Newtonian noise subtraction in 2G and 3G detectors using neural networks

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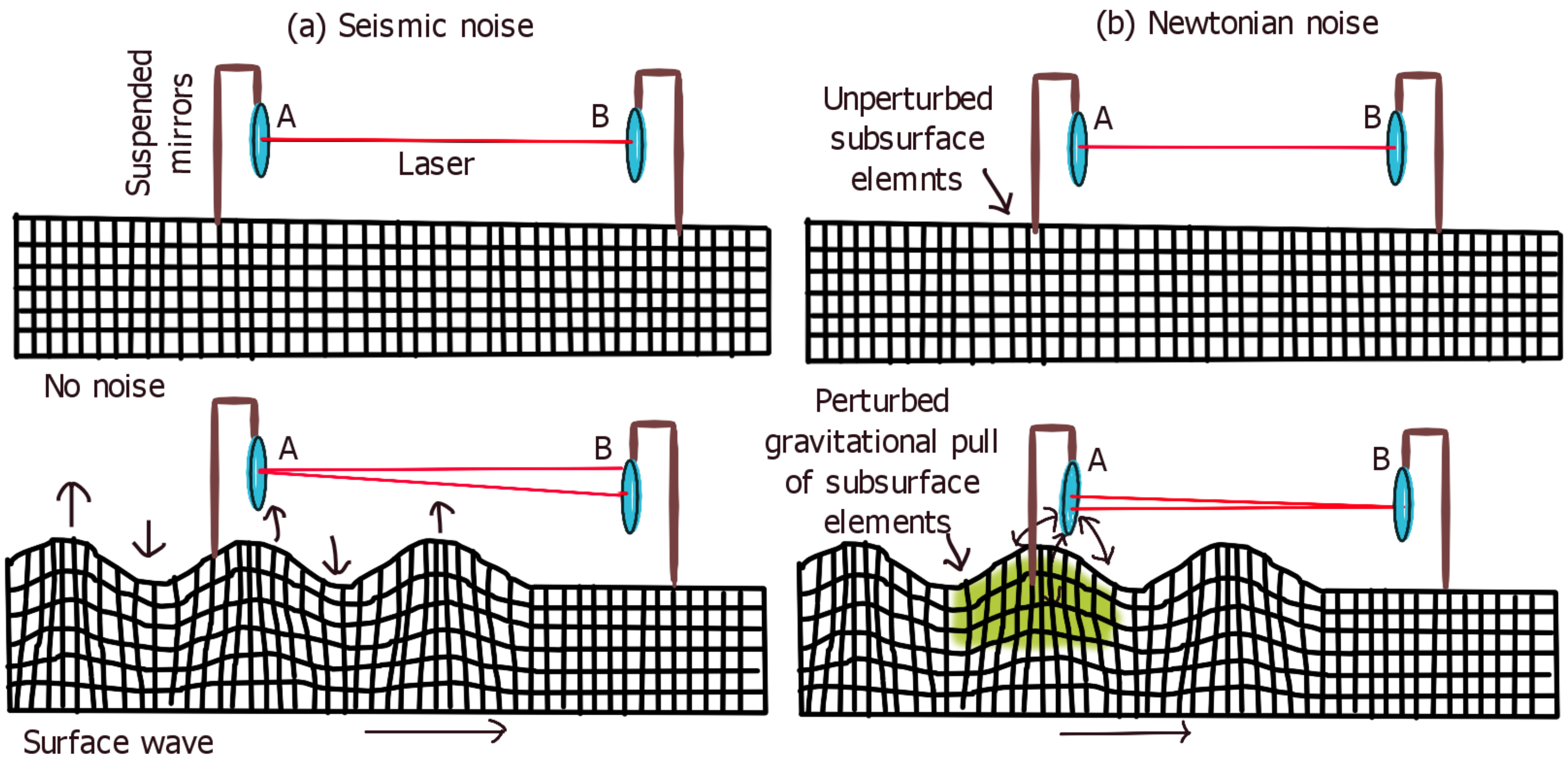
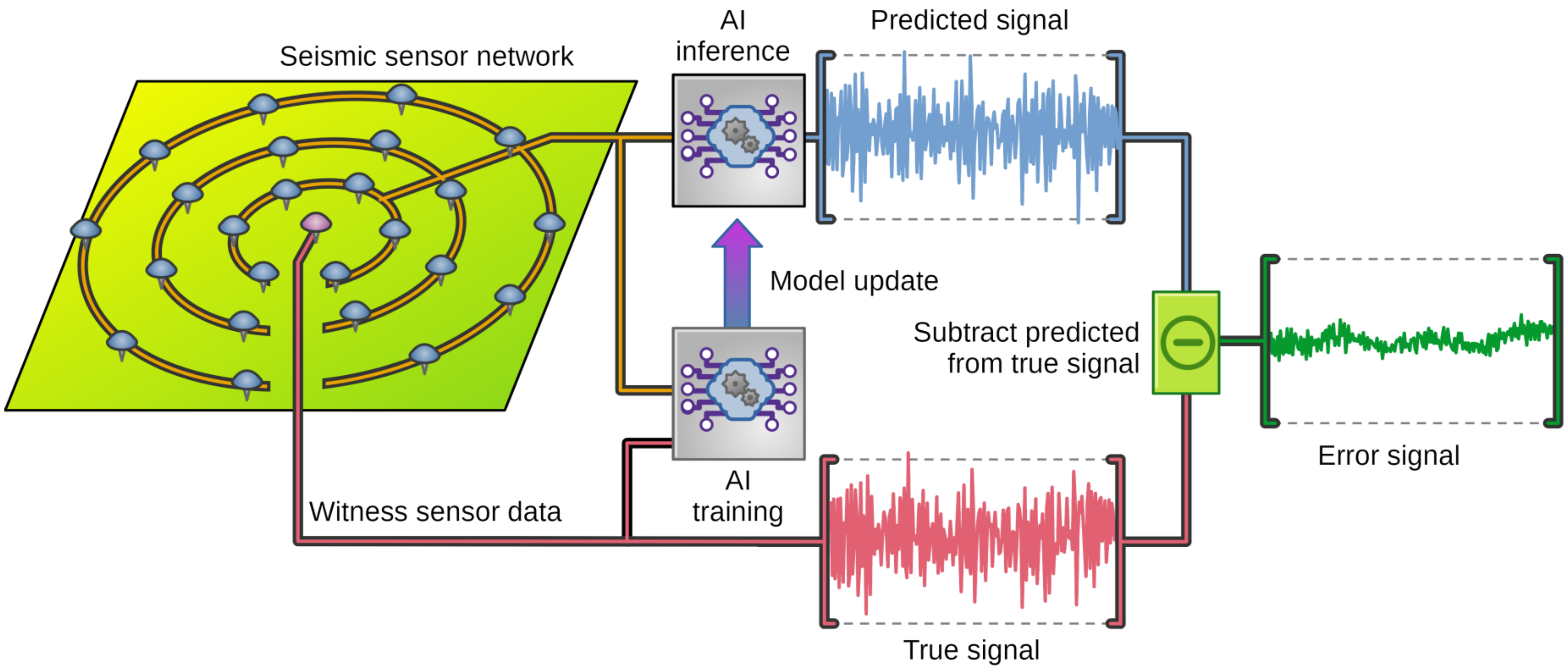
Newtonian noise - fundamentals

- Gravitational coupling of seismic motion to the suspended optics of the detector
  - Cannot be mechanically shielded from, due to the Newtonian coupling



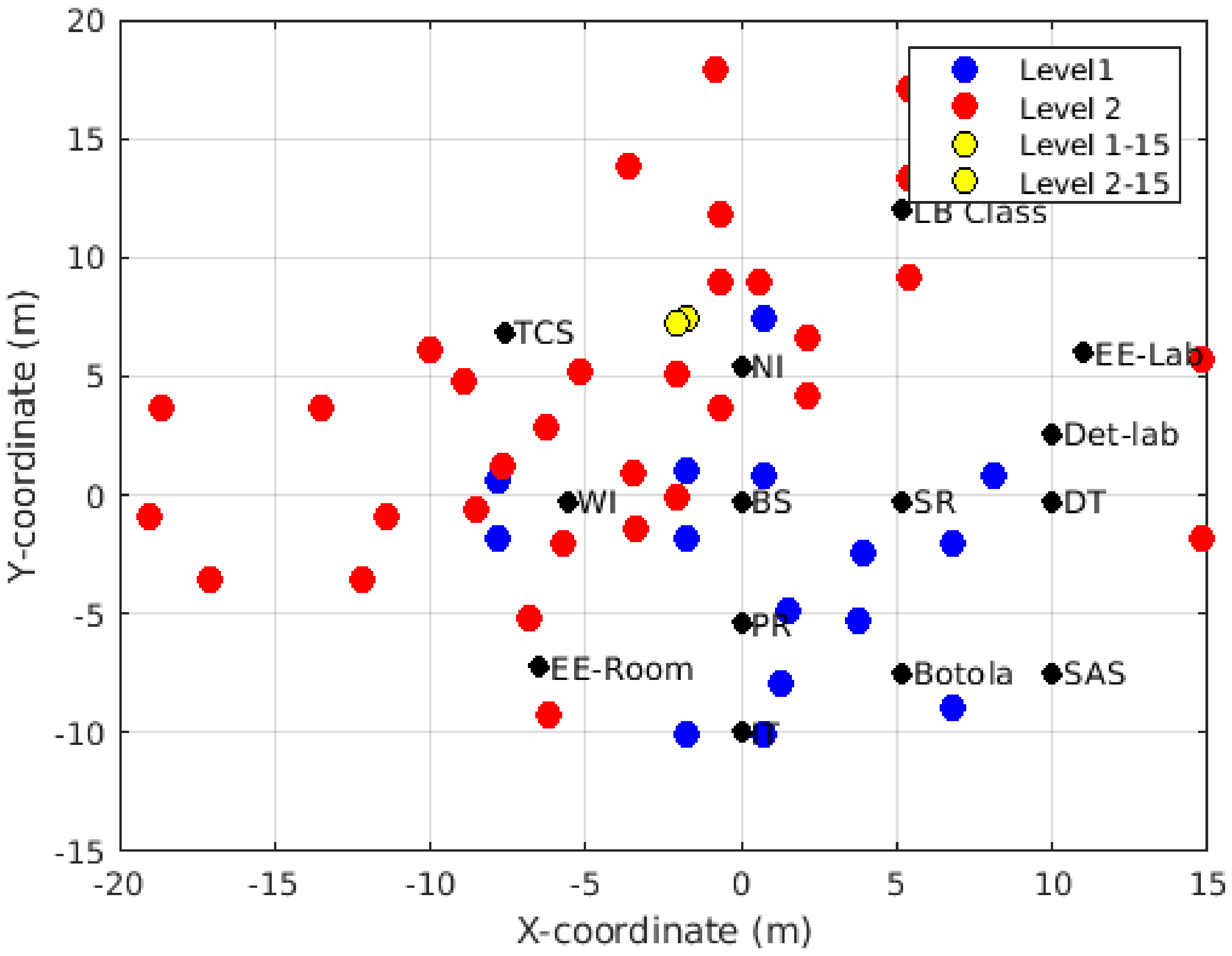
Newtonian noise subtraction for surface detectors

- Seismic noise data acquired by an array of seismometers positioned in the vicinity of the test-mass can be used to predict and subsequently subtract Newtonian noise (Tringali et al 2019, Badaracco et al 2020)
  - Wiener filtering
  - Convolutional neural network
- The subtracted noise might be due to residual seismic noise propagating through the filter-chains

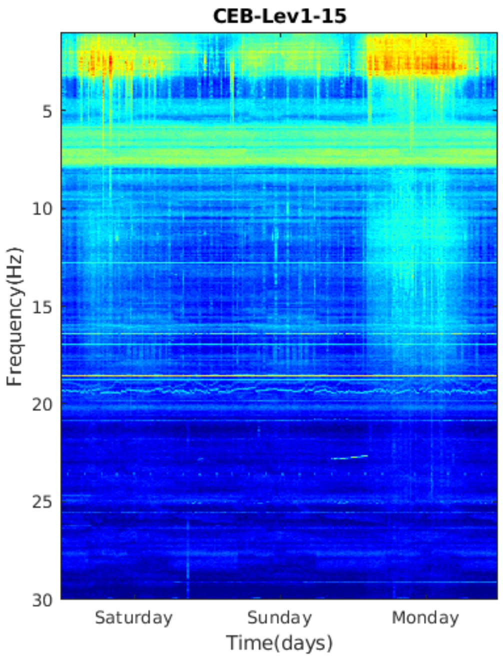


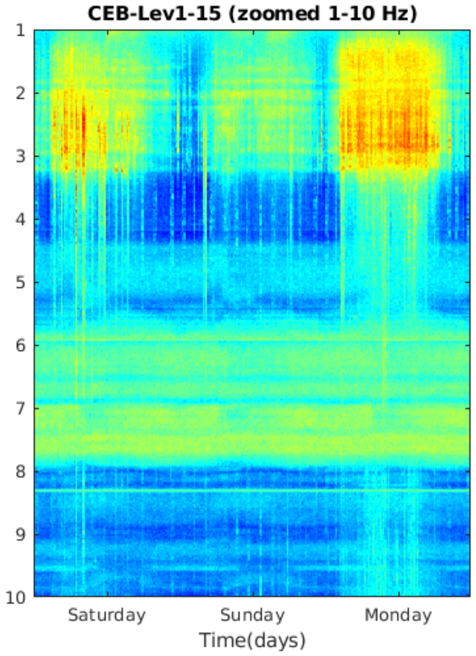
Seismic array set up at AdV+

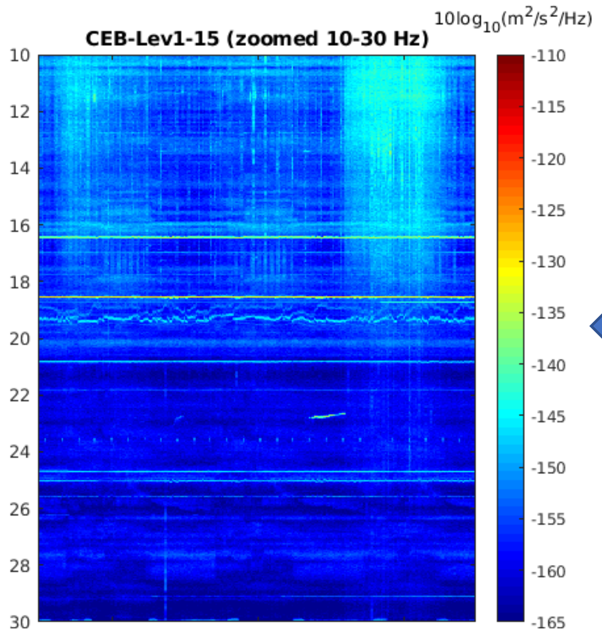
- An array of 50 vertical component 5 Hz geophones positioned at the Central-Building, and acquiring continuous data at 500 sps (https://logbook.virgo-gw.eu/virgo/?r=52559) – Polgraw Team
  - 36 stations installed at level 1, 14 at level 2
- 30 stations each at NEB and WEB
- Results presented only using the CEB stations, since NEB and WEB is based on a similar approach



Seismic array - noise characteristics

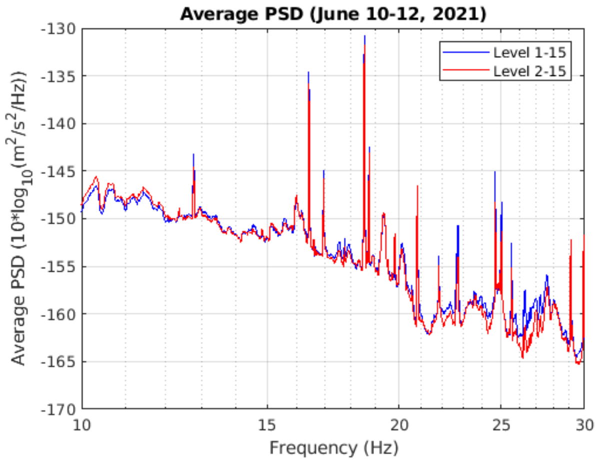


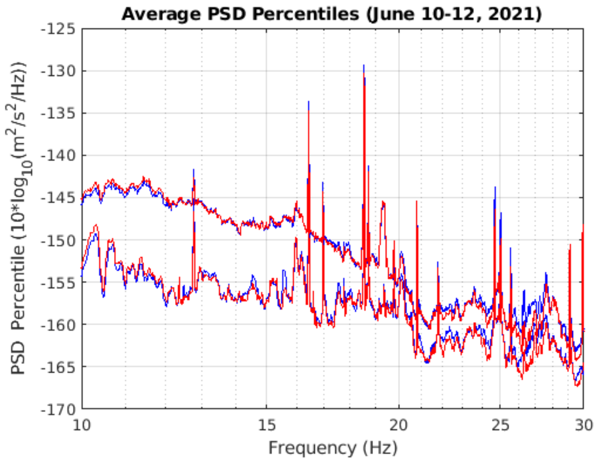




- Noise below 15 Hz have a typical diurnal variation and depicts non-stationarity
  - Traffic (Koley et al 2017)
- Noise above 15 Hz are mostly composed of sharp spectral noise originating from machinery at the site (Report)

- Seismic measurements at Level 1 and Level 2 of CEB are consistent





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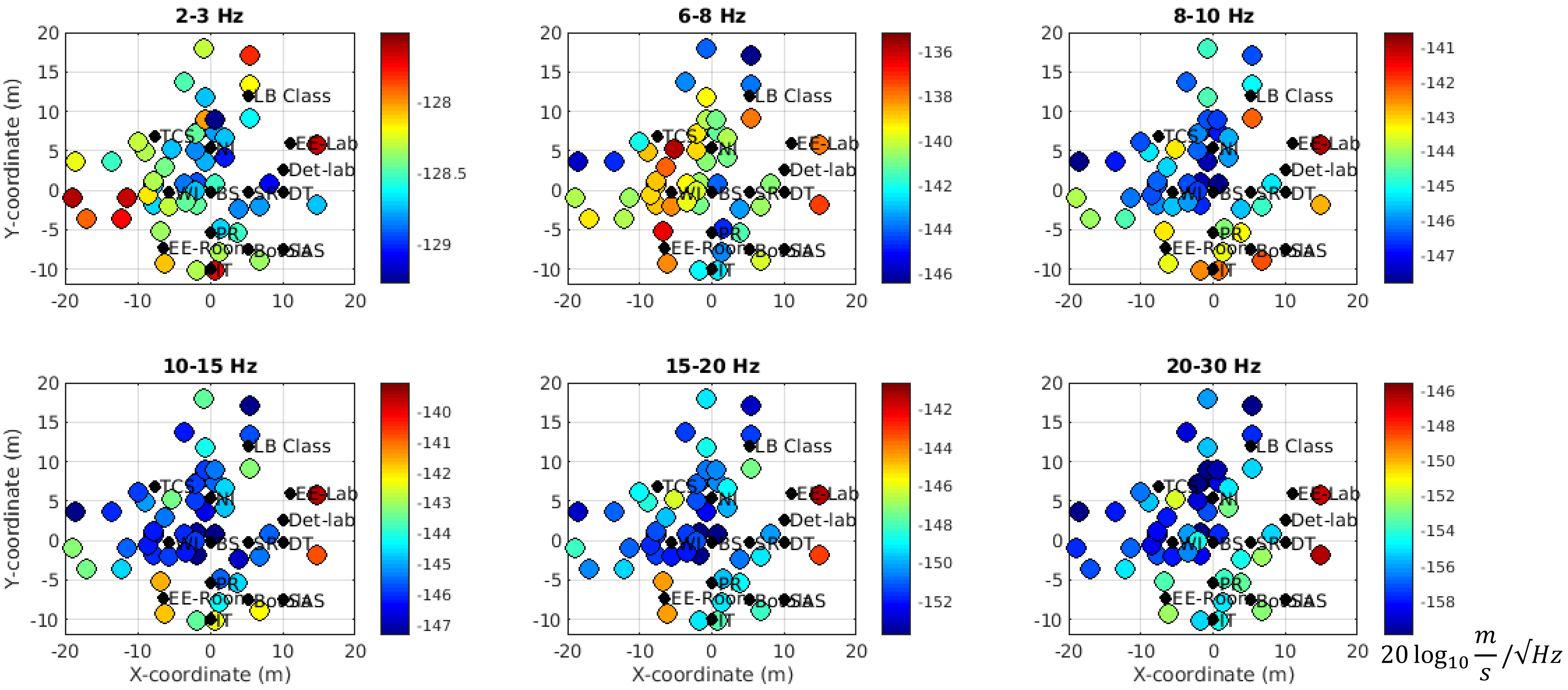
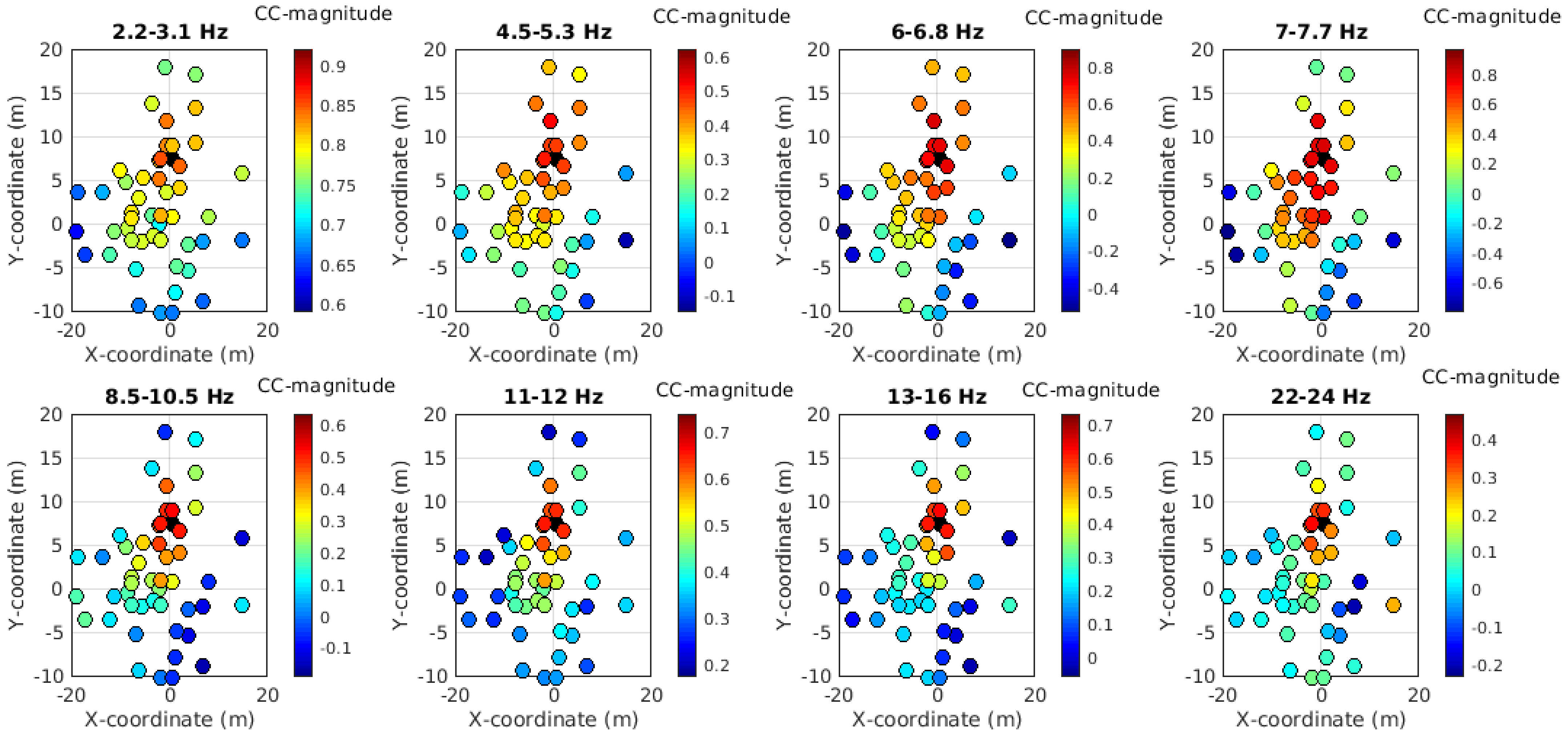
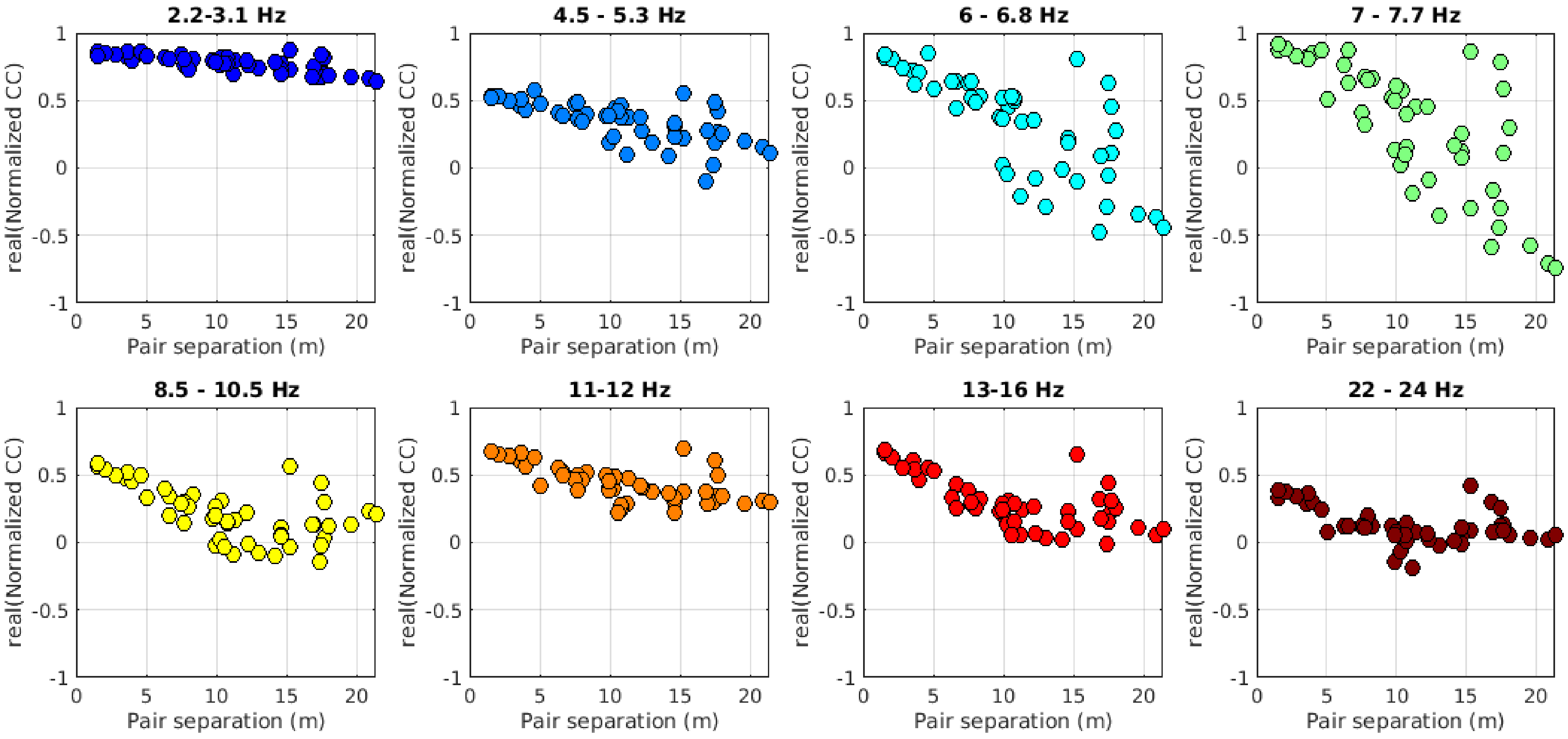


Seismic array - noise cross-correlations



Seismic array - noise cross-correlations vs distance

- Ideally a zeroth order Bessel function behavior is expected: $J_0\left(\frac{2\pi f r}{c(f)}\right)$
  - Non-isotropic illumination
  - Inhomogeneous propagation medium



Wiener filtering

- Problem formulation $Ax = b$ where A is the matrix of reference channel cross-correlations, b is the column vector of reference-target channel cross-correlations and x is vector of the filter-coefficients

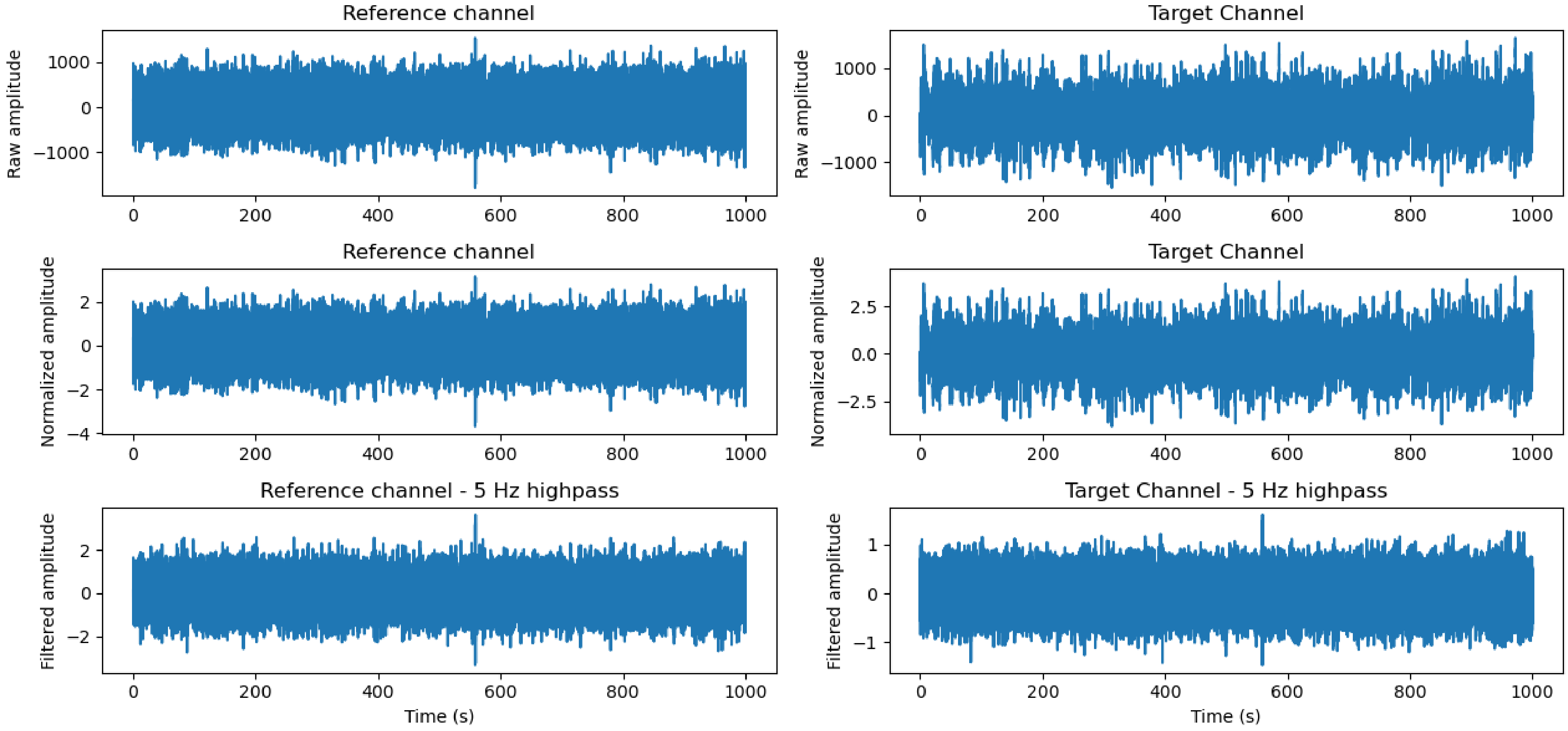
$$\begin{bmatrix} [s_1 * s_1] & [s_1 * s_2] & \cdots & [s_1 * s_n] \\ & [s_2 * s_2] & & [s_2 * s_n] \\ & \vdots & \ddots & \vdots \\ & . & \cdots [s_n * s_{n-1}] & [s_n * s_n] \end{bmatrix} \begin{bmatrix} x_{01} \\ x_{02} \\ .. \\ x_{0P} \\ . \\ . \\ . \\ x_{n1} \\ x_{n2} \\ .. \\ x_{nP} \end{bmatrix} = \begin{bmatrix} s_1 * t \\ s_2 * t \\ . \\ . \\ . \\ . \\ s_n * t \end{bmatrix}$$

where s_n are the reference channels, t is the target channel and x_{ij} corresponds to the j^{th} filter coefficient for the i^{th} reference channel

- Each sub-matrix $s_i * s_j$ is a Toeplitz matrix constructed using the causal and acausal time domain cross-correlations between reference channels

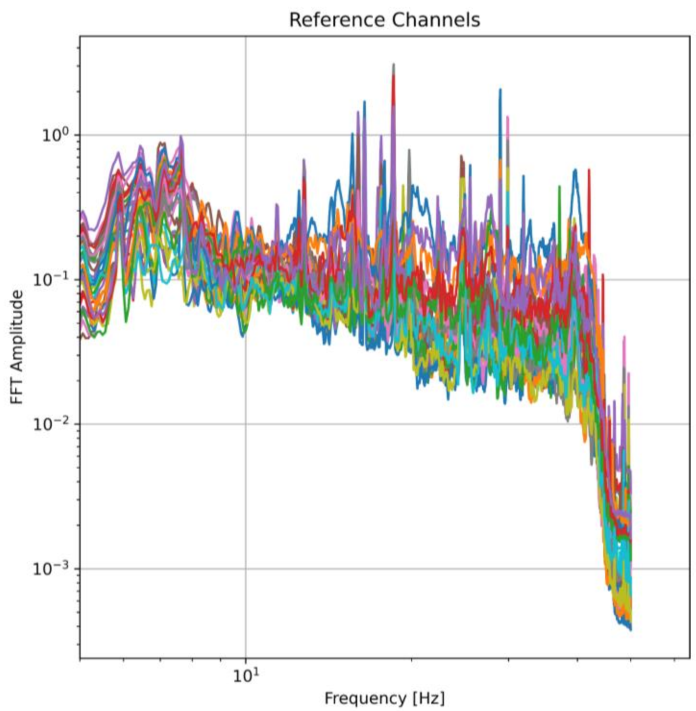
Wiener filtering and CNN data pre-processing

- The data is detrended, normalized using the data variance and filtered in the 5-50 Hz frequency band

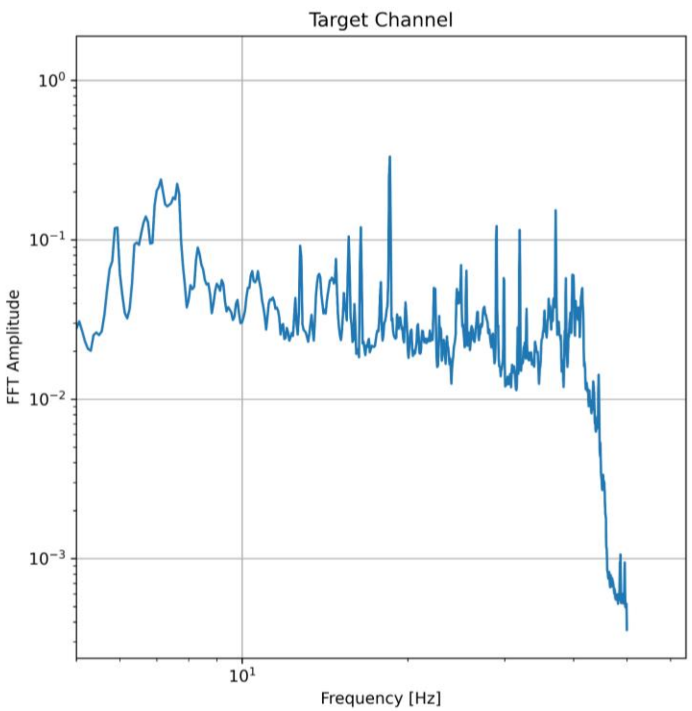


Wiener filter output

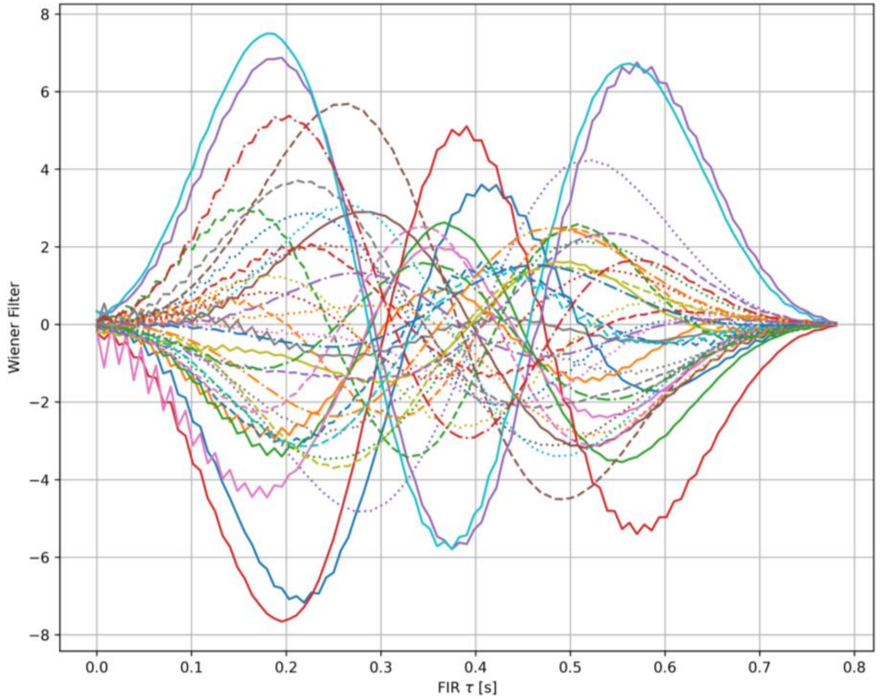
- For testing we use the data from the Guralp seismometer, since the interferometer output is not available due to locking stability issues



Reference channels



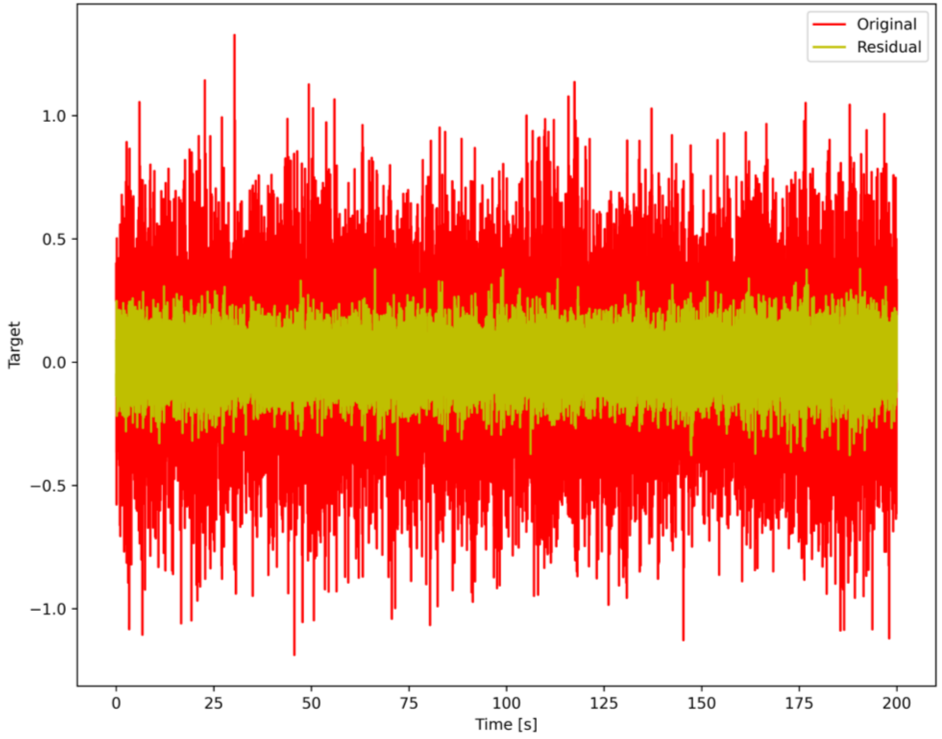
Target channel - Guralp



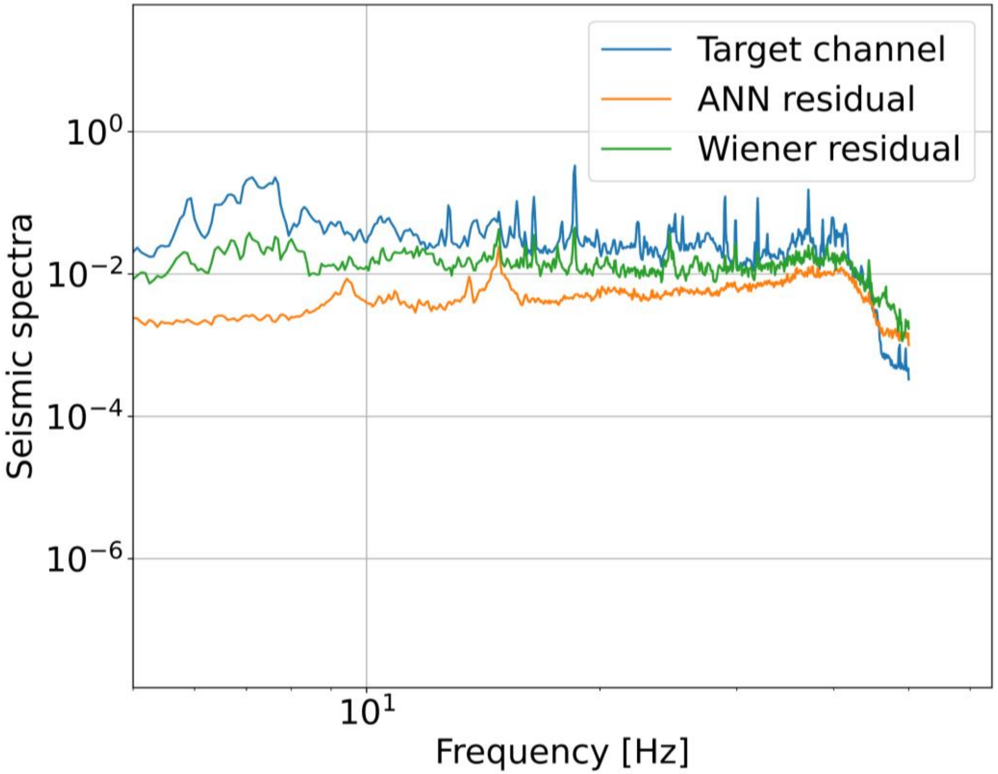
Wiener filter coefficients for every channel

Wiener filter vs CNN

- CNN was setup using the Keras TensorFlow API with Adam Optimizer and learning rate of 10^{-5}
- Training performed in batches of 50 s
- Mean square logarithmic loss function was found to perform best for the problem



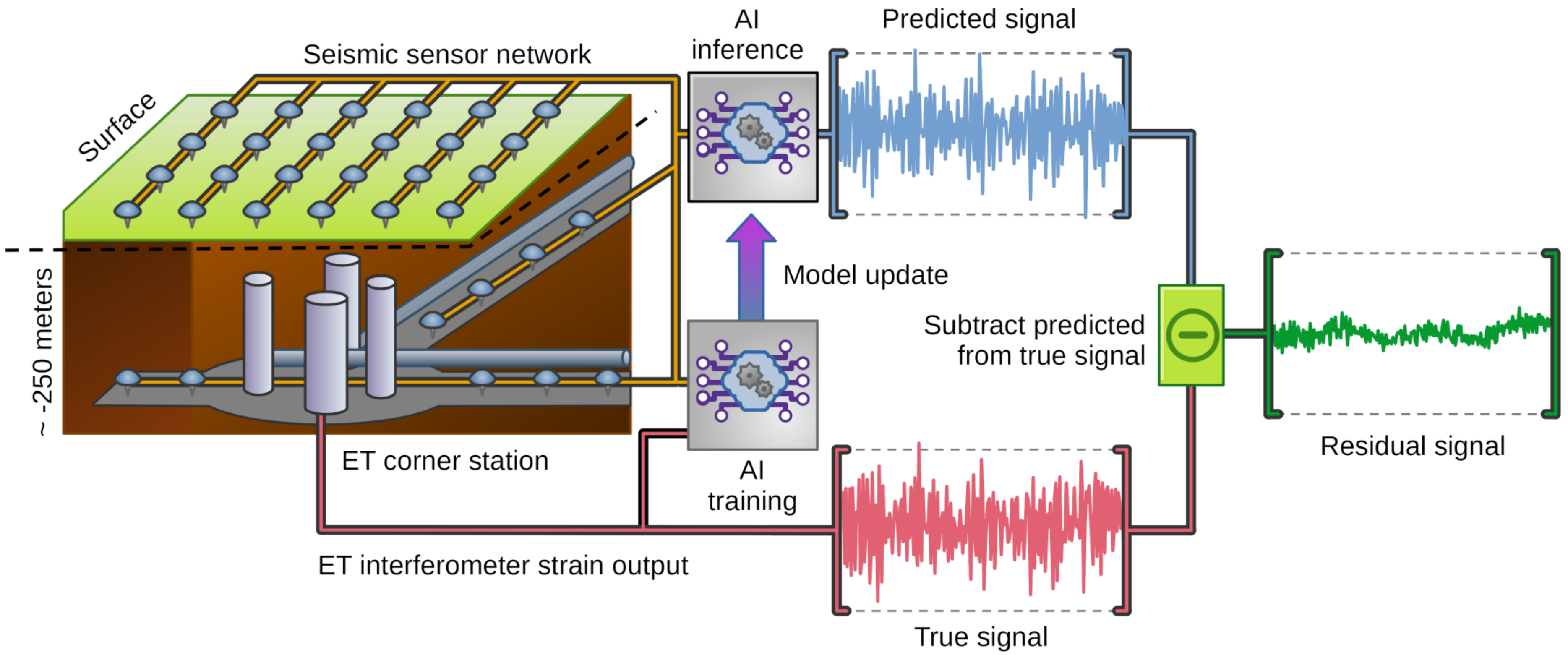
Time domain residual



Frequency domain performance comparison

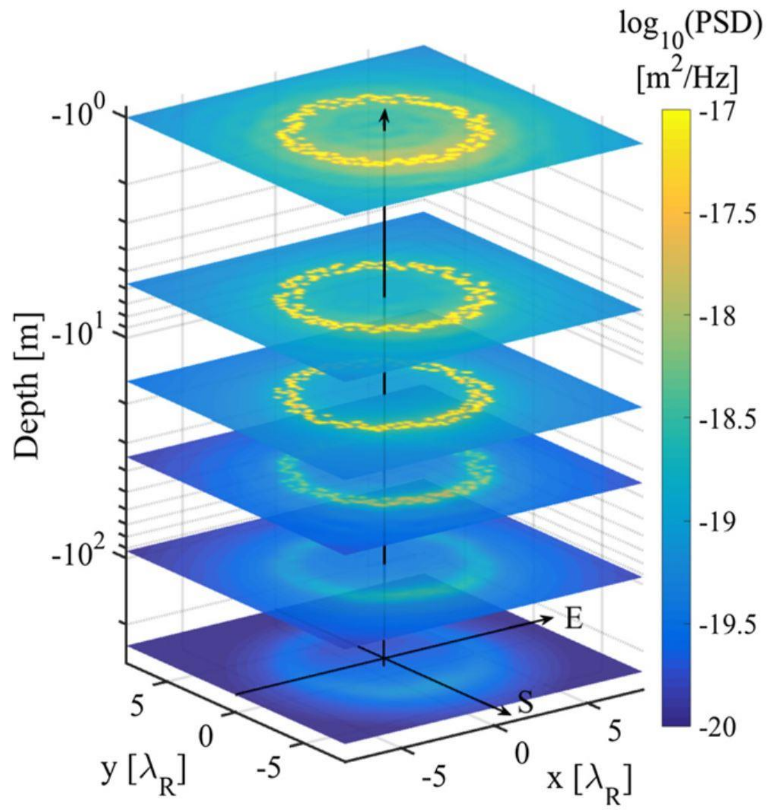
Newtonian noise subtraction for underground detectors

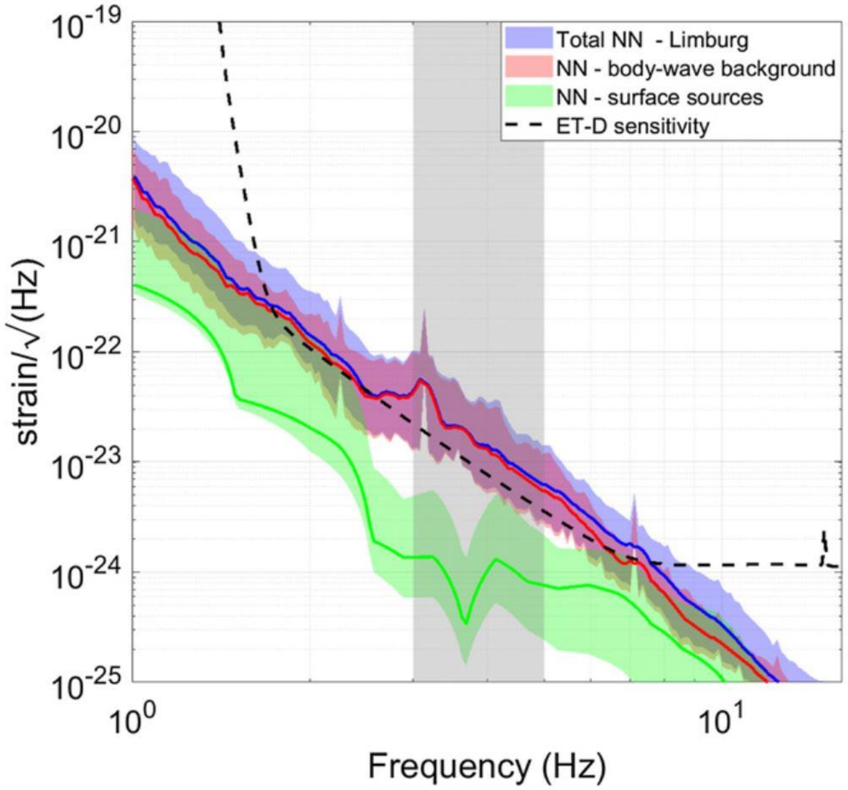
- NN subtraction for 3G detectors like Einstein Telescope is more relevant since the observation band goes down to 3 Hz and NN is expected to limit its sensitivity in the band about 3-8 Hz
- Relying in simulations
- Realization of what sensor locations to use is being researched (Jose&Kalaimani, 2021, Badaracco et al 2020)



Newtonian noise for Einstein Telescope – an initial estimate

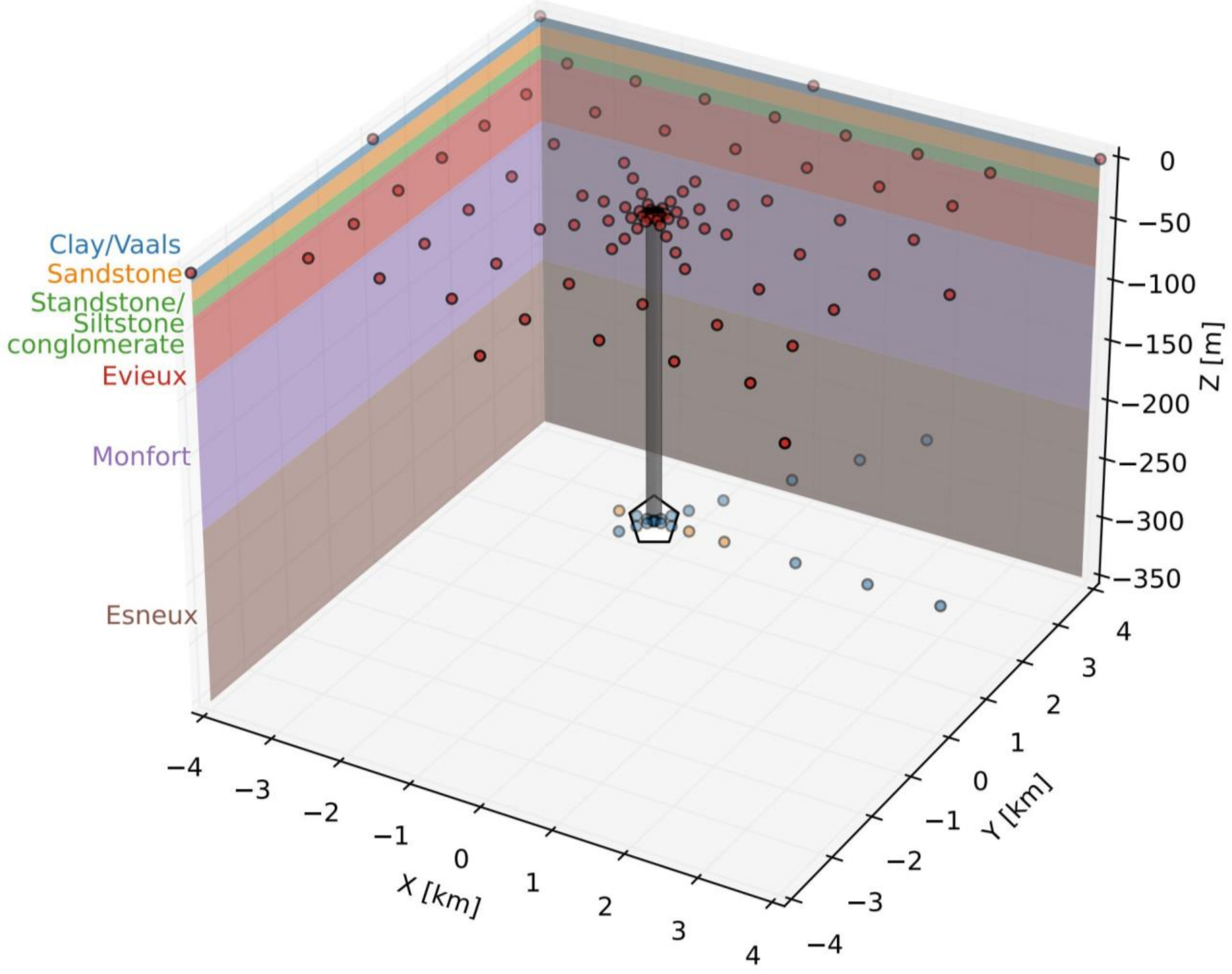
- An initial numerical estimate of Einstein Telescope is necessary to be able to validate the subtraction scheme
  - Elasto-dynamic simulations – based on geology and noise source distribution at the site
  - Plane body wave estimation (Bader et al 2022, Koley et al 2022)





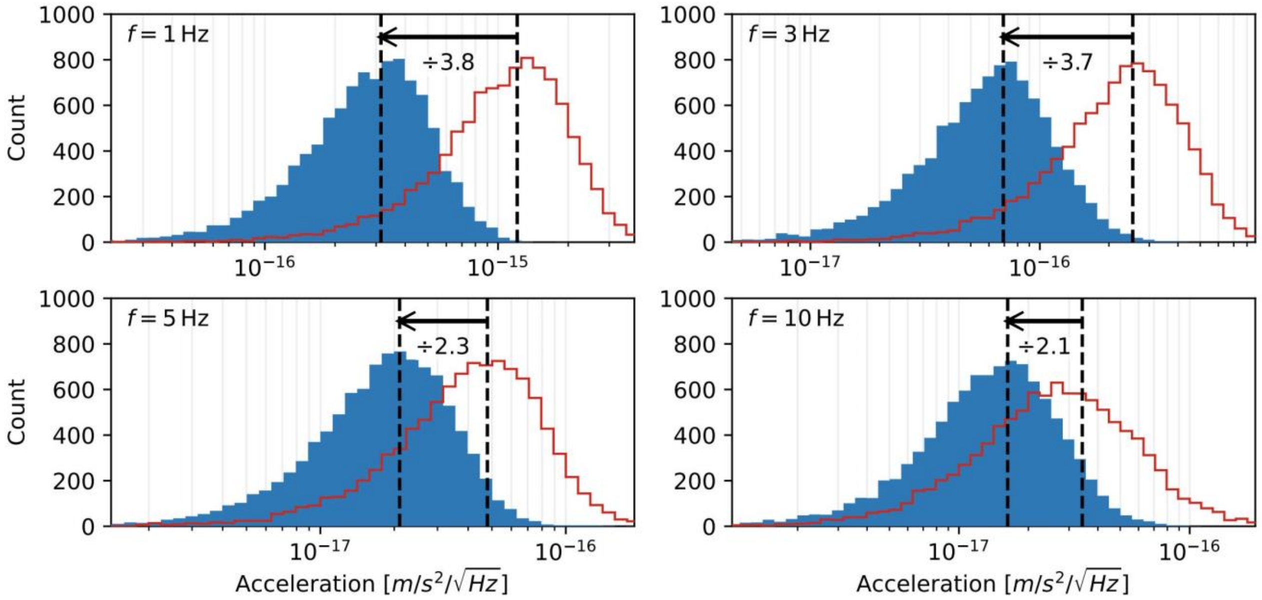
NN subtraction for Einstein Telescope – the setup

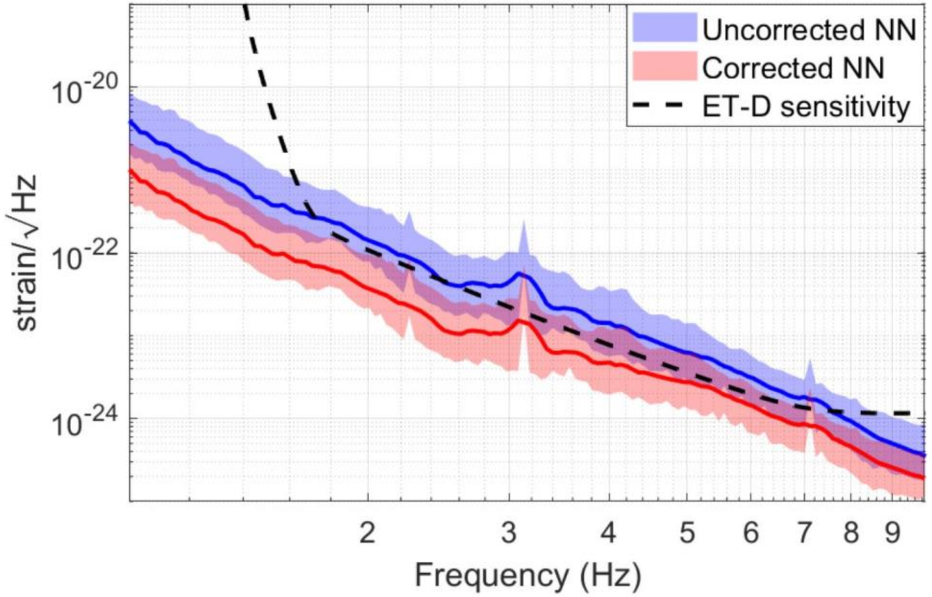
- Synthetic ground displacements simulated for a layered subsurface (Koley et al 2018, Koley et al 2022)
- Sensor self noise added to the simulated displacements
- Up to 15 underground stations used – at the test-mass and along the direction of the tunnels and the dense sensor-network on the surface is used
- Simulated displacement data at specific locations are used to reproduce the NN and the network is trained
- Simulations are repeated corresponding to noise varying stochastically between the 10th and 90th percentiles of the observed noise
- Network is trained to reproduce the NN-acceleration at one corner station of the triangular topology



NN subtraction for Einstein Telescope – result

- Up to a factor 4 reduction in strain could be achieved in the frequency band 3-10 Hz
- Publication in preparation (Beveren et al 2022, in Virgo DRS)





Questions