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Testing small scale gravitational wave detectors with dynamical mass distributions

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Abstract

The recent discovery of gravitational waves by the LIGO-Virgo collaboration created renewed interest in the investigation of alternative gravitational wave detector designs, such as small scale resonant detectors. In this article, it is shown how proposed small scale detectors can be tested by generating dynamical gravitational fields with appropriate distributions of moving masses. A series of interesting experiments will be possible with this setup. In particular, small scale detectors can be tested very early in the development phase and tests can be used to progress quickly in their development. This could contribute to the emerging field of gravitational wave astronomy.

1. Introduction

The first observation of gravitational waves by the LIGO-Virgo collaboration in November 2015 [1] is seen as the dawn of the age of gravitational wave astronomy. In the next few years, new interferometric detectors will be built and developed, enabling us to learn more about the sources of gravitational waves and the cosmos. The success of the LIGO-Virgo collaboration also sparked renewed interest into the development of alternative detector designs on much smaller scales than the kilometers required for an interferometric detector. Among such proposals are some that consider detectors on scales between meters and micrometers, we shall refer to these as small scale detectors. Proposed systems range from electromagnetic cavity resonators [2–5] and resonant mass detectors [6, 7] over Bose–Einstein condensates [8, 9] to a microwave cavity resonator coupled to a superfluid helium container [10, 11]. Some proposals for small scale detectors are based on quantum technologies, for example the one presented in [8, 9]. With the advancement of quantum technologies that will be promoted by funding initiatives like that by the European Commission in the next years, we expect many more proposals for small scale gravitational wave detectors to appear.

The main advantage of small scale detectors is that a single detector would be cheap in comparison to an interferometric detector and a lot of them could be built to achieve high directional resolution. One could even imagine a network of hundreds of small scale gravitational wave detectors throughout the world with collective data analysis. The disadvantages of small scale detectors are: they are usually narrow band, they often operate in a high frequency band and they need long integration times to achieve the necessary sensitivity for a detection. This makes most of them only applicable for persistent sources of gravitational waves. The disadvantages could be possibly overcome by design adjustments and long term development. In particular, it would be beneficial if prototypes could be tested and evaluated with artificially created gravitational signals of larger amplitudes than those expected from gravitational wave sources. Unfortunately, it is nearly impossible to artificially create gravitational waves of significant amplitude. However, the effect of local oscillating gravitational fields on a small scale detector can resemble the effect of gravitational waves sufficiently to serve as test signals which can be created with comparatively large amplitudes. In this article, we propose tests of small scale gravitational wave detectors that could be performed by employing moving masses, creating local gravitational fields that resemble gravitational waves on the length scale of the detectors.

Note that the approach presented in this article is similar in spirit to the calibration methods developed for interferometric detectors [12] and resonant mass detectors [13–19]. However, the size of the small scale detectors considered in this article allows for sizes of the sources of gravitational fields, and the amplitudes of their oscillations to be significantly reduced as well. This can lead to a high level of control of systematics as discussed in [20]. More importantly, the reduced scales allow for the gravitational field of a plane gravitational wave like those expected from distant astronomical sources to be mimicked as we show in this article. In general, as we are facing a new generation of resonant gravitational wave detector proposals, we consider it worthwhile to start a new discussion about possibilities for tests and calibrations adopted to the new detector proposals.

The basic framework that we will employ in this article is linearized gravity, where the spacetime metric $g_{\mu\nu}$ is considered to differ just slightly from the flat Minkowski metric $\eta_{\mu\nu}$. We define the perturbation of the metric as $h_{\mu\nu} = g_{\mu\nu} - \eta_{\mu\nu}$ and we assume that $|h_{\mu\nu}| \ll 1$ for all μ, ν in an appropriately chosen set of coordinates.

2. Gravitational wave metric

Since sources of gravitational waves are usually very distant, we can restrict our considerations to plane gravitational waves. The perturbation of the spacetime metric $h^{\mathrm{w}}_{\mu\nu}$ (the superscript w standing for wave) corresponding to a plane gravitational wave that propagates in the positive or negative z-direction has only four non-zero components $h^{\mathrm{w}}_{11} = -h^{\mathrm{w}}_{22} = h_+$ and $h^{\mathrm{w}}_{12} = h^{\mathrm{w}}_{21} = h_\times$ in the transversal-traceless (TT) gauge which is a specific coordinate system in which freely falling massive test particle at rest stay at rest. Here, h_+ and $h_\times$ are the strains corresponding to the two polarization directions $+$ and $\times$, respectively. If we assume propagation in the positive z-direction and consider a monochromatic wave of angular frequency ω, the corresponding strains can be written as

$$\begin{aligned} h_{+,\omega}(t, z) &= h_{0,+,\omega}\cos(\omega(t - z/c) + \varphi_+) \\ h_{\times,\omega}(t, z) &= h_{0,\times,\omega}\cos(\omega(t - z/c) + \varphi_\times). \end{aligned} \tag{1}$$

The TT gauge corresponds to an appropriate coordinate system for the analysis of interferometric detectors such as LIGO and Virgo, since their mirrors are, in approximation, freely falling along the beam line of the interferometer. For the analysis of local detectors, a different coordinate system is much better suited—the proper detector frame [7], which was introduced in [21]. The proper detector frame corresponds to the coordinate system constructed by an observer using rigid rods to define spatial coordinates from the center of the observer's laboratory and a clock at the center of the observer's laboratory to define time. This leads to an expression of the spacetime metric in the constructed coordinates which is valid up to quadratic terms in the spatial coordinates as long as the wavelength of the gravitational wave is much larger than all extensions of the detector system. For a freely falling observer, the proper detector frame is commonly called Fermi normal coordinates [22].

For a freely falling laboratory in the spacetime defined by $\eta_{\mu\nu} + h^{\mathrm{w}}_{\mu\nu}$, the metric perturbation in the laboratory's proper detector frame has the form

$$h^{\mathrm{w,P}}_{\mu\nu} = \ddot{h}_+(t, 0)M_{+,\mu\nu}/c^2 + \ddot{h}_\times(t, 0)M_{\times,\mu\nu}/c^2, \tag{2}$$

where the superscript P stands for proper detector frame, the dots denote the second time derivative of the strain functions and the components of the matrices $M_{+,\mu\nu}$ and $M_{\times,\mu\nu}$ are second order polynomials in x and y. They are explicitly given as

$$M_{+,\mu\nu} = \begin{pmatrix} \frac{x^2-y^2}{2} & \frac{xz}{3} & -\frac{yz}{3} & -\frac{x^2-y^2}{3} \\ \frac{xz}{3} & \frac{z^2}{6} & 0 & -\frac{xz}{6} \\ -\frac{yz}{3} & 0 & -\frac{z^2}{6} & \frac{yz}{6} \\ -\frac{x^2-y^2}{3} & -\frac{xz}{6} & \frac{yz}{6} & \frac{x^2-y^2}{6} \end{pmatrix} \text{ and } M_{\times,\mu\nu} = \begin{pmatrix} xy & \frac{yz}{3} & \frac{xz}{3} & -\frac{2xy}{3} \\ \frac{yz}{3} & 0 & \frac{z^2}{6} & -\frac{yz}{6} \\ \frac{xz}{3} & \frac{z^2}{6} & 0 & -\frac{xz}{6} \\ -\frac{2xy}{3} & -\frac{yz}{6} & -\frac{xz}{6} & \frac{xy}{3} \end{pmatrix} \tag{3}$$

Equations (2) and (3) can be derived using the general expressions for the proper detector frame metric in equation (1.87) of [7] and expressions for the components of the Riemann curvature tensor of the metric perturbation in the TT-gauge above[3]. Note that earthbound detectors will never be freely falling. Instead of equation (1.87) of [7] one would need to employ equation (1.88), which contains rotation and acceleration of the detector system. Effects of the upward acceleration of the detector against the gravitational field of the Earth can

[3] Explicit expressions for the curvature components corresponding to a plane gravitational wave propagating in the negative z-direction can be found in equation A.14–16 in [23].

be neglected if x and y are assumed to be the horizontal directions. Remaining contributions to the proper detector frame metric are the rotation of the Earth, vibrational and rotational noise. Those have to be analyzed taking specific experimental conditions into account once a realization of our proposal is considered. This is not part of this article.

From the geodesic equations that govern the motion of massive particles in the field of the gravitational wave, we obtain the following acceleration for any part of the small scale detector that does move with non-relativistic velocity v^j:

$$\frac{d^2\gamma^i}{dt^2} \approx \frac{c^2}{2}(\partial_i h_{00}^{\mathrm{w,P}} - 2\partial_t h_{0i}^{\mathrm{w,P}}/c + 2v^j(\partial_i h_{0j}^{\mathrm{w,P}}/c - \partial_j h_{0i}^{\mathrm{w,P}}/c - \partial_t h_{ij}^{\mathrm{w,P}}/c^2)), \tag{4}$$

where $i, j \in \{x, y, z\}$. Equation (3) gives the tidal forces induced by the gravitational wave that deform the small scale detector. This deformation is the fundamental mechanism on which measurement is based for all examples of small scale detectors mentioned in the introduction.

We find that the dynamical effects of all components of the metric perturbation besides $h_{00}^{\mathrm{w,P}}$ are suppressed in comparison to the strongest dynamical effects of $h_{00}^{\mathrm{w,P}}$ (which are, above all, used for the detection processes in the examples for small scale detectors considered here); either by at least a factor v/c, where v is the largest speed in the detector system (see also section 17.4 of [24]) or by at least a factor $l\omega/c$, where l is the largest extension of the detector system. For all the examples of detectors given in the introduction, the detector's parts used for sensing the gravitational field are moving very slowly in comparison to the speed of light. So we can assume that $v/c \ll 1$. Furthermore, for frequencies between kHz and MHz and extensions of the detector systems at or below the meter scale, we have $l\omega/c \ll 1$. Of the various local detectors that we mentioned in the introduction, only the electromagnetic resonators [2–5, 10, 11] contain parts that move at high speeds—namely the electromagnetic radiation in the resonator. However, the light is only used to 'read out' deformations of the resonator, a slowly moving system of massive matter; what is used for measurement is not a direct effect of the gravitational field on the light. Therefore, this effect can be neglected[4].

There is also an effect on length scales by the purely spatial components of the metric perturbation; the spatial components contribute to the length scale associated with rigid rods associated with the proper length $l_p = \int d\varsigma \sqrt{g_{\mu\nu} s'^{\mu} s'^{\nu}}$, where s' is the tangent to a space like geodesic along which the length is measured. Therefore, the change of proper length due to the metric perturbation l_p is proportional to $h_{\mu\nu}^{\mathrm{w,P}}$. The deformation of the detector systems due to tidal forces, the basic mechanism of the detection process, can be derived from the acceleration $d^2\gamma^i/dt^2$ in equation (3) via Hook's law. If we assume that the detector system is constructed from rods and shear forces are neglected, the observations of [28], in particular, equation (30) with $a^x = 0$ can be applied; deformations of the matter system are proportional to $c^2\rho h_{\mu\nu}^{\mathrm{w,P}}/Y$, where Y is Young's modulus and ρ is the mass density for the material the detector system consists of (note that $Y/\rho = c_s^2$, where c_s is the speed of sound in the material). We find that the proper length change is smaller than the tidal length change by roughly a factor $Y/\rho c^2$. The stiffest material per density is carbyne, with a specific modulus Y/ρ of the order of 10^9 m^{2}s^{-2}. The specific modulus of the used solid state matter is usually much smaller than the extreme value for carbyne. For example, the specific modulus of aluminum is 2.6×10^7 m^{2}s^{-2}. This corresponds to $Y/(\rho c^2) \sim 10^{-10}$. Due to the size of this factor, we can expect that even when different geometries of the detector systems or shear forces are considered, proper length changes can be neglected in comparison to material deformations.

In summary, we are justified to restrict our considerations to the component

$$h_{00}^{\mathrm{w,P}} = \ddot{h}_+(t, 0)(x^2 - y^2)/2c^2 + \ddot{h}_\times(t, 0)xy/c^2. \tag{5}$$

Due to our arguments above, these deformations are the only significant gravitational effects on the small scale gravitational wave detectors[5]. Then, a metric perturbation that generates, to a good approximation, the same physical effects as $h_{\mu\nu}^{\mathrm{w,P}}$ can be generated by an appropriate distribution of masses, as we will show in the following.

3. Newtonian limit

Restricting our considerations to $h_{00}^{\mathrm{w,P}}$ and setting all other components of the metric perturbation formally to zero, we obtain a perfect Newtonian frame for the case of a gravitational wave; the spatial part of the metric is flat,

[4] If the light is used for the sensing like in the detector proposal described in [25–27], the response of the detector on $g_{\mu\nu}^{\mathrm{N}}$ has to be evaluated explicitly.

[5] This statement is also derived in [7] using the equation of geodesic deviation and the curvature tensor).

diagonal and normalized and there are no space-time mixed terms in the metric (see section 17.4 of [24]). A similar situation arises for the mass distribution if we assume that the source masses that are used to mimic the gravitational wave metric move with non-relativistic speed. Since we already assumed that the parts of the detector used for sensing the gravitational field are moving non-relativistically, we obtain the Newtonian limit which is well defined in linearized gravity (see section 6.3 of [29] and section 17.4 of [24]). More explicitly, for an oscillatory motion of the source masses with frequency ω on length scales l_s, we obtain velocities of the order $l_s\omega$. Therefore, the time derivatives of the metric perturbation are smaller than its spatial derivatives by a factor $l_s\omega/c$ and the corresponding non-Newtonian effects are suppressed by the same factor. For frequencies in the kHz regime and amplitude of the source mass motion of the order of millimeters, this amounts to the order 10^{-8}. Therefore, time derivatives of the metric perturbation and the corresponding non-Newtonian effects can be safely neglected for our considerations. Sometimes, gravitational fields of this kind are called quasi-stationary [30]. The slow motion of the detector parts in comparison to the speed of light leads to a suppression of all other non-Newtonian effects as those are at least proportional to the velocity of the affected system.

Now, we write the spacetime metric as $g^{\rm N}_{\mu\nu} = \eta_{\mu\nu} + h^{\rm N}_{\mu\nu}$. In the Newtonian limit, the only component of the metric perturbation that we have to take into account is the component $h^{\rm N}_{00} = -2\Phi/c^2$, where Φ is the Newtonian potential [24, 29]. Depending on the design of the small scale gravitational wave detector, the effect of the other components of the metric perturbation on the detector may be investigated explicitly. In a specific set of coordinates (the Lorenz gauge), we can identify $h^{\rm N}_{00} = -2\Phi/c^2$ as before and have only three other non-zero components of the metric perturbation; the three diagonal spatial components. Furthermore, they are all equivalent to the time-time component, i.e. $h^{\rm N}_{11} = h^{\rm N}_{22} = h^{\rm N}_{33} = h^{\rm N}_{00}$[6]. However, for the detector proposals mentioned in the introduction, the same arguments that we used above to neglect all components of $h^{\rm w,P}_{\mu\nu}$ besides $h^{\rm w,P}_{00}$ can be applied to $h^{\rm N}_{ii}$. Therefore, we can restrict our considerations to $h^{\rm N}_{00} = -2\Phi/c^2$ in the following.

4. Gravitational wave substitutes

The only step that remains in order to mimic a gravitational wave for small scale gravitational wave detectors is the creation of a situation in which $h^{\rm N}_{00}$ matches $h^{\rm w,P}_{00}$. We consider two examples here—a distribution of spheres and a distribution of cylinders. First, let us consider four oscillating spheres of the same mass M placed at the same distance from the detector. Two of these spheres are placed along the x-axis on opposite sides of the detector. They oscillate along the x-axis in opposite directions. We assume a similar situation for the two other spheres along the y-axis (see figure 1). Such a situation could be realized by holding the spheres by levers. This would be similar to the experimental proposal described in [20], where the gravitational field of a single oscillating mass is planned to be measured. The x-y-plane could be arranged horizontally and the levers could be attached such that the space between the spheres would be empty except for the detector. In particular, we assume that the spatial positions of the centers of the spheres (x, y, z) are given as $(\pm(L - \delta L(t)), 0, 0)$ and $(0, \pm(L + \delta L(t)), 0)$, where $\delta L(t) = \delta L_0 \cos(\omega t + \phi)$. For the time-time component of the metric perturbation in the Newtonian limit expanded up to quadratic terms in the spatial coordinates, we then obtain

$$h^{\rm N}_{00} = \frac{2GM}{c^2}\left(\frac{r^2 - 3z^2}{L^3} + \frac{9}{L^4}(x^2 - y^2)\delta L(t)\right), \tag{6}$$

where G is Newton's constant and $r = \sqrt{x^2 + y^2 + z^2}$. The constant term in equation (5) can be considered as a small offset that has at most a time-independent effect on the detector readout. The constant term vanishes if one places two more spheres at the static spatial positions $(0, 0, \pm L)$. Comparison of the oscillating term in equation (5) with the metric perturbation due to a plane gravitational wave in equation (4) and equation (1) leads to the conclusion that we need the conditions $18GM\delta L_0/L^4 = \omega^2 h_{0,+,\omega}/2$ and $\phi = \varphi_+ + \pi$ to be fulfilled to create the effect of the plane gravitational wave of + polarization specified above. Accordingly, we can rotate our whole setup in the x-y plane by 45° to create the effect of a plane gravitational wave of × polarization. Since we are working in linearized gravity, we can superimpose the two setups by using 8 spheres (10 to eliminate the offset) to mimic a gravitational wave of any polarization. Furthermore, we can simulate a general gravitational wave pattern by superimposing oscillations of the masses of different frequencies.

Another possibility to eliminate the constant term in $h^{\rm N}_{00}$ is to replace the spheres with long cylinders oriented in the z-direction. Let us assume that the centers of the cylinders follow the same trajectories in the x-y-plane as we assumed for the centers of the spheres above. Furthermore, let us assume that the cylinders are much longer than the extension of the detector. Then, the Newtonian potential of a single rod can be written as $\Phi^{\rm rod} = 2\rho AG\ln(R/R_0)$, where ρ is the mass density of the rod, A is its cross section and R is the distance to the

[6] This metric can be derived directly from the linearized Einstein equations and the energy momentum tensor for a non-relativistic point particle in the Lorenz gauge [31].

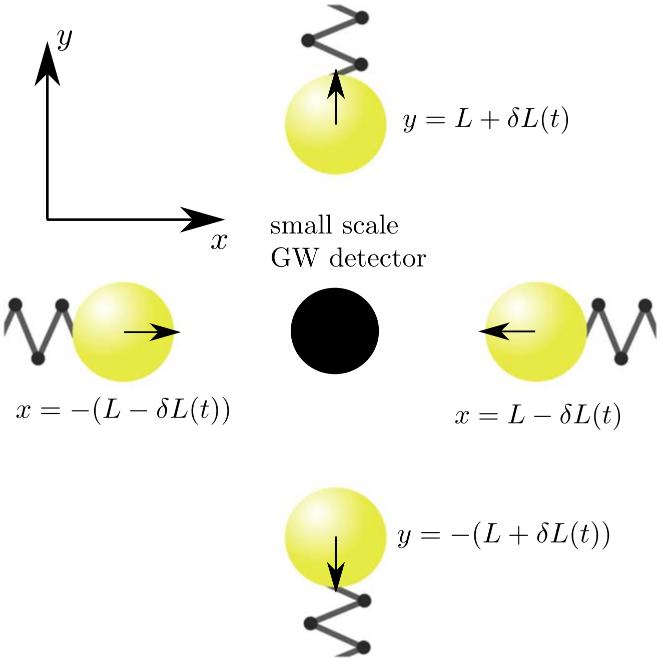

Figure 1. Schematic representation of the setup to mimic the effect of a gravitational wave on a small scale gravitational wave detector. The detector is placed at the center of a distribution of four spheres (possibly hold by levers [20]) that oscillate towards and away from the detector. Opposing spheres have half a period phase shift, while there is a phase shift of quarter of a period between neighboring spheres. A gravitational wave of ×-polarization can be mimicked by rotating the setup by 45° in the *x*-*y*-plane. Another two masses placed along the *z*-axis above and below the detector are needed to cancel constant tidal forces induced by the spheres in the *x*-*y*-plane.

center of the rod. In this work, R_0 can be considered as an arbitrary constant of the same dimension as R that is only introduced to obtain a dimensionless expression in the logarithm. It will not contribute to any physical effect here. The time-time component of the metric perturbation for the set of four moving cylinders expanded up to quadratic terms of the spatial coordinates becomes

$$h_{00}^{\mathrm{N}} = \frac{16\rho AG}{c^2L^3}(x^2 - y^2)\delta L(t), \tag{7}$$

and we can identify $16\rho AG\delta L_0/L^3 = \omega^2 h_{0,+,\omega}/2$ and $\phi = \varphi_+ + \pi$.

To accurately mimic the component h_{00}^{N} of the metric perturbation due to a gravitational wave, the masses and the detector have to be positioned precisely. Small displacements from the setup described above may lead to a net gravitational force on the center of mass of the detector or additional tidal forces. However, the positioning of the masses and the detector can be achieved with sufficient precision[7], so that the acceleration/additional gravitational effects/tidal forces would be small in comparison to the mimicked effect of a gravitational wave.

Note that the designs of the detectors mentioned in the introduction are so that their detection efficiency is maximal for a certain orientation of the detector with respect to polarization plane of the gravitational wave. In the setup proposed in this article, the polarization plane is fixed (*x*-*y*-plane) and the local detector can always be oriented to maximize detection efficiency.

5. Signal amplitudes

Let us evaluate the effective signals that one can mimic with spheres and cylinders for some specific experimental parameters. We found that $h_{0,+,\omega} = 36MG\delta L_0/L^4\omega^2$ for the spheres and $h_{0,+,\omega} = 32\rho AG\delta L_0/L^3\omega^2$ for the cylinders. Let us assume that the detector systems that we consider have dimensions below the meter scale. Accordingly, we assume that the distance from the detector to the source masses L is of the order of 1 m. Furthermore, let us assume that the angular frequency ω of interest is around $2\pi \times 10^3$ Hz. Let us assume that we are able to move spheres from tungsten or gold of $M = 20$ mg (corresponding to a diameter of about 1 mm) at this frequency by a distance of about 100 μm. Then, we obtain that we can mimic a strain of the order of 10^{-25}. For gold or tungsten cylinders with diameters of about 0.5 mm as source masses, we find a mimicked strain of

[7] Positioning is usually possible with a relative error of, at most, the order of 10^{-3} and, in principle, down to an absolute error of 0.1 μm given a good reference point using commercially available high accuracy positioners.

the order of 10^{-23}. For the case of gravitational wave detectors on the centimeter scale like that proposed in [8], the distance between the detector and the source masses L can be reduced to the order of 10 cm, which leads to mimicked strains of the order of 10^{-21} for spheres and 10^{-20} for cylinders or strings.

A strain of the order of 10^{-20} is 5 orders of magnitude larger than the strain that is claimed to be detectable with the design proposed in [8]. In [10], it is claimed that a sensitivity for strains of the order of 10^{-26} could be expected for the first generation detector proposed in the article (denoted as Gen1 in the article). The dimensions of this detector would be about 50 cm. Therefore, L can be of the order of meters and strains could be mimicked that are up to 3 orders of magnitude larger than the expected sensitivity of the Gen1 detector in [10]. Therefore, the mimicked strains could be used as a tool to experimentally test the proposed detector designs.

For frequencies of the order of MHz, larger masses have to be moved to obtain large strains. However, besides very extreme sources like galactic center branes, most expected sources of gravitational wave signals of frequencies at or above the MHz regime give rise to strains of the order of 10^{-29} and less [32]. To test appropriate proposals for small scale detectors for the MHz range already during the engineering phase, gravitational waves with strains of the order of 10^{-27} could be mimicked with steel strings with diameters of about 100 μm using oscillation amplitudes of the order of 100 μm and a distance of 10 cm between the sources and the detector.

Note that smaller strains of exactly the same order as the expected gravitational waves can always be mimicked by increasing the distance between the source masses and the center of the detector system.

How vibration isolation of sources and detector can be achieved for experiments with oscillating masses in the milligram range was discussed in [20] and in much detail in the thesis of Jonas Schmöle at the University of Vienna [33]. An experimental proposal is presented in which a source mass of about 100 mg is moved at a frequency of about 10 Hz and its gravitational effect on a test mass is measured. The vibration isolation is implemented through several mechanical vibration isolation stages in the suspension of detector and source. The experiment proposed in [20] is currently set up in the laboratories of Markus Aspelmeyer in Vienna. Vibration isolation with mechanical isolation stages in the suspension is similar to the techniques developed for vibration isolation of the parts of interferometric gravitational wave detectors like LIGO and Virgo. There, up to 7 individual isolation stages are used in the suspension of the test masses leading to a significant suppression of seismic noise [34]. Similar techniques should be used for the test of small scale gravitational wave detectors. A more detailed analysis will be necessary to obtain the precise experimental requirements.

Furthermore, for the design of an explicit experimental realization of our proposal, an extensive modeling of the gravitational fields induced by all parts of the source system and the surrounding devices would need to be conducted. However, all parts can, in principle, be taken into account and engineered appropriately. In particular, levers that are used to move the source masses can be positioned respecting the same symmetries as the source masses which only leads to an increase of the mimicked strain. In the case of the oscillating rods or strings as source masses, those could be made long enough such that the devices that set them in motion are far from the detector system.

6. Conclusions

We found that the effect of a gravitational wave on a small scale gravitational wave detector of any type mentioned in the introduction can be mimicked by a system of 10 oscillating spheres or a system of 8 oscillating cylinders. In principle, strains can be mimicked that are several orders larger than the sensitivities claimed by some of the proposals [8, 10]. Additionally, the orientation of the polarization plane of the mimicked gravitational waves is known and the local detectors can be oriented so that their signal is maximized. Therefore, the setup proposed in this article can be used to test prototypes of small scale detector designs. Viable detector designs could be singled out and developed with concentrated effort. The possibility to mimic gravitational wave signals of any type could also be extremely helpful in the engineering and development stage of the detectors, as problems could be identified and performances could be optimized. The great advantage of the scheme presented here is the possibility of mimicking persistent sources. Most of the small scale detector proposals need large integration times, which makes them more useful for the detection of persistent sources. The parameters of the setup needed to test a specific small scale gravitational wave detector proposal have to be specified depending on the parameters of the detector design; most importantly the frequency band and the size of the detector.

In our derivation, we assume the Newtonian limit of linearized gravity which requires the assumptions of non-relativistic motion of the source masses that are used to mimic the effect of a gravitational wave. Furthermore, we assumed that all parts of the detector that are directly interacting with the gravitational field to realize the sensing process are moving with non-relativistic speed. This is not the case for some proposals, such as those presented in [25–27]. For these proposals, the additional relativistic effects have to be taken into account.

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