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Providing priors to Bayesian array optimization

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ET – Site studies and characterization
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www.gssi.it

Program

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Workflow

Prior

1. Obtain information on geology, topography, and perform numerical simulations of seismic correlations in 3D

Likelihood

2. Observe seismic correlations with seismometer arrays

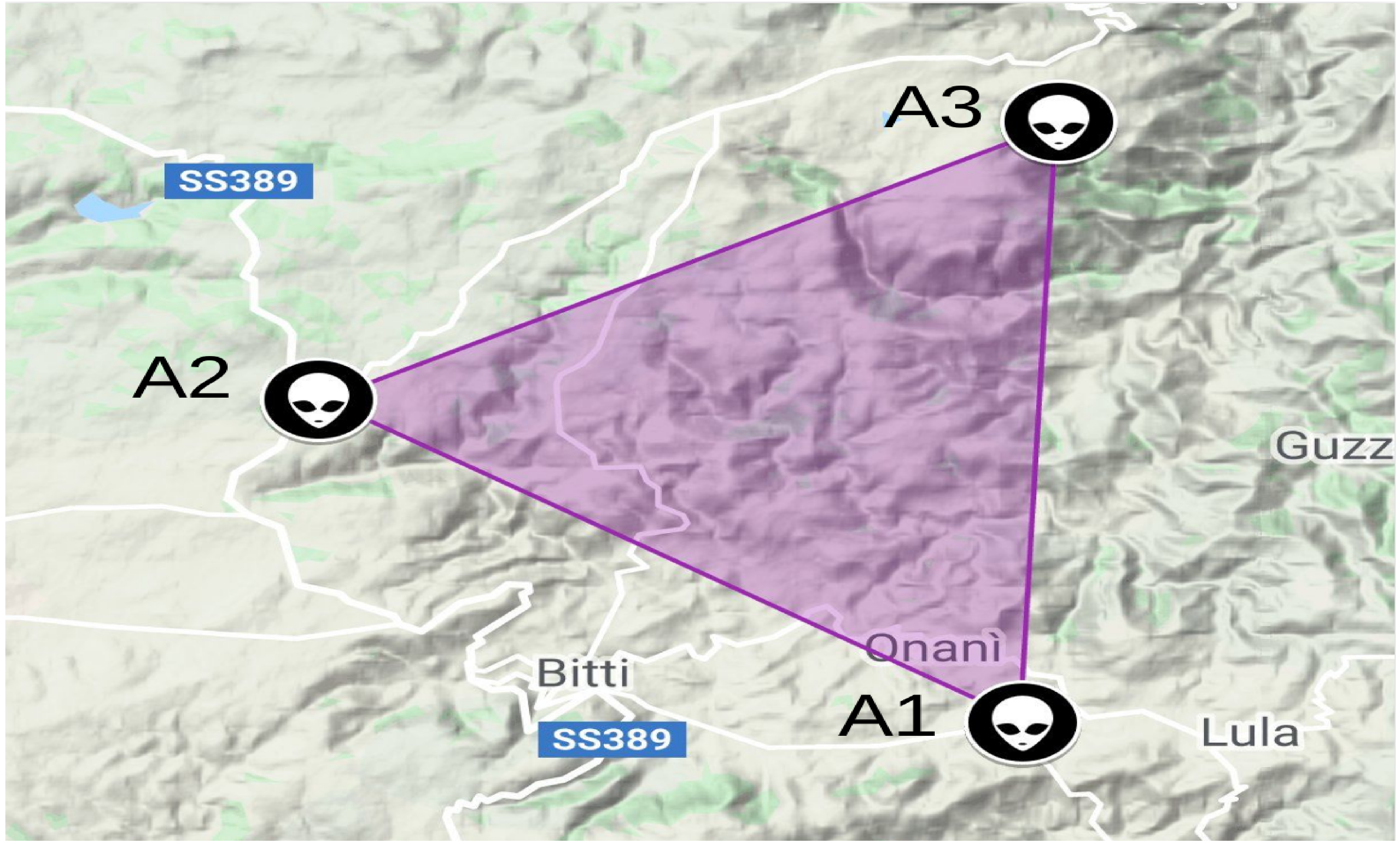
Posterior

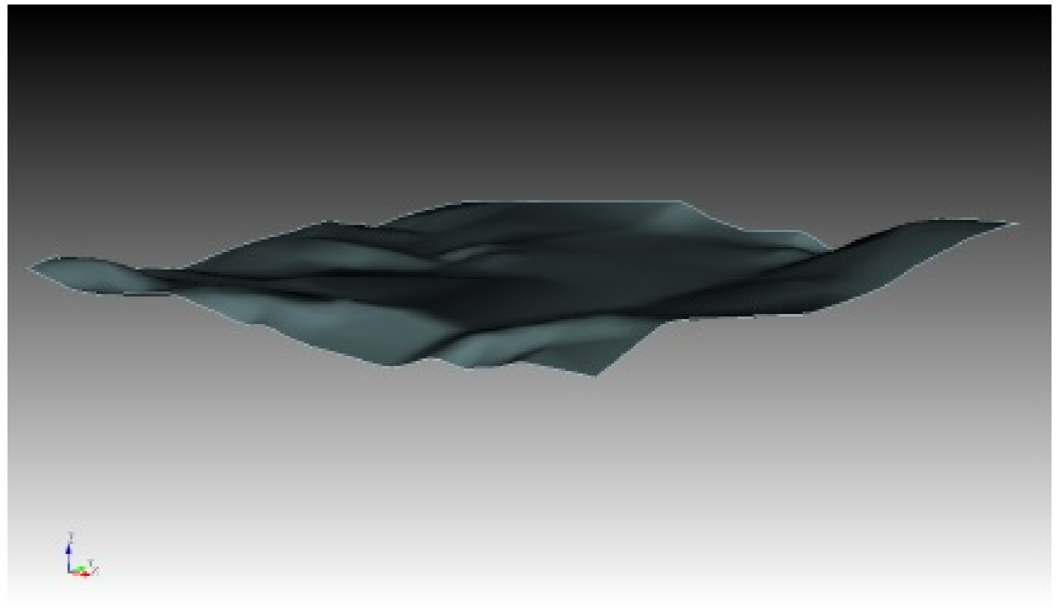
3. Use Bayesian surrogate models of Wiener filters (obtained using GPR) for array optimization in 3D

Introduction

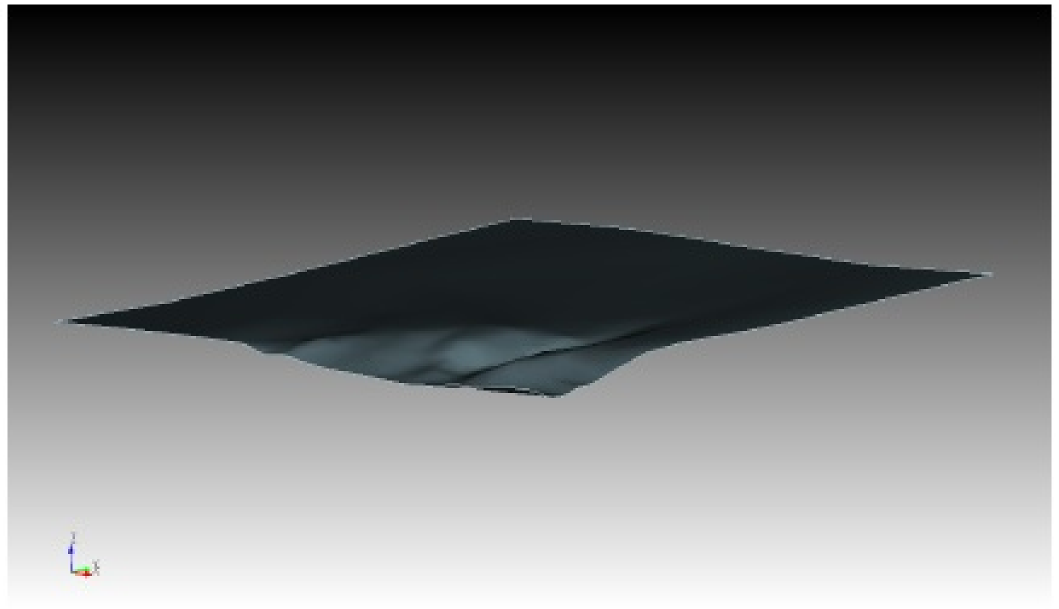
- Seismic Newtonian noise:
  1. Seismic surface displacement
  2. (De)compression of rock
  3. Displacement of underground cavern walls

- Topographic scattering
- Vertex A3

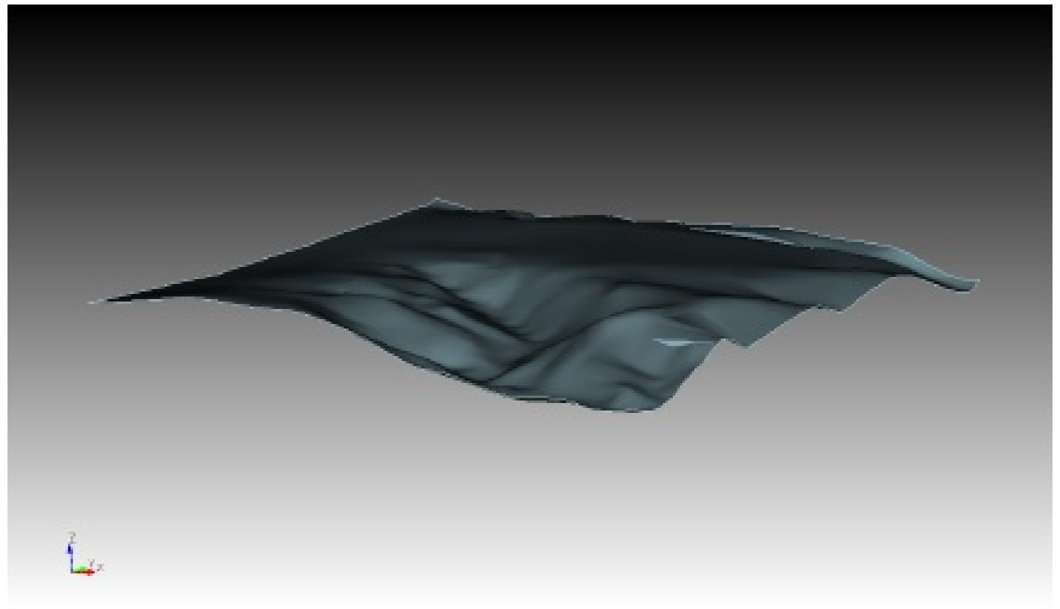




(a) Vertex A1



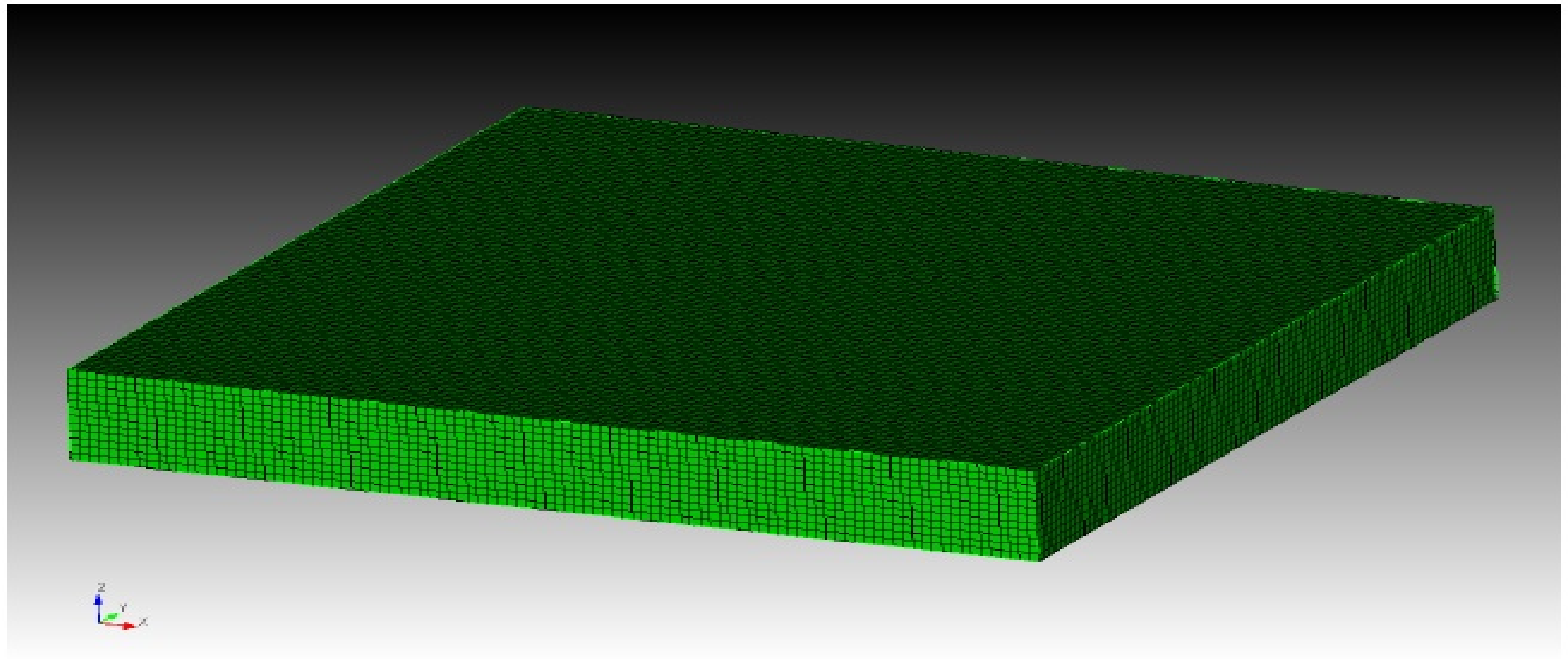
(b) Vertex A2



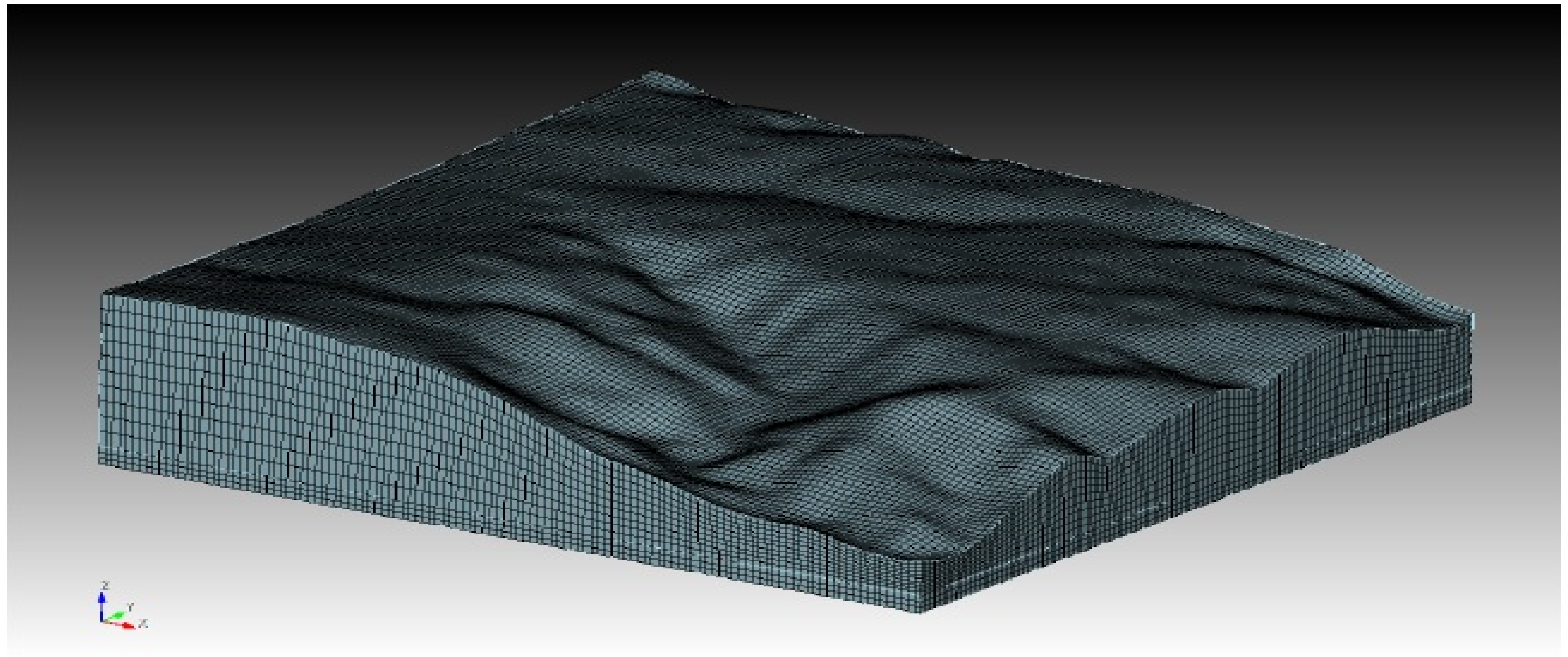
(c) Vertex A3

Finite-element simulations

- Trelis
- SPECFEM3D Cartesian
- Convolutional perfectly matched layer (C-PML)

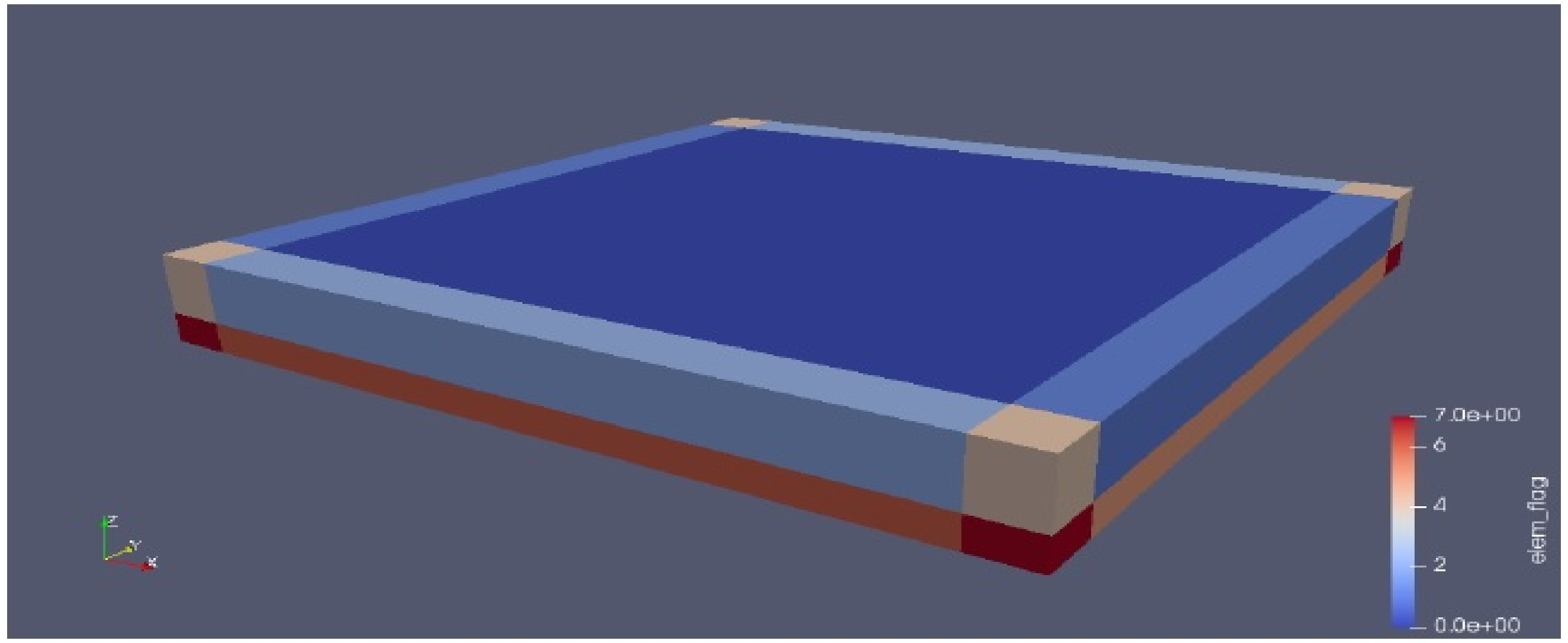


(a) Flat

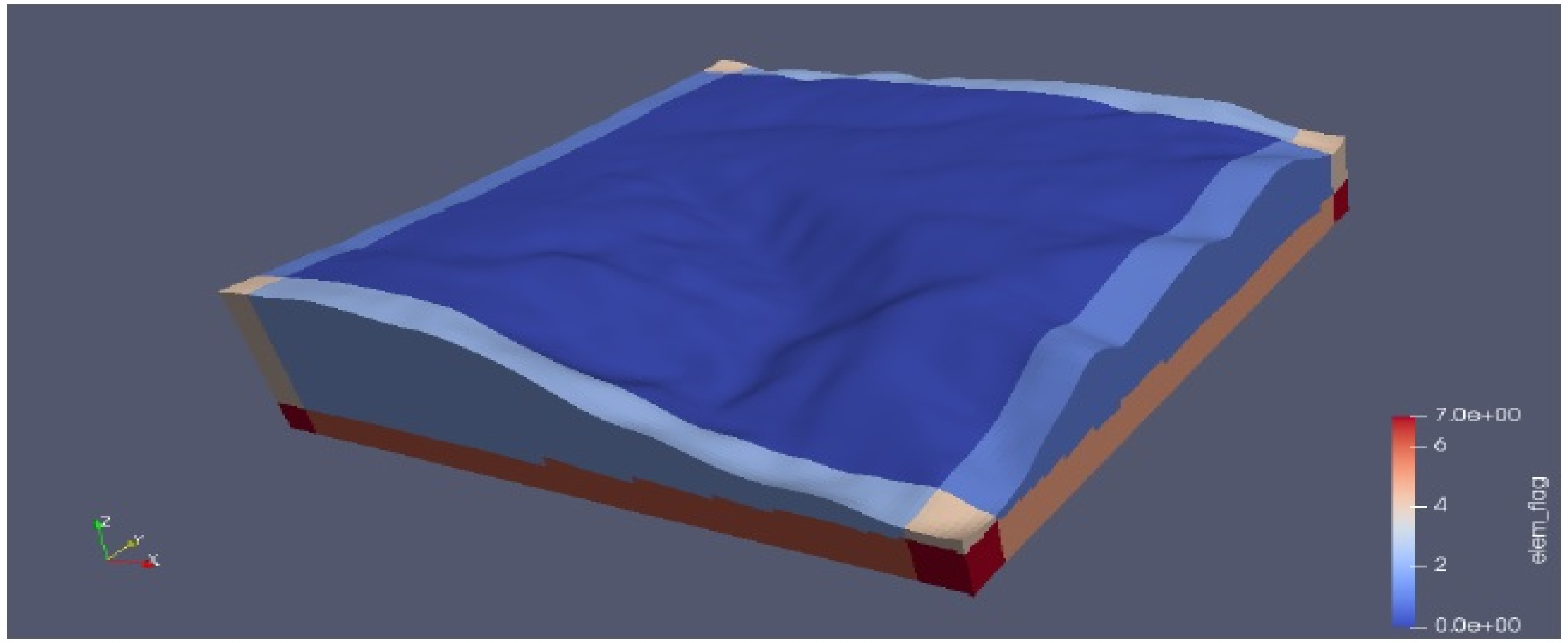


(b) Topography

Meshed models



(a) Flat



(b) Topography (A3)

Models with C-PML

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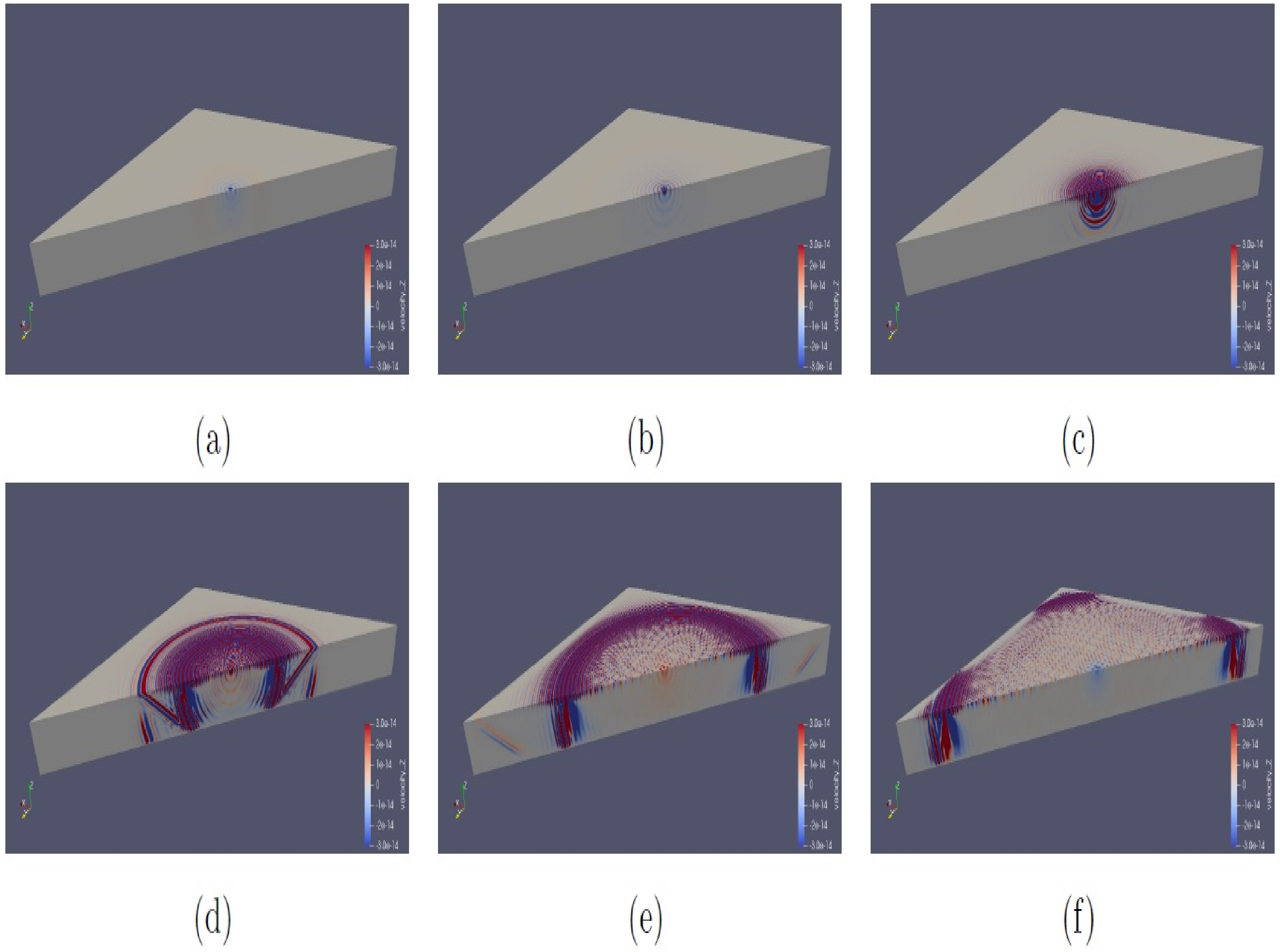
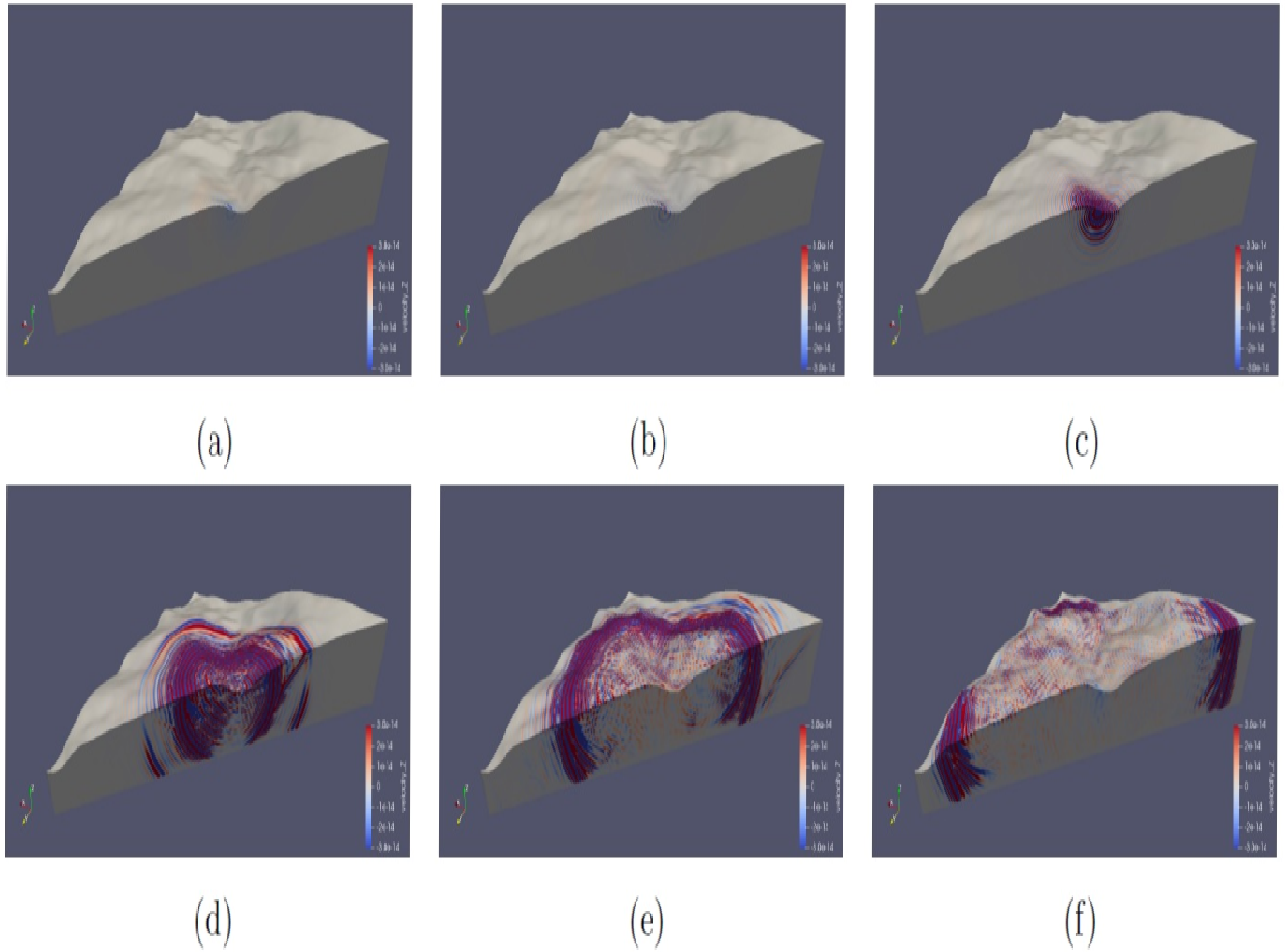
Finite-element simulations



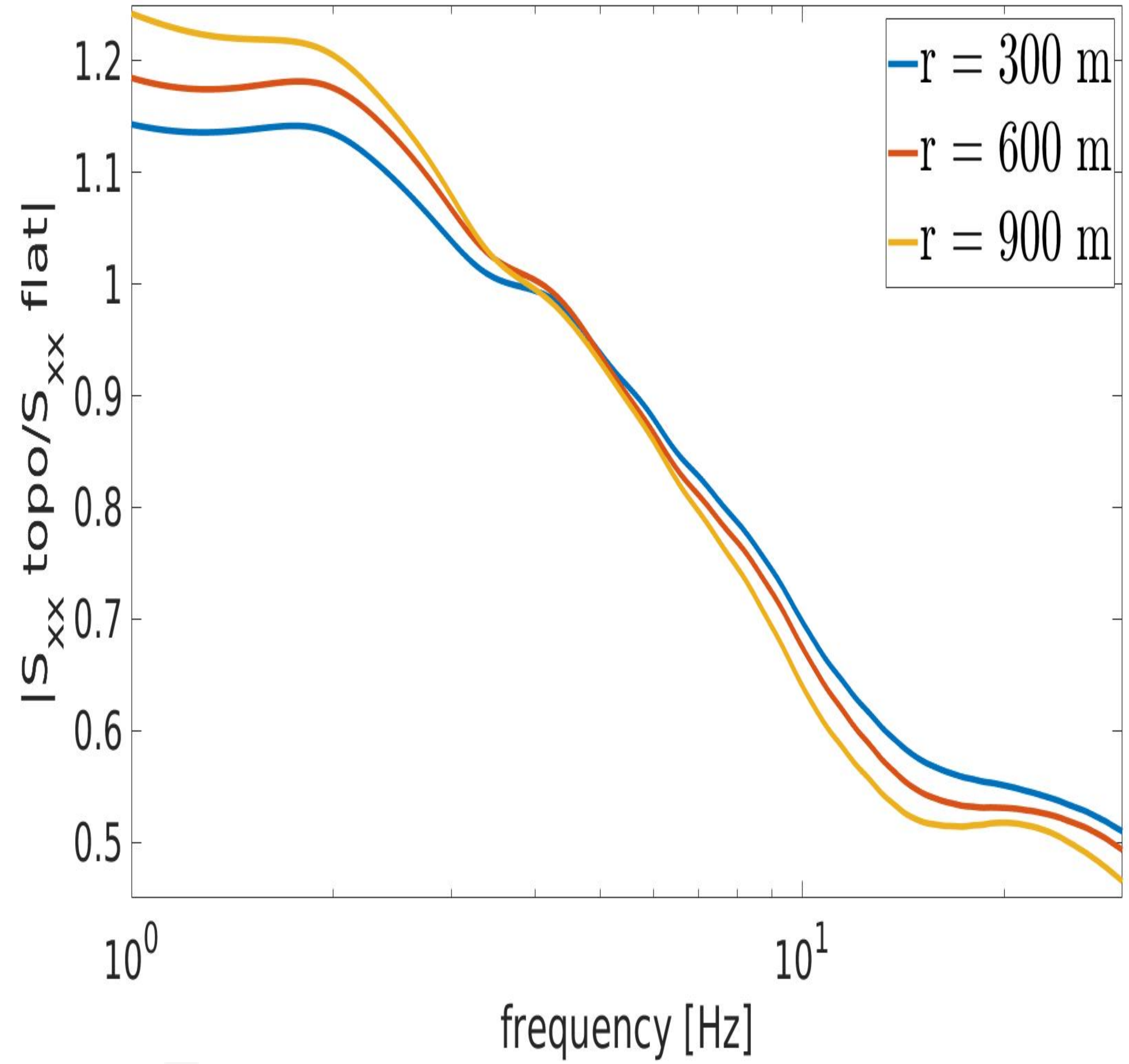
Flat surface model

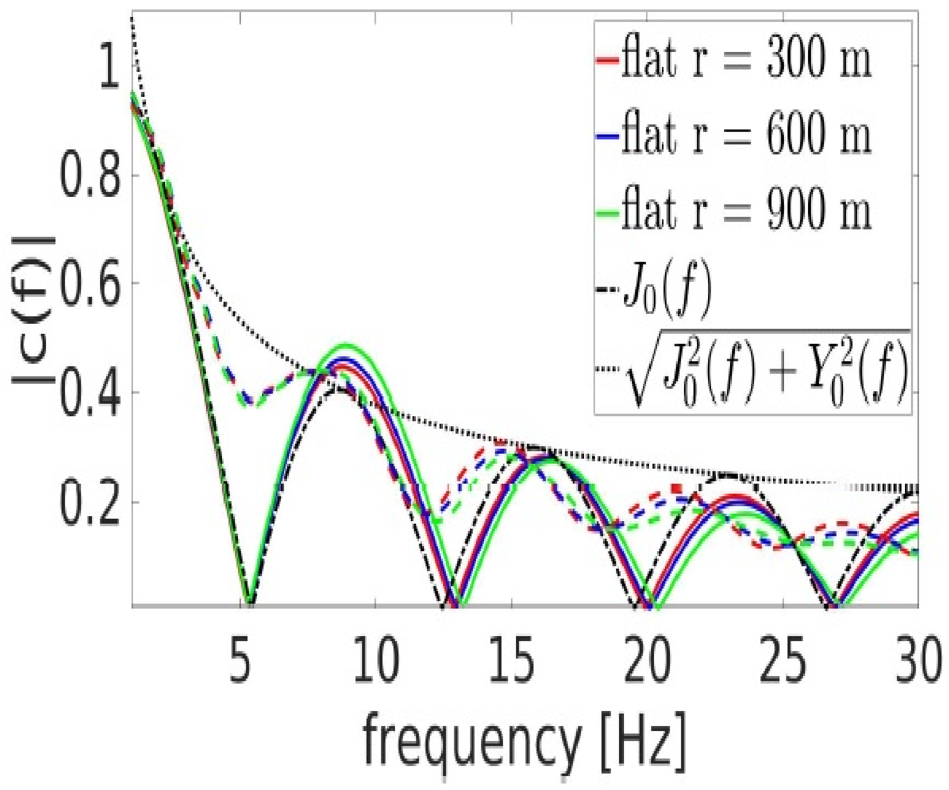


A3 topography model

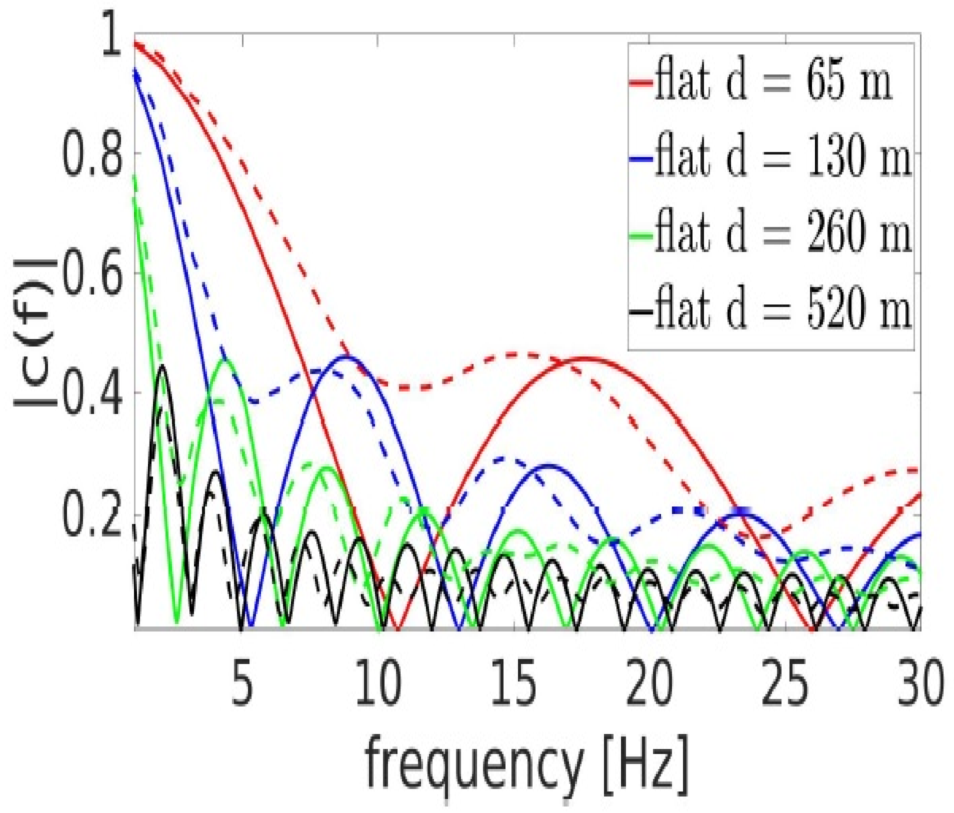
Results

- Seismic coherence $$c_{ij}(f) = \frac{S_{ij}(f)}{\sqrt{S_i(f)S_j(f)}}$$

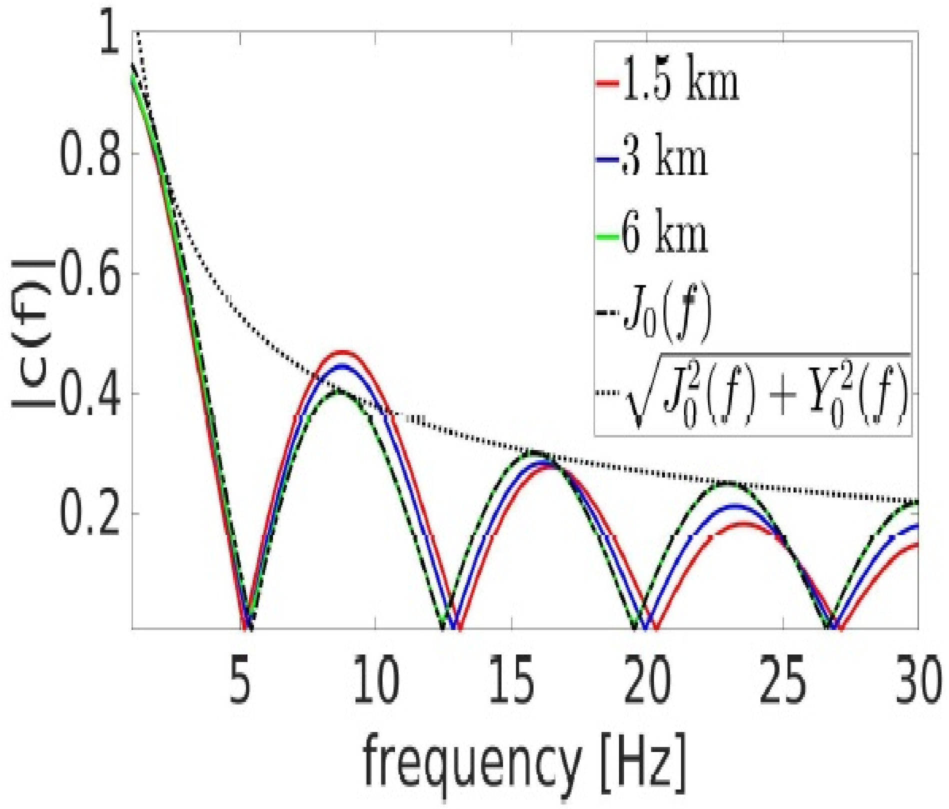




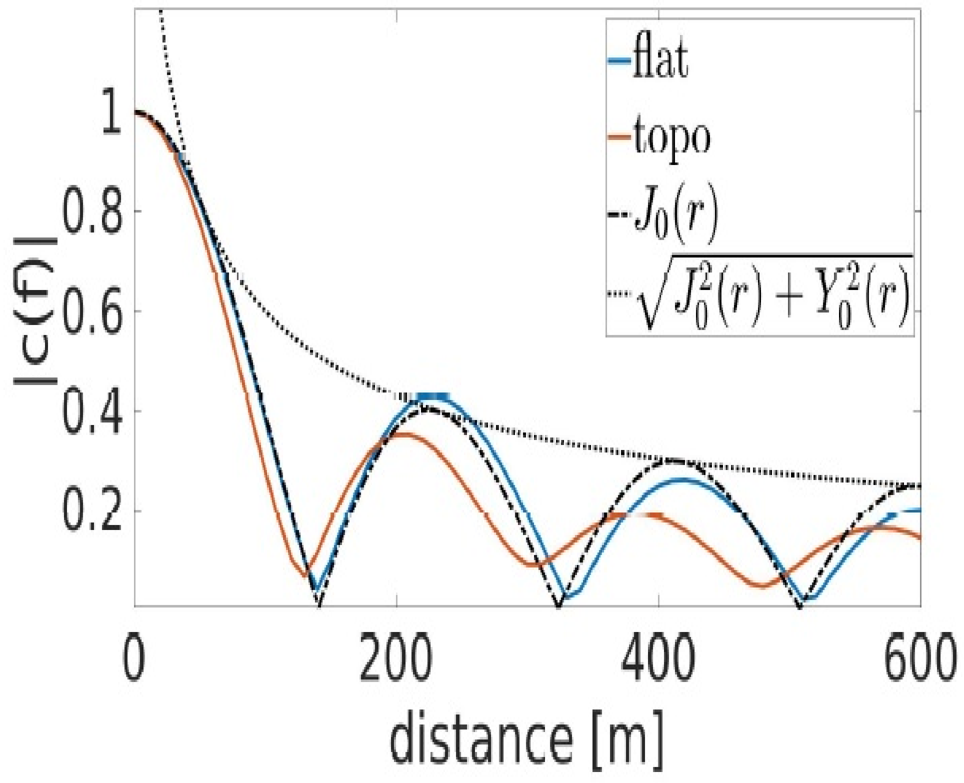
(a) Varying sizes of source-exclusion zones.



(b) Varying distances between receivers.



(c) Varying FEM sizes.

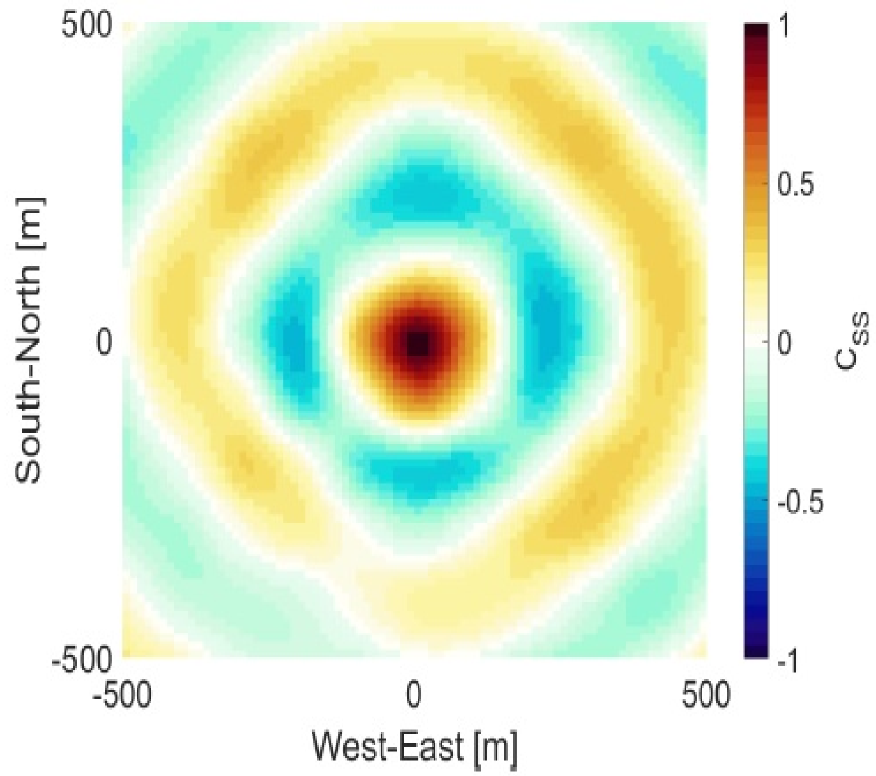


(d) As a function of distance at 5 Hz.

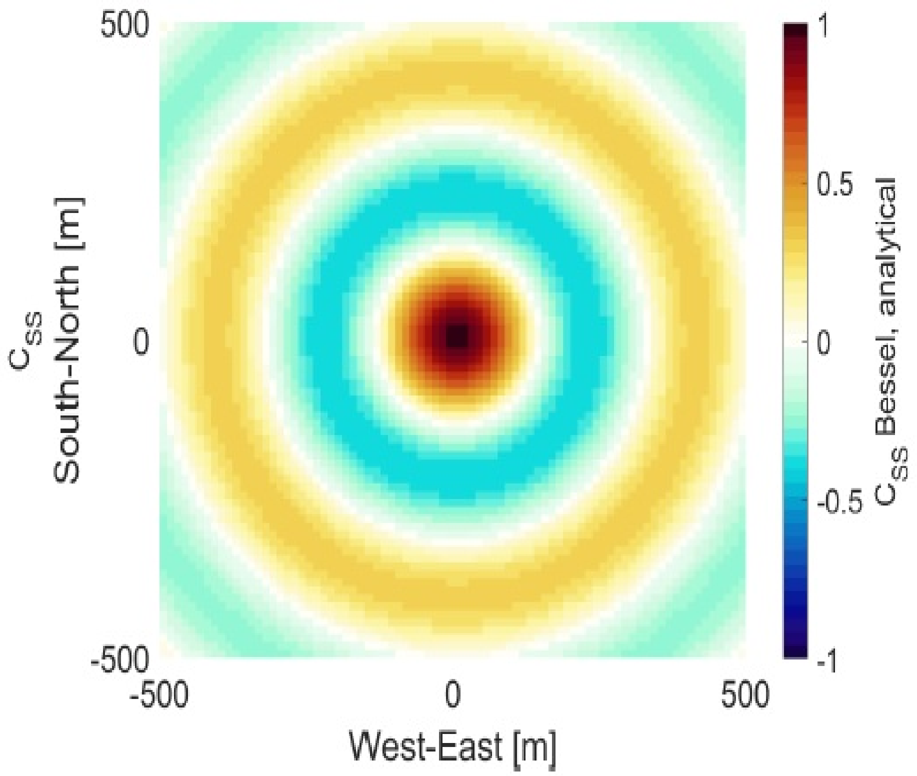
Results

$$\text{Posterior probability} \propto \text{Likelihood} \times \text{Prior probability}$$

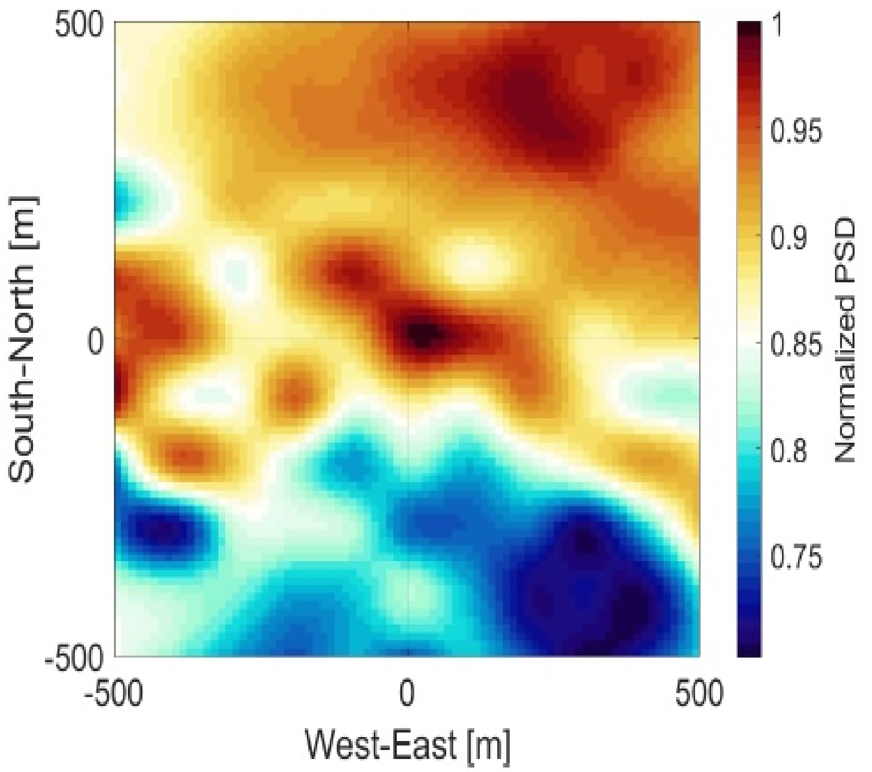
- Seismic correlations



(a) SPECFEM3D simulation.

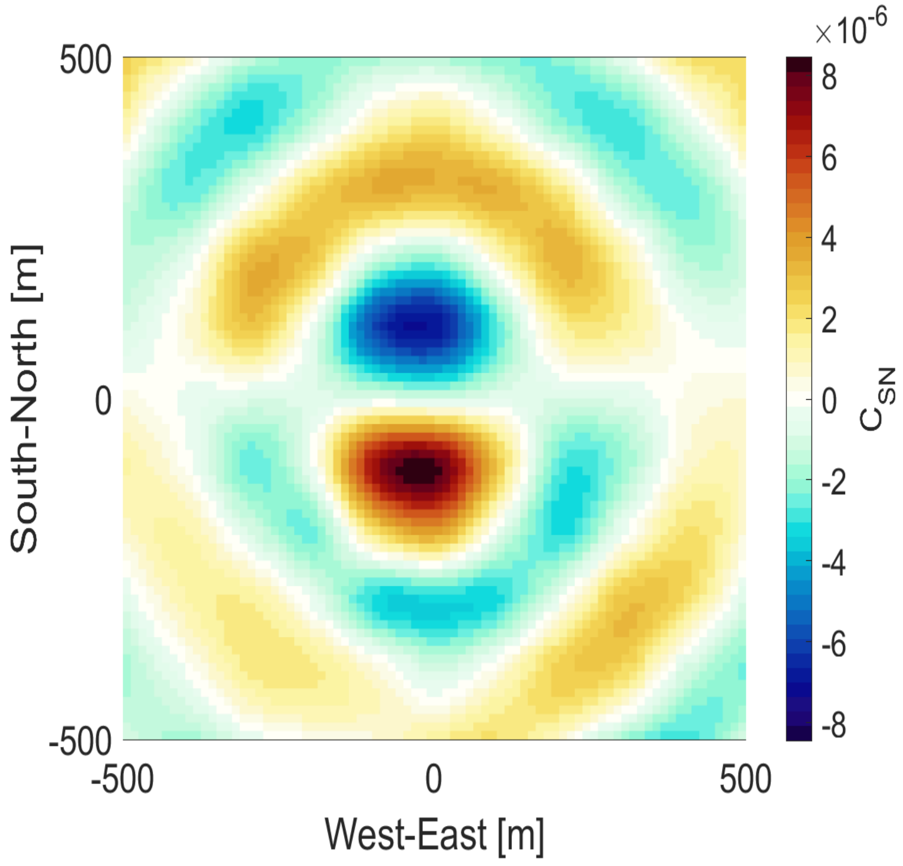


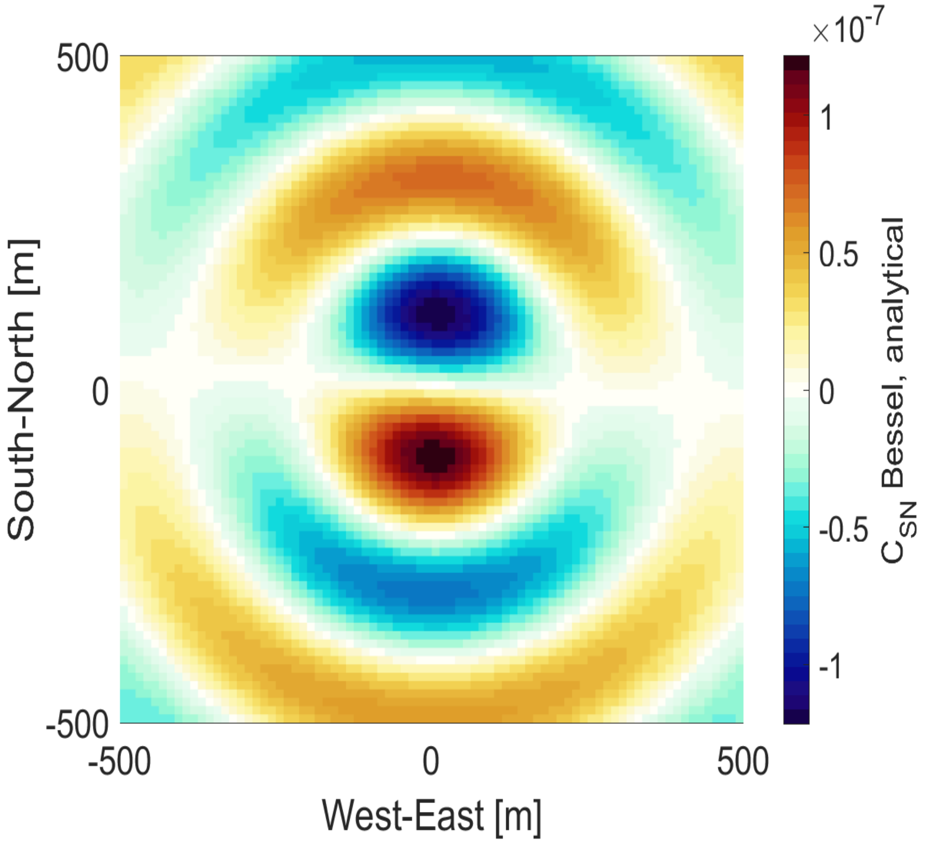
(b) Flat-surface, isotropic.

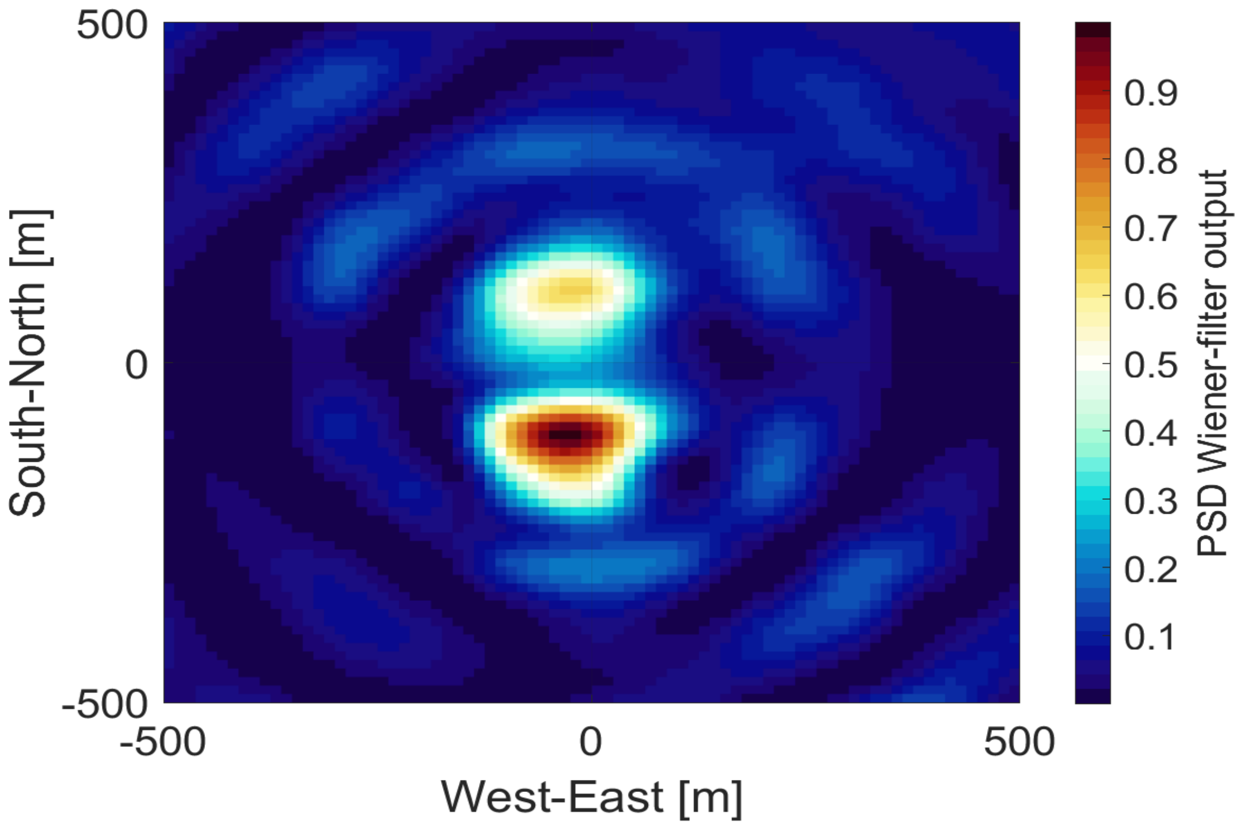


(c) Simulated vertical seismic displacement.

- Gravity-displacement correlations







Significance

- Estimates of gravitoelastic correlations – optimization of surface arrays
- Effects of topography on correlations and NN cancellation
- Important milestone, but one step in a series of tasks (include the remaining two contributions in simulations of seismic correlations)
- Importance of simulations: we cannot hope to have all the important seismic measurements (seismic displacements at all caverns, underground measurements)
- Observation of seismic correlations - likelihood

JGR Solid Earth

Research Article

Simulations of gravitoelastic correlations for the Sardinian candidate site of the Einstein Telescope

Tomislav Andric, Jan Harms

First published: 28 September 2020 | https://doi.org/10.1029/2020JB020401

Abstract

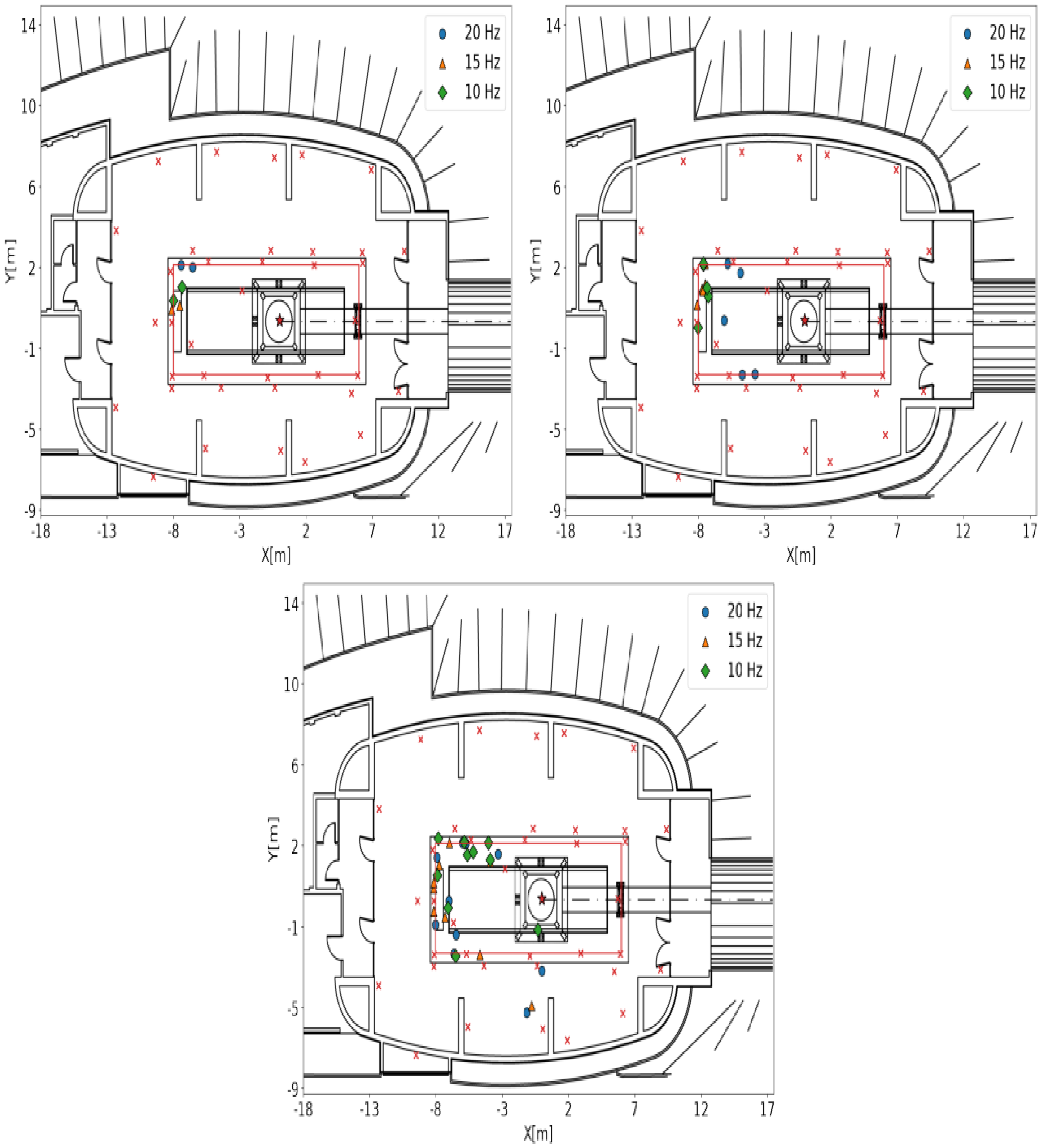
Gravity fluctuations produced by ambient seismic fields are predicted to limit the sensitivity of the next-generation, gravitational-wave detector Einstein Telescope at frequencies below 20 Hz. The detector will be hosted in an underground infrastructure to reduce seismic disturbances and associated gravity fluctuations. Additional mitigation might be required by monitoring the seismic field and using the data to estimate the associated gravity fluctuations and to subtract the estimate from the detector data, a technique called coherent noise cancellation. In this paper, we present a calculation of correlations between surface displacement of a seismic field and the associated gravitational fluctuations using the spectral-element SPECFEM3D Cartesian software. The model takes into account the local topography at a candidate site of the Einstein Telescope at Sardinia. This paper is a first demonstration of SPECFEM3D's capabilities to provide estimates of gravitoelastic correlations, which are required for an optimized deployment of seismometers for gravity-noise cancellation.

https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2020JB020401

Bayesian surrogate model of Wiener filters

$$\text{Posterior probability} \propto \text{Likelihood} \times \text{Prior probability}$$

- Numerical results to define priors for a Gaussian Process Regression
- Combine priors and observed seismic correlations for a Bayesian inference of seismic correlations everywhere in the medium – forms the basis of the optimization algorithm



Machine learning for gravitational-wave detection: surrogate Wiener filtering for the prediction and optimized cancellation of Newtonian noise at Virgo

F Badaracco[8,1,2], J Harms[1,2], A Bertolini[3], T Bulik[4], I Fiori[5], B Idzkowski[4], A Kutynia[4], K Nikliborc[4], F Paoletti[6], A Paoli[5] + Show full author list

Published 10 September 2020 • © 2020 IOP Publishing Ltd
Classical and Quantum Gravity, Volume 37, Number 19

+ Article information

Abstract

The cancellation of noise from terrestrial gravity fluctuations, also known as Newtonian noise (NN), in gravitational-wave detectors is a formidable challenge. Gravity fluctuations result from density perturbations associated with environmental fields, e.g., seismic and acoustic fields, which are characterized by complex spatial correlations. Measurements of these fields necessarily provide incomplete information, and the question is how to make optimal use of available information for the design of a noise-cancellation system. In this paper, we present a machine-learning approach to calculate a surrogate model of a Wiener filter. The model is used to calculate optimal configurations of seismometer arrays for a varying number of sensors, which is the missing keystone for the design of NN cancellation systems. The optimization results indicate that efficient noise cancellation can be achieved even for complex seismic fields with relatively few seismometers provided that they are deployed in optimal configurations. In the form presented here, the optimization method can be applied to all current and future gravitational-wave detectors located at the surface and with minor modifications also to future underground detectors.

https://iopscience.iop.org/article/10.1088/1361-6382/abab64

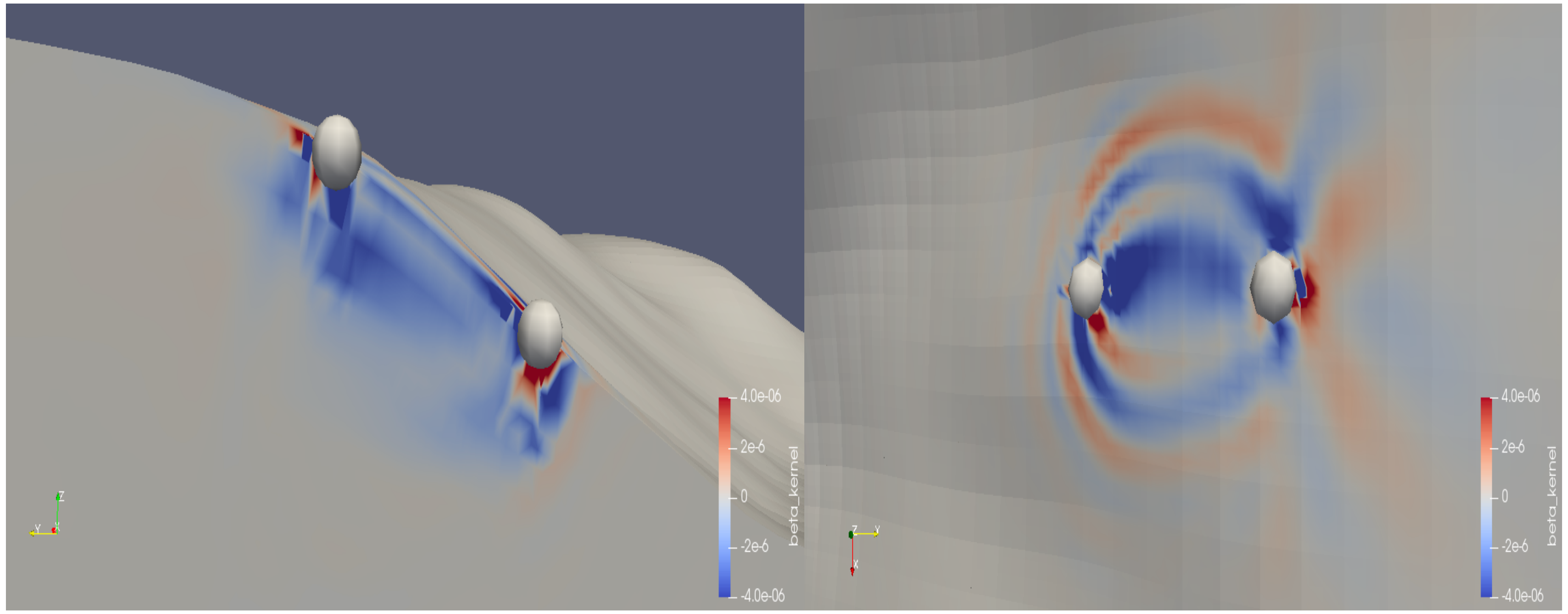
Summary

- Simulation + measurement – to improve the estimation of seismic correlations everywhere in the medium
- Wiener surrogate model allows to calculate the Wiener filter for an arbitrary number of seismometers placed at arbitrary locations

- Calculation of optimal sensor locations – array optimization in 3D (Bayesian seismic-array design)
- Allows us to change the positions of seismometers to maximize NN cancellation via Wiener filtering (using multi-sensor numerical optimization routines)

- Important advantages – where to put sensors for more robust estimates (at which locations we should put other seismometers during site-characterization campaigns to achieve a better overall estimate of the field of seismic correlations) – tells us where it becomes too model dependent

- Other important remarks:
  1. Calculations including optimization will come with a great request for computational resources
  2. Investigate what type of seismic sensor helps most for efficient NN cancellation
  3. SPECFEM3D can also tell us where we should improve our knowledge of geology (sensitivity kernels)



- Importance:
  1. Decrease the required effort and therefore cost of a NN mitigation system
  2. Optimal arrays for the best NN reduction – increased sensitivity of ET

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Thank you for your attention

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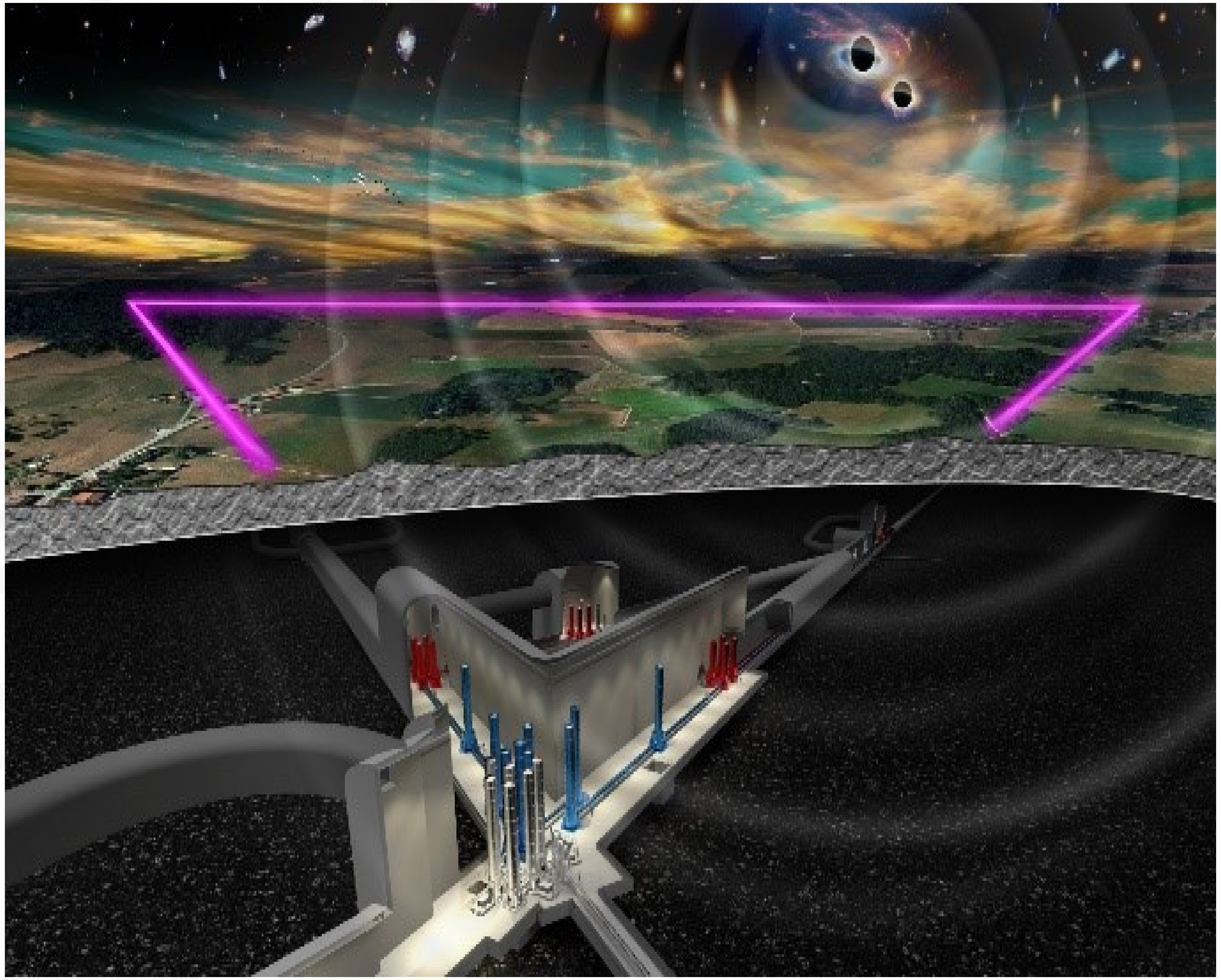
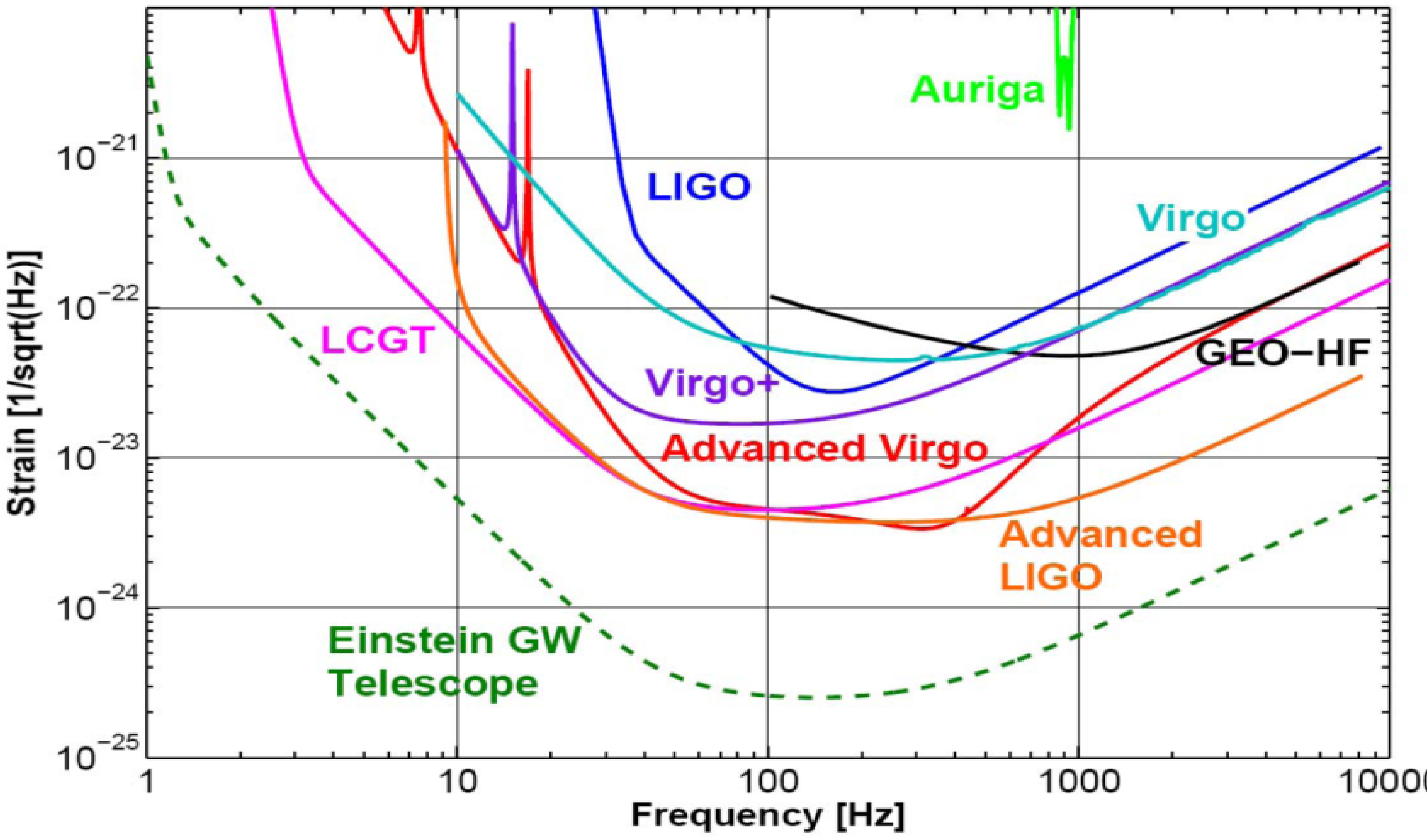
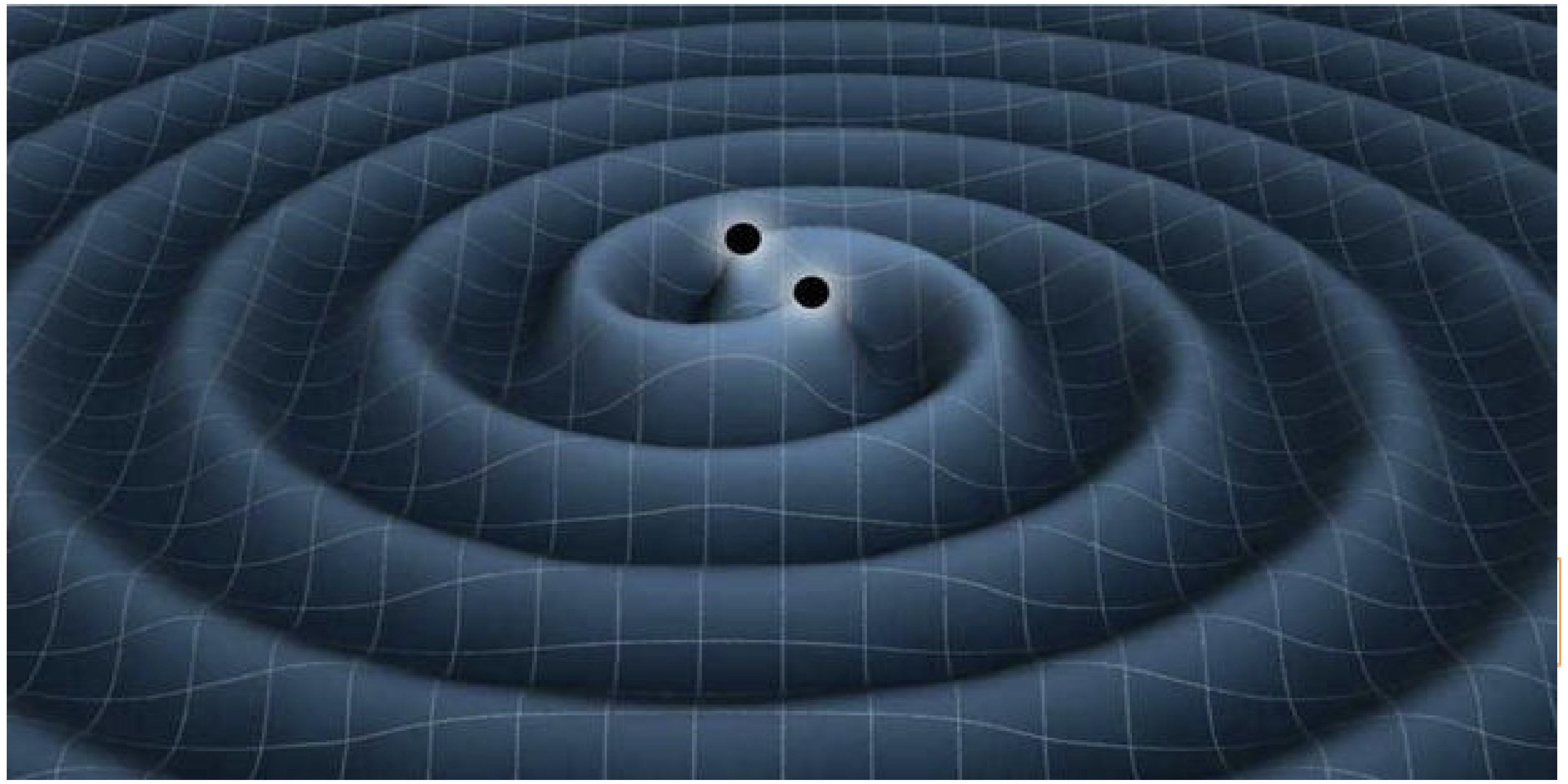
Backup slides

Introduction

- Einstein Telescope
- Inspiral phase of compact binaries (NS, IMBH)







Introduction

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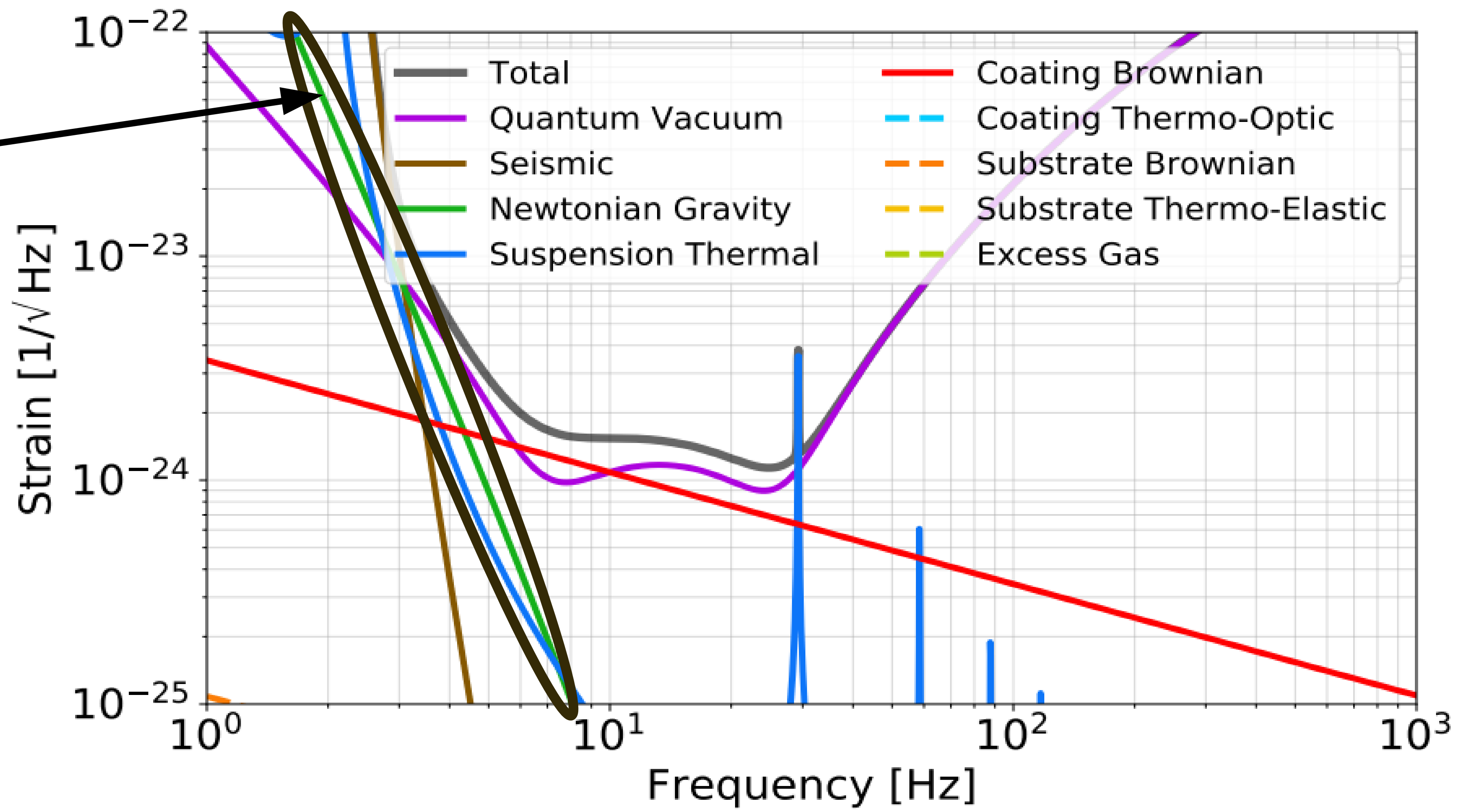
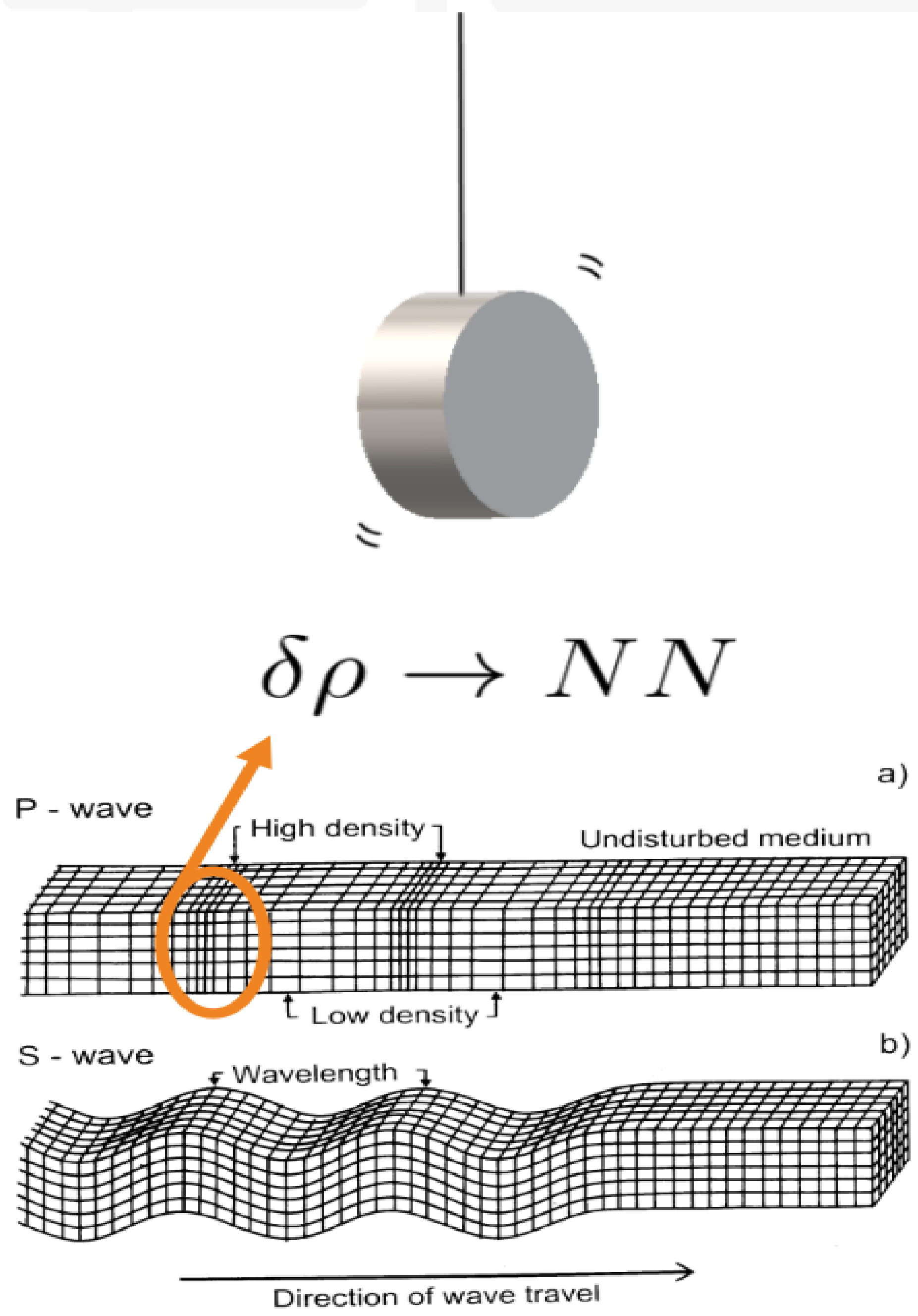
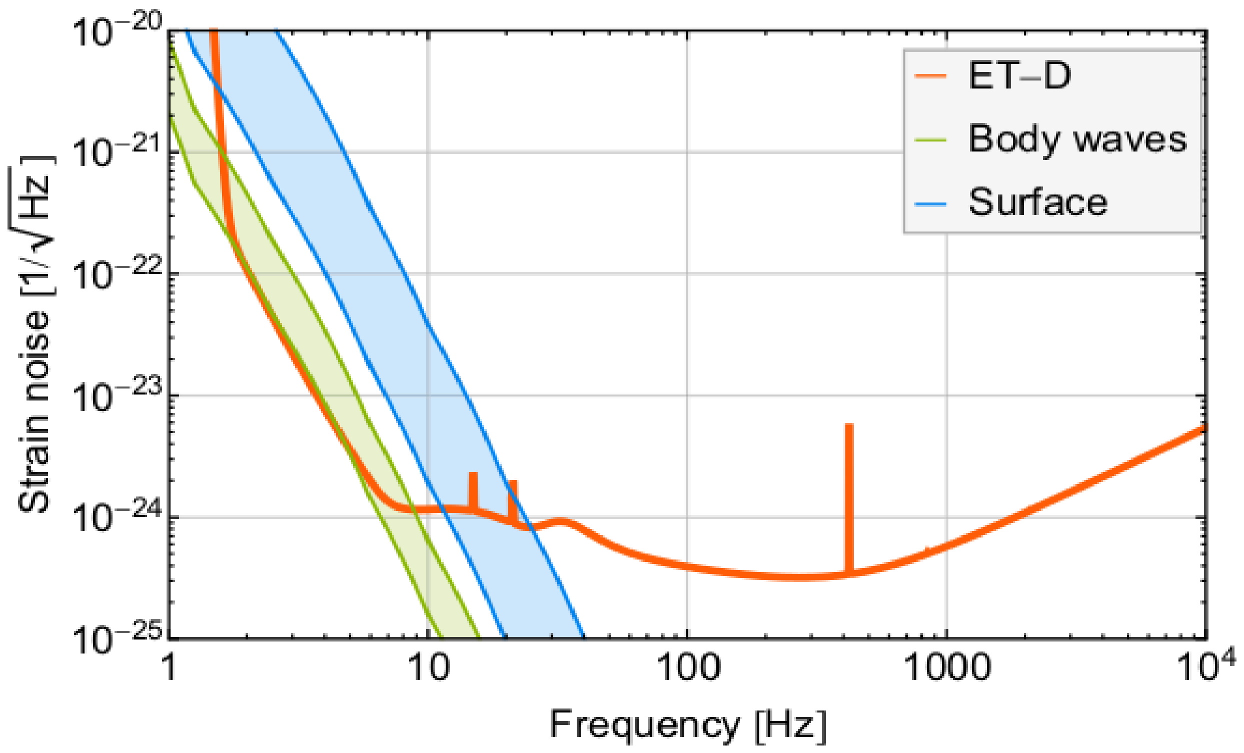
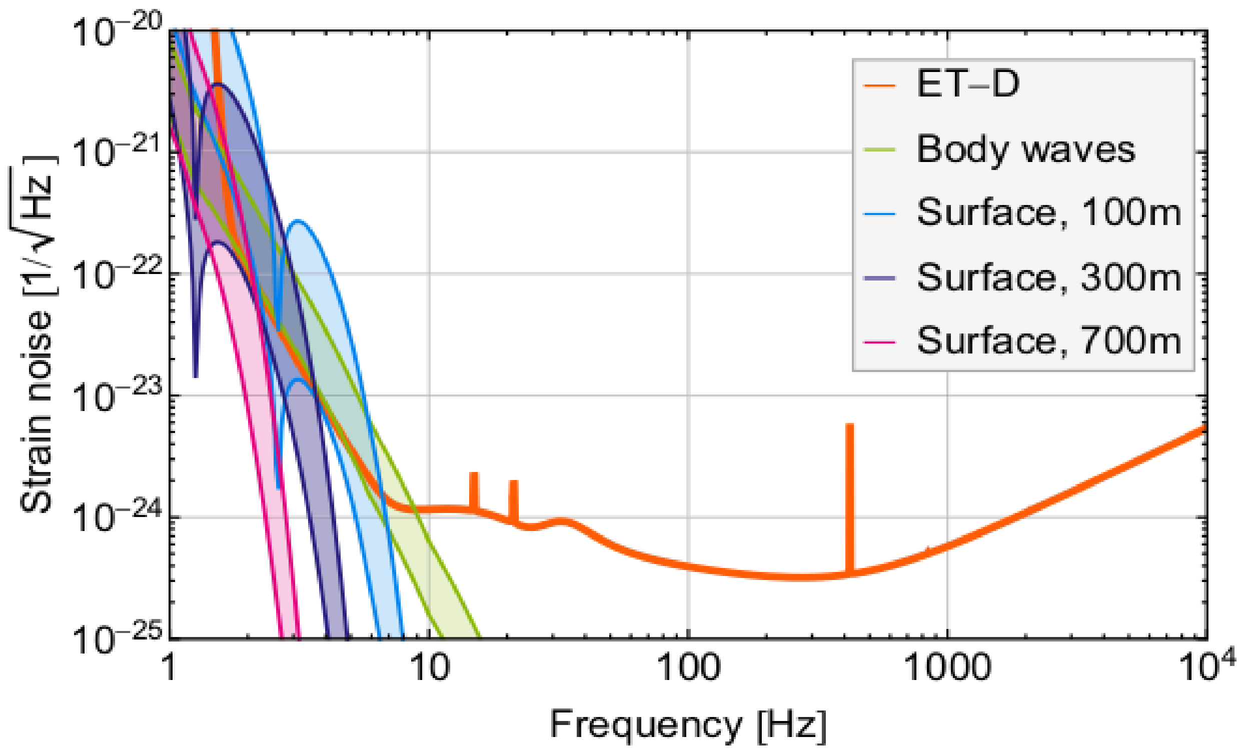
  3. Displacement of underground cavern walls





- Surface and underground locations of ET





F Badaracco and J Harms 2019 Class. Quantum Grav. 36 145006

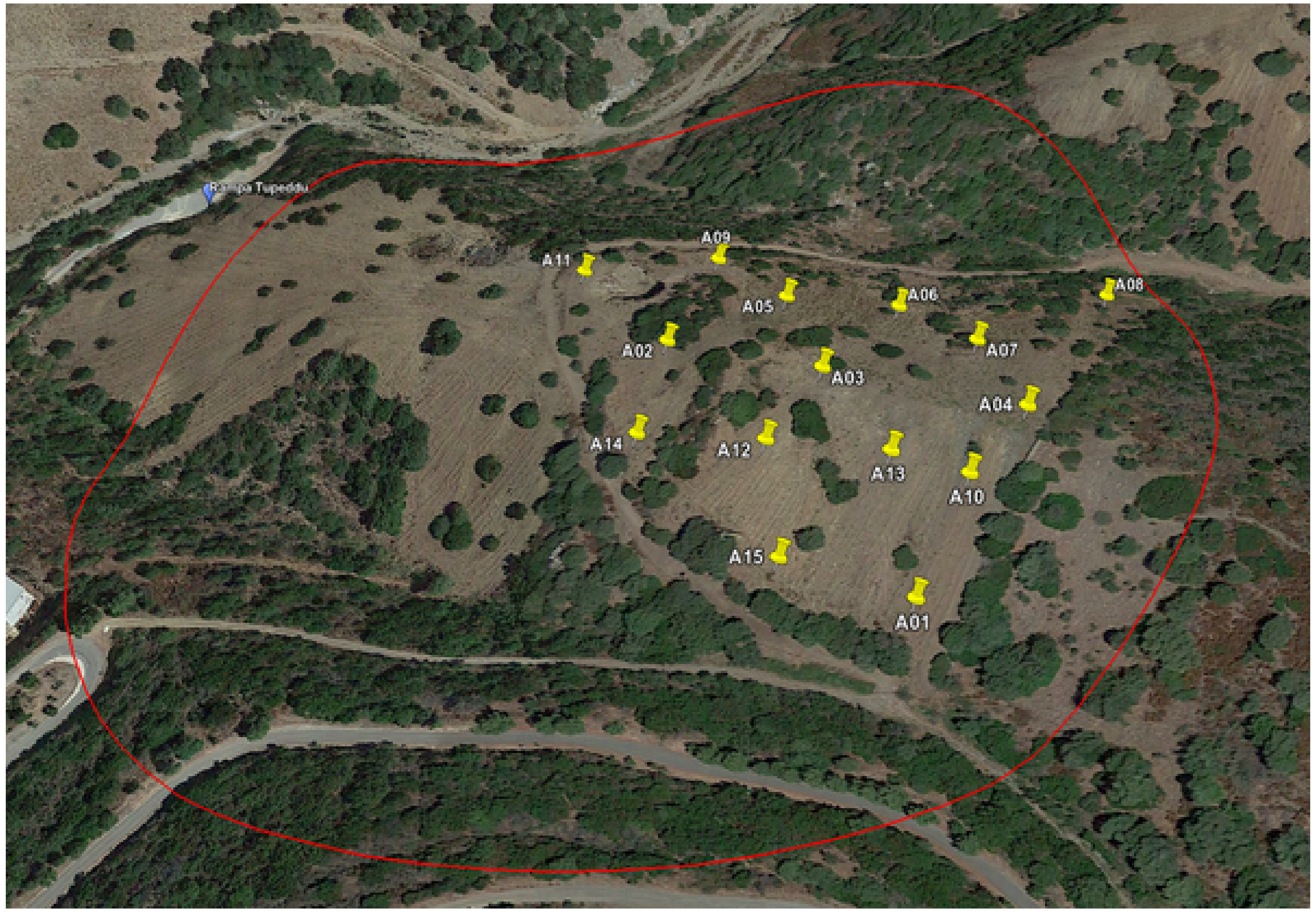
Observation of seismic correlations

- Trilium 120
- 2 Hz geophones (Sercel L-4A)
- 40 of 5 Hz geophones
- At least 7 days of continuous recording

$$\text{Posterior probability} \propto \text{Likelihood} \times \text{Prior probability}$$

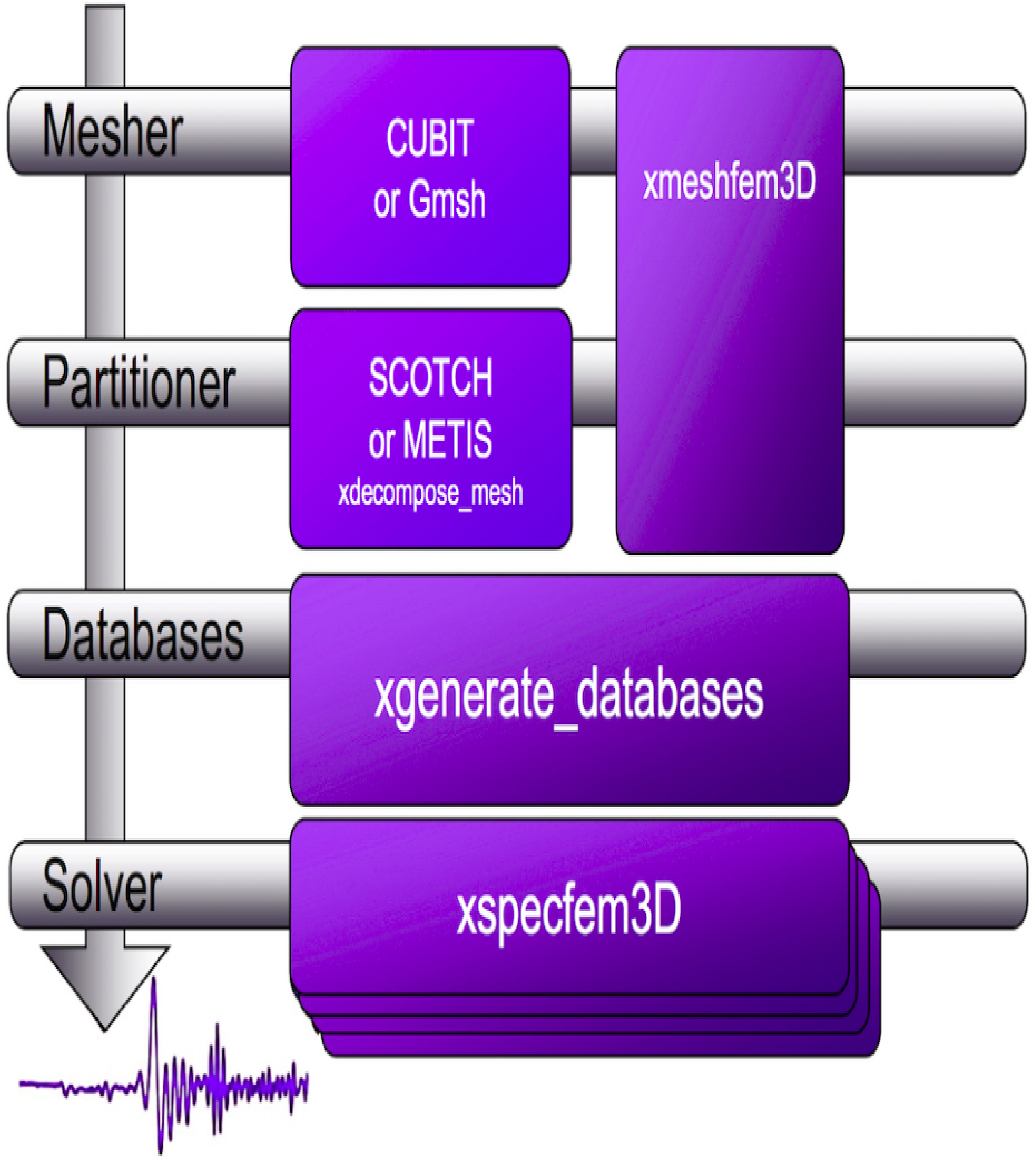
- Vertex-by-vertex site characterization campaign
- Provides the likelihood for the GPR

- We can observe at lower frequencies
- Tremornet sensors – target frequency is beyond 5 Hz
- The configuration is not decided yet

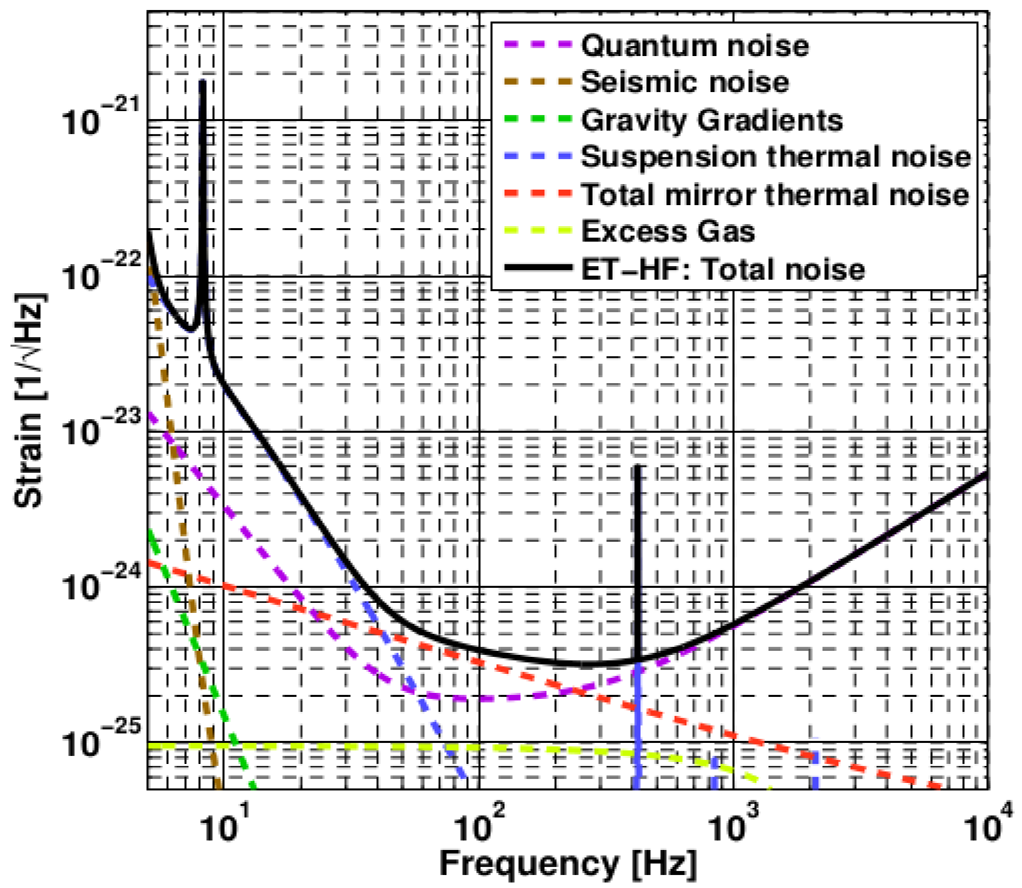


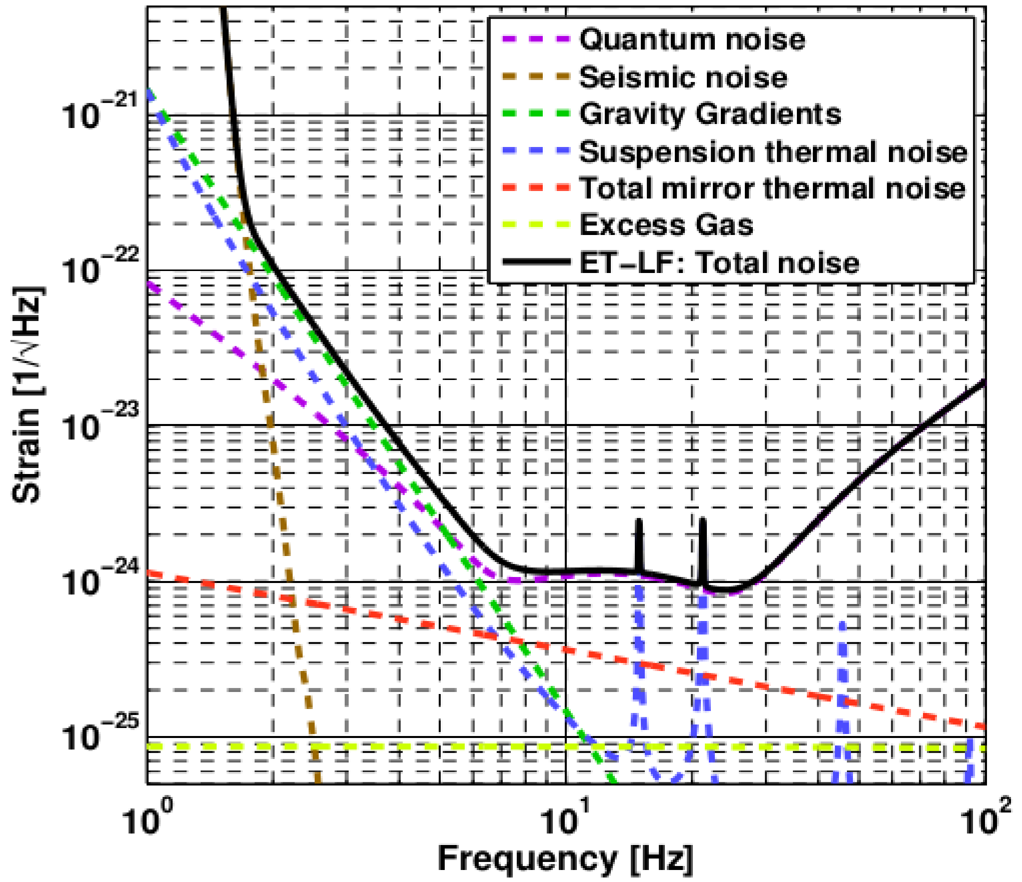
SPECFEM3D:

- It uses a mesh of hexahedral finite elements on which the wave field is represented in terms of high-degree Lagrange polynomials on Gauss–Lobatto–Legendre interpolation points
- The distribution of noise sources in is constrained to the surface
- We used Trelis for the creation of models and their exporting into a SPECFEM3D Cartesian file format

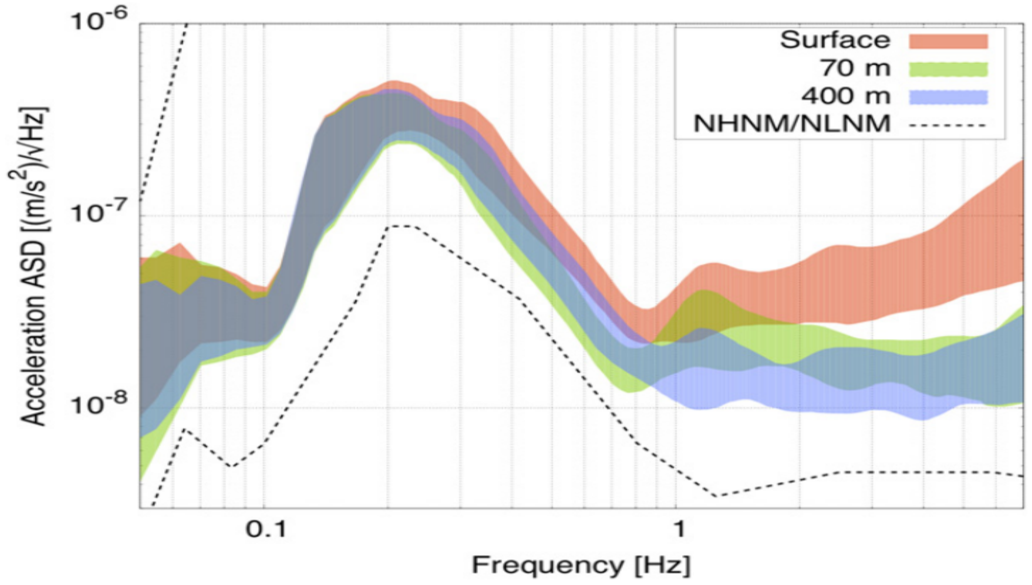


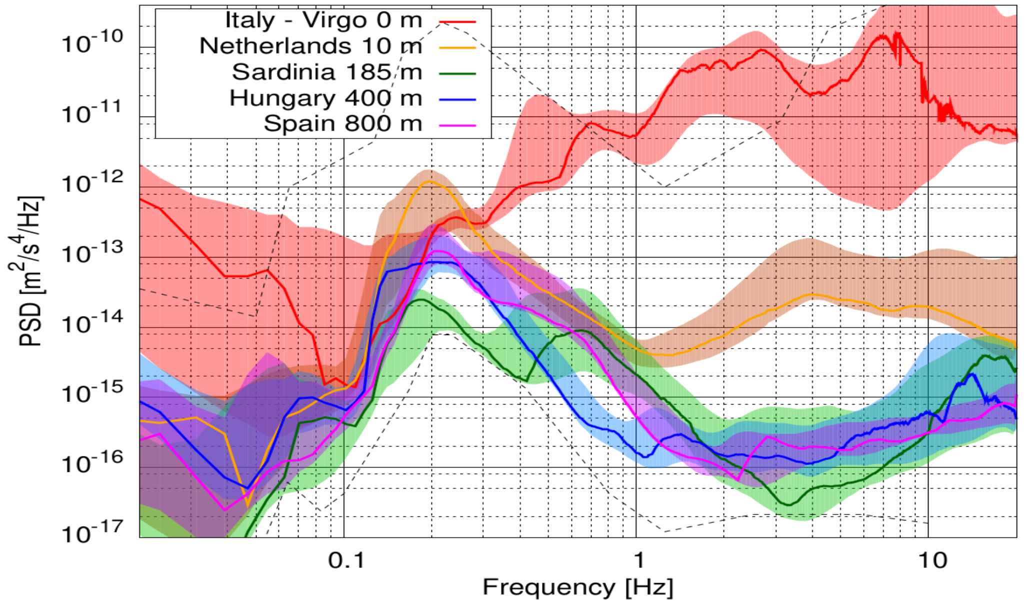
Noises:

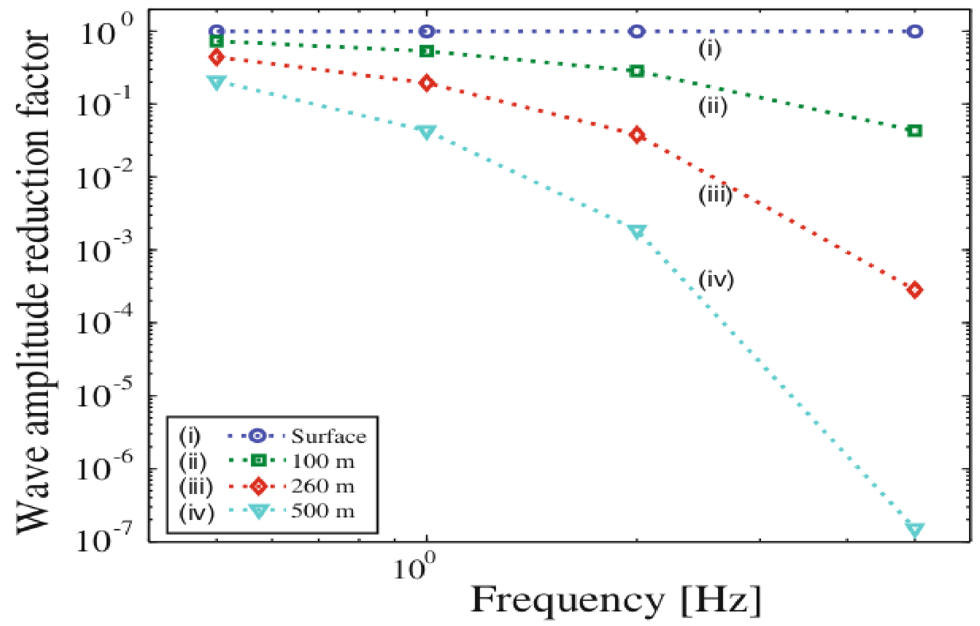




Seismic spectra:







Some formulae:

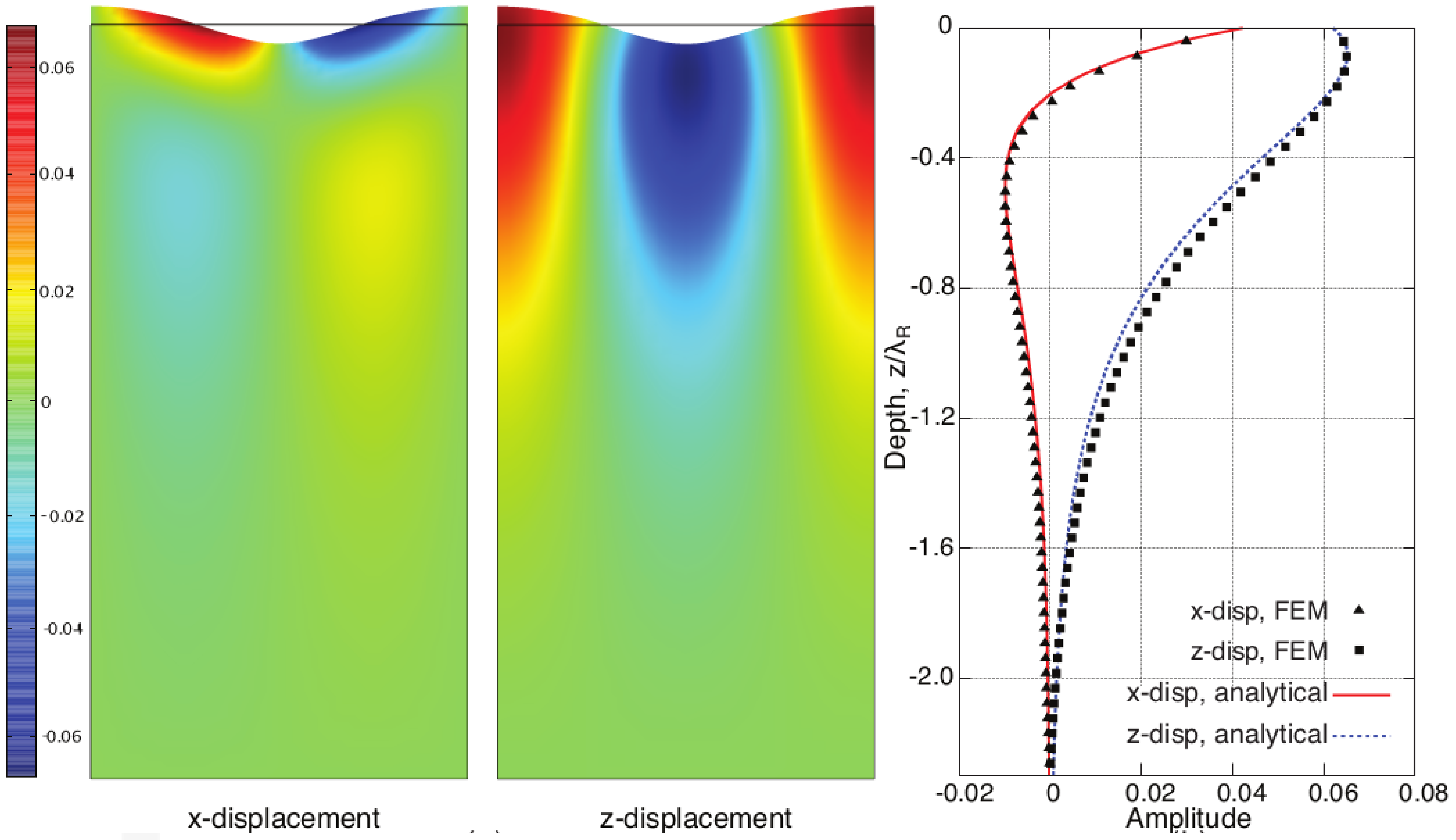
$$c_{ij}(f) = J_0(2\pi f|\vec{r}_j - \vec{r}_i|/c)$$

$$C\left(\delta a_{\mathrm{arm}}(0), \xi_z(\boldsymbol{r}); f\right) = 2\pi G\rho_0 S\left(\xi_z; f\right) \mathrm{e}^{-hk(f)} \cos(\phi) J_1\left(k(f) r\right),$$

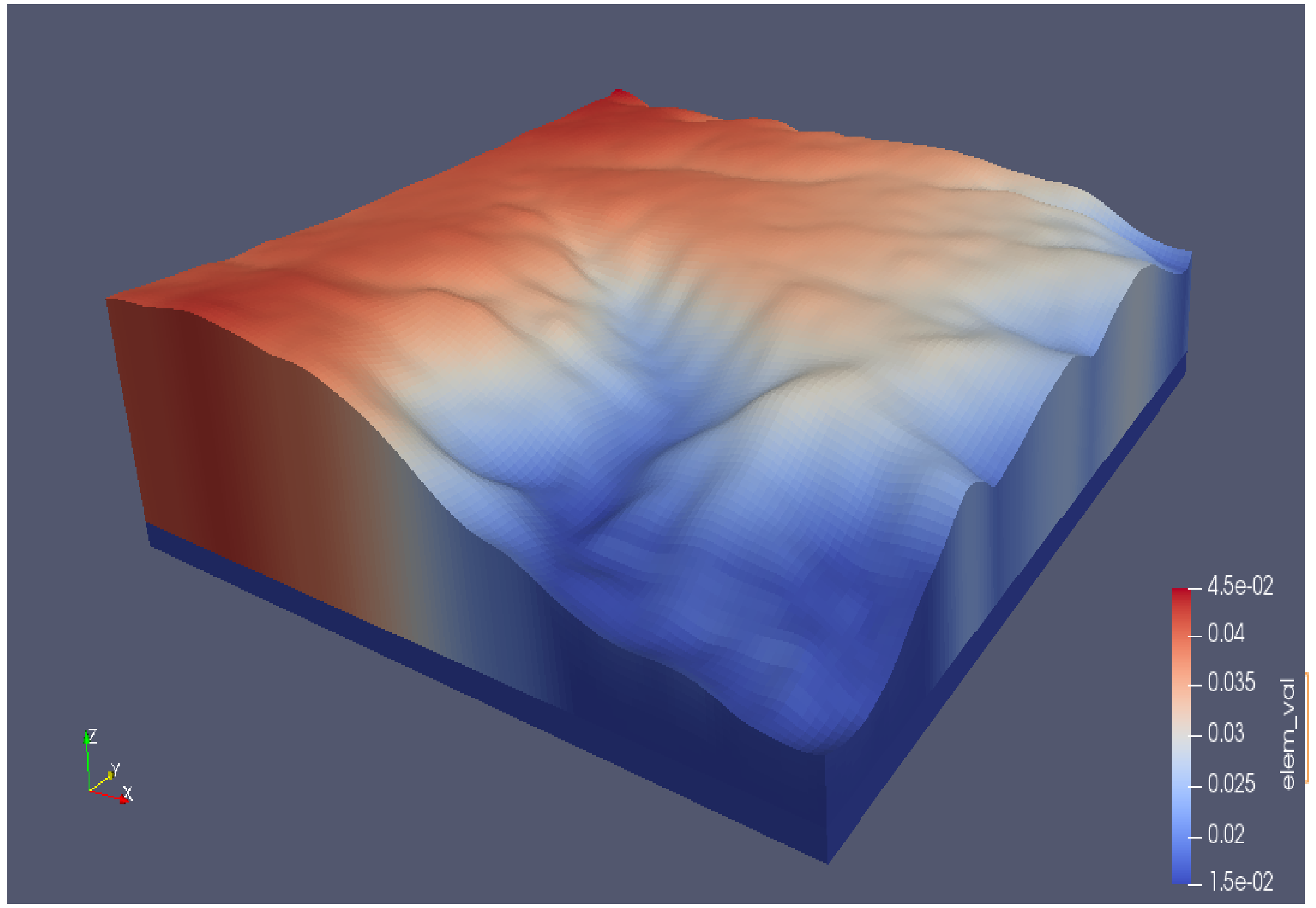
$$C\left(\delta a_{\mathrm{arm}}(\boldsymbol{r}_0), \xi_z(\boldsymbol{r}); f\right) = G\rho_0 \int \mathrm{d}^2 r' C\left(\xi_n(\boldsymbol{r}'), \xi_z(\boldsymbol{r}); f\right) \frac{(\boldsymbol{r}' - \boldsymbol{r}_0)\cdot \boldsymbol{e}_{\mathrm{arm}}}{|\boldsymbol{r}' - \boldsymbol{r}_0|^3}$$

$$S(w; f) = \left|C\left(\delta a_{\mathrm{arm}}(\boldsymbol{r}_0), \xi_z(\boldsymbol{r}); f\right)\right|^2 / C\left(\xi_z(\boldsymbol{r}), \xi_z(\boldsymbol{r}); f\right)$$

Rayleigh waves:

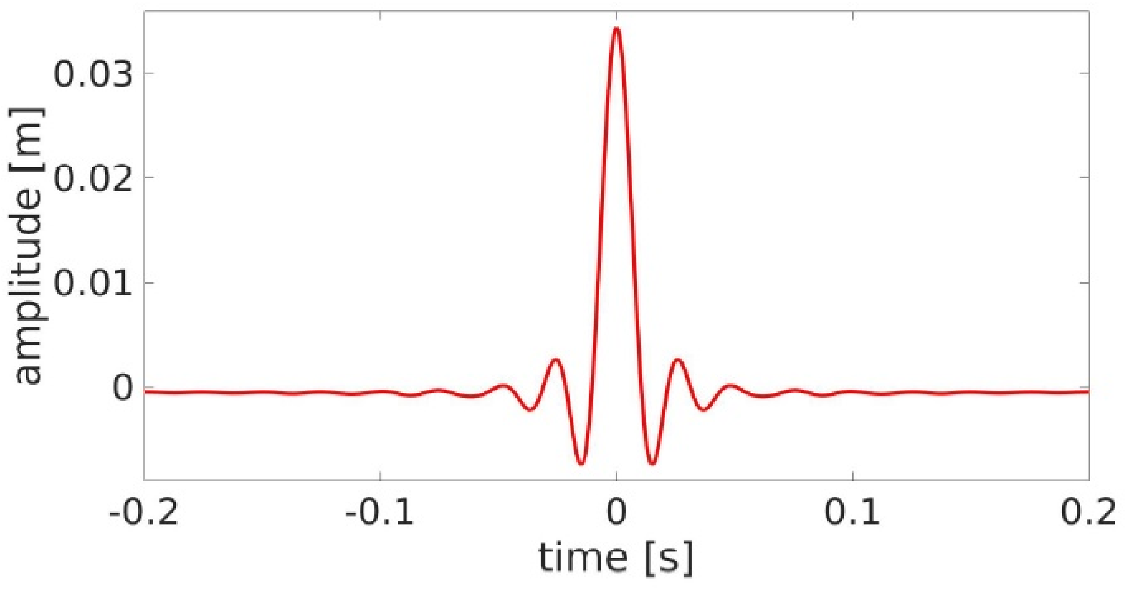


Minimum wave period resolved in each element of A3 topography model:

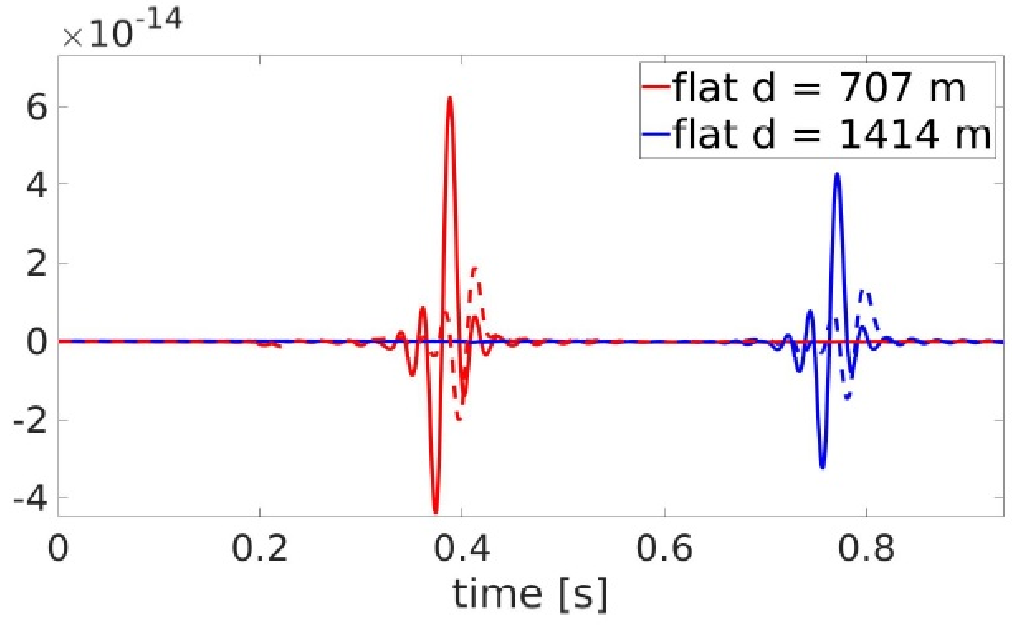


Noise cross-correlation simulations

- Two steps of simulations:
  1. Injection
  2. Noise emission



(a)



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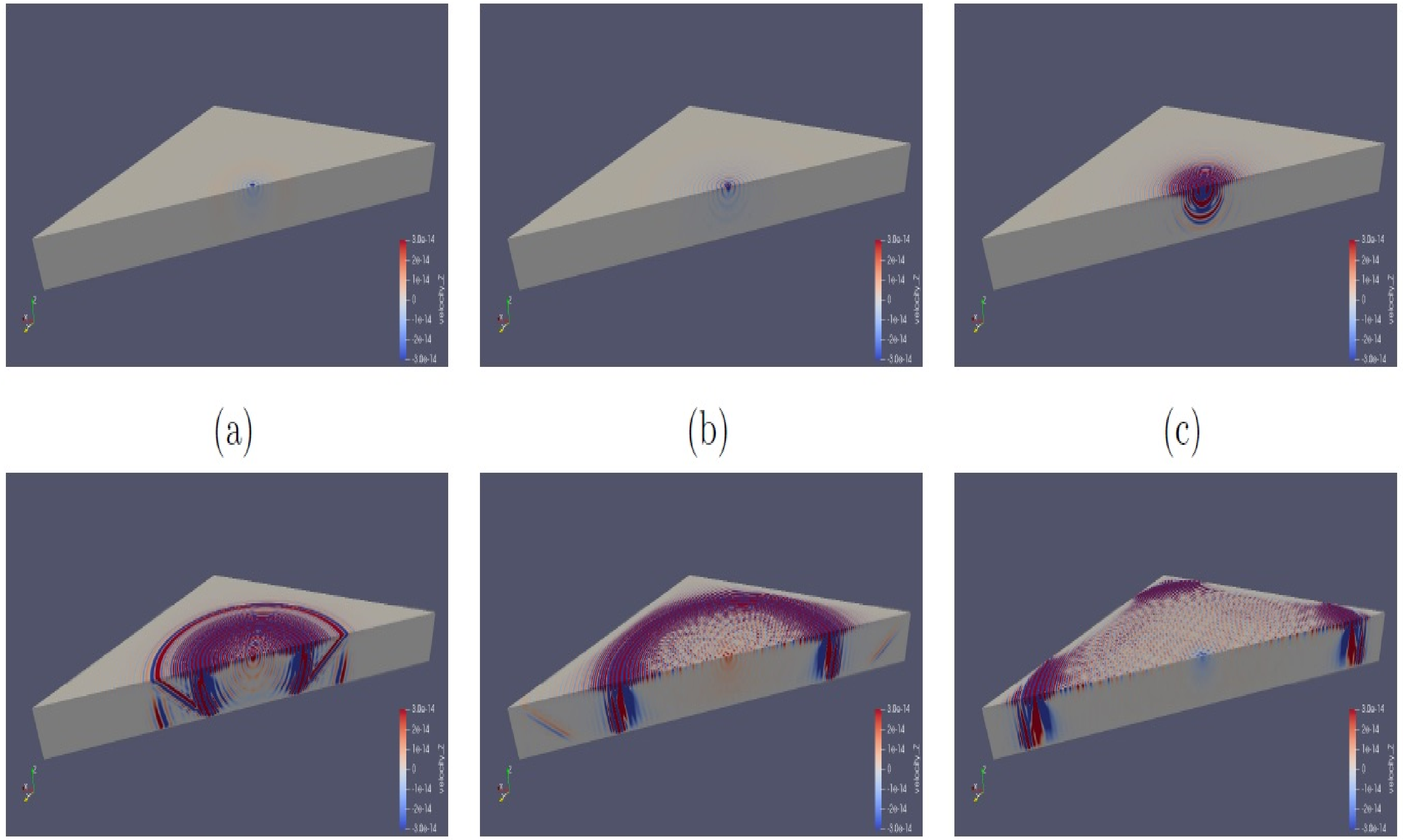
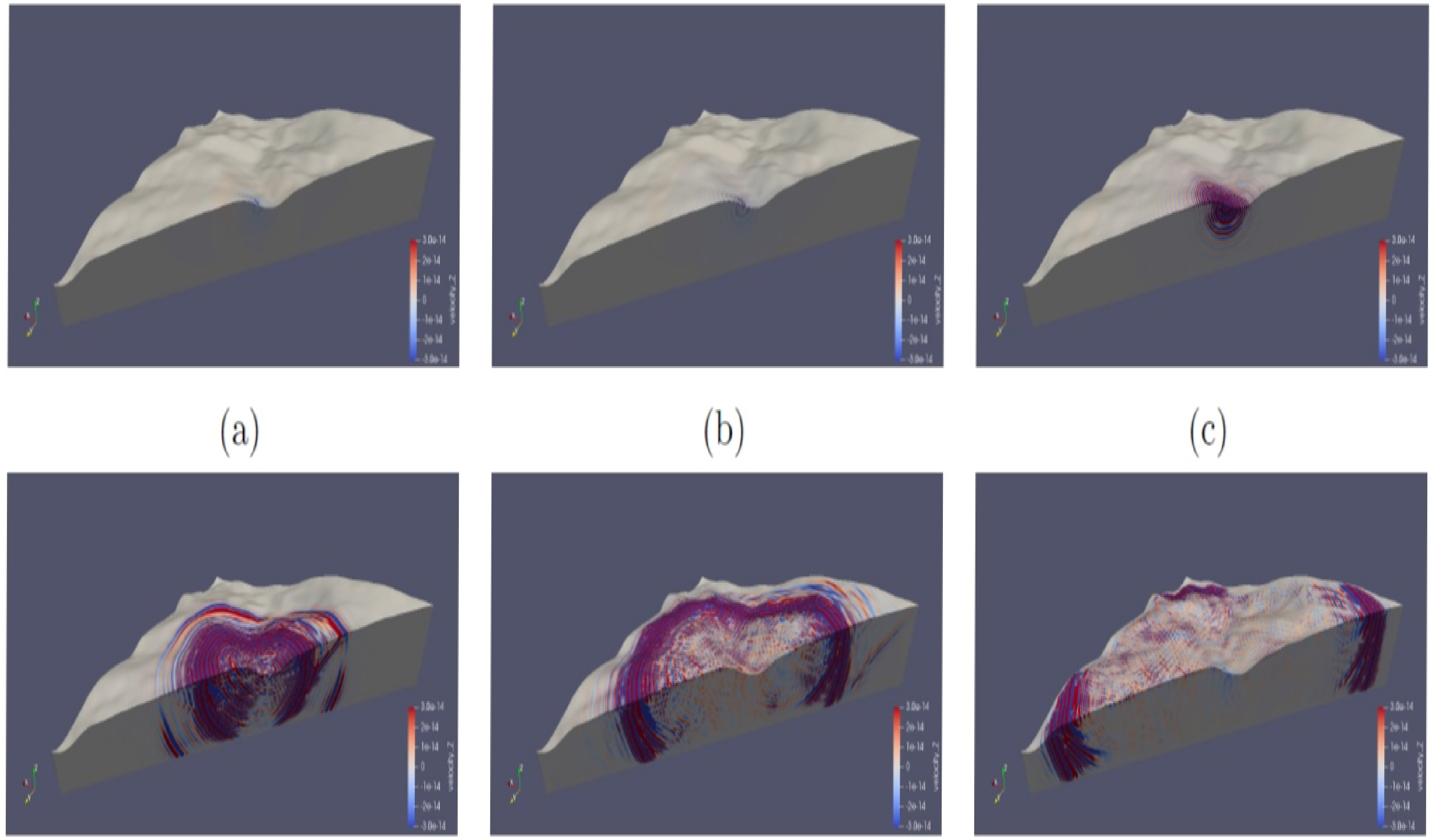


(a) (b) (c)

(d) (e) (f)



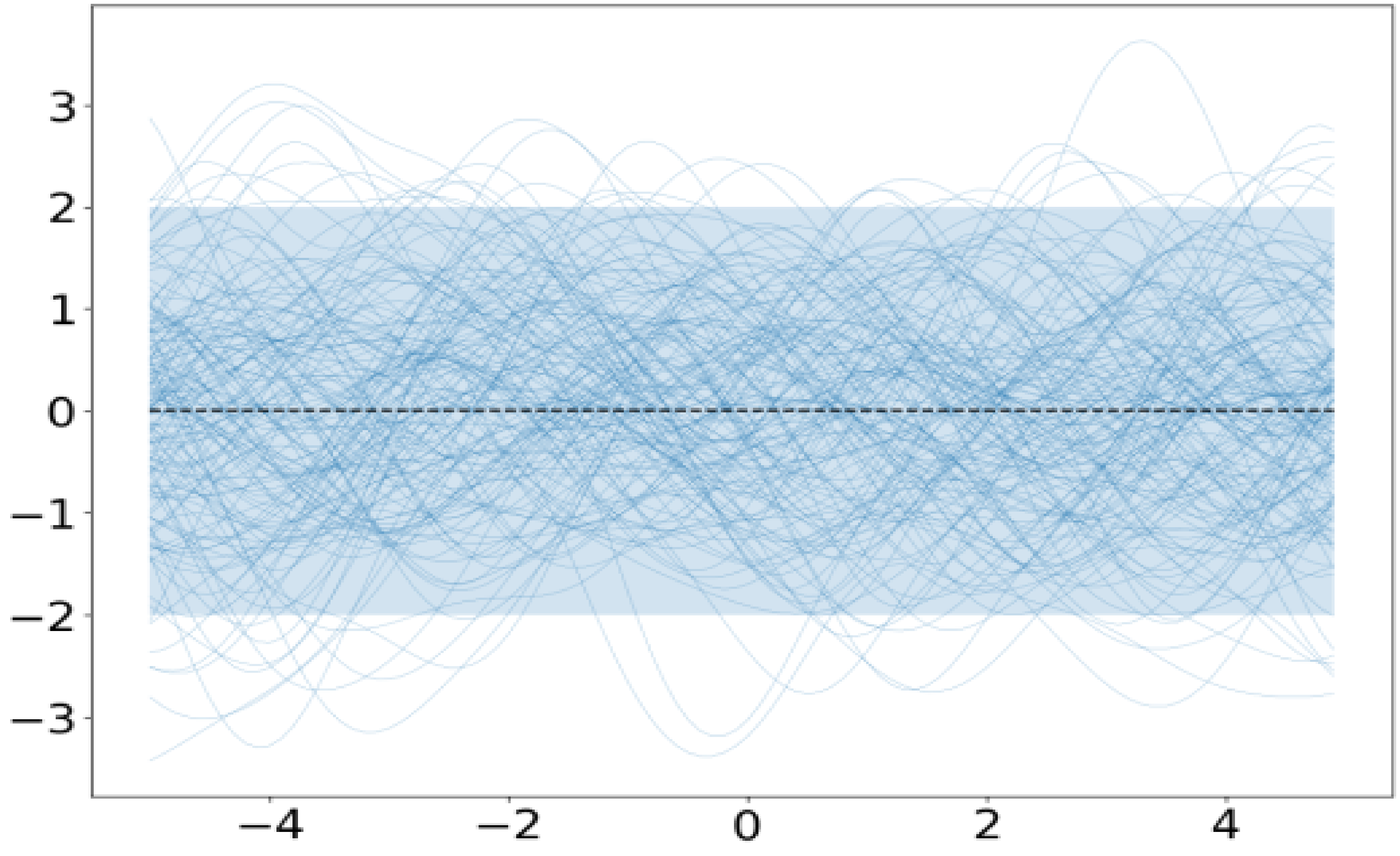
(a) (b) (c)

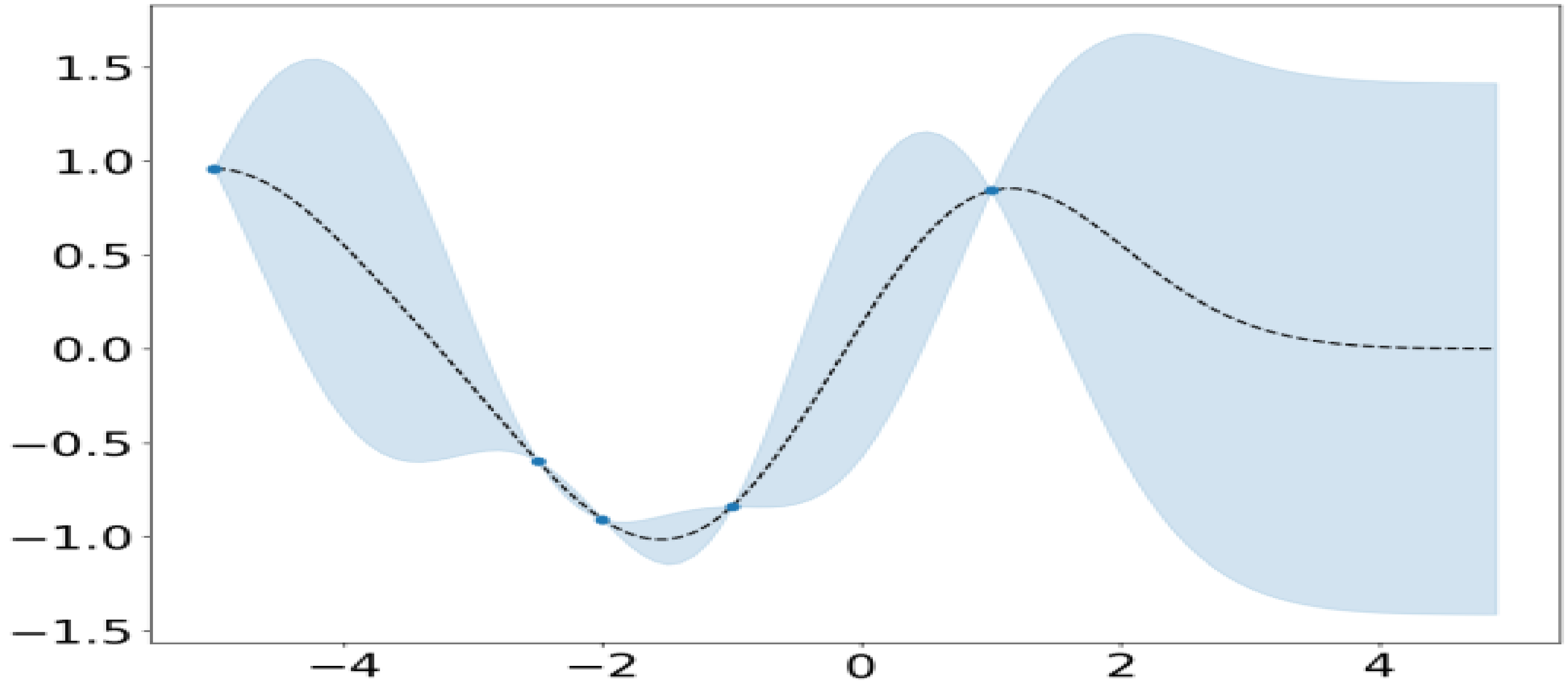
(d) (e) (f)

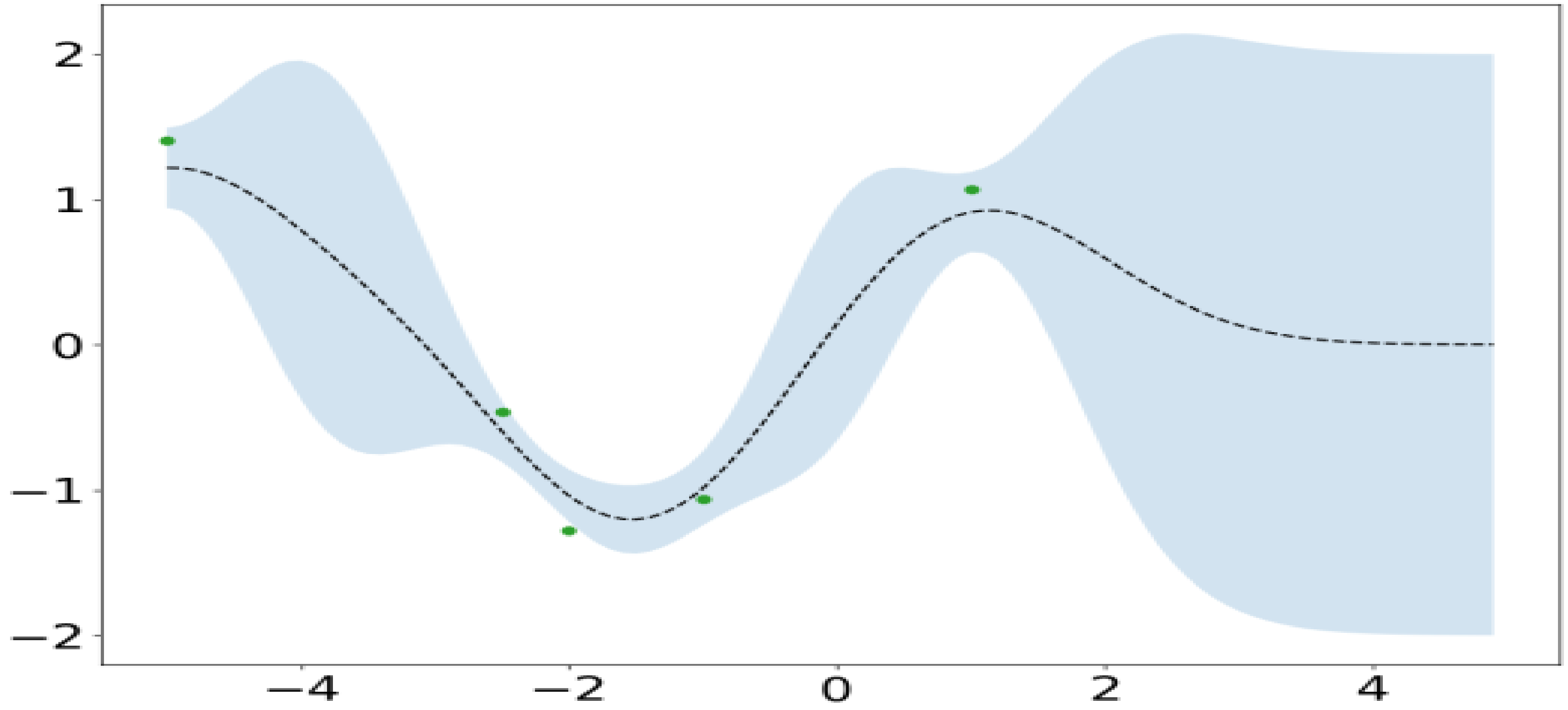
Gaussian process regression

$$\text{Posterior probability} \propto \text{Likelihood} \times \text{Prior probability}$$

- Gaussian processes
- For a proper regression – infer the values of the hyperparameters from the data
- Relying on the Bayesian framework







Significance

- Estimates of gravitoelastic correlations - optimization of surface arrays
- Effects of topography on correlations and NN cancellation

- Important milestone, but only one step in a series of tasks:
  1. Include the remaining two contributions in simulations of seismic correlations
  2. Measure seismic correlations at Sardinia site
  3. Simulation + measurement – to improve the estimation of seismic correlations
  4. Multi-sensor numerical optimization routines

- Importance:
  1. Decrease the required effort and therefore cost of a NN mitigation system
  2. Optimal arrays for the best NN reduction – increased sensitivity

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