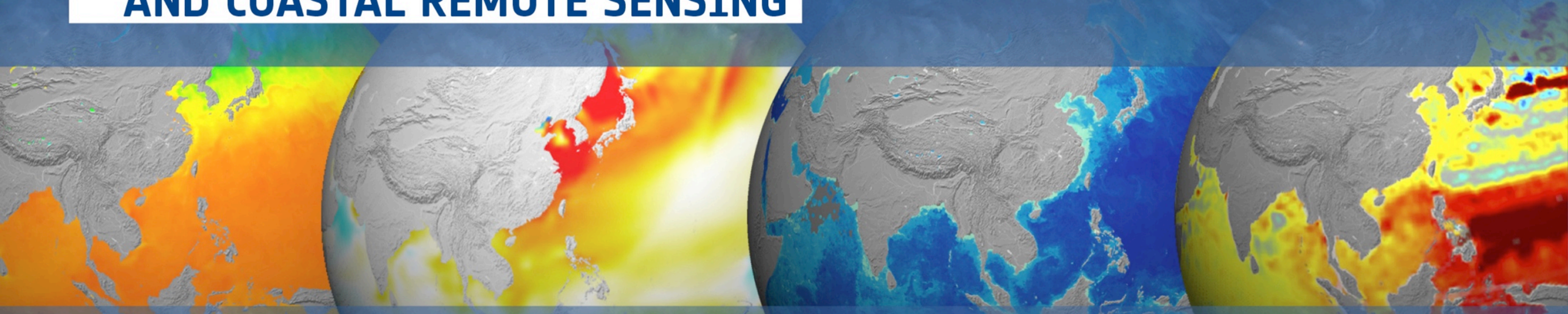
ESA–MOST China Dragon 4 Cooperation

→ ADVANCED TRAINING COURSE IN OCEAN AND COASTAL REMOTE SENSING

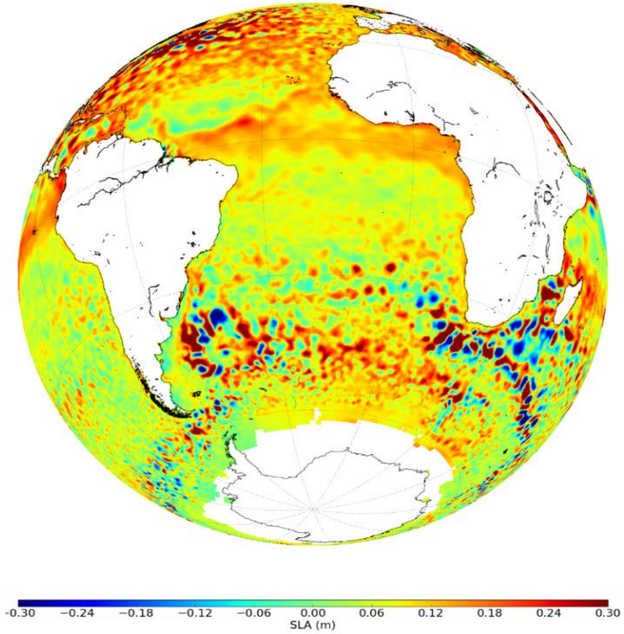


12 to 17 November 2018 | Shenzhen University | P.R. China

Radar Altimetry Principle and Data Processing *by* M.-H. Rio

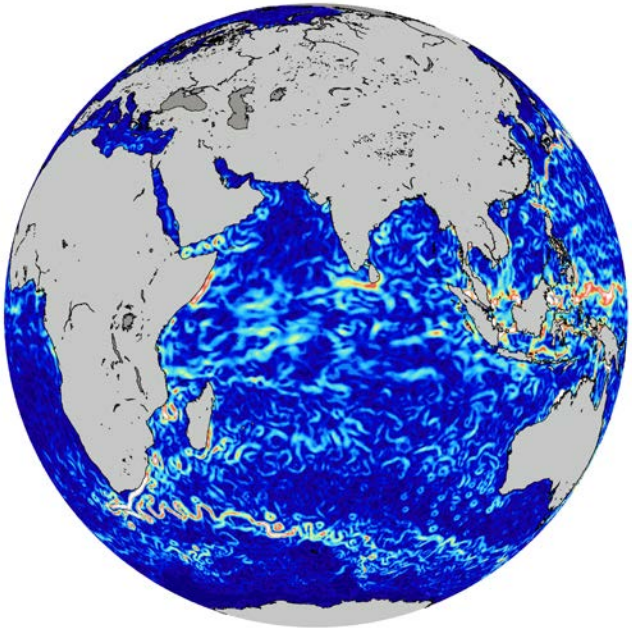
Hosted by

Sea Level Anomalies maps



Lecture #1

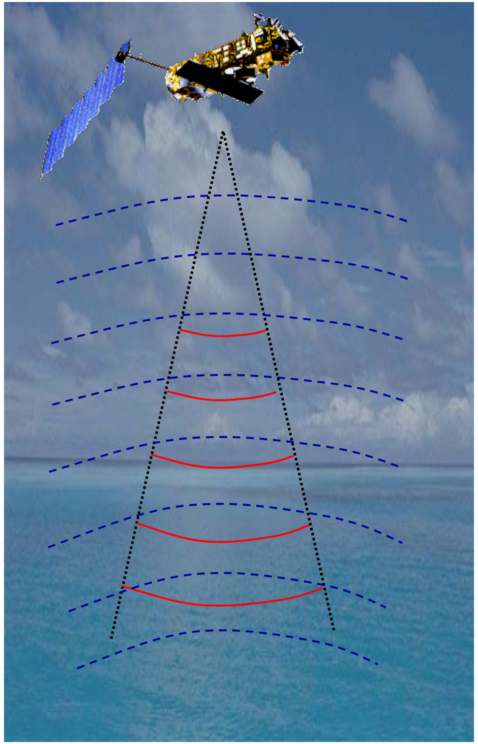
Ocean surface Currents



Lecture #2

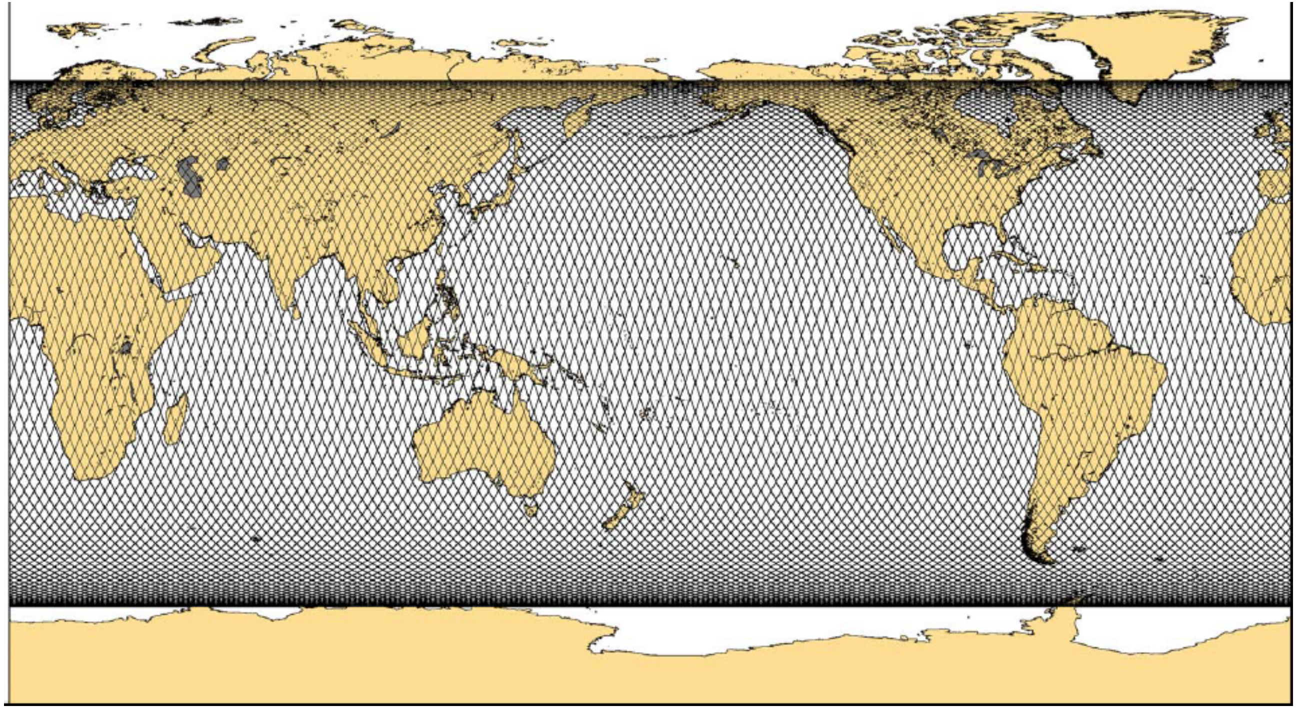
Basic radar altimetry principle

- Active radar sends a microwave pulse towards the ocean surface at a given frequency.
- The radar signal is reflected by the sea surface and goes back to the satellite.
- The backscattered power as a function of time is called the **altimeter waveform**.
- The time needed by the signal to go and come back provides information about the distance satellite-sea surface = **the range**.
- Other parameters (**wave height, wind speed**) are deduced from the waveform shape.



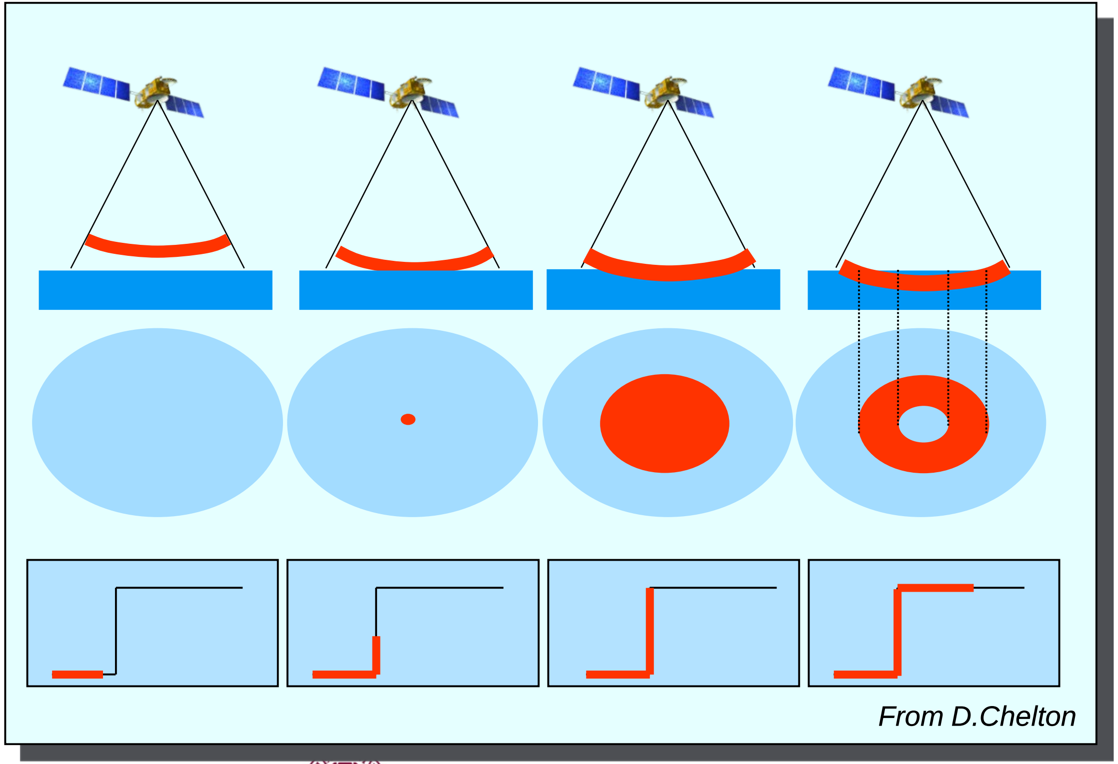
Altimeters provide pointwise, along-track measurements (no imaging!)

Global coverage in a few days or weeks **= 1 cycle**



Calm sea

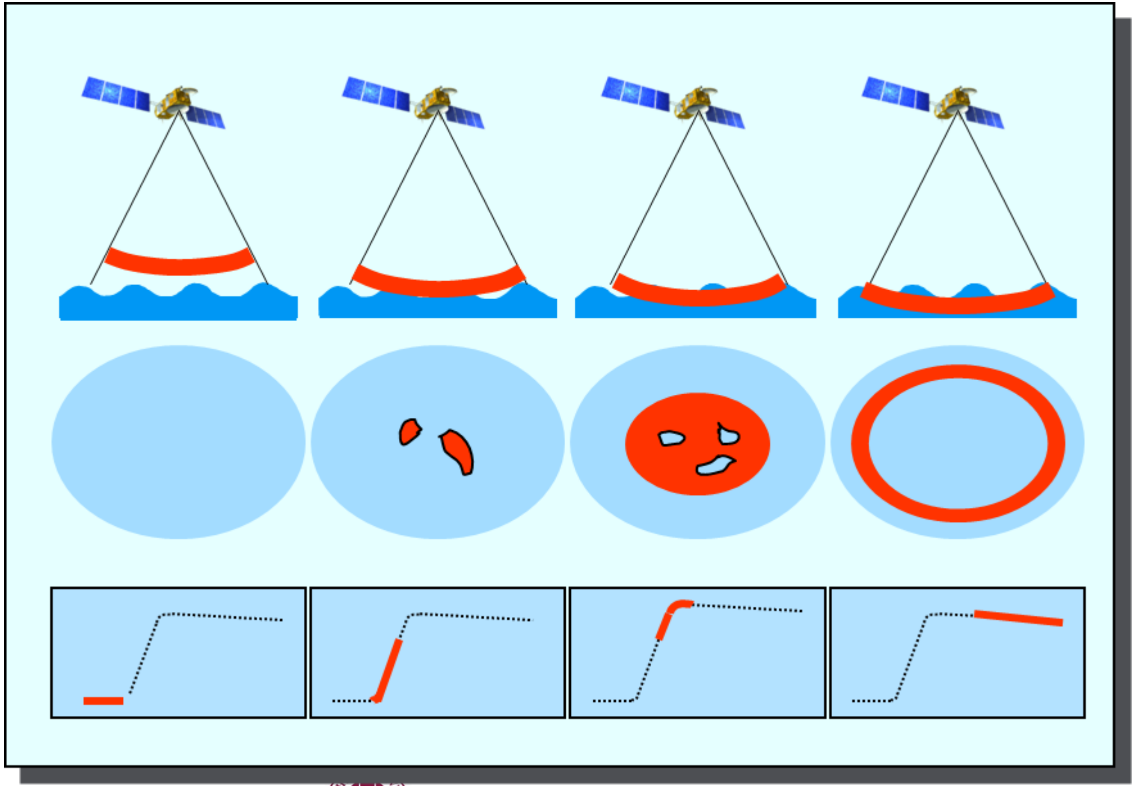
In case of a perfectly flat surface, the backscattered power as a function of time is characterized by a very sharp, linear rise



Rough sea

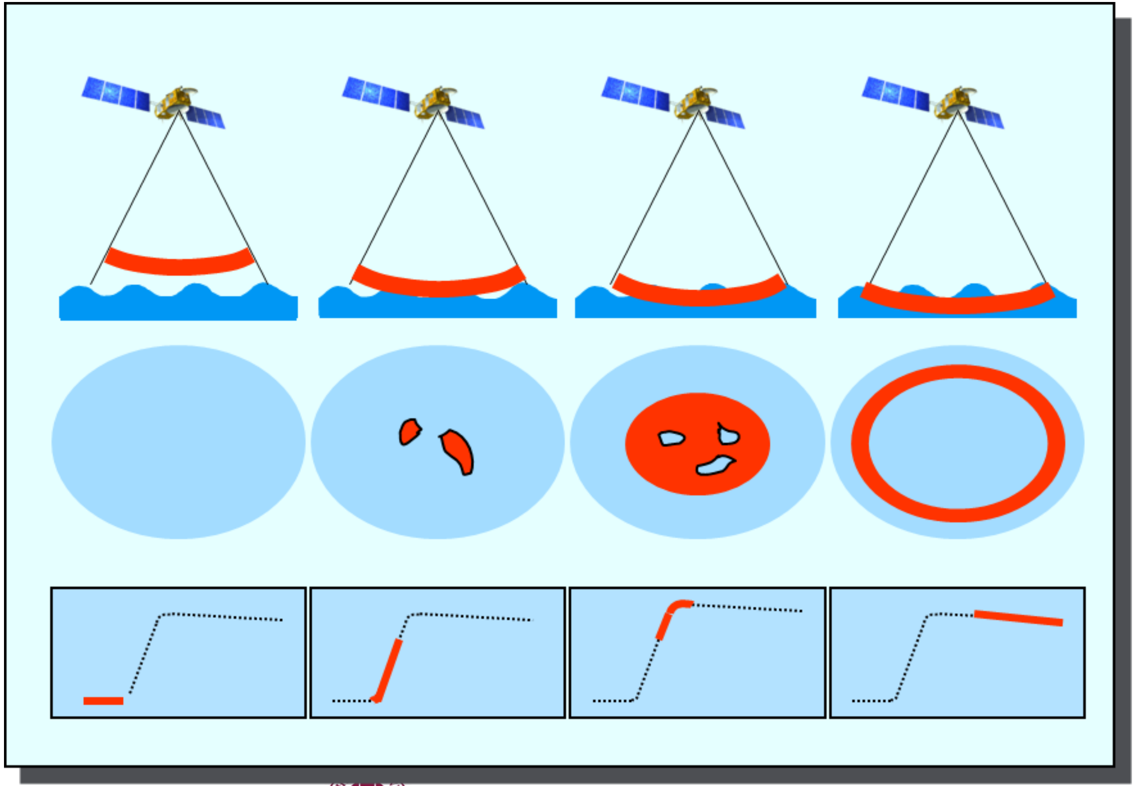
- In sea swell or rough seas, the radar signal strikes the crest of one wave and then a series of other crests which cause the reflected signal's amplitude to increase more gradually.

- the slope of the curve is proportional to **wave height**

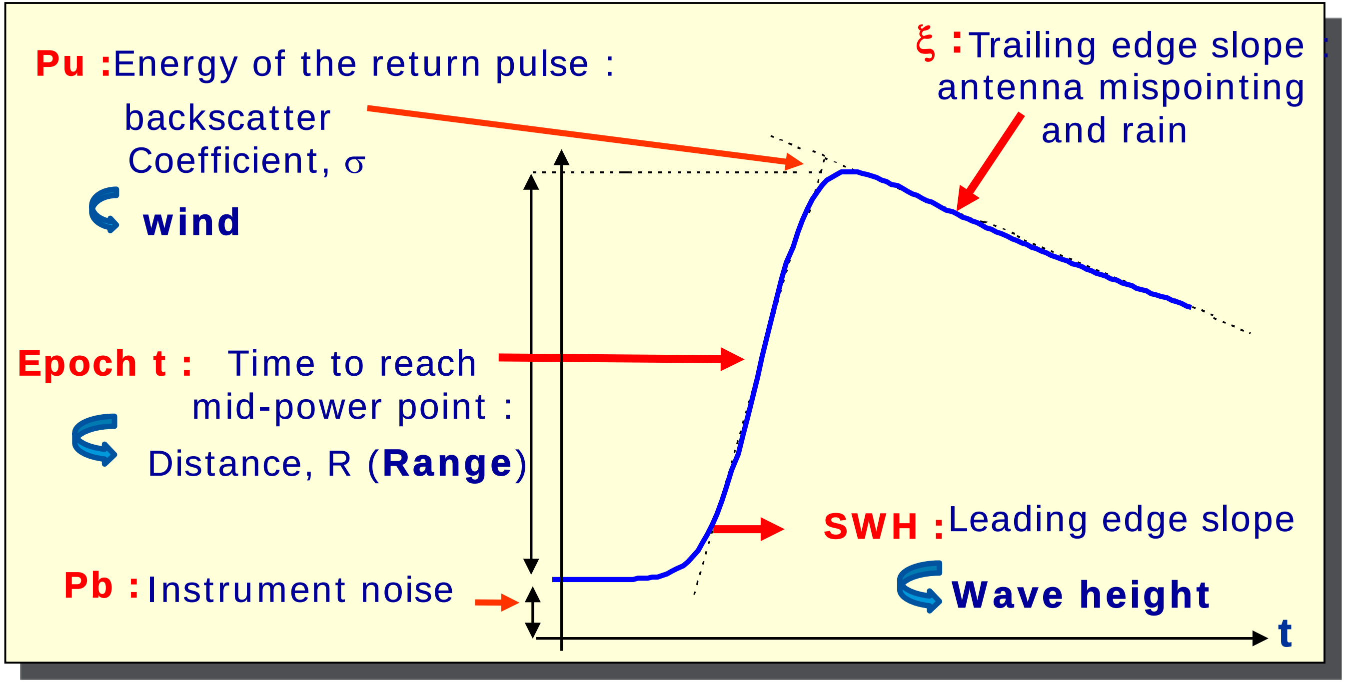


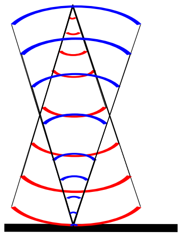
The altimeter waveform

- The amplitude of the waveform depends on the mean roughness over the altimeter footprint, which can be empirically related to **wind speed.**



Physical parameters in the waveforms





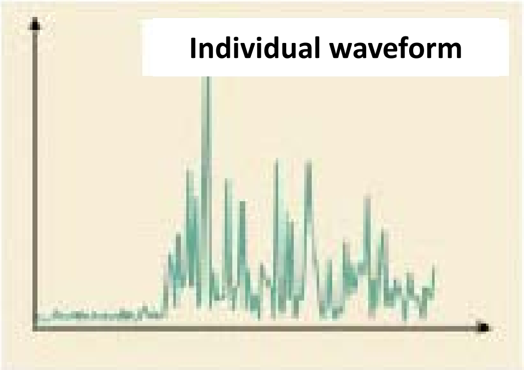
Various noises alter the signal. As it is difficult to directly extract the information from the individual waveform (~ 2000 / s)

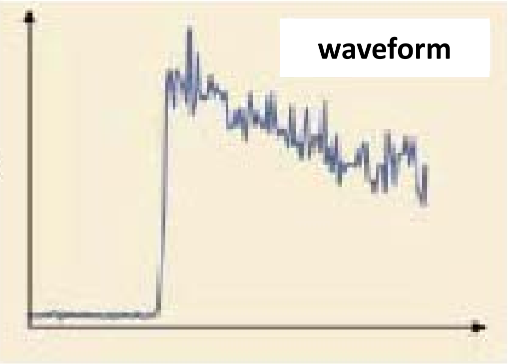
⇩

We average them to consider the **mean of individual waveforms**

20 Hz signal (i.e. 20 waveform estimations per second) ↔ ~**350 m along-track**

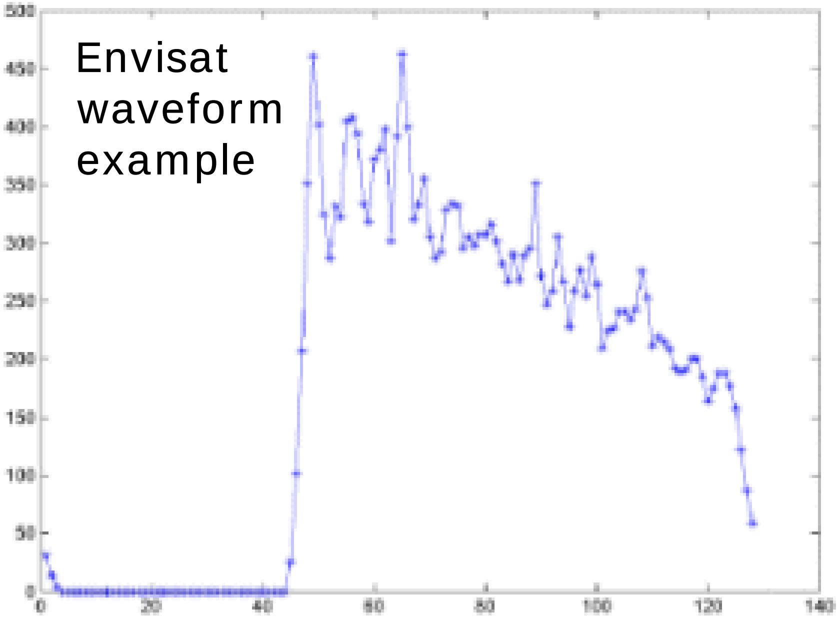
1 Hz signal (i.e 1 waveform estimation per second) ↔ ~ **7km along the track**

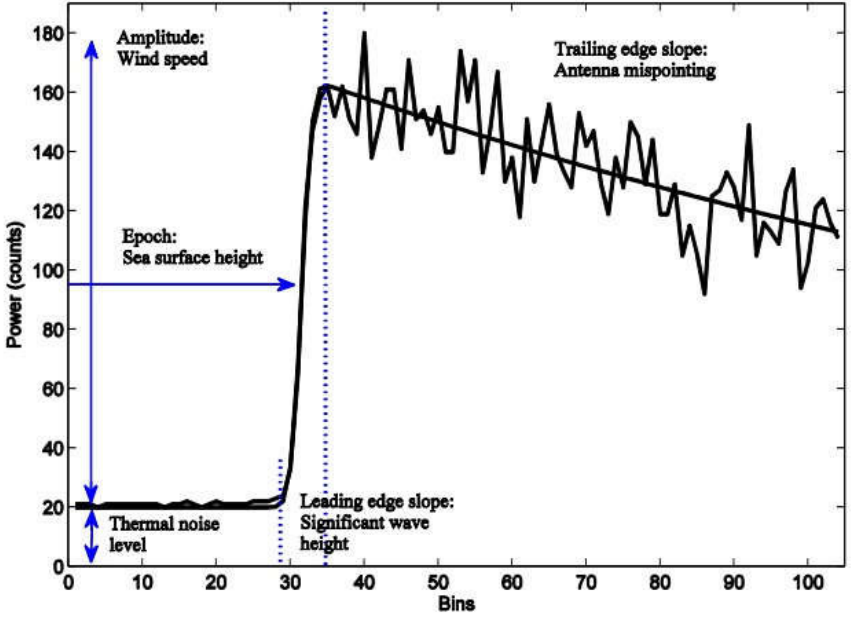




The retracking function

A mathematical model is used to adjust the ideal waveform and extract the different parameters (**Epoch, amplitude, Leading edge slope**). This is the **RETRACKING** step.





The retracking function

A mathematical model is used to adjust the ideal waveform and extract the different parameters (**Epoch, amplitude, Leading edge slope**). This is the **RETRACKING** step.

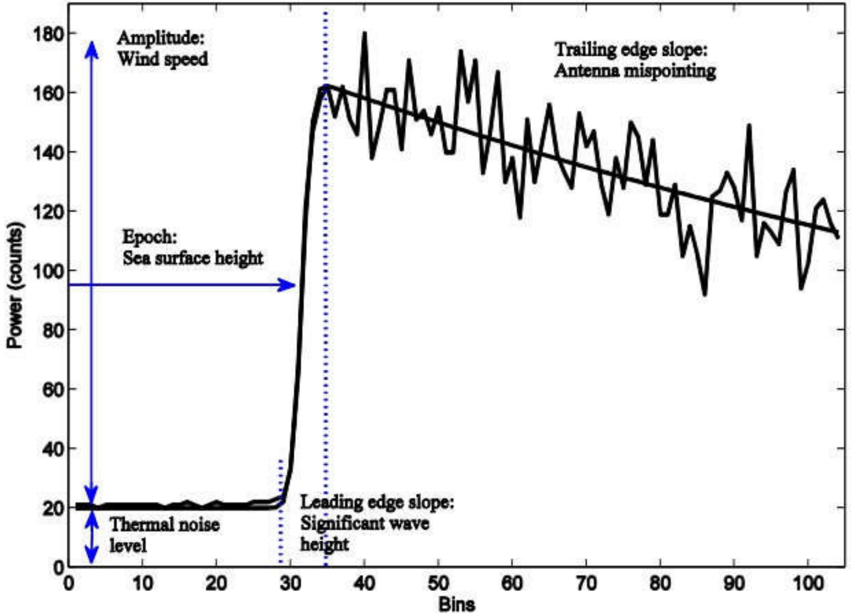
$$S(t) = RI(t) \otimes Q(t) \otimes PFs(t)$$

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

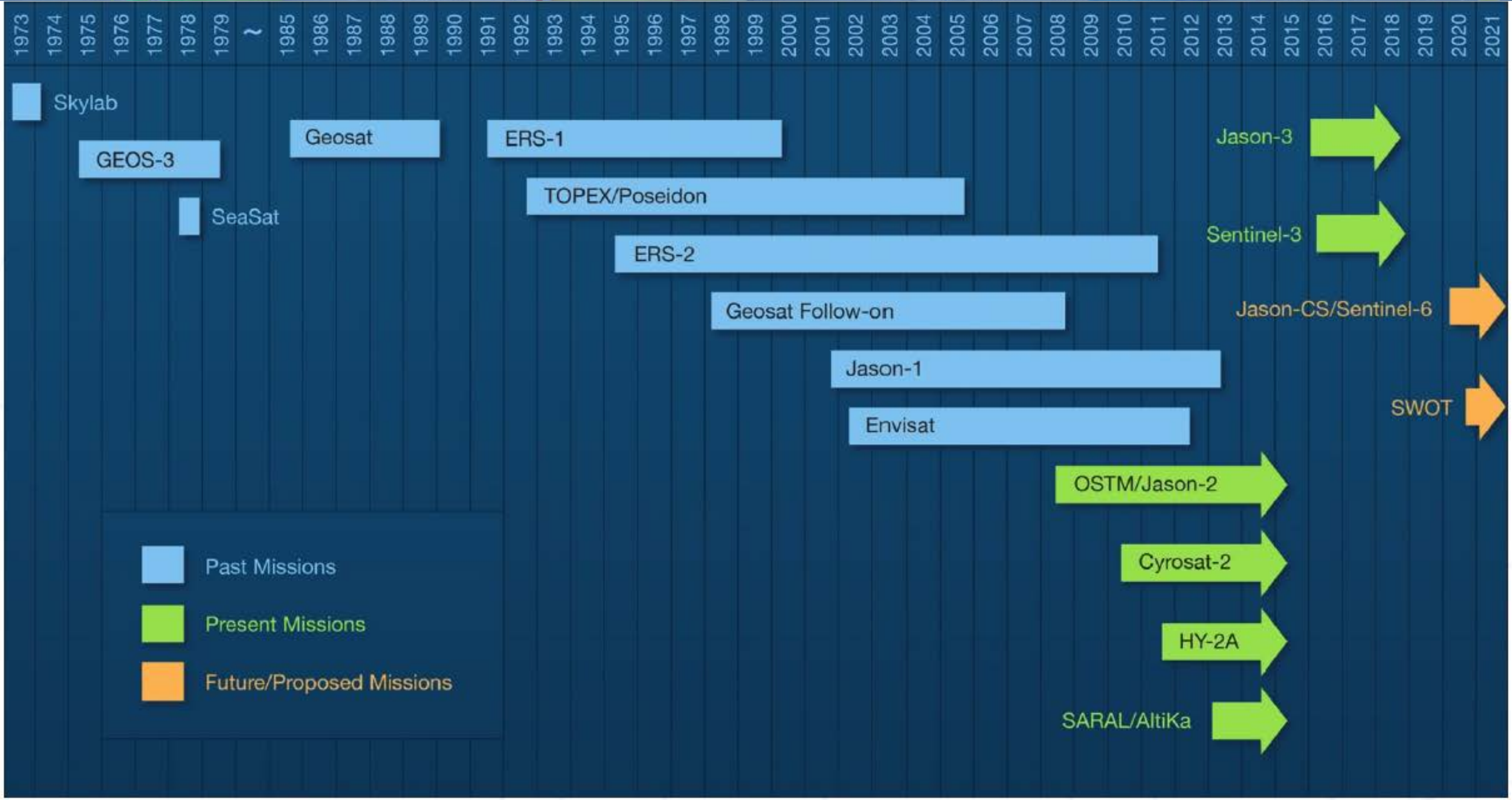
$$S(t) = \frac{hc\pi p_0\sqrt{2}}{\varkappa}[1 + \mathrm{erf}(\eta)]exp(-\alpha\tau)$$

c propagation speed of radar pulse
h altitude of the radar
r radius of the annulus
K=1+h/R $\quad \eta = {}^{\tau}/_{\sqrt{2}\sigma}$

Brown (1977)



More than 30 years of altimeter measurements

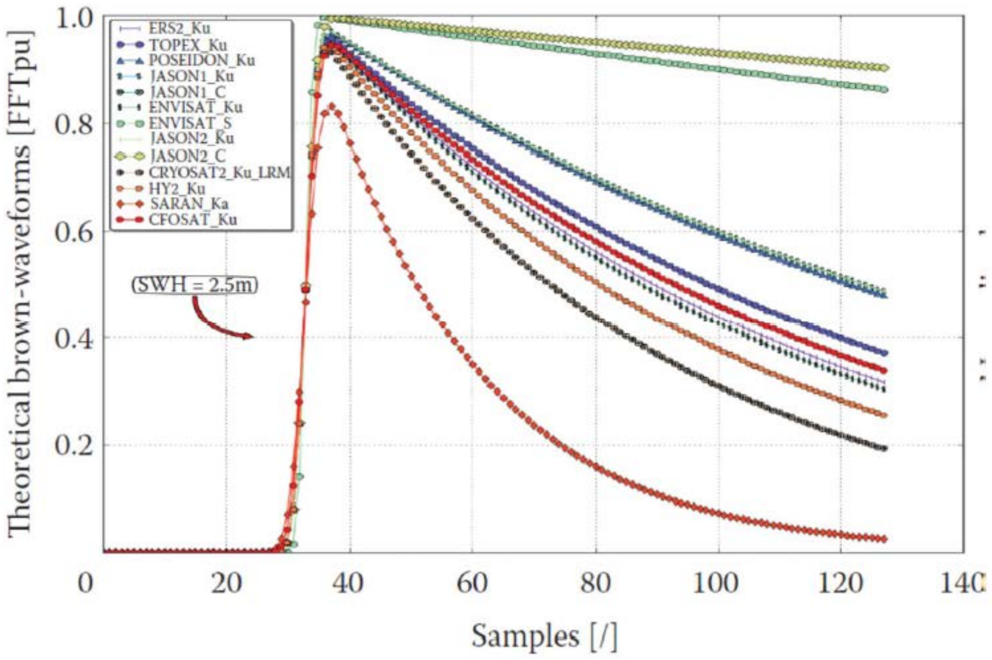


More than 30 years of altimeter measurements

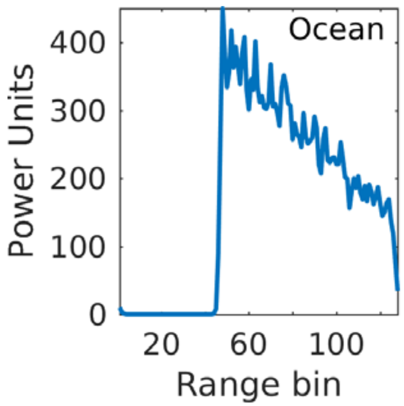
Satellite	Agency	Launch	Altitude	Frequency	Repetitivity	Inclination
Geosat	US Navy	1985	800 km	Ku-band	17 days	108
ERS-1	ESA		785	Ku	35	98.5
TOPEX / Poseidon	NASA / CNES	1992	1336	Ku and C	10	66
ERS-2	ESA	1995	785	Ku	35	98.5
GFO	US Navy / NOAA	1998	800	Ku	17	108
Jason-1	CNES / NASA	2001	1336	Ku and C	10	66
Envisat	ESA	2002	800	Ku and S	35	98.5
Jason-2	CNES / NASA	2008	1336	Ku and C	10	66
Cryosat	ESA	2008	720	Ku	369	92
HY2	China	2010	963	Ku and C		99.3
Saral	ISRO / CNES	2013	800	Ka	35	92
Sentinel-3	ESA	2016 (A) 2018 (B)	814	Ku and C	27	98.5
Jason-3	CNES / NASA / EU METSAT / NOAA	2016	1336	Ku and C	10	66

Illustration of the waveform diversity

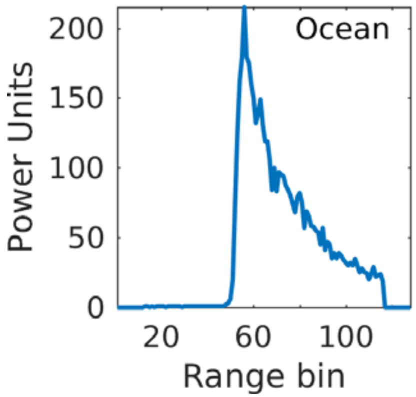
Theoretical waveform shapes for classical altimetry missions



Envisat (Ku)



SARAL (Ka)

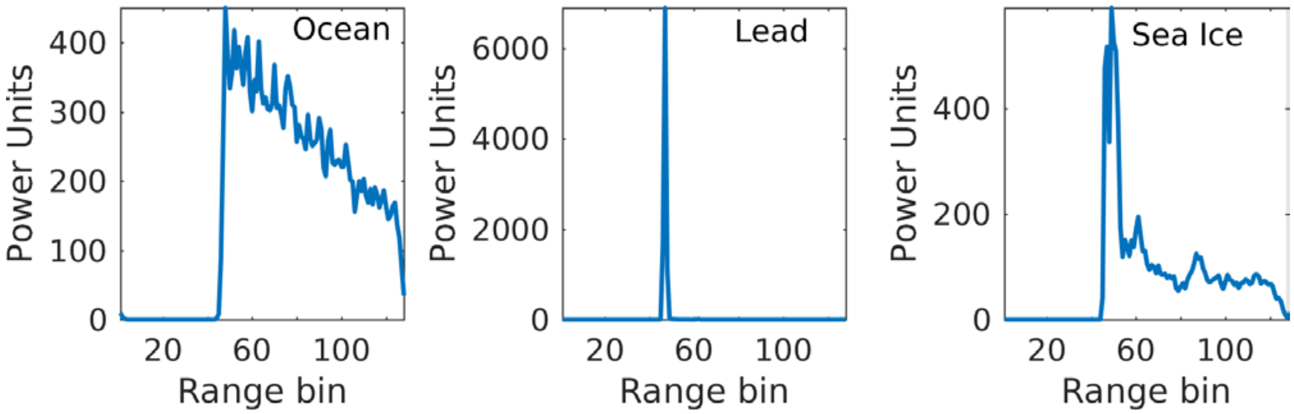


Muller et al, 2017

Illustration of the waveform diversity

In addition, each overflown surface has its own reflecting properties (ocean, hydrological and polar regions)

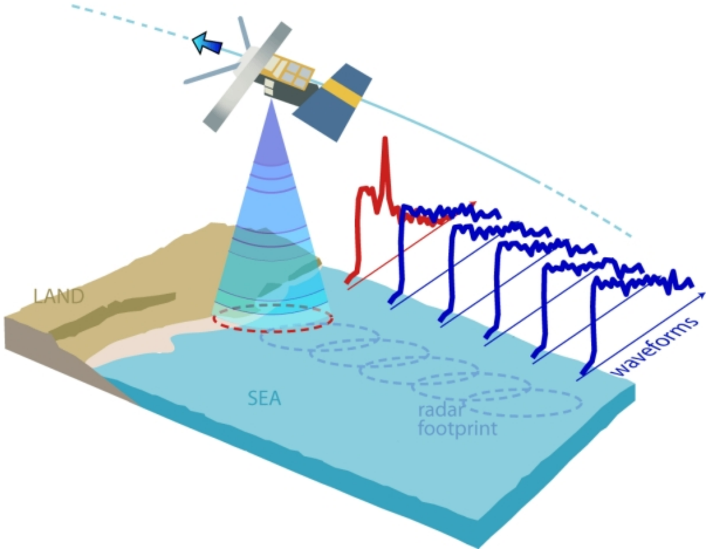
Envisat (Ku)



Muller et al, 2017

Illustration of the waveform diversity

Coastal waveforms



When the satellite nadir point reaches the coast line, the presence of land in the footprint may alter the shape of ocean waveforms.

➔ ***How*** the waveform is affected depends on $Area_{Land}$ times $\sigma_{0,Land}$ relative to $Area_{Ocean}$ times $\sigma_{0,Ocean}$.

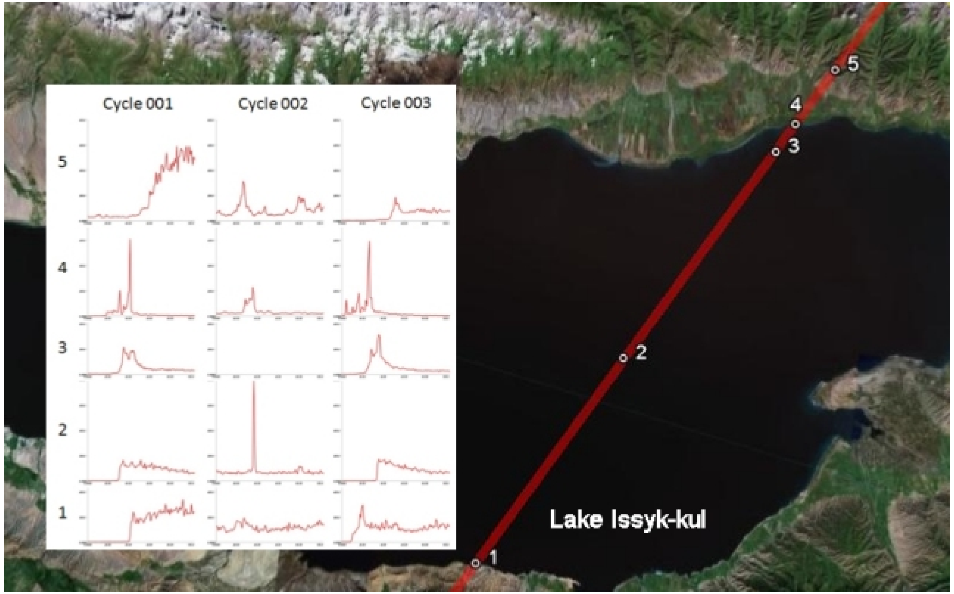
- **Small effect** if $\sigma_{0,Land} < \sigma_{0,Ocean}$ (often true). If the coastal land is not mountainous and σ_0 is low, the waveform distortion may be mild until quite close to the coast, and simple (Brown model) retracking may work
- In some environments, however (coral atolls) $\sigma_{0,Land} > \sigma_{0,Ocean}$ and **the effect is large** on the waveform

➔ The waveform can also be corrupted by the modification of the sea state within its footprint (basic assumption of the Brown ocean model = homogeneity of the reflective surface)

In addition, each overflown surface has its own reflecting properties (ocean, hydrological and polar regions)

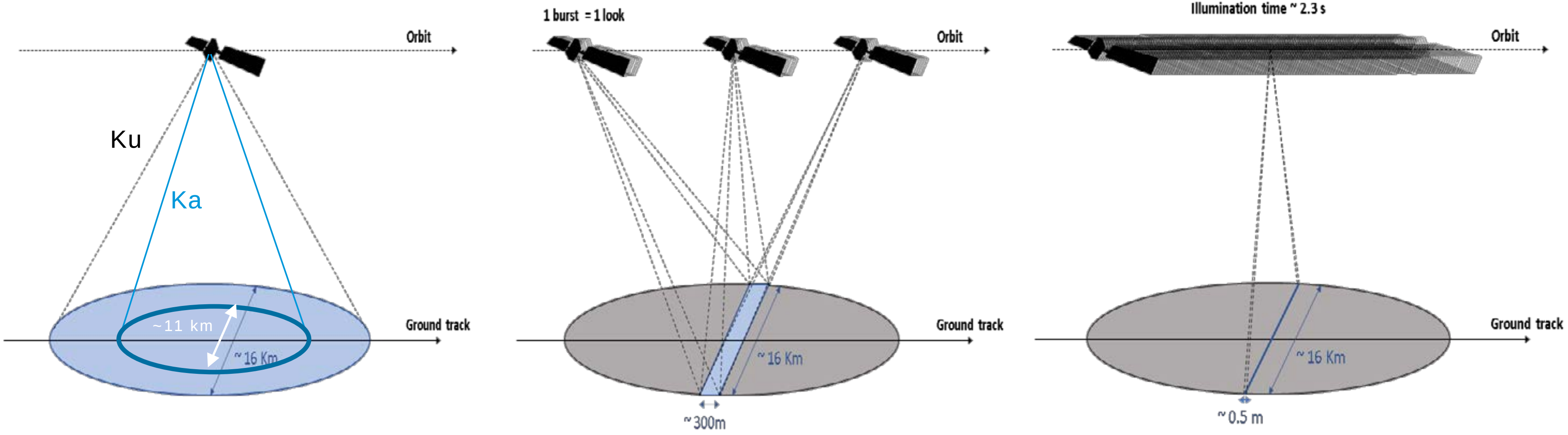
Analysing the altimeter waveform shape, backscatter coefficient and return power can also be useful tools for determining:

- topographic changes over ice sheets, lakes and rivers, and over other surfaces
- for estimating ice and snow thickness (see Cryosat).
- for dectecting sea ice



From conventional altimetry to Fully Focused SAR.

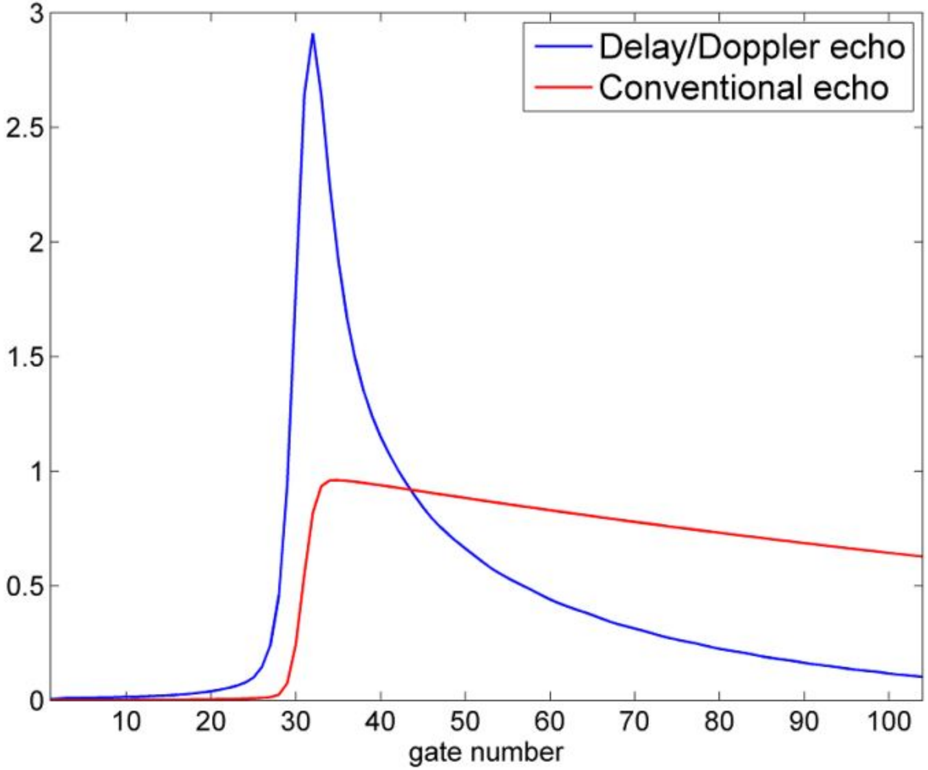
Conventional Altimetry (LRM / PLRM mode)	Unfocused SAR (SAR mode / DD mode) (Raney & al)	Fully Focused SAR (FF-SAR) (Egido & al, 2017)



No coherent processing (Phase not exploited) ➔ AT resolution = 16 km	Coherent processing on a burst (3,5ms) ➔ AT resolution ~ 320 m	Coherent processing over the entire illumination time (2.5 s) ➔ AT resolution = 0.5 m

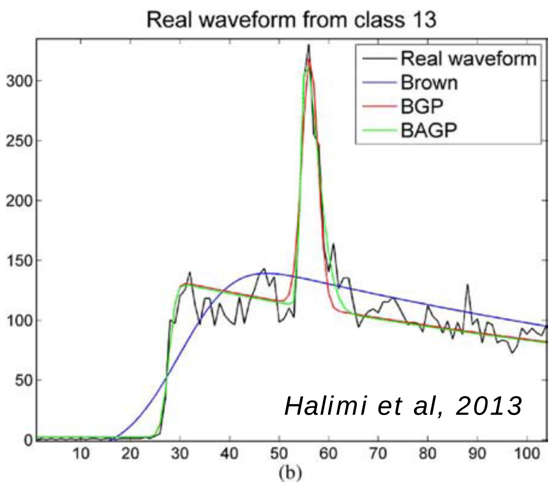
See Practical 1

SAR mode altimeter waveform



Many retrackers for many waveforms

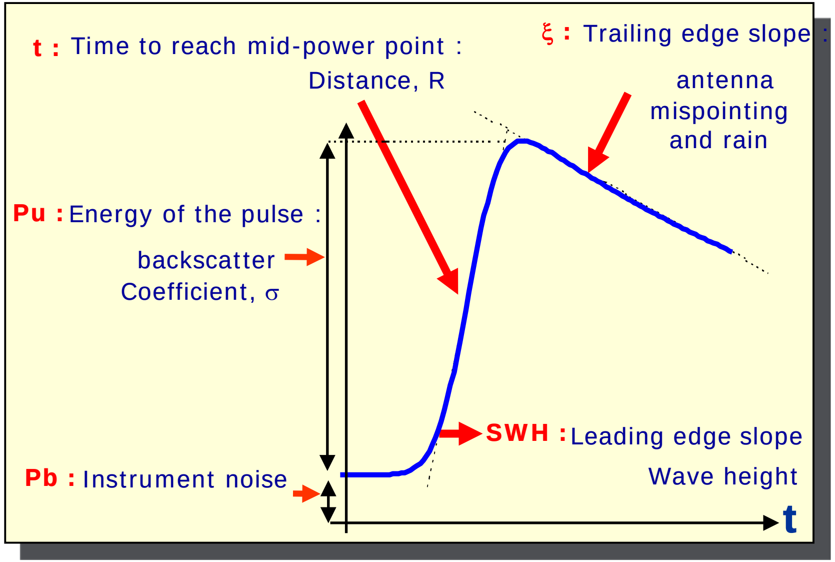
- During the last 30 years, numerous studies have been conducted to define, to implement and to analyze the results of many versions of the retracking function trying to adapt their designs to a particular context and optimize their performances :
  - Many versions of retrackers have been developped over **ocean**, **cryosphere**, **hydrological** and **coastal** zones, but also solutions for estimation over **rain cells**, **sigma0 bloom** events (J.Tournadre or G.Quartly in particular) and **sea-ice** regions



  - Specific retrackers to account for **instrumental issues** (on Topex for example :E.Rodriguez and P.Callahan) or **platform mispointing** (for Jason-1)
  - Specific retrackers for the new SAR and SARin modes (The SARvatore and the SARINvatore retrackers)
  - **the retracker must clearly be designed/chosen depending on these features and depending on the final application**

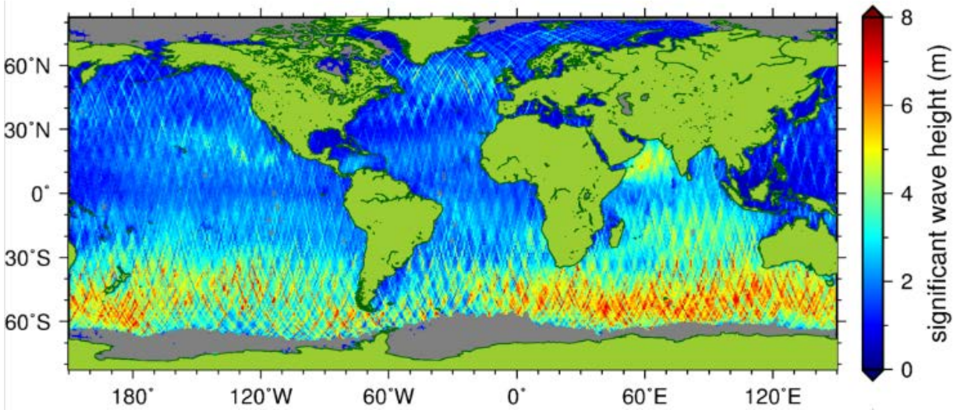
Wave height estimations

Significant wave height is estimated from the slope of the waveform's leading edge.



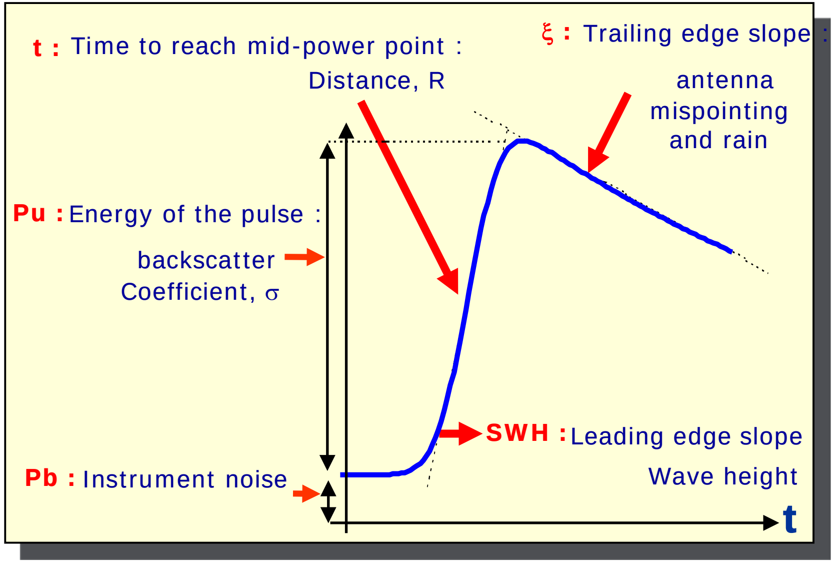
Sentinel-3A Significant Wave Height

One full repeat cycle of 27 days, from 28 June to 25 July 2016



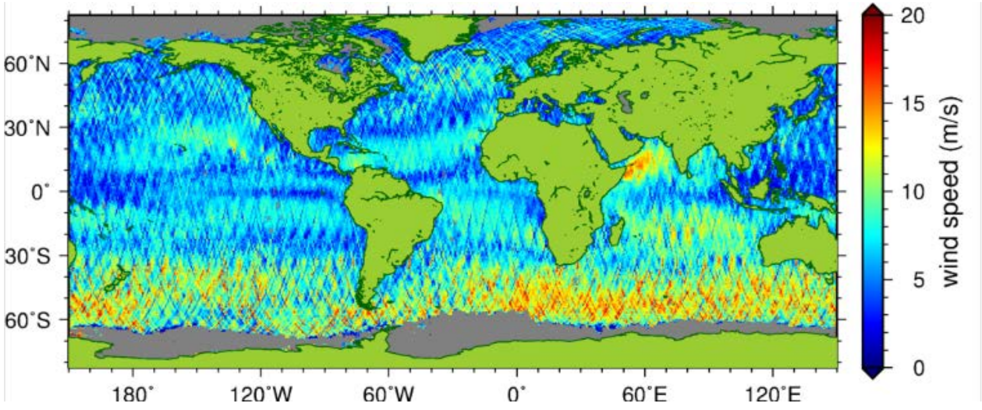
Wind speed estimations

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.



Sentinel-3A wind speed

One full repeat cycle of 27 days, from 28 June to 25 July 2016



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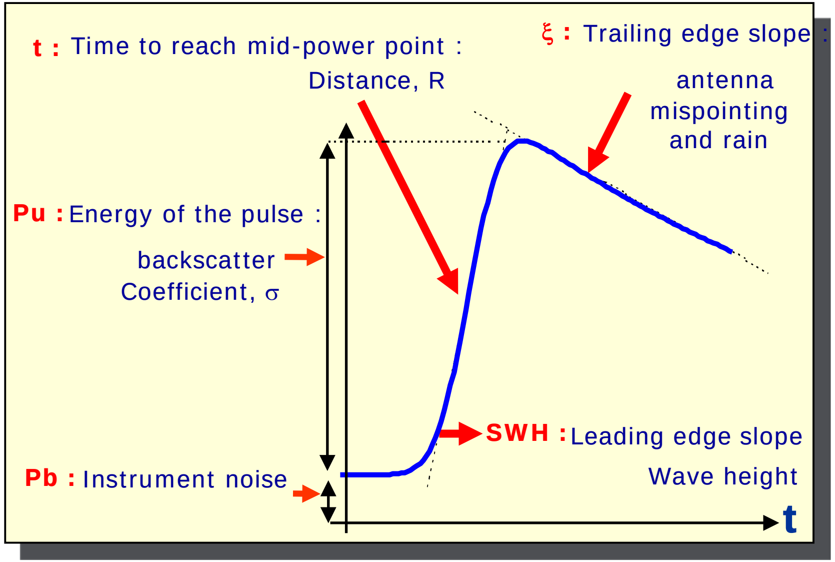
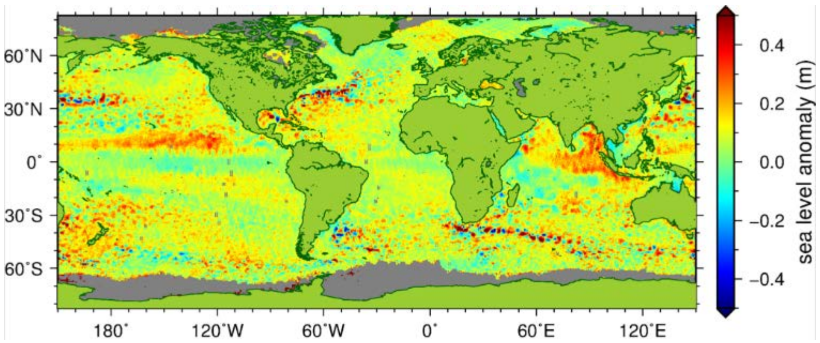


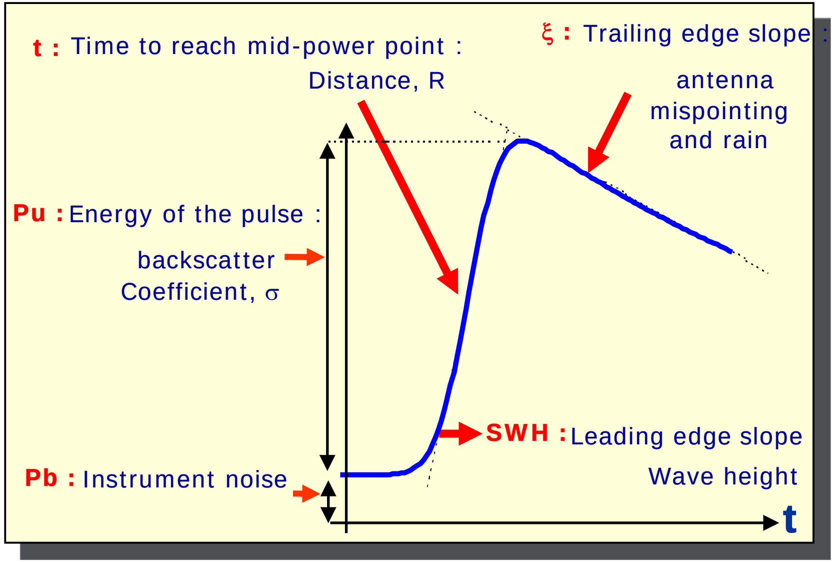
Sentinel-3A Sea Level Anomaly

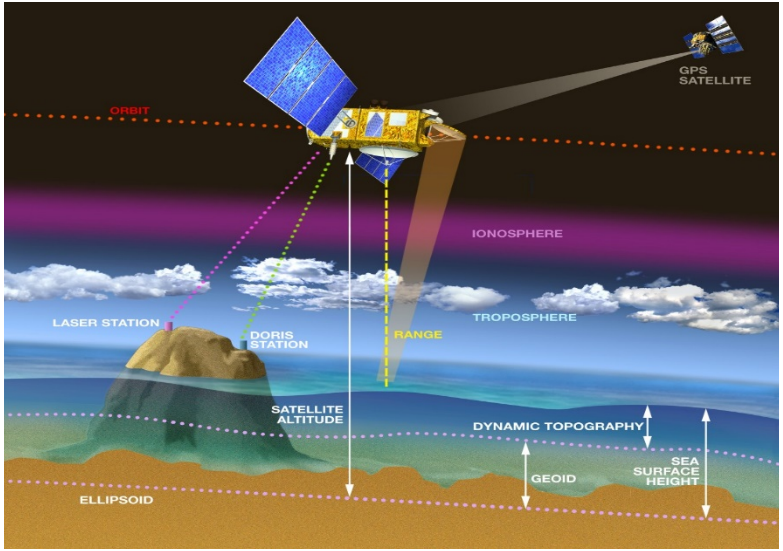
One full repeat cycle of 27 days, from 28 June to 25 July 2016



Sea Surface Height (SSH) estimations

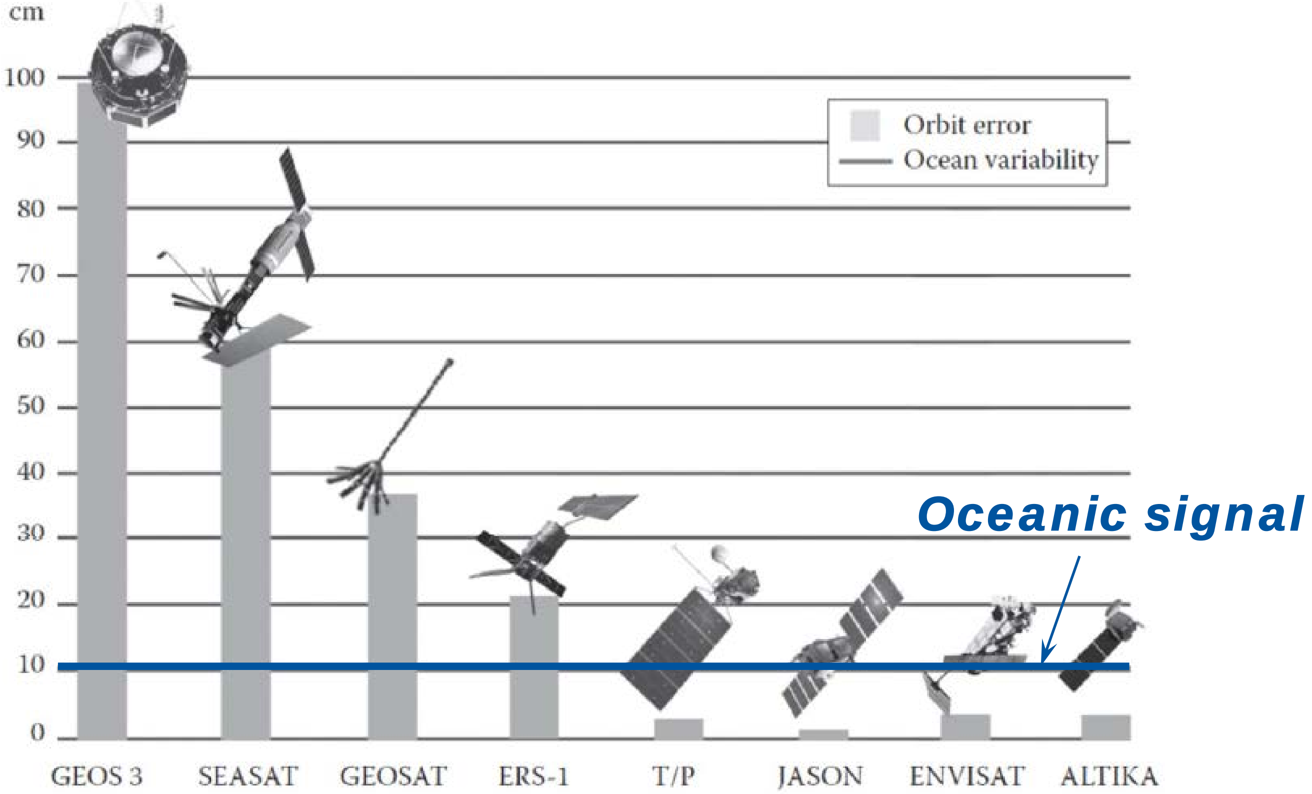
SSH = Orbit – Range = Sea Surface Height above a reference ellipsoid





The evolution in precise orbit determination

Tracking system on board altimeter missions for precise orbit determination (DORIS, LRA, GPS)



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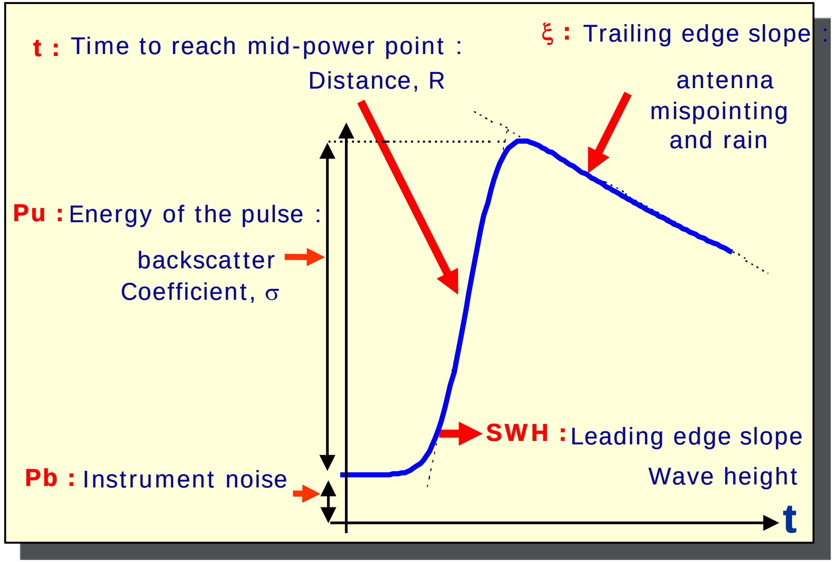
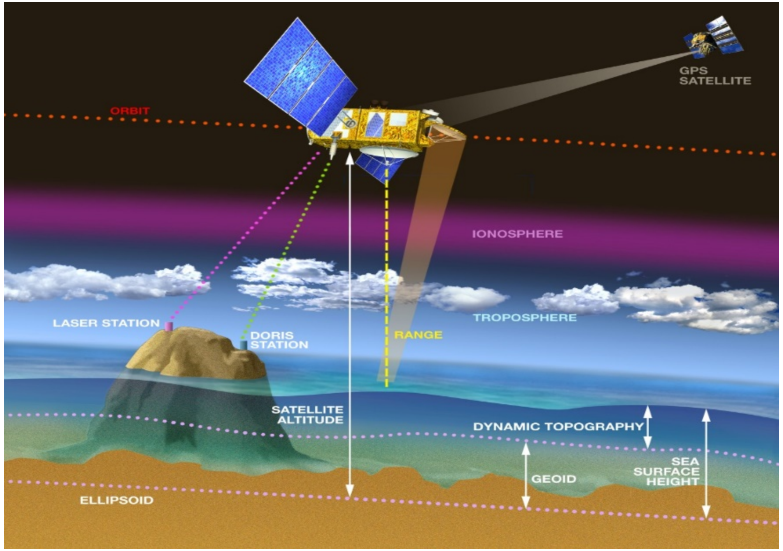
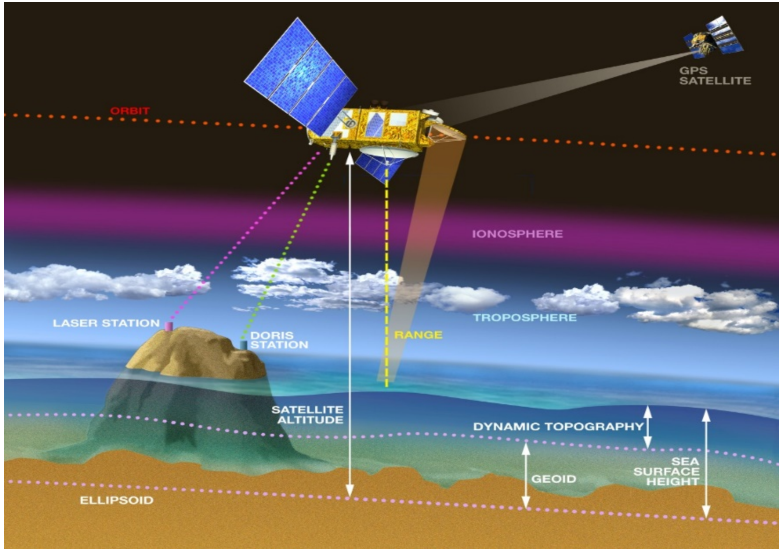




Sea Surface Height (SSH) estimations

SSH = Orbit – Range = Sea Surface Height above a reference ellipsoid

- Errors on the range affected by :
  - Instrumental noise
  - Instrumental errors
  - Environnemental errors (wet and dry troposphere and ionosphere)
  - Sea state



Sea Surface Height (SSH) estimations

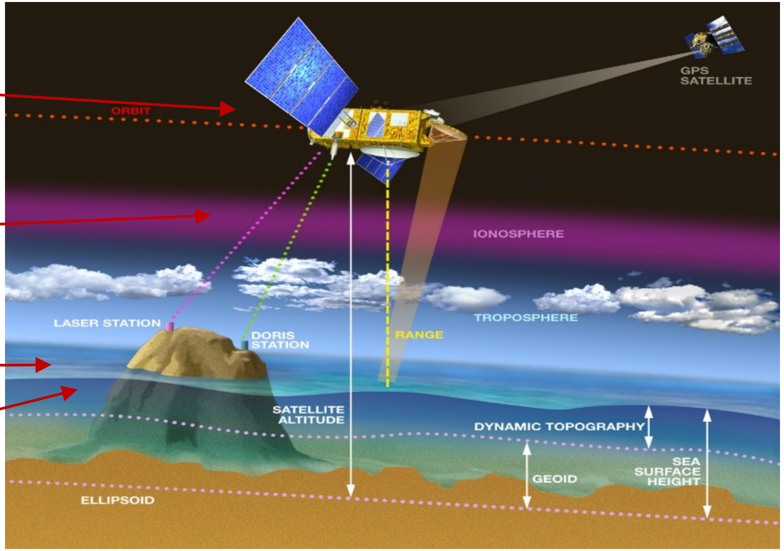
$$SSH = Orbit - Range - \sum Correction$$

Instrumental corrections
The satellite is moving during the measure, the instruments are not perfect …

Environmental corrections
The atmosphere modifies the signal propagation

Sea surface state corrections
The sea surface is not flat …

Geophysical corrections
For different reasons, some physical signals are removed (tides, inverse barometer effect…)



Instrumental corrections

- **USO (Ultra-Stable Oscillators) :**

The internal clock that controls the system of the measure. The ageing of the instrument leads to measure errors of some mm/year

- **Doppler Effect :**

To take into account the fact that the satellite is moving during the measurement
Ex : ± 13 cm for Topex/Poseidon

- **Mispointing :**

To correct the angle of the antenna respect to the nadir
Ex: ~2 cm for a 0.2° mispointing

- **Pursuit bias :**

To take into account the imprecision of the algorithm on board the satellite
It varies from some cm to ~45 cm

- **Internal Calibration :**

To take into account the transit-time inside the instruments that induces an error of some cm

Environmental corrections

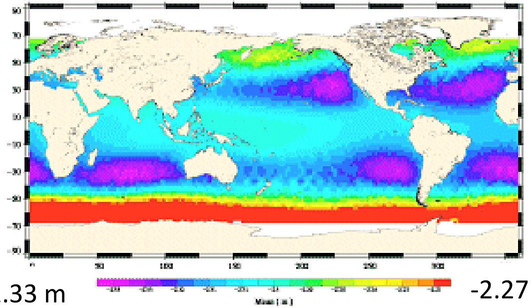
The radar signal is not absorbed by the atmosphere, but the unhomogeneities of the atmosphere modify the propagation of the signal (deviation and slowing)

- **Dry troposphere :**

Due to the presence of dry gas in the atmosphere. Estimated thanks to meteorological models (ECMWF 6h – N400 ~ 1/4°)

Ex: 1 year of the Jason 1 mission (2004 : cycles 73 to 109).

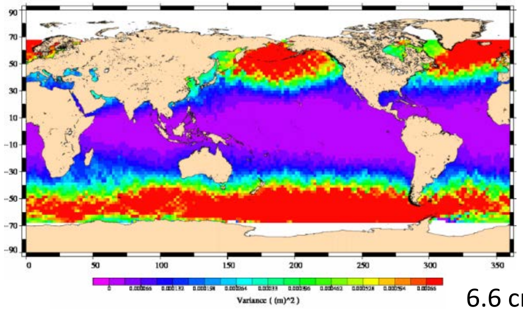
Correction mean



-2.33 m

-2.27 m

Correction variance



6.6 cm²

Environmental corrections

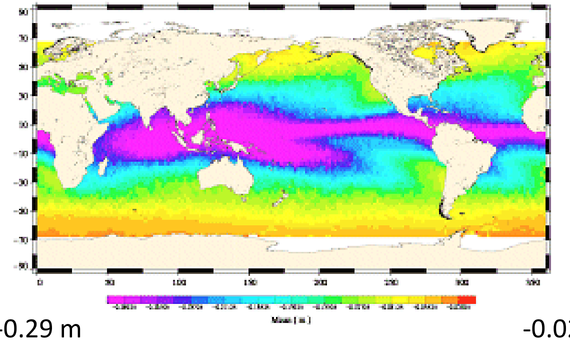
The radar signal is not absorbed by the atmosphere, but the unhomogeneities of the atmosphere modify the propagation of the signal (deviation and slowing)

- **<u>Wet troposphere</u> :**

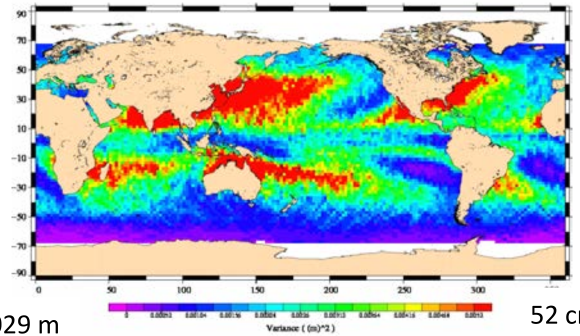
Due to the presence of water vapor into the atmosphere. It is calculated from **radiometer measurements** and/or meteorological models (ECMWF).

Ex: 1 year of the Jason 1 mission (2004 : cycles 73 to 109).

Radiometer correction mean



Radiometer correction variance



The radar signal is not absorbed by the atmosphere, but the unhomogeneities of the atmosphere modify the propagation of the signal (deviation and slowing)

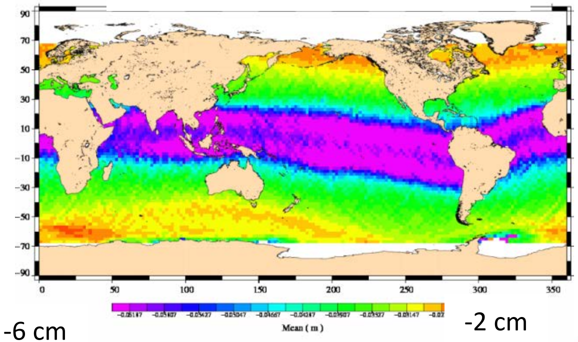
- **Ionosphere** :

Due to the presence of free electrons. Estimated thanks to the bi-frequency measure when available: Ku (13.6 GHz) and C/S (5.3-3.2 GHz) band

If not (case for Envisat for instance): use of models (GIM)

Ex: 1 year of the Jason 1 mission (2004 : cycles 73 to 109).

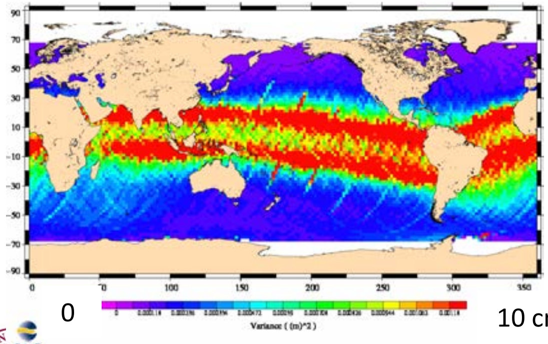
Bi-frequency correction mean



-6 cm

-2 cm

Bi-frequency correction variance



0

10 cm²

Surface State corrections

- **<u>Sea-state bias</u> :**

The energy reflected by the trough of the wave is more important than the one reflected by the ridge.

The sea surface state is continuously modified by various parameters : Wind speed and direction, air/water temperature, water viscosity, non linear wave interaction, ...

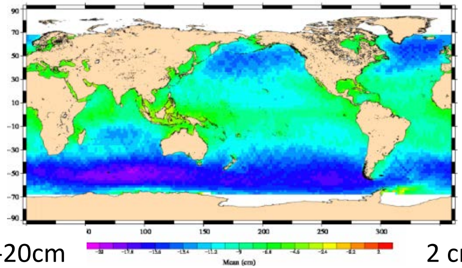
➢One of the most difficult corrections

➢At this time determined thanks to an empirical model but still room for further improvements

➢Error on this correction is particularly difficult to assess. It is geographically correlated at basin scale: residual long wavelength signal in the SLA

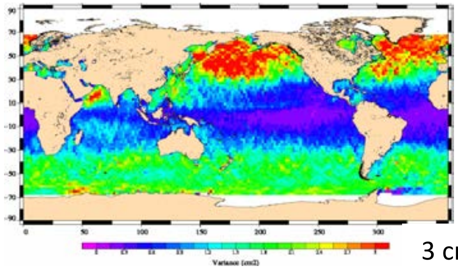
Ex: 1 year of the Jason 1 mission (2004 : cycles 73 to 109).

SSB correction mean



-20cm 2 cm

SSB correction variance



3 cm²

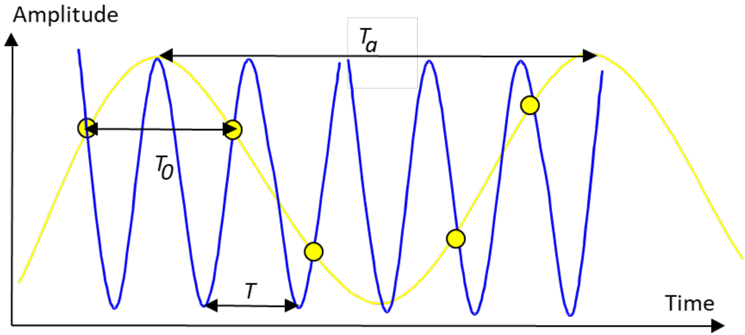
Geophysical corrections

- **<u>The ocean tides:</u>** Periodic variations of the ocean sea level due to the actions of celestial bodies in rotation around the Earth. More than 400 tidal waves with periods ranging from less than half a day to years.

Major tidal waves have much higher frequency (12-24 h) than the sampling of the altimetry satellites (10 days at best), which generates aliased signals in the altimetry SSH (example : the semi-diurnal M2 main tidal constituent is aliased at a period of 62 days in the TP/Jason SSH data).

- ➢ Need to remove tides from altimeter measurements
  => need accurate global tide models !
- ➢ Amplitude from a few centimeters in the open ocean to several meters in the shelf regions (up to ~10 m in the Bay of Fundy and in the English Channel)

The aliasing issue



With a sampling period of T_0, we cannot reconstruct a periodic signal of period lower than $2T_0$ (Nyquist period)
If $T_0 > T/2 \rightarrow T_a$ is the aliased period

- **<u>Load effect</u>** :
Earth deformation due to the weight it is supporting.
Directly depending on the ocean tide effect

The ocean tide correction

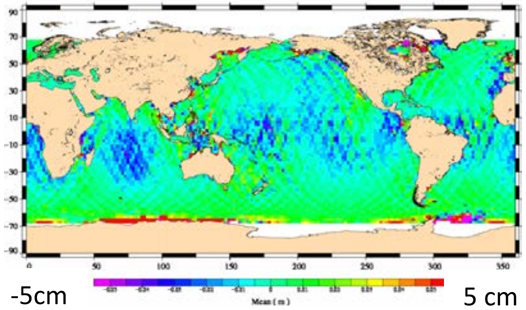
Global tidal models can be categorized into three groups: hydrodynamic, empirical and assimilation models

- Hydrodynamic models are derived by solving the Laplace Tidal Equation and using bathymetry data as boundary condition. *Example: HIM, OTIS-GN, STORMTIDE, OTIS-ERB, STM-1B, HYCOM*
- Empirical models are derived by extracting ocean tidal signal from satellite altimetry and they describe the total geocentric ocean tides, which include the ocean loading effect. *Example: GOT, OSU, DTU, EOT*
- Assimilation models are derived by solving the hydrodynamic equations with altimetric and tide gauge data assimilation. *Example: HAMTIDE, FES, TPXO*

All above mentioned models are barotropic models. However barotropic tides may interact with the bottom topography giving rise to baroclinic tides (internal tides). Contribution may be significant in coastal areas.

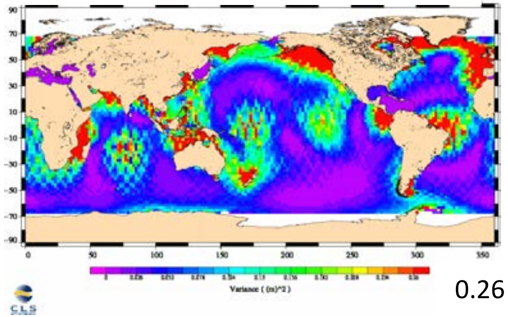
Ex: 1 year of the Jason 1 mission (2004 : cycles 73 to 109).

GOT00.2 correction mean



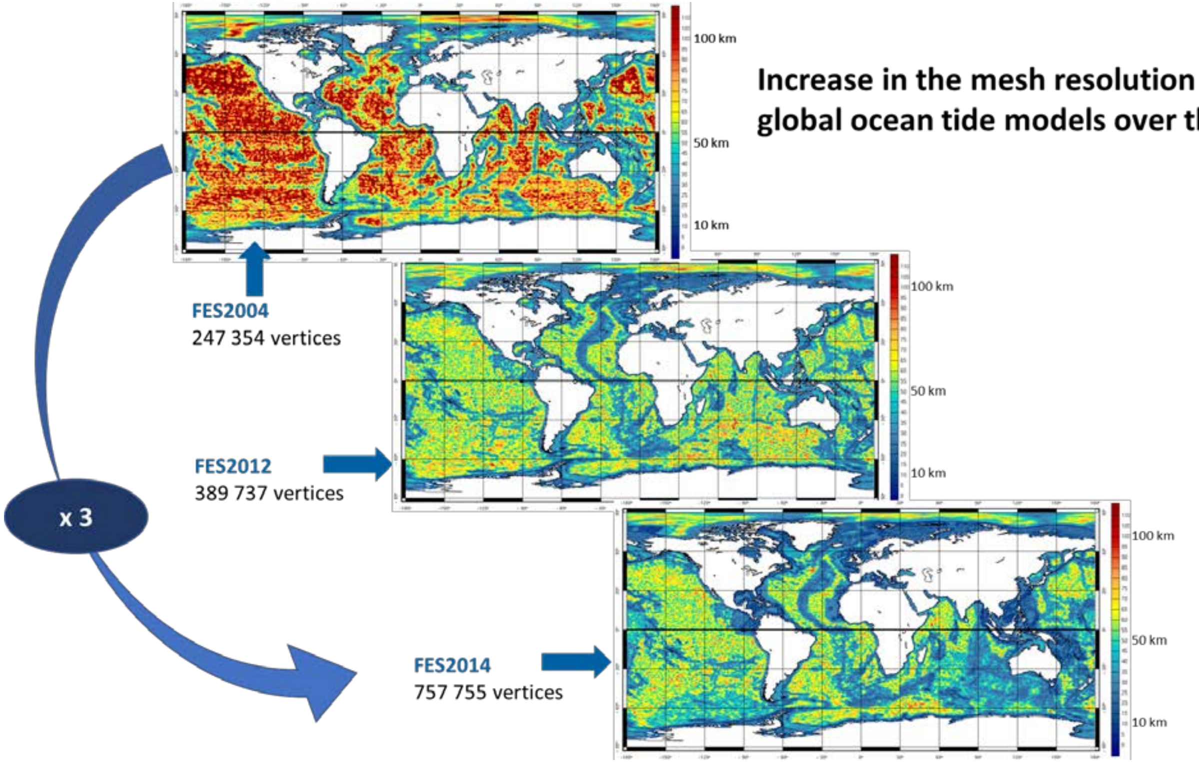
-5cm 5 cm

GOT00.2 correction variance



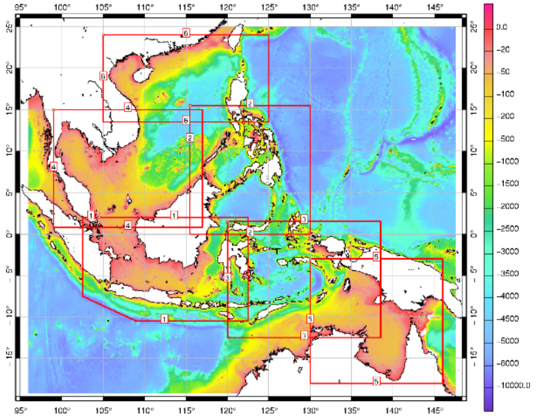
0.26 m²

Geophysical corrections



Increase in the mesh resolution of the global ocean tide models over the time

+ Improved Bathymetry

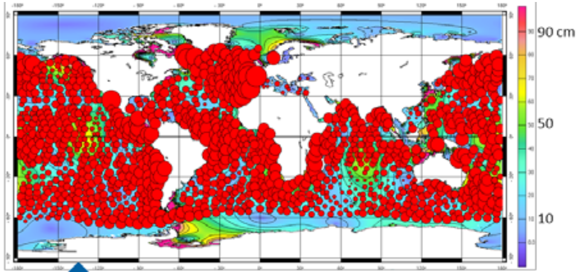


- Data mapping, adding SRTM elevation
- Merging with global database

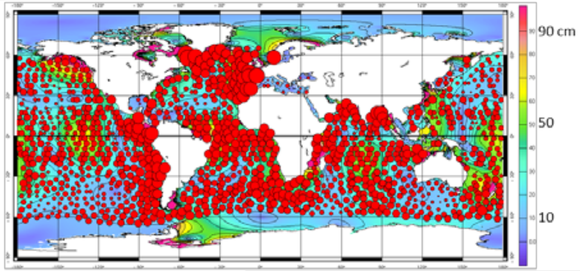
Geophysical corrections

Improvement of the hydrodynamic modelling over the time

+ Improved modelling/assimilation techniques
+>20 years altimeter time series



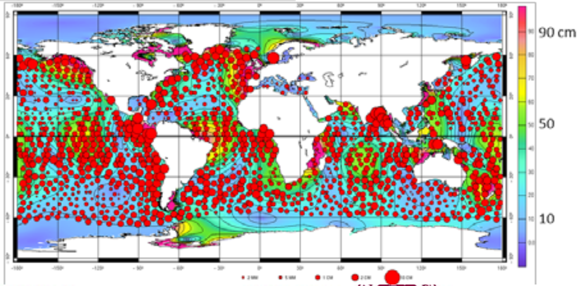
FES2004
Deep ocean:45 mm



FES2012
Deep ocean: 24 mm
Shelf Seas: 93 mm

/ 3.5

Vector differences between hydrodynamic solution and TP/J1/J2 crossover points (M2)



FES2014
Deep ocean: 13 mm
Shelf Seas: 54 mm

Geophysical corrections

- **Dynamical Atmospheric Correction (DAC)**

❑ **The ocean static response to atmospheric pressure forcing (inverse barometer) is removed along-track: (1 mbar ↔ 1 cm)** **[Low frequency (> 20 days) signal only]**

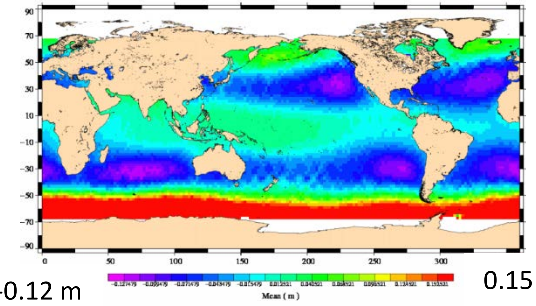
- ✓ Pressure anomalies P' are calculated using pressure estimates from the ECMWF model
- ✓ P'=Pressure-<P> where <P> is the spatial average (over the ocean) of the instantaneous pressure map (every 6 hours).
- ✓ **Motivation:** known, static response + necessity to remove this signal before mapping

❑ **Barotropic response to pressure and wind from the MOG2D model is removed along-track** **[High frequency (<20 days) signal only]**

- ✓ **Motivation :** avoid high frequency oceanic signal to be aliased in the final products.

Ex: 1 year of the Jason 1 mission (2004 : cycles 73 to 109).

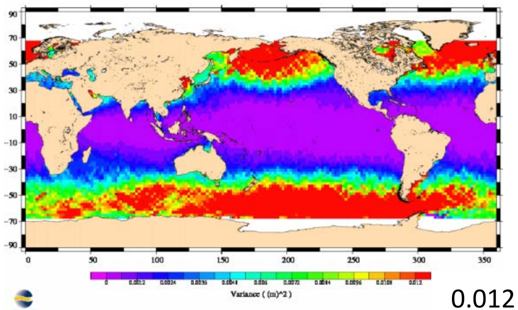
MOG2D-HR correction mean



-0.12 m

0.15 m

MOG2D-HRcorrection variance

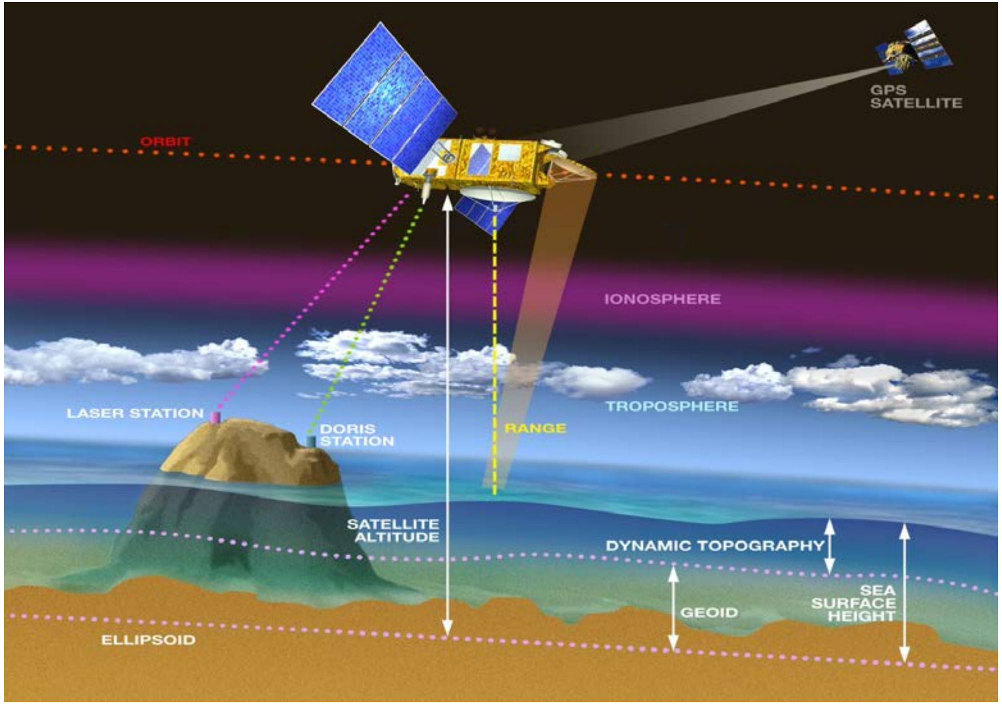


0.012 m²

Corrections depend on missions

	ERS-1	ERS-2	EN	T/P	J1	J2	GFO	C2
Orbit	Reaper	Reaper	GDR-D	GFSC STD08	GDR-D	GDR-D	GSFC	GDR-D
Major Instr. correction			PTR FPAC					
Sea State Bias	BM3 (Gaspar, Ogor, 1994)	Non parametric Mertz et al., 2005	Tran 2012 compatible enhanced MWR	Non parametric SSB [N. Tran et al. 2010]	Tran 2012 (OSTST)	Tran 2012	Non parametric SSB [Tran and Labroue, 2010]	Non parametric SSB from J1 (GDR-C) with unbiased sig0
Ionosphere	Reaper	Bent (cycle 1-49), GIM from cycle 50	Bi frequency (c≤64), GIM (c≥65) corrected for 8mm bias	Bi frequency (TOPEX) DORIS (POSEIDON)	Dual frequency		GIM	GIM
Wet troposphere	MWR	MWR+Minimisation of TB drift [Scharoo et al. 2004]	c≤64 :MWR(dist≥50km from the coasts), ECMWF (dist≤50km from th coast) <≥65: MWR	TMR (Scharoo et al, 2004)	MWR replacement product	GDR-D (MWR JPL enhancement product)	From GFO radiometer	From ECMWF model
Dry troposphere	Era Interim based		ECMWF Gaussian grids based	Era Interim based	ECMWF rectangular grids based	ECMWF Gaussian grids based	ECMWF rectangular grids based	ECMWF Gaussian grids based
Combined atmospheric correction	MOG2D High Resolution forced with Era Interim pressure and wind fields		MOG2D High Resolution forced with ECMWF pressure and wind fields + IB	MOG2D High Resolution forced with Era Interim pressure and wind fields	MOG2D High Resolution forced with ECMWF pressure and wind fields + IB computed from rectangular grid			MOG2D High Resolution forced with ECMWF pressure and wing fields + IB from rectangular grids
Ocean tide	GOT4V8							
Solid Earth tide	Elastic response to tidal potential [Cartwright and Tayler, 1971], [Cartwright and Edden, 1973]							
Pole tide	[Wahr, 1985]							
MSS	CNES-CLS-2011 + reference period change [1993, 2012]							

From SSH to Absolute Dynamic Topography

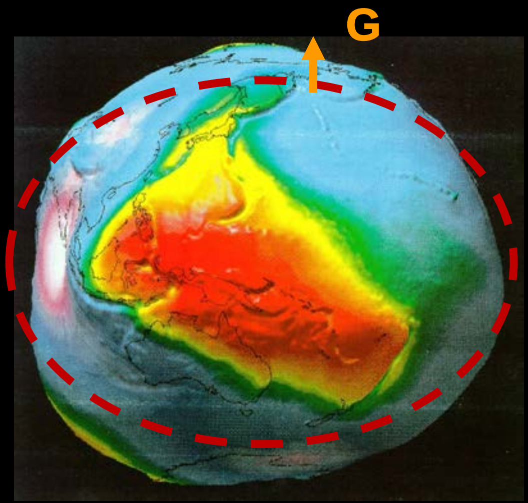


SSH = Orbit – Range $-\sum Correction$

SSH = **h** + Geoid

h = Absolute Dynamic Topography

The surface of an ocean of homogeneous density covering an Earth at rest would coincidate with an Earth Gravity Equipotential surface called GEOID



E : Reference Ellipsoid

Equipotential of the gravity field

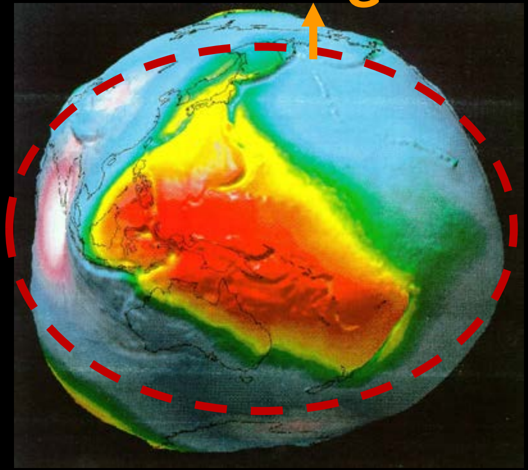
The surface of an ocean of homogeneous density covering an Earth at rest would coincide with an Earth Gravity Equipotential surface called GEOID

Gravity forces generating tides

Thermal forcing

Variations of the Atmospheric pressure

G



Wind effects

Hydrological Cycle

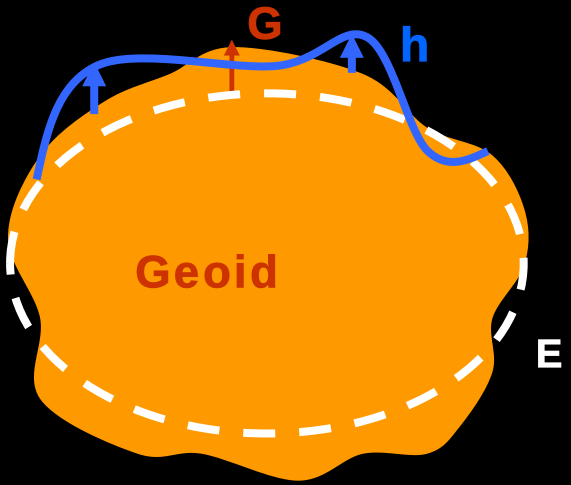
Coriolis Force due to the Earth Rotation

As a consequence, at a given time, at a given place, the sea level differs from its position at rest, the geoid. The difference between the two positions is the **ocean dynamic topography h**

Tidal currents

Geostrophic currents

Stokes drift



Ekman currents

Inertial oscillations

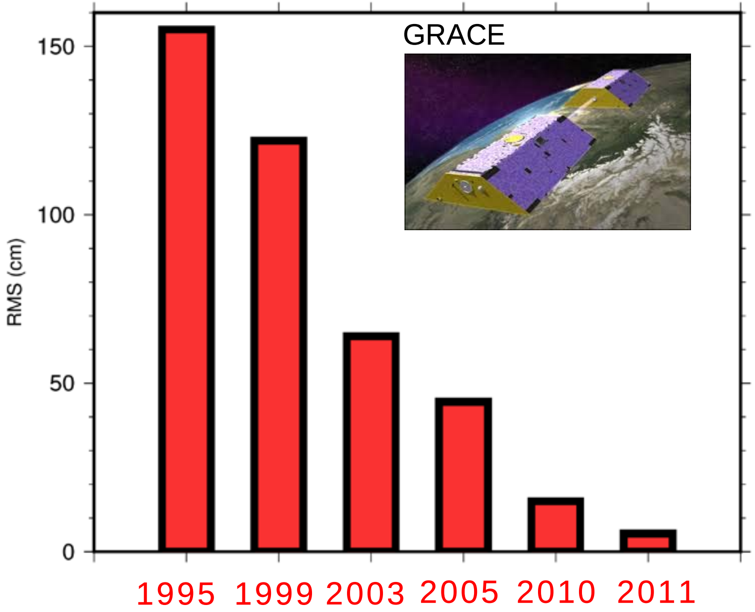
High frequency ageostrophic currents

Geoid estimation

Satellite-only geoid models

Model	Year	Max DO	Data
GRIM4S4	1995	70	Geodetic satellites
GRIM5S1	1999	99	Geodetic satellites
CHAMP3S	2003	140	33 months of CHAMP
GGM02S/ EIGEN3S	2005	150	2 years of GRACE
ITG-GRACE2010s	2010	180	7 years of GRACE
GOCE 	2009-2013	200-250	2 months (R1) 6 months (R2) 1 year (R3) Full mission (R5)

RMS differences (in cm) between geoid models and GOCE-DIR-R5 filtered at 100km (on oceans)



ADT amplitude: +/- 100 cm

From SSH to SLA

Some very simple equations

$$SSH = h + G$$

$$MSSH = MDT + G$$

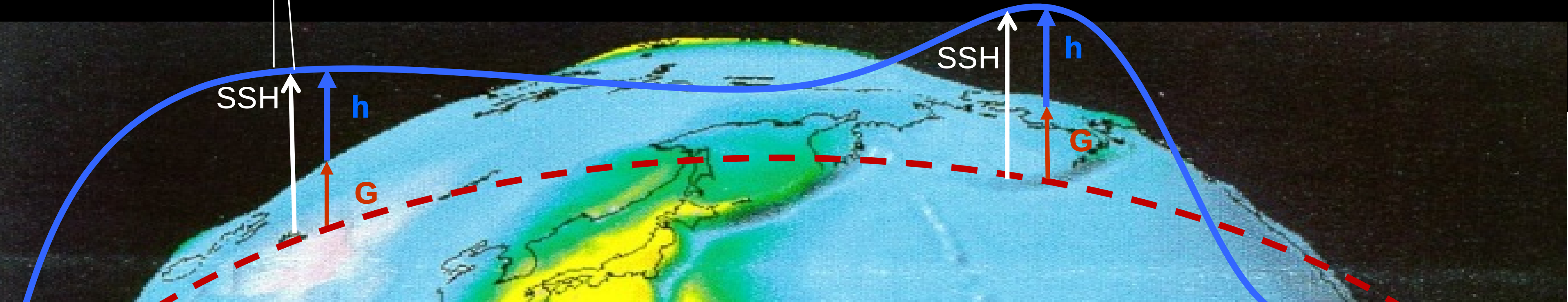
$$SSH - MSSH = h - MDT \cancel{+G-G}$$
$$= SLA$$

Along-track processing: would require a cm accuracy geoid at the SSH resolution (300m-7km)!

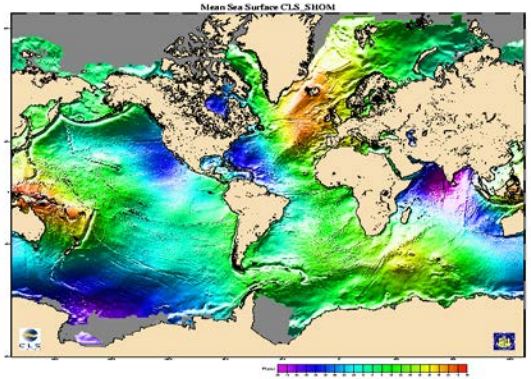
MSSH=Mean Sea Surface Height

MDT=Mean Dynamic Topography

SLA=Sea Level Anomaly
= Time variable part of the signal in reference to a given time period (1993-2012 for the latest MSSH)



Mean Sea Surface estimation:
25 YEARS IMPROVEMENTS



MSS OSU 95

MSS CLS_SHOM98

MSS CLS01

MSS DNSC08

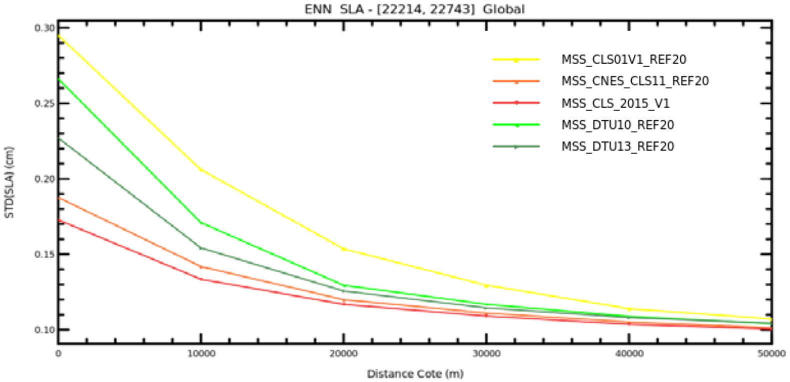
MSS DTU10

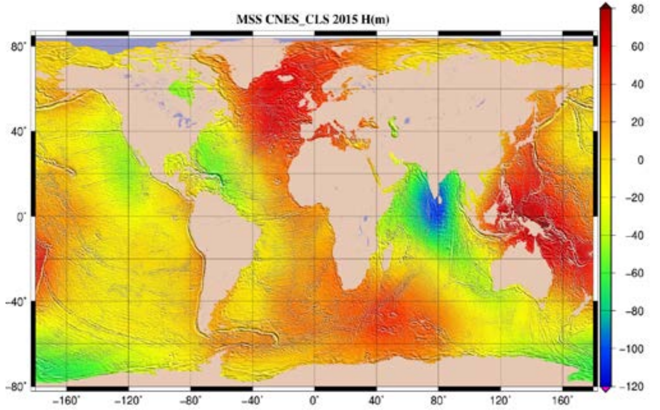
MSS CNES_CLS_2011

MSS DTU15

MSS CNES_CLS_2015

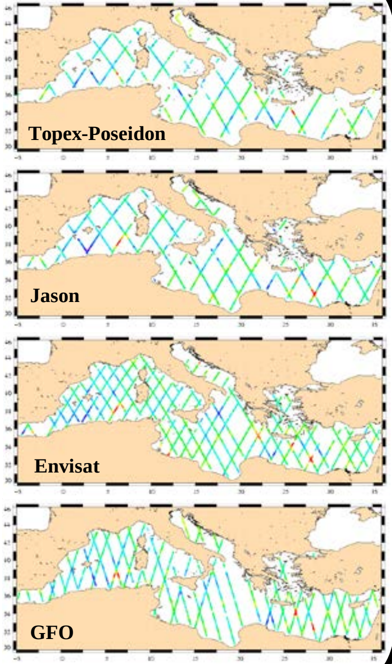
Standard Deviation of Envisat New orbit (ENN) SLA as a function of coastal distance when using different MSS solutions





Hosted by

From SSH to gridded maps of SLA



Sea Surface Height (SSH)
relative to the ellipsoid

- Instrumental Corrections
- Environmental Corrections
- Surface State Corrections
- Geophysical Corrections

Corrected SSH
relative to the ellipsoid

Repeat-track Method

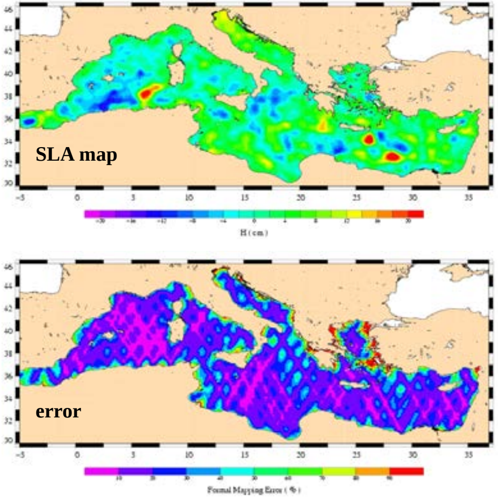
Corrected SLA ↔ **Level 2**

- Multimission calibration
- Selection/editing
- Filtering and subsampling

SLA ↔ **Level 3**

Mapping (Objective Analysis)

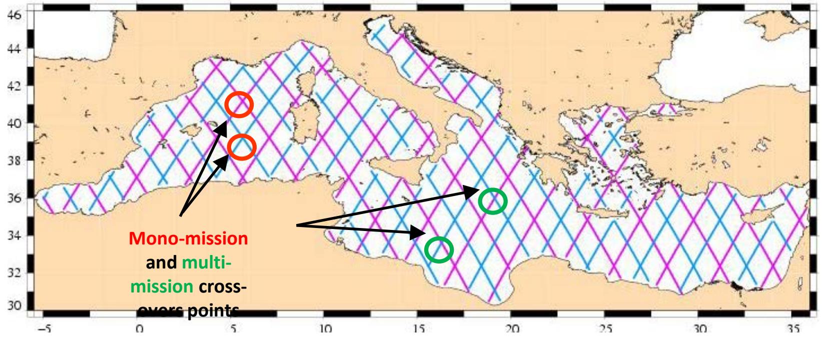
Maps of SLA ↔ **Level 4**



Step 1 : Reduction of the crossover differences

•**Purpose** : Reduce orbit error and ensure coherence between different altimetric missions by using the most accurate mission as a reference to correct the others.

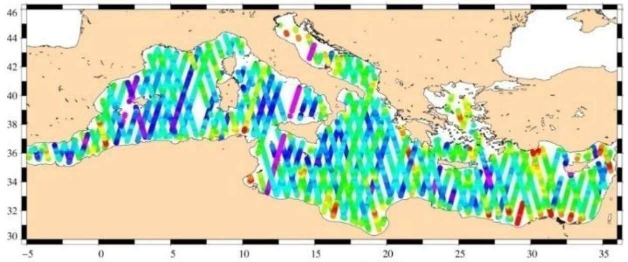
•**Method** : Estimation of errors with a cubit-spline estimator *(Le Traon and al., 1995, JAOT 12)*



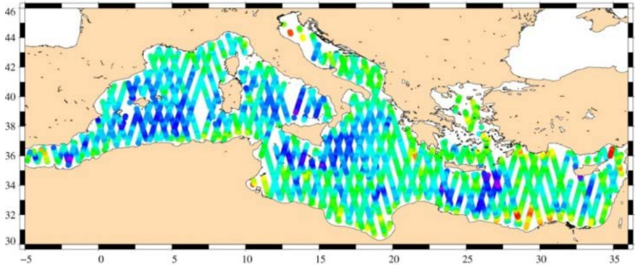
At a same point (crossover) and within less than 5 days, the difference in measured SLA is considered as a mono-mission or multi-mission orbit error. Smooth cubic-spline functions provide a continuous estimation of the orbit error over time.

Step 2 : Empirical reduction of Long-Wave Errors (LWE)

•**Purpose** : Correction of the long-wavelength errors (LWE) due to residual errors on tides, aliased HF residual signals, …



LWE correction



•**Method** : Reduction of the inter-track bias with **Objective Analysis** *(Le Traon and al., 1998, JAOT 15)*

✓ Spatial scales considered for LWE : 300 to 800 km

✓ A-priori mean LWE Variance : 8.5 (TP/J1) to 9 (EN) cm². Can locally reach 30-40 cm² or more

Data Selection & Validation

•**Purpose** : To be sure of their reliability, the data are submitted to successive tests of selection/ validation of increasing complexity, in order to eliminate inaccurate data

•**Selection 1**: **data over the ocean**

→ use of a geographical mask

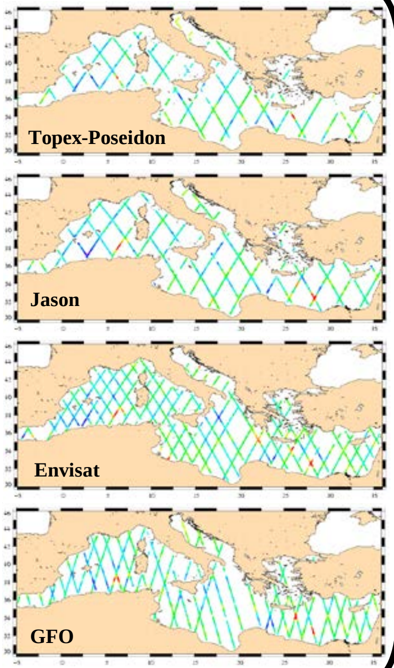
→ use of radiometric measure (sensitive to the presence of emerged land and ice)

Editing of ~30% of the data flow

•**Selection 2 : pertinent data**

→ selection by analysis of the quality the MSSH used as reference : no SLA computation where MSSH's quality is not assured.

•**Purpose** : Construct a regular-gridded data set merging along-track SLA data from different altimetric missions, taking into account the errors due to the measure's imperfections



Objective Analysis

Regular-gridded points

Along-track points

$$SLA_{Estimated}(x) = \sum_i \sum_j w_{xi} \cdot SLA_{Observed}(i)$$

Weight estimated to minimize the misfit between estimated/real data

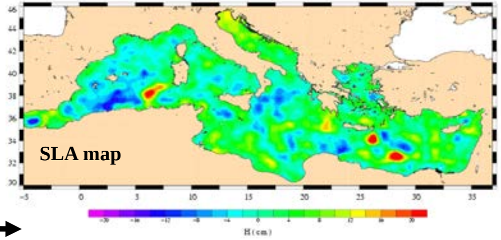
$$W_{xi} = A_{ij}^{-1} C_{xj}$$

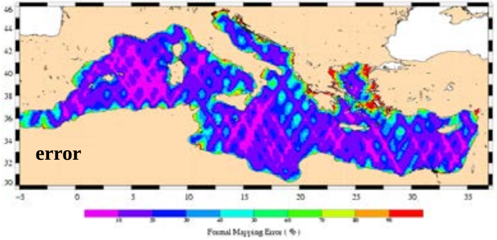
$$C_{xi} = \langle SLA_{True}(x) SLA_{Obs}(i) \rangle = \langle SLA_{True}(x) SLA_{True}(i) \rangle$$

$$A_{ij} = \langle SLA_{Obs}(i) SLA_{Obs}(j) \rangle = \langle SLA_{True}(i) SLA_{True}(j) \rangle + \langle \varepsilon_{Obs}(i) \varepsilon_{Obs}(j) \rangle$$

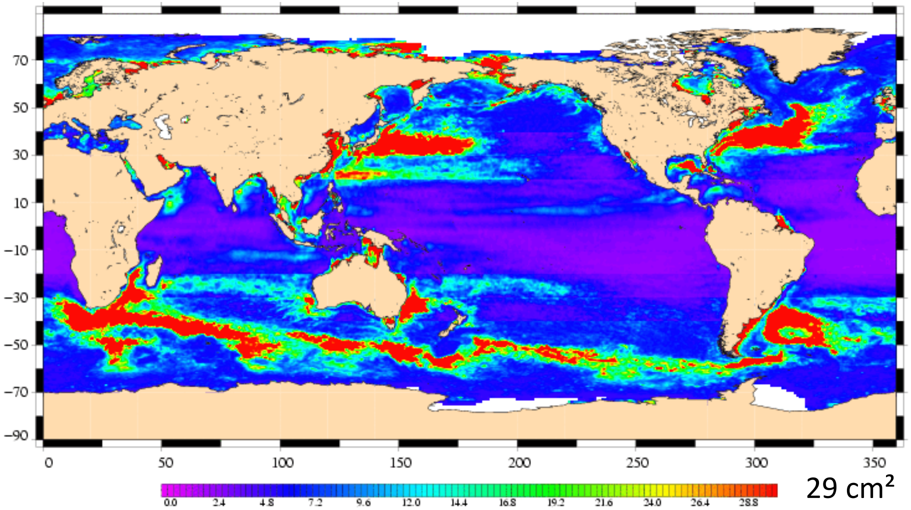
The construction of C and A therefore necessitates the knowledge of:

- The observations errors (non correlated errors hyp.)
- A-priori correlation function of the ocean sea level variability





Example of JASON altimeter noise



29 cm²

•A-priori correlation function

Isotropic field hypothesis is made

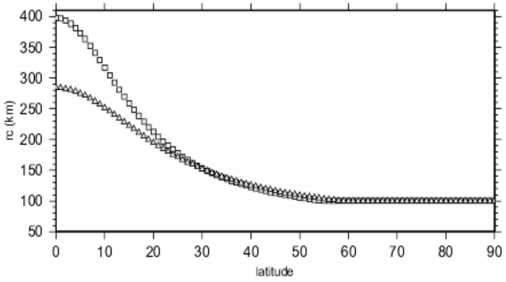
→ $\langle SLA_{True}(i) SLA_{True}(j) \rangle$ only depends on the distance δr,δt between points i and j

→Use of correlation function model defined by Le Traon et Hernandez (JAOT 1992):

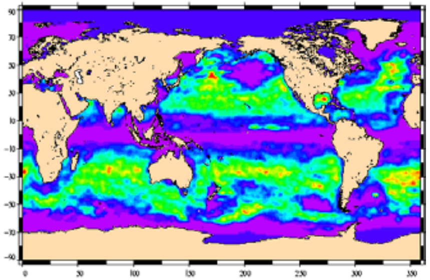
$$C(r,t) = \left(1 + r + \frac{1}{6}r^2 - \frac{1}{6}r^3\right)e^{-r}e^{-t} \qquad r = \frac{\delta r}{r_0} \qquad t = \frac{\delta t}{t_0}$$

Correlation Radii r_0 and t_0 depend on:

- ✓Spatial and temporal scales characteristic of the observations
- ✓Spatial and temporal sampling of the observations
- ✓Spatial and temporal sampling of the maps constructed / characteristics of the field to be reconstructed.



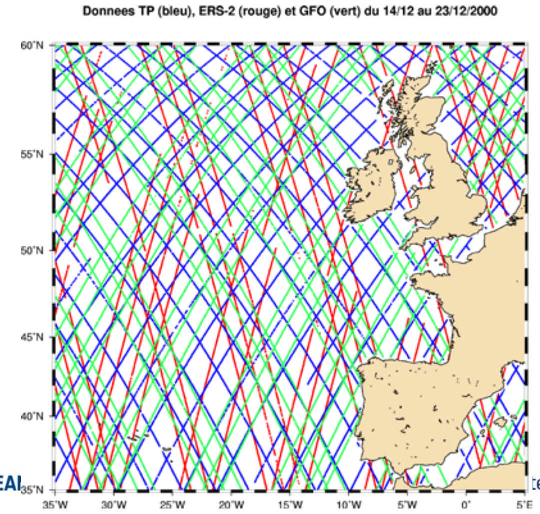
Global : spatial correlation scales range from 400 (zonal)-300 (meridian) km at the equator to 100km in sub-polar regions. Time correlation scales vary from 10 days (equator) to 30-50 days in subtropics and middle latitudes.



Mediterranean Sea / Black Sea : 100 Km / 10 days

Multi-missions mapping

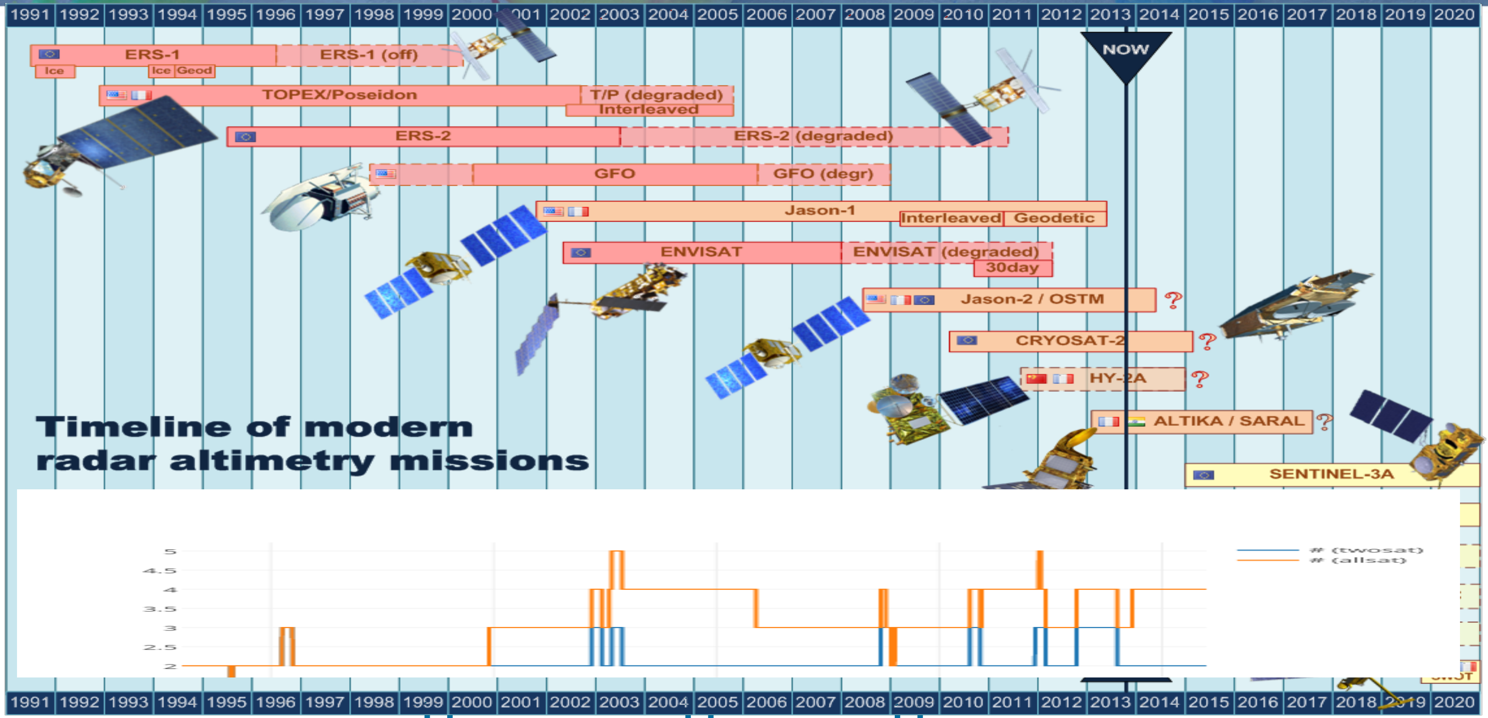
	GEOSAT	ERS/ENVISAT	TOPEX/JASON
Altitude	785 km	800 km	1336 km
Inclinaison	108°	98.5°	66°
Inter-trace à l'équateur	163 km	77 km	315 km
Répetitivité	17 jours	35 jours	10 jours



The spatio-temporal resolution of the mapped SLA depends on the number of flying altimeters at a given time.

Multi-missions mapping

System resolution



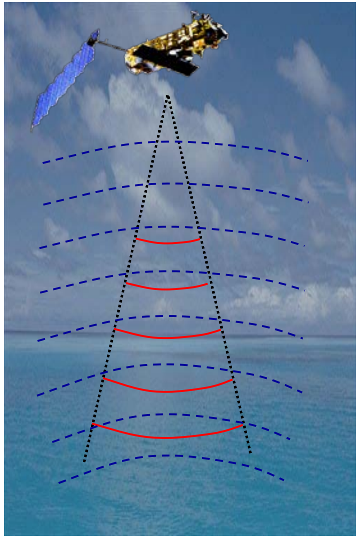
Spatial resolution achieved for a 10 days temporal resolution

2 satellites
250-300km

4 satellites
100 km

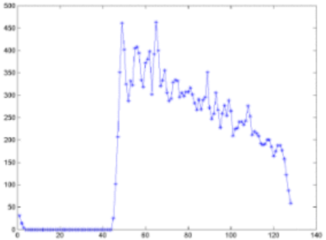
3 satellites
150 km

From radar echo to gridded maps of Sea Level Anomalies



Altimeter radar echoes

waveform



Precise Orbit Determination → **Satellite altitude**

Retracking → **Altimeter range**

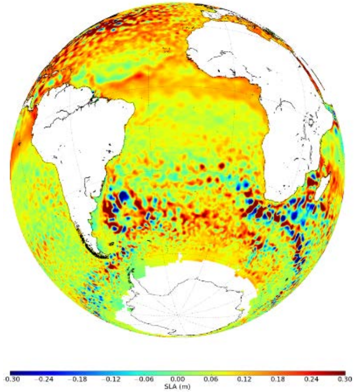
Satellite altitude − Altimeter range →

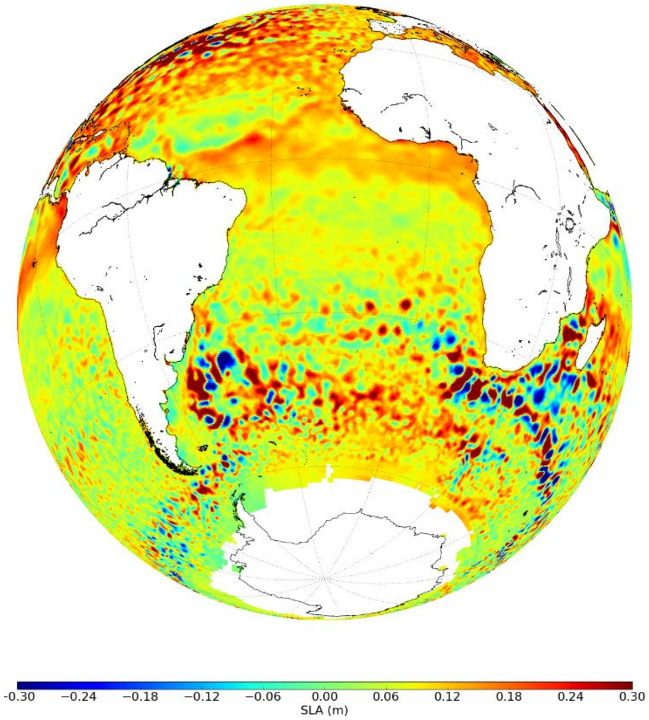
Sea Surface Height (SSH)
Relative to the ellipsoid

Data Processing

Altimeter Products (Level 2-3-4)

Multi-mission map of Sea Level Anomalies





Next talk!