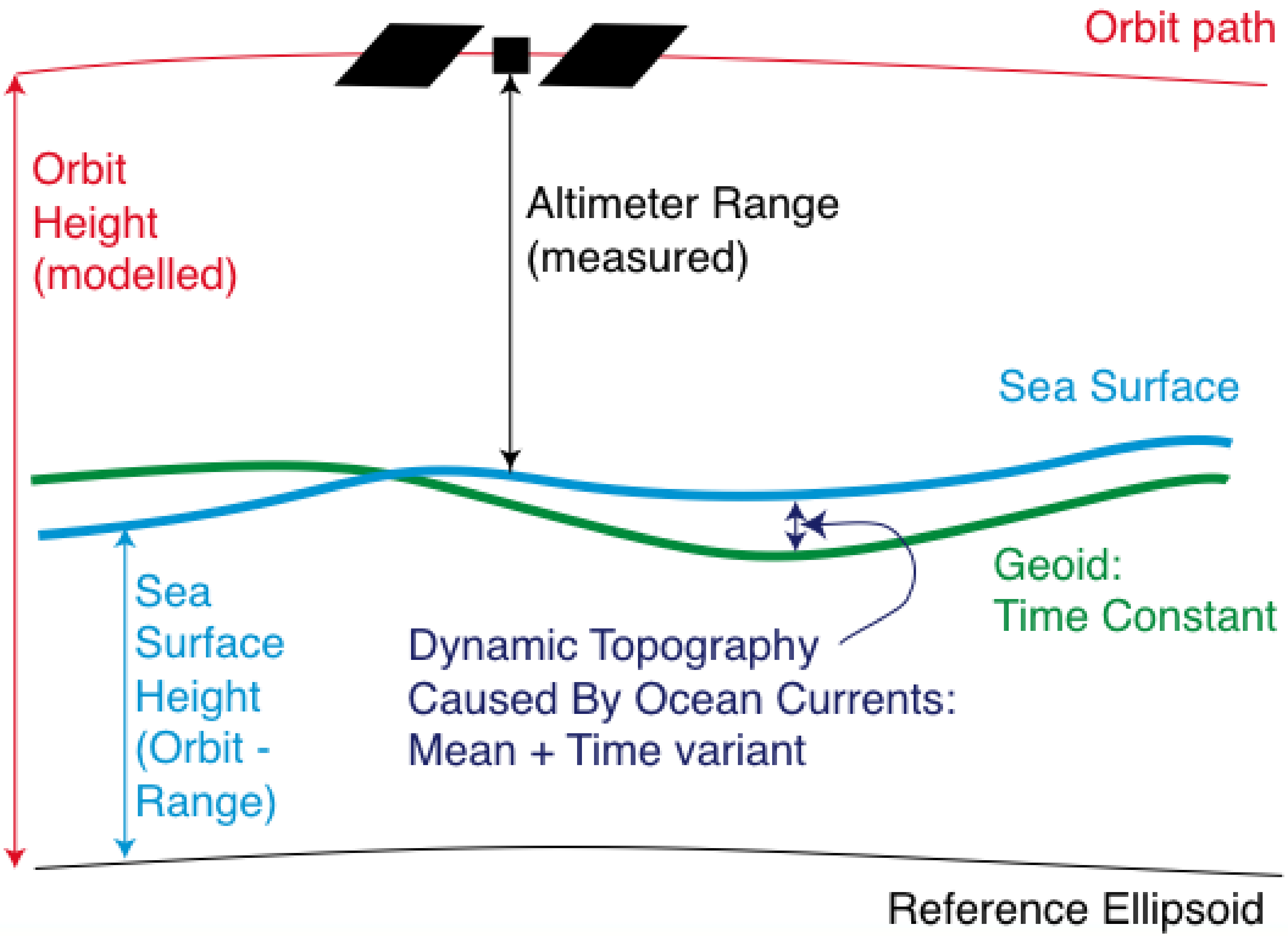
P. Cipollini, H. Snaith - A short course on Altimetry

Altimetry 2 - Data processing (from satellite height to sea surface height)

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


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

➯ 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

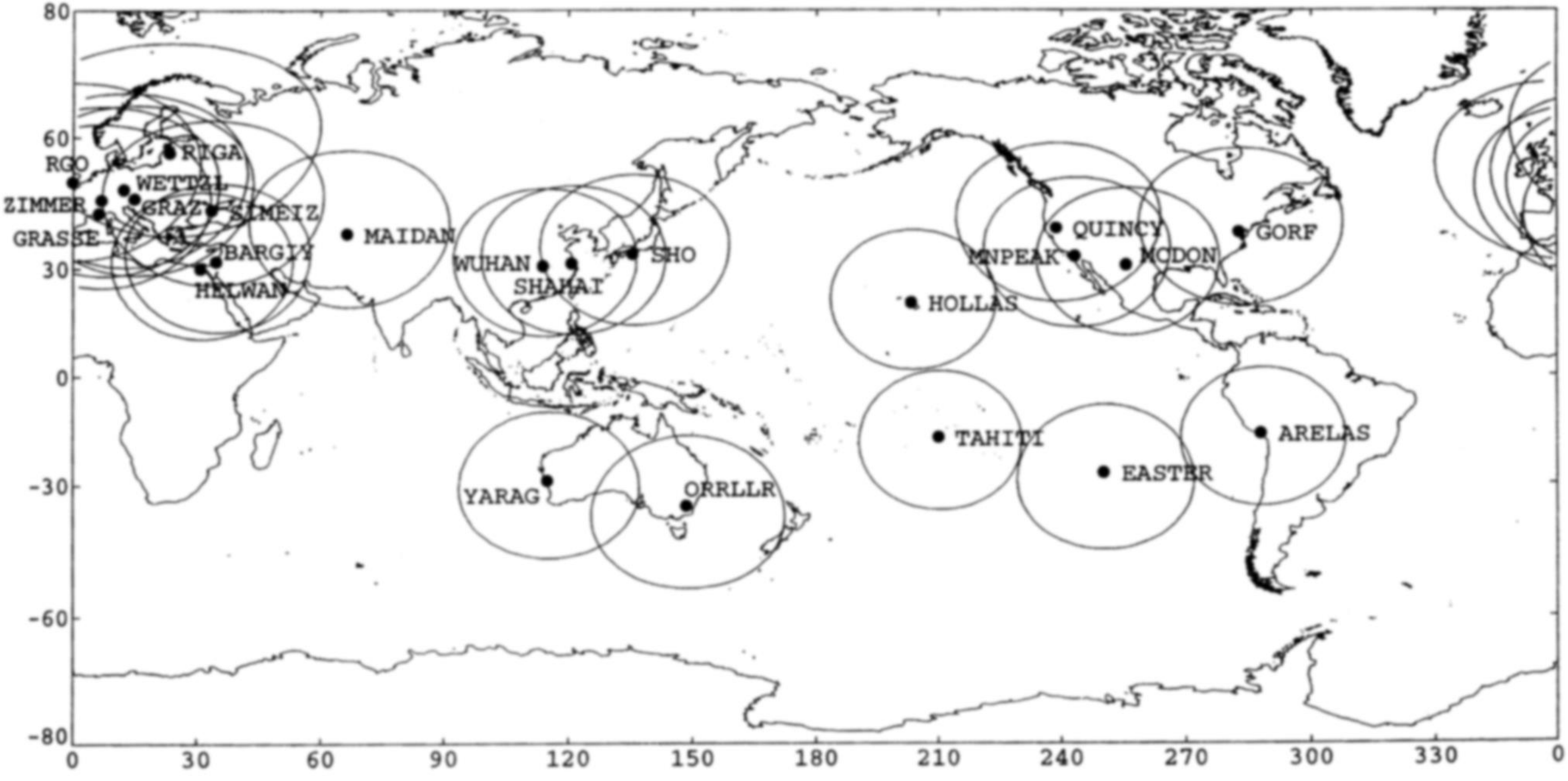
Orbits

- 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 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

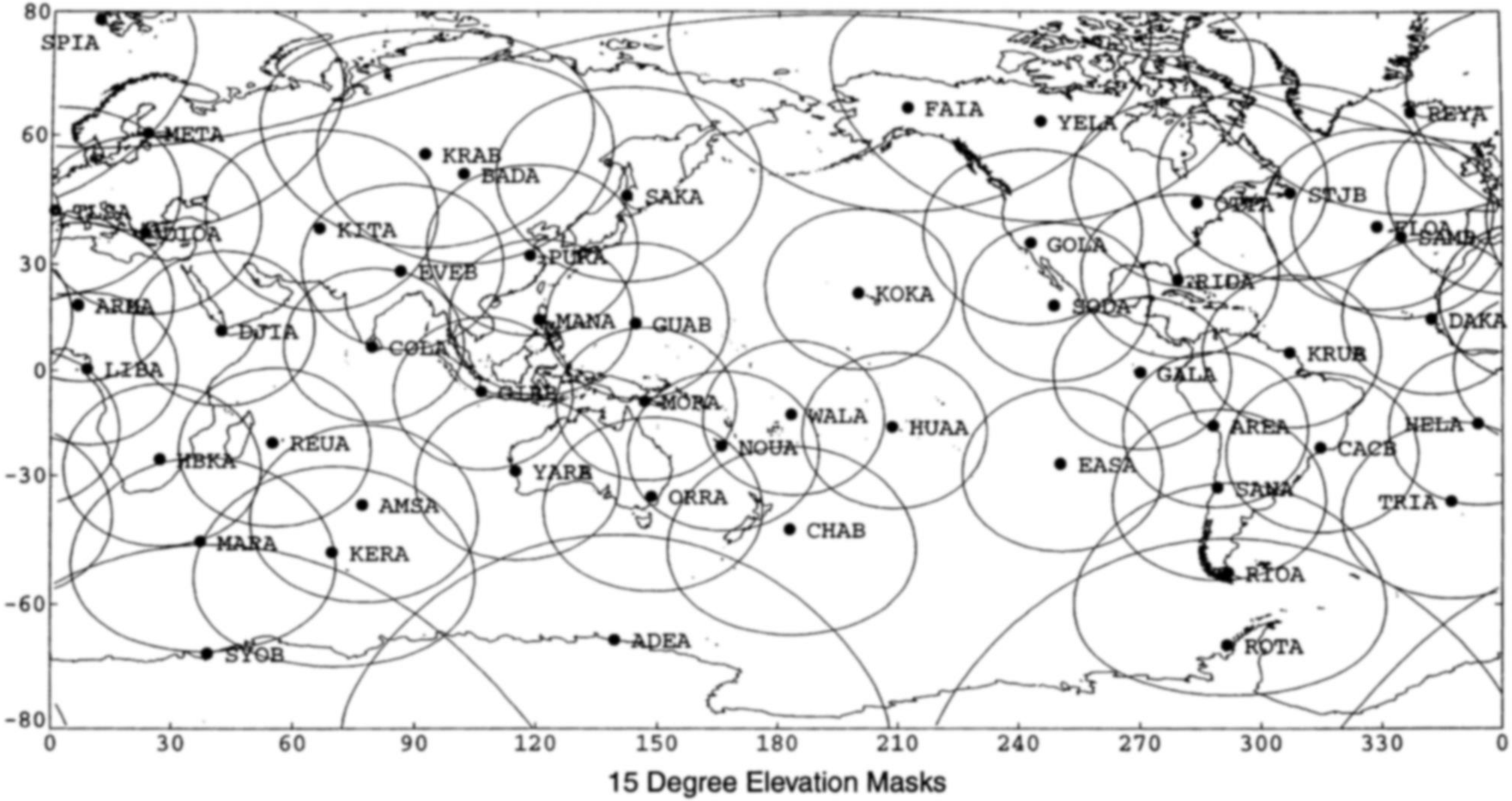
SLR

SLR Stations



20 Degree Elevation Masks

DORIS stations



Quality of orbits

- 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

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 ~2.0 cm**

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

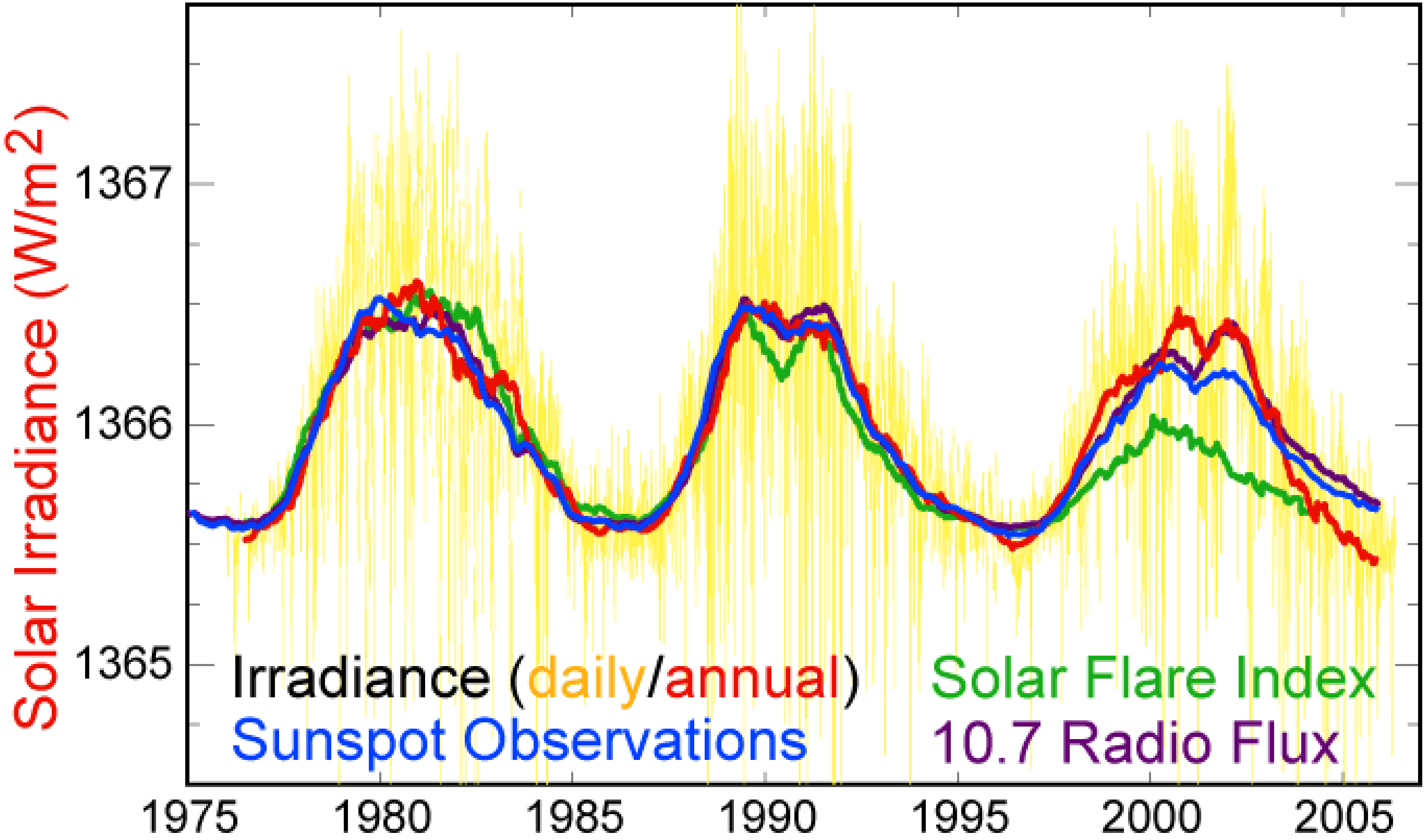
Ionospheric correction

- 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 ✔ Envisat ✔ (only up to 17/01/08) GFO × Cryosat × AltiKa ×

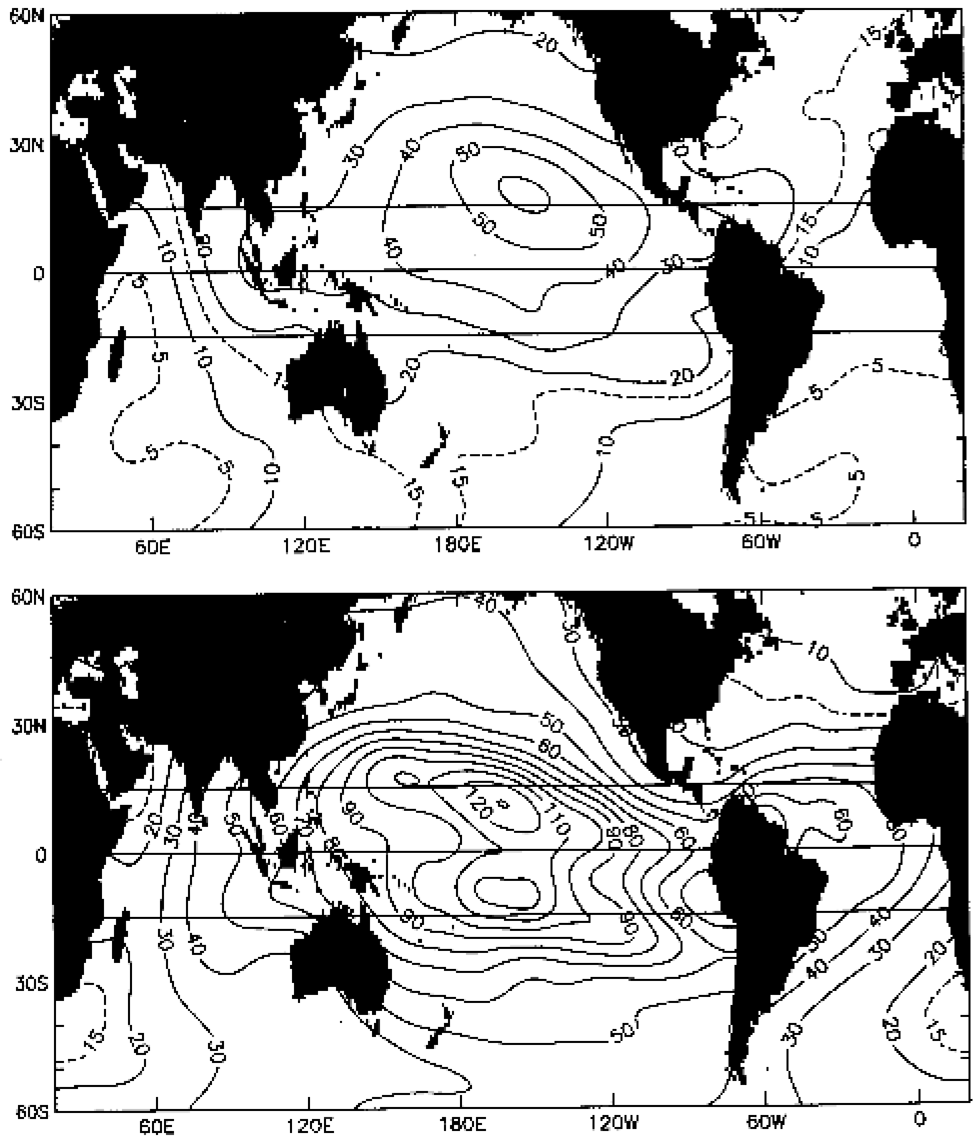
- Otherwise use a model or other observations from another dual frequency radar system (GPS, DORIS)
- Average value 45mm, s.d. 35mm
- Depends on solar cycle and time of day
- GIM (based on GPS, produced by JPL) is a good product to use for single-frequency altimeters

Solar Cycle Variations



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

Typical Iono correction values (mm)



Low solar activity

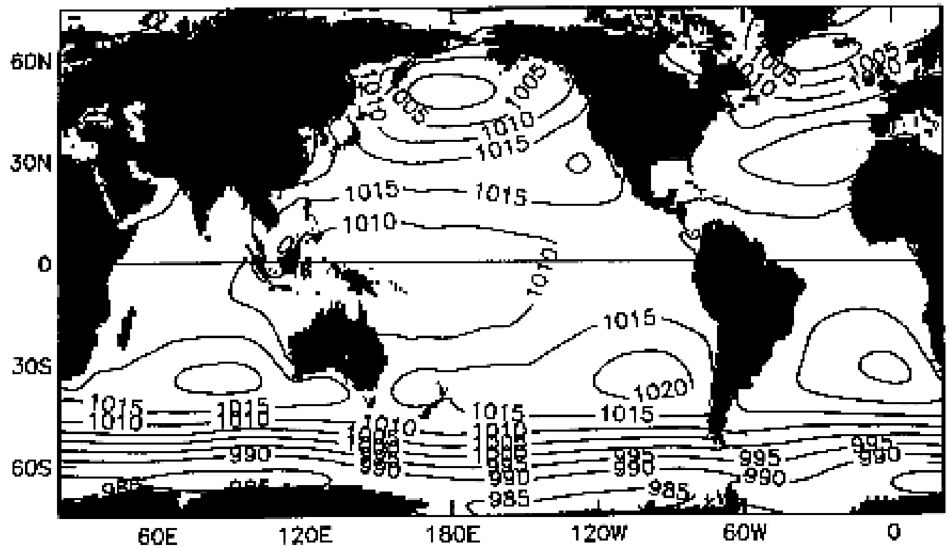
High solar activity

Dry Tropospheric Correction

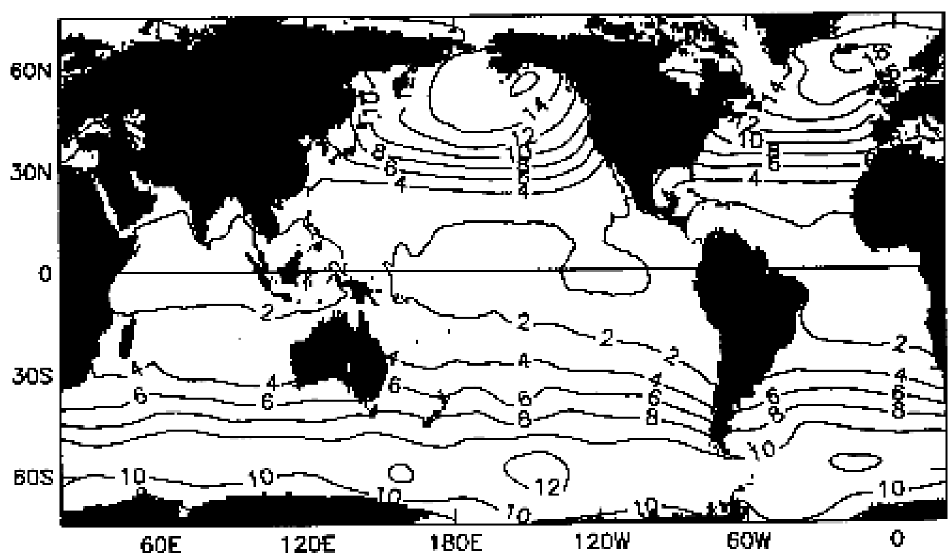
- Due to O_2 molecules in the atmosphere
- Derived from atmospheric pressure (from met models) by:

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

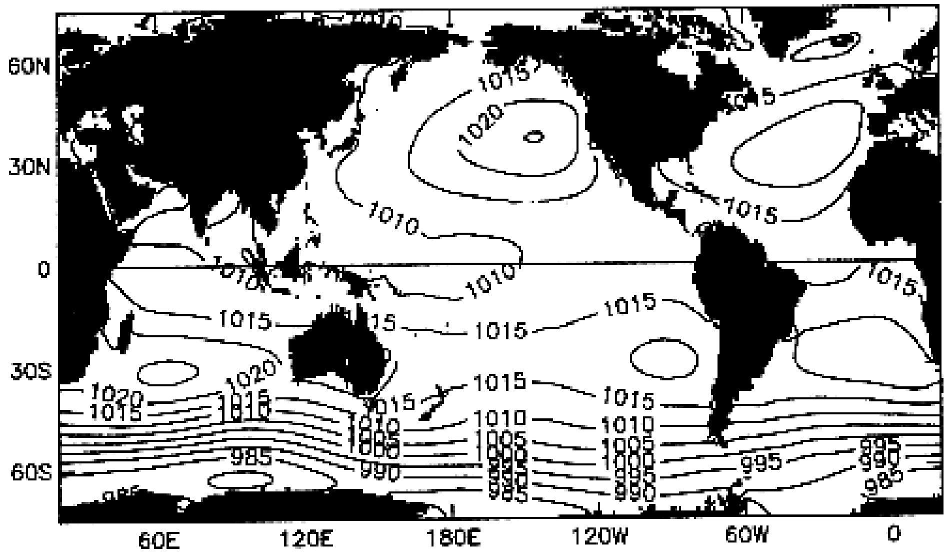
- Average value 2300 mm, s.d. 30 mm



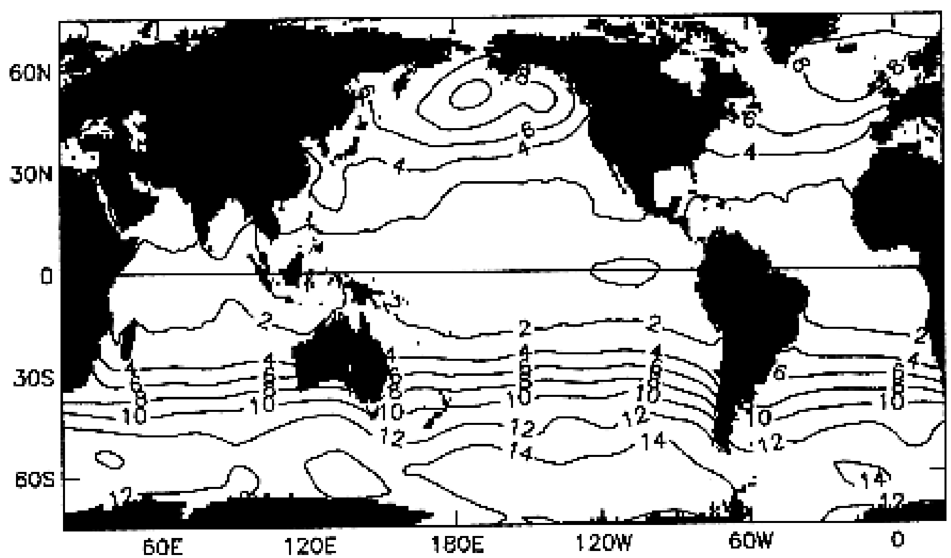
Winter DJF
Air Pressure
Mean (hPa)



Standard
deviation



Summer JJA Atmospheric Pressure Mean (hPa)

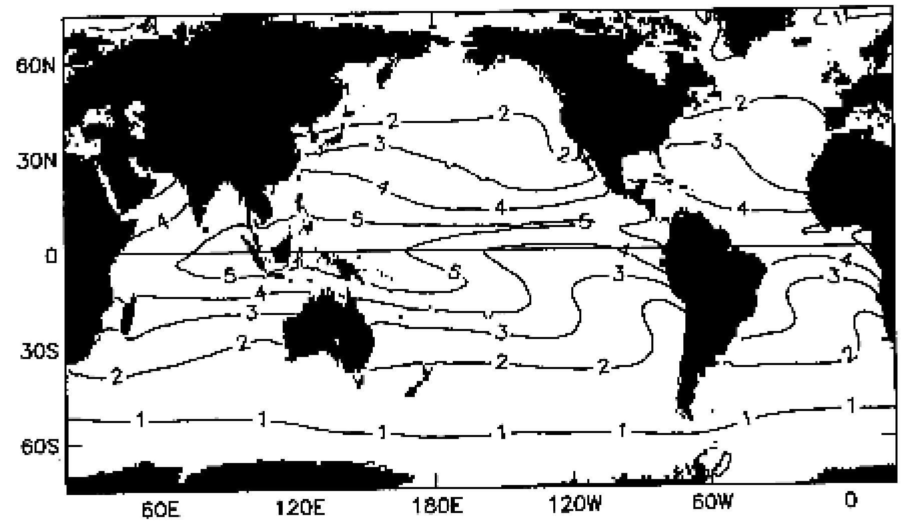


Standard Deviation

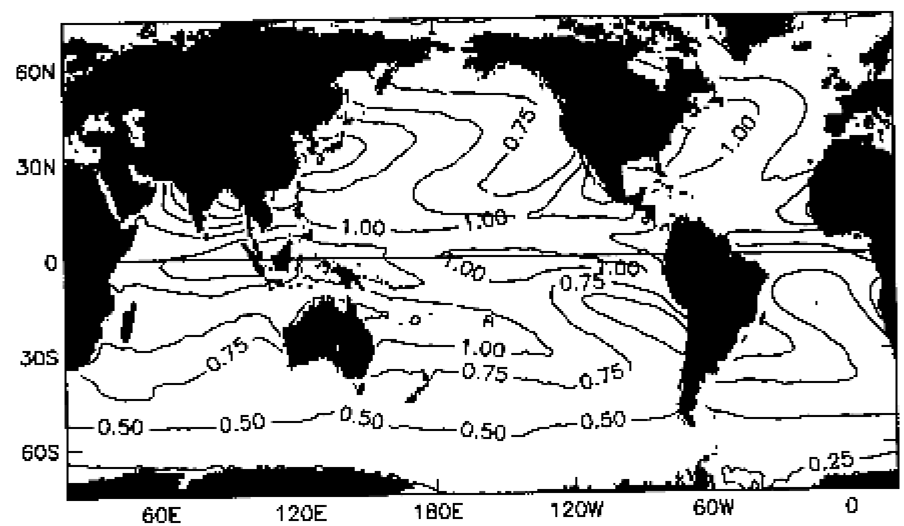
Wet Tropospheric Correction

- Caused by water vapour in the atmosphere
- 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)
- Or (new!) from GPS measurements
- This is a difficult correction due to the high temporal and spatial variability of water vapour
- Average value 150 mm, s.d. ~50 mm

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



Standard deviation

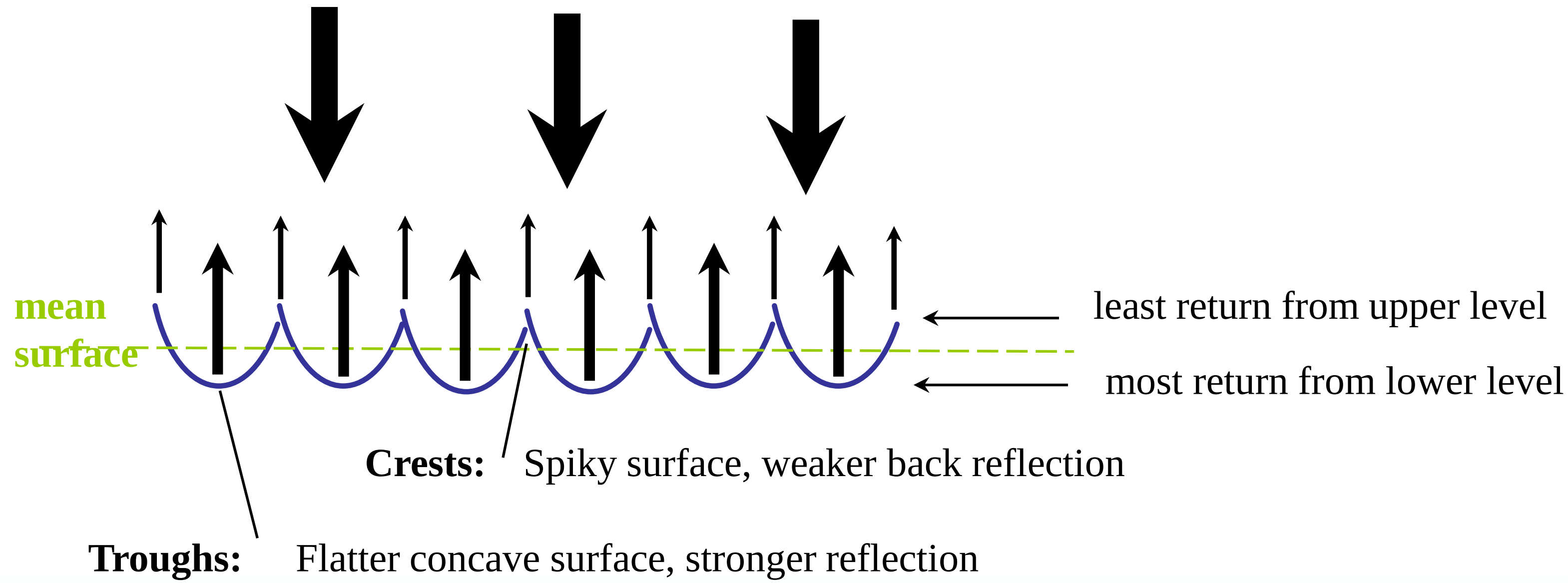


Atmospheric corrections - summary

- 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
  - Radar return from the troughs is stronger than from the crests
- First approx: empirical correction based on H_s (~5%)



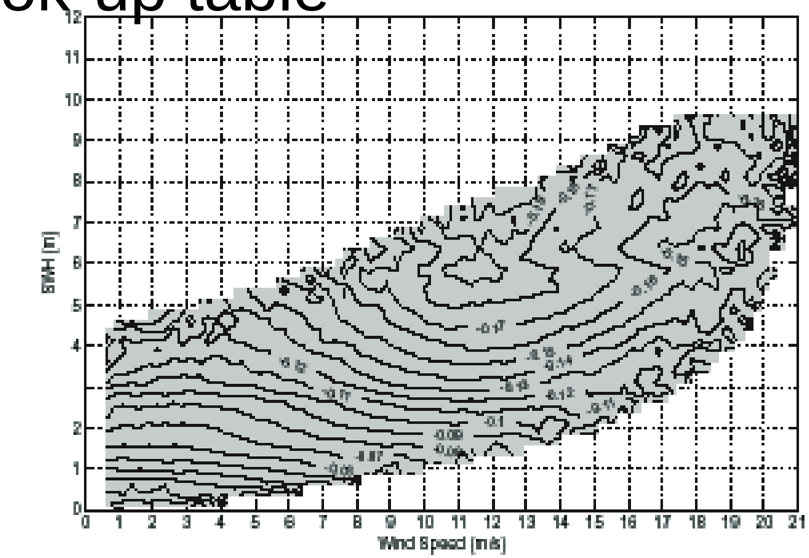
State of the art in sea state bias

- There is as yet no **theoretical method** for estimating the sea state bias.
- We are therefore forced to use **empirical methods**
- 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)

Parametric vs non-parametric

- 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

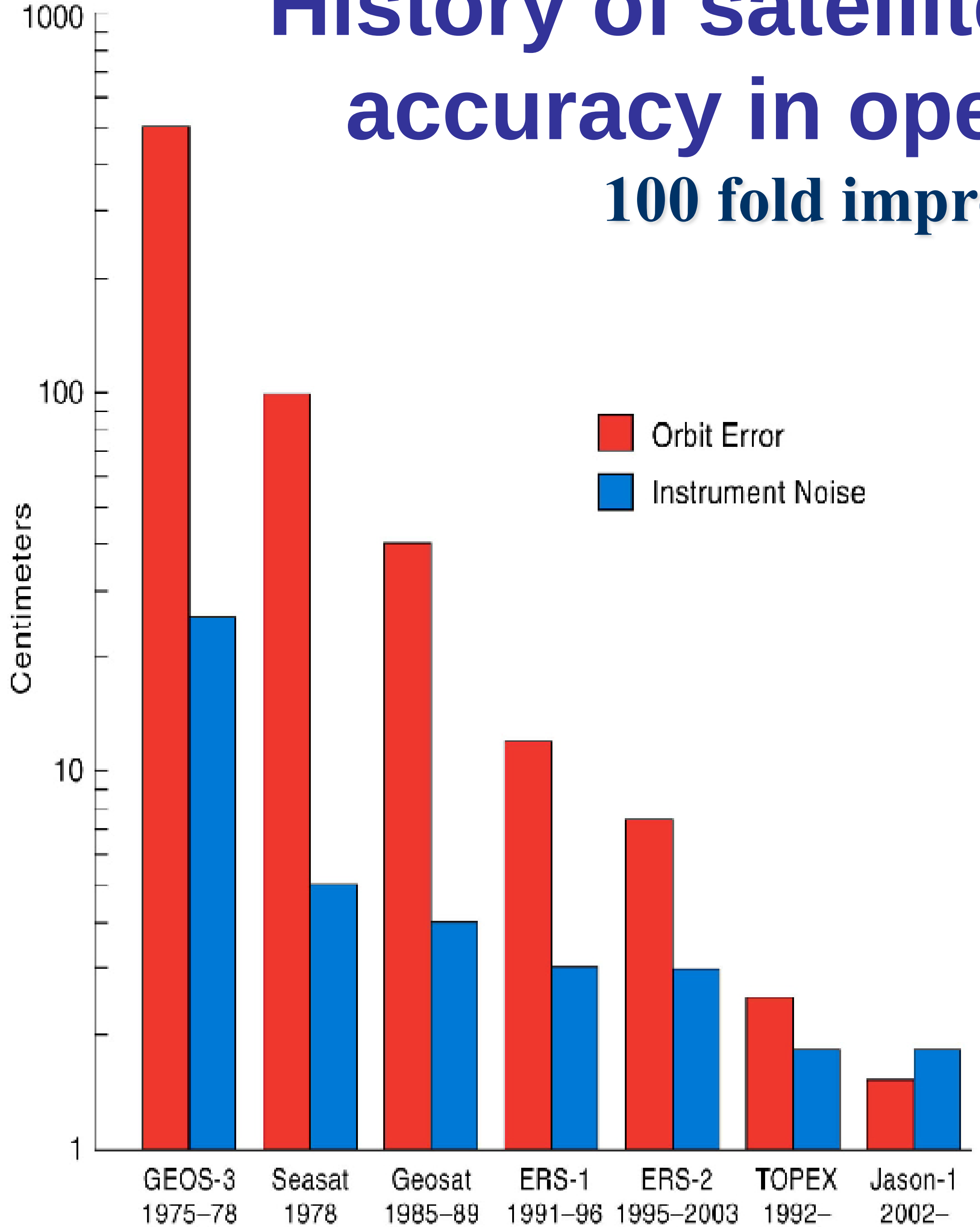


Example of TOPEX Error Budget for 1-Hz measurement (from Chelton et al 2001)

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**

History of satellite altimetry accuracy in open ocean

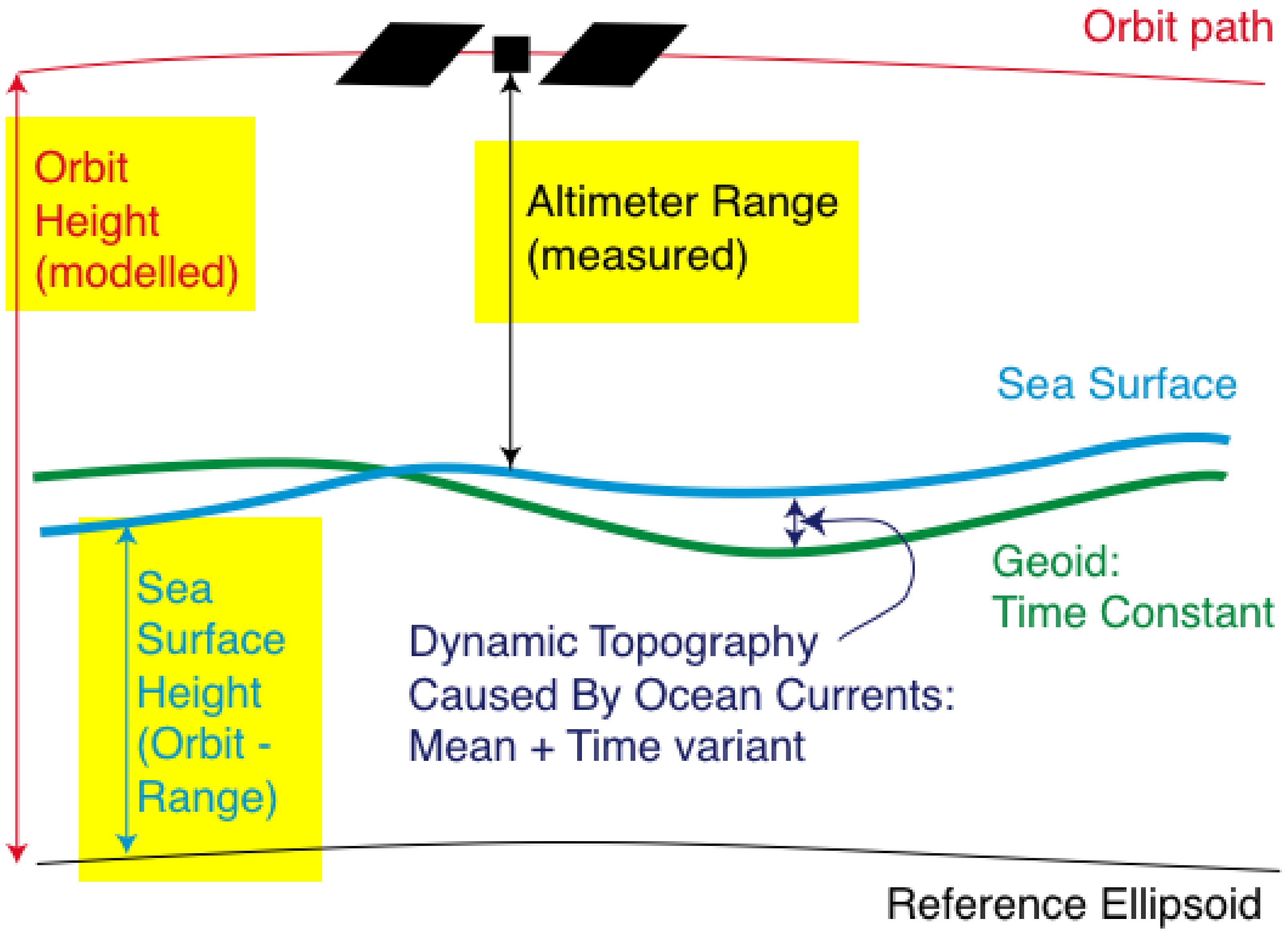
100 fold improvement in 25 years !



Now at ~2 cm level!!

Courtesy of Lee-Lueng Fu., NASA

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



Next: what is there in the SSH? ….