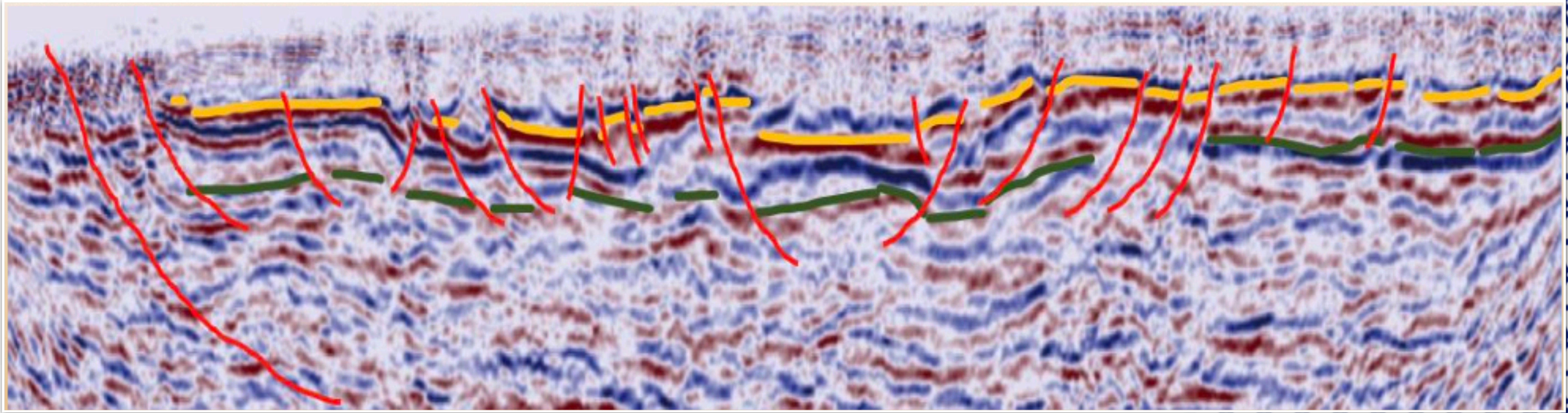

NOISE MODELING AT EMR:
PLANNING THE DEVELOPMENT OF SOPHISTICATED MODELS

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Newtonian Noise

We like to evaluate the ongoing discussions on NN

- We currently do not have an approved model of NN for complex geological settings
- EMR demands, and develops, adequate noise modeling that suits the region

We aim to develop a numerical framework to compute NN to account for arbitrary heterogeneities and sources distribution

  - i.e. finite elements for the seismic wavefield and Gaussian quadrature to integrate the NN on FE mesh
- Suitable for any geology - and applicable to EMR
  - So far, NN predictions are based on homogeneous geology
- Suitable for adequate geometries/topographies
  - So far only very simplistic geometries considered (Harms et al. Eur. Phys. J. Plus (2022) 137)
- Suitable for variety of noise sources and mitigation effects
  - So far magnetic and electric disturbance have not been considered

Specific geology

So far EMR has only TERZIET as benchmark

- EMR subsurface measurements are expected late summer 2025
- TERZIET is not on target depth, and hence not representative of EMR

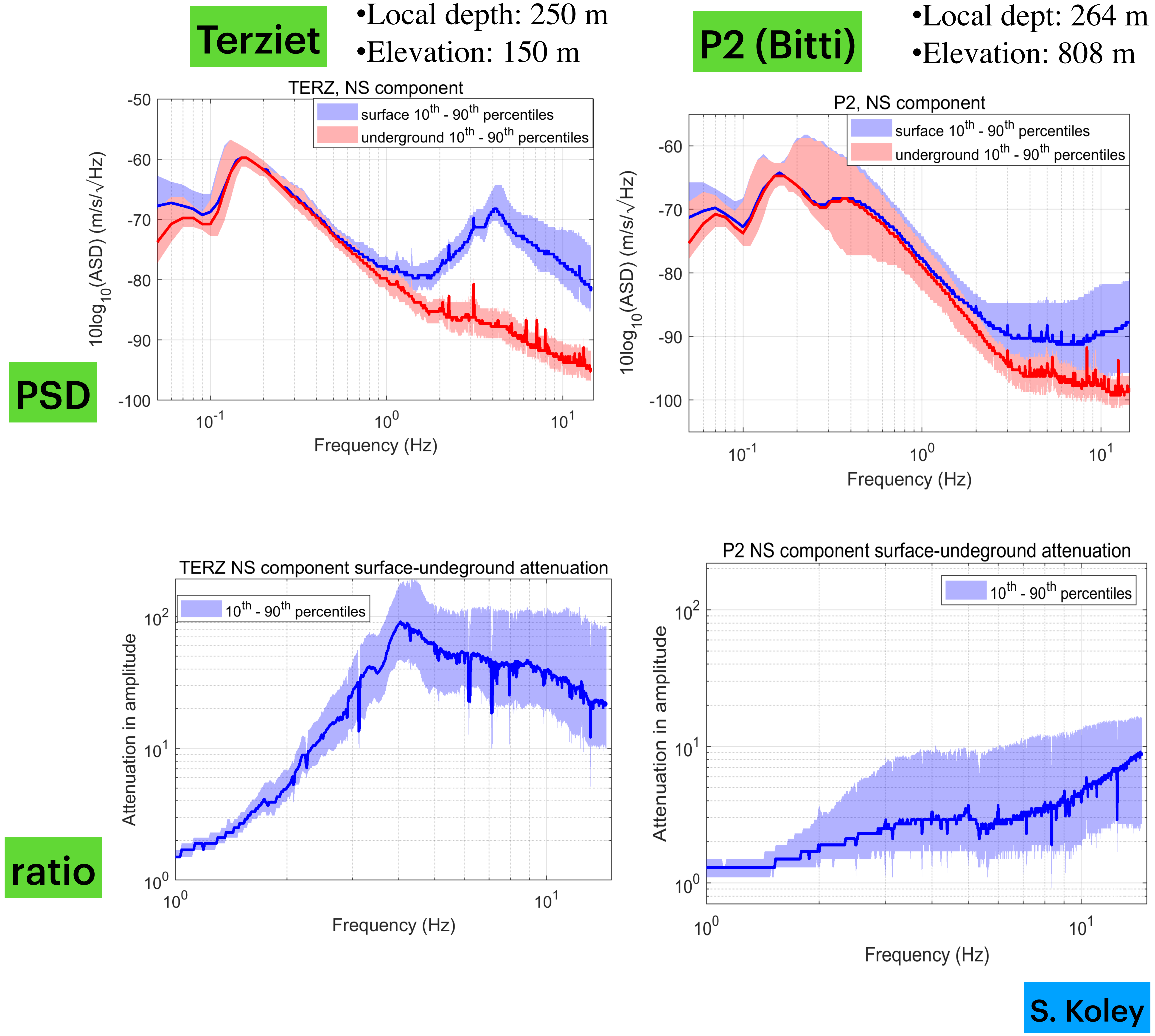
Geology challenges

- EMR has special geological environment where infrastructure is 'protected' by soft layers on top
  - Vertical attenuation is much larger compared to other sites

EMR is relatively insensitive to future changes in surface activities

- *This robustness is an important aspect for an infrastructure that will run for >50 years!*

Comparing surface with subsurface



Noise for EMR: the issue

Structured geology provides (additional) opportunity for noise mitigation

- *Requires careful and approved NN modeling for the EMR region*

- Installation dedicated workshop to connect to geology modeling
  1. Measuring the noise at surface and subsurface
     - Quantify attenuation effect for subsurface
  2. Propagation to the corners points
     - Propagation of seismic waves depend on the geology structure and lithology
     - Full account of the complex geology with softer top-layers
  3. Effect of the residual PSD noise on the ET instrument
     - Calculation of NN contribution, using adequate models for geology and sources
  4. Mitigation efforts
     - Active and passive mitigation (e.g. geometry of the caverns)

Liège
RWTH
Nikhef
KULeuven
Hamburg
Ghent

Understanding Newtonian Noise

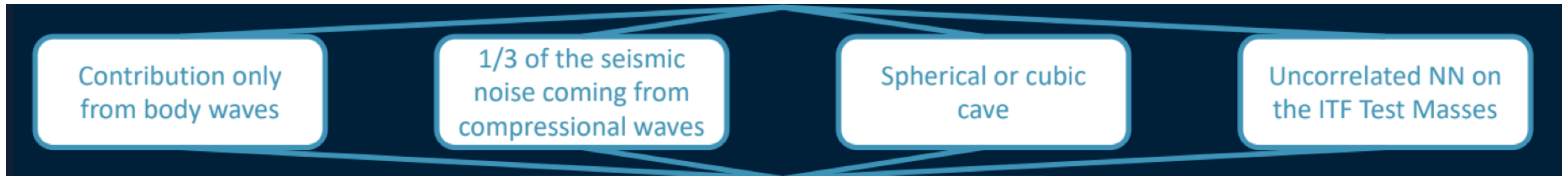
The NN effect for planar body waves can be expressed by

- Opposite contributions on the mirror between p- and s-waves

$$\delta\vec{a}(\omega) = \frac{4\pi}{3} G\rho_0 \left(2\vec{\xi}_P(\omega) - \vec{\xi}_S(\omega)\right)$$

Recent ET-0453C-24 paper estimates the NN contribution between 2-10 Hz as

$$\tilde{h}_{\mathrm{NN}}(f) = \frac{4\pi}{3} G\rho_0 \frac{2\sqrt{2}}{L} \frac{1}{(2\pi f)^2} \tilde{x}(f)$$



- This relation between PSD and NN is based on the following assumption:
  - Considering the small cavern limit and neglect any possible correlations between s- and p-waves, i.e. adding quadratically the NN from p-waves and s-waves
  - Uniform geology

Is this the right procedure?

Understanding Newtonian Noise (2)

Rather confusing to me!

The minimal NN contribution is derived from (2202.12841-harms)

- "As mentioned earlier, the NN model contains a bulk contribution and another one from cavern-wall displacement. The bulk contribution depends on geology, and for the definition of the lower limit, we will make the conservative assumption that it does not contribute. So, the idea is to only use the cavern-wall contribution to define a lower NN limit"

$$\delta\vec{a}_{\mathrm{low}}(\vec{r}_0,t) = G\rho\int \mathrm{d}S\,\left(\vec{n}(\vec{r})\cdot\vec{\xi}(\vec{r},t)\right)\frac{\vec{r}-\vec{r}_0}{|\vec{r}-\vec{r}_0|^3} = -\frac{4\pi G\rho}{3}\vec{\xi}(\vec{r}_0,t) \quad \longleftarrow \quad \delta\vec{a}(\omega) = \frac{4\pi}{3}G\rho_0\left(2\vec{\xi}_P(\omega) - \vec{\xi}_S(\omega)\right)$$

We ask ourselves

- Do the P- and S-waves cancel each other out due to the relative minus sign?

Understanding Newtonian Noise (2)

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We ask ourselves

- At any given moment in time, the displacement in any direction at the mirror is a result of many different noise sources. If the source distribution is isotropic (both for the direction of the wave vector and the direction of the displacement vector) then on average one has ⅓ p-wave and ⅔ s-wave.

  Of course at some times there is more p-wave in the displacement and at some times more s-wave, but on average it washes out.

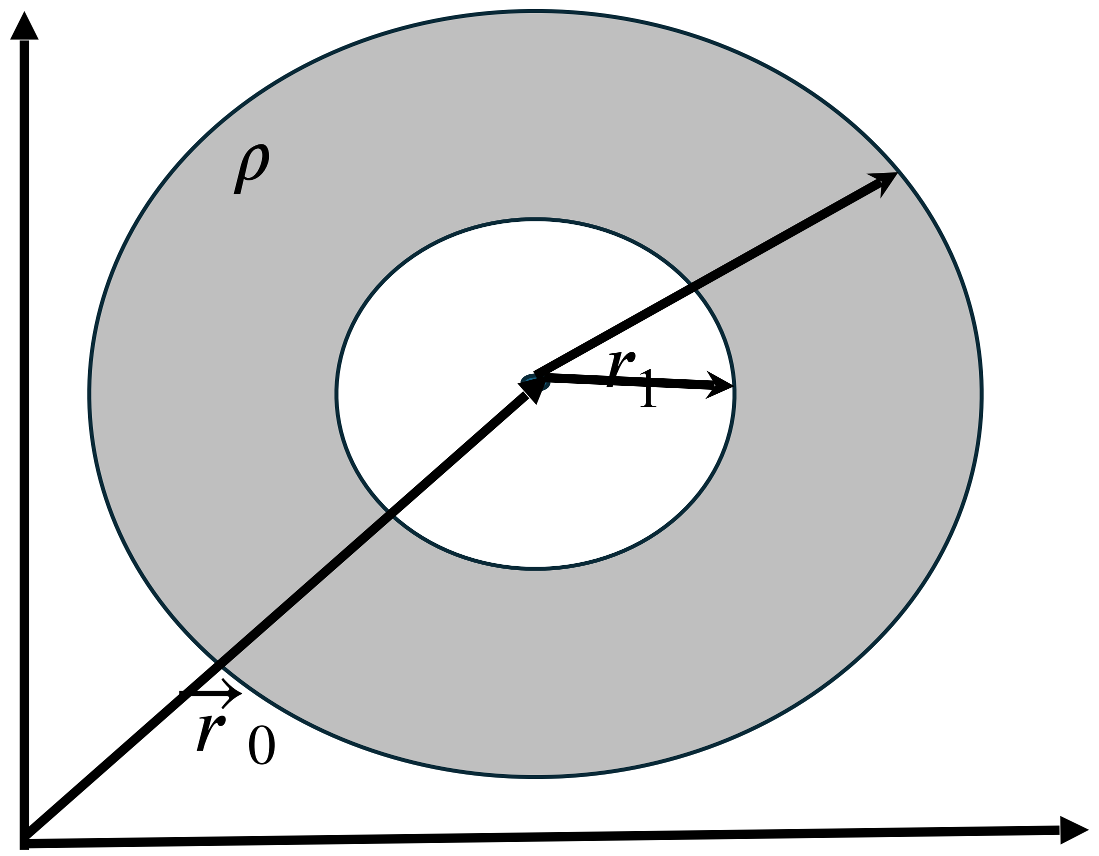
  The part of the displacement coming from p-waves causes acceleration parallel to the displacement vector (so parallel to the seismic noise at the mirror) and the part from the s-waves anti-parallel. The more random sources you average, the closer the newtonian noise tends to zero.

HJ Bulten

Lets test this out

$$\delta \boldsymbol{a}_N = G\bar{\rho}_s \int_{V_{shell}} \left[\frac{\boldsymbol{\xi}}{|\boldsymbol{r}-\boldsymbol{r}_0|^3} - \frac{3\xi_{\boldsymbol{r}-\boldsymbol{r}_0}(\boldsymbol{r}-\boldsymbol{r}_0)}{|\boldsymbol{r}-\boldsymbol{r}_0|^5} \right] dV, \text{ where } \xi_{\boldsymbol{r}-\boldsymbol{r}_0} = (\boldsymbol{\xi}\cdot(\boldsymbol{r}-\boldsymbol{r}_0))$$

Check the numerical evaluation on simple geometry

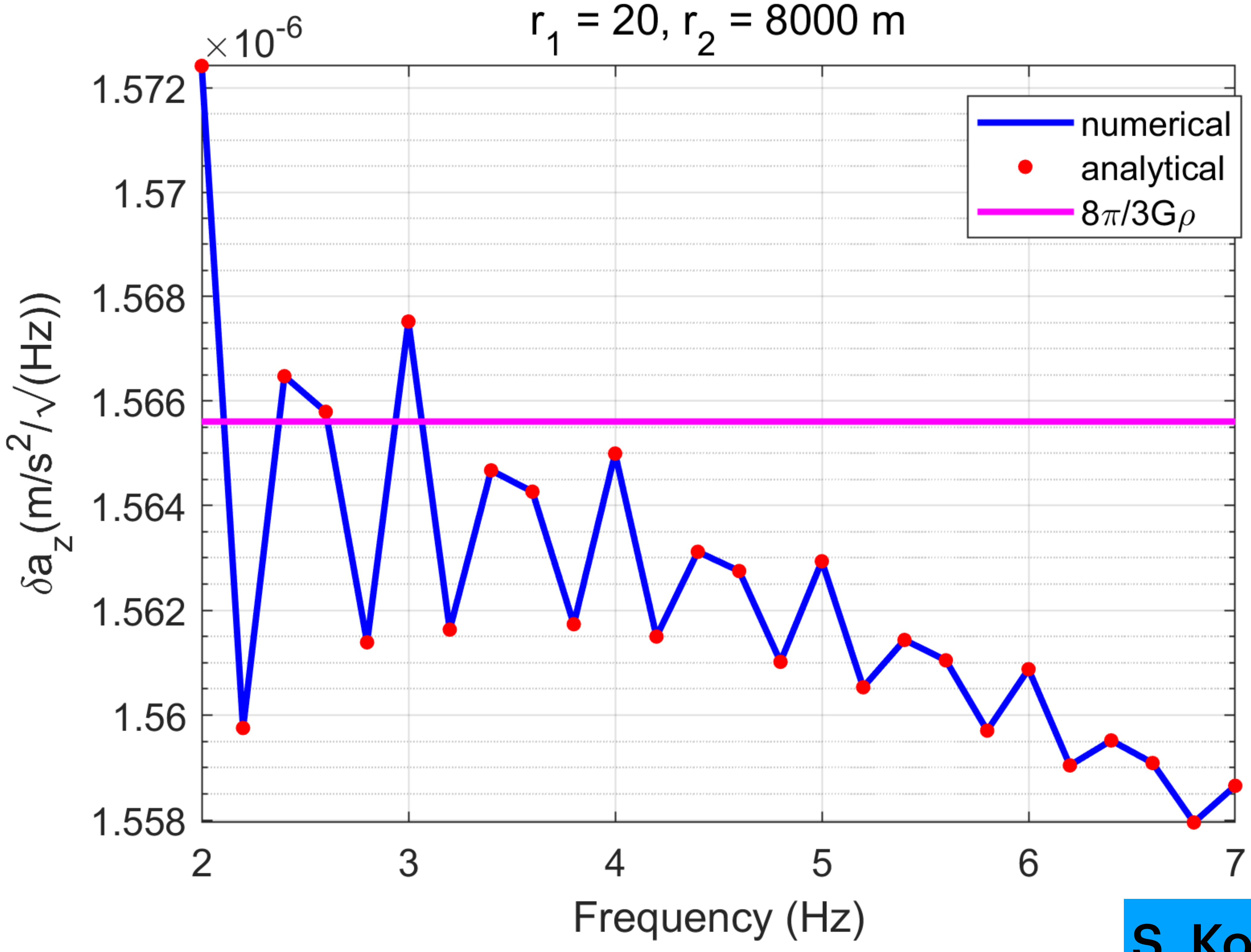


- For a plane P-wave $\vec{\xi}(\vec{r}, t)$ propagating in the shell , the volume contribution is expressed as

$$8\pi G\rho\vec{\xi}\left[\left(\frac{\cos kr_2}{k^2r_2^2} - \frac{\sin kr_2}{k^3r_2^3}\right) - \left(\frac{\cos kr_1}{k^2r_1^2} - \frac{\sin kr_1}{k^3r_1^3}\right)\right]$$

- For $r_1 = 20\ m,\ and\ r_2 = 8000\ m$, we see that the analytical and numerical results are accurate up to 10^{-12}

Simulation of dipole formulation in spherical coordinates



Perfect agreement with numerical simulation

S. Koley

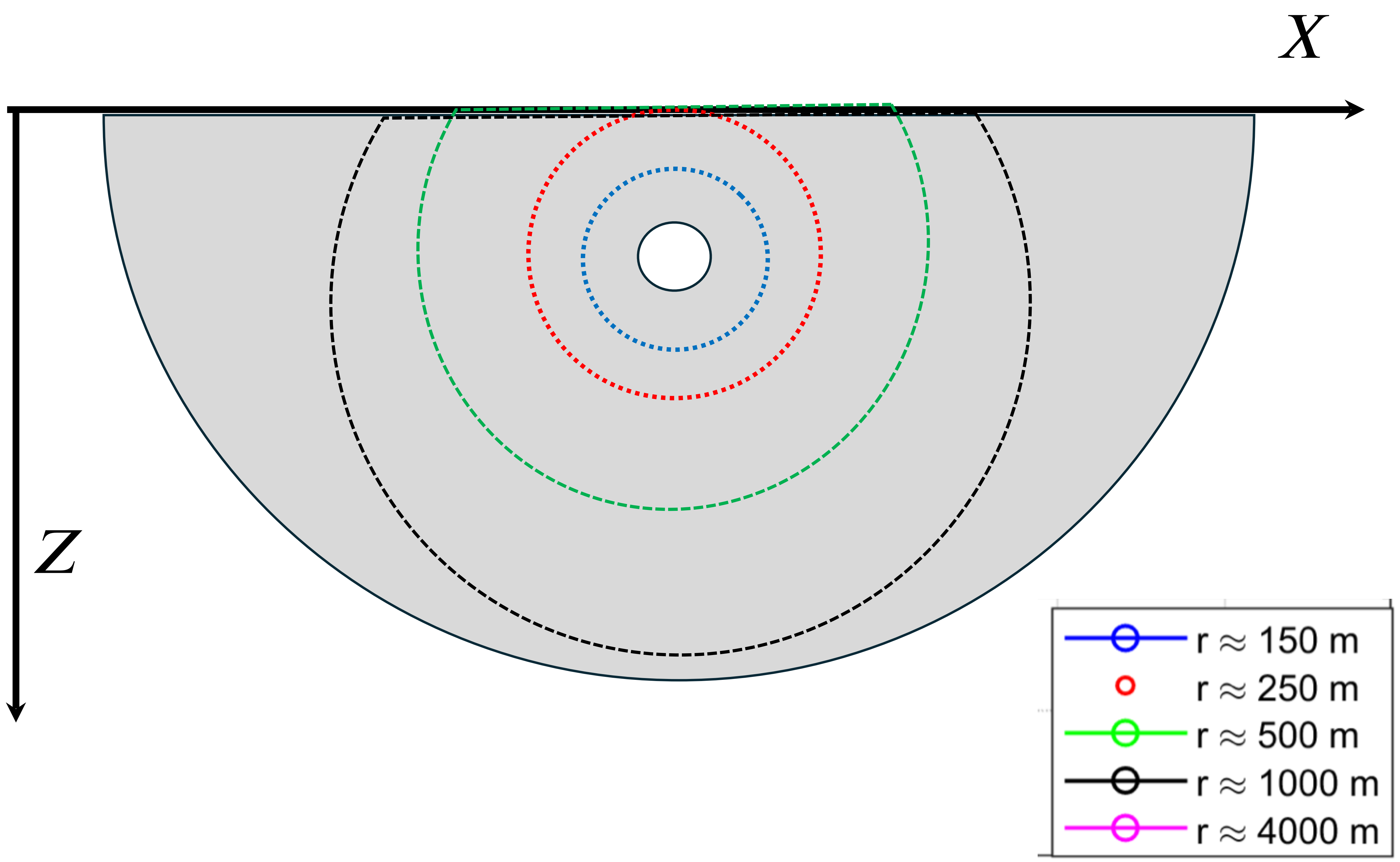
Numerical simulations

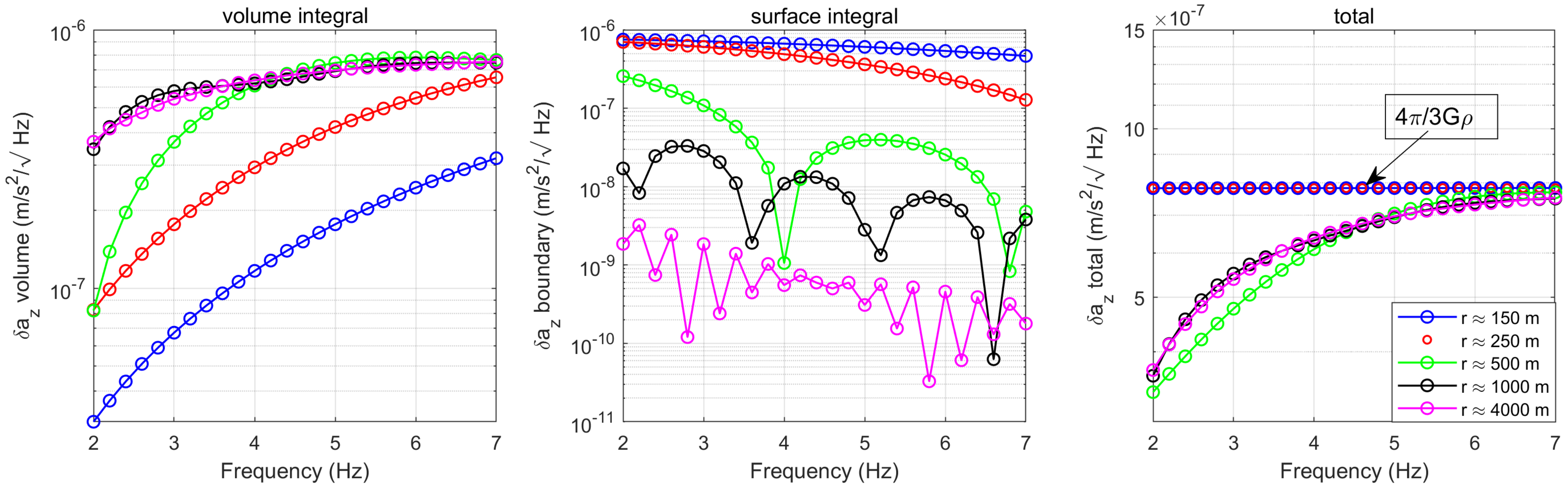
Evolution of contribution of volume and surface terms with increasing radius of integration

- SV wave propagating along +x, and displacement field along +z
- Origin of the coordinate system is at the test-mass which is at 250 m depth from surface

With larger radii, the contribution of the surface terms decreases

- For r~150 and 250 m, the total NN equals $4\pi/3G\rho$
- Volume contribution increases with increasing radii and doesn't change much after 4000 m
- Reduction from $4\pi/3G\rho$ for larger integration radius



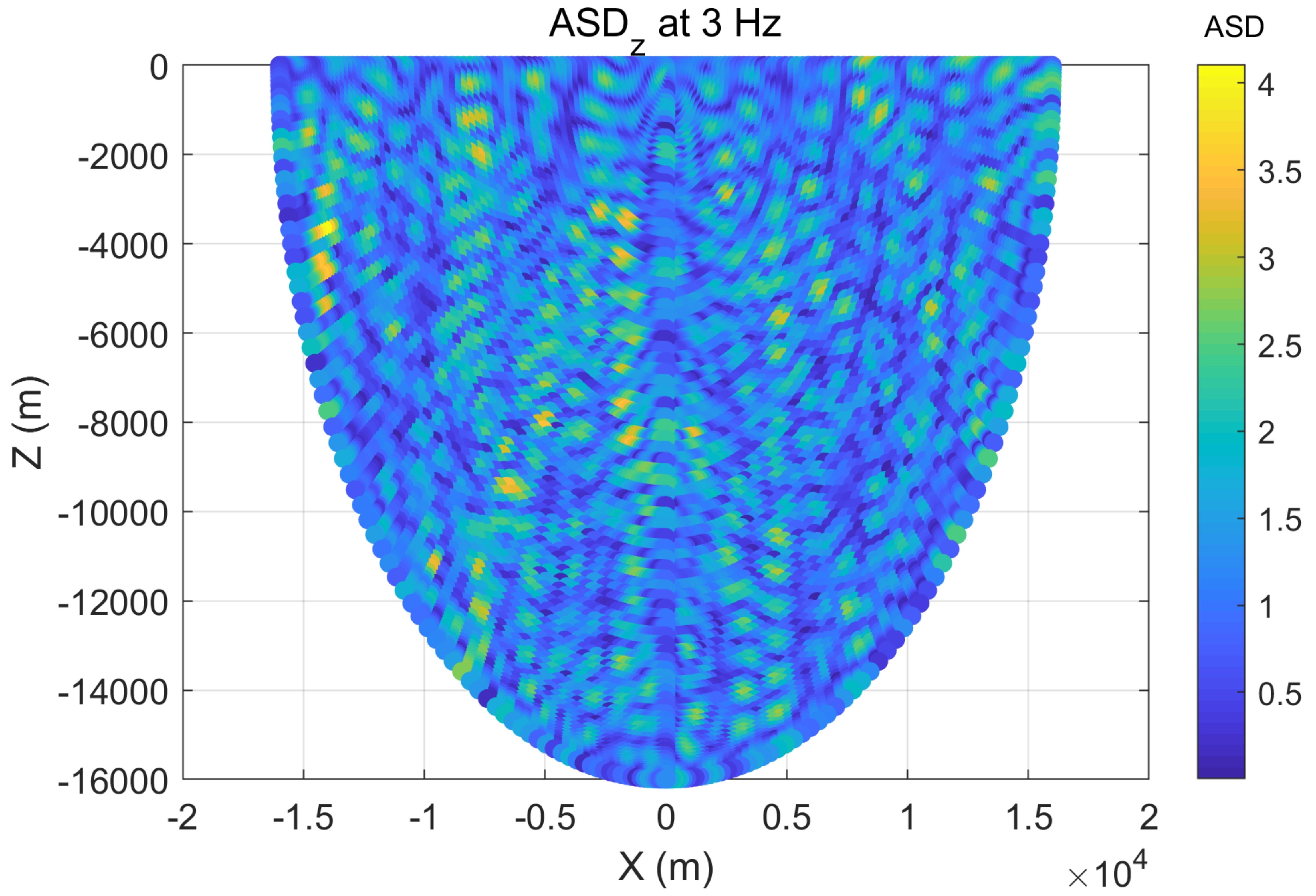


$$\delta \boldsymbol{a}_N = G\int_{V_{int}} dV\,\bar{\rho}_s\left[\frac{\boldsymbol{\xi}}{|\boldsymbol{r}-\boldsymbol{r}_0|^3} - \frac{3\xi_{\boldsymbol{r}-\boldsymbol{r}_0}(\boldsymbol{r}-\boldsymbol{r}_0)}{|\boldsymbol{r}-\boldsymbol{r}_0|^5}\right] - G\int_{S_{out}} dS\,\frac{\bar{\rho}_s(\boldsymbol{\xi}\cdot\hat{\boldsymbol{n}}_{out})(\boldsymbol{r}-\boldsymbol{r}_0)}{|\boldsymbol{r}-\boldsymbol{r}_0|^3},$$

Simulating an underground stochastic displacement field

Simulation of a stochastic field

- Produce 500 P- and 500 S-waves for every realization the underground displacement field
- Each S-wave has both SV and SH component active
- A total of 100 realizations performed
  - Rescale ASD using scale factor α to ensure $\alpha\left\langle \left| \vec{\xi}\left(\vec{r}_0\right) \right|^2 \right\rangle = 1.0$
    - The ASD of the underground stochastic field after this rescale factor will exceed 1 at certain points and will be less than 1 elsewhere, however, we ensure that at the location of the cavity the ASD is 1.
  - Note: we have obtained a realistic correlation of the 3D displacement field between any two points which approaches $\frac{\sin(kr)}{kr}$ on increasing the number of realizations

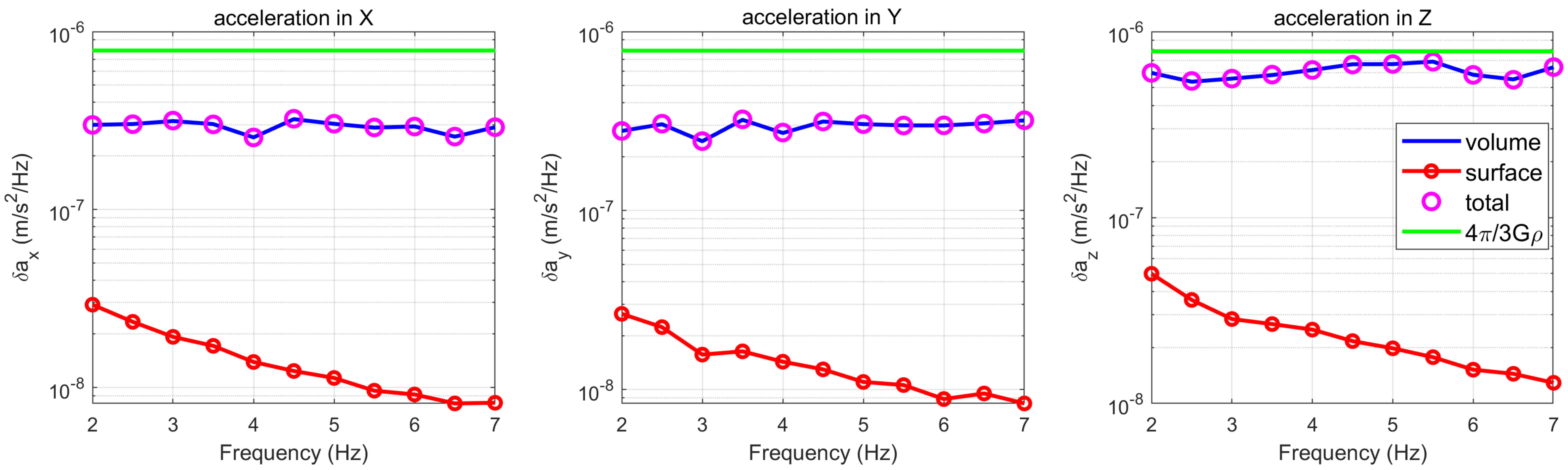


We see several blobs of low and high ASD: this essentially reduces the NN

Simulating an underground stochastic displacement field

NN from an underground stochastic field

- ASD of the NN from an underground stochastic field over 100 realizations is a factor 2 – 2.5 below $4\pi/3G\rho$ along the X and Y directions
- ASD of NN along Z direction is close to but still less than it



We observe the cancelation of P- and S-wave contributions, as anticipated

- Violating the 'minimal NN contribution' $4\pi/3G\rho$

Understanding the NN

Literature on NN is sometimes confusing, and there are conflicting statements

- Lets create clarity on these issues together!
- In our work-group we follow our internal 'work plan'

Until we have a better understanding

- We have mentioned our concerns at earlier occasions
- *Please wait with simple comparisons between TERZ and P1, P2 on NN before we have correct model!*

Start with a study of a number of 'simple' geometries

- Compare analytic models with numerical simulations
  - Gain trust in both the models and the simulations

We incorporate step-by-step more complex geologies

- To understand the effect of layered and more complex geometries
- This will take until end 2026 to get a full picture
  - Seismic studies are underway (see presentation S. Koley and M. Kiehn)

We will study the effect of geometries

- Numerical results on varying cavern geometries, including tunnels

We will study mitigation effects

- Both active and passive mitigations