PROCEEDINGS OF SCIENCE

Characterizing the Sardinia candidate site for the Einstein Telescope

L. Naticchioni,[1,*] A. Allocca,[3,4] V. Boschi,[5] M. Cadeddu,[7] M. Cadoni,[6,7] E. Calloni,[3,4] G. L. Cardello,[8] A. Cardini,[7] M. Carpinelli,[9,10,11] D. Cittadino,[10] A. Contu,[7] M. D'Ambrosio,[12] L. D'Onofrio,[1] D. D'Urso,[8,10] N. Davari,[8] R. De Rosa,[3,4] L. Di Fiore,[4] M. Di Giovanni,[2,1] F. Dordei,[7] I. Fiori,[11] C. Giunchi,[12] J. Harms,[13,14] S. Koley,[13,14] V. Longo,[8] V. Mangano,[1] M. Marsella,[2,1] C. Migoni,[7,17] I. Molinari,[15] M. Olivieri,[15] F. Paoletti,[5] P. Puppo,[1] P. Rapagnani,[2,1] M. Razzano,[16,5] F. Ricci,[2,1] D. Rozza,[8,10] G. Saccorotti,[12] G. Schillaci,[10] V. Sipala,[8,10] M. C. Tringali,[11] L. Trozzo[4] and M. Tuveri[6,7]

[1]*Istituto Nazionale di Fisica Nucleare - Sezione di Roma, 00185 Italy*
[2]*Università degli studi di Roma "Sapienza", 00185 Italy*
[3]*Università degli studi di Napoli "Federico II", 80126 Italy*
[4]*Istituto Nazionale di Fisica Nucleare - Sezione di Napoli, 80126 Italy*
[5]*Istituto Nazionale di Fisica Nucleare - Sezione di Pisa, 56127 Italy*
[6]*Università degli studi di Cagliari, 09124 Italy*
[7]*Istituto Nazionale di Fisica Nucleare - Sezione di Cagliari, 09042 Italy*
[8]*Università degli studi di Sassari, 07100 Italy*
[9]*Università degli studi di Milano-Bicocca, 20126 Italy*
[10]*Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali del Sud, 95125 Italy*
[11]*European Gravitational Observatory - EGO, 56021 Italy*
[12]*Istituto Nazionale di Geofisica e Vulcanologia - Sezione di Pisa, 56125 Italy*
[13]*Gran Sasso Science Institute, 67100 Italy*
[14]*Istituto Nazionale di Fisica Nucleare - Laboratori Nazionali del Gran Sasso, 67100 Italy*
[15]*Istituto Nazionale di Geofisica e Vulcanologia - Sezione di Bologna, 40127 Italy*
[16]*Università degli studi di Pisa, 56126 Italy*
[17]*Istituto Nazionale di Astrofisica - Osservatorio astronomico di Cagliari, 09047 Italy*

E-mail: luca.naticchioni@roma1.infn.it

[*]Speaker

Due to its unique geophysical features and to the low density population of the area, Sos Enattos is a promising candidate site to host the Einstein Telescope (ET), the third-generation Gravitational Wave Observatory. The geophysical characterization of the Sos Enattos former mine, close to one of the proposed ET corners, started in 2010 with the deployment of seismic and environmental sensors underground. Since 2019 a new extensive array of seismometers, magnetometers and acoustic sensors have been installed in three stations along the underground tunnels, with one additional station at the surface. Beside a new geological survey over a wider area, two boreholes about 270 m deep each were excavated at the other two corners, determining the good quality of the drilled granite and orthogneiss rocks and the absence of significant thoroughgoing fault zones. These boreholes are instrumented with broadband seismometers that revealed an outstanding low level of vibrational noise in the low-frequency band of ET-LF (2-10 Hz), significantly lower than the Peterson's NLNM and resulting among the quietest seismic stations in the world in that frequency band. The low seismic background and the reduced number of seismic glitches ensure that just a moderated Newtonian noise subtraction would be needed to achieve the ET target sensitivity. Geoelectrical and active seismic campaigns have been carried out to reveal the features of the subsurface, revealing the presence of small-sized fractured areas with limited water circulation. Finally, temporary arrays of seismometers, magnetometers and acoustic sensors are deployed in the area to study the local sources of environmental noise.

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1. Introduction

The Einstein Telescope (ET) [1–3] will be a third generation Gravitational Wave (GW) Observatory with a target sensitivity ten times better than GW advanced detectors (Virgo [4] and LIGO [5]). In the low frequency (LF) band 2-10 Hz, ET aims to improve the sensitivity up to a factor 10^6 with respect to current GW interferometers. This requirement will be possible only by building the ET infrastructure underground in a very quiet site, where environmental noises are extremely reduced. For this reason, the site characterization is a crucial task to verify if a proposed site meets the project requirements, to evaluate the impact of the environmental noise -in particular seismic and electromagnetic noises- on the detector performances, and to prepare the proper noise mitigation strategies. There are two candidate sites to host the observatory: EMR at the border region between Netherlands, Belgium and Germany, and the Italian island of Sardinia. The latter was initially studied in 2010-2014 [6], monitoring the former mine of Sos Enattos as potential underground site for a 3G GW detector. Since 2019, following the site candidature to host ET, we started a new large scale site characterization campaign, extending the monitored area to two of the possible corner stations of ET, named P2 and P3, about 10 km far from Sos Enattos, that in turn is close to the first corner P1.

2. Geological and geophysical survey

The area of Sos Enattos is located in the north-east of Sardinia, in metamorphic rock widely intruded by Carboniferous-Permian granitoids. This sector belongs to the Corsica-Sardinia microplate, which shows a peculiar geodynamic stability, absence of capable faults and low crustal deformation resulting in an extremely low seismicity rate in the historical data recorded. As supported by recent geological and geophysical survey, including active seismics and electric resistivity tomography, the rock formations in the area north of Sos Enattos (e.g. orthogneiss and granitoids) have good geomechanical properties, a important feature considering the large volumes that will be excavated to build the main caverns of ET. In particular, a limited amount of groundwater was found at the former mine and in the boreholes at P2 and P3, consistent with low-permeability of the units cropping out in the area.

3. Seismic noise background

Sardinia is known for having a low seismic noise background due to its geological features and to the low population density of the region, in particular in the LF band. The seismic noise at the Sos Enattos former mine is measured with a permanent network consisting of one surface station and three underground stations (84 m, 111 m and 150 m below the surface), instrumented with broadband seismometers and low-noise DAQs [9, 10]. One of the underground stations (SOE2/SENA) is also part of the Mediterranean Very Broadband Seismographic Network (MN). Two other permanent installations are located at the P2 and P3 corners, each consisting of a surface and a borehole broadband seismometers, the latter deployed at a depth of about 260 m. Moreover, since 2019, tens of seismometers and geophones have been installed in temporary arrays located in the studied area. Several papers have been published so far from the analysis of the data produced by these installations [9, 11–14]. Locally, the amplitude decay of surface Rayleigh waves (RW) become significant only above 2 Hz, reaching a factor ∼ 5 at 10 Hz, considering a depth of 100 m [12]. The measured RW phase velocity in the 1-10 Hz band ranges between 1.5 and 2.5 kms^{-1}, implying a wavelenght of the order of 150-2500 m. The model retrieved from the measured seismic velocities suggests a substantial homogeneity of the shallow velocity structure [10]. The Horizontal-to-vertical spectral ratio, that is HVSR∼ 1 and shows no peaks, indicates the absence of significant amplification effects, allowing to infer that there are not significant impedance contrasts down to depths of about 2500-3000 m [12], These results were confirmed by active seismic surveys around the P2 and P3 boreholes [15]. Wind speed in the area, resulting in a excess noise observed at the surface stations between 1 and 60 Hz, has a limited effect on the noise measured in the underground stations.

3.1 Microseisms and local sources of noise

In the microseismic band (0.1-1 Hz) the main source of seismic noise is the sea climate [7, 8]. In particular, it is possible to correlate the sea wave height with the seismic PSD measured at Sos Enattos, as shown in [6, 9], following a seasonal trend. The higher correlation is for waves of period 4.5 s, which corresponds to ground vibrations of frequency $f = 0.22$ Hz, producing the main peak observed in the seismic PSDs. From satellite data it is also possible to localize the sea area where most of the observed microseism is produced, corresponding to the Northwestern Mediterranean Sea (Gulf of Lion). The PSDs analysis indicates that the Mediterranean storms have a frequency peak between 0.17 Hz and 0.22 Hz, while Atlantic storms show a lower frequency peak at about 0.12 Hz. The polarization analysis of the array data suggest a coherent source of noise below 2 Hz pointing NW from the site, thus confirming the microseismic source. At higher frequencies the polarization is more sensitive to the local topography, showing an orientation E-NE, consistent with the vibrations of pillars induced by vehicles when travelling on two road bridges located near the former mine [9, 14]. Windfarms are also a known source of ground vibrations that could spoil the sensitivity of a GW detector. Some medium-sized wind mills are located around the candidate area for ET. Recently, a temporary array of seismometers has been deployed along the line between the P2 corner and a large windfarm located at about 13 km NW from the borehole station. Preliminary data analysis suggests that, even though the LF noise level is still extremely low at P2, a small peak around 3 Hz can be correlated with the vibrations produced by the studied windfarm.

4. Electromagnetic noise

In the detection band of ET the main direct disturbances come from ULF ($10^{-3} - 3$ Hz), ELF ($3 - 3 \cdot 10^3$ Hz) up to VLF ($3 - 30$ kHz) frequency bands. The main natural sources of magnetic noise are in ULF and ELF, thus possibly impacting the ET LF-band. These disturbances are produced by resonance phenomena in Earth's magnetosphere and/or ionosphere cavities, in particular geomagnetic pulsations Pc1 ($0.2 - 5$ Hz) and Schumann resonances ($5 - 100$ Hz). The magnetic noise is measured with high-sensitivity magnetometers deployed at Sos Enattos (underground and at surface level), and at the borehole stations (P2, P3). The level of noise is extremely low ($5 \cdot 10^{-13}$ $\mathrm{T/Hz}^{1/2}$ at 10 Hz in all these locations, allowing a clear observation of all the Schumann resonances up to the seventh, and transient geomagnetic pulsations produced by solar wind interacting with Earth's magnetic field.

5. Acoustic noise

Acoustic noise could couple with the interferometric detectors of ET through vibrations and gravitational interaction of fluctuating air mass densities (Newtonian noise). An acoustic array has been deployed along the underground tunnels of the former mine of Sos Enattos, composed of infra-sound microphones and microbarometers. Currently, in the former mine there is no active ventilation, therefore the tunnels are very quiet and high sensitivity microphones with low electrical noise conditioning electronics and DAQ are required to measure the acoustic background, that is below 10^{-4} Pa/Hz^{1}/2 at 10 Hz. A infra-sound microphone array is under deployment at the borehole stations to assess the expected level of atmospheric Newtonian noise.

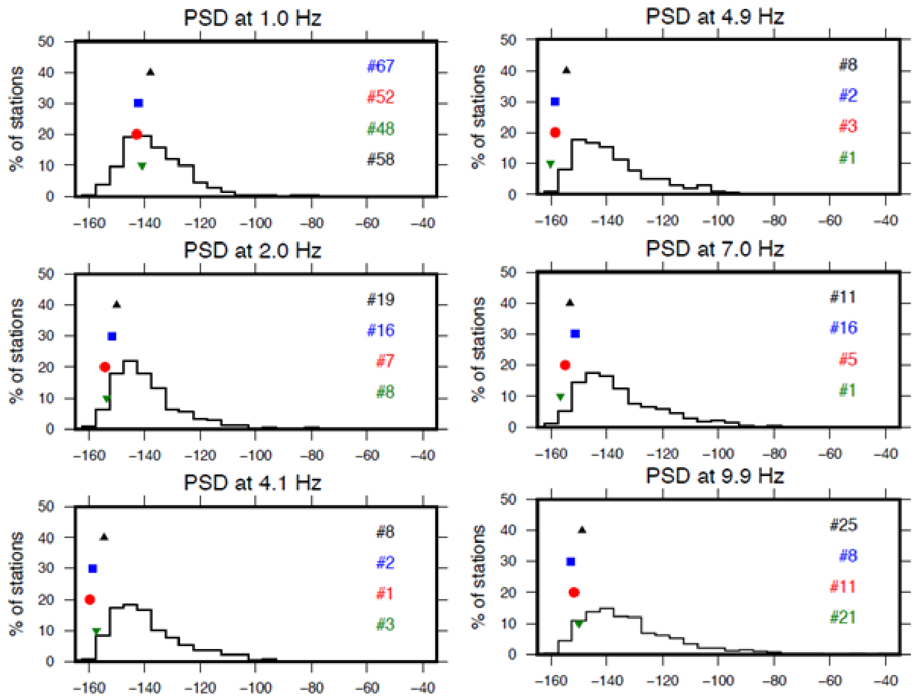

Figure 1: Ranking of Sardinia seismic stations in the quietest selection of GSN in the 1-10 Hz band: P2 (blue), P3 (red), SOE1 (green), SOE2 (black).

6. Site ranking for ET

Seismic noise and the correlated Newtonian noise represent probably the main environmental noise limit to ET LF sensitivity. Given the peculiar geophysical setup, and the local low population density, the Sardinia site is among the quietest in the world in the LF band, as shown in figure 1. Here, we compare the seismic PSDs at several frequencies ranging from 1 to 10 Hz for the Sardinia measurement stations, with those of the quietest ones in the Global Seismographic Network (GSN).

In particular, three Sardinia stations are the three quietest stations in the world between 4 and 5 Hz, while one is also the quietest at 7 Hz.

6.1 Seismic noise comparison

In figure 2 we compare the seismic probabilistic PSDs obtained from one year of data measured at the bottom of two boreholes: Terziet at the EMR site and P2 in Sardinia. In the ET LF band the seismic noise in the Sos Enattos area is about a factor 6-7 lower with respect of the other candidate site. Remarkably, at 4 Hz the PSD median correspond to the Peterson's New Low Noise Model (NLNM) [16], and the tenth percentile is well below the NLNM between 2 and 10 Hz.

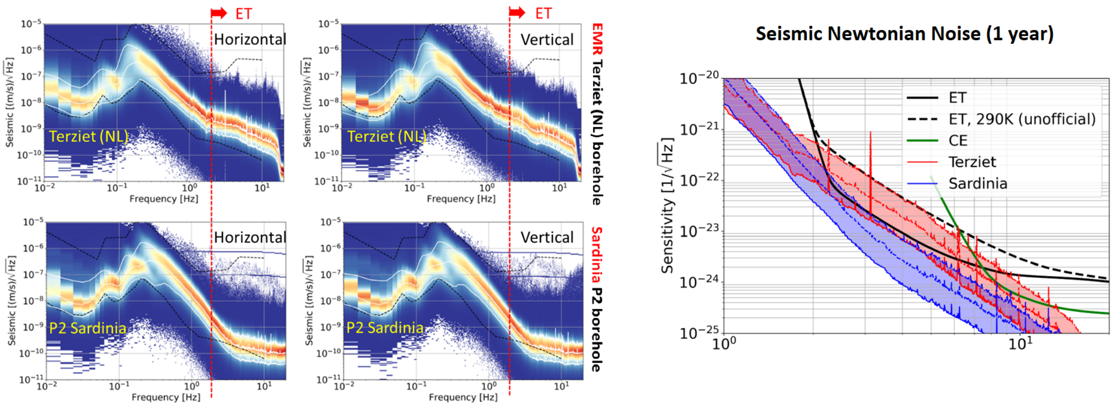

Figure 2: Left panel: Probabilistic power spectral densities of seismic noise measured in one year at the bottom of the boreholes at the candidate sites, white dashed lines represents 10^{th}, 50^{th} and 90^{th} percentiles, black dashed lines represents the NLNM. Right panel: 10^{th}, 50^{th} and 90^{th} percentiles of the expected seismic Newtonian noise at the ET candidate sites, calculated as described in [17] for one year of data (2022-2023) and compared to the ET-LF (black solid line) and Cosmic Explorer [18] (green solid line) design sensitivity.

6.2 Seismic Newtonian noise

Following the analytical approach used in [17], we calculate the expected contribution of seismic Newtonian noise induced by the seismic background measured about 250 m underground at the two candidate sites. An estimate for one year of data (2022-2023) is shown in figure 2, compared to the ET-LF design sensitivity.

7. Conclusions

The area surrounding Sos Enattos, one of the two candidate sites to host ET, is under geological and geophysical characterization and it is monitored by an extensive network of environmental sensors. We demonstrated that the site shows a favourable geophysical setup, with an extremely low environmental noise background. For these reasons, this site is optimal for the ET infrastructure, being able to host the observatory either with 10 km-long arms in a triangle baseline or with 15 km-long arms in a classic "L" baseline.

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