A xylophone configuration for a third-generation gravitational wave detector

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Abstract

Achieving the demanding sensitivity and bandwidth, envisaged for third-generation gravitational wave (GW) observatories, is extremely challenging with a single broadband interferometer. Very high optical powers (megawatts) are required to reduce the quantum noise contribution at high frequencies, while the interferometer mirrors have to be cooled to cryogenic temperatures in order to reduce thermal noise sources at low frequencies. To resolve this potential conflict of cryogenic test masses with high thermal load, we present a conceptual design for a 2-band xylophone configuration for a third-generation GW observatory, composed of a high-power, high-frequency interferometer and a cryogenic low-power, low-frequency instrument. Featuring inspiral ranges of 3200 Mpc and 38 000 Mpc for binary neutron stars and binary black holes coalescences, respectively, we find that the potential sensitivity of xylophone configurations can be significantly wider and better than what is possible in a single broadband interferometer.

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1. Introduction

Over the last decades scientists pioneered the field of laser-interferometric gravitational wave (GW) detection, culminating in the establishment of a worldwide network of large-scale gravitational wave detectors [1–3].

The design and construction of a second generation of GW observatories is well underway and observation with ten times improved sensitivity is expected to start in about 5 years.
[4–6]. Triggered by the Einstein GW telescope (ET) design study within the European FP7 framework [7], research has started on design options for a third-generation GW observatory [8, 9], aiming for a sensitivity 100 times better than first-generation instruments and thus allowing us to detect (amongst other sources) millions of compact binary mergers up to redshifts 2–8 [10]. In addition to improved sensitivity, a key feature of observatories such as ET will be their strongly expanded bandwidth, covering the range from 1 Hz to 10 kHz. Especially the extension of the detection band toward the lower frequency end will increase the number and signal-to-noise ratio of observable gravitational wave signals and therefore significantly enhance the astrophysical impact of third-generation observatories [11].

As we will show in section 2, for achieving the immense bandwidth envisaged for instruments such as ET, it might be highly beneficial, if not even technically unavoidable to split the detection band into several optimized detectors of moderate bandwidth, forming altogether a so-called *xylophone* interferometer covering the full detection band. In section 3, we present for the first time a potential design for a third-generation xylophone configuration, consisting of a low-power, cryogenic interferometer optimized for the low-frequency band and a higher power, room-temperature interferometer covering the high-frequency band.

### 2. Potential benefits of xylophone configurations for third-generation gravitational wave detectors

Spanning the detection band over four orders of magnitude in frequency, as is asked for third-generation GW observatories such as ET, is technically extremely challenging. Different noise types dominate the various frequency bands and often show opposite response for different tuning of the same design parameter.

A well-known example of such behavior is the correlation of the two quantum noise components: photon shot noise (PSN) and photon radiation pressure noise (PRPN). In order to improve the PSN-limited sensitivity at high frequencies, one needs to increase the circulating optical power of the GW detector, which at the same time increases the PRPN and therefore worsens the low-frequency sensitivity. Vice versa, lowering the circulating power reduces PRPN and improves the low-frequency sensitivity, while the PSN contribution will rise and reduce the high-frequency sensitivity.

This dilemma can be resolved by following the path of electromagnetic astronomy, where telescopes are built for a specific, rather narrow-banded, detection window (visible, infrared, etc) and later on the data from different frequency bands are combined to cover the desired bandwidth. Building two or more GW detectors, each optimized for reducing the noise sources in one specific frequency band, can form a xylophone observatory providing substantially improved broadband sensitivity.

The xylophone concept was first suggested for Advanced LIGO, proposing to complement the standard broadband interferometers with an interferometer optimized for lower frequency, thus enhancing the detection of high-mass binary systems [12–14]. The concept was then taken forward for underground observatories [15]. In this paper, we extend the xylophone concept for application in third-generation GW observatories.

One may think that a xylophone might significantly increase the required hardware and its cost by the need to build more than one broadband instrument. However, such an argument does not take into account the technical simplifications that it would allow, the better reliability of simpler instruments and the more extensive scientific reach allowable. For example, splitting a third-generation observatory into a low-power low-frequency and a high-power high-frequency interferometer not only provides the potential to resolve the above-mentioned conflict of PSN and PRPN but also allows us to avoid the combination of high optical power and cryogenic
Table 1. Summary of the most important parameters of the 2-band xylophone detector shown in figure 1.

| Parameter                        | ET-HF       | ET-LF       |
|----------------------------------|-------------|-------------|
| Arm length                       | 10 km       | 10 km       |
| 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 | 62 cm/30 cm |
| 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        | 10 dB       | 10 dB       |
| Beam shape                       | LG13        | TEM00       |
| Beam radius                      | 7.25 cm     | 12 cm       |
| Clipping loss                    | 1.6 ppm     | 1.6 ppm     |
| Suspension                       | Superattenuator | 5 × 10 m |
| Seismic (for f > 1 Hz)           | $1 \cdot 10^{-7}$ m/f² | $5 \cdot 10^{-9}$ m/f² |
| Gravity gradient subtraction     | None        | Factor 50   |

Test masses. To reduce thermal noise to an acceptable level in the low-frequency band, it is expected that cryogenic suspensions and test masses are required. Even though tiny, the residual absorption of the dielectric mirror coatings deposits a significant amount of heat in the mirrors. Since this heat is difficult to extract, without spoiling the performance of the seismic isolation systems, it imposes a limit on the maximum circulating power of a cryogenic interferometer.

3. Example of a 2-band xylophone configuration for the Einstein GW telescope (ET)

Starting from the single-detector ET configuration described in [9], we developed a 2-band xylophone detector configuration to resolve the high-power low-temperature problem of a single-band ET observatory. We consider the xylophone detector to be composed of a low-frequency (ET-LF) and a high-frequency (ET-HF) detector. Both interferometers are Michelson interferometers featuring 10 km arm length and an opening angle of 90°. Due to their similar geometry, both detectors could share a single facility, if beneficial or required. Table 1 gives a brief overview of the main parameters of the analyzed low-frequency (ET-LF) and high-frequency (ET-HF) detector.

3.1. ET-HF detector

The high-frequency interferometer, ET-HF, is an up-scaled but otherwise only moderately advanced version of a second-generation interferometer. We considered an arm length of 10 km and a circulating light power of 3 MW. In order to reach the high-frequency sensitivity aimed at we also assumed the implementation of squeezed light [17] as well as tuned signal recycling (SR) [16], which allows us to simultaneously extract both signal sidebands.
To reduce the thermal noise contributions, limiting the medium frequency range, without resorting to cryogenic temperatures, we considered increasing the beam size as well as the application of alternative beam shapes, such as mesa beams [18] or a higher order Laguerre Gauss (LG) mode [19, 20]. Assuming test mass curvatures of 5070 m results in a beam radius of about 12 cm at all main test masses. Increasing the beam size even further would require polishing accuracy and surface flatness beyond what currently can be achieved. Using the LG33 mode, the coating Brownian and the substrate Brownian noise are reduced by factors 1.61 and 1.40, respectively [21]. Please note that the suspension system of ET-HF is identical to a second-generation GW observatory, but scaled up to cope with the higher mirror mass of 200 kg, required to manage the larger beams with a feasible mirror aspect ratio [22]. The sensitivity curve and the noise budget of ET-HF are shown in the upper subplot of figure 1.

![Graph](image-url)
3.2. ET-LF detector

Unlike ET-HF, the low-frequency xylophone interferometer, ET-LF, will require several innovative techniques, well beyond the scope of first- and second-generation GW interferometers. In order to reduce seismic noise, we assumed an extremely long suspension system, composed of five stages, each 10 m tall, in addition to the reduced seismic level of an underground location [23]. Even though the reduced seismic excitation of an underground site decreases the gravity gradient noise significantly, a further reduction of a factor 50 is required from subtraction of gravity-gradient noise.

The main feature of the LF detector is that all thermal noise sources are significantly reduced by using cryogenic test masses, which is made possible by the reduced optical power of only 18 kW, comparable to that of a first-generation GW detector. Sapphire [24] and silicon have been proposed as test mass material for a cryogenic GW detector. However, material costs and material properties, as well as the available boule dimensions\(^5\) seem to slightly favor silicon. Therefore, we considered silicon test masses cooled to a temperature of 10 K in this paper. The most important material parameters used in our analysis are the Young’s modulus of 10 K silicon of 164 GPa and the loss angles of \(5 \times 10^{-5}\) and \(2 \times 10^{-4}\) for the low and high refraction coating materials, respectively.

Unfortunately the available measurements indicate higher loss angles for the coating materials at cryogenic temperatures than at room temperature [27]. However, since research on cryogenic coatings has just started, we optimistically assumed\(^6\) that by the time construction of third-generation instruments starts, coatings will be available featuring the same loss angles as current coatings at room temperature [25, 26]. The resulting thermal noise contributions of a single cryogenic silicon test mass are shown in figure 2.

\(^5\) It seems for sure that in a few years silicon boules with a diameter of 45 cm will be available. It is not clear whether by the time of ET construction the here-considered diameter of 62 cm will be available. However, even in the case that ET-LF were to be constructed with silicon test masses of only 45 cm diameter, the coating Brownian noise would only be increased by a factor \(62/45 = 1.38\), which would not significantly change the sensitivity of ET-LF (see figure 1).

\(^6\) Please note that even in the case that loss angles of cryogenic coatings cannot be improved in the future, the total mirror thermal noise trace in figure 1 would only increase by about a factor of 2, yielding only a very minor decrease of the ET-LF sensitivity.
Using silicon mirrors also implies changing the laser wavelength from 1064 nm to 1550 nm where silicon is probably highly transmissive and has very low absorption [28]. Changing the laser wavelength has an impact on coating Brownian noise and quantum noise. Due to the fact that for 1550 nm light the mirror coatings have to be about 1.5 times thicker\(^7\), the overall coating Brownian noise is increased by a factor \(\sqrt{\frac{1550}{1064}} = 1.2\). In addition, the PSN is also increased by a factor 1.2, while the PRPN is improved by a factor 1.2.

The resulting noise budget of ET-LF, limited by gravity gradient noise at low frequencies and quantum noise at all other frequencies, is shown in the lower subplot of figure 1. Please note that we omitted suspension thermal noise from our analysis of ET-LF, as this is the subject of ongoing research and so far no mature noise estimate exists. However, it appears likely that the low loss characteristics of crystalline fibers at low temperature may not be a limitation above the gravity gradient level.

3.3. Projected sensitivity of the xylophone configuration

Depending on the requirements of the various data analysis algorithms, the data sets of the two xylophone detectors (ET-LF and ET-HF) can be combined and analyzed either coherently or incoherently. The overall strain sensitivity of the proposed xylophone configuration is shown in figure 3 and compared to the sensitivity of the single broadband ET described in [9]. The resulting inspiral ranges\(^8\) of the xylophone are 3200 Mpc and 38 000 Mpc for binary neutron stars (BNS) and binary black holes (BBH), respectively, significantly larger

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\(^7\) This assumes coating materials with the same index of refraction as used for a wavelength of 1064 nm.

\(^8\) We considered NS of 1.4 solar masses and BH of 30 solar masses. The inspiral ranges are calculated for averaged sky location and a snr of 8. Please note that the stated inspiral ranges neglect any redshifts and are therefore only considered as figure of merit in order to allow quantitative comparison of the different interferometer sensitivities. For such distant objects as the ones ET will be able to measure, the redshift considerably influences the GW signals.
than the ones for the ET single configuration (BNS range = 2650 Mpc, BBH range = 25 000 Mpc). The sensitivity of the xylophone in the intermediate frequency range (50–300 Hz) is slightly worse than that of ET-single, but the overall inspiral ranges improve due to the strongly increased sensitivity around 10 Hz. While the ET-single interferometer is limited by RPN between 2 and 30 Hz, ET-LF can make use of narrow-band detuned signal recycling to further decrease the quantum noise.

4. Summary and outlook

We presented an initial design of a xylophone interferometer for a third-generation GW observatory, composed of a high-power, high-frequency interferometer complemented by a cryogenic low-power, low-frequency interferometer. The xylophone concept provides a feasible alternative (decoupling the requirements of high-power laser beams and cryogenic mirror cooling) compared to a single broadband interferometer (ET-single) and is found to potentially give significantly improved sensitivity.

Future efforts will focus on investigating the prospects of additional xylophone interferometers either to improve the peak sensitivity around 100 Hz or to push the low-frequency wall further down in frequency.

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