Newtonian Noise Simulations

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Terrestrial Very-long-baseline atom interferometry workshop

Overview

Goal: Briefly summarize state of Newtonian Noise simulations

- Background – What is Newtonian Noise?
- Current studies – Sources and models
- Simulations – Time domain, Frequency domain
- What's next?

What is Newtonian Noise?

- Density perturbations affecting acceleration of test masses
- Modeled through continuity equation

$$\delta\phi(\boldsymbol{r}_0) = G\int dV\,\frac{\delta\rho(\boldsymbol{r})}{|\boldsymbol{r}-\boldsymbol{r}_0|}$$

Sources

Anthropogenic

Human foot-fall

Motors/pumps

Vehicles
Trains/Planes/Automobiles

Earth generated

Seismic:
Long-duration standing waves
Transient impacts (earthquakes)

Atmospheric:
Pressure/Infrasound waves

Atmospheric:
Temperature gradients

Anthropogenic

Characteristics and Concerns

Human foot-fall*	Spurious, ~1-3 Hz frequency band, difficult to control
Motors/pumps	US 60 Hz – 120 Hz, UK 50 – 100 Hz, easily monitored
Vehicles Trains/Planes/Automobiles	Difficult to control and track

* Or Rat foot-fall (See poster by John Carlton, KCL)

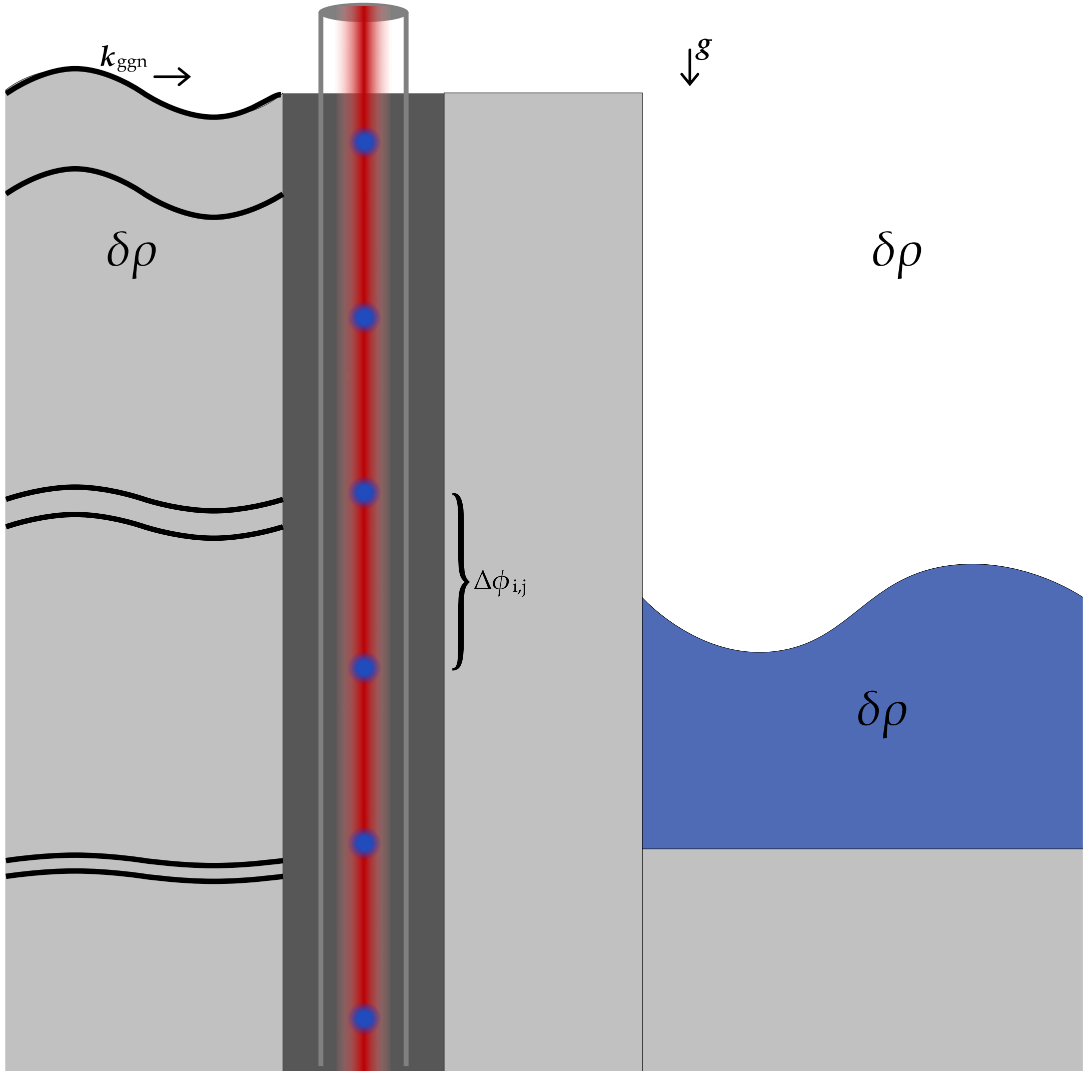
Earth generated

Characteristics and Concerns

		Characteristics and Concerns
Seismic: Long-duration standing waves, Transient impacts (earthquakes)	→	mHz – 10 Hz, seasonal variation, spurious events
Atmospheric: Pressure/Infrasound waves	→	mHz – 10 Hz, seasonal variation, scale sharply with low frequency
Atmospheric: Temperature gradients	→	Dependent on turbulence

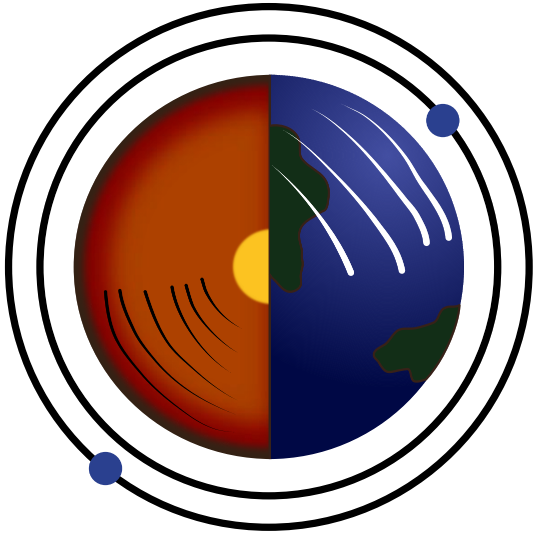
Note: Gravity gradient noise (GGN) usually in reference to indirect coupling

Earth Generated



Workshop dedicated to investigating the interplay between Earth Sciences and atom interferometry

Atom Interferometric Sensing of Earth's Spheres



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Natural Environment Research Council

Investigations

- Research into Newtonian Noise strongly initiated by laser interferometry gravitational wave community

  Saulson. Phys. Rev. D **30,4**, (August 1984)

  Hughes, Thorne. Phys. Rev. D **58**, 122002 (1998)

  Teviet Creighton. 2008 *Class. Quantum Grav.* **25** 125011

  Harms. Living Reviews in Relativity **Volume 22**, Article number: 6 (2019)

- First investigations for atom interferometry advanced by MIGA also being investigated by MAGIS and VLBAI

  MIGA. Proc. SPIE 9900, Quantum Optics, 990008 (29 April 2016)

  Mitchell et al. 2022 *JINST* **17** P01007

Simulations

1. Choose a source
2. Derive gravitational potential perturbation
3. Simulate AI phase shift in response
4. Study output

$$\Delta\phi = k_{eff} g T^2 \rightarrow k_{eff}(g + \delta g) T^2$$

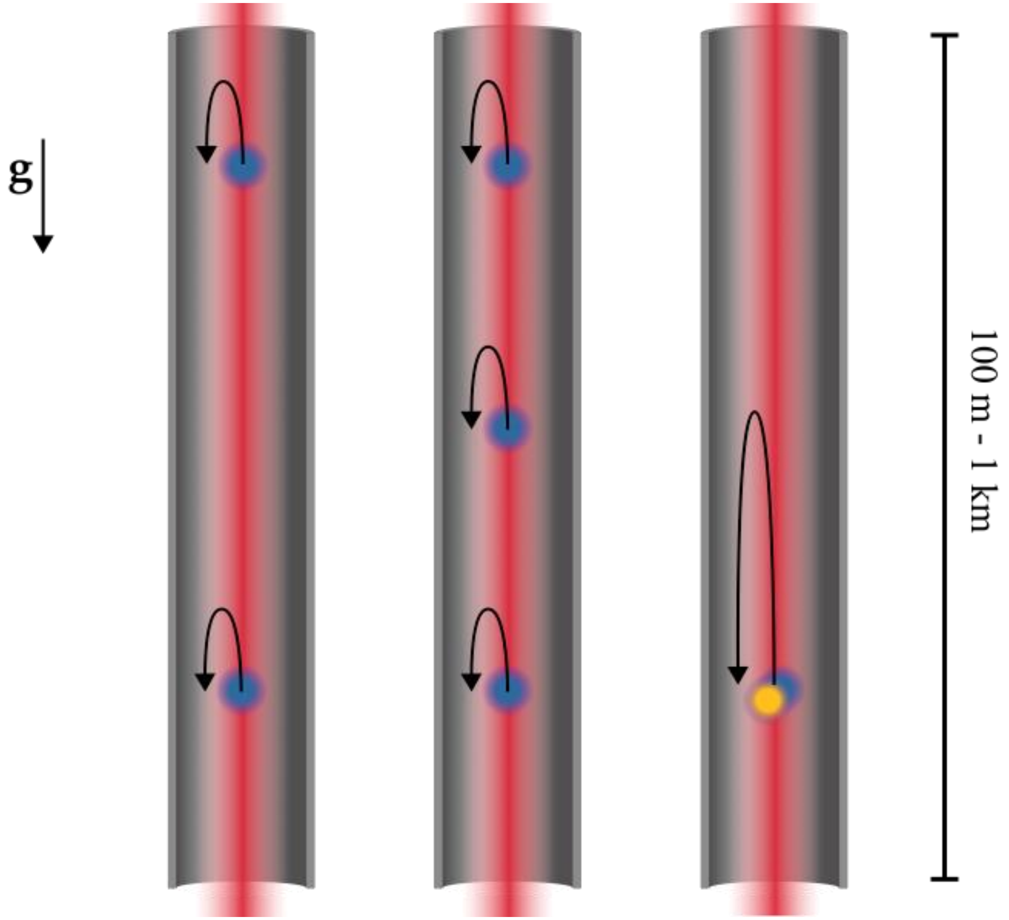
Models give us intuition on experimental parameter scaling

Simulation outputs informs necessary passive levels and site requirements

Highlights needs for extra monitoring systems

Used to understand feasible methods of mitigation

Simulations



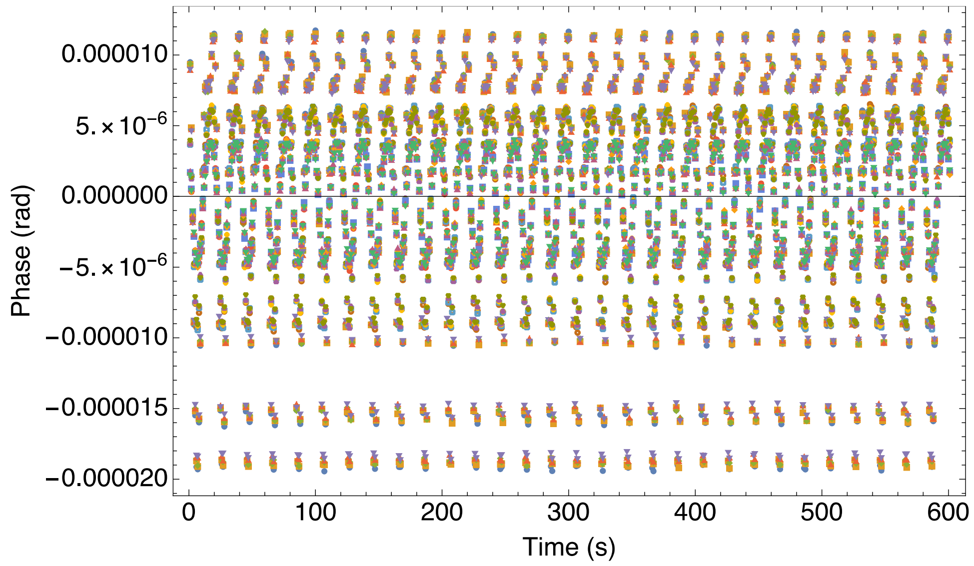
$$\Phi^{(i)}_{\mathrm{GGN},m} = \sum_a \xi_a \left(\widetilde{A}_a \exp\left(-q\frac{\omega z_i}{c_H}\right) + \widetilde{B}_a \exp\left(-\frac{\omega z_i}{c_H}\right)\right) \cos\widetilde{\phi}_{a,m} \,.$$

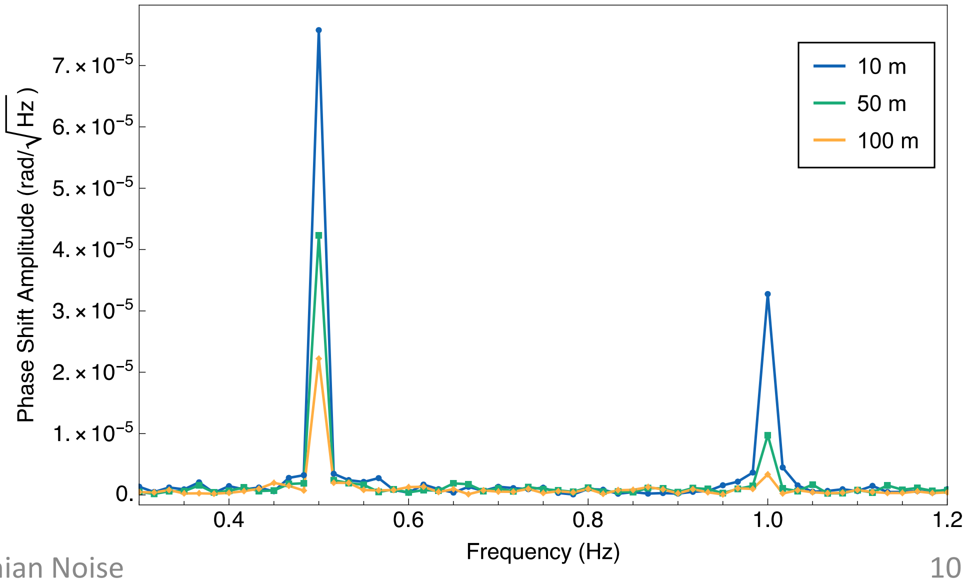
$$\widetilde{A}_a = -\frac{16\, G\, \pi\, \rho_0}{\omega_a^2\,(s^2-1)}\, n\, k_A q(1+s^2) \sin\left(\frac{\omega_a T}{2}\right)^2$$
$$\widetilde{B}_a = \frac{8\, G\, \pi\, \rho_0}{\omega_a^2\, q\,(s^2-1)}\, n\, k_A(1+(1+2q)s^2) \sin\left(\frac{\omega_a T}{2}\right)^2$$
$$\widetilde{\phi}_{a,m} = \omega_a\,(T + m\,\Delta t) + \widetilde{\theta}_a\,,$$

Badurina, et al. Phys. Rev. D **107**, 055002

Simulations guide us

- Methods predominantly used:
  - Fourier analysis and power spectral densities
  - Filtering via Weiner filters
  - Kalman filtering for active feedback and feedforward
- Serve to derive strategies for measuring and controlling





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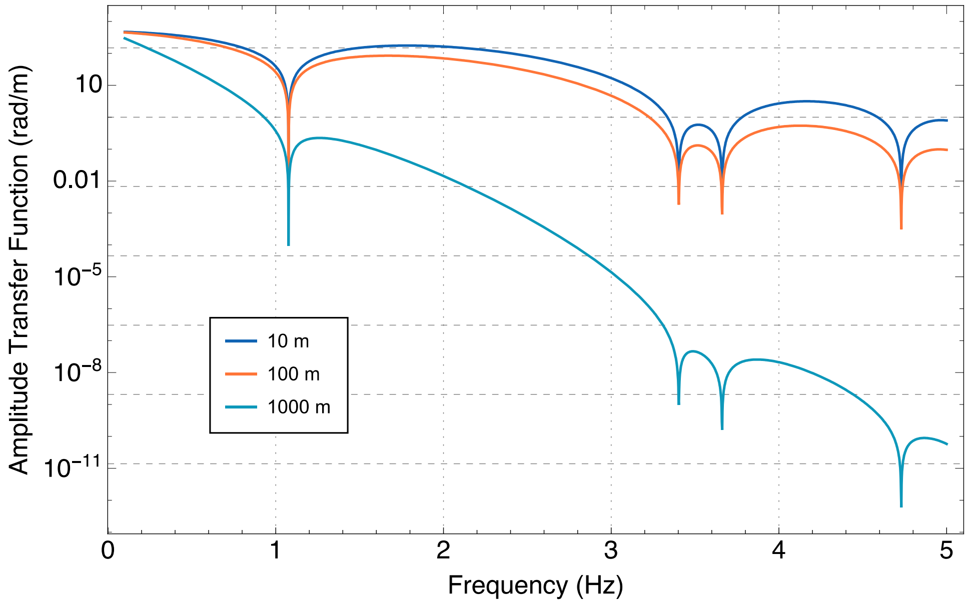
What's next?

- Generate general formalisms for use with input spectra
- Find transfer functions for various atom interferometry configurations
- Understand the atmospheric effects and turbulence more robustly



Summary

- Newtonian noise and specifically GGN is a crucial aspect of very-long-baseline AI detectors
- Understanding impact theoretically and experimentally helps us to prepare for data analysis
- Simulations provide framework to guide designs and instrumentation

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MAGIS-100

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