Skylab, S193	14/5/73	100	13.9			2000		8	435, 50
GEOS-3, ALT	9/4/75	25	13.9	1	12.5	2000	38	3.5	843, 115
SEASAT, ALT	27/6/78	5	13.5	3.2	3.1	2000	22	1.7	800, 108
GEOSAT, Radar Alt	12/3/85	4	13.5	102.4	3.1	20	29	1.7	800, 108
ERS-1, RA-1	17/7/91	3	13.8	20	3	55	18	1.7	785, 98.5
Topex/Poseidon, ALT/Poseidon-1	10/8/92	2	13.6 / 5.3 13.65	102.4	3.1	20 5	26 / 65	2.2	1336, 66
ERS-2, RA-1	21/4/95	3	13.8	20	3	55	18	1.7	785, 98.5
Piroda (Greben)	23/4/96	10	13.76	1.7	12.5	40	13	2.3	400, 52
GFO-1, RA	10/2/98	3.5	13.5					2	800, 108
Jason-1, Poseidon-2	7/12/2001	2	13.6 / 5.3	105		58			1336, 66
Envisat, RA-2	1/3/2002	2-3	13.575 / 3.2	20		60 / 60		1.7	800, 98.55
ICESat-1, GLAS	12/1/2003	<10	[1064nm / 532nm]	0.004			0.07	0.7	705, 94
Jason-2	20/6/2008	1	13.6 / 5.3						1336, 66
Cryosat, SIRAL	2009	<1	13.6	51		25			720, 92
AltiKa	2009		35						


TOPEX/POSEIDON ground tracks over a 10-day cycle
60
50
40
30
20
10
latitude
-75
-65
-55
-45
-35
-25
-15
-5
longitude

Altimetry II
From satellite height to sea surface height

- The altimeter measures the altitude of the satellite
- The oceanographer wants a measurement of sea level
- Steps that need to be taken
  - Instrument corrections
  - Platform corrections
  - Orbit determination
  - The effect of refraction
  - Sea surface effects


Orbit path
Orbit Height (modelled)
Altimeter Range (measured)
Sea Surface
Geoid: Time Constant
Sea Surface Height (Orbit - Range)
Dynamic Topography Caused By Ocean Currents: Mean + Time variant
Reference Ellipsoid

Altimeter Corrections & Orbits

- 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**

Platform corrections

- 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.
- This means that the satellite is constantly moving towards and away from the earth. A Doppler correction is therefore needed (applied by the space agencies)
- There are other platform 'corrections'
- e.g. a correction needs to be made for the distance between the centre of gravity of the spacecraft and the altimeter antenna
- All these corrections are applied by the space agencies and need not worry the scientist (unless something goes wrong)

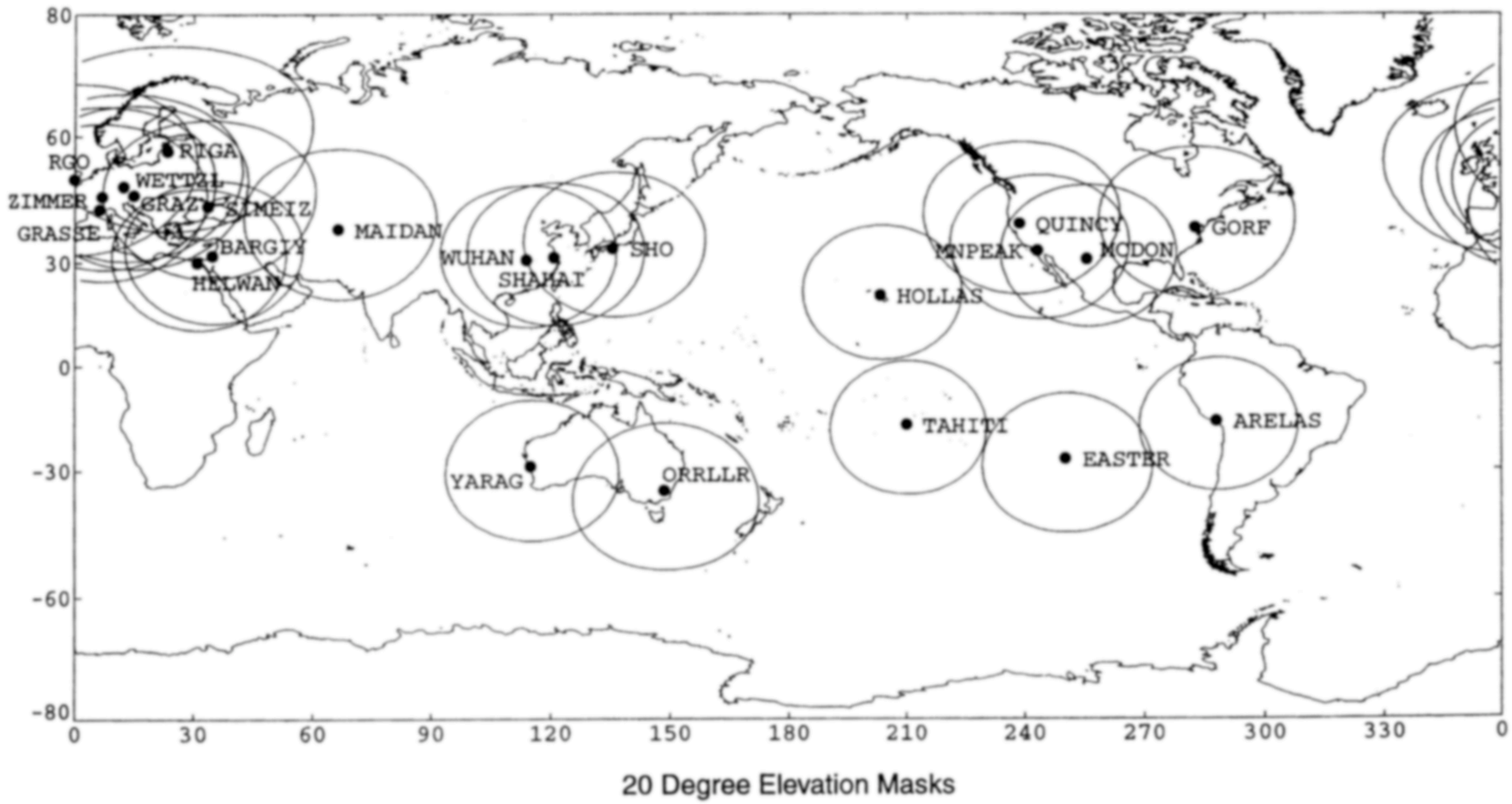
Orbits

- 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 the geoid (ellipsoid)
- Therefore we need to know the satellite orbit (to a few cm's or less)
- 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)

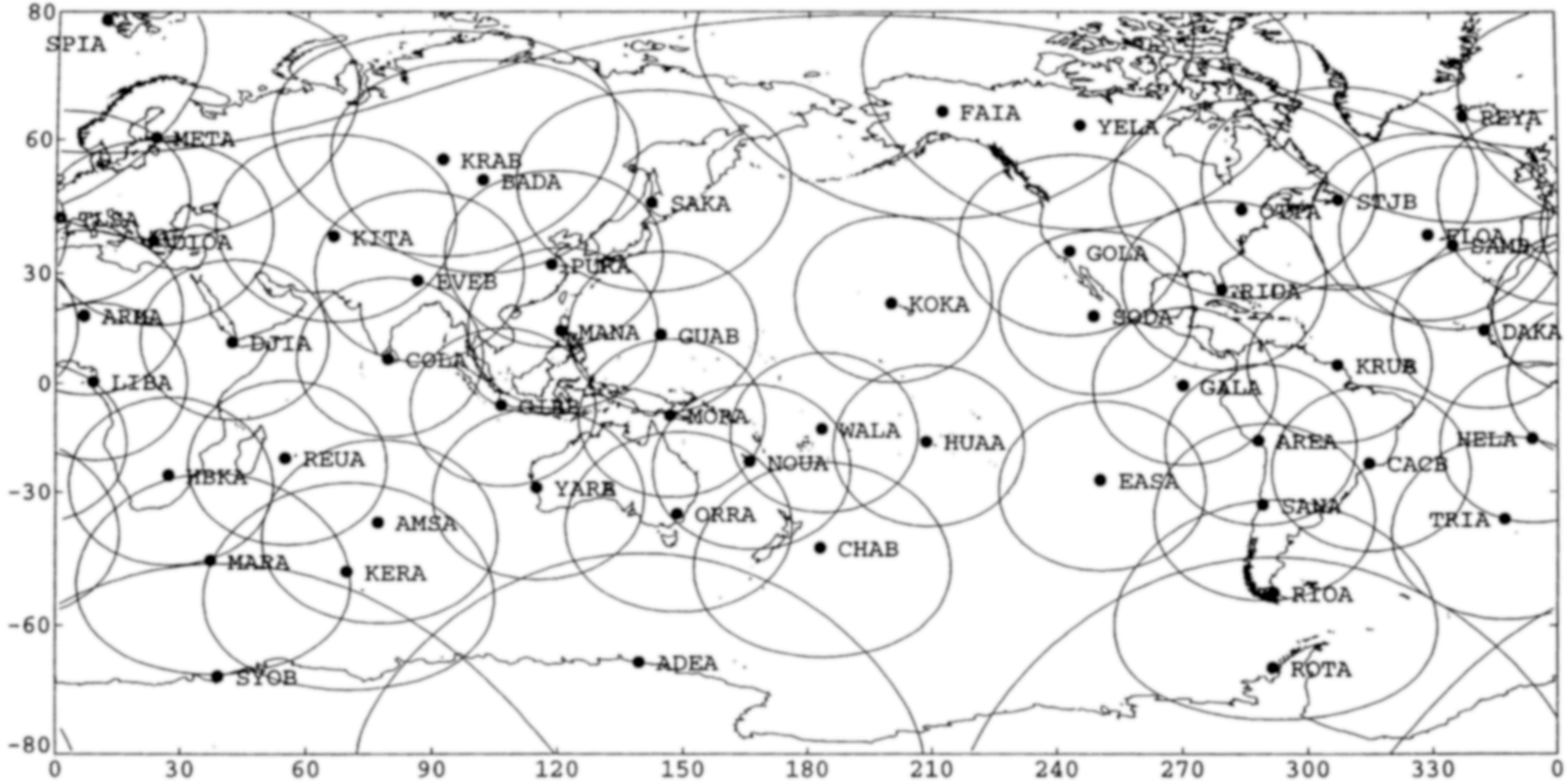
DORIS

SLR

SLR Stations



DORIS stations



15 Degree Elevation Masks

Quality of orbits for today's altimeters

- The quality of orbits are measured by the reduction of crossover differences and by comparison to SLR stations
- TOPEX/POSEIDON and JASON orbits are good to about 3-5 cm
- ERS-2 and ENVISAT 5-10 cm (much more affected by drag, as in orbit lower than T/P and Jason)

Topex/Poseidon Orbit Error Budget

- 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 ~2.5 cm**

Empirical orbit removal

–If orbit errors dominate

–Either: Use repeat tracks

Subtract average of all tracks

Fit linear or quadratic function to each pass to remove trend

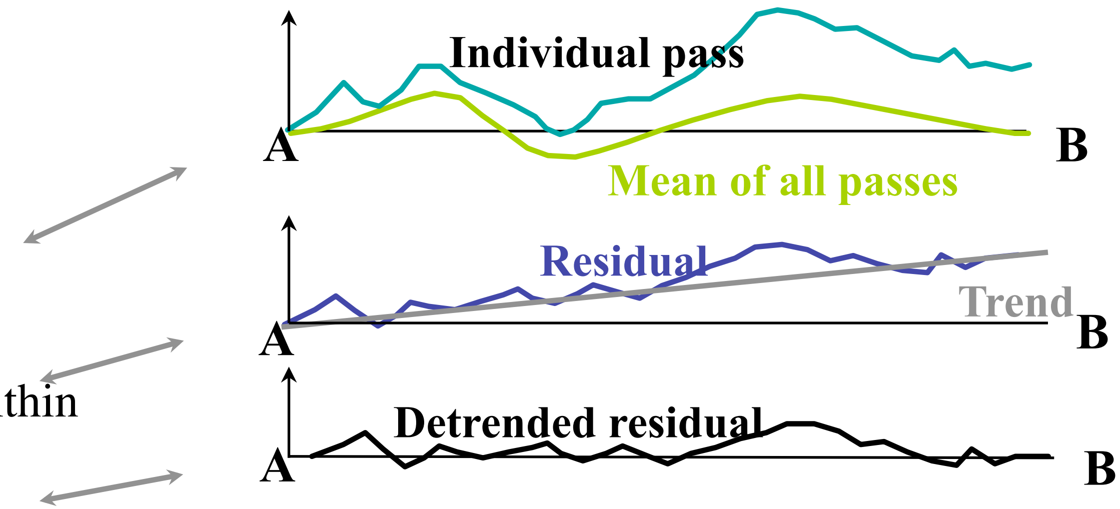
Residuals give the time varying signal within the region

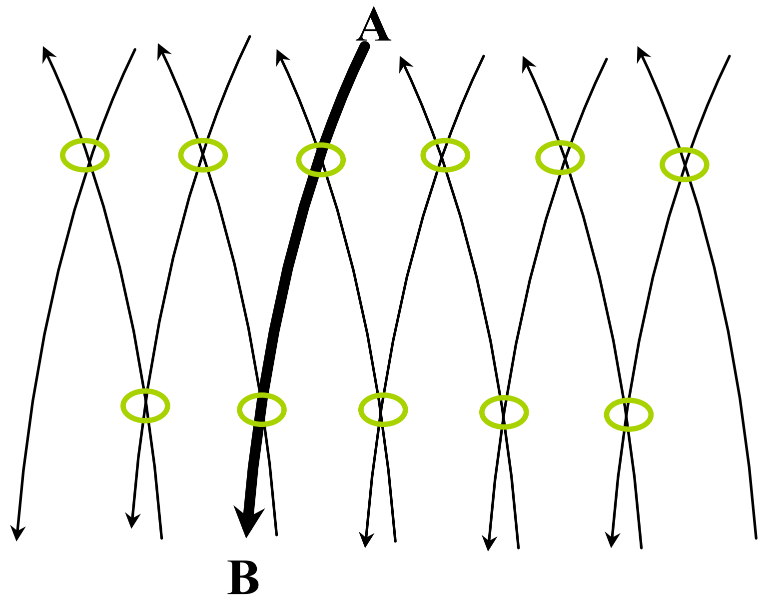
–Or: Use cross-over points

Compute height difference between ascending and descending tracks

Fit smooth function to each pass to minimise cross-over differences

Subtract this function to give SSH residual



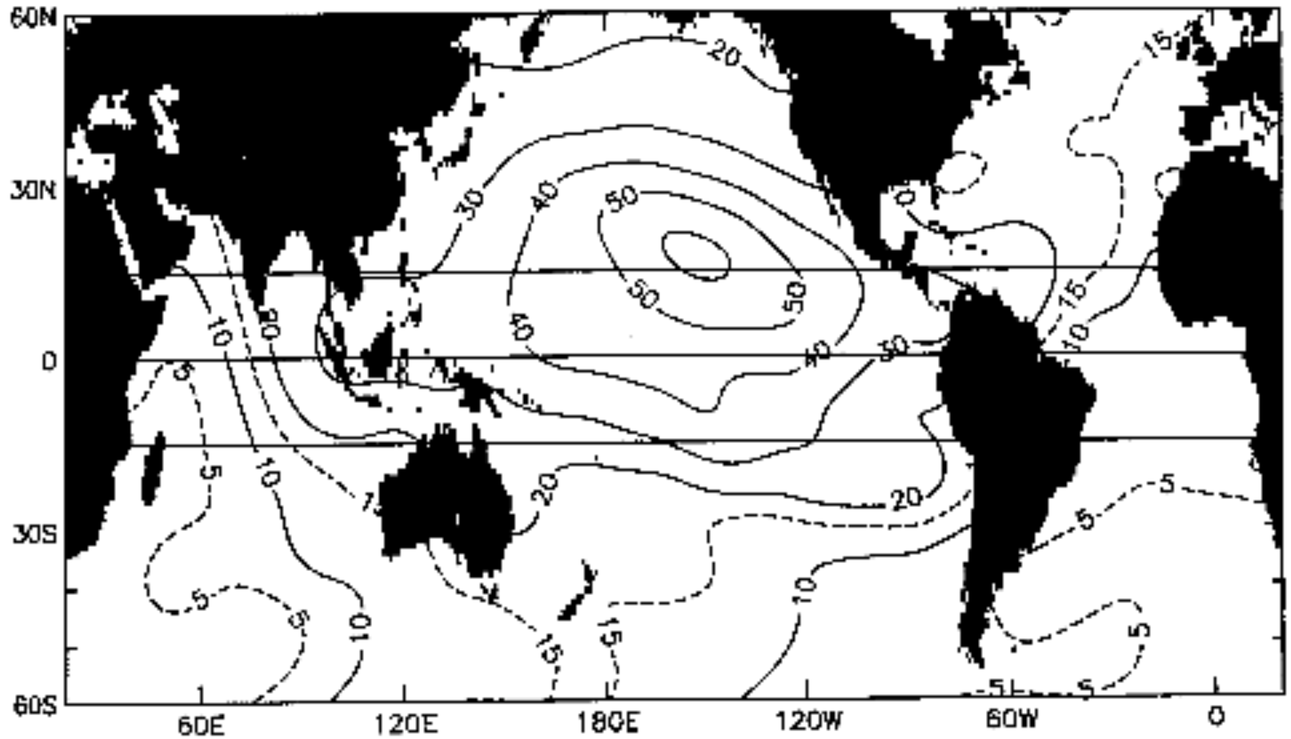


Atmospheric Corrections

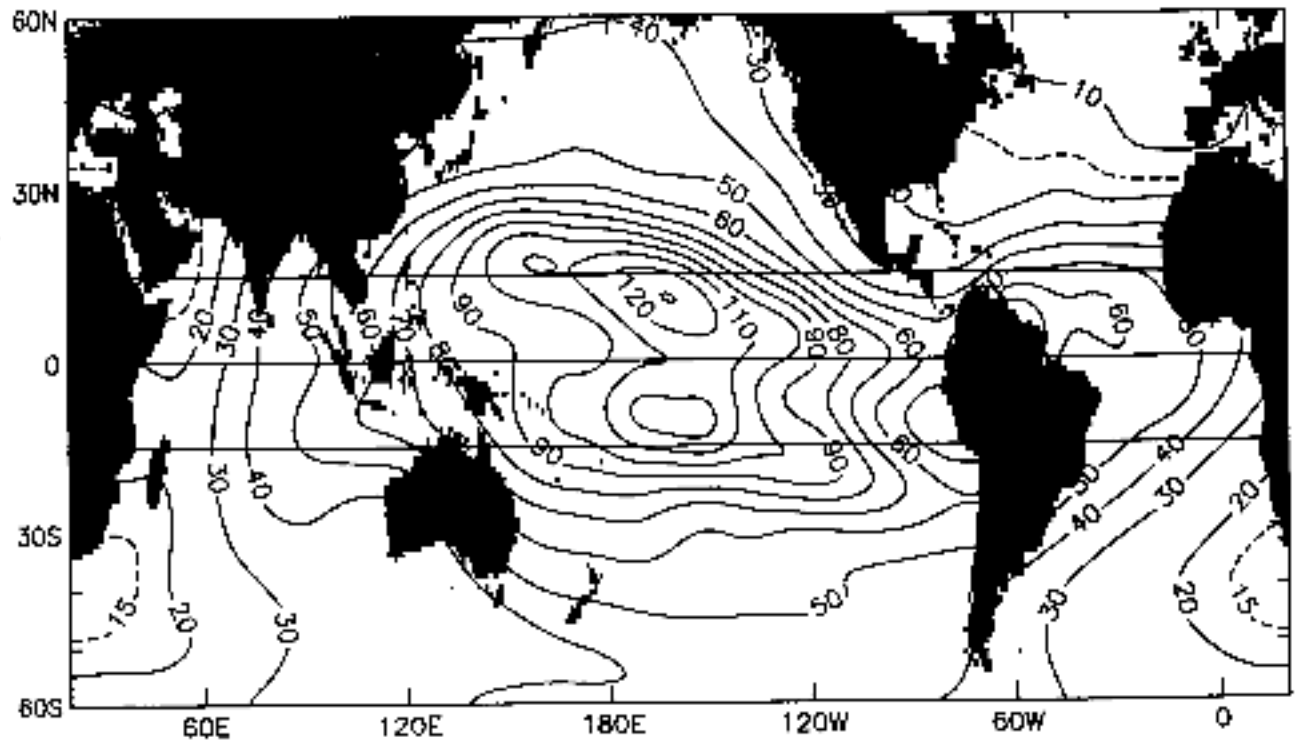
- As the radar signal travels through the atmosphere it is slowed down w.r.t. speed of light in the vacuum
- Since we need speed to estimate range, we must correct for this effect.
- There are three parts of the atmosphere that must be taken in to account
  - Ionospheric correction
  - Dry tropospheric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

Ionospheric correction

- Caused by free electrons in the ionosphere
- Frequency dependent so it can be measured with a dual frequency altimeter
- Otherwise use a model or other observations from a dual frequency radar system (GPS, DORIS)
- Average value 45mm, s.d. 35mm
- Depends on solar cycle



Low solar activity



High solar activity

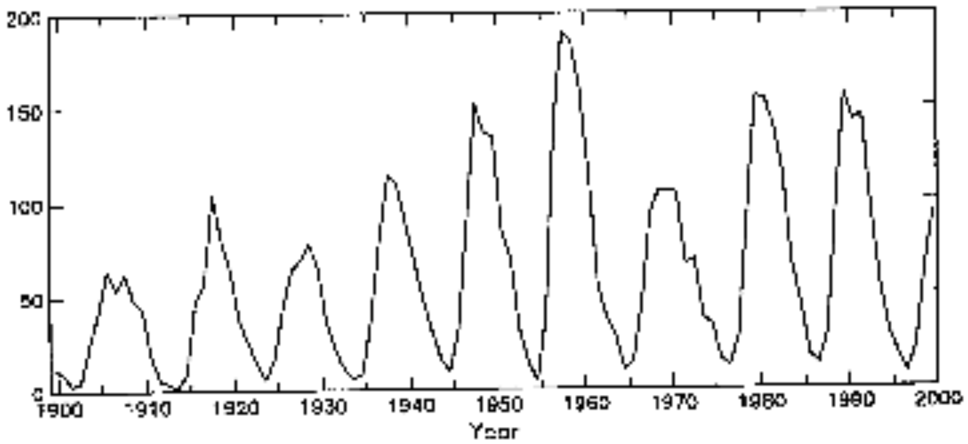


FIGURE 31 Annual average number of sunspots over the time period 1900–1999.

Annual sunspot numbers

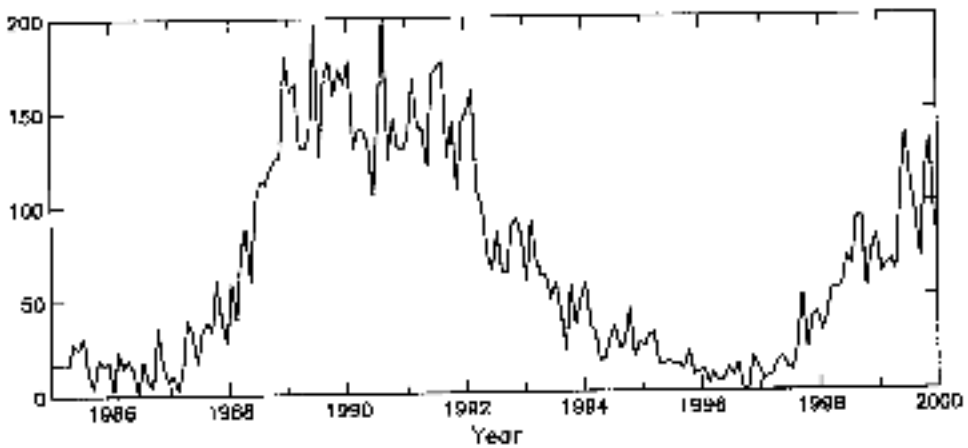
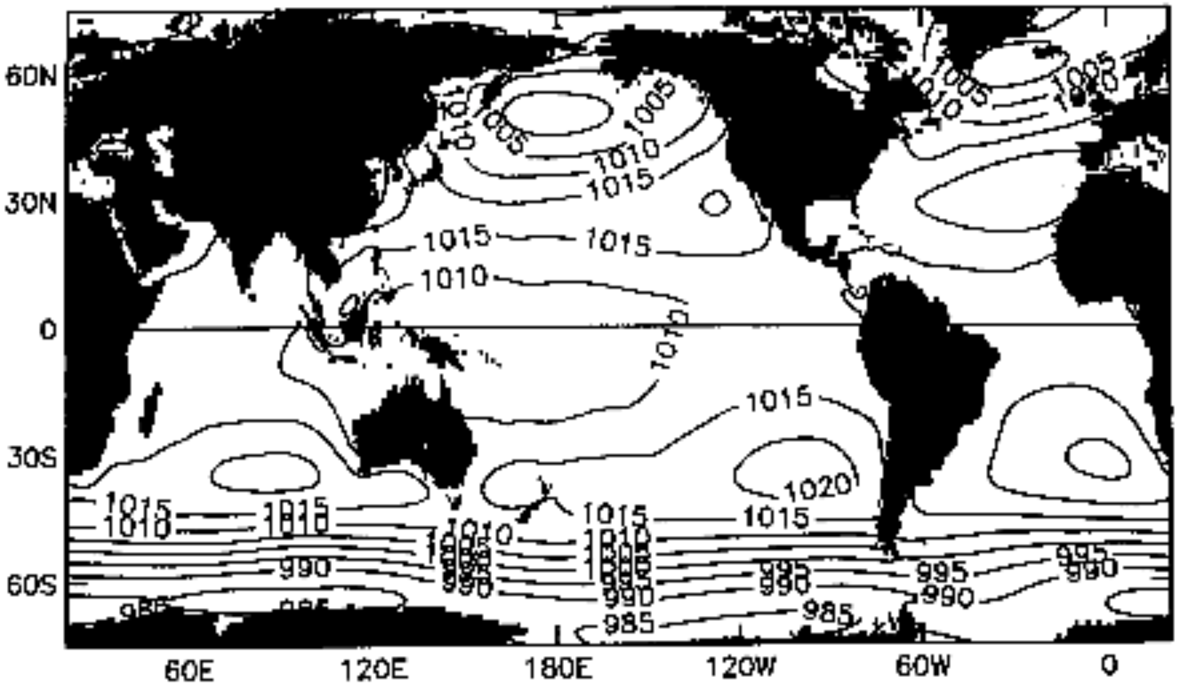


FIGURE 32 Monthly average number of sunspots over the time period 1985–1999.

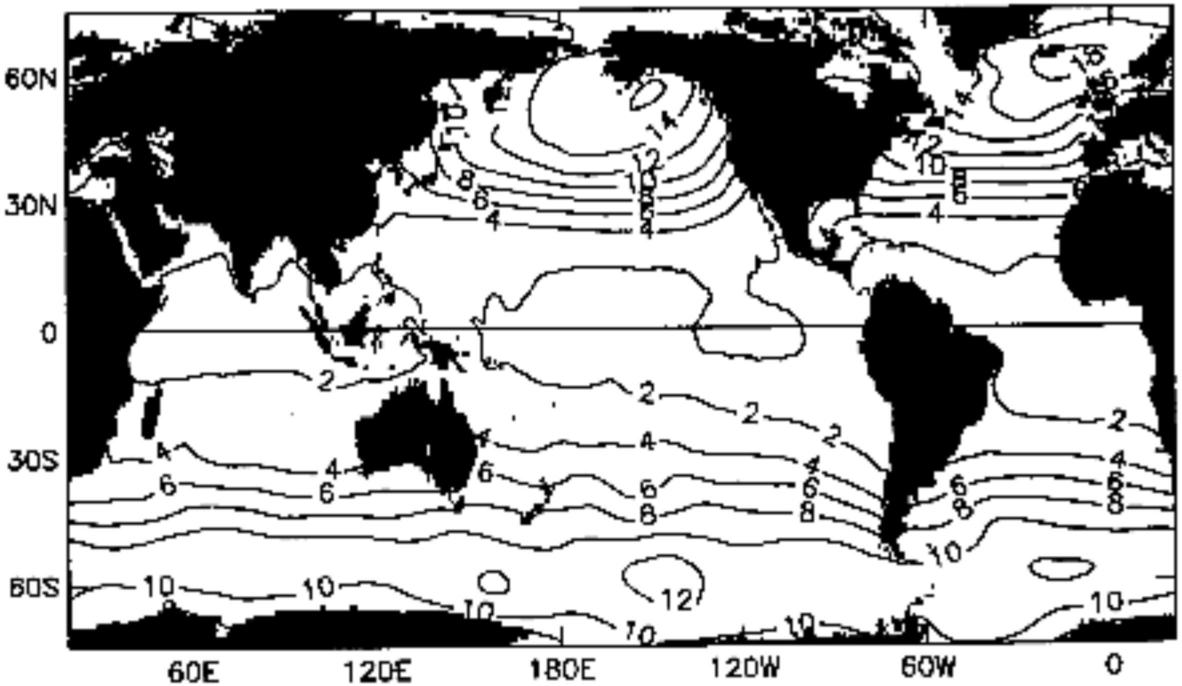
Monthly sunspot numbers

Dry Tropospheric Correction

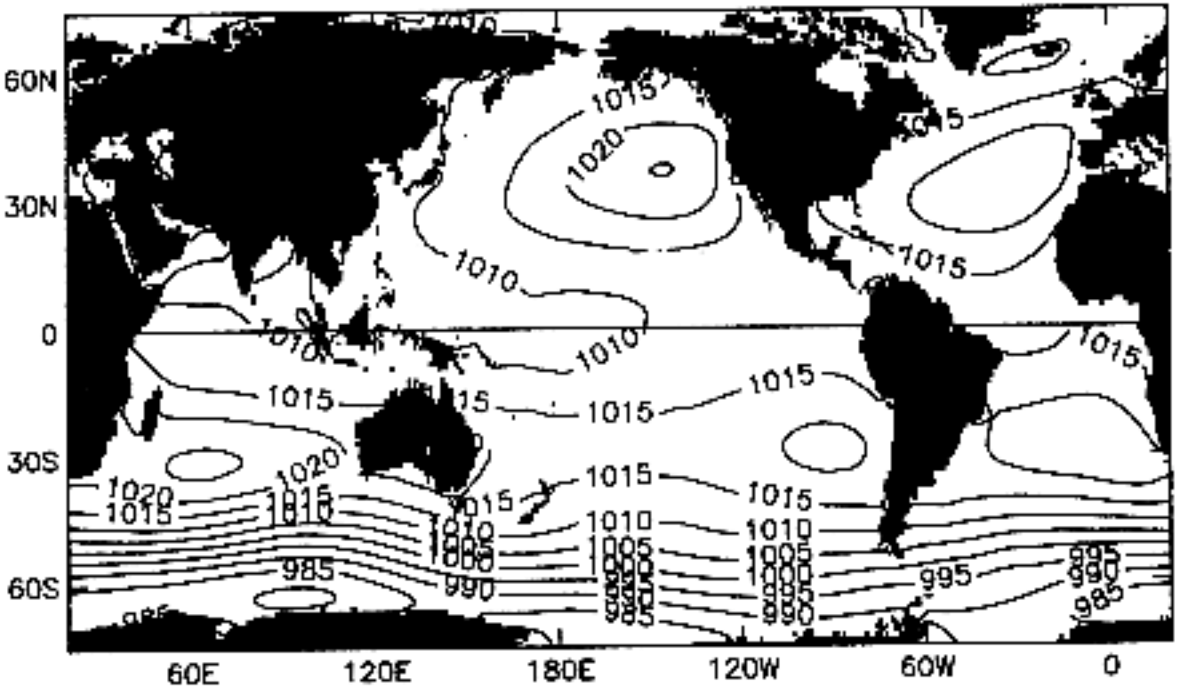
- Due to O_2 molecules in the atmosphere
- Derived from atmospheric pressure (from met models) by:
  - Dry_trop=2.277(p)(1+0.0026cos(2lat))
  - (mm) (hPa) (°)
- Average value 2300mm, s.d. 30mm



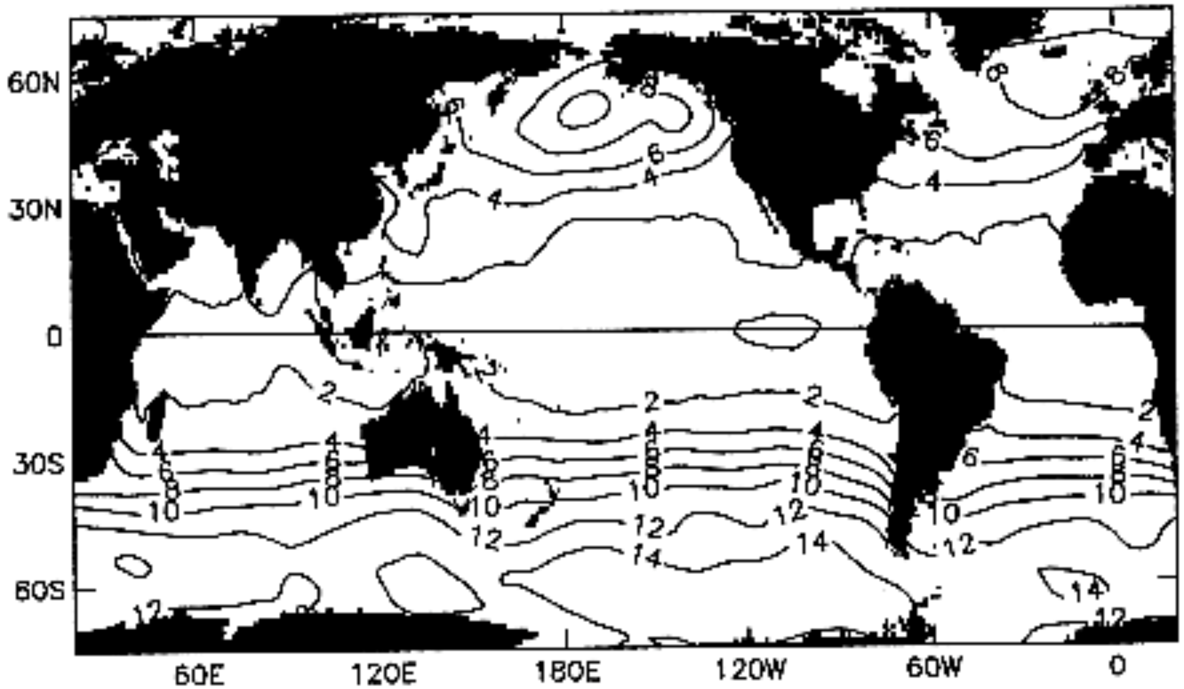
Winter DJF
Air Pressure
Mean (hPa)



Standard
deviation



Summer JJA
Atmospheric
Pressure
Mean (hPa)

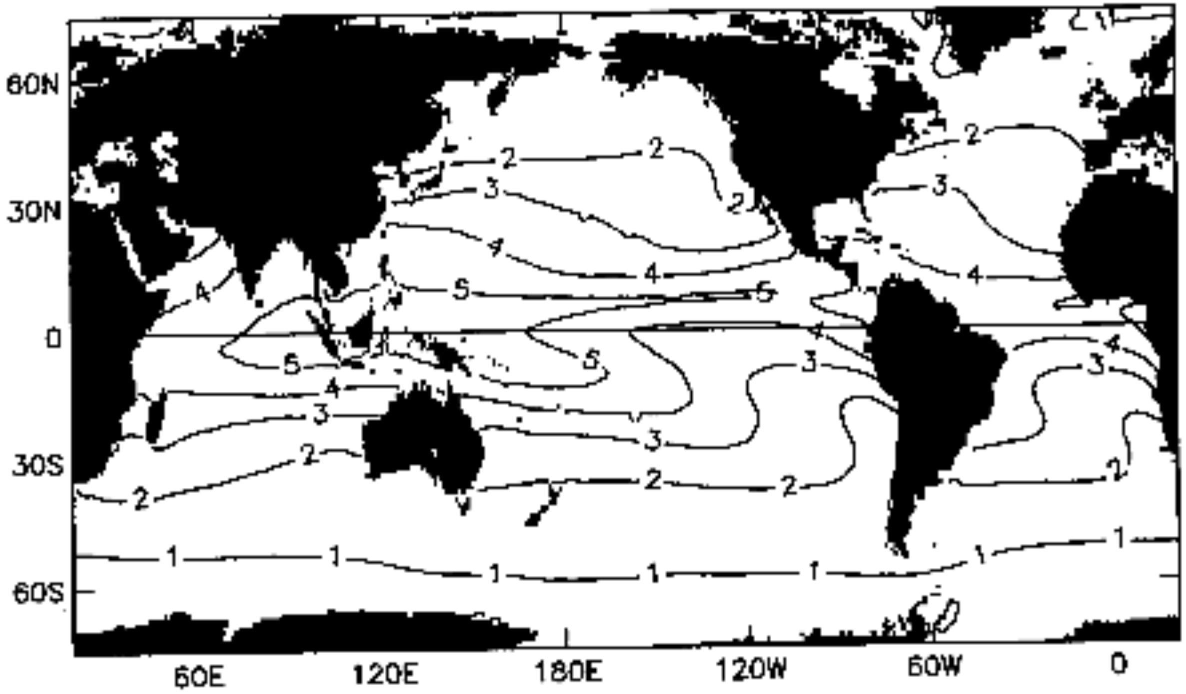


Standard
Deviation

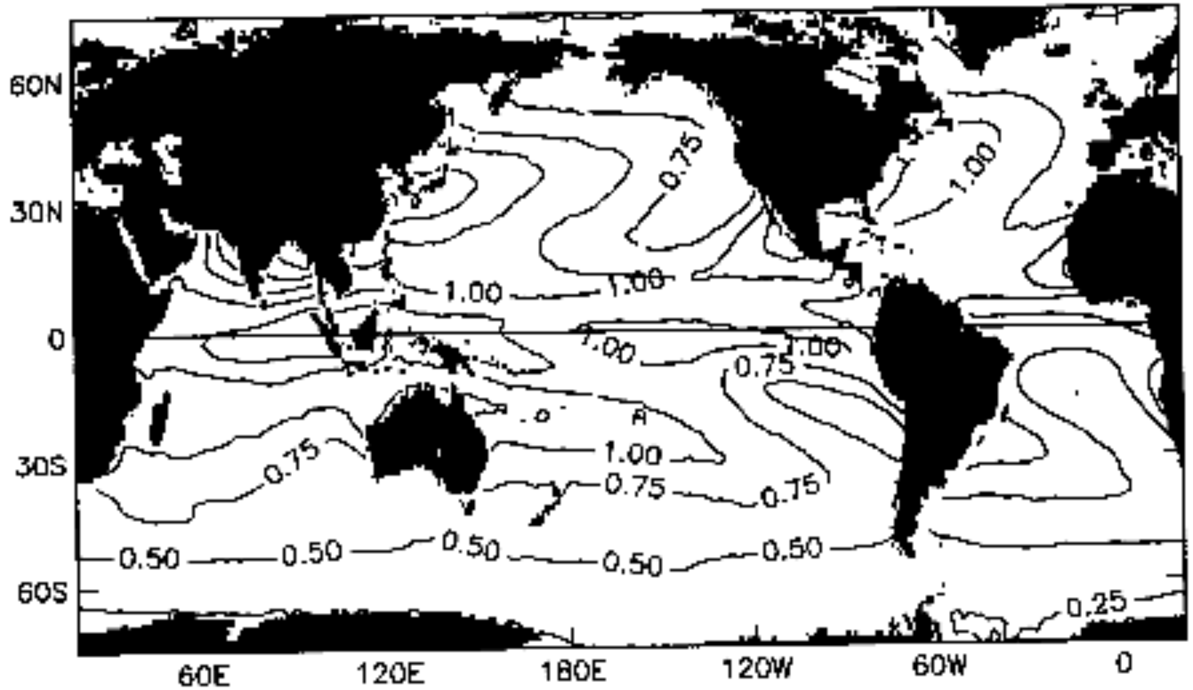
Wet Tropospheric Correction

- Caused by water vapour in the atmosphere
- Obtained by microwave radiometer on satellite
  - two frequency on ERS and ENVISAT
  - three frequency on T/P and JASON
- Or from weather forecasting models
- Average value 150mm, s.d. 40mm

Tropospheric water vapour from SSM/I Mean (g/m^2)



Standard deviation



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]

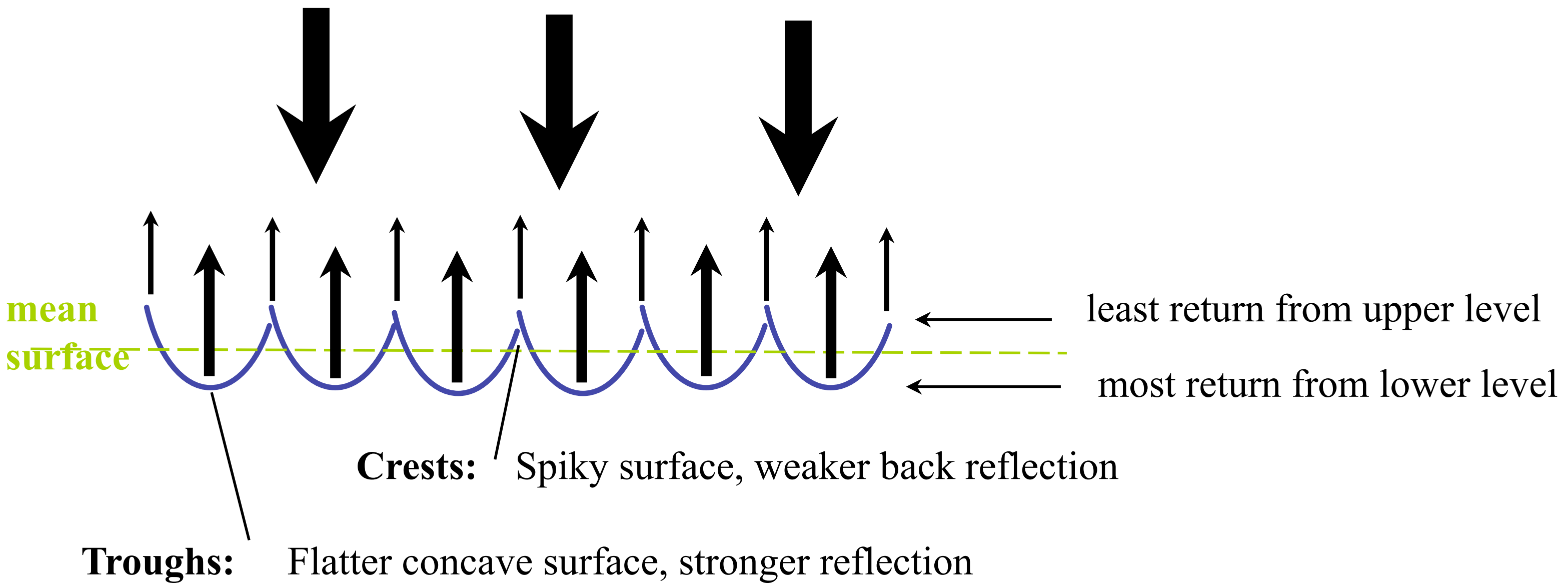
Caused by clouds and rain (variable)

Measure H_2O with microwave radiometer

Or use weather model predictions

Sea State Bias Corrections

- Tracker bias
  - Problem with "tracking" the pulse when the sea is rough
- Electromagnetic Bias
  - The radar return from the troughs is stronger than from the crests
- Empirical correction based on H_s (approx 5%)



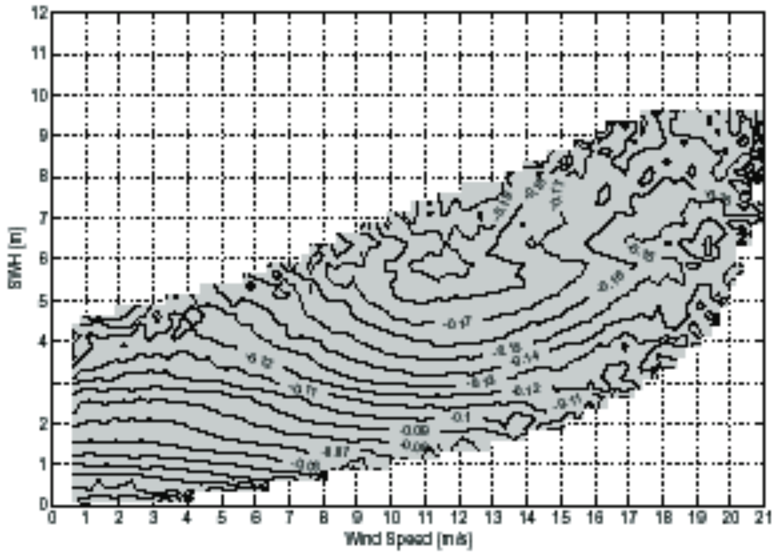
State of the art in sea state bias

- There is as yet no theoretical method for estimating the sea state bias.
- We are therefore forced to use empirical methods
- Find the function of H_s (and U_{10} - that is wind) that minimises the crossover differences

Parametric vs non-parametric methods

- 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
- With non-parametric methods we compile statistics and smooth the resulting 2-d histogram

An example non-parametric SSB

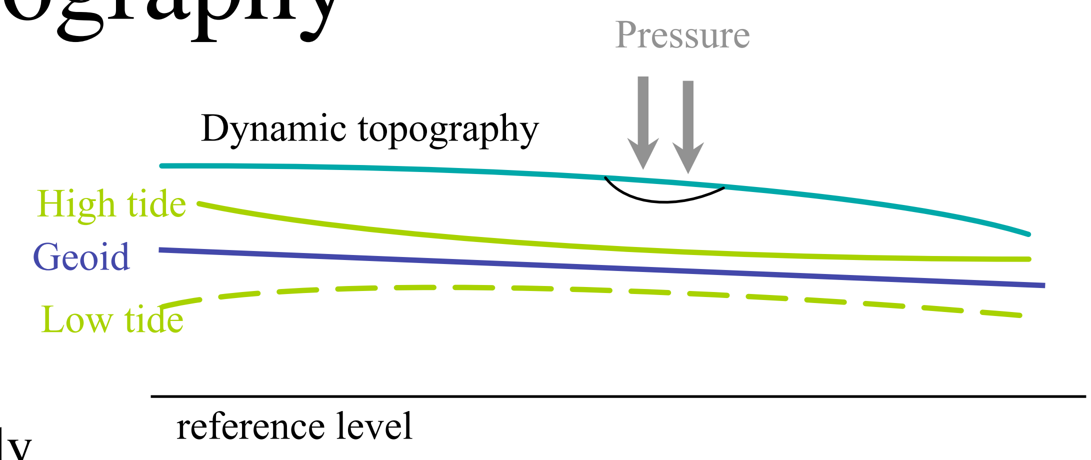


TOPEX Latest Error Budget

for 1-Hz measurement - from Chelton et al 2001

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
Total	4.1cm

Interpreting the Ocean Surface Topography



- 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

Inverse Barometer Correction

- 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)

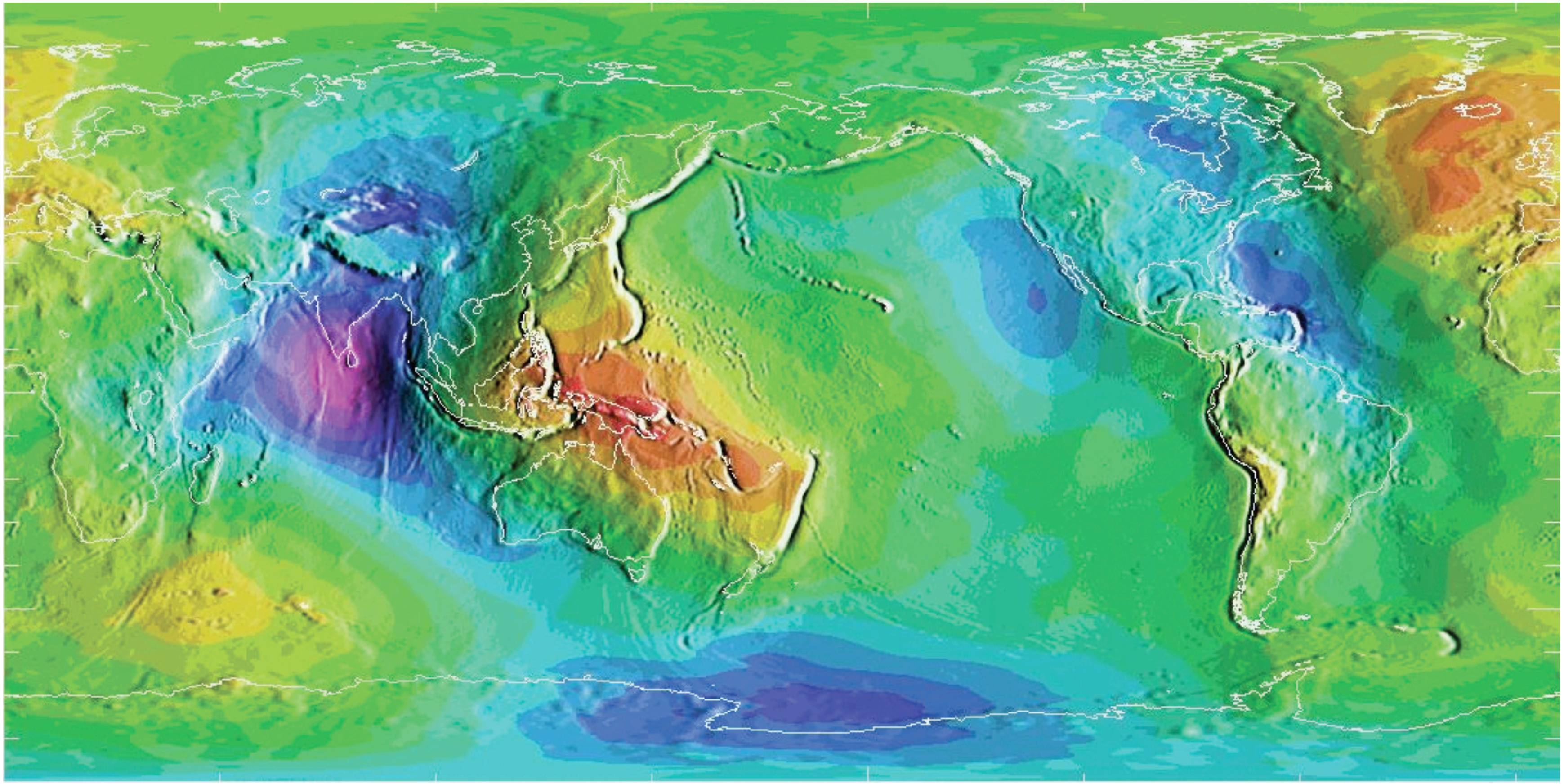
Barotropic Models

- An alternative to an IB correction is to use a correction from a barotropic model of the ocean
- Barotropic (non-depth dependent) motions move very quickly and can be aliased by the altimeter ground tracks
- Barotropic models are quick to run but have proved hard to validate

The problem of the Geoid

- 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



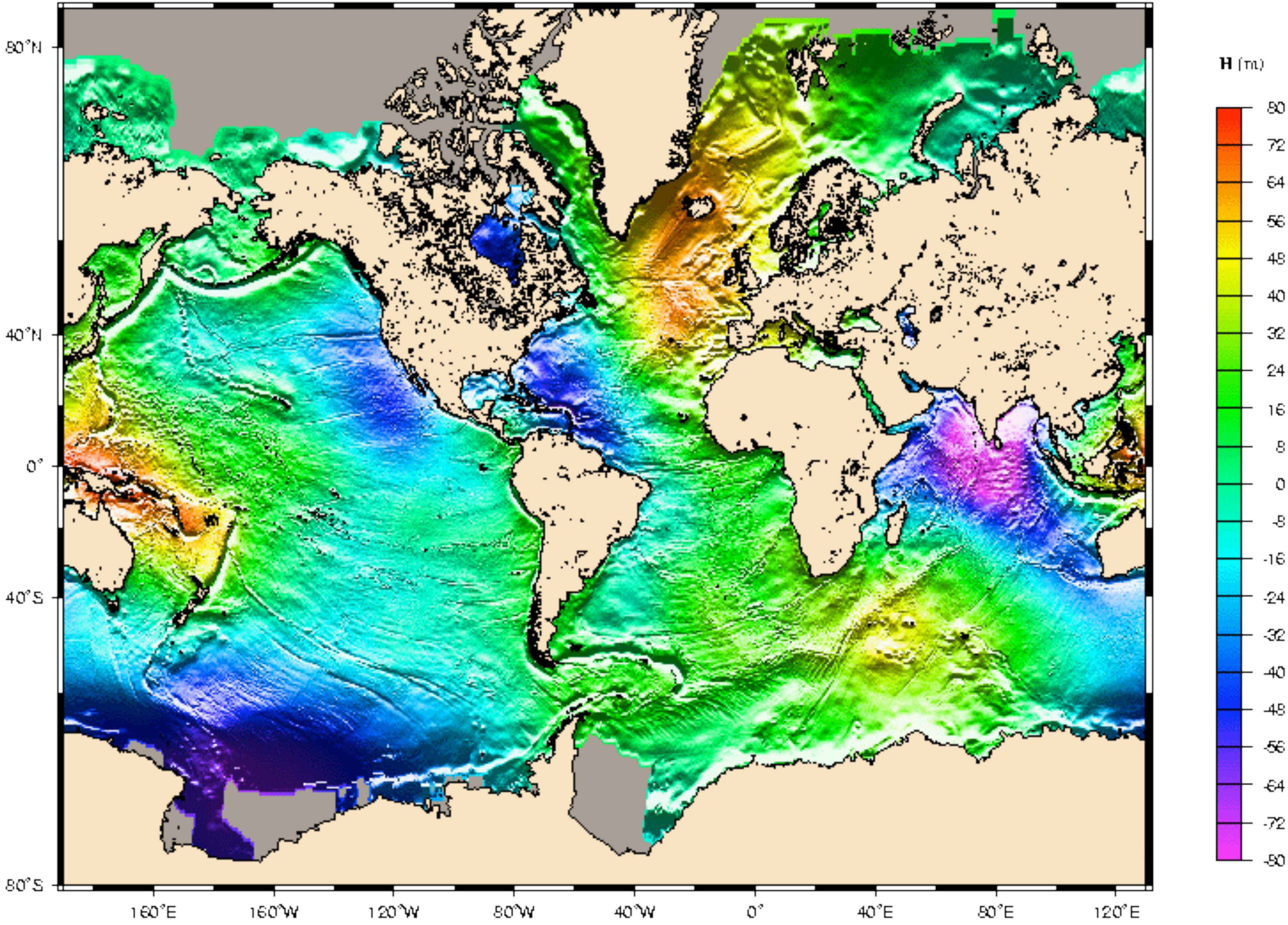
Scale: magenta (-107 m) to red (84.5 m)

- 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 approximately a resolution of 1°
- Sea surface pressure and hence geostrophic currents are in terms of sea surface height relative to the geoid. We measure currents (sea surface slopes) relative to the ellipsoid.

- 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



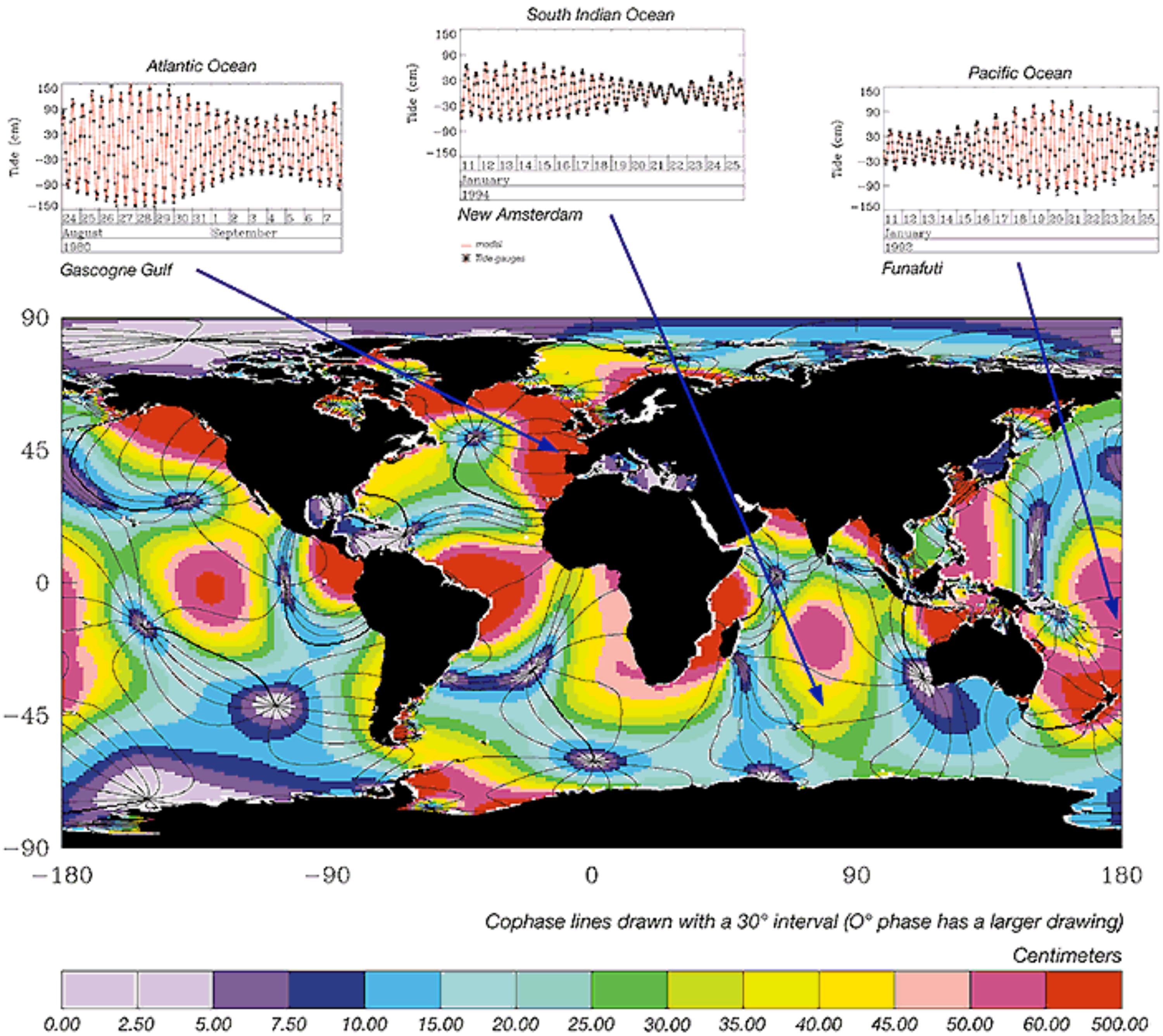
SSH residuals

- 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
  - Unremoved tidal or barometric signal
  - Orbit error
- Important note: nowadays, with new independent accurate geoid models (GRACE and the forthcoming GOCE) we are starting 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

The up and down of the ocean tides



Source : IMG/LEGI, Grenoble 1995

- As well as the ocean tide we have to consider

1.the loading tide (the effect of the weight of water). This is sometimes included in the ocean tide

3.the solid earth tide

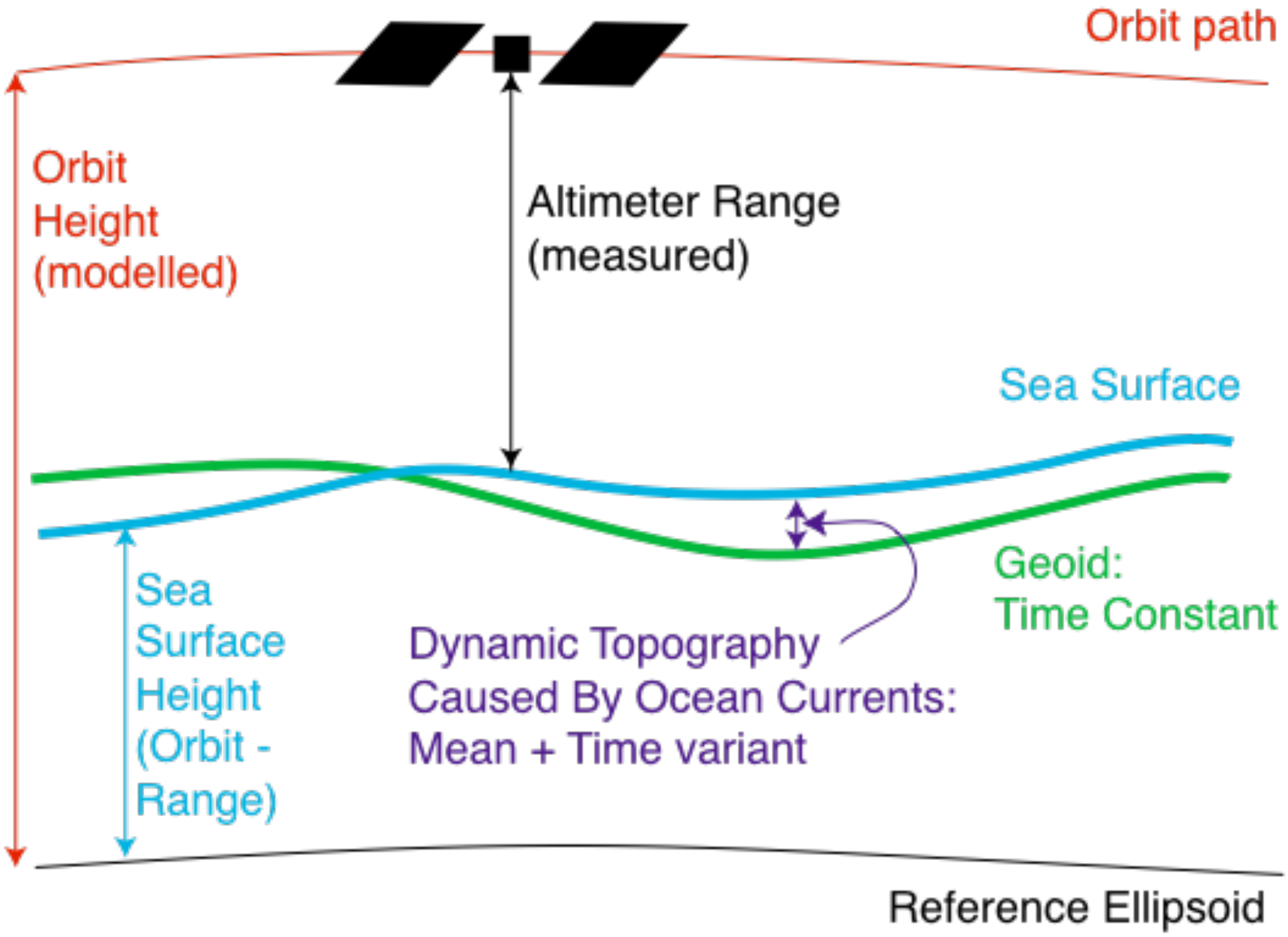
5.the polar tide

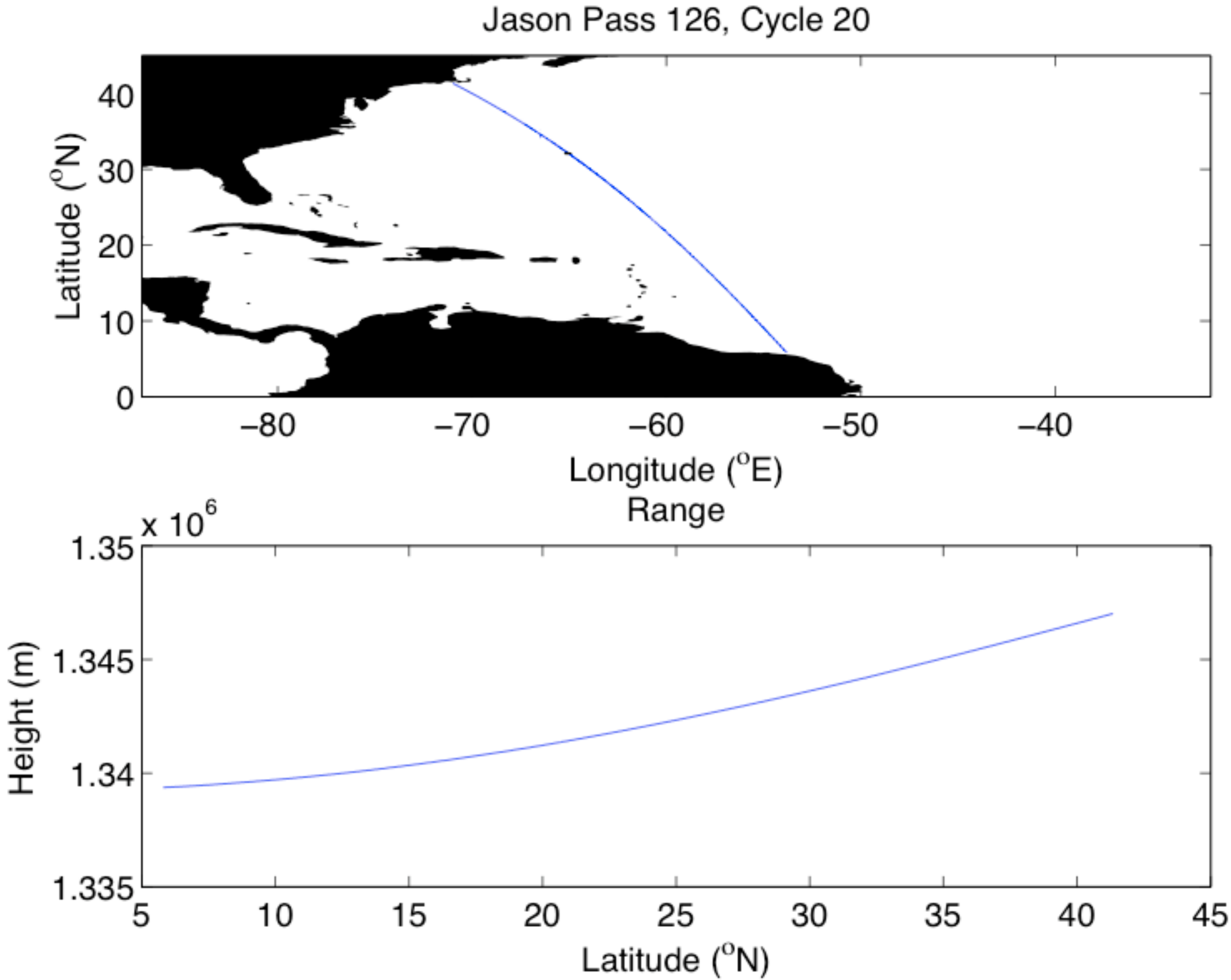
- On continental shelves the global models are not very accurate and local models are needed
- Any residual tidal error is going to be aliased by the sampling pattern of the altimeter

Aliasing Periods

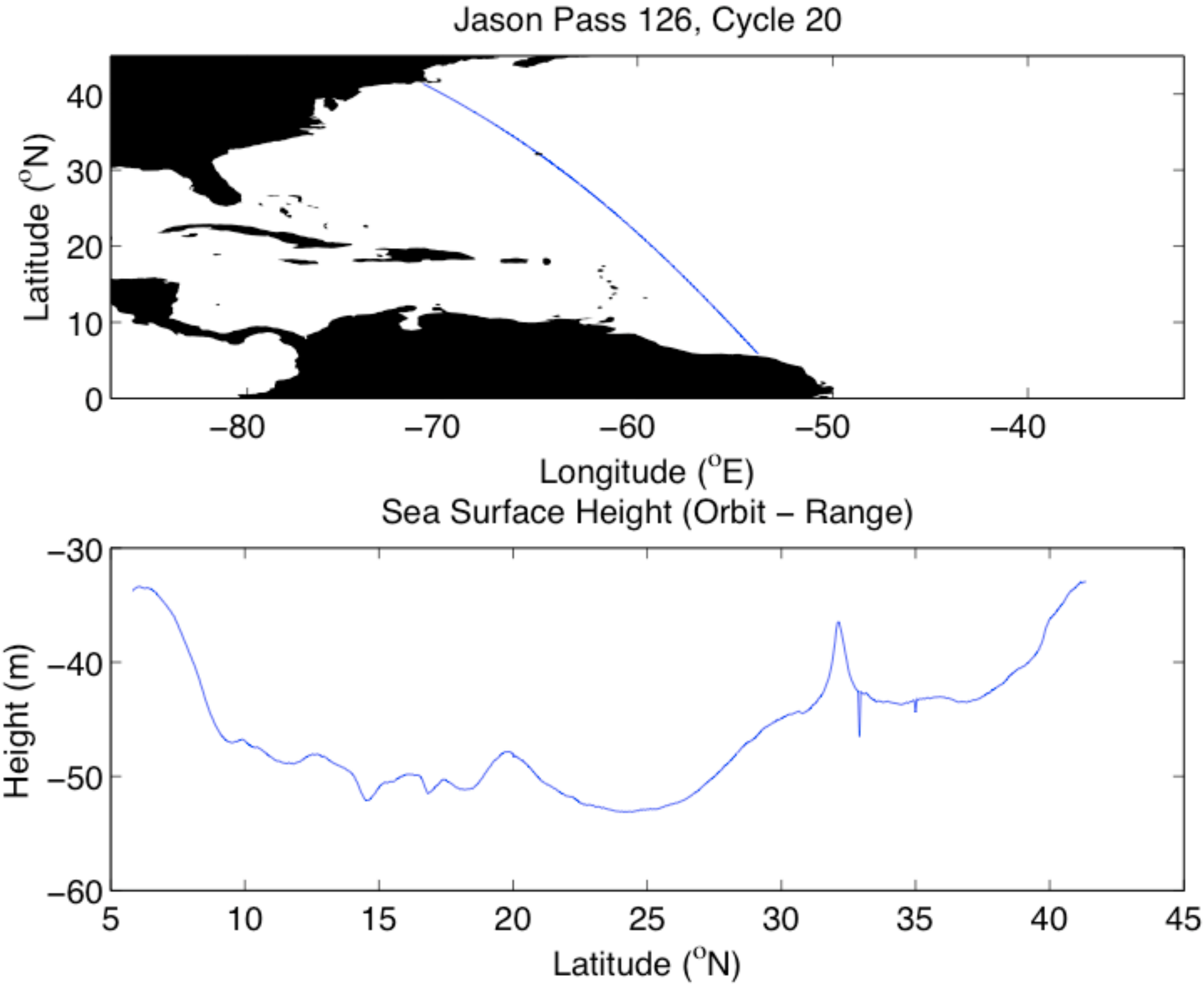
		T/P		ERS	
Tide	Period (h)	Alias (days)	wave length (°)	Alias (days)	wave length (°)
M2	12.42	62	9E	95	9E
S2	12	59	180W	0	∞
N2	12.65	50	9W	97	4W
K1	23.93	173	360W	365	360E
O1	25.82	46	9.23E	75	9E
P1	24.07	89	360W	365	360W

Example of corrections over a pass

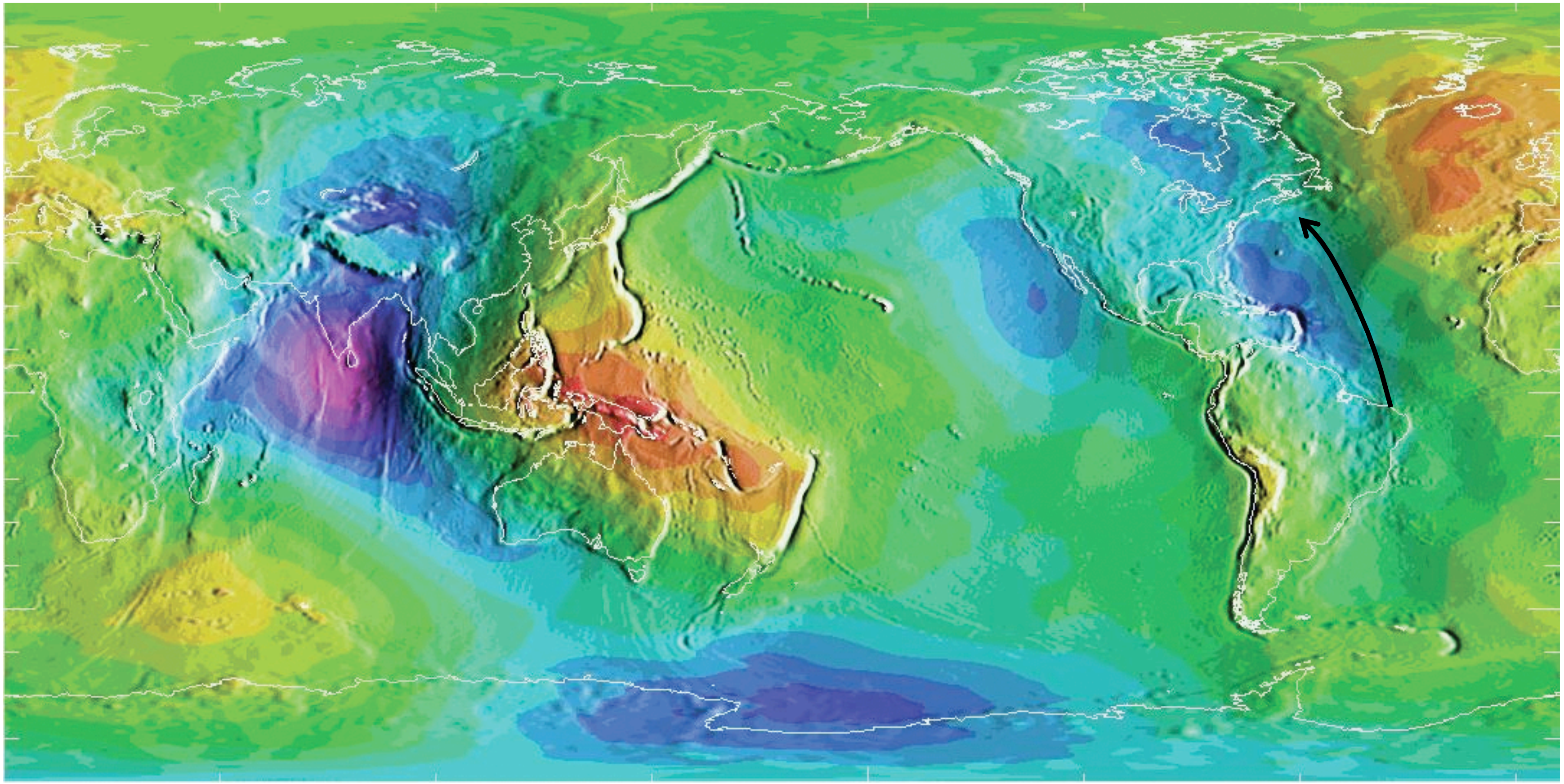




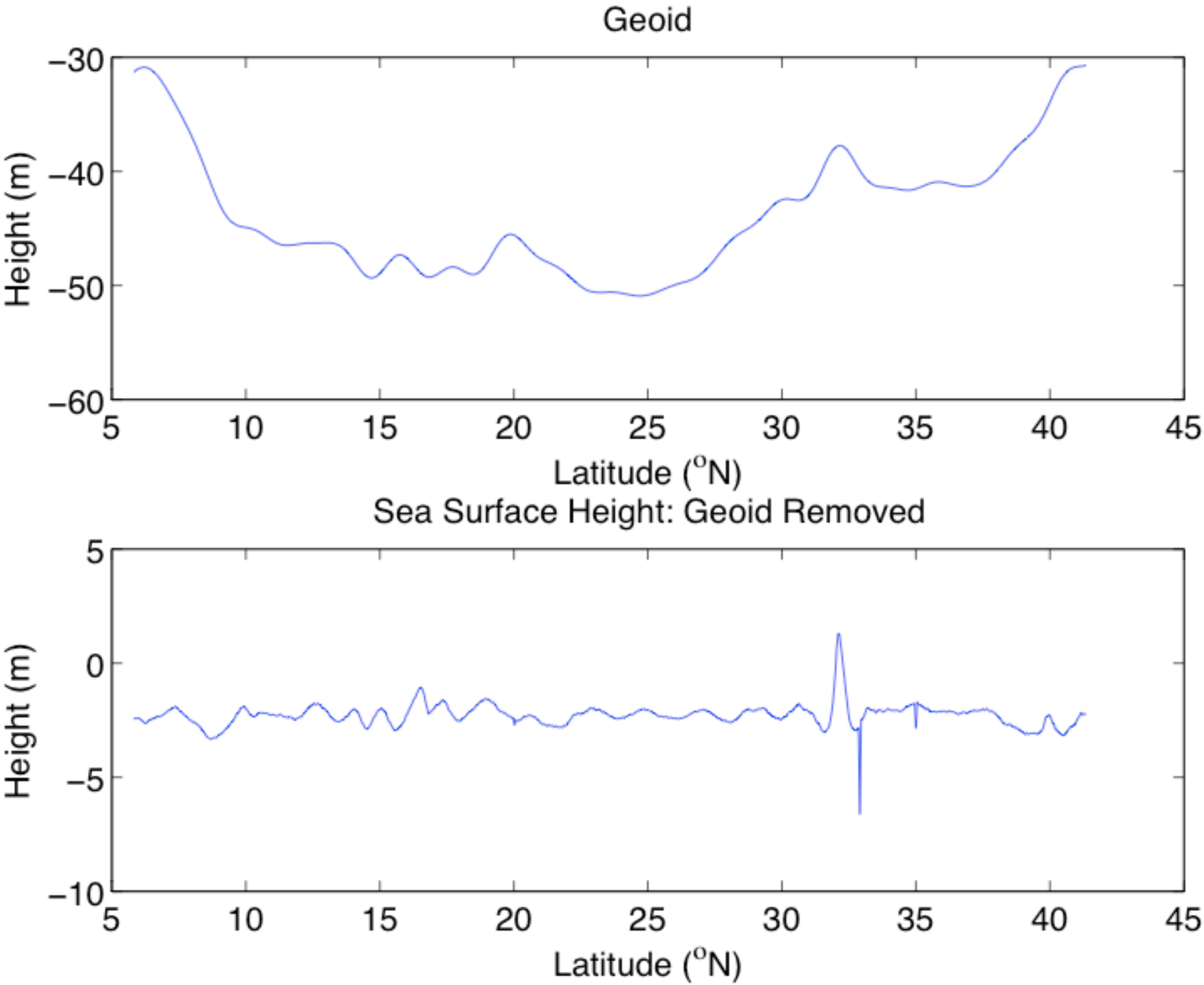
Jason Pass 126, Cycle 20
Latitude (°N)
40
30
20
10
0
−80
−70
−60
−50
−40
Longitude (°E)
Range
x 10^6
1.35
1.345
1.34
1.335
Height (m)
5
10
15
20
25
30
35
40
45
Latitude (°N)

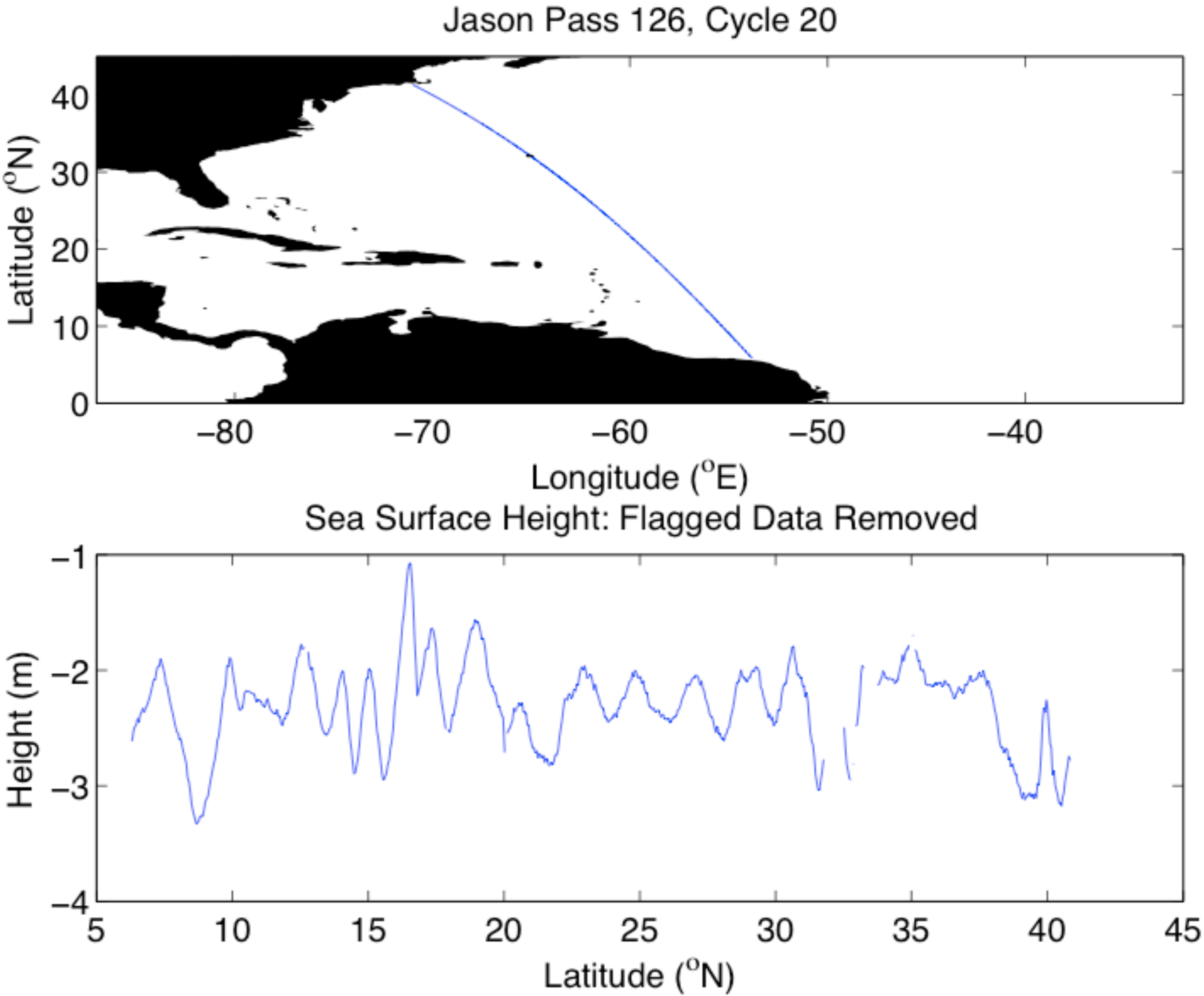

Jason Pass 126, Cycle 20
Latitude (°N)
40
30
20
10
0
−80
−70
−60
−50
−40
Longitude (°E)
Sea Surface Height (Orbit − Range)
Height (m)
−30
−40
−50
−60
5
10
15
20
25
30
35
40
45
Latitude (°N)

The Geoid

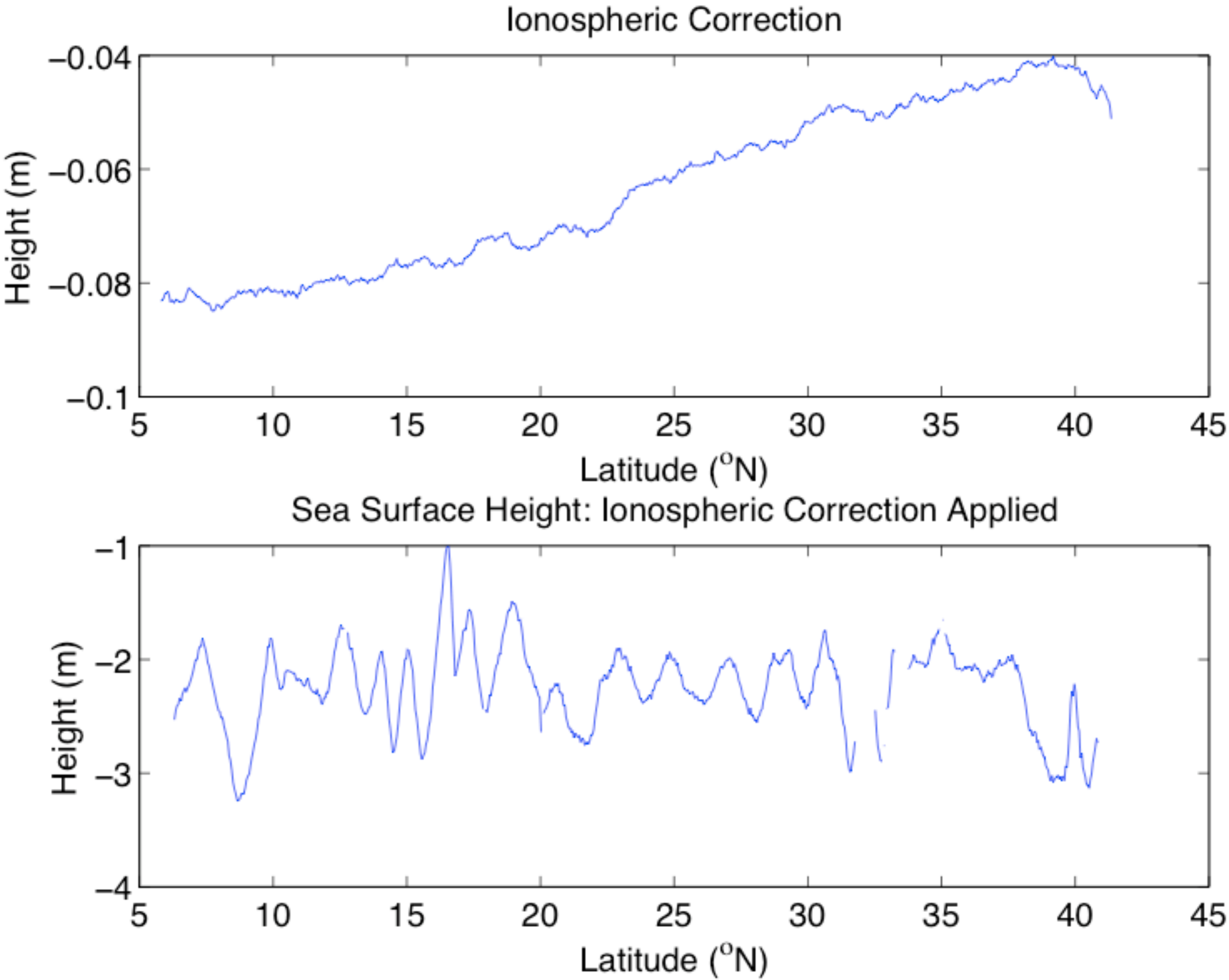


Scale: magenta (-107m) to red (84.5m)

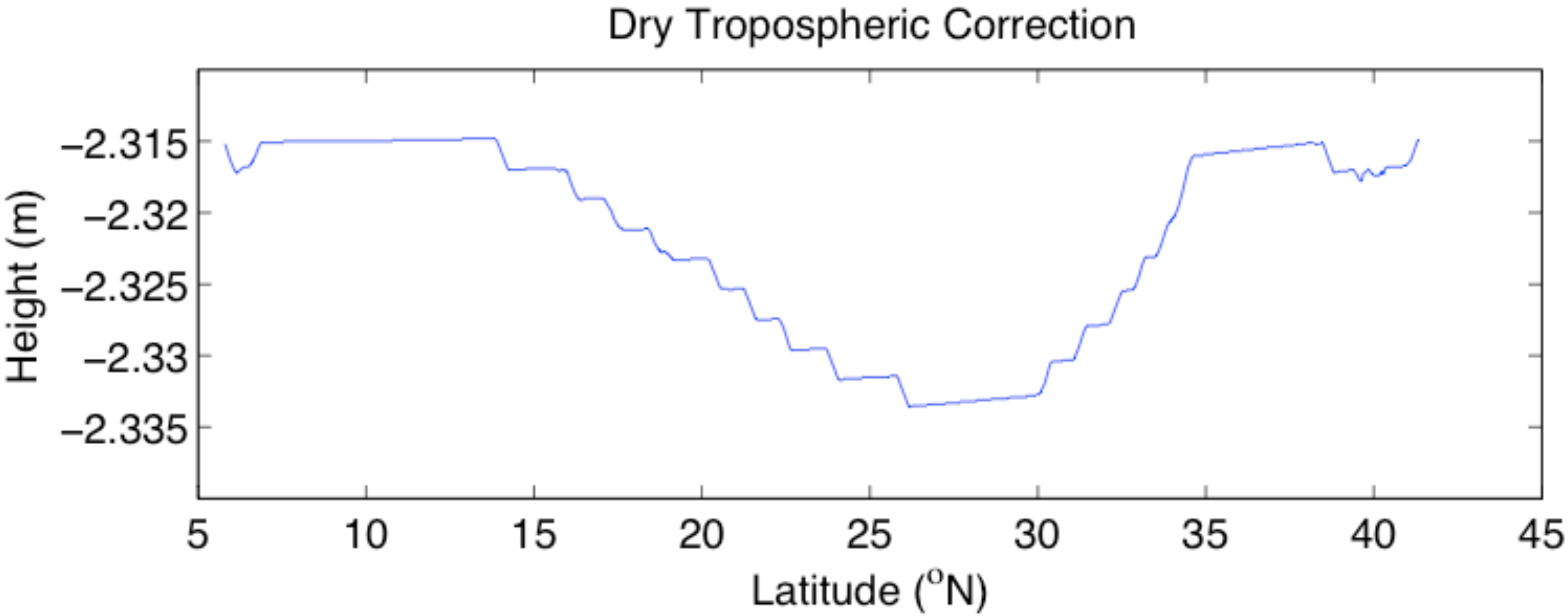

Geoid
Height (m)
−30
−40
−50
−60
5
10
15
20
25
30
35
40
45
Latitude (oN)
Sea Surface Height: Geoid Removed
Height (m)
5
0
−5
−10
5
10
15
20
25
30
35
40
45
Latitude (oN)



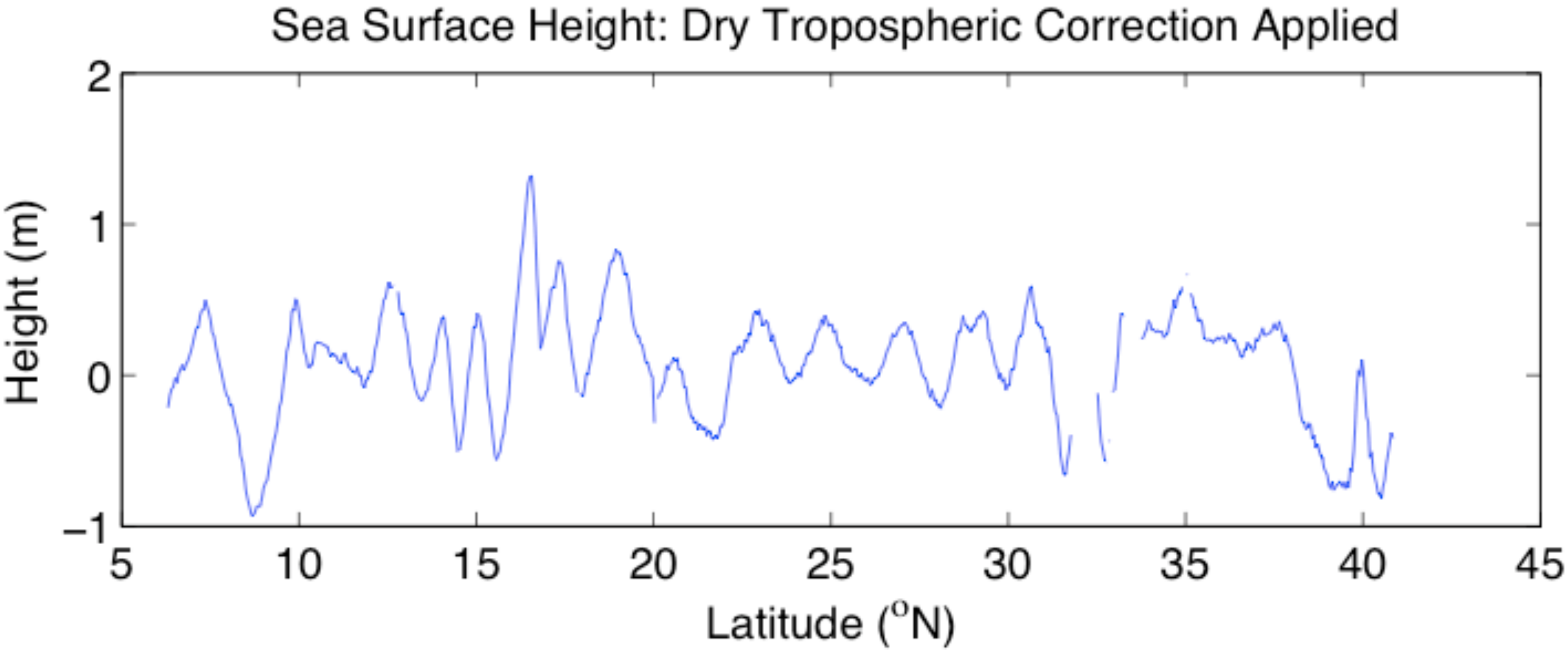
Jason Pass 126, Cycle 20
Latitude (°N)
40
30
20
10
0
−80
−70
−60
−50
−40
Longitude (°E)
Sea Surface Height: Flagged Data Removed
Height (m)
−1
−2
−3
−4
5
10
15
20
25
30
35
40
45
Latitude (°N)



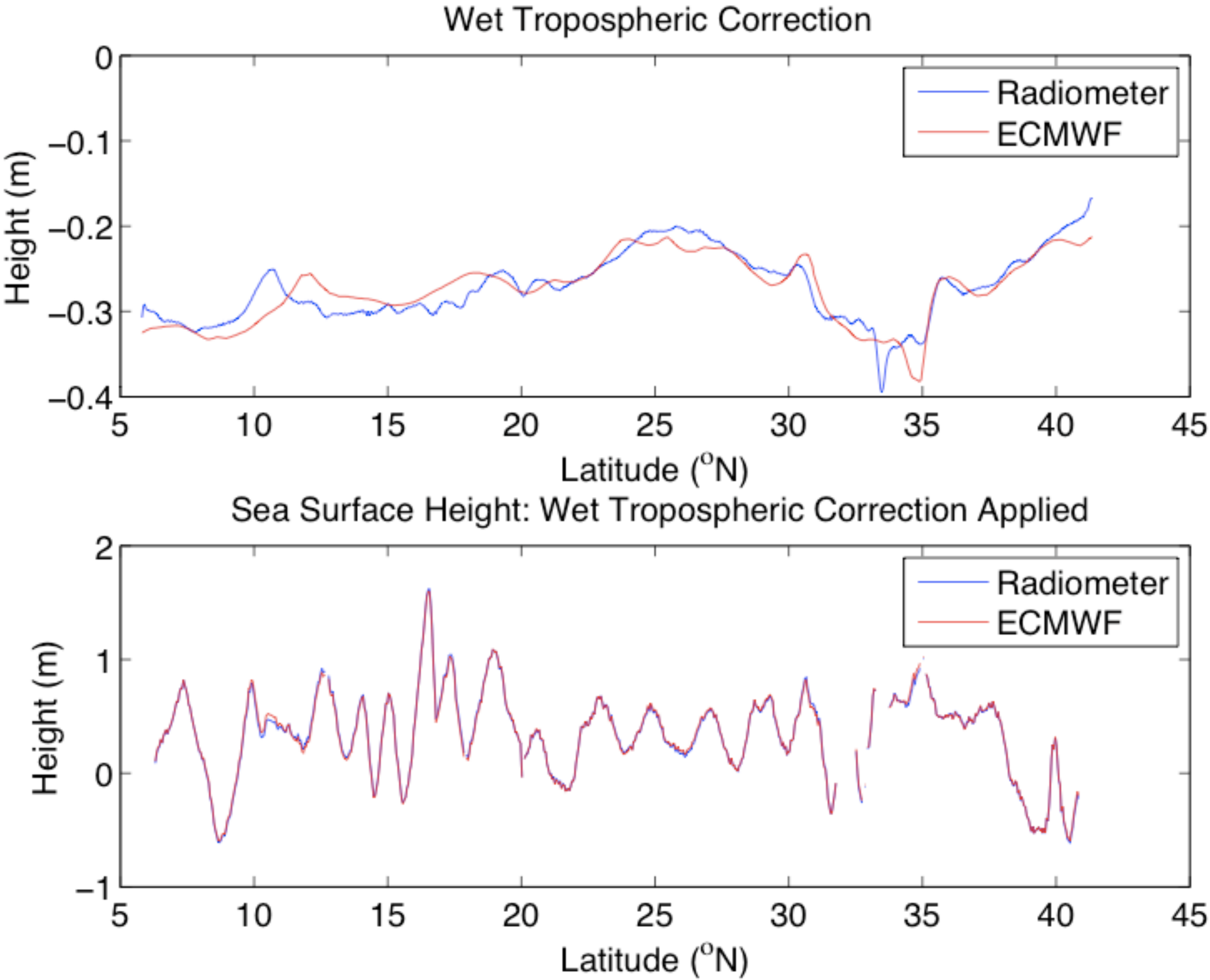
Ionospheric Correction
Height (m)
−0.04
−0.06
−0.08
−0.1
5
10
15
20
25
30
35
40
45
Latitude (°N)
Sea Surface Height: Ionospheric Correction Applied
Height (m)
−1
−2
−3
−4
5
10
15
20
25
30
35
40
45
Latitude (°N)



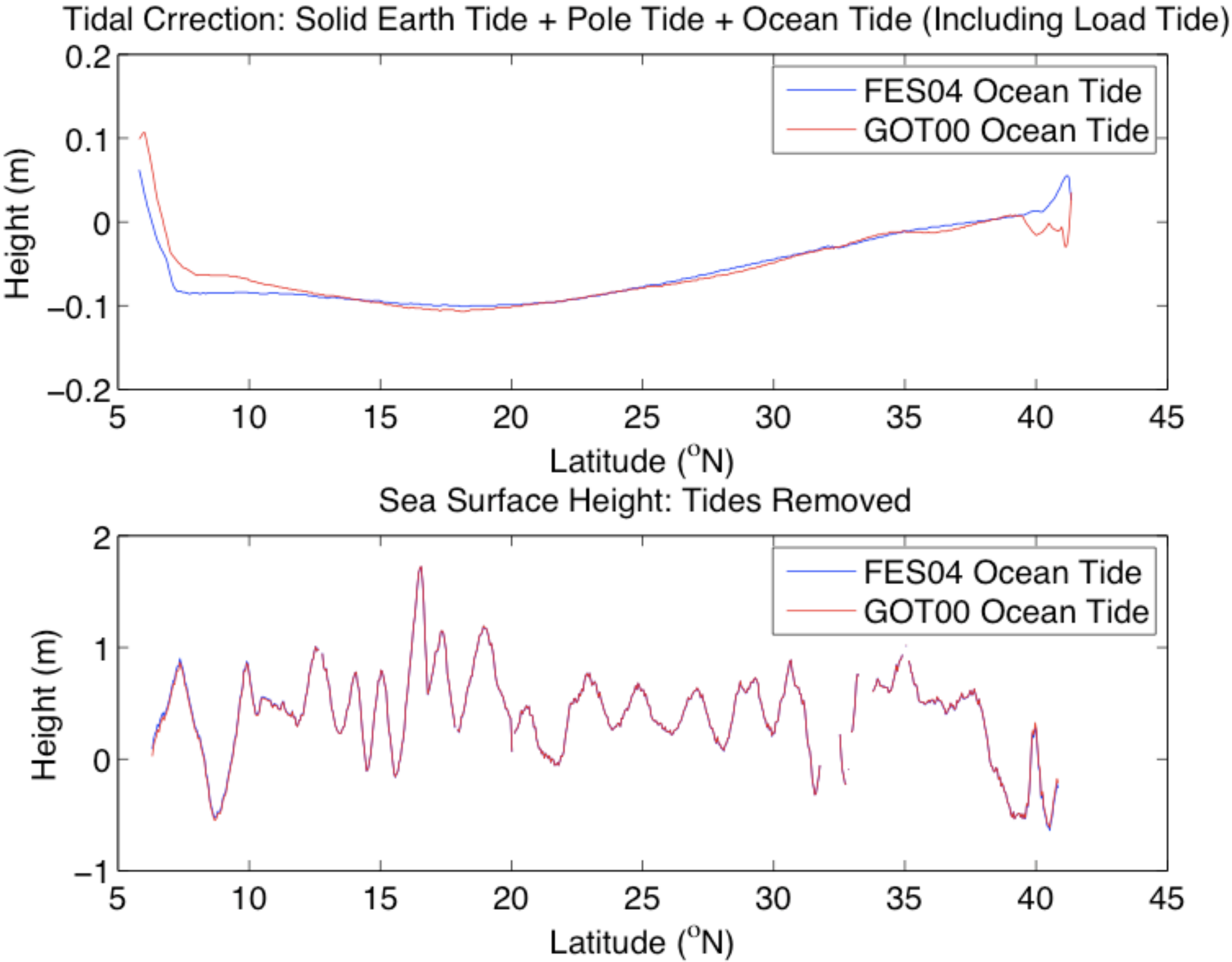
Dry Tropospheric Correction
Height (m)
−2.315
−2.32
−2.325
−2.33
−2.335
5
10
15
20
25
30
35
40
45
Latitude (°N)

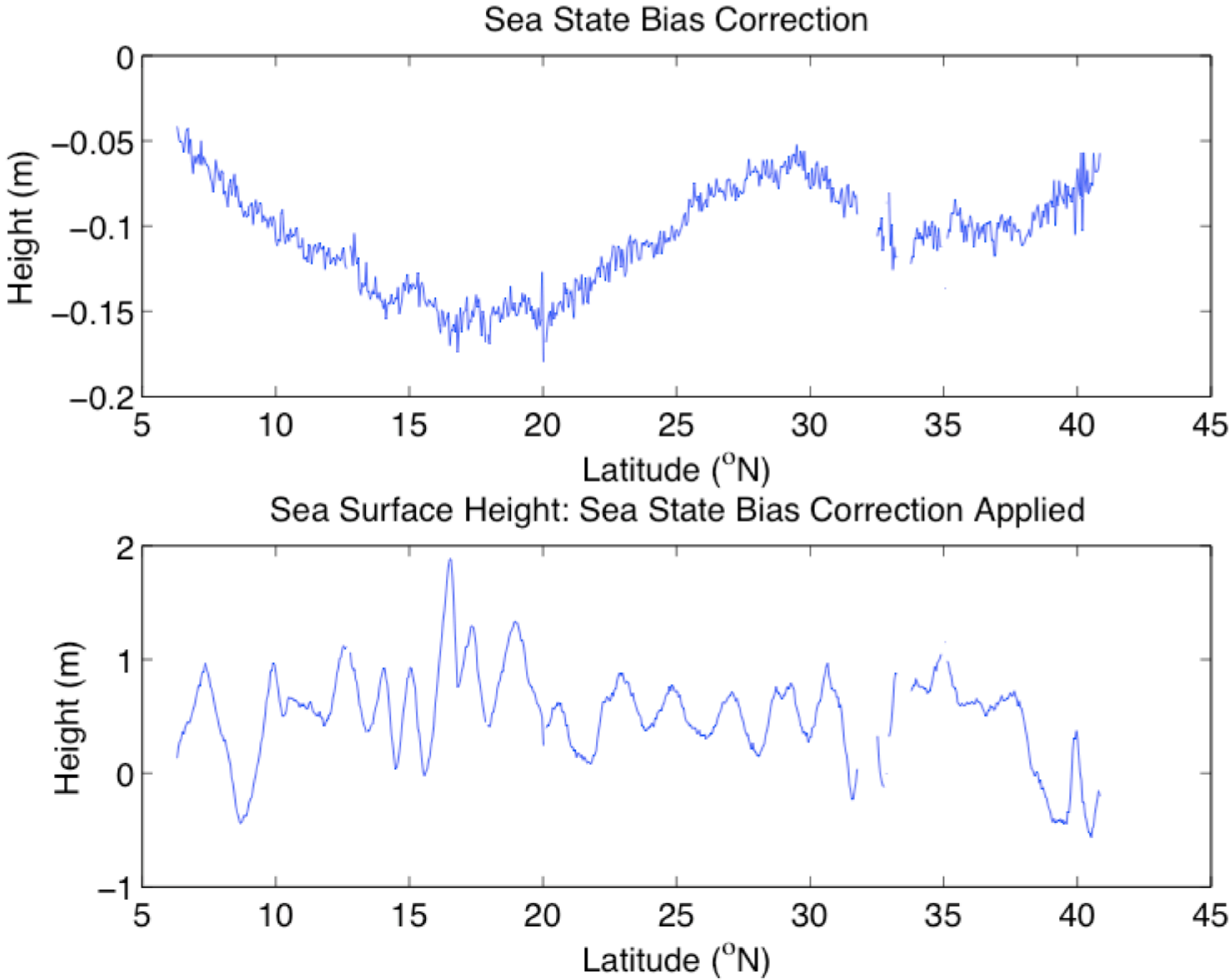


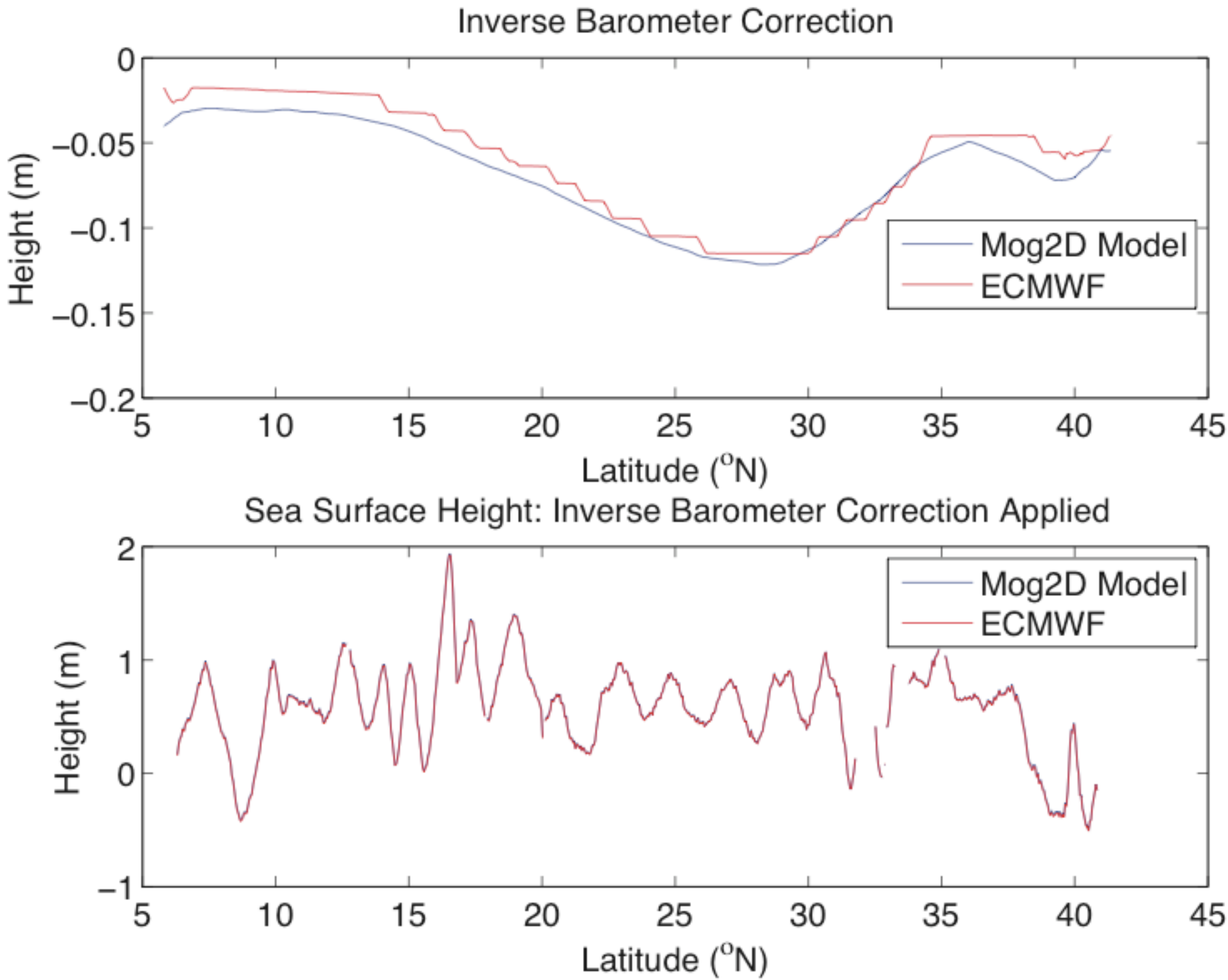
Sea Surface Height: Dry Tropospheric Correction Applied
Height (m)
2
1
0
−1
5
10
15
20
25
30
35
40
45
Latitude (°N)



Wet Tropospheric Correction
Radiometer
ECMWF
Height (m)
0
−0.1
−0.2
−0.3
−0.4
5
10
15
20
25
30
35
40
45
Latitude (oN)
Sea Surface Height: Wet Tropospheric Correction Applied
Radiometer
ECMWF
Height (m)
2
1
0
−1
5
10
15
20
25
30
35
40
45
Latitude (oN)


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


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

Altimetry III
Geophysical parameters we can measure

- Sea Surface Height Anomaly
  - Varying part of ocean circulation, eddies, gyres, tides, long waves, El Nino, etc
  - Variable currents
- In near future (with accurate geoid): absolute SSH
  - Absolute currents
- From shape of return: wave height
- From radar cross-section: wind

Geostrophic currents from Altimetry

- Assume geostrophic balance
  - geostrophy: balance between **pressure gradient** and **Coriolis force**

$$\frac{\partial H}{\partial x} = \frac{fv}{g} \qquad f = 2\Omega \sin(latitude)$$

$$v = \frac{g}{f}\frac{\partial H}{\partial x}$$

- Unavoidable limitations
  - Measures only cross-track component of current
  - Cannot recover currents near the equator (geostrophy does not hold there)
  - Only variable (non-steady) currents are detectable

Absolute currents / absolute topography - an example

- Kuroshio Current - important current system in North pacific
- We will see a model animation first
  - Model data from OCCAM model at NOCS, courtesy of Andrew Coward
- Then we will see the combination of all Altimeter mission available subtracting the latest geoid (from GRACE mission)
  - Courtesy of Doug McNeall, NOCS

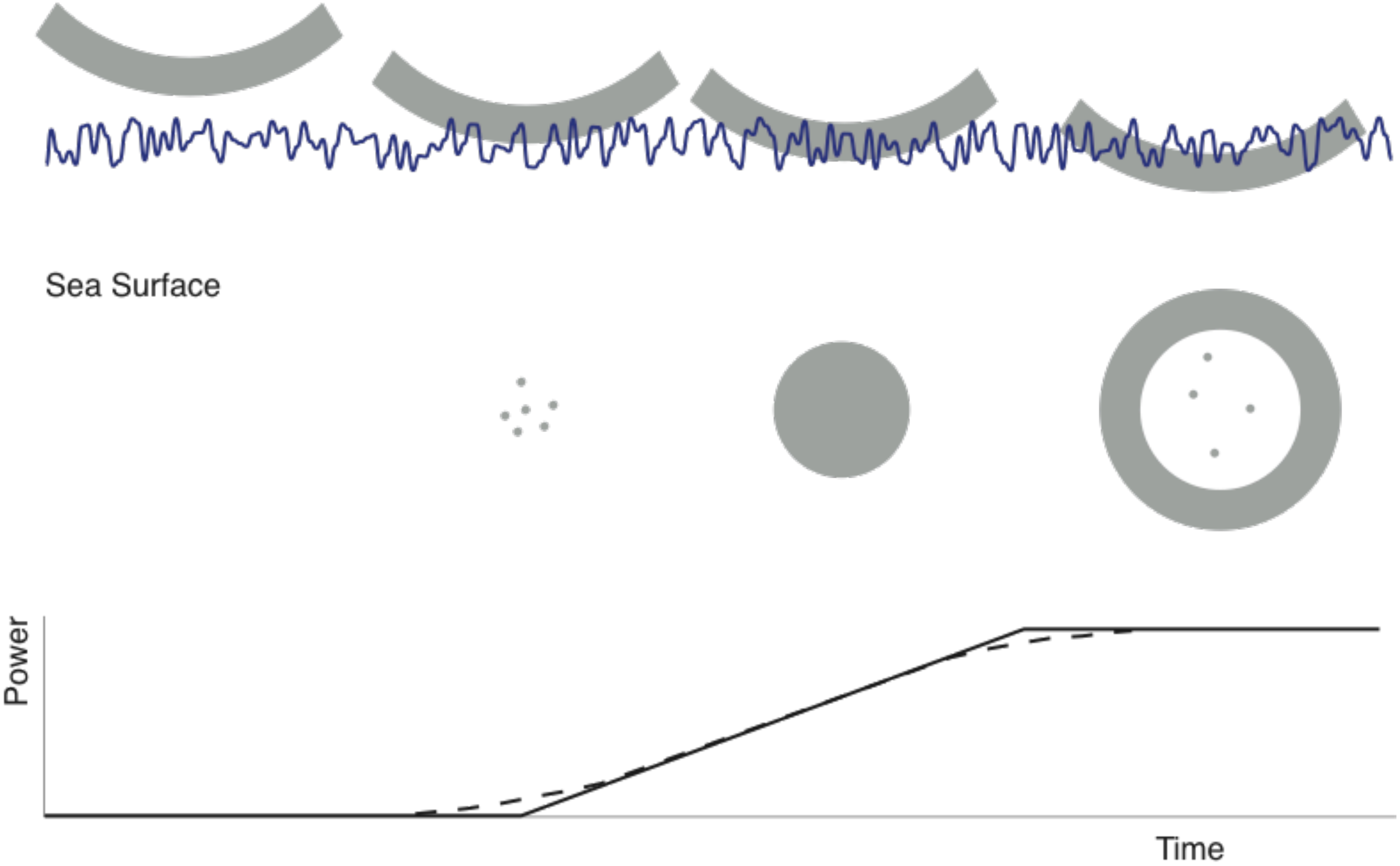
Waves, winds and other altimeter parameters

- Significant wave height
- Altimeter winds
- Calibration/validation
- Wave climate

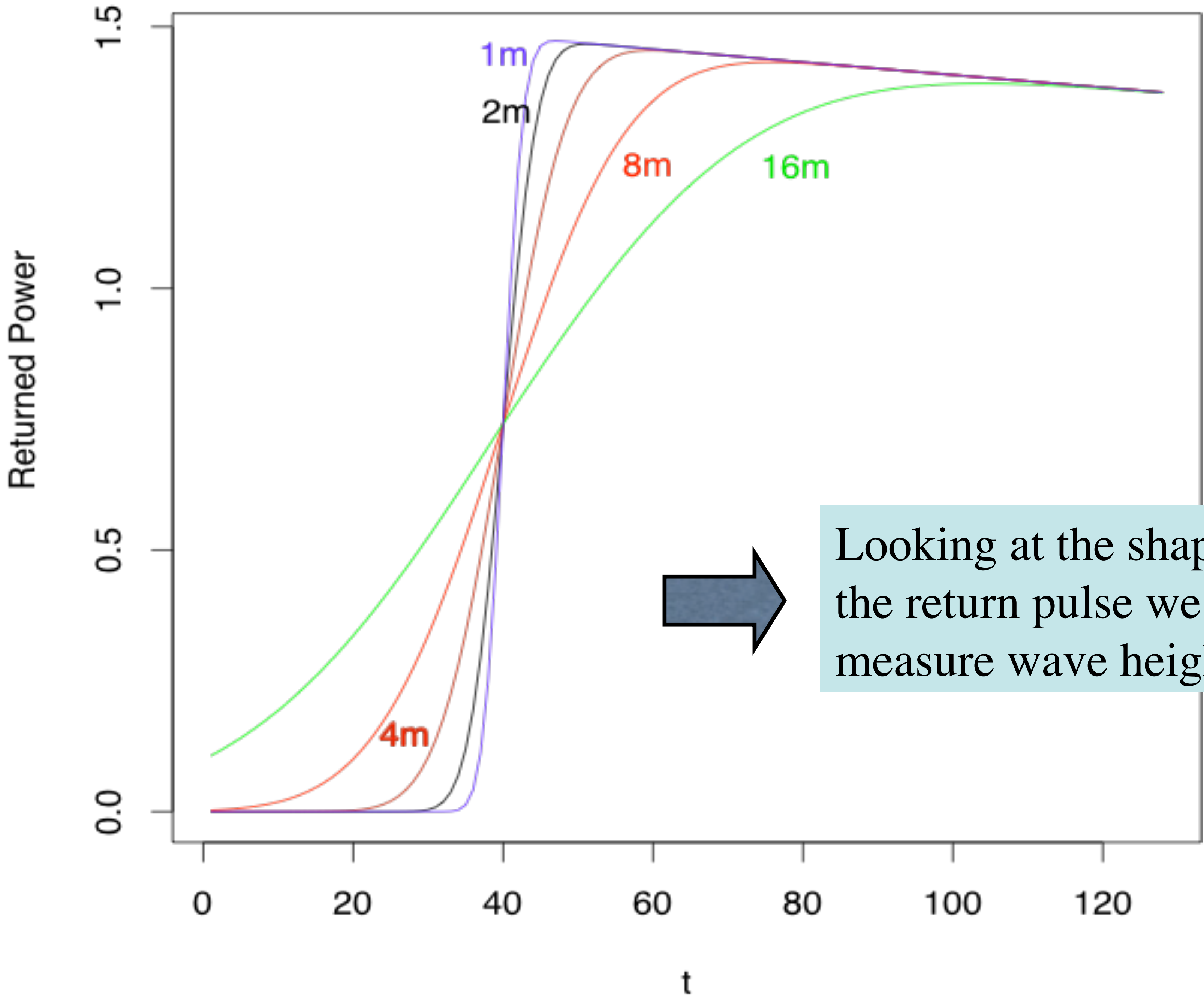
What is significant wave height?

- H_s (or SWH) is defined by
- H_s=4 s.d.(sea surface elevation)
- Used to be defined ($H_{1/3}$) as
- Mean height (highest third of the waves)
- ≈ visual estimate of wave height

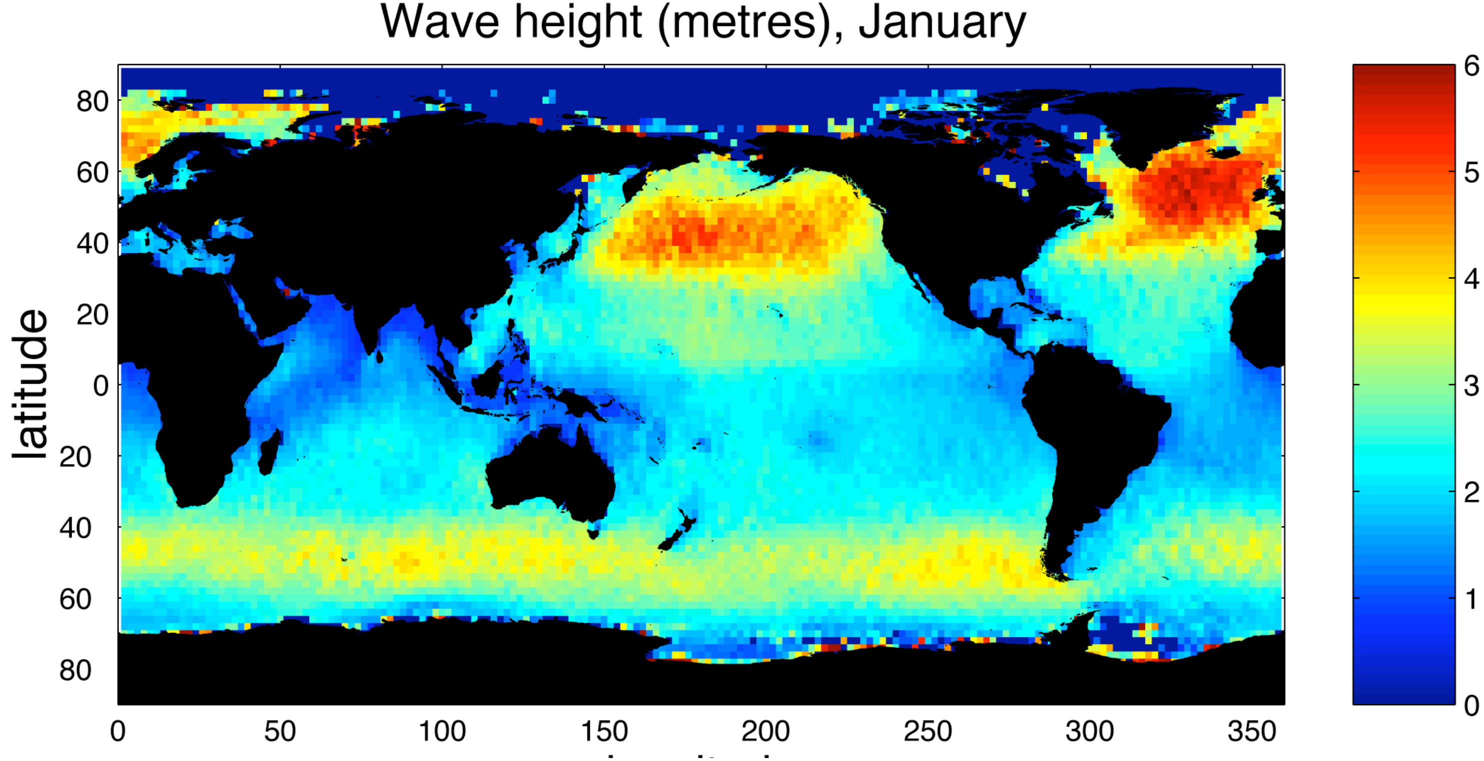
How an altimeter measures H_s

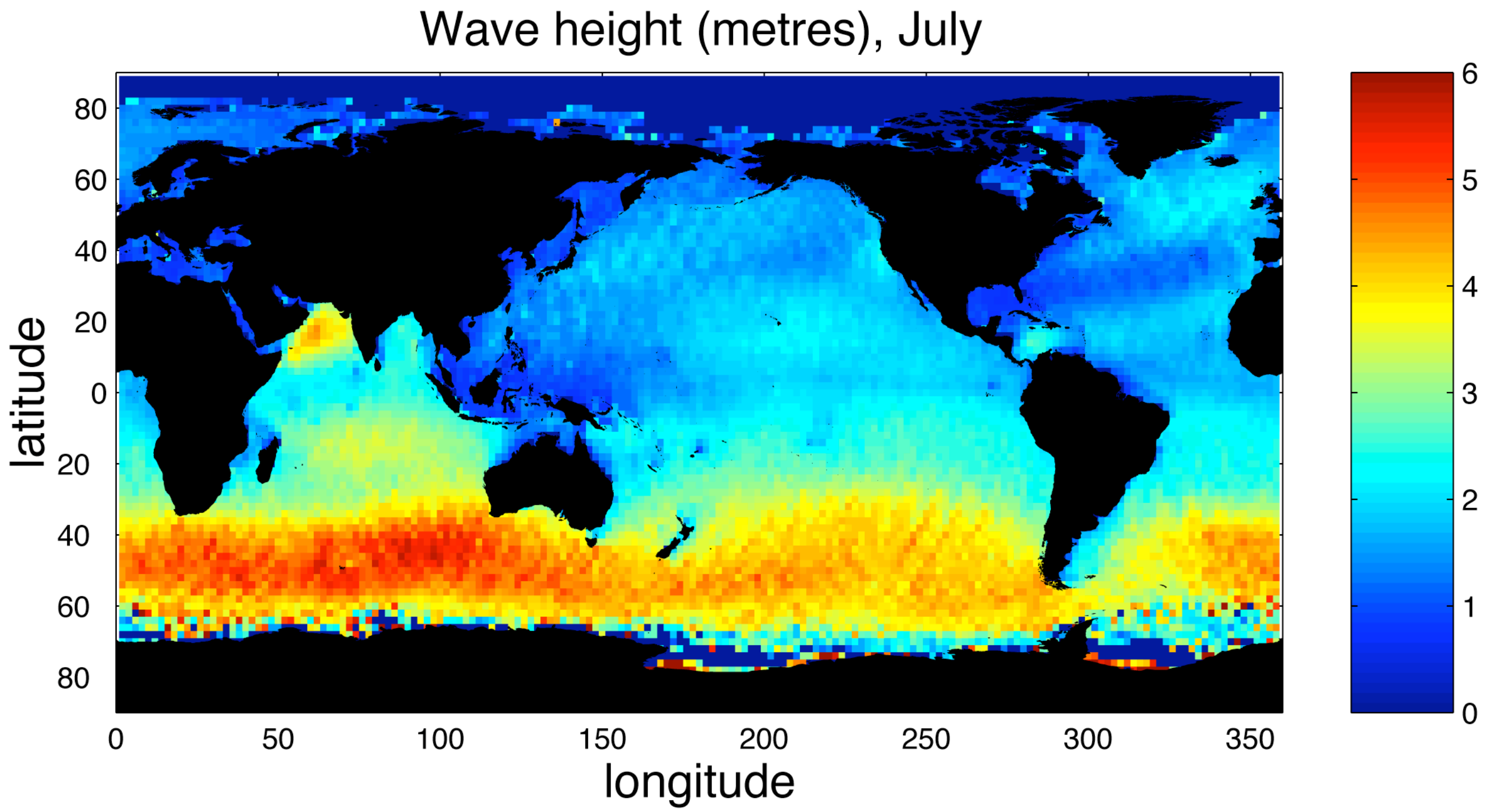


Some example waveforms

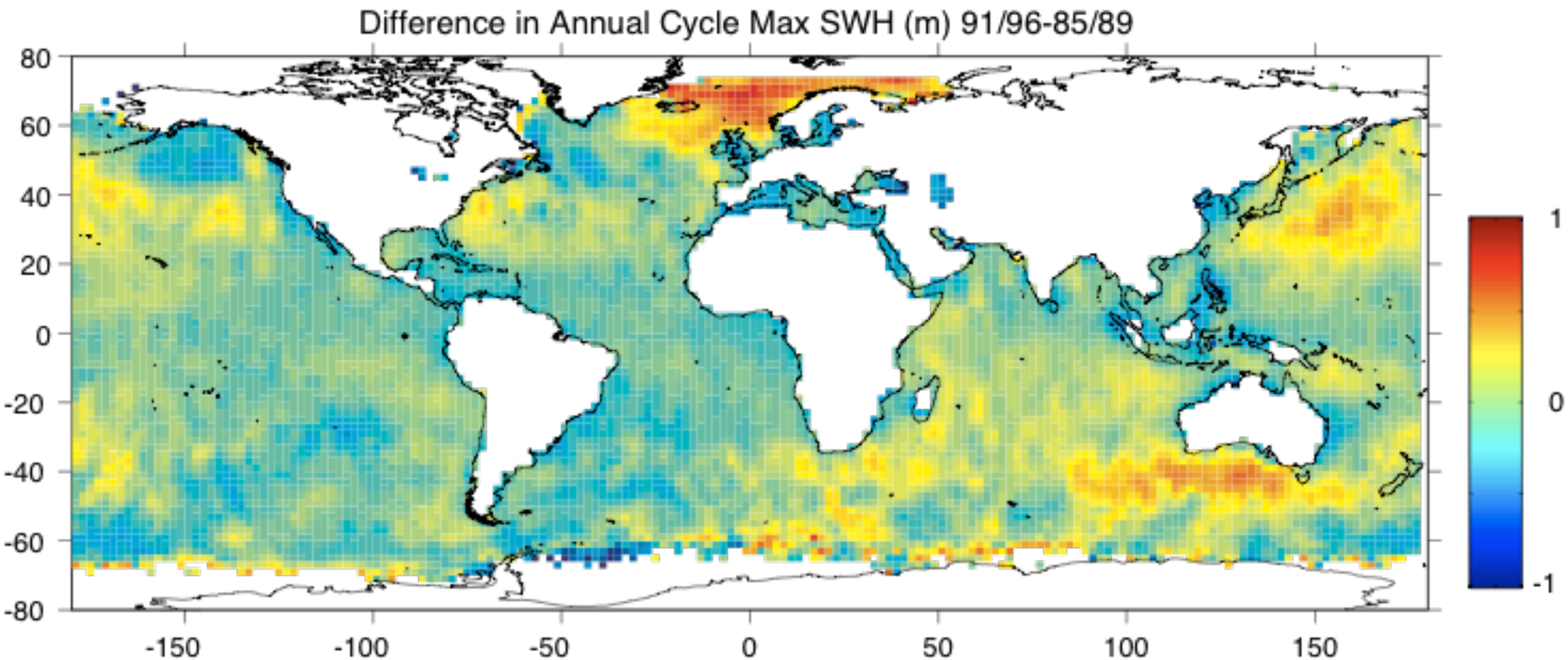


Looking at the shape of the return pulse we can measure wave height


Wave height (metres), January
latitude
longitude
80
60
40
20
0
20
40
60
80
0
50
100
150
200
250
300
350
6
5
4
3
2
1
0

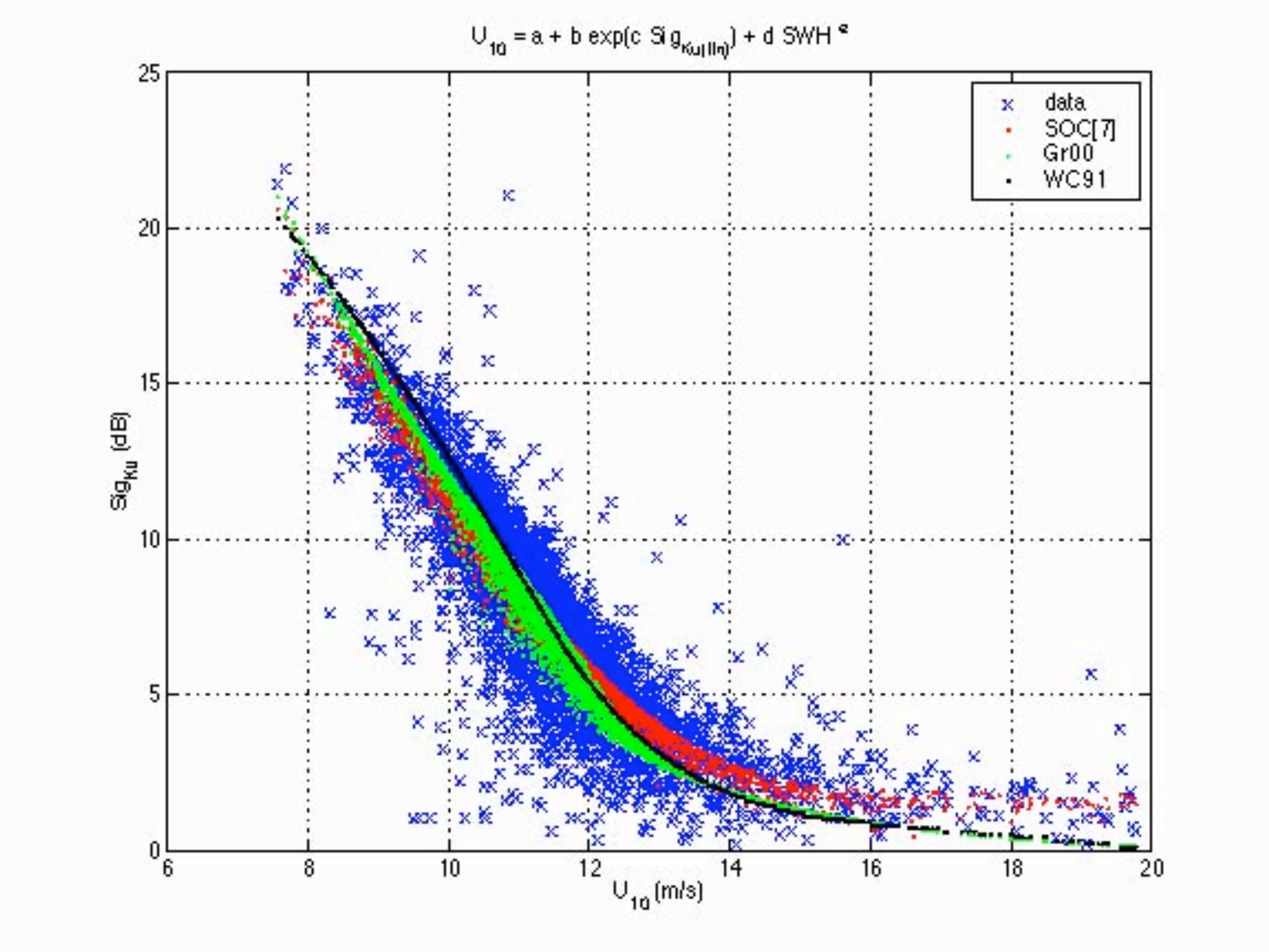

Wave height (metres), July
latitude
longitude
80
60
40
20
0
20
40
60
80
0
50
100
150
200
250
300
350
6
5
4
3
2
1
0

Climate changes



Altimeter wind speeds

- The radar backscatter coefficient can be related theoretically to the mean square slope of the sea surface **at wavelengths comparable with that of the radarnd**
- Ku band is ~2 cm, so it will depend on capillary waves
- …these, in turn, depend on the wind!!
- Empirically we relate this to wind speed (U_{10})
- Wind stress?



$U_{10} = a + b \exp(c\ Sig_{Ku(lin)}) + d\ SWH^{e}$
data
SOC[7]
Gr00
WC91
Sig_{Ku} (dB)
U_{10} (m/s)
0
5
10
15
20
25
6
8
10
12
14
16
18
20

Why altimeter wind speeds?

- Scatterometers measure wind velocity over wide swathes
- Passive microwave measures wind speed over wide swaths
- Altimeters give us wind speed on a v. narrow swath
- Wind speed information coincident with wave height and sea surface height (e.g. sea state bias)

Other parameters

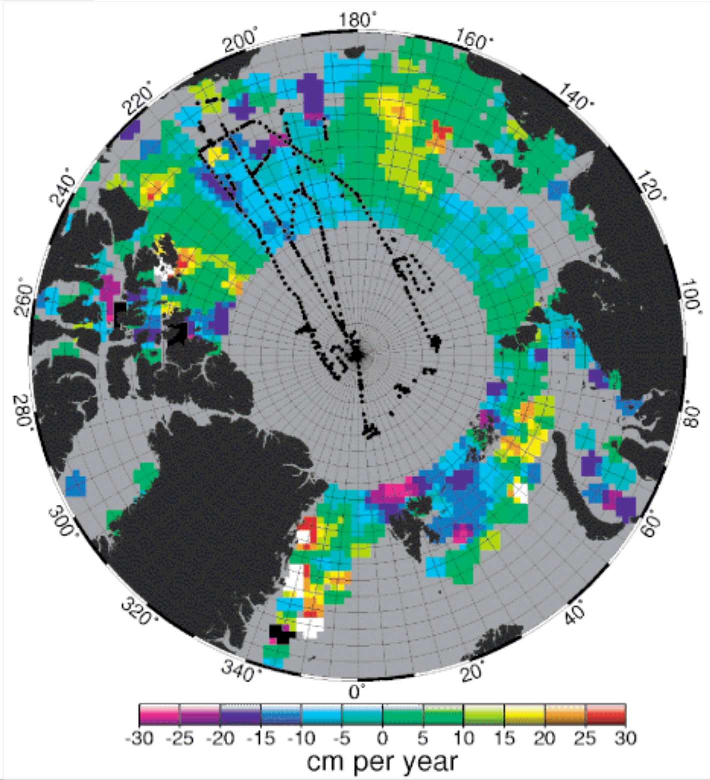
- Ice
- Rain

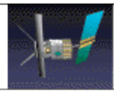
Ice

- Ice edge can be detected by a change in σ^0
- Re-tracking of the altimeter pulses over sea-ice can give
  - Sea surface topography in ice covered regions
  - Sea ice thickness

Trends in Arctic Sea Ice Thickness 1993-99 from ERS Altimetry

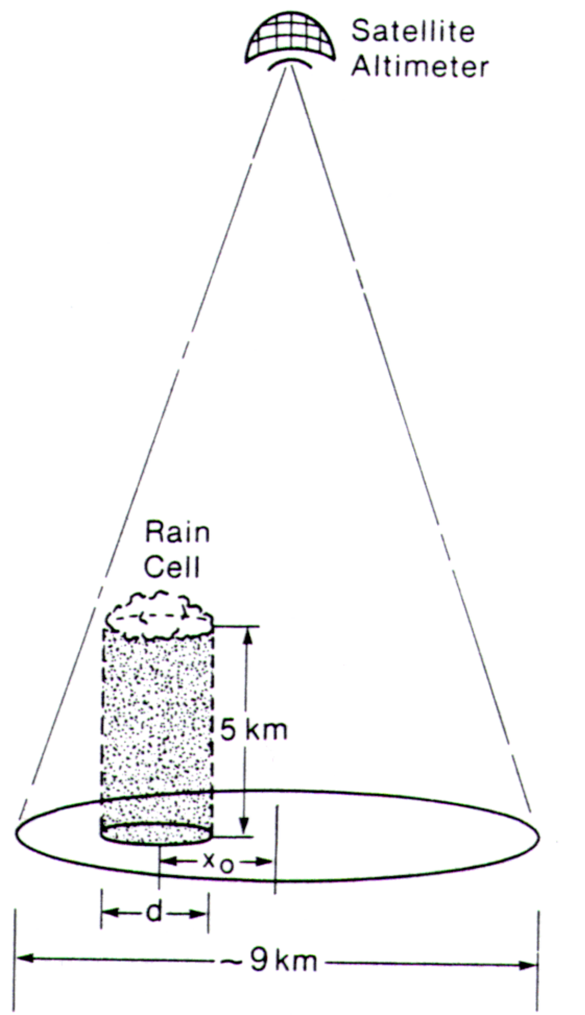
[Laxon and Peacock, 2000]



Reference	Source	Trend	Period
Laxon and Peacock, 2000		$+1$ mm yr^{-1}	1993–1999
Johannessen, et. al., Science, 1999	Swell Propagation	-0.5 cm yr^{-1}	1972–1992
Rothrock, et. al., GRL, 1999		-4 cm yr^{-1}	1958–1997

Rain effects in altimeter data

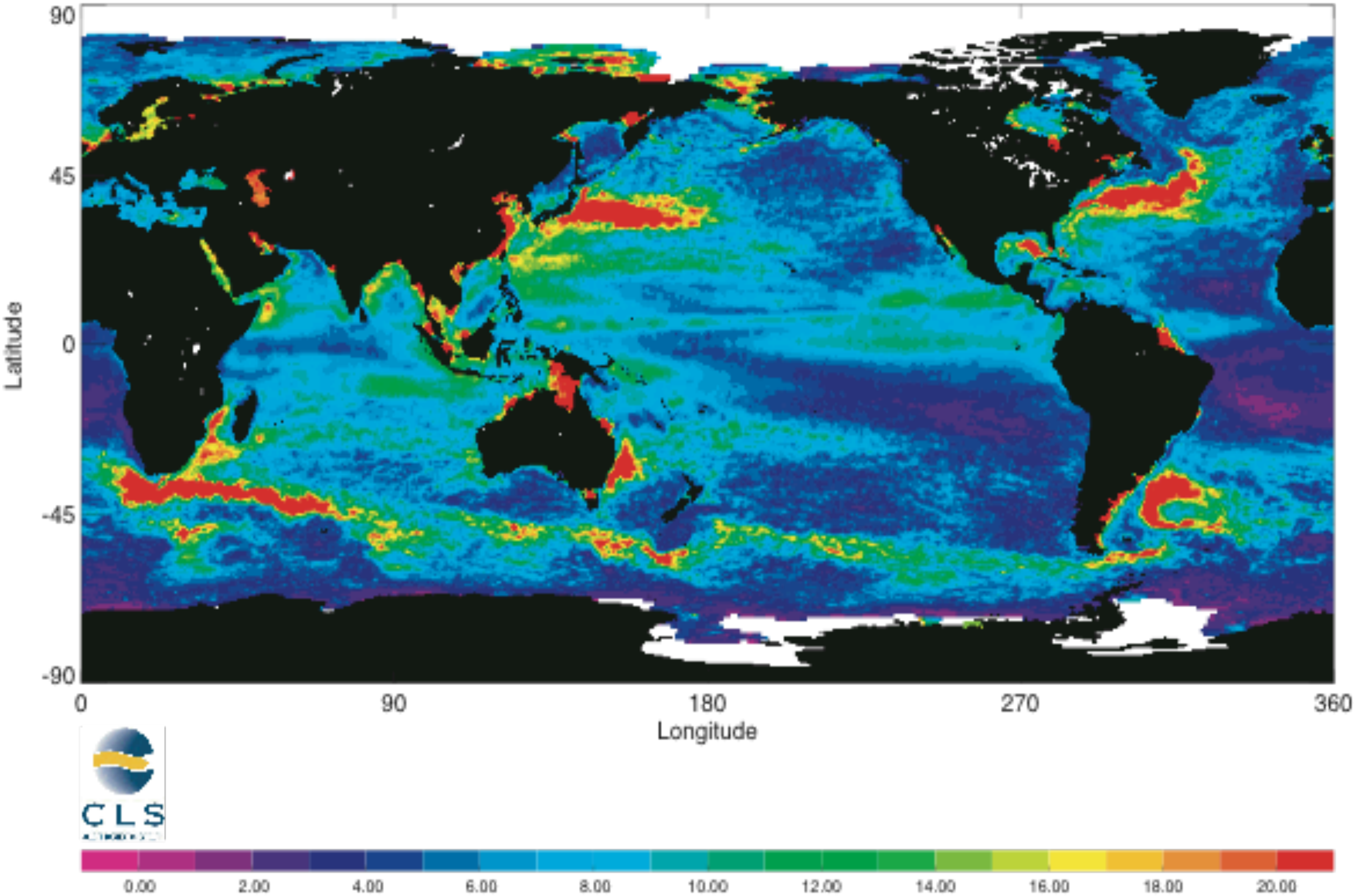
- Dual frequency Topex altimeter (C and Ku band)
- Ku band attenuated
- C band is not
- Ku/C difference gives information on rain rate



Altimeter IV - some applications into Ocean dynamics & Climate studies

- Detect large scale SSH anomalies
  - e.g. El Niño, Antarctic Circumpolar Wave, etc.
  - Identify global connections
- Isolate seasonal current variability
  - e.g. Monsoon dynamics
- Detect and follow mesoscale (50-200 Km) eddies
  - Use transect time series
- Identify planetary waves
  - Use longitude/time (Hovmüller) plots
  - Measure phase speed from gradients of wave signatures

Example: ocean meso-scale variability



Rossby Waves