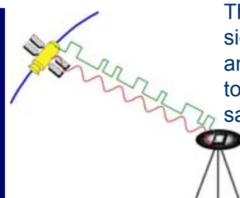
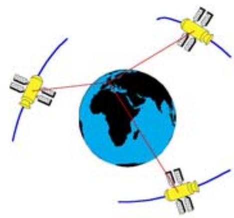
GPS (Global Positioning System)

GPS was created in the 80s' by the US Department of Defense for military purposes. The objective was to be able to get a precise position anywhere, anytime on Earth.

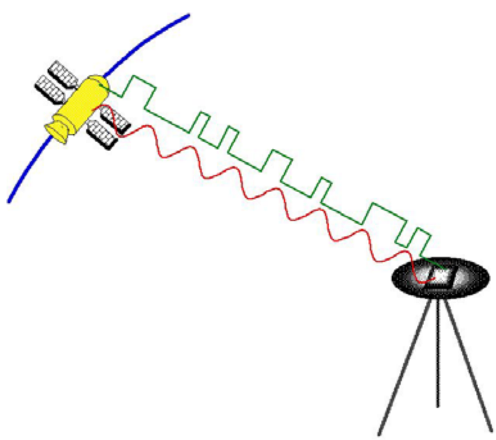


The satellites send a signal, received by a GPS antenna. Again, this allow to measure the distance satellite to antenna

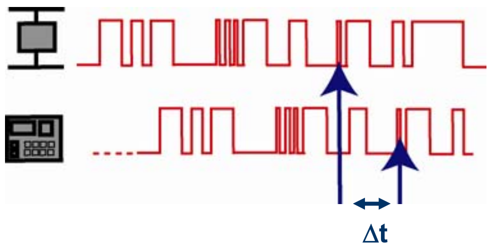


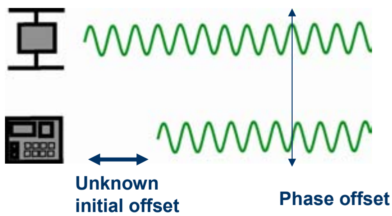
With at least 3 satellites visible at the same time, we can compute instantaneously the station position. The precision can be as good as 1 millimeter

Fundamentals of GPS



GPS (Global Positioning System)





pseudo-distance Measurement:

Accurate to 30 m if C/A code (pseudo frequency of 1 MHz)

Accurate to 10 m if P code (pseudo frequency of 10 MHz)

Easy because code never repeats itself over a long time, i.e. no ambiguity

Phase Measurement:

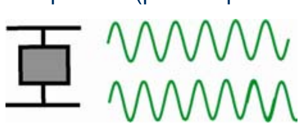
Accurate to 20 mm on L1 or L2 (1.5 GHz)

But difficult because the initial offset is unknown.

=> Post processing of a sequence of measurements on 1 satellite give final station position

GPS signals

•2 carrier phases (phases porteuses)



-L1 =1575.42MHz, λ=19 cm

-L2 =1227.60 MHz, λ=24 cm

•2 carried codes (codes portés)

-P1 (C/A) ~1.023 MHz, λ~293 m

-P2 (précis) ~10.23 MHz, λ~29.3 m

C/A : Coarse acquisition = code “grossier” carried on L1

P : Precise = code “précis” carried on L2

P code is encrypted (by US army). This is known as “AS: Anti spoofing”. the encrypted P-code is usually called the Y-code. Deciphering the Y-code is done through Z tehcnology (squaring of Y-code).

US army - limiting access to civilians: SA & AS

SA: Selective availability

- Until May 2000, US DoD artificially degraded stability of satellite clocks
- No solution for absolute and/or real time positionning. Solved by double differences (provided that GPS receivers sample the GPS signal at the same time).
- Stopped after 2000 (by Al. Gore)

AS: Anti Spoofing

- P-Code encrypted into Y-code
- done by multiplying P by an unknown code at 20KHz
- deciphered by "Z-tracking" (squaring of Y-code) receivers
- Still active today

Offsets measurements are biased by Clocks

Satellites

- "Stable" atomic clocks (unless SA is active).
  Instability= $\sim 10^{-14}$ (=> $\sim 10^{-9}$sec./day)
- Synchronized between all satellites
- Navigation message contains clocks corrections ==> can be modeled

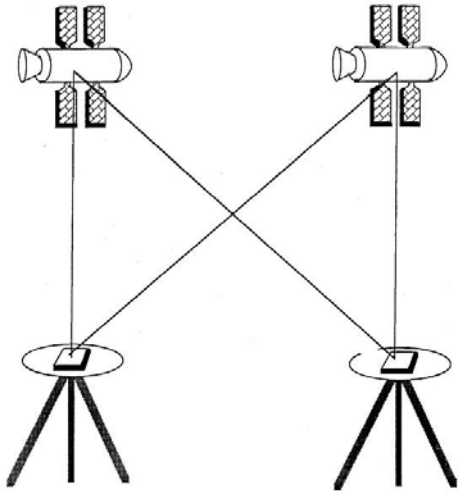
Receivers

- Unstable cheap clocks: (10^{-5} - 10^{-6}) (=> ~1 sec./day)

Problem : at 300 000 km/s, satellite-station distance is covered in 70 ms, and a 1m difference in position corresponds to 10^{-9} seconds…

Solution: Double difference

Double differences



One way phases are affected by **stations and satellites** clock uncertainties

Single differences are affected by

stations clock uncertainties

Or

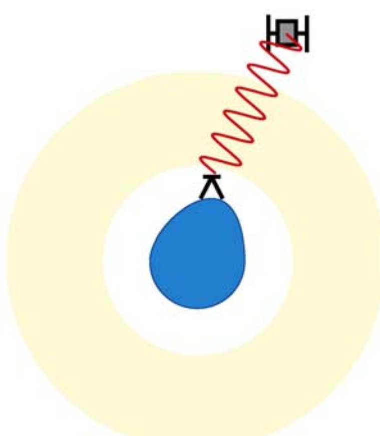
satellites clock uncertainties

Double differences Are free from all clock uncertainties **but**

=> Measurement of distances between points (**= baselines**)

=> **Relative positioning**

Other perturbation : The Ionosphere



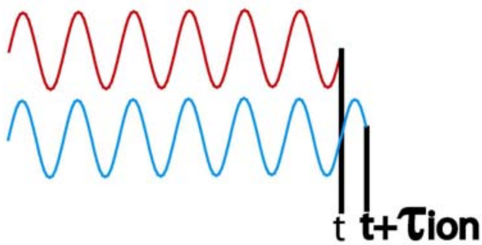
Correct measurement in an empty space

But the ionosphere perturbates propagation of electric wavelength …..

… and corrupts the measured distance

… and the inferred station position

Ionosphere theory



Ionospheric delay τion depends on :

• ionosphere contains in charged particules (ions and electrons) : **Ne**

• Frequency of the wave going through the ionosphere : f

$$\tau ion = 1.35\ 10^{-7}\ Ne / f^2$$

Ionosphere : solution = dual frequency

Problem : **Ne** changes with time and is never known

solution : sample the ionosphere with 2 frequencies

$\tau ion_1 = 1.35\ 10^{-7}\ Ne / f_1^2$ $\tau ion_2 = 1.35\ 10^{-7}\ Ne / f_2^2$

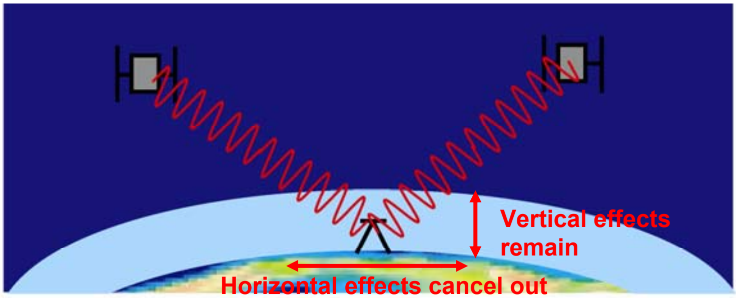
$$\Rightarrow \tau ion_2 - \tau ion_1 = 1.35\ 10^{-7}\ Ne\ (1/ f_2^2 - 1/ f_1^2)$$

$$\Rightarrow Ne = \left[\tau ion_2 - \tau ion_1\right] / 1.35\ 10^{-7}\ (1/ f_2^2 - 1/ f_1^2)$$

Using dual frequency GPS, allow to determine the number Ne and then to quantify the ionospheric delay on either L1 or L2.

(*in fact, GPS can and is used to make ionosphere Total Electron Containt (TEC) maps of the ionosphere*)

Second perturbation : The Troposphere

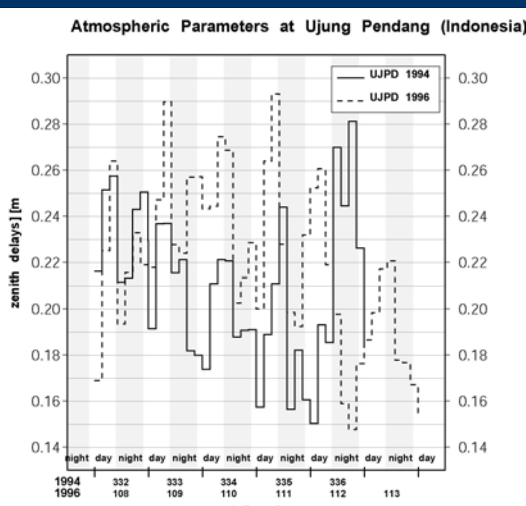


The troposphere (lower layer of the atmosphere) contains water. This also affects the travel time of radio waves.

But the troposphere is not dispersive (effect not inversely proportional to frequency), so the effect cannot be quantified by dual frequency system. Therefore there a position error of 1-50 cm.

Thanks to the presence of many satellites, the effect cancel out (more or less) in average, on the horizontal position. Only remains a vertical error called **Zenith tropospheric delay**

Troposphere zenith delay



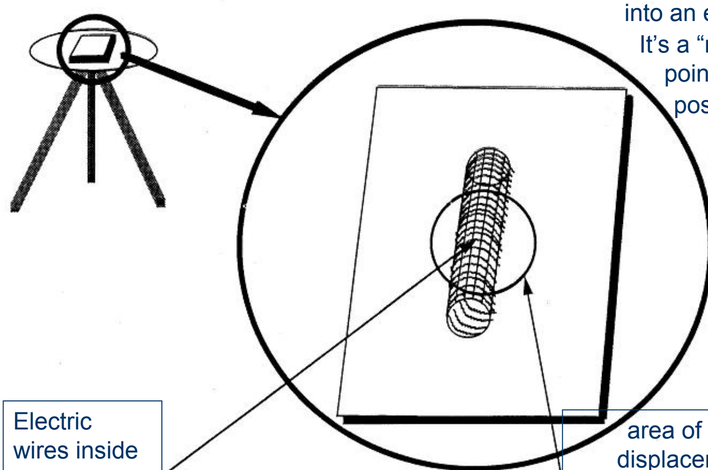
The tropospheric zenith delay can be estimated from the data themselves…
if we measure every **30s** on **5** satellites, we have **1800** measurements in **3 hours.**
We only have **3** unknowns : station **lat**, **lon**, and **altitude** !

So we can add a new one :
1 Zenith delay every 3 hours

The curves show that the estimated Zenith delay vary from 15 cm to 30 cm with a very clear day/night cycle

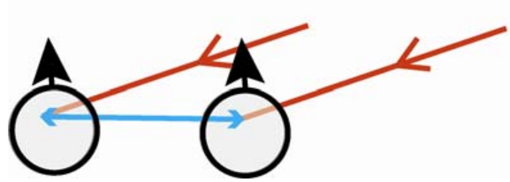
Antenna phase center offset and variations

The Antenna phase center is the wire in which the radio wave converts into an electric signal.
It's a "mathematical" point, which exact position depends on the signal alignment with the wire (azimuth and elevation)



Antenna phase center offset and variations

Solution : use **identical** antennas, oriented in the **same direction**



As the signal rotates, the antenna phase centers move

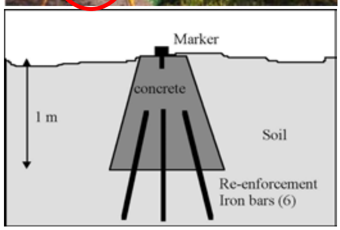
But they move the same quantity in the same direction if antennas are strictly identical because the incoming signal are the same (satellite is very far away)

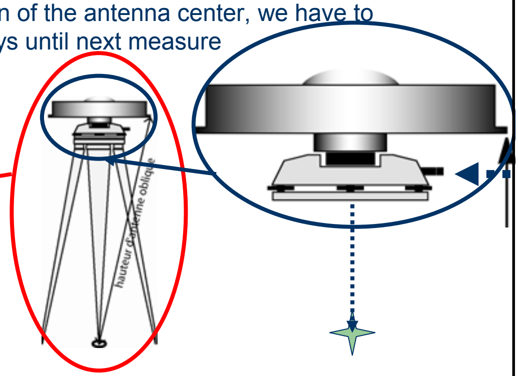
Therefore, the **baseline** between stations remains unchanged

But this works for small baselines only (less than a few 100 km)

Tripod and tribrachs source of errors

The measurement give the position of the antenna center, we have to **tie** it to the GPS marker which stays until next measure





The antenna has to be leveled horizontally and centered perfectly on the mark. Then :

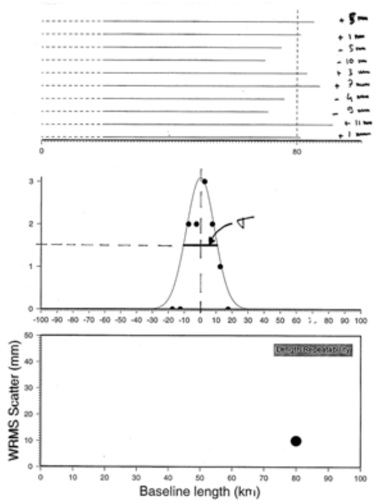
Horiz. position of marker = horiz. position of antenna

Altitude of marker = altitude of antenna – antenna height

GPS est précis, à condition de :

1. GPS **bi-fréquence** pour éliminer l'ionosphere
2. **Mesures longues** pour « moyenner » la troposphère
3. Mesures **relatives** de distances entre stations
4. Utilisation d'antennes **identiques**, orientées **parallèlement**, et du **centrage forcé** sur les repères pour éviter les biais instrumentaux

Precision and repeatability



10 measurements of the same baseline give slightly different values :

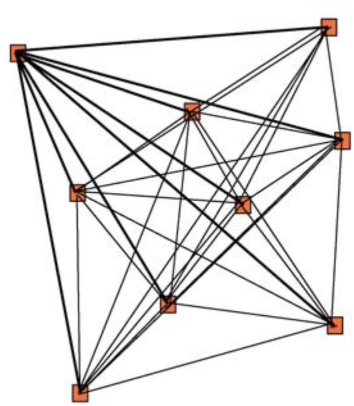
80 km +/- 10 mm

How many measurements are between 80 and 80+δ

The histogram curve is a Gaussian statistic

The baseline **repeatability** is the **sigma** of its Gaussian scatter

Network repeatabilities



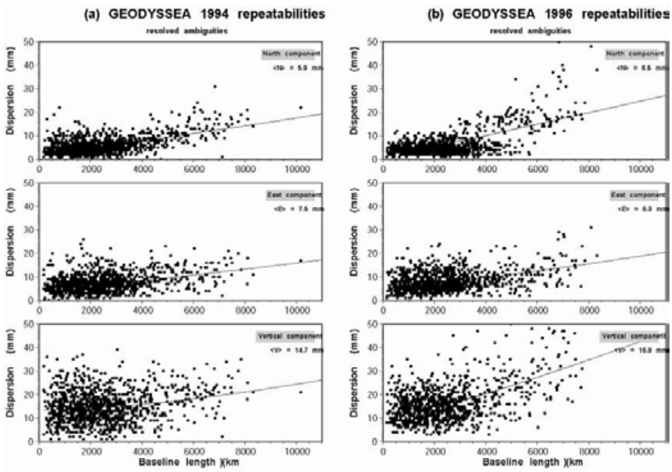
Network of N points (N=9)

(N-1) (=8) baselines from 1st station to all others

(N-2) (=7) baselines from 2nd station to all others
=> subtotal = (N-1)+(N-2)

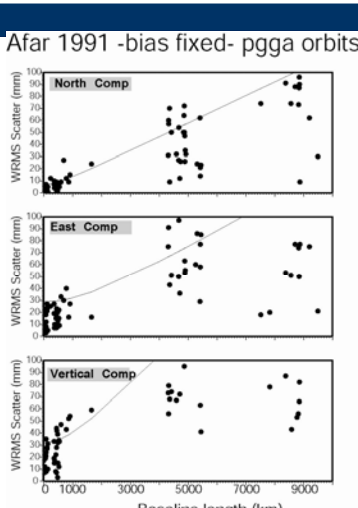
total number of baselines
= (N-1)+(N-2)+…+1
= N(N-1)/2 (*36 in that case*)

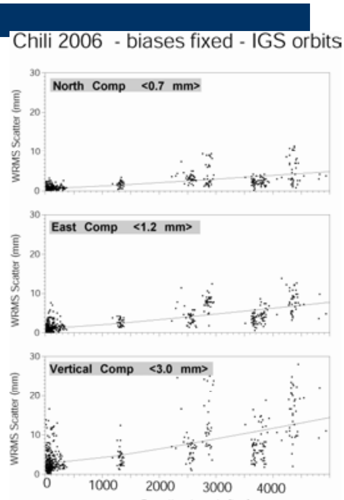
Typical repeatabilities (60 points => ~1800 bsl)



Repeatabilities are much larger than formal uncertainties !

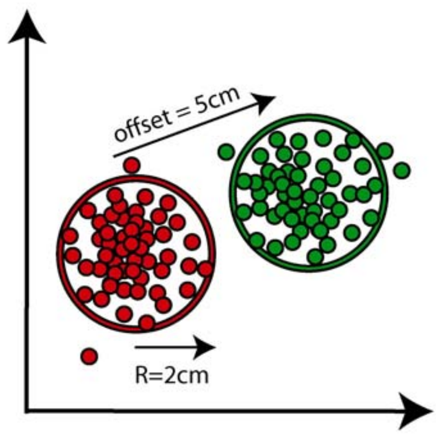
1 order of magnitude Improvment over a decade





1-2 cm 1-10 cm 1-2 mm 1-10 mm

Accuracy vs. precision (1)



Fix point :
measure 1 hour every 30 s

=> 120 positions

with dispersion ~+/- 2 cm

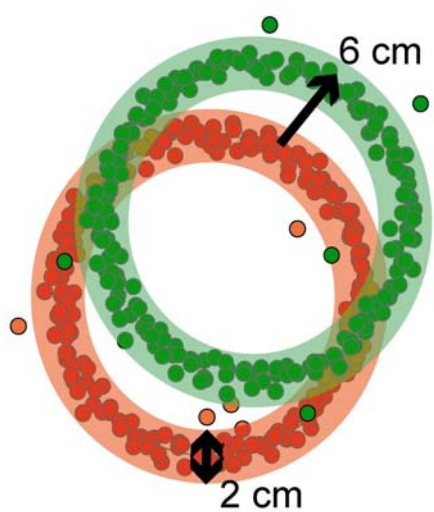
5 hours later, measure again
1 hour at the same location

=> Same dispersion but
constant offset of 5 cm

Precision = 2 cm

Accuracy = 5 cm

Accuracy vs. precision (2)



Measure path, 1 point every
10s

=> 1 circle with 50 points

10 circles describe runabout
with dispersion ~ 2 cm

Next day, measure again

=> Same figure but constant
offset of 6 cm

Precision = 2 cm

Accuracy = 6 cm

Mapping in a reference frame (sketch)

Measure short lines with a good precision is easy.

⇒

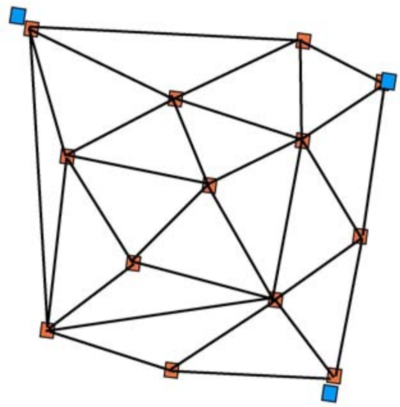
Quantify deformation within a small network is easy

BUT

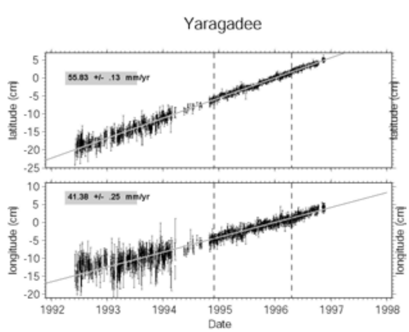
Determine the motion of the whole network with respect to the rest of the world is more difficult

In order do do this…

We need to know how to map into a **reference frame** ⇒ **compute Helmert transformations**



Mapping in a reference frame (1)

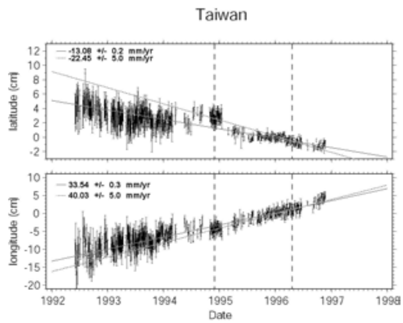


Constraining campaign positions (and or velocities) to long term positions (and or velocities) works fine …

… when station displacement is constant with time

if the station motion is **linear** with time, then estimating the velocity on any time span will give the same value

Mapping in a reference frame (2)

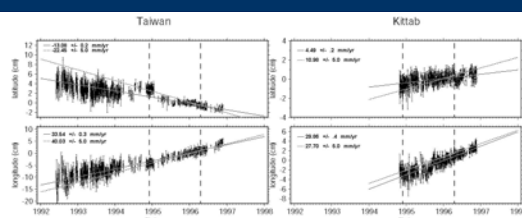


Constraining campaign positions (and or velocities) to long term positions (and or velocities) **does not work** …

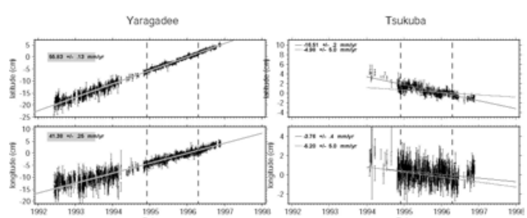
… when station displacement is **not** constant with time

if the station motion is **not linear** with time, then estimating the velocity on **different** time span will give **different** values

Mapping in a reference frame (3)



some stations are better than others …



From position to velocity uncertainty

If one measures position P_1 at time t_1 and P_2 at time t_2 with precision ΔP_1 and ΔP_2, what is the velocity V and its precision ΔV ?

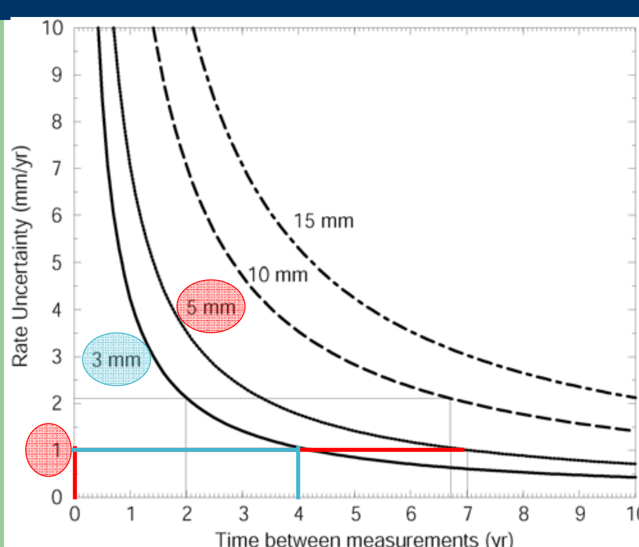
$$V = (P_2 - P_1) / (t_2 - t_1)$$

$$\Delta V = (\Delta P_2 + \Delta P_1) / (t_2 - t_1)$$ ✗

Uncertainties don't add up simply, because sigmas involve probability.

$$\Delta V = \left[(\Delta P_2)^2 + (\Delta P_1)^2 \right]^{1/2} / (t_2 - t_1)$$

Velocity uncertainties



It is only needed that we wait a given time between position measurements to detect deformation velocities

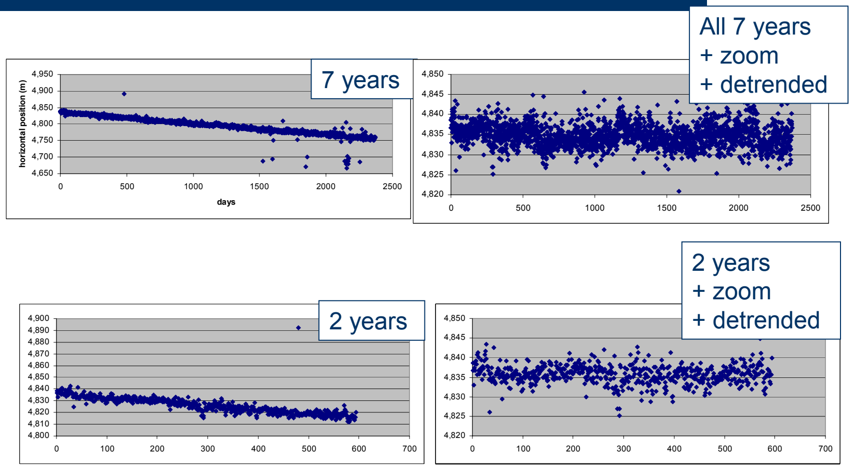
The more we wait, the more precise the velocity is

⇩

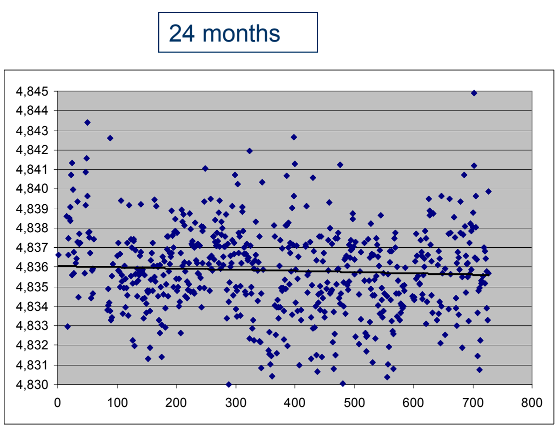
Reasonnable (but wrong) idea:

Geodesy is like good wine: measurements, even (and mostly) bad ones, gain value by aging

In practice…: BRAZ : 2000->2007

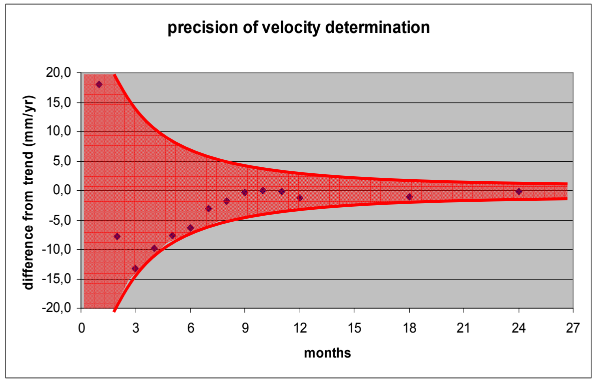


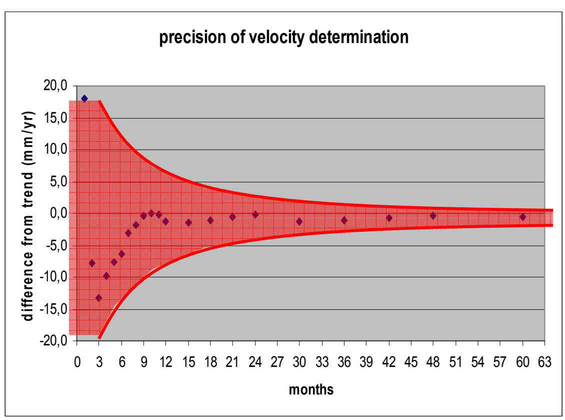
In practice…: BRAZ : 2000->2007



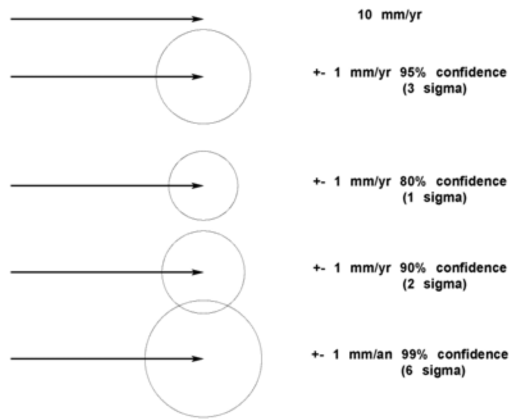
month	deviation
1	18,0
2	-7,8
3	-13,2
6	-6,4
12	-1,3
18	-1,0
24	-0,2

month	deviation
1	18,0
2	-7,8
3	-13,2
4	-9,9
5	-7,7
6	-6,4
7	-3,1
8	-1,8
9	-0,3
10	0,0
11	-0,1
12	-1,3
18	-1,0
24	-0,2



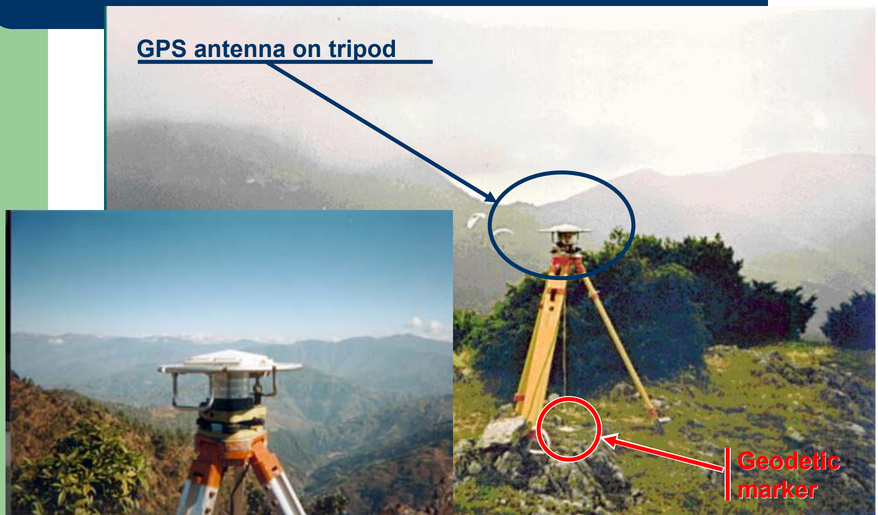


Velocity ellipses

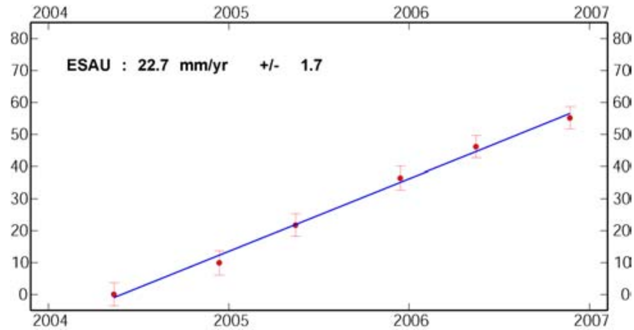


Maintenant, que mesure-t-on exactement avec GPS ?

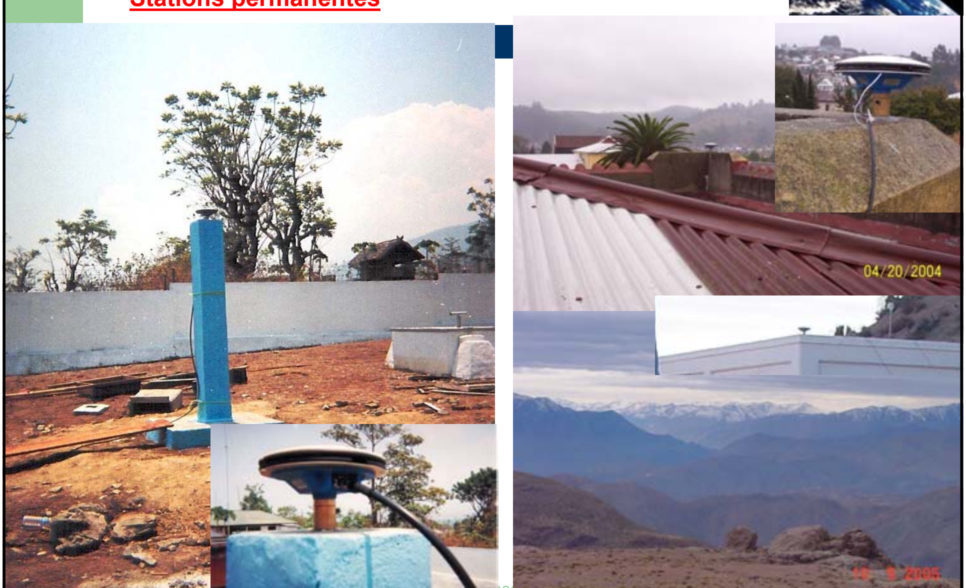
Campagnes de répétition



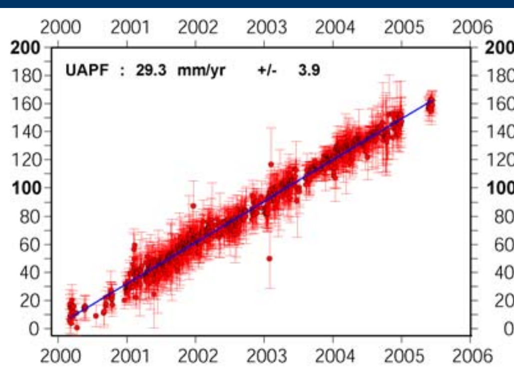
Repeated Campaigns



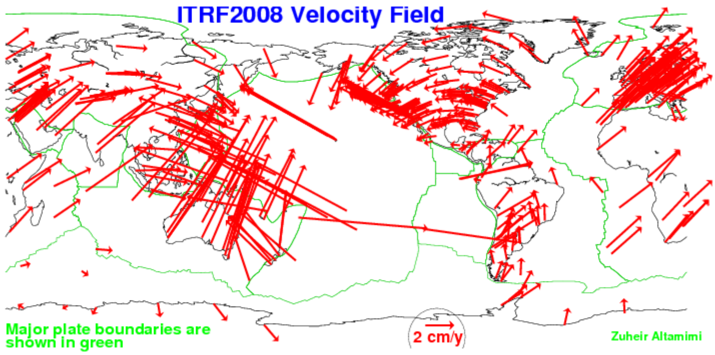
Stations permanentes



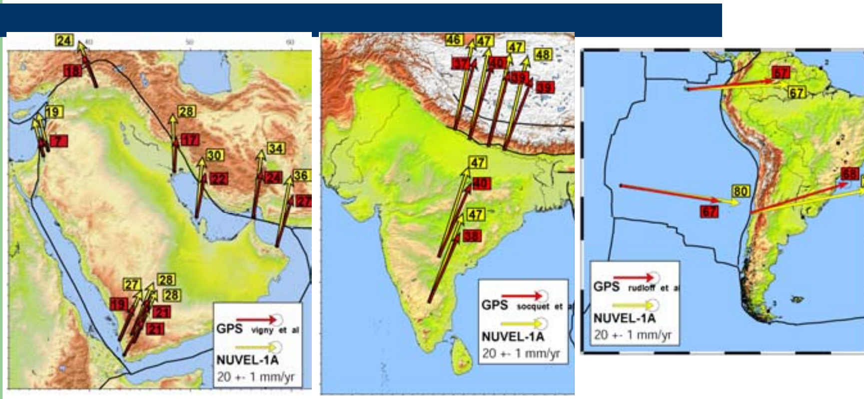
Permanent station



Champ de vitesse global => ITRF

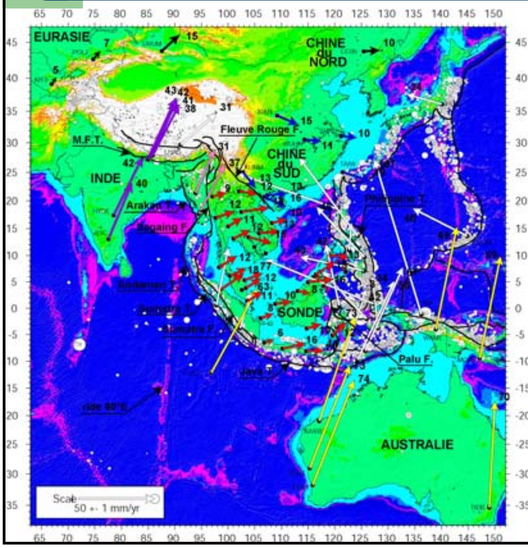


À grande échelle: les plaques



Au premier ordre, la géodésie sur une décennie « colle » bien avec la géologie sur 3 Ma!
=>Les plaques ont donc des déplacements stables sur ce type de durée mais…. GPS trouve Arabie, Inde et Nazca plus lentes actuellement
Arabie et Inde => ralentissement
Nazca => incertitude ?

l'Asie du Sud-Est, une zone compliquée



SUNDA plate:
60 GPS sites
12 years of measurements

independent from Eurasia and moves 1 cm/yr Eastward

INDIA plate:
6 GPS sites
10 years of measurements

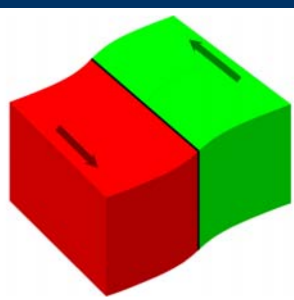
only <u>4 cm/yr</u> wrt GPS Eurasia even less (3.5 cm/yr) wrt Sunda

BURMA platelet (or sliver):
22 GPS sites
2 years of measurements

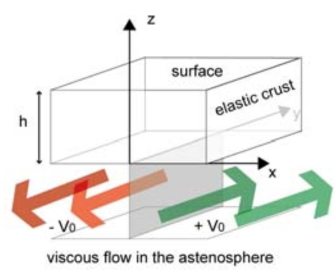
Nor India, nor Eurasia, not even Sunda

South China ????

La déformation autour des frontières de plaques



Le concept: déformation élastique à cause du frottement



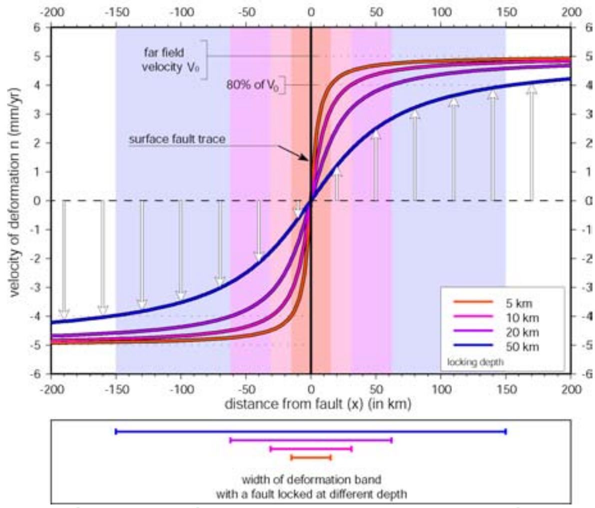
Le modèle: le flux mantellique localise la déformation sous une plaque élastique

⇒ La solution analytique: une courbe en arctangente

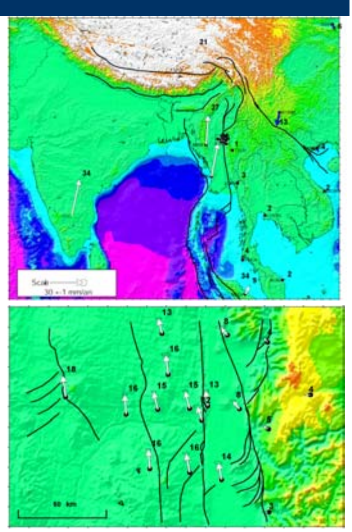
$$U_y = 2 \cdot {}^{V_0}/_{\Pi} \text{ arctang } ({}^{x}/_{h})$$

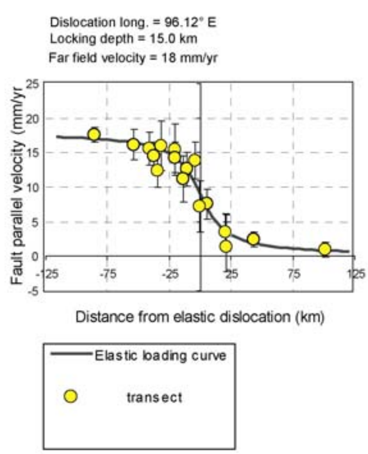
Arctang profiles

$U_y = 2 . {}^{V_0}/_{\Pi}$ arctang $({}^{x}/_{h})$



La faille de Sagaing en Birmanie





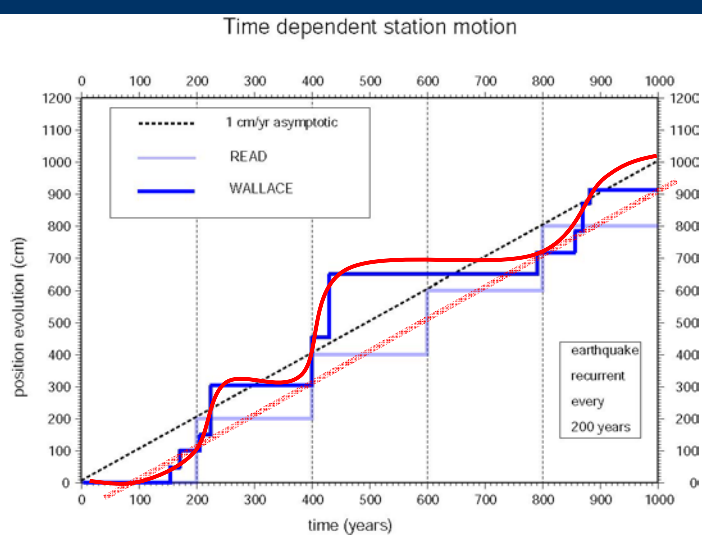
Remarques importantes (1):

- Quand les stations sont bien à l'intérieur des plaques (loins des marges qui se déforment) GPS mesure la **tectonique des plaques**
- Quand les stations sont dans les marges qui se déforment, **GPS ne mesure pas la vitesse des failles** (qui est en général zéro si la faille est bloquée), mais **la déformation élastique qui s'accumule** en réponse au blocage. C'est au travers d'un modèle (Okada par exemple) que l'on retrouve …. La vitesse limite (càd la tectonique) et l'épaisseur élastique, mais toujours pas la vitesse de la faille, concept qui ne veut pas dire grand-chose.

Le cycle sismique:

Shimazaki et Nakata, 1980

Wallace, 1987



Vitesse court terme de la faille:

~variable

~constante

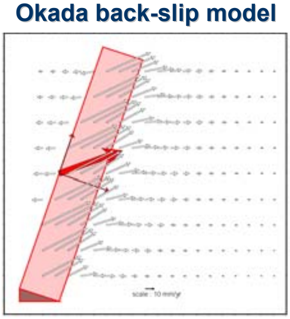
Remarques importantes (2):

- **La tectonique active basée sur le décalage de marqueurs de part et d'autre d'une faille ne mesure donc pas forcément non plus la « vitesse de la faille » (et donc la tectonique des plaques).**

  Cela dépend du nombre de cycles sismiques moyennés dans la mesure

Déformation intersismique aux frontières de plaques

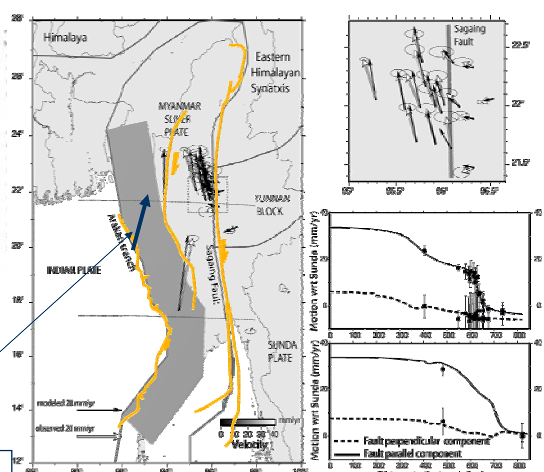
Okada back-slip model



Best fit dislocation:

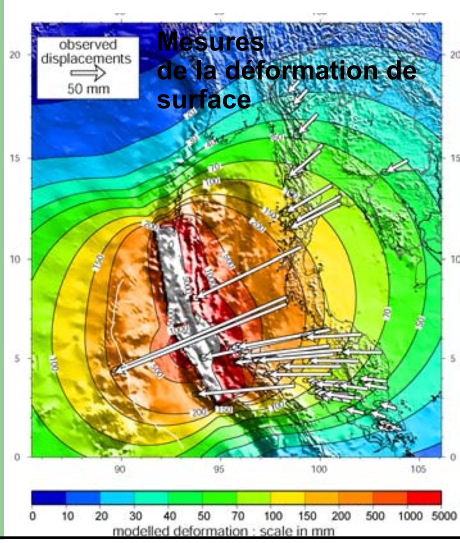
2 – 2.5 cm/yr

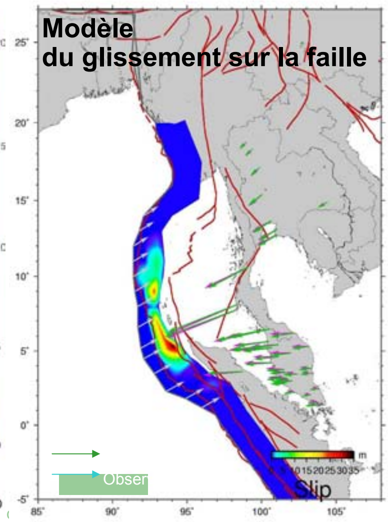
N 30°-35°



⇒ Potentiel pour un séisme Mw ~8.5 tous les siècles

Mesure d’un séisme: Sumatra 2004 – Mw 9.2





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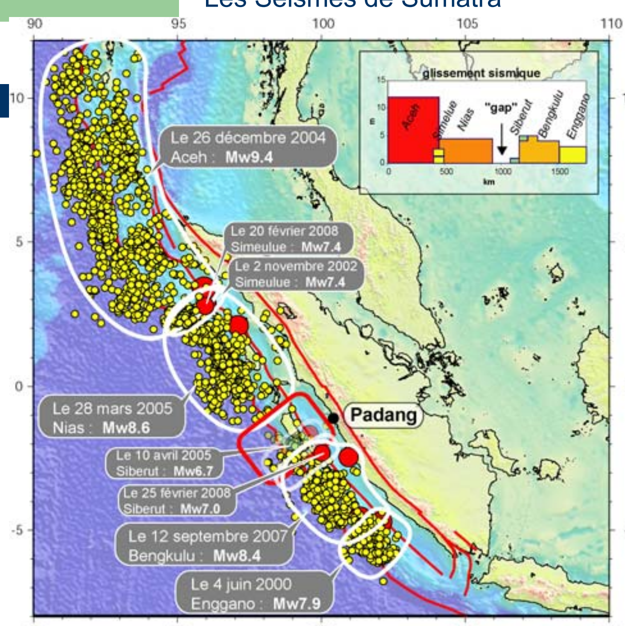
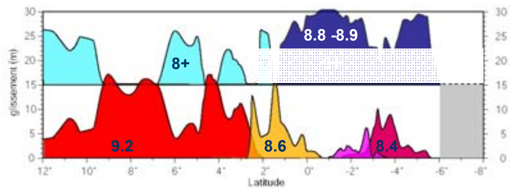
Les Séismes de Sumatra

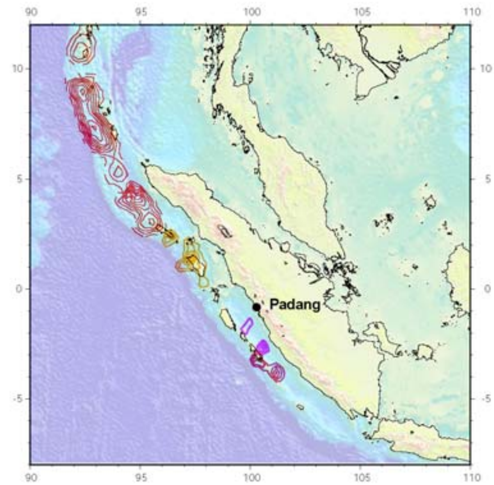




7.5 m uniform slip

=

250 years at 3 cm/y



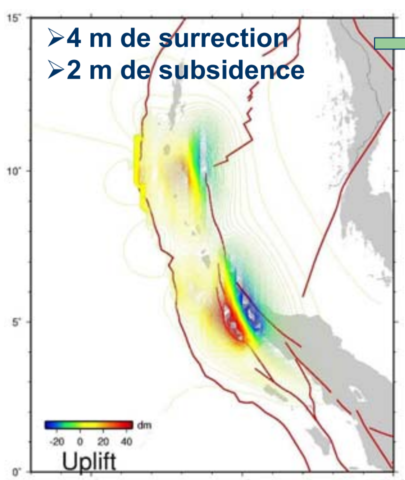
Chen Ji (Caltech)

slip distribution

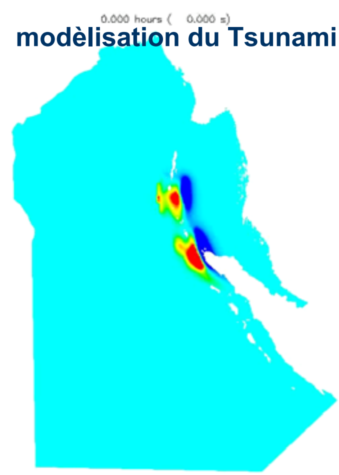
Inverted from seismic & GPS data

Les mouvements verticaux prédits par le modèle

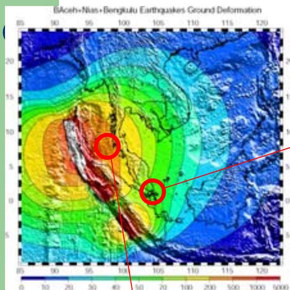
- **4 m de surrection**
- **2 m de subsidence**

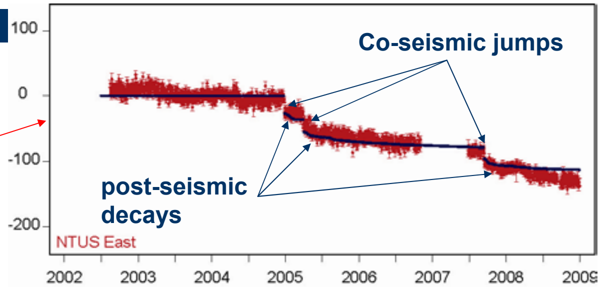


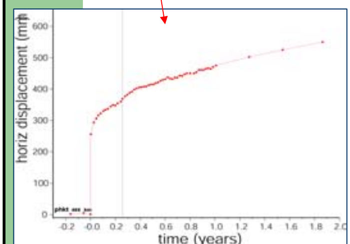
modèlisation du Tsunami



Déformations Post-sismique







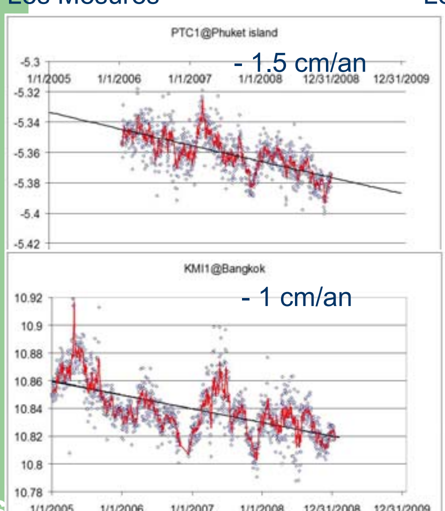
La relaxation visqueuse après le séisme :

1-10 cm/an !!!!

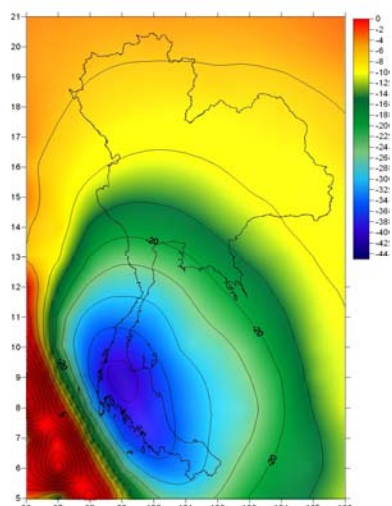
va durer des années, peut être des décennies !

Thailande: Subsidence déclenchée par le séisme de Sumatra

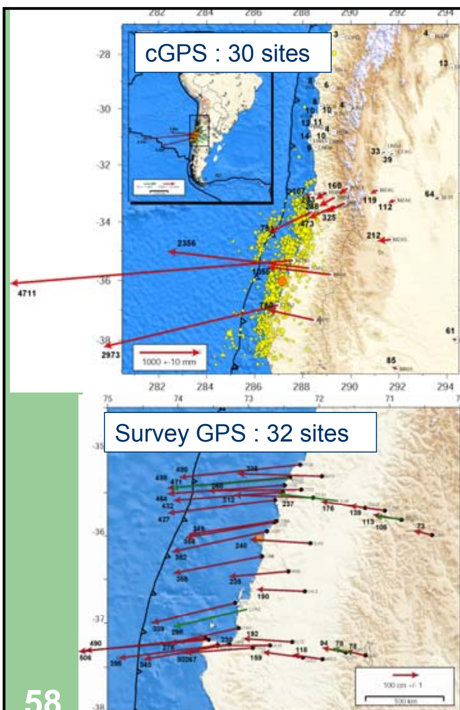
Les Mesures

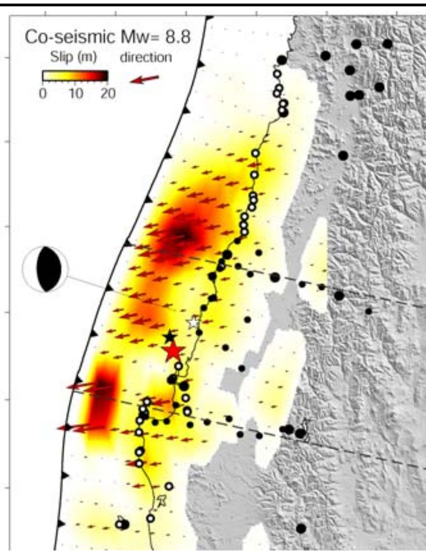


Le Modèle



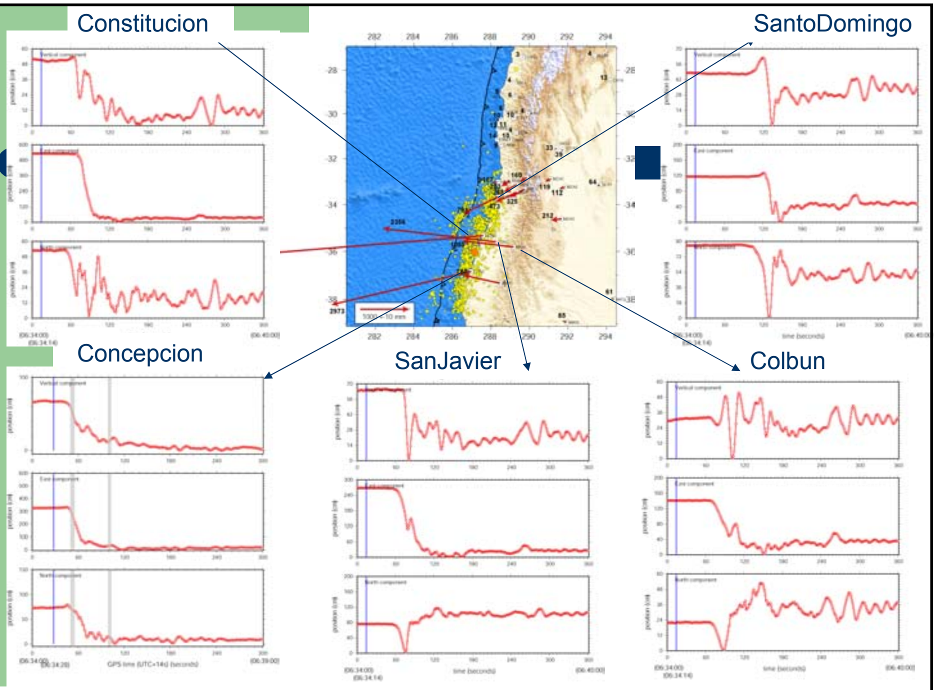
Les conséquences





Chili février 2010

Déplacement des stations GPS et modèle de glissement sur la faille contraint par les mesures



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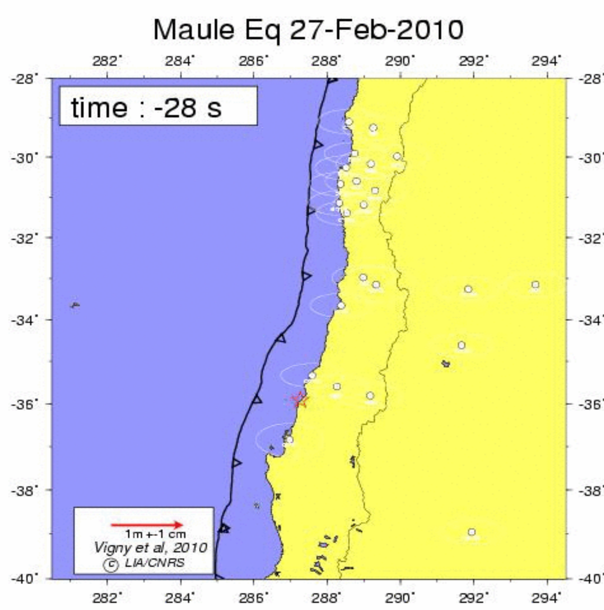
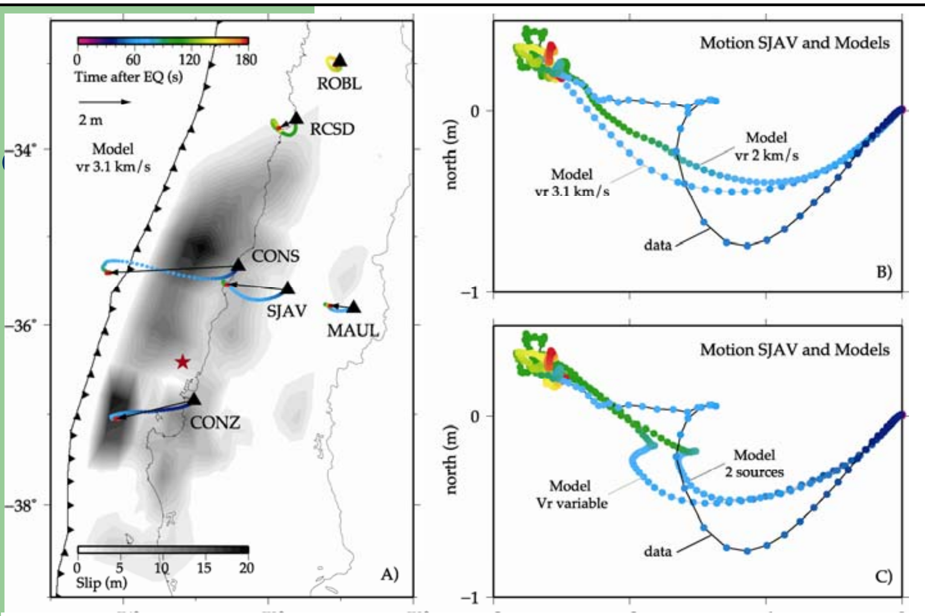


Maule Eq 27-Feb-2010
time : -28 s
1m +-1 cm
Vigny et al, 2010
© LIA/CNRS



GPS haute fréquence: 1 point par seconde => trajectoire des stations pendant le séisme. Comparaisons avec modèles théoriques