

Seismic noise study in the underground Baksan Neutrino Observatory

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Abstract. In this paper we report a study of the seismic noise measured in the underground Baksan Neutrino Observatory. The main spectral feature below 1 Hz is the oceanic microseism, while for greater frequencies the measured horizontal and vertical accelerations approaches the Peterson low noise model. Using two synchronized seismometers we also studied the coherence in the microseismic band (0.1 – 0.5 Hz) between three underground stations located at 0.3 km , 1.4 km and 3.7 km from the tunnel entrance. Finally, on the base of our measurements we evaluate the Newtonian noise limit at this site using the Saulson's model.

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1. Introduction

Gravitational waves predicted in the context of the Einstein theory of Relativity causes space to be stretched in one direction while simultaneously being squeezed in the perpendicular direction. The space-time strain, or change in length divided by length, induced by these waves can be up to ten thousand times smaller than the diameter of a proton. The relative change in length is so low, $\sim 10^{-21}$, (corresponding to a displacement sensitivity of $\sim 10^{-18}$ m over a distance of 1 km) that the detectors must be incredibly sensitive to the strain change and screened from any source noise as for example ground motion, storms, lightning strikes, and in general seismic noise that can mimic a gravitational wave signal.

The environmental noise is attenuated by enclosing the sensitive detector in ultra high vacuum chambers and adopting active and passive techniques. Both types of isolation increase the frequency bandwidth of the detector but, because of the huge gap between

the residual r.m.s. motion of the ground ($\sim 10^{-7}$ m) and the displacement sensitivity of the detector, non-linear effects can limit significantly the performances and the design of the active control loops is a challenge. In addition the microseismic random motion of the ground results in the stochastic gravitational force acting on the detector test masses of the space metric and subsequently produces an addition noise at the detector output. This is the Newtonian noise source limiting the detector in the frequency range below ~ 5 Hz. It is a direct gravitational coupling between the interferometer test masses and the surrounding geology that cannot be shielded or suppressed. Therefore, finding a suitably quiet seismic environment is the first step in reducing these effects.

As part of the design project of a GW detector of new generation (3G) we have studied the seismic noise characteristics of various sites. In particular, we explored underground locations that yield significant reduction in seismic power spectral density (PSD) in comparison with the sites hosting on surface the current GW interferometric detectors, as LIGO and Virgo. These PSD measurements are usually compared with the Peterson new high (NHNM) and low (NLNM) noise models [1] to give a theoretical reference of extremely high and low ambient seismic motion respectively.

In this paper we report the results of our measurement campaigns performed in the Baksan Neutrino laboratory. Two series of data have been collected with different instruments at distance of few years. In the following sections after a presentation of the Baksan laboratory, we summarize the results obtained in 2013 and in 2018, then we conclude with a Newtonian noise estimation given the measured seismic background at the site.

2. The Baksan Neutrino Observatory and its rock composition

The Baksan Neutrino Observatory (BNO) is a scientific laboratory of the Institute for Nuclear Research of the Russian Academy of Sciences (INR RAS) located in the the Caucasus mountains of the Karbardino-Balkaria Republic in Russia. It started operations in 1977 [9], hosting mainly neutrino experiments already at the USSR epoch . The laboratory itself was built in a 4 km long horizontal tunnel under the Mount Andyrchi, 4,000 m high. The entrance is at 1,700 m from sea level, in the gorges of the Baksan river. BNO was conceived to carry on studies and experiments of both fundamental and applied physics. The Observatory includes surface installations for cosmic ray physics and underground laboratories for neutrino physics physics and physics of rare processes: it host also the Optoacoustic GRavitational ANtenna, OGRAN [10].

Geologically, the Caucasus Mountains belong to the Alpide belt system that extends from southeastern Europe into Asia; it is a border between the two continents and one of the world's higher mountain chain. The Greater Caucasus Mountains are mainly composed of Cretaceous and Jurassic rocks with the Paleozoic and Precambrian rocks

in the higher regions. The laboratory entrance is located in the gorge of the Baksan river, not far from the Mont Elbrus (5642 m), a dormant volcano. This is the largest Quaternary volcano in the European part of the Russia, situated within the central part of Greater Caucasus. North of the Greater Caucasus the deep sedimentary Terek and Kuban foreland basin (more than 6000 m thick; up to 1,600 m elevation) forms the transition to the Scythian platform. North-North-West of Mount Elbrus, the Stavropol “high” forms a basement uplift. In the North Caucasus and in particular in basin of Baksan river, the volcanic and plutonic rocks are interpreted as parts of a single magmatic system with an age of 2.8-3.0 Ma, similar to the magmatic system of the molybdenum-bearing *Questa* caldera complex of New Mexico. [8]



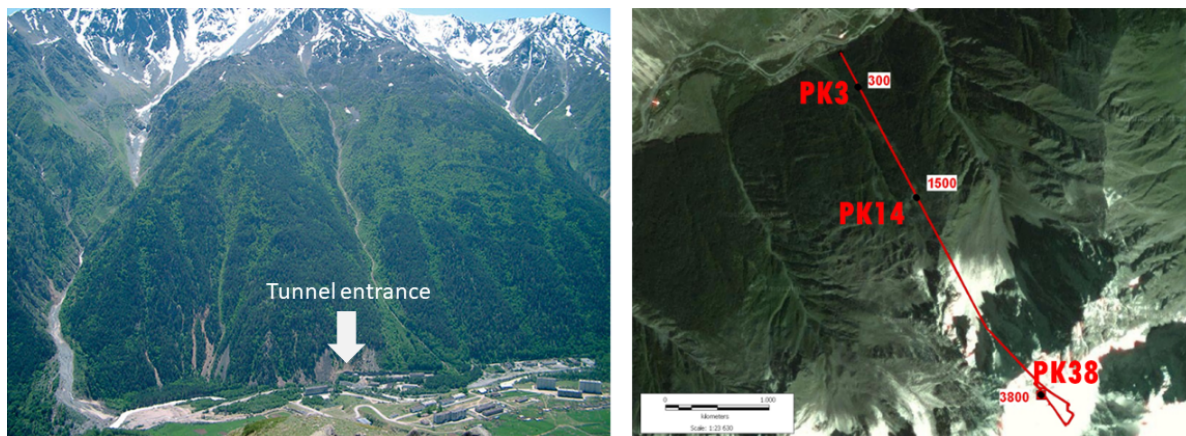
Figure 1. The location of the Baksan Neutrino Observatory - BNO

The surrounding rock geological minerals of the laboratory location are the plagiogneiss down to the depth 800 m, and plagiogranites at more deep levels. The main rock of the massif is shale, which has a thorium and uranium radioactive concentration close to that of granite. A density of these rock species practically is equal in average to $\rho = 2800 \text{ kg/m}^3$. The chemical composition of rocks is reported in the table 1 [11].

The underground laboratories, conceived to search for rare processes predicted in theories of elementary particle physics and cosmology, are distributed along the tunnel and they differ in their volume and depth. However, all laboratories have been designed to have the special feature of a reduced background caused by a surrounding radioactivity. The experimental areas can be divided into two groups: the first one is the group of moderately deep zone with the largest one reserved for scintillation telescope laboratory. The second one is the group of very deep experimental areas including the gallium-germanium solar neutrino laboratory. The OGRAN experiment is hosted in a dedicated room located almost at half the away of the horizontal tunnel[12].

Table 1. Chemical composition of the Baksan laboratory rocks from [11].

Element	Chondrite	Ultrabasic	Basalt	Granite
O	0.350	0.4057	0.3848	0.0068
Na	0.068	0.0040	0.00166	0.0286
Mg	0.144	0.1997	0.0465	0.0067
Al	0.013	0.119	0.0907	0.0909
Si	0.178	0.1821	0.1949	0.3008
K	0.0009	0.0017	0.0116	0.0469
Ca	0.014	0.0284	0.0938	0.0259
Mn	0.002	0.0048	0.0257	0.0025
Fe	0.251	0.1612	0.1355	0.0540
Th	$4 \cdot 10^{-8}$	$9 \cdot 10^{-9}$	$2.5 \cdot 10^{-6}$	$1.5 \cdot 10^{-5}$
U	$1.5 \cdot 10^{-8}$	$3 \cdot 10^{-9}$	$6 \cdot 10^{-7}$	$5 \cdot 10^{-6}$

**Figure 2.** Left: front view of the Andyrchi mount with the BNO tunnel entrance. Right: tunnel path on the satellite view of the BNO area, with the studied locations indicated.

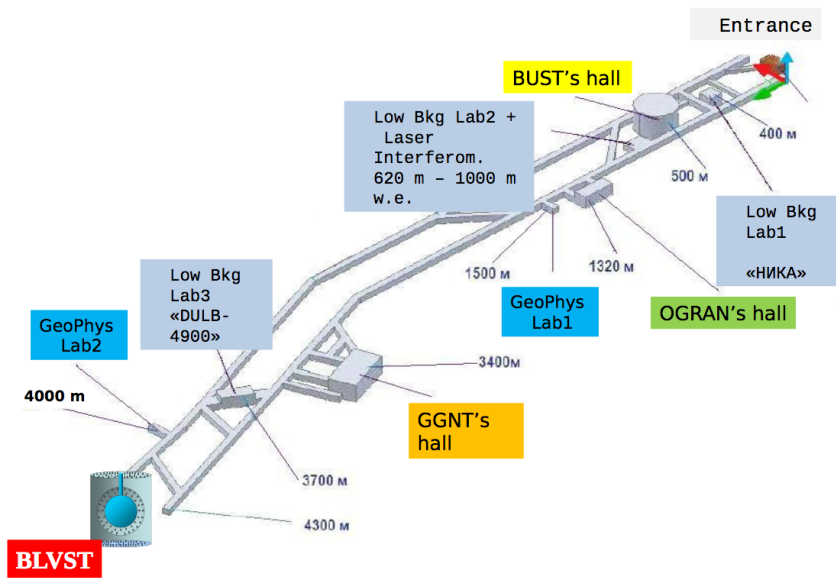


Figure 3. Laboratories hosted along the BNO tunnel. The depth from the surface increases with distance along the tunnel from the entrance (right). Image credit: Y. Gavriluk.

3. The 2013 data taking

In 2013, the measurements were carried out by the SAI MSU group with the assistance of GSRAS (Geophysical Service of the Russian Academy of Sciences [13]), which has a stationary underground laboratory at the picket PK-38 of the BNO main tunnel, equipped with a full range of geophysical meters. Investigations of the seismic background along the main tunnel were carried out with a portable seismometer within the EU program F7 (ASPERA grant entitled "Einstein's Telescope" [14]). In 2013 measurements have been taken with conventional three coordinate seismometers type of Guralp CMG-3T/ESPC, an instrument consisting of three sensors, which can measure the north-south, east-west and vertical components of ground motion simultaneously, and it is equipped with a built-in digitiser vibrations in the frequency range 3×10^{-3} – 50 Hz. The measurement campaign have been carried on by monitoring the seismic activity in three different locations along the 4 km horizontal tunnel, named PK3, PK14, PK38.

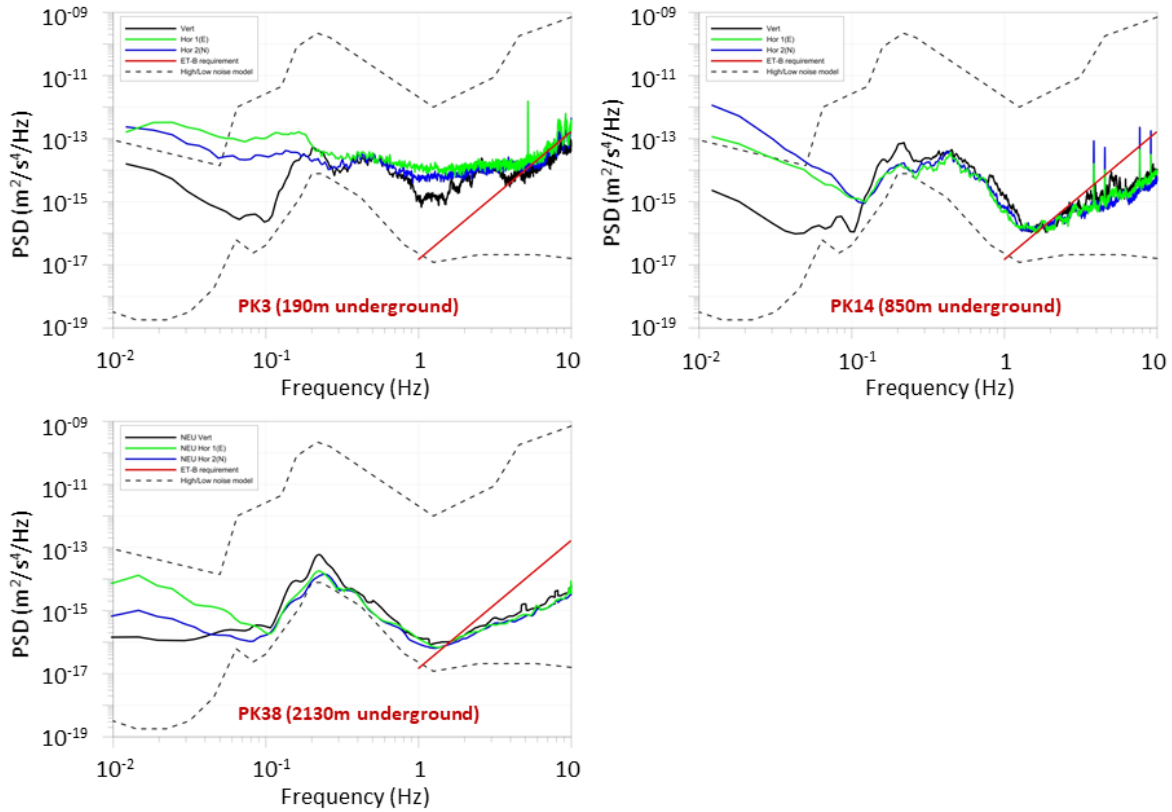


Figure 4. Horizontal (green and blue lines) and vertical (black line) acceleration averaged power spectra at PK3 (top left), PK14 (top right), PK38 (bottom left) measured at BNO in 2013, compared to NLNM and NHRM (dotted lines) and to the ET requirement (red line) extrapolated from [14].

PK3 is the station ~ 300 m far from the tunnel entrance and with a depth of ~ 190 m from the daily surface.

PK14 is at a distance of ~ 1500 m from the entrance of the main tunnel: the instrumentation was in the vicinity of OGRAN, the detector hosted in a facility constructed using principles of solid-state and laser interferometer gravitational antennae. The tunnel depth from the surface in this point is ~ 850 m.

PK38 is the station at ~ 3800 m from the tunnel entrance, at a depth of ~ 2130 m; in this area in the past there was a geophysical complex with tilt indicators, magnetometers, gravimeters, thermometers as well as earthquake detection stations devoted to carry on a geophysical survey.

Results of measurements are presented in figure 4 as a spectral density of horizontal and vertical acceleration in the logarithmic scale. At the deepest mark 3800 m in the frequency range of 10^{-1} Hz, the acceleration spectral density decreases from $\sim 1 \cdot 10^{-14} \text{ m}^2/\text{s}^4$ Hz to $\sim 1 \cdot 10^{-16} \text{ m}^2/\text{s}^4$ Hz.

4. The 2018 data taking

The second data taking was carried on during three days in 2018, from September 25th to September 27th, using two kind of seismometers:

- a broadband triaxial Trillium 240 seismometer made by Nanometrics Inc [5] that some of the authors (LN, MP and FR) used also to characterise other sites, which are candidates to host the Einstein Telescope 3G-GW detector;
- SM3 seismometers developed by the Russian Academy of Sciences based on a pendulum with negative feedback[7]. One of them was initially installed close to the Trillium 240 in the PK14 station, then moved to the other stations.

The Trillium 240 seismometer was installed on the floor of the OGRAN laboratory, which is cemented to the bedrock of the tunnel, horizontally oriented towards the north direction and leveled. After the installation the sensor was left in position for about 24 hours to reach the thermal equilibrium with the local environmental temperature, The Trillium 240 was connected to a DAQ Taurus [6] to record the acquired data. The frequency response of the three channels is nearly flat in the microseismic band, and it rolls off at 40db/decade at lower frequencies. The analog output of the sensor is sampled at 30 kHz and then down-sampled at 40 Hz with a anti-aliasing filter.

In figure 5 we show the acceleration spectrum along three axis measured during the night between the 26th and the 27th of September 2018: the most prominent feature is the secondary oceanic microseismic peak at $f = 0.195 \text{ Hz}$ [3],[4], with a knee between 0.4 and 1 Hz that is likely related to the waves in Black and Caspian seas. Above 1 Hz both the horizontals and vertical spectra are close to the minimum level given by the NLNM. Comparing the spectrum with the previous measurements made in 2013, and taking in mind the square factor between amplitude and power spectral densities, it is possible to note an extra-noise above 2 Hz in the previous measurements, probably due to the self-noise of the Guralp sensor and its digitiser at these frequencies.

In figure 6 we report the spectrogram obtained from one hour-long averaged spectra measured between 20 PM of the 26th and 5 AM of the 27th of September.

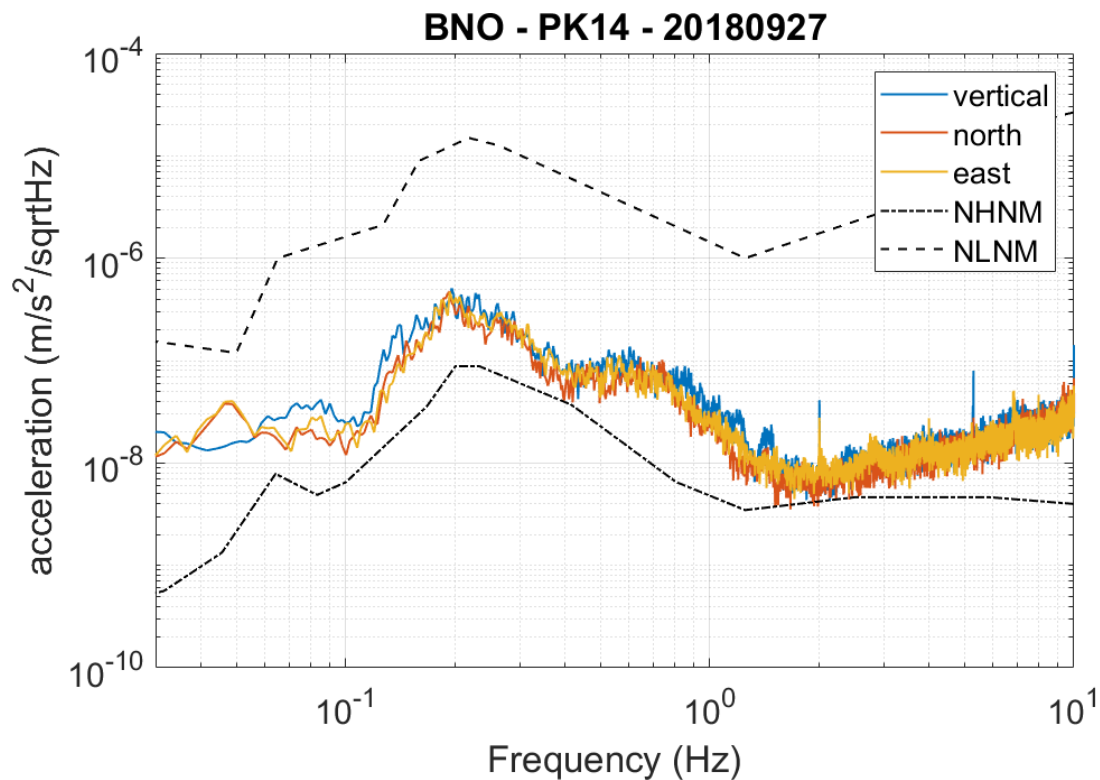


Figure 5. Amplitude spectral density of the acceleration (median) along the vertical, E-W and N-S axis measured in OGRAN laboratory (near PK14) at BNO during the night of 27th of September 2018.

In the figure 7 we show for comparison the vertical seismic spectrum measured in BNO at station PK14 and that measured at a depth of ~ 110 m in the mine Sos Enattos, located in a central zone of Sardinia, Italy, in the same period.

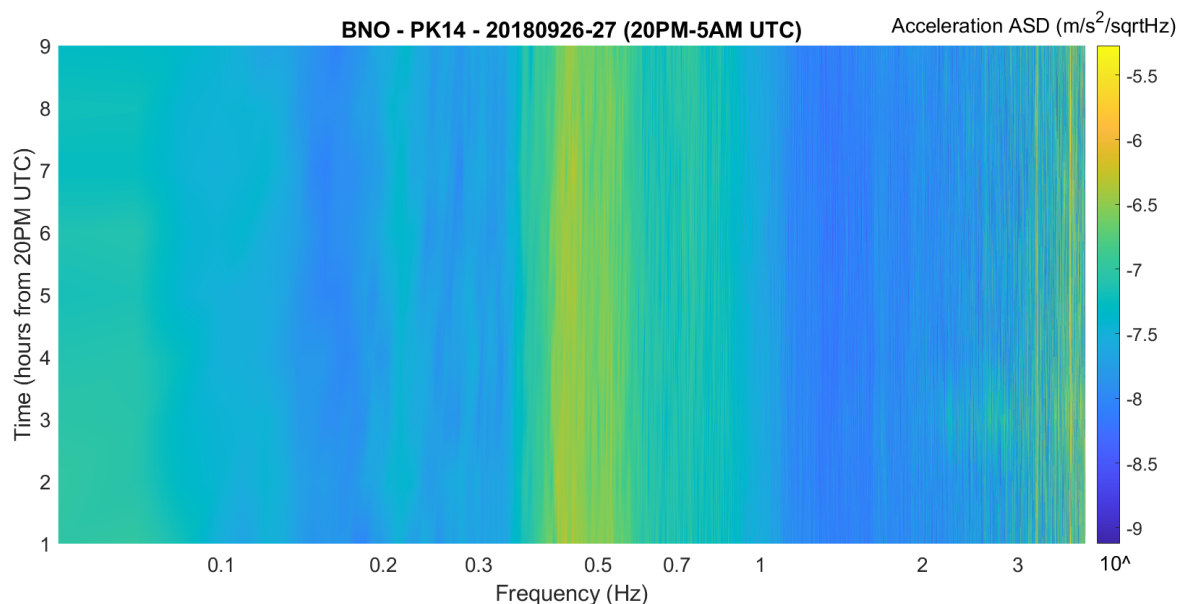


Figure 6. Acceleration spectrogram along the vertical axis measured in station PK14 at BNO in the night between the 26th and the 27th of September 2018 with the Trillium 240 seismometer.

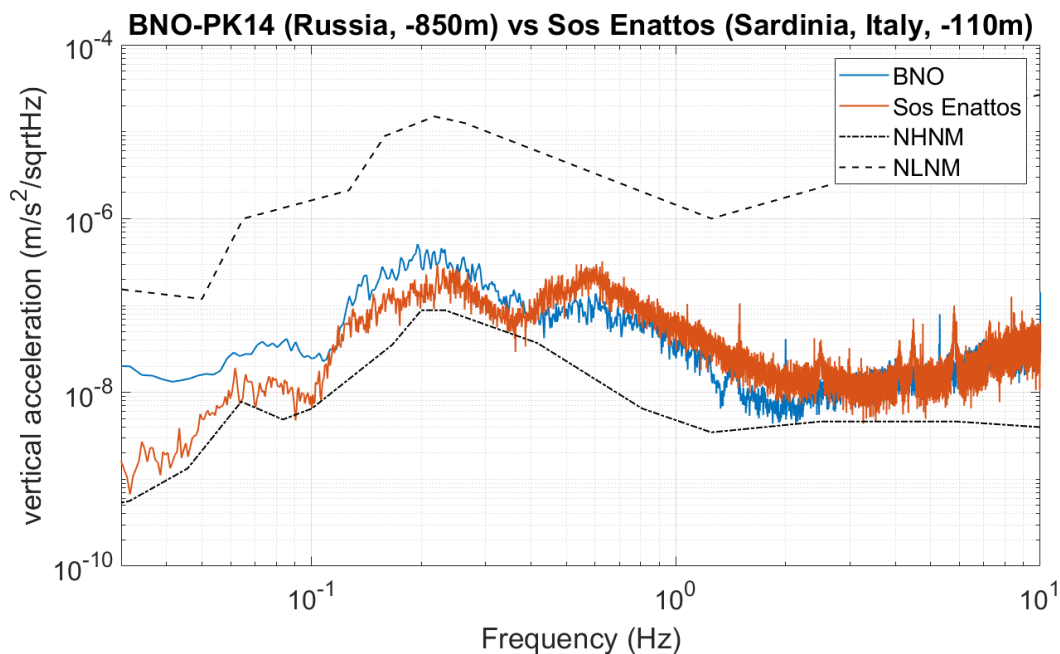


Figure 7. Comparison between amplitude spectral densities of the vertical acceleration (median) measured at BNO in the PK14 station (~ 850 m underground) and at Sos Enattos former mine in Sardinia (~ 110 m underground). Both spectra are taken during night-time.

5. Microseismic coherence across the tunnel

During the period of June 2013 we had dedicated data taking with the purpose to evidence of the existence of space coherence of the microseismic noise in the tunnel.

This data taking was relatively short (few hours) and we focused the attention just on the vertical microseismic displacement. The noise spectrum of data sampled at 100 Hz, have been analysed up to maximum frequency of 10 Hz. We note that the noise was rather stationary during the short period of data taking, and no glitches or special event have been detected.

We assumed as base reference, the PK38 station (3800 m from the main entrance of the tunnel) and the synchronisation of the data streams collected in the other two stations were corrected to the respect of the reference station.

Then, we computed the the coherence in the frequency range from 10^{-3} to 10 Hz both in the case of PK3-PK38 and of PK14-PK38. The two coherence plots in function of the frequency are shown in figure 8

It is evident from the two plots that the coherence is significant in the frequency range 0.2 – 0.4 Hz, the region dominated by the microseismic peak. In other frequency intervals the correlation is weak or absent.

Similar result has been obtained using data collected in 2018. We monitored still the vertical microseismic displacement using synchronised data of two SM3 sensors located at PK3 and Pk38 data. The measurement confirms the presence of a peak in the same frequency range for the cross correlation between the Pk3 and Pk8 stations.

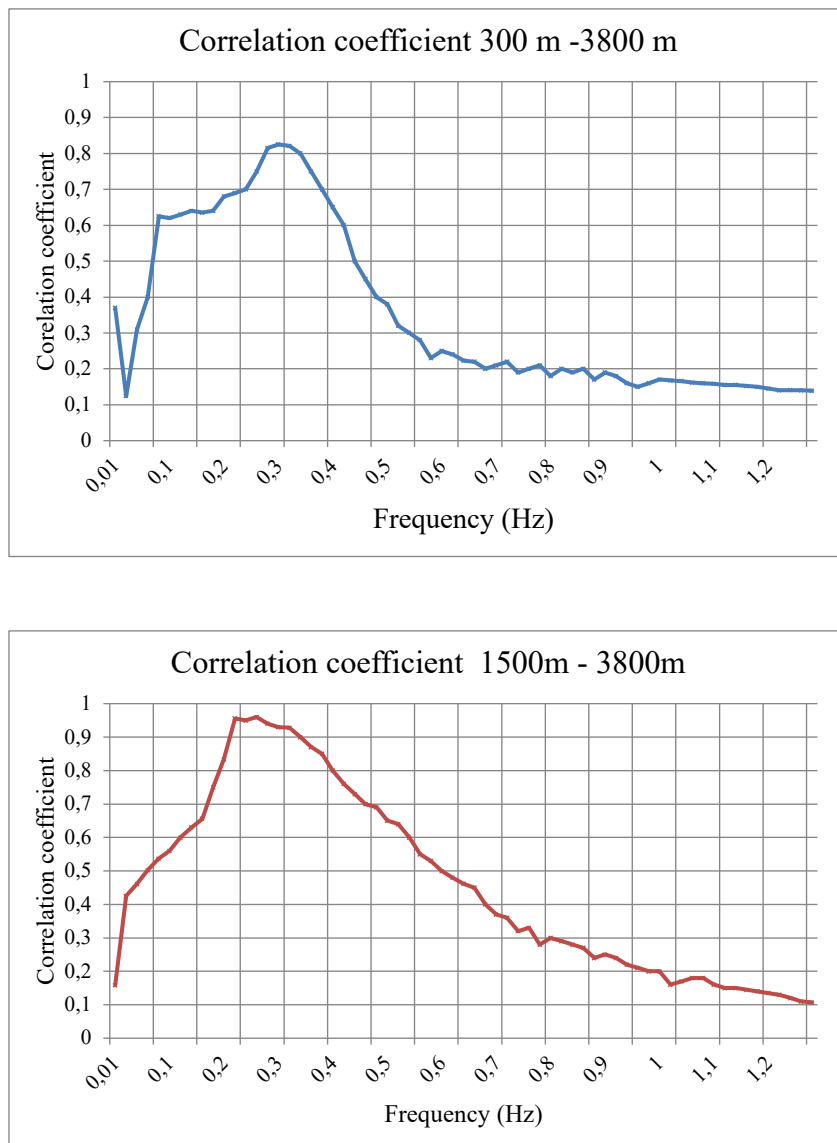


Figure 8. Microseismic correlation in function of the frequency measured between the stations Pk3- Pk38 (top view) and Pk14-Pk38 (bottom view).

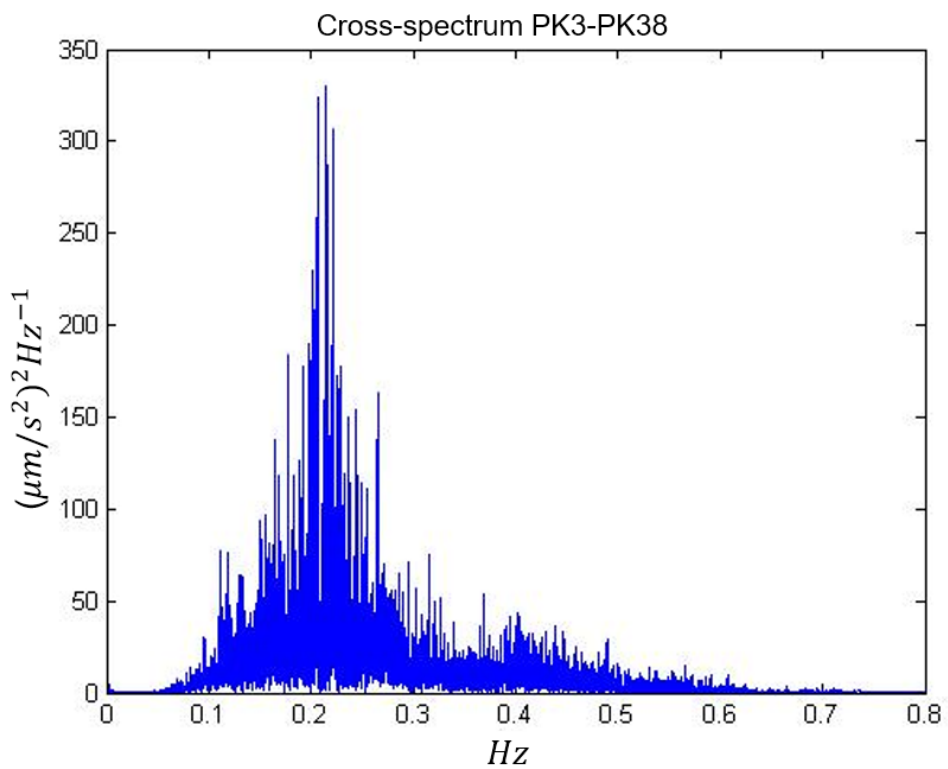


Figure 9. Cross spectrum of the data collected in 2018 between the stations Pk3-Pk38.

6. Newtonian noise evaluation

A simple estimate of correspondent spectral intensity of the Newtonian noise due to the measured seismic background can be derived using the Saulson's model [2]. According to it, we can evaluate the power spectral density (PSD) of displacements of the interferometric system, whose mirrors are suspended as pendula. The mirrors experience the action of the random Newtonian gravity field induced by seismic perturbations of the ground. We have:

$$S_{xx}^{NN}(\omega) = \frac{16\pi^2 G^2 \rho^2}{3 \omega^4} S_{xx}^{seis.}(\omega) \quad (1)$$

where $S_{xx}^{NN}(\omega)$ is the spectral density of mirror's displacement along the horizontal axis of the optical detector, produced by the stochastic Newtonian force generated by rock density variations associated with the seismic spectrum $S_{xx}^{seis.}$, ρ is the average rock density and G is the Newtonian constant.

The equation 1 expresses the bilateral displacement PSD $S_{xx}^{seism.}$, meanwhile we measured the unilateral acceleration PSD $2S_{aa}^{seis.}$. Assuming the linear harmonic approximation, $S_{xx}^{seis.} = S_{aa}^{seis.}/\omega^4$, we end up with the following expression valid for both bilateral PSDs:

$$S_{xx}^{NN}(\omega) = \frac{16\pi^2 G^2 \rho^2}{3 \omega^8} S_{aa}^{seis.}(\omega) \quad (2)$$

In figure 10 we plot the limit imposed by the Newtonian noise to the strain measurement done over a length of $L = 10$ km. This limit is computed by using the formula 2 and taking into account the seismic noise spectra measured at the stations PK14 and PK38 with the Guralp CMG-3T/ESPC seismometer.

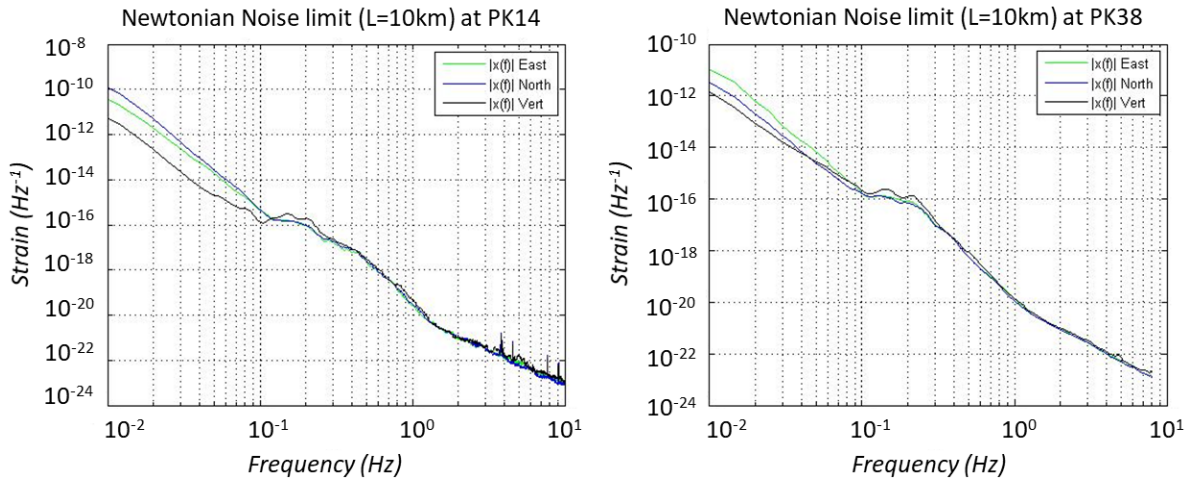


Figure 10. Sensitivity limits on strain measurements carried on a length of $L = 10$ km assuming the seismic noise spectrum measured at PK14 (850m underground) and PK38 (2130m underground).

7. Discussion and conclusion

We have presented the experimental results of our campaign on seismic measurements carried on in the Baksan neutrino Observatory. The two series of measurements taken at a distance of 5 years show similar PDS behavior. The spectra reported in figure 4 show clearly that the deeper location (PK34 station) is more quiet above 1 Hz, the frequency range interesting for the site qualification of a 3G-GW detector. We notice also that microseismic spectrum of the Baksan above $3Hz$ overlaps the Sos Enattos (Sardina) spectrum, while between $3 - 1 Hz$ the difference is mainly due to the attenuation effect associated to the deepness of the two locations. Down to 1 Hz the spectrum is affected by the sea motion, the Caspian and Black sea for Baksan and the Tyrrhen and Mediterranean seas for Sos Enattos[3] [4]. No evidence of the dynamic effects due to magma movements of the near volcano have been detected.

In addition, we have computed the potential contribution of the Newtonian background using the microseismic data taken in the OGRAN laboratory: this limit is well below the requirements of the proposed Einstein Telescope detector.

Finally, we note that the cross spectrum of seismometers located in different positions along the tunnel shows the main peak at 0.21 Hz. The interpretation of this result is not straightforward: the correlation on the microseismic spectrum in the range $0.1 - 0.4Hz$ can be simple due to the secondary (dominant) microseismic peak produced by standing waves in the oceans, usually at $f \sim 0.2Hz$, or it may also show a resonance effect of the sound propagation in the tunnel. Future measurements with infra-sound microphones should permit to assess the correct interpretation of this result.

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