Site Characterization/Preparation Board

WD1 - M1.1 Report

Physical variables and measurements required for the characterization of the ET candidate sites

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1 Introduction

In this document we define the physical variables and measurements that must be acquired to fully characterize the site that will host the Einstein Telescope (ET). Indeed, the environment has an important role in a third-generation gravitational wave (GW) observatory like ET. Site conditions (e.g. geological and geodynamical features, ground water) has an effect on the construction feasibility, costs and lifetime of the infrastructure, while environmental noises (e.g. seismic motion) have a direct impact on the detectors sensitivity and duty cycle. In particular, this document is divided into four sections reflecting the work package organization of division 1 within the Site Preparation Board.

2 WP1.1: seismic measurements

A thorough knowledge of the seismic field at the candidate sites carries crucial information both for the construction and operation of ET. In particular, it is advisable to know the properties of the local wavefield in terms of frequency, amplitude and type of dominant waves and assess its time variability, possibly identifying the seismic sources. Amann et al. 2020 [1] have already pointed out which kind of seismic measurements are suitable for site characterization. Generally speaking, long term measurements (one or more years of continuous seismic waveforms recordings from broadband instruments can be used to assess the seismic noise levels and its variability as a function of the seasons and anthropic activity. These measurements should be carried at several sites that allow the sampling of the candidate site area (e.g. stations placed at the three vertices of the infrastructure) simultaneously recording signals at surface and in boreholes at depth.
Short term seismic measurements (Amann et al. 2020 [1]) on the other hand can provide detailed information about the physical properties of the subsurface rocks and the composition of the seismic wavefield. These require a certain number of stations (tens to hundreds) arranged in an array configuration with a spacing and configuration suitable to sample the target frequency bands and the isotropic or anisotropic properties of the expected seismic sources. These measurements can be conducted either passively (using the ambient noise) or by active surveys using sources such as vibrators.
Host teams should provide these useful studies to assess how the ET duty cycle can be affected by ambient disturbances:

1) Correlations between the seasonal variations of the microseismic peak and the storm surge or wave heights in the surrounding oceans. Indeed, microseisms could couple with the residual tilt of suspended elements of the ET detectors affecting the control loops. Di Giovanni et al. 2021 [2.1] showed that in the Sardinia candidate site there is a clear correlation between the seismic noise at 0.22 Hz and the wave height in the western Mediterranean Sea, including signatures from storms in the north Atlantic Ocean. We recommend monitoring the amplitude and variability of the microseisms at all the candidate sites, at least for a period of one year.
2) Effects of regional and local seismicity, both for natural events (earthquakes) or anthropogenic (e.g. quarry blasts). For the period of observation a catalogue of events should be provided, including the peak ground acceleration (PGA) or peak ground velocity (PGV). This can be useful to estimate the frequency and the amplitude of ground motions that we may expect at each site.
3) Similarly to point 2, the effects of the teleseismic phase arrivals should be provided, together with PGA and PGV. Acernese et al. 2022 [2.2] showed that during the 03 observation run at Virgo the 65% of control losses due to earthquakes were caused by teleseismic phases.
4) Based on the information provided by points 1, 2 and 3, a statistical study of the resilience of the detector to the above-mentioned disturbances should be done by taking into account the ET design sensitivity and one (or more) particular target. An example is provided by Allocca et al. 2021 [2.3] focusing on the detection of intermediate-mass black holes (IMBH) constrained by seismic ambient noise data measured in Sardinia.

3 WP1.2: gravimetry & geodynamics studies

The geodetic site characterization aims to study the low frequency response of surface and sub-surface variable processes (i.e. in the range of 0 to 0.01 Hz. Thus concerning mainly the impact on the infrastructure life time and quality preservation. In particular, the focus is on the role played by subdaily, seasonal and slow varying processes induced by the groundwater cycle and other geodynamic and anthropic-induced ground deformations. The physical quantities to be monitored are:

- the local and instantaneous gravity variations.
- the gravity anomalies in the area of interest. Collecting all available gravity data available for the area and eventually planning a new dedicated survey to gain more details.
- the strain, strain-rates and tilt variations measured on the Earth surface and eventually below the surface. Differential deformations in a region may arise from regional geodynamic processes, hot springs and faults that provide pathways to the surface for water flowing, large gravitational slope deformations or groundwater level variations that causes deformations in sedimentary basins (poroelastic) as well as in limestones outcrops (elastic). Mapping the surface deformations and monitoring time dependent 3D deformations define the long-term stability of the monitored area.

The simultaneous knowledge of the time variable gravity field and deformation field should allow us to discriminate processes due to overpressures (e.g. in confined aquifers or gas storage reservoirs) or mass flow in the ground (e.g. groundwater flow, tectonic/volcanic processes).

4 WP1.3: magnetic noise

Electromagnetic (EM) fields, with natural or artificial origin, are present almost everywhere in our environment and, depending on their intensity or frequency band, could act as a disturbance for any electronic equipment and for magnetic or charged materials. For this reason, they represent a significant source of noise for ET: indeed, noise generated by EM fields can affect the detector in different ways. First, the EM noise can directly couple with magnetic actuators placed on the suspended mirror, or also along the suspension chain; secondly, it can induce currents on electronic equipment, cables, and connectors, potentially affecting critical signals used for the interferometer control and producing, in this way, an indirect disturbance on the detector output. The first kind of coupling is more significant at low frequency [4.1], since the shielding of the vacuum chambers is not effective in this band, while the second is more important at higher frequencies [4.2].

The natural EM noise, in the ET frequency band, comes from resonance phenomena occurring in magnetosphere and ionosphere cavities [4.3]. Between them, the most important, because of their intensity, frequency, and large-scale coherence, are the Schumann Resonances (SR). These are a set of broad peaks, in the extremely low frequency (ELF: 3-3000 Hz) band of EM spectrum, produced by the global lightning activity and propagating in the ionosphere [4.4]. The first five SR modes are at 8, 14, 20, 26, 32 Hz; their intensity decreases with frequency. The SR are detectable, in quiet environments, from any location of the Earth, showing significant coherence even at far location [4.5] and present peculiar daily and seasonal variation [4.6]. Given these characteristics they can directly limit the sensitivity of ET [1,4.7] by acting as a local EM disturbance, but can also have an impact on search for stochastic gravitational waves, based on correlation between far detectors [4.8].

Other sources of natural EM noise also exist, especially at higher frequency; they are still related to atmospheric electric discharges and have larger frequency spectrum, typically ranging from 1 to 40 kHz [4.3]. However, for these events the direct coupling is expected to be very low [4.9, 4.10] giving no significant contribution even for third generation gravitational wave detectors. Of course, exceptions are possible for lightning events very close to the detector [4.11]. At higher frequencies the natural sources are very weak and only include cosmic EM in the high and very high frequency band (HF: 3-30 MHz, VHF: 30-300 MHz).

Apart from natural ones, a lot of artificial EM sources are present in our environment. At extremely low frequency, the main source is represented by power lines, while a large variety of electronic devices is an important noise source at very low frequency (VLF: 3-30 kHz) [4.3]. Other contributions, most significant at higher frequencies (30 kHz – 300 MHz) come from radio communications (AM and FM), TV transmissions (VHF-UHF), mobile phones and automotive ignition [4.3]. Due to their high frequency content, these EM fields cannot affect the ET detector directly in its frequency band but can produce disturbances in phase/amplitude RF modulation/demodulation of the laser beams used for locking and alignment purposes.

The physical variables that are representative of the EM noise are electric and magnetic fields. For low frequency measurement both electric and magnetic field probes can be used, even if magnetic probes are normally more compact. Instead, for high frequency measurement, electric field probes are better suited. The site characterization cannot include the noise produced by the electrical or electronic equipment that are necessary to manage and operate the full ET detector, but it is necessarily limited to the characterization of the site typical noises. Since the most relevant source is the natural noise at low frequency, namely the Schumann Resonances, and given the availability of small and compact magnetic field probes, with very high sensitivity in the ELF band, it comes that very convenient probes to use for the EM site characterization are coil induction broadband magnetometers. Such probes have typical frequency bands extending from fraction of mHz to several kHz, with intrinsic noise levels as low as 10^{-4} nT/Hz$^{1/2}$ at 1 Hz: about one order of magnitude lower than the typical natural spectrum. Moreover, such probes are usually sealed, so they can be safely buried for more accurate and low noise measurements.

Since the SR have usually only horizontal magnetic field components, a set of two orthogonal horizontal magnetometers is often sufficient to monitor the most important fraction of SR dynamics in a given location, even if, in case of geological irregularities in the surrounding crust, a vertical magnetic component may arise [4.4], requiring a third vertical magnetometer for its monitoring.

5 WP1.4: other environmental noises

Among the other environmental noises of interest, the variations of air pressure can lead to a source of noise for the gravitational wave detector. The noise will most likely be determined by the noise in the cavities and therefore it is impossible to measure it before the actual construction. However, some part of the work can already be done. We can measure the acoustic and barometric noise on the surface at the locations of the end stations of ET. The aim is to characterise the noise as it is now, including such characteristics as spectra, amplitudes, time variability, as well as identification of sources of noise. The sources can be related to weather - wind, rain, water flow, sea waves; seismic activity and noise, and also be due to human activity. In the sites where underground facilities exist, we can estimate the transfer function of the noise on the ground to the underground.

Therefore, host teams should measure the following quantities:

- infrasound noise on the ground (frequency range 0.1Hz to 30Hz)
- micro barometric noise - this is the low frequency extension of the infrasonic noise with frequency down to microhertz.
- weather at sites: temperature, wind, pressure, precipitation, humidity.

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