IL NUOVO CIMENTO **45 C** (2022) 183
DOI 10.1393/ncc/i2022-22183-7

Communications: SIF Congress 2021

Providing priors to Bayesian array optimization for the Sardinian candidate site of the Einstein Telescope

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received 31 January 2022

Summary. — Gravity fluctuations produced by ambient seismic fields will limit the sensitivity of the next-generation, gravitational-wave detector Einstein Telescope at frequencies below 20 Hz. In addition to hosting the detector underground, mitigation will be required by monitoring the seismic field, using the data to estimate the associated gravity fluctuations, and subtracting the estimate from the detector data. In this paper, I present the plan for a Bayesian seismic-array design. I am focusing on a calculation of correlations between the surface displacement of a seismic field and the associated gravitational fluctuations using the spectral-element SPECFEM3D Cartesian software. These simulated seismic correlations will be implemented as priors in a Gaussian Process Regression and combined with observed seismic correlations for Bayesian inference of correlations everywhere in the medium.

1. – Introduction

The sensitivity goal for gravitational waves (GW) signals emitted by astrophysical and cosmological sources for Einstein Telescope (ET), the third-generation GW observatory, is predicted to be about a factor of 10 better than current detectors [1]. One of the fundamental infrastructure limitations, which affects the sensitivity of GW detectors is Newtonian noise (NN). This noise, relevant mostly below 20 Hz, is caused by gravity fluctuations that originate from the density fluctuations in the surrounding ground and atmosphere [2-4]. There are three main contributions to the seismic NN: seismic surface displacement, (de)compression of rock, and displacement of underground cavern walls [5]. The most prominent one and the one that is taken into account in our simulations is from seismic surface displacement [6]. This frequency band is particularly interesting, since improving sensitivity in this band it will be possible to follow better the inspiral phase of compact binaries composed of stellar-mass black holes, intermediate-mass black holes, and neutron stars [7]. It will also enable more accurate estimates of the sky location of the binary systems [8]. In this paper, along with the main remarks from our previous paper [6], I present all pieces together for a Bayesian seismic-array design for NN cancelation. The array can be designed based on seismic correlations since these determine how exactly seismic gravity noise is produced in a GW detector.

2. – Finite-element simulations of noise cross correlations

This section mostly summarizes my previous work [6]. Namely, the homogeneity of the seismic field is one of the crucial things in NN cancelation. Seismic scattering causes heterogeneity of the seismic field and could pose a serious challenge to NN subtraction since it might increase the required effort and therefore cost of a NN mitigation system [9]. For this reason, we showed the effects of topographic scattering, in an ambient seismic field, on surface seismic correlations and on correlations between underground test mass acceleration and vertical seismic surface displacement. We ran simulations in SPECFEM3D Cartesian, which is a state-of-the-art finite-element simulation software for seismic fields, based upon the spectral element method [10, 11]. Besides earthquake simulations, SPECFEM3D Cartesian can perform ambient noise cross correlation simulations. For the study of the influence of topographical scattering the vertex with the roughest surrounding topography and therefore the largest scattering potential is chosen. We assumed that the excitation is along the vertical direction of the surface. For the vertical forcing, more than two-thirds of the total energy is radiated as Rayleigh waves [12]. For boundary conditions of our finite-element model, we used a convolutional perfectly matched layer for all sides of the model except the free surface. The important parameter values of the model are the P-waves speed, S-waves speed, and density and they are 3500 m/s, 2000 m/s, and 2750 kg/m^3, respectively. The simulations were performed without attenuation and anisotropy. The ensemble of seismic sources used for the cross correlation simulations has a minimum distance to the center of the surface of the model since we assume that these areas will be protected in the future.

Our analyses of seismic scattering effects on seismic correlations, seismic coherence, and seismic-gravitational correlations show that there is a mixed wave content with Rayleigh waves and scattered waves of different wavelengths. The impact of topography is significant, but the pattern that exists in the case of the flat surface, isotropic Rayleigh wave field, is approximately preserved. Also, in the case of the variation of power spectral densities of vertical surface displacement, the topography leaves a clear imprint on the seismic field in the form of an inhomogeneity. Topography scatters out Rayleigh waves above 4 Hz providing protection from the influence of distant seismic sources. Symmetries of the field of gravitoelastic correlations are broken by topography leading to unique solutions of optimal seismometer placement for gravity noise cancellation. The problem gets significantly more complicated for the deployment of multiple seismometers since the placement of sensors also depends on their mutual cross power spectral densities [9]. Nonetheless, the quantities required for such a multisensor optimization are provided by SPECFEM3D.

An additional step can be taken with noise cross correlation simulations to obtain sensitivity kernels. These kernels quantify the sensitivity of the cross correlations to parameters of the ground medium such as seismic speeds and mass density. They can be used to improve Earth and source models (tomographic inversion) since they illuminate the parts of the models that are inaccurate [13].

3. – Bayesian seismic-array design

Since seismic measurements can only provide an incomplete understanding of seismic fields especially underground, estimates of NN and the optimization of sensor arrays can profit from numerical simulations. One needs to construct a surrogate model of the seismic field in terms of its two-point spatial correlations, which allows one to estimate seismic correlations between any two points in the field. It ideally uses both, information from seismic measurements and results from numerical simulations of seismic correlations. This can be done with a Bayesian approach, for example, using Gaussian Process Regression (GPR). This optimal modeling approach was developed for the Virgo detector, where however only displacements on the surface had to be considered [14]. The task is computationally much more challenging for the simulation of seismic correlations in three dimensions. We had limited computational resources of only about 100–200 cores for calculating two-point spatial correlations for a surface array [6]. Based on computational time in this case, the requirement for having the deeper model now and with a new estimate for how many pairs of points we need to simulate seismic correlations (which is much more in 3D), the computational time with old resources would be measured in months. So, we need to search for a new, suitable computer cluster.

For the Virgo array optimization, data from a very dense array were available, which means that the construction of the surrogate model was possible using only data (no numerical simulation of the seismic field was required). In Bayesian language, the analysis used uniform priors on seismic correlations. The situation will be different for ET with a sparse sampling of underground seismic displacement. As a consequence, numerical models that implement topography and geology will be needed and used as priors of an otherwise data-based surrogate model of seismic correlations. The optimization of the array configuration will actually be based on a surrogate model of the Wiener filter, which depends on seismic correlations. The optimal array configuration minimizes the estimated residuals of a NN cancellation.

The Wiener filter surrogate model makes it possible to optimize the array of sensors, allowing the evaluation of the cost function for an arbitrary number of seismometers in any location. With this Bayesian seismic-array design we will be able to calculate the optimal sensor locations to maximize NN cancellation via Wiener filtering, *i.e.*, to optimize the array in 3D using multi-sensor numerical optimization routines, which will come with a great request for computational resources. Surrogate Wiener filter will allow us to make the best use of cross correlation measurements. Another interesting result of the GPR is that it will tell us where to put sensors for more robust estimates, *i.e.*, at which locations we should put other seismometers during site characterization campaigns to achieve a better overall estimate of the field of seismic correlations. It tells us where it becomes too model-dependent since on the places where there are no data it relies too much on the prior. As one very important step, we would still need to investigate what type of seismic sensor helps most for efficient NN cancellation.

4. – Conclusion

Using SPECFEM3D Cartesian software, in our previous work, we showed the effects of topography on correlations and NN cancellation in ambient seismic fields. This is an important milestone for the optimization of seismic surface arrays for NN cancelation, but one step in a series of tasks. The future plans are to include the remaining two contributions of seismic NN in simulations of seismic correlations. SPECFEM3D can also tell us where we should improve our knowledge of geology. The proposal is to use the numerical results to define priors of a GPR, to eventually improve the estimation of seismic correlations everywhere in the medium. For the optimal array configuration, it is expected that deployment of several tens to hundreds of seismometers in boreholes around test masses of the ET will be needed. Bayesian seismic-array design is close to the optimal that can be done to design a NN cancellation system for ET. By doing this process properly we will decrease the required effort and therefore cost of a NN mitigation system and increase the low-frequency sensitivity of ET.

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