The Prompt ElastoGravity Signals (PEGS) : Detection capabilities and limitations of very broadband seismometers

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Introduction on PEGS

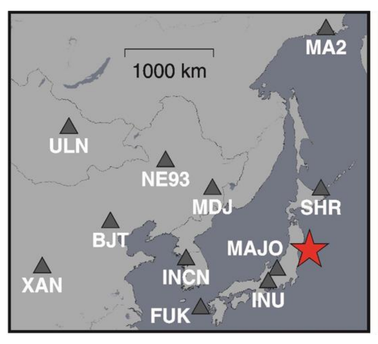
Context

Gravitational perturbations due to mass redistribution associated with tectonic processes :

- **Static (final) gravitational perturbations:**
  - **Known solution for shear or tensile faults in half-space** [*Okubo et al.*, 1992]
  - **Observed by Earth gravimeters** [2003 Tokachi earthquake, Imanishi et al., 2004] **and space gravimetry** [static gravitational changes of the 2011 Tohoku earthquake detected by GRACE, e.g. Matsuo &Heki, 2011]
- **Dynamic gravitational perturbations :**
  - **Such perturbations also occur immediately after an earthquake** [*Harms et al., 2015; Montagner et al., 2016*] :
    - **The Earth masses are perturbed, both at the source location and at the places affected by the transient dilatant/compressive elastic waves**
    - **These perturbations propagate at the speed of light… even if their signature is small, the quiet period before the P-wave arrival may allow to observe them**

Such a tiny signal requires large earthquakes and excellent stations to be recorded

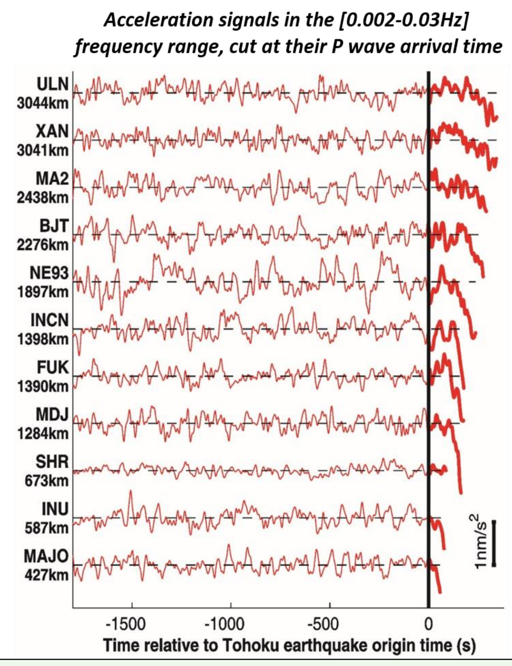
The 2011 (Mw=9.1) Tohoku earthquake



After downloading all the available stations from IRIS Wilber III (hundreds of stations), map of all the stations able to detect the signal, based on a Signal-to-Noise ratio criterion

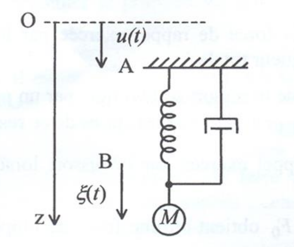
Most of the stations are FDSN stations (IRIS or GEOSCOPE) known for their high quality

Some stations from F-NET are also included



But what are exactly these signals that we observe ?

What do we expect to record with a ground-attached seismometer (or gravimeter) ?



Without gravitational changes, gravity only controls the equilibrium position of the mass, and we have :

$$\frac{d^2\xi}{dt^2} + \frac{D}{M}\frac{d\xi}{dt} + \frac{k}{M}\xi = -\frac{d^2u}{dt^2} \quad (1)$$

With Δg, (1) is simply modified as :

$$\frac{d^2\xi}{dt^2} + \frac{D}{M}\frac{d\xi}{dt} + \frac{k}{M}\xi = \Delta g - \frac{d^2u}{dt^2} \quad (2)$$

A seismometer is therefore a **seismo-gravimeter, which records**, after correction from the instrumental response, **the difference between the ground acceleration and the gravitational perturbations**

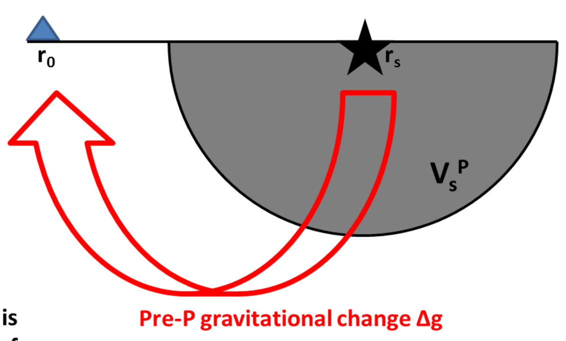
One approach to understand and model PEGS

How to compute Δg ?

Let us consider an earthquake in r_s, starting at *t=0*, and generating elastic waves, with the fastest (*P*) one arriving at T_P at the station in r_0

- **At a given time t (*0<t<TP*), transient elastic displacements affect the volume V_s^P around the source**
- **These displacements can be calculated in every point r of V_s^P (use of AXITRA method, moment tensor version) with :**
  $u_i(\mathbf{r},t) = M_{jk}m(t) * \mathcal{G}_{ij,k}(\mathbf{r_s},\mathbf{r},t)$
- **The pre-P gravitational perturbation is controlled by an integral over V_s^P of the form (Dahlen & Tromp 1998):**

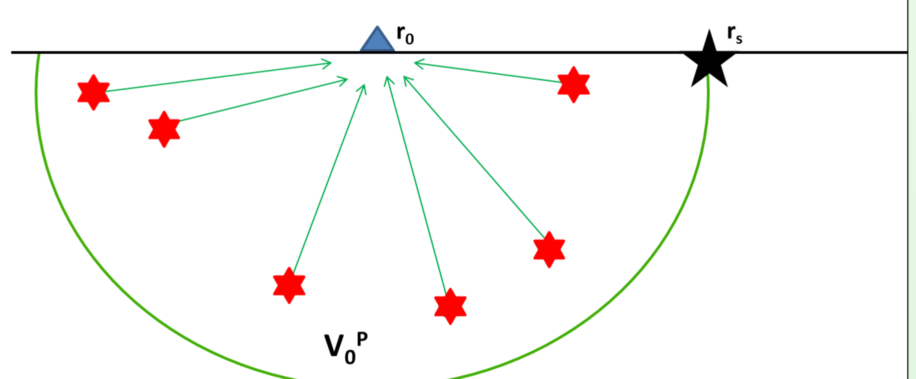
$$\Delta \mathbf{g}^P(\mathbf{r},t) = G\int_{V_s^P} \frac{\rho(\mathbf{r}')[\mathbf{u}(\mathbf{r}',t) - 3(\mathbf{e}_{\mathbf{r}'\mathbf{r}}.\mathbf{u}(\mathbf{r}',t))\mathbf{e}_{\mathbf{r}'\mathbf{r}}]}{|\mathbf{r}'-\mathbf{r}|^3}d\mathbf{r}'$$



But note that there is a gravitational perturbation not only at r_0, but everywhere in the medium

Δg is also a body force acting in the whole medium, which will cause the station to move EVEN BEFORE the arrival to the direct P wave. This can be seen as a try of the Earth to elastically re-equilibrate after the gravitational perturbations.

Concretely, all the gravitational perturbations occurring in the volume V_0^P defined by $V_0^P = \{\mathbf{r}' \in V \,/\, T^P(\mathbf{r_0},\mathbf{r}') < T_P\}$ can generate elastic waves arriving before the hypocentral P arrival at the station



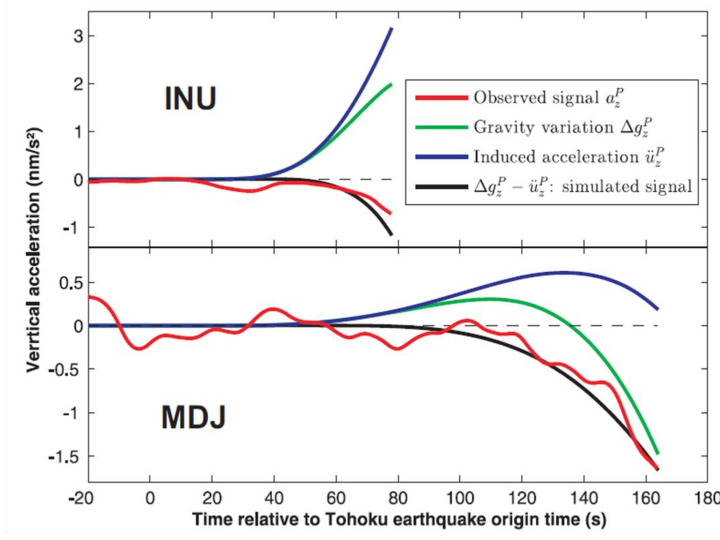
This gravitational-induced acceleration can be computed with the integral

$$\ddot{u}_z^P(\mathbf{r},t) = \frac{d^2}{dt^2}\int_{V_0^P}\rho(\mathbf{r}')\Delta g_i^P(\mathbf{r}',t) * \mathcal{G}_{iz}(\mathbf{r}',\mathbf{r},t)d\mathbf{r}'$$

AXITRA method (single force)

We now have all the ingredients to compute the prompt vertical acceleration recorded by the broadband seismometers $= \Delta g_z^P(\mathbf{r_0},t) - \ddot{u}_z^P(\mathbf{r_0},t)$

Data & simulations at INU (GEOSCOPE, G) and MDJ (IRIS-China, IC)



Vallée et al., Science, 2017

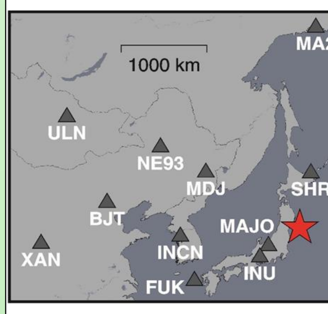
Remark : at INU station, the recorded signal is negative while the gravitational perturbation is positive : the signal is dominated by the induced acceleration

PEGS observations to date

PEGS observations and modeling for 5 additional earthquakes of the last 25 years (Mw =7.9-8.8). PEGS detection is made using individual (yellow) of stacked (green) seismometers signals

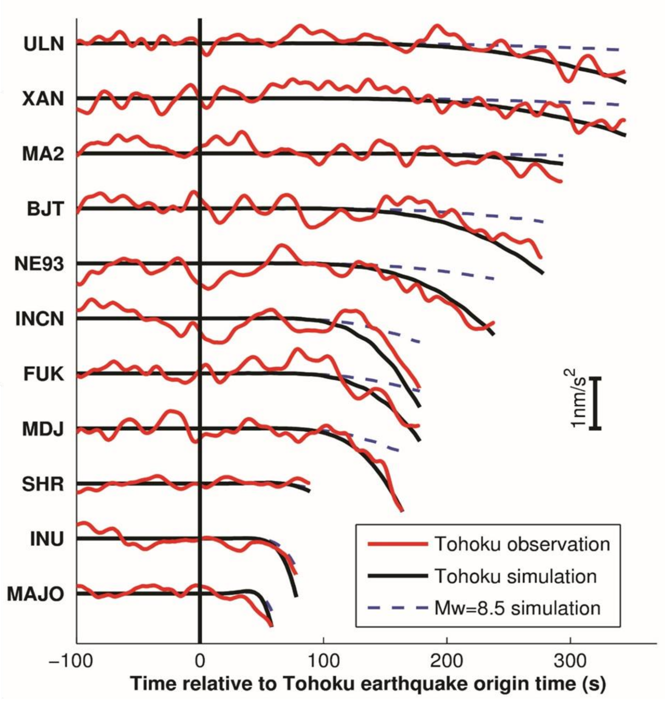
PEGS observations and modeling for the 2011 (Mw=9.1) Tohoku earthquake

Complete simulation at all stations

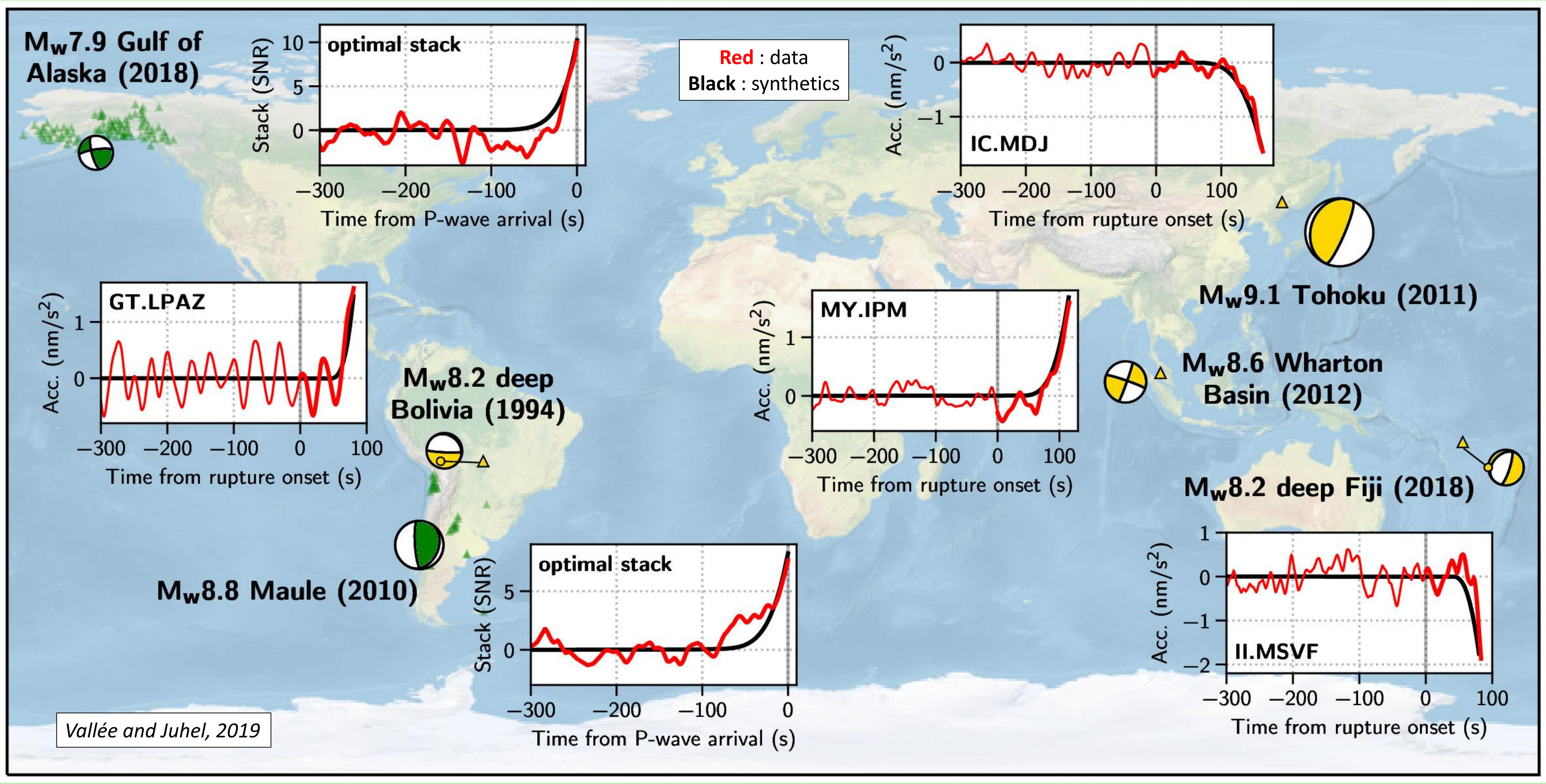


Good agreement between observed and modeled signals

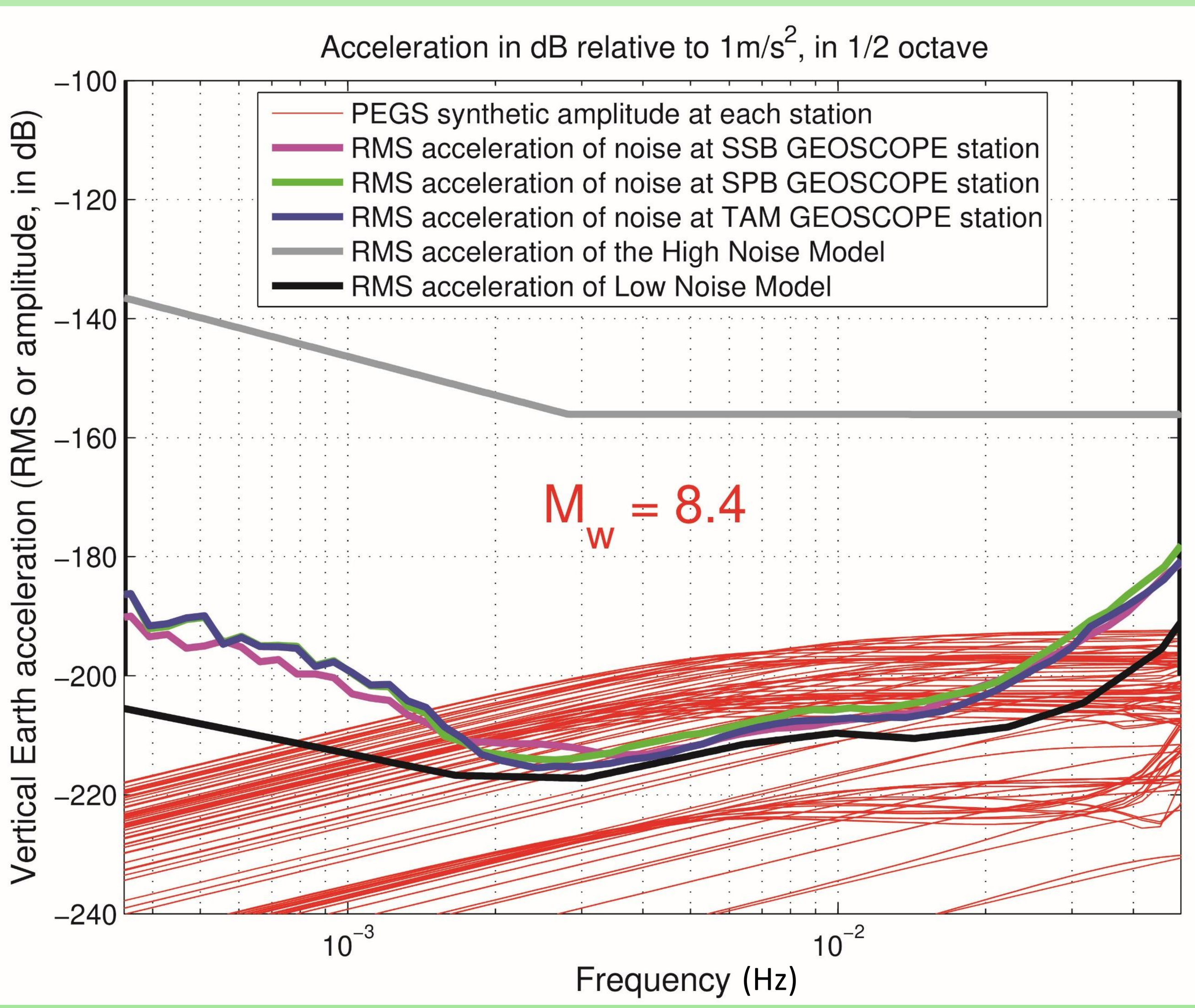
Strong sensitivity to earthquake magnitude [A smaller Tohoku-type earthquake (Mw <8.5) would not have been detected]



Vallée et al., Science, 2017

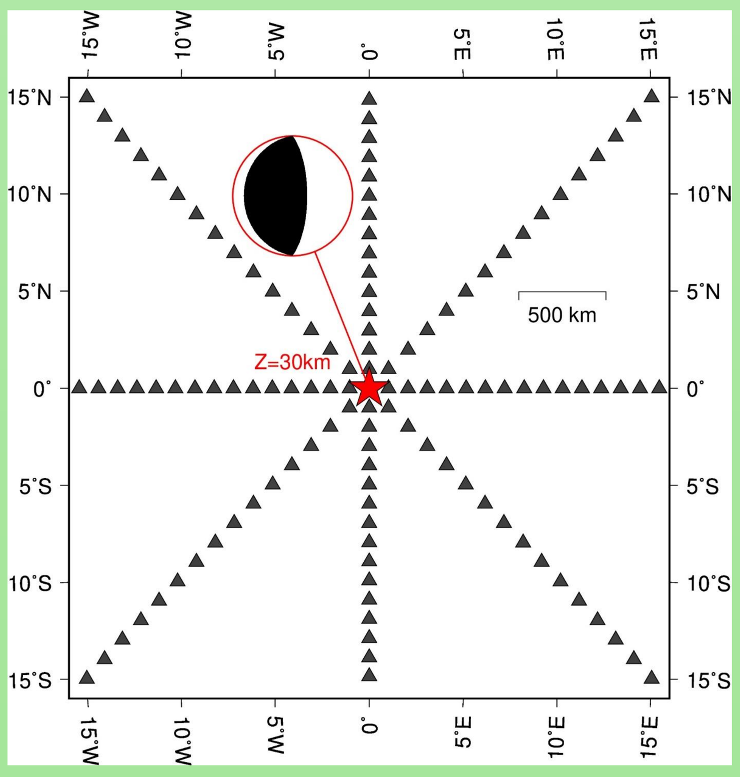


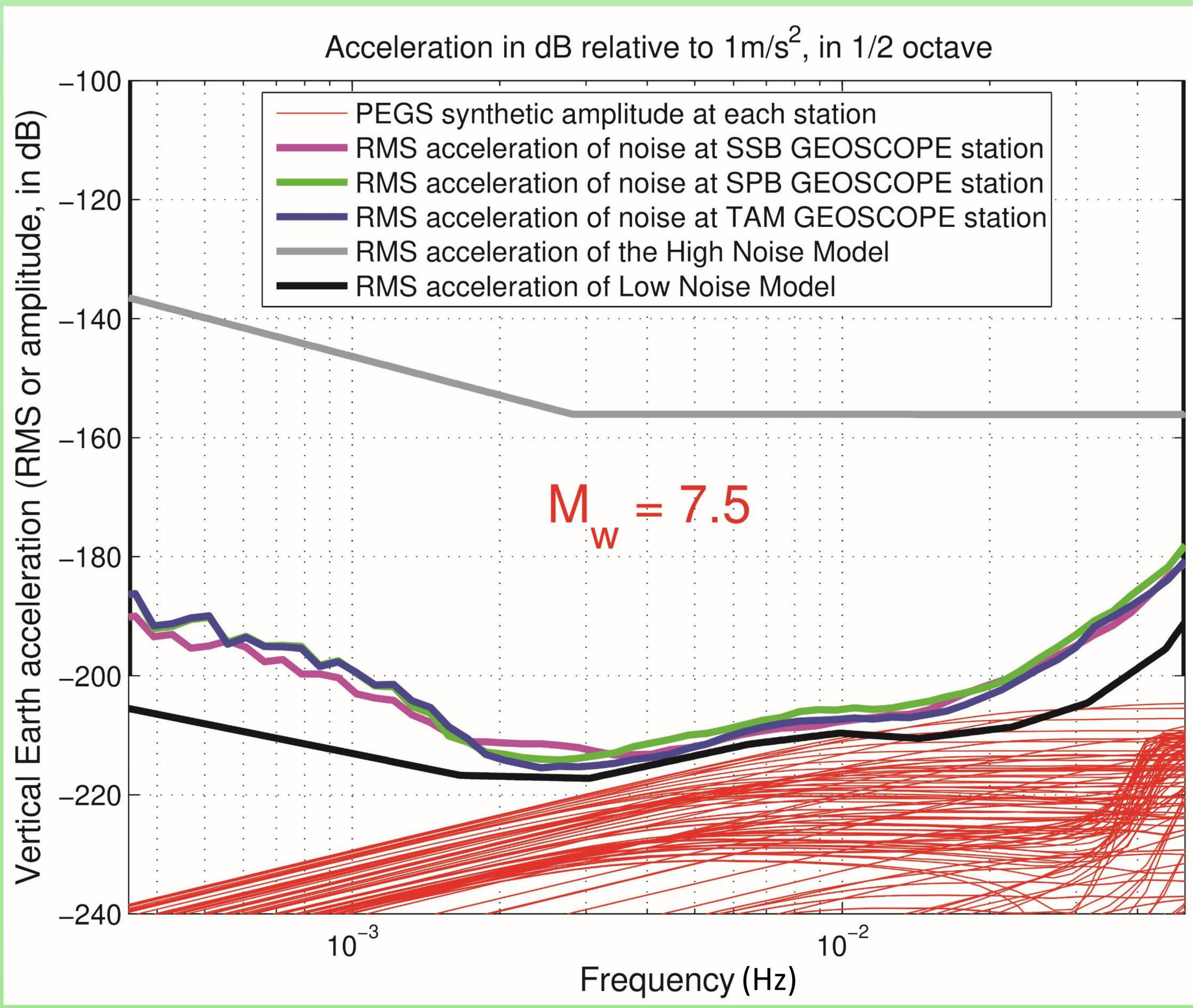
What are the limitations of PEGS observation with today seismometers ?



Spectrum amplitude of PEGS signals, compared to rms noise amplitudes (model and observed at some stations), for an Mw=8.4 scenario

- PEGS simulation for a **typical subduction mechanism at 120 fictitious stations** around the earthquake, in the **100-~2000km** distance range
- For a typical **Mw=8.4 scenario**, good quality **very broadband seismometers** are expected to **detect the signal in the [0.002-0.03Hz]** frequency range, except if sensors are located in unfavorable directions (here along the N-S direction)
- For a typical **Mw=7.5 scenario, signals never reach values above the « noise »** (physical or instrumental) :
  - Detection requires to **model/mitigate the background seismic noise**, or **to develop fully new instruments which are much less sensitive to it**.





Spectrum amplitude of PEGS signals, compared to rms noise amplitudes (model and observed at some stations), for an Mw=7.5 scenario

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