Newtonian-noise modeling and mitigation for Cosmic Explorer

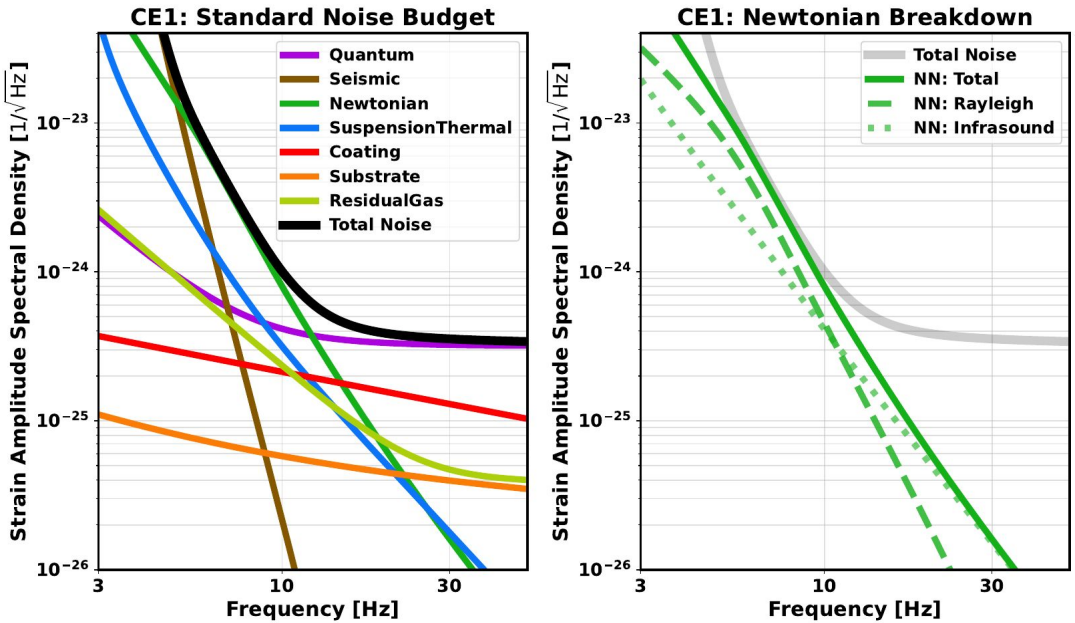
XGCD · Next Generation Collaborative Design · 19 October 2026



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with material from Ravi Kumar (U. Minnesota)
for the joint LIGO and CE Newtonian-noise working group

CE-G2600073

CE needs ~20 dB less Rayleigh-wave Newtonian noise than projected no-mitigation LIGO Hanford levels



Requirement: Newtonian noise (NN) below the CE curve (green), 90% of the time, after active cancellation.

20 dB

Rayleigh-wave NN suppression needed, relative to LIGO Hanford

passive(f) + active(f) ≥ 20 dB at every frequency. 20 dB = 10× lower NN amplitude.

Plan, as of ~2025:

10 dB

passive: building and basement design

10 dB

active: feedforward cancellation using seismometer arrays

Likely update to the plan based on work over the last ~year: Set the requirements for active and passive in a frequency-dependent way (see later slides)

CE R³ draft, Newtonian noise (CE-E2500007) §2–3, Fig. 1 · Hall et al., PRD 103, 122004 (2021)

Not included in this presentation

Other types of Newtonian noise sensors than seismic arrays. Groups are working on

- Torsion sensors (eg. TorPeDO at ANU)
- Rotation sensors (eg. Newtonian Rotation Sensor at UWash, or sensor at UWA)
- Fiber strainmeters (eg. DAS installed at LIGO Hanford by Helmut Schmidt U)

Other areas of Newtonian noise simulation and testing that have not yet been folded in to the estimate of NN at CE. Groups are working on

- Adding sensor noise to additional SpecFEM simulations
- Understanding wind-induced seismic noise, including realistic topographies near KAGRA

Please see summaries of all the group's exciting work at the Joint LIGO/CE NN Notes Document, CE-T2500020

What CE asks of the site

Wave speed sets basement size

A basement works once the Rayleigh wavelength is ≲ ~5× its depth. At 250 m/s: 50 m at 5 Hz, 25 m at 10 Hz. Faster ground: scale everything up.

Seismic environment

No worse than LIGO Hanford (provisional target).

Noisier sites may require larger / different basements, or more sensors in an array

Wind

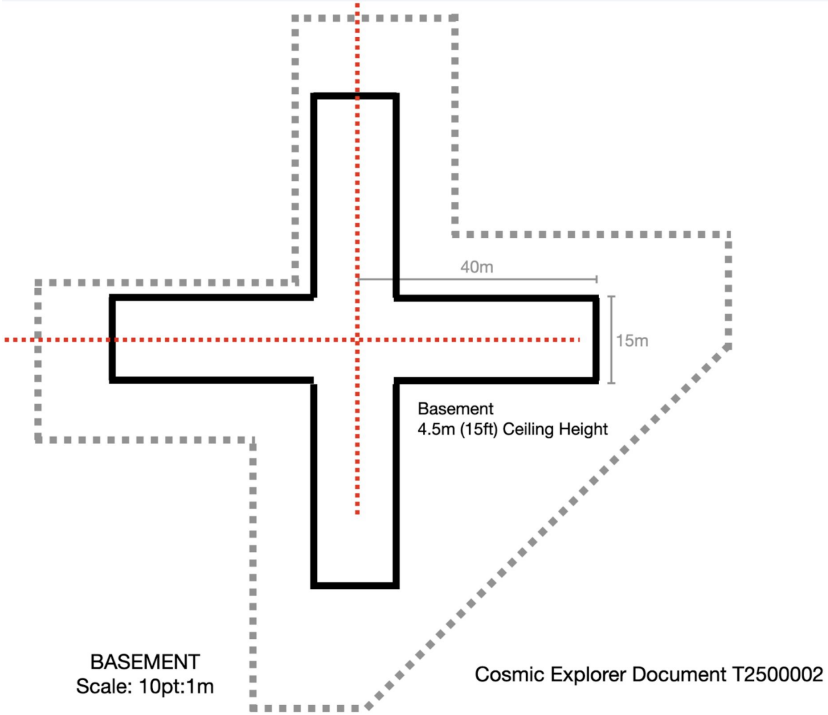
90th-percentile wind ≤ 10 m/s at 10 m height, in every month.

Reference geology

Shear-wave speed 200–500 m/s near the surface, so Rayleigh speed ≈ 180–460 m/s.

Still to characterize at candidate sites: velocity profiles (surface-wave surveys, boreholes [although we hope to avoid these]) · 1–30 Hz ambient noise spectra · layering · wind at several heights; long-term 1–30 Hz arrays at finalist sites.
To do by NN team: describe what data needs to be collected (eg., time series in addition to spectra from seismometers, at 128 Hz minimum data rate) for already-planned Site Eval measurements. Understand what we can say about NN from those already-planned measurements. Propose further measurements if there are gaps in what we'll be able to learn (eg., more dense seismic array in the general vicinity of the candidate site). Understand if we can "get away" with no boreholes at Site Evaluation measurements, and in final CE.

Baseline: basements plus feedforward arrays



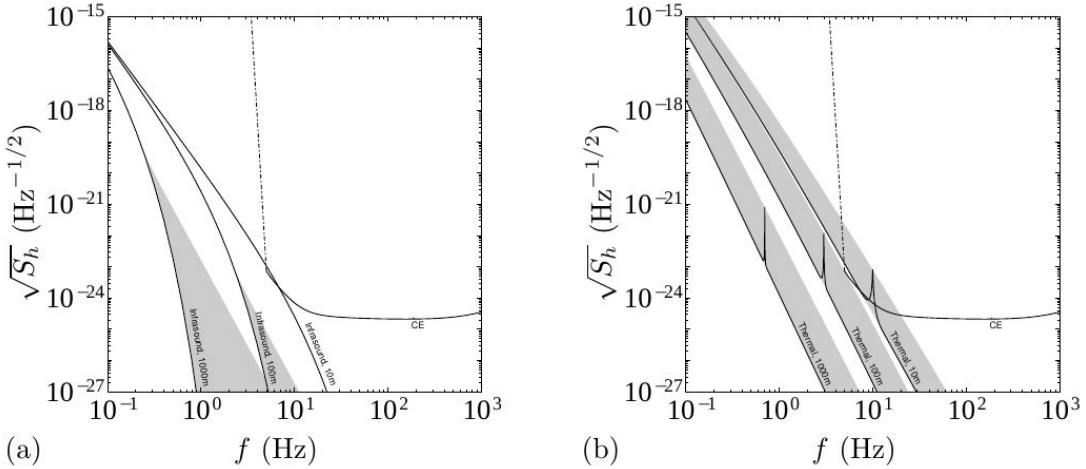
1. Seismically quiet, well-characterized site
2. Halls shaped to keep wind turbulence away
3. Basement excavation under each test mass
4. Surface seismic arrays for feedforward

Reference basement

- Plus-shaped, concrete-walled, 4.5 m deep
- Arms 15 m wide, 40 m from centre to tip
- Test mass 1 m above ground (~5.5 m above floor)
- Keep walls, floors, columns away from test masses

CE R³ draft, Newtonian noise (CE-E2500007) §3, §3.3.1, Fig. 2 (from CE-T2500002)

Atmospheric NN: a surface-site concern



Estimated NN in CE from (a) infrasound and (b) wind-carried temperature changes, with no air motion within 10 m, 100 m or 1 km of the test masses.

Surface sites: temperature-driven NN might, pessimistically, exceed CE's design noise at 5–10 Hz.

Underground: the authors Wang and T.Creighton recommend ≥ 100 m depth for ET.

CE plan
Experimental halls that keep the air still within ≥ 5 m of each test mass. Not yet modeled (readiness level 2/3).
No active mitigation planned at this time.
To do: understand impact of 'outbuildings', and whether they can help keep moving air farther from experimental halls and test masses.

W. Wang & T. Creighton, arXiv:2505.05690 (2025), Fig. 5 · CE R³ draft, Newtonian noise (CE-E2500007) §2.2, §3.2

Passive mitigation of seismic NN: full 3-D elastic simulation in SPECFEM3D

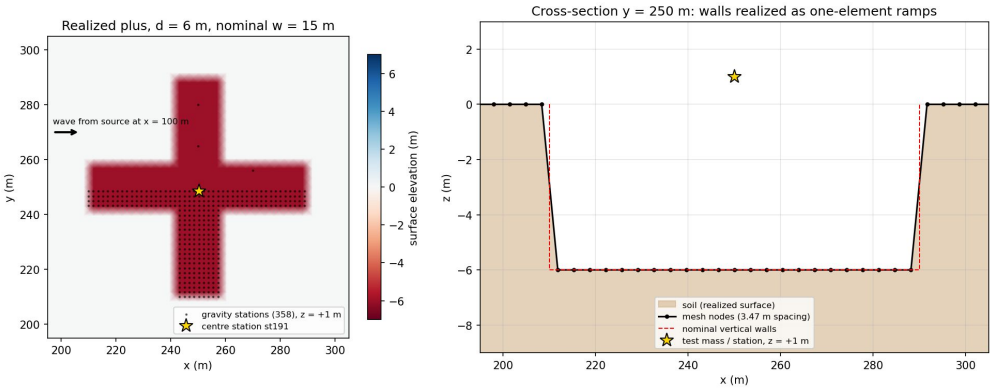
Source
Vertical point force, 10 Hz Ricker pulse, 150 m west of the basement; 1 s simulated

Wavefield
SPECFEM3D (open-source spectral-element code): P, S, Rayleigh waves, all scattering

Gravity readout
Volume integral at the test mass, every step, on GPU

Reduction factor R
NN amplitude with ÷ without basement (along-arm δg_x). 0.32 = 10 dB, 0.1 = 20 dB

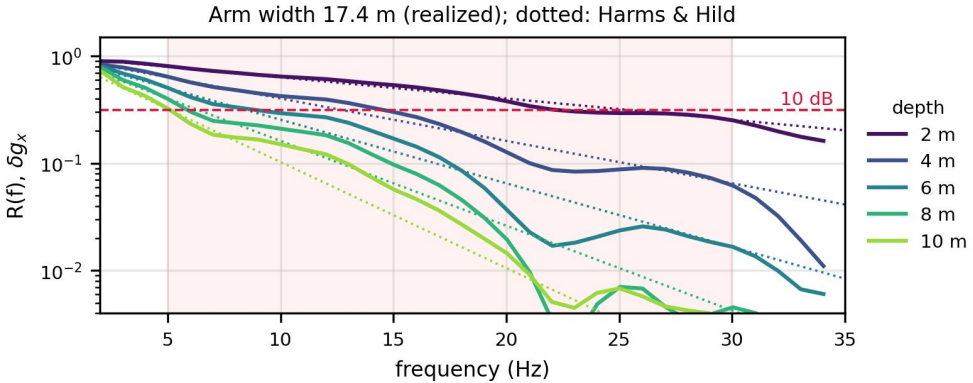
- Basement = ground surface lowered inside the plus (an open pit)
- 500 × 500 × 60 m of uniform ground: P / S speeds 600 / 300 m/s, 1800 kg/m³
- Test mass 1 m above original ground level, as in the requirement
- Mesh elements 3.47 m across, 1 m tall.
- Walls snap to element edges, so a nominal 15 m arm is 5 elements = 17.4 m wide, with sloped walls (right)



6 m deep, nominal-15 m plus as meshed: walls slope across one element; dots are the 358 virtual test-mass positions, 1 m up.

specfem-nn (git.ligo.org/NewtonianNoise/specfem-nn), notebooks 05–10 · method: CE R³ draft, Newtonian noise (CE-E2500007) §4.2

At 6 m: ≥ 10 dB at every frequency above 9 Hz



Dotted: Harms & Hild analytic estimate (removed soil only, uniform ground); matches below ~8 Hz. The 8–10 m dips near 22–28 Hz are too uncertain to quote.

Target: passive + active ≥ 20 dB at every frequency; the basement's share is 10 dB. Down to 5 Hz that takes ~10 m depth with wide arms (mesh-sensitive).

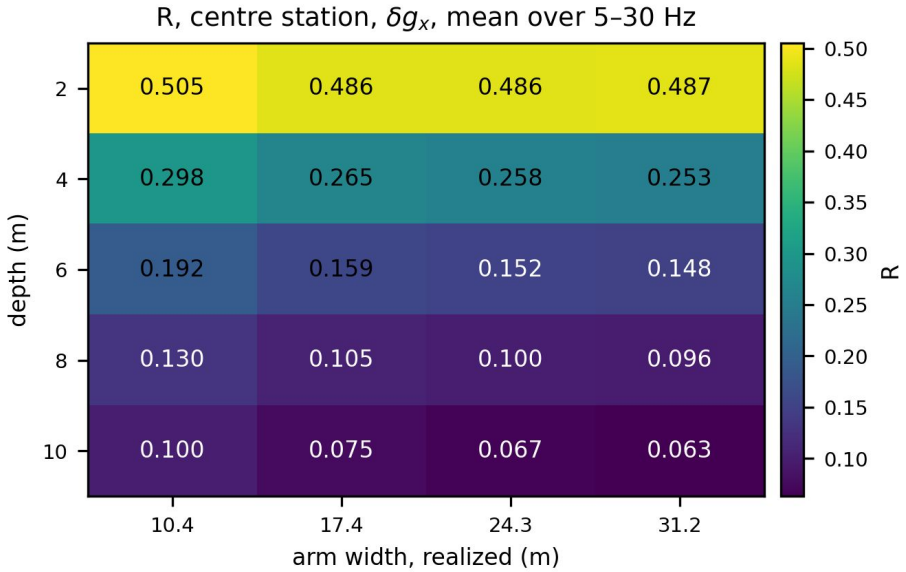
5–10 Hz	**≥ 10 dB only above 9 Hz**
10–20 Hz	**≥ 10 dB at every frequency**
20–30 Hz	**≥ 10 dB at every frequency** detail provisional

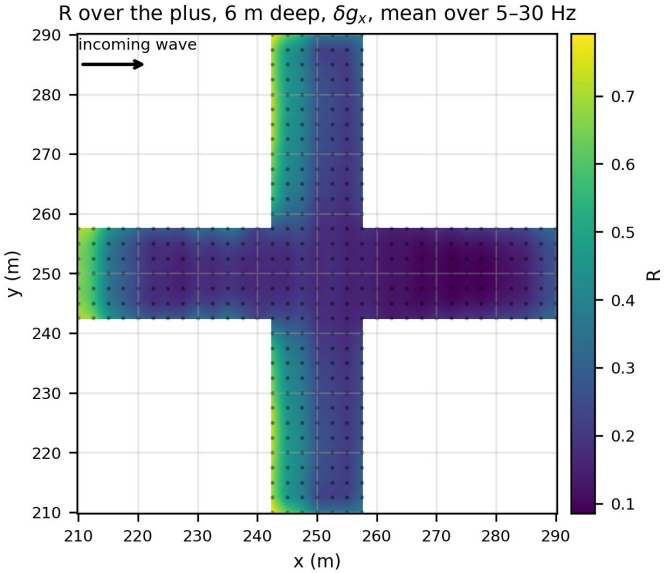
CE reference basement, 4.5 m (interpolated)
≥ 10 dB only above ~12–14 Hz

Preliminary one source direction · uniform ground · 20–30 Hz detail provisional · 4.5 m point interpolated · not yet applied to a real site noise spectrum

specfem-nn (git.ligo.org/NewtonianNoise/specfem-nn), notebook 10 (6 m deep, 17.4 m arms, centre point; per-frequency R(f), 1 Hz resolution) · Harms & Hild, CQG (2014)

Bigger helps; protection varies across the plus





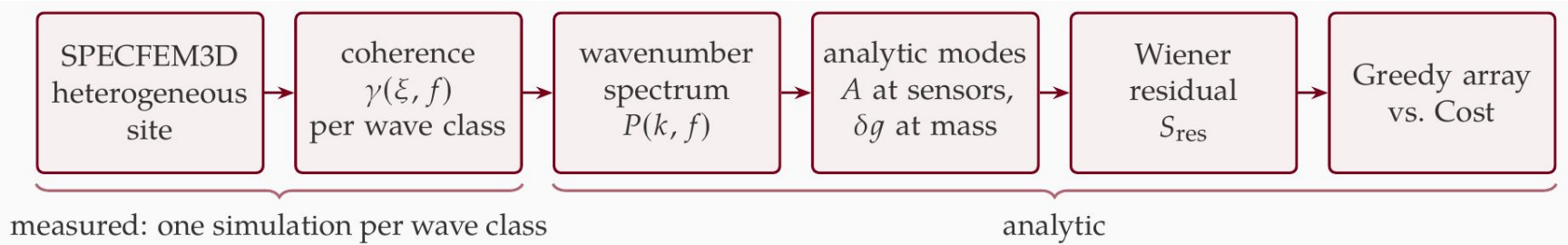
By size: centre value, mean over 5–30 Hz. Deeper always helps through 10 m; wider helps most at depth.

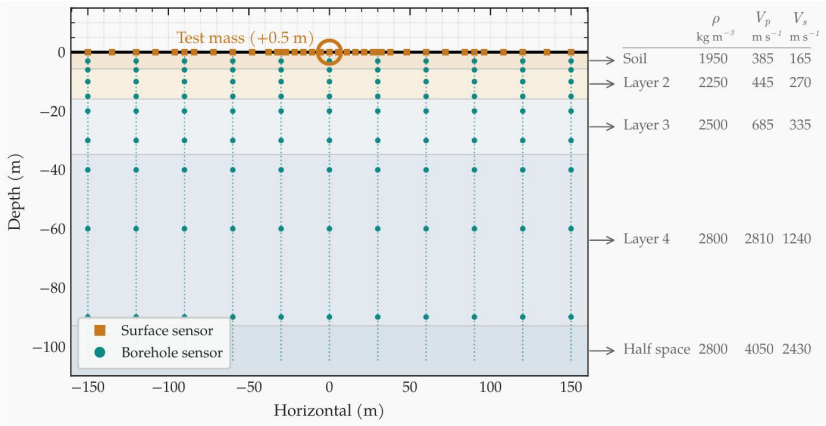
Across a 6 m plus: one source from the west. ~0.1 on the sheltered east arm, $\gtrsim$ 0.6 at walls facing the wave. Real noise comes from all directions.

Recall: smaller R means less residual noise

specfem-nn (git.ligo.org/NewtonianNoise/specfem-nn), notebook 10 · depth × width scan (3.5 m mesh) and dense map (413 points, 5.2 m mesh)

Active mitigation: designing arrays from site geology

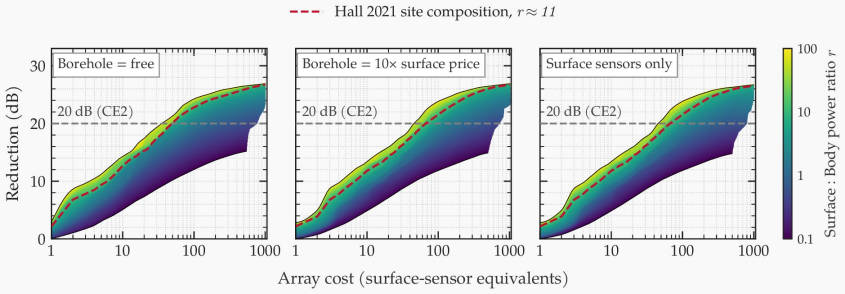


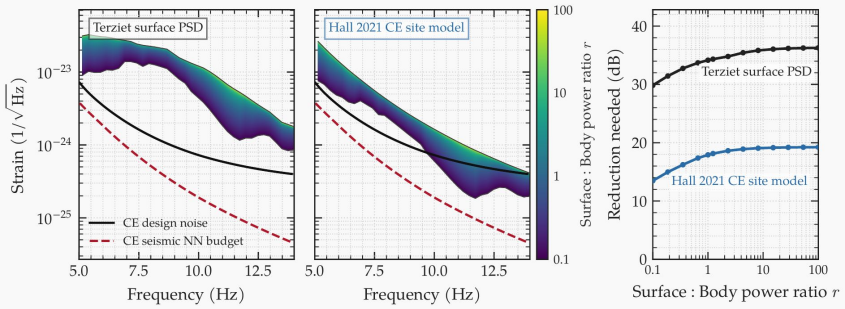


- SPECFEM3D measures how coherent each wave type is in a layered model of Terziet (an Einstein Telescope (ET) candidate site) with random variations
- New Rayleigh / Love wave injector; built-in plane-wave injection for body waves
- Test mass 0.5 m up; L-4C geophone noise at signal-to-noise 15, as in ET array studies

R. Kumar, slides 4, 7, 20 and working notes §1–4 (Sept 2026) · Bader et al. 2022

Arrays alone: what the full 20 dB would take





Hall et al. 2021 site model: about 50–70 sensors reach 20 dB. If body waves dominate the field, no array up to 1000 sensors gets there.

Reduction needed from arrays alone: 13–19 dB with the Hall site model, 30–36 dB with the noise measured at Terziet. *A basement lowers the share the arrays must carry*.

Caveats: one random version of the ground; results depend on the assumed sensor noise. These dB are summed over three axes at the worst frequency in 5–14 Hz.

D · SHARED TOOLING

SPECFEM3D for NN: what our versions can do

Gravity readout

- GPU readout at hundreds of points; memory flat with point count
- Double-precision GPU readout for a few test-mass targets
- Faster gravity setup; CPU-readout switch for cross-checks
- Fixed: GPU runs wrote all-zero gravity output

Geometry and ground

- Basements as a lowered ground surface, any footprint
- Exact-geometry meshing: vertical walls for square and rectangular recesses (round and elliptical as steps), and buried cavities
- Layered site profiles; random velocity variations

Incoming waves

- Point sources (the passive results so far)
- Plane Rayleigh and Love waves
- Plane body waves (built-in injection, three fixes)
- Wave injection on the GPU

Running at scale

- Checkpoint and restart for long runs
- Current with SPECFEM3D's development code (Oct 2026)
- Build recipe; config, batch and analysis pipeline
- Fixes to report to the SPECFEM3D developers

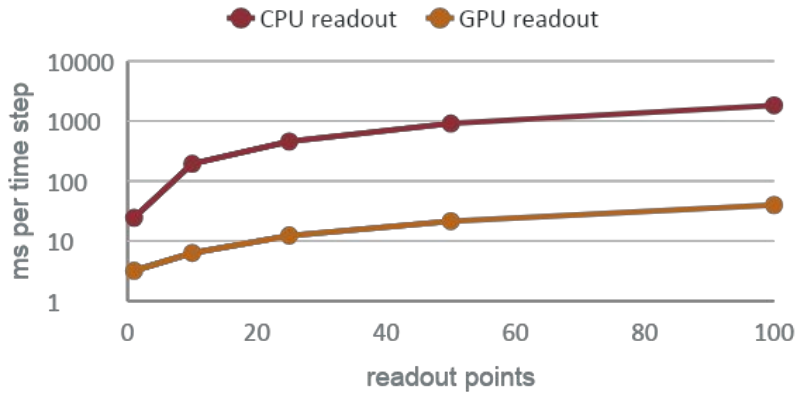
Where it lives git.ligo.org/NewtonianNoise/specfem3d and /specfem-nn (LIGO–Virgo–KAGRA members) · github.com/ravioli1369/specfem3d (public)

SPECFEM3D versions at the locations listed · state as of 16 Oct 2026

GPU gravity readout makes dense maps practical

1.8 s → 40 ms

gravity readout per time step at 100 points, CPU → GPU: 8× faster at 1 point, 46× at 100



Measured on a shared GPU held at 100% by another job, so the speedups are lower bounds. The CPU readout is the original single-core loop.

Checked against the original CPU readout

- 1 point vs a double-precision reference: agree to ~10^{-6} of peak
- 3 points, full run: GPU and CPU agree to 7×10^{-5} of peak
- After updating to SPECFEM3D's latest code: results unchanged ($\leq 1.3\times10^{-6}$)

Extra readout points cost no extra GPU memory (checked from 1 to 100 points on one mesh). A dense map needs hundreds of points; on the CPU the readout alone would dominate the run.

specfem3d (git.ligo.org/NewtonianNoise/specfem3d), devel 9290dcb8 · readout sweep of 15 Oct 2026

E · OUTLOOK

What we don't know yet

The site

No site chosen: geology, noise spectrum and wave mix open; seismic requirement still a placeholder. Recall that quieter sites may require less NN mitigation

Simulation realism

Uniform ground, one source direction, a 10 Hz source: 20–30 Hz detail provisional

Validation

Matches the Harms & Hild estimate below ~8 Hz; ~4% change with mesh refinement at 6 m, more when deeper; no experimental check

Building physics

Structural mass not modeled; possible low-frequency amplification; no air-flow modeling yet

Basement ↔ array

Scattering by the basement may move the optimal sensor positions

Field and sensors

How noise splits between surface and body waves, and sensor noise, set how many sensors are needed. What is the minimum number of borehole seismometers (hopefully zero)?

CE R³ draft, Newtonian noise (CE-E2500007) §2.1, §3.3–3.4, §4.3, §6.1 · specfem-nn notebooks 06–10 · R. Kumar notes §5–6

Next steps on the CE side

Passive (basements)

- Waves from all directions (by symmetry, 0°, 22.5°, 45° cover all)
- Higher-frequency source: are the 20–30 Hz features real?
- Reduction vs excavation → a justified reference basement
- Rectangle vs plus; layered ground; plane-wave sources

Active (arrays)

- More random versions of the ground
- Array search on the measured Terziet spectrum
- Wind and localized sources
- Time-domain subtraction; underground arrays

Combined: design basements and arrays together: sensors on basement floors and walls, and how scattering from the basement changes what an array can subtract. What is the full frequency dependent mitigation we can achieve when combined?

To Do: Projections of candidate location measurements (taking, eg, LHO as first example) with anticipated mitigation residuals, to project expected NN from a given site. Adjust basement / array parameters to target noisy frequency ranges if needed.

Where CE and ET can help each other

Code	SPECFEM3D versions with GPU gravity readout, buried cavities and plane-wave sources. What does ET use for 3-D NN modeling?
Benchmark	One shared test case to cross-check codes.
Shared inputs	CE's array study already uses the Terziet ground model and the sensor-noise level from ET array studies. Agree on common assumptions?
Feedforward	Virgo NN-cancellation lessons for scaling up CE arrays (help move readiness level 4/5 → 6).
Underground	Do cavities around the test mass matter underground?

CE R³ draft, Newtonian noise (CE-E2500007) §4.3, §6.1 · R. Kumar notes §2, §4, slide 15 · Andric & Harms 2020

Backup

CE NN section · XGCD 19 October 2026

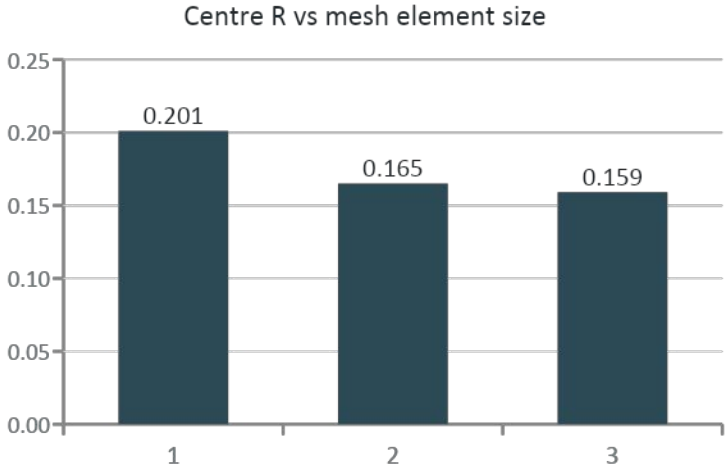
BACKUP · PASSIVE

Numerical checks behind the passive results

1.36×10^{-5}
numerical noise floor, from comparing mirror-image points

9.2×10^{-7}
run-to-run reproducibility, from repeated independent runs

$< 0.1\%$
effect of self-gravity (the ground's own gravity) in band; cancels in R

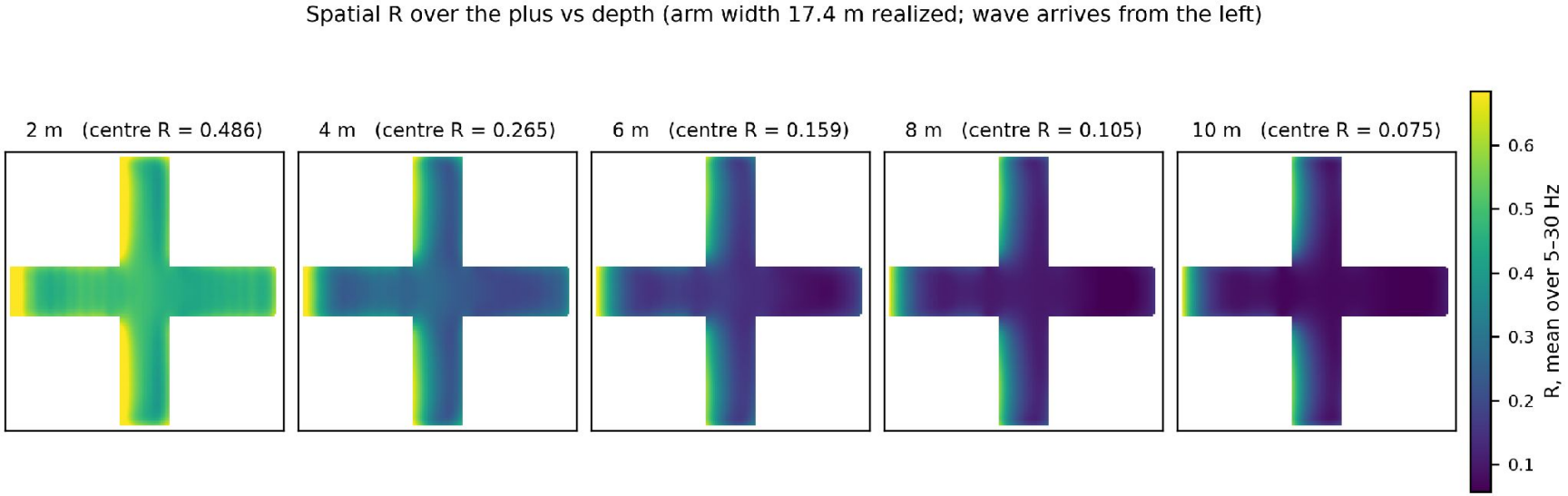


- Refining 5.2 → 3.5 m elements changes centre R by 3.8%; about half is the arm width changing with the mesh (15.6 vs 17.4 m).
- Deeper basements are more mesh-sensitive: 5.2 vs 3.5 m elements differ ~25% at 8–10 m. A finer (2.6 m) check is planned.

specfem-nn (git.ligo.org/NewtonianNoise/specfem-nn), notebooks 06, 09, 10

BACKUP · PASSIVE

Spatial R over the plus, 2–10 m deep

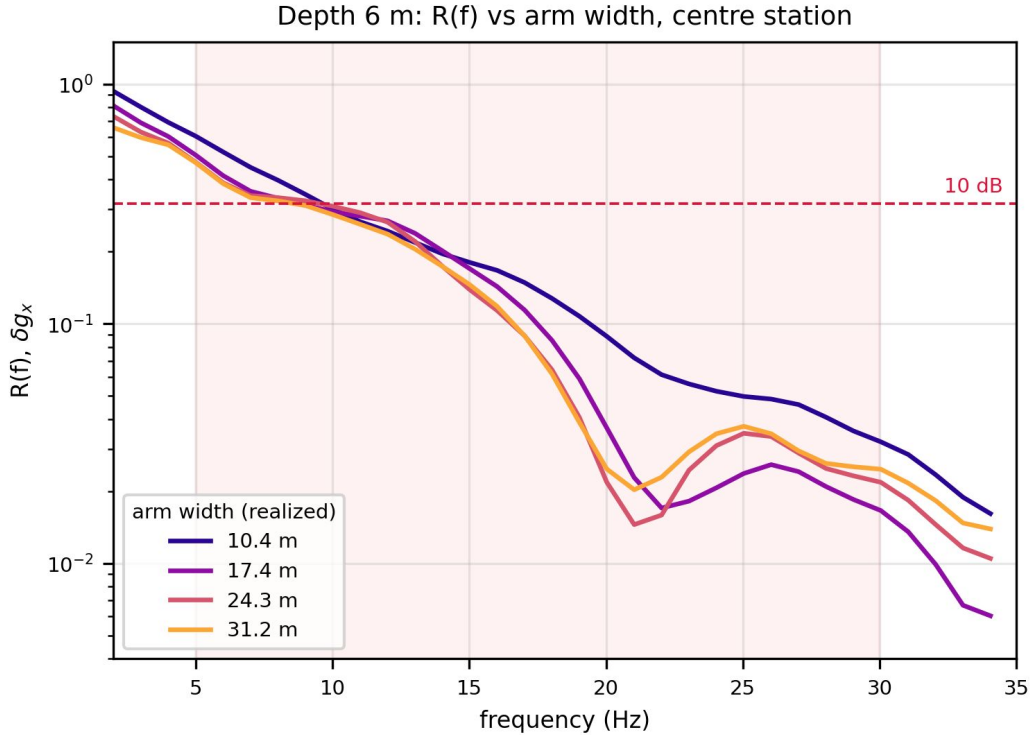


17.4 m realized arms, wave from the left, shared colour scale; centre R in each title.

specfem-nn (git.ligo.org/NewtonianNoise/specfem-nn), notebook 10 (depth × width scan, 3.5 m mesh)

BACKUP · PASSIVE

Width series at 6 m: widening helps most at ~14–22 Hz



- Widening helps most at ~14–22 Hz.
- Above ~22 Hz the 24–31 m recesses sit above the 17 m one.
- Every width still beats 10 m.

Above 20 Hz the 10 Hz source is weak (~3% of peak at 25 Hz): treat this ordering as provisional.

specfem-nn (git.ligo.org/NewtonianNoise/specfem-nn), notebook 10 (depth × width scan)

BACKUP · PASSIVE

Reduction by band and depth

17.4 m arms, centre point: mean of R(f) over each band

Depth	5–10 Hz	10–20 Hz	20–30 Hz*	5–30 Hz	≥10 dB from (Hz)
2 m	0.732	0.542	0.307	0.486	23
4 m	0.529	0.308	0.090	0.265	15
6 m	0.380	0.185	0.022	0.159	9
8 m	0.278	0.117	0.006	0.105	6
10 m	0.213	0.075	0.006	0.075	6

Width matters most at 5–10 Hz, at depth

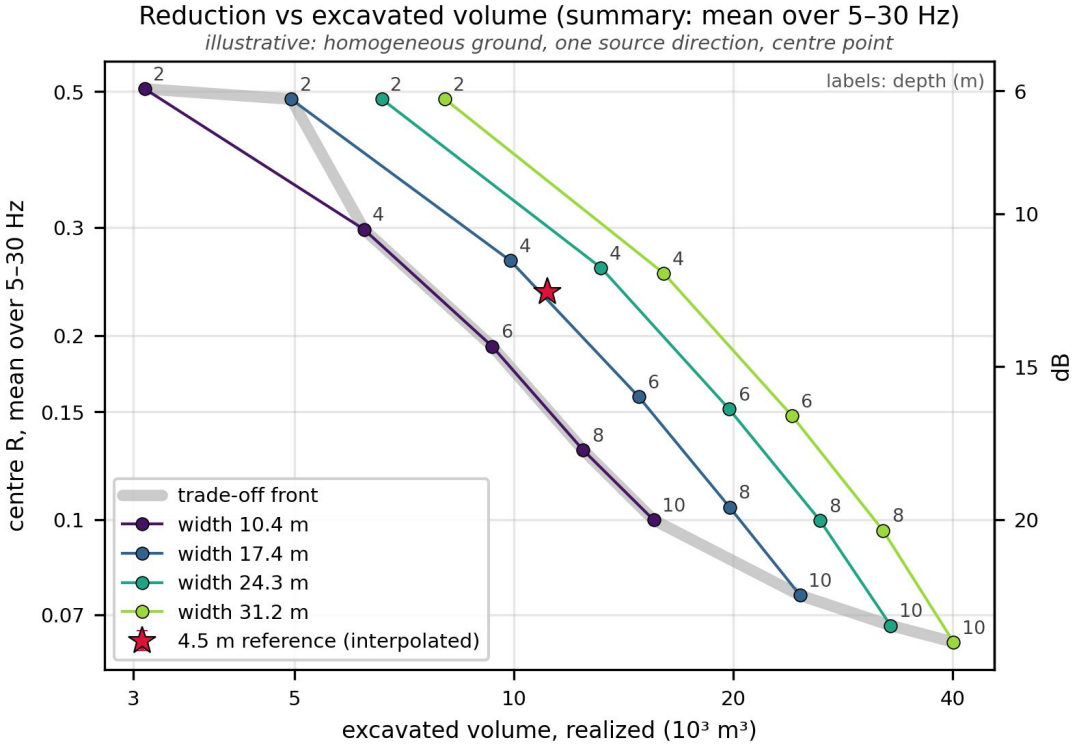
5–10 Hz	10.4 m	17.4 m	24.3 m	31.2 m
2 m	0.781	0.732	0.720	0.719
4 m	0.608	0.529	0.515	0.513
6 m	0.463	0.380	0.369	0.363
8 m	0.348	0.278	0.264	0.252
10 m	0.274	0.213	0.191	0.174

** 20–30 Hz provisional (weak source content). 8–10 m rows are mesh-sensitive; the 10 m row used a more distorted mesh. Columns are realized widths (nominal 10 / 15–20 / 25 / 30 m).*

specfem-nn (git.ligo.org/NewtonianNoise/specfem-nn), notebook 10 (depth × width scan, centre point)

BACKUP · PASSIVE

A cost/benefit question the simulations can answer



ILLUSTRATIVE

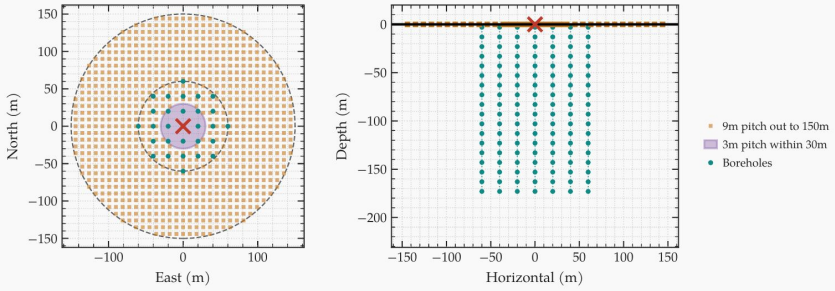
Reduction against excavated volume for 16 basement shapes: how much each extra cubic metre of depth or width buys.

Uniform ground, one source direction, centre point, 5–30 Hz summary. Too early to recommend a reference basement; this will be redone with realistic sources and ground profiles.

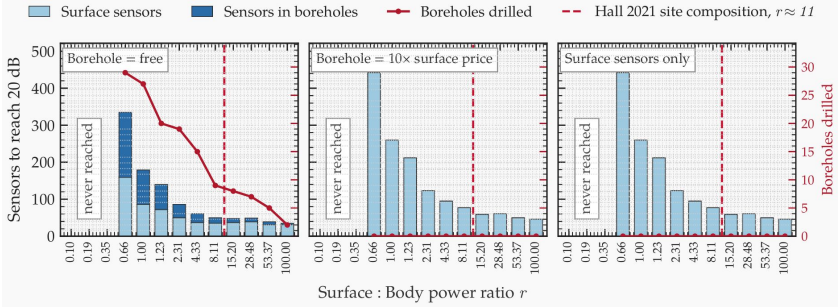
specfem-nn (git.ligo.org/NewtonianNoise/specfem-nn), notebook 10 (depth × width scan; volume from the realized mesh surface)

BACKUP · ACTIVE

Array search: candidates and arrays that reach 20 dB



Candidates: 3 m pitch within 30 m, 9 m to ±150 m; boreholes on a 20 m grid to 60 m, sensors every 10 m to −173 m.

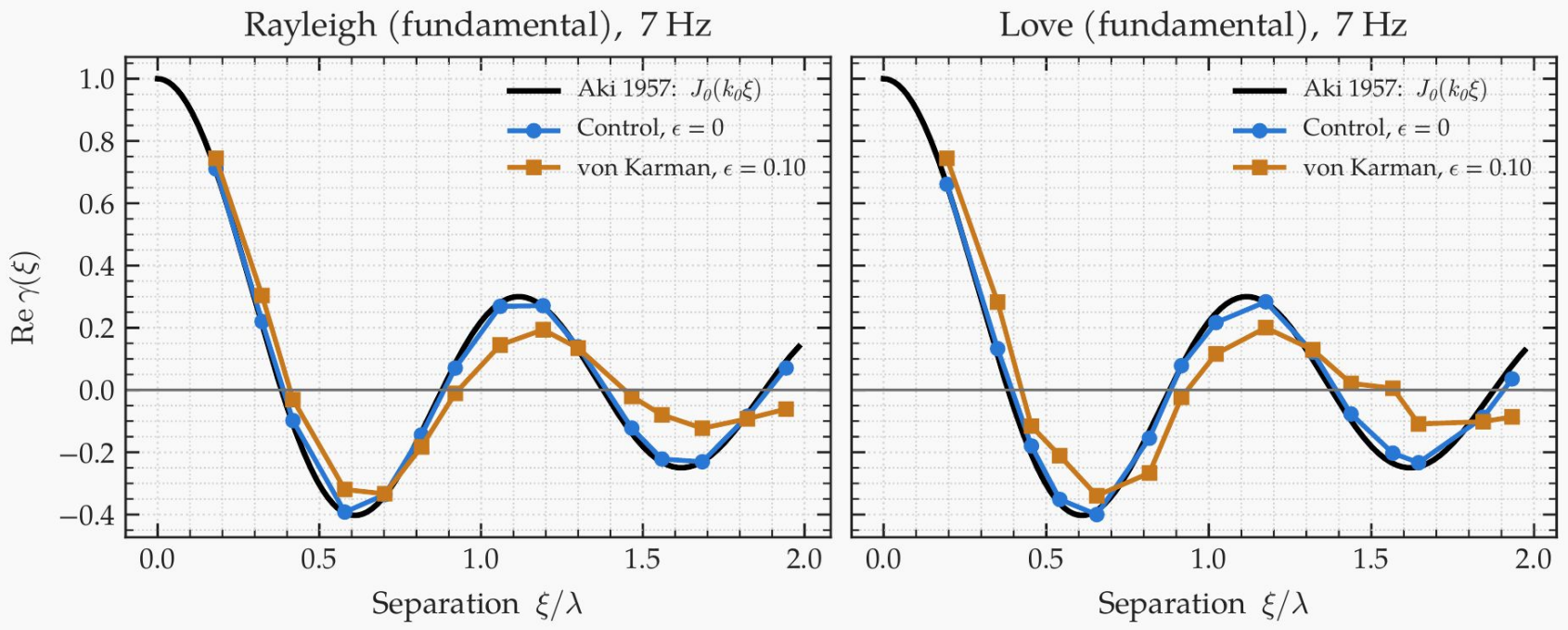


Free boreholes cut the sensor count most when the field is body-dominated (r = 1: 179 vs 260).

R. Kumar, slides 9, 11 and working notes §4–5 (Sept 2026)

BACKUP · ACTIVE

Heterogeneity damps the coherence oscillation



Rayleigh and Love waves at 7 Hz: layered ground without variations reproduces the textbook isotropic result $J_0(k\xi)$; random variations damp it.

R. Kumar, slide 25 and working notes §3 (Sept 2026) · Aki 1957

BACKUP · CONTEXT

Technology readiness levels (TRL) of CE NN mitigation

Design element	TRL	R&D needed
Seismic arrays for feedforward	**4/5**	Demonstrated at LIGO; scaling study for CE arm length and station geometry
Basements for passive NN reduction	**2/3**	3-D simulations in progress; no experimental validation
Simulation infrastructure	**3/4**	Validate against analytic predictions; convergence at finer meshes
Atmospheric NN (building design)	**2/3**	Air-flow (CFD) modeling; wind-tunnel validation

TRL of 1 indicates low readiness, TRL of 9 indicates very high readiness

CE R³ draft, Newtonian noise (CE-E2500007) §6.1, Table 2