Geophysical noises in gravitational wave detection final report

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1. Introduction

The primary goal of our proposed research was the scientific preparation of the Hungarian participation in the Einstein Telescope (ET), the future European underground gravitational wave observatory. The participation level of Hungary was not decided at the beginning of the research period; therefore, our original plan considered and accommodated several possibilities. We had a multilevel plan with various possible outcomes: in the case of Hungarian establishment of ET, in case of non-Hungarian establishment but strong Hungarian participation and in case of institutional level participation in the preparations.

During the proposal period, the following events influenced the focus point of our research: According to the preliminary studies, the Mátra Mountain range has one of the best seismological properties in Europe. Therefore Hungary was a strong site candidate, and our first research goal was the site preparation and characterisation of Mátra.

In December 2018, the Division of Physical Sciences of the Hungarian Academy of Sciences decided not to support a Hungarian ET site. After that, our goal was shifted, and the focus of our research was the preparation of Hungarian participation in other European site studies and developing related gravitational research. Then the preparation of Hungarian technological support of the future infrastructure – for in-kind contributions – become our main activity. The importance of material characterisation and theoretical studies has been increased. The development of infrasound detectors has been continued, and we have started to develop an instrument that, in principle, is capable of directly measuring Newtonian noise, the primary limiting factor of the low-frequency sensitivity of ET.

In 2019 March, it was decided that Hungarian participation in ET remains at the institutional level; therefore, the emphasis of our research has been shifted accordingly. Instead of the correlation noise measurements in prepared cabines of the mine we elaborated numerical simulations. Instead of seismological measurements in other Hungarian underground sites we prepared our site noise evaluation code for the use of ET community and uploaded to the Italian server.

We have participated in preparing the ESFRI proposal (the European Strategy Forum on Research Infrastructures evaluates large European infrastructures). We were active in five boards and participated in the international effort of elaborating the site selection criteria, published in [38]. After a covid related delay, it was announced in June 2021 that ET is on the ESFRI roadmap (https://www.esfri.eu/latest-esfri-news/new-ris-roadmap-2021).

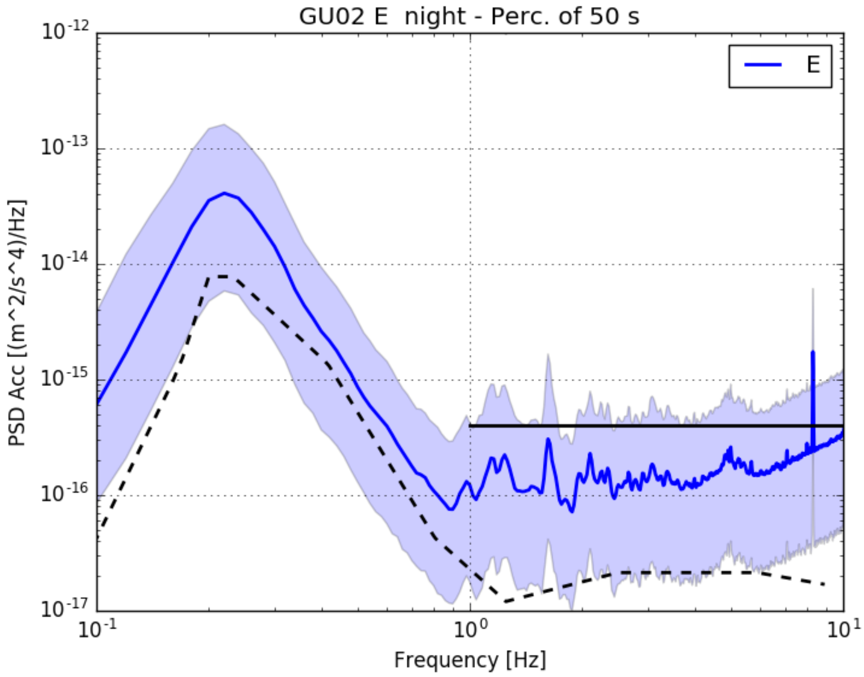
Our research plan has three legs:

- site characterisation and instrument development,
- theoretical background studies for material characterisation,
- gravity and gravitational wave research.

In the following, the results are mentioned according to these research directions.

2. Mátra site characterisation, instrument development and rock mechanics studies

We have published a large, many author paper that summarised our various studies performed in the Mátra Gravitational and Geophysical Laboratory. That includes seismological, seismic, infrasound, electromagnetic research, rock mechanics, and muon tomography measurements [31]. One of the representative figures is shown in Figure 1.



1. ábra. Acceleration ASD values in a representative two-week period seismic measurement of (-404 m) in one of the horizontal directions. The median is solid blue, and the borderlines of the blue area are the 10th and the 90th percentiles. The dashed line is the NLNM curve of Peterson; the solid black Black Forest line is a reference. This figure is the title page of [31].

2.1. Seismic noise analysis

In this direction, our main activity was analysing the long-term noise data considering the requirements of underground gravitational-wave observatories. Our data collection extends for four years, and we have analysed two years of data in [31]. Our research validated the preliminary studies, the underground noise in the Mátra in the critical frequency range 1-10Hz is low, seasonal, weakly, and daily changes are not less than expected [31]. The Mátra site is the most researched in Europe up to now; the Sardinian and Limburgian sites did not finish their long term characterisation studies yet.

We have developed reliable performance characteristics with the special requirements of long-term data [18,33]. Then we characterise the Mátra site considering both the new, improved characteristics and the previous less reliable measures used in the preliminary short term studies. Also, we have analysed the microseismic noise in the Gyöngyösorosyi mine to identify possible sources and reasons. The goal was to separate the ongoing internal work-related and external noise contributions in the particular frequency range and estimate the minimal noise level in silent tunnels [7]. We have also tested a new, noise-filtered Fourier transform method for seismic data in [15].

Publications [7,15,18,31,33,38].

2.2. Infrasound measurement and instrument development

During the research period, a new infrasound detector was developed, specifically for the requirements of the Einstein Telescope, optimised for underground measurements at the frequency range 1-10Hz [38,39]. Infrasound noise measurements in Mátra were reported [25,31]. This detector is a joint project with Atomki. COVID prevented our international measurements (in Sardegna, at the ET candidate site); those will be performed in 2021 autumn with a different budget.

Publications: [25,27,38,39]

2.3. Electromagnetic measurements

We have performed several ELF range EM investigations in the close environment of the MGGL, which aims to estimate the EM signal's attenuation with the depth in the Mátra andesite rock [2]. Lemi-120 probes and Lemi-423 instruments have been installed at the backfilled end of a 400m deep cave and in the close vicinity of the surface projection of the subsurface measurement site. Several difficulties with these measurements led to inventive evaluations methods with a combination of various reference measurements. Therefore the publications are not yet completed; some of them are in a conference paper form.

First, the subsurface and surface recordings could have been run with no overlapping in time for technical reasons. Therefore we applied an indirect processing method utilising the poor recordings of a very low-noise ELF EM observation site of Hylaty station. The indirect method is based on the determination of amplitude transfer coefficient (ATC) between MGGL and Hylaty in period I. and ATC in the relation of the surface site and Hylaty in period II. The estimation of the attenuation is accounted to the relation of the former two [10]. Furthermore, we have extended the magnetic observations with telluric measurements for several one day long periods and made a comparative study between EM variations of MGGL and Nagycenk Geophysical Observatory. The parallel geomagnetic and telluric measurements aim to estimate the bulk resistivity of the underlying andesite block [11].

The indirect experimental determination of the electromagnetic (EM) attenuation in the Mátra mountains has been supplemented with an estimation based on direct comparative measurement scheduled in agreement with a downtime of the mine facilities, temporally parallel at a surface and the subsurface sites. The natural ELF range EM signal utilised is the global thunderstorm activity excited Earth surface-ionosphere resonance cavity, the so-called Schumann background [24,31].

Aside from that approach, dielectric properties of the Earth's within its 140 m deep uppermost layer have been estimated at the Matra Gravitational and Geophysical Laboratory, using Q-bursts from Africa, i.e. ELF-band radio atmospherics produced by intense lightning strikes. From the ratio of signal amplitudes measured at the surface and inside a mine shaft, the conductivity of the ground layer was estimated to be 0.05 S/m (20 Ωm). The obtained dielectric parameters are characteristic for wet soil, which matches the local soil type (clearing in woodland in spring, after the snow had melted) [31].

The covid postponed geophysical measurements have been carried out, altogether 7 in situ magnetotelluric measurements were realised in the reported period near the Mátra Gravitational and Geophysical Laboratory. The aim was to verify the integrated conductivity values, those were determined previously according to the attenuation of the fundamental mode of Schumann resonance (7.83Hz). Therefore the records were performed at the maximum sample frequency (2kHz); the first inverted specific resistance represents the upper 200m region. The uncertainty of the inversion is significant because of the human electric noise. We have also performed a multielectrode geoelectric measurement through an MT penetration point with a Wenner-Schlumberger and dipole-dipole arrangement. The aim was to have realistic values of the specific resistance near the surface, and then the MT inversion initial value can be started from there. We have conference abstracts and several submitted publications in this respect [52,56].

Publications: [2,10,11,24,31,52,56]

2.4. Experimental gravity, and instrument development

We have started extending our gravity-noise investigations and participate in the Eötvös balance modernisation project of BME in the Jánossy Underground Physical Laboratory for testing the balance. The Eötvös balance modernisation aims to improve the device's sensitivity by about two magnitudes, compared to its original sensitivity level. From the point of view of our NKFIH project, an Eötvös balance is an extremely sensitive instrument, and the most essential part of the project is noise insulation and noise filtering.

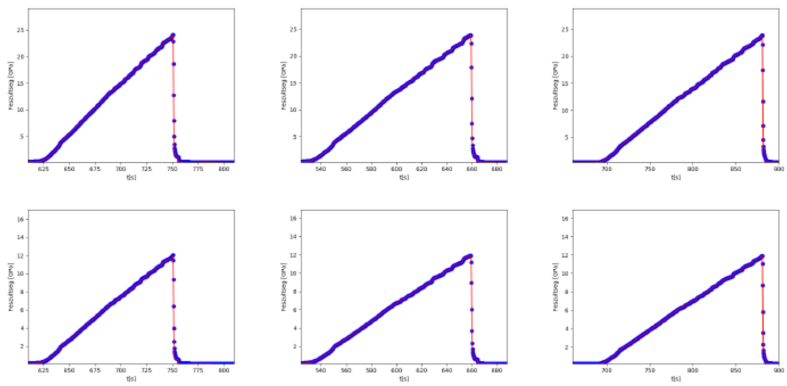
We have already proved that Eötvös balance can reliably detect earthquakes, and also we have proved that pressure variations are correlated with the balance noise and, therefore, active noise mitigation is necessary for reliable gravity gradient measurements. However, this property makes Eötvös balance a particular instrument of environmental noise detection, with combined gravity and seismic origin. We have promising experiments and calculations that indicate a final improved sensitivity capable of detecting Newtonian noise directly and indirectly.

Publications: [21,32]

3. Rock mass and rock rheology

Investigations of various mechanical rock properties with standard methods of rock mechanics were reported in several papers. There the effects of water content [3,34,44], the relation of Poisson ratio to strength parameters [27,58] and various complex researches were performed in [28,29,45], Rock mass properties with GSI were investigated in [9,22,23,55,58]. These analyses were connected to the Hungarian site preparation. A suggested new method of rock mass characterisation from borehole data is probably our most interesting rock mass related result [23].

The rheological rock mechanics experiments for the andesite from Mátra and their evaluation were reported in [19,32]. These experiments confirm the central hypothesis of our proposal about the rheological properties of andesitic rocks. Here, the measured two different propagation speeds agree with the time-dependent deformation-stress laboratory measurements and confirm the validity of the thermodynamic model. The observed difference of dynamical and static elastic moduli in various rocks confirm the thermodynamic based rheological model [37]. The publication of the detailed Mátra data is in progress [60].



2. ábra. Dynamic rock experiments with three andesitic samples and their related fit with Kluitenberg-Verhás body. In the upper line is the deviatoric, in the lower one is the spherical part of the stress as a function of time [60]. The fitted differential equation gives the red line.

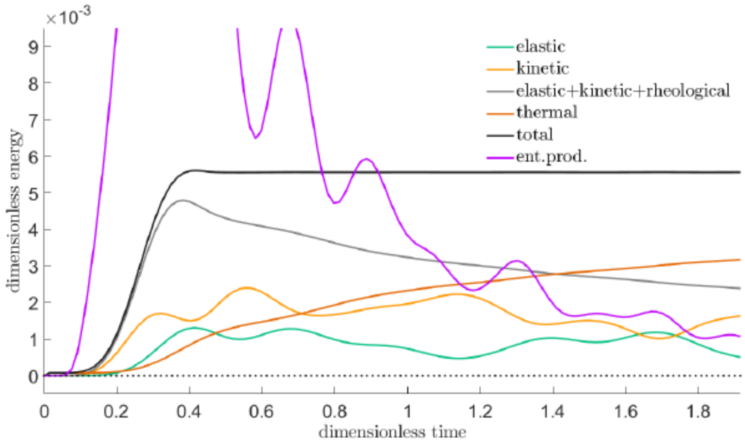
We have started to develop numerical methods for modelling dissipative wave propagation [16,29]. Finally, we have developed a general numerical method that is capable of calculating wave propagation in anelastic media [40,48]. It was compared to various other algorithms, e.g. the COMSOL built-in procedures. Our method is faster, its numerical dispersion is minimal and more reliable. It is due to the four spacetime dimensional approach, which is nonrelativistic nevertheless, and the respect of the dissipative structure with thermodynamic principles. This is one of the major achievements of the whole project.

Here we emphasise that this result is also a consequence of several developments of non-equilibrium thermodynamics theory. These theoretical results revealed a close connection between non-Fourier heat propagation, gravity and gradient theories (like phase fields). The related connective publications are [12,16,20,30,41,49,54]. A remarkable result is our new method of dissipative wave propagation analysis [59].

Publications: [3,9,16,19,22,23,27,28,29,34,37,40,44,45,48,55,58,60], theoretical background [12,16,20,30,41,49,54,59]. A Springer book summarizes several practical aspects our work [41].

4. Theoretical non-equilibrium thermodynamics and gravity

Coupled elastic, rheological and thermal effects play the most important role in Newtonian noise. Therefore, our main effort here was to develop a complete theory of non-equilibrium thermodynamics, including



3. ábra. Wave propagation in a Poynting-Thomson-Zener rheological medium. The energy is exactly conserved in the 3D numerical code (black line) and entropy production rate indicates stability (purple line)) [48].

gradient effects. Our most important result is that gravity is a gradient (weakly nonlocal) theory from a thermodynamic point of view [46,47,49]. Coupled thermomechanical models are investigated for gases, too, because the flux of the heat flux is closely related to the mechanical stress, which is the key element of understanding the thermodynamic generalisation of elasticity. Non-Fourier heat conduction is analysed in [1,8,12,13,16,17,50,53,54], where the emphasis is on numerical modelling or various theoretical aspects. The thermomechanical coupling of continua with various memory properties was researched in [26,35,42,47,57,58]. Weakly nonlocal, that is, gradient theories are developed in [20,30,46,47].

Theoretical gravitational wave research was part of the project. In this direction, propagation in medium, inspiralling, among others was researched in a general relativistic framework [5,6,14,51]. These researches are related to our noise studies because then the detectability of the waves can be calculated from real site data [62].

The extension of extensivity requirements of thermodynamics leads to the elimination of the negative heat capacity of black holes in black hole thermodynamics [4,36,61]; this is another result of the proposal when thinking about thermodynamic aspects of gravity.

Publications: [1,4,5,6,8,12,13,14,16,17,20,26,30,35,36,42,46,47,49,50,51,53,57,58,61,62]

5. Other

We have made elongated the project by one year due to covid. We wanted to finish the electromagnetic measurements and the planned conference participations and research visits. The electromagnetic measurements were finished successfully, but unfortunately, we could not perform some of the journeys at the end. The two visits at the Eurock Conference in Norway were cancelled, because the Conference was cancelled. Also the visit at the USA was postponed two times, and the final plan in this August was also cancelled because of the covid situation in USA.

The scientific activity of our research group was reported in more than 50 conference presentations, and posters; among them are 27 international presentations, some of them were invited ones. The nonscientific public appearances are reported on our homepage: http://www.einsteintelescope.hu. The PhD dissertations of Edit Fenyvesi (under evaluation) and László Somlai (in preparation) are based on this research. Also, the MTA doctoral dissertation of Balázs Vásárhelyi uses some result of this research.

We have planned initially 24 publications for the three years. The enthusiasm of our group leads to more and also more interesting scientific results beyond our expectations. Thank you for the support!