Site and seismic survey of the Einstein Telescope in Hungary

Thesis booklet

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Background and objective of the research

In 2016, there was the first detection of the gravitation waves, opening up a new era in astronomy. The first signal came from a pair of merging black holes, but since then we have also observed neutron star merges. We are now living in an era of so-called second-generation gravitational wave detectors, such as Europe's Virgo, the two US LIGOs and Japan's Kagra. These are sensitive to signals approximately from $10Hz$ to $10kHz$. Development of the detectors currently in use is ongoing, but is limited by the equipment infrastructure. Examples of such limitations are the arm length of the detectors or the location of the detectors. Preparations for next generation detectors such as the European Einstein Telescope (ET) have therefore started.

For a third generation detector – such as the ET would be – we would expect an improvement in amplitude sensitivity of about an order of magnitude, and a lower limit on its frequency sensitivity of $1Hz$. Thanks to these, we could detect the signal from the merging binaries days in advance[1]. The primary limitation is Newtonian noise, which is nothing more than the gravitational effect caused by the time variation of the density of the layers of soil surrounding the mirrors[2].

The ET would be a triangular detector with a side length of $10km$, i.e. the interferometers would be angled at $120°$. Furthermore, it would be placed underground, which is of particular importance as it allows to achieve the desired frequency sensitivity, i.e., to reduce the effect of Newtonian noise.

In my thesis, I took forward the seismic analysis of the Gyöngyösoroszi mine (Mátra), identified in the first ET survey as a potential earlier site, which provided the opportunity for a long-term site survey and thus for the early detection of merging neutron stars based on real data.

Summary of the research

For the Einstein Telescope, a Europe-wide site survey was launched before the 2010s. The short-term seismic survey of the Hungarian site was conducted by the MGGL, what was set up by the Wigner Research Centre for Physics, and has collected nearly 2 years of data. During my PhD, I mainly processed and evaluated the seismic data measured by the MGGL, in order to help the Hungarian site as a former potential location [T2-T3].

During the site survey, I compared my results with previous measurements, and I also proposed new quantities and methods to comparing potential sites. Such new cumulative quantities were the two new rms, which not just focus on the noise greater than $2Hz$, but both fit better to the desired frequency range. I also proposed to introduce new methods, such as intermediate averaging, which not only speeds up longer-term evaluations, but also makes it easier to interpret longer time averaged results. In addition, I have called for percentiles to be used in comparisons rather than the most frequent value [T1].

Finally, I studied the observability of neutron stars. Here I have introduced a quantity that can also be a key factor in comparing the locations. I examined simple source signals to measure early detectability. Not only, this is not so sensitive to spontaneous noise, and but also, it makes it easy to compare different sites using the uniform Newtonian noise model and suspension[1], in which I investigated the entire two-year period based on data from the $-88m$ depth station [T4].

I hope the construction of the ET will start soon, so that the observation of gravitational waves can enter a new era and I hope my work can help to make this a reality.

Results

The scientific results presented in my thesis are summarised in the following four thesis points.

1. First, I processed nearly two years of seismic data measured at the Mátra Gravity and Geophysics Laboratory. In the evaluation I mainly followed the procedures and quantities already accepted by the ET community. This was a unique situation, because

[1] I extended this initiative in the framework of a successfully awarded New National Excellence Program of the Ministry for Innovation and Technology

the Hungarian site was the only one where longer-term data were collected. I published my results in [**T1**] and in [**T3**].

2. As a second thesis point, I developed and proposed new quantities and processing methods to better compare the potential locations of the Einstein Telescope. I considered it important to be able to extract as much information as possible from the available data during longer-term evaluations. To do this, I considered it essential to create a processing procedure that would facilitate the comparison of sites and give as accurate picture as possible. Furthermore, the short term and intermediate averaging I have introduced in the evaluations can be helpful, as it allows an evaluation adapted to the most important gravity waveforms to be carried out easily and quickly with large amounts of seismic data. The cumulative quantity I introduced – interpreted over a different frequency range – also gave me the opportunity to observe seasonal variations, without it, I would not have been able to detect. I have regu-

larly presented my results at professional conferences in the community, and have had the opportunity to work with prominent researchers in the field. Relevant publications related to this thesis point: [**T1**] and [**T2**].

3. I investigated the sensitivity curve of a prospective gravitational wave detector at low frequencies for the Mátra site. I used a Newtonian noise model available in the literature and the transfer function of the Kagra gravity wave detector suspension. This is used to estimate to the sensitivity curve of the proposed $10km$ arm-length Einstein Telescope at low frequencies. Thus, I was able to produce time-dependent sensitivity curves, choosing windows of roughly $300s$ [**T2, T4**].

4. Finally, I investigated the early observability of neutron stars using estimated suspension curves. To do this, I calculated the gravitational wave profiles produced by previously detected merging binaries. For the computed waveforms, I set the masses of the

merging binaries such that the signal they produce was sufficiently short. This was necessary to obtain results in the low frequency range comparable to the two-week measurement period. My related publication: [**T1**] and [**T4**].

Related publications

[**T1**] L. Á. Somlai et al. "Seismic noise measures for underground gravitational wave detectors", Acta Geodaetica et Geophysica, 54(2):301–313; doi: 10.1007/s40328-019-00257-5

[**T2**] P. Ván et al., "Long term measurements from the Mátra Gravitational and Geophysical Laboratory", Eur. Phys. J. Spec. Top., **228**, 1693–1743 p. (2019); doi: 10.1140/epjst/e2019-900153-1

[**T3**] G. G. Barnaföldi et al., "First report of long term measurements of the MGGL laboratory in the Mátra mountain range", Class. Quant. Grav., Vol. 34, No. 11 (2017); doi: 10.1088/1361-6382/aa69e3

[**T4**] L. Á. Somlai, "Low frequency detectability of gravitational waves at Mátra mountains", VIII. INTERDISZCIPLINÁRIS DOKTORANDUSZ KONFERENCIA 2019 - TANULMÁNYKÖTET, 8th INTERDISCIPLINARY DOCTORAL CONFERENCE 2019 - CONFERENCE BOOK (B. Csiszár (Szerkesztő),F. Bódog (Szerkesztő),E. Mező (Szerkesztő), B. Závodi (Szerkesztő)), Pécsi Tudományegyetem Doktorandusz Önkormányzat (2019)

Other own publications

[P1] L. Á. Somlai et al, "Silence measurements and measures for ET: characterisation of long term seismic noise in the Mátra Mountains", arXiv:1804.07200 (2018); doi: 10.48550/arXiv.1804.07200

[P2] L. Á. Somlai and M. Vasúth, "The effect of the cosmological constant on a quadrupole signal in the linearized approximation", International Journal of Modern Physics D, Vol. 27, No. 02, 1850004 (2018); doi: 10.1142/S0218271818500049

[P3] E. Cs. Debreceni and L. Á. Somlai, "Az MGGL laboratórium szeizmikus zajforrásainak vizsgálata", Mér-

nökgeológia Kőzetmechanika sorozat, 33–47 p. (2018); IBSN:978-615-5086-11-3

[P4] P. Kicsiny, L. Á. Somlai and Z. Zimborás, "Analysis of the MGGL seismic data by noise-filtered Fourier transform method", Mérnökgeológia Kőzetmechanika sorozat, 47–52. p. (2018); IBSN:978-615-5086-11-3

[P5] F. Amann et al., "Site-selection criteria for the Einstein Telescope", REVIEW OF SCIENTIFIC INSTRUMENTS 91 : 9 Paper: 094504 , 20 p. (2020); doi: 10.1063/5.0018414

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[1] ET Science Team, "Einstein gravitational wave Telescope, Conceptual Design Study" (2011).

[2] Scott A. Hughes and Kip S. Thorne, "Seismic gravity-gradient noise in interferometric gravitational-wace detectors", Phys. Rev. D, 58:122002 (1998).