Future technology : Wide Swath Altimetry

SWOT

(Surface Water Ocean Topography)

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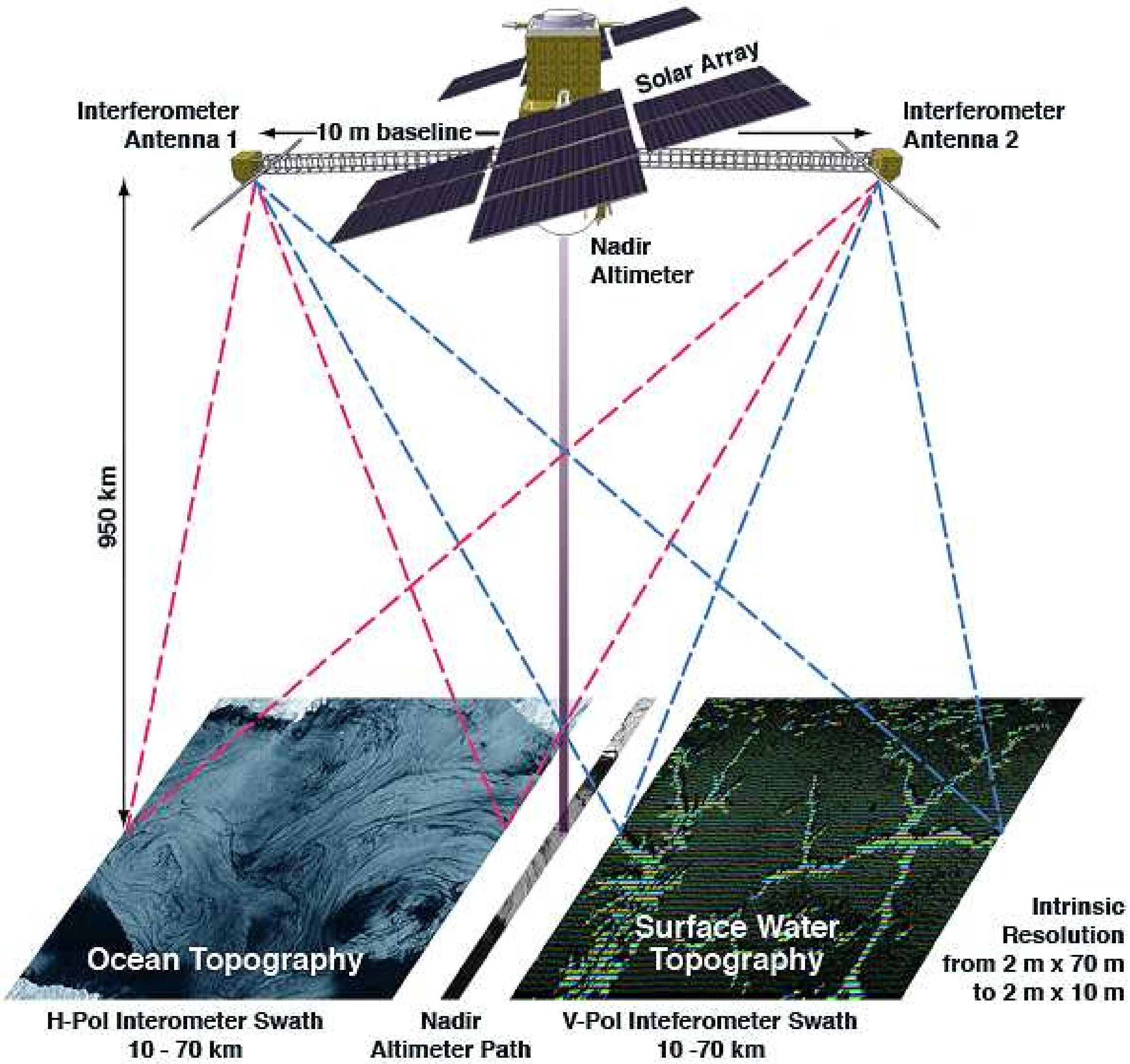
Schematic of the SWOT measurement system



SWOT

Fine spatial and temporal observations of :

Surface Water
Ocean Topography

Why do we need satellite observations?

Surface water storage includes rivers, lakes, artificial reservoirs, swamps, and flood plains.

Due to climate variability, climate change and direct anthropogenic forcing, land water storage fluctuates both in time and space.

However due to limited and heterogeneous in situ networks, the spatio-temporal distribution of surface waters remains poorly known.

=> Satellite observations allow monitoring of the continental water volume and discharge.

Satellite altimetry measures water level fluctuations of :

- continental lakes,
- major rivers
- flood plains

Satellite gravimetry (eg GRACE) measures fluctuations in :

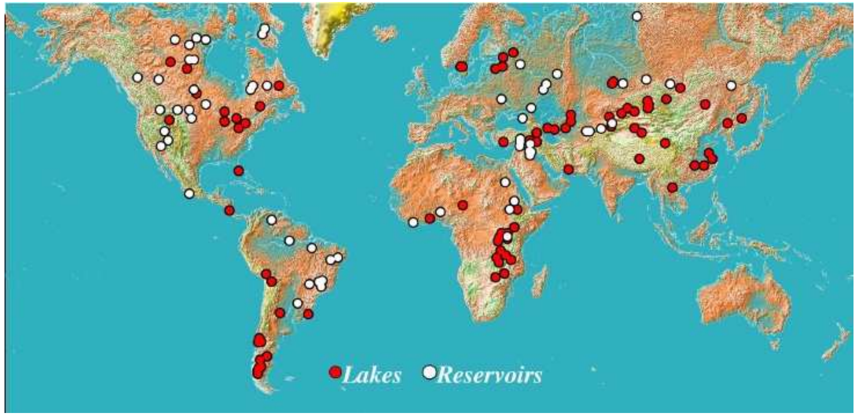
- water storage in soils,
- underground reservoirs
- snow pack

Altimetric water level data base

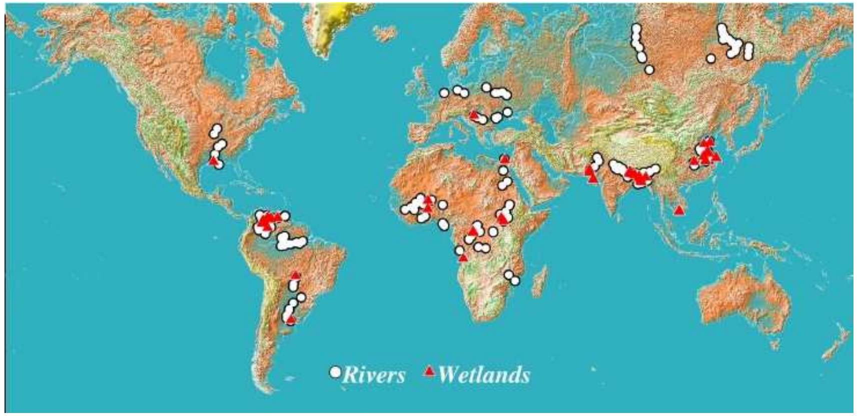
http://www.legos.obs-mip.fr/en/soa/hydrologie/hydroweb/

Altimetric data base at CTOH / LEGOS contains time series over water levels of **large rivers, lakes** and **wetlands** around the world.

• based on altimetry data from Topex/Poseidon for rivers, ERS-1 & 2, Envisat, Jason-1 and GFO data are also used for lakes.



100 lakes are available



250 « virtual stations » along rivers

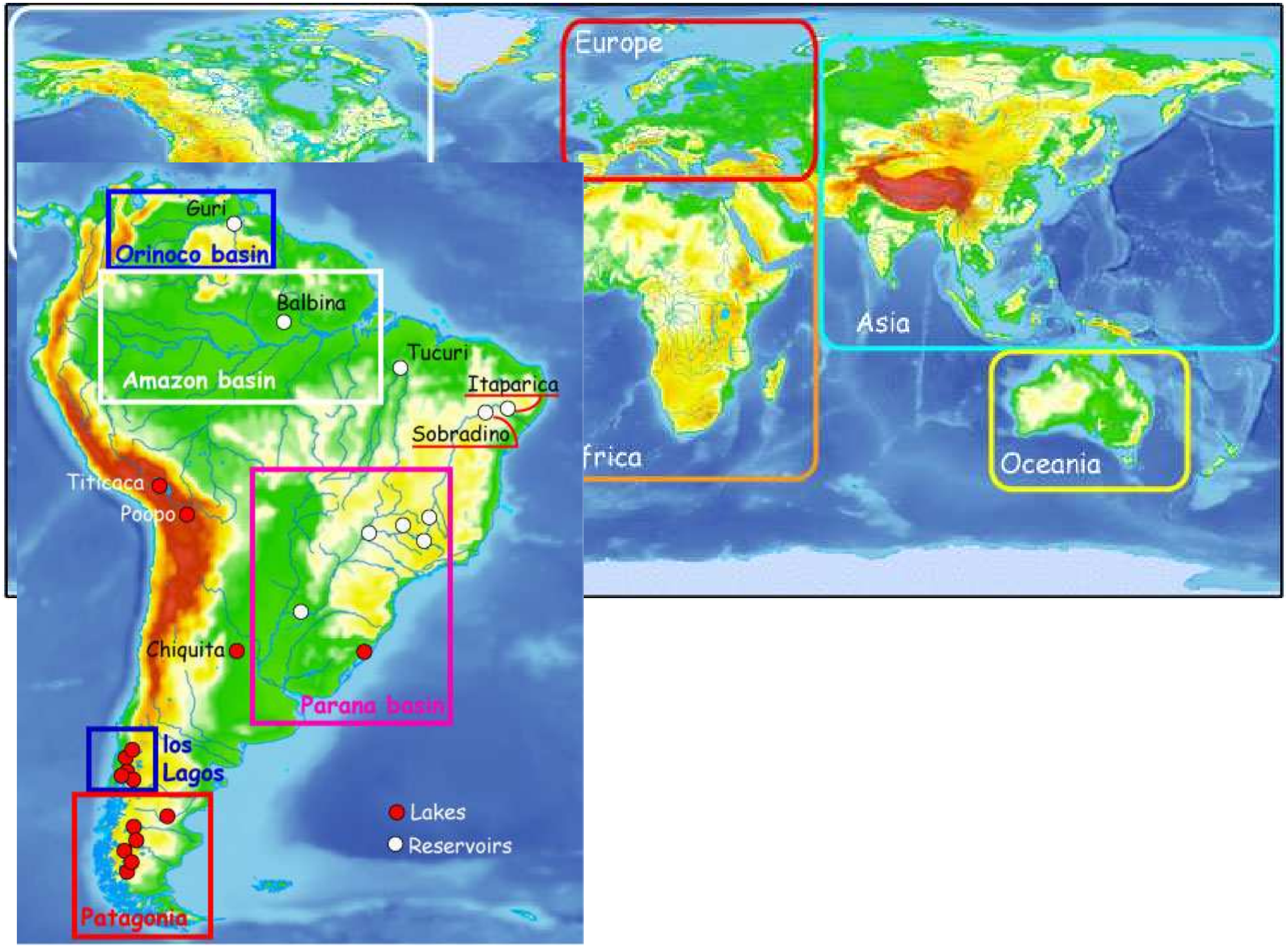
Ex: Monitoring South American lakes and rivers

South America:

- **Lakes**
  Argentino
  Chiquita
  Huapi
  Lagoa do Patos
  Lagoa Gen Carrera
  Llanquihue
  Nahuelhuapi
  Poopo
  Ranco
  Rinihue
  San Martin
  Strobel
  Titicaca
  Todos los Santos
  Viedma

- **Reservoirs**
  Balbina
  Furnas
  Guri
  Ilha Solteira
  Itaparica
  Novaponte
  Posadas
  Sobradino
  Tres Marias
  Tucurui

River basins
Amazon
Orinocco
Parana



Lake levels are based on merged Topex/Poseidon, Jason, ENVISAT and GFO data provided by ESA, NASA and CNES data centers.

Processing :

1Hz (1 sec) altimeter range measurements are used.

Classical corrections are applied (orbit, ionospheric and tropospheric corrections, polar and solid Earth tides and sea state bias).

Geoid corrections are not accurate over land lakes : so the mean lake surface is calculated from the repeat altimetry data.

Multi-satellite data is computed in a 3-step process:

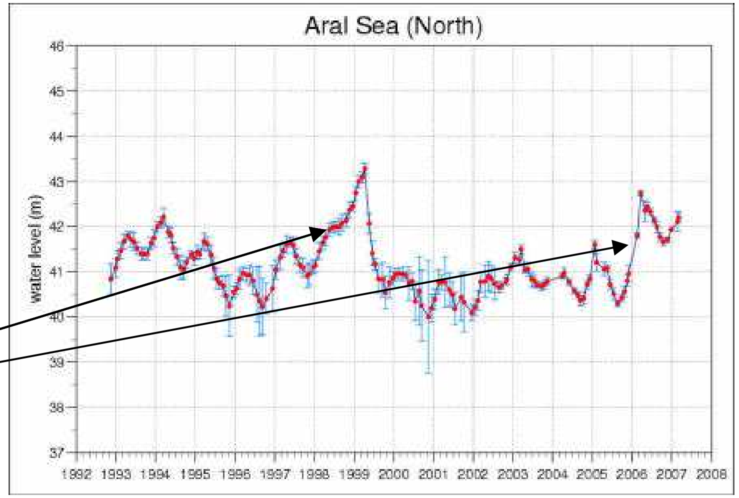
1. Each satellite data set are processed independently.
2. Biases between different satellites are removed using T/P data as reference.
3. Lake levels from the different satellites are merged on a monthly basis (recall that the orbital cycles vary from 10 days for T/P and Jason, to 17 days for GFO and 35 days for ERS and Envisat).

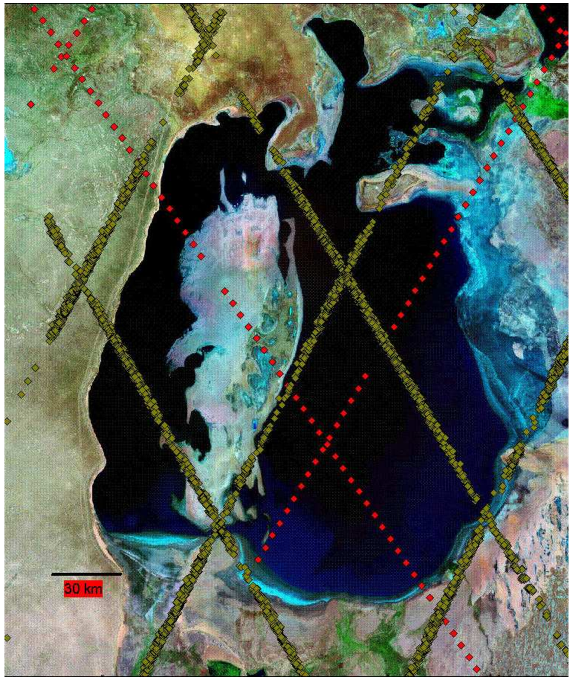
We generally observe an increased precision of lake levels when multi-satellite processing is applied.

Monitoring levels of the Aral Sea

Northern
Aral Sea

Barrage





Southern
Aral Sea

Monitoring river levels

Virtual stations are defined at the intersection of the T/P track with the river.

All available 10Hz (1/10 sec) data within a rectangular «window» are used.

For each 10-day T/P cycle, 10Hz data are geographically averaged to give mean river height.

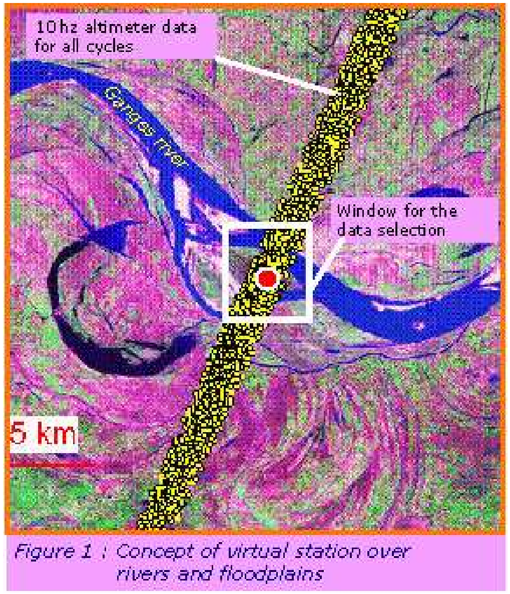
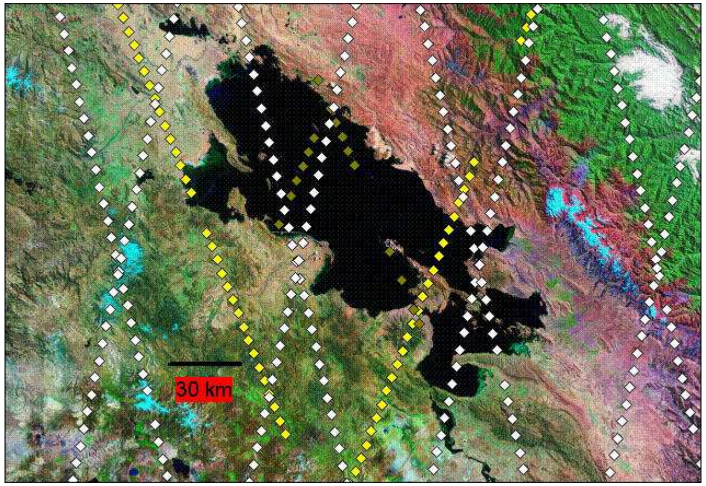
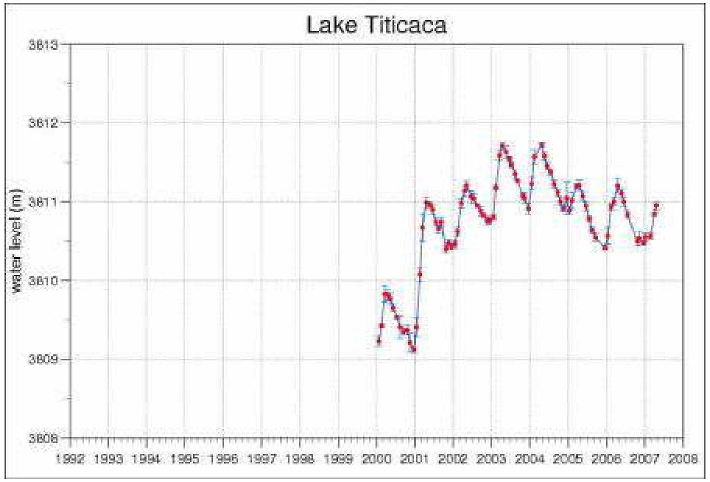


Figure 1 : Concept of virtual station over rivers and floodplains



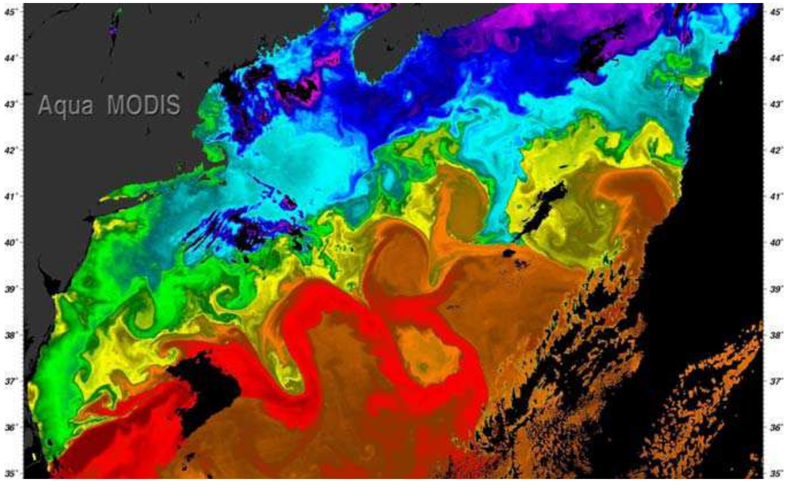
Lake Titicaca



Problems with traditional altimetry

- Water movement in wetlands and flood plains is essentially unmeasured
- Number of in-situ river gauges decreasing
- Monitoring with traditional altimetry is limited :
  - Wave forms optimised for open ocean surfaces
  - Inter-track distances miss small water bodies, and undersample rivers and lakes

=> Need high resolution measurements over the continental water surfaces

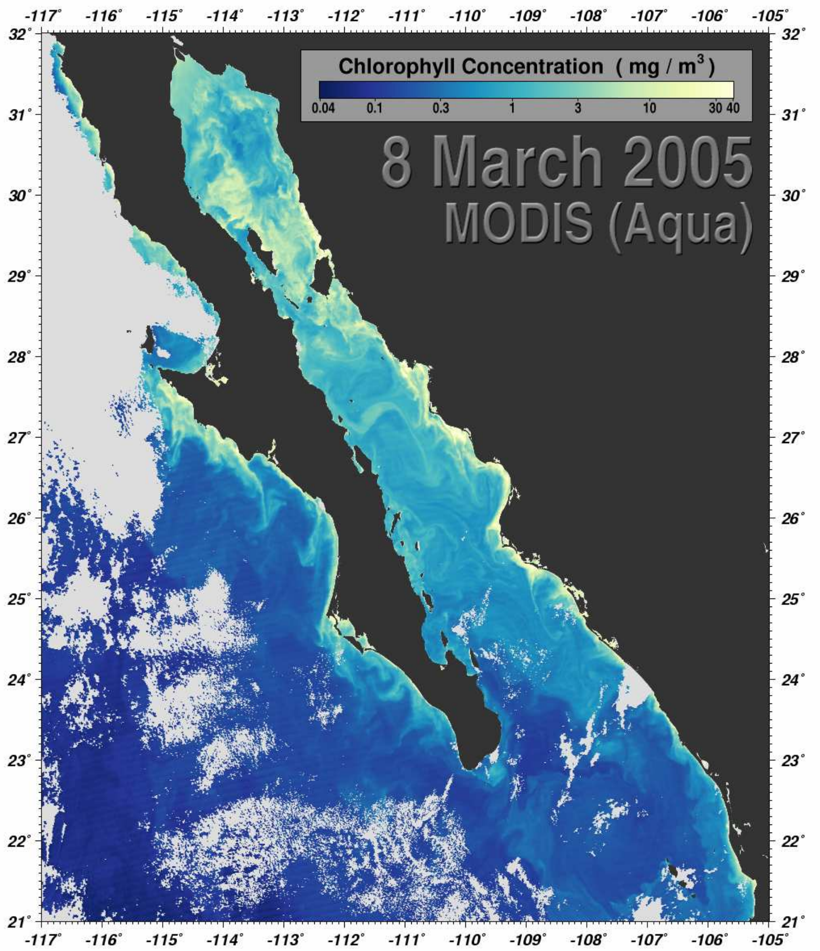


Ocean fronts and filaments studied with SST and ocean colour

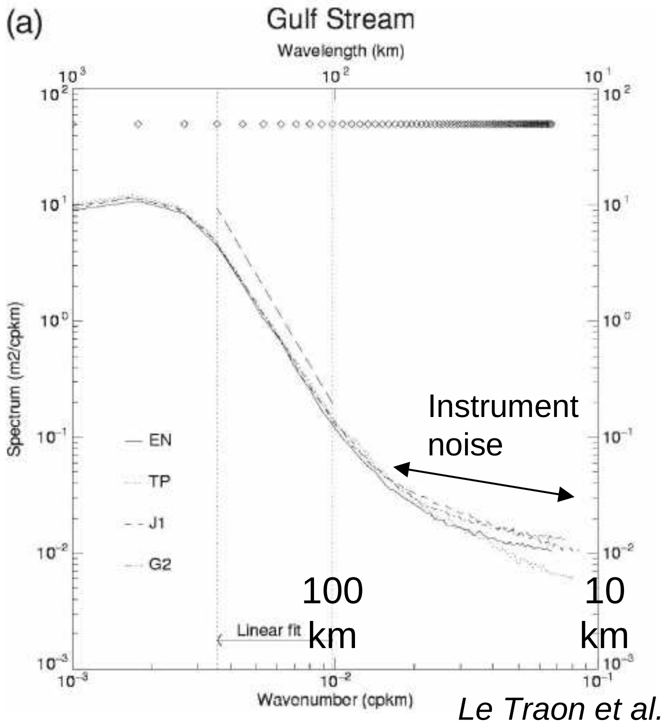
- Scales 1-50 km, 2-30 days

- Important for vertical exchange of heat, carbon, nutrients

- Important regions of mixing

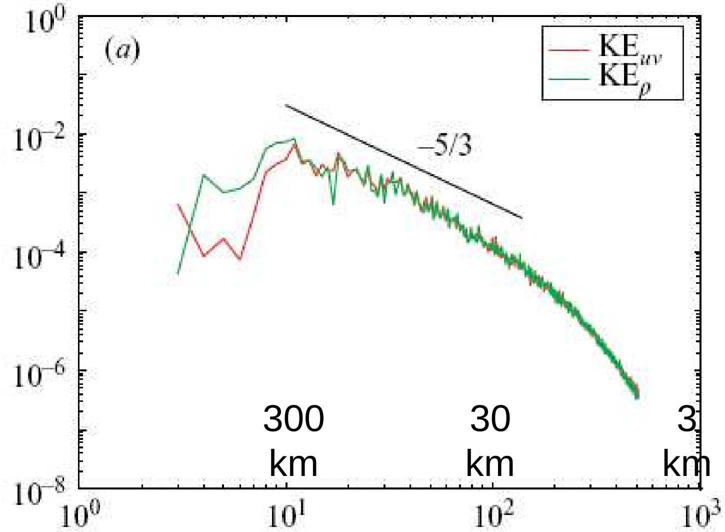


Scientific Rationale : Ocean .. 2



Le Traon et al. 2008

Altimetric sea level spectra
White noise < 50-70 km



Capet et al. 2008

1/54° Model velocity spectra : spectrum remains red

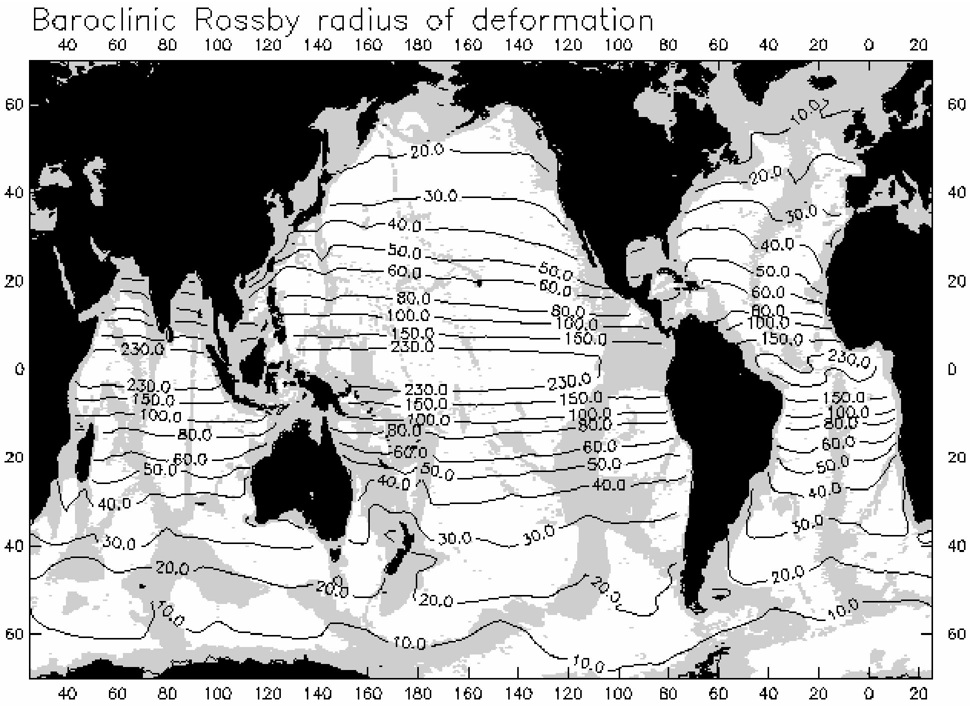
Ocean remains energetic at small space scales < 100 km

Traditional altimetry cannot resolve these small space and time scales

1. Missing mesoscale eddy energy

- 100 km spatial resolution of multi-mission altimetry : missing part of the mesoscale eddy energy (Rossby radius) at mid to high latitudes, and higher-order modes

Eddy scales
= $2\pi R$



Chelton et al. 1998

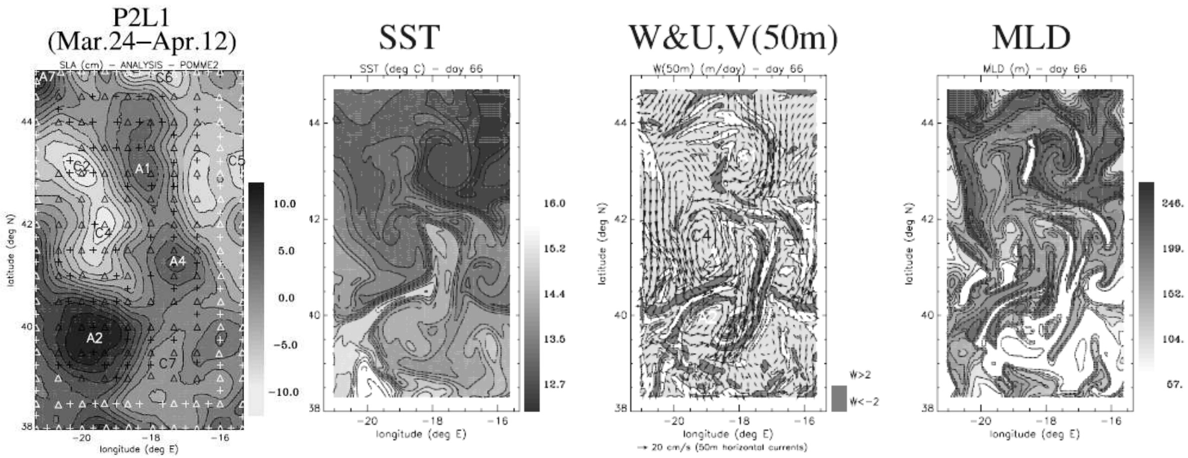
SWOT

2. Sub mesoscale ocean processes

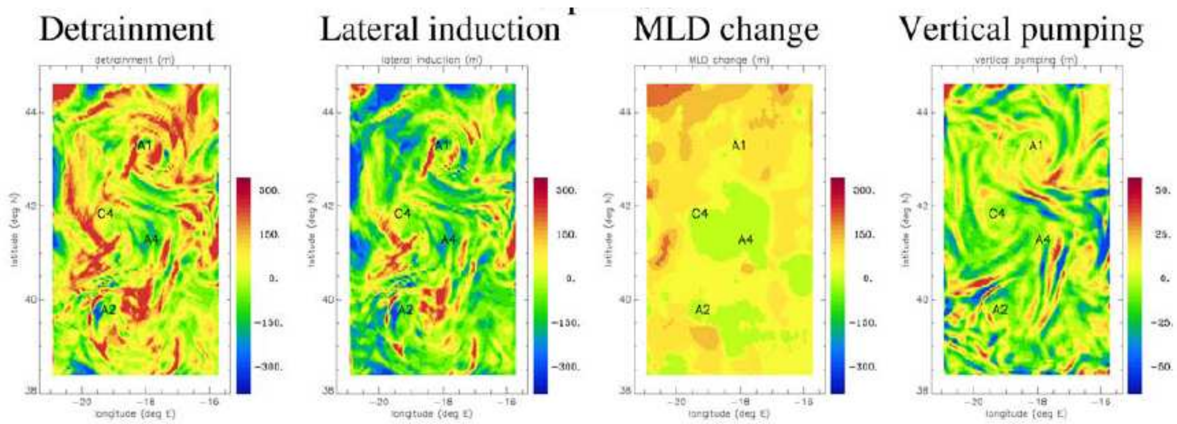
Small-scale filaments (10-20 km) surrounding mesoscale eddies important for :

- advecting tracers (SST, chlorophyll)
- inducing strong **vertical velocities** > 25 m/day
- MLD changes - exchange of nutrient-rich deeper water with surface layer
- formation of mode and intermediate water masses
- Biogeochemical cycles

Very high resolution regional ocean models (1/20° or 5 km with 69 vertical levels)



1-day snapshots 7 Mar 2001 - spring

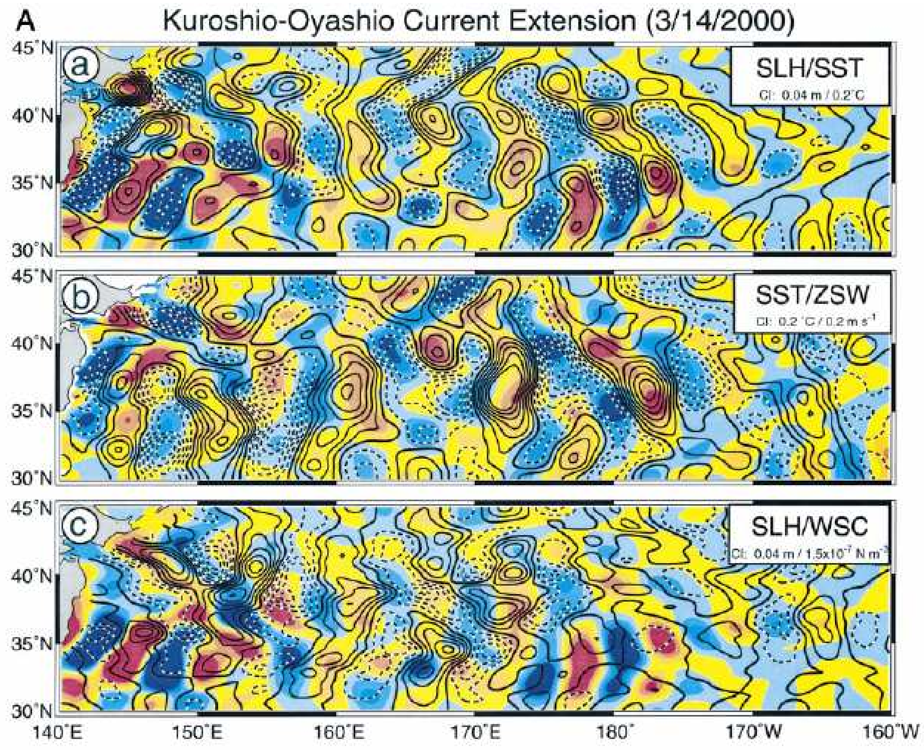


3-month cumulative averages over spring

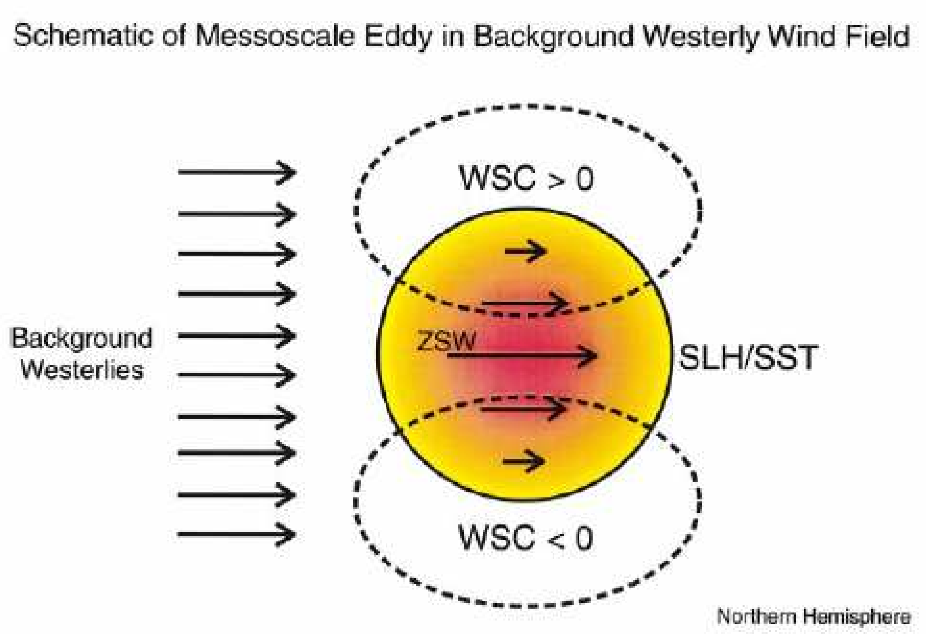
Paci et al., JGR, 2005; 2007.

Mesoscale ocean eddies can also impact back onto the atmospheric circulation.

Mesoscale instabilities can be generated by wind anomalies *(Stammer and Wunsch, 1999; Ducet et al., 2000; Eden and Boening, 2003).*



White and Annis, JPO, 2003

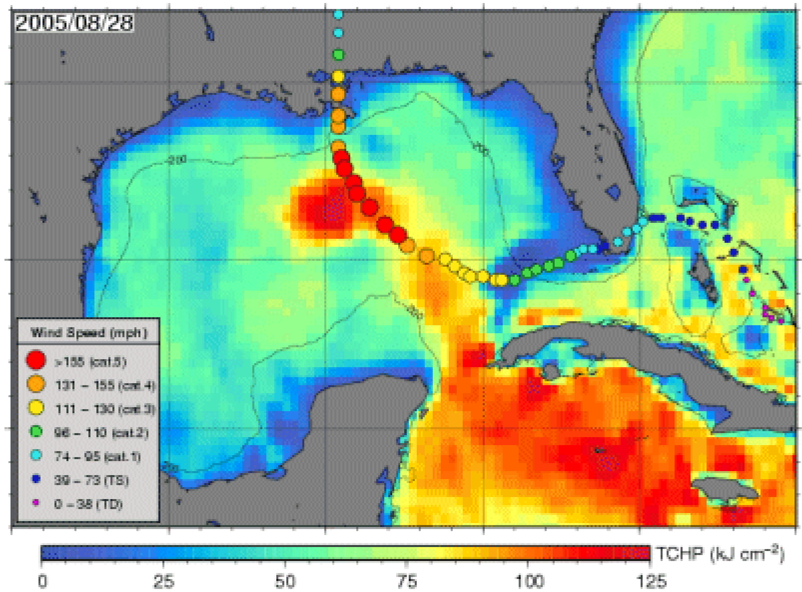


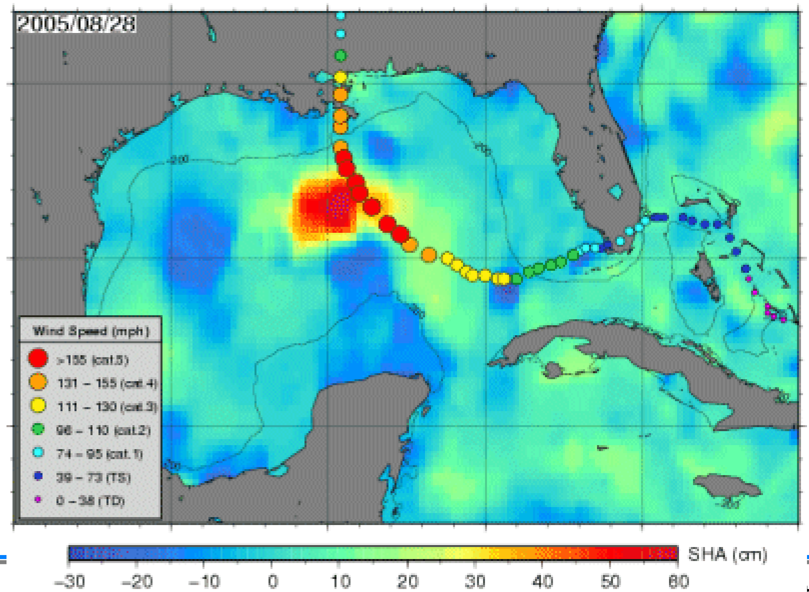
- Feedback onto the ocean
- Deplace warm eddies equatorward

4. Hurricane Predictions

- Higher-resolution altimetry could improve our knowledge of upper ocean heat content and circulation, for improving prediction of extreme events

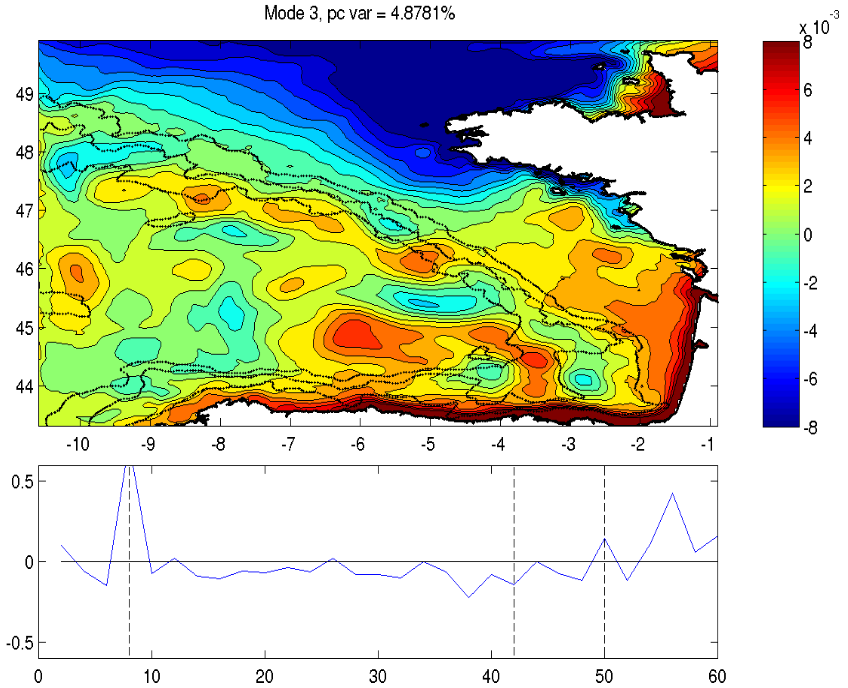
- These images from US Naval Research Lab. illustrate altimetry combined with sea surface temperature and a two-layer model to monitor ocean heat content for Hurricane Katrina in August 2005.



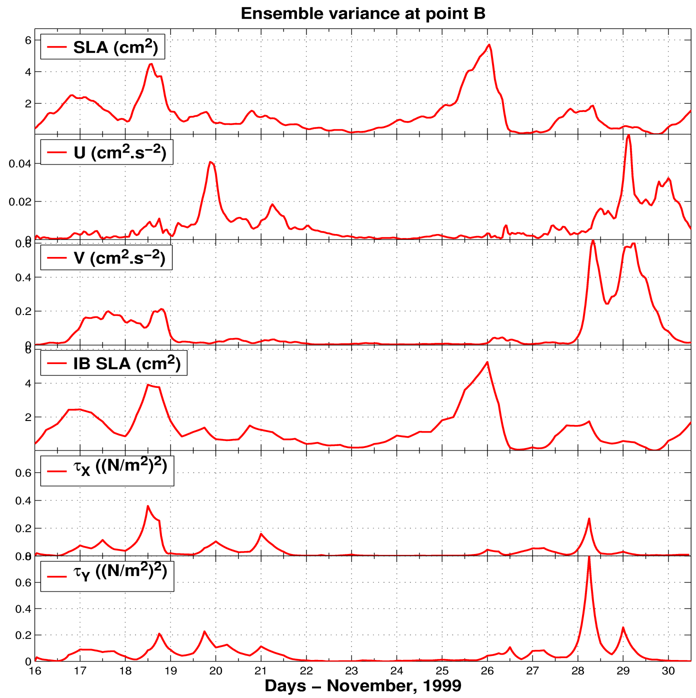


5. Coastal altimetry and storm surges

Spatial structure of a high-resolution coastal model response to atmospheric forcing perturbations



Temporal response of different model parameters to atmospheric forcing perturbations



For predicting extreme events in the coastal zone, we need fine spatial resolution altimetry right up to the coast, and at high temporal resolution (~1 day)

Problems with traditional altimetry

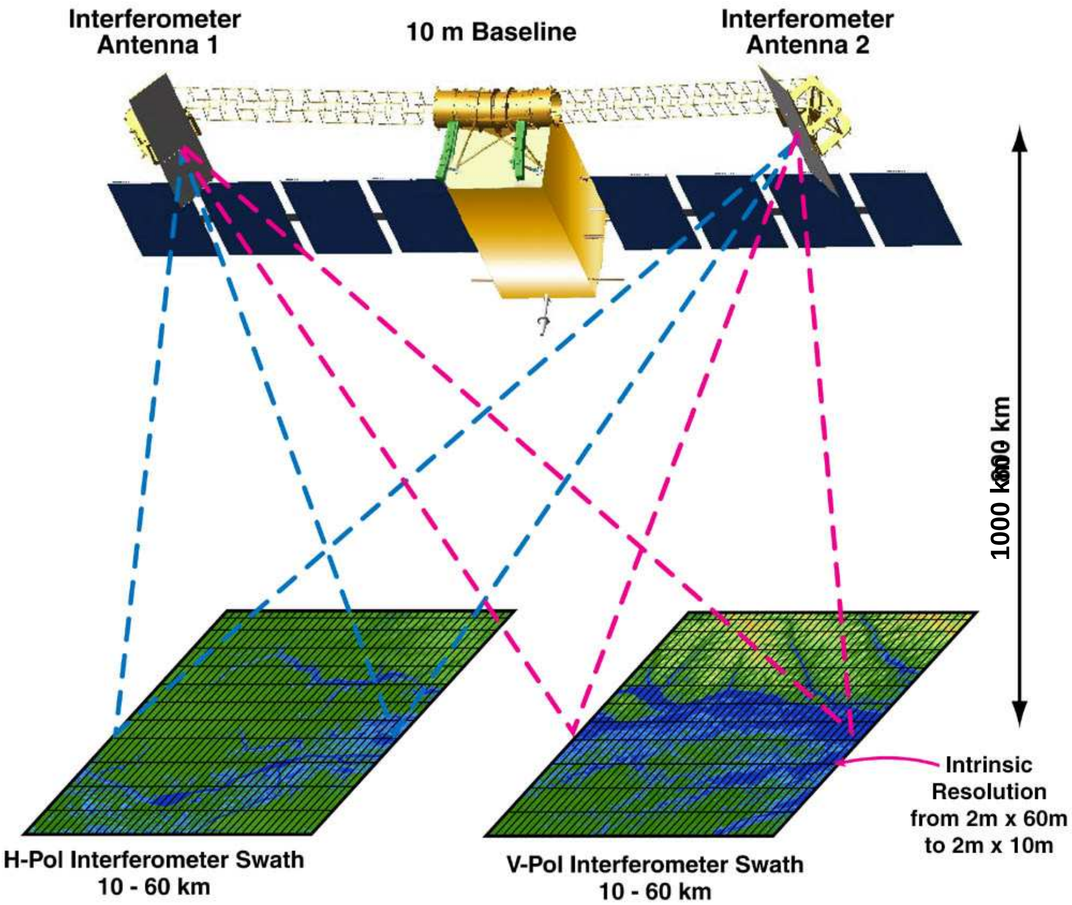
15 years of precise satellite altimetry has revealed many new features of the mesoscale ocean circulation, but :

- **Missing** part of the **mesoscale eddy energy** (10-100 km) at mid to high latitudes
- Cannot measure the **sub-mesoscale signals** accurately – important for vertical exchange of heat, carbon, nutrients, biomass
- **Atmosphere** « feels » the ocean's mesoscale eddy field – and perhaps the sub-mesoscale?
- **Coastal regions** are poorly sampled by present altimeters, yet have small cross-shelf space scales and respond over rapid time scales

=> Need for high resolution altimetric measurements in open ocean and coastal zones

SWOT

Solution : Radar Interferometer



Ka band interferometer penetrates clouds and relies on small canopy openings to penetrate to underlying water surfaces (openings of only 20% are sufficient).

Two Ka-band SAR antennae at opposite ends of a **10 m boom**

Both antennae transmit and receive the emitted radar pulses along both sides of the orbital track.

Look angles are limited to 4.5° to reduce the baseline roll-error.

Provides a **120 km wide swath**.

Specular scatter : water bodies scatter more strongly than land.

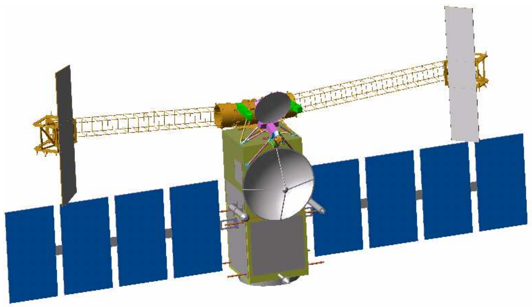
Interferometric SAR processing of the returned pulses yields a **5 m alongtrack resolution**

Crosstrack resolution is 10 m in far swath to 70 m in near swath,

Elevation precision is ± 50 cm.

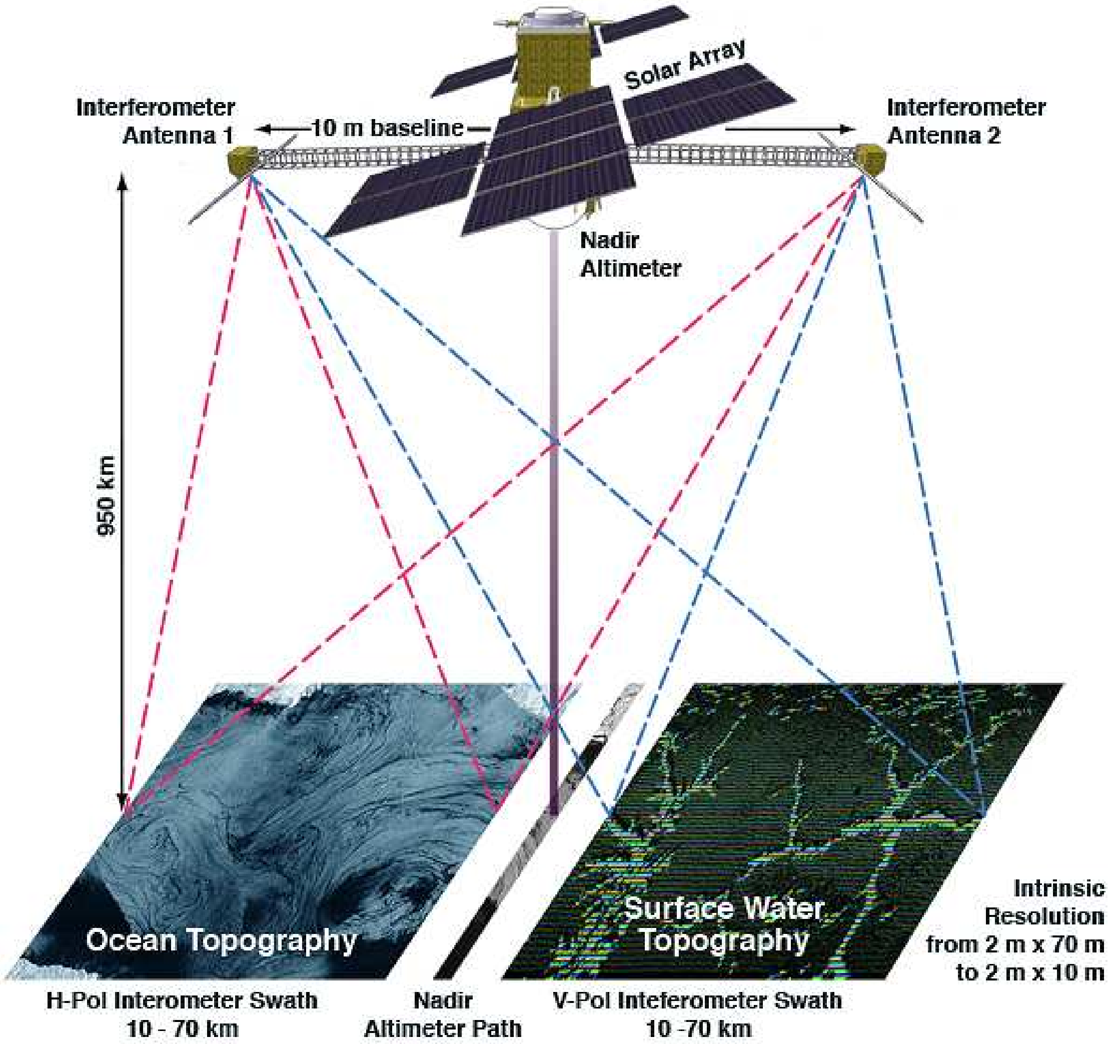
Polynomial based averaging over areas less than 1 km^2 increases the **height precision** to less than ± **1 cm**.

Interferometer/Altimeter Heritage



- **Nadir altimeters**: TOPEX/Poseidon & Jason & ERS & EnviSAT Altimeters: sea surface topography (1992 to present)
  - **Heritage:** Error budget for propagation delays, algorithms for range corrections, water reflectivity near nadir
- **Radar Interferometers:**
  - **TOPSAR/AIRSAR:** early 1990's-present: C-band airborne platform
  - **Star3I:** X-band airborne radar interferomer (1990's-present)
  - **GeoSAR:** X-band P-band radar interferometer
  - **Europe:** DLR airborne IFSSAR, DLR X-band spaceborne interferomer with SRTM
  - **Shuttle Radar Topography Mission:** spaceborne land topography (2000)
    - Also imaged rivers and the ocean
  - **Wide-Swath Ocean Altimeter** : centimeter level precision concept funded by NASA past design reviews, but deferred due to budget problems
  - **Cryosat:** forthcoming studies will investigate the use of cryosat interferometric/altimeter modes for surface water.
  - **SWOT:** phase A supported by CNES and NASA in 2008.
  - **Heritage:** error budget verification, instrument design and manufacture, processing algorithms, ground system, mission management, calibration and validation
- **High-frequency Radars:**
  - **CloudSat:** the proposed instrument uses technology and lessons learned from the high-frequency CloudSat mission (EIK, High Voltage Powser Supply)

KaRIN: Ka-Band Radar Interferometer



Ka-band SAR interferometric system with 2 swaths, 60 km each

Produces heights and co-registered all-weather imagery ***required by both communities***

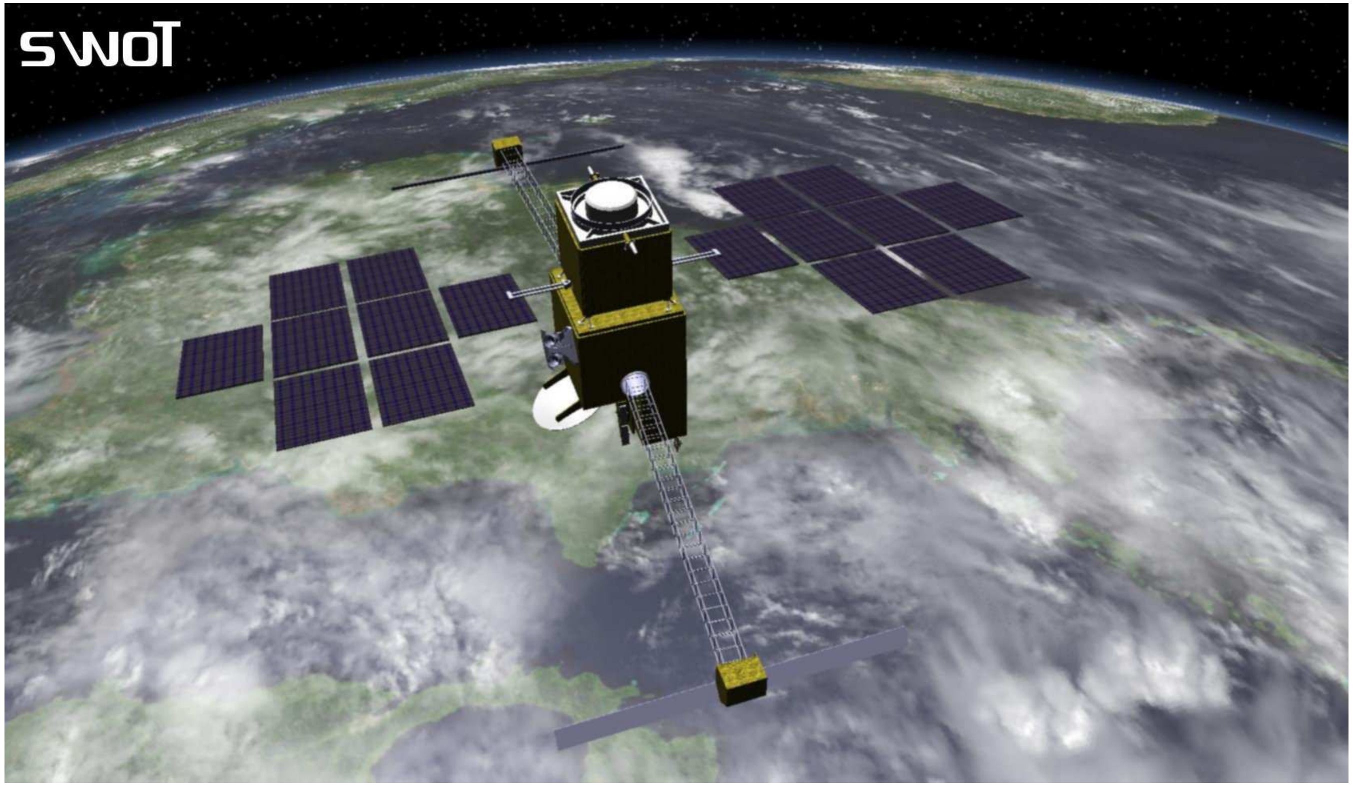
Additional instruments:

- conventional Jason-class altimeter for nadir coverage
- AMR-class radiometer (with possible high frequency band augmentation) to correct for wet-tropospheric delay

No land data compression onboard (50m resolution)

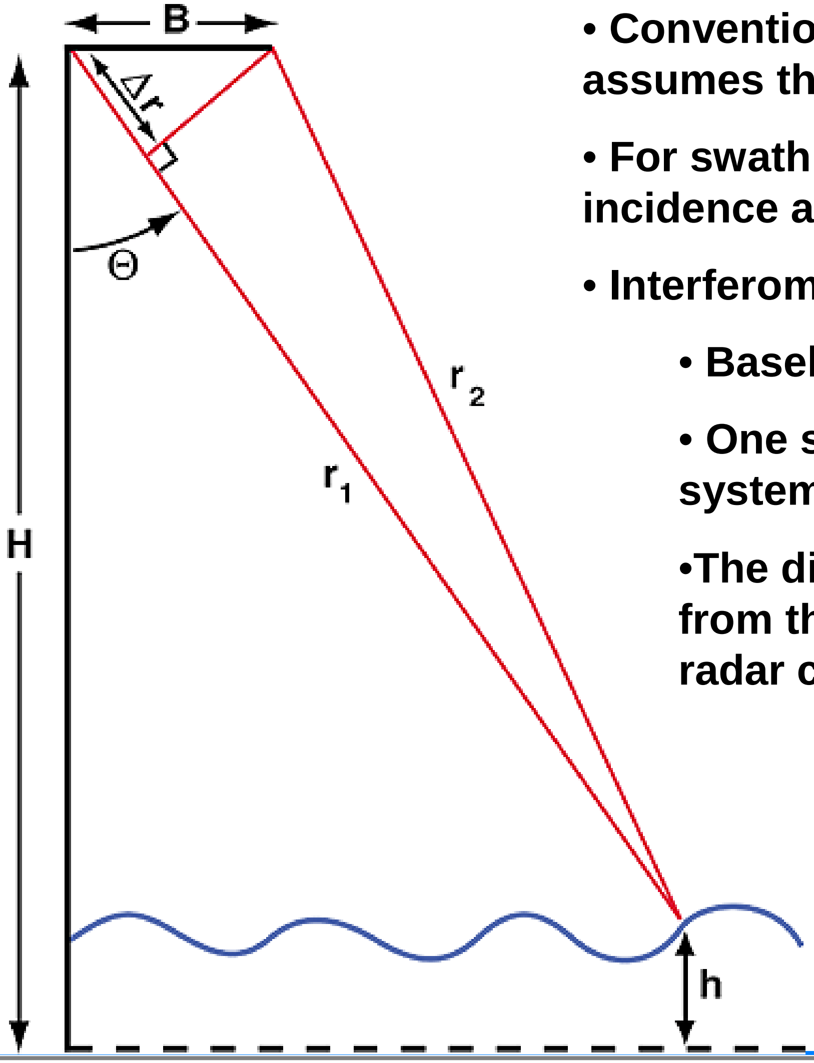
Onboard data compression over the ocean (1km resolution)

SWOT Configuration



CNES conceptual drawing

Interferometric Measurement Concept



- Conventional altimetry measures a single range and assumes the return is from the nadir point
- For swath coverage, additional information about the incidence angle is required to geolocate
- Interferometry is basically triangulation
  - Baseline B forms base (mechanically stable)
  - One side, the range r1, is determined by the system timing accuracy
  - The difference between two sides (Δr) is obtained from the phase difference (Φ) between the two radar channels.

$$\Phi = 2\pi \, \Delta r/\lambda = 2\pi B \sin \Theta/\lambda$$

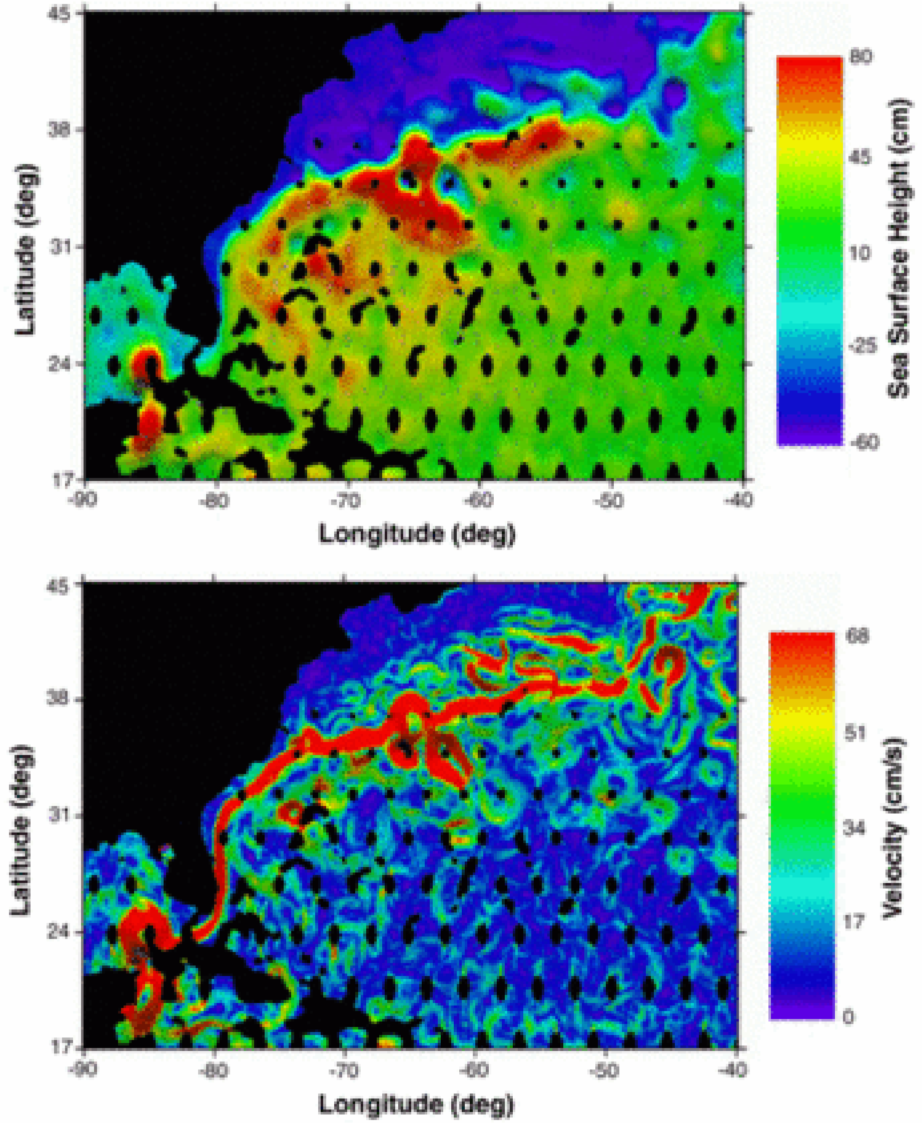
$$h = H - r1 \sin \Theta$$

SWOT

Height and velocity from SWOT

Typical spatial coverage from a 10-day Jason-1 orbit

Mid-to-high latitude, « crossover » points covered many times in 10 days.



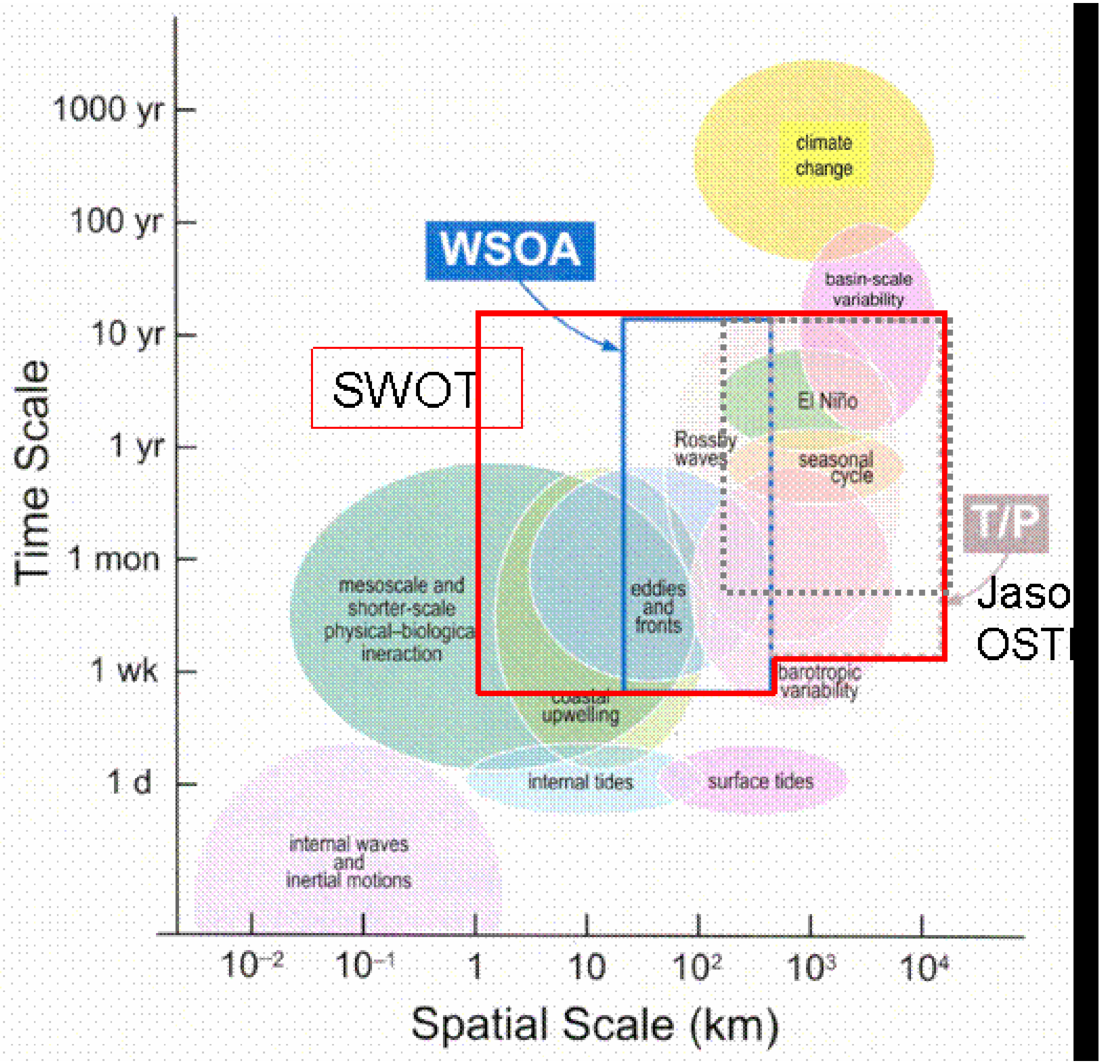
Space-time scales resolved by SWOT

Original WSOA technology could resolve to 15-20 km resolution.

SWOT resolves to 1 km resolution

Good for sub-mesoscale ocean dynamics

Excellent for monitoring small lakes and river levels



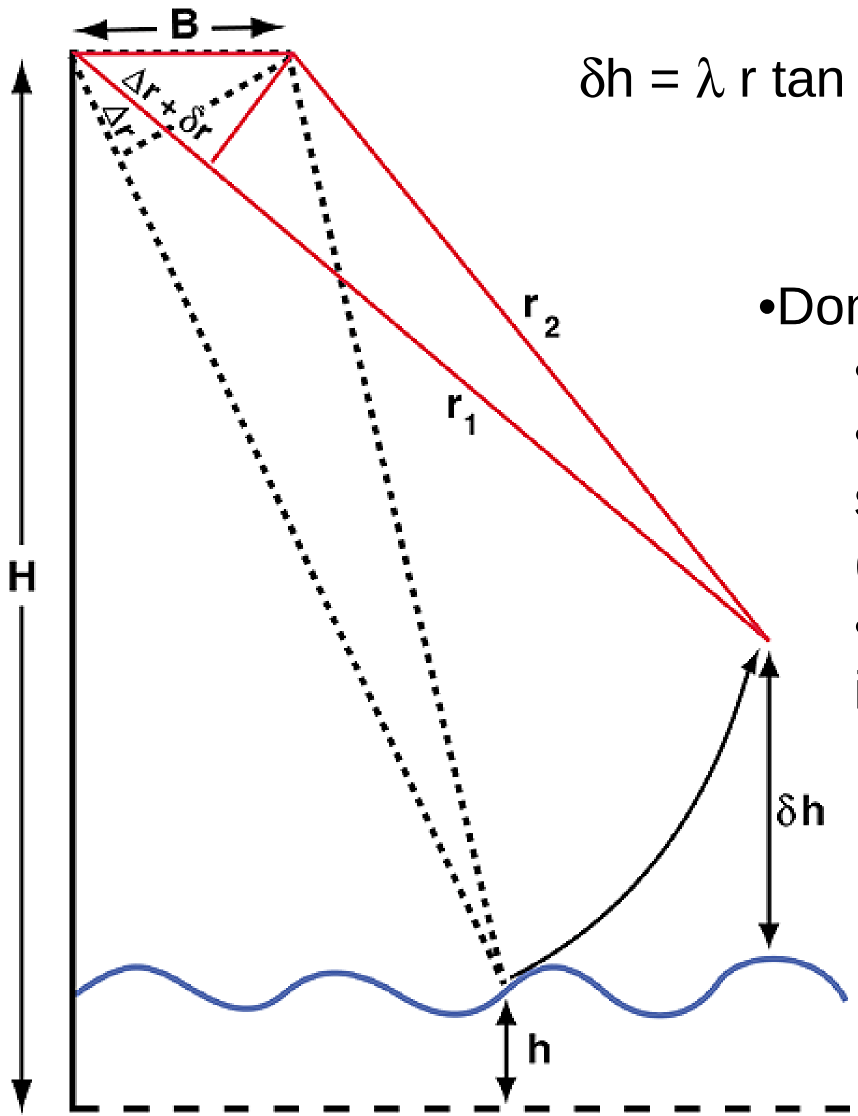
Error Budget Dominant Contributors

$\delta h = \delta H -$	Orbit Error
$\cos(\theta)\delta r +$	Media Delay Error (Iono, Tropo, EMB)
$r\sin\theta \frac{\partial\theta}{\partial\Phi}\delta\Phi +$	Phase Error
$r\sin\theta\delta\theta$	Baseline Roll Error

Other error sources (e.g., baseline length, yaw errors) can be controlled so that errors are smaller by an order of magnitude, or more.

- Errors can be divided into spatially correlated and uncorrelated
  - Uncorrelated: thermal/speckle noise. Precision improves linearly with the area
  - Correlated: geophysical, orbit. Precision does not improve significantly with averaging
- Slope (~velocity) is affected differently than height by spatially correlated errors
  - Relatively large height errors can result in relatively small slope errors
- For ocean, geostrophic velocity ~slope. Sea-level rise ~height. Heat content ~height
- For hydrology, velocity (discharge) ~slope (or assimilated height). Storage ~ height

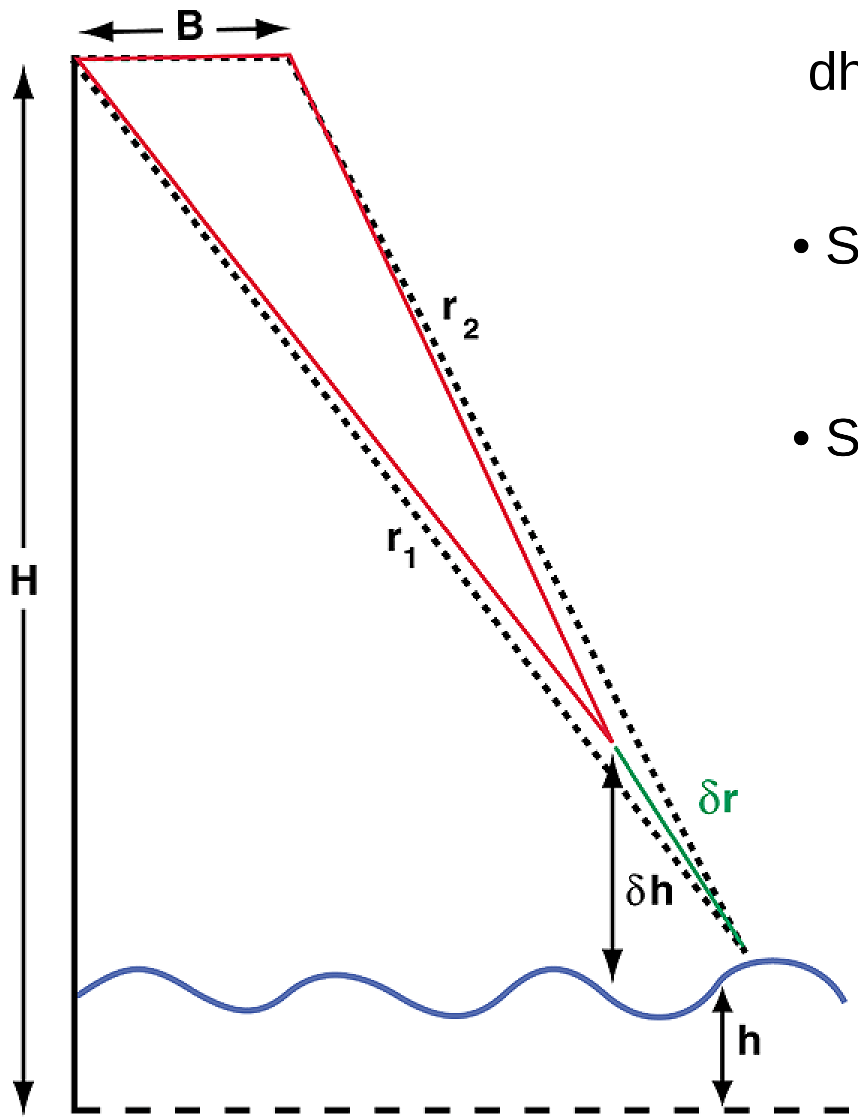
Interferometric Phase Error



$$\delta h = \lambda \, r \tan \Theta / (2 \pi B) \, \delta \Phi$$

- Dominant sources of phase noise:
  - Thermal noise in radar signal (random)
  - Decorrelation of the two returns due to speckle decorrelation of scattered fields (random)
  - Phase imbalance between the two interferometric channels:
    - Temperature driven (slow change)
    - Can be calibrated using calibration loop.

Media Delay Errors

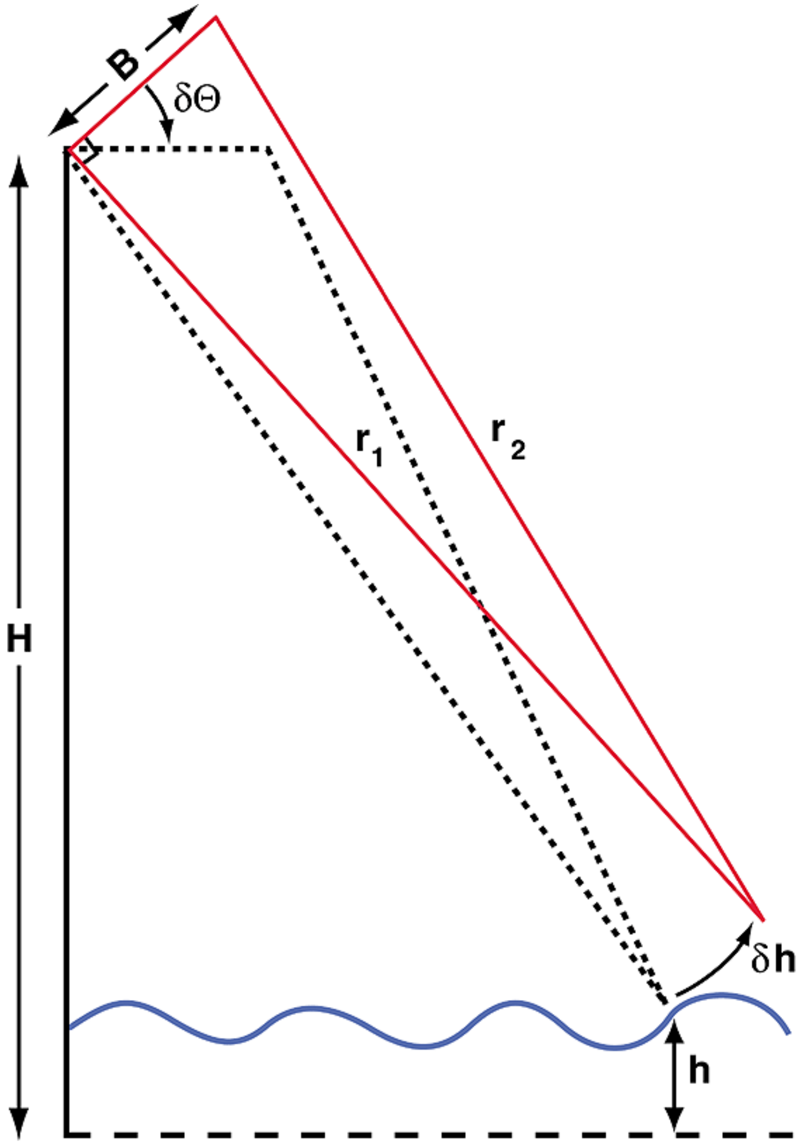


$$dh = -\delta r \cos \Theta$$

- Similar to nadir altimeter range errors

- Sources of range error:
  - Ionospheric delay
  - Dry and wet tropo delays
  - EM Bias

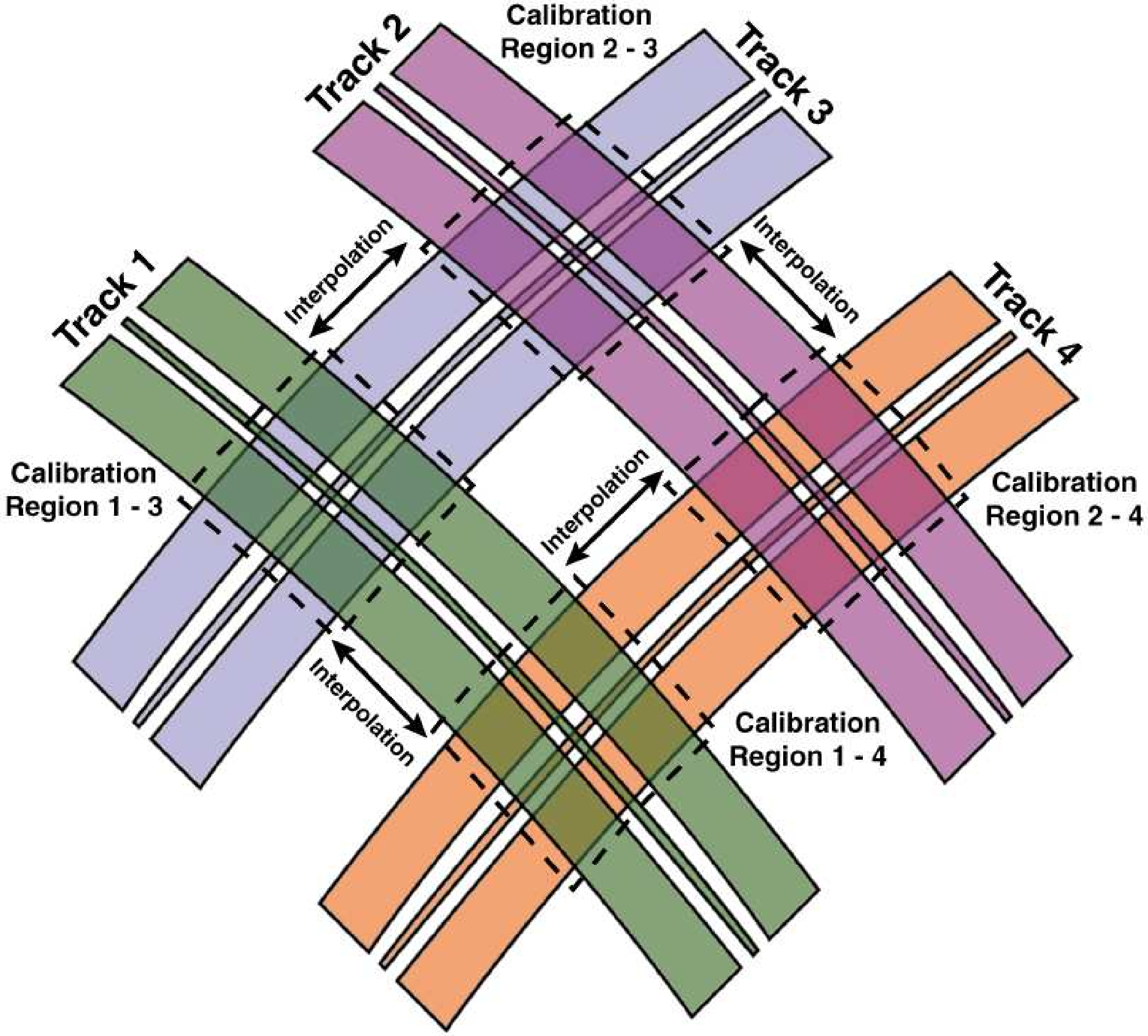
Baseline Roll Error



$\delta h = r \sin \Theta \, \delta \Theta$

- An error in the baseline roll angle tilts the surface by the same angle.
    - This is equivalent to introducing a constant geostrophic current in the along-track direction
- As an order of magnitude, a 0.1arcsec roll error results in a 4.5cm height error at 100km from the nadir point
- Roll knowledge error sources:
    - Errors in spacecraft roll estimate
    - Mechanical distortion of the baseline (can be made negligible if the baseline is rigid enough)

Cross-Over Calibration Concept



- Roll errors must be removed by calibration

- Assume the ocean does not change significantly between crossover visits (< 10 days)

- For each cross-over, estimate the baseline roll and roll rate for each of the passes using altimeter-interferometer and interferometer-interferometer cross-over differences, which define an over-constrained linear system.

- Interpolate along-track baseline parameters between calibration regions by using smooth interpolating function (e.g, cubic spline.)

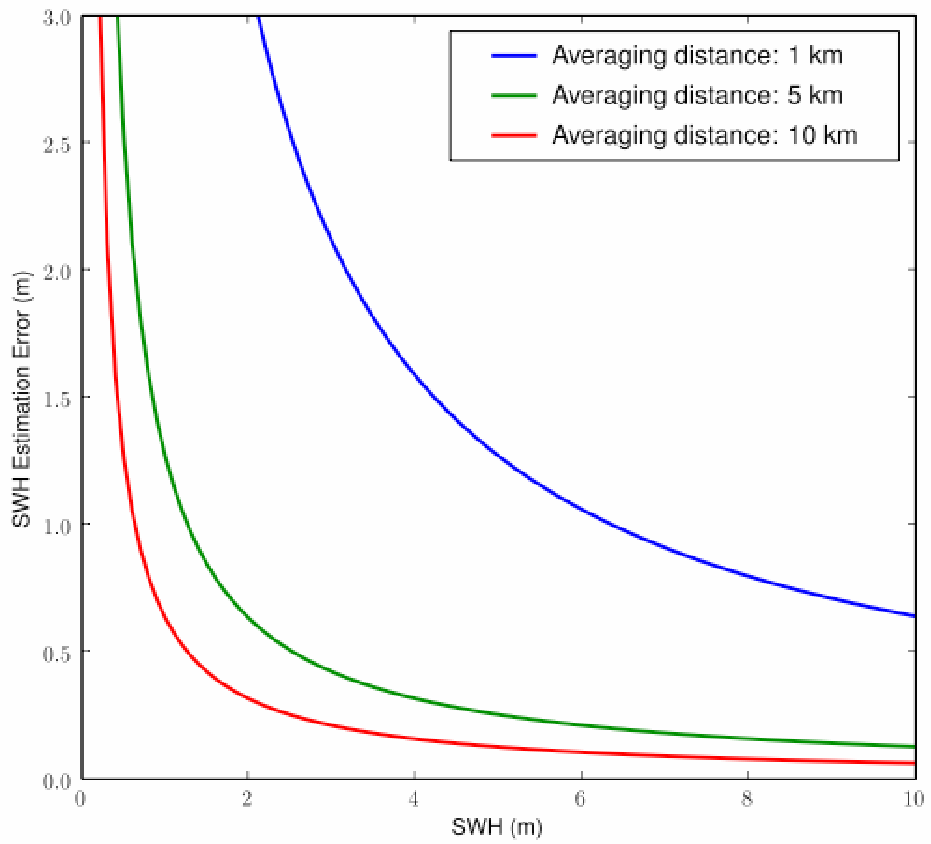
Error Budget Allocations

	Height Error	Typical wavelength	Typical geophysical magnitude	Slope error
Phase error	1cm @ 1km^2 area	uncorrelated	NA	0.7µrad @ 5km 0.15µrad @ 10km
Roll errors	2cm (max) at swath edge	200km	Depends on platform dynamics	0.1µrad (max)
Wet Troposphere	1cm (Ocean) <5cm (Land)	>100km	3-6cm	0.1µrad
Dry Troposphere	<1cm	>1000km		0.01µrad
Ionosphere	1cm	>900km	50cm	0.2µrad
EM Bias	1-2cm	100km	<5cm	0.1µrad
Orbit	1cm	>8000km		

Other geophysical parameters

Significant Wave Height

- The effect of waves is to increase the observed height variance
- This is a small effect on the height precision (on a single pixel, random noise ~ 2m SWH)
- SWH can be estimated by estimating the excess variance relative to the predicted variance
- To make a meaningful measurement, a large area must be used for averaging
- The area required is not that different from the altimeter area used for SWH



Wind Speed

- SWOT will measure radar sigma0 at 1km resolution
- Sigma0 can be converted to wind speed (without direction)
- Similar to traditional altimetric data

Tides and Internal tides

The SWOT orbit has been chosen to resolve the major tidal frequencies

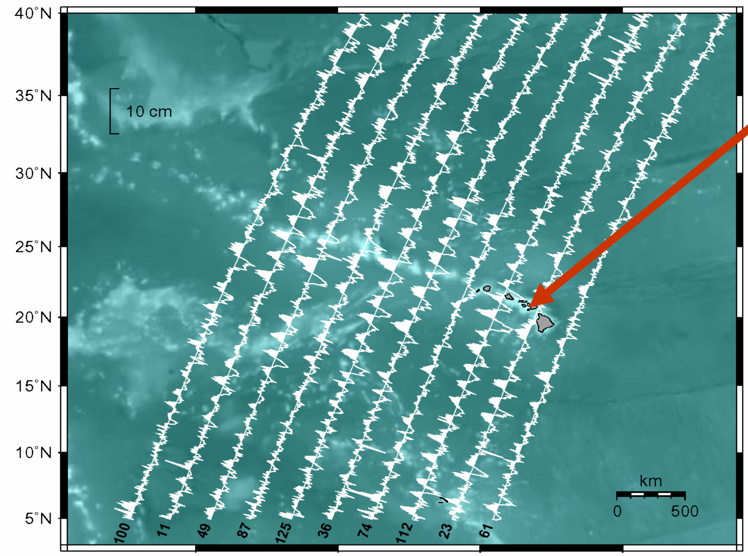
After a few years :

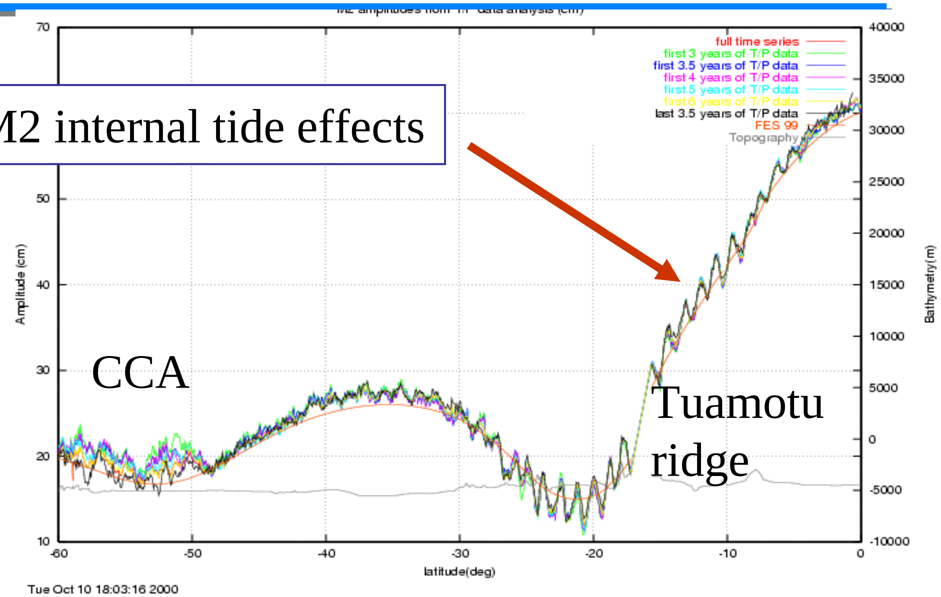
- Fine resolution repeat observations will greatly improve tidal models, especially in coastal zones.
- Possibility of resolving internal tide amplitudes

Initial tidal corrections for SWOT will be imprecise in regions not sampled by traditional altimetry (between groundtracks, coastal zones)

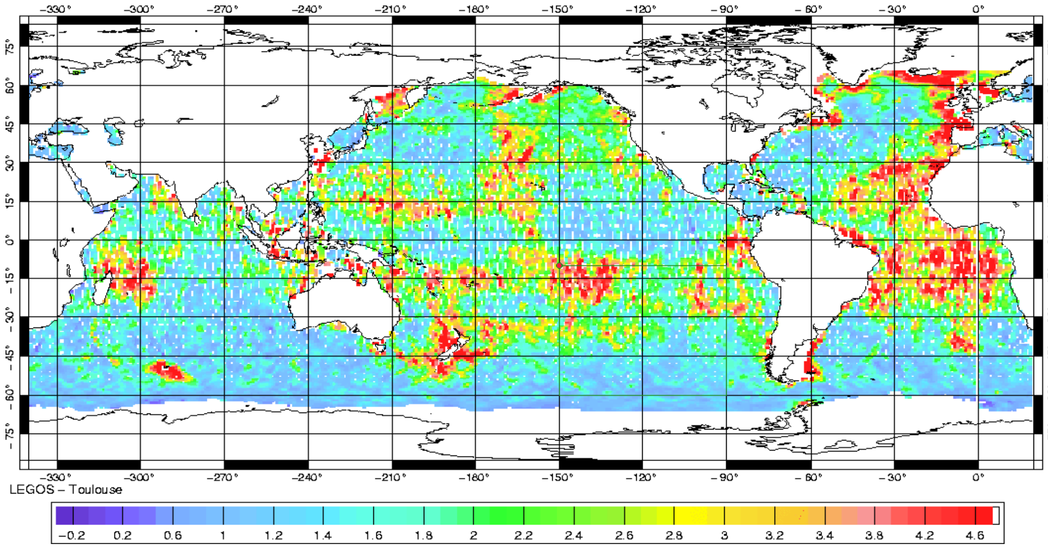
SWOT

M_2 internal tide surface effects





Signal–to–Noise ratio for the M2 baroclinic tide
(last 3.5 years analysis vs. full time series analysis)



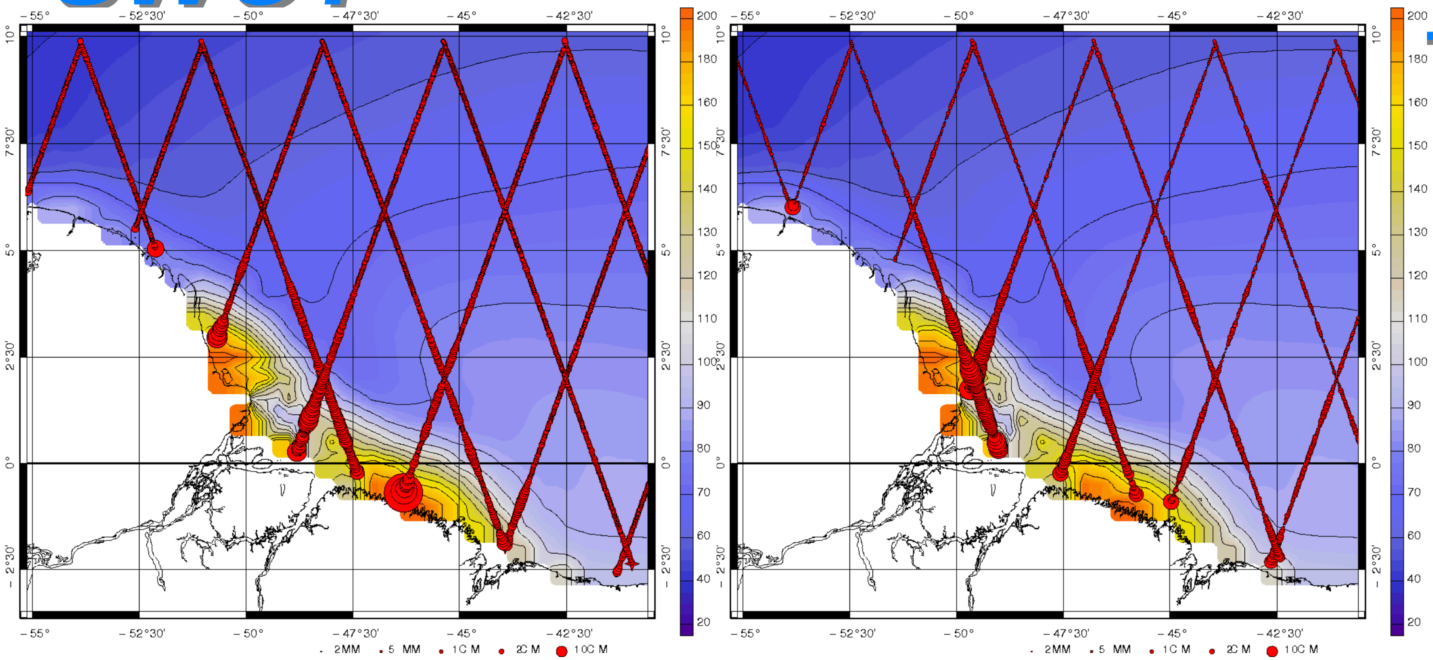
Internal tide signal (2-3 cm) can de resolved from traditional alongtrack data with long time series

SWOT will provide data between groundtracks – finer resolution around bathymetry

M2 internal tide signal to noise ratio

SWOT

Improving Shelf/coastal tides

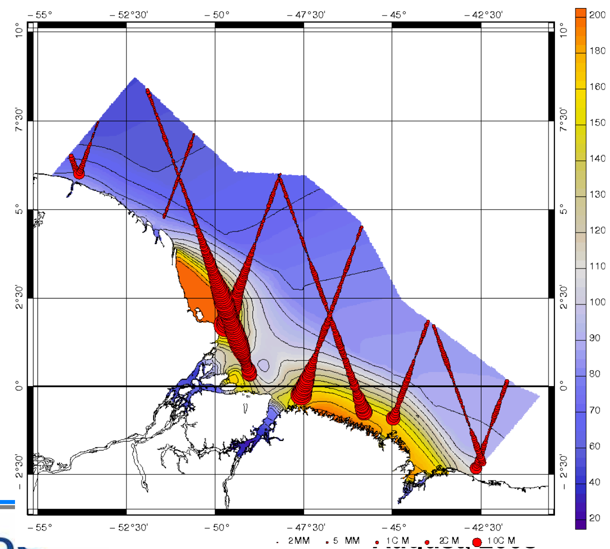


GOT00 M2 tide (amplitude in cm) against T/P (right) and T/P interlaced (left)

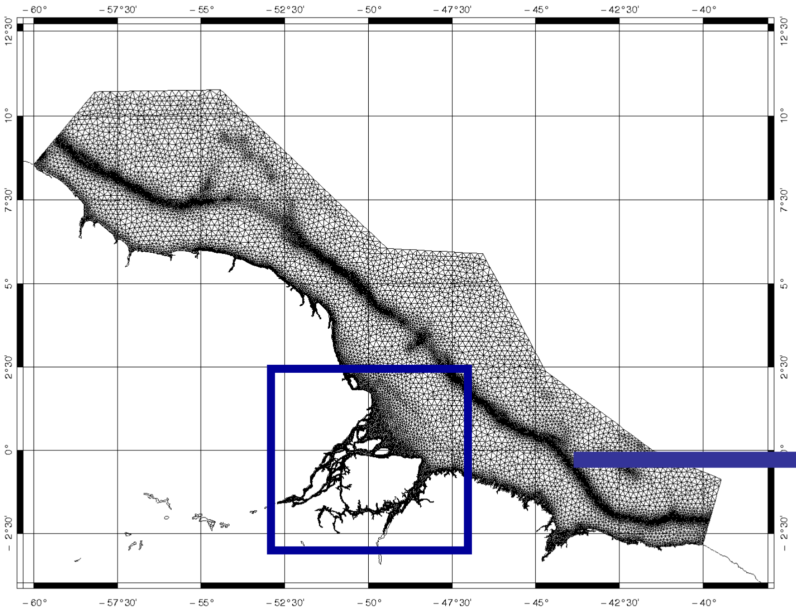
- **Loss of data in coastal regions induce an increased error budget in tidal analysis, thus in tidal models**

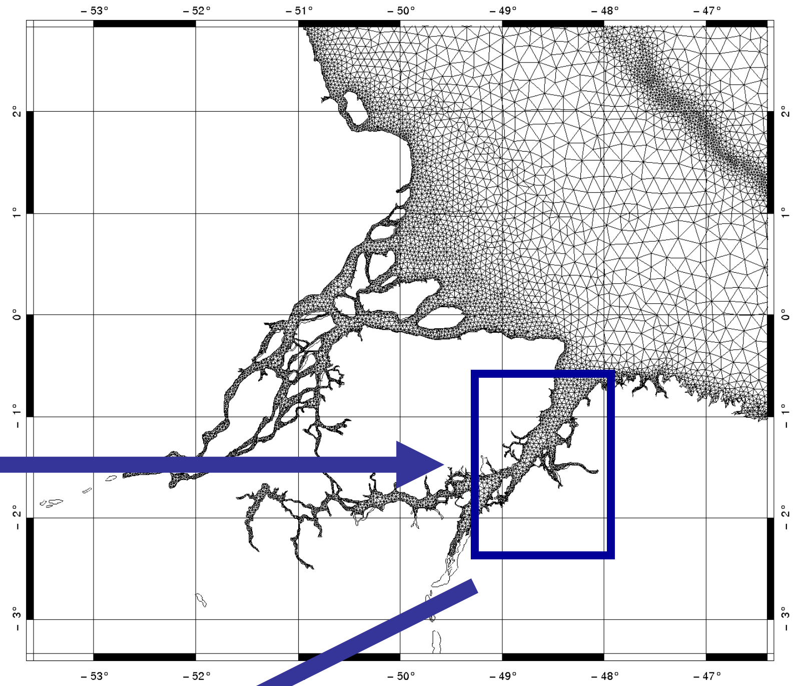
- **Harmonic analysis accuracy is limited by local effects**

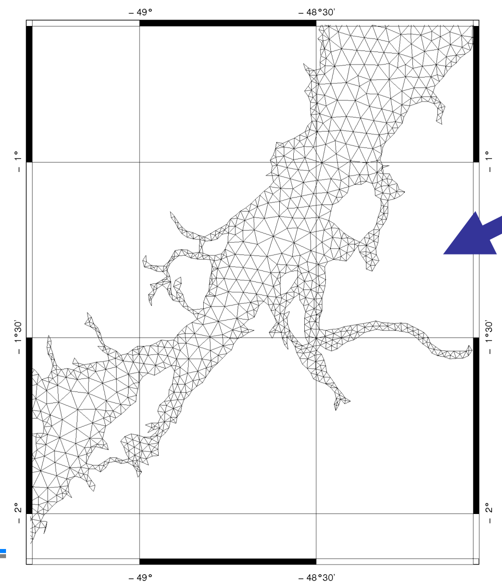
We need to improve the shelf/coastal tidal atlases using as regional models-> then SWOT



Regional modelling



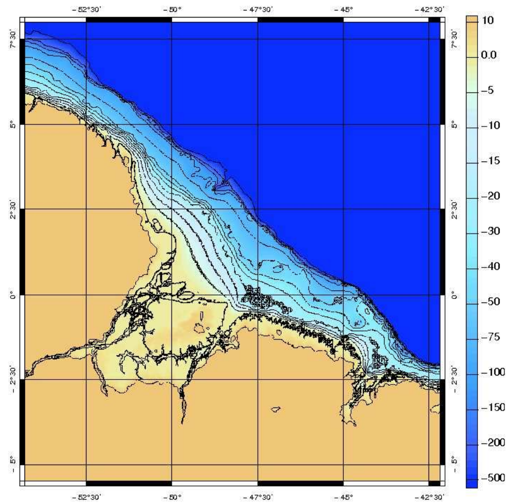




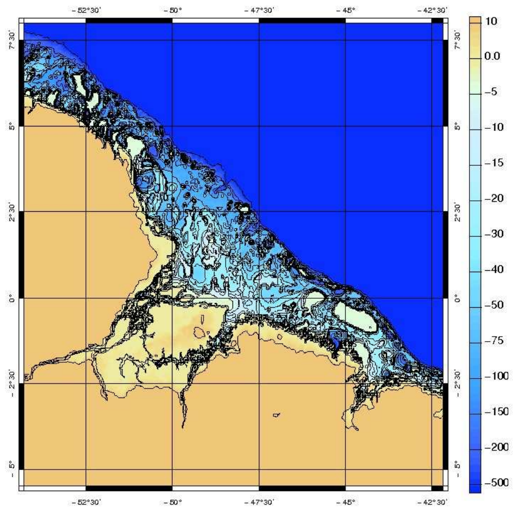
FE mesh useful to properly describe the regional, estuary and river channel details

Bathymetry: 1st order error

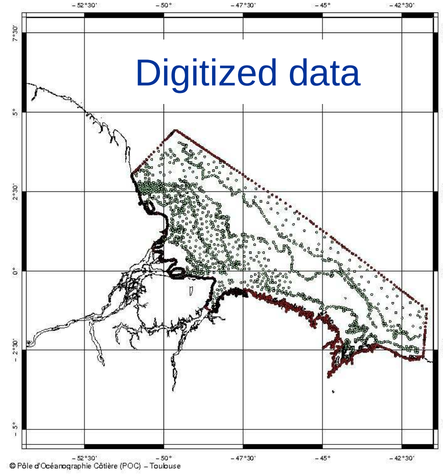
Amazon river shelf

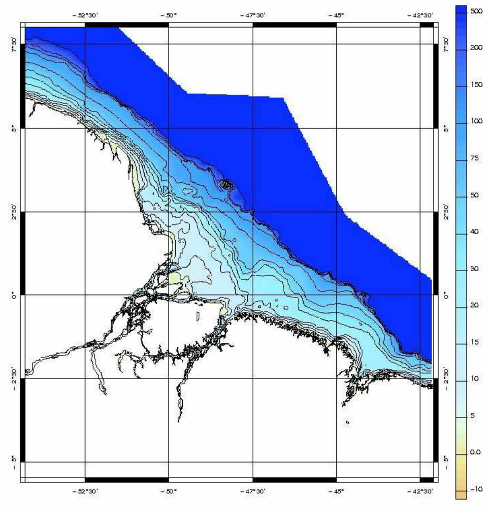


GEBCO (gridone) : lack of details



Smith & Sandwell : noisy and unrealistic





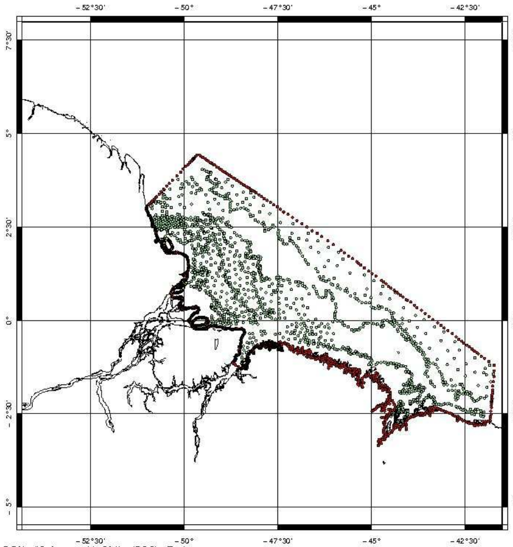
improved model bathymetry

Large bathymetry errors are found in available databases. Effects on tidal simulation are dramatic.
Scan and digitize bathymetric and nautical charts.
Mapped and merged into global database

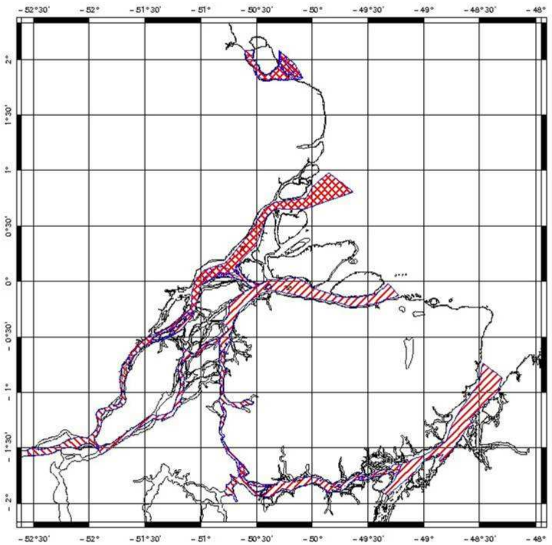
Urgent need to improve regional bathymetries…

Re-creating regional bathymetries

fastidious…

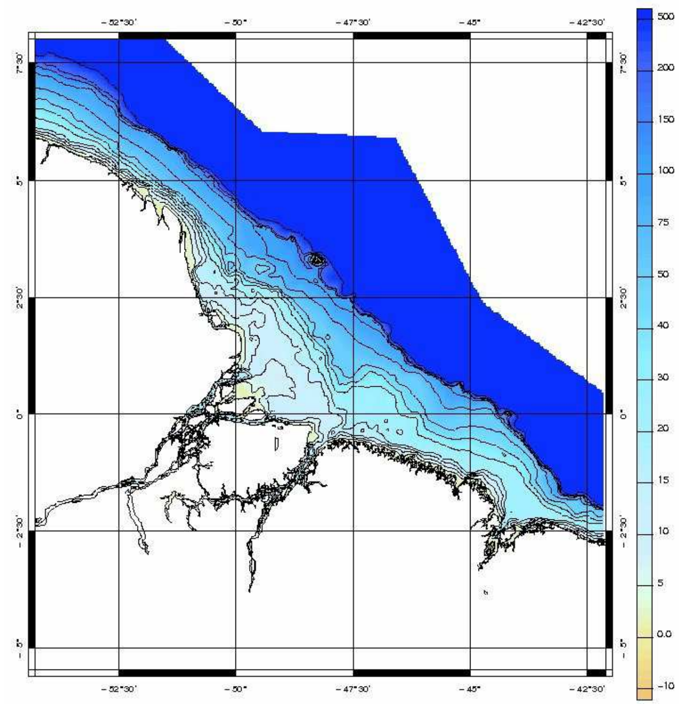


Digitized data



Re-worked channel path

improved model bathymetry

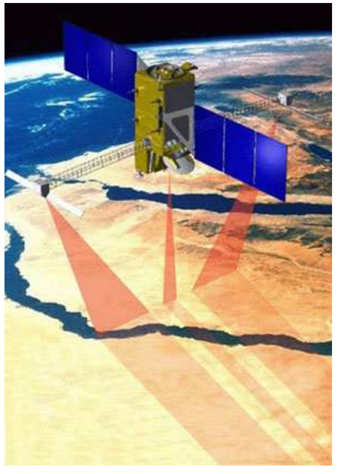


Scan and digitize bathymetric and nautical charts

Special care to estuarine channels

Mapped and merged into global database

SWOT Conclusion

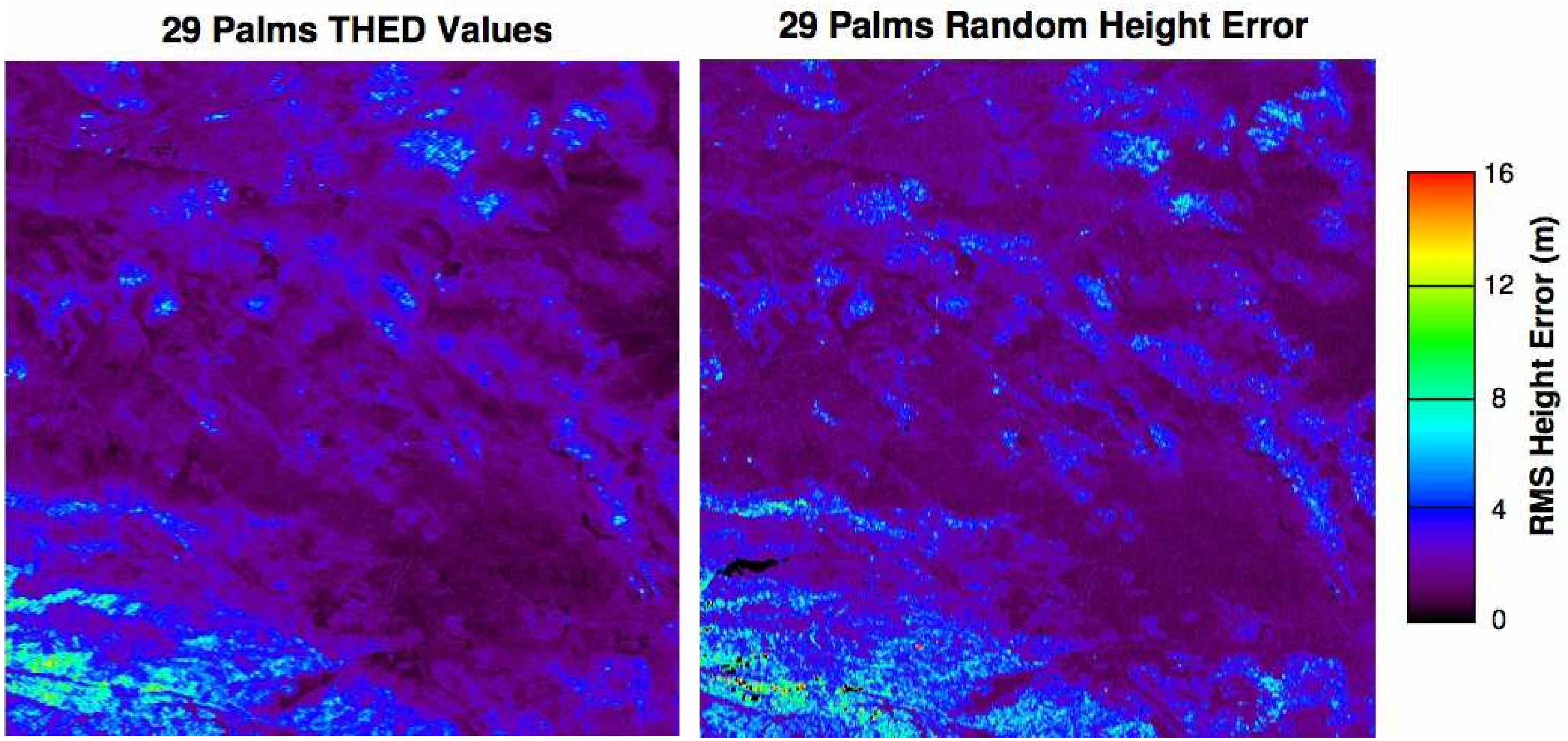


SWOT will be the **first satellite mission dedicated to surface water land hydrology**. SWOT will measure water storage changes in all wetlands, lakes, and reservoirs and estimate river discharge.

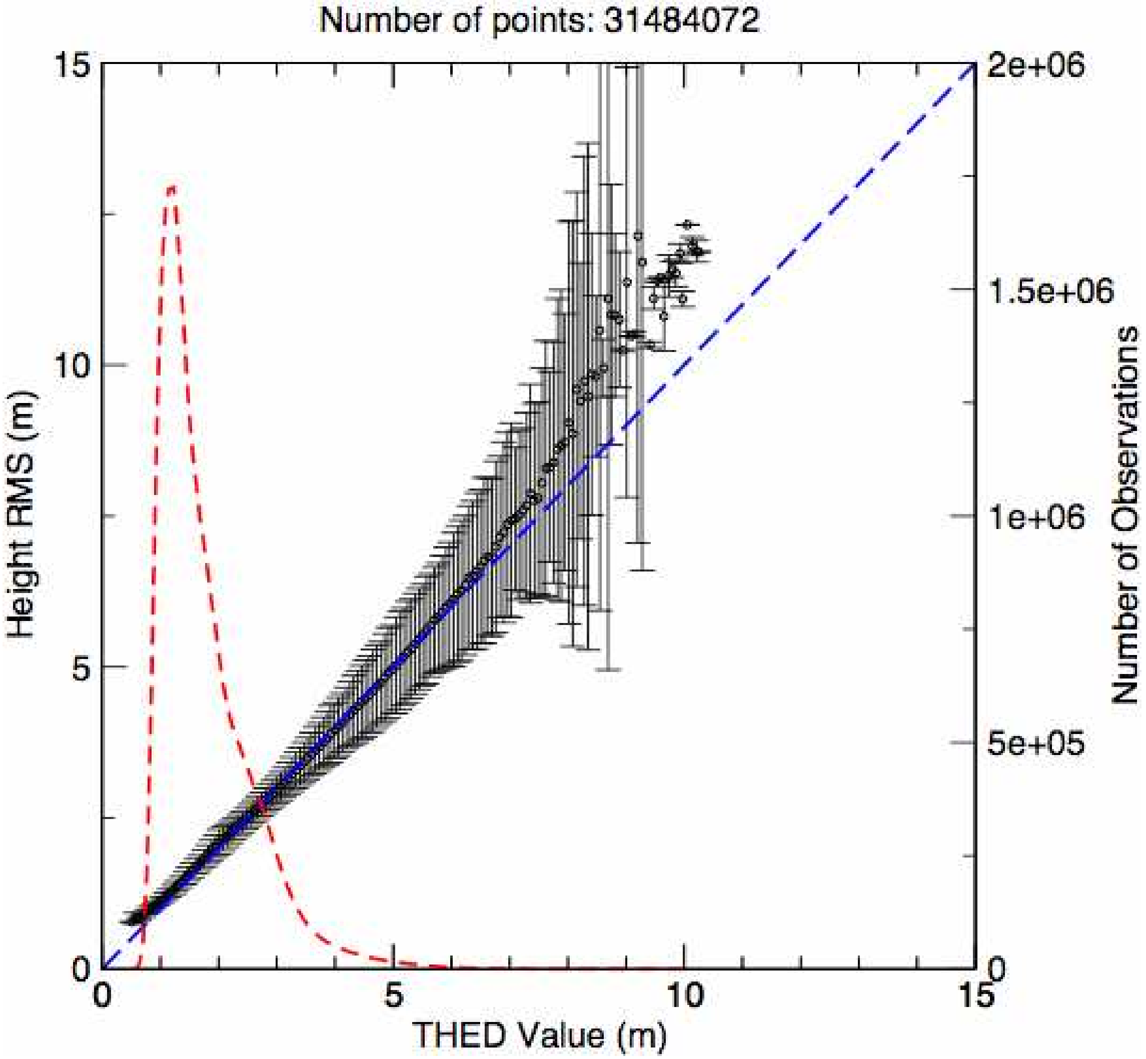
Global, high-spatial resolution measurements of ocean surface topography will monitor the **full range of ocean currents and eddy fields**, help determine their role in the **air-sea exchange**, and finely map the **coastal transport**. For the first time, we will observe the sea level variations driving **fine-scale filament structures**, which play a decisive role in the vertical exchange of heat, carbon and nutrients.

Extras

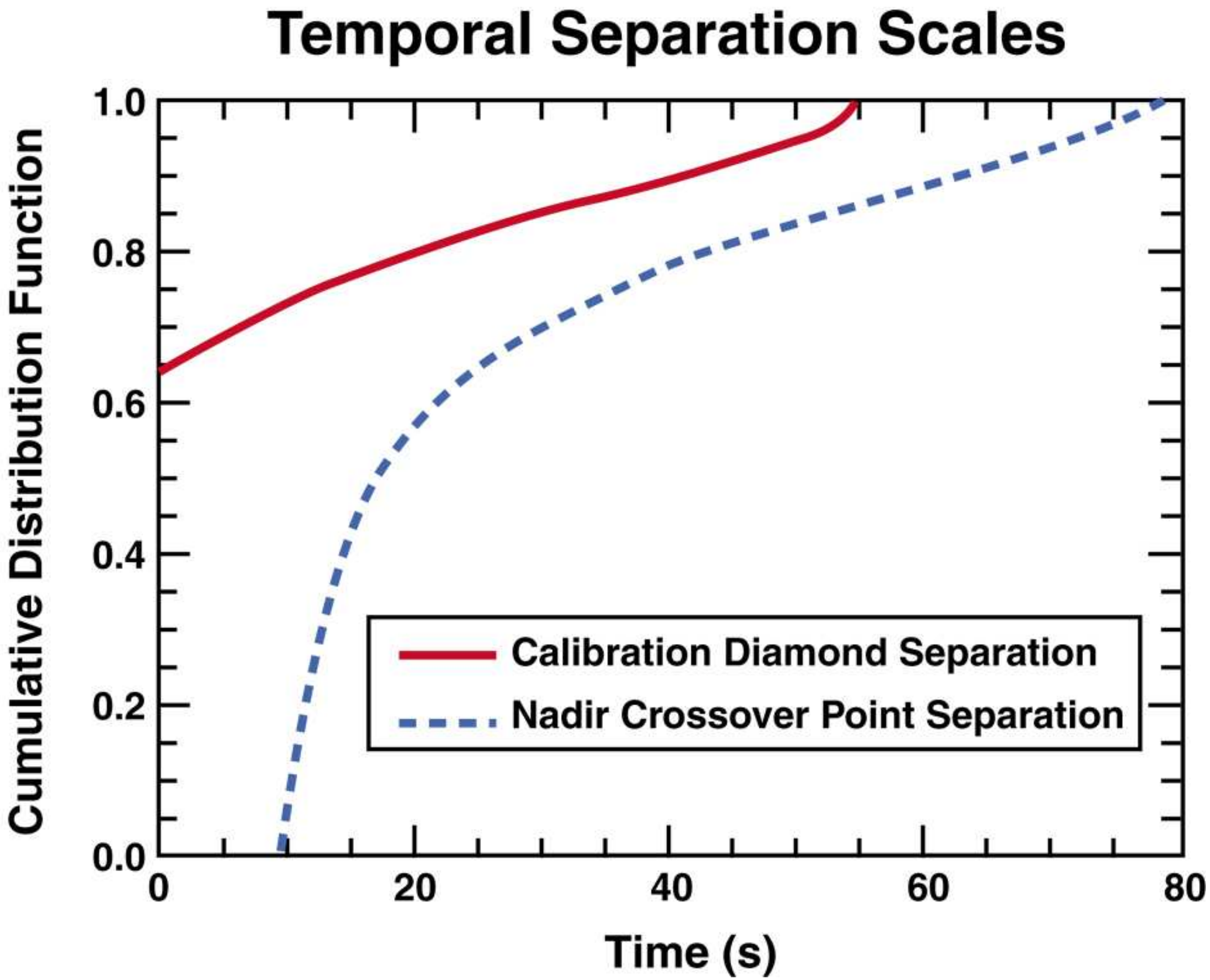
Random Height Error Validation



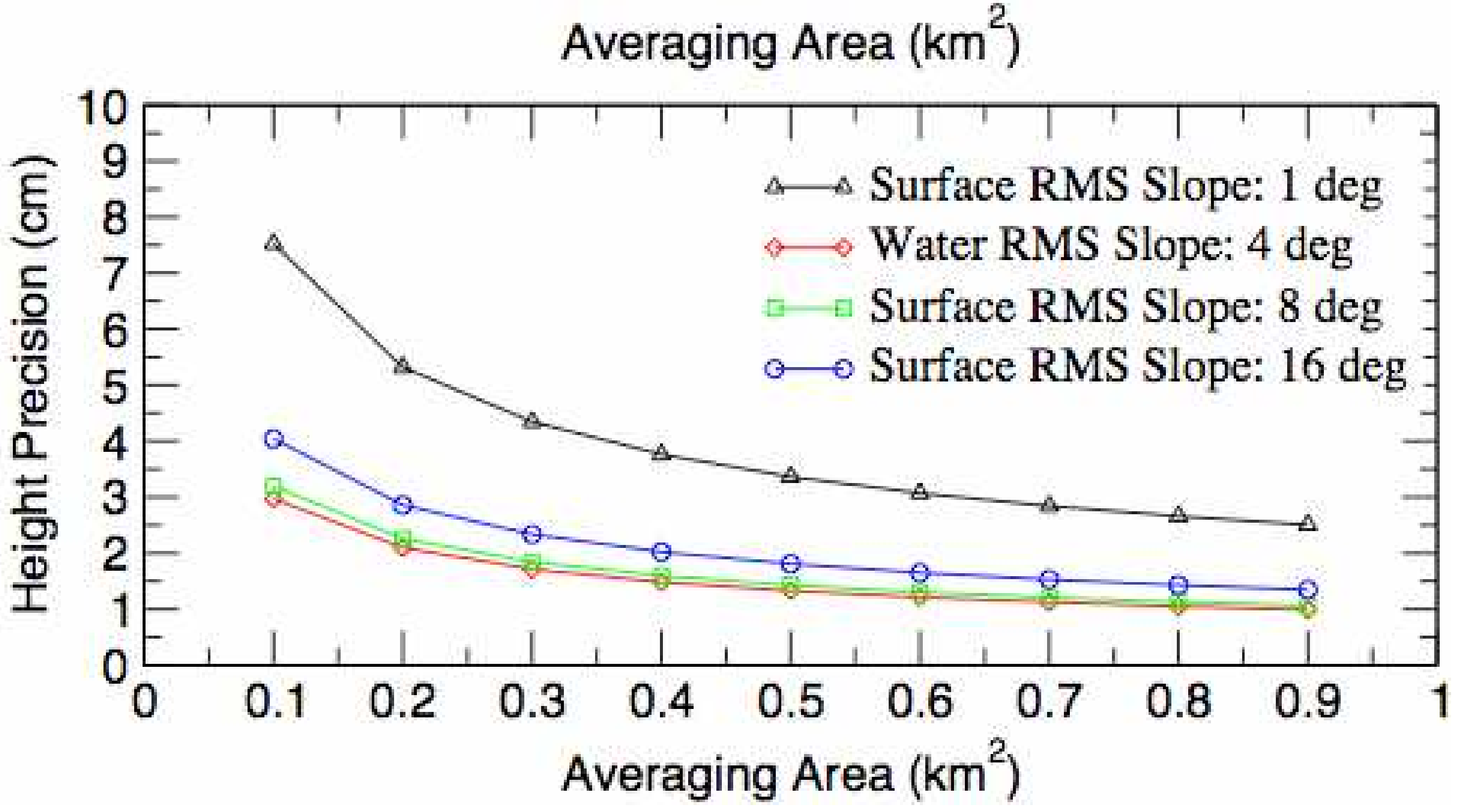
Random Height Error Validation



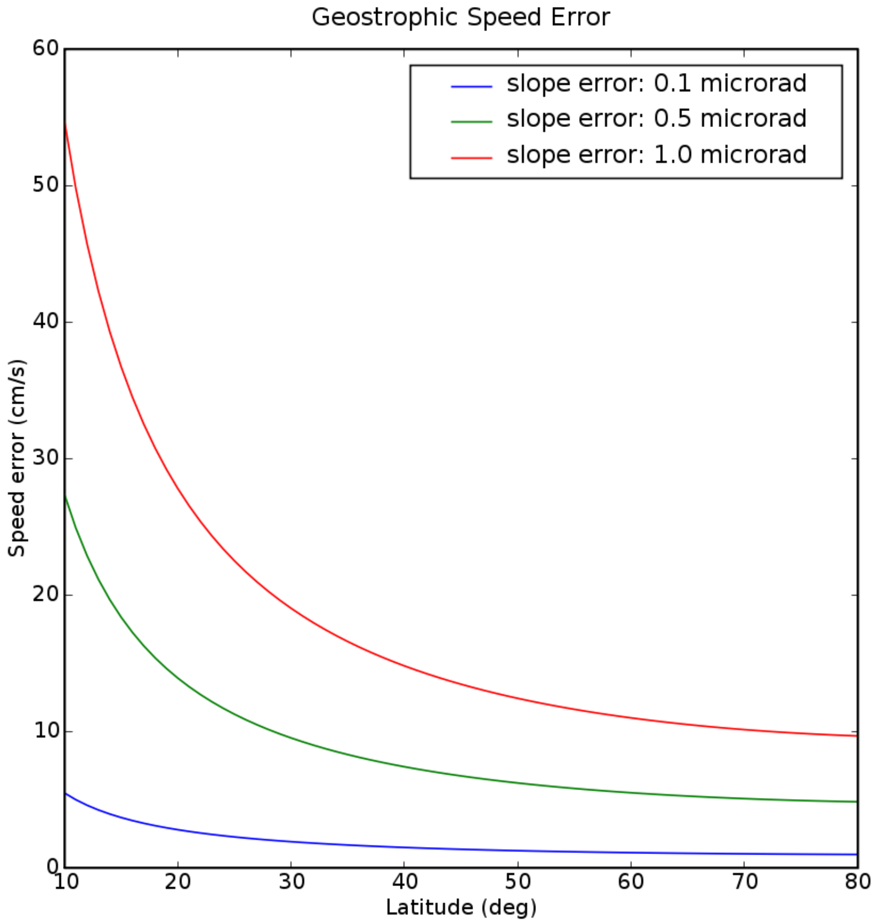
Distribution of Time Separation Between Calibration Regions



KaRIN Random Noise Performance



Slope Errors to Geostrophic Velocity Errors



$$\sigma_s \approx \sqrt{\frac{12}{N}}\frac{\sigma_h}{L}$$

$$\sigma_V = \sqrt{2}\,\frac{g}{f}\sigma_s$$

σ_s : Slope std

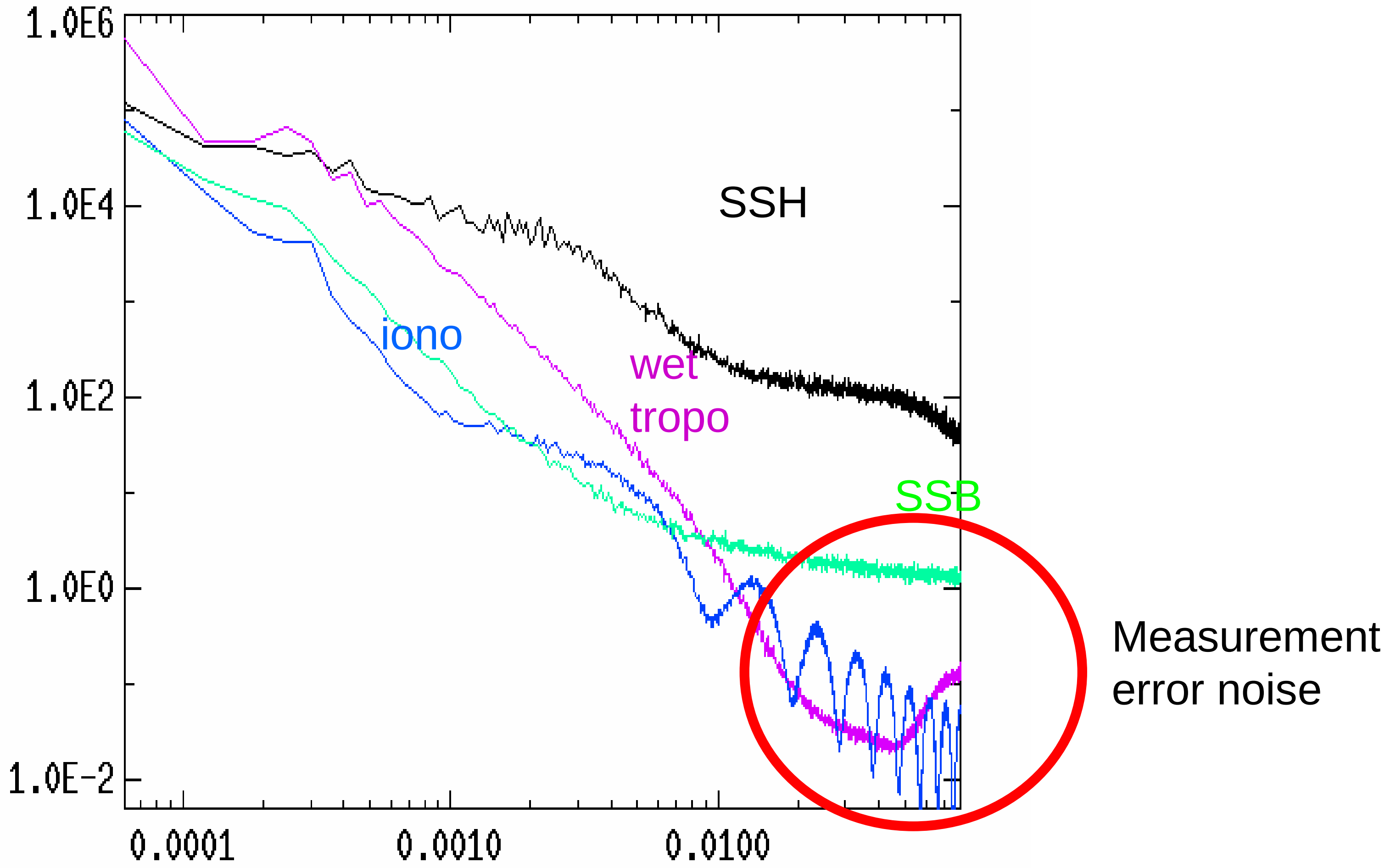
σ_h : Height std

L : Distance for slope calculation

Δx : Sample spacing

N : Total number of samples

Geophysical Correction Spectrum

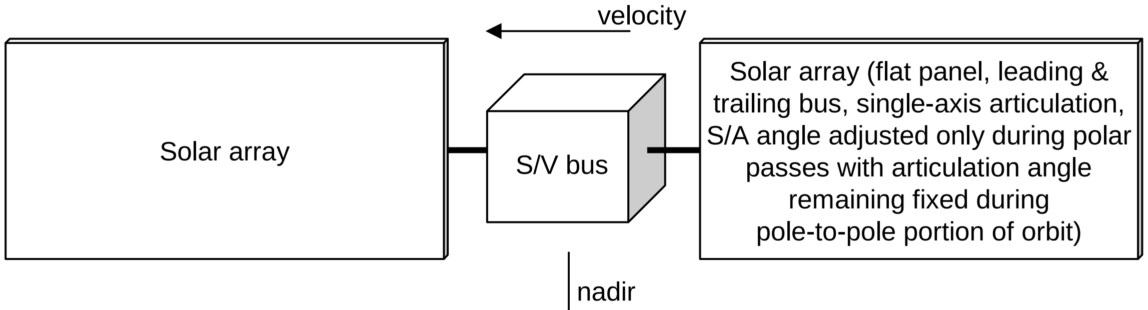


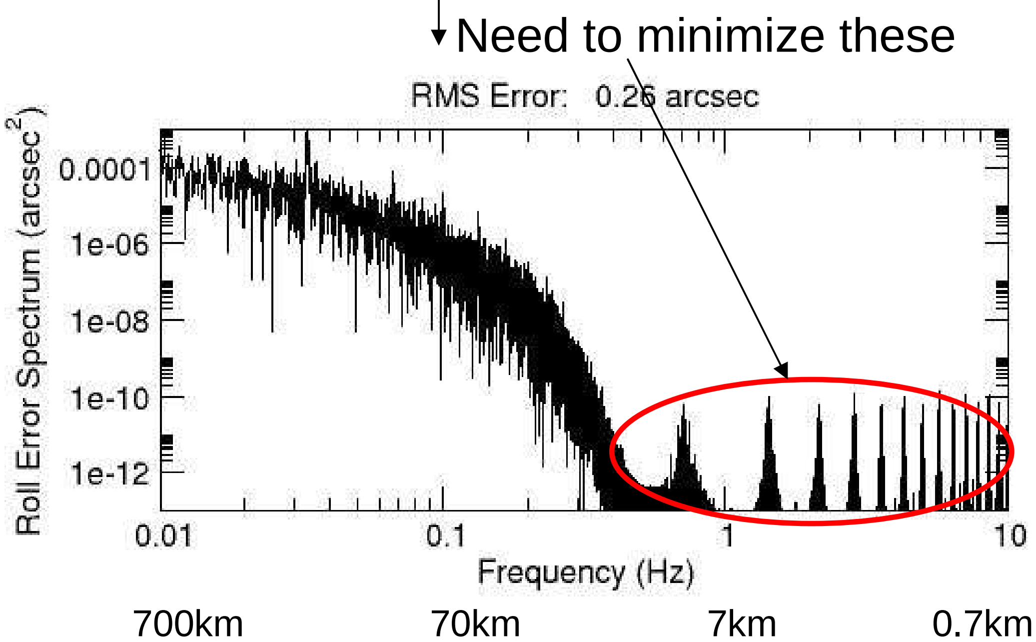
Media errors and sea-state errors have scales larger than 100 km and not affecting submesocale SSH measurement.

Mitigating Roll Errors: Minimize Spacecraft Dynamics

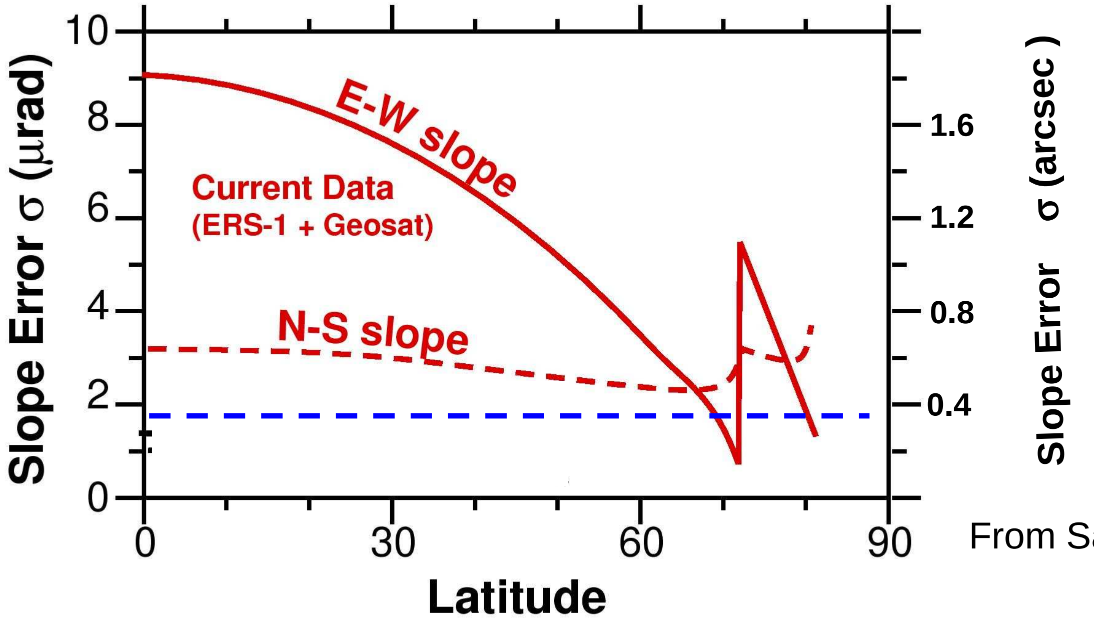
Minimizing high-frequency motion errors can be achieved with an appropriate architecture (e.g., Grace has no moving panels)

Both CNES and JPL have determined that a feasible architecture exits where no high-frequency spacecraft component motion will occur during data collection





- The slope accuracy and spatial resolution are compatible with Abyss mission requirements, for even 1 repeat cycle (not taking into account ocean mesoscale contamination)
- Using compromise orbit and expanded swath (120km -> 140km), there are no holes in the coverage



From Sandwell et al.