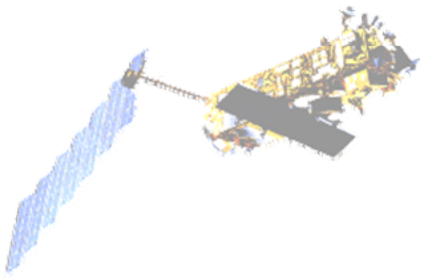
Satellite Altimetry



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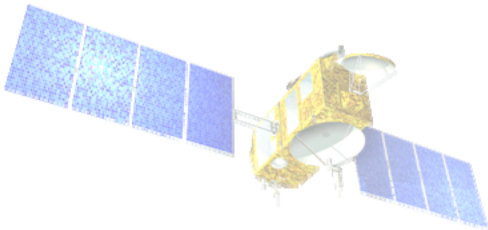
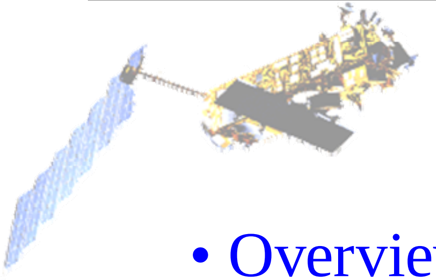
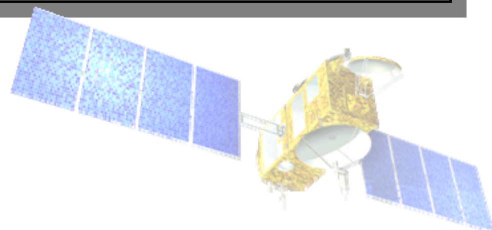


- **Lecture 1: Principles of satellite radar altimetry**
- **Lecture 2 : Altimetry data processing**
- **Lecture 3 : Altimetry and oceanography**
- **Lecture 4 : Applications of altimetry**

Lecture 1

Principles of satellite radar altimetry





- Overview/history of satellite altimetry
- Altimeter mission and orbits
- Radar altimeter : principles
- Instrumental and geophysical corrections
- Sea level, geoid and dynamic topography

Satellite altimetry - overview

One of the most important satellite technique for physical oceanography. Unique capabilities for ocean forecasting. It provides measurements of sea surface topography (sea level) which is an integral of the ocean interior => Strong constraint for the 4D ocean circulation estimation.

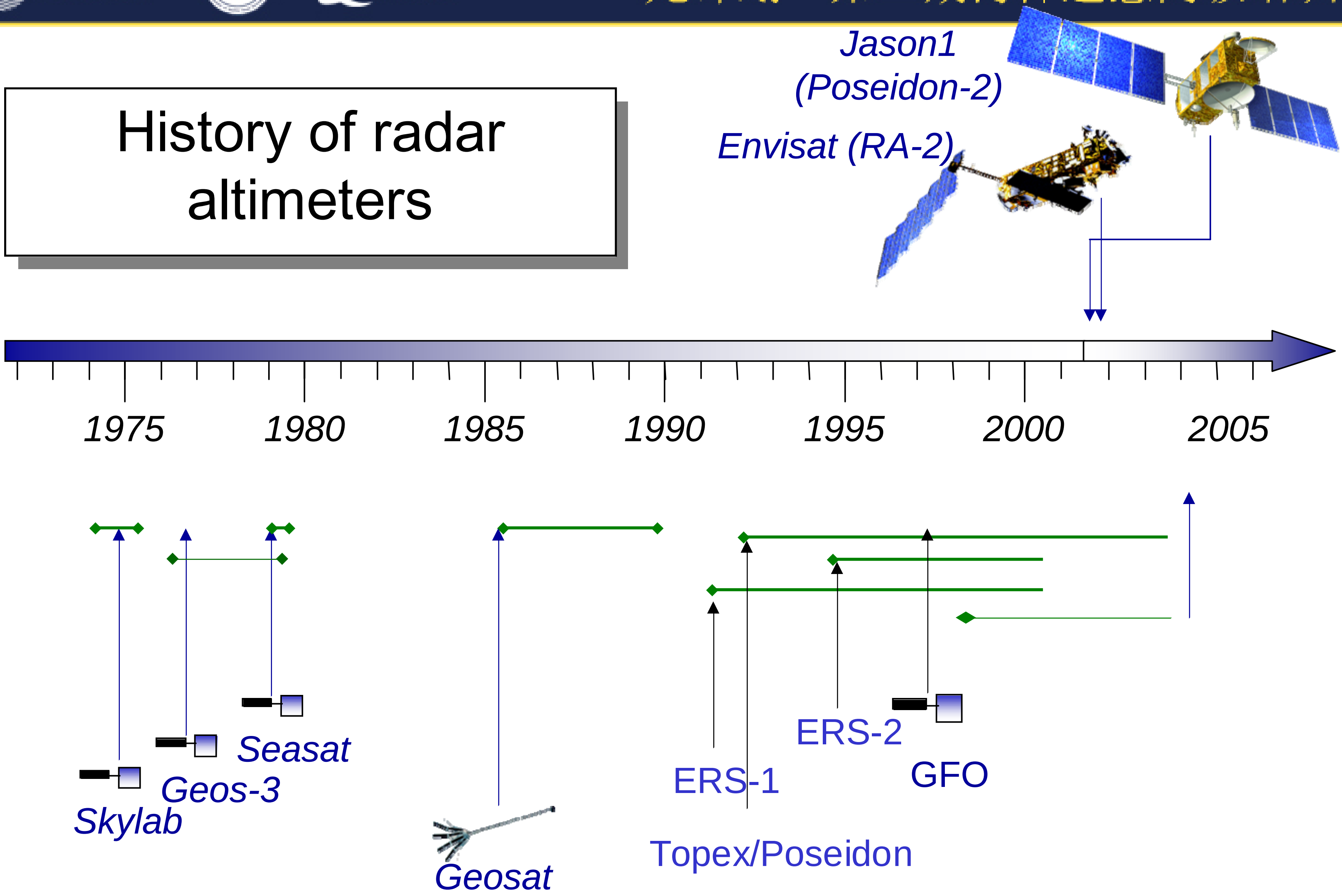
Very mature technique (> 20 years) : GEOS-3 (1975), SEASAT (1978), GEOSAT (1985-1989), ERS-1 (1991-1996), ERS-2 (1995- 2002), GFO (1998 - ?), TOPEX/POSEIDON (1992-), Jason-1 (2001 - ?), ENVISAT (2002 - ?).

but also one of the most challenging in terms of accuracy.

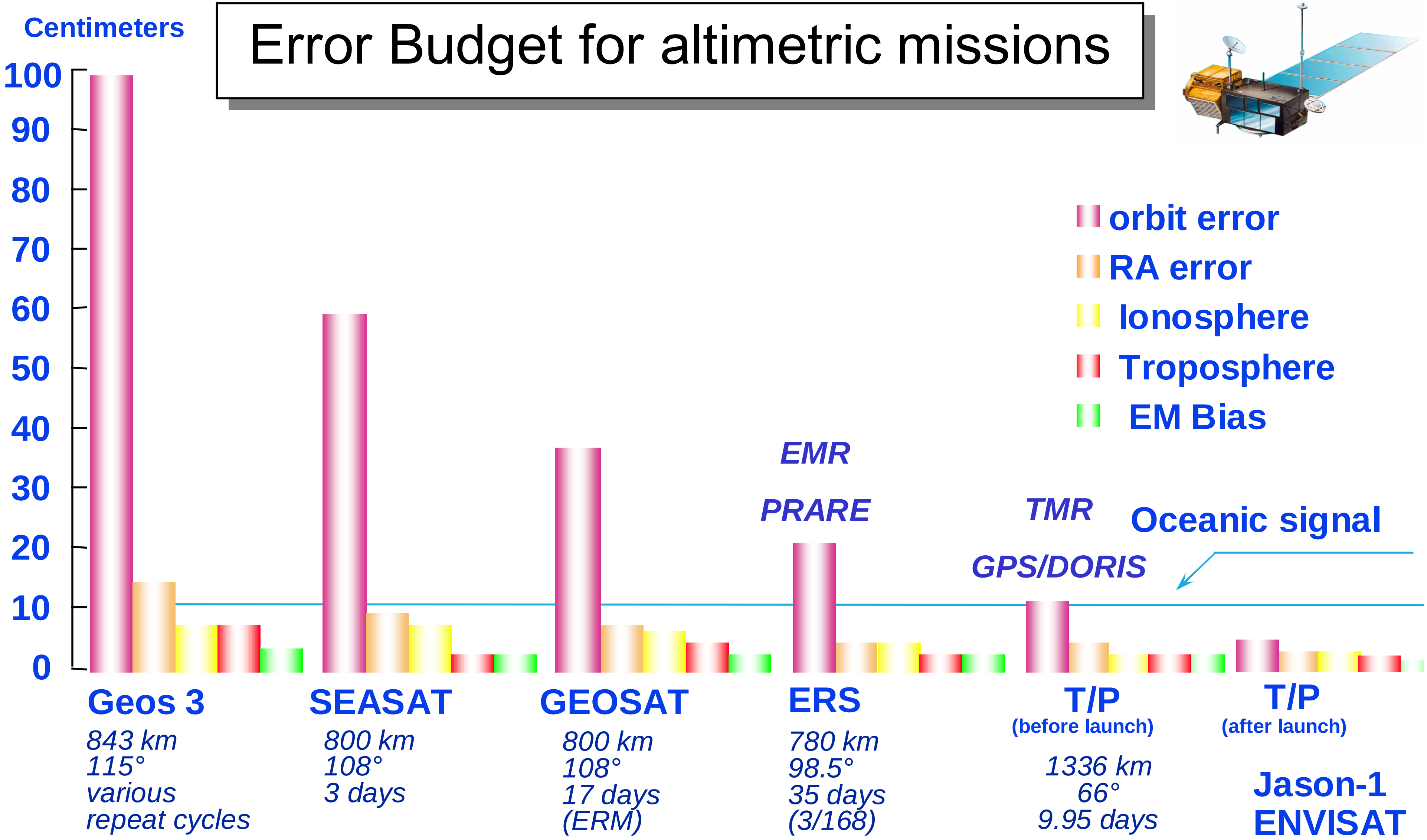
Major advances in sensor and processing algorithm performances over the last 20 years. Only possible through a continuous dialogue between engineers and scientists.

As a result, accuracy evolved from several meters to a few cm only

History of radar altimeters



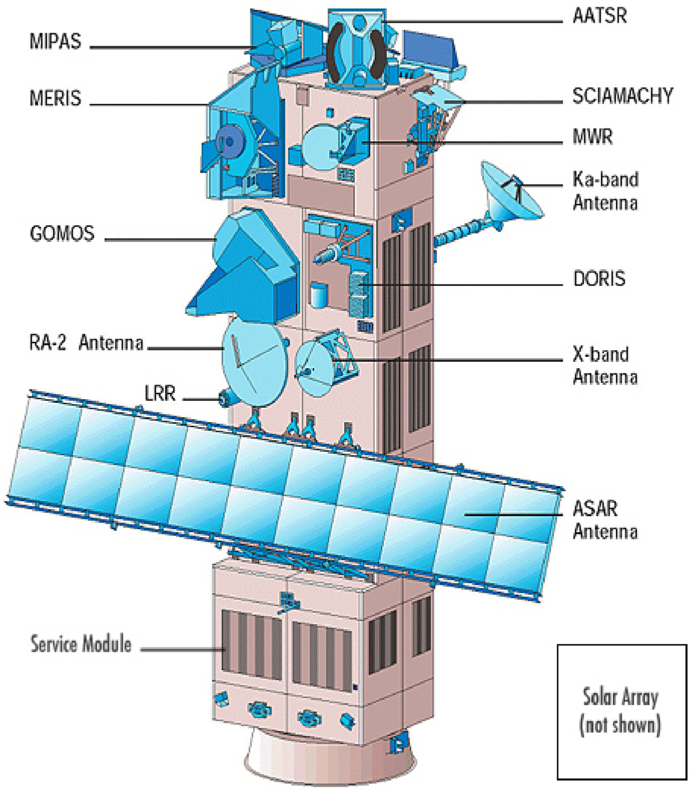
Error Budget for altimetric missions



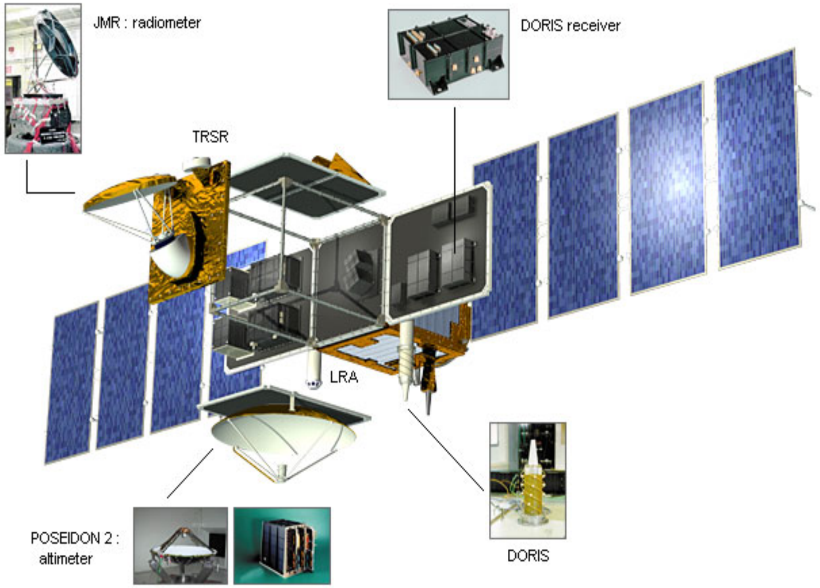
Altimeter mission

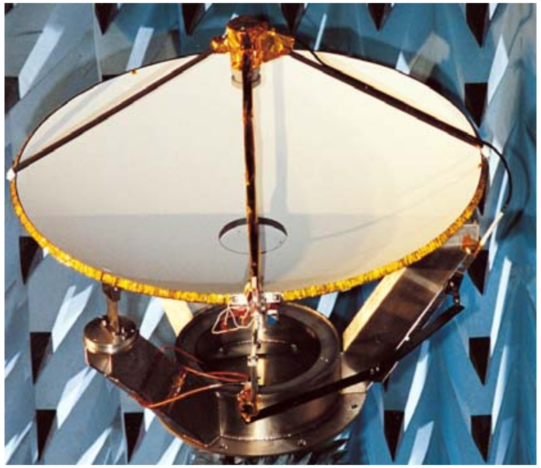
1. <u>Radar altimeter – Ku band (13.5 GHZ).</u>
2. C or S band for ionospheric correction.
3. Microwave radiometer for atmospheric corrections.
4. Tracking system for precise orbit determination (DORIS, LRA, GPS)

ENVISAT

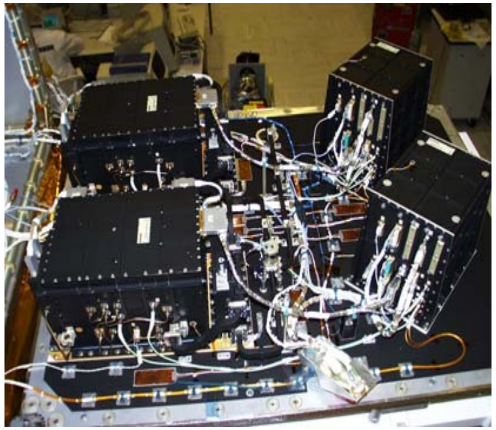


Jason-1





Altimeter antenna



Altimeter

Radiometer

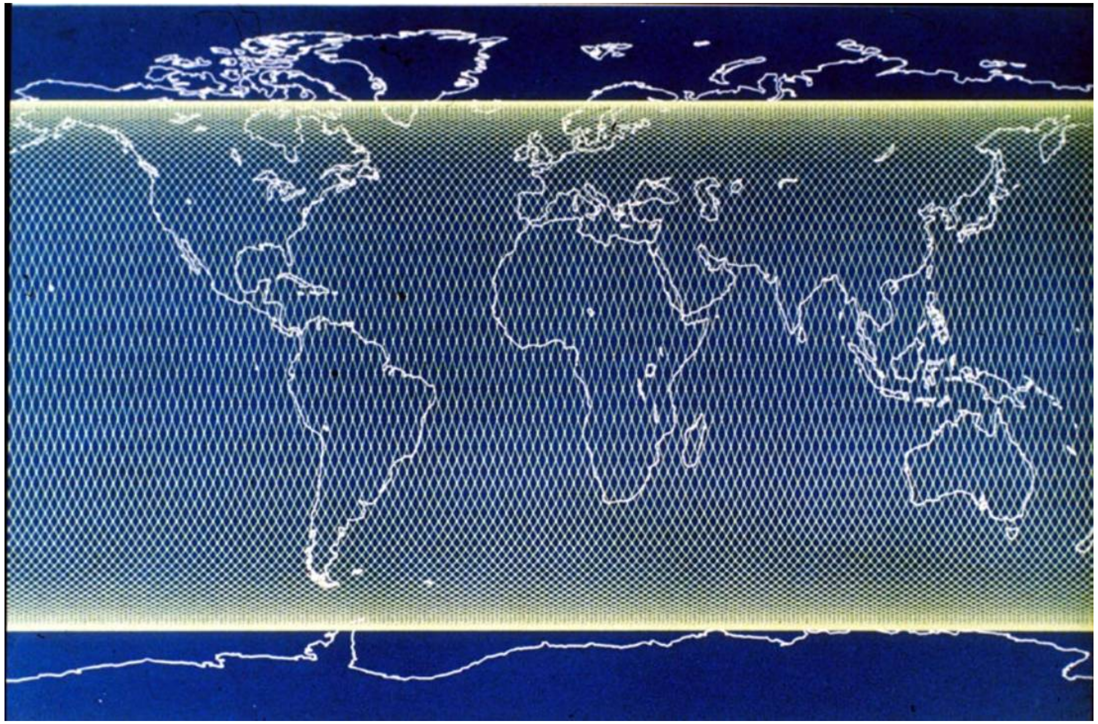
DORIS receiver

Jason-1 mission

Satellite altimetry coverage

Exact repeat orbits (to within 1 km)

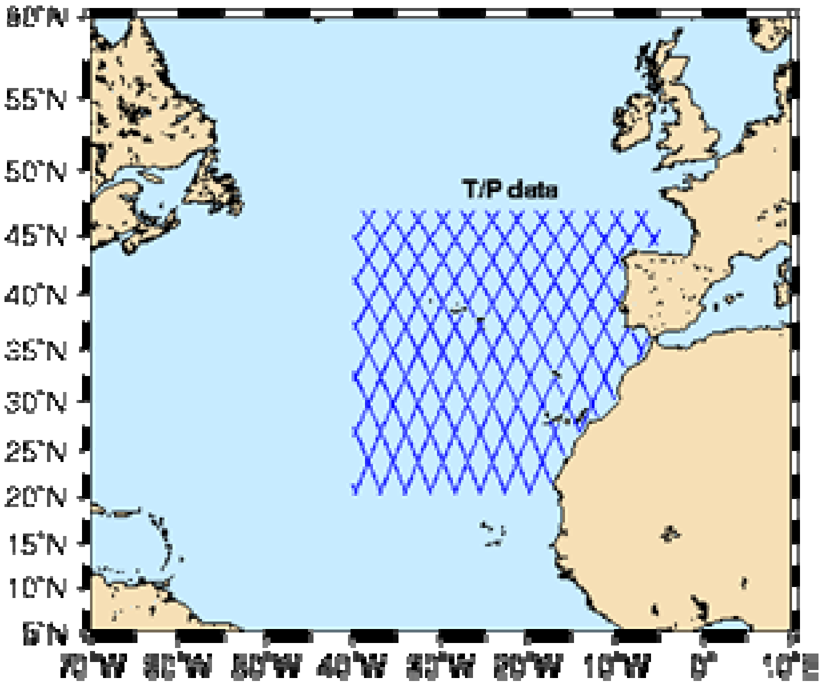
- Spatial coverage :
  - global
  - homogeneous
  - Nadir (not swath)
- Temporal coverage :
  - repeat period
    10 days, T/P-Jason-1
    35 days
    ERS/ENVISAT



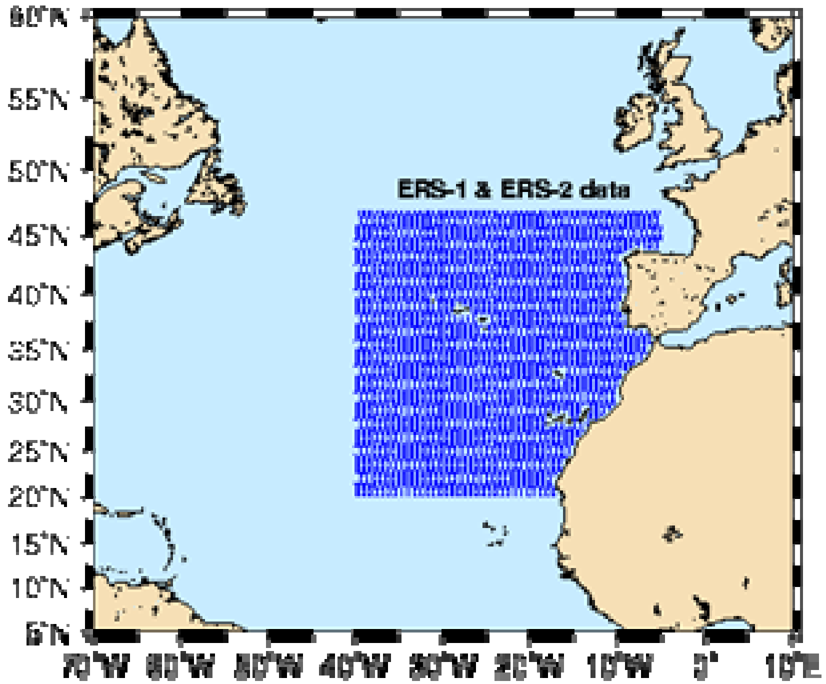
TOPEX/Poseidon Sampling

1 measure/1 s (every 7 km)
all weather (radar)

Repeat Period and Groundtracks



1336 km
66.03°
9.915 days
1h52
Jason-1

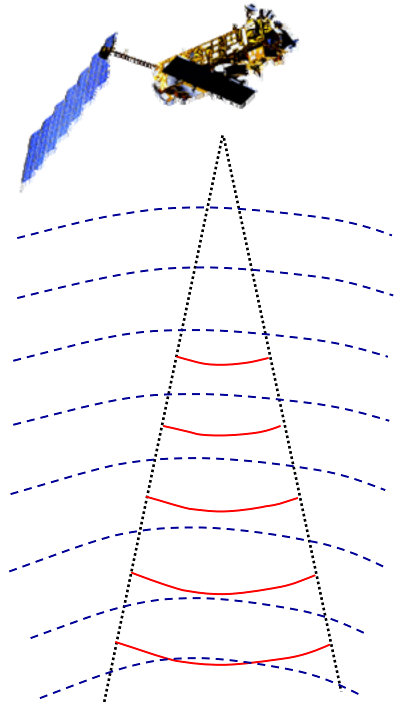


780 km
98°
35 days
ENVISAT

Mission Parameters

	Geosat	ERS	TOPEX	Poseidon-1	Poseidon-2	ENVISAT
Altitude	785 km	800 km	1336 km	1336 km	1347 km	800 km
Inclination	108 °	98.5 °	66 °	66 °	66 °	98.55°
Trajectory	Retrograde	Retrograde	Prograde	Prograde	Prograde	Retrograde
Repeat Period	17 days	35 days	10 days	10 days	10 days	35 days
Track Spacing Equator	163 km	77 km	315 km	315 km	315 km	77 km

Principles of radar altimetry 1



- Active radar sends a microwave pulse towards the ocean surface, f = 13.5 Ghz
- Precise clock onboard mesures the return time of the pulse, t

$$t = 2d/c$$

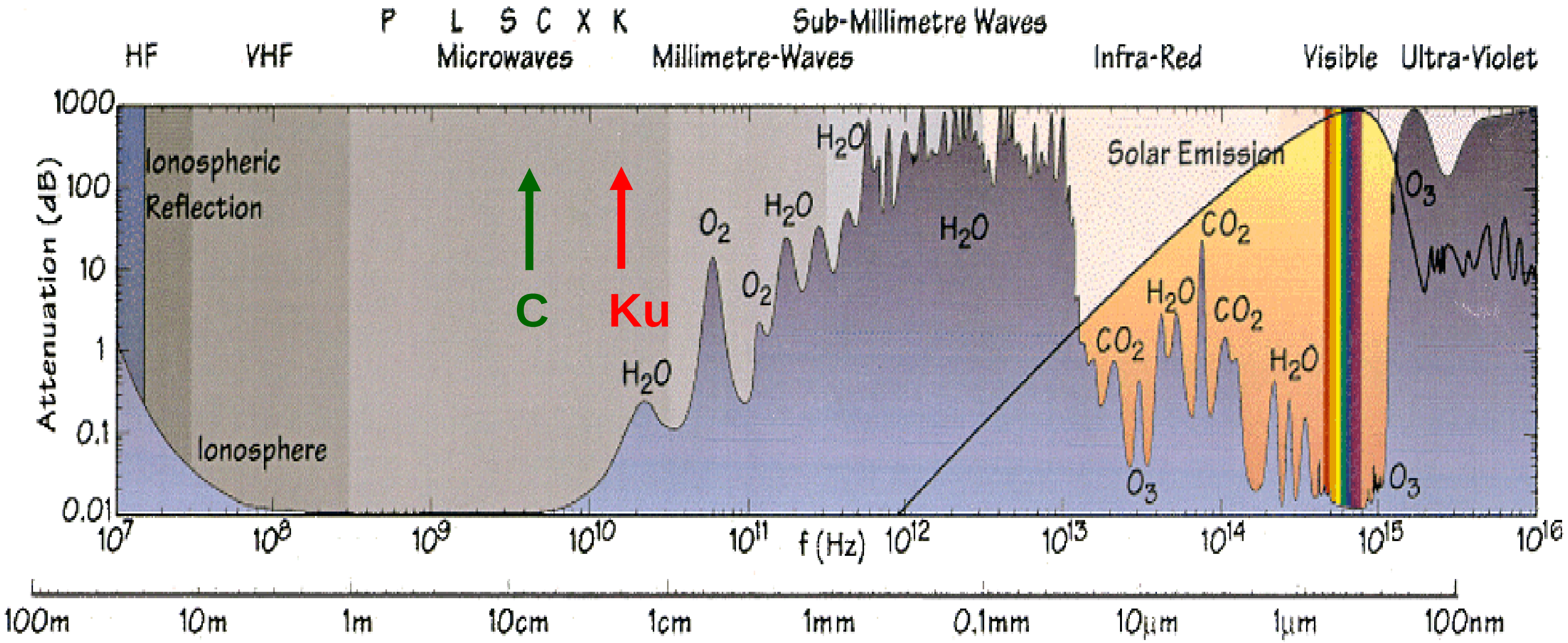
Centimetre Precision (10^{-8})
from an altitude of 800 – 1350 km

- *Mesures the backscatter power*
- *Mesures ocean wave height*

Choosing the frequency band

- Atmospheric attenuation
- International regulations
- Science Objectives (rain, ocean, vegetation)
- Technological constraints (e.g. antenna)

Precipitation rates
Surface roughness
Radar reflectivity (φ,Fresnel)
Surface diffusion



Characteristics of a radar altimeter (1)

The Radar altimeter determines the 2-way delay of the radar echo from the Earth's surface (sea, land, ice). It also measures the power/shape of the reflected radar pulses.

Nadir-pointing, pulse-limited (not beam-limited).

Interpretation of the measured radar echoes can be performed with more or less accuracy according to the surface characteristics. The best results are obtained over the ocean, which is spatially homogeneous, and with a surface which follows known statistics.

Characteristics of a radar altimeter (2)

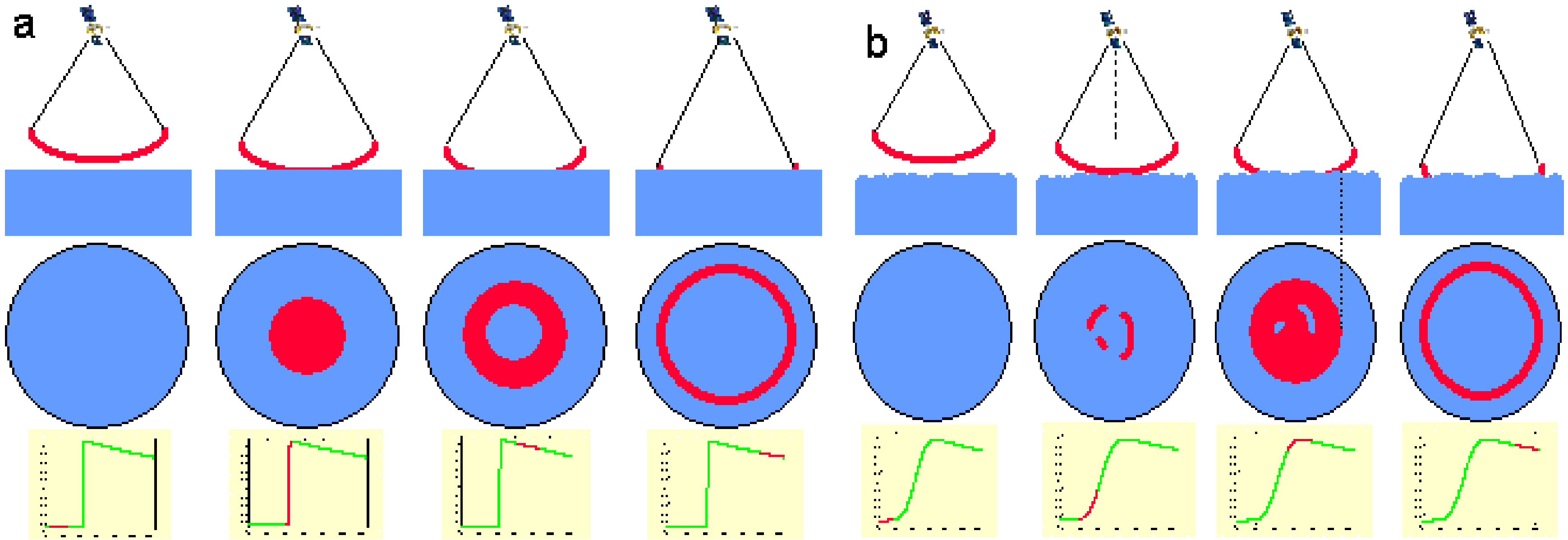
The range resolution of an altimeter is about half a metre (3.125 ns) but the range measurement performance over ocean is about one order of magnitude better. This is achieved by fitting the shape of the echo waveform to a model function which represents the form of the echo (Brown, Hayne) + averaging over a large number of echoes (PRF > 1000 Hz)

Transmits frequency modulated pulses (chirp). This frequency modulation is a coding of the signal which spreads the energy of a short pulse over a longer time interval, thus allowing reduced peak power in the pulse. Compressed time resolution is inversely proportional to the chirp bandwidth

Equivalence time, frequency and distance. ENVISAT: three bandwidths (320, 80, 20MHz).

Highest resolution (320 MHZ -3ns- 45 cm) used over the ocean.

The radar altimeter wave form

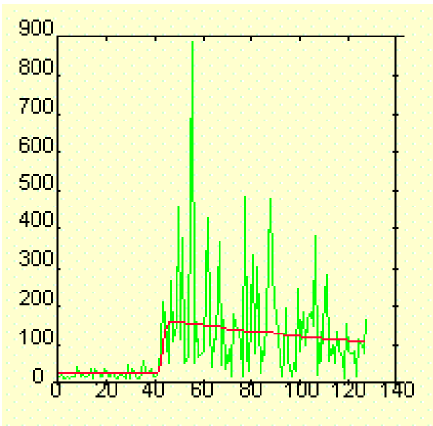


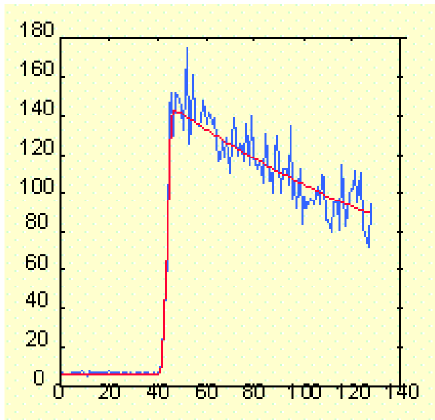
Ideally calm sea | **Rough sea**

The footprint size is determined by the pulse duration (3 ns ⇔ 2 km for calm seas)

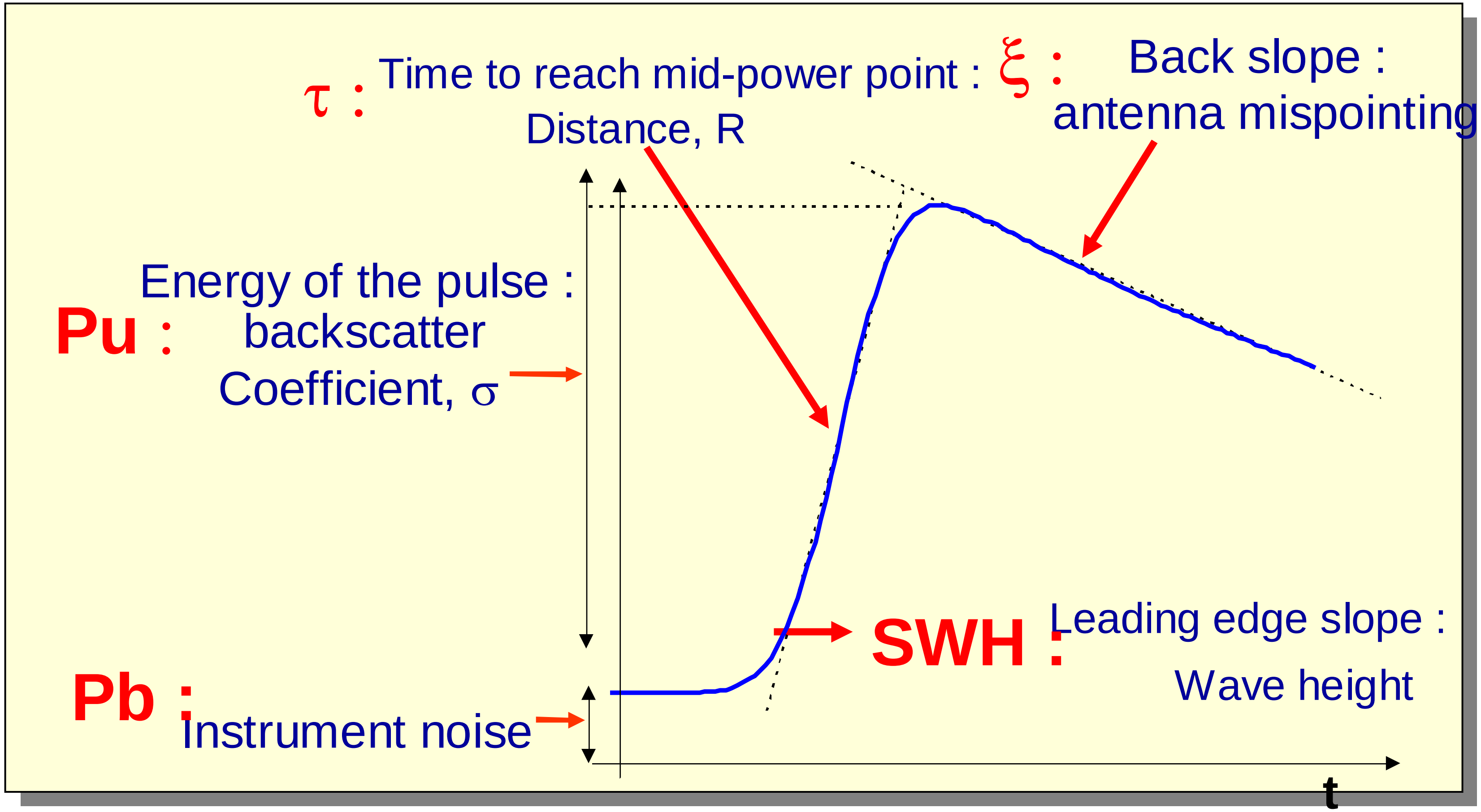
**Green :
Individual
return pulse:**

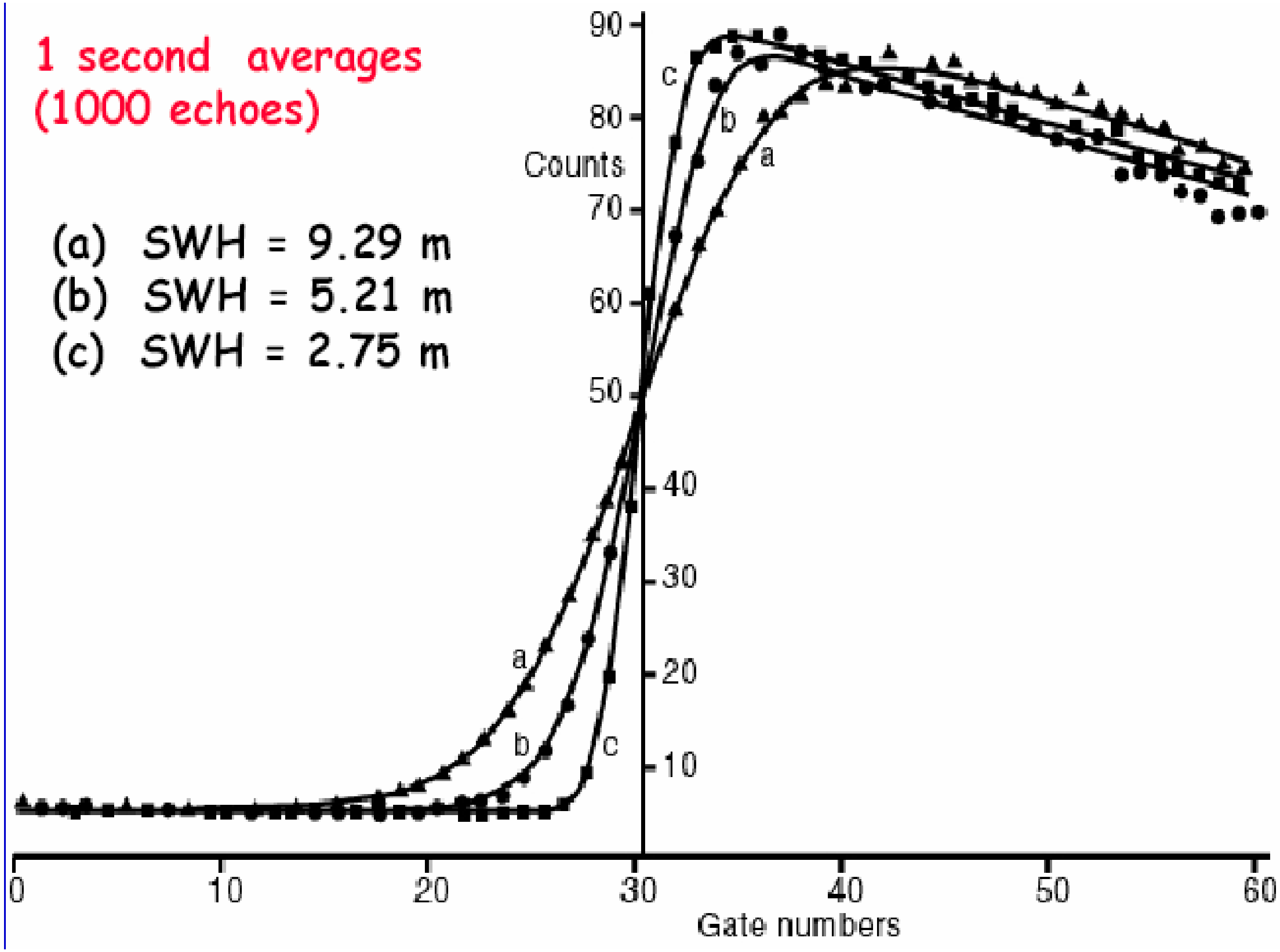
**Red :
Average of
90 return
pulses**





Physical parameters from the waveform



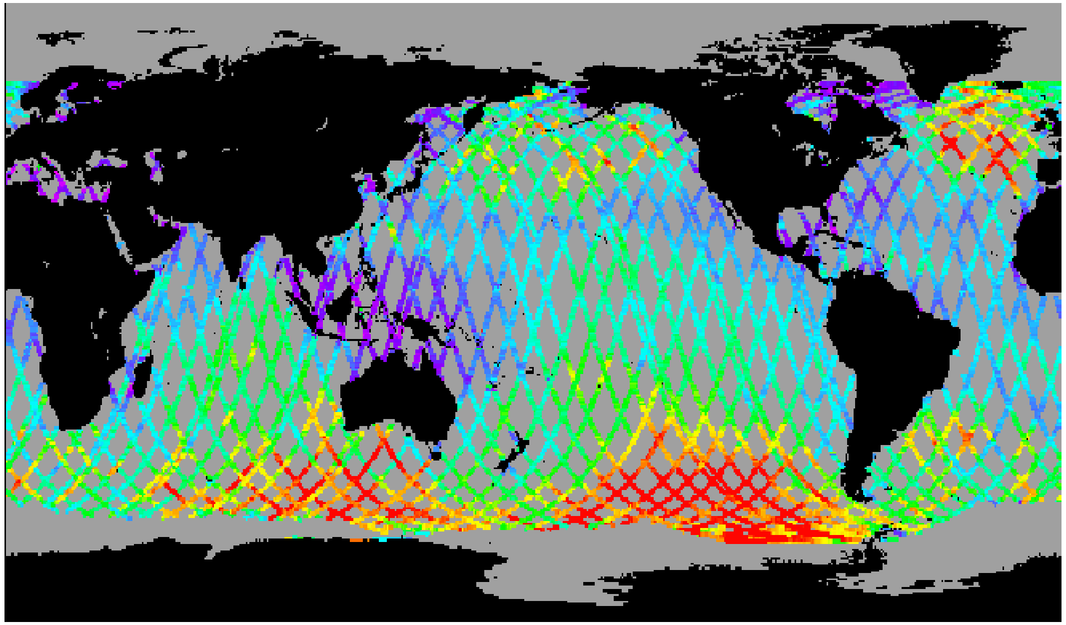

1 second averages
(1000 echoes)
(a) SWH = 9.29 m
(b) SWH = 5.21 m
(c) SWH = 2.75 m
Counts
Gate numbers
0
10
20
30
40
50
60
70
80
90
a
b
c

Main parameters measured by an altimeter

1. **Sea Surface Height (ocean)**
2. Significant wave height
3. Wind speed
4. Ice/land/lakes characteristics,…

Wind and wave height estimations

Significant wave height is estimated from the change in slope of the wave form’s leading edge.



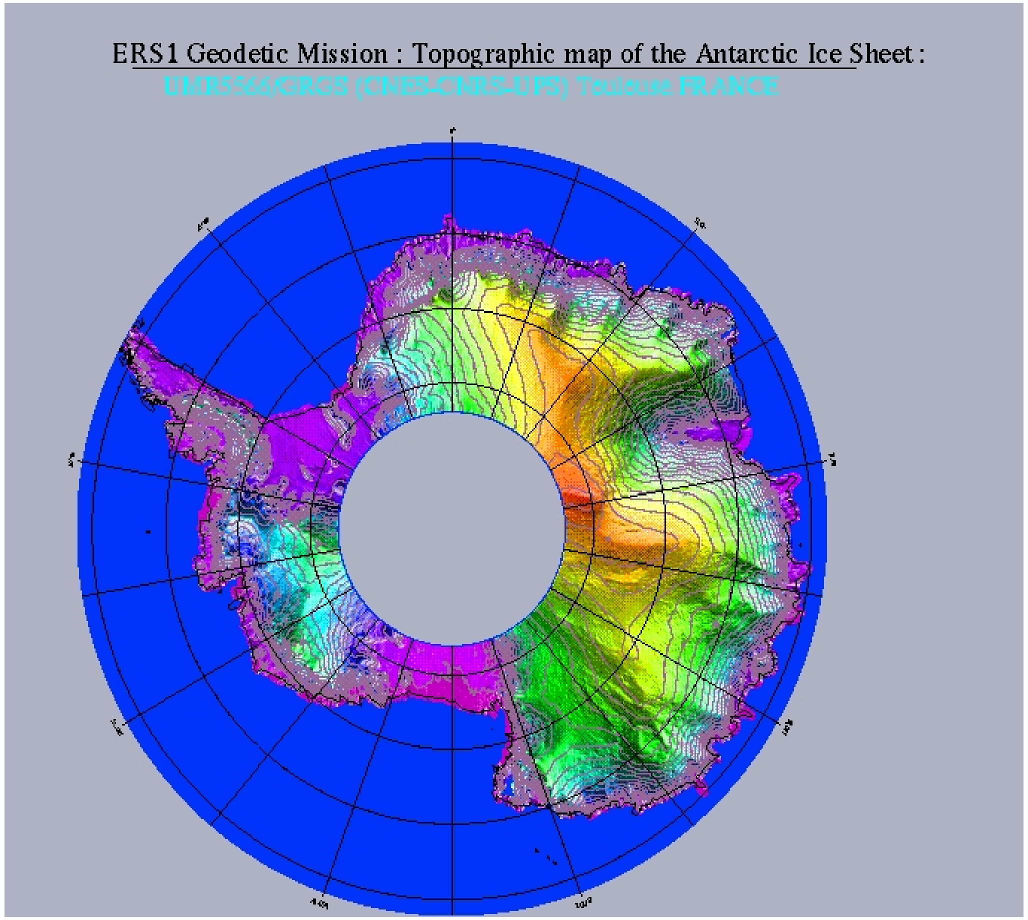
The power of the return signal is related to the wind-induced roughness of the sea-surface. **Wind speed** is then estimated from empirical formulae. Wind direction cannot be resolved.

Other geophysical applications

Analysing the altimeter waveform shape, backscatter coefficient and return power can also be useful tools for determining:

• topographic changes over ice sheets, lakes and rivers, and over desert areas

• for estimating ice and snow thickness (see Cryosat).



Principles of radar altimetry. SSH measurements. 2

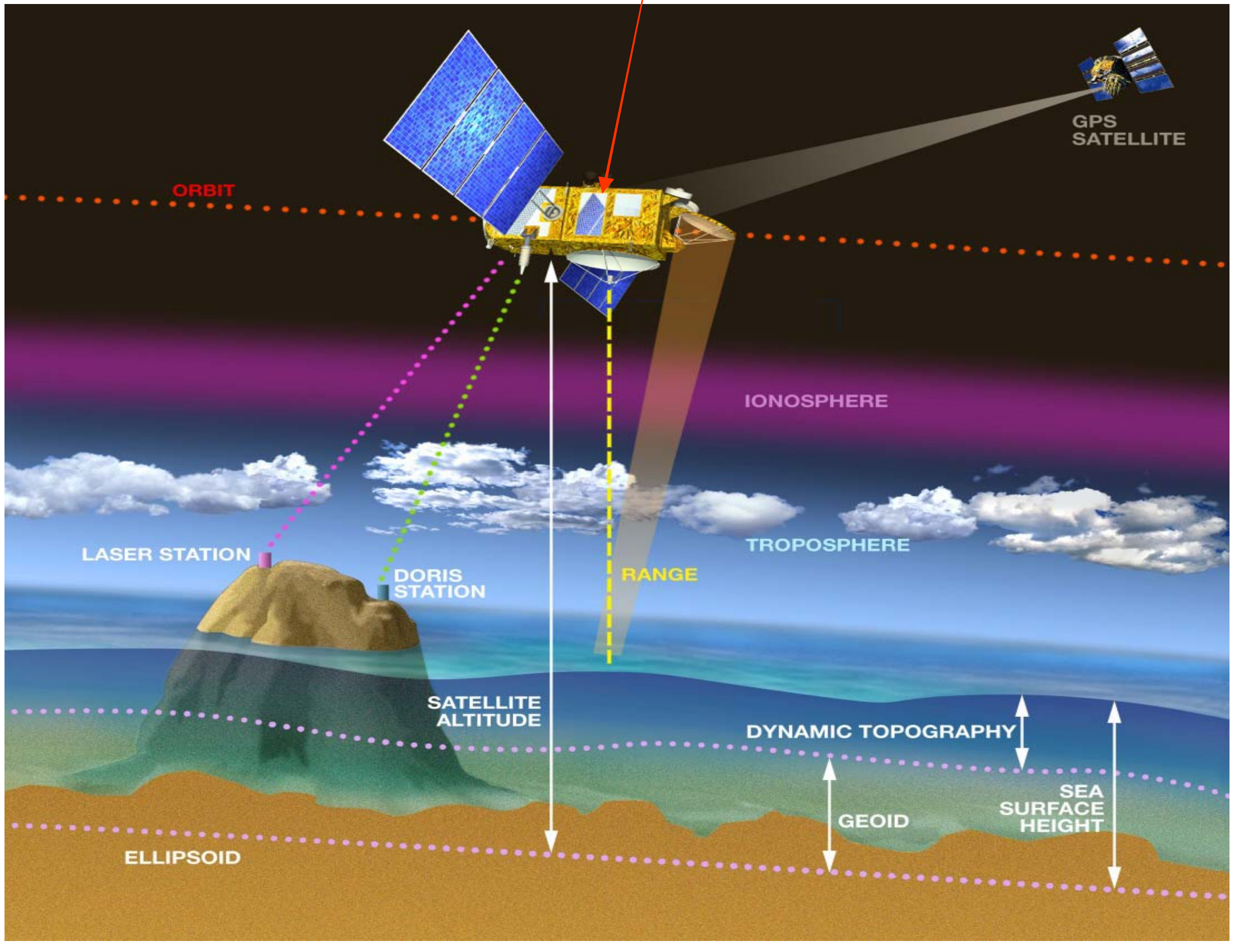
Sea Surface Height (SSH) (relative to an earth ellipsoid)= Orbit height – Range

SSH = Orbit – Range – Σ Corr

Precision of the SSH :

- **Orbit error**
- **Errors on the range**
  - **Instrumental noise**
  - **Various instrument errors**
  - **Various geophysical errors (e.g., atmospheric attenuation, tides, inverse barometer effects, …)**

Orbit errors in position of satellite



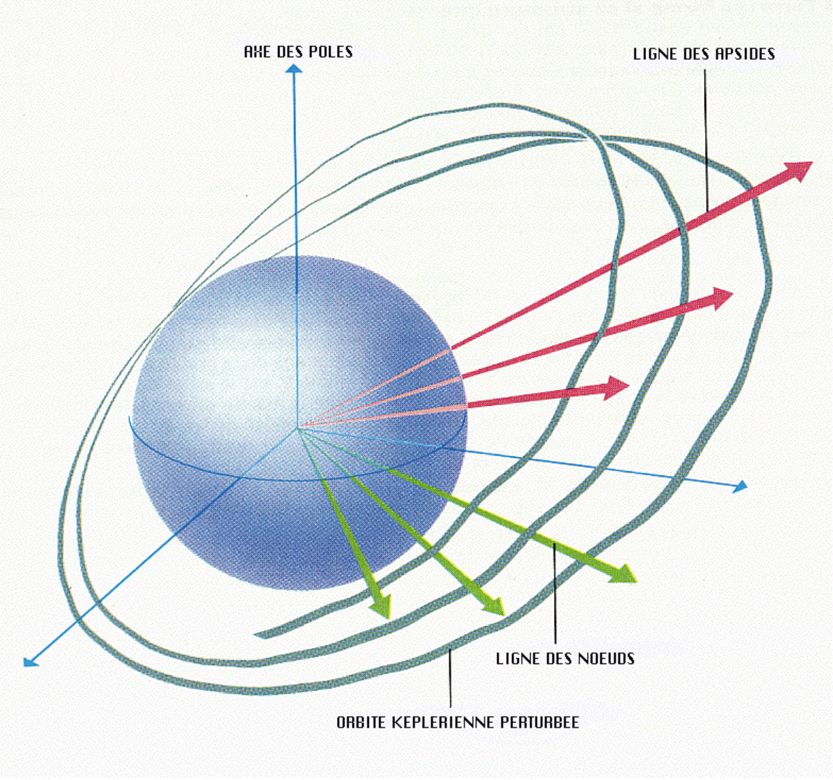
Altimeter measurements of sea surface topography are affected by a large number of errors :

- **propagation effects in the troposphere and the ionosphere, electromagnetic bias,**
- **errors due to inaccurate ocean and terrestrial tide models, residual geoid errors,**
- **inverse barometer effect.**

Some of these errors can be corrected with dedicated instrumentation : dual-frequency altimeter for ionospheric correction and radiometer for wet tropospheric correction.

Satellite Altimetry Orbits

Satellite orbits are the reference frame for the altimetric measurements. T/P flies at 1336 km altitude and the satellite's exact position needs to be accurately determined O(2 cm).



• An error in the radial orbit component (z) produces the same magnitude error in SSH.

• An error in the satellite's alongtrack position, multiplied by the orbit slope, gives an error in SSH.

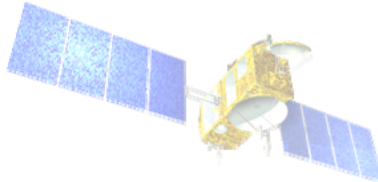
• An error in the onboard clock is similar to an error in alongtrack position

Precise orbit determination is made by specialist teams at the space agencies, using:

• force perturbation models on the satellite

• tracking data.

Perturbation Forces on a satellite orbit



Different forces can perturb a satellite’s orbit and these need to be modelled precisely to accurately determine the satellite’s position.

Gravitational Forces:

• the earth’s gravity field is not equally distributed – the earth is non-spherical, and gravity varies with the internal density distribution

• gravity perturbations caused by the moon, sun and other planets.

• ocean and solid-earth tides

Forces on the Satellite’s surface:

Atmospheric drag : depends on the complex shape of the satellite, its surface roughness, and variations in atmospheric density (eg, diurnal and annual solar cycles)

Radiative pressure : direct solar radiation, radiation reflected from the earth’s surface (albedo effect, vaies with cloud cover), earth’s IR radiation

Satellite Tracking Systems … Laser Tracking and GPS

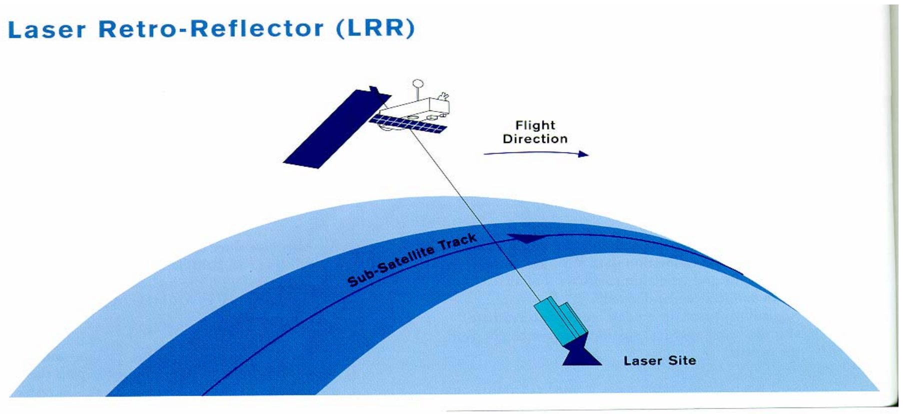
Satellite tracking is also made using complementary systems : Laser tracking, DORIS and GPS

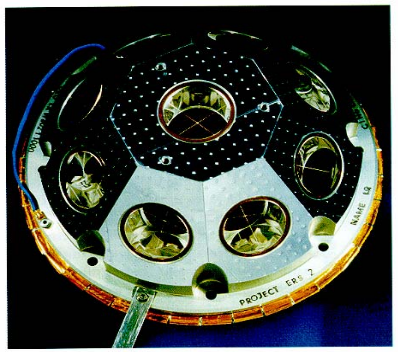
Satellite Laser Ranging (SLR).

A network of laser ground stations make direct, precise measurements of the distance between the satellite and the laser ground station.

GPS

An onboard GPS receiver provides precise, continuous tracking of the satellite by monitoring range and timing signals from up to 6 GPS satellites at the same time.

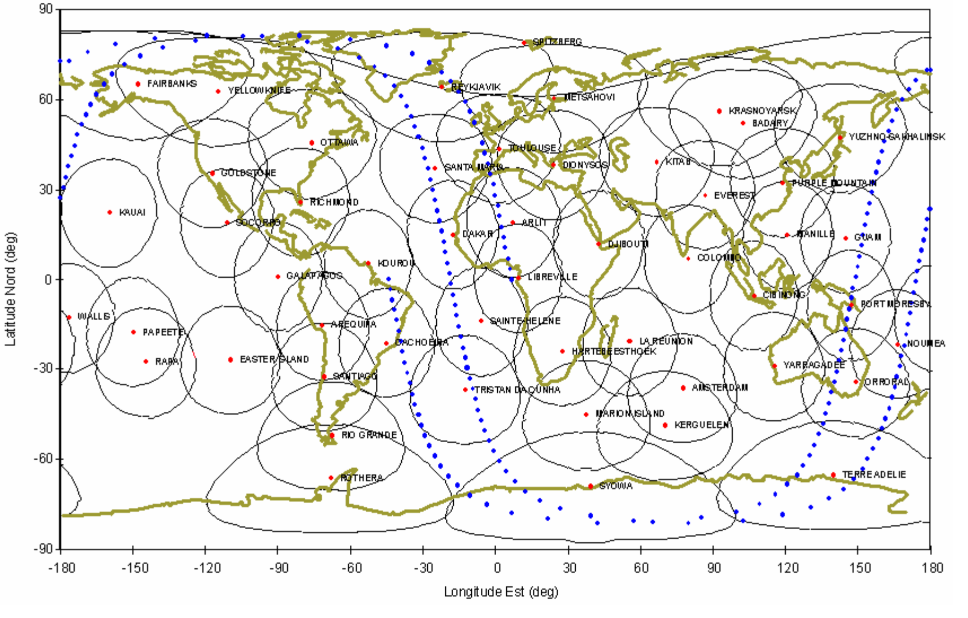




ERS-2 Laser Retro-Reflector
An identical LRR will be flown on ENVISAT-1
(Photo courtesy of AEROSPATIALE)

Satellite Tracking Systems … DORIS

DORIS is a Doppler tracking system. A network of DORIS beacons emit 2 signals at different frequencies. An onboard captor mesures the Doppler shift between the signals to determine the distance between the satellite and the ground beacon.



Instrumental Corrections …

- Oscillator Drift Error :
  - Altimeter measures time by counting oscillator cycles
  - Error is due to a drift in the oscillator frequency (of the order of 1 cm)
- Doppler Shift Effect :
  - due to the relative velocity between the satellite and the sea surface
  - depends on the range rate, and the emitted frequency
  - range errors of + - 13 cm for the Ku band, +-5 cm for C band
- Tracker response error :
  - The on-board tracker does not account for range accelerations
  - largest accelerations occur over deep-ocean trenches
  - correction is a few cms
- Pointing angle error
  - Off-nadir pointing errors affects the two-way travel time
  - For 0.2° pointing error : 2 cm error (<< than for beam limited radar)
- Internal Calibration
  - internal transit time in the altimeter
  - correction is a few cm

Range Delay due to Atmospheric Refraction

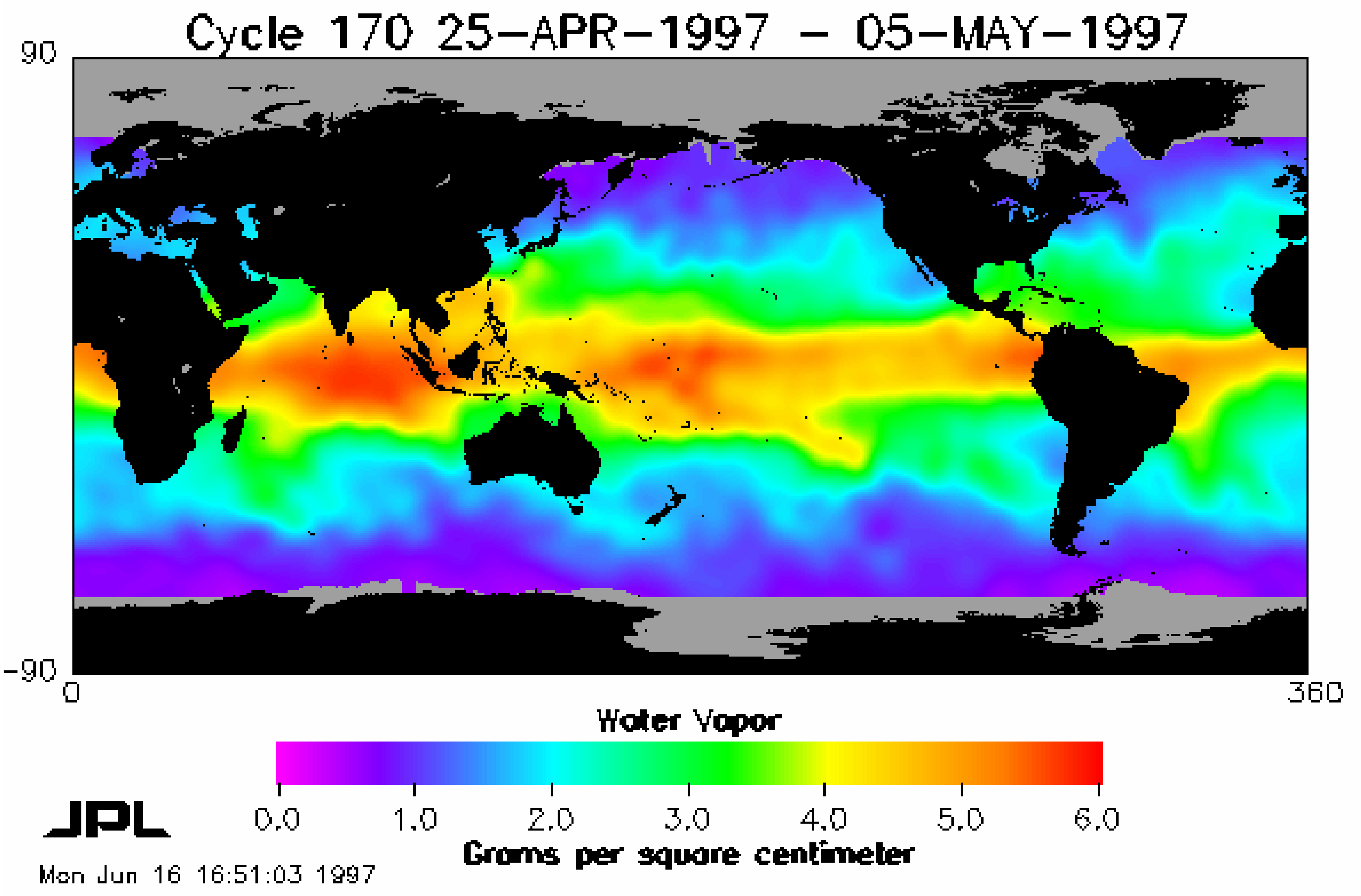
Dry Troposphere

The mass of dry air molecules in the atmosphere causes a range delay called the dry tropospheric effect. It is directly proportional to the sea level pressure, with an average magnitude of 2.3 m. This correction is computed using atmospheric model pressure forecasts. The error is of the order of 1 cm / 4 mbar, or on average 0.7 cm.

Wet Troposphere

The range delay due to the atmospheric water vapor, the wet tropospheric effect, varies considerably both spatially and temporally, with magnitudes from 5 cm to 30 cm (maximum in the tropical convergence zones, where atmospheric convection is important).

The wet tropospheric correction is computed using either the on-board microwave radiometer measurements, with a precision better than 1.1 cm, or the water vapor content is calculated from atmospheric models.


Cycle 170 25-APR-1997 - 05-MAY-1997
90
-90
0
360
Water Vapor
0.0
1.0
2.0
3.0
4.0
5.0
6.0
Grams per square centimeter
JPL
Mon Jun 16 16:51:03 1997

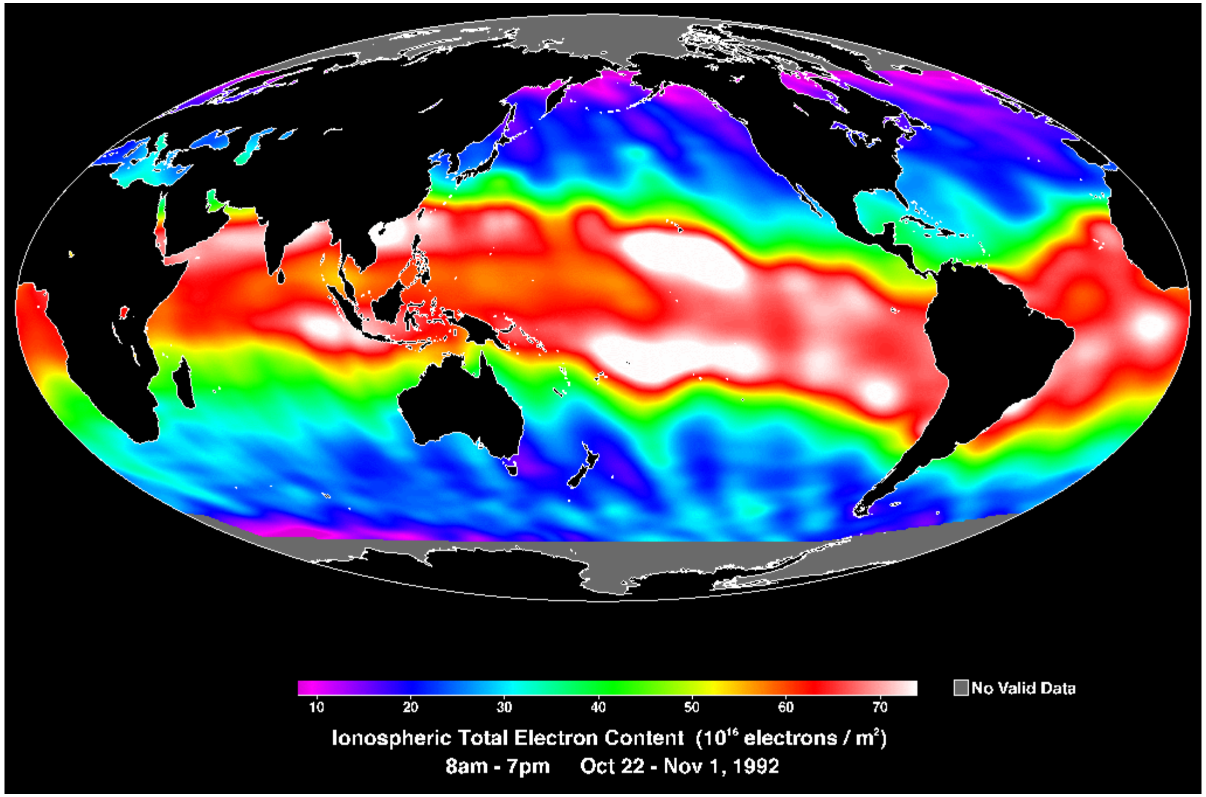
Ionospheric Refraction

- The radar pulse is delayed in the ionosphere (altitude of 50 - 2000 km) due to the presence of electrons, produced by the ionization in the high atmosphere by the incident solar radiation.
- The range delay is related to the EM radiation frequency, so the correction can be estimated using two different radar frequencies (e.g. TOPEX, or DORIS). Otherwise estimated from models of the vertically integrated electron density.
- The delay can produce range errors from 1 to 20 cm. The accuracy of the dual-frequency correction is 0.5 cm.

Ionospheric Correction – spatial variability

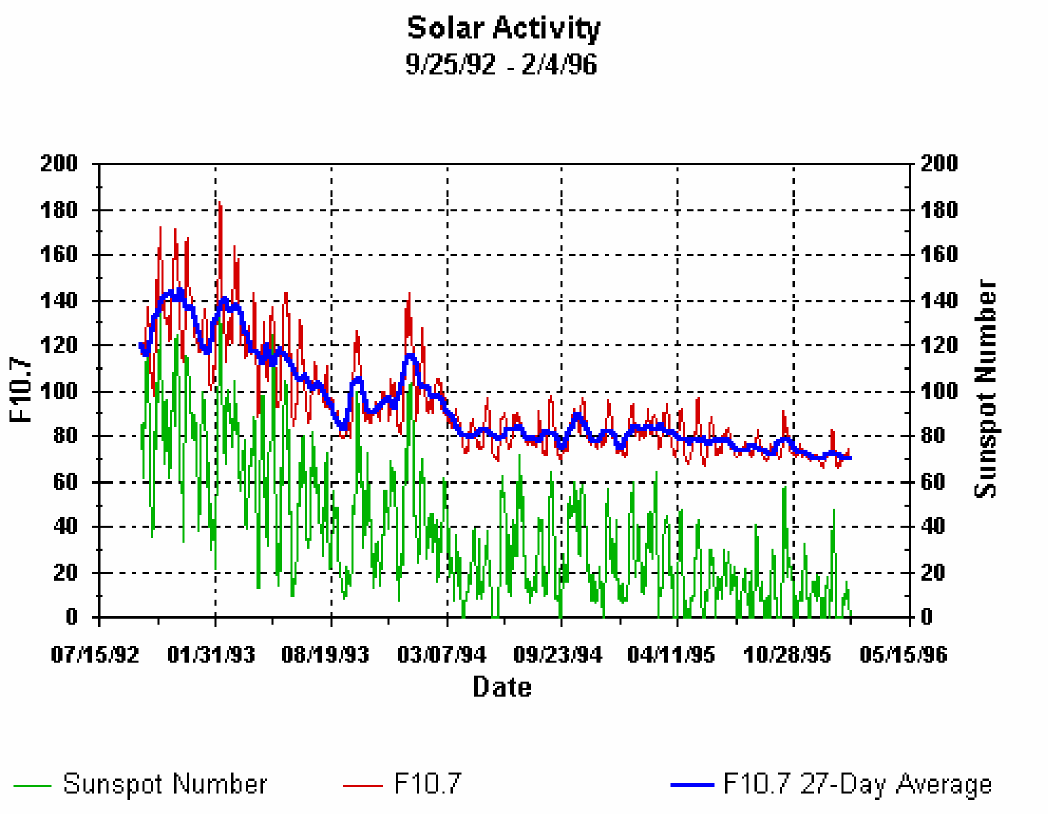
Spatial distribution

- the Total electron count is mainly correlated to the geomagnetic field, maximum in the tropical band
- the highest electronic perturbation occurs at a 400 km altitude



Ionospheric Correction – temporal variability

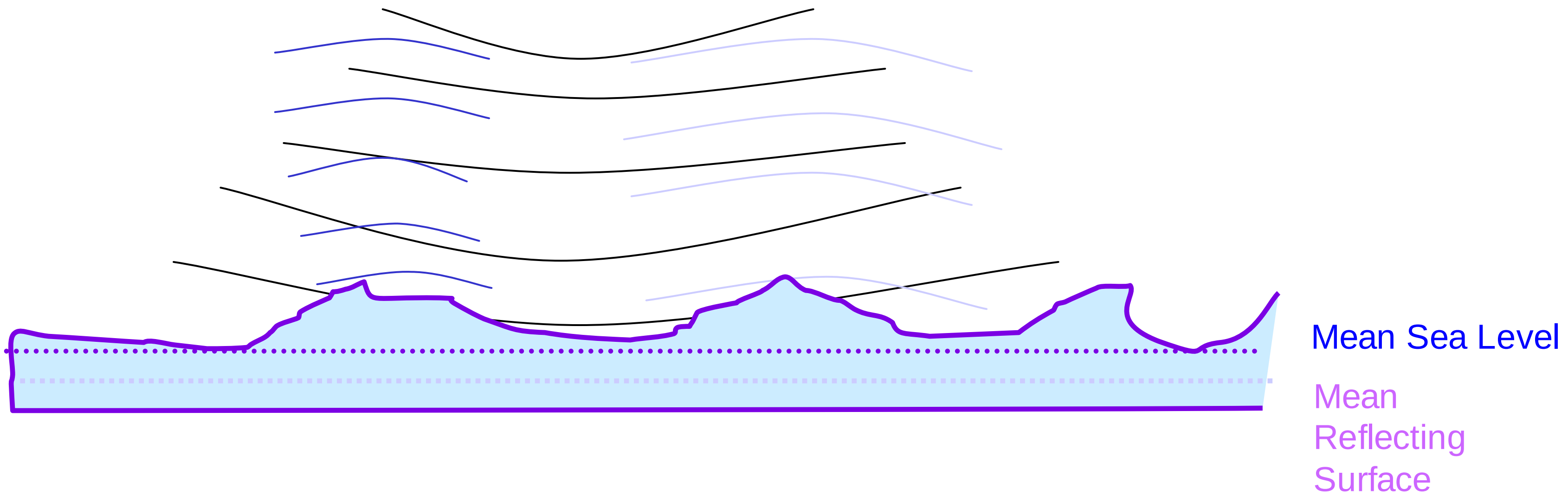
- **Temporal variability**
  - Strongly diurnal, maximum at 2 pm and minimum around 5 am
  - the TEC has seasonal variations
  - the TEC is correlated with the solar activity, and the geomagnetisn



Sea State Effects

Electromagnetic bias

The concave form of wave troughs tends to concentrate and better reflect the altimetric pulse. Wave crests tend to disperse the pulse. So the mean reflecting surface is shifted away from mean sea level toward the troughs.



Sea State Bias

Skewness bias

For wind waves, wave troughs tend to have a larger surface area than the pointy crests – the difference leads to a skewness bias.

Again, the mean reflecting surface is shifted away from mean sea level toward the troughs

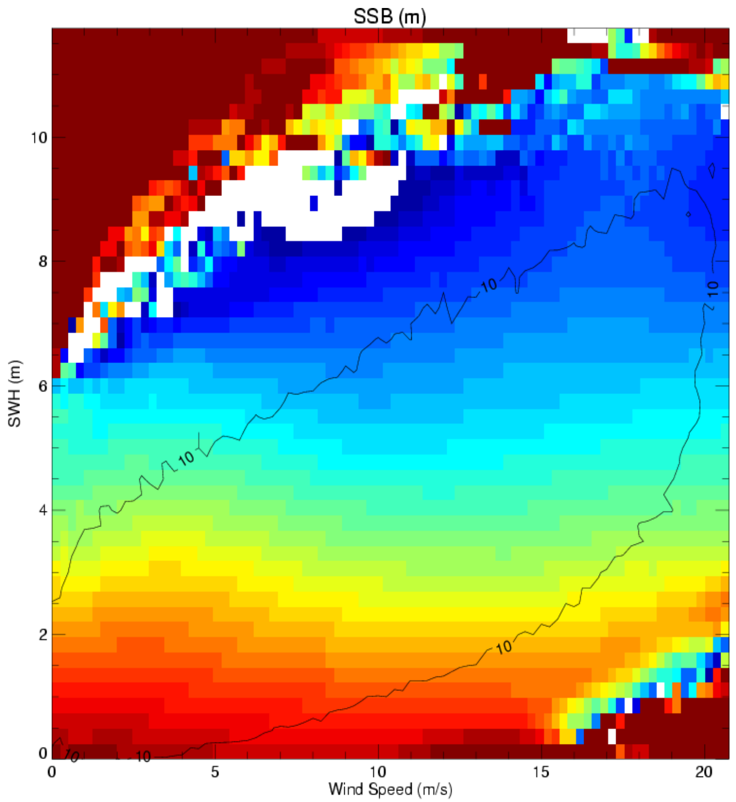
The EM Bias and skewness bias (= Sea State Bias or SSB) vary with increasing wind speed and wave height, but in a non-linear way.

SSB is estimated using empirical formulas derived from altimeter data analysis (crossover, repeat-track differences and parametric/non-parametric methods). The range correction varies from a few to 30 cm. EM bias accuracy is ~2 cm, skewness bias accuracy is ~1.2 cm.

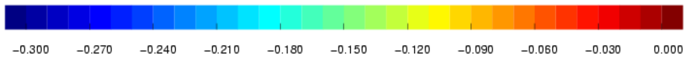
Empirical estimation of the SSB also includes tracker bias (depends on H1/3).

S. Labroue

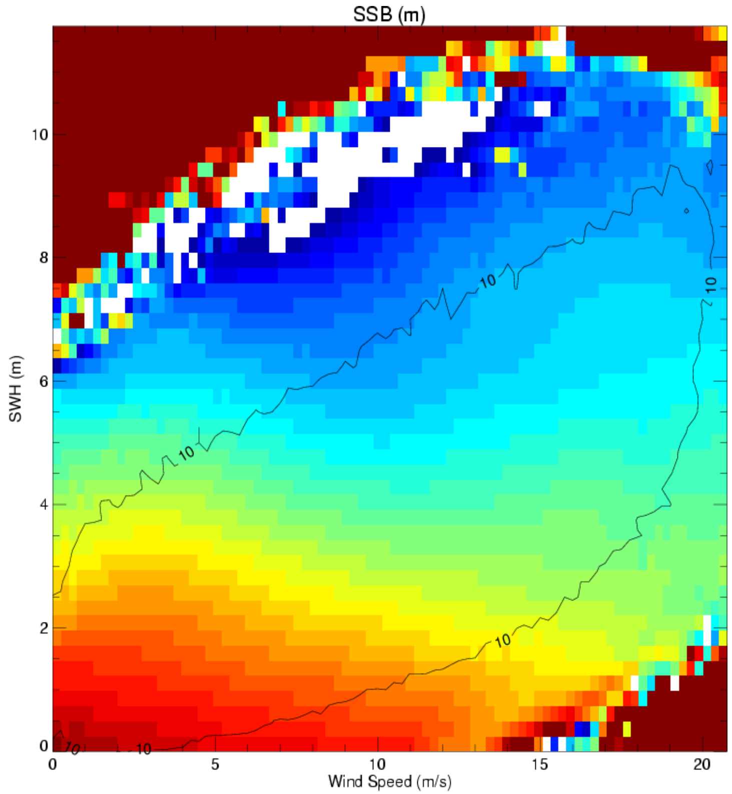
Jason SSB



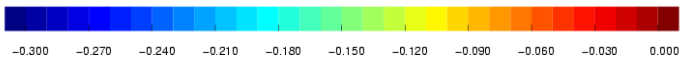
-30 cm 0 cm



Topex LSE

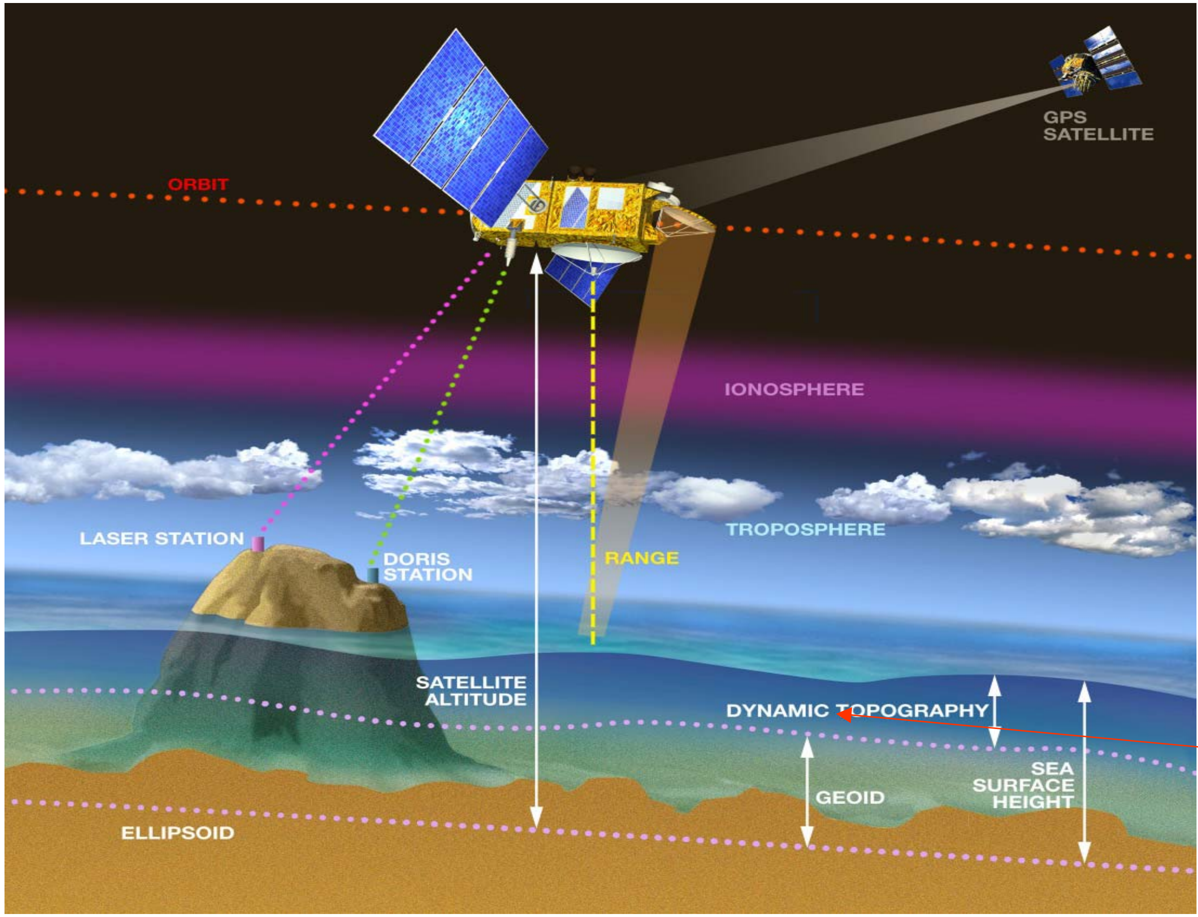


-30 cm 0 cm



Use of non-parametric methods to estimate SSB (SWH, Wind) (Labroue, 2007)

SSH and Geoid



SSH = GEOID + η

η = Dynamic topography

Separating the observed sea surface into ocean dynamic topography and marine geoid

Dynamic topography (i.e. sea level relative to the geoid) is the quantity of interest for oceanographers as it is related to ocean circulation (see lecture 3)

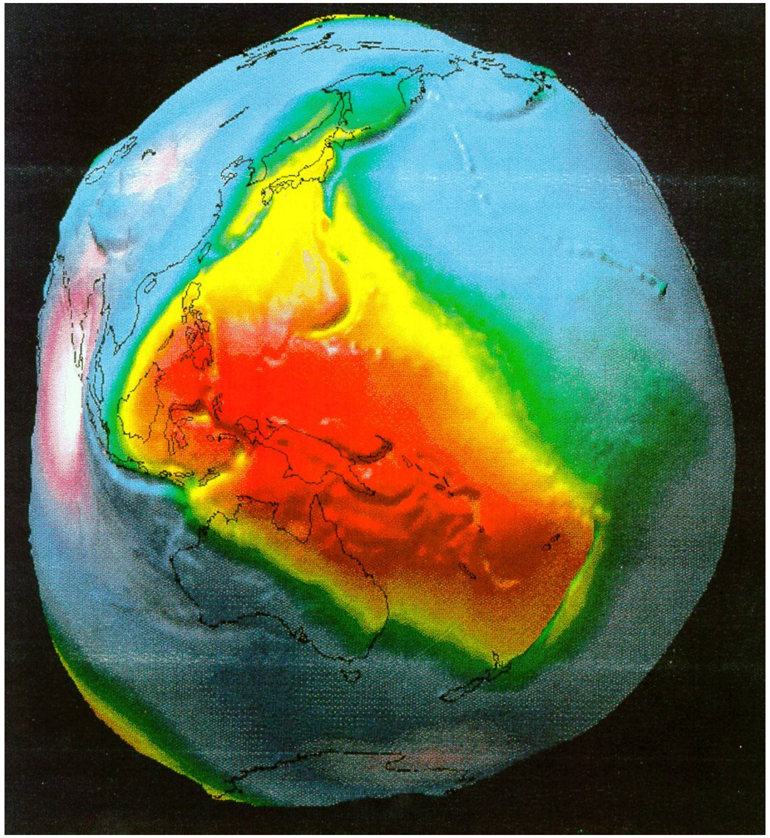
Marine Geoid

The earth has large bumps and troughs due to variations in the ocean bottom topography and inhomogeneous density distributions in the earth’s interior.

These density variations create a bumpy geoid. The geoid is an equipotential of the gravity field; if the ocean were at rest, the sea surface would exactly follow the geoid.

Marine geoid can be modelled with a good accuracy at large spatial scales (> 2000 km wavelength) but it is not well known at small spatial scales (will improve with GRACE and mainly GOCE).

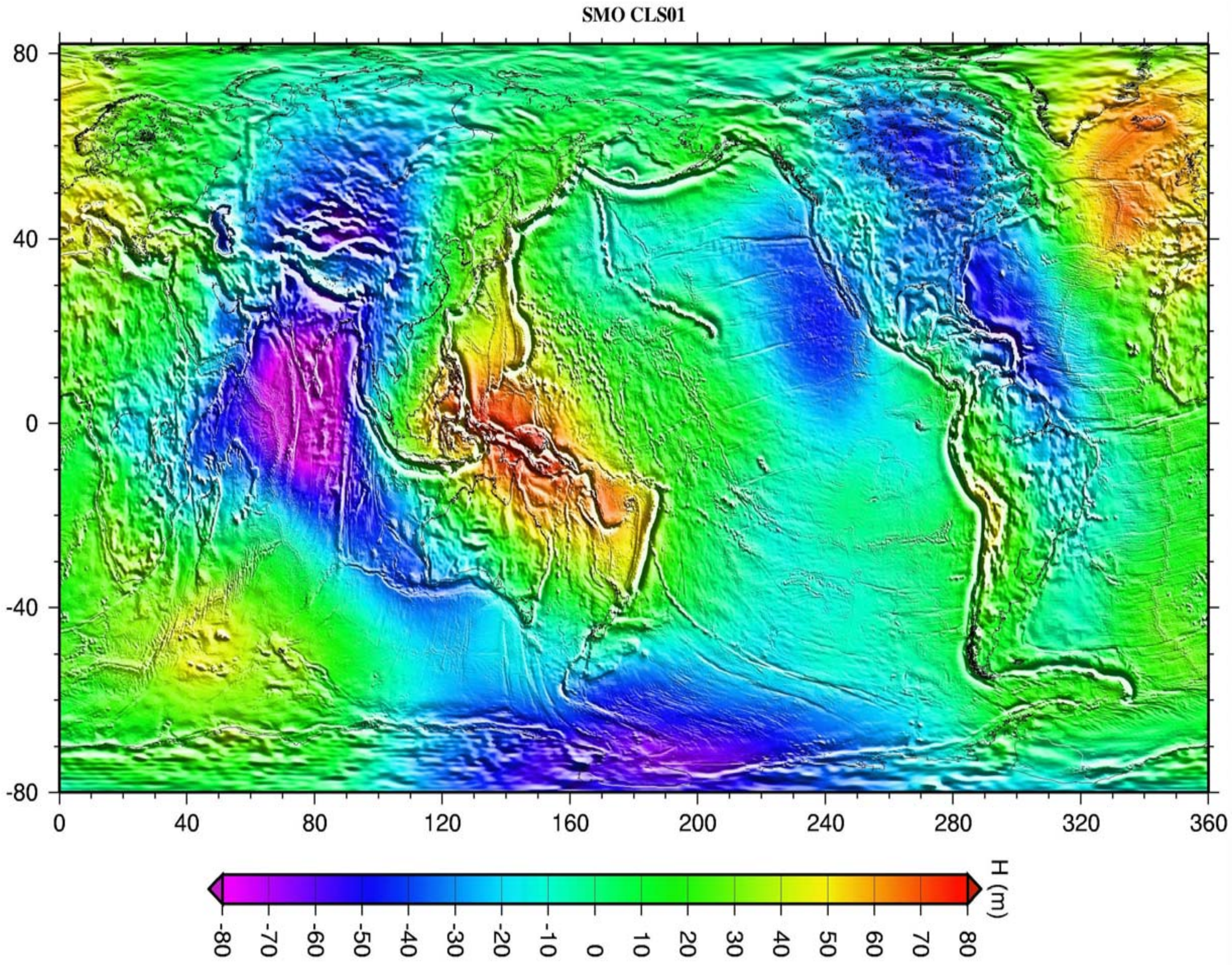
Local errors in the marine geoid can reach 2m, over steep bathymetric features.



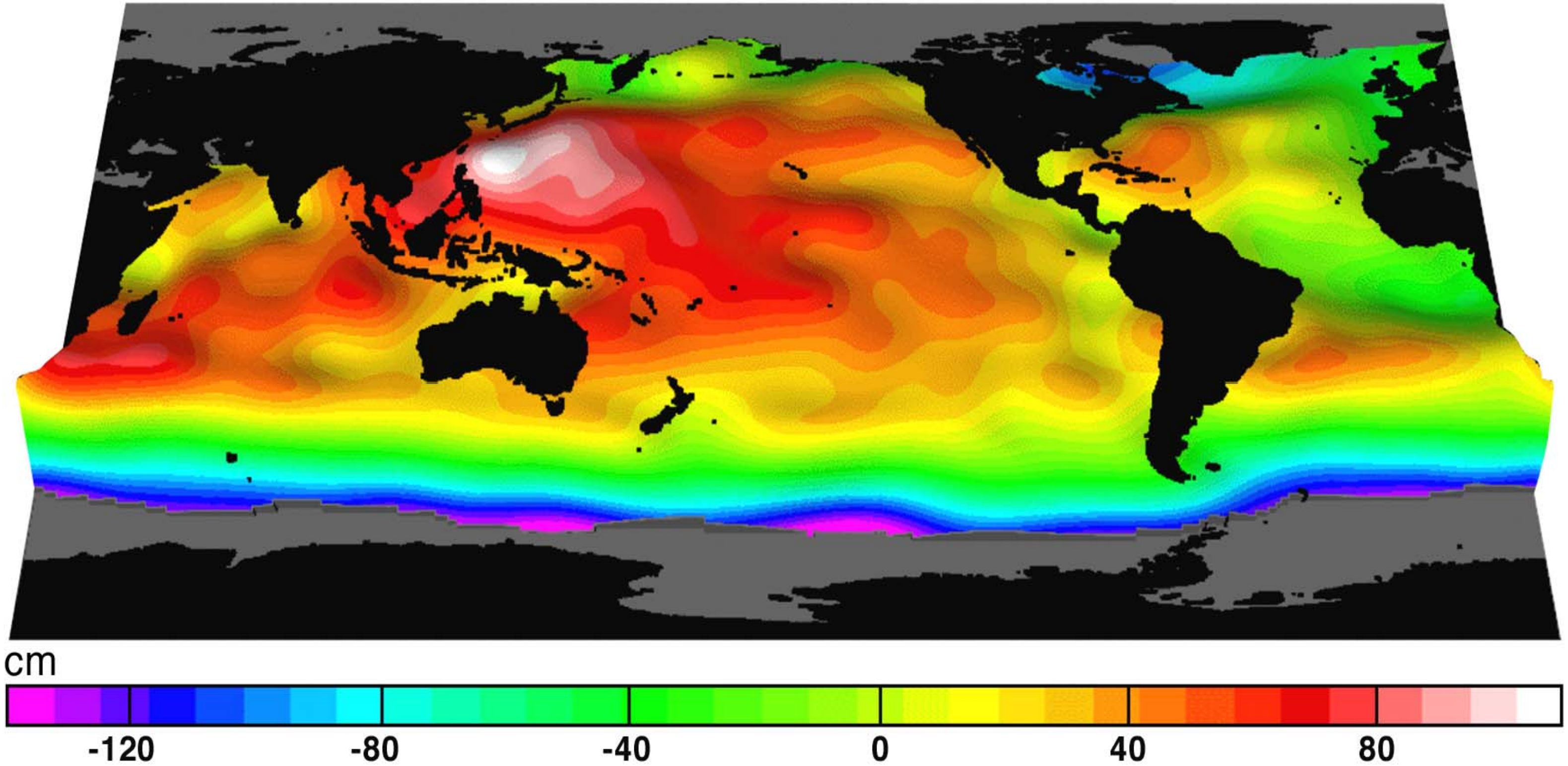
Geoid varies by –100 to + 60 m.

Geoid is near-stationary on oceanographic time-scales : by differencing data along exactly repeating satellite tracks we remove the geoid and its errors.

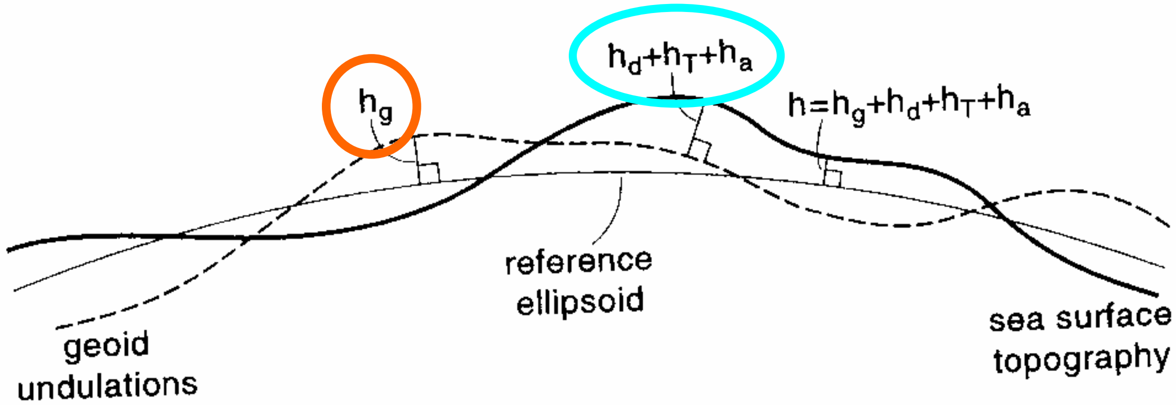
At small scales, geoid reflects the bathymetry (variations of a few meters)



Dynamic topography (sea level relative to geoid)



SSH = Geoid + dynamic topography + «noise»



- h_g : geoid — 100 m
- h_d : dynamic topography — 2 m
- h_T : tides — 1-20 m
- h_a : inverse barometer — 1 cm/mbar

Corrected Altimetric Sea Surface Heights

SSH = Orbit Altitude - Range – corrections

Σ corrections =

- **instrumental corrections**
- **sea state bias corrections**
- **ionospheric correction**
- **tropospheric corrections (wet, dry)**
- **Tides (ocean, earth) + Inverse barometer**

Errors = errors in orbit, in corrections and instrumental noise

Sea level signals

Dynamic sea surface height (the signal of interest here) : surface currents in geostrophic balance have a sloping sea surface, so the dynamic topography responds to the mean ocean circulation, mesoscale variability, planetary waves, etc. Sea surface height varies by 5 to 30 cm, with slopes of up to 1 m over 100 km (Gulf Stream).

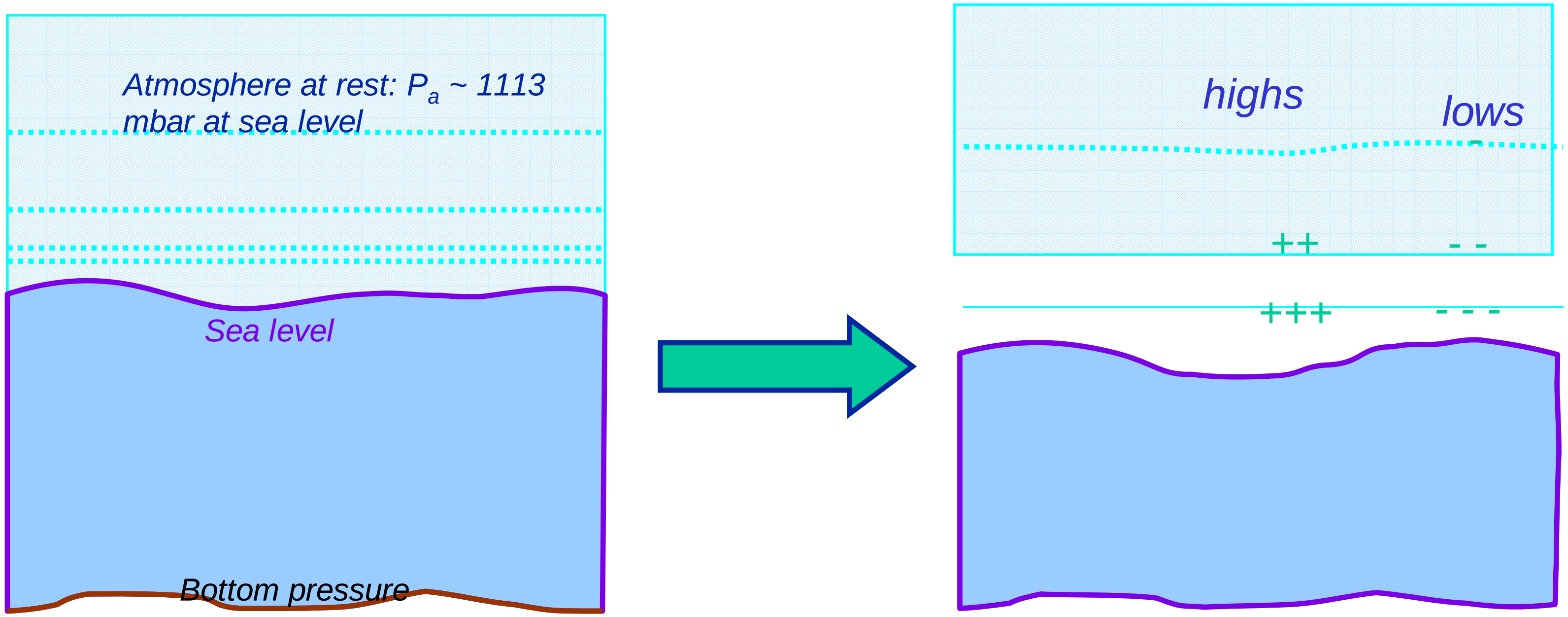
Ocean (and earth) Tides : 10-60 cm in the open ocean, larger amplitudes in coastal regions. Tidal signal is the most important variable signal in altimetric data. This signal is only partially corrected using global ocean tide models (thanks to T/P, these models have now an accuracy of about 2 cm rms in the open ocean). The residual errors are then aliased at certain periods depending on the repeat-period of the satellite (around 60 days for T/P for M2 tide).

Atmospheric pressure loading : increased atmospheric pressure by 1 mbar pushes the sea level down by 1 cm – the isostatic inverse barometer effect. Good approximation in the open ocean but not adequate for very short time scales (dynamic response) and in semi-enclosed seas.

High-frequency Barotropic motions : wind and pressure forcing creates a high-frequency barotropic response at periods < 20 days which is not resolved by the altimeter sampling. Could be corrected by ocean models.

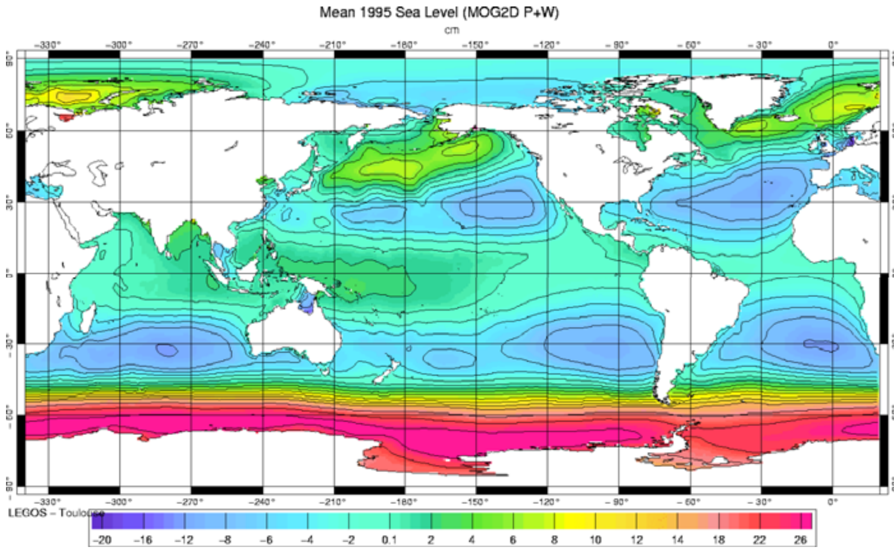
Atmospheric Pressure Forcing

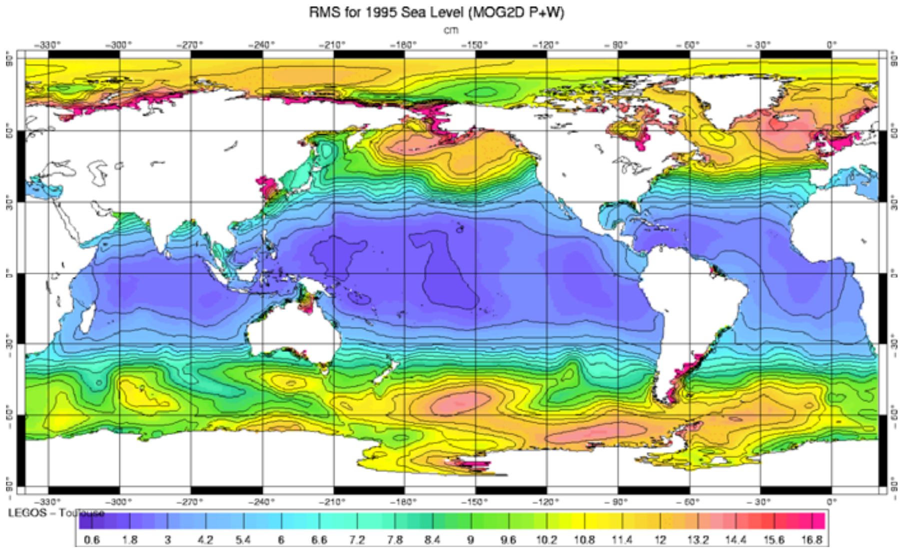
Evolving atmospheric pressure field with highs and lows leads to spatial and temporal variation of the sea level pressure



The ocean responds directly to atmospheric pressure changes: sea level rises (falls) as the low (high) pressure systems pass. At the first order, there is a static response (the inverse barometer effect) : 1 mbar of relative pressure change leads to a 1 cm sea level change

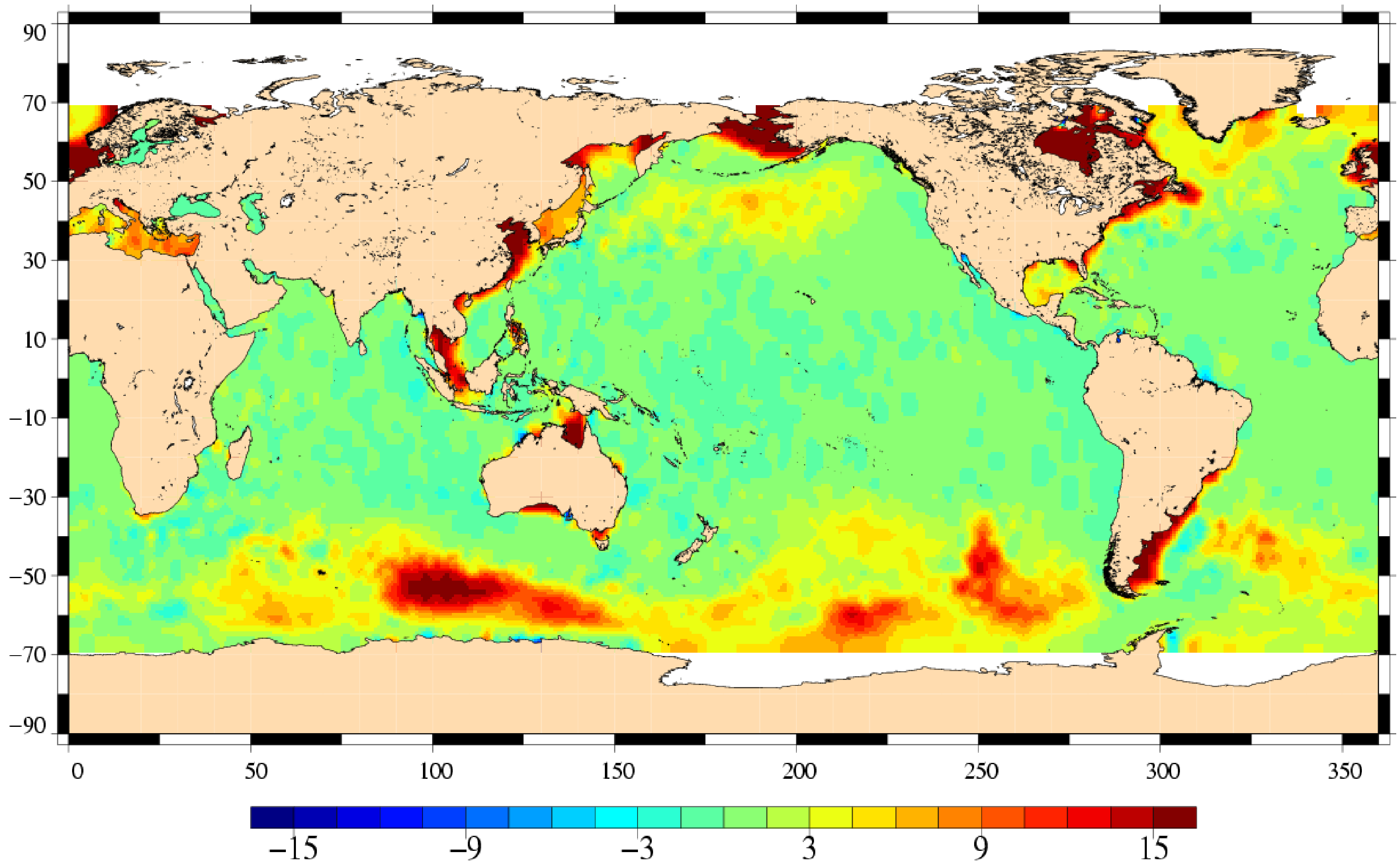
The barotropic response to combined wind and pressure forcing





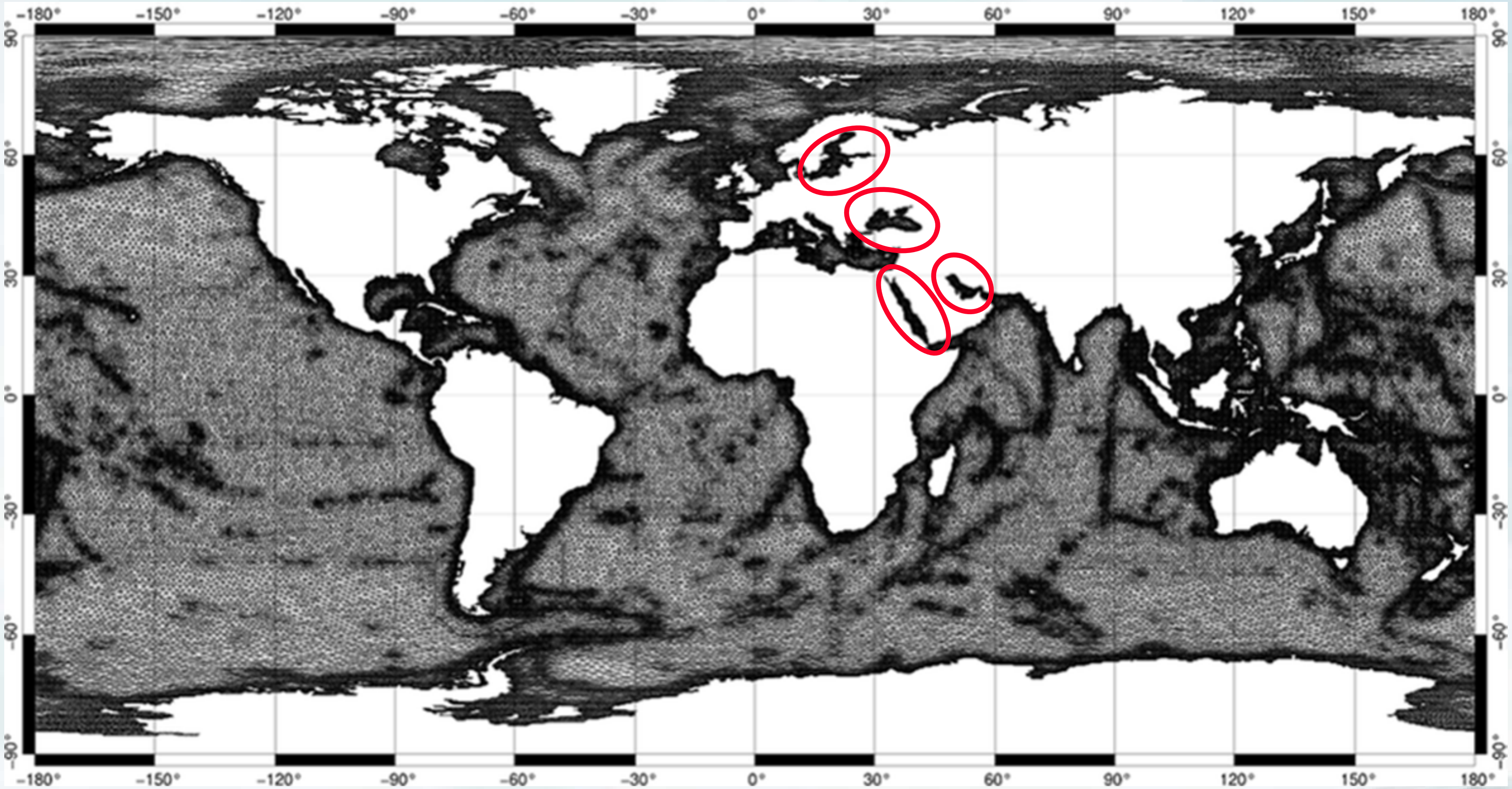
These figures show the mean sea level response (left) and the rms variability of sea level (right) for a barotropic ocean model forced by 6-hourly winds and sea surface pressure. The largest barotropic response (mean and variability) is at higher latitudes, especially in the Southern Ocean. These regions have weak vertical stratification.

In altimetry, this sea level response is mostly at periods < 20 days, and appears as large-scale noise.



SLA variance differences (cm²) : VAR SLA with IB – VAR SLA with MOG2D

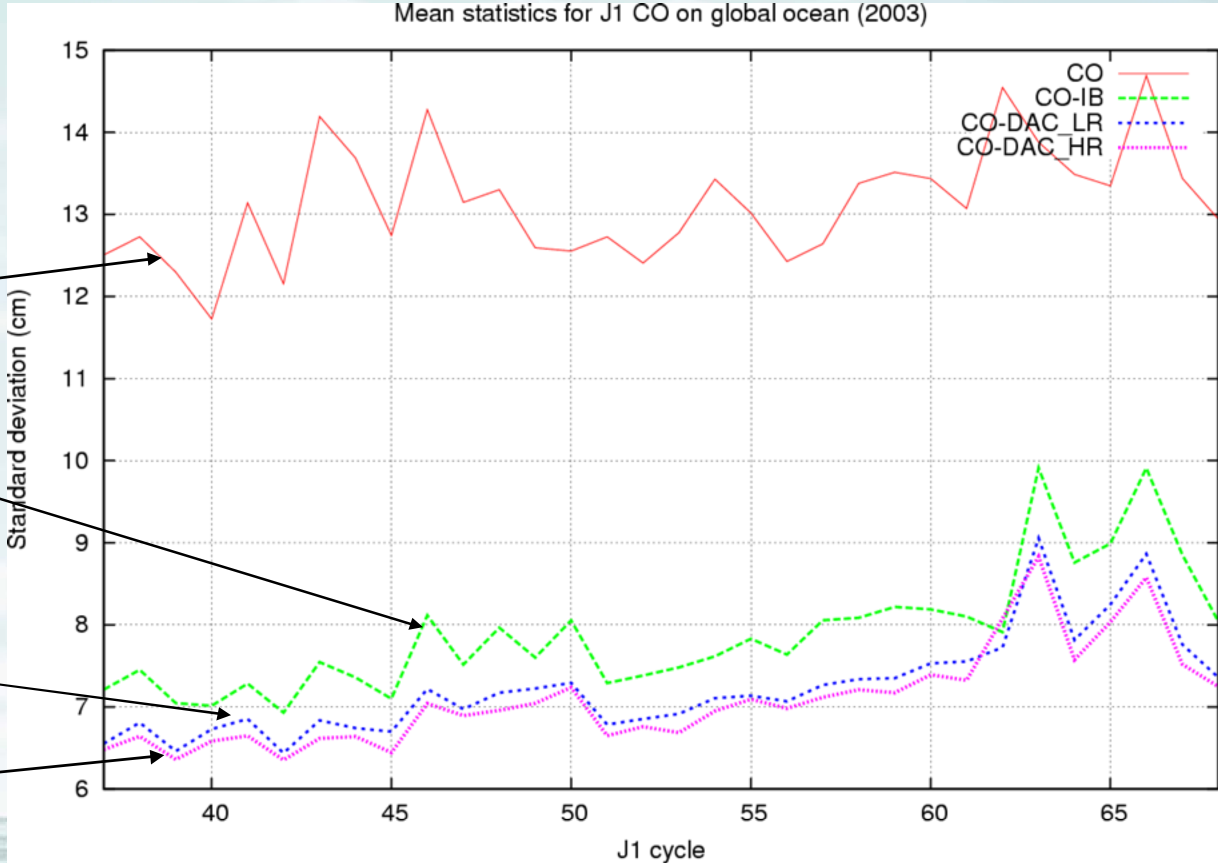
High resolution MOG2D finite element mesh



- ~300.000 nodes - resolution: ~150 km in deep ocean and ~15 km in shallow water
- Gradients of topography are better represented
- Semi-enclosed seas: Baltic Sea, Black Sea, Persian Gulf and Red Sea

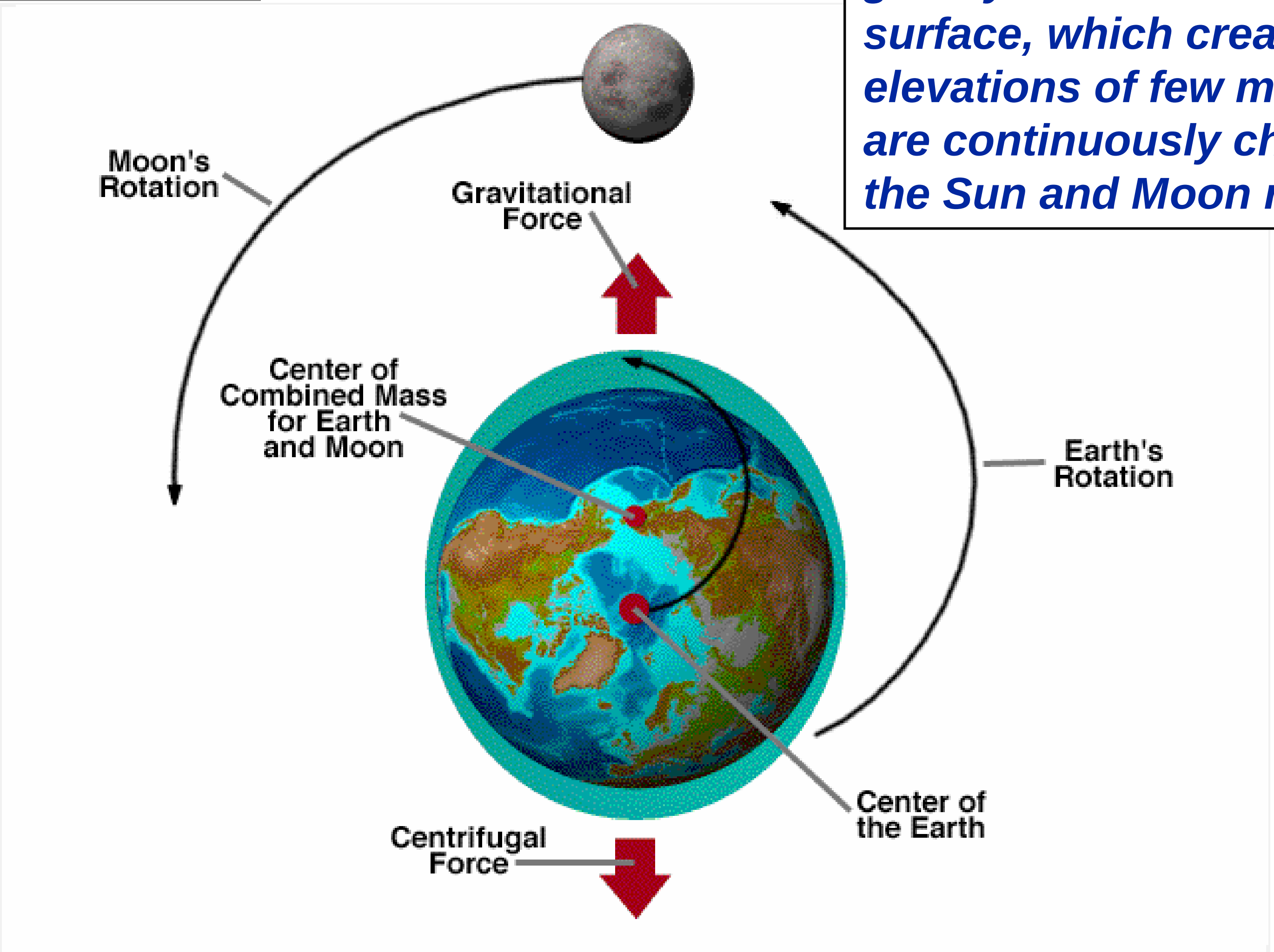
Crossover differences: Jason-1 cycles

- Global ocean
- SSH without atmospheric correction at crossovers: red
- SSH with IB correction: green
- SSH with DAC_LR: blue
- SSH with DAC_HR: purple



Tides

The Moon and the Sun generate gravity forces a the Earth surface, which create sea elevations of few meters, which are continuously changing with the Sun and Moon rotations.



Tidal Corrections for altimetry data

•Sea level exhibits **ocean tide** perturbations of 5 cm – 10 m,

•The Earth interior is also perturbated by the Moon and the Sun gravitational attractions, this phenomena is known as the **solid earth tide**: the Earth underneath the ocean is slightly deformed, nearly in phase with the ocean tide (amplitude ~50 cm)

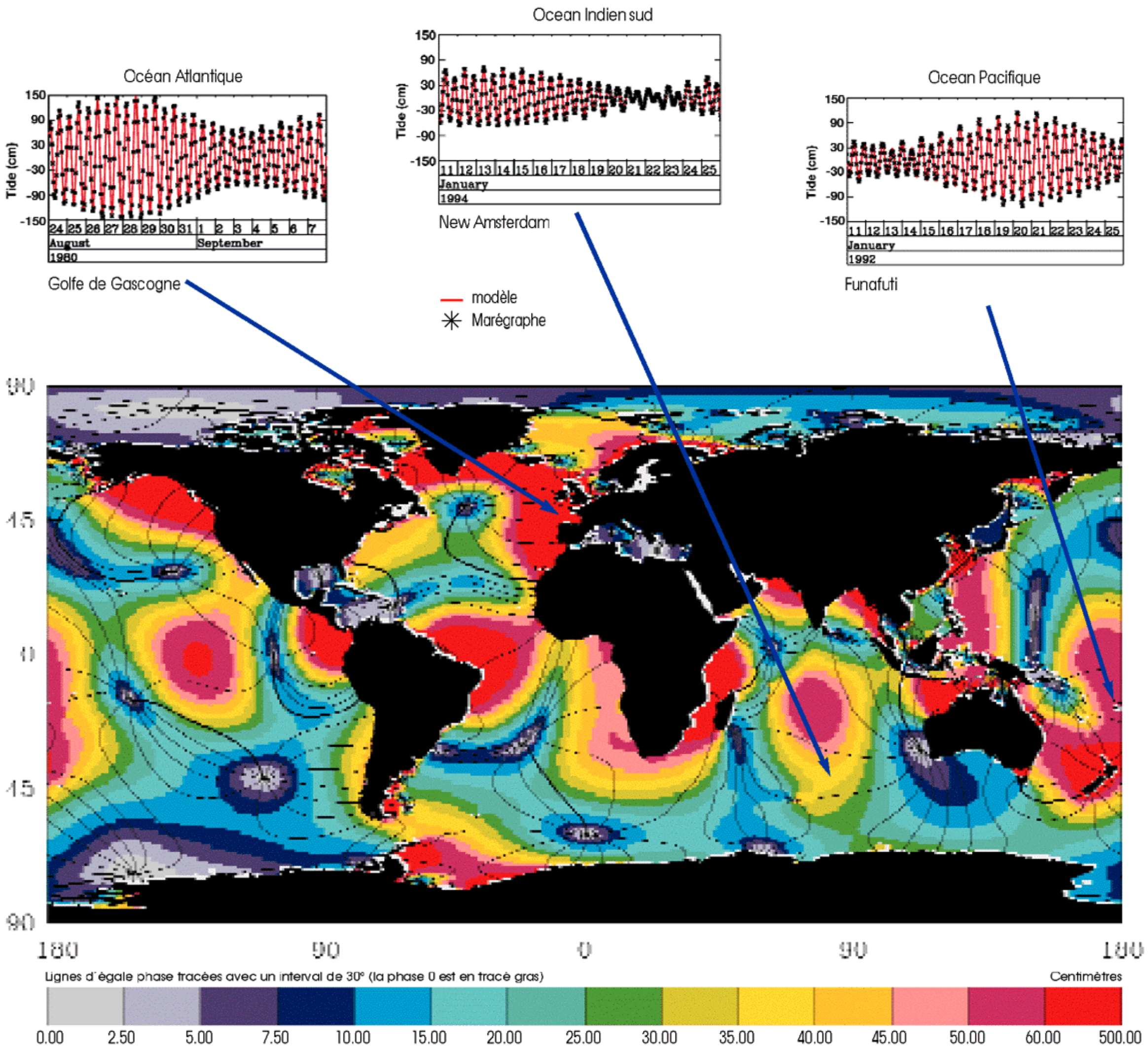
•The changing “weight” of the water column due to tides variations generates a **loading effect** on the sea floor (elastic response), causing a few centimeter vertical displacement.

•The Earth’s rotation axis deviates slightly from the Earth’s ellipsoid axis over a period of several months, which generates a translation of the Earth ellipsoid with respect to a stationary reference ellipsoid. This causes a 2 cm change in the relative Earth surface, called the **polar tide**.

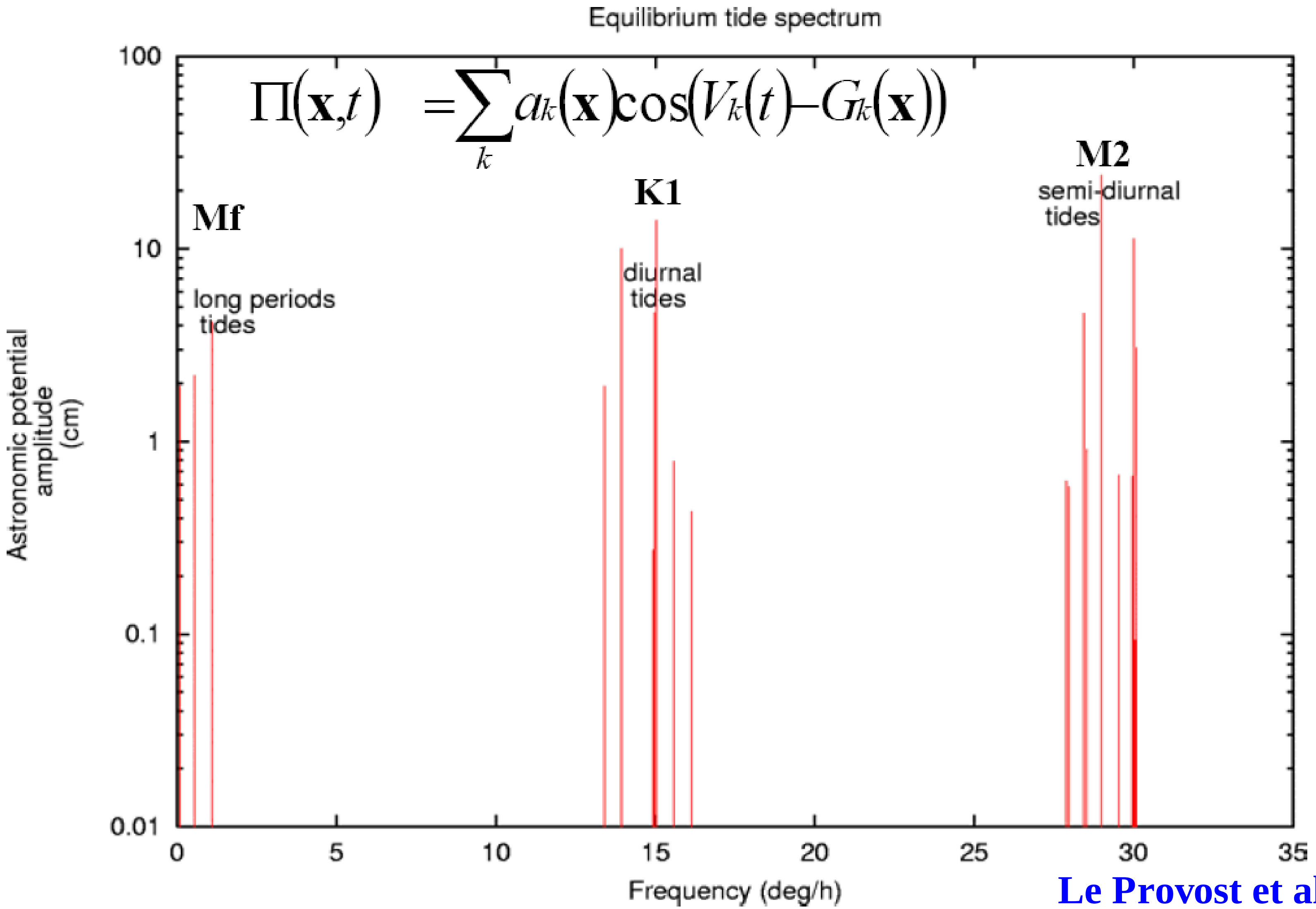
M2 tide

The main lunar tidal component is the M2 tide. The sum of the major tidal components are modelled (sometimes with altimetry data assimilated) to provide tidal corrections for altimetry.

The figure shows the amplitude (colour) and phase lines (black contours) of the M2 tide, with some time series at different locations.



$$\Pi(\mathbf{x},t) = \sum_k a_k(\mathbf{x}) \cos(V_k(t) - G_k(\mathbf{x}))$$



M4

Higher non linear

Le Provost et al., 2003

Tidal corrections for altimetry (Le Provost, 2003)

Before the T/P and ERS era, the standard was : Schwiderski (1980)

1991- first empirical altimetric solution GEOSAT: Cartwright and Ray (1991)

1995 – first set of T/P solutions:

Empirical: Schrama and Ray (1994), Eanes / CSR3 (1995), Andersen (1995), Desai-Whar (1995)…

Hydrodynamic +Assimilation : Egbert et al (1994), Le Provost et al / FES 95(1995), Kantha(1995), ...

2001: preliminary JASON 1 tide solutions:

Empirical: Ray / GOT 99(2000), Eanes / CSR4 (2001), …

Hydrodynamic +Assimilation : Egbert (2000), Lefevre et al/ FES 99 (2002), NAO(2002)

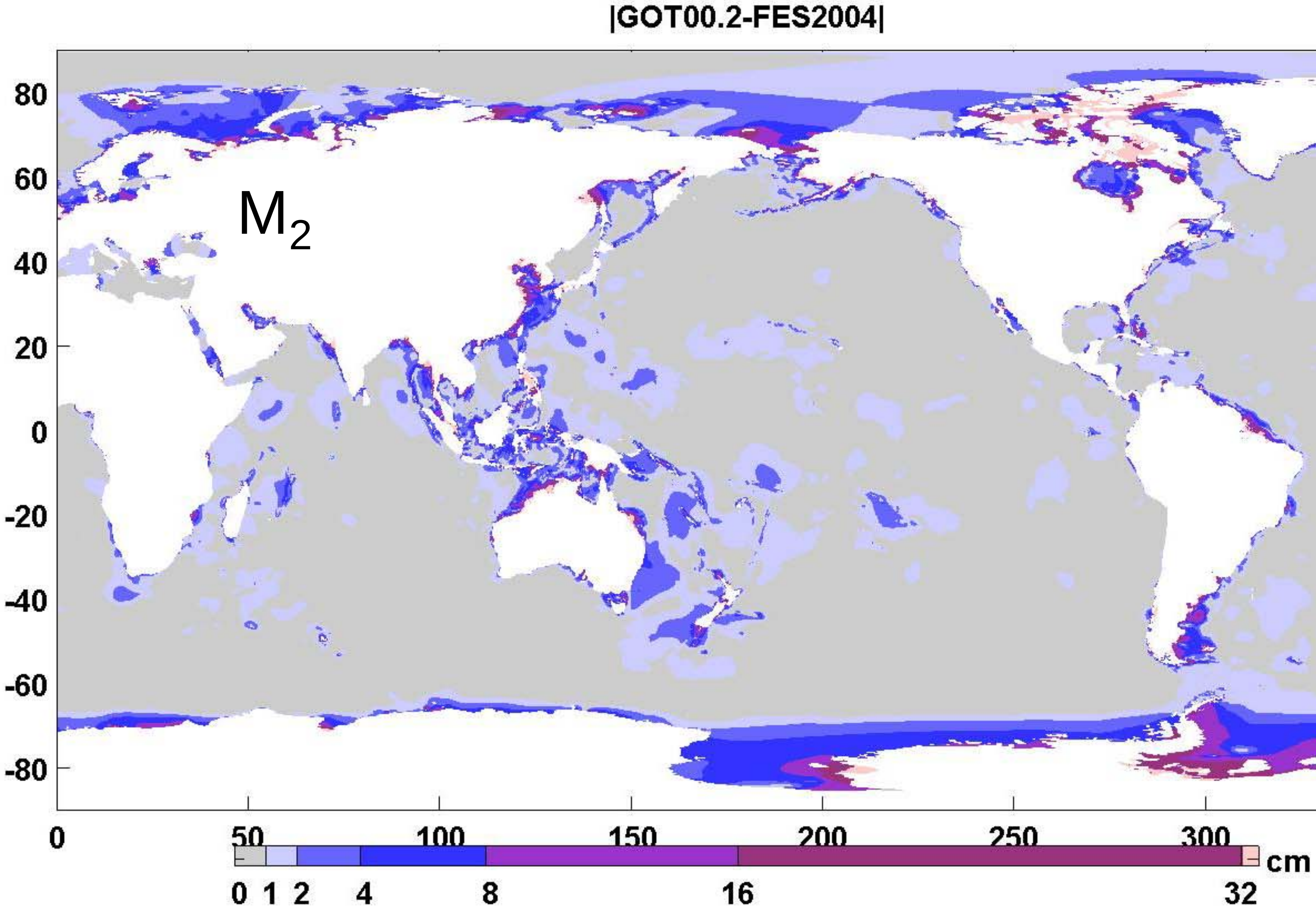
2002 + : more recent gobal solutions

Empirical: Ray (2002) / GOT2001

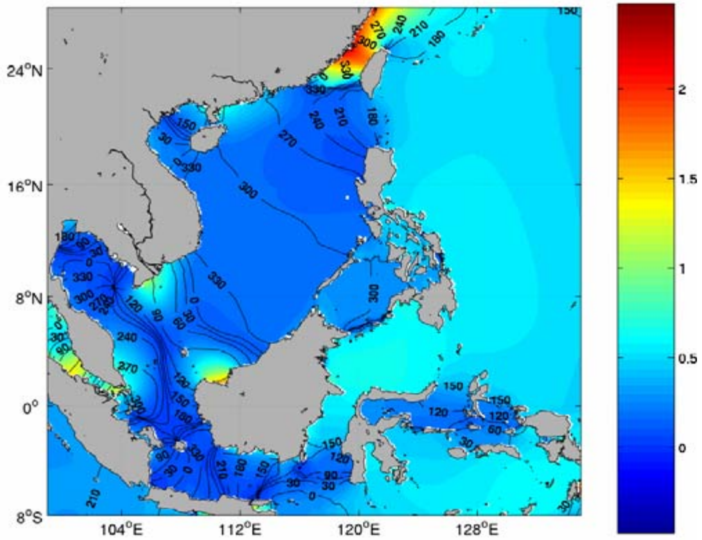
Hydrodynamic +Assimilation : Le Provost et al (2003)/ FES 2002/3/4

Regional/coastal solutions

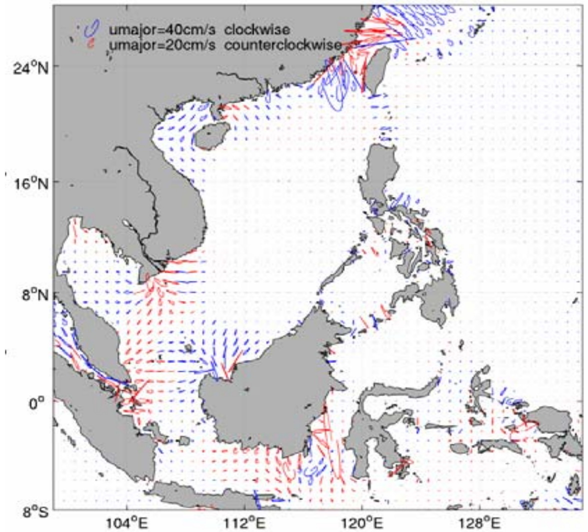
Difference between GOT00.2 and FES2004



South China Sea: Assimilation solution (T/P using OTIS) Zu and Gan (Hong Kong Univ. Sci. Tech.)



M_2 elevations



M_2 currents

RMS TG Misfit (cm; 45 mostly coastal gauges)

Constituent	M2	K1
Inverse Solution	4.72	2.22
FES2004	6.55	5.03
GOT00.2	7.08	4.24

Egbert, OSTM, 2007

Tides in shallow seas

- Accuracy of global models in shallow seas has steadily improved over the past decade, but there is still substantial room for improvement
- Further progress requires regional modeling/assimilation
  - high resolution (and accurate!) bathymetry
  - more data: multiple satellites, wide-swath
  - including non-linear shallow water tides
- Potential for interesting scientific studies of tidal non-linearities in shallow seas

Egbert, OSTM, 2007

Topex-Poseidon – Jason-1 – ENVISAT

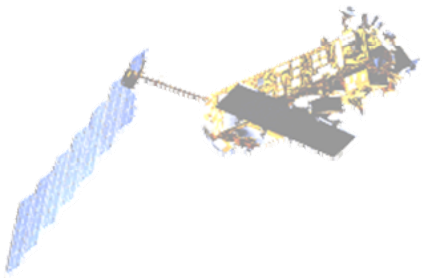
Performances

- **Altimeter**

Instrumental noise	1.7
E-M bias	2.0
Skewness	1.2
Ionospheric corr.	0.5
Wet Tropospheric corr.	1.1
Dry tropospheric corr.	0.7
SWH	0.2 m
Wind Speed	2 m/s

- **Range total error** — 3.2 cm
- **Orbit error (radial)** — <2.5 cm (T/P-Jason-1); < 5 cm (ENVISAT)
- **Instantaneous sea level error** — <4.1 cm (T/P-Jason-1); <6 cm (ENVISAT)

Satellite Altimetry



Pierre-Yves Le Traon

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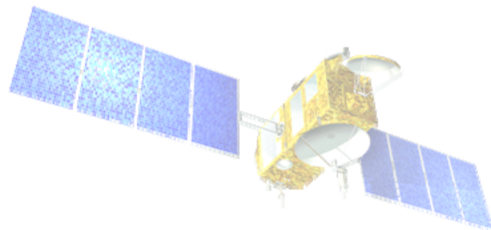
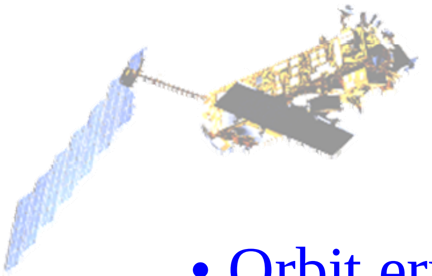
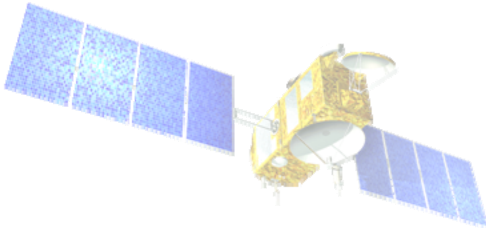


- **Lecture 1: Principles of satellite radar altimetry**
- **<u>Lecture 2 : Altimetry data processing</u>**
- **Lecture 3 : Altimetry and oceanography**
- **Lecture 4 : Applications of altimetry**

Lecture 2

Altimeter data processing





- Orbit error correction
- Repeat Track analysis
- Mapping and multiple altimeter data merging
- Absolute dynamic topography and the geoid

Altimeter data processing (1)
Orbit error

- This error is caused by imperfect knowledge of the spacecraft position in the radial direction. It is actually the largest error on altimetric measurements of sea surface topography (except for T/P). It is also more important for real time applications.

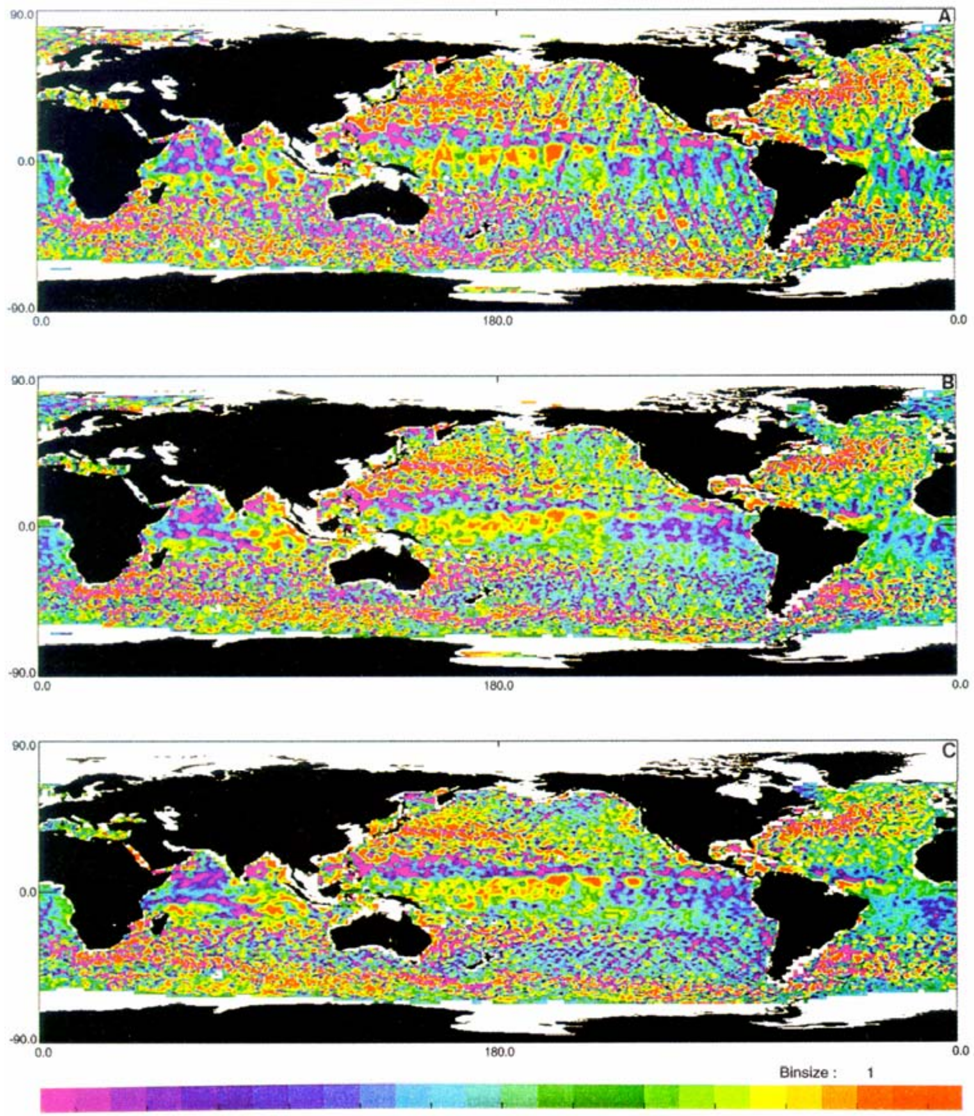
- This error will depend on the quality of the satellite tracking system. T/P radial orbit error is thus obtained with an accuracy of about 2 cm. This is to be compared to the 10 cm accuracy of the ERS-1/2 and Geosat orbits.

- Orbit error is at very long wavelength (40 000 km). It can be reduced by analyzing the altimeter data :
  - An empirical approach, commonly used, is to approximate the orbit error by a first or second degree polynomial over a given arc length. This removes long wavelength oceanic signals together with the orbit error and other long wavelength errors => acceptable for mesoscale applications
  - To minimize the oceanic signal removal, one should use more sophisticated methods (global crossover minimization, inverse methods)

ERS

ERS adjusted onto T/P

T/P



Le Traon and Ogor, JGR, 1998

Use of TOPEX/POSEIDON (Jason-1) as a reference for the other missions

Global minimization of dual (TP-ERS) and (ERS-ERS) crossover differences

Reduce biases and orbit error for the other missions

Altimeter data processing (2)

Oceanic signal extraction from altimetry

The sea surface topography S(x,t) measured by altimetry can be described by:

$$S(x,t) = N(x) + \eta(x,t) + \varepsilon(x,t)$$

N is the geoid, η the dynamic topography and ε are measurement errors. Present geoids are not generally accurate enough to estimate globally the absolute dynamic topography h except at very long wavelengths.

The variable part of the dynamic topography η' (η - $<\eta>$) is, however, easily extracted using the so-called repeat track method. For a given track, h' is obtained by removing the mean profile over several cycles, which contains the geoid N and the mean dynamic topography <h> :

$$S'(x,t) = S(x,t) - <S(x)>_t = \eta(x,t) - <\eta(x)>_t + \varepsilon'(x,t)$$

To get the absolute signal, one has thus to use a climatology (from historical in-situ data) or to use existing geoids together with altimeter Mean Sea Surface (MSS) (or both through inverse modelling). One can also rely on a model mean.

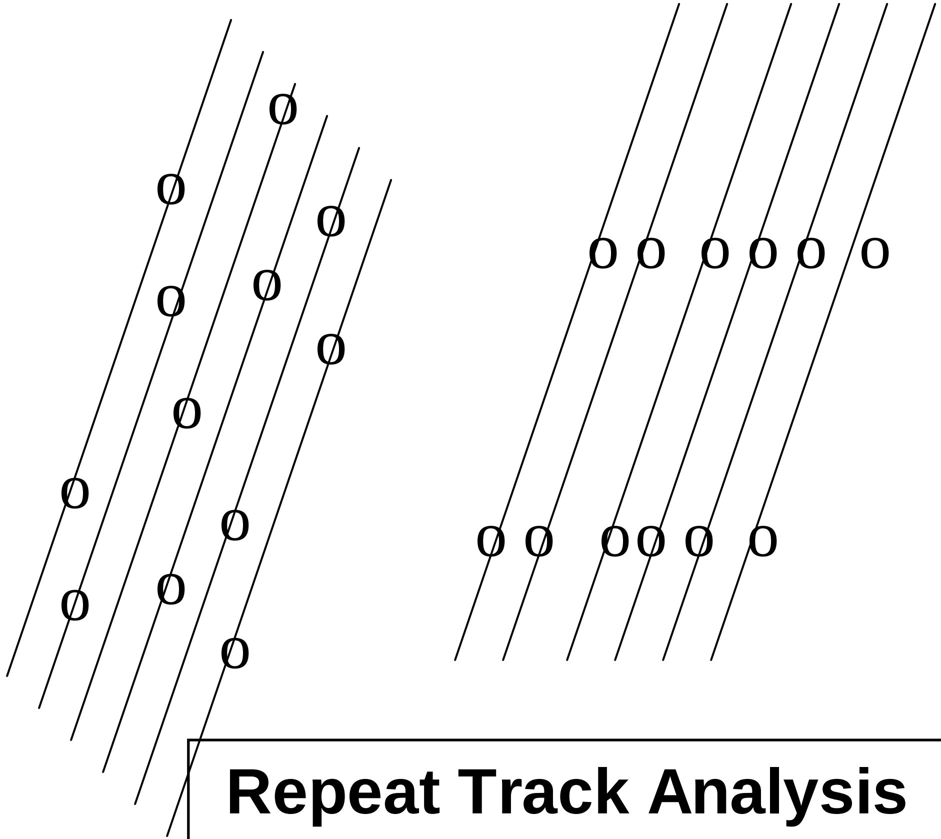
Gravimetric missions (CHAMP, GRACE) are now providing much more accurate geoids. Need to wait for GOCE to (almost) « solve » the problem. Even with GOCE, however, repeat-track analysis will still be needed because of small scales of geoid. GOCE will be used with an altimetric MSS to derive $<\eta>_t$ that can then be added to η'.

Due to the problem of geoid errors at small space scales (< 500 km), most altimetric analyses for oceanographic purposes have concentrated on the time-varying signal.

The mean signal can be removed by a collinear or **repeat-track analysis**, which removes the marine geoid (stationary in time), any mean errors, but also the mean ocean circulation.

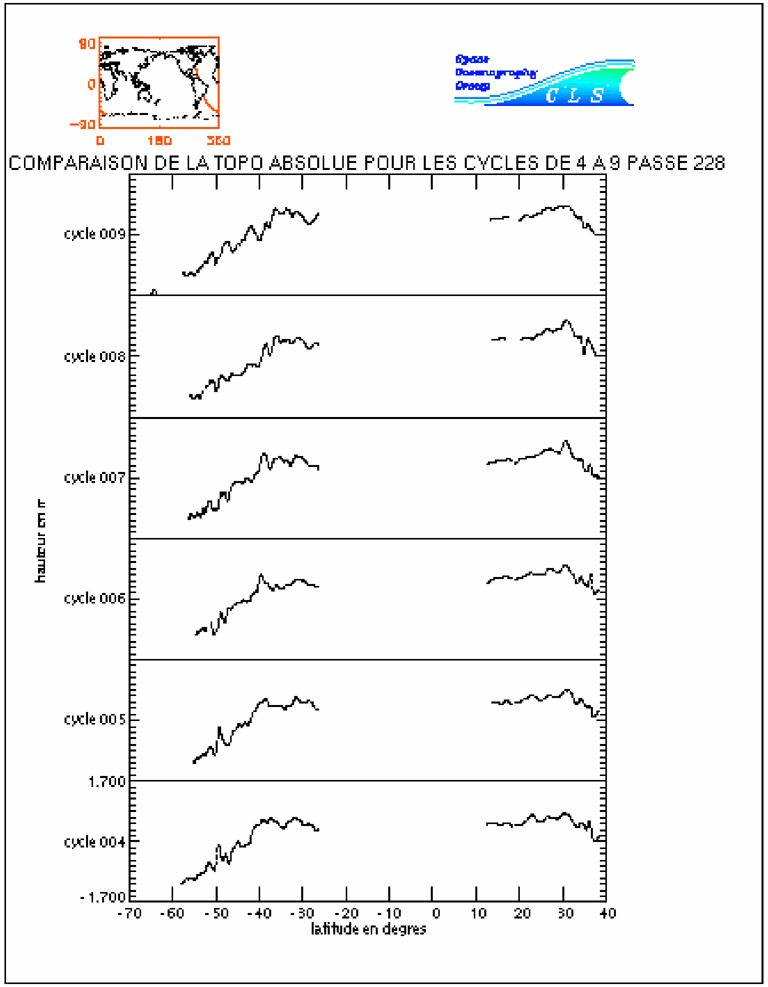
Steps for each track :

1. Calculated the corrected sea surface height at each point.
2. Edit the 1 sec (7 km) alongtrack data to remove anomalous points.
3. For each cycle, synchronise the alongtrack data onto a regular 7 km latitude grid by interpolation.
4. Remove a mean profile or reference profile (the most complete).
5. Remove any long wavelength radial orbit error using a chosen model (sinusoid, bias and tilt, etc). Not necessary for T/P / Jason.

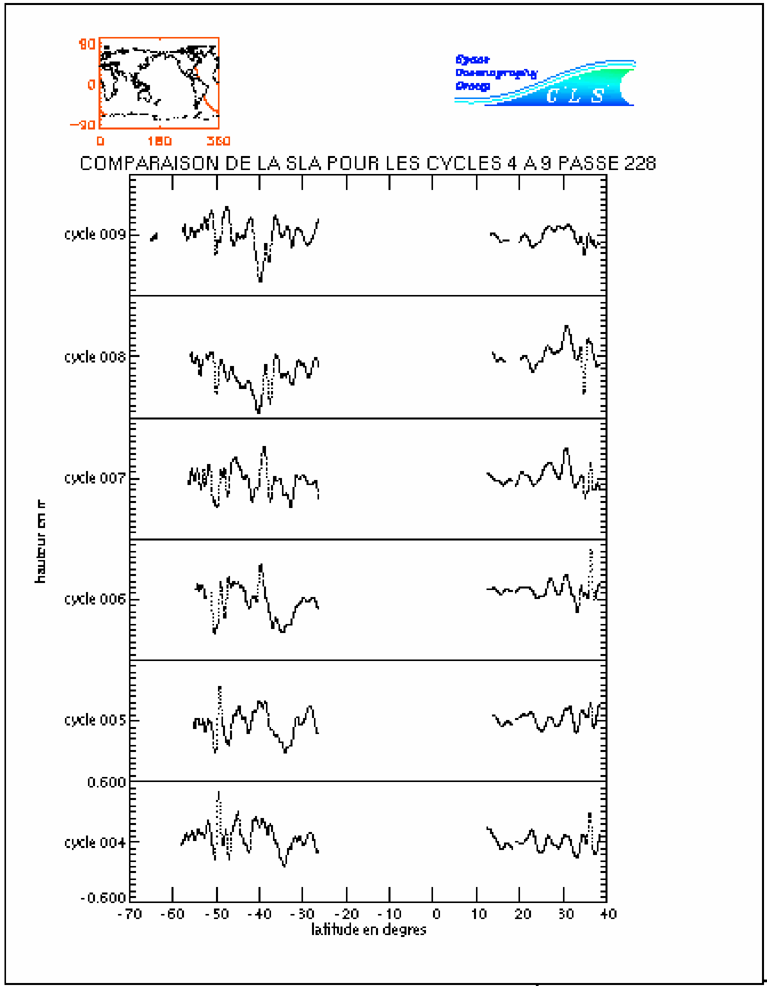


Repeat Track Analysis

Corrected SSH including mean ocean profile



After removal of mean profile



Example

Altimeter data processing (3)
Mapping

For most applications, it is necessary to construct map (and error) of the altimetric signal (SLA) on regular space/time grids

This can be done using optimal interpolation methods which use an a priori knowledge of the space and time scales of the ocean signal.

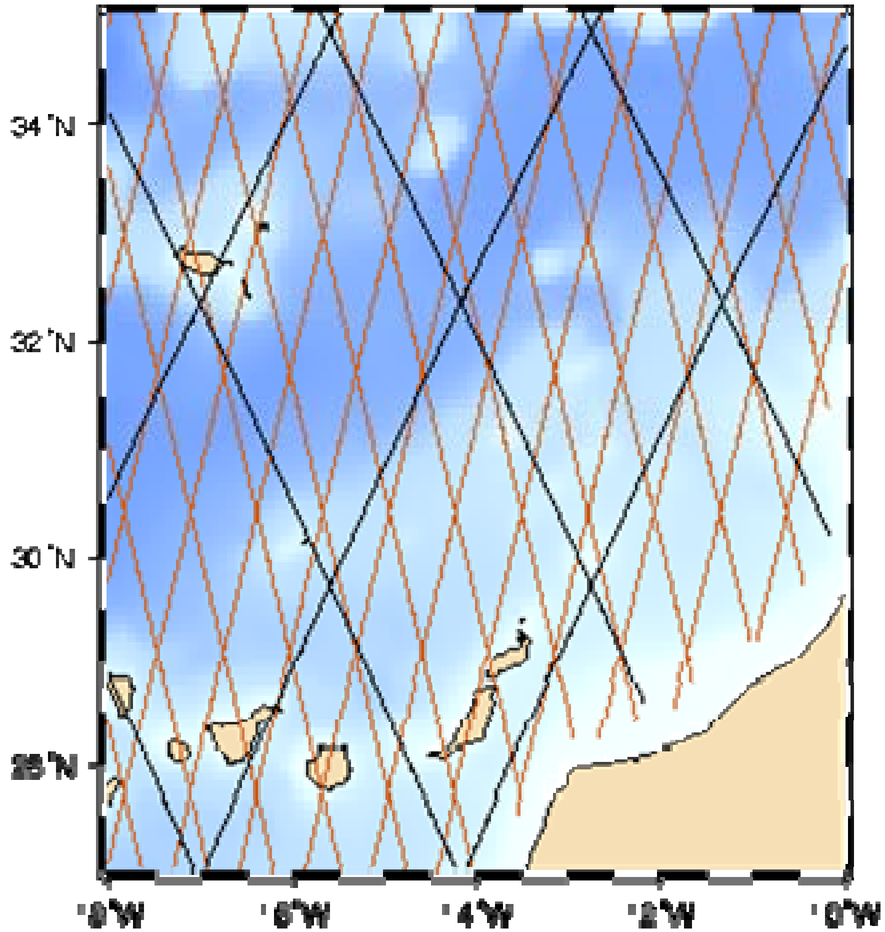
For altimetry, it is preferable to take into account an along-track Long Wavelength Error (LWE) (correlated noise) (e.g. due to orbit, tidal or inverse barometer errors) in the method (Le Traon et al., 1998).

Mapping alongtrack data onto a regular grid

This Figure shows a 35-day coverage of T/P tracks (black) and ERS tracks (brown). During this time, there will be 3.5 T/P cycles and one single repeat of the ERS tracks.

For many oceanographic applications using time series analysis or spatial analysis, the data are easier to use on a regular grid.

Thus optimal mapping techniques are developed to transform alongtrack SSH measurements with irregular space and time distributions onto a regular grid.



Mapping altimeter data with objective analysis

Determine the value of a field θ (θ is here SLA) at a point in time and space, given various measurements of the field unevenly spread over time and space , i = 1,...,n. The best least-squares linear estimator $\theta_{est}(x)$ is given by (Bretherton et al., 1976):

$$\theta_{est}(\mathrm{x}) = \sum_{i=1}^{n}\sum_{j=1}^{n} A_{ij}^{-1} C_{xj} \Phi_{obs^i}$$

with $\Phi_{obs^i} = \Phi_i + \varepsilon_i$, where Φ_i is the true value and ε_i the measurement error.

A is the covariance matrix for the observations themselves, and C the covariance vector for the observations and the field to be estimated:

$$A_{ij} = \left\langle \Phi_{obs^i} \Phi_{obs^j} \right\rangle = \left\langle \Phi_i \Phi_j \right\rangle + \left\langle \varepsilon_i \varepsilon_j \right\rangle \qquad C_{xi} = \left\langle \theta(x)\, \Phi_{obs^i} \right\rangle = \left\langle \theta(x)\, \Phi_i \right\rangle$$

Objective analysis has been used in many altimetric applications to map sea level variations from along-track data. Given the high number of altimetric measurements, the method is “sub-optimal” : only useful data, i.e. values close to the point to be estimated, are used.

Objective analysis for mapping altimetry data

Objective analysis mapping uses a **weighting scheme** to **map irregular data onto a regular grid**.

Space-time covariance model used, e.g. :

$F(r,dt) = [1 + br + 1/6(br)^2 – 1/6(br)^3]e^{-br}\ e^{-(dt/rct)2}$

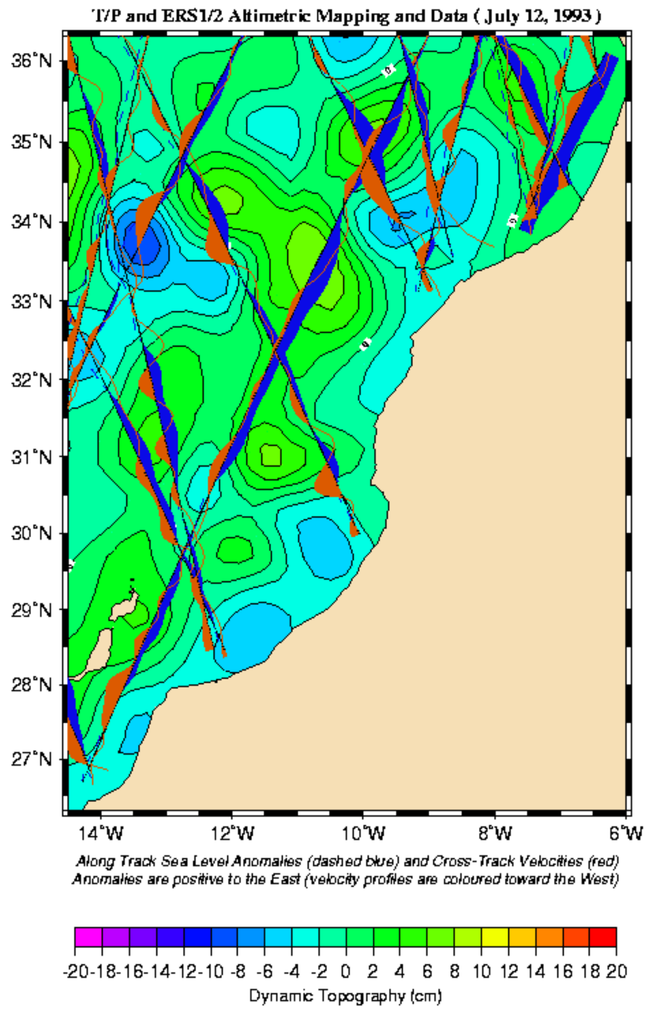
Here r is the non-dimensional radius :

$r = \sqrt{(dx^2/rcx^2 + dy^2/rcy^2)}$

This function uses different space lags (dx, dy) and time lags (dt).

The choice of decorrelation space and time scales is a balance between resolving the mesoscale ocean signals and having enough data, taking into account the altimetry groundtrack separation and repeat period.

At mid-latitudes, **typical decorrelation space scales** are rcx/rcy = 100/200 km, with **time scales**, rct = 20 days.

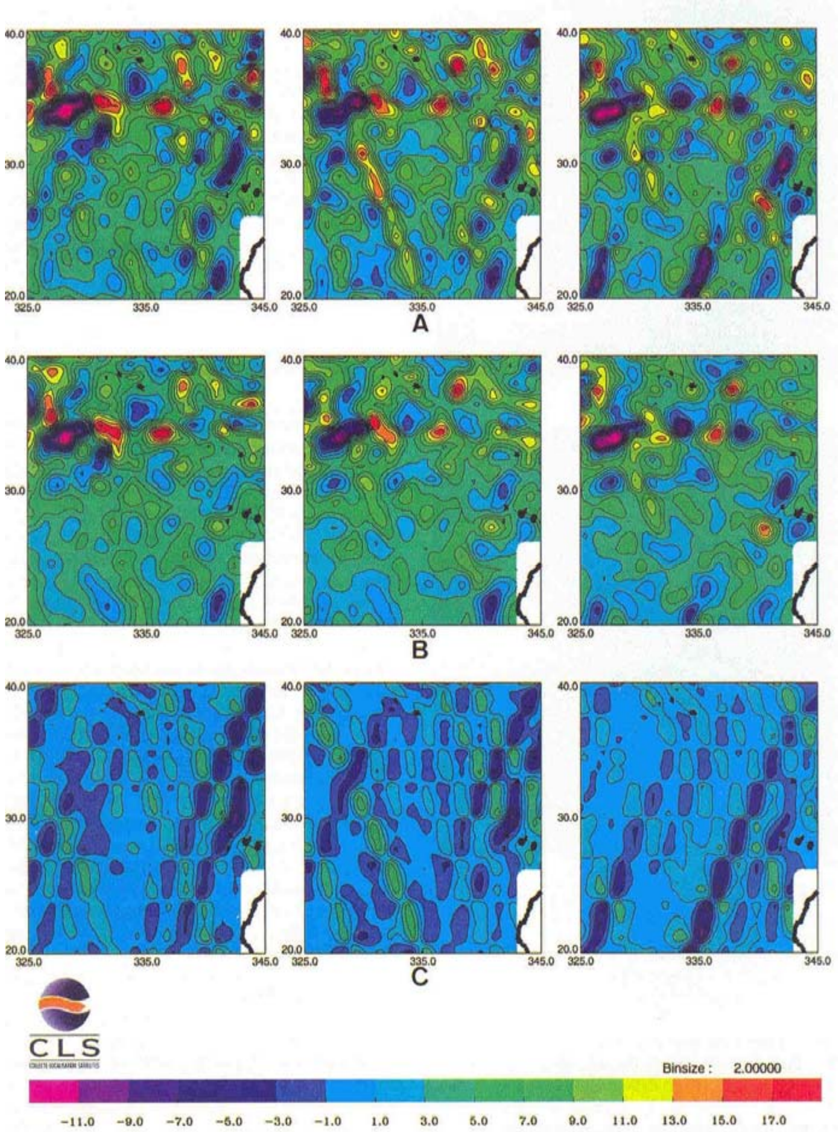


Taking into account long wavelength errors in the mapping technique

Without LWE

With LWE

Diff.



The noise covariance $<\varepsilon i\ \varepsilon j>$ is usually diagonal. Here is takes the following form:

$<\varepsilon i\ \varepsilon j> = \delta i,j\ b^2$ for points i, j not on the same track or in the same cycle

$<\varepsilon i\ \varepsilon j> = \delta i,j\ b^2 + E_{LW}$ for points i, j on the same track and in the same cycle

B^2 is the variance of the white measurement noise and E_{LW} is the variance of the long wavelength error.

Le Traon et al. (1998)

Altimeter data processing (4)

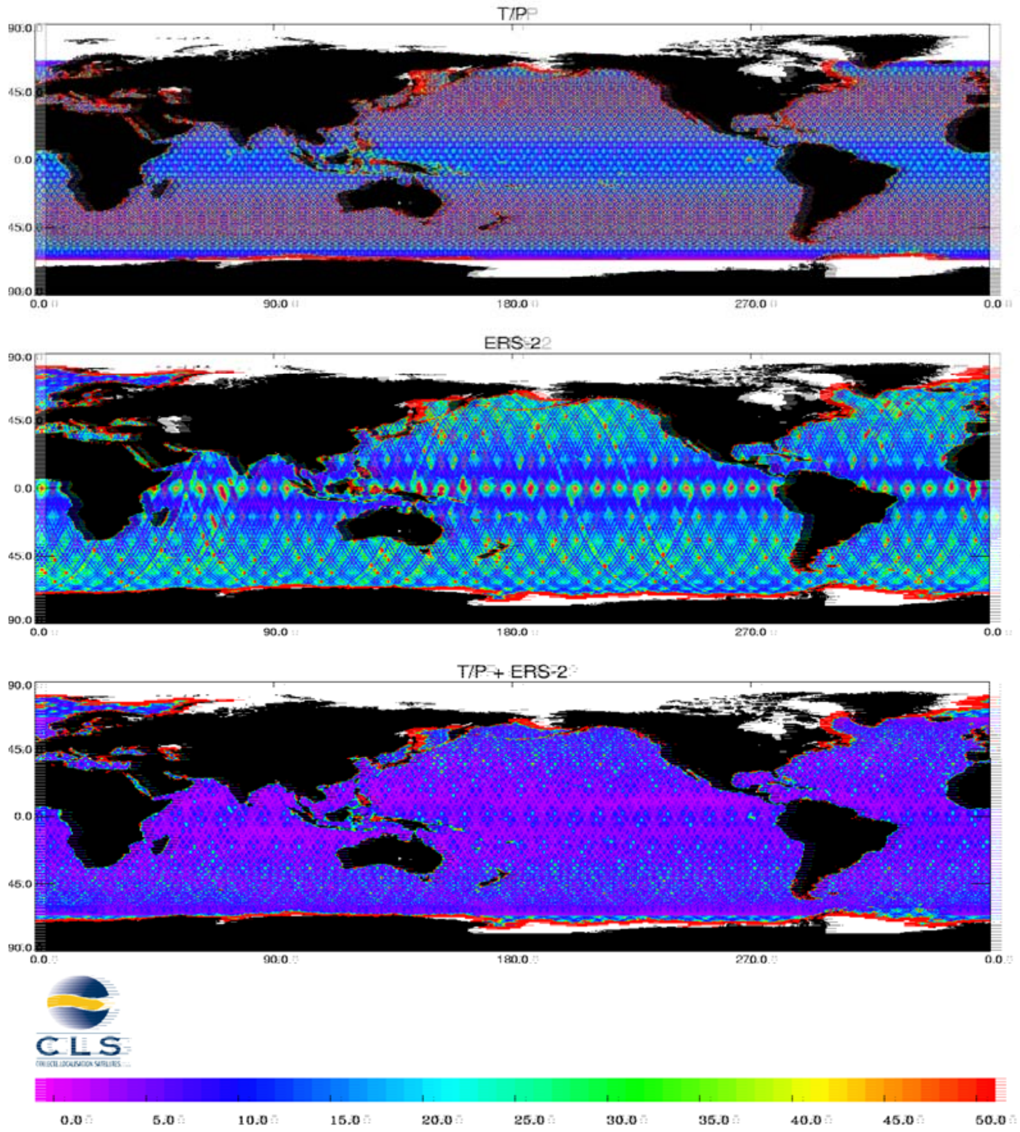
Merging of multiple satellite altimeter data

The merging of multi-satellite altimetric data sets is necessary for a better mapping of sea level and oceanic circulation variations

To merge muti-satellite altimetric missions, it is first necessary to have homogeneous and inter-calibrated data sets. Proposed methodology = use the most precise mission (T/P, JASON) as a reference for the other satellites (Le Traon and Ogor, 1998).

To extract the SLA, it is preferable to use a common reference surface to get the SLA relative to the same ocean mean.

The different data sets can then be merged them via a mapping technique (or directly in the assimilation procedure).



Formal Error (in % of signal variance) derived from objective analysis

Altimeter data processing (5)

Real-time aspects

Altimeter data (if required during the mission design) can be acquired and processed in near real time (1-2 days) (e.g. ERS-1/2, JASON, ENVISAT).

Data are, however, less accurate because the orbit computation need environmental parameters which cannot be obtained in real time.

Need specific processing for correcting orbit error

Need continuous comparison of real time products with precise delayed products to assess the accuracy

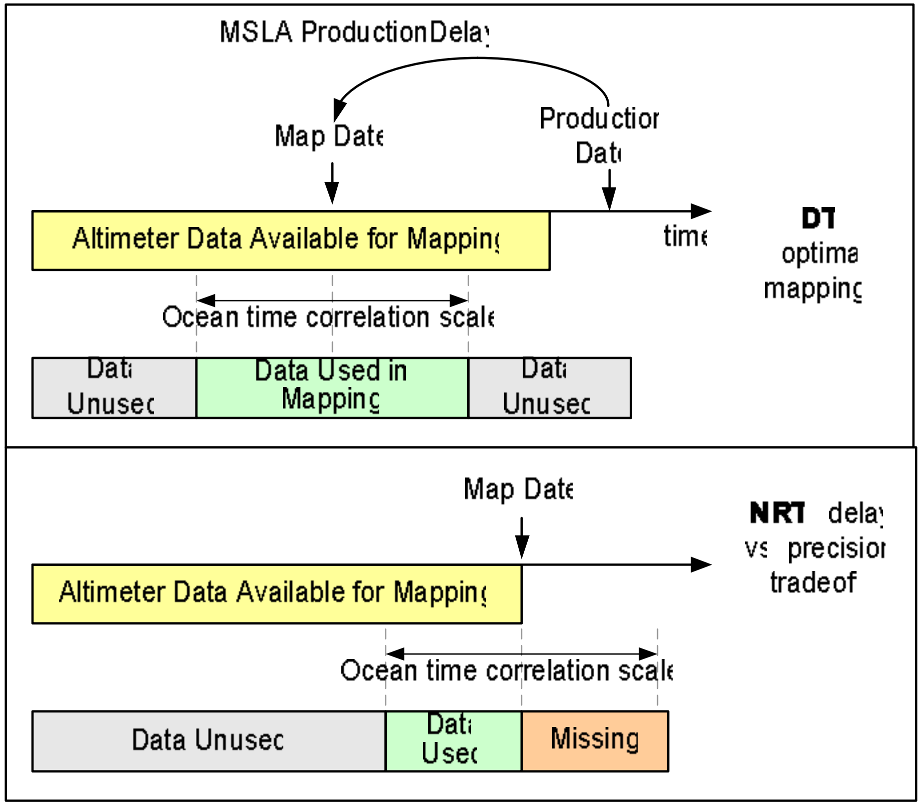
Assess the quality of NRT altimeter observing system

Main sources of errors in near real time

• Orbit error (POE → MOE)
minor error thanks to the long wave length error correction procedure

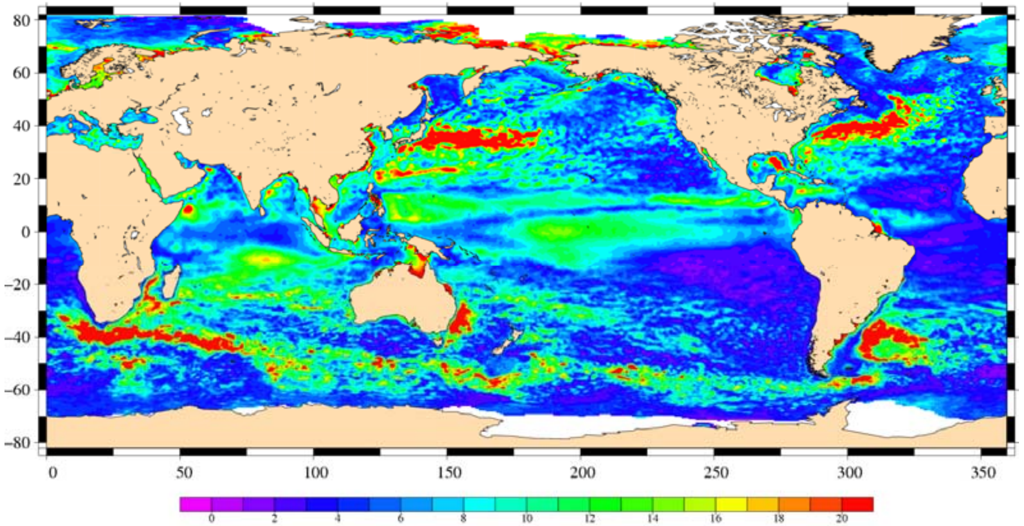
• Data availability
delay in the data delivery
number of missions available

•**Time window** used for data selection in the mapping since we need estimation as recent as possible in NRT



Dibarboure et al., 2007 (SSALTO/DUACS system)

Impact of the satellite configuration (DT analysis)

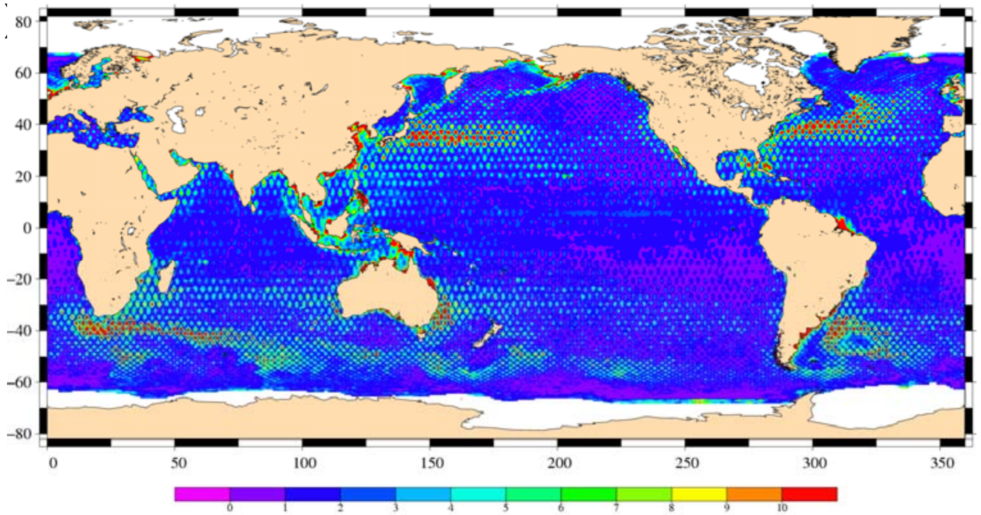


0 10 20(cm)

rms of sea level anomaly (SLA) estimated with 4 altimetric missions

2 DT satellite configuration is a minimum to provide a relatively good description of mesoscale activity

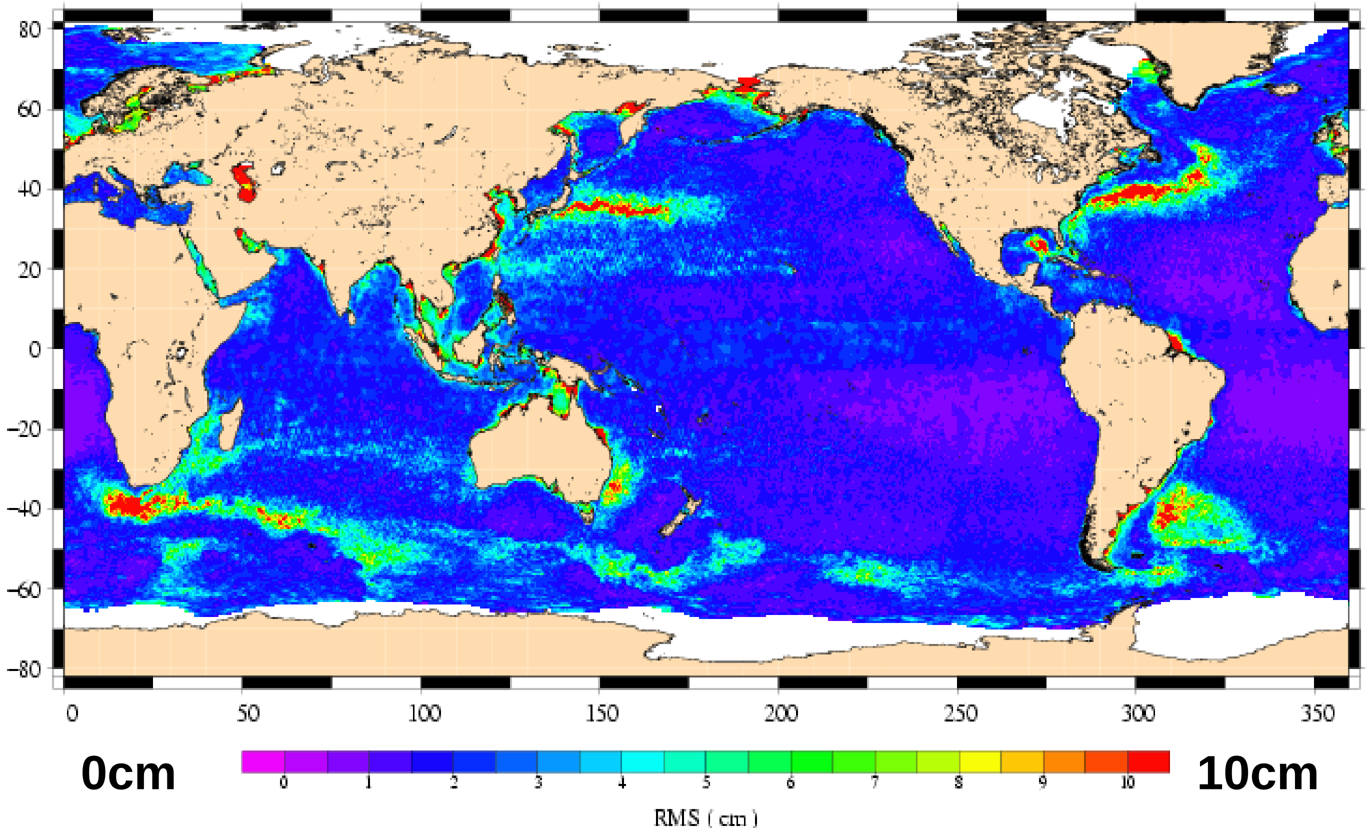
4 satellites configuration improved this description and could be indispensable for specific area (Med for instance)



0 5 10(cm)

rms of SLA differences between 4 and 2 satellites

Degradation of the NRT products (versus DT)



RMS of the differences between delayed and real time SLA
Estimation done with 4 satellites configuration

Comparison with drifters data

	Delayed Time		Real Time	
	2 missions	*4 missions*	*2 missions*	*4 missions*
U	26.6	24.2	31.0	26.9
V	33.1	28.1	41.2	33.4

Mean square differences between drifter and surface velocities (AVISO+ Ekman= SURCOUF)
Units are % of drifter variance.

Comparison with tide gauge data

	2 missions	*4 missions*
Dealyed time Old corrections *(GOT99+IB)*	46.7	35.3
Delayed time new corrections *(GOT00+DAC)*	36.7	29.7
Real time Orbit error No-centring	45.2	37.1

Mean square differences between tide gauge and altimeter sea level.
Units are % of tide gauge variance.
DAC = IB+MOG2D (Dynamic Atmos. Cor.)

“On the quality of real time altimeter gridded fields: comparison with in situ data“, Pascual A., C. Boone, G. Larnicol, P. Y. Le Traon (submitted to JAOT)

Mean dynamic Topography

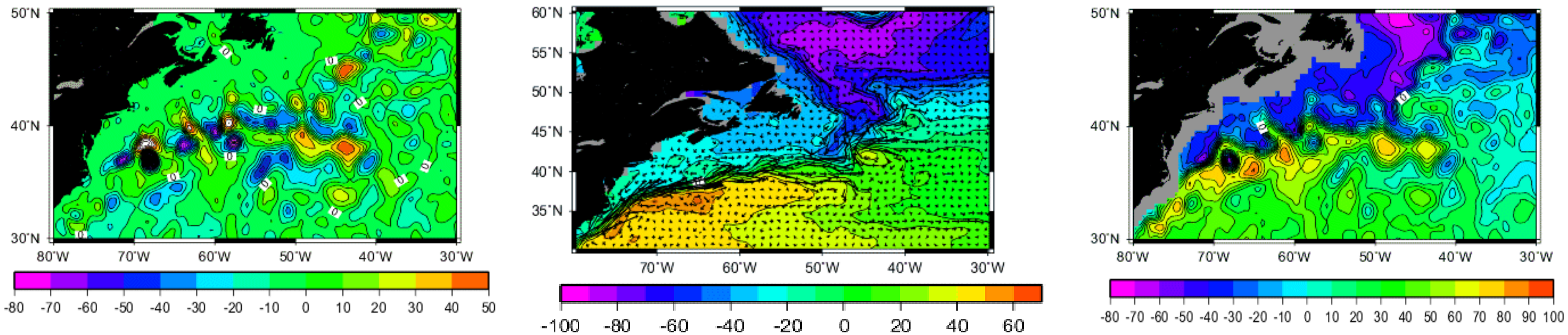
- Most altimeter studies have been focused on the analyis of sea level and velocity anomalies because of geoid large errors
- With GRACE, GOCE and new techniques derived from in-situ, one can now compute precise MDT (not perfect though) that give access to abolute dynamic topography
- A major change in the use of altimeter data

Impact for oceanography

Compute the ocean Mean Dynamic Topography with unprecedented resolution and accuracy: MDT= MSS - Geoid

- Access to the ocean absolute dynamic topography **from all past, present and future** altimetric missions:

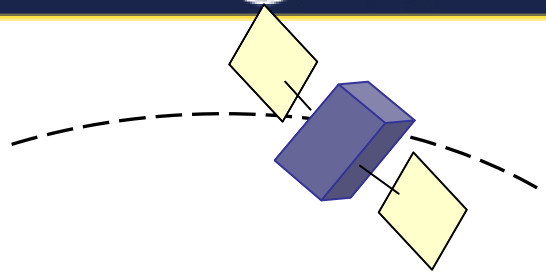
SLA + MDT RIO05 = ADT



- Assimilation of absolute altimetric data into operational ocean forecasting systems

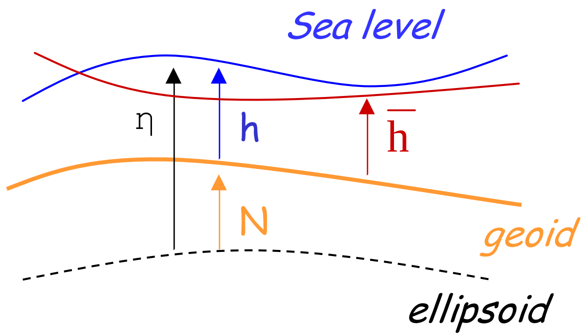
Improved analysis and forecasting capabilities
Improved transport estimates
Large impact for ocean and climate monitoring

Rio et al. , 2007



1 $h = \eta - N$ → **Yesterday** (EGM96): 3 cm 1200 km
Today (GRACE): 3 cm 200 km
Tomorrow (GOCE): 3 cm 70 km

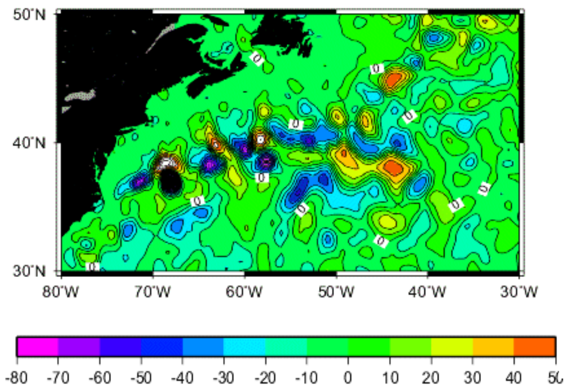
TOPEX 1 Hz (resolution 6-7 km) : error < 3 cm

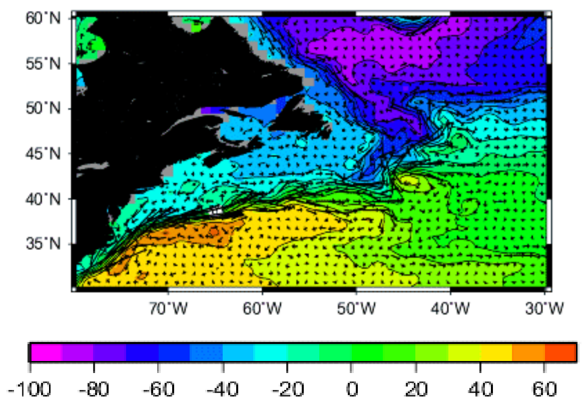


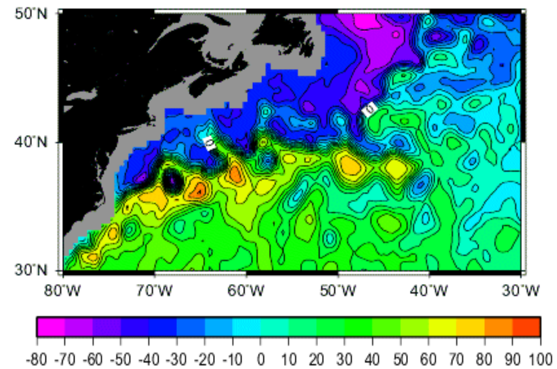
2 $\overline{h} = \overline{\eta} - \overline{N}$

3 $h = h' + \langle h \rangle$

1 - 2 $h' = \eta'$ SLA + MDT $\langle h \rangle_{93-99}$ = Absolute dynamic topography

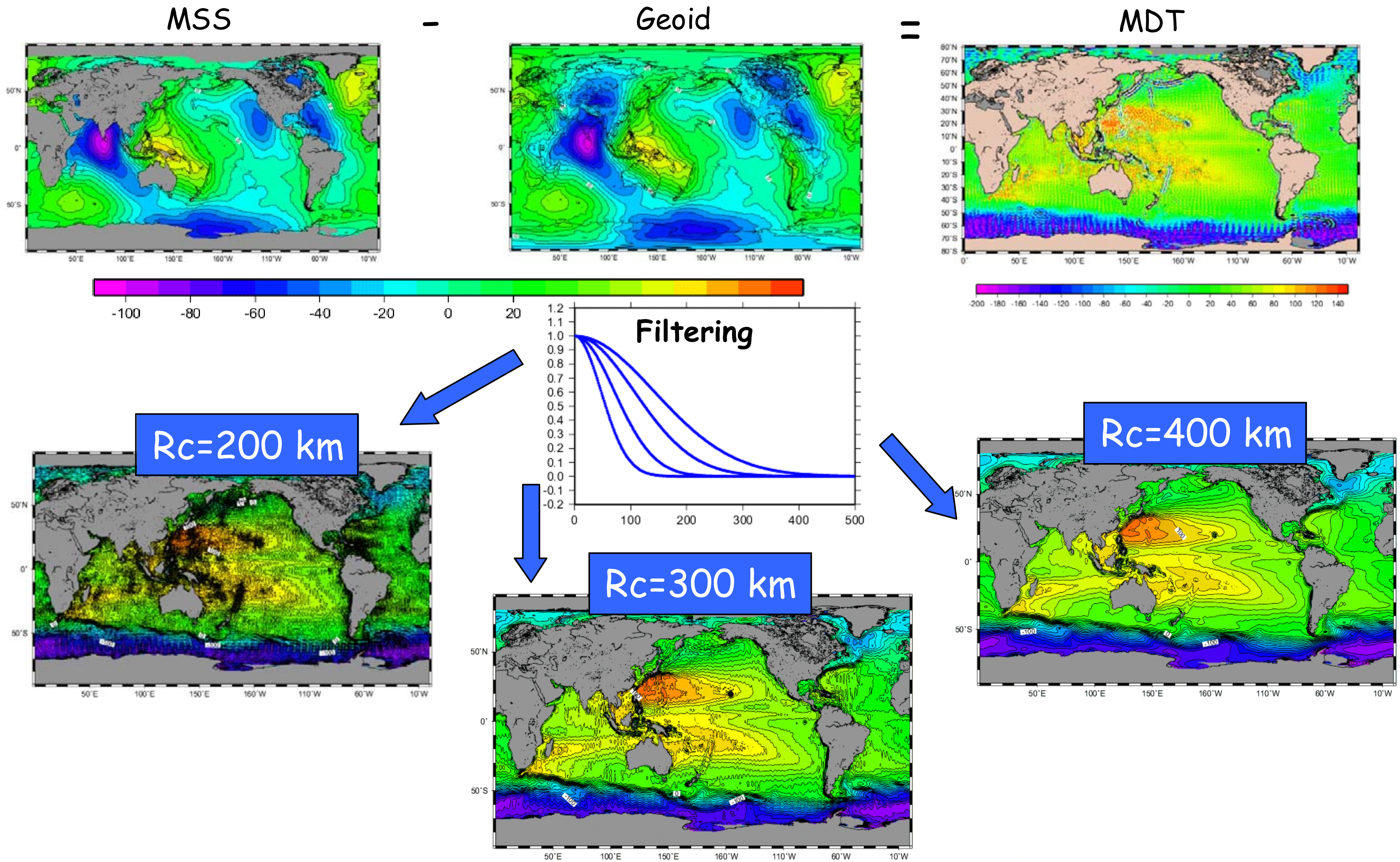






MDT estimation

A Direct method

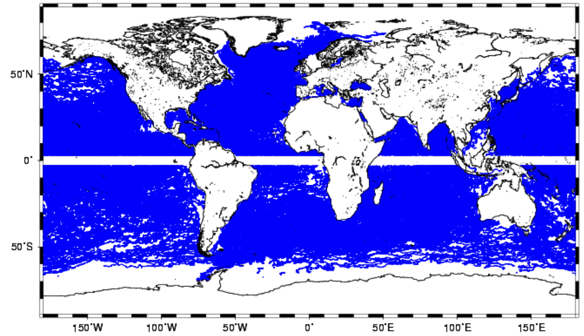


B Synthetic method (Rio et al., CLS)

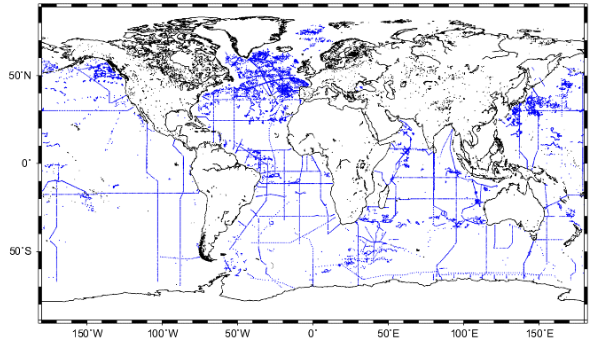
- **In-situ observations**

Drifting buoys 1993-2003

Dynamic Heights relative to 1500 m 1993-2003



Barotropic component approximated through (SMO-GRACE-Levitus1500)



- **Altimeter data**

Maps of SLA distributed by AVISO

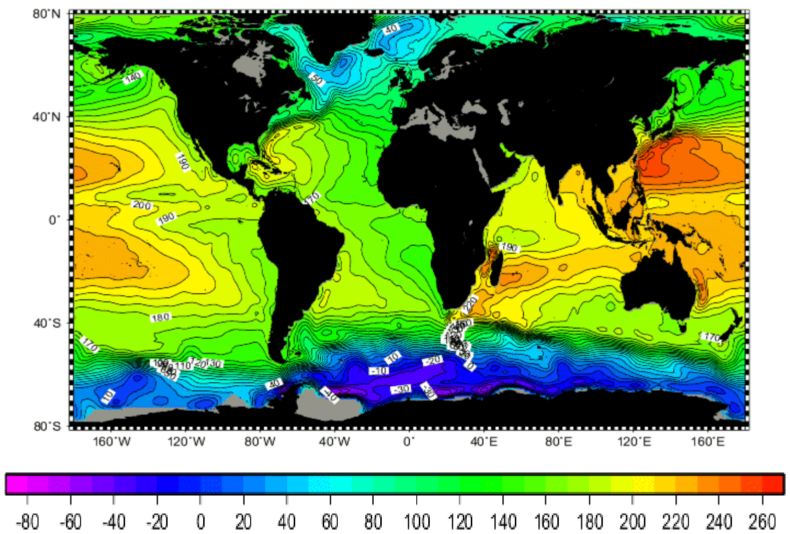
Interpolation altimeter anomalies (h',u',v') at the in-situ measurement point

$$\langle h \rangle_{93\text{-}99} = h - h' \qquad \langle u \rangle_{93\text{-}99} = u - u' \qquad \langle v \rangle_{93\text{-}99} = v - v'$$

High resolution MDT (direct + synthetic)

Step 1

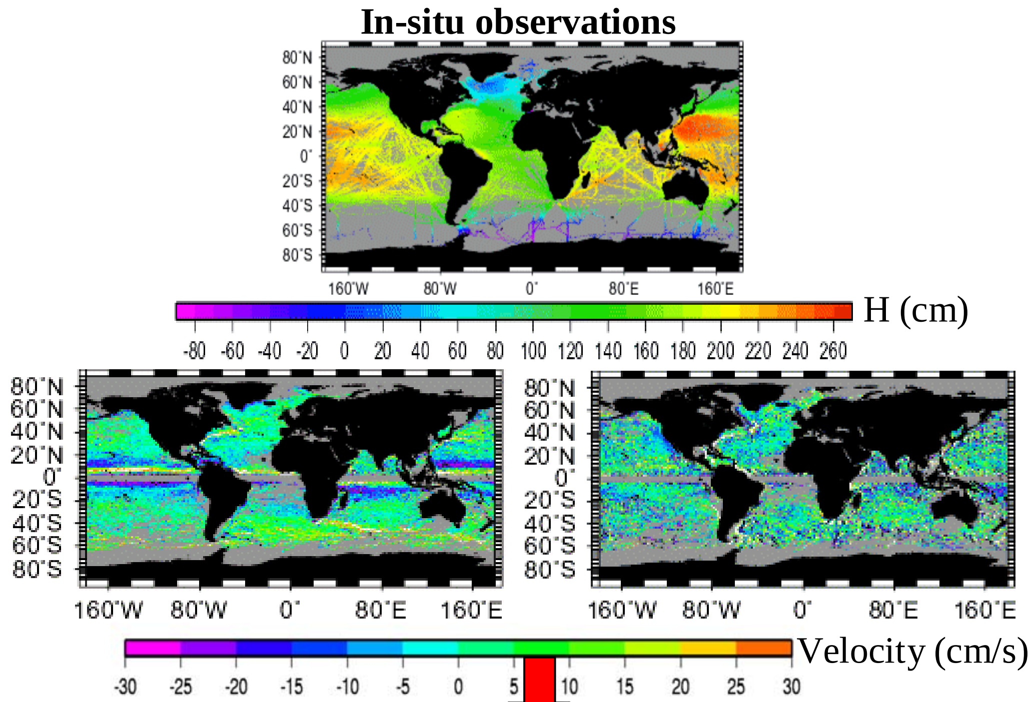
Direct Method
MSS-Geoid



guess

2nd step

Synthetic Method



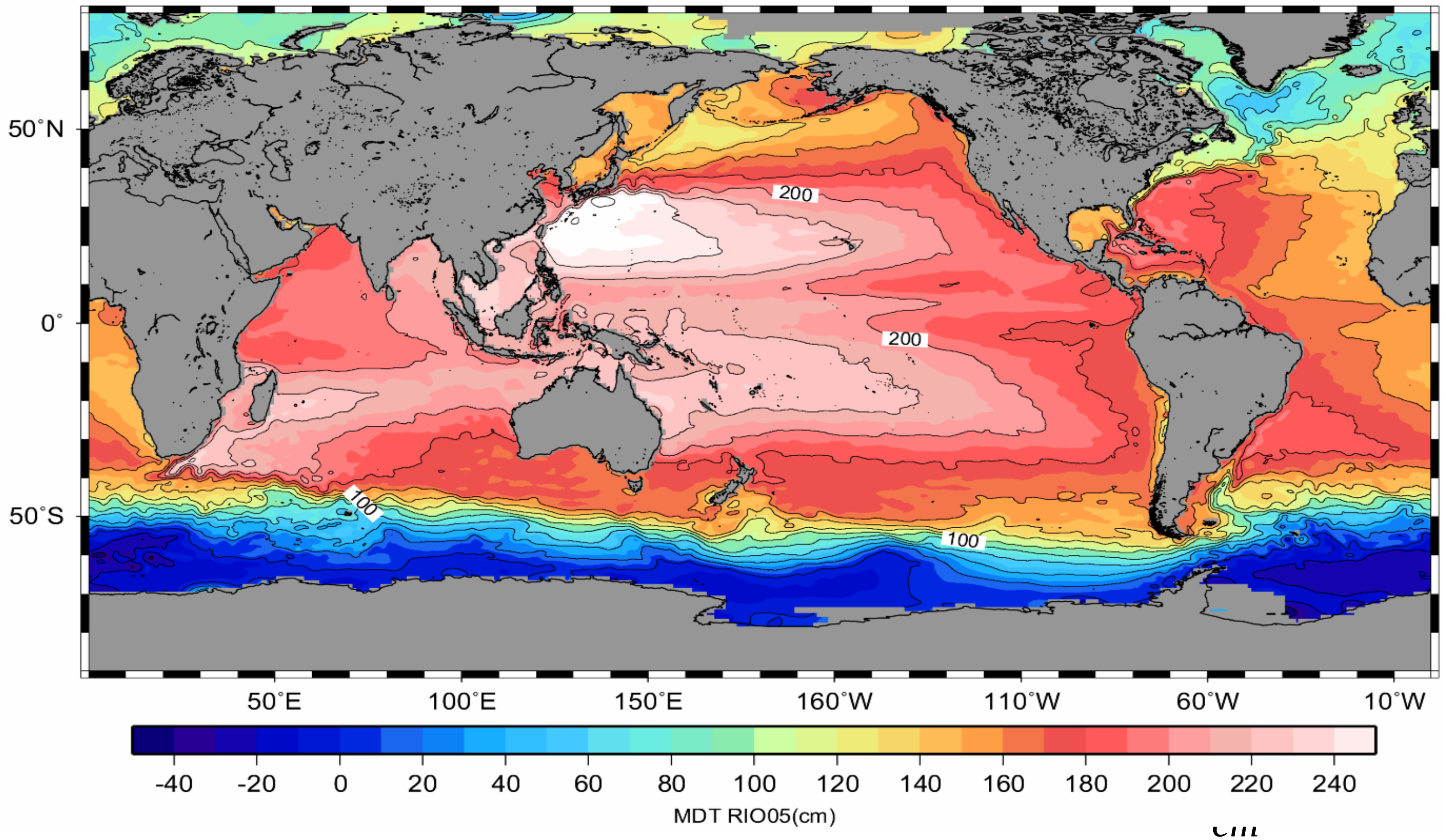
Multivariate optimal analysis

Mean dynamic Topography

Rio and Hernandez, 2004

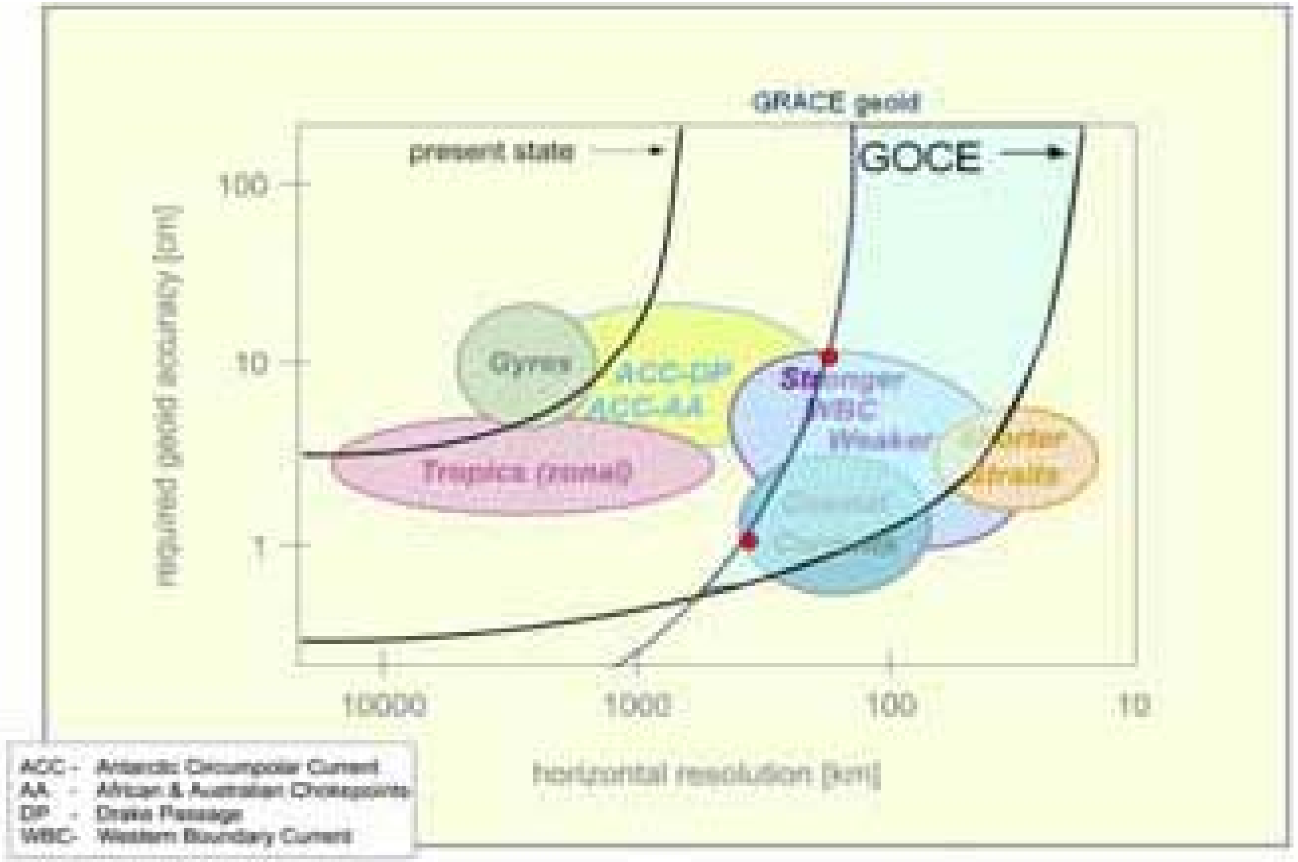
Merged Mean Dynamic Topography RIO05

Guess :EIGEN-GRACE03S 400 km
In-Situ data : drifting buoys and dynmaic heights 1993-2002
0.5°x0.5° grid



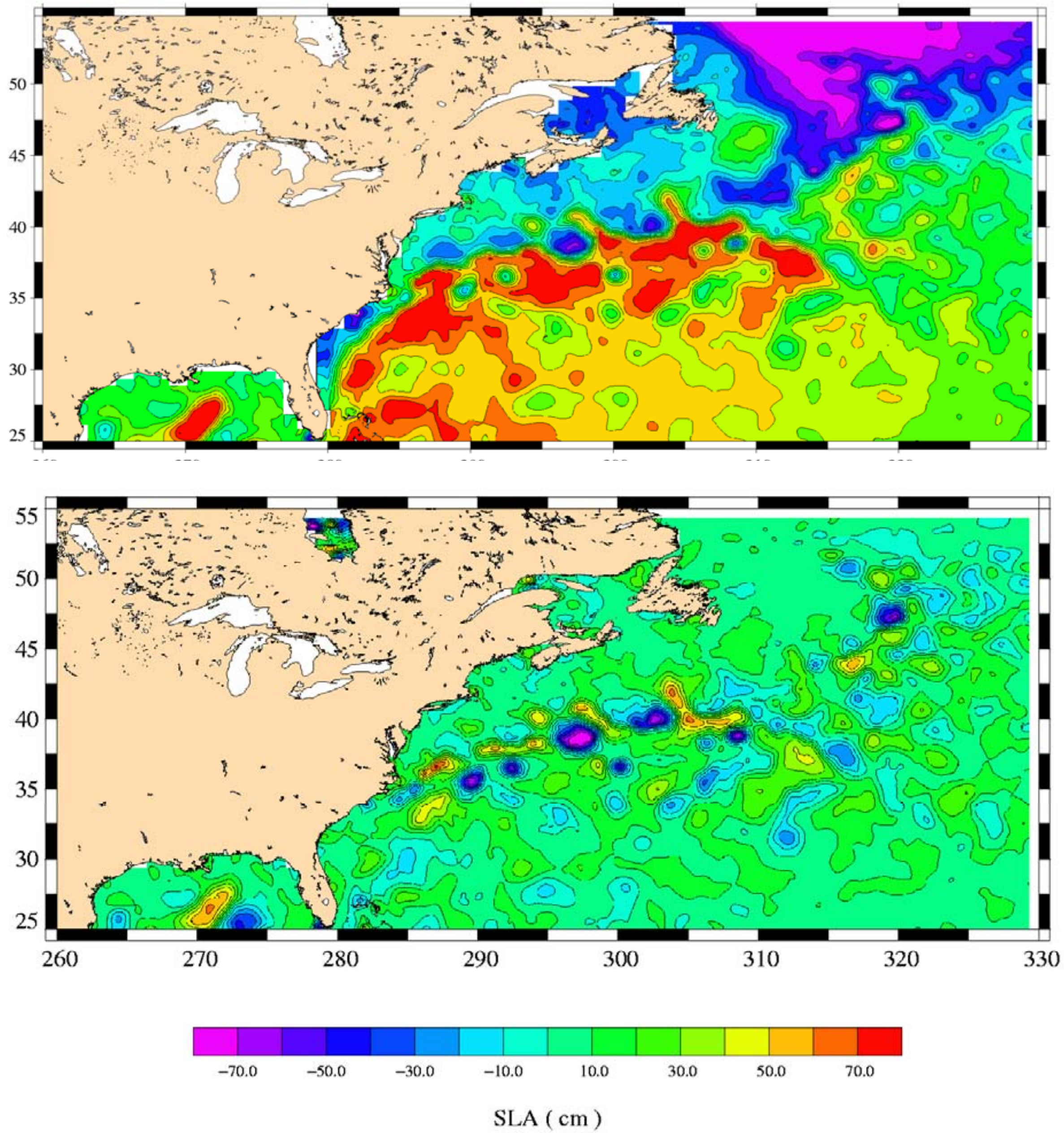
Rio et al, 2005

Yesterday (EGM96), Today (GRACE) and Tomorrow (2008) (GOCE)



Absolute dynamic topography (using Rio et al., MDT) versus sea level anomaly in the Gulf Stream area.

Large impact for ocean forecasting models and data interpretation (Le Traon et al., 2003)



THANK YOU !