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DTW (Dispersive Tsunami Wave): a new **tool** for **computing** the **tsunami dispersion travel time**.

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Introduction/motivations

- Compute **tsunami travel times** including the **dispersion** effects over a **wide range of periods.**
- **Quantify** the part of **dispersion** effects in the **coda of tsunami: separation** of **dispersion** effects of **reflection, diffraction**.
- Forecast **late arrivals** of **tsunami** waves with **possible resonances** for a given bay at **higher frequencies** than the **gravity mode**.

Other existing tools

- ***TTT*** *(Tsunami Travel Time, Paul Wessel, 2009)*:

Very **usefull, rapid, simple**

Only gravity mode (shallow water approximation)

- **Numerical modeling**

The **most precise**

Boussinesq modeling includes the **complete dispersion**

Computation time may be **prohibitive**

The basis: **relation of dispersion**

The complete relation for hydraulic waves:

$$\omega^2 = k^2 \left[\frac{g\lambda}{2\pi} + \cancel{\frac{2\pi\sigma}{\rho\lambda}} \right] \tanh(kH)$$

The **second term** is totally negligible:
σ superficial stress = 0.072 N/m
10^{-4} for λ = 1 m

Thus :
$\omega^2 = gk \tanh(kH)$, *H depth, k : wave number,* ω *pulsation*

*Rewritten as **phase velocity** dispersion:*

$c^2 = g/k \tanh(kH)$

*While the **group velocity** is related by:*

$U = c - \lambda\,(dc / d\lambda)$

Yielding:

$$\boxed{U = c - \lambda \frac{d\,(g/k\ \tanh kH)^{1/2}}{d\lambda}}$$

The basis: relation of dispersion (cont).

After **derivation**:

$$\boxed{U = \frac{c}{2} + \frac{gH}{2c}\left(1 - \tanh^2 kH\right)}$$

Asymptotic properties:

1) The case of **long period** (long wave-length, **shallow water**)

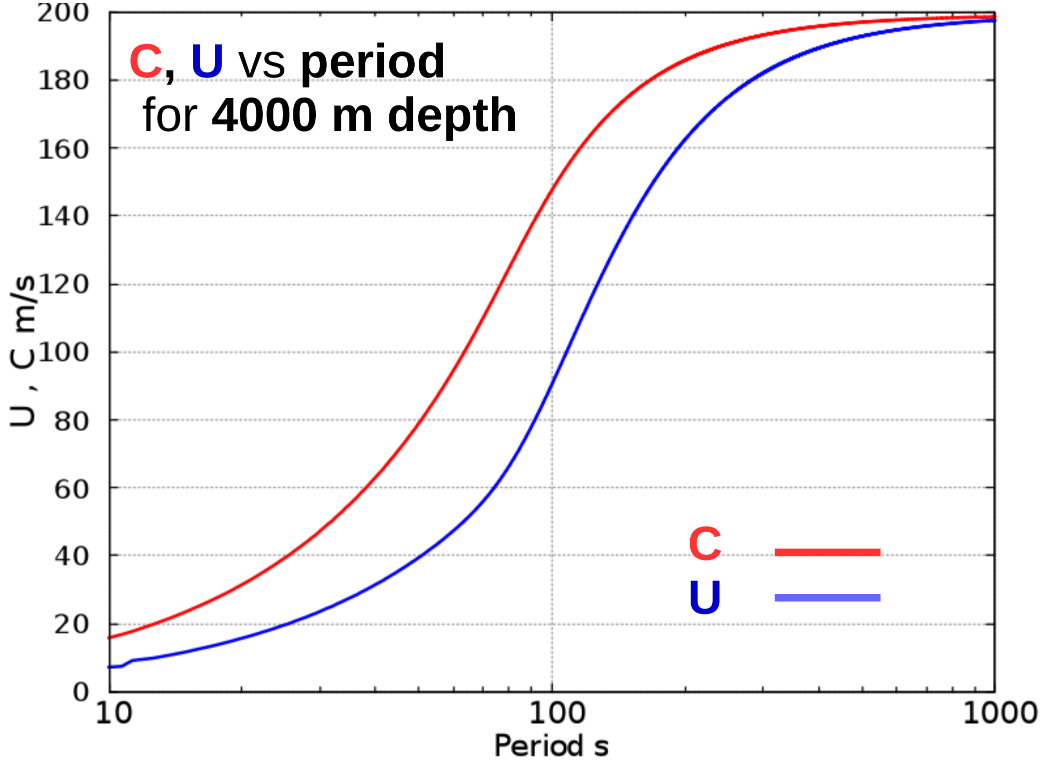
$$\lim_{kH \to 0} U = \frac{c}{2} + \frac{gH}{2c} = \frac{c}{2} + \frac{c}{2} = c = \sqrt{gH}$$

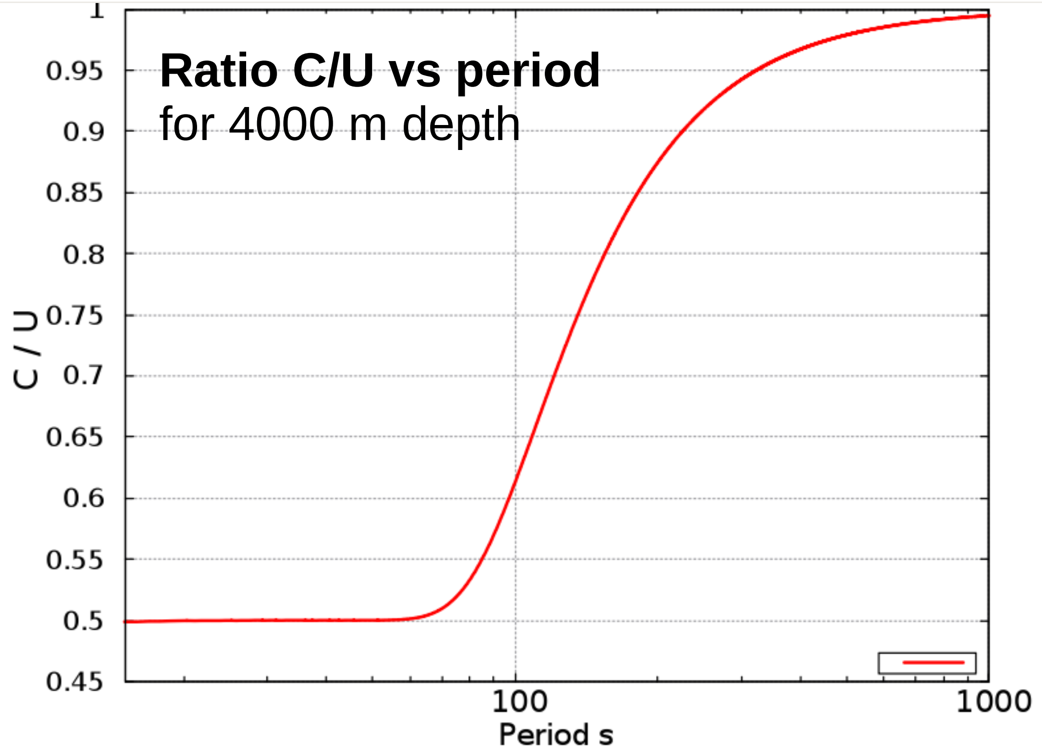
2) The case of **short wave-length**: propagation in deep water

$$\lim_{kH \to \infty} U = \frac{c}{2}$$

U varies simply in the interval [***c/2, c***], with ***c*** given by:

$c = (g/k \tanh (k H))^{1/2}$



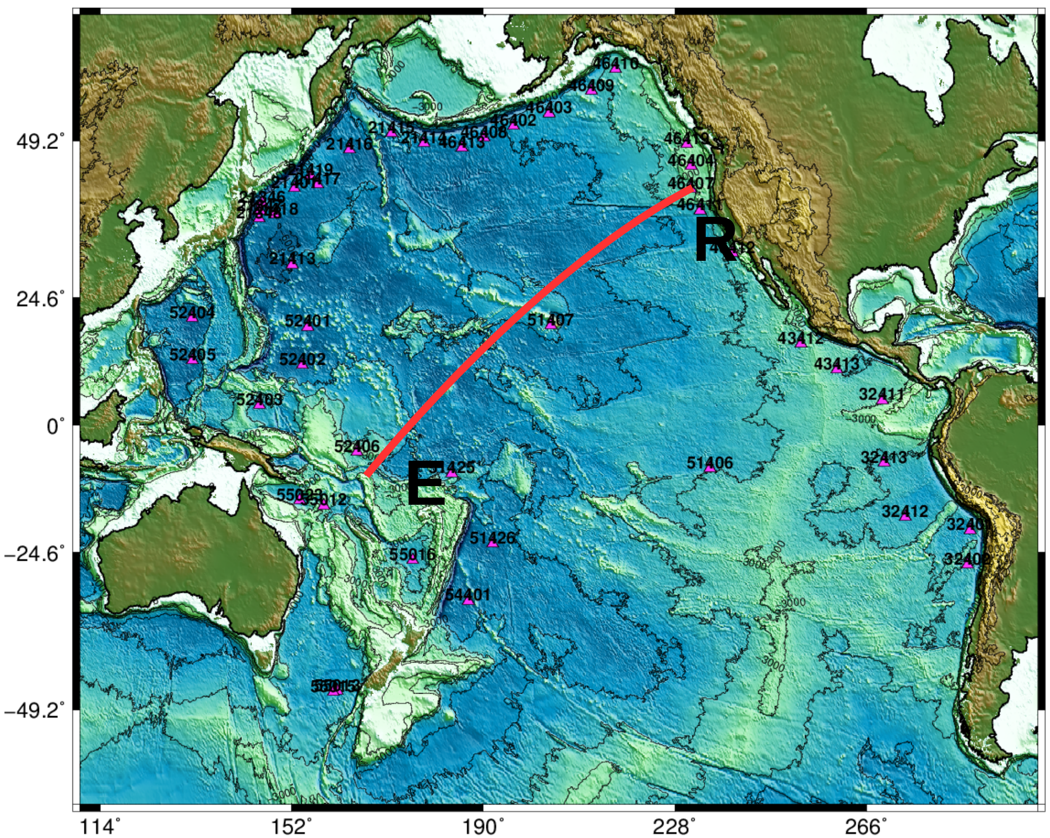


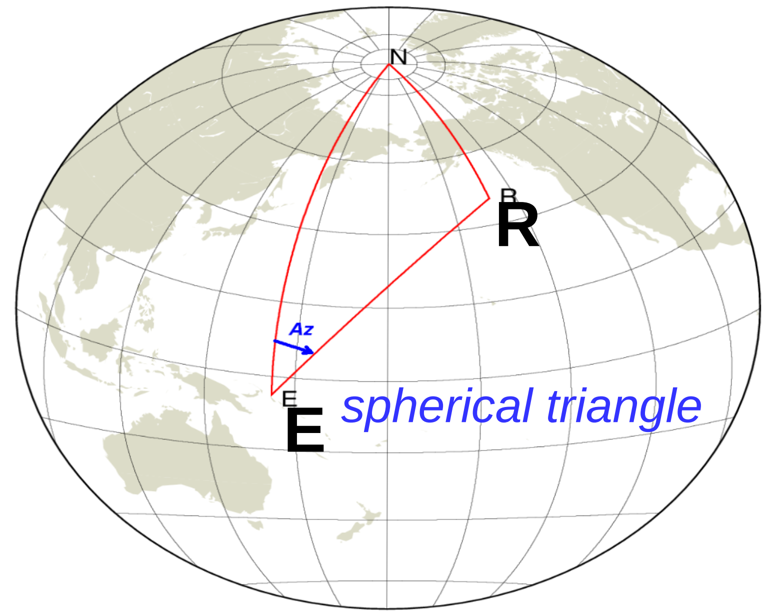
The **longest periods** arrive **always the first**

The **gravity waves** (shallow water approximation) arrive **always the first**.
or:
Dispersed waves are **always slower** than **gravity waves**.

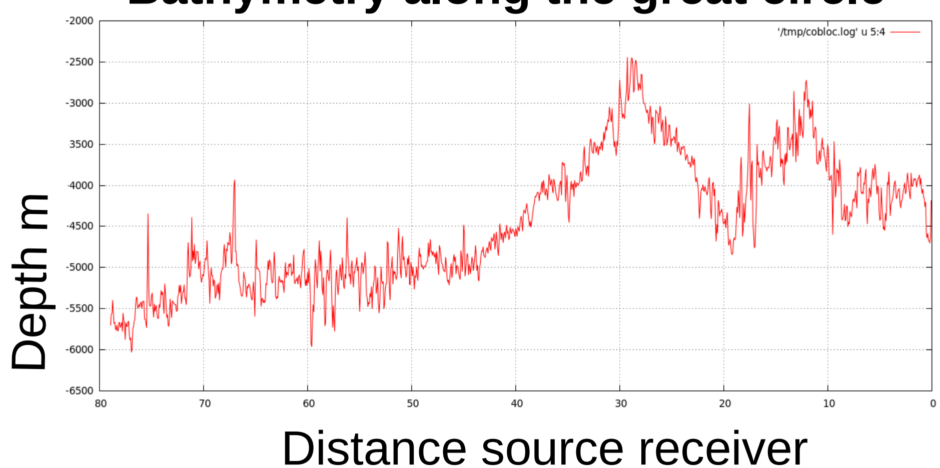
The algorithm to compute (c,U)

* Having a **bathymetry grid** (digital data)
* Compute the **ray path** along **great circles** source-receivers *(spherical geometry)*
* Extract the ocean **depth** across **each elementary bloc** of the **grid**.





Bathymetry along the great circle



The algorithm to compute *(c,U)* continue

* Having the **bathymetry along the ray path: {dH_i}**

DO
for each **period T**:
  for each **small bloc** of the grid **along the ray**:

1. Estimate the **phase-velocity** for a **given period *(T)*: c_i =*fct*(H_i, T)**
2. Calculate the **group-velocity** $U_i(T)$.
3. Calculate the propagation time for an unitary bloc : $dt_i = d\delta_i / U_i$.
4. **Sum** the elementary **propagation times along** the **ray**.

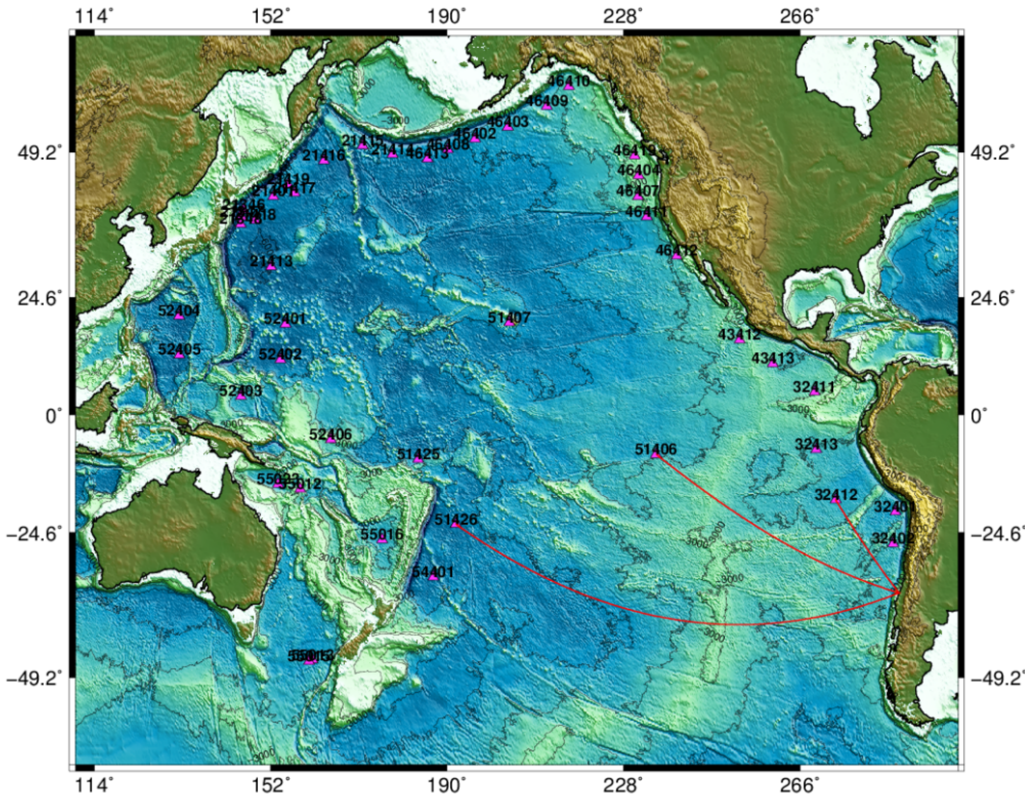
Parenthesis:

calculation of the **phase velocity**, at a given ***period T, depth H***

$\omega^2 = gk \tanh(k H)$ *rewritten* as: $$\boxed{c = \frac{gT}{2\pi}\tanh\left(\frac{2\pi H}{cT}\right)}$$

Transcendental equation
solved ***iteratively***

Computation of **travel times**:
First tests with **Chile 2010**: with a point source

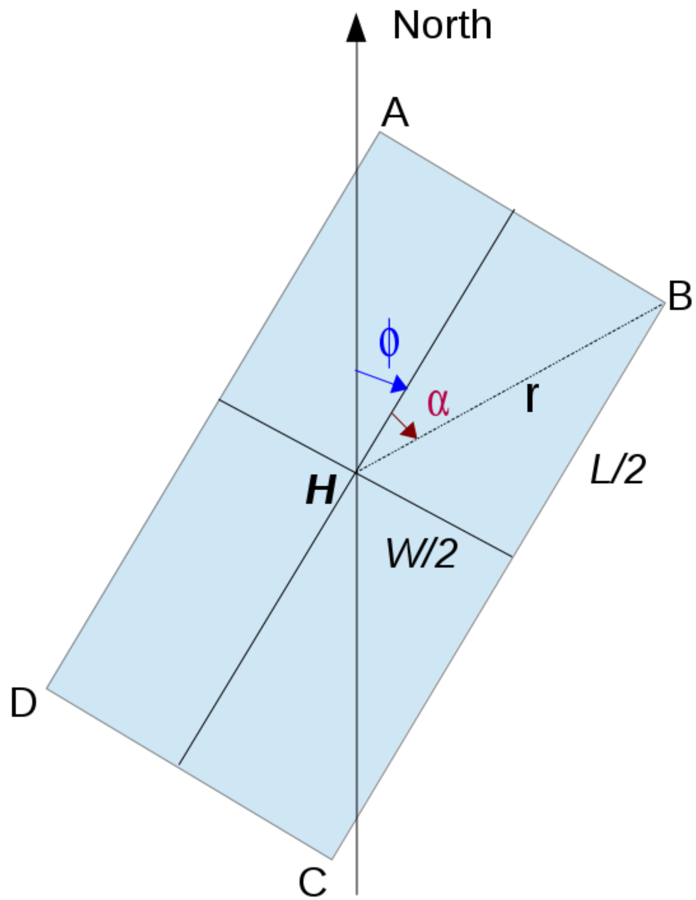


Results are deceiving : the source is not a point source !

Tobs	Tcal	DART
2010-02-27 09 :41 :00	2010-02-27 10 :13 :00	32412
2010-02-27 15 :19 :00	2010-02-27 15 :51 :30	51406
2010-02-27 18 :20 :00	2010-02-27 19 :05 :08	51426

Difference:
32 min
32 min
45 min

Taking into account the source dimensions



From **scaling laws**[(1)] :
Length $L = \beta M_0^{1/3}$, $\beta = 1.32E\text{-}2$
$W = L/2$, $W < 200$ km

Focal geometry: NP_1:{ϕ, δ, λ}

* **Try each points source** *(A,B,C,D,H)*

* Retain the **minimum** of propagation time

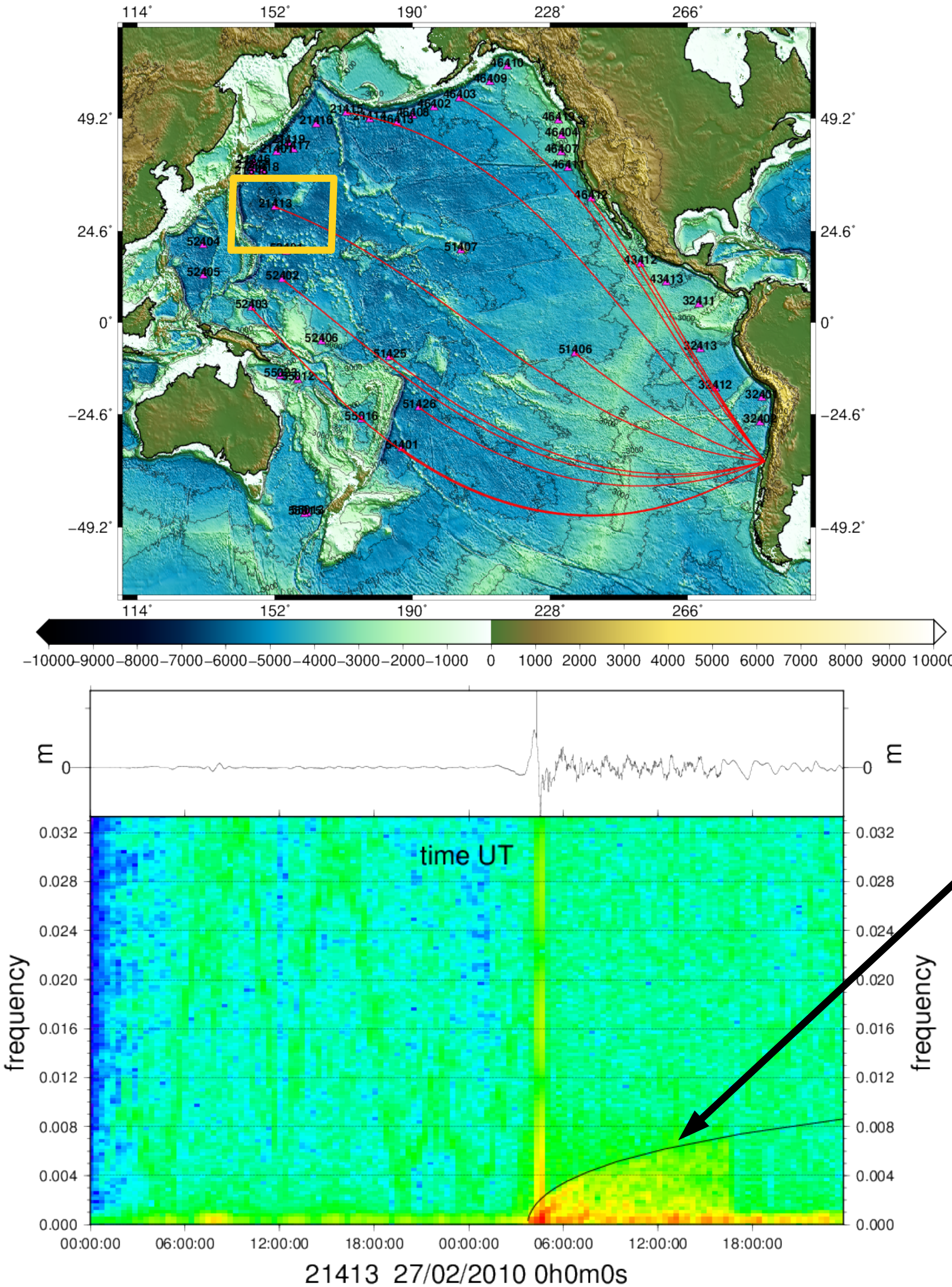
The **improvement** is spectacular

Tobs	Tcal	DART
2010-02-27 09 :41 :00	2010-02-27 09 :41 :23	32412
2010-02-27 15 :19 :00	2010-02-27 15 :24 :03	51406
2010-02-27 18 :20 :00	2010-02-27 18 :24 :08	51426

Difference:
0 min
4 min
4 min

[(1)] *refs: Kanamori & Anderson 75, Geller 76, Wells & Coppersmith, 94.*

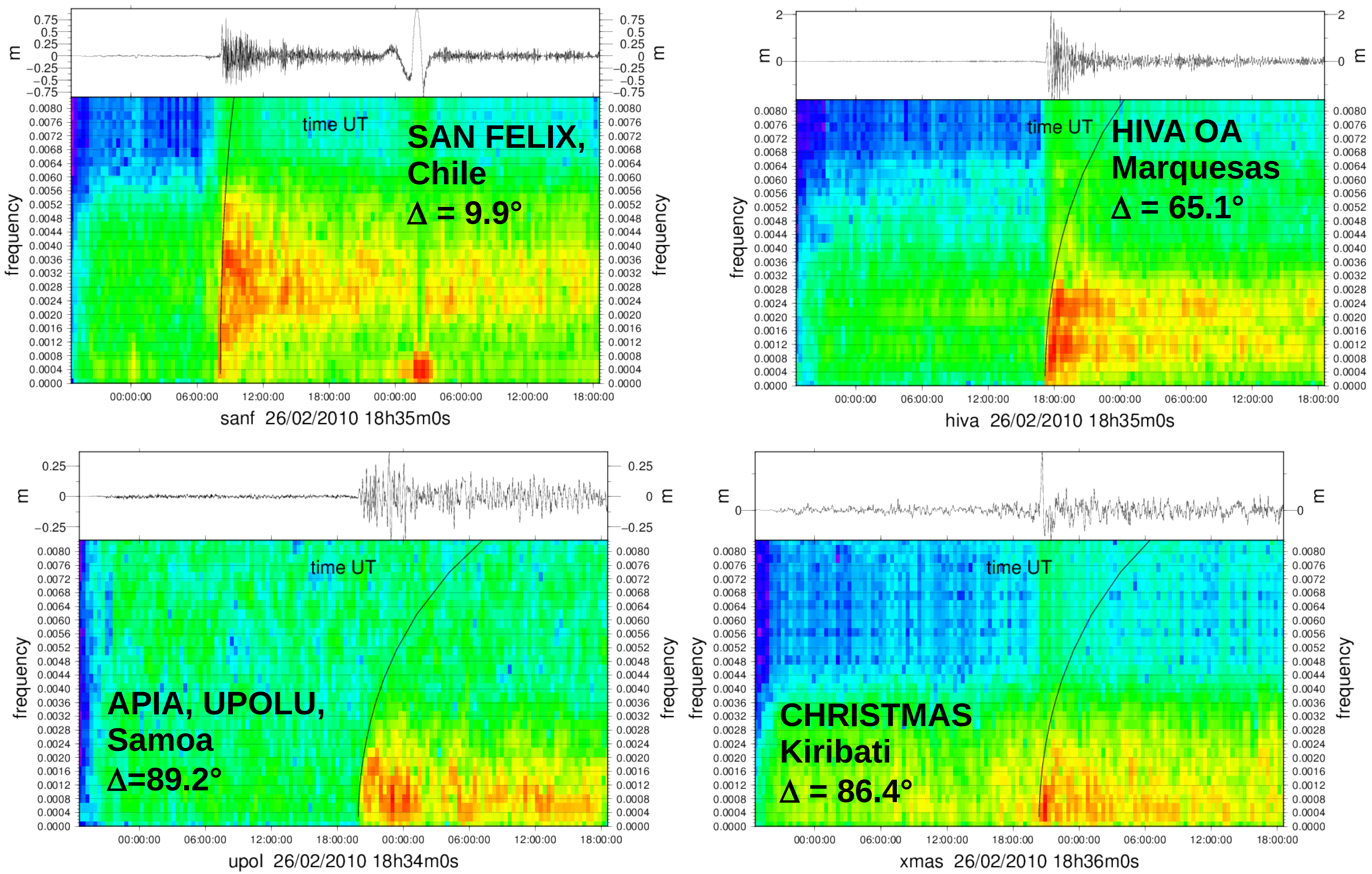
Example of results for Chile 2010: DART 21413

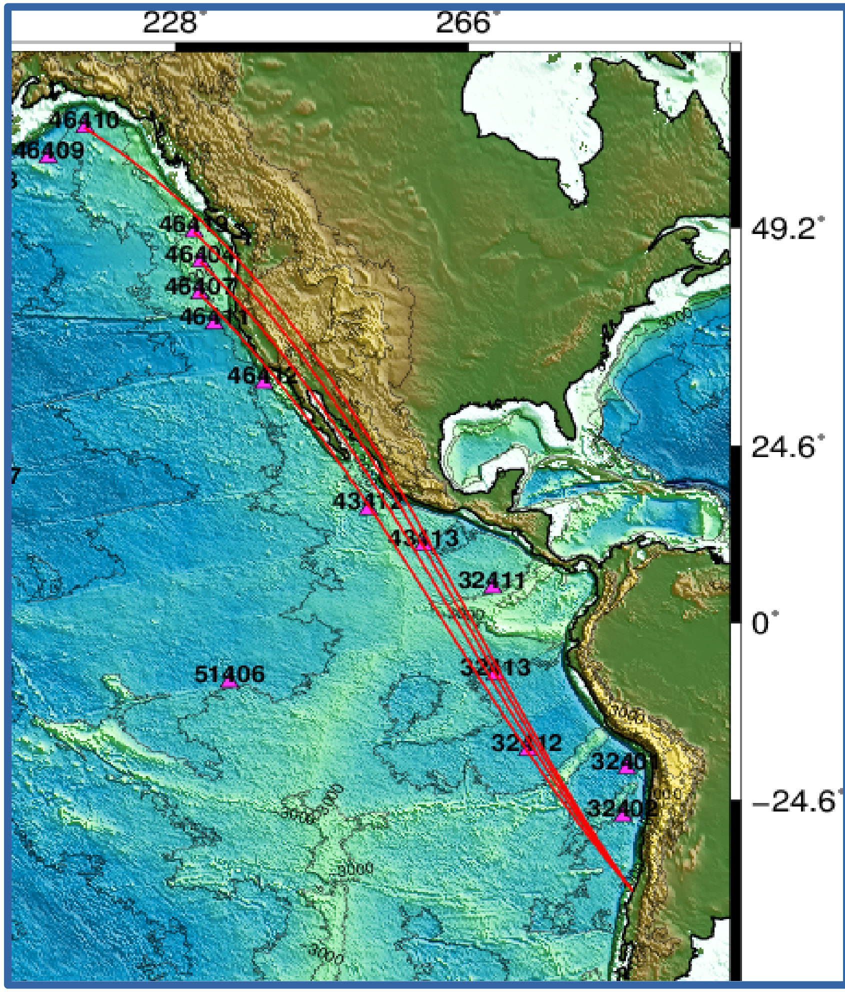


DART 21413, distance: 141°

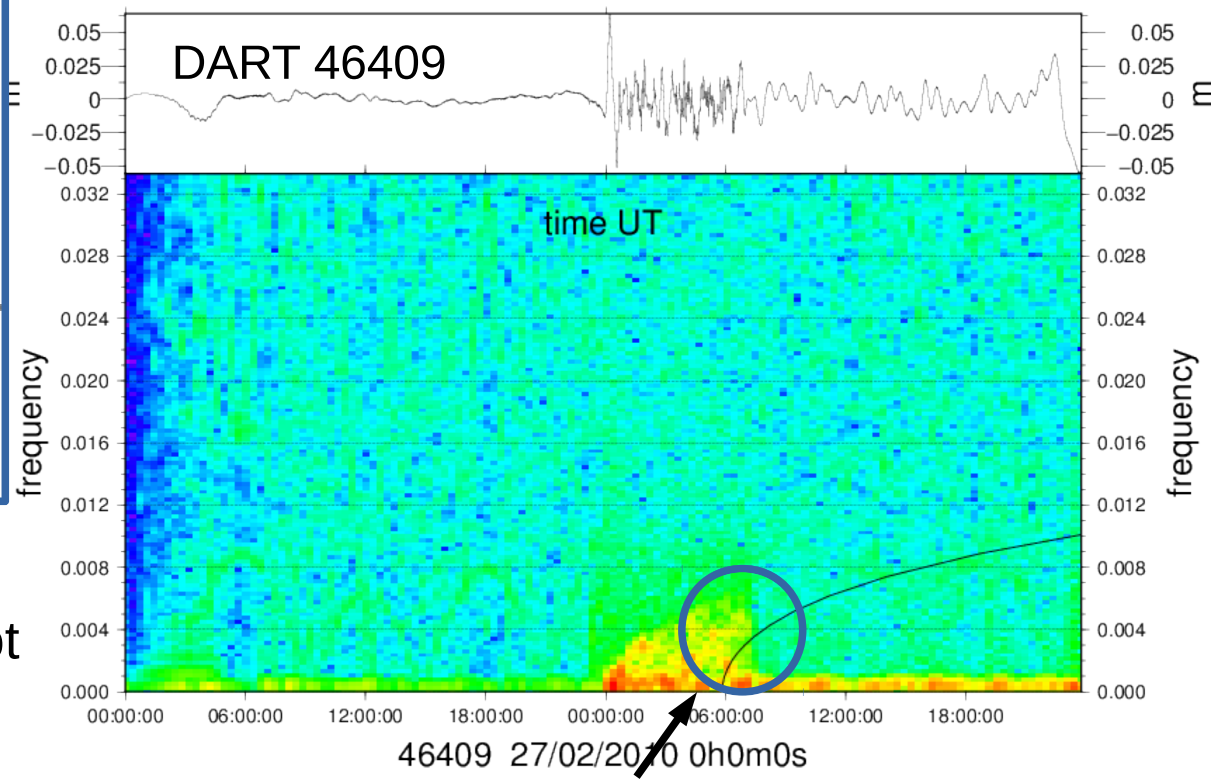
Arrival time	Freq hz	Per s
2010-02-28 03:45:17	2.778e-04	3600
2010-02-28 03:45:40	3.333e-04	3000
2010-02-28 03:46:12	4.000e-04	2500
2010-02-28 03:46:59	4.800e-04	2083
2010-02-28 03:48:07	5.760e-04	1736
2010-02-28 03:49:45	6.912e-04	1447
2010-02-28 03:52:07	8.294e-04	1206
2010-02-28 03:55:31	9.953e-04	1005
2010-02-28 04:00:27	1.194e-03	837
2010-02-28 04:07:35	1.433e-03	698
2010-02-28 04:17:57	1.720e-03	581
2010-02-28 04:33:03	2.064e-03	485
2010-02-28 04:55:11	2.477e-03	404
2010-02-28 05:27:52	2.972e-03	336
2010-02-28 06:16:40	3.566e-03	280
2010-02-28 07:30:33	4.280e-03	234
2010-02-28 09:24:36	5.136e-03	195
2010-02-28 12:25:01	6.163e-03	162
2010-02-28 17:16:15	7.395e-03	135
2010-03-01 01:02:58	8.874e-03	113
2010-03-01 12:33:19	1.065e-02	94
2010-03-02 03:00:40	1.278e-02	78
2010-03-02 18:54:03	1.534e-02	65

Examples of results for the tide-gauges





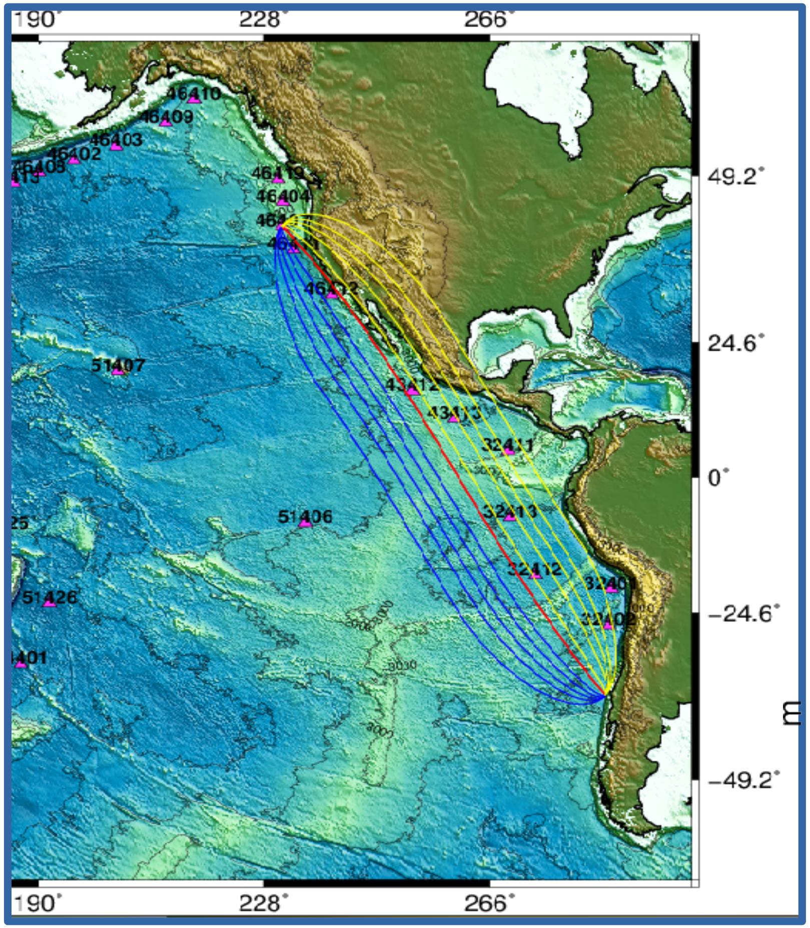
Case of **non-direct path:** **not** a **great-circle** path



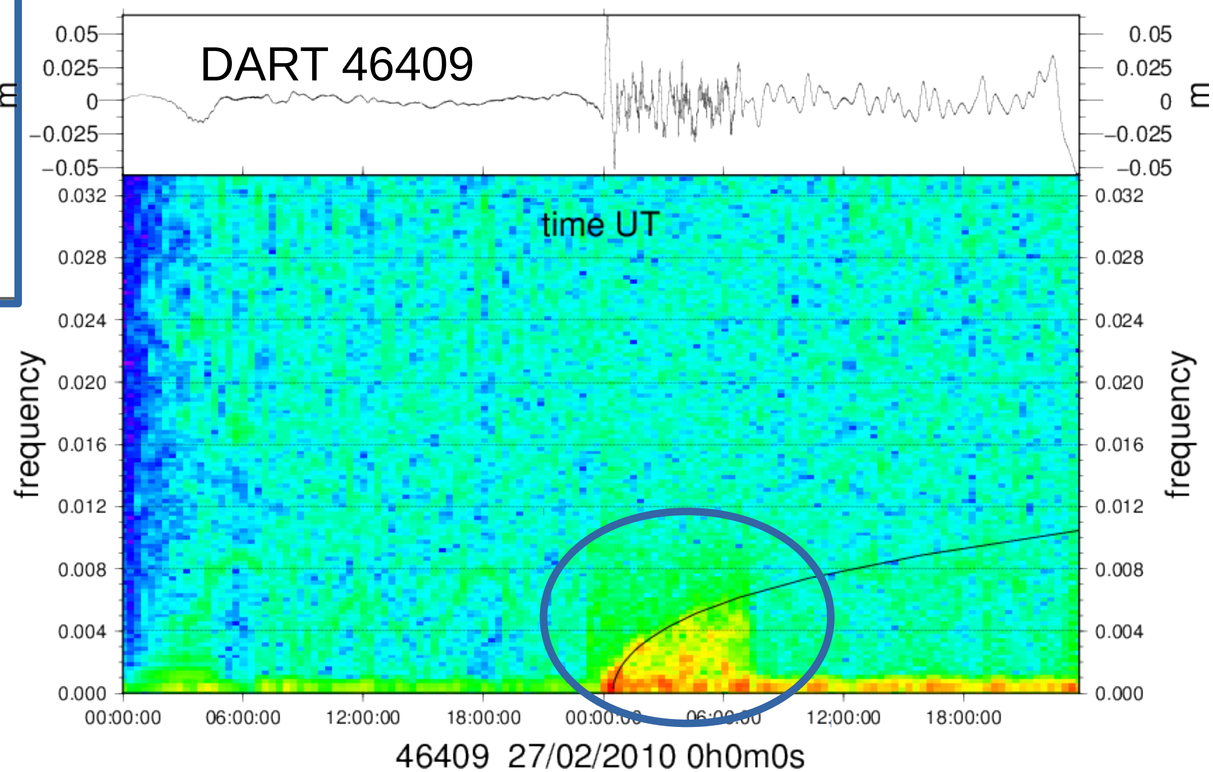
- The **algorithm** - too simple- is not adapted.
- The computed **propagation time** are dramatically **wrong**:

calculated **arrivals: # 6 hours late !**

Solution for non-direct path



- **Construction** of a **family** of **deviated rays** by **step of 5°** from the great circle.
- Retain **minimum propagation** time.

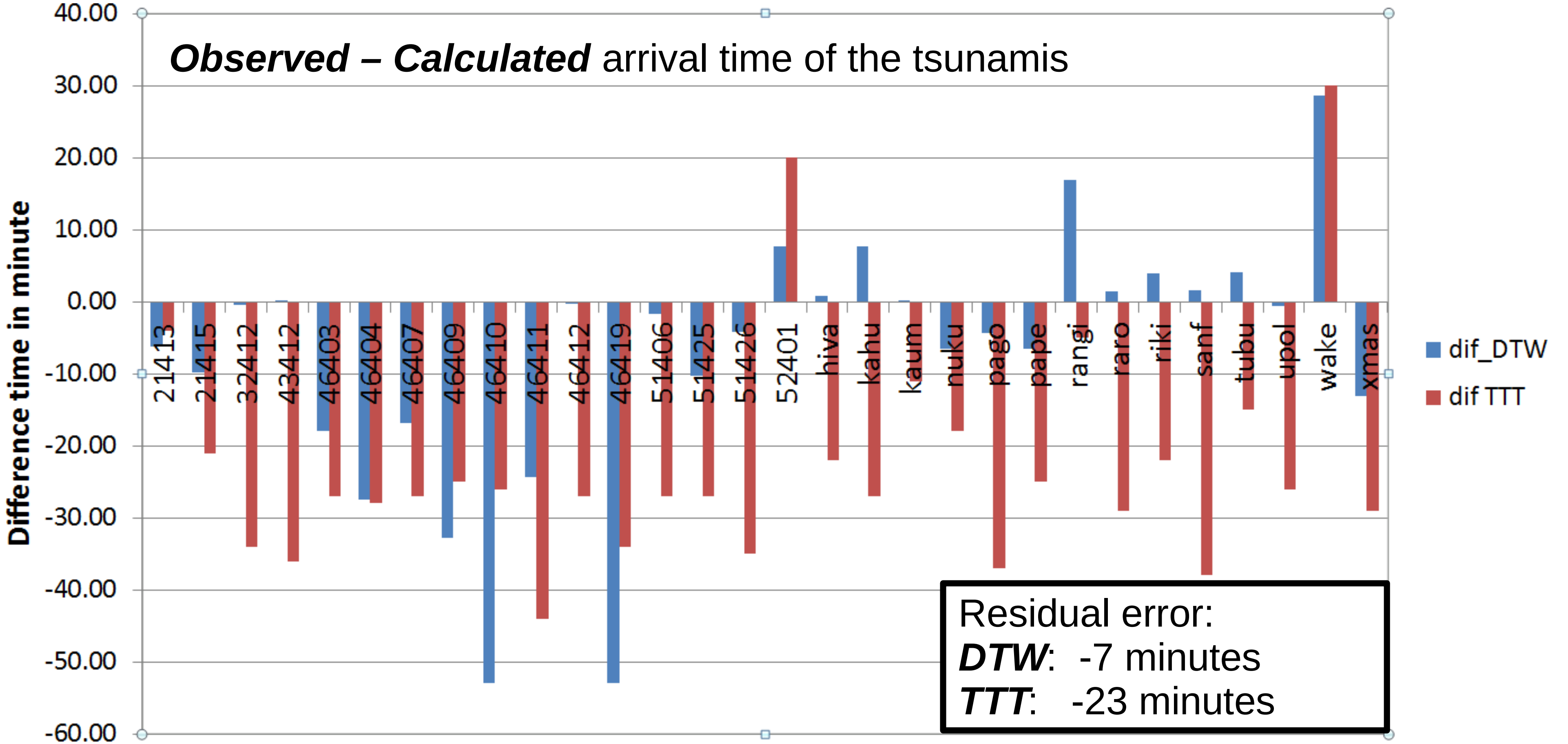


Better estimation of the **arrival time**

Final results and **comparison** with ***TTT***

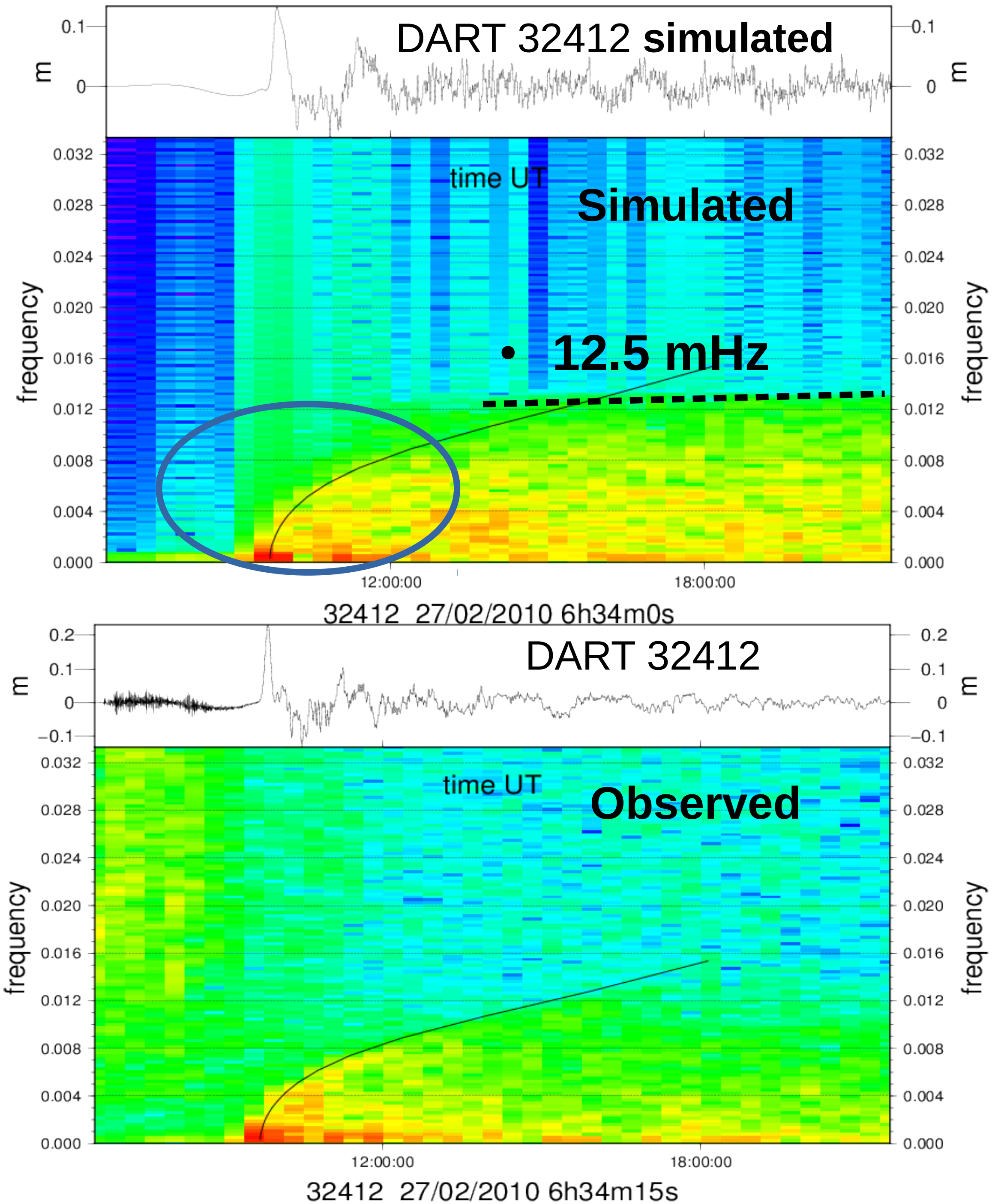
TTT: *Tsunami Travel Time (P. Wessel, 2009)*

DTW*: Dispersive Tsunami Wave (this study)*



- On the average: ***O- C*** are larger for ***TTT*** than for ***DTW***
- Only **2 values** > **20 minutes** (non direct rays)
- **Positive values** of ***O-C*** for stations in a **very shallow lagoon (WAKE, RANGIROA, RIKITEA, …)**
- Works well for **direct path**

Comparison with **numerical simulations** *(Saint-Venant code)*



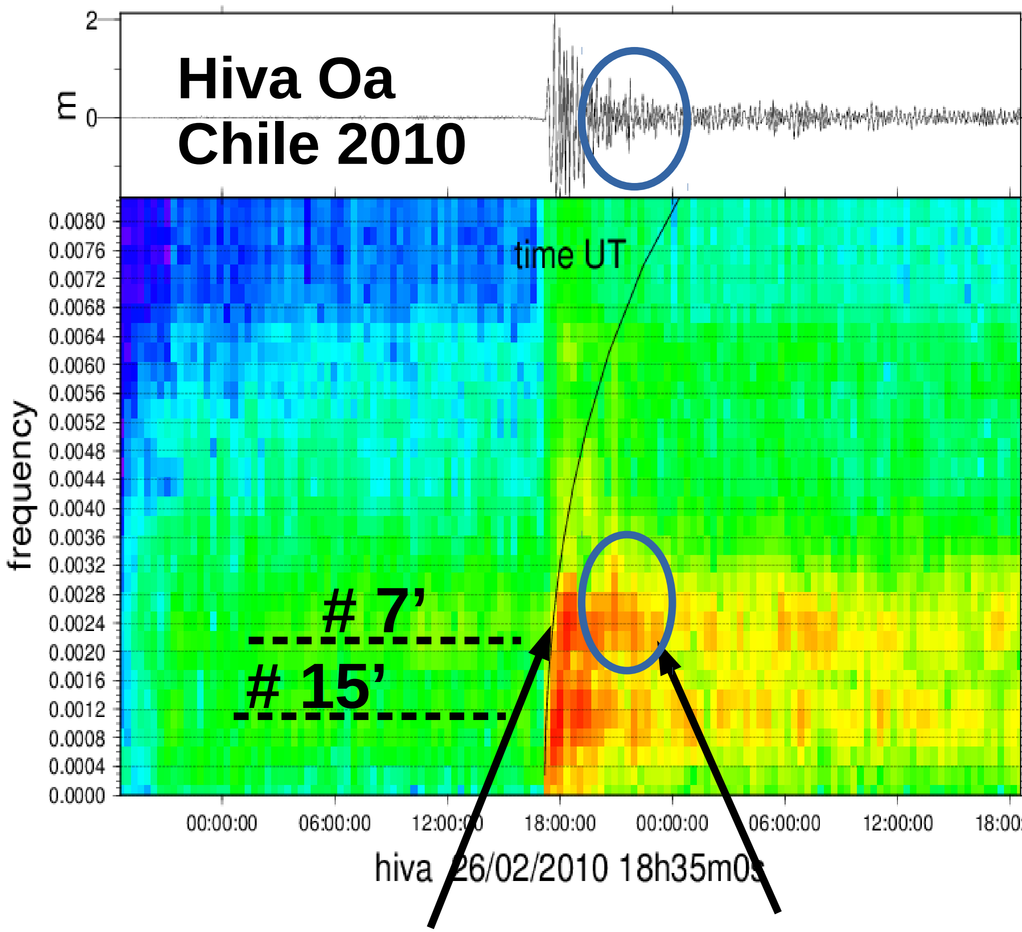
- **Artificial dispersion** well produced **until 8 mHz (125 s)** by *Saint-Venant code*
- **Limit** at **12,5 mHz** probably given by the spatial **step** imposed **by the grid (dx=4')** :
  2 x dx= 8' # 15 km

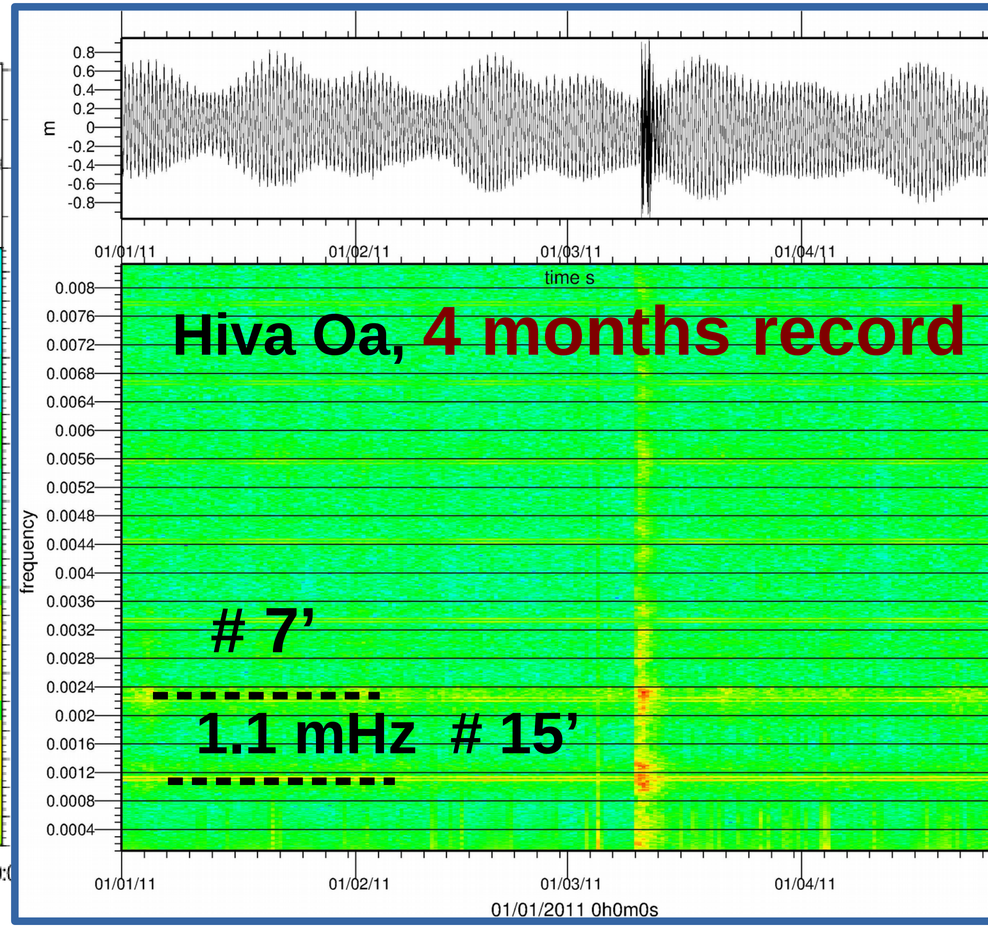
with H = 4000 m depth,

T = λ/c = 15 000/(gH)$^{1/2}$= 75 s

1/T = 13 mHz

Resonance, dispersion, coda and others





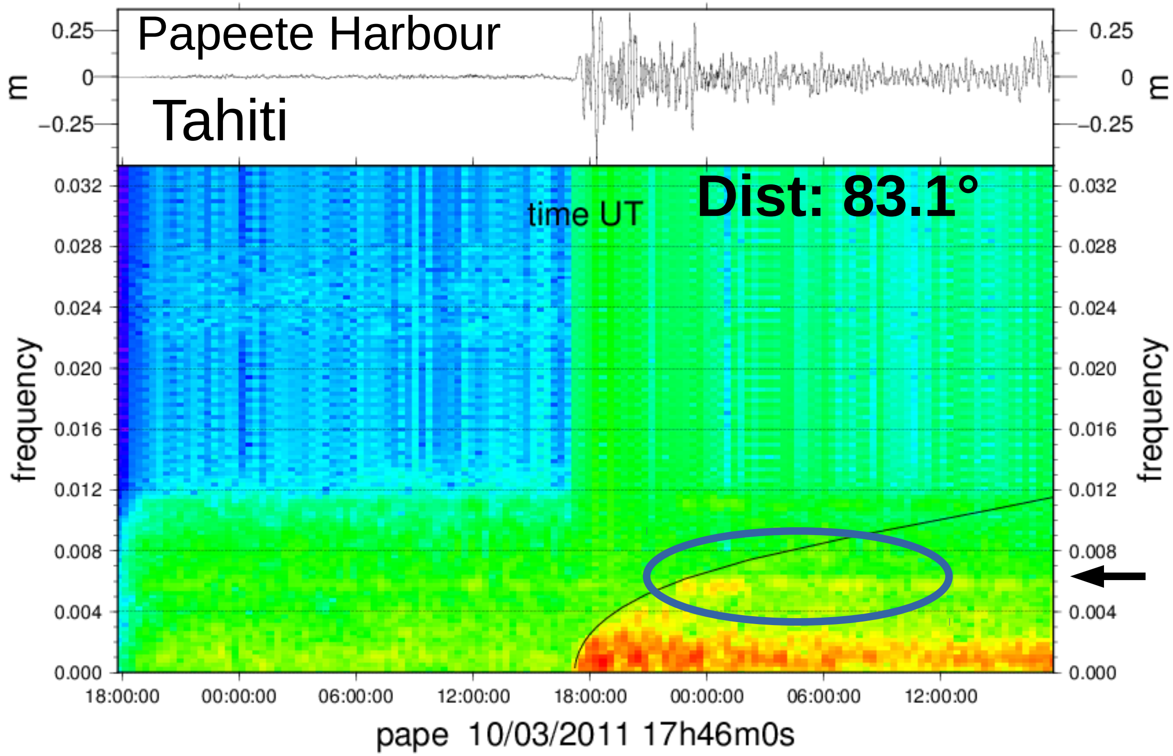
Excitation of the **resonance** by the **dispersive wave**

Other arrival: Not dispersion

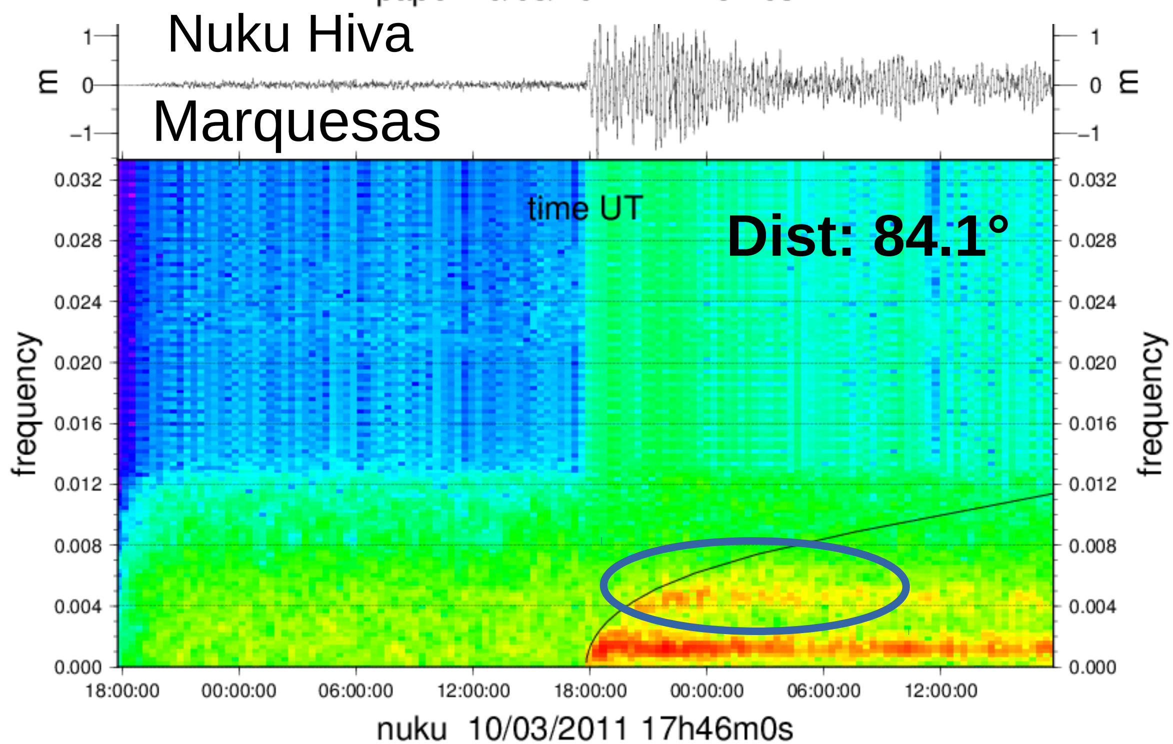
Hiva Oa, Marquesas

4 months record

Japan, Tohoku 2011



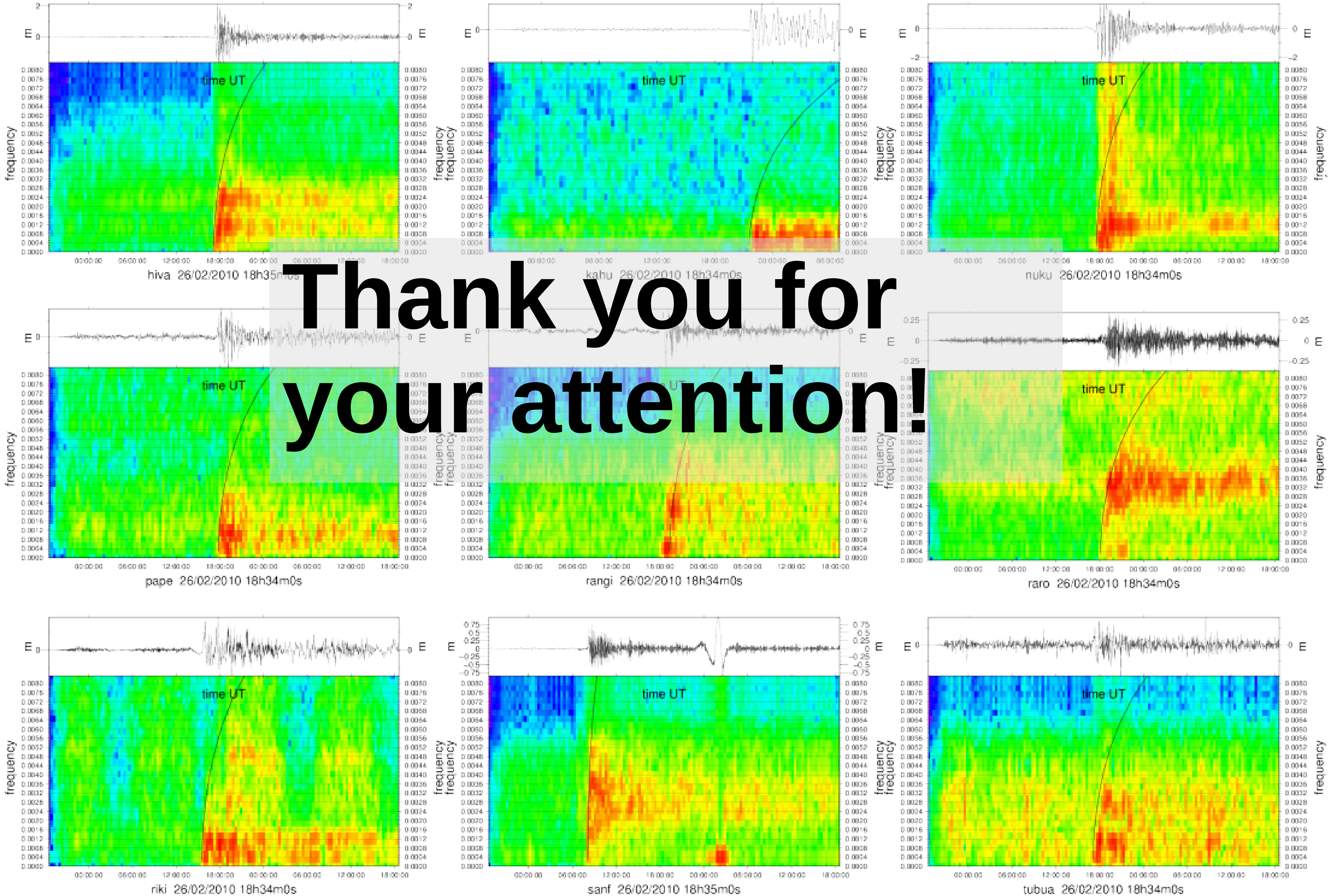
Resonance **0.005 Hz = 200s** excited by the **late arrival 3h40 after first arrival time**



 # 0.004 Hz = 250s
excitation by the late arrival
2h30 after first arrival time

Conclusions: *DTW (Dispersive Tsunami Wave)*

- An implemented **tool** for computing the **arrival times of tsunami**, including **continuous dispersion** from 3600 s to 65 s.
- **Method** uses **projection** of a **great-circle** on the **bathymetric profile**.
- **Results** for Chile 2010 show the **necessity** to take into account the **source dimensions** (#500x 200 km for Chile 2010).
- **Non direct path** partially resolved with construction of deviated rays from the great circle.
- **Resonances** and **dispersion effects** observed in **Tahiti** and **Marquesas** bays, 3 – 4 hours after first arrival.
- **To do**:
  - sensitivity to **bathymetric** resolution
  - Other tests with **other sources**
  - True ray path algorithm



Thank you for your attention!