Earthquake detection and early warning systems with gravitational-wave detectors

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A multi-disciplinary collaboration:

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Prompt earthquake detection with high-precision gravity strain meters

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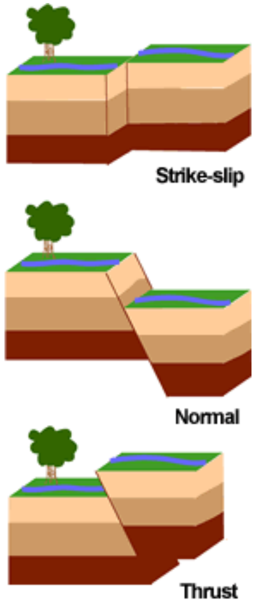
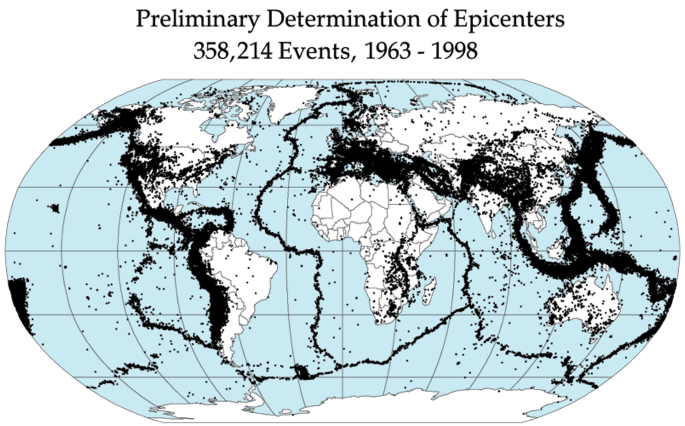
submitted to Journal of Geophysical Research

Earthquakes





Huge mass displacement
in tens of seconds

Can we detect the gravity change due to an earthquake?

Superconducting gravimeters and satellites

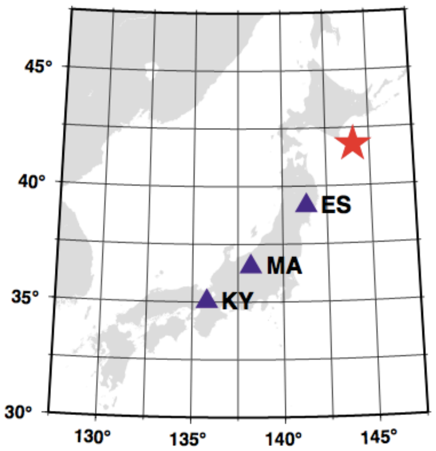


Fig. 1. Epicenter (asterisk) of the 2003 Tokachi-oki earthquake and SG station locations (triangles). ES, Esashi; MA, Matsushiro; KY, Kyoto.

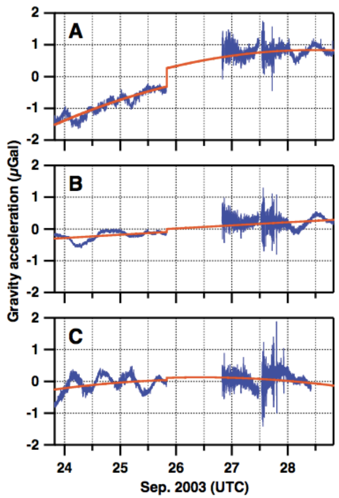


Fig. 2. Residual gravity data (blue) recorded by SGs for the 2003 Tokachi-oki earthquake. (**A**) Esashi, (**B**) Matsushiro, and (**C**) Kyoto. Red curves are best-fit functions given by Eq. 1.

~ $0.6\ 10^{-8}\ m/s^2 = 0.6\ \mu gal$

Imanishi et al., *A Network of Superconducting Gravimeters Detects Submicrogal Coseismic Gravity Changes*
Science 306, 476 (2004)

S. Okubo (1991), *Potential and gravity changes raised by point dislocations*, Geophysical Journal International, 105(3), 573– 586.

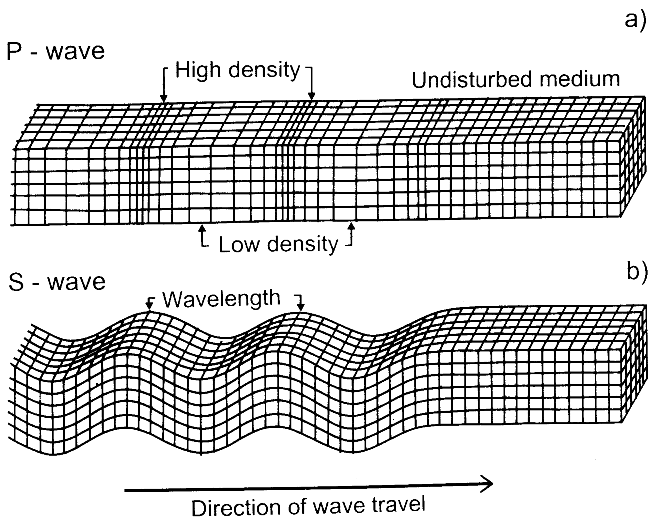
S. Okubo (1992), *Gravity and potential changes due to shear and tensile faults in a half-space*, Journal of Geophysical Research, 97(B5), 7137–7144.

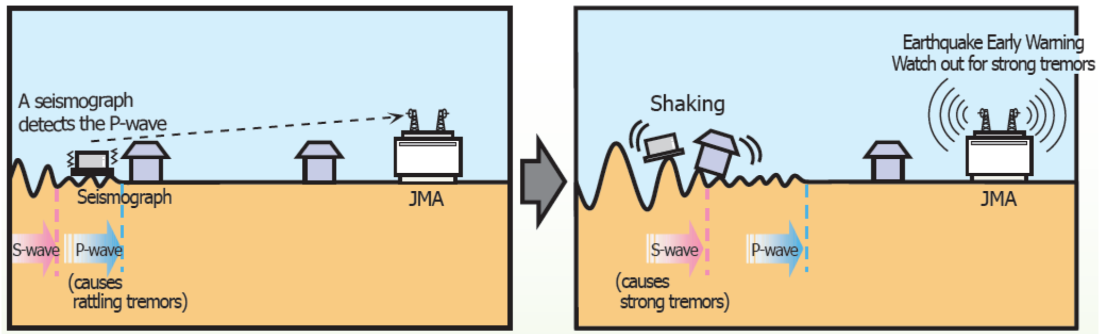
Those experiments detect static changes (from before to after the event)

Can we detect the gravity change due to an earthquake ***promptly*** (few seconds after the fault rupture)?

Not published results
(to our knowledge)

Main motivations:
Earthquake early-warning systems





Source: Japan meterological agency

For example, for some densities: P-waves ~ 5 km/s S-waves~ 2.5 km/s

What an early warning system can do ?

Public Alert

- warn people to take protective measures (drop-cover-hold on)
- move people to safe positions
- prepare physically and psychologically for the impending shaking

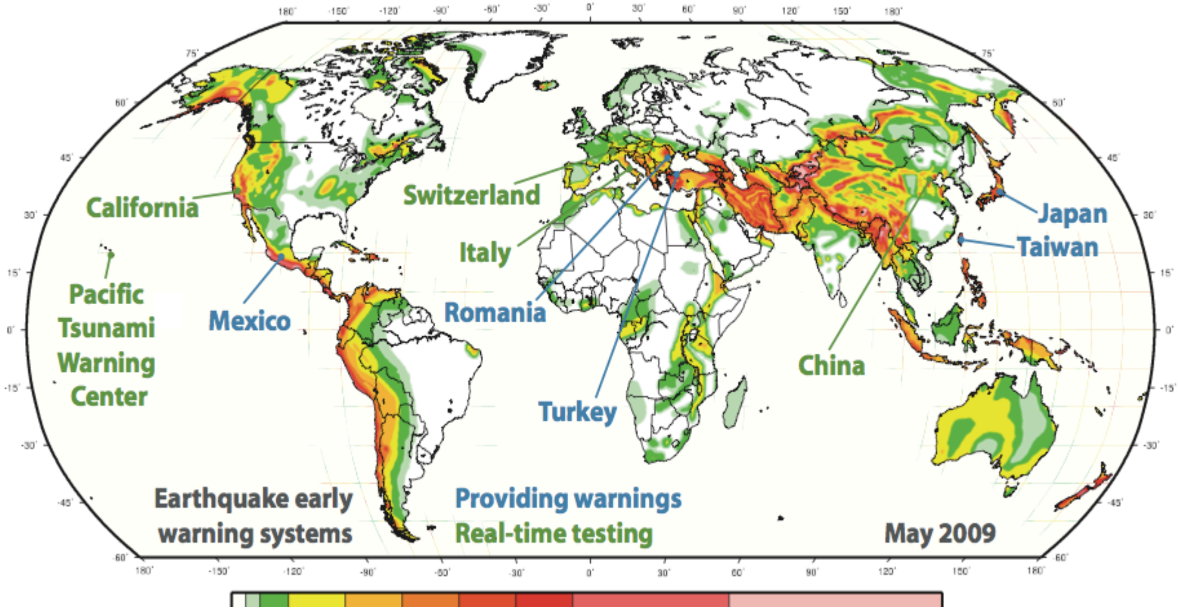
Trigger Automatic Responses

- slow down/stop trains
- control traffic by turning signals red on bridges, freeway entrances
- close valves and pipelines
- stop elevators
- save vital computer information

Limitations:

- chance of false alarms
- no warning in blind zone

Earthquake early warning systems around the world



▲ **Figure 1.** Map of global seismic hazard showing locations where active EEW systems are providing warnings to one or more users (blue) and where EEW systems are currently being tested as part of a real-time seismic system (green).

The status of earthquake early warning around the world: an introductory Overview , Allen et al, Seismological Research Letters Volume 80, Number 5, 2009

Gravity-based early warning system

Potential gains

- Increase of available time for warning
  - Conventional system at 100 km: 40s (s-waves)-20s (p-waves) -5s (comp) ~ 15s
  - Gravity based system at 100 km: 40s (s-waves)-5s (comp) ~ 35s
- Reduction of the blind zone
- Quick estimation of the magnitude (information about the magnitude completeley contained in the rupture time)

Is it feasible?

To do:

1) Computation/simulation gravity signals due to the fault rupture (Signal)

2) Feasibility of a detector (noise)

3) Detection pipeline (signal to noise ratio – warning time – false alarm rate)

Computation of gravity signals

$$\delta\psi(\boldsymbol{r}_0\,,t) = -G\int \mathrm{d}V\,\frac{\delta\rho(\boldsymbol{r}\,,t)}{|\boldsymbol{r}-\boldsymbol{r}_0|}$$

$$\delta\rho(\boldsymbol{r}\,,t) = -\rho_0\boldsymbol{\nabla}\cdot\boldsymbol{\xi}(\boldsymbol{r}\,,t)$$

Assumption: point-source earthquake in an infinite elastic medium

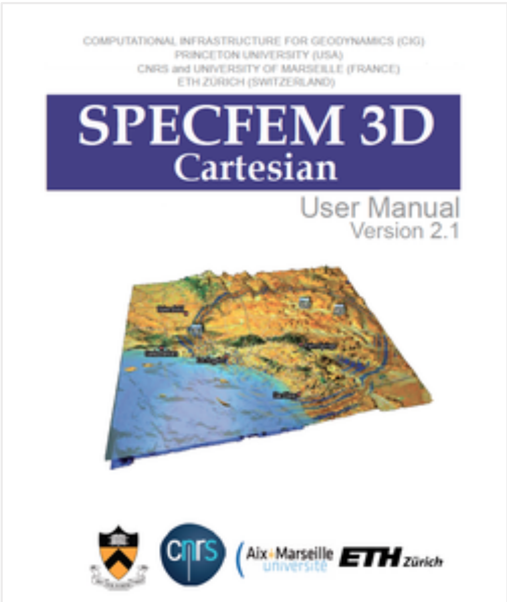
→ known solution for the displacement fields as function of the seismic moment

$$\delta\psi(\boldsymbol{r}_0\,,t) = -\frac{6G}{r_0^3}R_{\mathrm{P}}(\theta_0,\phi_0)\;I_2[M_0](t) \longrightarrow \ddot{\mathsf{h}}(\boldsymbol{r}_0\,,t) = -\frac{6G}{r_0^5}\,\mathbf{S}(\theta,\phi)\;I_2[M_0](t)$$

Average strain $$\langle h_+(\boldsymbol{r}_0\,,t)\rangle = \langle h_\times(\boldsymbol{r}_0\,,t)\rangle = \frac{6\sqrt{14/5}\,G}{r_0^5}I_4[M_0](t)$$

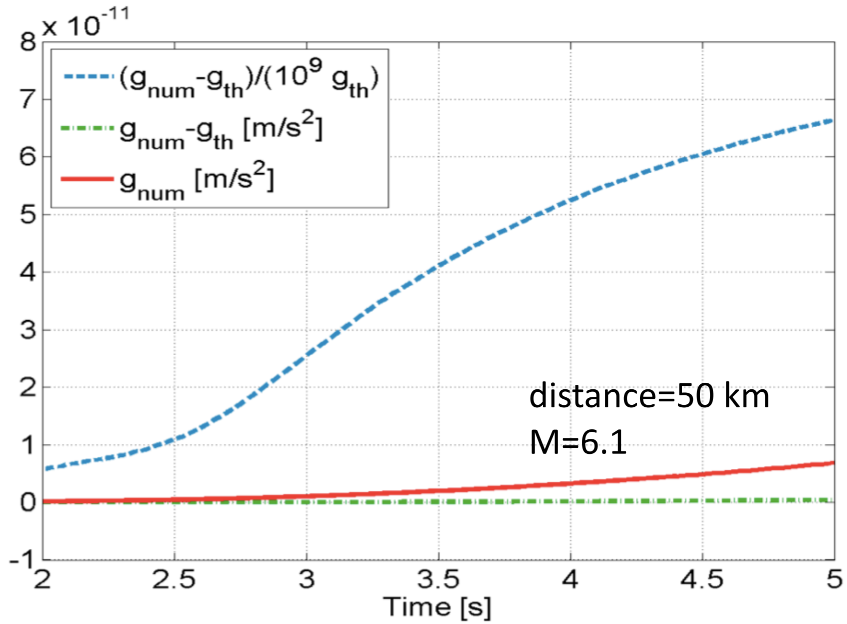
Gravity signals: simulation vs calculation

computation of gravity field implemented in the program SPECFEM3D



http://geodynamics.org/cig/software/specfem3d/

m/s^2



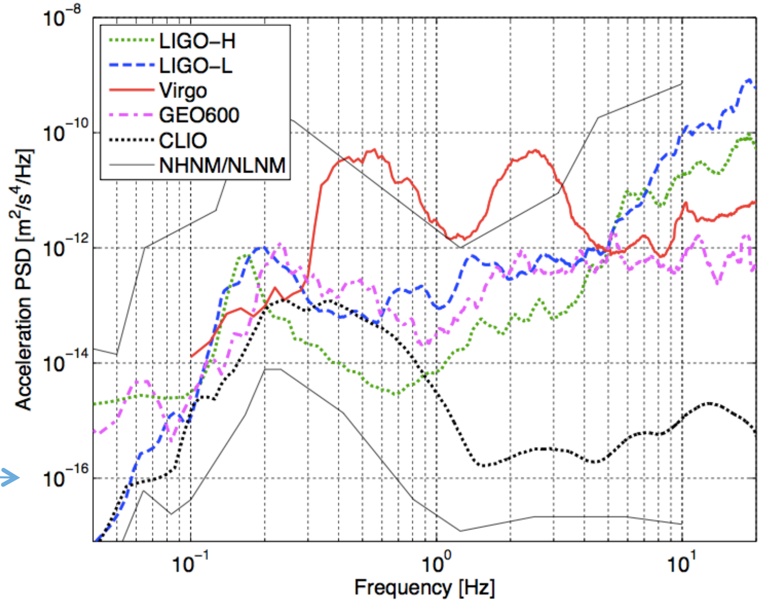
1 ngal

Why gravitational-wave detectors are interesting for this problem

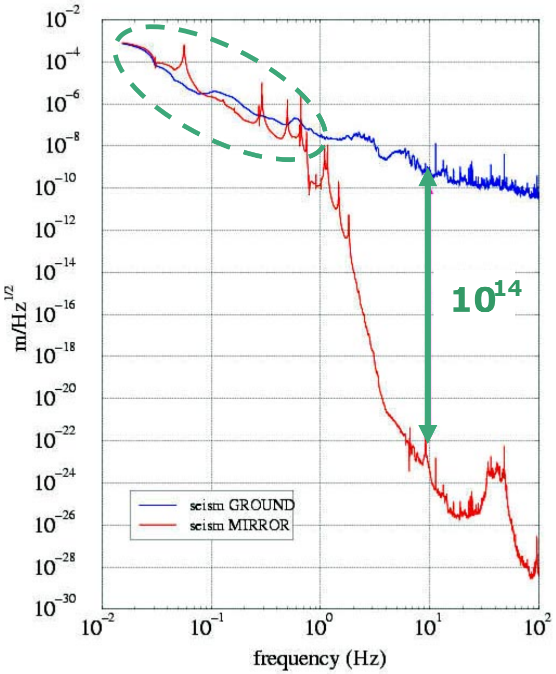
→Superconducting gravimeters at 0.1-1 Hz (for M~6) are limited by the seismic noise (inertial effects)

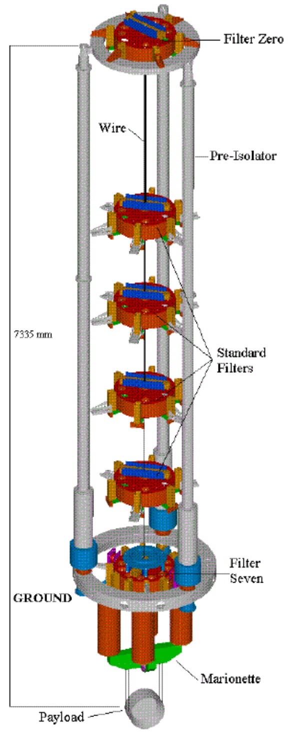
→ Use a strainmeter with seismic isolated test masses

1 microgal →



Advanced interferometers: seismic wall at f>1 Hz





Sub-Hz gravitational-wave detectors

Low-Frequency Terrestrial Gravitational-Wave Detectors, Jan Harms, Bram J. J. Slagmolen, Rana X. Adhikari, M. Coleman Miller, Matthew Evans, Yanbei Chen, Holger Muller and Masaki Ando, Phys. Rev. D 88, 122003 (2013)

1) Torsion bar antenna

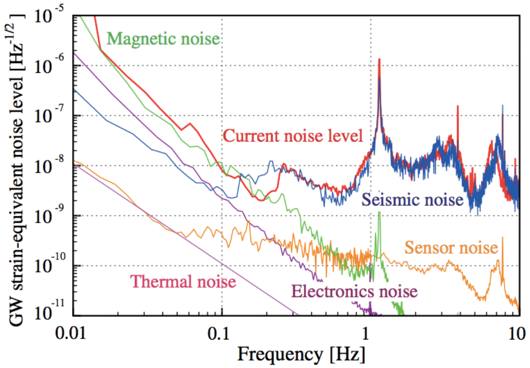
M. Ando et al., *Torsion-Bar Antenna for Low-Frequency Gravitational-Wave Observations,* PRL 105, 161101 (2010)

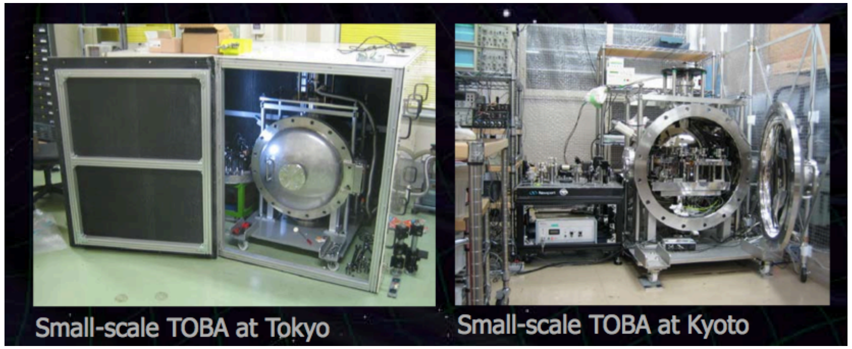
K.Ishidoshiro et al., *Upper Limit on Gravitational Wave Backgrounds at 0.2 Hz with a Torsion-Bar Antenna,* PRL 106, 161101, (2011)

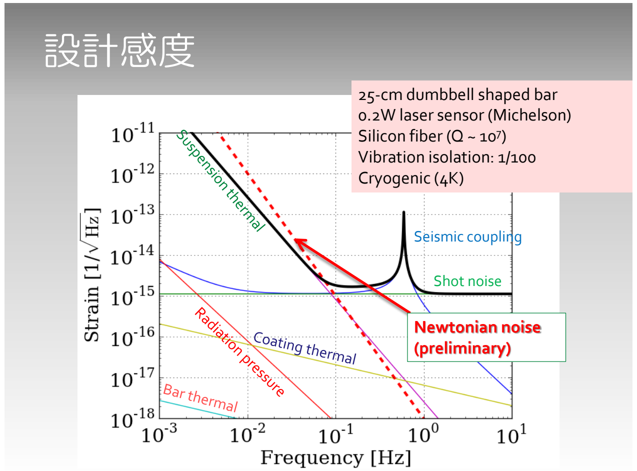
2) Atom interferometer

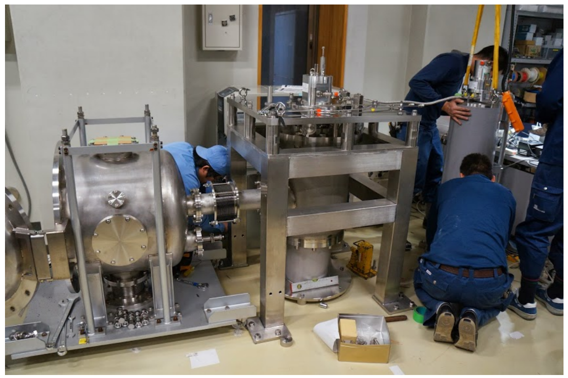
3) Novel seismic attenuation concept for Michelson interferometer

TOBA



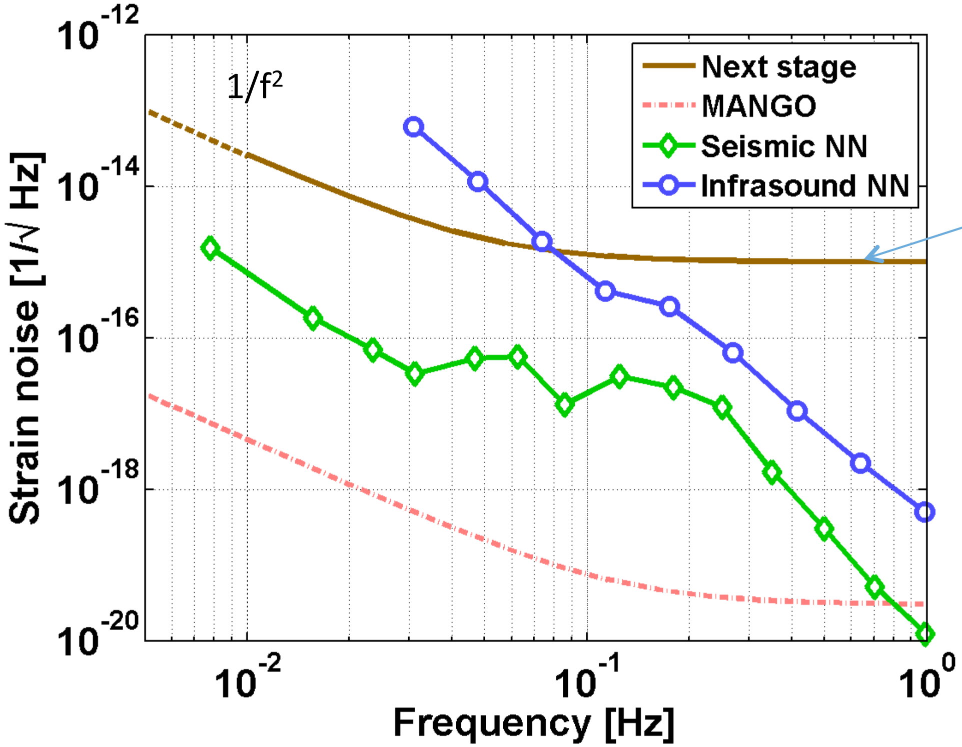






Courtesy: A.Shoda and TOBA team

Possible sensitivity curve



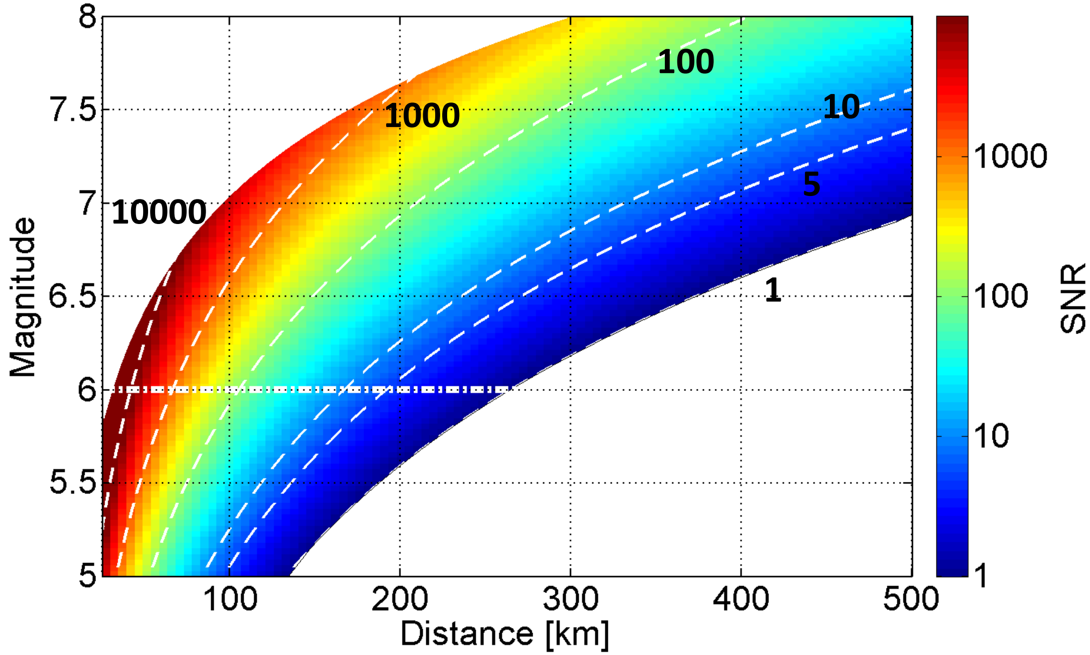
h=10^{-15} Hz$^{-1/2}$

Low-Frequency Terrestrial Gravitational-Wave Detectors, Jan Harms, Bram J. J. Slagmolen, Rana X. Adhikari, M. Coleman Miller, Matthew Evans, Yanbei Chen, Holger Muller and Masaki Ando, Phys. Rev. D 88, 122003 (2013)

MANGO: GW detector

Signal to noise ratio

$$\mathrm{SNR}^2 = \int \mathrm{d}f\, \frac{|H(\vec{r}_0\,, f)|^2}{S(f)}$$



$$\langle h_+(\boldsymbol{r}_0\,, t)\rangle = \langle h_\times(\boldsymbol{r}_0\,, t)\rangle = \frac{6\sqrt{14/5}\,G}{r_0^5} I_4[M_0](t)$$

$$M(f) = \frac{1}{2\pi f}\,\frac{M_0}{1+(f/f_c)^2}$$

Brune, J. N. (1970), *Tectonic stress and the spectra of seismic shear waves from earthquakes*, Journal of geophysical research, 75(26), 4997–5009

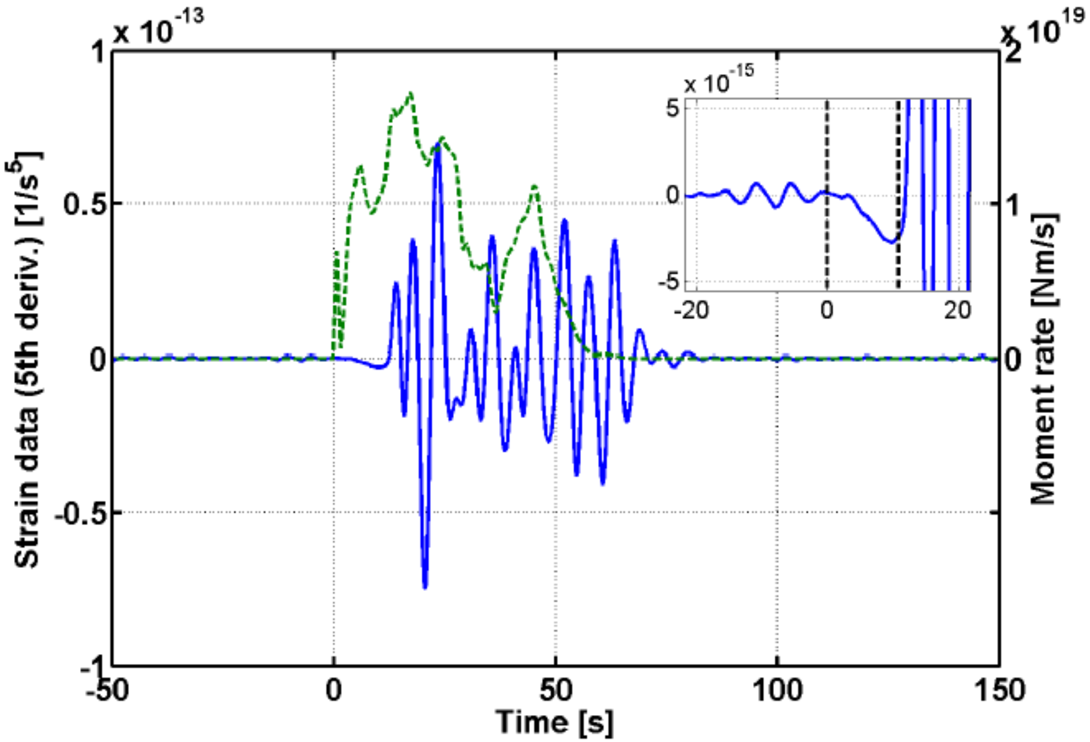
Madariaga, R. (1976), *Dynamics of an expanding circular fault*, Bulletin of the Seismological Society of America, 66(3), 639– 666

Time domain analysis

Pakistan M=7.5 earthquake (2011)
Detector at 70 km

Data bandpassed between 10 mHz and 0.2 Hz

Matched filtering analysis on going, preliminary results coherent with the SNR frequency analysis



Conclusions

- We address for the first time the problem of detecting gravity perturbations produced by an earthquake during fault rupture
  - Original computation (and simulation) of the prompt signal
  - Considerations on the sensitivity and feasibility of a gravity-based detector
  - Computation fo SNR and time domain analysis
- Potential advantages of a gravity-based early warning system: increase of the available warning time, reduction of the blind zone, faster estimation of the magnitude
- Considering the sensitivity model used (~ next stage TOBA at 0.1 Hz), a frequency domain analysis (best SNR) suggests that a M=6 event (and above) at ~100 km can be detected

Next steps

- Computation of gravity signals: incorporate realistic effects (free surface, non homogeneities of the medium, etc…)
- Demonstrate the feasibility of the detector
- Develop realistic signal detection pipelines and compute warning times
- Other geophysical applications? Direct observation of the earthquake source (not through seismic waves)