Alternative Seismic Sensors for NN Cancellation

1

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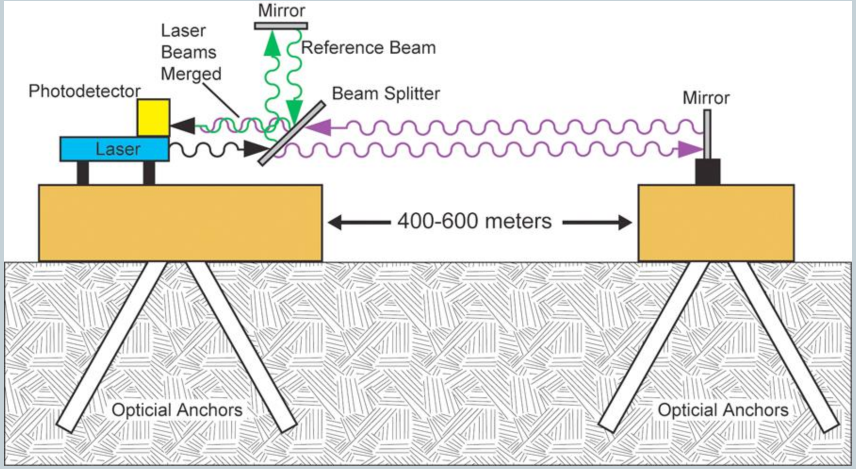
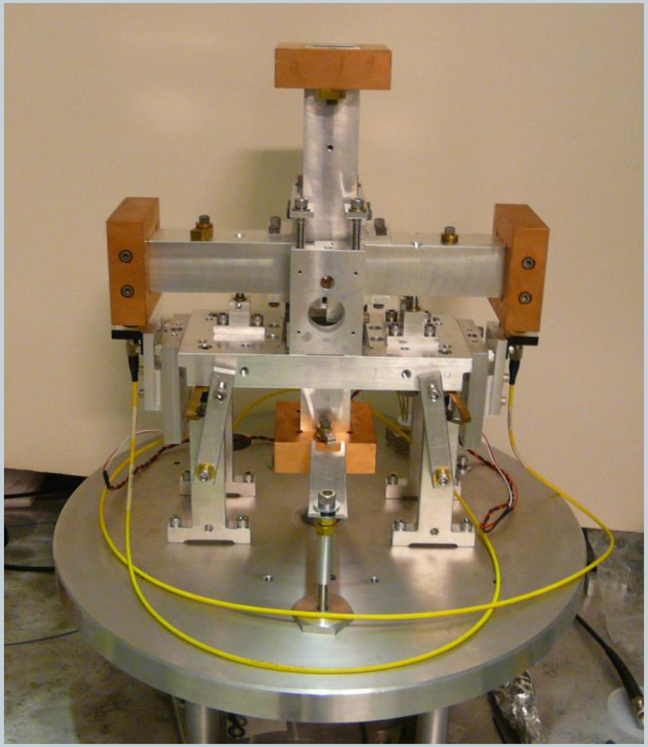
Alternative Seismic Sensors

Strainmeter



Tiltmeter



Venkateswara, 2016

- **Tiltmeter**: best imitation of Rayleigh NN in large-scale GW detectors
- **Strainmeter**: best imitation of body-wave NN in gravity gradiometers

Rayleigh NN

Seismic surface displacement of Rayleigh wave

$$\vec{\xi}(\vec{\varrho},t) = (\mathrm{i}\alpha_k \cos(\phi), \mathrm{i}\alpha_k \sin(\phi), 1)\xi_z \mathrm{e}^{\mathrm{i}(\vec{k}\cdot\vec{\varrho}-\omega t)}$$

Rayleigh-wave test-mass acceleration

$$\delta a_x(\vec{\varrho}_0,t) = 2\pi \mathrm{i}\gamma G\rho_0\xi_z \mathrm{e}^{-hk}\mathrm{e}^{\mathrm{i}(\vec{k}\cdot\vec{\varrho}_0-\omega t)}\cos(\phi)$$

These equations suggest that surface displacement along direction x and gravity acceleration along x are maximally correlated.

Rayleigh NN Cancellation

Why not use x-displacement for NN cancellation?

- Love waves contribute to horizontal displacement reducing correlation between x-displacement and NN.

What is the solution to this problem?

- Use z-displacement, which only has contributions from Rayleigh waves, but then you need a seismometer array.

Are there alternative solutions?

Tiltmeters for Rayleigh NN Cancellation

Seismic tilt (rotation around y-axis)

$$\tau_y(\vec{\varrho}, t) = \partial_x \xi_z = \mathrm{i}k \cos(\phi) \xi_z \mathrm{e}^{\mathrm{i}(\vec{k}\cdot\vec{\varrho} - \omega t)}$$

Tiltmeter has maximal correlation with Rayleigh NN, and at the same time, it does not respond to Love waves.

Since the tiltmeter signal is also in phase with NN, the tiltmeter can be deployed directly under the test mass.

Other Examples

Displacement of P-wave and associated underground NN:
(Problem here are S-wave contributions)

$$\vec{\xi}(\vec{r},t) = \frac{\vec{k}}{k}\xi_{\mathrm{P}}\mathrm{e}^{\mathrm{i}(\vec{k}\cdot\vec{r}-\omega t)}$$

$$\delta a_x(\vec{r},t) = \frac{8\pi}{3}G\rho_0\frac{k_x}{k}\xi_{\mathrm{P}}\mathrm{e}^{\mathrm{i}(\vec{k}\cdot\vec{r}-\omega t)}$$

Seismic strain of P-wave and associated underground gravity-gradient noise:

$$\mathbf{h}(\vec{r},t) = \mathrm{i}\frac{\vec{k}\otimes\vec{k}}{k}\xi_{\mathrm{P}}\mathrm{e}^{\mathrm{i}(\vec{k}\cdot\vec{r}-\omega t)}$$

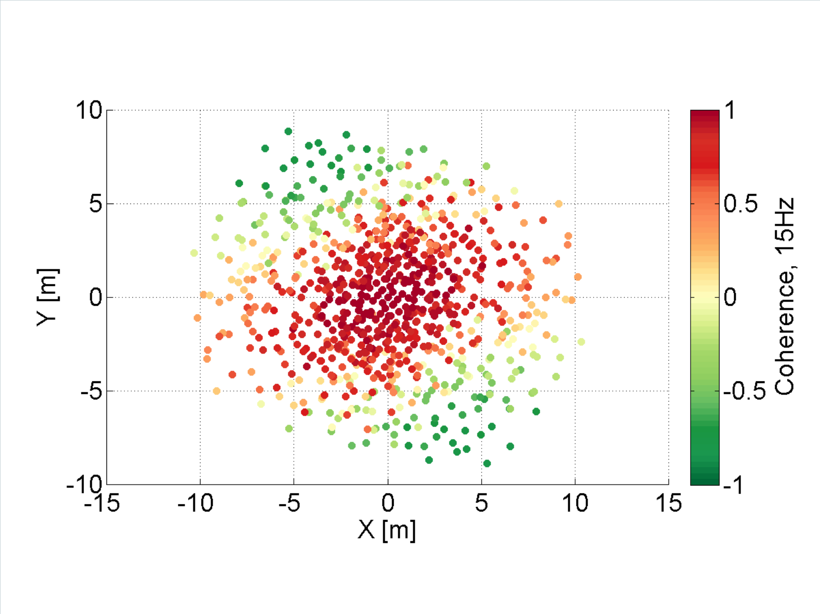
$$\partial_x\delta a_x(\vec{r},t) = \frac{8\pi}{3}G\rho_0\mathrm{i}\frac{k_x^2}{k}\xi_{\mathrm{P}}\mathrm{e}^{\mathrm{i}(\vec{k}\cdot\vec{r}-\omega t)}$$

Some Comments

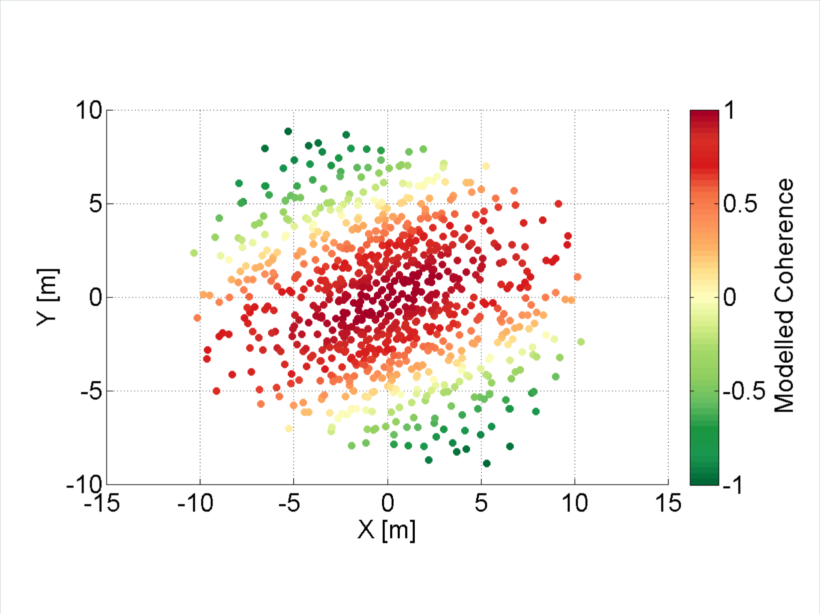
- **Optimal array configuration** for NN cancellation is **not affected by anisotropies** of the seismic field.
- In Wiener filtering, the **NN suppression factor** using a maximally correlated channel is fully **determined by the sensor SNR** (i.e. suppression is 1/SNR).
- Using a maximally correlated channel, the only possible **additional limitation** can come from **inhomogeneities of the seismic field**.

LIGO Hanford Measurements (2012)

Observation



Plane-wave model



- Anisotropic, plane-wave model gives good match with observation
- Still, local seismic sources lead to observable inhomogeneities.

Two Seismometers as Tiltmeter

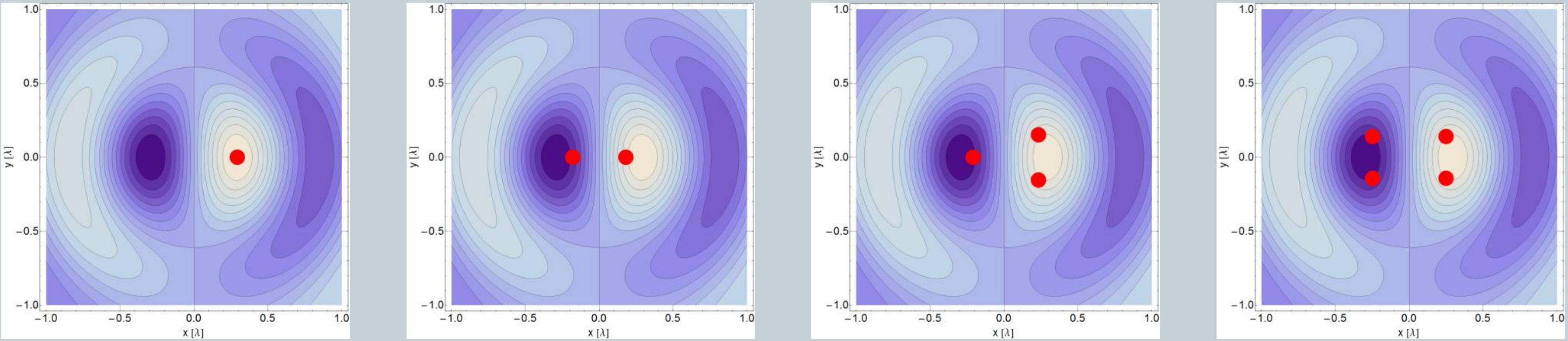
Two seismometers can in principle act like a tiltmeter, but this scheme doesn't take advantage of the differential character of tilt measurement.

NN cancellation with two sensors in "tiltmeter configuration" (suppression by 0.01 with SNR = 340, e.g. L4-C):

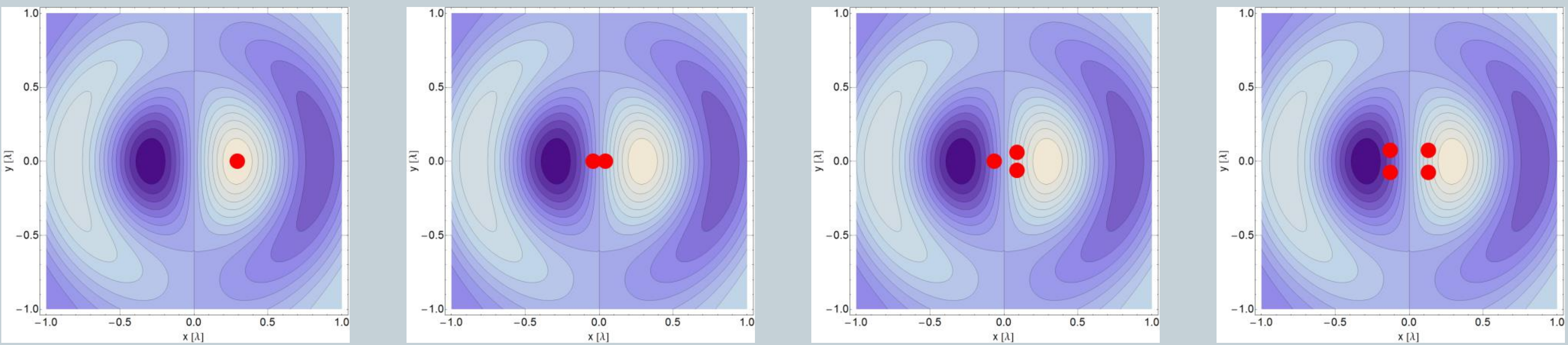
SNR	NN suppression	NN/SNL	Separation [m] (15 Hz optimized)
10	0.12	1.7	±3.6 Wilcoxon
100	0.023	3.2	±1.7
1000	0.0048	6.8	±0.82 GS-13

Optimal Arrays

SNR=10



SNR=1000



Assuming plane-wave fields, optimal array configuration is independent of SNR for N≥6, with distance of about $\lambda/3$ (i.e. 7m) from test mass.

NN Cancellation with Arrays