Seismic attenuation technology for the advanced Virgo gravitational waves detector

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Virgo is a 3 km arm-length interferometer designed to measure gravitational waves.

Global detector network:

LIGO - USA:
- 4 km Hanford
- 4 km Livingston

GEO 600 m - Germany

(LCGT 3 km - Japan)
(AIGO 4 km - Australia)
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\[ h = \frac{\Delta L}{L} \approx 10^{-22} \]

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Seismic noise limits low frequency sensitivity of Virgo through vibration of optical components

- Main optical components suspended by “Super-attenuators”
  - $10^{14}$ suppression $> 10$ Hz
- To improve strain by factor of 10:
  - *Optical benches also need seismic suppression*
  - 4 external
  - 2 internal
  - Requirement: $40$ dB $> 10$ Hz
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Seismic isolation systems also needed for future high-energy experiments

Figure 7: Layout of the $e^+$ and $e^-$ parts of a linear collider near interaction region.

[Sery A.A., Naploy O., 1995]
Seismic isolation systems also needed for future high-energy experiments

- Linear Colliders CLIC / ILC
  - Sub nano-meter interaction points
- Quadrupole movement (ATL law)

![Diagram showing layout of e+ and e- parts of a linear collider near interaction region.](image)

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![Diagram of particle movement](image)

[Sery A.A., Naploy O., 1995]

[Zang L., Lesourd M., 2010]
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- Free electron lasers
  - DESY
  - FLASH Groningen
Seismic Attenuation System

- Passive
- Active
A passive isolation system utilizes the transfer function of harmonic oscillators

- Harmonic oscillator is a 2nd order low pass filter
- Transfer function:
  - $=1$ @ low frequencies
  - $>1$ @ $\omega_0 = \sqrt{\frac{g}{l}} / \omega_0 = \sqrt{\frac{k}{M}}$
  - $\sim\frac{1}{f^2}$ above resonance frequency
- Virgo/LIGO measure from 10 Hz
  - Want 40 dB suppression $> a$ few Hz
  - $f_0 \approx 0.3$ Hz $\Rightarrow l \approx 3$ m
  - Long pendulum / low stiffness and high mass
- Or, use short inverted pendulum and geometric anti-springs
Inverted pendulums are used for the horizontal attenuation stage

- Gravity acts as an anti-spring
- Maraging steel flex joints provide stiffness, $k$
- Tunable in eigenfrequency by adjusting the supported mass
- Counter weights can be tuned to adjust center of percussion

\[ \omega_0 = \sqrt{\frac{k}{M} - \frac{g}{l}} \]
Geometrical anti-springs are used to provide vertical attenuation

- 8 maraging steel blades in pairs
- Opposite blades push against each other
  - *High pressure in radial direction*
  - *Low vertical stiffness in equilibrium position*
- Low eigenfrequency (~300 mHz)
- Still capable of supporting high masses (~320 kg)
- Strong filtering (>40 dB @ 10 Hz)
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Movie GAS resonance
Feed-back control system used to actively damp resonant frequencies

- Order of magnitude damping of resonant frequencies required
- Calculations performed on Linux PC
- Feed-back done with electromagnetic actuators
- Sensing relies on displacement sensors and accelerometers
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Sensing of bench motion for resonance damping

- Linear Voltage Displacement Transducers (LVDT)
  - DC -> a few Hz
  - ~ 1 nm sensitivity
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- Linear Voltage Displacement Transducers (LVDT)
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- Accelerometers (Geophones)
  - Eigenfrequency ~ 1 Hz
  - 0.1 -> 100 Hz
  - Motion 4 orders of mag. above noise level
Putting it all together...

- Optical bench
- Balance mass
- 6 x LVDT
- 6 x geophones
- Vertical filters
- Inverted pendulum
- Realtime linux PC
- Virgo 18 bit ADC
- Cabling
Peaks at higher frequencies are understood internal modes that can be damped

- Eddy-current dampers
- Horizontal and vertical dampers tunable to mode frequencies

15 Hz

37 Hz
Eddy-current dampers reduce internal mode vibrations below requirements.
Active control system can damp resonant frequencies by an order of magnitude.
Summary

- Seismic motion
  - *Induces noise in gravitational waves detectors*
  - *Seismic noise also an issue in (future) high-energy experiments*
- Optical bench - Seismic attenuation system
  - *Passive*
  - *Based on harmonic oscillator transfer functions*
  - *Inverted pendulum and anti-springs used at low $f_0$*
  - *Attenuation of 40 dB available above 10 Hz*
  - *Resonant frequencies damped by active feedback system*
  - *Internal modes removed by tunable eddy-current dampers*
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Installation in Virgo ⇒ September 2011