Beyond the second generation of laser-interferometric gravitational wave observatories

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Abstract
This paper gives an overview of potential upgrades of second-generation gravitational wave detectors and the required key technologies to improve the limiting noise sources. In addition, the baseline design of the Einstein telescope, a European third-generation gravitational wave observatory, is briefly discussed.

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(Some figures may appear in colour only in the online journal)

1. Introduction

Over the last two decades, major advances have been accomplished in high-precision interferometry, targeting the direct observation of gravitational wave (GW) signals from astrophysical sources. A network of kilometre-scale laser-interferometric GW detectors (LIGO [1], Virgo [2], Tama [3] and GEO 600 [4]) has been constructed and has collected years worth of data from coincident observation at unprecedented sensitivity [5–8].

Currently, major programs are underway to upgrade these instruments (see [9] in this paper for details) and establish the so-called second generation of GW detectors (advanced LIGO [10], GEO-HF [11], LCGT [12] and advanced Virgo [13]). On reaching their target sensitivities in the second half of this decade, these advanced detectors are expected to ensure the first direct detection of GWs [14]. While this will mark the beginning of GW astronomy, only upgrades to the second-generation instruments [15] and subsequently construction of the third-generation instruments, such as the proposed Einstein telescope (ET) [16, 17], will allow us to observe high-SNR GW signals from astrophysical sources on a regular basis. Figure 1 shows the design sensitivity curves of various GW detectors, with blueish, reddish and greenish colours indicating first-, second- and third-generation instruments, respectively. For a summary of what science in terms of astrophysics, cosmology and fundamental physics will be within our reach with a third-generation instrument, such as the ET, please see [18, 19].

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This paper gives an overview of the techniques required to successfully advance beyond the second generation of laser-interferometric gravitational observatories. In addition, some experimental challenges, especially associated with the fundamental noise limitations, are discussed.

2. Paths for the reduction of fundamental noise sources

In order to understand how we can proceed beyond the second generation of laser-interferometric GW detectors, we have to understand by which noise sources instruments like advanced LIGO will be limited. The left plot of figure 2 shows the contributions of fundamental noise sources (coloured traces) to the advanced LIGO sensitivity (black trace) [23, 24]. Here the term fundamental noise source refers to instrument-inherent noise sources, characterized by the actual technical implementation of the GW detector (such as the thermal noise of the mirror coatings or the seismic noise on the test masses). In contrast to fundamental noise sources, the term technical noise source is applied to noise sources, such as beam jitter or laser frequency noise, which can in principle be reduced by implementing an improved performance of the corresponding subsystem. The advanced LIGO design sensitivity is limited over nearly the entire detection band, i.e. for all frequencies above 12 Hz, by quantum noise [25, 26] which consists of photon shot noise at high frequencies (HFs) and photon radiation pressure noise at low frequencies (LFs). In the range from about 50 to 100 Hz, coating the Brownian noise [27] is close to limiting the advanced LIGO sensitivity, while at the LF end of the detection band, the limit is a mixture of thermal noise in the fused silica suspension fibres [31], gravity gradient noise [28–30] and seismic noise. The remaining three noise traces included in the left plot of figure 2, Brownian thermal noise of the mirror substrates, coating thermo-optic noise [32] and excess noise from residual gas inside the vacuum systems [33] only play a secondary role for the advanced LIGO baseline design.

In general, for each fundamental noise source, there are several ways to further reduce it and by that improve the sensitivity beyond the advanced LIGO target sensitivity. These potential improvements vary extremely in terms of implementation cost and required hardware effort.
Quantum noise. There are various ways to decrease the quantum noise, at least in a specific frequency region. Increasing the light power inside the interferometer arms reduces the shot noise level, but at the same time increases the radiation pressure noise. Signal recycling [34] allows the quantum noise contribution to be shaped to optimize the overall detector response. The signal recycling bandwidth and the signal recycling tuning (i.e. the frequency of maximum sensitivity) can be adjusted by means of the reflectivity and microscopic position of the signal recycling mirror [35]. Moreover, the injection of squeezed light states [37] allows us to further manipulate the quantum noise level [36] (see the left plot of figure 3). The techniques mentioned so far require only rather small hardware changes. Other more hardware-intensive ways to further reduce quantum noise include the application of heavier test masses, yielding a reduced susceptibility to quantum radiation pressure noise, the injection of frequency-dependent squeezed light [38] and a multitude of other quantum-nondemolition techniques, such as optical bar [39–41] and speedmeter [42] configurations. Please note that the latter techniques might require a close-to-complete reorganization of the interferometer configuration inside the vacuum facilities (see figure 4). It is also worth mentioning that most of these techniques are not mutually exclusive, but any GW detector beyond the second generation is likely to employ a 'cocktail' of the above-mentioned techniques.

Coating Brownian noise. The techniques under consideration for the reduction of the Brownian noise of the dielectric mirror coatings can be divided into two strands: the first and more obvious class tries to directly reduce the coating noise by applying coating materials or doped materials with better mechanical properties (see for instance [43]), making use of optimized (non-quarterwave) coating layer thickness [44] or employing micro-structure coatings (so-called waveguide mirrors), which can yield as high reflectivity as conventional coatings but with significantly fewer coating layers [45, 46]. In addition, the coating noise can be pushed down by reducing the coating temperature [48, 47], which however would require significant hardware modifications and usually also demand a change of the test
Figure 3. (left) Quantum noise suppression factor versus losses along the path of the squeezed light from the generation to the detection. The differently coloured traces represent various initial squeezing levels. The plot illustrates the importance of a low-loss implementation of squeezed light in GW detectors. Even for a source with infinite squeezing level (red trace), it will be challenging to reduce the losses far enough to achieve a quantum noise suppression better than a factor 3. (right) Cavity g-factor and laser beam radius at the test masses of a 4 km-long Fabry–Perot cavity versus the radius of curvature of the two cavity mirrors. Coating the Brownian noise decreases from right to left, while at the same time the cavity comes closer and closer to its stability limit (g → 1).

Figure 4. Left: simplified schematic of a Michelson interferometer with Fabry–Perot arm cavities as well as power and signal recycling. (centre) Simplified schematic of a Sagnac interferometer featuring arm cavities as well as power and signal recycling. Right: quantum noise limited sensitivity of Michelson interferometer with detuned signal recycling versus a Sagnac speedmeter with similar parameters. As the speedmeter allows us to suppress back action noise (i.e. quantum radiation pressure noise), it provides better LF sensitivity and can therefore be designed to give a significantly larger detector bandwidth for roughly the same peak sensitivity.

mass and coating materials. The second class of techniques tries to reduce the effective coating noise level sensed by the laser beams. The simplest way of doing so would be to increase the beam size on the mirrors and therefore better averaging over the thermal fluctuations. However, the maximum feasible beam size may be limited by the size of the vacuum tubes, by the stability of the cavities (g-factor → 1, see the right plot of figure 3), by the commercially available maximal mirror substrate size or any combination of these three issues. More challenging interferometric techniques capable of reducing the coating contribution include the application of non-TEM\textsubscript{00} laser beam profiles, which yield the readout of a larger effective mirror surface area [49–52]. Furthermore, it has been proposed to decrease the coating noise level by replacing the arm cavity mirrors by anti-resonant cavities or etalons [53, 54]. Again it has to be noted that the above-mentioned techniques are not exclusive, but can often be combined.
• **Suspension thermal noise.** In principle, the least disruptive way to reduce suspension thermal noise is to change the material, especially of the last stage fibres, by the one with better mechanical properties. It has also been shown that a further reduction of suspension thermal noise can be achieved by improvements to the fibre profile, especially at the fibre necks [55]. More hardware-intensive improvements to suspension thermal noise include macroscopic changes of the suspension dimensions and cooling the relevant suspension elements to cryogenic temperatures [56].

• **Seismic noise.** The test mass displacement driven by direct coupling of seismic noise can be reduced by improving the seismic isolation systems. This can be achieved by either increasing the number of isolation stages in passive systems [57] or by reducing sensor and control noise in active seismic isolation systems [58]. Due to the steep slope of seismic noise, any major improvements of the seismic noise level rather requires a shift of the seismic noise wall towards lower frequencies than just improvement of the isolation system by a small factor [59]. One special case of an active seismic isolation is the so-called suspension point interferometer [60], which uses interferometric sensing techniques to stabilize the suspension points of several test masses with respect to each other. A completely different approach to reduce the seismic noise contribution is not to minimize the coupling of the seismic from the ground to the test mass, but to reduce the initial seismic excitation of the ground by building the GW observatory on a seismically quiet location, for instance, underground [61].

• **Gravity gradient noise.** In contrast to seismic coupling via the suspension system to the test masses, which can be tackled by better seismic isolation systems, there is no way to shield the test masses from acceleration caused by seismically driven fluctuations of the gravitational potential. Therefore, the only two discussed methods to reduce gravity gradient noise are building the GW observatory in a location with low intrinsic seismic noise, for instance underground [62] or the application of feedforward or subtraction techniques based on seismic sensor signals [63, 64].

• **Residual gas pressure noise.** The only feasible option to reduce the residual gas pressure noise is to improve the vacuum inside the beam tubes.

From the above discussion, it is clear that there are plenty of options to improve the sensitivity of the second-generation instruments significantly beyond their initial target sensitivity. Figure 2 shows the advanced LIGO sensitivity together with an orange area which indicates a range of illustrative sensitivity limits of advanced LIGO upgrades (see the caption for exact description). This plot also suggests a lack of a well-defined limit beyond which improvements of second generation cannot be pushed any further. In the end, the limits for any improvements are likely to be determined by the point at which further upgrades of the second-generation GW observatories will cost more than it would to reach a similar sensitivity with less hardware effort in a new facility.

3. **The Einstein telescope: a third-generation GW observatory**

In 2008 work started on a Framework Programme 7 funded design study for a third-generation GW observatory, named the Einstein GW telescope, aiming for a 10 times increased sensitivity compared to second-generation instruments. In addition, one of the major goals of this work was to evaluate the possibility of pushing the observation band down to frequencies as low as 1–2 Hz. A detailed description of the completed design study [65] is beyond the scope of this paper, but a brief overview of the corner stones of the ET design is given below.
Table 1. Summary of the key parameters of the ET HF and LF interferometers [22]. FP-MI with DR = Michelson with Fabry–Perot arm cavities and dual recycling, SA = super attenuator, freq. dep. squeez. = squeezing with frequency-dependent angle.

| Parameter                      | ET-HF               | ET-LF               |
|--------------------------------|---------------------|---------------------|
| Arm length                     | 10 km               | 10 km               |
| Interferometer type            | FP-MI with DR       | FP-MI with DR       |
| Input power (after IMC)        | 500 W               | 3 W                 |
| Arm power                      | 3 MW                | 18 kW               |
| Temperature                    | 290 K               | 10 K                |
| Mirror material                | Fused silica        | Silicon             |
| Mirror diameter/thickness      | 62 cm/30 cm         | min 45 cm/ TBD      |
| Mirror masses                  | 200 kg              | 211 kg              |
| Laser wavelength               | 1064 nm             | 1550 nm             |
| SR-phase                       | tuned (0.0)         | detuned (0.6)       |
| SR transmittance               | 10%                 | 20%                 |
| Quantum noise suppression      | freq. dep. squeez.  | freq. dep. squeez.  |
| Filter cavities                | $1 \times 500$ m    | $2 \times 10$ km   |
| Squeezing level                | 10 dB (effective)   | 10 dB (effective)   |
| Seismic isolation              | SA, 8 m tall        | mod SA, 17 m tall   |
| Seismic (for $f > 1$ Hz)       | $5 \times 10^{-10}$ m$^2$ | $5 \times 10^{-10}$ m$^2$ |

The ET observatory will be built in an underground location in order to suppress seismic noise and associated gravity gradient noise, as well as to simplify potential gravity noise subtraction schemes. The observatory will have the overall shape of an equal-sided triangle of 10 km length, housing three GW detectors with an opening angle of 60° each and therefore allowing us to fully reconstruct the polarization of the GW source as well as providing redundancy [66, 67].

Initial design efforts for the ET focused on using one interferometer to cover the full frequency range from 1 to 10 000 Hz [68]. However, analysis of competing noise sources and their corresponding design requirements [69] revealed the difficulty of designing one interferometer that could be extremely sensitive over the full frequency range. For example, achieving good LF sensitivity requires cryogenic test masses to minimize the various thermal noise contributions, but at the same time one would need to use optical power in the megawatt range to obtain good HF sensitivity. Residual absorption in the test masses and their coatings would then cause considerable amounts of heat to be deposited in the test masses, and this would need to be extracted via the mirror suspension fibres. It turns out that this would set impractical requirements on the suspension fibres and their associated thermal noise. Therefore, the ET baseline design adopted a ‘xylophone’ strategy [70–72] and each of the three detectors within the triangle will consist of two individual interferometers, one optimized for the LF range and the other for the HF range [73].

Table 1 gives an overview of the key design parameters of the ET baseline configuration [22]. While the HF detector features technologies similar to what an upgraded second-generation detector might look like, the ET LF detector features a low-power (only 18 kW of circulating power), low-temperature (10 K) design. Going from room temperature operation to cryogenic temperatures requires a change of the test mass material [74] from fused silica to silicon [75], which in turn demands a change of laser wavelength from 1064 nm to $\approx$1550 nm. In addition, the ET LF interferometers employ two 10 km long low-loss filter cavities for the generation of frequency-dependent squeezed light [76]. The left plot of figure 5 shows the resulting sensitivities of the ET LF and HF interferometers, together with their combined sensitivity. A simplified layout of the full ET observatory is shown in the right plot of figure 5.
4. Summary and outlook

As we have seen, the baseline designs of the second-generation gravitational wave (GW) detectors will not exhaust the sensitivity limits of their facilities. A multitude of techniques has been suggested to upgrade the second-generation instruments. Currently, efforts are on the way for down selection of these technologies and the preparation of design proposal for second-generation upgrades.

With the completion of the ET design study, a baseline design for a third-generation GW detector has been presented. Over the next few years, this design will be further refined. The key technologies required to build future GW detectors have been identified over the past few years and current and future research efforts will reveal which of these technologies will provide the highest robustness and the best sensitivity gain.

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