Interferometric gravitational wave detectors: state of the art and fundamental noise issues

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Abstract. Interferometric gravitational wave detectors, such as Virgo in Italy, LIGO in the US and GEO600 in Germany, have already completed scientific data runs. 2nd generation detectors, such as Advanced Virgo and Advanced LIGO will start operation within the next 5 years and preliminary design studies have already begun for 3rd generation detectors. It is hoped that we will soon be able to reach the holy grail of the first direct detection of gravitational radiation and start the exciting field of gravitational wave astronomy. The LIGO Scientific Collaboration (LSC) and the Virgo collaboration have published many observational results of great scientific relevance. For the future, the main challenge is to further increase the detector sensitivity by reducing the instrumental noise, in particular quantum noise, i.e. a fundamental noise term intrinsic to the measurement process itself. This can be achieved by the implementation of forefront quantum optics techniques.

1. Introduction
Several large km-scale interferometric gravitational wave detectors, like the Virgo detector in Italy, near Pisa, and the two Laser Interferometric Gravitational Observatory (LIGO) in the US, one in Hanford, WA and the other in Livingstone, LA, have taken scientific data on and off for the last three years. No detection claim has been made so far, but some scientifically important results in the form of upper limits have been obtained for the amplitude of the Stochastic Gravitational Wave Background and for the ellipticity of the pulsars. In this paper we will briefly describe their main results, then we will describe the noise terms which limit their sensitivity and possible schemes to improve the sensitivity.

2. Main scientific results obtained so far
One of the most important results obtained by the LSC and the Virgo collaboration is the result on continuous waves. According to astrophysical estimates there are roughly $\mathcal{O}(10^4)$ electromagnetically quiet neutron stars within a radius of 500 pc. Only a tiny fraction of them is in the band of interest for gravitational wave detectors. Pulsars in the frequency band between 50 and 1100 Hz were studied, and a new limit on the ellipticity was placed: $\epsilon \leq 10^{-6}$ [1]. This limit is more stringent than previous limits that were based on population synthesis models. The second result of great importance was published on Nature: it is an observational result about the Stochastic Gravitational-Wave Background [2]. The indirect but very stringent limit on the Stochastic Background coming from the Primordial Nucleosynthesis theory was surpassed, as shown in Figure 1, and even some cosmic string models were ruled out.
3. Advanced detectors
2nd generation detectors will start operation around 2015. Their sensitivity is expected to be an order of magnitude better than current interferometers'. GW detectors measure the amplitude which scales as $1/r$, and not the power which scales as $1/r^2$. For GW detectors, the number of detectable sources grows linearly with the volume. An improvement in one order of magnitude in the sensitivity means an horizon one order of magnitude bigger and therefore an accessible volume $10^3$ times bigger. For example Virgo can see a coalescence of Neutron Stars up to $d = 15$ Mpc and the event rate is $0.01 \rightarrow 0.1$ per year. A detector with a sensitivity better by an order of magnitude would thus be able to see up to $d = 150$ Mpc, with an expected event rate of $10 \rightarrow 100$ per year. Advanced detectors will hopefully mark the birth of gravitational-wave astronomy.

4. Noise issues
Test masses in interferometric GW detectors do move also because of effects that have nothing to do with a real GW signal. These effects are generically called displacement noise. Seismic noise is the noise due to human activity (cars, trains, etc) as well as to a micro-seismic background (sea tides). Seismic isolation systems make this noise relevant only below a certain frequency threshold, also called seismic cutoff; currently, the lowest cutoff, at 3 Hz, is obtained by Virgo thanks to its superattenuator system [3]. Newtonian noise is given by the fluctuations of the static gravitational field. It is negligible in the whole Virgo-LIGO band, 1 Hz − 10 kHz but represents a fundamental limit for ground-based detectors [4]. No ground-based detector can go below 1 Hz, although noise reduction schemes based on accelerometers have been proposed [5].
Thermal noise induces vibrations both in the suspension wires and in the mirrors. Its effects can be understood in terms of the Fluctuation-Dissipation Theorem. The main contribution between 3 and 30 Hz comes from the pendulum thermal noise (horizontal displacement of test masses). Violin modes, i.e. fluctuations of the normal modes of the wire, give some spikes from 300 Hz onwards. Test-mass thermal noise is largely dominated by the Brownian motion of the mirrors, which is the limiting noise source between 30 and 250 Hz. Another important contribution is the thermo-refractive noise (refraction index of the coating depends on temperature). To these noise terms we must add what we call “accidental noise”, i.e. noise such as the residual pressure of the vacuum, micro-roughness of the mirrors, fluctuations of the laser power as well as technical noise (longitudinal control noise) and spurious coupling between seismic noise and the electromagnetic fields.

5. Quantum noise and the Standard Quantum Limit
Quantum noise is intrinsic to the measurement process. Quantum theory introduces an intrinsic uncertainty into the amplitude and phase. There are two major contributions: Radiation-pressure noise and Shot noise [5]. Radiation-pressure noise is given by uncertainties in the mirror position due to quantum fluctuations exerting fluctuating radiation pressure on the mirrors. Shot-noise uncertainties are due to quantum mechanical Poissonian fluctuations in the number of photons at the interferometer output. Radiation-pressure noise and shot-noise are associated with two orthogonal quadratures of the electromagnetic field [6]. An important concept is that of the Standard Quantum Limit (SQL). For gravitational-wave detectors, the SQL is obtained by exactly balancing radiation-pressure and shot-noise. It is the intrinsic limit on the accuracy with which any position-sensing device can determine the position of a free mass. The SQL in a GW detector with input power $I_0$ can be written as $S_x S_p \geq 1/4$, where $S_x \propto 1/I_0$ is the power spectral density of position fluctuations due to the uncertainty in the number of photons and $S_p \propto I_0/f^2$ is due to the back-action (radiation-pressure). The two noise terms dominate in different frequency regions. For current detectors, whose laser input power is low, radiation-pressure is completely negligible. For Advanced detectors radiation-pressure will also be important. Optical noise sources implement the SQL only if they are uncorrelated. In Figure 4 we show the contributions of the two quantum noise sources.

There exists an optimal quantum power that minimises the total quantum noise. Quantum noise is due to vacuum fluctuations entering the unused port at the beam-splitter. Shot noise can be reduced by rendering asymmetric the noise entering that port. A squeezed state is asymmetric by definition and can thus reduce shot noise. Injecting squeezed vacuum (non-linear crystals) into the unused port can reduce the dominant noise source by a factor $S_0 \propto \exp(-2R)$ where $\exp(-2R)$ is the power squeeze factor. This configuration is equivalent to an unsqueezed interferometer with an increase to the laser power by the squeeze factor. Squeezing can thus help reduce the circulating power without losing in sensitivity. Injected squeezed vacua is not the only possibility to use squeezed states: if carrier light with side bands reflects off a mirror, the side bands are ponderomotively squeezed. Correlations are created between the two quadratures. If the position signal is measured in the phase quadrature, we have $b = \kappa(f) \Delta A + \Delta \phi + h$. These correlations are not useful if direct photon detection is used, because in this case we would reduce the noise in one quadrature, but increase it in the other. If we manage to measure an admixture of quadratures with frequency dependent homodyne detection scheme (angle) that is function of $\kappa$, then it is possible to completely remove radiation-pressure noise from the measurement [7]. There are some experimental requirements that have to be met, in order for squeezing to be useful: Squeezing in the whole detection band 10 Hz $\rightarrow$ 10 kHz; this is experimentally feasible, as shown by R. Schnabel’s group in Hanover and by P K Lam’s group in Canberra. Other requirements are a high level of squeezing, ideally 10 dB or higher (and the current record is currently 13 dB), long term stability, which, like the previous item, is
mainly a technical problem and a frequency-dependent squeezing angle, which is perhaps the most challenging issue. 3rd generation detectors, i.e. detectors that will follow Advanced LIGO and Advanced Virgo, such as the Einstein Telescope (ET) are likely to be quantum noise limited over the whole frequency range and therefore will certainly implement squeezing [8], as well as other techniques of non-classical interferometry [9].

6. Holographic noise

Quantum theory implies a minimum time, the Planck time \( t_{\text{Pl}} = \sqrt{\frac{\hbar G N}{c^5}} = 5 \times 10^{-44} \) s and a minimum length, the Planck length \( l_{\text{Pl}} = \sqrt{\frac{\hbar G N}{c^3}} = 1.616 \times 10^{-35} \) m. According to Craig Hogan, the minimum interval of time might be studied directly with GW interferometers [10]: the discretisation of the space-time manifold would give rise to transverse uncertainties in position. This phenomenon is called holographic noise and it is a precise, parameter-free prediction. Interferometers could in principle detect quantum indeterminacy of holographic geometry because the indeterminacy in the beam splitter position would insert holographic noise into the signal. At a frequency \( f = c/2L \) the shear fluctuations have a power spectral density \( S^2_{\text{H}} = L \Delta \theta^2 = t_{\text{Pl}} \). Planck’s time is the only relevant quantity in this expression. The power spectral density of shear perturbations is flat \( h_{\text{H}} = \sqrt{t_{\text{Pl}}} = 2.3 \times 10^{-22} \) Hz\(^{-1/2} \). This is a general property of holographic quantum geometry. GEO600 measured an unaccounted for excess of noise: by adding the holographic contribution, the agreement is better (although not perfect), as can be seen from Figure 5, a slide taken from a talk by Craig Hogan himself.

Subsequent measurements however have not confirmed the detection of the holographic noise. GEO 600 was very sensitive to transverse displacements because it was the only detector to use the Signal-Recycling mirror. Advanced detectors are likely to have a signal-recycling mirror too so hopefully the issue will be clarified.
7. Summary

Interferometric GW detectors such as LIGO and Virgo have not yet detected gravitational radiation but the data they have collected have led to very interesting scientific results, such as an improvement on the BBN bound for the stochastic gravitational radiation of cosmological origin. Advanced detectors, which will start operation in 5 years’ time, will almost surely mark the first direct detection of gravitational radiation and hopefully also give birth to a new and exciting branch of astronomy, gravitational-wave astronomy. Such detectors, and their successors, will be quantum limited and will make use of non-classical light states, thus relating a purely classical theory such as Einstein’s General Relativity to frontier research in Quantum Optics. As a side-effect, GW-detectors might also give us some hints towards a quantum theory of gravity.

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