Pushing towards the ET sensitivity using 'conventional' technology

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1 The Scope of this Document

Recently, the design study 'Einstein gravitational wave Telescope' (ET) has been funded within the European FP7 framework [1]. The design study represents the first coordinated effort towards the design of a third-generation gravitational wave detector. The ambitious goal of this project is to provide a conceptual design of a detector with a hundred times better sensitivity than currently operating detectors, which corresponds to a capability of scanning a one million times larger volume of the universe! It is expected that this challenging goal requires the development and implementation of new technologies, which go beyond the concepts employed for the first and second detector generations, especially for the reduction of quantum noise. One task within the design study is to review such new technologies and study their feasibility for gravitational wave detection. In this context, also the application of completely different detector geometries and topologies is being discussed [3].

However, it is a very interesting and educational exercise to imagine a Michelson interferometer in which conventional technologies have been pushed to - or maybe beyond - their limits to reach the envisaged sensitivity for the Einstein Telescope. In this document we present a first sketchy analysis of what modifications and improvements are necessary to go, step-by-step, from second generation gravitational wave detectors to the Einstein Telescope. We restrict our analysis to a configuration similar to Advanced LIGO (Dual-Recycled Michelson interferometer featuring arm cavities) but with an increased arm length of 10 km and we explicitly put a focus on rather conventional techniques.

2 Assumptions and Constraints

As described above we want to restrict ourselves to more or less *conventional* technologies which fulfill at least one of the following two criteria:

- The technology was already successfully demonstrated on prototypes, such as the injection of squeezed light into a Michelson interferometer or interferometry with cryogenic mirrors.

- The technology is an up-scaling of currently used technology without any change of the fundamental physics involved, for instance using suspensions of 50 m length.

Thus, we consider 'non-conventional', any technique or technology which so far only exist on paper, or has been demonstrated only in proof-of-principle experiments which are very different from the target interferometers. Examples for such technologies include displacement-noise-free interferometry, optical bars and optical levers or
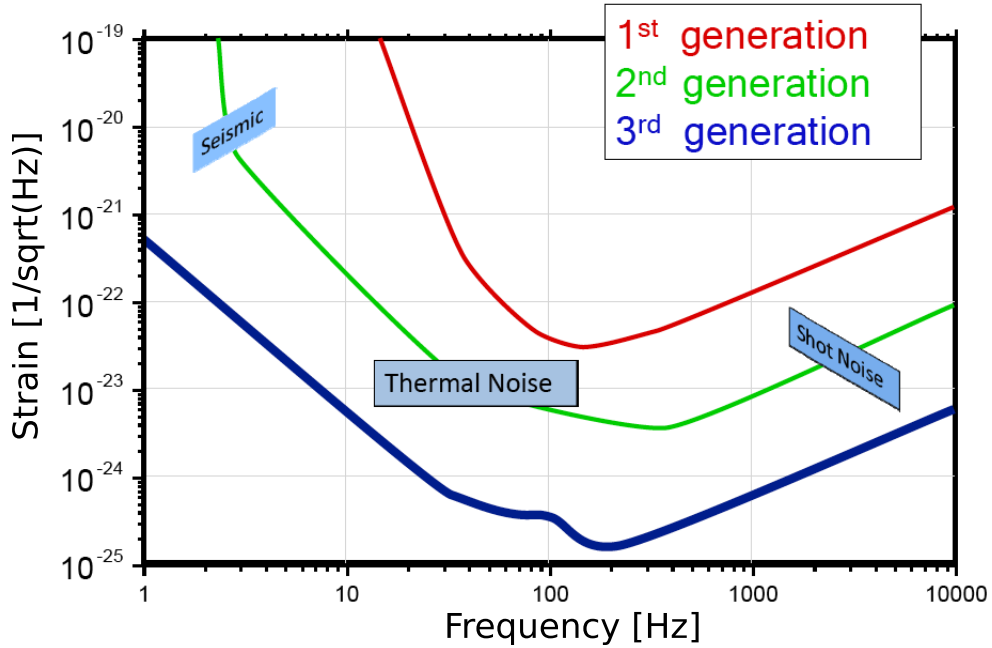
Figure 1: Originally proposed target sensitivity of the Einstein Telescope (blue) from [4]. For comparison a rough estimate of the average sensitivity of first (red) and second generation (also called 'advanced') gravitational wave detectors (green) are included.

the use of higher-order Laguerre-Gauss-modes. These 'non-conventional' techniques have been omitted in our analysis.

A further constraint we imposed on our analysis is that we did not consider the possibility to split ET into separate smaller, optimised interferometers, for example a high-power high-frequency device and a low-power low-frequency device. Although such an approach might be promising for reducing the quantum noise, it would not show the limits of conventional techniques as clearly as a single broadband detector.

Restricting our analysis to a single interferometer also implicates, that we do not evaluate any properties which are closely related to a potential network of detectors, such as for instance sky-coverage, null-stream availability or redundancy.

3 A GWINC Model for ET

The Advanced Virgo design group makes use of a well documented noise model [2], which is based on the GWINC code [7] developed within the LIGO scientific collaboration. We use this Advanced Virgo noise model as starting point for our investigations.

Figure 2 shows the fundamental noise contributions of an detector with basic parameters similar to a possible Advanced Virgo design, using an arbitrary detector configuration. Please note that the resulting sensitivity (solid blue line) is for an imaginary advanced detector only and is not connected to the ongoing design process for Advanced Virgo. The solid red line is an approximation of the ET design target (blue line from Figure 1). Please note that every single noise source reaches above the ET target, at least for some signal frequencies. Therefore, each of the displayed noise curves has to be lowered by changing the interferometer performance. In the next section we will change step by step the relevant parameters of our noise model, starting with a noise model for an advanced detector, in order to suppress each individual noise contribution until we achieve compatibility with the ET design target.
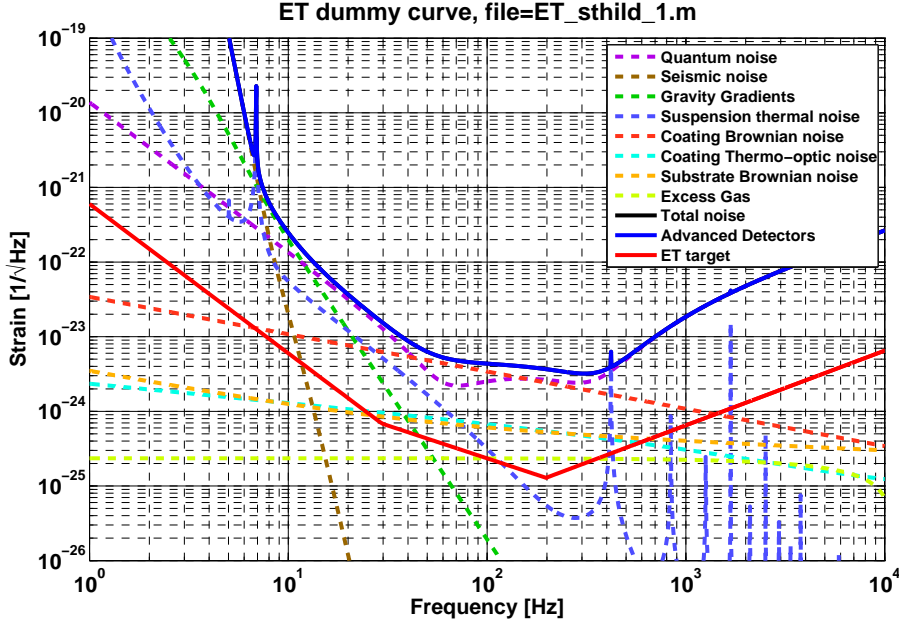
Figure 2: Fundamental noise contributions to the sensitivity of a potential advanced detector (blue solid line). The solid red line is an approximation of the ET design target (blue line from Figure 1). Please note that every noise source is at least at some frequencies above the ET design target, thus we have to improve every single noise contribution to guarantee compatibility with the targeted ET sensitivity.

4 From Advanced Detectors to the ET Design Target

The following list indicates briefly which parameter changes were performed to go from an advanced detector to the Einstein Telescope. Please note: The items listed below represent only **one** possible approach to achieve the ET target sensitivity. There might be other, perhaps more elegant or more feasible scenarios even with conventional technologies. A realistic detector design will very likely contain some of the techniques labeled as non-conventional in this document.

- In a first step we **increased the arm length from 3 to 10 km** (ET_sthild_2.m), which reduces all displacement noises (seismic, gravity gradients, suspension thermal, coating Brownian, coating thermo-optic and substrate Brownian noise) by a factor 3.3 and the residual gas pressure noise by about a factor $\sqrt{3.3}$. Please note that all other detector parameter, such as the beam size at the test masses are kept constant.

- Then we adjusted the Signal Recycling from detuned (SR-phase = 0.15) to **tuned Signal Recycling** (SR-phase = 0) in order to maximize the detector bandwidth (by resonant enhancement of both signal sidebands). Additionally we have modified the Signal Recycling mirror transmittance slightly from 11% to 10% as a compromise of peak sensitivity and detector bandwidth (ET_sthild_3.m).

- In a further step we **increased the laser input power** from 125 Watt to 500 Watts which yields an intracavity power of about 3 MW (ET_sthild_4.m). The value of 500 Watts has been chosen by eye as a trade off between improved shot noise at high frequencies and higher radiation pressure noise at low frequencies.

- Then we introduced a **quantum noise suppression factor** of 10 dB (ET_sthild_5.m), which yields a broadband reduction of photon shot noise and radiation pressure noise of about a factor 3.

- Next we chose to decrease coating Brownian noise by **increasing the beam size** at the main test masses. We enlarged the beam radius ($1/e^2$ in power) from 6 to 12 cm (ET_sthild_6.m). This requires test mass
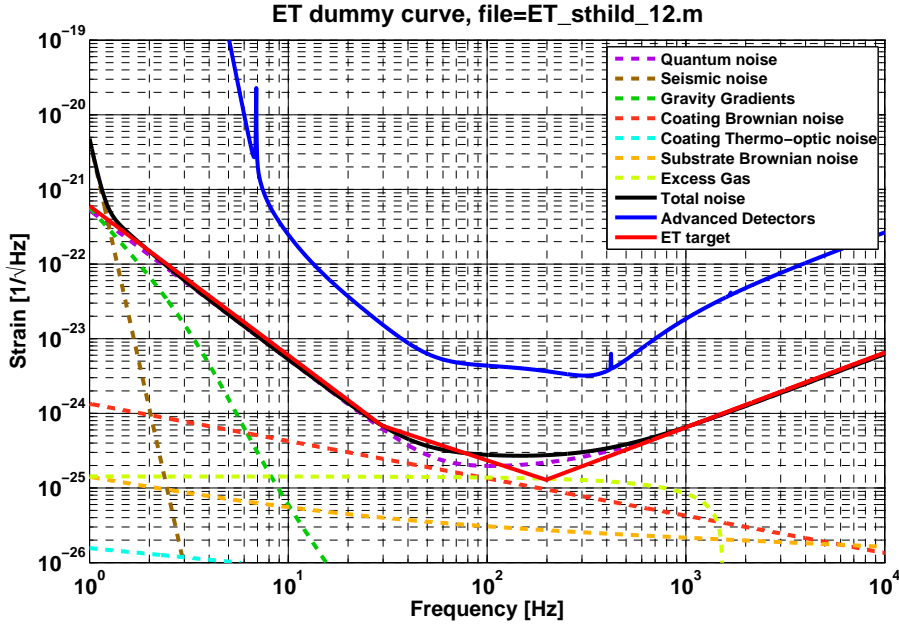
Figure 3: Result from the analysis presented in this document. With the changes suggested above we can roughly achieve (black solid line) the ET design target (red solid line) only using conventional technology. However, in the end it should be possible to further increase the peak sensitivity by simultaneously improving shot noise, coating Brownian noise and residual gas pressure.

radii of curvature of 5070 m for input and end mirrors. This increase of beam size reduces coating and substrate thermal noise by about a factor of 2. In addition, also the residual gas pressure is slightly improved, due to the larger volume of the beam. Please note that assuming such large beams has the consequence that the mirror coatings have to have a diameter of 60 to 70 cm in order to keep the clipping losses within an acceptable range.

- Since the coating noise was still limiting we also had to consider cooling of the optics. Consequently we introduced a **reduction of the temperature** from 290 to 20 K (`ET_sthild_7.m`). Please note that going to cryogenic temperatures could involve a change of the test mass material from fused silica to sapphire.

- In order to reduce the noise from residual gas pressure we had to **improve the vacuum** from $1.2 \cdot 10^{-7}$ to at least $5 \cdot 10^{-9}$ mbar. This challenging value is necessary to get the residual gas pressure noise just a tiny bit below the ET target (`ET_sthild_8.m`).

- The next step was to reduce the seismic noise. We replaced the Virgo super attenuator by a **suspension consisting of 5 stages each 10 m long**.[1] We used a very simplistic model for the suspension transfer function comprising of just 10 simple poles with a corner frequency of 0.158 Hz. For the seismic we used a simplified spectrum ($1 \cdot 10^{-7}$ m/f^2 for $f > 1$ Hz) of the horizontal seismic measured at Virgo site [8] (`ET_sthild_9.m`). Please note that for our new suspensions the suspension thermal noise is considered to be not limiting the ET sensitivity and has therefore been omitted in the following.

- In order to further improve the seismic noise we had to go **underground**. We assumed the underground seismic to be about $5 \cdot 10^{-9}$ m/f^2 for $f > 1$ Hz which corresponds roughly to the seismic level measured in the Japanese Kamioka mine (Slide 26 of [4]). This is assumed to reduce both the seismic noise as well as the gravity gradient noise by a factor of 20 (see `ET_sthild_10.m`).

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[1]A completely different but also somewhat conventional approach to tackle the seismic noise would be to use suspension point interferometry [5].

	advanced detector	potential ET design
Arm length	3 km	10 km
SR-phase	detuned (0.15)	tuned (0.0)
SR transmittance	11 %	10 %
Input power (after IMC)	125 W	500 W
Arm power	0.75 MW	3 MW
Quantum noise suppression	none	10 dB
Beam radius	6 cm	12 cm
Temperature	290 K	20 K
Vacuum	$1.2 \cdot 10^{-7}$ mbar	$5 \cdot 10^{-9}$ mbar
Suspension	Superattenuator	5 stages of each 10 m length
Seismic	$1 \cdot 10^{-7}$ m/f^2 for $f > 1$ Hz (Cascina)	$5 \cdot 10^{-9}$ m/f^2 for $f > 1$ Hz (Kamioka)
Gravity gradient reduction	none	factor 50 required (cave shaping)
Mirror masses	42 kg	120 kg
BNS range	150 Mpc	2530 Mpc
BBH range	800 Mpc	17500 Mpc

Table 1: Summary of the parameter changes necessary to go from the advanced detector sensitivity to the ET design target.

- Even when going underground the gravity gradient noise seems still to be above the ET target sensitivity for frequencies below 6 Hz (see Figure ET_sthild_10 in the Appendix section). Therefore it will be necessary to find some way to further reduce this noise by another factor 50 (maybe by a clever shaping of the caves) to finally get it below the ET sensitivity target (`ET_sthild_11.m`). Please note that this somehow *magic* reduction of gravity gradient noise is the only aspect of our analysis which is not compatible with our initial definition of *conventional*.

- Finally, in order to bring the radiation pressure below the ET design target we had to **increase the weight of the mirrors** from 42 kg to 120 kg (`ET_sthild_12.m`).

The final result of our analysis is shown in Figure 3. With the changes described above we can achieve a sensitivity (black solid line) close to the ET design target (red solid line). Table 1 shows a summary of the parameter changes to transform an advanced detector into a new detector which achieves a sensitivity compatible with the ET design target. Our detector model gives an inspiral range for binary neutron stars of about 2530 Mpc and of about 17500 Mpc for binary black hole systems.

5   Summary and Outlook

The analysis presented in this document indicates that it is, in principle, possible to achieve the ET target sensitivity with *conventional* technology. Only the rather unexplored gravity gradient noise needs to be suppressed by non-conventional techniques in order to be compatible with the ET sensitivity at the very low end of the detection band (below 6 Hz). However, we already know that some of the required up-scalings of existing technologies will introduce new noise couplings. The best example for that is of course the high circulating light power which can introduce stability problems to the arm cavities. Therefore we do not believe that up-scaling existing technologies is always the best or even a viable option for the design of a third generation detector. It is important to explore new detector topologies and new technologies (such as broadband QND-techniques, Sagnac-topologies, displacement noise free interferometry, to list only a few examples) and compare their costs and feasibility to conventional technologies. The purpose of this document is simply to provide the parameters shown in Table 1 as a reference for that work.

6 Acknowledgment

References

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`http://wwwcascina.virgo.infn.it/collmeetings/presentations/2008/2008-07/AdV/hild_160708.ppt`.

[7] `http://ilog.ligo-wa.caltech.edu:7285/advligo/GWINC` (this page requires authentication).

[8] I Fiori, E Marchetti, G. Mayer, F. Paoletti, S. Hild, G. Losurdo, L. Giordano: 'Study of the seismic disturbances produced by the wind park near GEO600', Virgo note VIR-NOT-PIS-1390-317, available at:
`https://pub3.ego-gw.it/codifier/`.

7 Appendix: Intermediate Steps of our Analysis

This section contains all noise budgets from each intermediate step of our analysis presented in Section 4. The file names in the title of each plot corresponds to the item containing the same file name as reference.

ET dummy curve, file=ET_sthild_6.m

ET dummy curve, file=ET_sthild_4.m

ET dummy curve, file=ET_sthild_7.m

ET dummy curve, file=ET_sthild_5.m

ET dummy curve, file=ET_sthild_10.m

ET dummy curve, file=ET_sthild_8.m

ET dummy curve, file=ET_sthild_11.m

ET dummy curve, file=ET_sthild_9.m