Tsunami observations by satellite altimeters

J.F. Legeais, M. Ablain, E. Sanz (CLS)
E. Bronner, N. Picot (CNES)

Ocean Surface Topography Meeting
Lisbon
19-10-2010

Overview

- **What are tsunamis ?**

  High frequency phenomena whose amplitude and speed depend on depth:

  - Propagation through an ocean basin within **a few hours**
  - Amplitude of only a few **tens of centimeters** in the deep ocean and several meters close to the coast due to energy conservation.

- **Question:** In which extent is it possible to observe tsunami waves by altimetry?

- **Conditions for tsunami observation**:

  1. A **strong earthquake magnitude** that generates high enough tsunami wave to be distinguished among ocean mesoscale variability
  2. Altimeters must **fly over the tsunami wave** within the very few hours following the earthquake so that the wave hasn't vanished or reached the coast.

  ⇒ The probability of observation by satellite altimeters is thus rather low

- **Interest:** Altimetry could provide an **independent measurement** of the tsunami wave propagation with high accuracy which could help to **improve** the parametrization of propagation **models**. These are **the only one which provide quick enough warning to inhabitants**

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Method

1) A basic way to detect tsunami from altimeter measurements is to compare the ocean state (SLA) a **few days before and after** the tsunami occurrence

=> Cycle N-1 / Cycle N / Cycle N+1

2) Mesoscale ocean variability strongly limits tsunami detection

- Use of a specific ocean variability mapping technique (Le Traon et al., 1998) to better extract the tsunami signal
- Optimal **interpolation of all altimeters data** in space and time using 40 days of data before and after tsunami day (excluded) via objective analysis

⇒ Gives an estimation of the **ocean state as if tsunami had not occurred**

40 days of all altimeters	Tsunami day	40 days of all altimeters

Filtered SLA = Original SLA – Interpolated SLA

- The **filtered SLA** reflects periods lower than ~15 days, which is only possible thanks to a very good space / time sampling of the ocean with several altimeters (Pascual et al., 2006)

⇒ Gives a good estimation of the tsunami wave

2004 Indian ocean tsunami

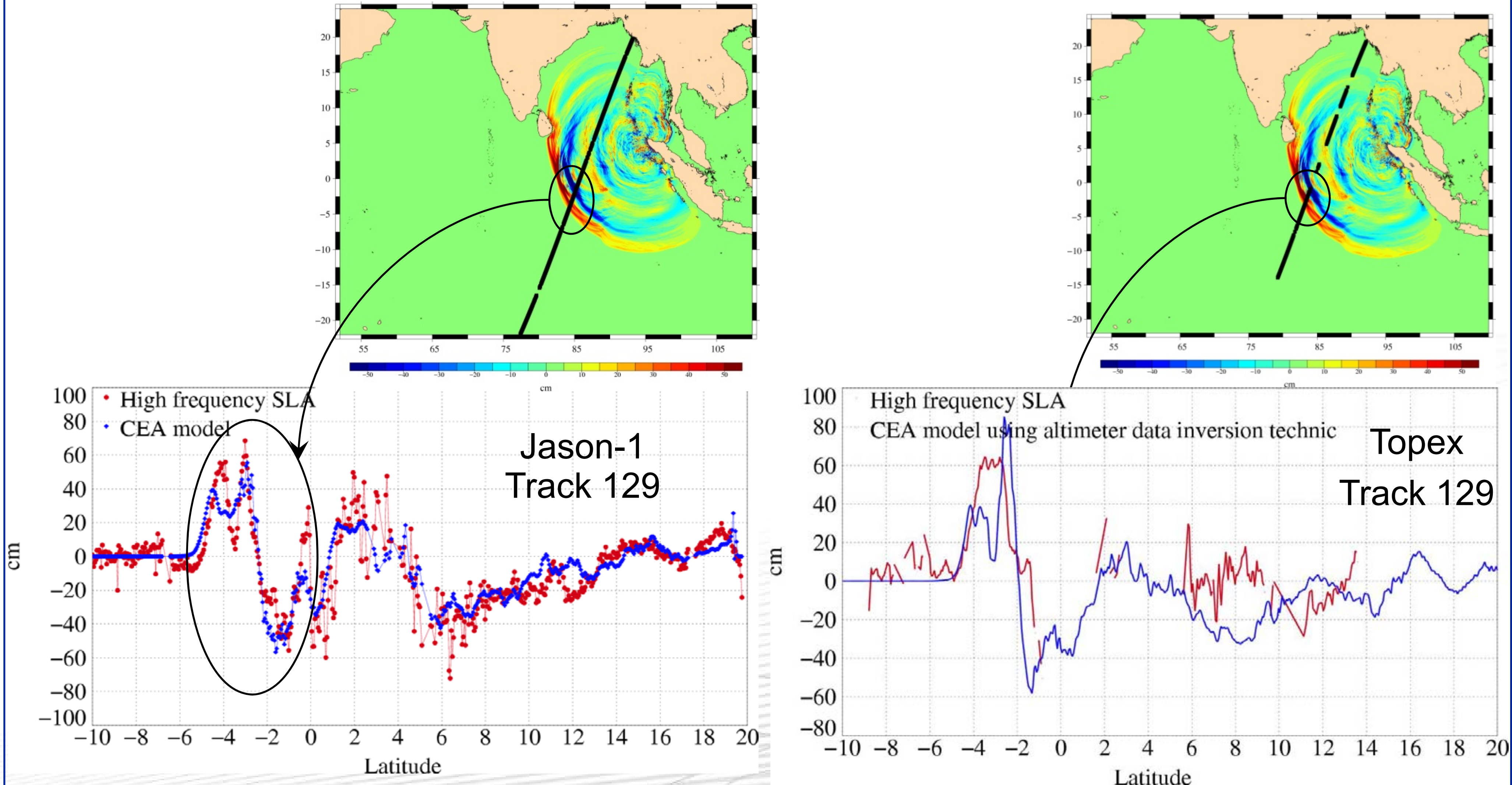
- The Indian Ocean earthquake of December 26th 2004 (magnitude of 9) generated a tsunami which has been well observed by satellite altimeters in the open ocean (Ablain et al., 2006, Geophys. Res. Lett., 33).

- **Observation of tsunami waves in altimeter measurements**
  - Jason-1, TOPEX, Envisat and Geosat Follow-On overflew the wavefront from 2h00 until 9h00 after the earthquake.

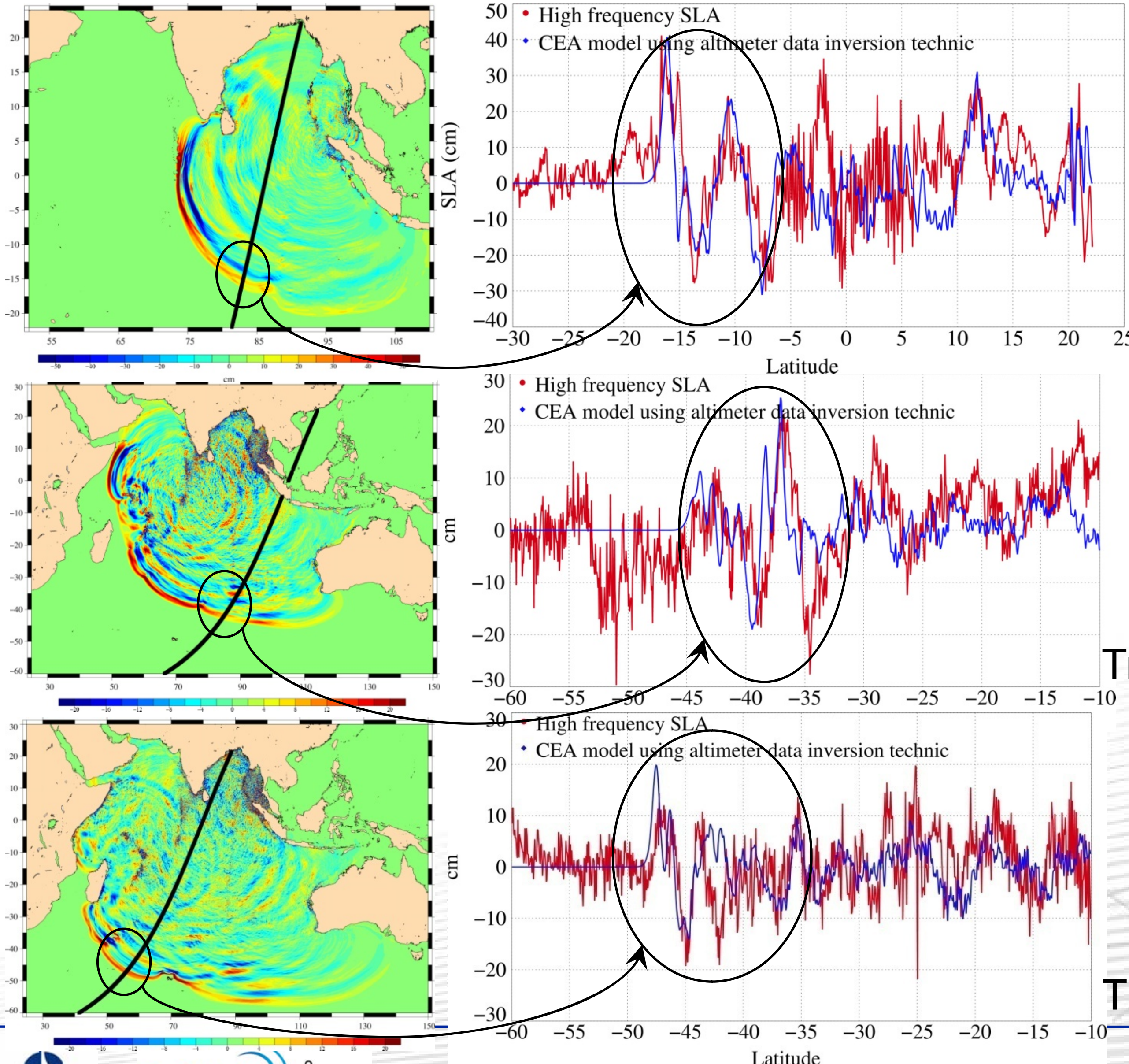
- **Comparison of altimeter observations with the CEA propagation model** (A. Sladen and H. Hebert, 2006). For all the following results,
  - initial displacement conditions of the model were refined thanks to the altimeter data
  - It significantly improved coherence between model and in-situ observations compared with 1st initial model outputs.

2004 Indian ocean tsunami

2 hours after the earthquake: 60 cm amplitude



2004 Indian ocean tsunami



3h15 after the earthquake:
35 cm amplitude

Envisat
Track 352

7h00 after the earthquake:
20 cm amplitude

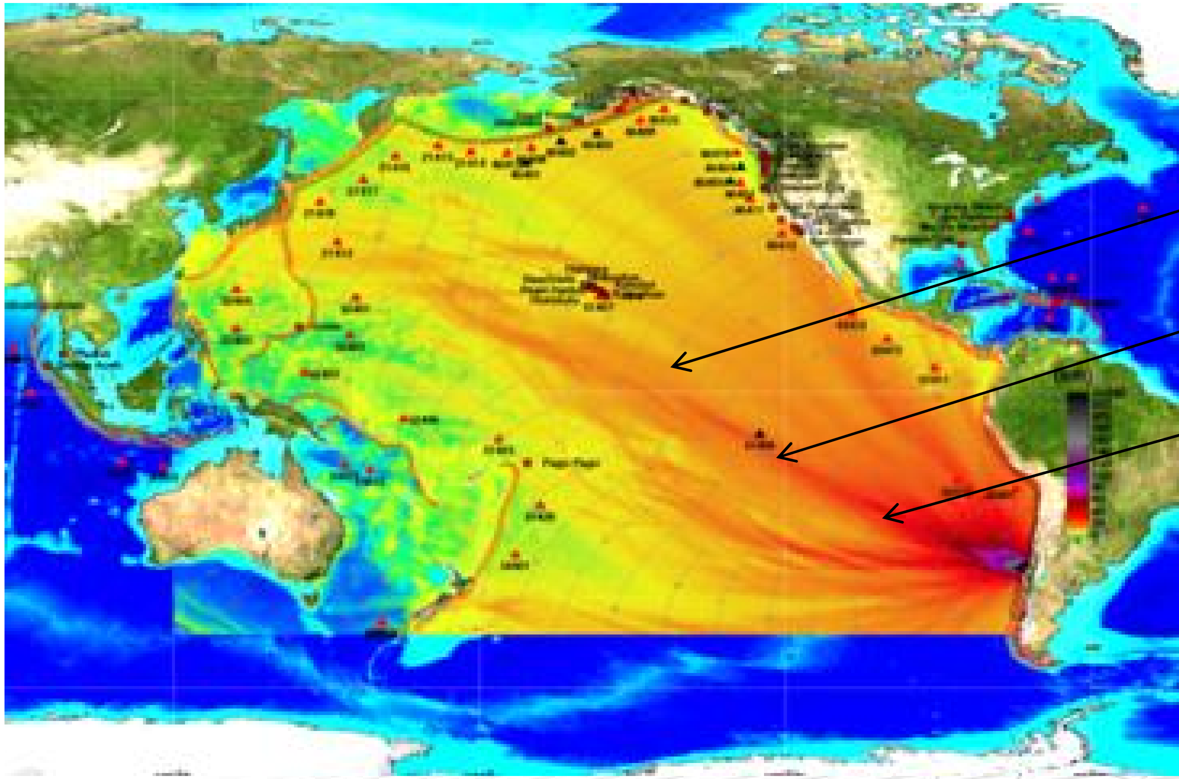
GFO
Track 208

9h00 after the earthquake:
15 cm amplitude

GFO
Track 210

2010 Chilean tsunami

- On February 27th 2010, an **8.8 Mn earthquake** occurred off Chilean coast and generated a **tsunami wave** that propagated across the **Pacific ocean within 15 hours**.

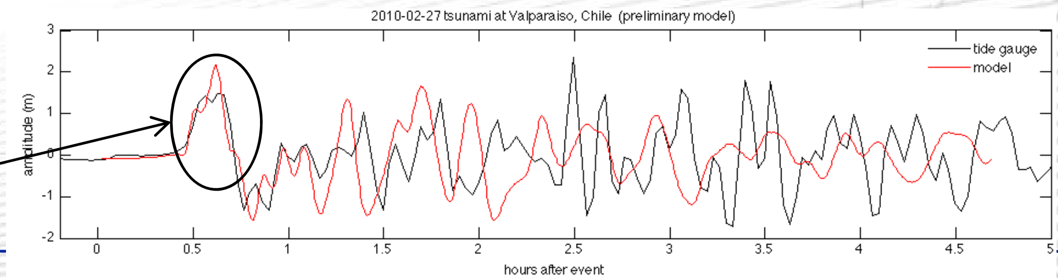


+12h: < 10 cm

+8h: < 20 cm

+4h: < 40 cm

From NOAA



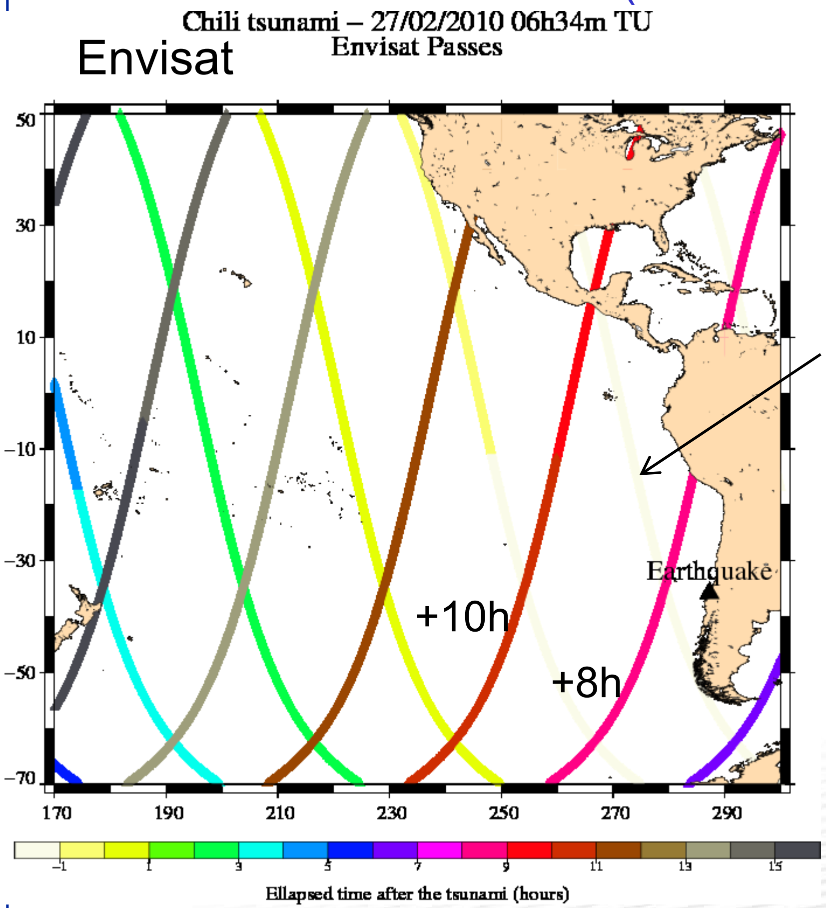
2m amplitude

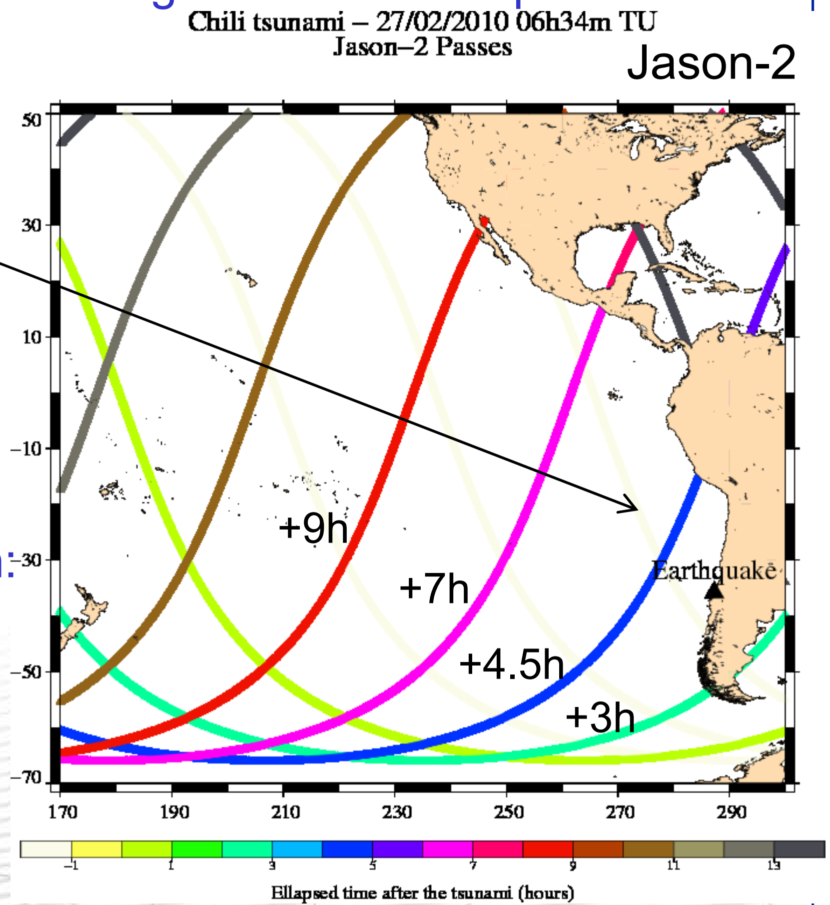
Tide gauge *vs* model
(MOST from NOAA)

2010 Chilean tsunami

- **Observation of tsunami waves in altimeter measurements:**

  3 altimeters available (Jason 1 & 2, Envisat) but their configuration wasn't optimal:





Bad configuration:

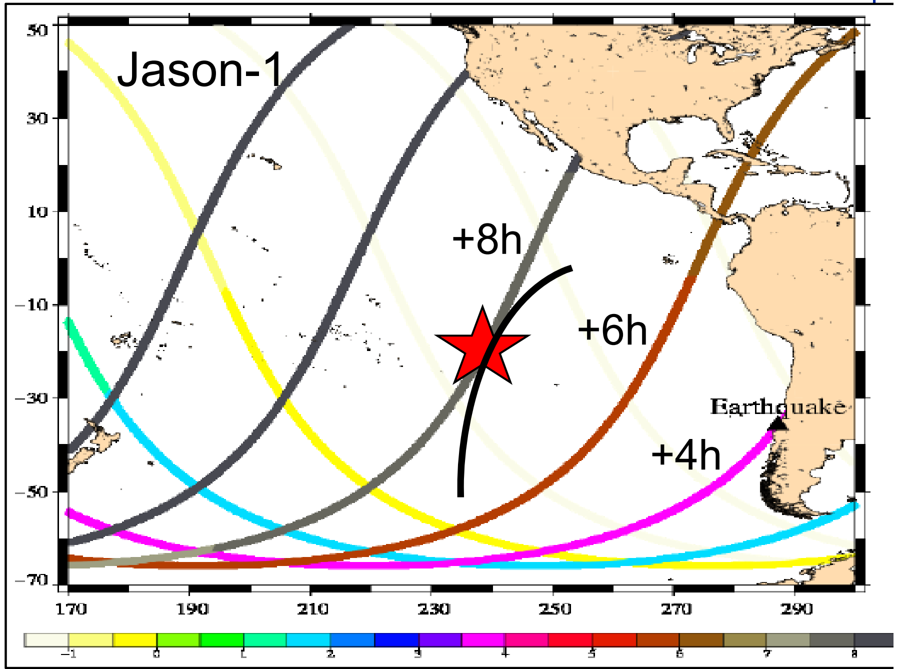
=> No detection although large coverage and amplitude

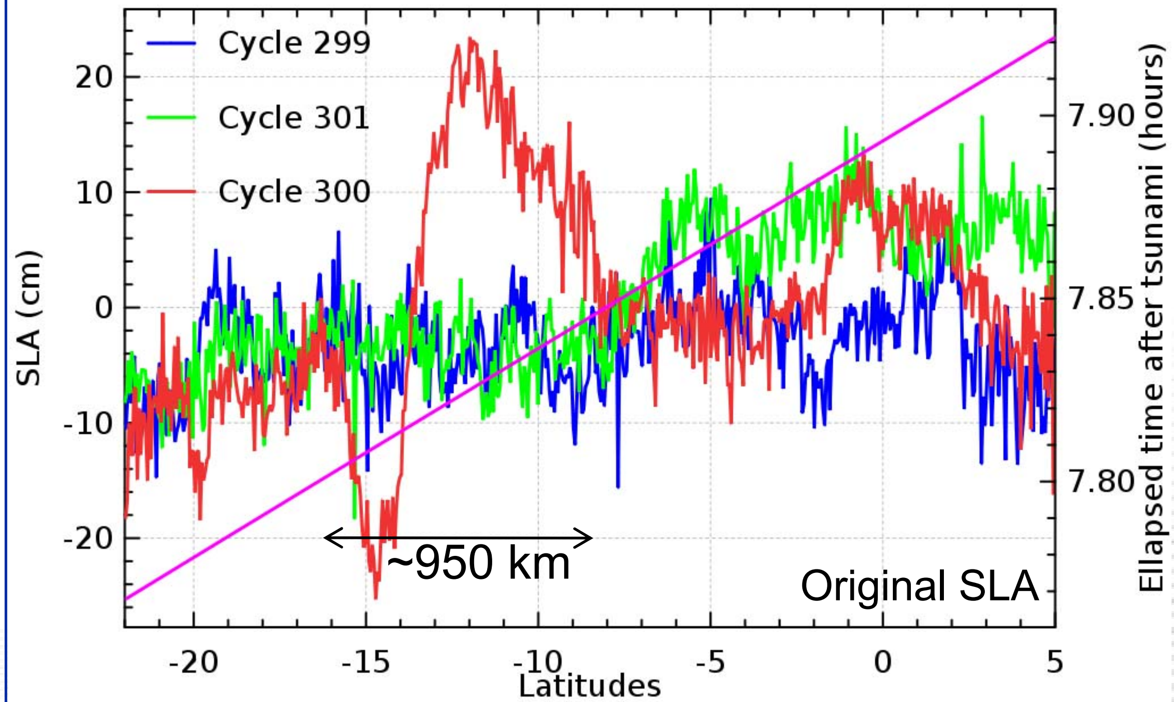
- ➢ Ascending tracks: 2h too early
- ➢ Descending tracks: 8h and 10h later
- ➢ 4 tracks 3h to 10h after earthquake

2010 Chilean tsunami

- Among 3 altimeters measurements, although:
- → the tsunami had large amplitude and coverage,
- → ocean variability had been removed,

  the wavefront has only been detected with J1 8h after the earthquake with a 20 cm wave amplitude





- The almost zero angle prevents us from estimating the real **wavelength** (~400km expected)
- Detection is strongly limited by the ocean variability, especially by ACC fronts in the southern part of the area.

Analysis of past tsunamis in historical altimetric data

- We have good quality of altimeter measurements **from 1992** onwards
- Use of systematic approach to **detect potential tsunami wave** associated to earthquake of **magnitude from 6.9 to 9.0** (22 earthquakes)

- It has never been checked
- 12 had a magnitude ≥8.0
- 2 already discussed have the highest magnitude (8.8, 9.0)

Date	Mn	Lat/Lon	Date	Mn	Lat/Lon
12/07/93	7.7	42.47 / 139.12	03/05/06	7.9	-20.13/185.836
08/08/93	7.8	12.92 / 144.80	7/07/06	7.7	-9.222 / 107.32
14/10/94	8.3	43.60 / 147.63	13/01/07	8.3	46.272/154.455
03/07/95	8.1	-23.34/ 289.71	01/04/07	8.1	-8.481/156.978
17/02/96	8.2	-0.63 / 136.59	08/08/07	7.5	-5.968/107.655
21/02/96	7.5	-10.06/ 279.83	15/08/07	8.0	-13.354/283.491
17/07/98	7.0	-2.96 / 141.92	12/09/07	8.4	-4.52 / 101.374
23/06/01	8.4	-16.26/ 286,36	07/10/09	7.8	-12.554/166.320
25/09/03	8.3	41.775/143.904	12/01/10	7.0	18.457/ 287.467
23/12/04	8.1	-50.145/ 160.3	27/02/10	8.8	-35.846/287.281
26/12/04	9.0	3.307 / 95.947	18/07/10	6.9	-5.939 / 150.572

Analysis of past tsunamis in historical altimetric data

- The only two tsunamis which have been detected are those we have discussed (Indian ocean, 2004 and Chili, 2010).
- Such few observations are explained by:
  - **Wave amplitude** not high enough or signal lost in the surrounding ocean variability AND
  - **Bad configuration of altimeters**: no over flight of the wave or too long delay after the earthquake so that the wave has vanished or reached the coast

    (eg: Envisat and Jason-2 with 2010 Chili tsunami)
  - ⇒ Even if a strong earthquake produces high wave, **at least 1 altimeter** must have overfly the wave **AND** we need **up to 4 altimeters** to **remove** at best the **ocean variability** to better extract the tsunami signal

- This analysis of historical data:
  - shows high difficulties to have adapted tsunamis observations
  - Even if data acquisition were quick enough, **altimetry could not be used to produce tsunami alerts**

Conclusions

- It is possible to detect tsunami waves with altimetric SLA
  - ➢ The 2004 **Indian ocean** tsunami has been detected with 4 altimeters

    Good accuracy has been demonstrated by consistent comparisons with CEA model.
  - ➢ The 2010 **tsunami** off **Chili** has been detected with Jason-1 measurements

    Altimeters configuration wasn't optimal but the amplitude was high enough to be detected by only one altimeter with no need of removing ocean variability.

- These are **the only tsunami waves** clearly measured in the open ocean by altimetry
  - ⇒ Need of strong earthquake magnitude and **up to 4 altimeters** to extract at best short periods (<15d) of tsunami signals from ocean variability (Pascual et al., 2006)

- This study shows that tsunami alert is NOT possible with altimetry, due to:
  - ➢ Delay of data acquisition and processing
  - ➢ Low probability of observation

- These observations highlight the essential role of altimetry to better understand and to **improve models** of tsunami wave propagation and dissipation

Perspectives

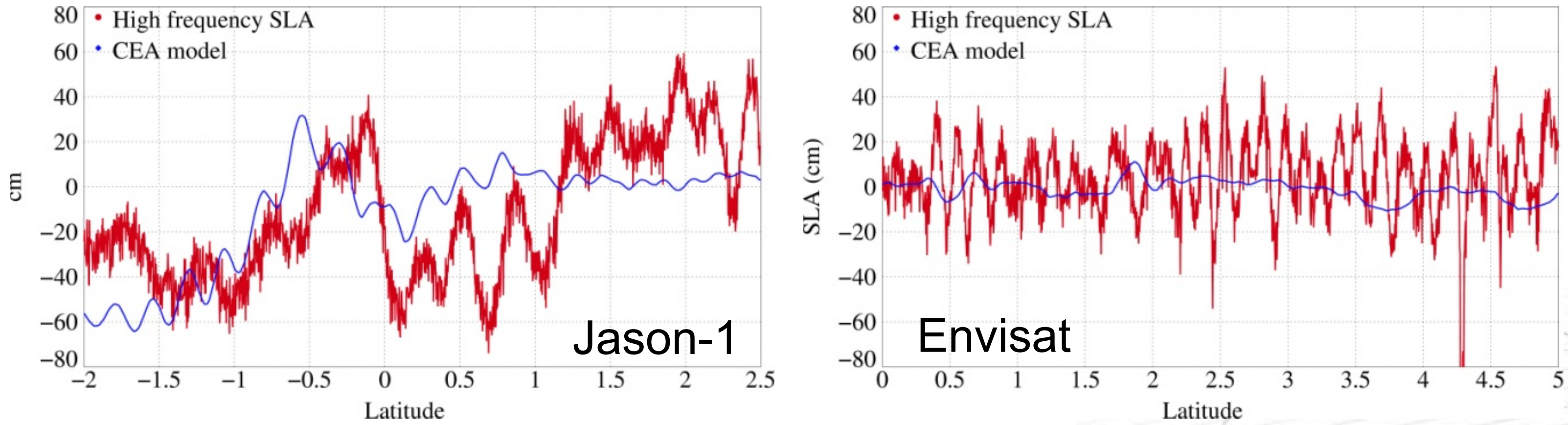
- Several aproaches were used to **extract tsunami signals from ocean variability** (Gower 2007; Ablain et al., 2006; our study) but this problem still limits tsunami observation by altimetry.
  - ⇒ **Improvement of the method** to remove the ocean variability to better extract tsunami signal

- Use of an automatic detection tool which could be used to detect other phenomena (hurricanes,…)

- Collaboration with studies on tsunami waves detection via the altimeter backscattered coefficient – σ_0 (B. Leben et al.) could help to improve altimeter products

2004 Indian ocean tsunami

- **Analysis of short wavelength signals**
- Jason-1 and Envisat SLA seem quite noisy at some latitudes
- SLA from 20Hz measurements show coherent **oscillations with short wavelengths** (between 20 km and 40 km according to the latitude)



- CEA model outputs don’t reproduced such oscillations but they are probably associated with the **tsunami** (Altimetric parameters were checked to exclude error in SLA calculation)
- Indeed, at these short wavelengths, **propagation is dispersive** and the dispersive relation for wave propagation (Le Blond and Mysask, 1978) provides us with the theoretical wavelengths:

$\lambda_{theo} = \lambda_{obs} \pm 3$ km => **Remarkable agreement**

2010 Chilean tsunami

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