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Milestone 04.02

Common methodology to estimate impact of site characteristics on ET sensitivity and operation and, if required, a scheme to compensate it

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EXECUTIVE SUMMARY

This document, Milestone 4.2 “Common methodology to estimate impact of site characteristics on ET sensitivity and operation and, if required, a scheme to compensate it”, is a milestone of the ET-PP Project, which is funded by the European Commission Framework Programme Horizon Europe Coordination and Support action under grant agreement 101079696.

This Milestone is a crucial step towards the definition of a scientific site evaluation procedure, and it requires a full understanding of the role of environmental noise and site characteristics on detector performance.

The environment may play an important role, affecting cost, lifetime and detector behavior. The report will describe the methodology defined to evaluate the detector site dependent detector performances.

Contents

1 Introduction	1
2 Methodology Scheme	2
2.1 Definition of Science Cases, tools and analysis recipes	2
2.2 Definition of Tools for detector behavior and Mitigation Strategy and evaluation of Detector Sensitivity	4
2.3 Definition of Relevant Measurements	8
2.4 Site Noise Measurements: data acquisition and validation	9
2.5 Validation	9
2.5.1 Internal Validation	9
2.5.2 External Validation	10
2.6 Risk assessment of mitigation effectiveness	10
3 Scientific Benchmarks	10
4 Milestones and Timeline	12

1 Introduction

Site evaluation for ET construction is a very complex procedure, in which many aspects should be considered: construction feasibility, cost, authorization and legal aspects and possible site-dependent detector performance. The Einstein Telescope is expected to reach a sensitivity well beyond those obtained by current detectors (at 3 Hz, the targeted sensitivity improvement is more than 5 orders of magnitude), which amplifies the importance of environmental noise. Site conditions (e.g., geological and geodynamical features, ground water) influence the construction feasibility, cost and lifetime of the infrastructure and, at the same time, may impact detector performance (e.g. underground water flow may produce terrestrial gravitational noise). On the other hand, environmental noises (e.g. seismic motion) have a direct impact on the detector sensitivity and duty cycle. Based on the experience of managing current detectors, the ET Collaboration has been able to identify site characteristics that may have an impact on the detector [1], and the collaboration is evaluating their effects on the interferometer. Seismic fields need special attention since the main environmental noise predicted to set a low-frequency limit to ET's bandwidth is from gravity perturbations produced by seismic fields, the so-called Newtonian Noise (NN). For site characteristics that may limit the detector performance, special mitigation strategies should be implemented. For NN mitigation, data from an expensive 3D seismometer array can be used to subtract a noise estimate from the ET data. Local magnetic noise as well as Schumann resonances could introduce limitations to the gravitational-wave detection of future Earth-based gravitational-wave detectors. The purpose of this document is to establish a methodology for assessing the impact of environmental noise at a candidate site

on the apparatus, taking into account detector functionality and the various scientific objectives defined by the Einstein Telescope Collaboration (ETC).

2 Methodology Scheme

A possible methodology that can be applied for a site evaluation on scientific basis can be summarized in the following steps:

1. Define science cases relevant for site-dependent detector performance.
2. Define tools to be used to estimate detector behavior, given a specific environmental configuration.
3. Define analytical methods to be followed to evaluate detector potentialities with respect to science cases of point [1](#)
4. Define relevant measurements to be performed, following specific standards
5. Measurements of environmental noise, acquisition and validation
6. Evaluation of detector performance
7. Validation of the results by ETC
8. Analysis of noise-mitigation strategies and evaluation of possible additional costs
9. Evaluation of detector performance considering mitigation strategies of point 8
10. Result validation
11. Risk assessment of mitigation effectiveness, considering additional costs, time and needed person-power

In Figure [1](#) the diagram of the process is summarized.

2.1 Definition of Science Cases, tools and analysis recipes

There is a concerted effort in the ETC to define the science case for the Einstein Telescope. This involves studies of different detector configurations, construction of the data-analysis platform, exploration of the computational needs for optimal science extraction and the interaction between ET and other GW/non-GW observatories. The Observational Science Board (OSB) of ETC is fully devoted to identifying ET science goals and providing common tools and an analysis platform.

A first systematic discussion of the ET science case was presented in [2](#) and was included in the ESFRI proposal. A comprehensive overview of the current

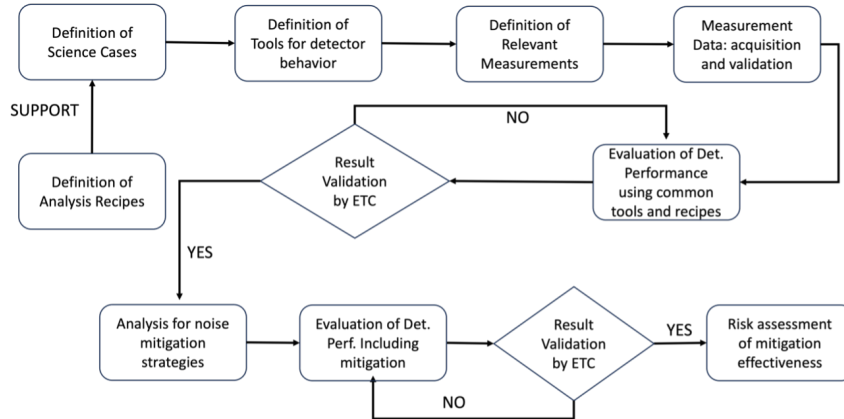


Figure 1: Methodology Scheme

knowledge of GW sources detectable by ground-based observatories, identifying the major open questions and the predicted impact of ET on the widest range of science cases can be retrieved in [3]: test fundamental aspects of gravitational interactions, compact objects and near-horizon physics, and dark matter candidates; measurements of stochastic GW backgrounds; study of astrophysical populations like binary black holes (BBHs) and binary neutron stars (BNSs), black holes from the first stars (Population III stars) primordial black holes, population of intermediate-mass black holes up to $10^4 M_{\odot}$; multi-messenger astronomy; nuclear physics under extreme conditions (from the merging of BNS) and so on. Therefore a site evaluation process have to take into account all the physics goals addressed in [3].

A list of public tools, described in [3] have been developed within the OSB to assess the scientific potential of ET in different configurations or networks, such as tools for performing relatively fast forecasts on large populations of compact binaries, ringdown studies or stochastic searches. Those tools allow us to quickly evaluate the effect on the ET science output of possible variations of its design such as sensitivity curve, geometry, or geographical location. This makes it possible to assess the scientific potential of different detector configurations with standardized, official figures of merits (FOMs). Most of these tools, based on Fisher matrix methods, have been extensively used to study costs and benefits of ET configurations in [4]. In the following, we present a few cases as examples. A more extensive and detailed list can be found in [3].

For Compact Binary Coalescences (CBCs). These tools enable the estimation of signal-to-noise ratios, alongside uncertainties on source parameters, including intrinsic ones (e.g., masses and spin) and sky localization; the use of analytic, hybrid, and phenomenological waveform models for CBC signals; population-level inference analyses for large-scale astrophysical studies; forecasting constraints on the population properties of merging compact objects.

For Ringdown Analysis of CBCs. There is a dedicated tool for assessing the post-merger gravitational-wave emission of CBCs. It allows us to forecast the measurement accuracy on the parameters characterizing the ringdown phase of compact binary mergers, enabling detailed analysis of post-merger signals.

For Stochastic Gravitational-Wave Searches. Tools designed to characterize the detectability of stochastic backgrounds from astrophysical and cosmological sources via the power-law sensitivity and to subtract the residual “confusion noise” caused by unresolved CBC signals from the astrophysical background in the search for cosmological contributions.

Null Stream Tools for Noise Reduction. A tool to apply null stream techniques in the triangle configuration and exploit its potentialities.

2.2 Definition of Tools for detector behavior and Mitigation Strategy and evaluation of Detector Sensitivity

The ET detector will have unique characteristics: it will be a xylophone consisting of two different machines specialized to operate at low frequencies (ET-LF) and at high frequencies (ET-HF) respectively; cryogenics, to suppress the thermal noise from core optics and suspension fibers relevant for ET-LF; underground, to limit the effect of human activities, seismic noise and, in particular of atmospheric and seismic-wave-induced gravitational disturbances, known as Newtonian Noise (NN), which sets the sensitivity limit at low frequencies.

In the ETC, the Instrumental Science Board (ISB) has been established to develop the ET Detector Technical Design Report. The ISB is structured in five Divisions, and it will provide the tools to estimate the effect of different site environmental noises on detector behavior and possible mitigation strategies to reduce their impact on the detector sensitivity. In particular, the Active Noise Mitigation (ANM) Division is devoted to identifying possible sources of noise for ET, to define the needed site-monitoring systems and to develop tools and systems to mitigate the impact of the noise. The targeted sensitivity of the Einstein Telescope is well beyond those obtained by current detectors (at 3 Hz the improvement will be more than 5 orders of magnitude), which amplifies the importance of environmental noise. The design sensitivity for both geometrical configurations (triangle and 2L) can be found in [4]. The projected noise budgets of the ET LF and ET HF interferometers are given in Figure 2 and Figure 3 respectively.

The High-Frequency (HF) detector is designed as a broadband instrument, with sensitivity extending over several kilohertz. Achieving the required broadband sensitivity necessitates high optical power—more specifically, high energy circulating in the interferometer arms—to reduce quantum shot noise, which dominates at high frequencies. Low-frequency noise sources—such as quantum radiation pressure noise, suspension thermal noise, Newtonian noise, and seismic noise—are less critical in the HF detector, as these are primarily addressed by the ET Low-Frequency (LF) interferometer. To suppress quantum noise, the HF detector will employ frequency-dependent squeezing. Thanks to the

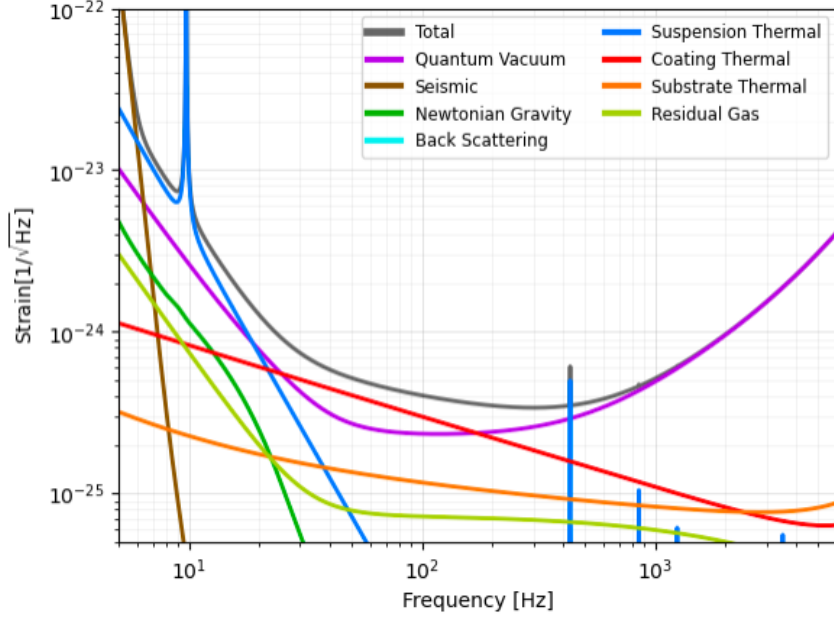


Figure 2: Strain noise budget of the HF detector. Noise traces shown in this figure correspond to a single interferometer with an intersection angle of 90 degrees (“L” shape)

underground installation and the low-frequency coverage provided by the ET-LF detector, the HF detector does not require a Newtonian noise cancellation system.

The ET-LF detector pushes the limits of infrastructure to approach the fundamental physical sensitivity bounds. Although the underground location significantly attenuates Newtonian noise from surface seismic waves and atmospheric sources—by several orders of magnitude—residual body-wave and cavern acoustic-wave contributions remain. These must be mitigated through local environmental monitoring and subtraction. To minimize thermal noise, the ET-LF will utilize ultra-low-temperature cryogenic technology. The ET-LF will also employ a frequency-dependent squeezing scheme to further reduce quantum noise across the detection band.

To fully understand the ET detector behavior, a large list of site dependent physical variables need to be measured (see section 2.3), ranging from seismic to acoustic, to magnetic noise. The contribution of all of them needs to be fully quantified in terms of detector sensitivity and duty cycle, and mitigation strategies should be implemented. As shown in Figures 3 and 2, site characteristics are in particular relevant for the ET-LF detector (see 5 for

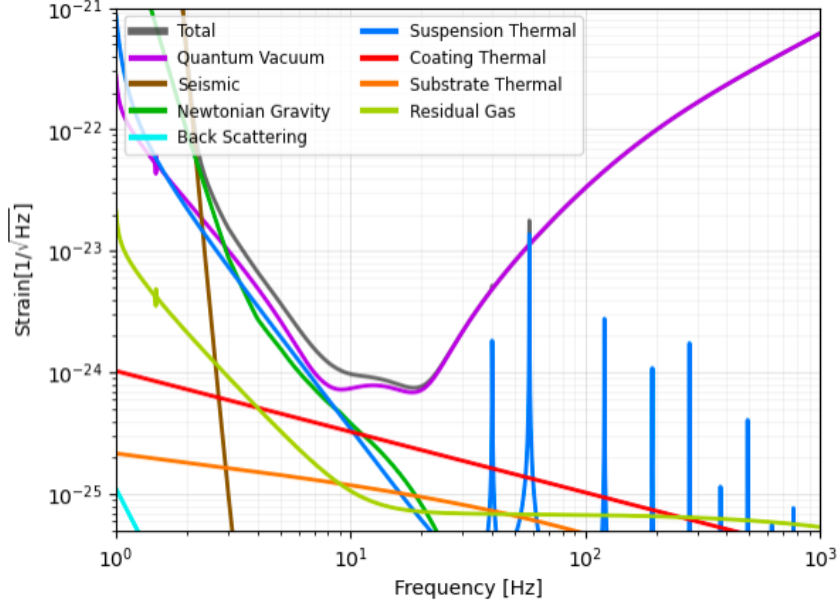


Figure 3: Strain noise budget of the LF detector. Noise traces shown in this figure correspond to a single interferometer with an intersection angle of 90 degrees (“L” shape)

a more detailed discussion of ET sensitivity curve and underlying noise budget). ET Sensitivity curves are publicly available at <https://gitlab.et-gw.eu/pub/et-sensitivity-curves>. The repository contains public data files for different noise contributions to current ET sensitivity, computed using pygwinc (<https://git.ligo.org/gwinc/pygwinc>).

Focusing on the ET-LF detector, in the frequency region between 2 and 10 Hz, the NN is the dominant contribution, while other contributions, like quantum and thermal noise from the detector hardware, dominate the noise budget above 10 Hz (in the Figure the [3](#) a factor of 3 suppression is already applied in the noise budget for the NN). Since the main environmental noise predicted to set a low-frequency limit to ET’s bandwidth is the NN special mitigation strategies should be implemented. For NN mitigation a very complicated method is required.

NN is caused by gravity fluctuations from mass distributions that change around the detector with time. These fluctuations are generated by variations of atmospheric and ground densities in the vicinity of the test masses of the detectors. Ground density variations are caused by ground motion, i.e., seismic waves. The effect of atmospheric NN can be neglected since the detector will be underground (see [\[6\]](#) for a detailed discussion of atmospheric NN and its

attenuation as a function of depth).

Models of NN are expected to become more and more complex and sophisticated as they incorporate an increasing amount of site-specific information like topography, geology, and observed or modeled inhomogeneities of seismic fields [7, 8, 9, 10]. Model predictions can be affected by systematic and significant numerical errors, and one needs to develop methods to constrain and validate simulation results (e.g. an analytical benchmark [11]).

The NN contribution to the ET instrument noise can be estimated as in [11] and [12] (a more detailed discussion can be found in section 3.3 of [13]). It serves as a reference model until more sophisticated models are produced. Following Newton's law, the acceleration δa of a mass placed at the point r_0 due to a seismic displacement $\xi(r, t)$ within a cavern is given by:

$$\delta a(r_0, t) = -G \int dV \rho(r) (\xi(r, t) \cdot \nabla_0) \frac{r - r_0}{|r - r_0|^3} \quad (1)$$

where the G is the Newton constant and the integration is over the whole volume of the cavern. In the first approximation, the underground cavities of the detector can be assumed to be much smaller than the seismic wavelengths so that corrections from the cavern geometry can be neglected. Assuming that the unperturbed density has the same value ρ_0 everywhere, the above integral can be solved in the frequency domain as:

$$\delta a(\omega) = \frac{4\pi G \rho_0}{3} (2\xi^P(\omega) - \xi^S(\omega)) \quad (2)$$

where ξ^P , ξ^S represent the compressional and shear content of the seismic fields. The equation holds for all seismic fields in infinite, homogeneous media of density ρ_0 , decomposing the seismic fields in ξ^P , ξ^S , e.g., homogeneity and isotropy of the seismic field are not required.

The Power Spectral Density (PSD) of the measured seismic noise $S(\xi, \omega)$ can be expressed as the superposition of P and S contributions by defining a mixing parameter p as the fraction of compressional contribution: $S(\xi^P, \omega) = p S(\xi, \omega)$ and $S(\xi^S, \omega) = (1-p) S(\xi, \omega)$. Following the discussion in [14], one may assume as a first approximation that all three body-wave polarizations carry the same average displacement power and set $p = 1/3$. Under these hypotheses, the amplitude spectral density (ASD) of the Newtonian noise contribution to the detector output $\tilde{h}_{NN}(f)$ is given by:

$$\tilde{h}_{NN}(f) = \frac{4\pi}{3} G \rho_0 \frac{2\sqrt{2}}{L} \frac{1}{(2\pi f)^2} \tilde{x}(f) \quad (3)$$

where the frequency (f) dependence of the NN budget is related to the gravitational constant (G), the density of the ground medium (ρ_0), the size of the arm-length of each interferometer (L) and the amplitude spectral density of the measured seismic displacement ($\tilde{x}$).

Currently, the NN contribution is evaluated assuming:

- underground seismic spectra representative of body and Rayleigh waves ;
- one third of the body waves contribution is from compressional waves;
- surface waves are negligible at depths of a few hundred meters;
- uncorrelated NN on the interferometer test masses.

Future NN models may become more and more complex and sophisticated considering an increasing amount of site-specific information. The here presented analytical solution is the first and the basic approach that can be followed. In the future, we may use more sophisticated tools, if available and approved by the ETC, taking into account a much more detailed 3D model of the area.

Site noise is typically not stationary, its variability can be due both to long night-day or seasonal variations and fast transients of anthropic or natural origin. Thus, ET sensitivity should be evaluated as a function of time, starting from data collected from long-term site monitoring campaigns, taking into account possible glitch and all possible noise sources.

The ANM Division is also studying the mitigation of the different noises impacting detector performance. In the case of NN, coherent noise cancellation using Wiener filters provides a way to mitigate its effect [9]. For long, perpendicular detector arms and isotropic seismic fields, NN on different test masses is uncorrelated. In this case, one needs to install an array of N seismometers around the test masses. The optimal array configurations (the numbers of sensors and their positions) and achieved residuals depend strongly on the composition of the seismic field in terms of average compressional-wave and shear-wave content. A possible solution to reduce NN by a factor 10 (in amplitude), in the case the spectral density of the seismic field is composed by 1/3 of compressional waves, is to distribute 15 sensors, installed at different depths and distances, around each test mass [9]. This assumes that the optimal seismometer positions are known.

2.3 Definition of Relevant Measurements

The environment has an important role in a third-generation gravitational wave (GW) observatory like ET, which one of the most crucial goals is to observe GW in the frequency range 2-10 Hz. ETC established a board fully devoted to defining the relevant site parameters for detector functionality, the Site Characterization Board, that is providing the list of relevant measurements to be performed in each candidate site and the standard to be followed. Site characteristics that may have an impact on the Einstein Telescope (ET) are summarized in [1, 15]. They have been divided in physical variables and geological, geophysical and geo-technical aspects. Measurement standards and procedures that must be carried out in the characterization of the Einstein Telescope candidate site for the physical variables have been described in [1, 16].

2.4 Site Noise Measurements: data acquisition and validation

Measurements should follow standards set by ETC. Local teams must provide all the quantities identified by ETC with verified and well-documented tools to perform a basic analysis. Data and tools should be well documented and shared to the whole ETC as described in [1][15][16].

2.5 Validation

Results of local team studies should pass a double level verification:

- by the relevant ETC bodies that provided tools and recipes to ensure that they have been correctly used;
- by an external international board of experts in the field.

2.5.1 Internal Validation

ETC established the Editorial Committee, as outlined by the ET Bylaws document [17]. The Editorial Committee is a Standing Committee of the Collaboration Board created to oversee the publication of ET papers, including conference and internal Notes, and to ensure their high quality. The EC is responsible for maintaining adherence to the Publications and Presentations policy, following the procedure in the ET Collaboration publication and presentation policy document, to be realized and updated by the EC and endorsed by the CB by simple majority vote. The duties of the EC are:

- to manage all publications and proceedings involving the ET Collaboration and its members.
- to oversee papers led by the Collaboration or by one of its Specific Boards (EIB, ISB, OSB, and SPB);
- to organize internal reviews to meet scientific as well as editorial standards by setting up “Paper Review Committees” (PRC) which will manage circulation of such papers and collect feedback.
- to manage the author list of such Collaboration or Specific Board papers.
- to collect exceptional requests beyond the nominal author list.
- to recommend the approval of Collaboration or Specific Board papers to the CB and EB.
- to manage the review of conference proceedings written by Collaboration members on ET work or results.
- to manage the review of short author-list papers involving Collaboration members to ensure rules are followed. To manage the circulation of such papers and collect feedback on content and author list.

- to maintain an archive of publications accessible to all members of the Collaboration.
- to advise the CB and EB on publications and rules.

2.5.2 External Validation

ETC and ET Organization should appoint an international board of experts. The board may be composed by experts in cosmology, multi-messenger astronomy, in gravitational wave detector and data analysis, geophysicist and seismic noise measurements.

2.6 Risk assessment of mitigation effectiveness

Based on the obtained results, local teams should assess the risk of a possible scientific descope due to mitigation effectiveness, considering additional costs, time and person-power. Risk assessment should be done in agreement with standards defined by ETC and ET Organization.

3 Scientific Benchmarks

3G detectors have a large list of science goals and one should consider many parameters to express the detector scientific capabilities. The scientific potential of various detector configurations has been evaluated through a set of standardized, official Figures of Merit (FOMs). A detailed and comprehensive list of these FOMs has been established to compare the prospective performance of the ET detector across different configurations [4], and has been employed in the development of the ET Science Case [3]. In the following, a few selected Figures of Merit (FOMs) are listed as illustrative examples.

Detector Capability. The capabilities of a given GW detector to detect a source is expressed through the Signal-to-Noise Ratio (SNR), by using the eq. 9.8 of [3], as optimal SNR. A source is considered detectable if its optimal SNR exceeds a certain detection threshold. FOMs for Compact Binary Coalescences (see sect 9.3 of [3]):

1. Number of events are obtained using an SNR detection threshold of 12.
2. Angular sensitivity (Mollview plots).
3. Horizon. The maximum redshift out of which a binary with optimal sky position and orientation can be observed above a chosen SNR threshold, as a function of the total mass. Equal mass, non-spinning binaries are also assumed.
4. Inference horizon. The largest redshift one can possibly put a claim on for a given confidence level (a C.L. of 90% is customary in GW astronomy, denoted by $z_{90\%}$). The sources with best lower bound on the redshift are

found not to be those at the horizon. One can define another notion of horizon, z_{peak} , as the true value of the redshift where the $z_{90\%}$ is largest.

5. Early warnings. An important aspect related to the detection of BNS systems is the possibility of detecting the source prior to merger, in order to alert electromagnetic observatories for potential coincident detections. To study this possibility, it is useful to determine how the SNR accumulates in time, as the frequency of the signal increases.
6. SNR and detection rates. The cumulative number of observed events as a function of the SNR.
7. Angular localization and luminosity distance accuracy. Redshift distribution of the relative error on the luminosity distance for BNSs, with cuts at 50%, 20%, 10% and 1% on relative accuracy. Redshift distribution of the uncertainty on sky-localization of BNSs considering different cuts on localization precision 1000 deg², 100 deg², 10 deg² and 1 deg².
8. Pre-merger alerts. The number of sources that would be detected on a given period before the coalescence, with a sky-localization of (10, 100, 1000 deg²), within redshift $z=1.5$.
9. Inference of intrinsic parameters. Cumulative distribution of errors on some intrinsic parameters like masses, spins and eccentricity of a binary system.
10. Golden binaries. Redshift of BBHs with either SNR larger than 100 (resp. 30 for BNSs) or with reconstruction of the source-frame chirp mass smaller than 1% (resp. 5% for BNS).
11. Detection of population features. relative uncertainties for the population hyper-parameters as a function of observation time and of the corresponding number of detected events N_{det} , quantifying the time needed for achieving a 1% constraint. The hyperparameters are categorized in four groups broad mass features, mass cutoffs, redshift evolution and spins.

FOMS for Stochastic GW background (see sect 9.5 of [3]):

1. Power-law sensitivity (PLS) curve (also denoted as the power-law integrated sensitivity curve). It allows studying the detectability (for a chosen S/N threshold ρ) of a given power-law GW background.
2. The function $R_{ab}(f)$ that determines the signal-to-noise ratio of the astrophysical confusion noise through eq. 9.89 of [3]. There will be a confusion noise in ET generated by the unresolved sources and by the accumulation on the errors on the resolved sources. That noise can be significant, and could spoil the 3G sensitivity to cosmological backgrounds.

4 Milestones and Timeline

The estimation of impact of local noise on ET performance (deliverable D4.3), considering the implementation of possible mitigation strategies as well, requires the involvement of the ET Collaboration and the local teams. ETC has already defined the list of relevant measurements and just updated the ET Science Case (D6.1). On the other hand, the Collaboration has developed tools to study and optimize the detector design, at the best of the current knowledge. ETC established the Editorial Committee, and it is currently approving its policy. The ETC internal referee process will validate the data collected by each site, the estimation of the impact on detector performance and the implementation of possible mitigation strategies. ETC and ET Organization should define how to set up an international board of experts in the field to an external validation of the obtained results. In the following the list of needed milestones to complete the process:

1. Update of ET Science Case (already achieved).
2. Identification of analysis tools (already achieved).
3. Identification and implementation of tools to estimated detector behavior taking into account site specific characteristics. The identification and implementation of tools to more accurately estimate detector behavior—accounting for site-specific characteristics—is currently underway. While the Einstein Telescope Collaboration (ETC) has already provided initial tools for this purpose, efforts are ongoing to optimize these and to develop more advanced and sophisticated versions. Completion is expected by December 2026.
4. Definition of a validation procedure. Expected by Jan 26.

The deliverable is expected by July 2026.

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