SILENCING NEWTONIAN NOISE USING FUSION SENSOR ARRAYS

Presentation for the EMR meeting

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PAPER

Silencing Newtonian noise using fusion sensor arrays

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Abstract

Newtonian noise (NN) from seismic density fluctuations is expected to limit the low-frequency sensitivity of third-generation gravitational-wave detectors, in particular the Einstein Telescope (ET). Current NN mitigation relies on seismometer arrays and Wiener filtering, while distributed acoustic sensing (DAS) offers a complementary, low-cost means of obtaining dense strain measurements. We investigate fusion sensor arrays composed of both displacement-measuring seismometers and strain-measuring DAS-type sensors. We extend the Wiener filter formalism to mixed sensor types and introduce analytic S-wave strain correlation coefficients. Using a hybrid differential evolution and covariance matrix adaptation scheme, we validate our approach against established seismometer-only results and analyze the geometry, robustness, and performance of optimized fusion arrays. Fusion arrays enhance P/S-wave disentanglement and achieve NN cancellation levels comparable to, and sometimes exceeding, those of seismometer-only arrays, particularly for small sensor numbers. When sensors are constrained to the ET infrastructure, we find that six seismometers complemented by fourteen strainmeters inside the ET arms can match the performance of twenty seismometers in boreholes, achieving a residual at the 10% level, and thereby offering a cost-efficient pathway toward ET-scale NN mitigation.

1 Introduction

The Einstein Telescope (ET) promises new breakthroughs in gravitational-wave (GW) physics. For instance, it will enable the discovery of new GW sources, such as core-collapse supernovae [1, 2] and isolated neutron stars [3, 4], and further, the detector will advance multi-messenger astrophysics [5, 6]. The references listed above are illustrative rather than exhaustive, for a comprehensive overview of the science enabled by ET, see [7]. To reach these goals, the ET's sensitivity would have to be improved by a factor of 10 compared to the current advanced detectors, and its frequency band extended down to 3 Hz [8]. The GW detector's noise floor around 3 Hz is dominated by seismic and Newtonian noise (NN). By building the ET underground, both of these noise sources can be suppressed, since they have large surface contributions, such as, from Rayleigh waves. Nevertheless, relocating the detector to the underground on its own is not sufficient to mitigate seismic NN, as it may still limit the achievable design sensitivity [9].

Therefore, in order to reach the science goals for the ET, strategies must be developed to mitigate seismic NN. Current GW detectors of the second generation already employ a NN cancellation system. The Advanced Virgo detector, for instance, has deployed an array of seismometers measuring the seismic field around the interferometer for the purpose of NN mitigation [10]. By modeling the field with plane surface waves, for example, the NN can be calculated and removed from the data. Besides these efforts, no NN from seismic density fluctuations has been measured yet, and Newtonian noise mitigation was therefore not applied, but only tested for Virgo. While other approaches have also been evaluated for Advanced Virgo, such as recess structures [11, 12],

mitigating NN using sensor arrays seems to be the most principled approach for the ET.

The primary challenge associated with the installation of a sensor network for the mitigation of NN is the optimal placement of the sensors. The seismometer positions for the Advanced Virgo detector were optimized using a machine learning algorithm [13]. The NN is estimated using a Wiener filter (WF), which exploits the coherent component of the seismic field across the sensor array. The model for the seismic field is calculated analytically and assumes that the seismic noise floor is composed of an isotropic distribution of sources, which are further uncorrelated and stationary [14]. Using body instead of surface waves and a metaheuristic optimization algorithm to find the optimal positions, this seismic model was applied to optimize a sensor array mitigating NN for the ET in [15, 16]. In these works, different metaheuristic optimization algorithms, such as Differential

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Motivation

NEWTONIAN NOISE MITIGATION

ANALYSIS FRAMEWORK

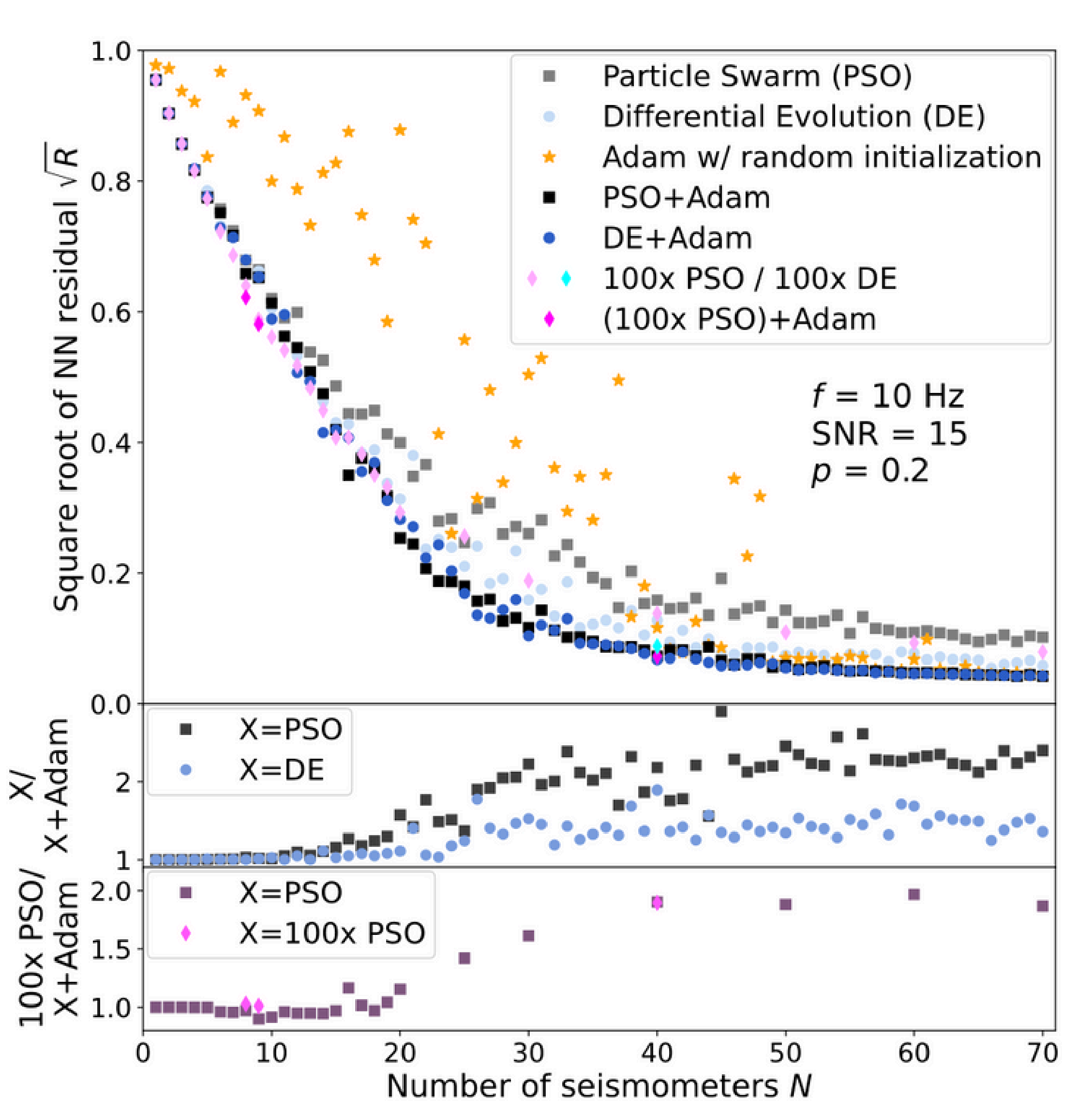
- Testing mitigation capabilities using a random stochastic seismic noise floor, described in detail in [1]
- Searching for the optimal underground configuration of seismometers
- Optimal means to minimise the Wiener filter residual:

$$\mathcal{R} = 1 - \frac{\mathbf{C}_{SN}^{T}\,\mathbf{C}_{SS}^{-1}\,\mathbf{C}_{SN}}{C_{NN}}$$

[1] J. Harms *Terrestrial gravity fluctuations*

CURRENT STATE OF NEWTONIAN NOISE MITIGATION FOR ET

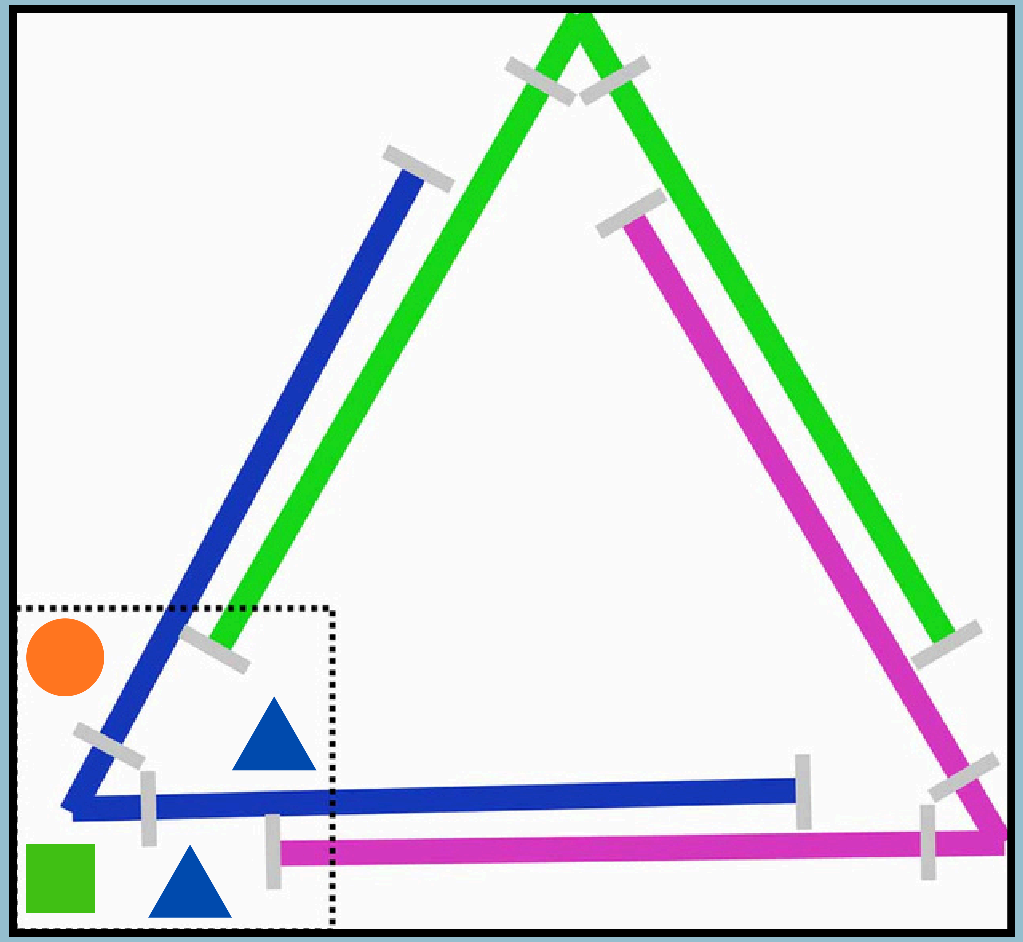
- Best results found up to date are reported in [2] and [3]
- Benchmark residual $\sqrt{\mathcal{R}} = 0.1 \Rightarrow \geq 60$ borehole for the seismometers (optimised at a single-frequency)
- Boreholes are a major cost factor for the ET :/



Taken from [3]

[2] F.Badaracco *Joint Optimization of seismometer arrays for the cancellation of Newtonian noise from seismic body waves in the Einstein Telescope*
[3] P.Schillings *Fighting Newtonian noise with gradient-based optimization at the Einstein Telescope*

NEWTONIAN NOISE MITIGATION USING FUSION SENSOR ARRAYS



*Not yet analysed, for future work

We investigate on the following questions:

Can we reduce the number of borehole for seismometers by fusing sensor arrays without losing NN mitigation performance?

How much NN mitigation performance do we lose by placing the sensors inside of the ET infrastructure instead of boreholes?

Methods

NEWTONIAN NOISE CALCULATION

Newtonian noise from a plane wave seismic field can be calculated according to

$$\delta\mathbf{a}(\mathbf{r}_0, t) = \frac{4\pi}{3}\, G\, \rho_0 \left(2\, \boldsymbol{\xi}^{\mathrm{P}}(\mathbf{r}_0, t) - \boldsymbol{\xi}^{\mathrm{S}}(\mathbf{r}_0, t)\right)$$

This formula was derived in [1] and contains the following assumptions:

- Full space
- Spherical cavern
- Neglectable cavern volume (large wavelength limit)
- Neglectable scattering from ET infrastructure

DEFINITION AMBIENT SEISMIC NOISE

I) Isotropic

We assume that the noise sources are distributed isotropically in the medium.

II) Unpolarized

We assume that there is a uniform distribution of polarisation directions.

III) Uncorrelated

We assume that the sources are all independent and therefore uncorrelated (also, P- and S-waves are uncorrelated).

IV) Stationary

We assume that the seismic noise floor’s distribution does not change over time.

SEISMOMETERS VS STRAINMETERS

Strainmeters measure a different quantity than seismometers, namely the strain field. E.g., for plane wave the fields are given by:

$$\boldsymbol{\xi}(\mathbf{r},t) = \mathbf{p}\, e^{-i(\mathbf{r}\cdot\mathbf{k}-\omega t)}$$

Displacement field

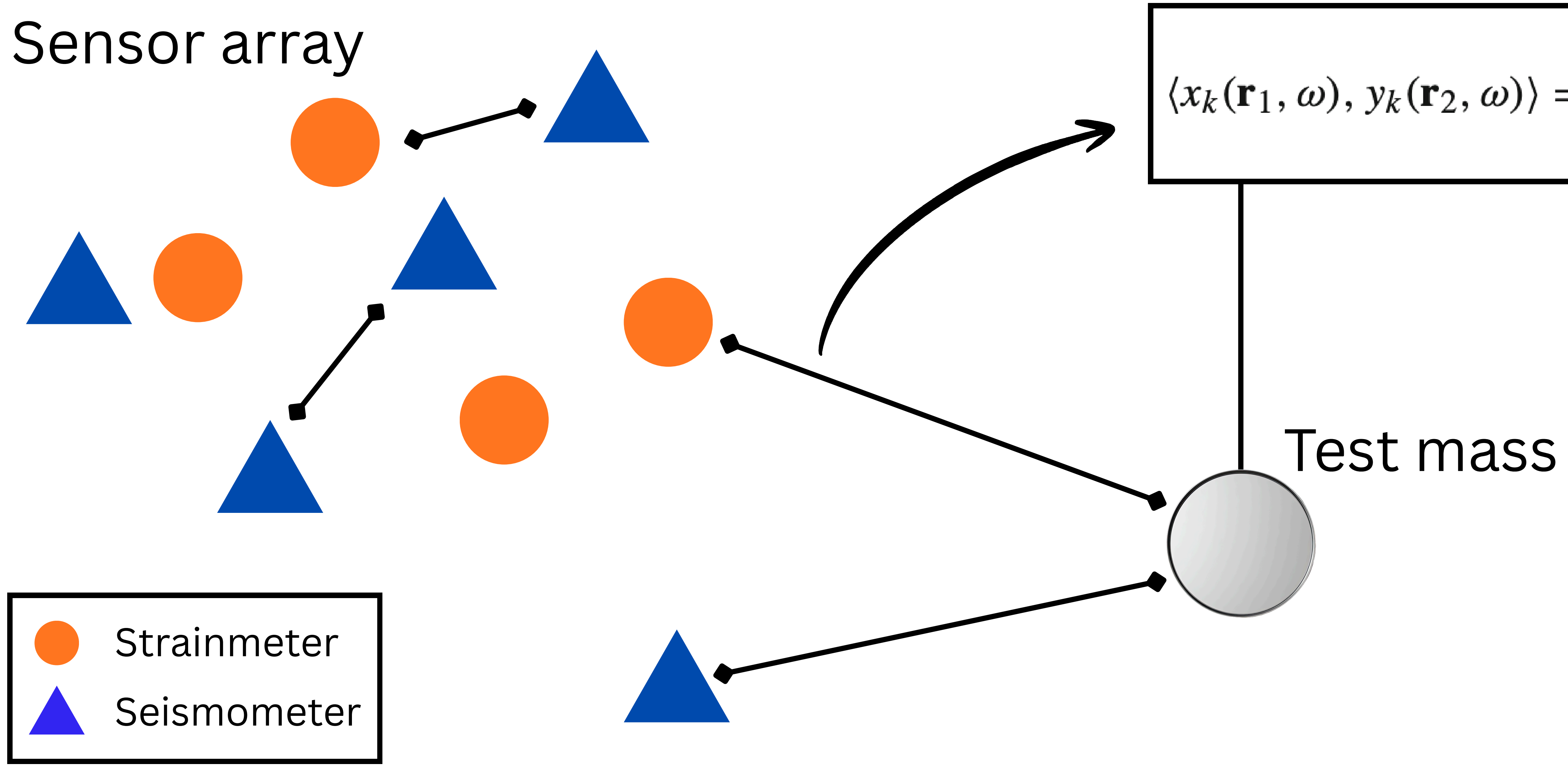
$$\boldsymbol{\epsilon}(\mathbf{r},t) = \partial_{\mathbf{r}}\boldsymbol{\xi}(\mathbf{r},t) = -i\,\mathbf{p}\otimes\mathbf{k}\, e^{-i(\mathbf{r}\cdot\mathbf{k}-\omega t)}$$

Strain field

Intuitively, one can also think of a strainmeter as the differential signal between two seismometers:

$$\boldsymbol{\epsilon}(\mathbf{r},t) = \lim_{L\to 0} \frac{\boldsymbol{\xi}(\mathbf{r}+L\mathbf{e}_L,t)-\boldsymbol{\xi}(\mathbf{r},t)}{L}$$

WIENER FILTER ANALYSIS FRAMEWORK FOR FUSION SENSOR ARRAYS

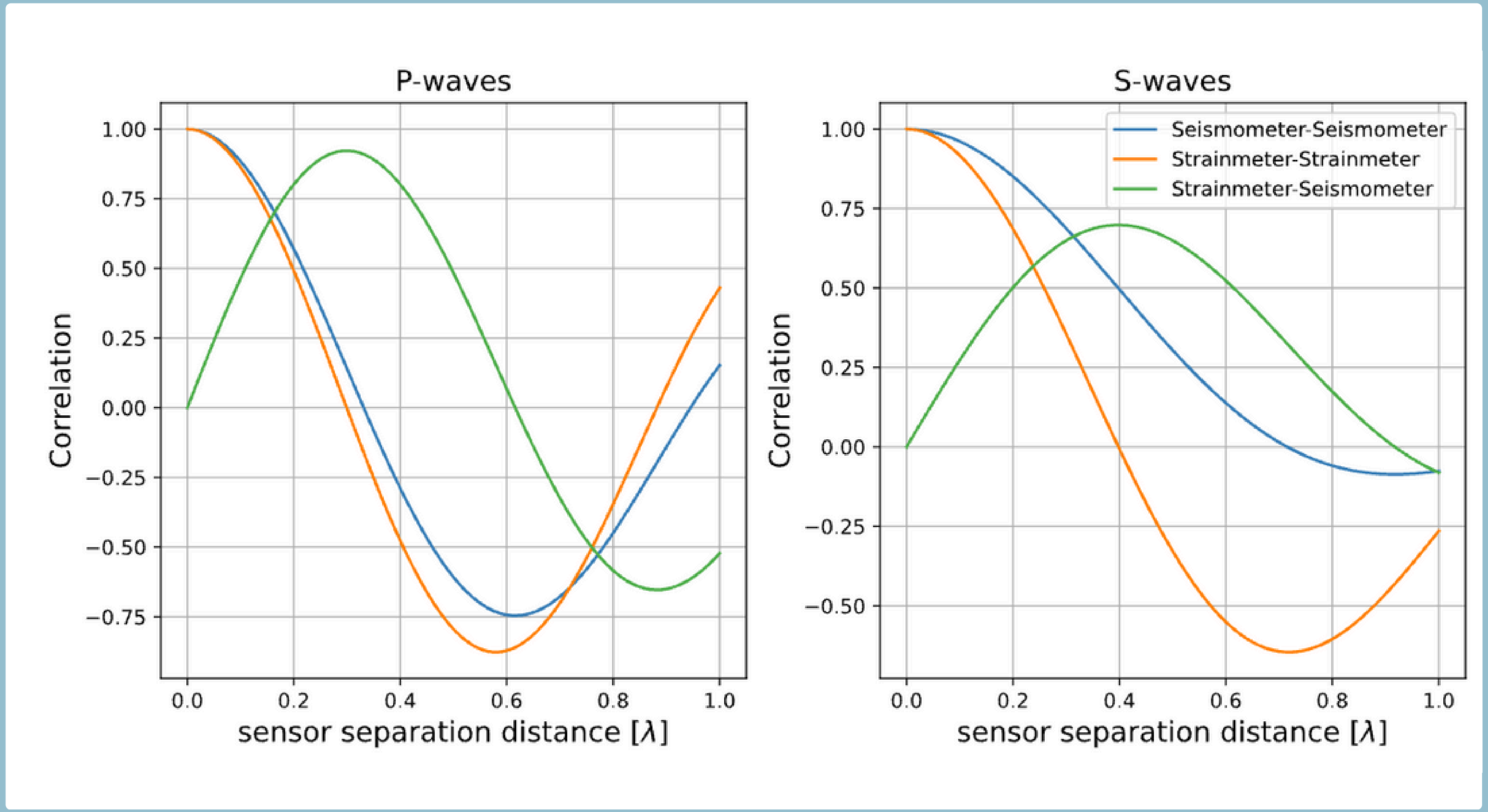


$$\langle x_k(\mathbf{r}_1, \omega), y_k(\mathbf{r}_2, \omega)\rangle = S(x, y; \omega)\frac{1}{4\pi P}\int \mathrm{d}\mathbf{p}\int \mathrm{d}\Omega_k\, s(\mathbf{k}, \mathbf{p})\mathrm{e}^{\mathrm{i}\mathbf{k}\cdot(\mathbf{r}_2-\mathbf{r}_1)}$$

- correlation $\langle .,. \rangle$
- sensor positions $\mathbf{r}_1, \mathbf{r}_2$
- sensor measurements x_k, y_k
- wave vector $\mathbf{k}$
- wave frequency ω
- polarization vector $\mathbf{p}$
- amplitude function $s(\mathbf{k}, \mathbf{p})$
- polarization normalization constant P
- cross-spectral density $S(x, y; \omega)$

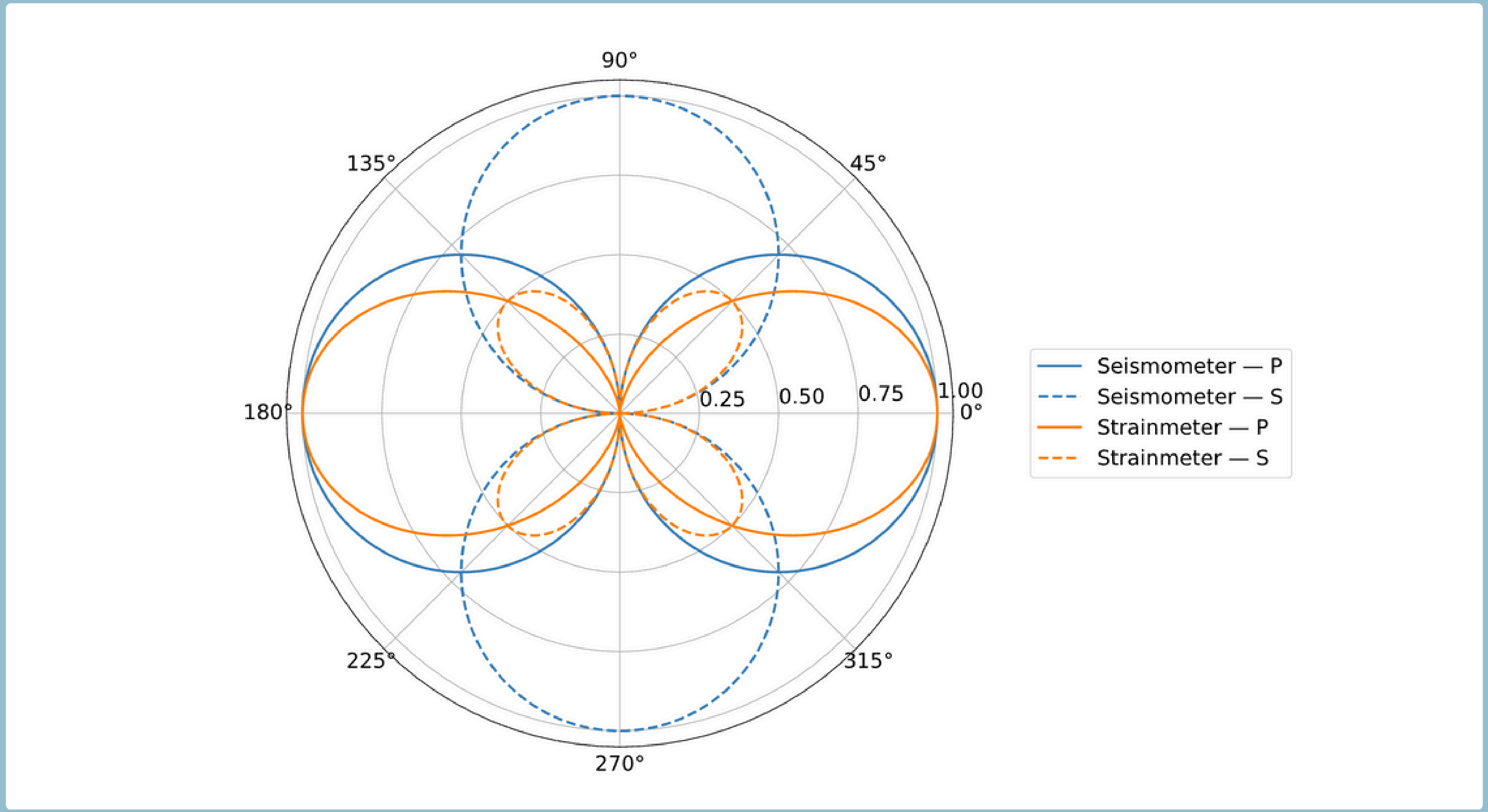
COMPARING SEISMOMETERS AND STRAINMETERS

Correlation coefficients



- Comparing the two sensor correlation coefficients (all measurement axes aligned) between seismometer and strainmeter
- Seismometers and strainmeters are uncorrelated when placed close to each other. This comes from the averaging in direction done for the correlation calculation

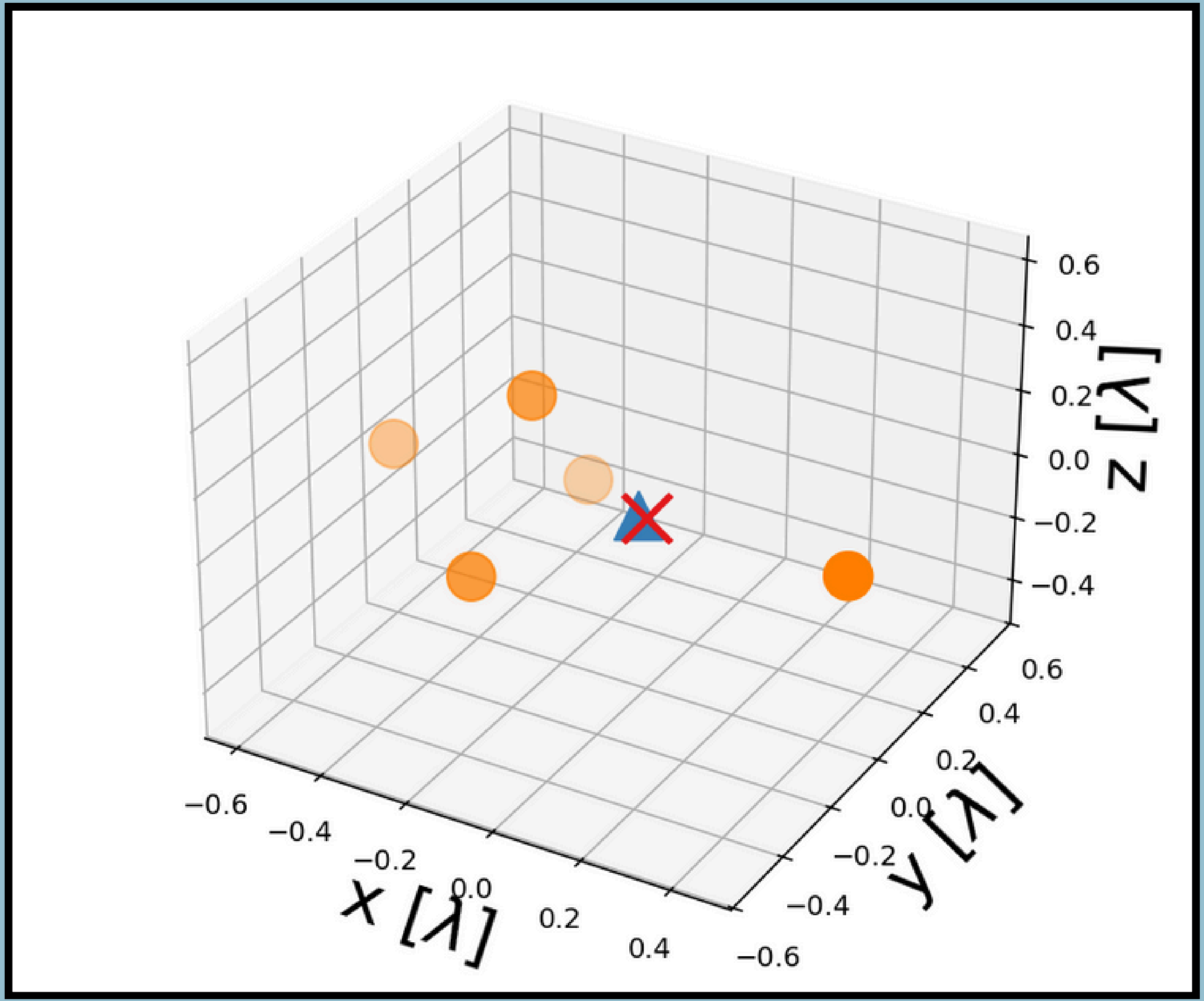
Angular Sensitivity Pattern

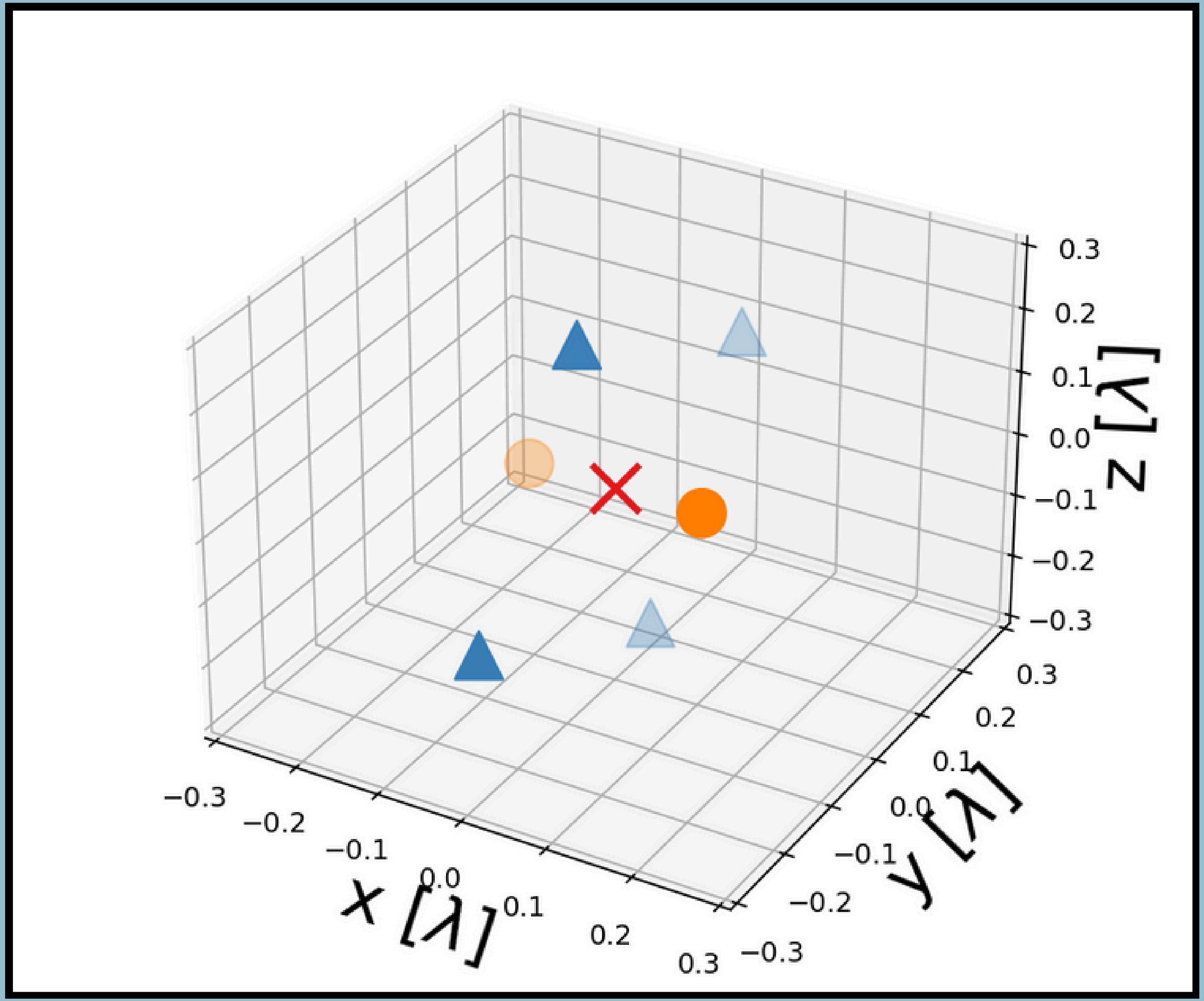


- The angular sensitivity pattern of strainmeters is different to seismometers
- Further, for strainmeter, it is different between P- and S- waves

Results

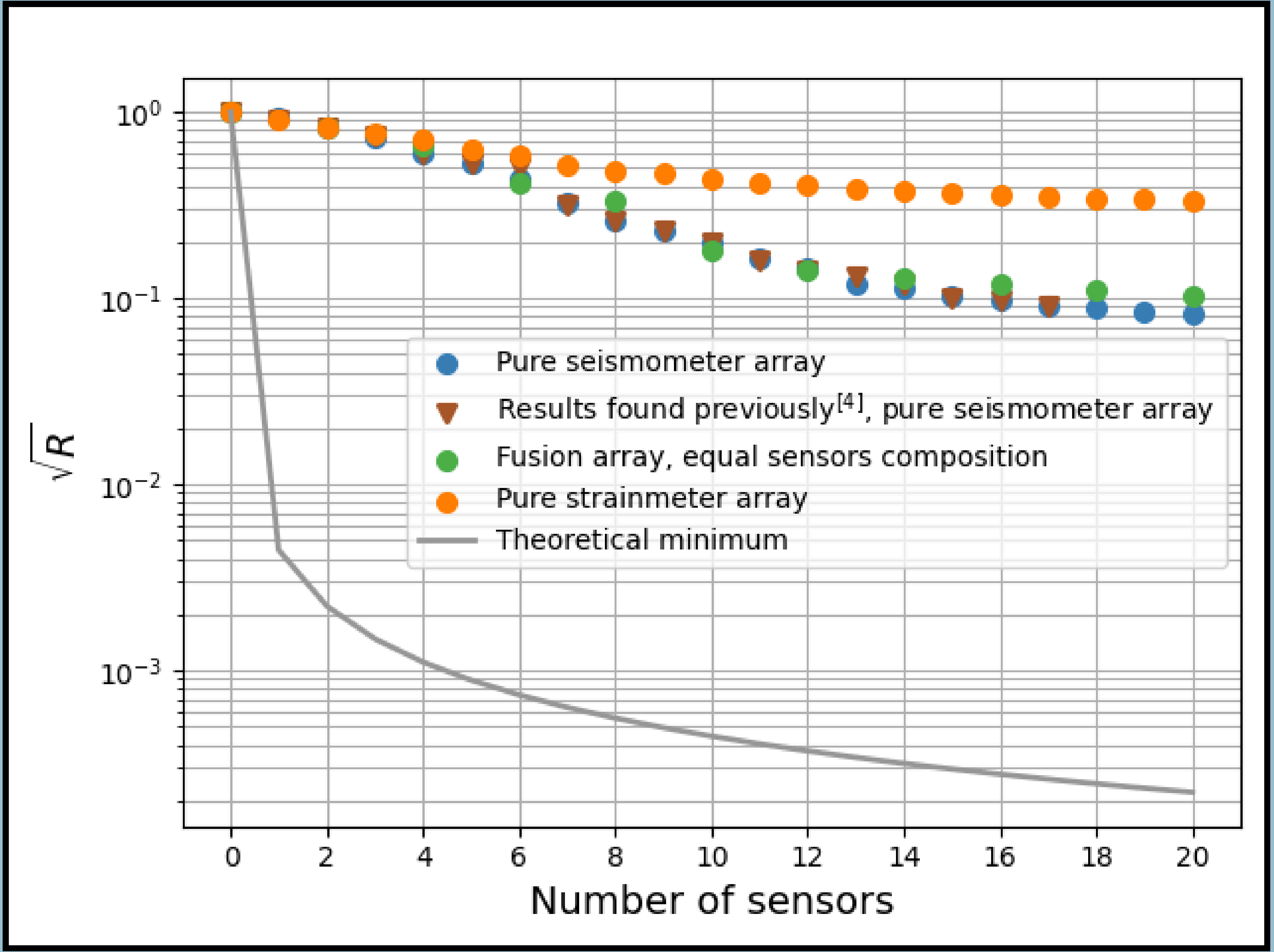
GEOMETRIES





Resulting configurations optimising the positions of a sensor array which contains seismometers and strainmeters

PERFORMANCE



- Seismic noise floor using a mixing ratio p, seismic speed c, frequency f and wavelength λ are given by

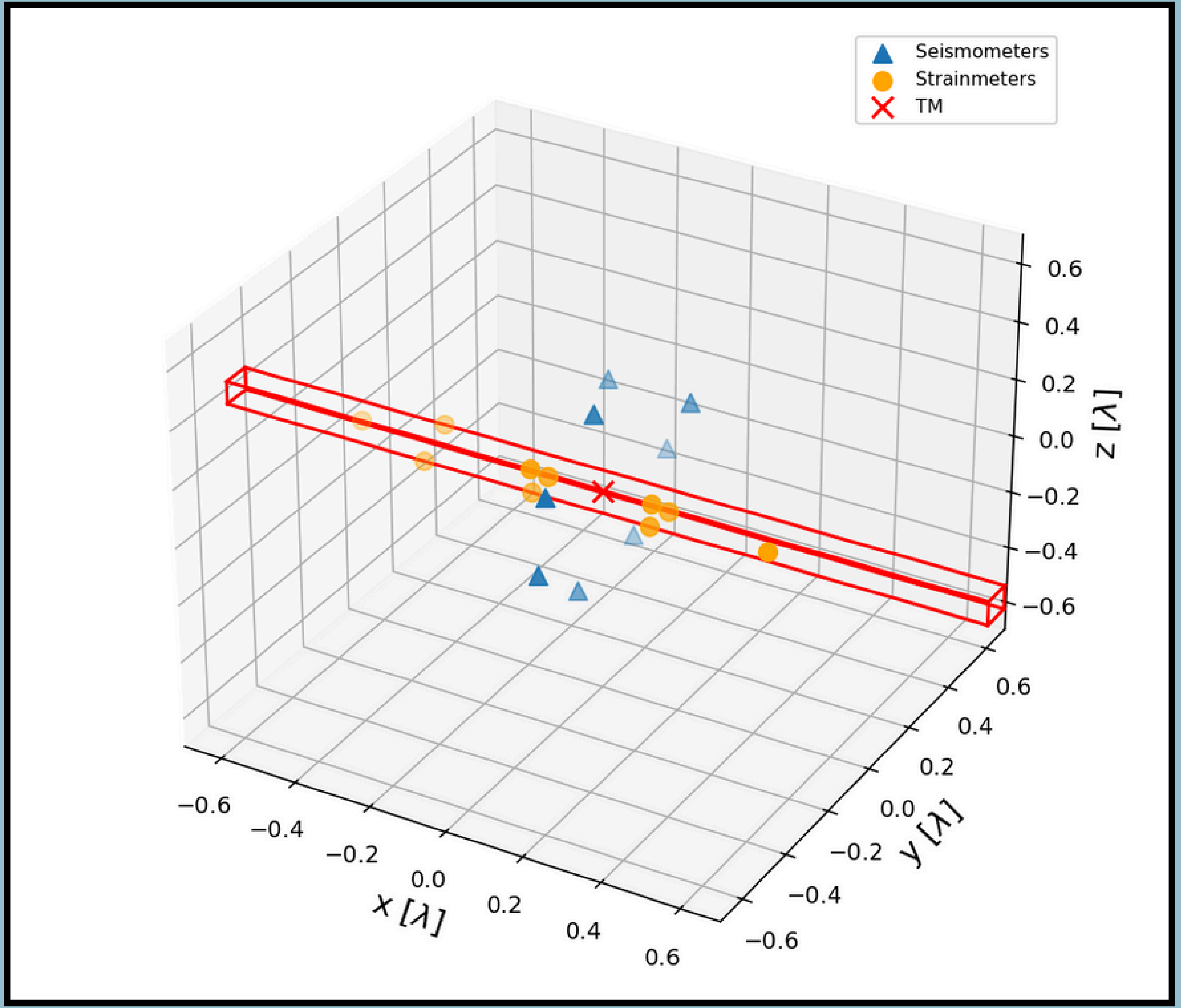
$$\{p = \frac{1}{3}, c_p = 6000\,\mathrm{m/s}, f_p = \frac{c_p}{\lambda_p}, c_s = 4000\,\mathrm{m/s}, f_s = \frac{c_s}{\lambda_s}\}$$

- Assume all sensors have SNR = 15
- Fusion sensor arrays (using the same amount of seismometers and strainmeters) perform similarly well as pure seismometer arrays

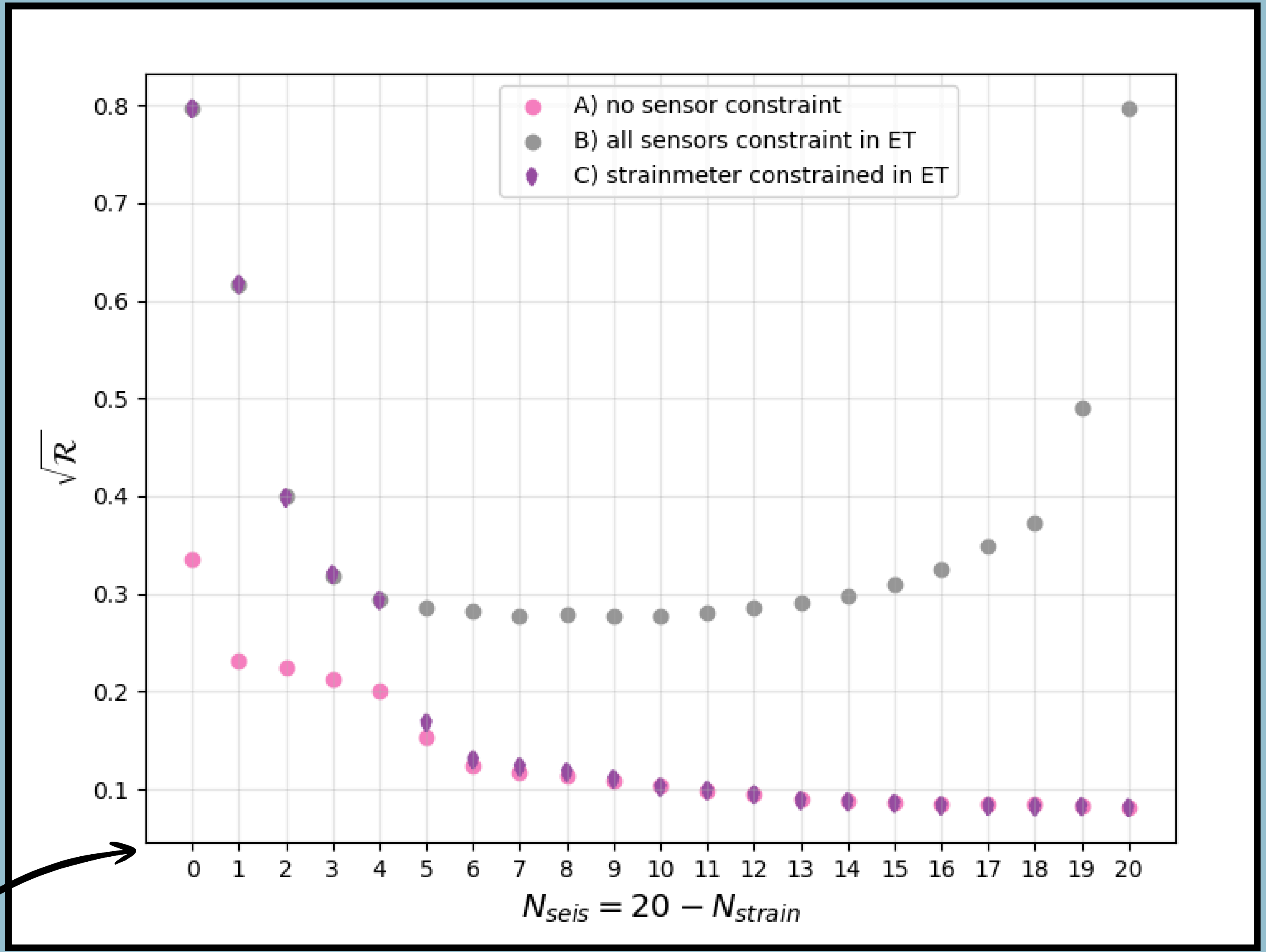
[4] F.Badaracco *Optimization of seismometer arrays for the cancellation of Newtonian noise from seismic body waves*

NN MITIGATION FROM SENSOR ARRAYS PLACED INSIDE OF THE ET

- Optimize in a bounded region instead of the usual global optimization
- For this, we use a box centred around the TM, shown as a red straight line
- We either restrict one sensor type or all sensors to the box



NN MITIGATION FROM SENSOR ARRAYS PLACED INSIDE OF THE ET

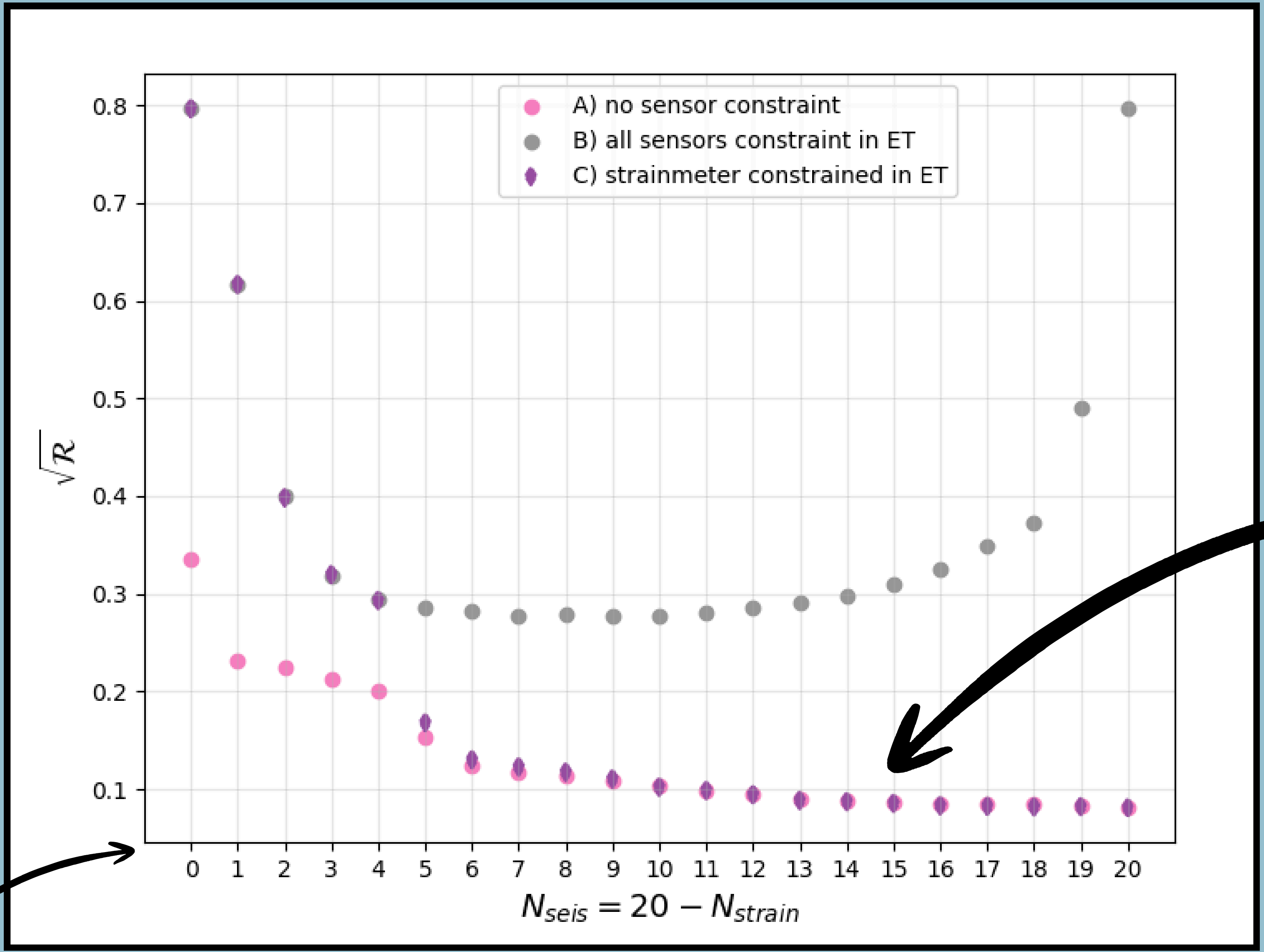


The number of total sensors is always given by 20,
x-axis shows the number of seismometers in fusion array

Comparison Cases A) and B):

Arrays constrained to the ET infrastructure perform considerably worse compared to unconstrained arrays

NN MITIGATION FROM SENSOR ARRAYS PLACED INSIDE OF THE ET



The number of total sensors is always given by 20,
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Comparison Cases A) and B):

Arrays constrained to the ET infrastructure perform considerably worse compared to unconstrained arrays

Comparison Cases A) and C):

For arrays which contain at least 5, arrays placed without constraints and arrays where the strainmeters are placed inside of the ET infrastructure perform similar!

Outlook

NEXT STEPS

- Improve fusion array setup using the same analysis framework, e.g. by including several TMs, test broadband mitigation capabilities…
- Improve mitigation analysis framework itself, relax assumption regarding the seismic noise floor (e.g. isotropy would change correlation properties of strainmeters) -> *very interested to see how Patrick's simulations develop*
- Since the current framework depends much on the correlation coefficients, it would also be interesting to use a different type of correlation, e.g. in time domain, or to combine the signals using a different filter than the Wiener filter

WHAT NN MITIGATION COULD BENEFIT FROM

- Current analysis is done analytically, development of advanced and adaptable seismic simulations (e.g. FEM), which could then be used to build a mitigation model
- Analysis of how mitigation strategy changes when NN model changes (e.g. change cavity shape)
- Testing the NN mitigation using real seismic data, using a fusion sensor array and then one seismometer as the TM (virtual sensor)

Thanks for your attention :)