Future challenges of Newtonian noise filtering

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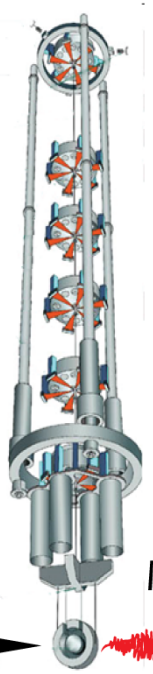
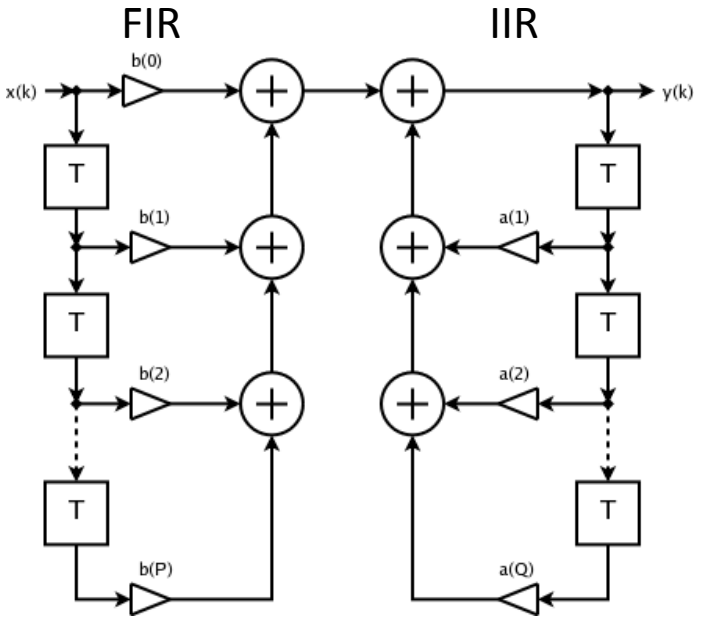
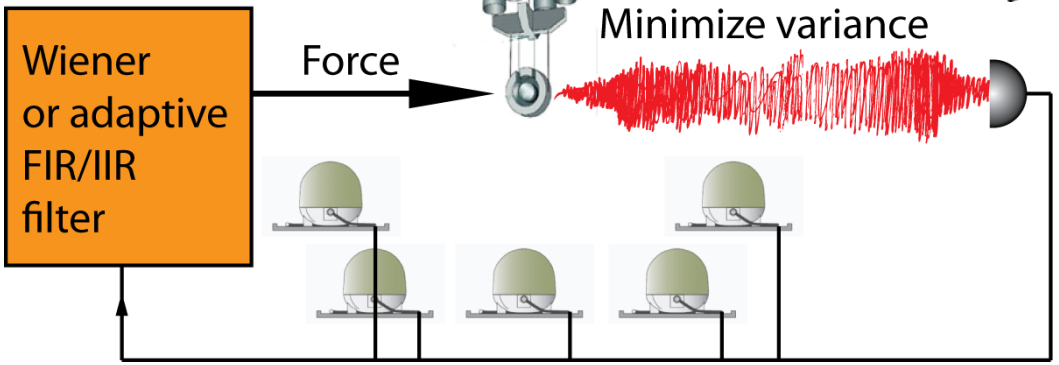
LIGO-G1000557-v1

Feed Forward

Wiener or adaptive filters are established technology and indispensable in modern industry





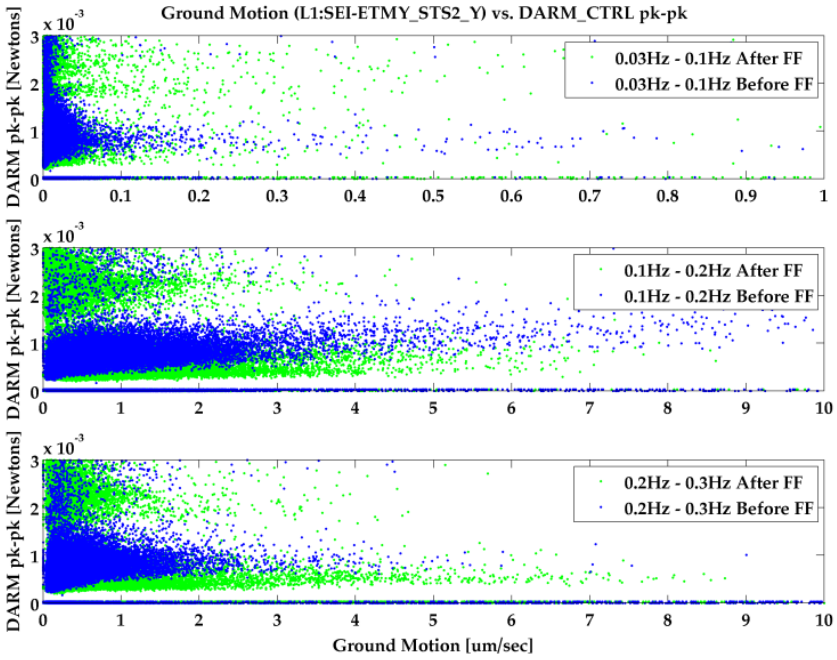


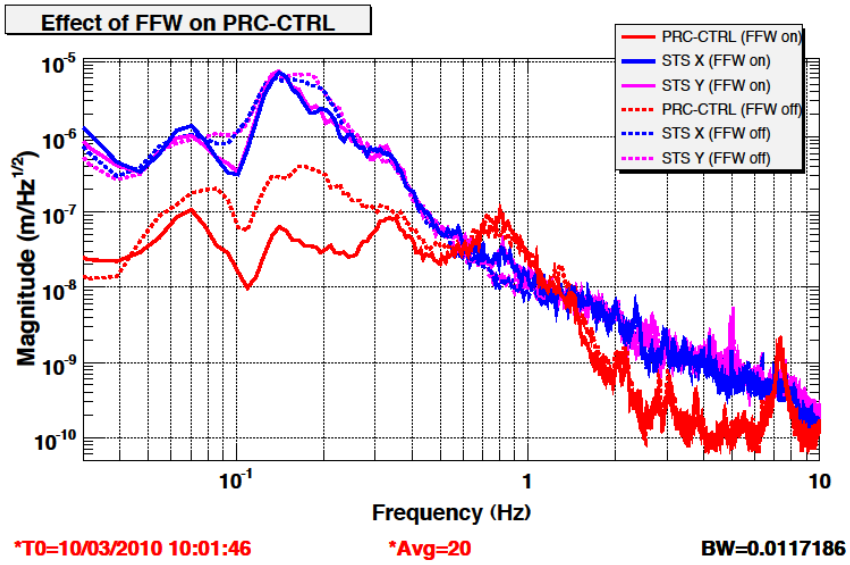
FIR is easy, IIR is not so easy

Adaptive-filter algorithms are related to

- MCMC
- Machine learning

Feed-Forward at LLO

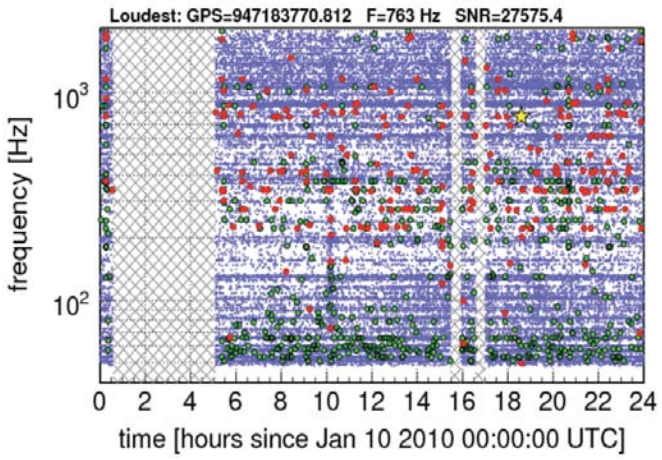


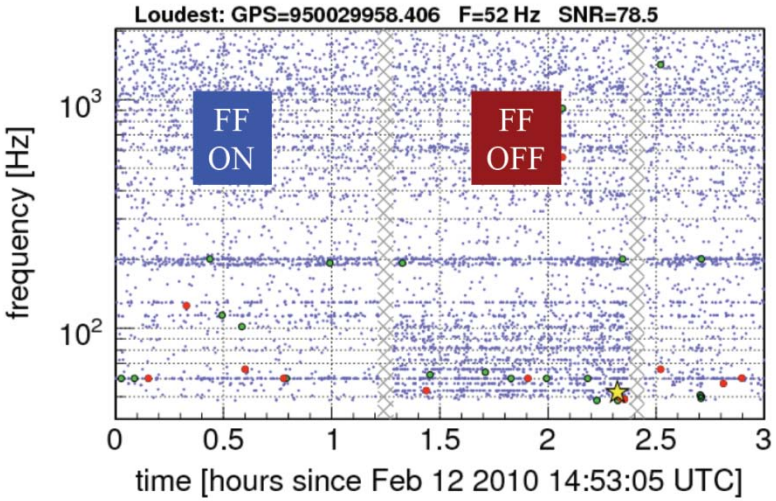


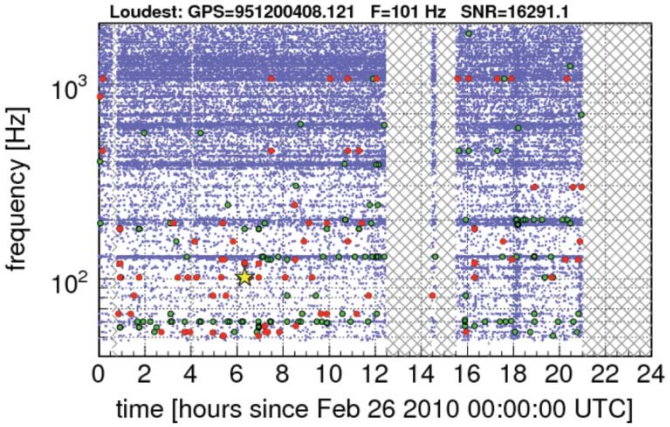
DARM_CTRL quantifies the force on the test masses. DARM_CTRL is reduced by FF (feed forward).

PRC-CTRL spectra prove that FF substantially decreases noise over many frequencies.

Glitch Rates at LLO



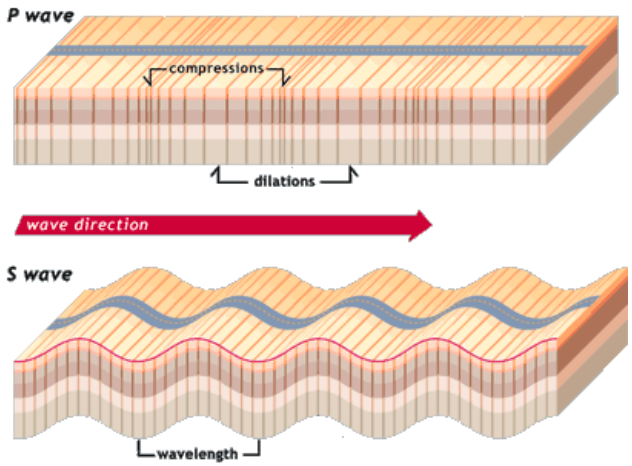




Cherry on the cake:
Glitch rate is reduced and interferometer operates more stably.

Seismic Waves

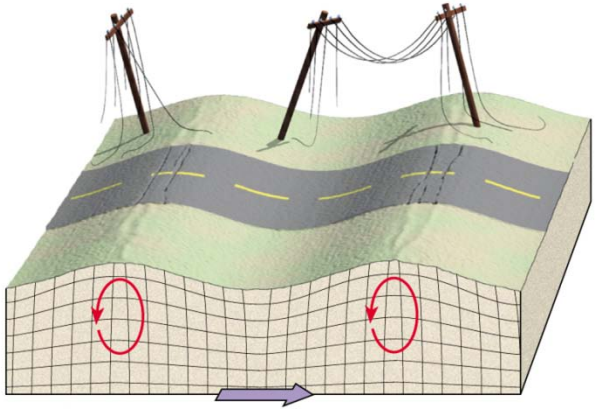
Body waves



Pressure (P) wave:
- Causes density perturbations
- Longitudinal wave

Shear (S) wave:
- Transverse wave
- Slower than P-wave (usually by a factor 2)

Rayleigh waves



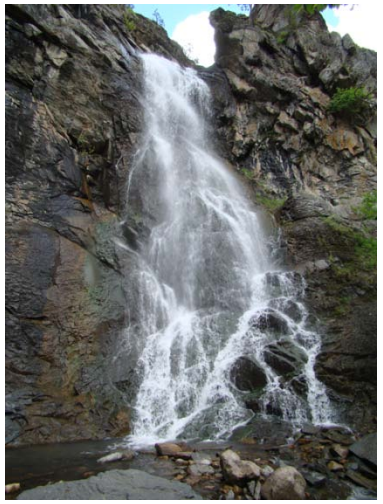
Rayleigh wave:
- Coherent superposition of pressure and (vertically polarized) S surface waves.
- Slower than S wave

Seismic Noise

Anthropogenic noise

Ocean waves

Rivers



Earth hum

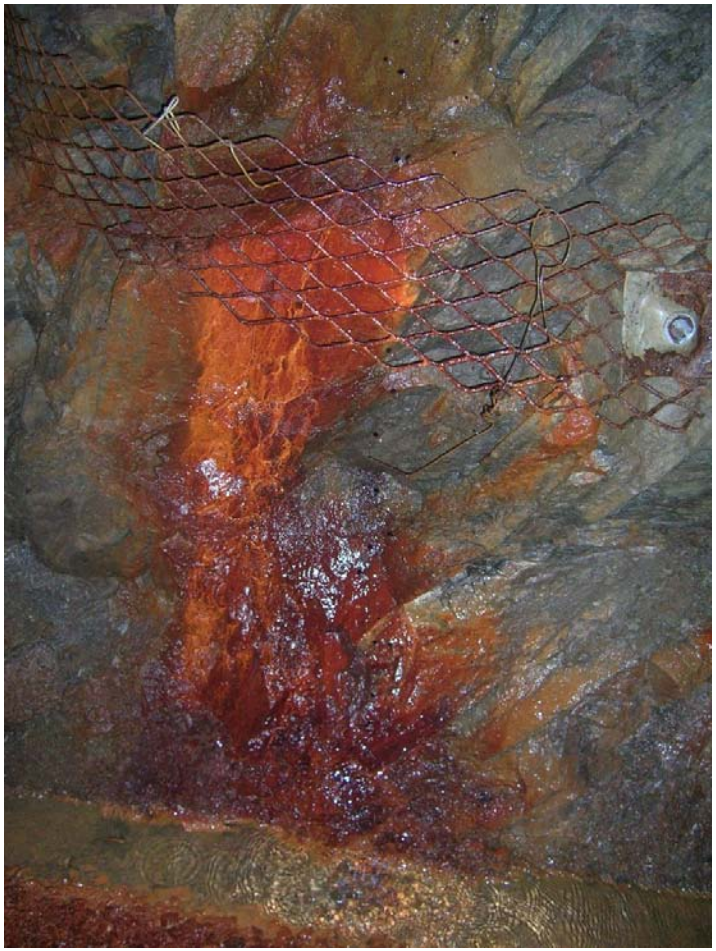
To understand seismic noise, you need to understand the sources of seismic waves and propagation effects.

Wind and atmosphere

Homestake Mine

Current extent of our mine access

Step 1: Drift Access



No access to any drift without safety inspection

Regularly check for loose rock at back and ribs

Bolting and grating

Additional support structures (cribbing)

Step 2: Environment

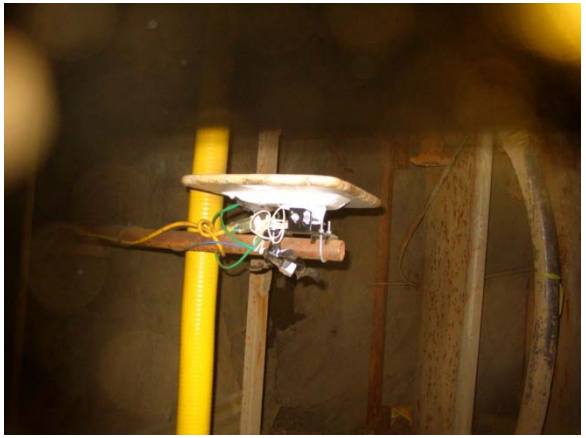
Humidity:
- RH close to 100% everywhere
- Protection of circuit boards and PCs
- Use of dehumidifier where necessary
- Solid enclosures for most sensitive instruments

Temperature:
- Below 0°C possible at shallow levels (e.g. 300ft)
- Higher temperatures at deeper levels (e.g. 25°C at 4100ft)
- Temperature can change considerably due to adjustments in the ventilation system

Step 3: Communication

Before

In between



After

Seismic array relies on fiber communication

10GByte of data per day per station (will increase by another factor 2)

Timing needs to be better than 0.1msec/sec (currently testing sub-microsec synchronization with GPS-time distribution system)

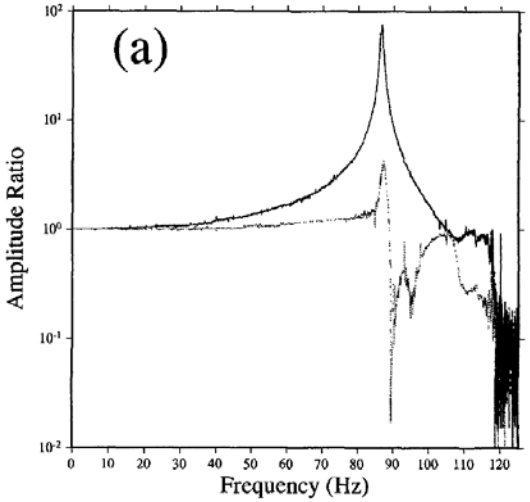
Step 4: Ground Preparation

Ensure proper coupling to hard rock (waste rock and cracks in drift walls due to blasting can prevent good coupling)

Ideally drill about 6ft into the tunnel walls

Provide a smooth surface

Ideally plaster seismometer feet to ground



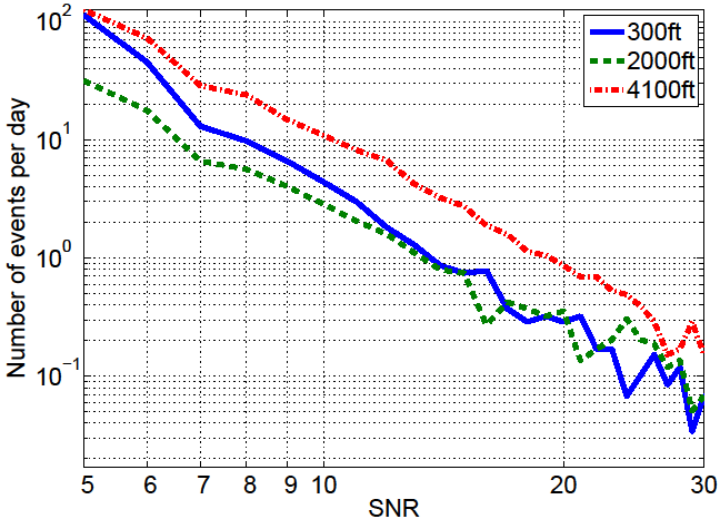
Pavlis and Vernon, BSSA 84/1243

Step 5: Shielding

- Prevent heat-driven air currents near seismometer (cover ground, use tight enclosures)
- Choose remote location
- Do not expose station to air currents
- Build multiple stages of panel walls (also acts as thermal stabilizer)

Holcomb and Hutt, *An Evaluation of Installation Methods (1992)*

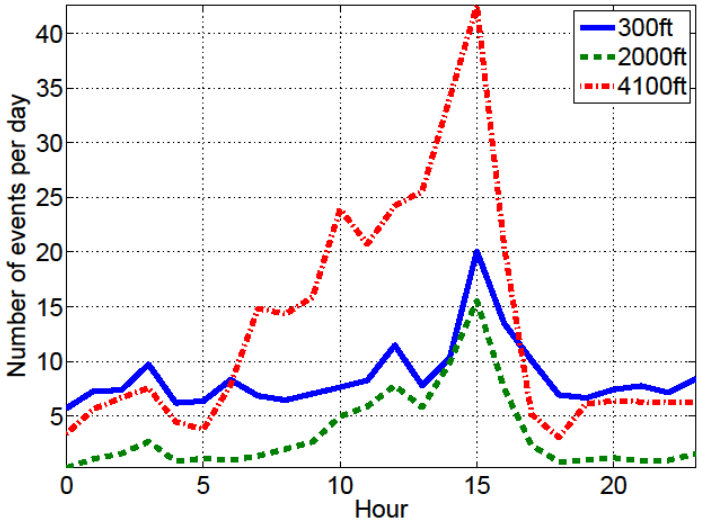
Seismic Events



$$\text{rate} \propto \text{SNR}^{-4}$$

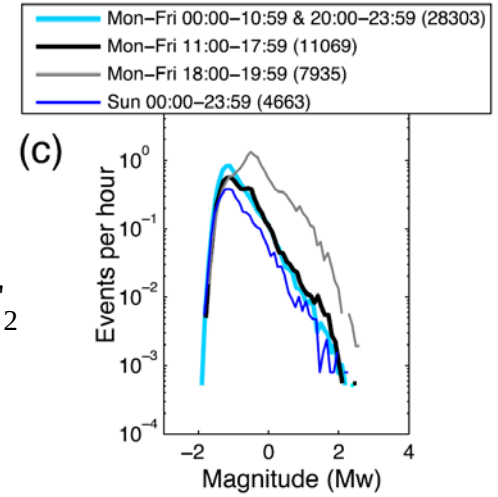
Gutenberg-Richter:

$$\log(\text{rate}) = C_1 * \text{SNR} + C_2$$



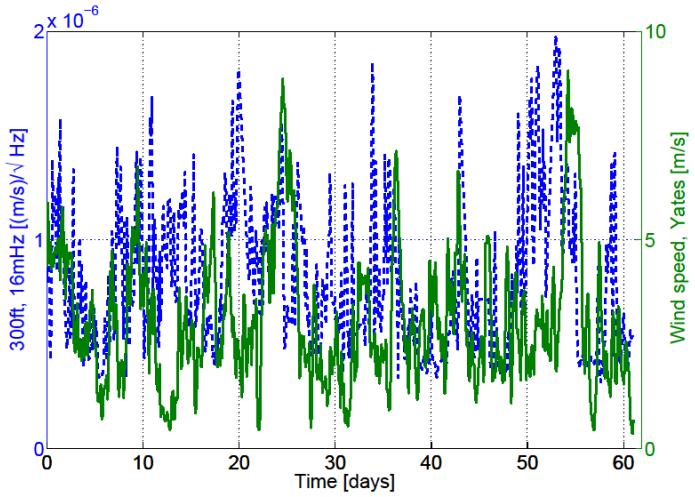
Event rates outside of working hours are very small (for events with SNR>4.9).

Geophys.Res.Lett.36,L10307

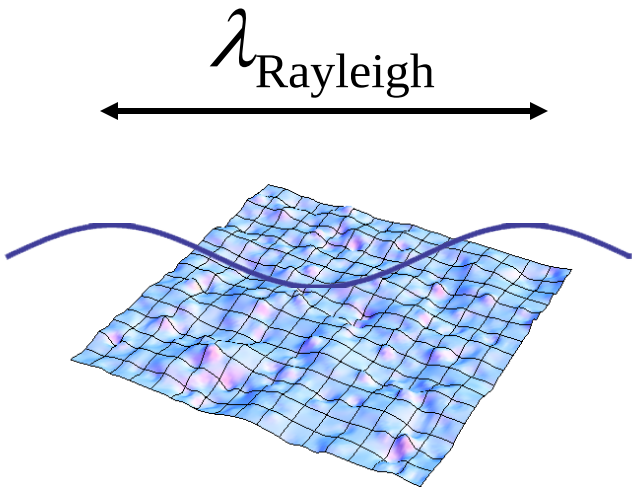


Event rates evolve at all magnitudes (and therefore frequencies) simultaneously

Wind-Generated Seismicity



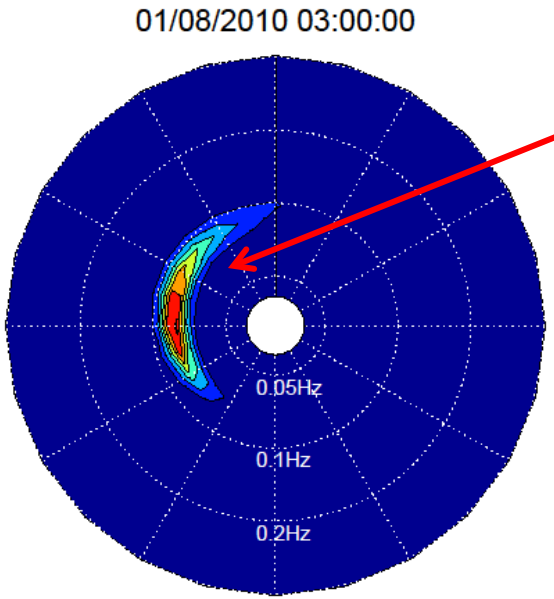
Coherence between wind and
- 300ft seismic data: 0.16
- 2000ft seismic data: 0.01



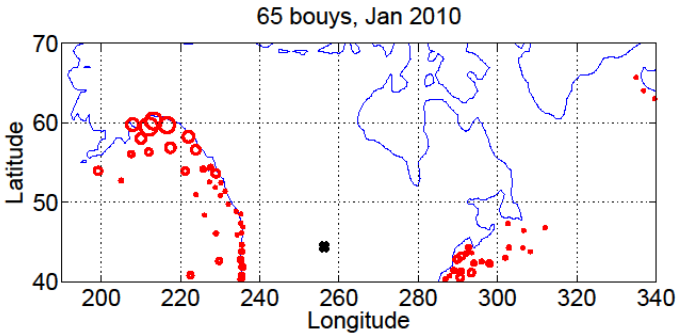
16mHz seismic spectrum has many sources (wind, anthropogenic, earthquakes). So one should not expect good coherence between any single source and seismic data.

Information about structures of size $d \leq \lambda$ decays exponentially: $\exp(-2\pi\, z / d)$

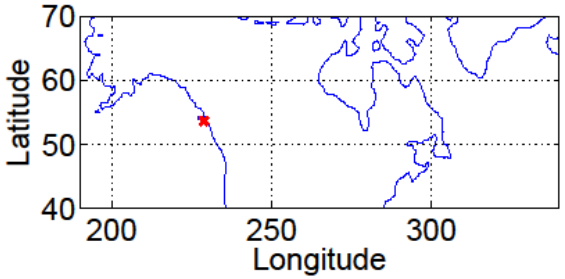
Secondary Microseisms



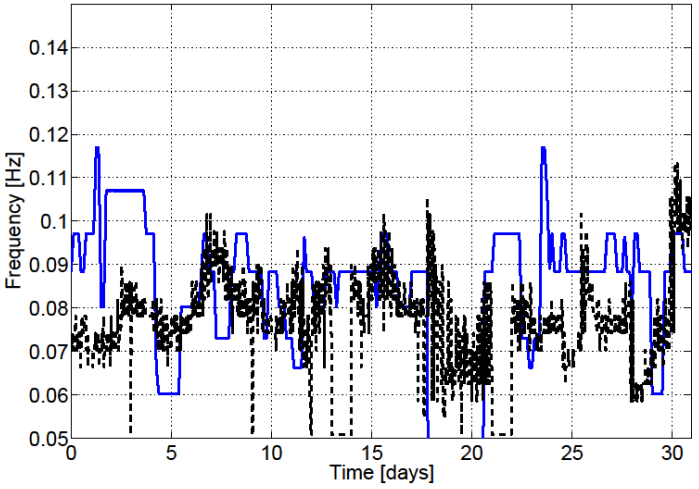
This wave field would produce weak standing waves. As it turns out, all fields that look like this also have a bad match with seismic data.



Blue: ocean wave
Black: microseismic peak



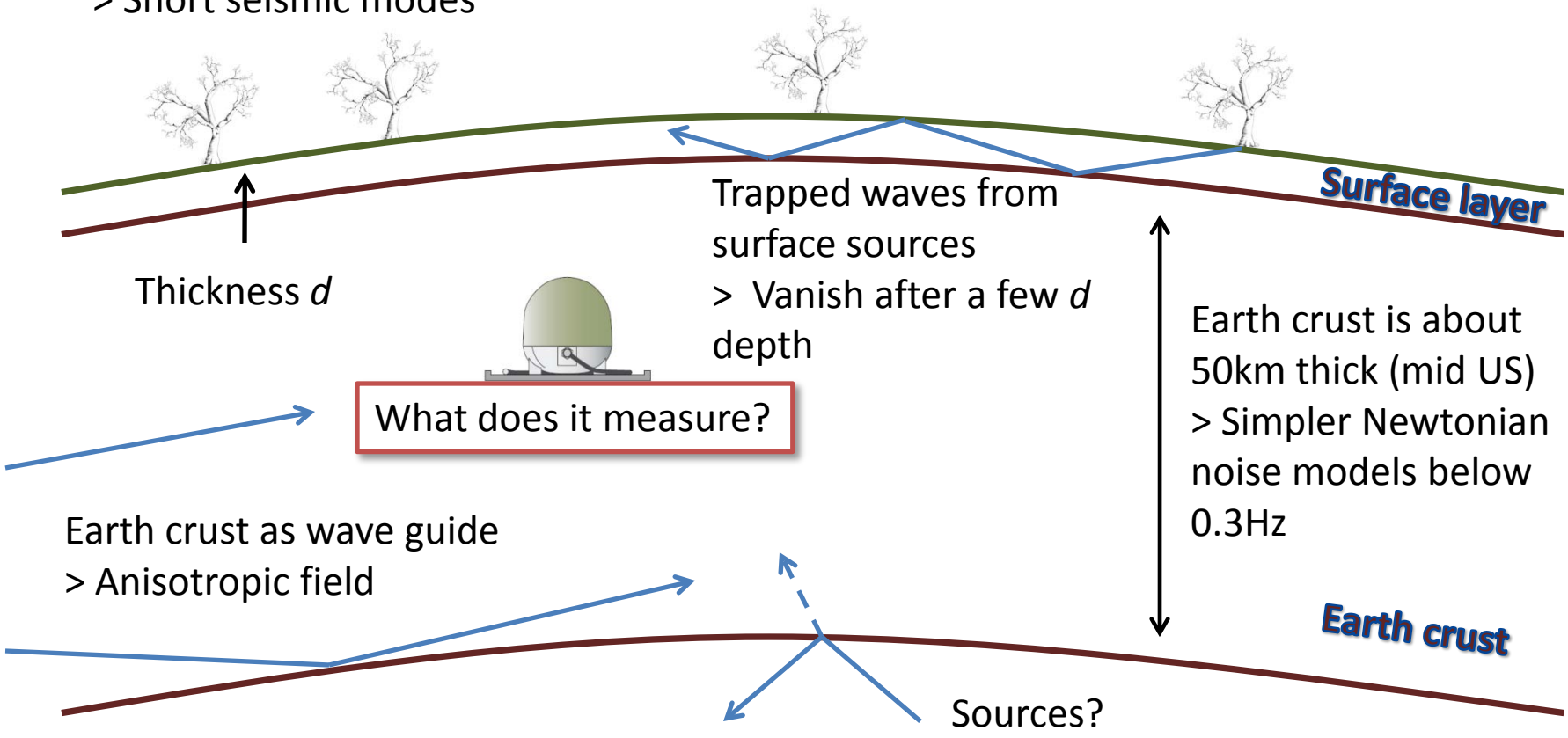
Take Wavewatch III model and search for ocean waves that have half the frequency of secondary microseism peak.



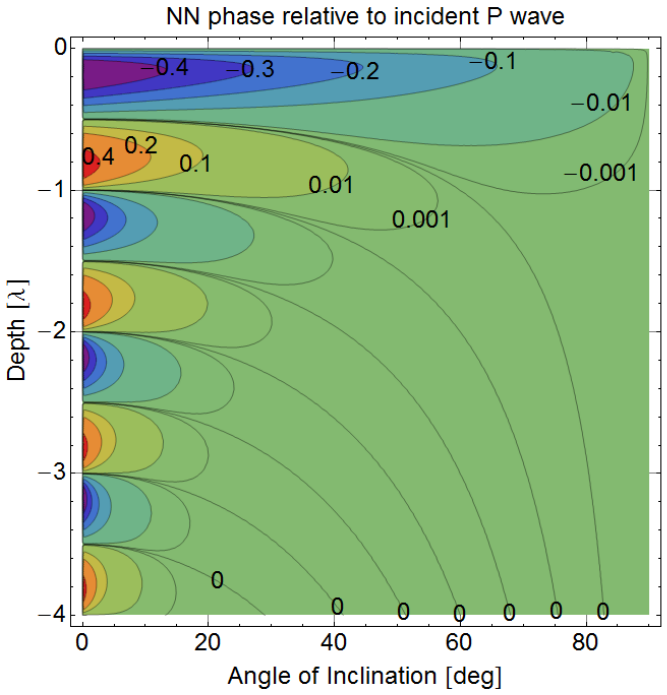
Seismic Sources

Dense population of surface sources
> Short seismic modes

Wind-generated seismicity uncorrelated at different trees



Surface Effects



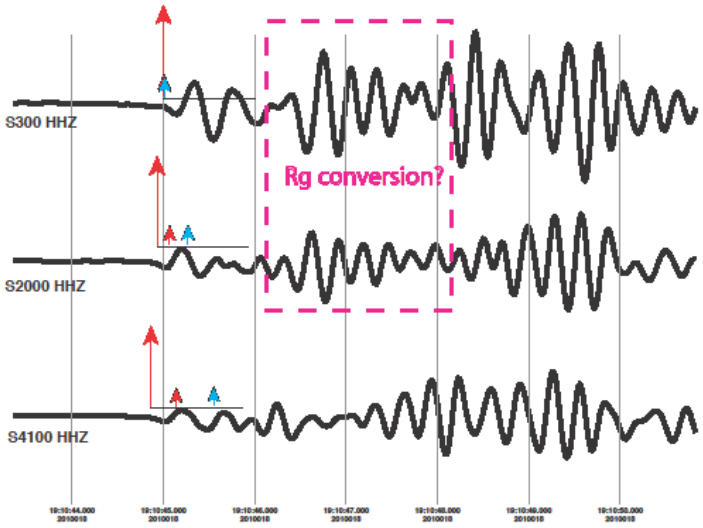
A plane surface induces a phase shift between incident seismic wave and Newtonian noise depending on propagation direction.

Infinite volume:

Gravity perturbations are proportional to seismic field at origin (if Q-value is sufficiently high).

$$\delta\vec{a}(t) \propto (2\vec{\xi}^{P}(\vec{0},t) - \vec{\xi}^{S}(\vec{0},t))$$

Wave from excavation blast

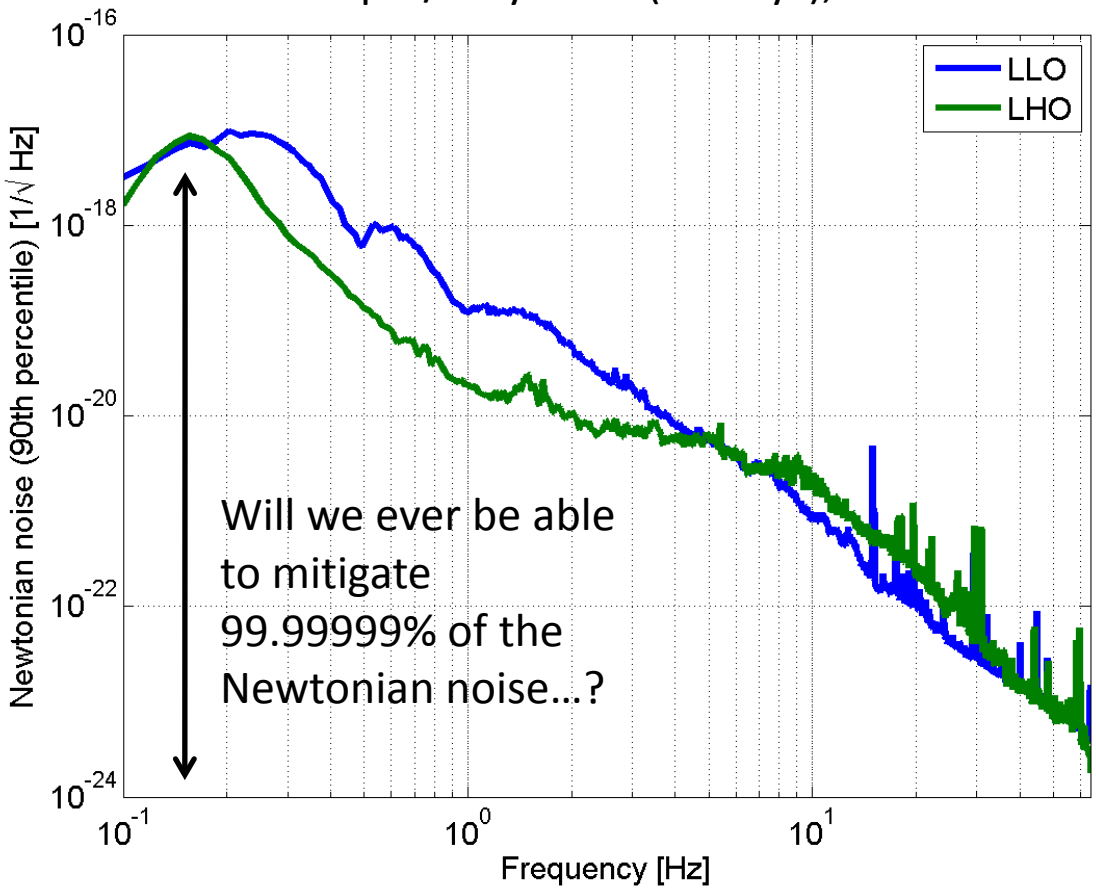


Mode conversion:

- P into S body waves and vice versa
- Body into surface waves (non-planar surface)

Newtonian Noise

Seismic spectra measured in
April/May 2010 (30 days), 10am



4 orders of magnitude noise mitigation required at 3Hz to achieve 10^{-24}

Correlation between test masses is taken into account (based on estimate of Rayleigh-wave speed).

LIGO

The following depends on many unknown variables.

Assumptions

1. Detector site is underground
   → neglect atmospheric NN above 1Hz
2. Detector site is chosen wisely
   → no large-scale scattering centers
   → below average seismic-noise spectra
   → plane surface
3. Sensitivity target is 10^{-24} per rtHz
4. Surface seismicity model from LIGO sites

Newtonian noise at 10Hz

Source mystery.
Easy to mitigate.
Seismometers already exist.
Zone of influence: about 200m $(\lambda / 2)$

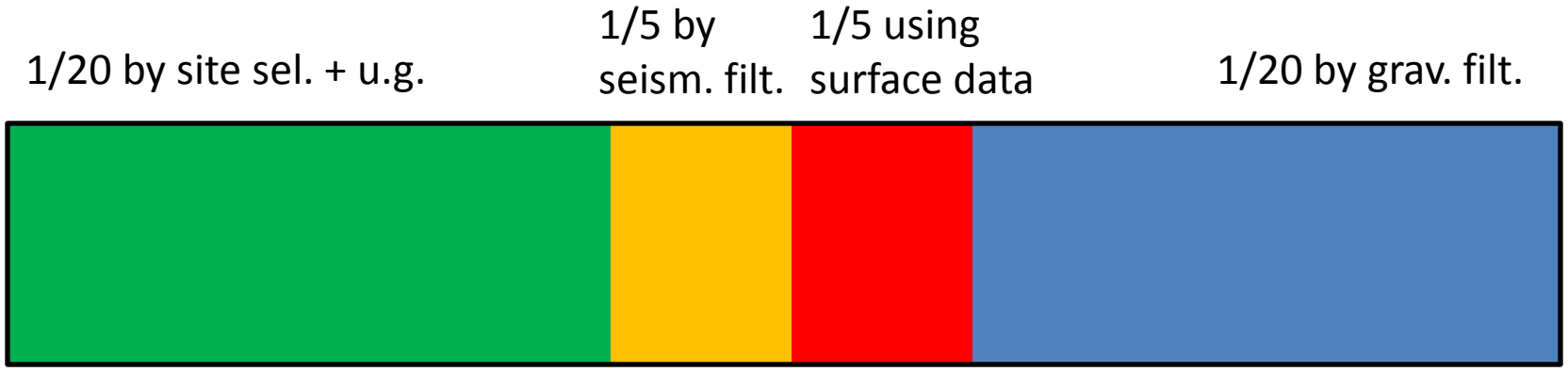
Seismic filter = local filter
Gravity filter = global filter
Zone of influence = distance to most distant significant density fluctuations

1/100 by site selection + underground

1/5 by seismic filtering

Newtonian noise at 1Hz

No source mystery.
Difficult to filter due to residual surface effects.
Seismometers already exist.
Zone of influence: about 12km (3λ)



Newtonian noise at 0.1Hz

No clue how to subtract it.
No need to go (deep) underground.
Atmospheric Newtonian noise is relevant.
Seismometers need to be developed.
Zone of influence: the whole Earth (400λ)

1/5 by site sel. 1/1000 by matched filtering 1/1000 by higher-order noise projection

Seismic=1,000 x Instr.

1/5 by site sel. 1/100 by seism. filt. 1/10000 by grav. filt.

Seismic=1,000,000 x Instr.

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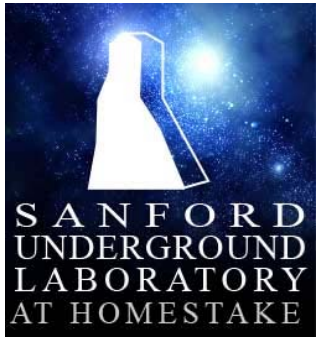
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