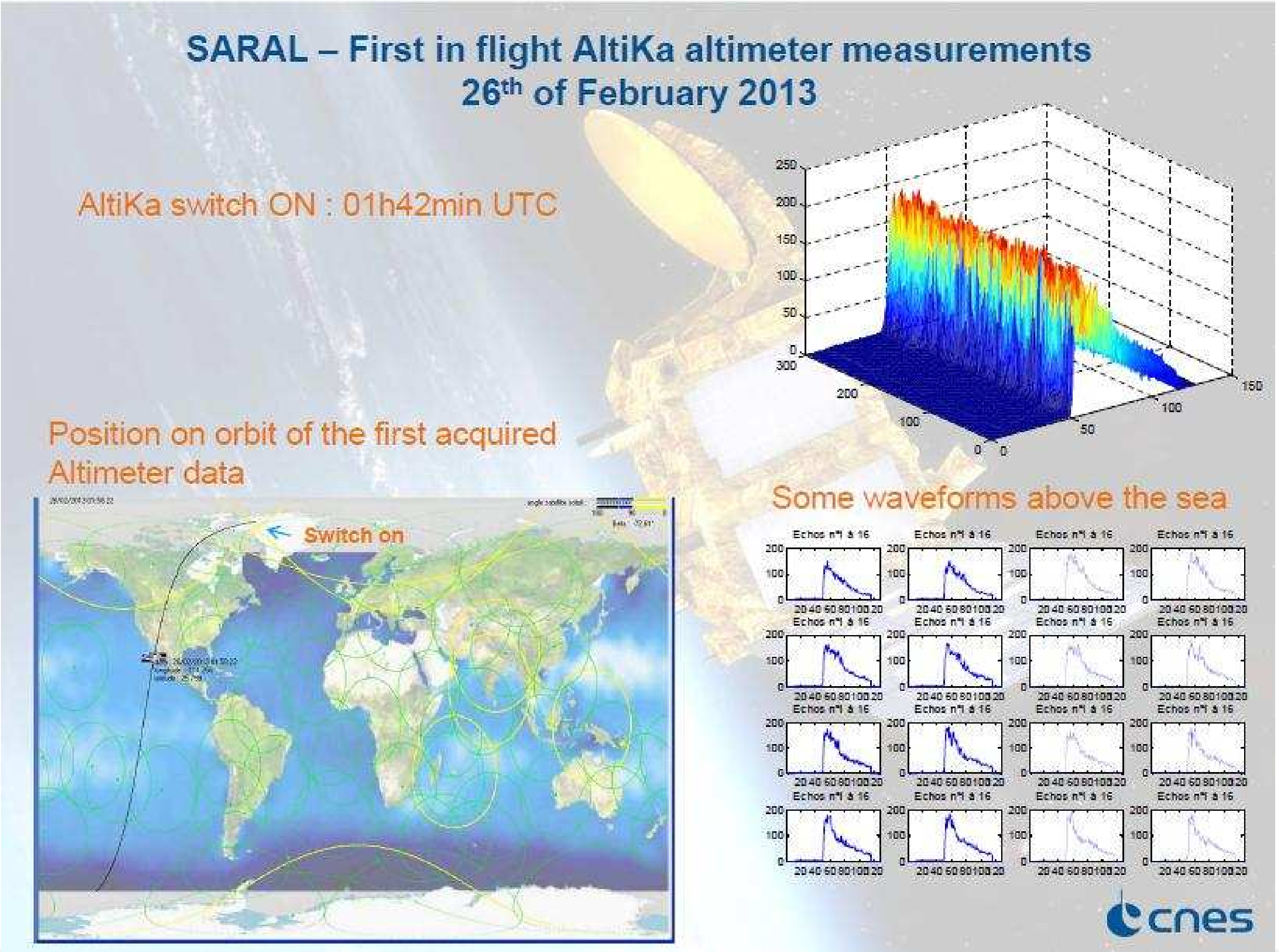
Altimétrie spatiale

Traitement de la mesure : des formes d'onde au bilan de performance système

N. Picot / CNES Toulouse

Traitement de la mesure : **des formes d'onde** au **bilan de performance système**

- ....De la forme d'onde ...



- A la performance système :

Table 6 : JASON-3 ERROR BUDGET (in centimeters)
(for 1 sec average, 2 meters SWH, 11 dB sigma naught)

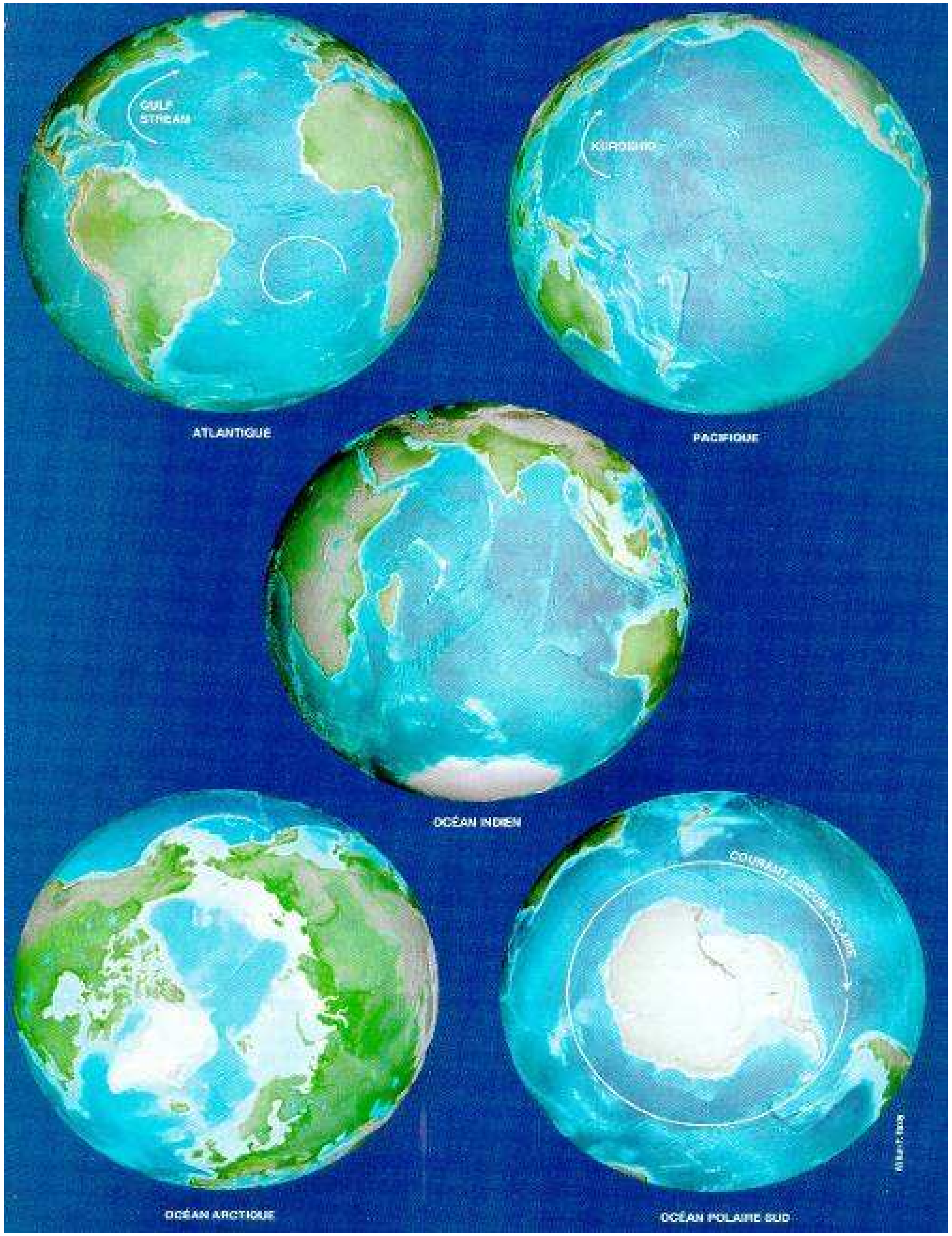
	OGDR 3 hours	IGDR 1 to 1.5 days	GDR 40 days	GOALS
Altimeter noise	1.7 (a)(c)(d)	1.7 (b)(c)(d)	1.7 (b)(c)(d)	1.5 (b)(c)(d)
Ionosphere	1 (e)(d)	0.5 (e)(d)	0.5 (e)(d)	0.5 (e)(d)
Sea State Bias	3.5	2	2	1
Dry troposphere	1	0.7	0.7	0.7
Wet Troposphere	1.2	1.2	1.2	1
Altimeter range RSS	4.5	3	3	2.25
RMS Orbit (Radial component)	6.8 (h)	2.5	1.5	1
Total RSS sea surface height	11.2	3.9	3.4	2.5
Significant wave height	10% or 0.5 m (i)	10% or 0.4 m (i)	10% or 0.4 m (i)	5% or 0.25 m (i)
Wind speed	1.6 m/s	1.5 m/s	1.5 m/s	1.5 m/s
Sigma naught (absolute)	0.7 dB	0.7 dB	0.7 dB	0.5 dB
System drift				1mm/year (j)

Traitement de la mesure : **des formes d'onde**

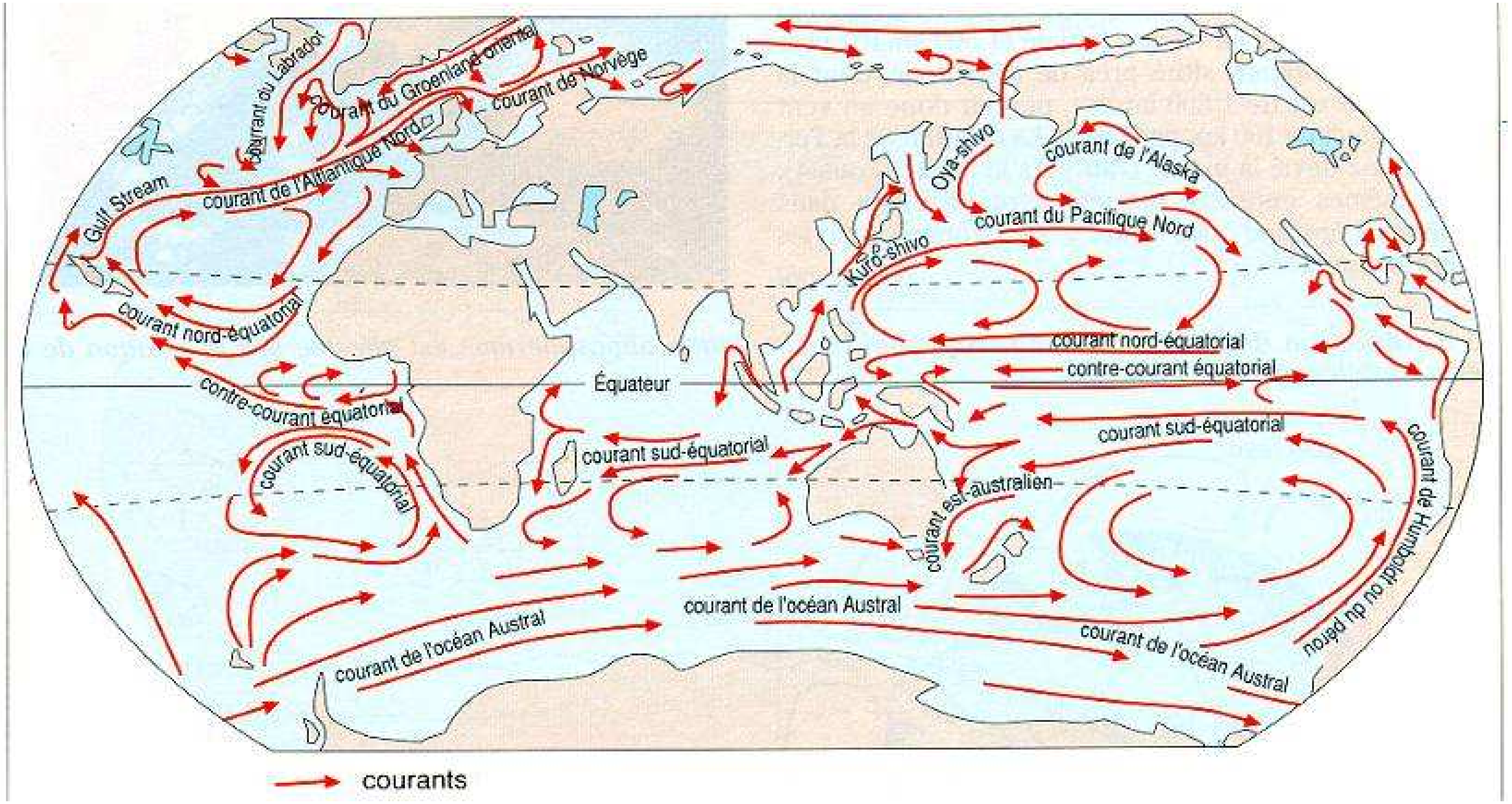
- Elément essentiel du système altimétrique : mais un des contributeurs parmi d'autres
- Très variable selon les différentes surfaces survolées :
  - L'altimètre fonctionne en continu et fournit une intégrale de l'énergie très dépendante de la nature du terrain – topographie mais aussi rugosité.
  - Information discrète avec une résolution spatiale (distance) relativement faible (environ 45 cms) par rapport aux attentes des utilisateurs (1.5 cms)
  - Des évolutions technologiques récentes : le mode SAR (Altimètrie Doppler Along track)
  - Ne couvre pas la future mission SWOT (interférométrie)

- au **bilan de performance système** :
  - Fortement dépendant des applications concernées,
  - Actuellement principalement sur les surfaces 'océaniques' : traduit la précision de détermination de la hauteur de mer et la stabilité temporelle requise pour les applications de type 'Niveau de la mer'.
  - Dépendant de nombreuses méthodes élaborées de traitement, de moyens de validation et de comparaison
  - Et bien sur d'équipes en charge des 'opérations-traitements-validations-évolutions-User_services- …. ', de scientifiques associés au projet, …

- Quelques mots sur la circulation : La topographie signature des courants géostrophiques
- Quelques mots sur les exigences/attentes des utilisateurs
- Le système altimétrique et les techniques de traitement
- L'observation obtenue avec une mission : le besoin de combinaison.

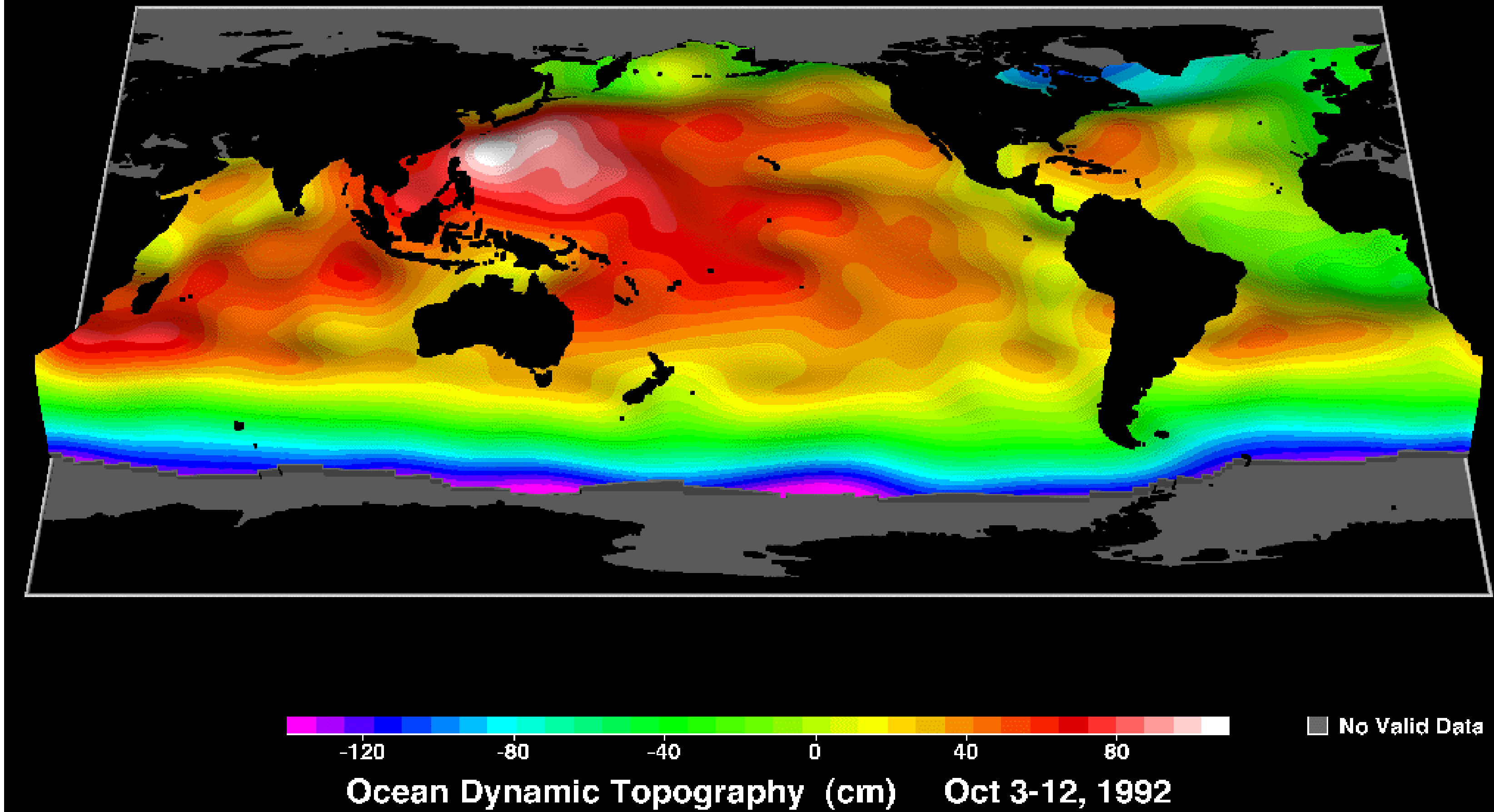


The Ocean is moving all around



An exemple: The Gulf Stream travels at ~ 4 km/hour
transports ~ 80 millions tonnes/second

Sea surface topography reveals ocean circulation Ocean Topography as seen from space by TOPEX-POSEIDON (or any other altimetric mission)

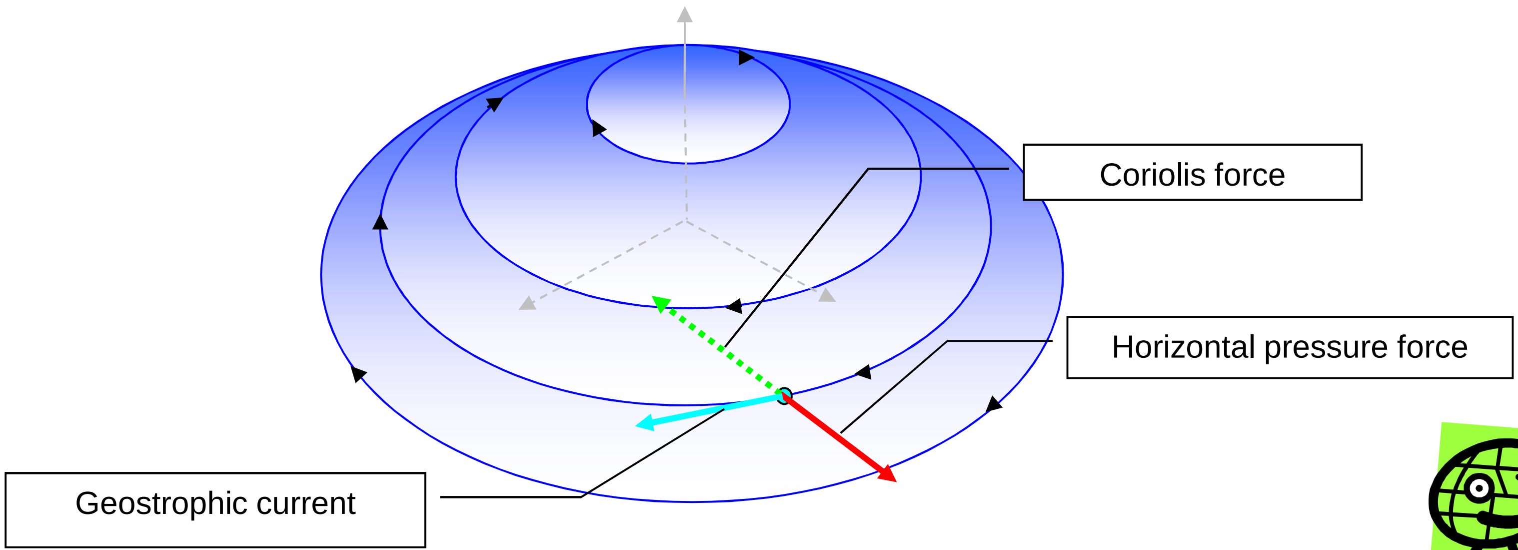


Sea surface topography reveals ocean circulation : the geostrophic equilibrium

A simple model: the geostrophic equilibrium

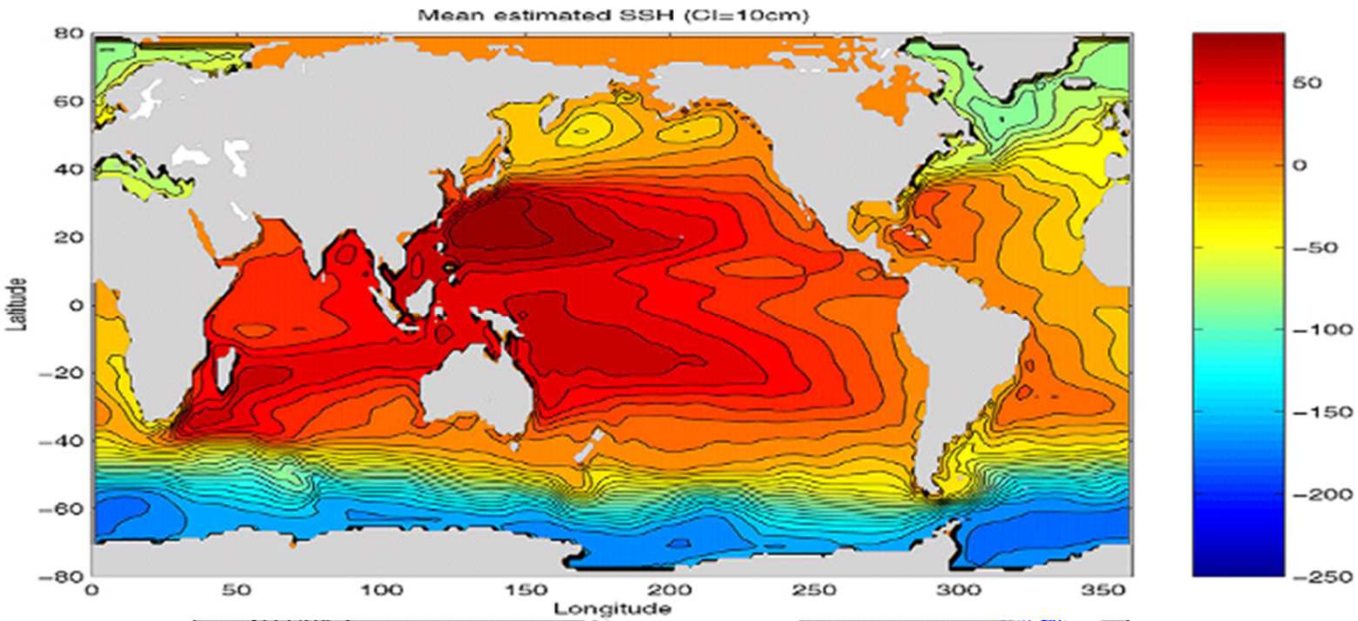
- Main long wavelength ocean currents are geostrophic currents:
    - Coriolis force balanced by gradient of the horizontal pressure force due to the slope of the sea surface (geostrophic equilibrium)
    - always perpendicular to the pressure gradient
- Currents are deduced from the maps of Sea Level Anomaly

- Generation of geostrophic currents on an oceanic bump in the northern hemisphere

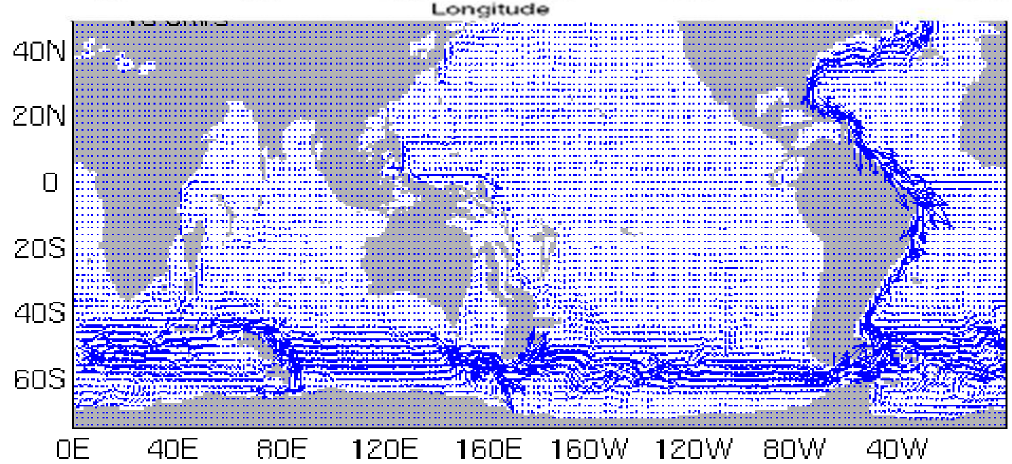


Radar altimetry gives us an “integrated view” of the Ocean circulation

From surface topography



To velocity at 2000 m depth



A very large set of applications

Forecasting the ocean, the Operational Oceanography

Marine meteorology and atmospheric studies

Studying tides

Climate previsions

Level of oceans, enclosed seas and lakes; hydrology

El Niño

Ocean circulation and its variations

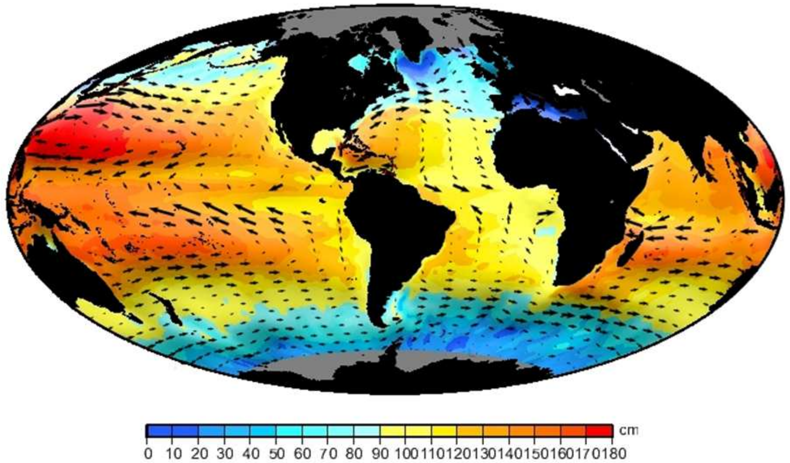
Ice, over seas and lands

Geophysics

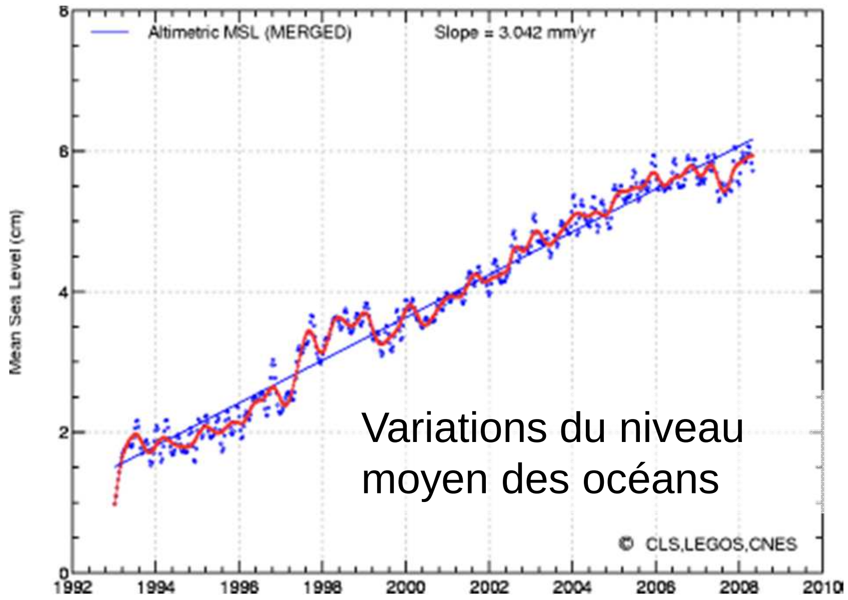
Geodesy

Coastal

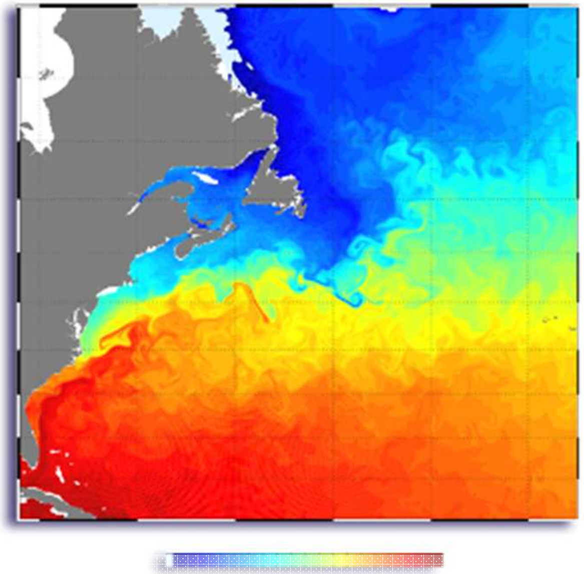
Sur océan : Que voit-on avec les données altimétriques ?



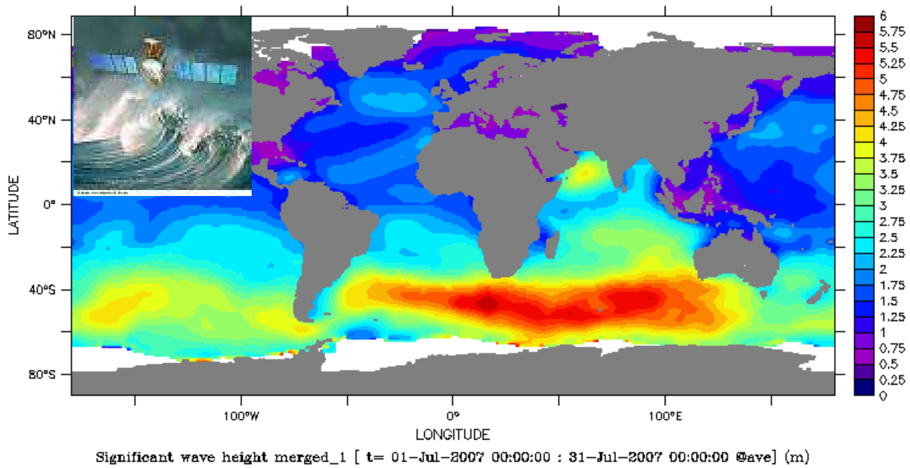
Géoïde et circulation grande échelle



Variations du niveau moyen des océans



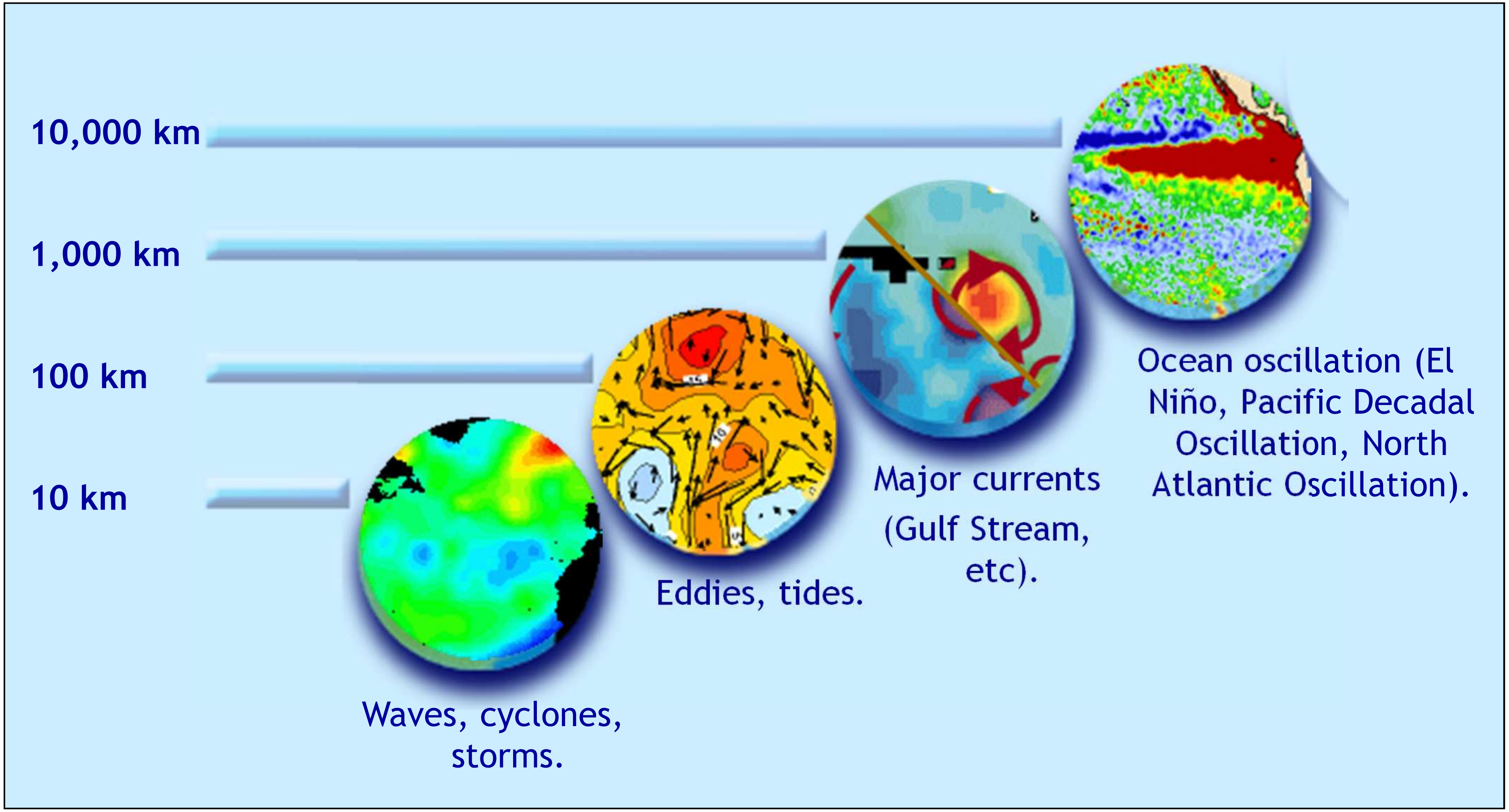
Dynamique océanique:
Courants, tourbillons, marées, 'el niño'



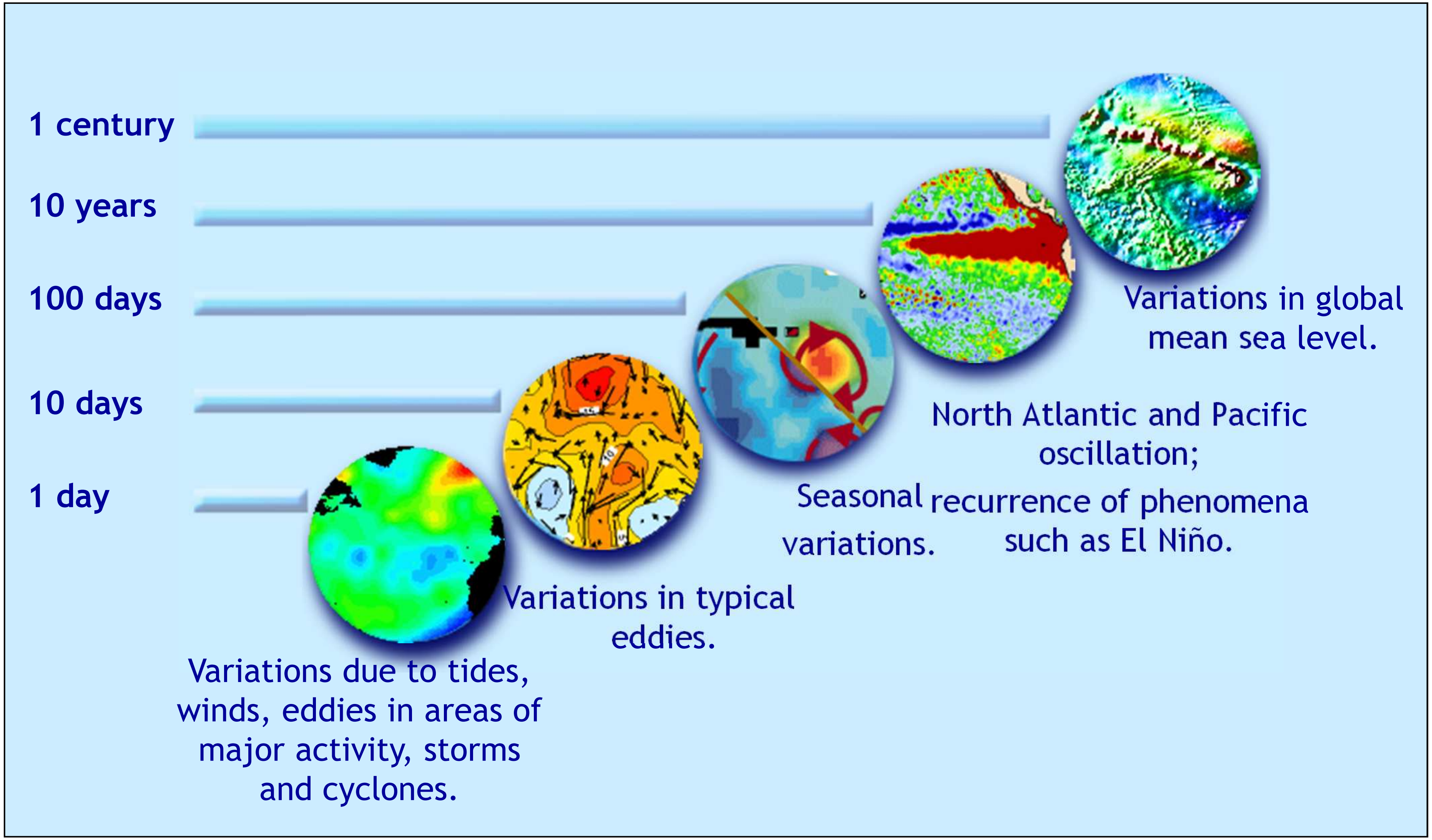
Météo marine: vent, vagues

To study wide spatial and temporal scales

Spatial scales



Time scales

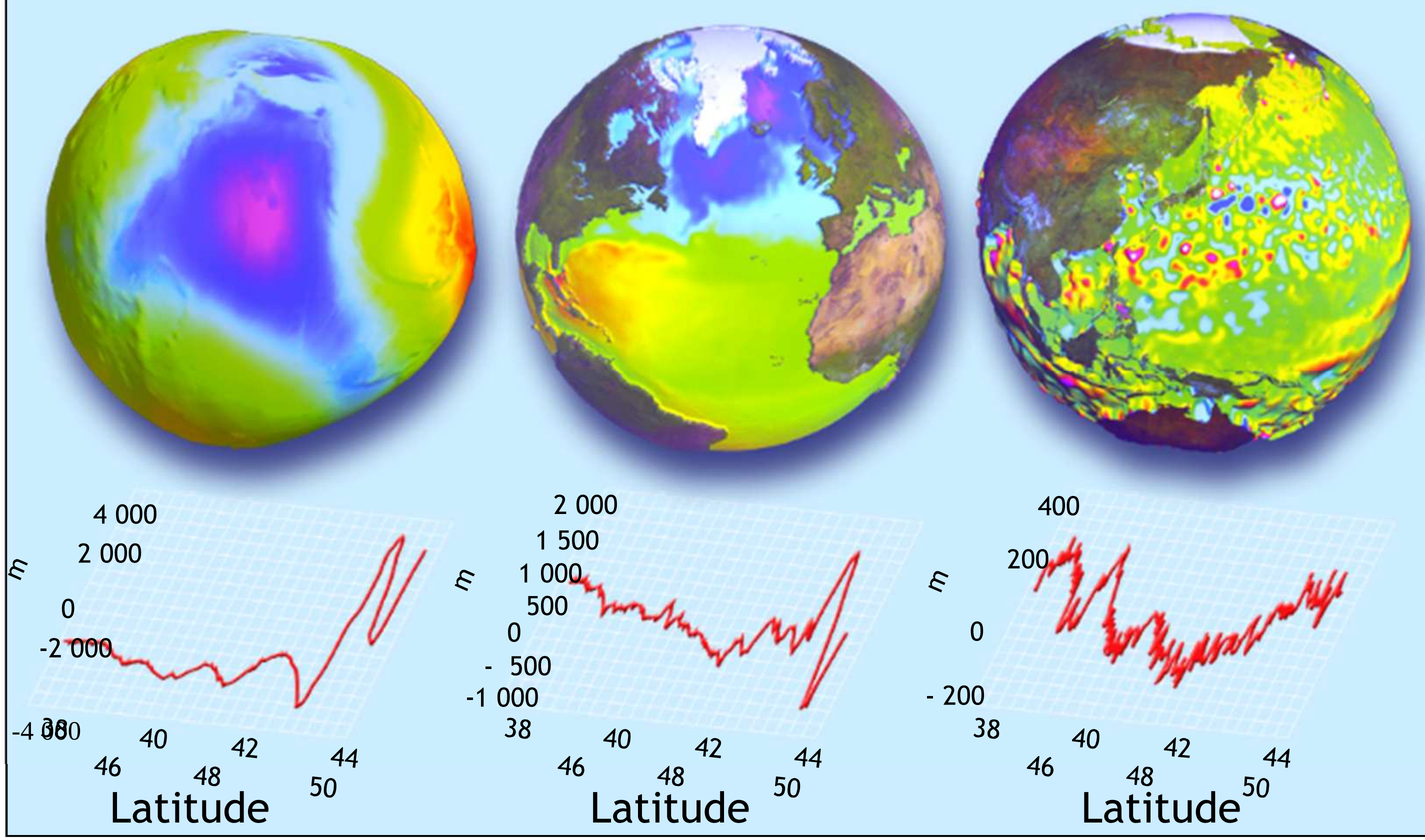

1 century
10 years
100 days
10 days
1 day
Variations in global mean sea level.
North Atlantic and Pacific oscillation; recurrence of phenomena such as El Niño.
Seasonal variations.
Variations in typical eddies.
Variations due to tides, winds, eddies in areas of major activity, storms and cyclones.

Varying amplitude

Geoid undulations:
Amplitude of a several tens of metres.

Major western boundary currents:
Amplitude of about 1 metre.

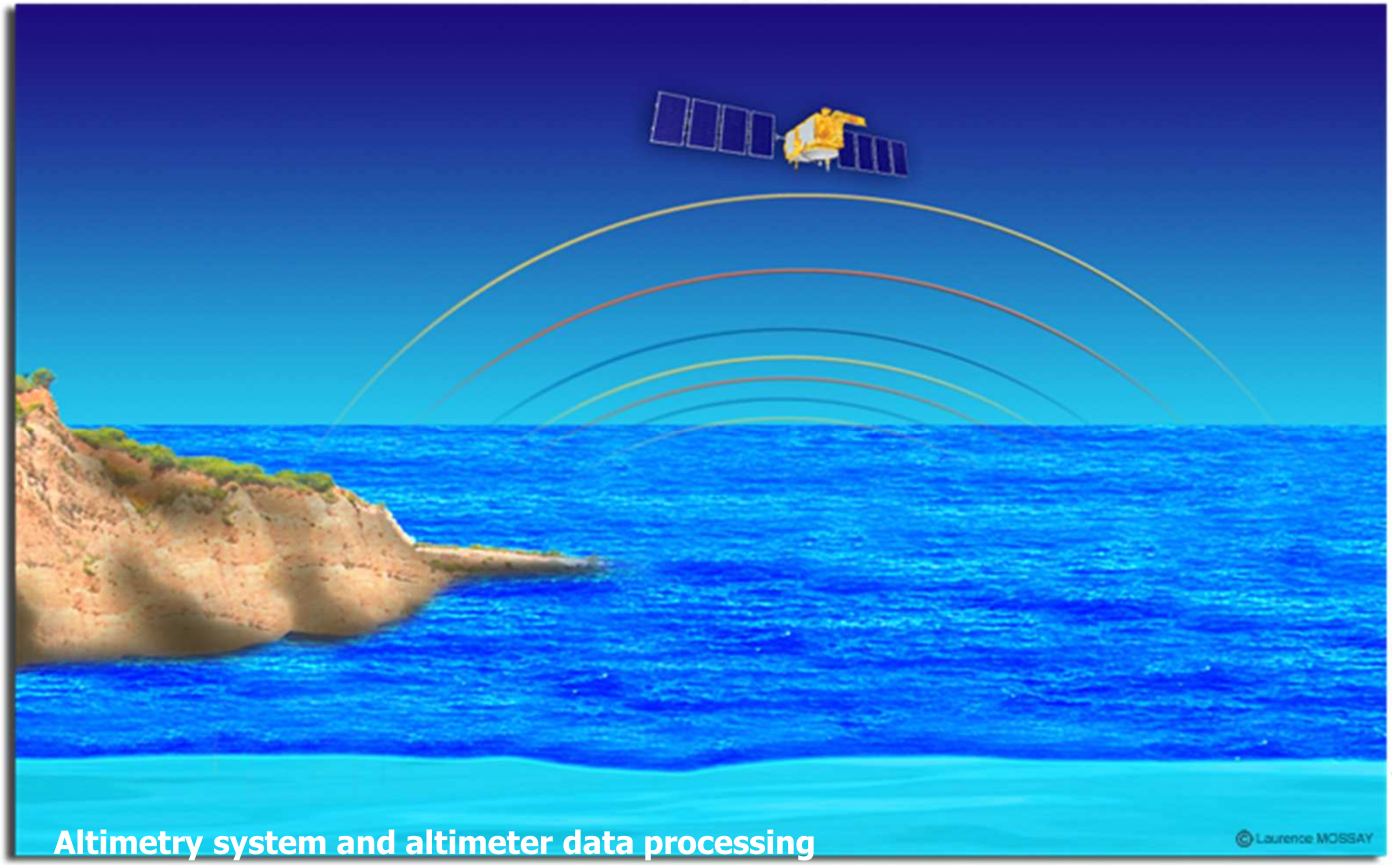
Mesoscale circulation:
Amplitude of about 1 decimetre.



The amplitude of the observed phenomena ranges from a few tens of metres to several millimetres for the mean sea surface height signal.

Key components of an altimetric mission

- Higly performing radar altimeters
- Precise orbit determination systems
- Additional systems (e.g. radiometer)



Principles of radar altimetry. SSH measurements

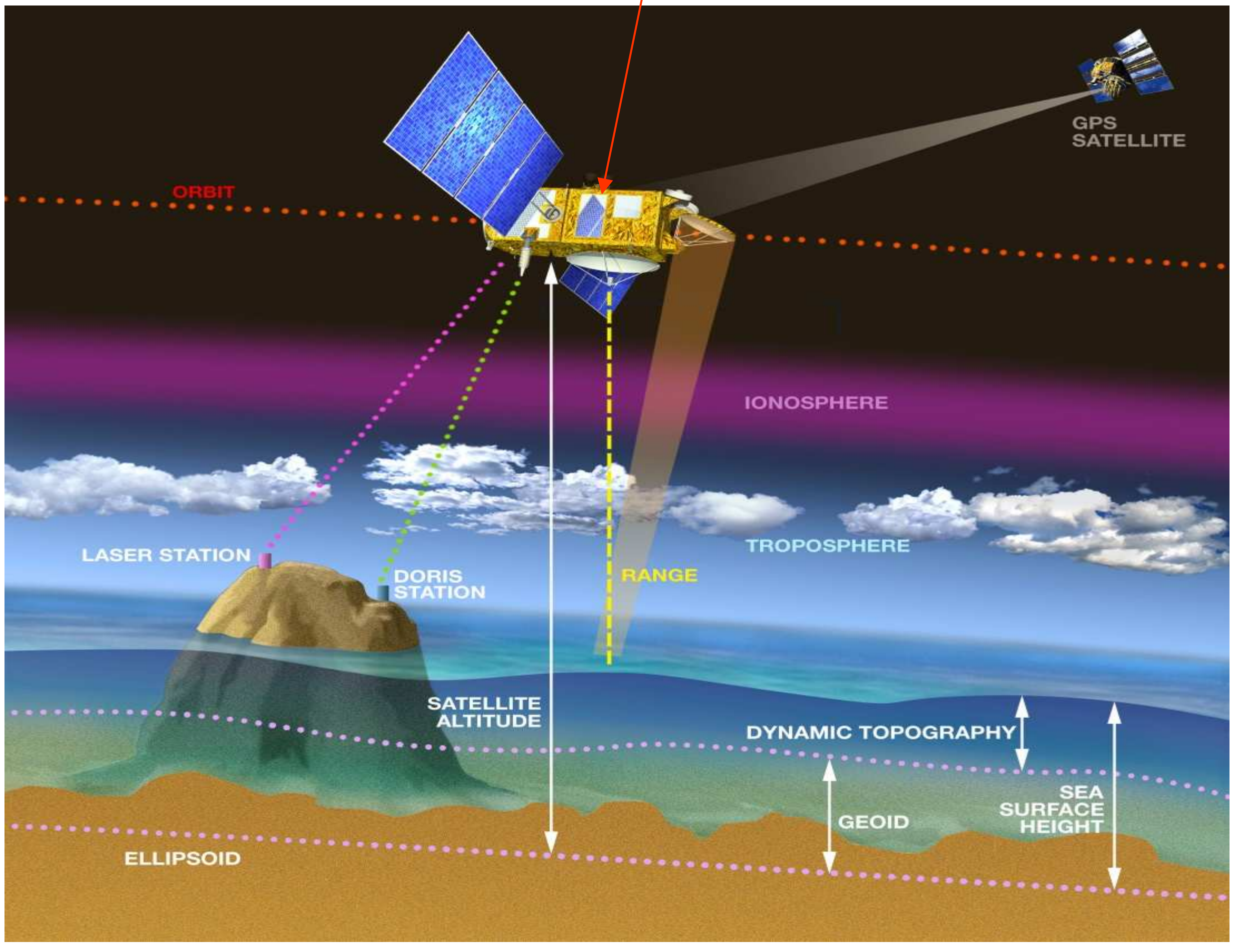
Sea Surface Height (SSH) (relative to an earth ellipsoid)= Orbit height – Range

SSH = Orbit – Range – Σ Corr

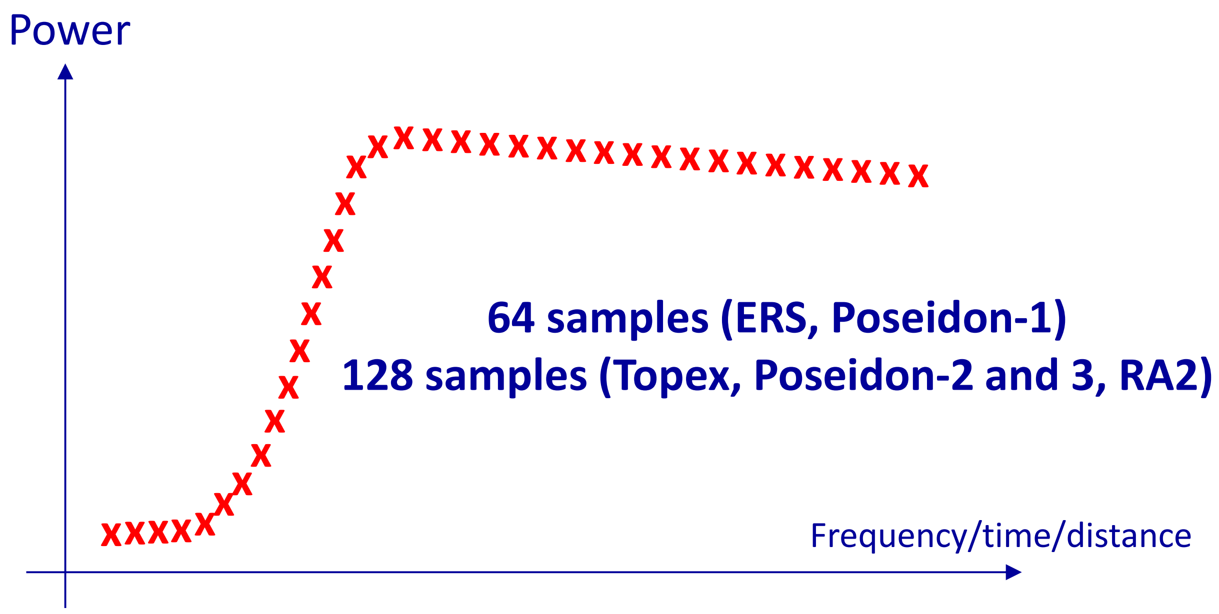
Orbit errors in position of satellite

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, …)**



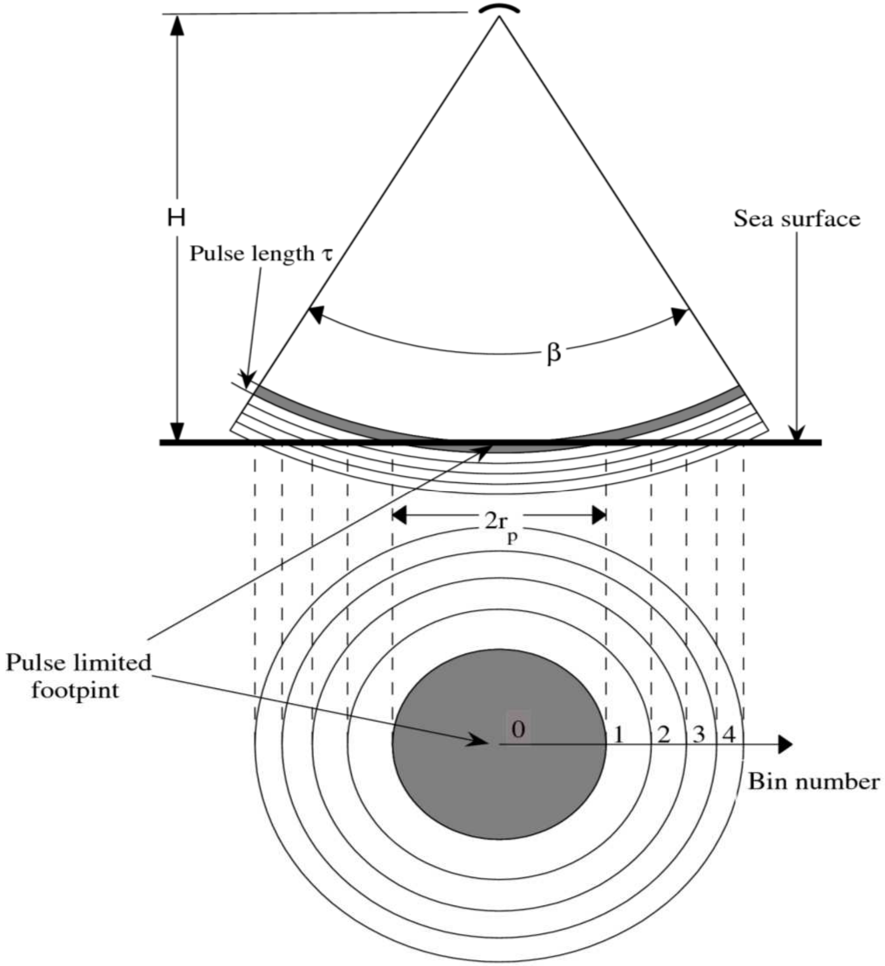
Sampling of the waveform



10 KHz ≡ 3.125 ns ≡ 47 cm

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 > 2000 Hz)

Nadir altimeter



- Altimeter over ocean: Classical Brown model
- Basic assumption: homogeneity of the surface backscatter over the footprint
- Not true in presence of small island, surface slick, currents etc.. i.e. Strong variations of surface backscatter at scale < footprint size
- In such cases: altimeter can be seen as an imager of the surface backscatter whose geometry is annular and not rectangular

Radar Equation

Radar equation
(in the case of a
punctual target)

$$P_r = T^2 P_e \frac{\lambda_0^2}{(4\pi)^3 R^4} G^2 \sigma$$

σ : backscattering section

Extended target = Sum of all the elementary scattering cells on the S surface

$$\sigma = \int_{\text{Surface}} \sigma_0 dS$$

σ_0 : backscattering coefficient
(sigma naught)

Example : POSEIDON2 emits 5W with SNR=20 dB if σ_0=11dB

Mathematical formulation of the echo

$$S(t) = RI(t) \otimes Q(t) \otimes PFs(t)$$

RI(t) : Point target response of the radar
Q(t) : Probability density function of the scatterers
PFs(t) : Radar response to a calm sea to a short pulse

Formulation of the HAYNE's model (simplified form without skewness)

$$S(t) = \frac{P_u}{2}\left[1 + \mathrm{erf}\left(\frac{t - \tau - \alpha\sigma_c^2}{\sqrt{2}\sigma_c}\right)\right]\exp\left[-\alpha\left(t - \tau - \frac{\alpha\sigma_c^2}{2}\right)\right] + P_n$$

with

$$\alpha = \frac{4c}{\gamma h\left(1 + \frac{h}{R_e}\right)}$$

$$\sigma_p = 0.5T$$

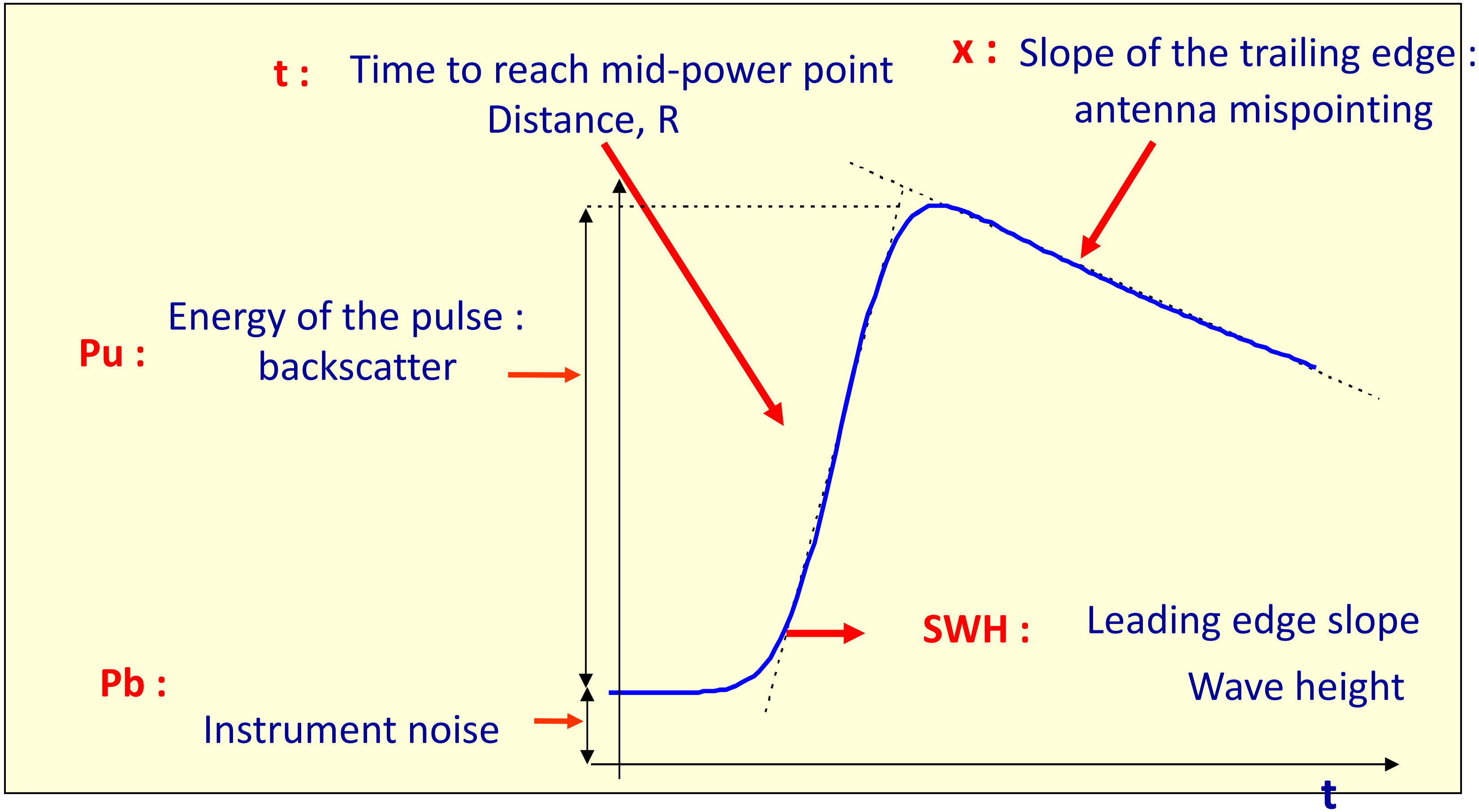
$$\sigma_s = SWH/(2c)$$

$$\sigma_c^2 = \sigma_p^2 + \sigma_s^2$$

$$\gamma = \frac{1}{2.\mathrm{Log}_e(2)}.\sin^2\left(\frac{\theta_0}{2}\right)$$

Application à SARAL : vous avez 2 heures ….

Retracking function : on-ground processing



For each averaged waveform (20Hz), fitting procedure between a model and the measured waveform

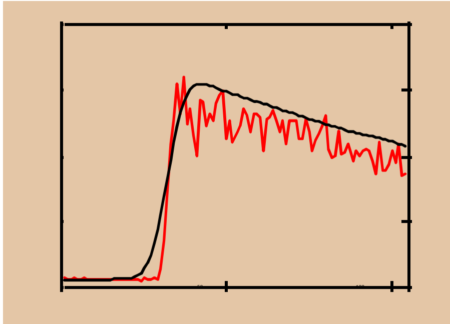
Retracking algorithm :

Iterative fitting procedure (LSE) solving for N parameters (range, SWH, Pu, $\xi 2$, λs, TN, ...)

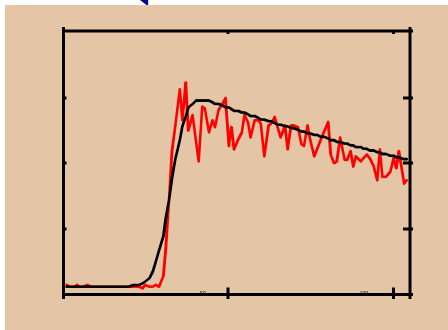
Many possible solutions

➔ On each waveform

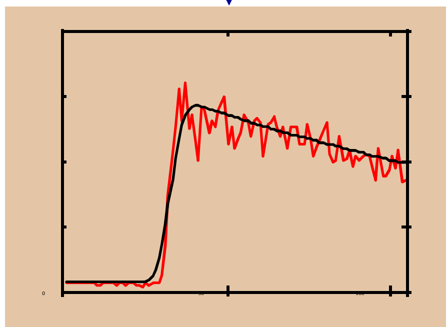
➔ On packet of waveforms



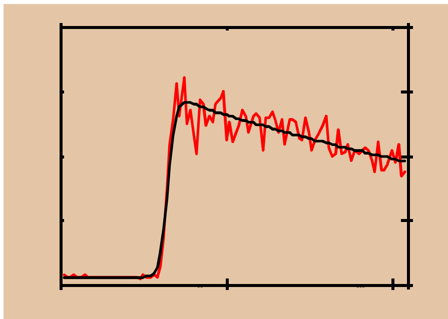
After 1 iteration



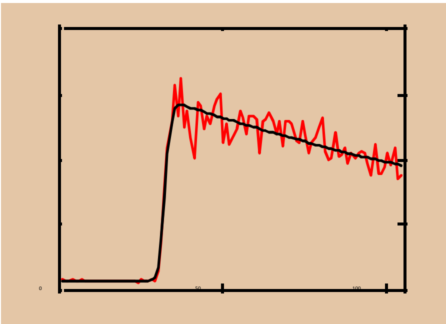
After 2 iterations



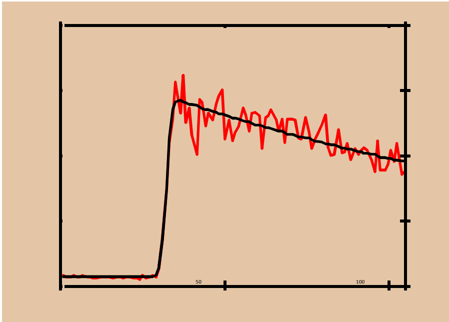
After 3 iterations



After 5 iterations



After 7 iterations



After 10 iterations

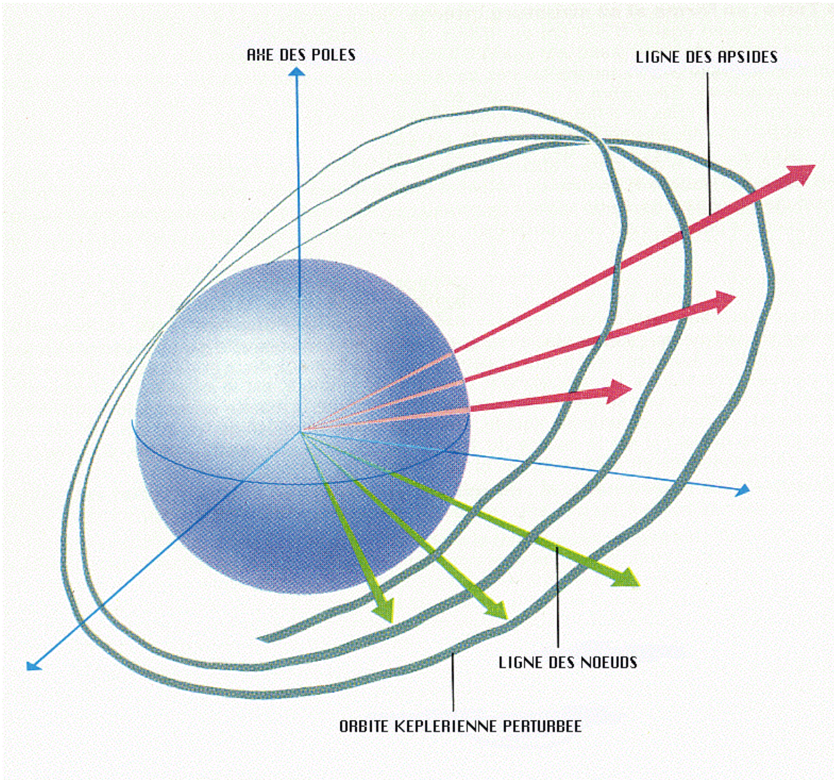
Satellite Altimetry Orbits

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.

• 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



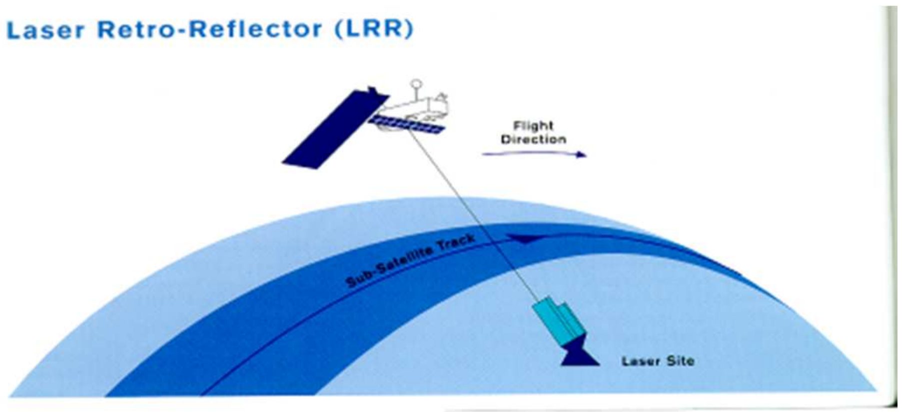
Precise orbit determination is made by specialist teams at the space agencies, using:

• force perturbation models on the satellite

• tracking data.

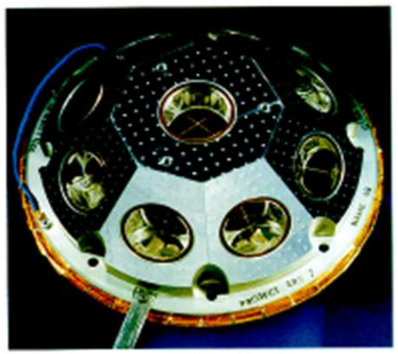
Satellite Tracking Systems … Laser Tracking and GPS

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.



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

GPS

An onboard GPS receiver provides precise, continuous tracking of the satellite by monitoring range and timing signals from up to 12 GPS satellites at the same time.

Errors on altimeter measurements

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.

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
- Pointing angle error
  - Off-nadir pointing errors impacts the return pulse shape
  - Processing algorithms allow to compensate for this effect (up to 0.7° pointing error), but side effects are encountered on estimated parameters (trailing edge)
- Internal Calibration
  - internal transit time in the altimeter
  - correction is a few cm

Range Delay due to Atmospheric Refraction

Dry Troposphere

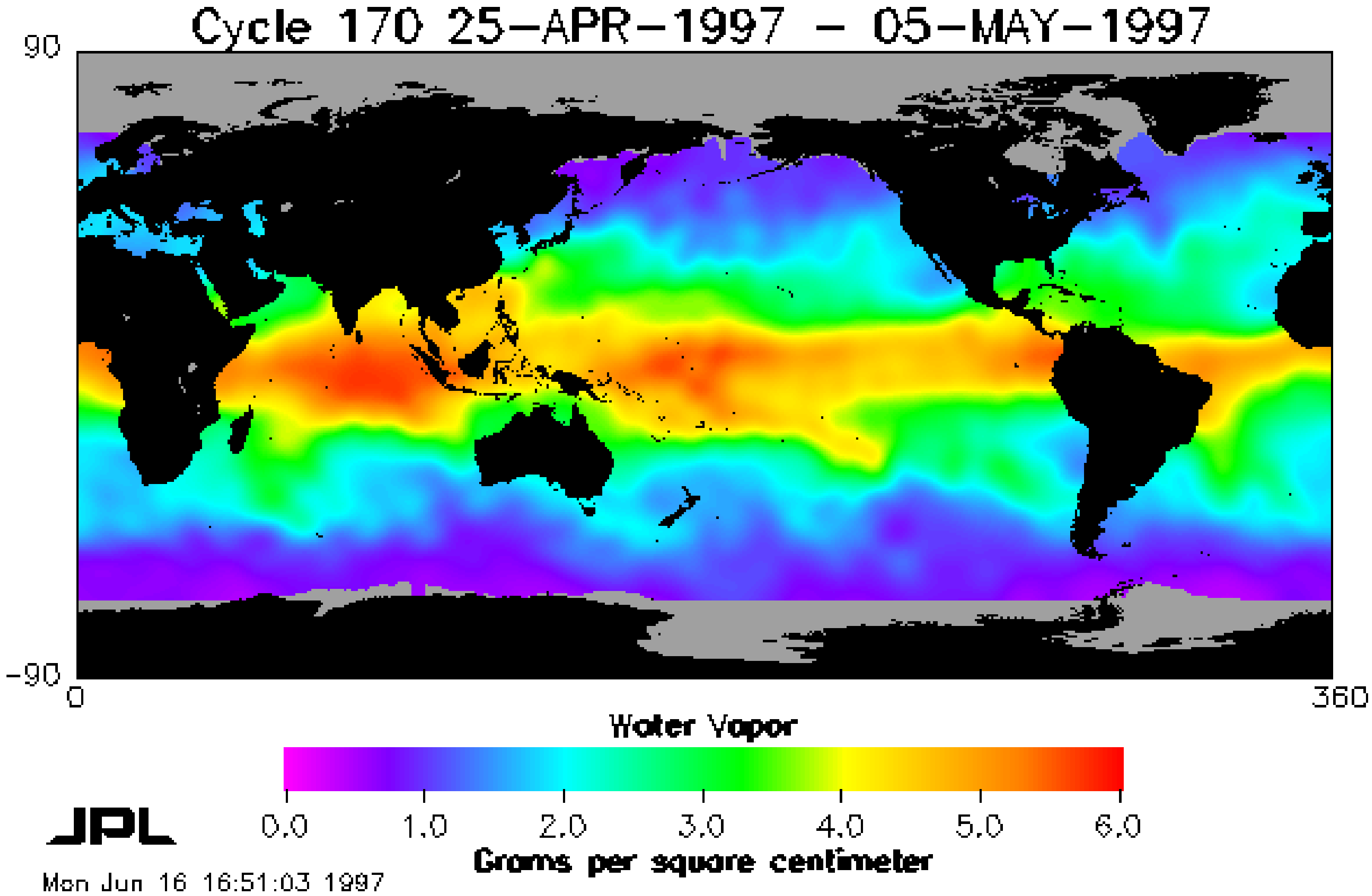
The mass of dry air molecules in the atmosphere causes a range delay called the dry tropospheric effect. It is directly proportional to the surface pressure, with an average magnitude of 2.3 m (over the ocean). This correction is computed using atmospheric model pressure forecasts. The error is of the 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 1.7 cm, or the water vapor content is calculated from atmospheric models.

Wet troposphere content as seen by Topex radiometer



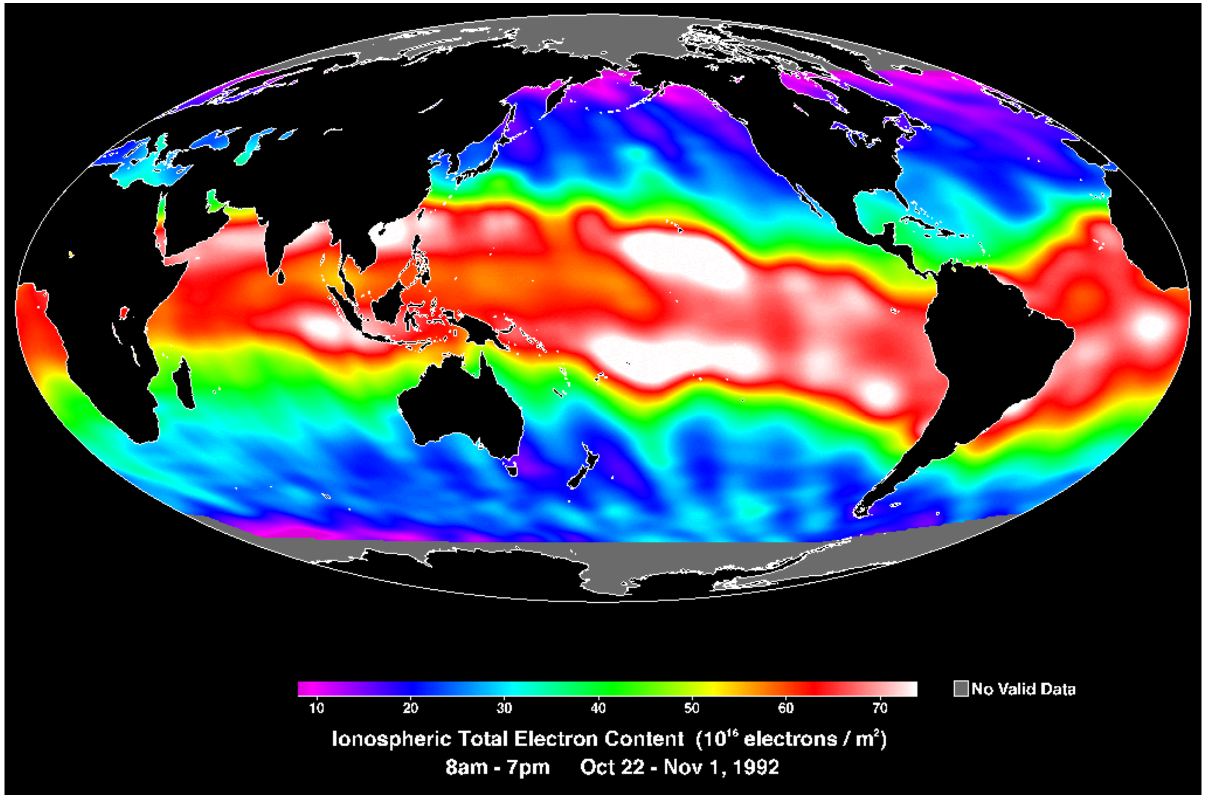
Ionospheric Refraction

- 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

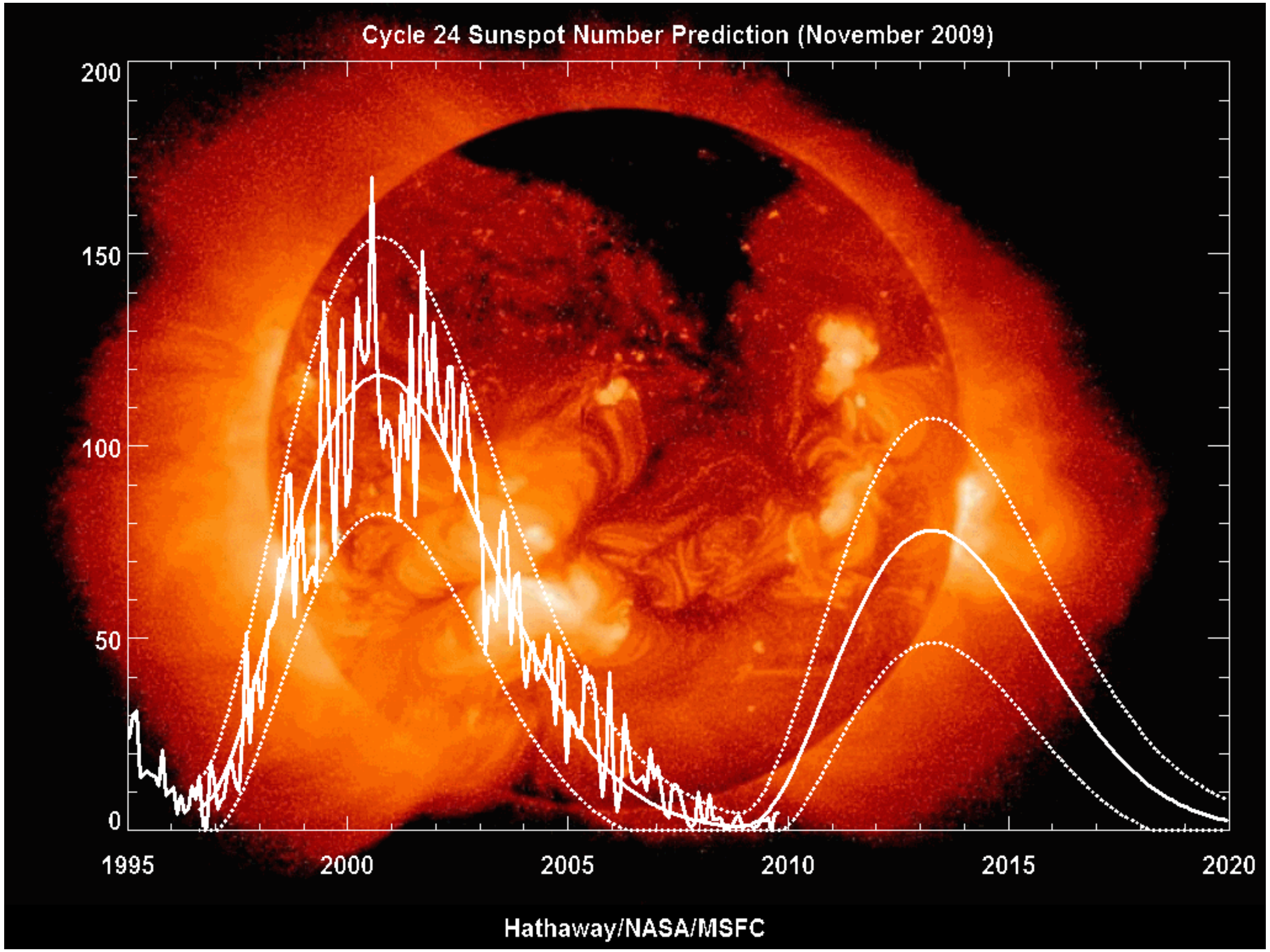
Spatial distribution

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



Ionospheric Correction – temporal variability

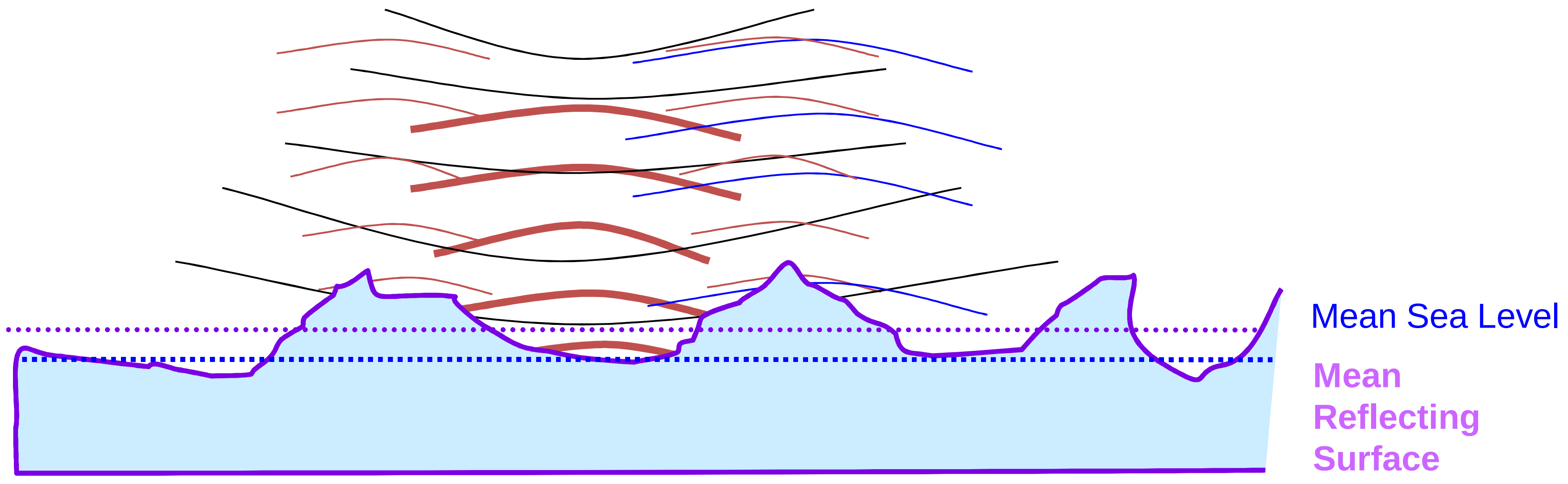
- **Temporal variability**
  - Strongly diurnal, maximum at 2 pm and minimum around 5 am
  - the TEC has seasonal variations
  - the TEC is correlated with the solar activity (sunspots) and the geomagnetism



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.

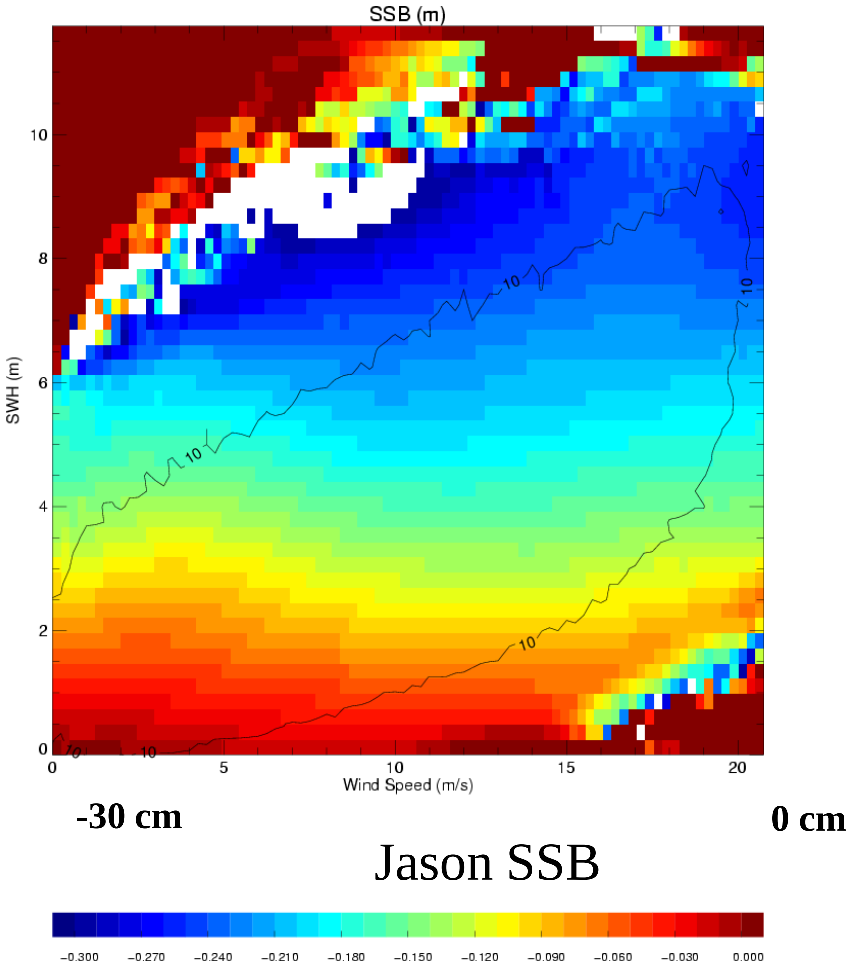
Again, the mean reflecting surface is shifted away from mean sea level toward the troughs

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.

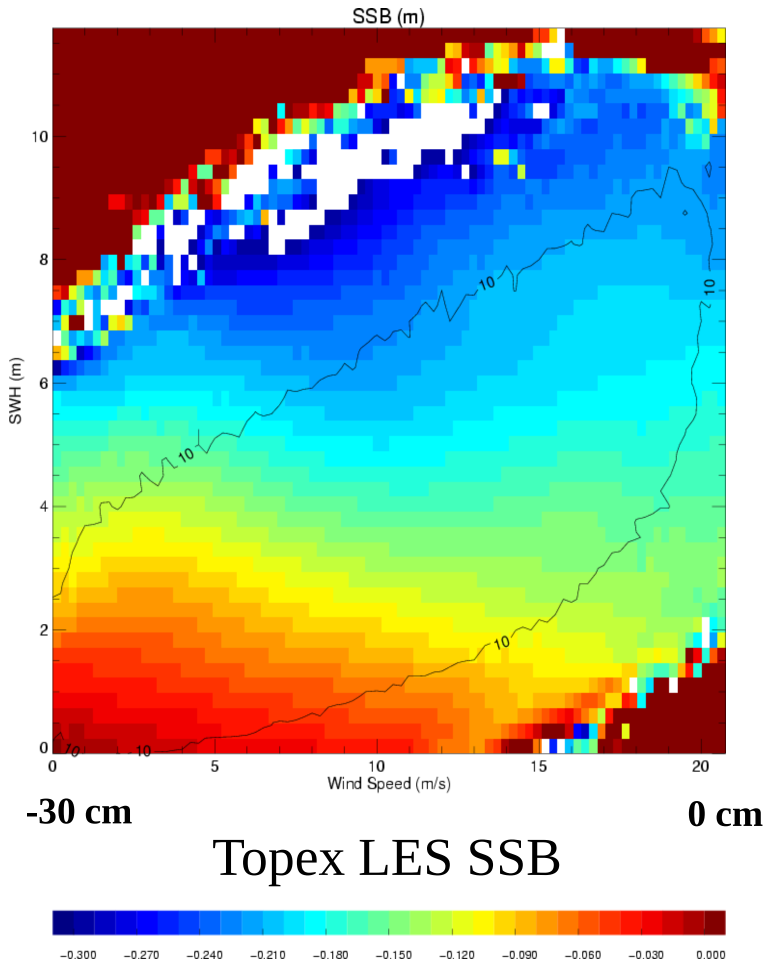
SSB is estimated using empirical formulas derived from altimeter data analysis (crossover, repeat-track differences and parametric/non-parametric methods). The range correction varies from a few to 30 cm. SSB bias accuracy is ~2 cm.

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

Sea State Bias



Jason SSB



Topex LES SSB

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

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

Topex-Poseidon – Jason-1 – ENVISAT

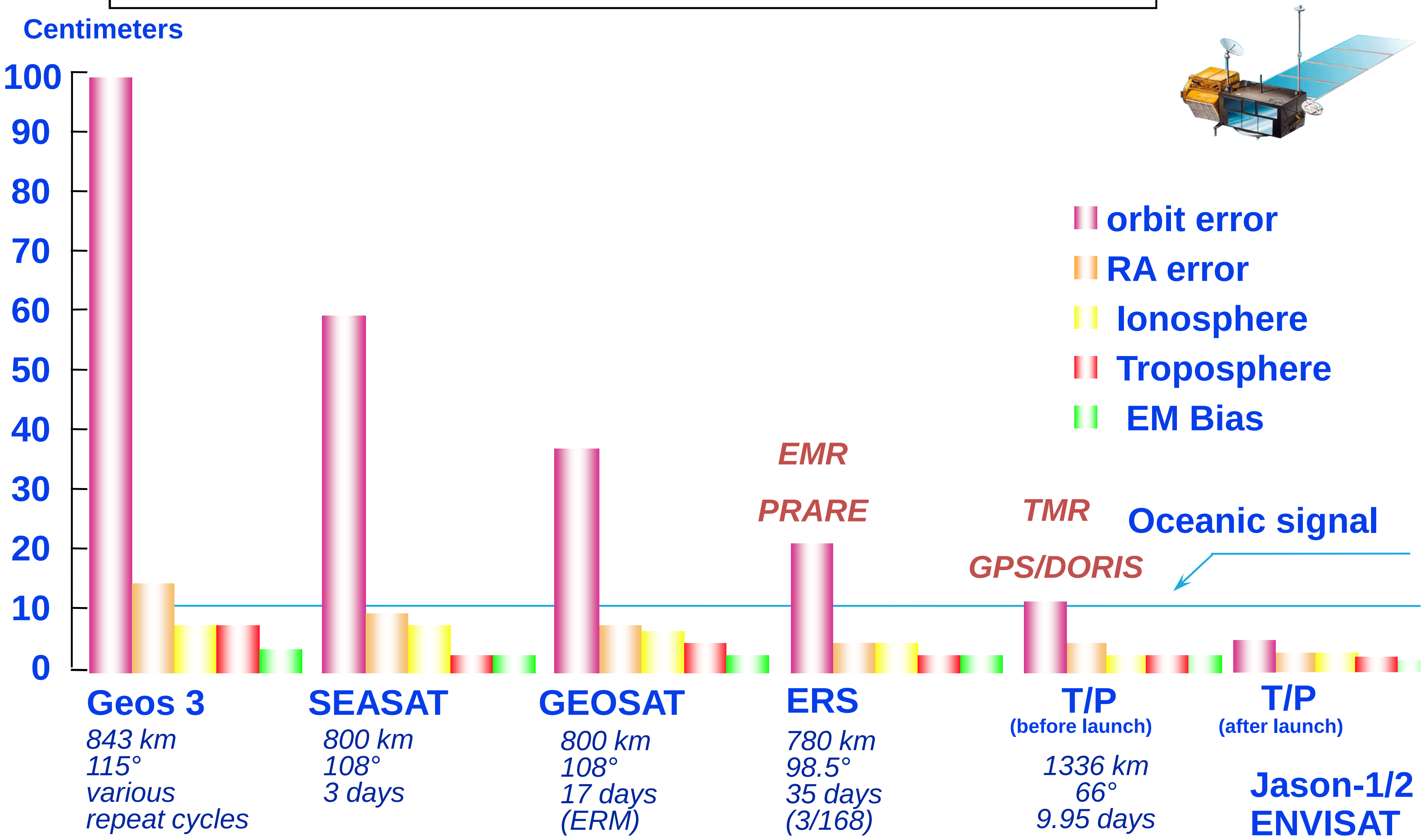
Performances

- **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)** — <1.5 cm (T/P-Jason-1); < 2.5 cm (ENVISAT)
- **Instantaneous sea level error** — <3.5 cm (T/P-Jason-1); <4.1 cm (ENVISAT)

Error Budget for altimetric missions



Satellite altimetry coverage

• Spatial coverage :

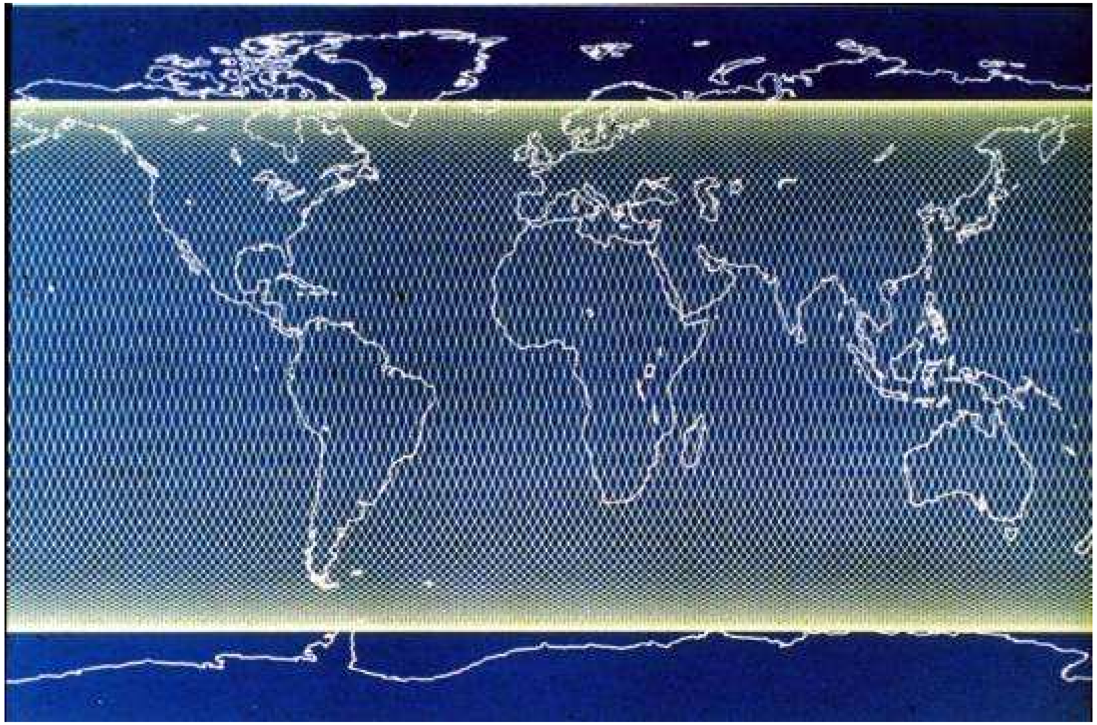
- global
- homogeneous
- Nadir (not swath)

• Temporal coverage :

- repeat period

10 days, T/P-Jason-1/2
17 days, GFO
35 days, ERS/ENVISAT

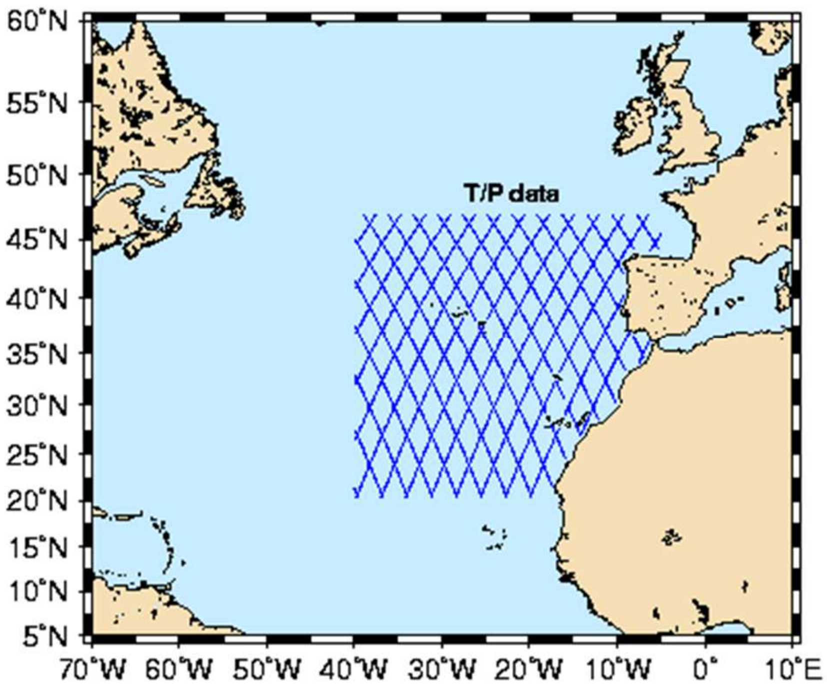
Exact repeat orbits (to within 1 km)



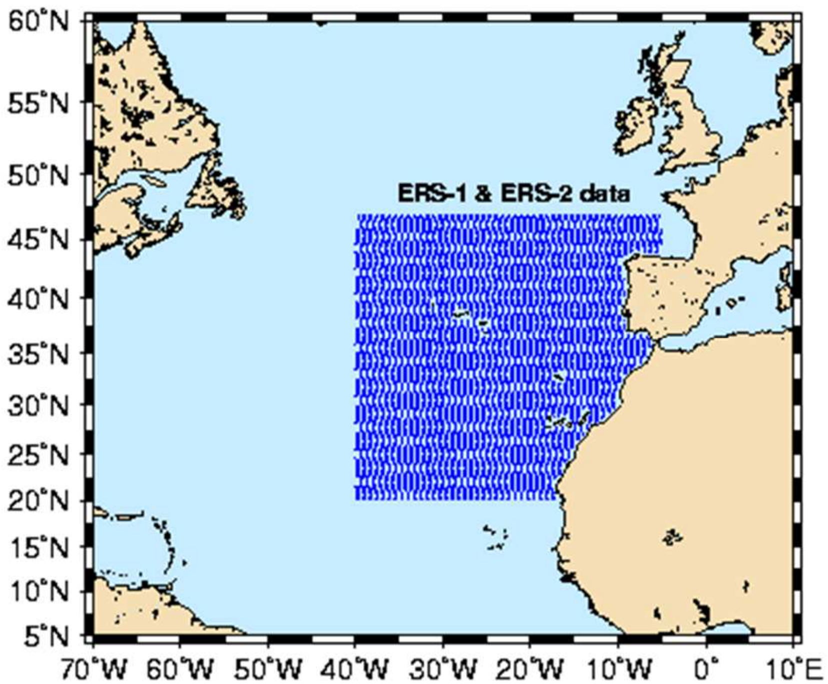
TOPEX/Poseidon or Jasons Sampling

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

Repeat Period and Groundtracks



1336 km
66.03°
9.915 days
1h52
Jason-1



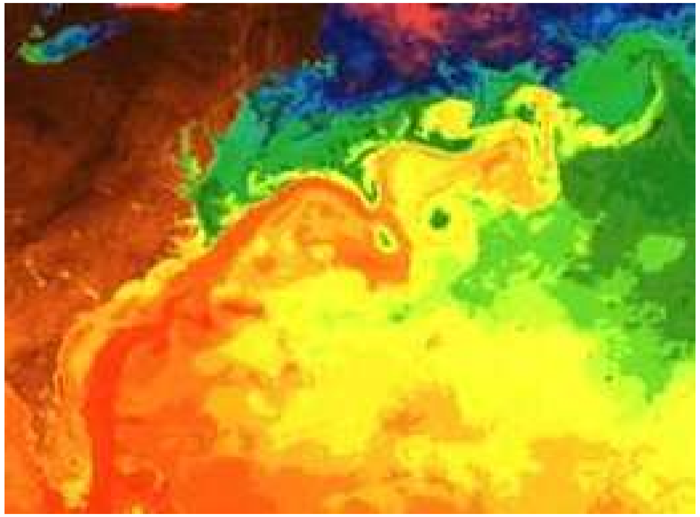
780 km
98°
35 days
ENVISAT

Sampling Issues

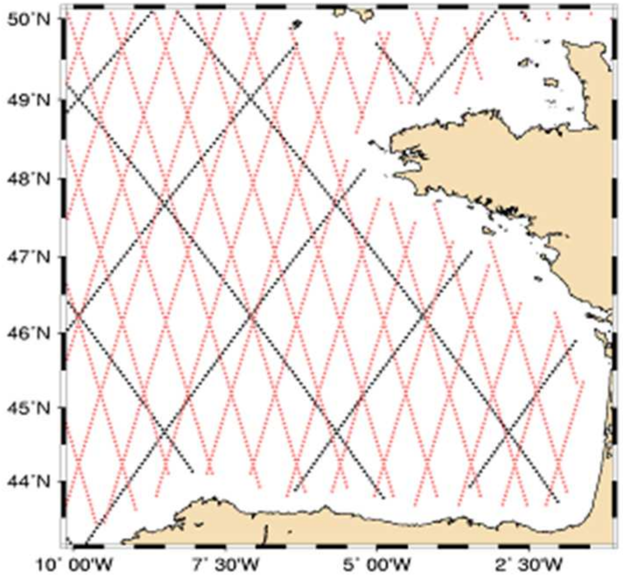
- How many altimeters are needed to monitor the ocean circulation ?
- Difficult issue. Depends on objectives (e.g. large scale circulation).
- Mesoscale variability sampling is a major objective for altimetry.

Mesoscale variability : a key factor

To better understand the ocean circulation and its role on climate, one needs to resolve the mesoscale variability



This is also required for most of the operational applications (e.g. marine safety, pollution monitoring, offshore industry, fisheries).



Two altimeter missions at least are needed to get a "good" representation of mesoscale variability (e.g. Koblinsky et al., 1992).

Complementarity of Jason-1 and ENVISAT

Mapping capabilities of Jason-1 (T/P) + ENVISAT (ERS)

Simulations with the Los Alamos model

(Le Traon et al., 2001 and Le Traon and Dibarboure, 2002)

Subsample model fields (sea level anomaly) along altimeter tracks. Add a random noise.

Use of a sub-optimal space/time mapping method to reconstruct the 2D sea level anomaly signal from simulated along-track data.

Compare the reconstructed fields with the reference (model) fields (sea level and velocity) => allows an estimation of the sea level and velocity mapping error

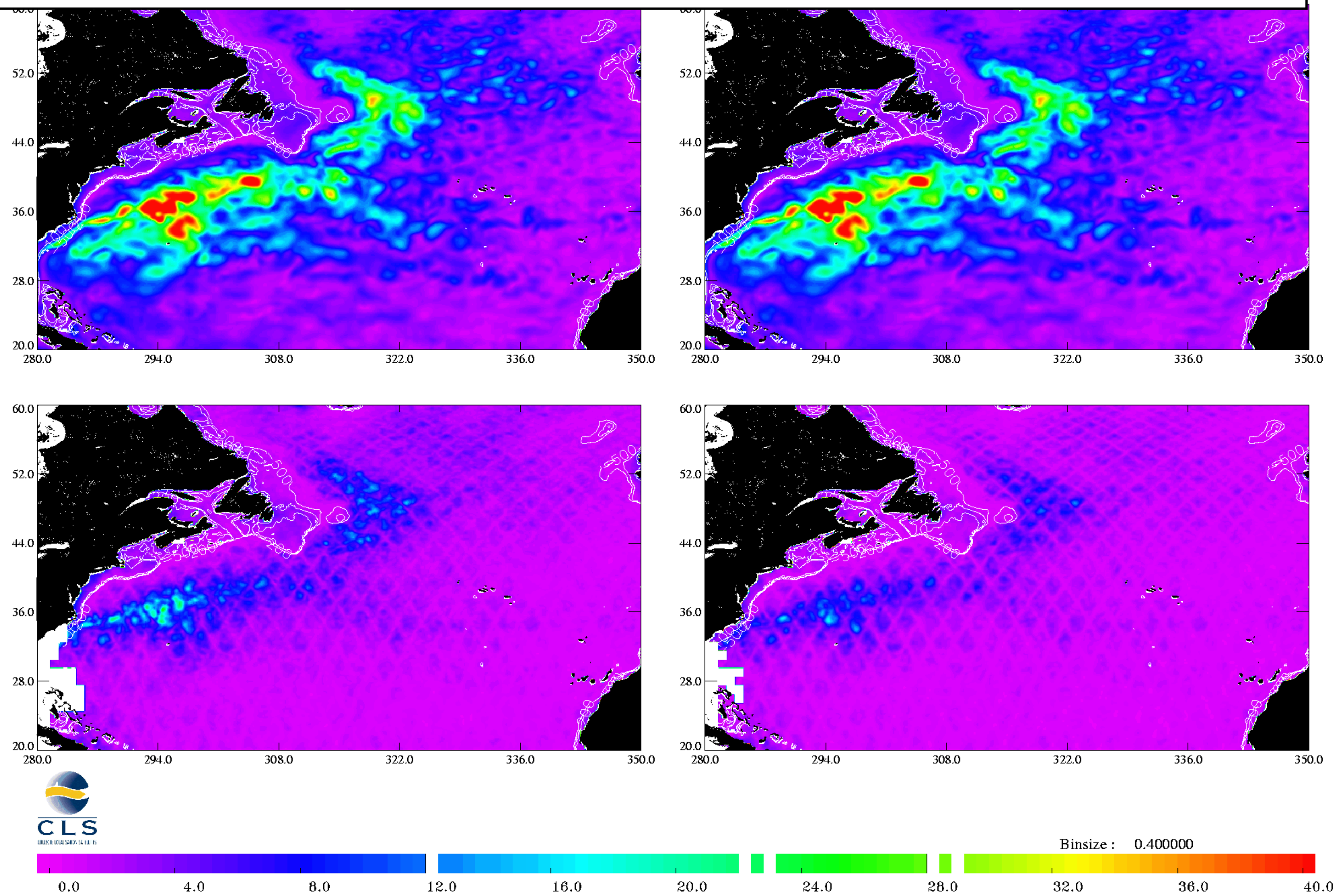
Add extra noise and compare the reconstructed fields with the 10-day average fields => allows an estimation of the mapping errors on 10-day average fields

Sea level mapping error from Jason-1+ENVISAT

simulated from the Los Alamos Model (instantaneous and 10-day averaged fields)

LAM rms SLA

Rms Mapping error



Summary of Jason-1 + ENVISAT mapping capabilities

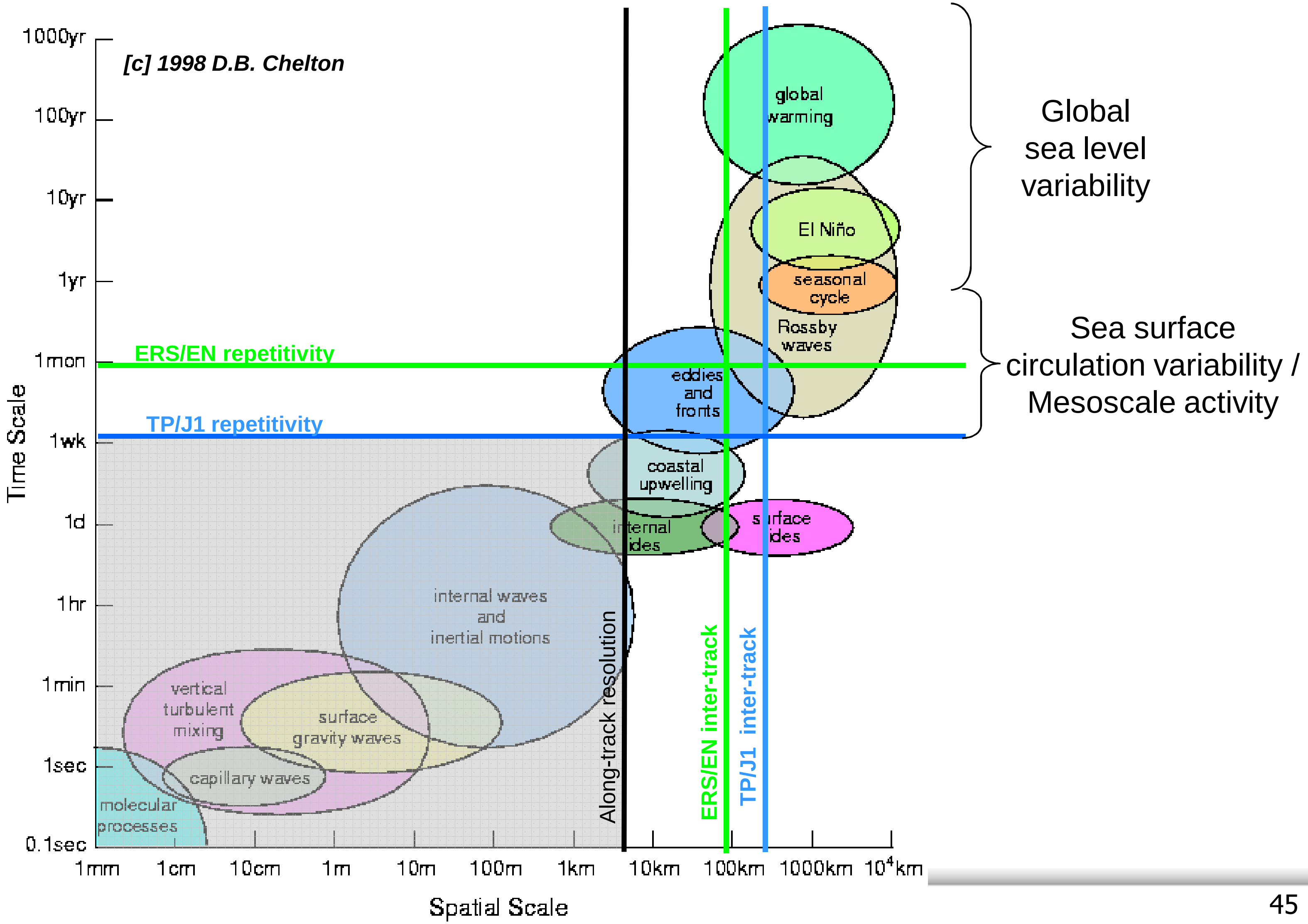
Sea level can be mapped with an accuracy of 5 to 10% of the signal variance

Velocity mapping error from 20 to 40% of the signal variance

A large part of the mapping errors is due to high frequency (< 20 days) and high wave numbers signals. Errors on 10-day averages are much smaller.

Not all the physical processes are observable with the altimeter

➔ **Merging information from different altimeters** leads to a better representation of the surface state (but not complete …)

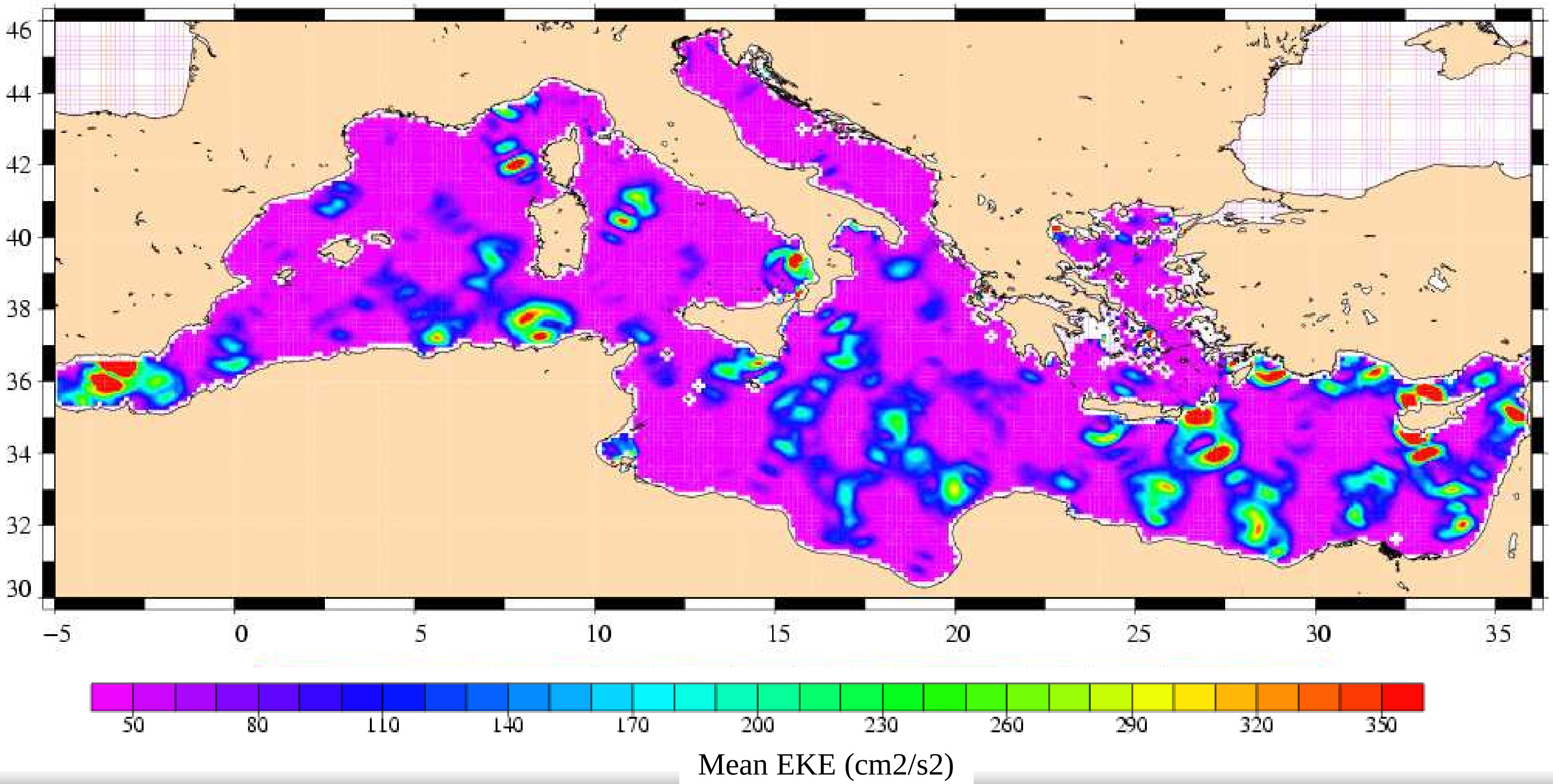


MERGING SATELLITE DATA
Eddy energy

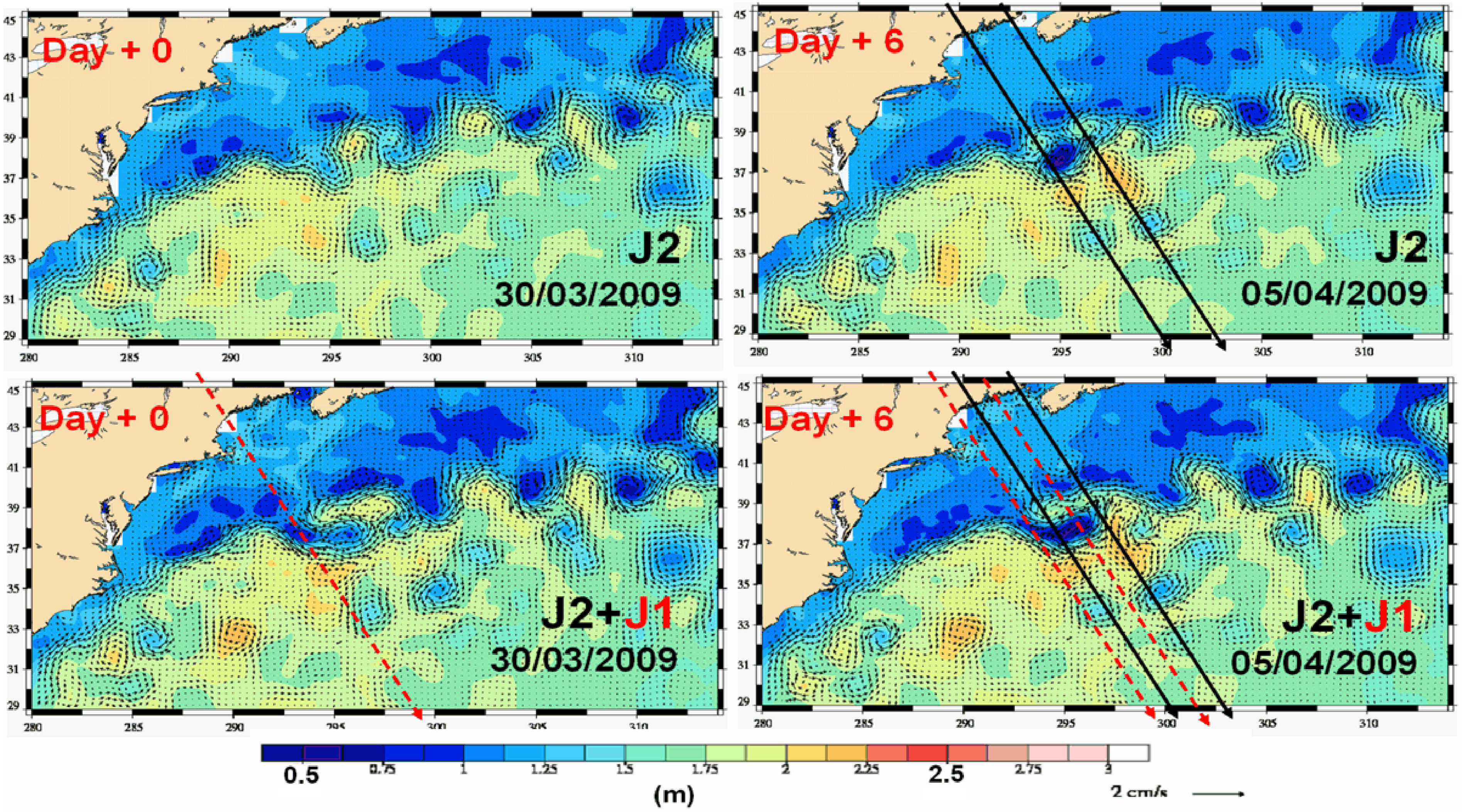
→ **Geostrophic speed anomalies (U', V') computed by finite differences**

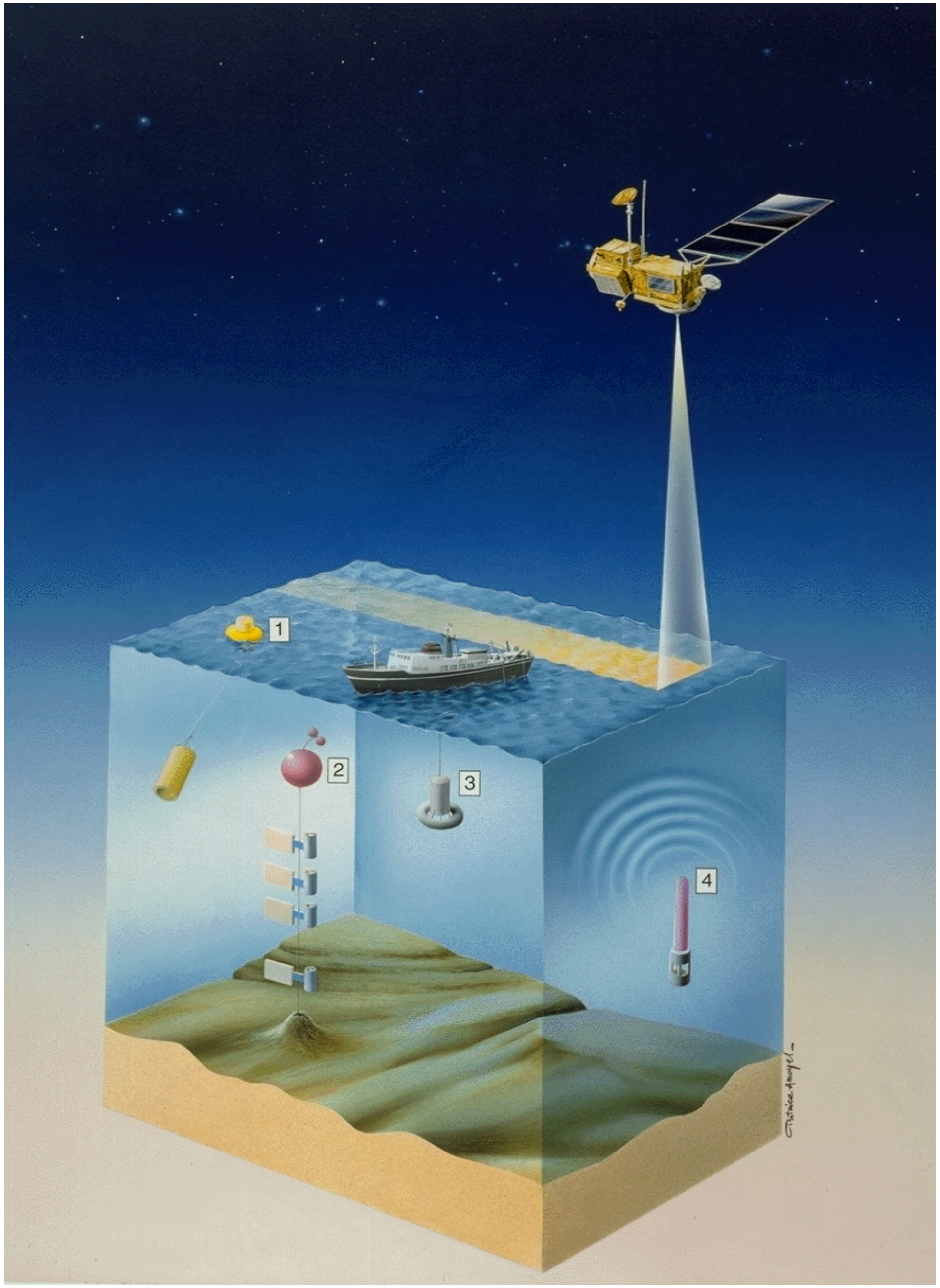
→ **EKE = ½ * (U'² + V'²)**

J1



MERGING SATELLITE DATA
Jason-2 and Jason-1 flying in tandem





Integrated Operational Oceanography

Space Observation

⇩

Assimilation Model

⇧

In situ Observation