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Characterization of four italian seismic fields

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ET – Einstein gravitational wave Telescope – Design Study * A joint European Project
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Contents

Abstract

Measurements of the seismic environment in several italian sites have been carried out by using a triaxial seismometer Trillium 240. The sites of Virgo (Cascina, near Pisa), the Laboratori Nazionali del Gran Sasso of the italian Istituto Nazionale di Fisica Nucleare (INFN-LNGS) and a Sardinian mine (Sos Enattos) have been explored, to get an estimation of the italian seismic fields, specially underground. This project aims to investigate the possibility of the realization of a third generation gravitational waves interferometer, like the Einstein Telescope, in an underground location, where the seismic and the newtonian noise are known to be lower compared to the surface. Seismic data from these sites have been analyzed and are shown here, together with a discussion about the noise level in other european locations.

1 Introduction

Current gravitational waves (GW) detectors are limited, in the low frequency range, by the seismic noise that enters in the detector sensitivity both through the seismic filter chain used to suspend the main optics of the interferometer and by direct gravitational coupling of the vibrating soil with the suspended masses, the so-called newtonian noise or gravity gradient noise.

Third generation detectors, such as the Einstein Telescope (ET) [1], will be designed with enhanced sensitivity below 10Hz: is thus fundamental to reduce both the seismic and the newtonian noise below this frequency. A possible solution, to improve the sensitivity of future generation GW detectors at such low frequencies, is to build an underground interferometer: the reduced seismic activity and the uniformity of the rock are expected to play a dominant role in the reduction of both the seismic and the gravity gradient noise.

Developing an underground GW detector would be beneficial for several reasons. First of all the natural improvement due to the exponential reduction of the seismic noise mainly due to the surface Rayleigh waves, which is proportional to $e^{-4d/\lambda}$ where d is the depth and λ the wavelength. Additionally, the atmospheric fluctuations would have negligible effects on the gravitational field deep underground and the air pressure and temperature variations could be reliably stabilized. Finally, the human-induced gravitational fluctuations are much more controllable underground. In this sense the newtonian noise, which estimation is based on seismic measurements, could be better monitored and subtracted from the GW data.

The first target of ET is the identification of an underground site with a lower seismic and newtonian noise. The definition of the site requirements and the proposition of possible locations in Europe, having satisfactory specifications, is the motivation of this work.

In this paper, we present a characterization of local seismic noise of three italian sites: the Virgo site in Cascina (Pisa) [2], the Laboratori Nazionali del Gran Sasso [3] of the italian National Institute of Nuclear Physics (INFN, near L'Aquila) and finally an underground location in Sardinia, the former mine of "Sos Enattos", Lula, Nuoro.

For completeness, we present also the analysis based on data collected at the Department of Physics of the University "Sapienza" of Rome, which is useful to show the impact of the human activity on high frequencies seismic data.

In section 2 we will show the experimental setup and features of our instrument, installation procedures and sites selection. In section 3 we will see the data analysis method, while in section 4 the results will be shown. Finally, in section 5, the conclusions will be presented.

2 Experimental setup

A symmetric triaxial seismometer, Trillium 240, has been used to collect seismic data. Trillium 240 has a response flat to velocity from 240 seconds to 35 Hz and a self-noise below the New Low Noise Model (NLNM) [4], [5] from 100 seconds to 10 Hz. The feedback mechanism is based on a force balance with capacitive displacement transducer; the automatic mechanical mass re-centering, together with a leveling integrated bubble and adjustable locking feet, allows to obtain a perfect alignment. The seismometer sensitivity is $1200 V/m/s$ nominal ±0.5% precision, and the velocity output is $40V$ peak-to-peak differential. The data acquisition system is a Taurus seismograph, fig.1, with a 24-bit resolution digitizer, a selectable input voltage range and a nominal sensitivity of $1 count/\mu V$ at hardware gain=1. With an input voltage range of $16V$ peak-to-peak, the total system sensitivity (Trillium 240 plus Taurus) is given by $S_{sens} = 1.196 \cdot 10^9 count/m/s$. Two acquisition modes can be selected, XYZ or UVW. They correspond to data taken in different reference systems, one related to the other by a rotation matrix: UVW are the index of the normal mode coordinates of the three masses inside the seismometer, XYZ are the coordinate system referred to the external metallic frame containing the triaxial sensor.

Figure 1: The Taurus acquisition system, remotely controllable, is connected to a $12V$ *battery and to the Trillium seismometer.*

At the data output a digital filter of 140dB attenuation is applied so that the whole system is characterized by a dynamic range $> 141dB$ at $100Hz$. The Taurus and the Trillium are connected with a $10m$ long cable, and powered by using a $12V$ battery of $100Ah$.

In all the locations where we collected data, the Trillium was installed either on solid and flat concrete platforms directly connected to the ground as in fig.2, or on a granite tile attached to the ground as well, through a mixture of concrete and sand as in fig.3.

An insulating cover was used to provide thermal insulation and protection from external air currents, fig.4. In addition to this, a rigid box made of wood and polystyrene was placed on the top of the instrument, to prevent acoustic disturbances. The temperature inside this rigid box has always been checked using a platinum thermometer: no significant daily variations have been found in the selected sites.

The seismometer was aligned in the NS direction using a compass and the sites plan. Data were acquired in UVW mode.

At the Virgo site the Trillium was installed at the 1500 West-hall in a 2 meter deep pool, directly connected to the ground.
At the INFN-LNGS site we set up the Trillium on the already existing concrete platform of one of the small rooms dedicated to the INFN experiment ERMES, out of the large caverns available for underground experiments and isolated from the daily laboratory activities.
In the mine of "Sos Enattos", Lula (Nu), instead, we used our granite tile, and the final location chosen was about 200 meters deep.

At the end of each installation procedure we had to wait a few days in order to collect data with a low background noise. This is due to an internal relaxation process affecting the instrument: we show in fig.5 the three components of the ground velocity (NS, WE and vertical) collected during the three days following the installation (the spike at $1.5 \cdot 10^5 sec$ was caused by an operator moving around the instrument in the installation room).

Figure 2: The Trillium 240 simply placed on a concrete platform, aligned by using a compass.

3 Analysis method

The seismic spectra that we present in this section are based on several days of acquisition, with data sampled at 40 Hz. This value has been chosen to be compatible with the corner frequency of the seismometer, after checking that no aliasing effect was present in our data.
For each of the three components (NS,WE and Vertical) we computed the signal power spectral density (PSD) over 3 days of continuous observation, using the fast fourier transform (FFT) in the Matlab environment. The final plots are obtained from the average of spectra calculated every $\sim$ 30 min, corresponding to a number of 65536 (2^n multiple) points per spectrum, after subtracting, from each of the data streams, the mean value of the time series data. To calculate the power spectral density of the signal, in order to get an accurate evaluation of the peak frequency presents in the PSD, we filtered the data using a Hann window function. This allows also a good estimation of the background noise. Moreover, since we are interested in the evaluation of the quasi stationary local seismic noise, in order to avoid the spectral effect of accidental signals mainly caused by

Figure 3: A granite tile is attached and leveled on the ground through a mixture of concrete and sand. After the concrete hardening the seismometer is placed on it.

Figure 4: The insulating cover includes a foam base gasket and a rigid form-fitting cover with form features matched to the Trillium 240.

human activity and small earthquake events, we calculated the residual of each spectrum from the average one, following eq. (1). The index i represents the single data point of the $j-th$ spectrum, so that the sum over the total number of data, N, gives an estimation of the deviation of every spectrum from the mean one in the whole frequency range.

$$Res_j = \sum_{i=1}^{N} \frac{1}{N} (\frac{PSD_i - PSDmean_i}{PSDmean_i})^2; \tag{1}$$

We did this analysis for all the $j-th$ spectra during the 3 quietest days over the entire acquisition period, studying the statistic of these residual quantities and in particular looking at the median and standard deviation of the empirical distribution. On the base of this study, we set a rejection threshold for those spectra with a residual value greater than the distribution median $+1\sigma$. We repeated this procedure twice, to get a better estimation of the seismic field in the four different locations. Typically, the amount of the neglected data was of the order of 5%. In the next section we will show in detail the experimental results, comparing the PSD of each site with the ET-B seismic noise requirements [6].

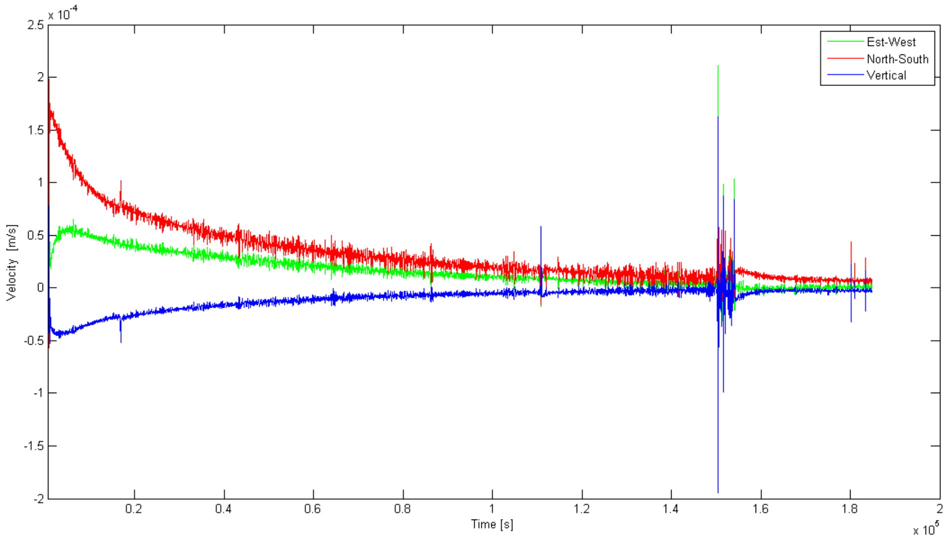

Figure 5: The relaxation of the three axis of the seismometer over 3 days.

4 Experimental results

4.1 "Sos Enattos" mine

The "Sos Enattos" mine, Lula (Nu), Sardinia, it's a former mine of schist rocks composed of sphalerite ([Zn,Fe]S) and galena (PbS). The map of the mine is shown in fig.6, where the yellow circle indicates the experimental area where we carried on our measurements. The area is located 206 meters above the sea level, while the top of the mountain is 395 meters high: in this scenario our seismometer was placed 189 meters in depth, underground with respect to the mountain. We collect data for several days, and we report here the most significant plots, obtained by applying the analysis method described in the previous section.

In fig.7 and fig.8 the acceleration PSD of 3 days of data, between July the 2^{nd} and the 4^{th}, and the spectrogram of the NS component are shown respectively. In fig.8, below 0.1Hz, some minor spikes are visible: they were mainly originated by a magnetic pick-up effect associated to the peculiar grounding configuration adopted in the first site. There we connected the ground of our instrumentation to a large steel infrastructure of the mine cavern, which acts as a pick coil of the electric signal sent every 2 hours to check the fire alarm sensors distributed all along the mine. Those spikes have been removed before performing the spectral analysis.

Setting the instrument in another location, it was possible to connect the ground of the acquisition system to that of the main electric power line of the mine. The above mentioned spikes disappeared, making thus possible a better exploration of the frequency range below 0.1Hz. In fact, we moved the instrument at 218 meters above the sea level, i.e. 177 meters underground, and we repeated the analysis between the 7^{th} and the 9^{th} of July, as in fig.9. The spectrogram of fig.10 refers to the NS axis over 1 day of data acquisition.

Let's now describe the frequency content of these PSDs. As expected, a number of peaks are present and the oceanic microseism is inferred as the source of this seismic wavefield in the low frequency range, below 1Hz.

The peak below 0.1Hz, which is visible in fig.9, is known to be the primary microseismic peak: it is caused by ocean waves exerting pressure on the ground in shallow waters near the coast. The second peak, usually found above 0.1Hz, visible in both fig.7 and fig.9, is the secondary microseismic peak, related to the oscillations due to standing waves that can propagate all the way down to the ocean bottom.

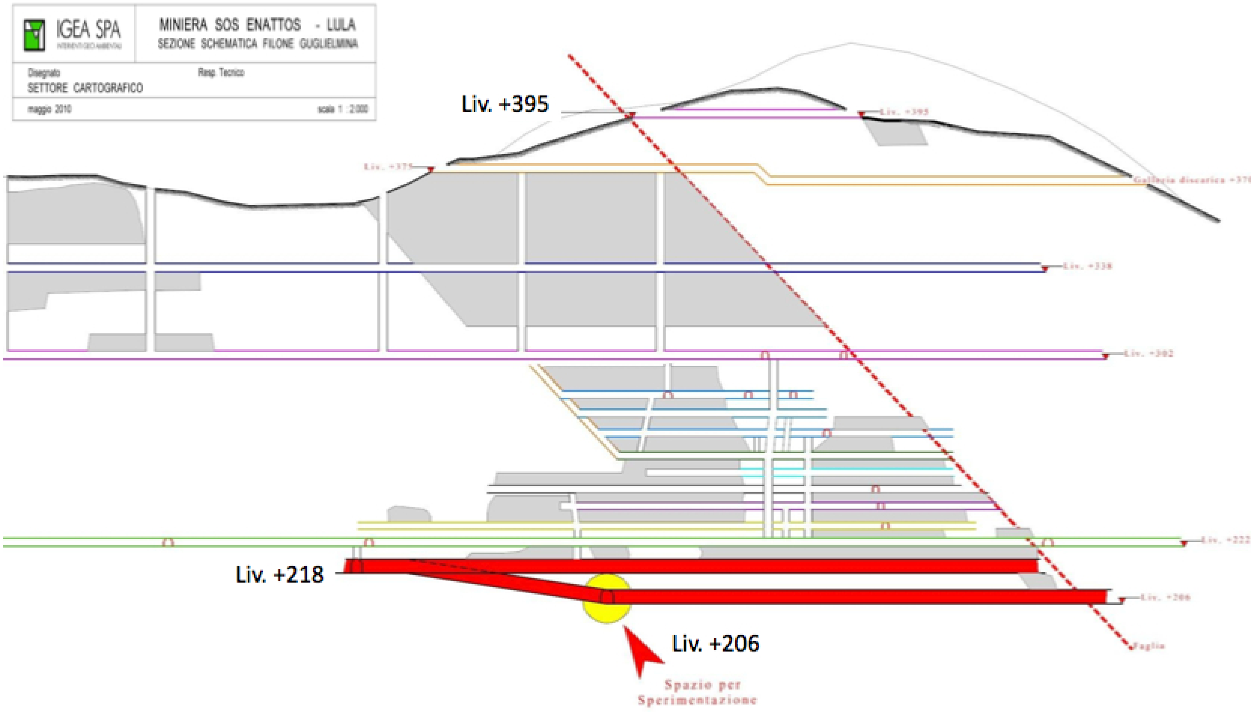

Figure 6: Schematic of the "Sos Enattos" mine. The experimental area used between July the 2^{nd} and the 4^{th} is indicated in yellow, while the site used from the 7^{th} to the 9^{th} corresponds to the +218 sign.

It is interesting to note that this last peak it has always been found at a frequency of ~ 0.2 Hz, both in European [7] and US [8] sites, while the PSDs reported here suggest a more complicated pattern between 0.1 and 0.9 Hz. The peak at 0.2 Hz is still visible in fig.7, together with 2 other peaks at ~ 0.4 and ~ 0.6 Hz, while in the PSD of fig.9 the shape and the frequency of these peaks have changed. The height of the peaks at 0.2 Hz varies between $4 \cdot 10^{-14}$ and $8 \cdot 10^{-14} (m^2/s^4)/Hz$.

As we will see in the next sections, this particular behavior of the seismic field below 1 Hz is a peculiarity of the Italian region, being present in all the studied sites. This common characteristic is probably due to the superposition of the effects coming both from the oceanic waves and the mediterranean ones. A deep understanding of this dynamic, however, is still missing [9].

At the PSD frequencies above 1 Hz we observe a very low seismic signal, almost as low as the NLNM. This is what we expected to find, since the anthropic activity, which is the main source of noise above 1 Hz, is reduced underground. The time variability of the PSD value at fixed frequencies is shown in fig.13, where the constant height of the PSD at 5 Hz underlines the quiet environment of the mine, which is not affected from cultural noise. The small variation of the two microseismic peaks at 0.2 and 0.4 Hz seems to be due to the local seismic activity: this is particularly evident for the peak at 0.2 Hz, whose maximum values at ~ 7 and ~ 33 hours can be easily related to the earthquakes occurred at the same time as in the spectrogram of fig.8.
We also think, following the work of [9], that the spectral amplitude in the $0.2-1$ Hz frequency range could be influenced by the swell activity of the nearby sea. This last point is still under investigation.

The "Sos Enattos" mine is found to be an exceptional low seismic noise environment, satisfying the ET-B requirement [6] of seismic background for frequencies > 2Hz, as in fig.11 and fig.12. The deepest points of these plots show a PSD which is 3 order of magnitude lower than the ET requirement.

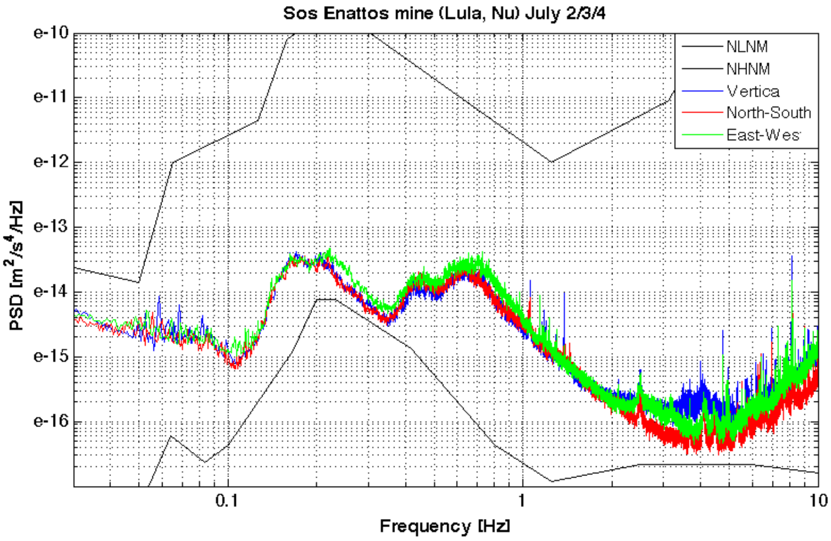

Figure 7: Acceleration power spectral density over 3 days of data acquisition, July 2^{nd} *to* 4^{th}*.The high and low noise models are shown as well.The seismometer was placed* 189 *meters underground.*

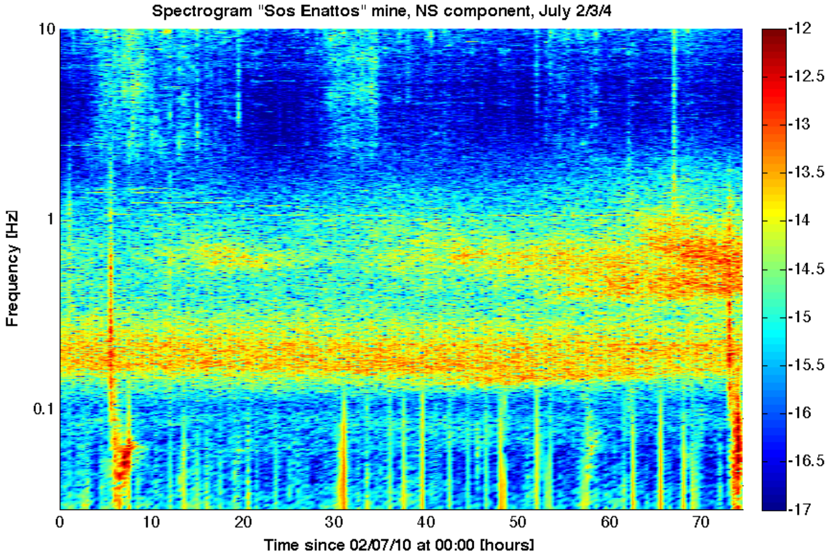

Figure 8: Spectrogram over 3 days of data acquisition of the NS component. The PSD height corresponds to the z scale. The disturbing spikes below 1 *Hz are clearly visible.*

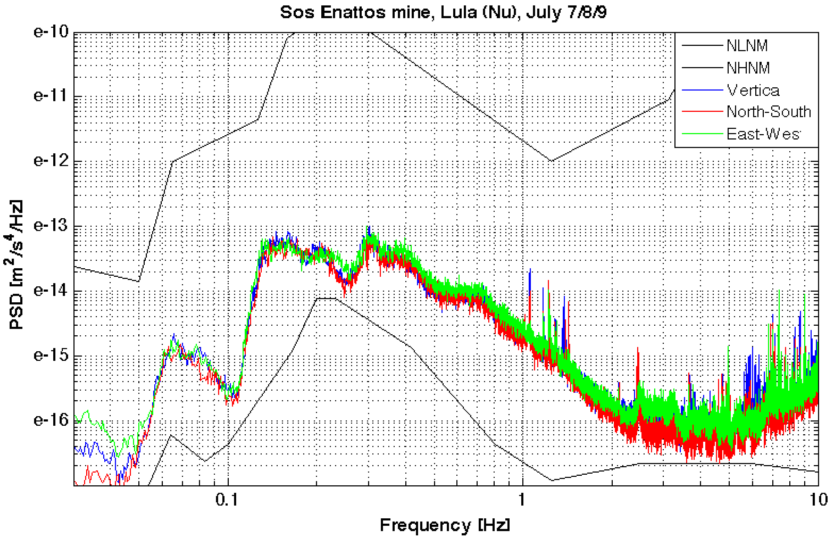

Figure 9: Acceleration power spectral density over 3 days of data acquisition, July 7th *to* 9th*.The high and low noise models are shown as well.The seismometer was placed* 177 *meters underground.*

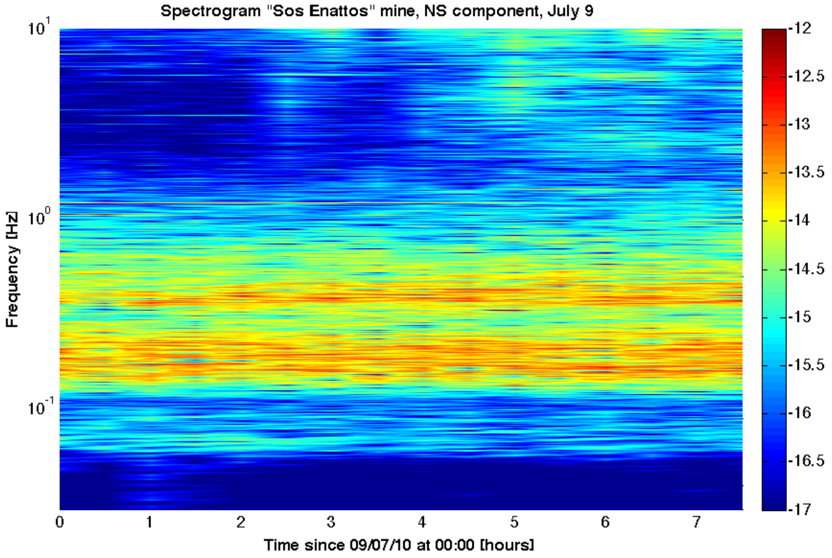

Figure 10: Spectrogram over 1 day of data acquisition of the NS component. The PSD height is indicated in the z scale.

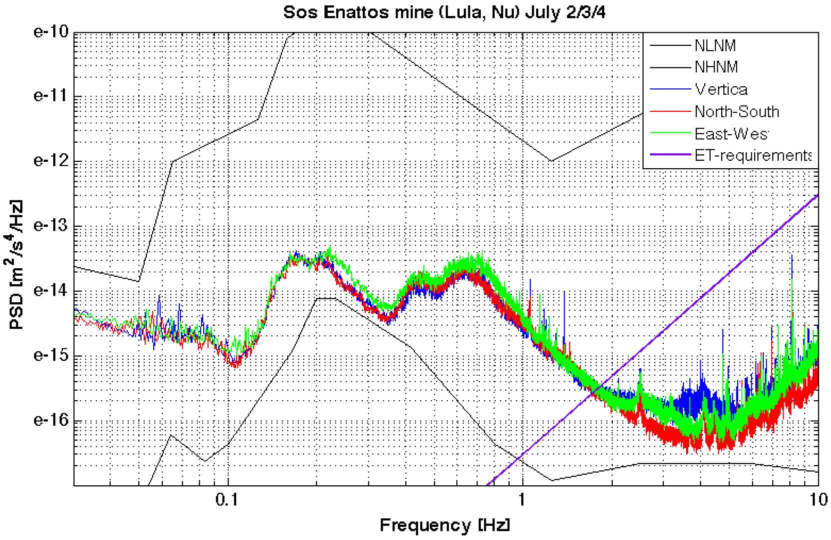

Figure 11: Acceleration PSD of the seismic field at the "Sos Enattos" mine, July 2^{nd} to 4^{th}, 189 meters of depth. The violet line is the ET-B requirement for the seismic noise.

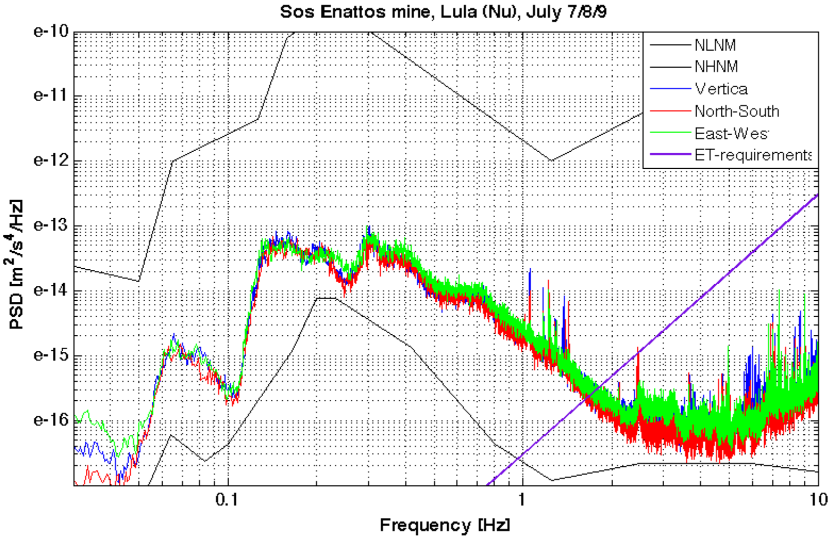

Figure 12: Acceleration PSD of the seismic field at the "Sos Enattos" mine, July 7^{nd} to 9^{th}, 177 meters of depth. The violet line is the ET-B requirement for the seismic noise.

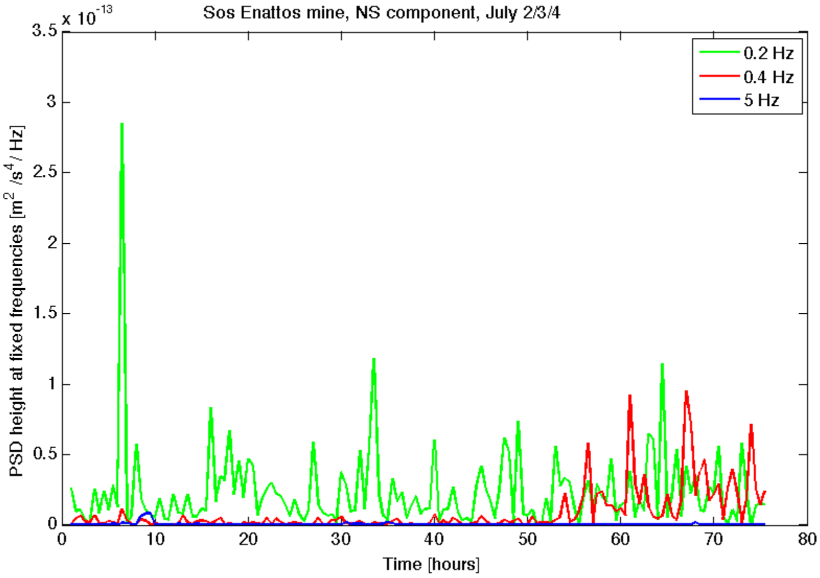

Figure 13: Variation of the PSD height of the NS component, over 3 *days of acquisition, at the "Sos Enattos" mine. The studied frequencies are* 0.2, 0.4 *and* 5 *Hz.*

4.2 INFN - Laboratori Nazionali del Gan Sasso

We took measurements and repeated the same analysis by installing the seismometer at the INFN-LNGS site, fig.14, which is located 1400 meters deep, near the city of L'Aquila in the middle of central Italy's largest massif, in the very heart of Gran Sasso's National Park within a large water-table.

The next plots show data collected during the days of May 27^{th} to 29^{th} and June 1^{st} to 3^{d}, to characterize the variability of the local seismic field.

An higher background seismic noise, with respect to the sardinian site, is visible in fig.15 and fig.17: at the characteristic frequency of 2 Hz the average value of the background changes from 10^{-16} to $10^{-15}(m^2/s^4)/Hz$, at the "Sos Enattos" mine and LNGS site respectively. This higher background noise above 1Hz is due to the highway traffic near the laboratory.

The two microseismic peaks, found at 0.2 and 0.4Hz, change their shape with respect to those of the "Sos Enattos" mine. The height of these peaks varies a little bit over different days of data acquisition, while their frequencies remain the same over the time. Such variability is evident in the spectrograms of fig.16 and fig.18. This effect could be related to the ground water level changing according to the rain rate. We noticed also few large spikes over the three days of acquisition, some of them due to small earthquakes, some others due to local anthropogenic activity: we vetoed those data when doing the average of the spectra.

As we did in the previous section, the PSD value at fixed frequencies has been monitored over 3 days of acquisition, for the NS component. In fig.21 it is easy to note that both at low and high frequencies the time variation of the PSD is higher than in the "Sos Enattos" mine. This is specially true for the 5 Hz frequency, at which the atrophic activity plays a relevant role, and for the peak at 0.4 Hz, whose variation probably depend from the site response to geological activity and weather conditions.

Comparing the PSDs found at the LNGS with the ET requirement, we conclude that it is satisfied above $3-4$Hz, as it is shown in fig.19 and fig.20.

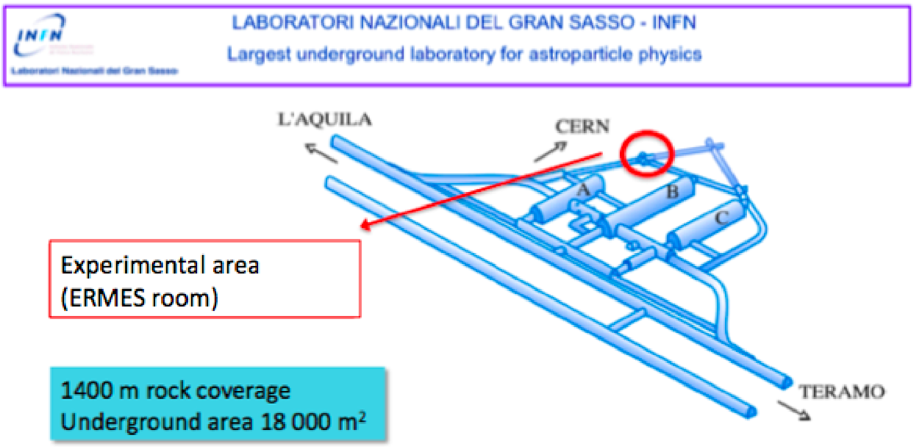

Figure 14: Map of the Laboratori Nazionali del Gran Sasso, Aq. The red circle indicates the instrument location.

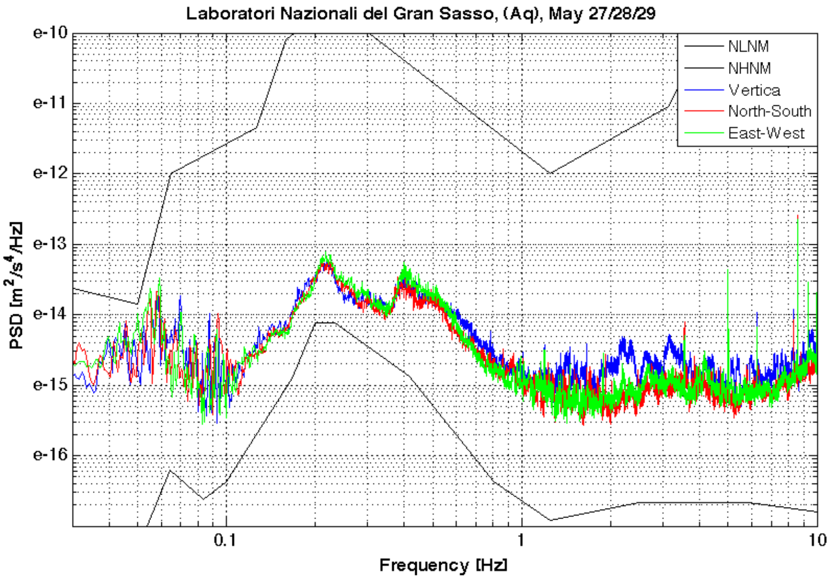

Figure 15: Acceleration power spectral density over 3 days of data acquisition, May 27*th* *to* 29*th*. *The high and low noise models are shown as well. The seismometer was placed* 1400 *meters underground.*

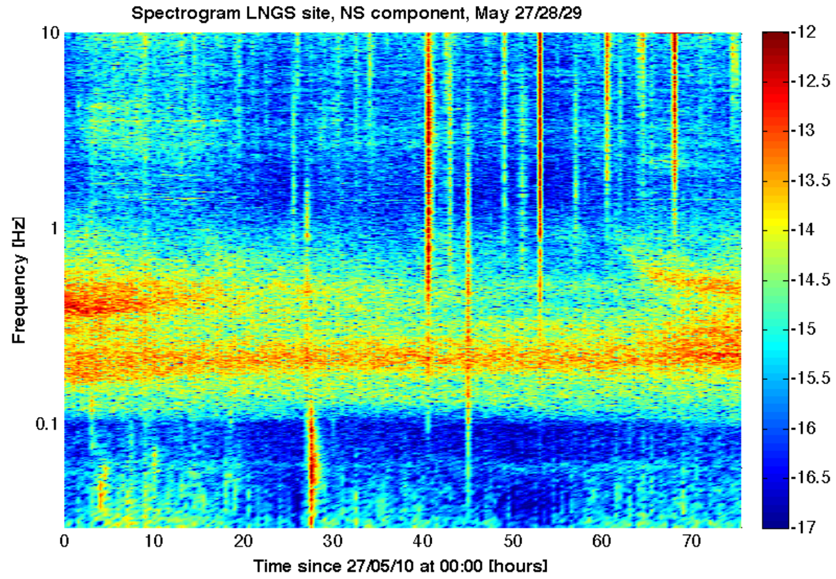

Figure 16: Spectrogram over 3 days of data acquisition of the NS component. The PSD height is indicated in the z scale.

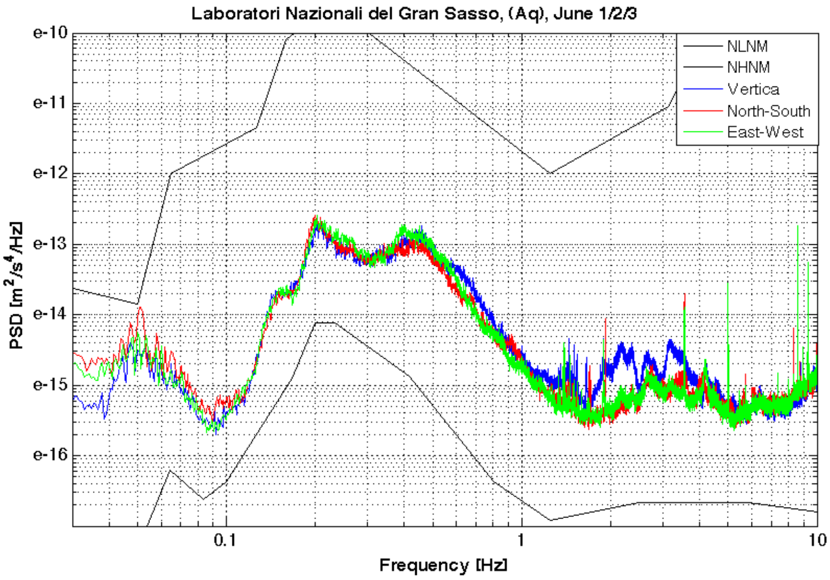

Figure 17: Acceleration power spectral density over 3 days of data acquisition, June 1^{st} *to* 3^{d} *.The high and low noise models are shown as well.The seismometer was placed* 1400 *meters underground.*

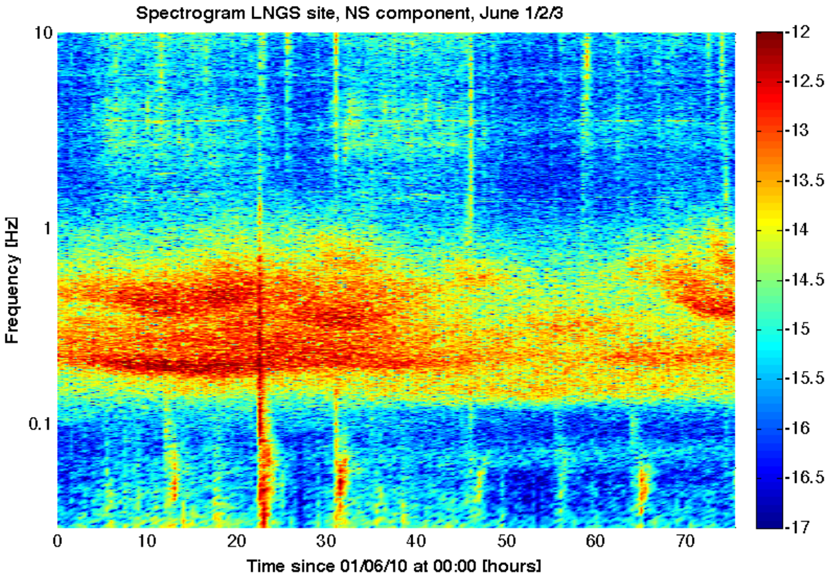

Figure 18: Spectrogram over 3 days of data acquisition of the NS component. The PSD height is indicated in the z scale.

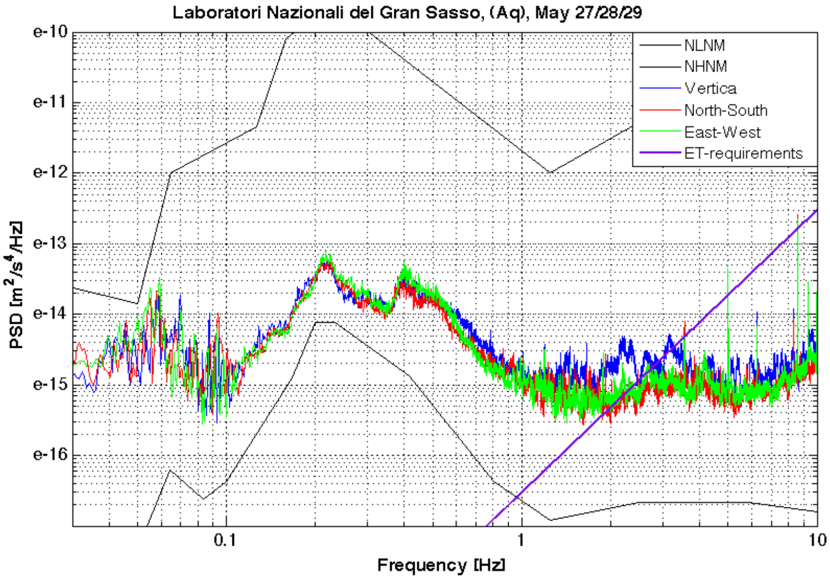

Figure 19: Acceleration power spectral density over 3 days of data acquisition, May 27th to 29th. The violet line is the ET-B requirement for the seismic noise.

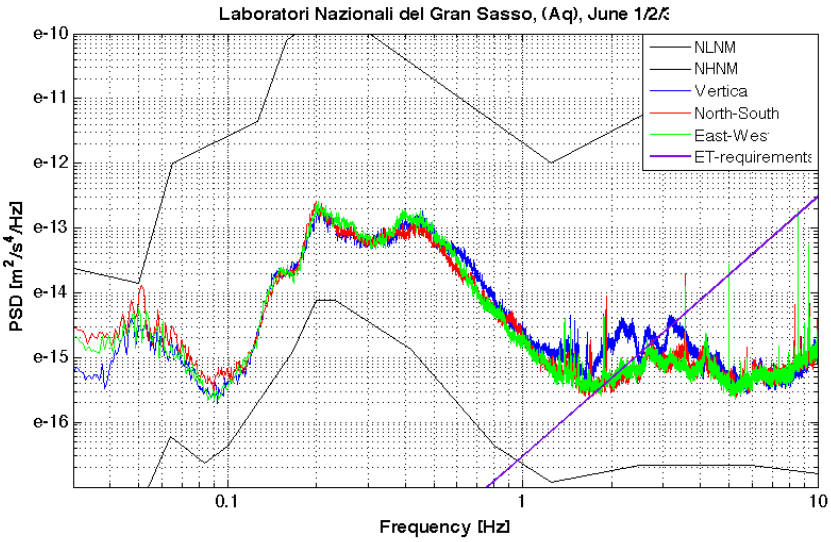

Figure 20: Acceleration power spectral density over 3 days of data acquisition, June 1^{st} *to* 3^{d}*.The violet line is the ET-B requirement for the seismic noise.*

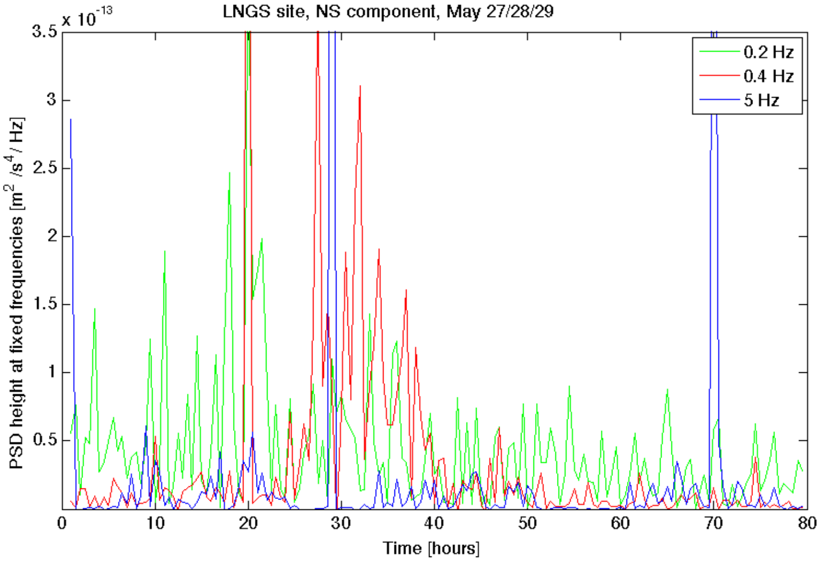

Figure 21: Variation of the PSD height of the NS component, over 3 *days of acquisition, at the LNGS site. The studied frequencies are* 0.2, 0.4 *and* 5 *Hz.*

4.3 Virgo site

In this section we present the results of the seismic activity monitored at the site of the European Gravitational Observatory, in the territory of Cascina (near Pisa), where the Virgo GW detector is located, far from the center of the village.
Virgo is a Michelson interferometer with perpendicular arms 3 km long (West and North direction). At the middle way of the two arms there are experimental halls dedicated to the research and development activity and as storage area of the spare parts of Virgo.

The seismometer has been placed in the interferometer 1500 West hall, fig.22, inside a 2 meters deep pool well anchored to the ground. As expected, the human activity plays a dominant role in the PSD at frequencies higher than 1Hz. The microseismic peaks, visible in fig.23 and fig.25 between 0.2 and 0.8Hz, are not constant in time, having a complex behavior possibly related to the waves activity in the Tyrrhenian sea and to the geology of the site. This pattern has been already observed in previous works [9], [10].
It is evident that the peaks below 1 Hz have heights, frequencies and shapes totally different compared to the ”Sos Enattos” mine and the LNGS laboratory.

The spectrograms of the two data sets are shown in fig.24 and fig.26. As usual, we removed the data corresponding to the microearthquakes before computing the PSDs of fig.23 and fig.25.

The time variation of the PSD values at fixed frequencies, over 3 days of continuous acquisition, is shown in fig.27: as expected this variability is higher than in any other site, being Virgo located on the surface. Please note that in all the studied locations the height of the microseismic peak at 0.2 Hz is always the stablest in time, independently from the underground or surface location of the site.

To summarize, the PSD of the Virgo site is compatible with the one already measured in [9] and [10]. Obviously, the noise at the surface location of the Virgo detector is not compatible at all with the ET requirement.

Figure 22: Air view of the Virgo site, Cascina.

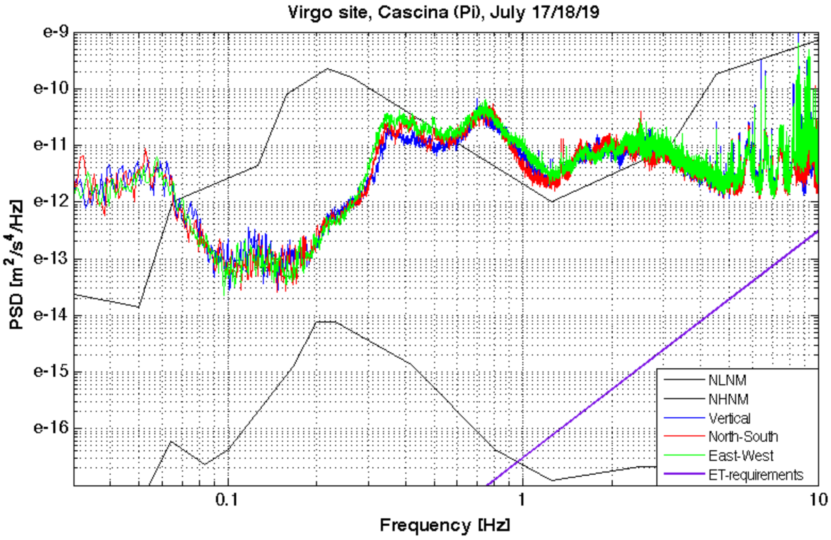

Figure 23: Acceleration power spectral density over 3 days of data acquisition, July 17th to 19th, Virgo site, Cascina. The violet line is the ET-B requirement for the seismic noise.

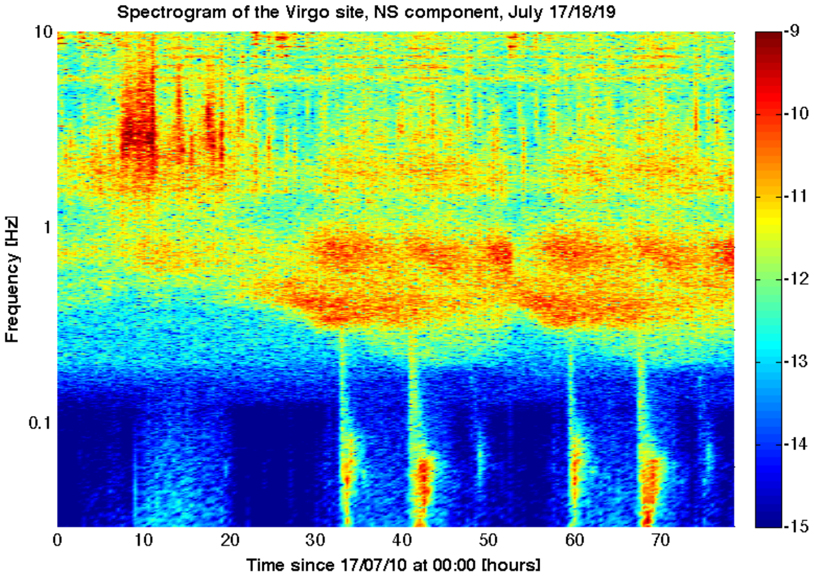

Figure 24: Spectrogram over 3 days of data acquisition of the NS component, Virgo site, Cascina. The PSD height is indicated in the z scale.

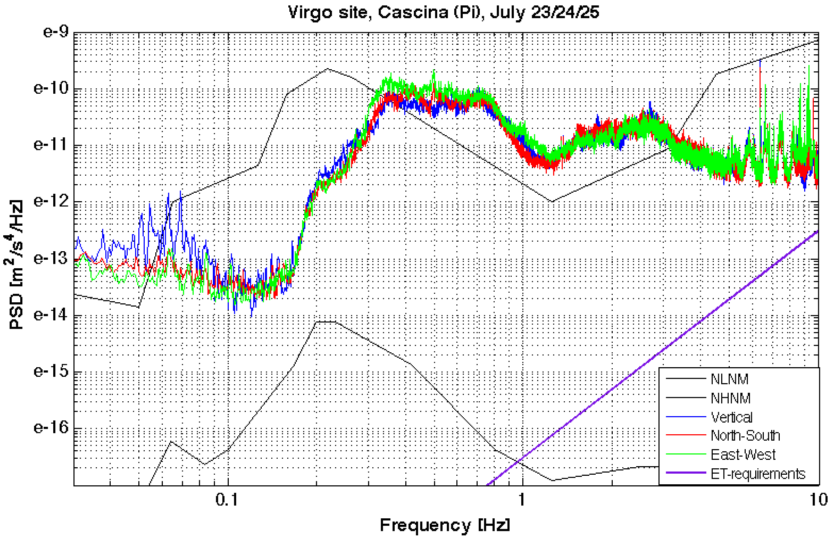

Figure 25: Acceleration power spectral density over 3 days of data acquisition, July 23^{th} *to* 25^{th}*, Virgo site, Cascina. The violet line is the ET-B requirement for the seismic noise.*

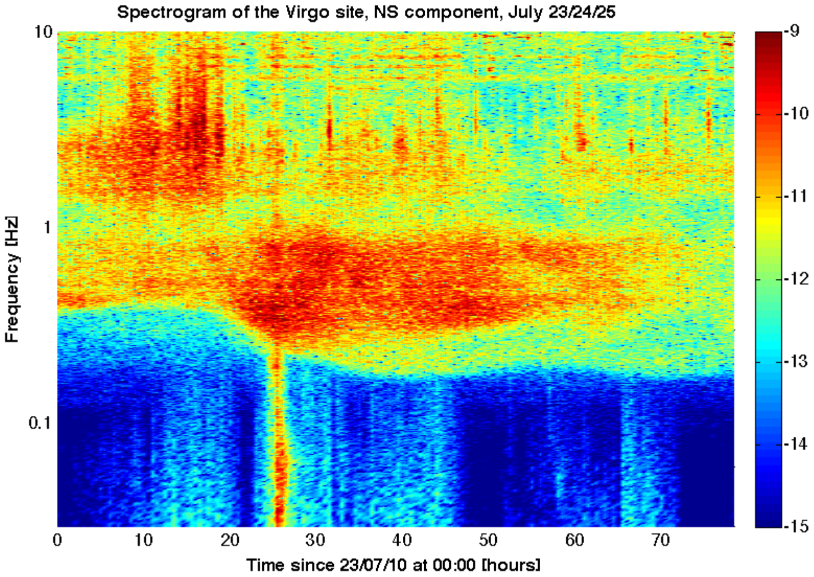

Figure 26: Spectrogram over 3 days of data acquisition of the NS component, Virgo site, Cascina. The PSD height is indicated in the z scale.

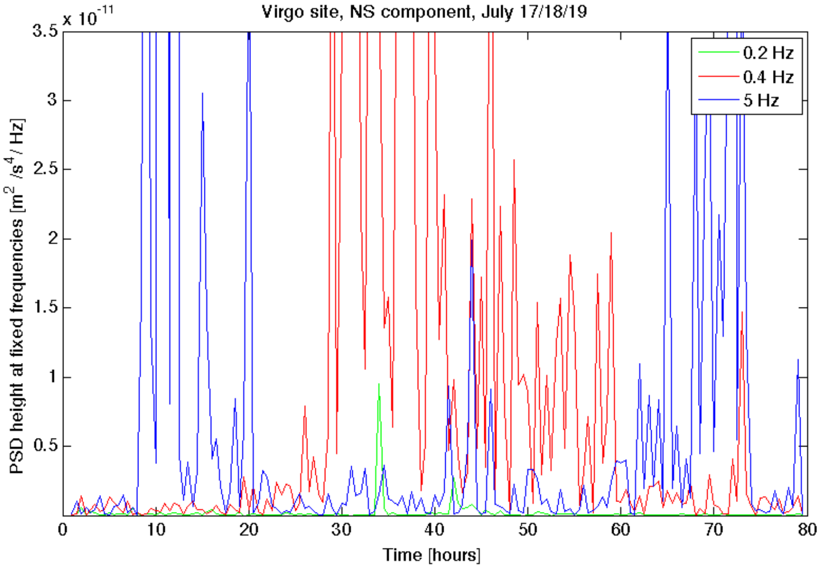

Figure 27: Variation of the PSD height of the NS component, over 3 *days of acquisition, at the Virgo site. The studied frequencies are* 0.2, 0.4 *and* 5 *Hz.*

4.4 Physics Department of the "Sapienza" University, Rome

In order to compare the quiet sites to the noisy ones in terms of seismic environment, we analyzed the seismic field of Rome by setting up the instrument in the sub-basement of the Department of Physics of the University "Sapienza". The Physics building is located in the old university campus of " Sapienza" at walking distance (∼15 minutes) from the central railway station of the italian capital.

As expected, while the microseismic peaks are still evident at 0.3 and 0.5 Hz, the contribution of the PSD at frequencies higher than 1 Hz is mainly due to the human activity and the local traffic near the University. Although we collect data during the less noisy days, i.e. during the week end, when only a few people work in proximity of the Department, the resulting PSD increases above 1 Hz, as in fig.28.[1]

The ET-B requirement has been included as well in the PSD plot: of course it is much lower than the seismic background in Rome, like at the Virgo site, since they are both surface locations. Looking at the spectrogram of fig.29 it is easy to recognize how the height of the main peak at 0.3 Hz varies with time, having an average value of $6 \cdot 10^{-12} m^2/s^4/Hz$.

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[1] The data collected at the site in Rome were sampled at 20 Hz.

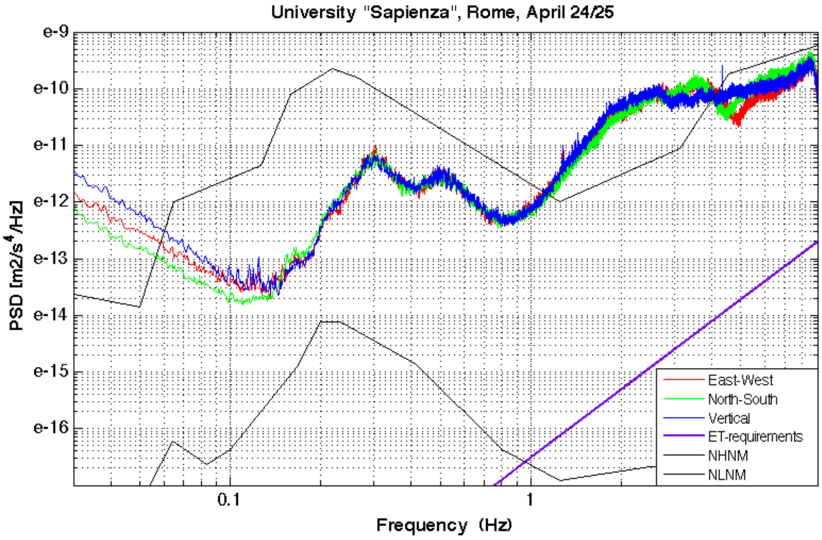

Figure 28: Acceleration power spectral density over 2 days of data acquisition, April 24th to 25th, Department of Physics, University "Sapienza", Rome. The violet line is the ET-B requirement for the seismic noise.

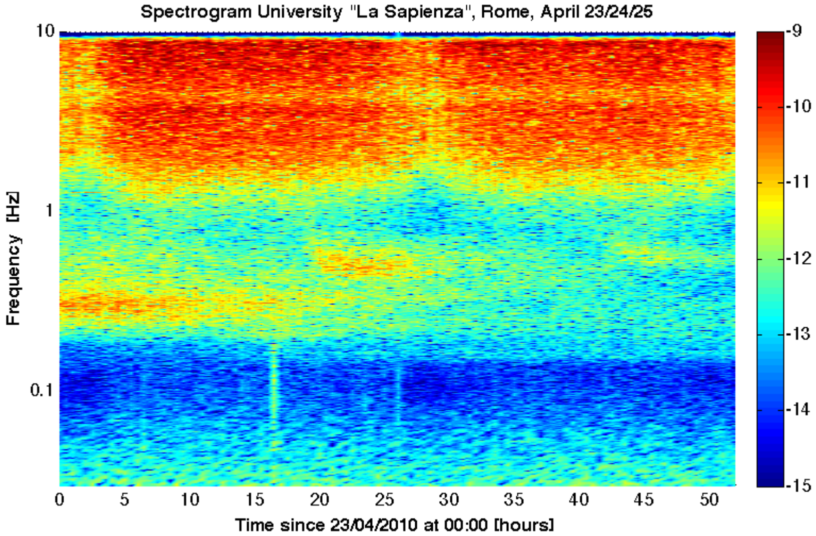

Figure 29: Spectrogram over 3 days of data acquisition of the NS component, Department of Physics, University "Sapienza", Rome. The PSD height is indicated in the z scale.

5 Concusions

We reported here the measurements of the seismic background noise in four italian sites, two of them, the ”Sos Enattos” mine and the LNGS site, being particularly interesting due to their underground location.
We performed the spectral analysis of the seismic signal and we reported the amplitude of the PSDs, over several days of acquisition, for all the sites.
Above 1 Hz the average values of the PSDs at the Virgo site and at the Department of Physics in Rome are high, as expected, being of the order of $10^{-10} - 10^{-11} (m^2/s^4)/Hz$.
Much lower values have been obtained in the Sardinian mine and at the LNGS site, about $10^{-15} - 10^{-16} (m^2/s^4)/Hz$.
The PSDs of the ”Sos Enattos” mine and the LNGS site are shown in fig.30, where the data have been smoothed in order to get an easy comparison with those of other european locations [7]. This plot refers to the NS component of the seismic signal and, as usual, to 3 days of continuous data acquisition.
The results of our work show that the 200 meters deep ”Sos Enattos” mine provides an exceptional low seismic noise environment, being inside the ET-B requirement for frequencies higher than 1.8Hz.
The comparison with the other italian sites and some european underground locations [7] still put the sardinian mine as one of the best site for the construction of a future, 3^d generation gravitational waves detector, having a PSD lower than any other site between 3 and 8Hz, i.e. above the ET-B requirement.
Moreover, in the whole frequency range, the ”Sos Enattos” mine has a lower PSD time variation with respect to the LNGS site, fig.31 and fig.32. The local seismic activity of this Sardinian mine is almost constant in time in the whole frequency range, specially at high frequencies, thanks to the absence of local cultural noise.
This feature allows to get a relatively simple model of the underground newtonian noise, which can be thus easily subtracted.

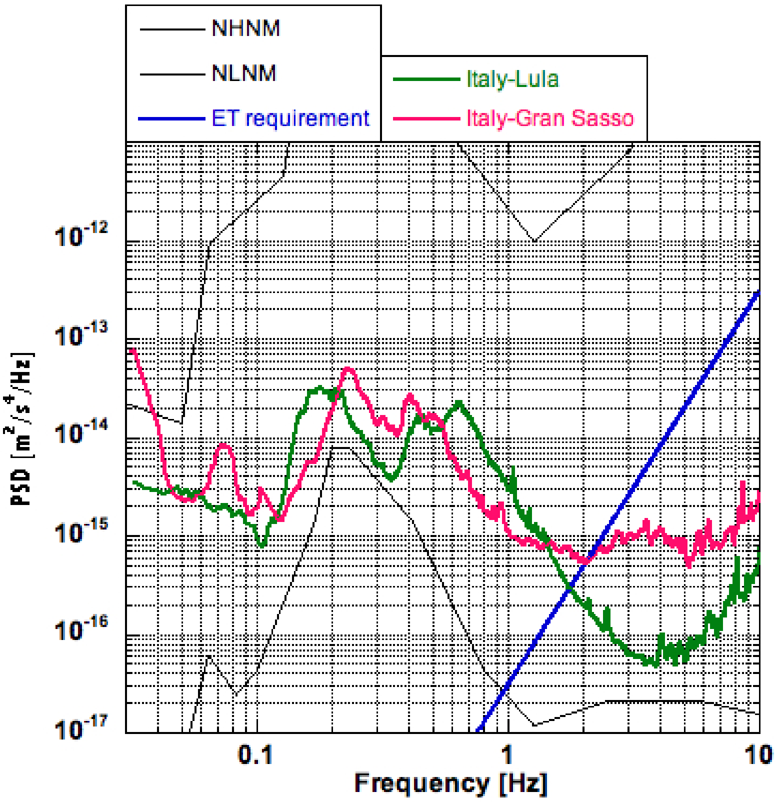

Figure 30: Comparison of the seismic field in the Sardinian mine and at the LNGS site.

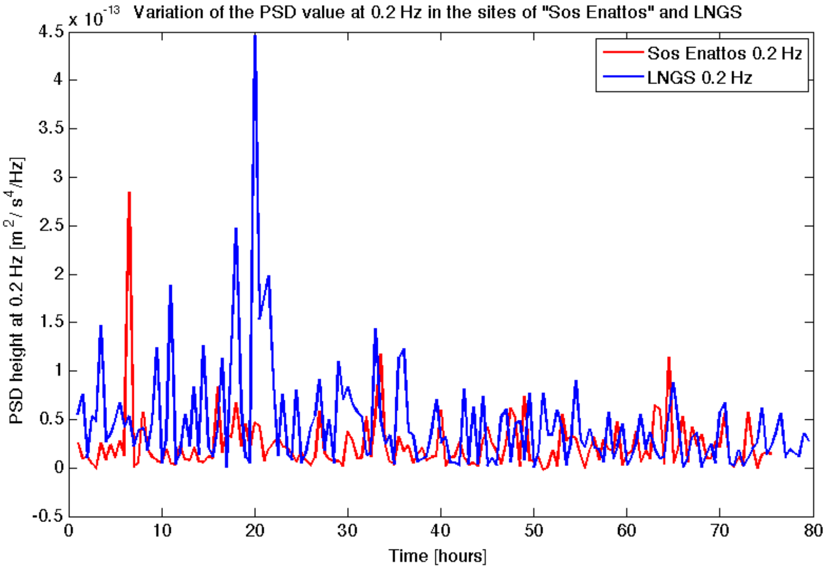

Figure 31: Height variation of the 0.2 *Hz microseismic peak, NS component. Comparison between the "Sos Enattos" mine and the LNGS site.*

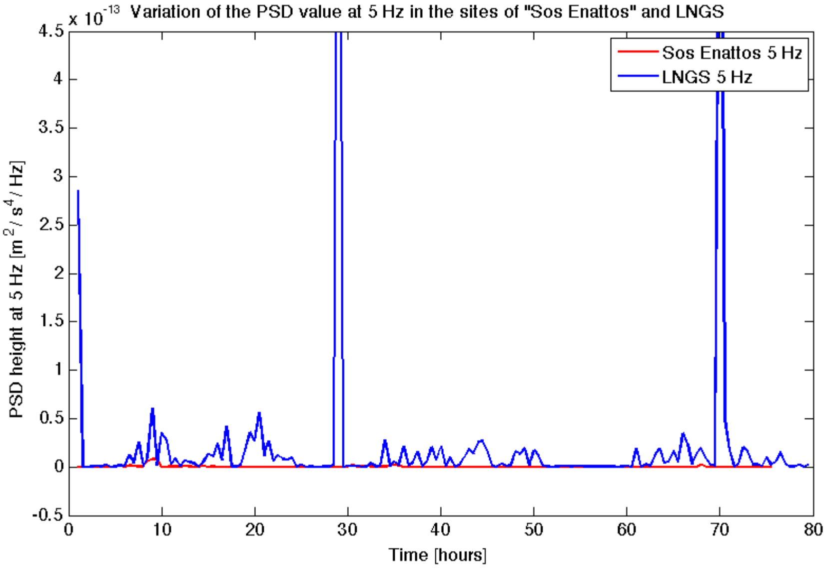

Figure 32: Height variation of the PSD at 5 *Hz, NS component. Comparison between the "Sos Enattos" mine and the LNGS site.*

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