INSTITUTE OF PHYSICS PUBLISHING — JOURNAL OF OPTICS A: PURE AND APPLIED OPTICS

J. Opt. A: Pure Appl. Opt. **7** (2005) S257–S264 doi:10.1088/1464-4258/7/6/001

REVIEW ARTICLE

Laser interferometry for the detection of gravitational waves

Jim Hough and Sheila Rowan

Department of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, UK

Received 3 December 2004, accepted for publication 7 March 2005
Published 9 May 2005
Online at stacks.iop.org/JOptA/7/S257

Abstract
Results are now appearing from the first generation of long baseline gravitational wave detectors that use laser interferometry for motion sensing. In this short review the history of the field will be briefly discussed, and the principles of the novel laser interferometry developed will be outlined in the context of present and future instruments.

Keywords: gravitational waves, interferometry

(Some figures in this article are in colour only in the electronic version)

1. Introduction

For many years there has been controversy over research into the existence of gravitational waves. Indeed several early relativists were sceptical about their existence. However, the field has been recognized by the 1993 Nobel Prize in Physics being awarded to Hulse and Taylor for their experimental observations and subsequent interpretations of the evolution of the orbit of the binary pulsar PSR 1913 + 16, the decay of the binary orbit being consistent with angular momentum and energy being carried away from this system by gravitational waves [1]. Further, long baseline detectors with a sensitivity sufficient to allow real possibilities for the detection of astrophysical sources—LIGO, VIRGO, GEO 600 and TAMA 300—are now coming into operation and the community is poised to herald the first detection of gravitational wave signals and thus the start of a new astronomy [2–5].

These detectors, using laser interferometry for motion sensing, are heading towards being limited in performance by the Heisenberg uncertainly principle and potentially may at some time be able to bypass this limit. This short review will target some of the optical techniques currently being used and their extensions for the future. References to other aspects of detectors will be given throughout the text.

2. Gravitational waves

Gravitational waves, predicted in general relativity to be produced by the acceleration of mass [6], are propagating strains in space that in their simplest form lead to tiny quadrupole deformations of mechanical systems with which they interact. The strain ($\delta l/l$) is represented by the gravitational wave amplitude (h) where $h = 2\delta l/l$. For quadrupole radiation there are two orthogonal polarizations of the wave at 45° to each other, of amplitude h_+ and h_x, and each of these is equal to twice the strain in space in the relevant direction. Thus an aluminium bar would undergo periodic extension and compression or a Michelson interferometer formed between freely hanging mirrors would undergo a differential change in its arm lengths.

Gravitational wave detectors will uncover dark secrets of the universe by helping us to study sources in extreme physical conditions: strong non-linear gravity and relativistic motion, extremely high density, temperature and magnetic fields, to list a few. Gravitational wave signals are expected over a wide range of frequencies, from 10^{-17} Hz in the case of ripples in the cosmological background to 10^3 Hz when neutron stars are born in supernova explosions. Because of the very weak nature of gravity and lack of dipole radiation, the efficiency of converting mechanical energy in a system into gravitational radiation is very low and thus signals produced by accelerating systems tend to be very weak. Indeed, the only sources of gravitational waves (GWs) that are likely to be detected are astrophysical, where there are potentially huge masses accelerating very strongly. There are many sources of significant astrophysical interest to be detected including black hole interactions and coalescences, neutron star coalescences, low-mass x-ray binaries such as Sco-X1, stellar collapses to

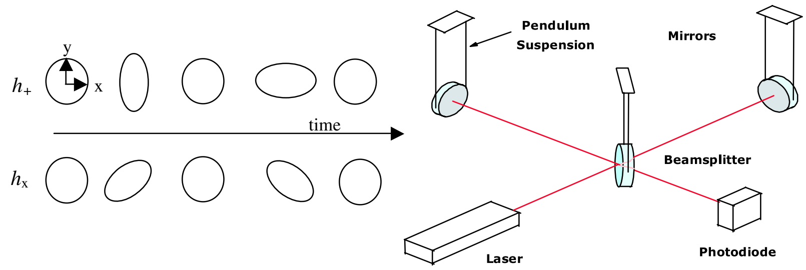

Figure 1. Schematic diagram of how gravitational waves interact with a ring of matter. The 'quadrupole' nature of the interaction can be clearly seen, and if the mirrors of the Michelson interferometer on the right lie on the ring with the beamsplitter in the middle, the relative lengths of the two arms will change and thus there will be a changing interference pattern at the output.

neutron stars and black holes (supernova explosions), rotating asymmetric neutron stars such as pulsars, and processes in the early universe. For a recent reviews see [7] and references therein and it is important to note that predicted strains in space at the earth are typically of the order of 10^{-21} or smaller.

Why are we interested in the detection of gravitational waves? We want to use them as a tool for looking into the heart of some of the most violent events in the universe and so start a new branch of astronomy.

3. History

There appears to have been little interest in the experimental detection of gravitational radiation for 45 years after its prediction. However, in the late 1950s this changed with Joseph Weber of the University of Maryland suggesting the design of some relatively simple apparatus for its detection [8, 9].

In the 1969/70 period Weber operated two aluminium bar detector systems at room temperature, one at the University of Maryland and one at the Argonne National Laboratory, and observed coincident excitations of the bars at a rate of one event per day [10, 11]. He claimed these events to be gravitational wave signals. However, other experiments—at various laboratories around the world—failed to confirm Weber's detections. An analysis of detector sensitivity of the Weber bar design suggested that the sensitivity was approximately 10^{-16} for millisecond pulses, far weaker than was predicted for any likely sources.

Thus the field had to find a new way forward, the driving force being the need to improve detector sensitivity. There are two fundamental ways to improve sensitivity in any detector system. The first is to reduce the background noise level, and the second is to increase the signal size. Post-Weber detector initiatives followed both of these routes, although the first method—the development of low temperature bars [12]—will not be discussed any further here. It is the second route—the quest for signal enhancement by moving the test masses apart and using laser interferometry to sense the relative motion—which is now coming to prominence.

4. Long baseline interferometric detectors on earth

This idea of using interferometric detectors was not new—indeed it had originally been proposed in 1962 [13] but for implementation it had been awaiting the availability of relevant laser and optical technology. Indeed Robert Forward (a former student of Weber) built the first laser interferometric prototype in the early 1970s at the Hughes Aircraft Laboratories in Malibu, although the sensitivity was limited by the short distance between the masses and the low power of the helium–neon laser used [14]. The concept is very attractive in that it offers the possibility of very high sensitivities over a wide range of frequency [15].

This technique is based on the Michelson interferometer and is particularly suited to the detection of gravitational waves as they have a quadrupole nature (figure 1). Waves propagating perpendicular to the plane of the interferometer will result in one arm of the interferometer being increased in length while the other arm is decreased and vice versa. The induced change in the length of the interferometer arms results in a small change in the intensity of the light observed at the interferometer output.

With the increasing availability of argon-ion lasers and then neodymium YAG lasers with the capability of producing watts of single-frequency light, a number of prototype detectors at MPQ, Glasgow, Caltech, MIT and Tokyo [16–24] were constructed, leading to the funding and building of the current generation of long baseline instruments—LIGO, VIRGO, GEO 600 and TAMA 300 [2–5]—which will be described in a later section.

In order to observe a full range of sources and initiate gravitational wave astronomy a sensitivity or noise performance in strain of below 10^{-23} Hz$^{-\frac{1}{2}}$ has to be achieved over most of the proposed operating range from 10 Hz to a few kilohertz. For an Earth based detector the distance between the test masses is limited to a few kilometres by geographical and cost factors. If we assume an arm length of 3–4 km, detecting a strain in space of the above level implies measuring a residual motion of each of the test masses of around 10^{-20} m Hz$^{-\frac{1}{2}}$. This sets a formidable goal for the optical detection system at the output of the interferometer.

4.1. Main noise sources

In this section we discuss the main noise sources which limit the sensitivity of ground-based interferometric gravitational wave detectors. Fundamentally it should be possible to build interferometric systems to monitor strains in space which reach or even supersede the standard quantum limit (SQL), i.e. the limit set by the Heisenberg uncertainty principle. Indeed the proposed performance for the next generation of detectors is

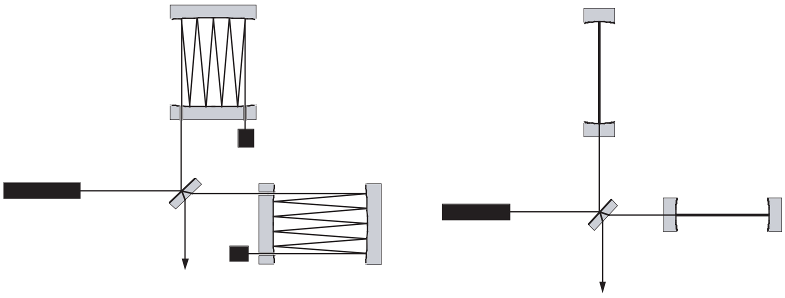

Figure 2. Michelson interferometers with (a) delay lines and (b) Fabry–Perot cavities in the arms of the interferometer.

close to this limit at mid-frequencies. The SQL and related issues will be discussed later.

There are other practical issues that must be considered. Fluctuating gravitational gradients pose one limitation to the interferometer sensitivity achievable at low frequencies. While schemes to monitor such gradients and cancel out their effects on the interferometers have been proposed [25], these are still far away from implementation. It is the level of gravity gradient noise which dictates that experiments to look for gravitational wave signals below 10 Hz or so have to be carried out in space [26, 27].

In general [28, 29], for the practical building of ground based detectors the most important limitations to sensitivity result from the effects of seismic and other ground-borne mechanical noise, thermal noise associated with the test masses and their suspensions [30, 31], shot noise in the photocurrent from the photodiode which detects the interference pattern, and radiation pressure recoil effects on the interferometer mirrors, these last two being intimately related with quantum limits to performance. This article will concentrate on the limitations imposed by the interferometry.

4.1.1. Photoelectron shot noise. For gravitational wave signals to be detected, the output of the interferometer must be held at one of a number of possible points on an interference fringe. While an obvious point to choose is halfway up a fringe since the change in photon number produced by a given differential change in arm length is greatest at this point, it can be shown that the best signal-to-noise ratio is obtained as the locking point approaches the bottom of the fringe [32]. The interferometer may be stabilized to the required point on a fringe by sensing any changes in intensity at the interferometer output with a photodiode and feeding the resulting signal back, with suitable phase and dc bias, to a transducer capable of changing the position of one of the interferometer mirrors. Information about changes in the length of the interferometer arms can then be obtained by monitoring the signal fed back to the transducer.

As mentioned earlier, it is very important that the system used for sensing the optical fringe movement on the output of the interferometer can resolve strains in space of less than 10^{-23} Hz$^{-\frac{1}{2}}$, or differences in the lengths of the two arms of less than 10^{-20} m Hz$^{-\frac{1}{2}}$, minute displacements compared to the wavelength of light (10^{-6} m). A limitation to the sensitivity of the optical readout scheme is set by shot noise in the detected photocurrent. From consideration of the number of photoelectrons (assumed to obey Poisson statistics) measured in a time $\tau \sim 1/(2\Delta f)$ it can be shown [32] that the detectable strain sensitivity depends on the level of laser power, P, of wavelength λ used to illuminate the interferometer of arm length L, and over a bandwidth Δf, such that

$$\begin{aligned}\delta x^2 &\cong \frac{\hbar c\lambda}{4\pi P\cos^2(\phi/2)}\Delta f \\ &\cong \frac{\hbar c\lambda}{4\pi P}\Delta f \qquad \text{when } \phi = 0\end{aligned}$$

where c is the velocity of light, ϕ is the phase difference between the light in the two arms of the interferometer, and $\hbar$ is the reduced Planck constant. We assume that the photodetectors have a quantum efficiency ~ 1. It should be noted that the best sensitivity is not actually obtained by locking half way up a fringe but by operating close to the point where $\phi \sim 0$ or the output intensity is zero. Achievement of the required strain sensitivity level requires a laser, operating at a wavelength of 10^{-6} m, to provide more than 10^8 W power at the input to a simple Michelson interferometer. This is a challenging requirement; however, there are a number of techniques which allow a large reduction in this power and these will be discussed in the next section.

4.2. Laser interferometric techniques for gravitational wave detectors

The requirements on laser power can be reduced if a multi-pass arrangement is used in the arms of the interferometer as this multiplies up the apparent movement by the number of bounces the light makes in the arms. The multiple beams can either be separate as in an optical delay line [15–18], or may lie on top of each other as in a Fabry–Perot resonant cavity [19–24] as shown in figure 2.

Optimally, the light should be stored for a time comparable to the characteristic timescale of the signal. Thus if signals of characteristic timescale 1 ms are to be searched for, the number of bounces should be approximately 50 for an arm length of 3 km. With 50 bounces the required laser power is reduced to $\sim 10^5$ W, still a formidable requirement.

4.2.1. Power recycling. As mentioned earlier, optimum signal to noise ratio in a Michelson interferometer can be obtained when the arm lengths are such that the output light is very close to a minimum and it is usual to make use of a modulation technique to operate the interferometer close

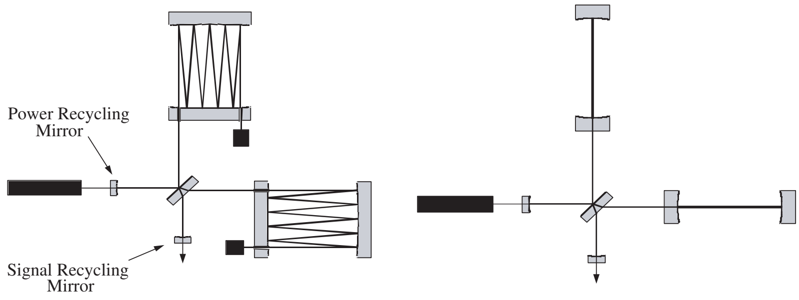

Figure 3. The implementation of power and signal recycling on the two interferometers shown in the previous figure.

to a null in the interference pattern. An electro-optic phase modulator placed in front of the interferometer can be used to phase modulate the input laser light. If the arms of the interferometer are arranged to have a slight mismatch in length this results in a detected signal which when demodulated is zero with the cavity exactly on a null fringe and changes sign on different sides of the null, providing a bipolar error signal; this can be fed back to a transducer controlling an interferometer mirror to hold the interferometer locked near to a null fringe.

In this situation, if the mirrors are of very low optical loss, nearly all of the light supplied to the interferometer is reflected back towards the laser. In other words, the laser is not properly impedance matched to the interferometer. The impedance matching can be improved by placing another mirror of correctly chosen transmission—a power recycling mirror—between the laser and the interferometer so that a resonant cavity is formed between this mirror and the rest of the interferometer (see figure 3); in the case of perfect impedance matching no light is reflected back towards the laser [33, 34]. There is then a power build-up inside the interferometer. This can be high enough to create the required laser light power at the beamsplitter, starting from an input laser light of the order of 100 W. To be more precise, if the main optical power losses are those associated with the test mass mirrors—taken to be A per reflection—the intensity inside the whole system considered as one large cavity is increased by a factor given by $(\pi L)/(cA\tau)$, where the number of bounces, or light storage time, is optimized for signals of timescale τ. The other symbols have their usual meaning. The first experimental implementation of this technique for a system with suspended cavities in the arms was demonstrated in Japan [35].

4.2.2. Signal recycling. To enhance further the sensitivity of an interferometric detector and to allow some narrowing of the detection bandwidth, which may be valuable in searches for continuous wave sources of gravitational radiation, another technique known as signal recycling can be implemented [36–38]. This relies on the fact that sidebands created on the light by gravitational wave signals interacting with the arms do not interfere destructively and so do appear at the output of the interferometer. If a mirror of suitably chosen reflectivity is put at the output of the system as shown in figure 3, then the sidebands can be 'recycled' back into the interferometer where they resonate, and hence the signal size over a given bandwidth (set by the mirror reflectivity) is enhanced.

The centre of this frequency band is set by the precise length of the cavity formed by the signal recycling mirror and the cavities in the interferometer arms. Thus control of the precise position of the signal recycling mirror allows tuning of the frequency at which the performance is peaked.

Often signal recycling will be used to provide a narrow bandwidth to search for continuous wave sources as mentioned above. However, it may also be used with a relatively broad bandwidth, centred away from zero frequency, and this application is useful for matching the frequency response of the detector to expected spectral densities of certain broadband or 'chirping' signals.

4.3. Prototype detectors and their evolution into large scale instruments

In Germany, a 3 m prototype (1975) using optical delay lines was followed by a 30 m instrument developed during the early 1980s at the Max Planck Institute for Astrophysics in Garching [16, 17]. In the UK, a 1 m instrument (1977) using a different form of multi-beam optical system was constructed [18]. However, it became clear that the potential sensitivity of the interferometer detectors under development was very challenging to achieve. In particular, while a Michelson interferometer arrangement should have the particular advantage of being relatively insensitive to laser frequency noise if the arm lengths were adjusted to be equal in length, this appeared not to be the case, as observed by both the Max Planck and Glasgow research groups. The problem was tracked down to scattering effects in the multi-beam arms that effectively spoiled the arm-length equality condition. Thus the need for high levels of laser frequency stability became pressing. This led to the use of Fabry–Perot cavities in the arms of the interferometer [19–24]. However, to keep the cavities in the arms resonant also required a very high degree of laser frequency stabilization and control. Cavities were installed in a new 10 m prototype developed in Glasgow in the early 1980s [19, 20]; then a 40 m instrument was developed at Caltech as a spin-off from the Glasgow instrument [21, 22]. The search for high frequency stability, in the multi-watt argon ion lasers ($\lambda = 514$ nm) then being used, led to the development of the now widely used Pound–Drever–Hall reflection locking technique for single-frequency lasers stabilized to Fabry–Perot cavities. This technique is related to one developed for microwave systems by Pound [39], and is now central to the operation of all long baseline gravitational wave detectors currently under development [40].

At this stage of detector development, given that there were successful prototypes operating in Germany, Britain and

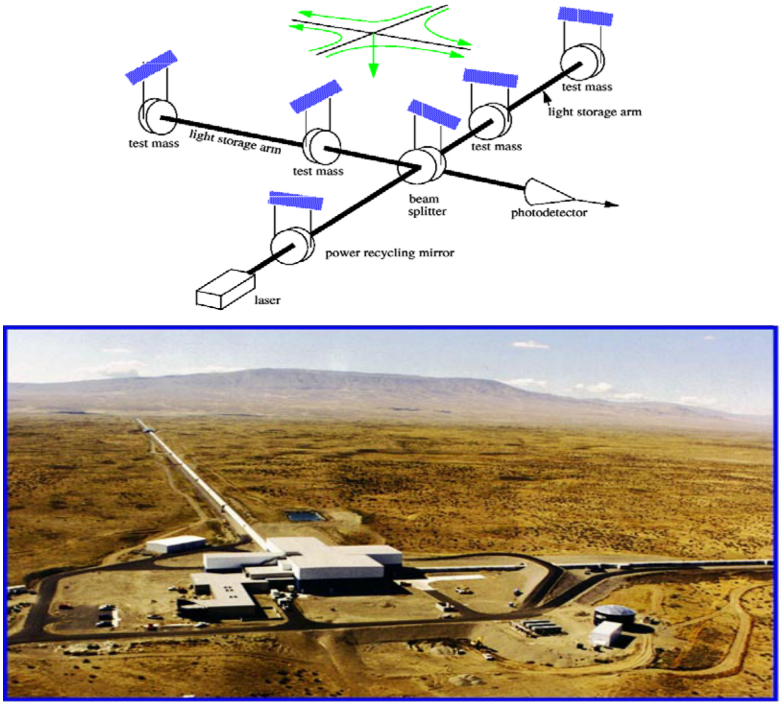

Figure 4. Schematic diagram and birds eye view of LIGO (Hanford). Image courtesy of the LIGO Scientific Collaboration.

America and that these had been joined by two prototypes in Japan [41, 42], the technology was considered sufficiently mature for the construction of detectors of much longer baseline, detectors that should be capable of having a real possibility of detecting gravitational waves.

Thus an international network of gravitational wave detectors came into being.

4.4. Current situation with interferometric detectors

The American LIGO project which sprang from the MIT and Caltech prototypes comprises two detector systems with arms of 4 km length, one in Hanford, WA, and one in Livingston, LA. One half length, 2 km, interferometer has also been built inside the same evacuated enclosure at Hanford [2]. A birds-eye view of the Hanford site showing the central building and the directions of the two arms is shown in figure 4. Construction of LIGO began in 1996 and progress has been outstanding with one of the LIGO detectors—the Hanford 4 km instrument—currently (November 2004) being almost at its design sensitivity over much of its frequency range [43]. Many research groups from the USA and other parts of the world are actively involved in the analysis of data from LIGO and in research towards future upgrades as part of the LIGO Scientific Collaboration (LSC).

The French/Italian VIRGO detector of 3 km arm length at Cascina near Pisa is designed to have lower frequency performance, down to 10 Hz, and is close to completion [3]. The Japanese TAMA 300 detector, which has arms of length 300 m, is operating at the Tokyo Astronomical Observatory [5].

All the systems mentioned above are designed to use resonant cavities in the arms of the detectors and use standard wire sling techniques for suspending the test masses. However, the German/British detector, GEO 600, is somewhat different [4]. It makes use of a four-pass-delay-line system with signal recycling [38], and utilizes fused silica suspensions of very low mechanical loss for the test masses to help reduce thermal noise [44]. GEO is expected to reach a sensitivity at frequencies above a few hundred hertz close to those of VIRGO and LIGO when they are in initial operation. GEO is now fully built and its sensitivity is being continuously improved. Currently it is within a factor of ten of design sensitivity over much of its frequency range.

It should be noted that current detectors use Nd:YAG lasers ($z = 1.06\ \mu$) of power 10 W or greater.

Three science runs, ranging from 17 to 70 days in length, have so far been carried out with these new interferometric detectors. All have involved the LIGO detectors, and two have involved the GEO and TAMA detectors. The bar detector Allegro in Louisiana has also taken part in the latest of these runs. From the first science run, upper limit results on the signals from a number of potential sources such as pulsars and coalescing compact binary stars, as well as on burst events and the level of a stochastic background, have been set [45–48]. Results from the second run are about to be published, and those from the third run are being analysed.

During the next few years we can expect to see a series of increasingly sensitive searches for gravitational wave signals at a sensitivity level of approximately 10^{-21} for millisecond pulses or close to 10^{-26} for pulsars, to take two examples. This latter level is equivalent to a neutron star having an ellipticity of $\sim 10^{-8}$ and is astrophysically feasible. Thus the detection of gravitational waves from pulsars in the short term is a real possibility. Further, the recent discovery of another compact binary system in the galaxy—the double pulsar J0737-3039—has improved the statistics for the expected rate of binary coalescences by a significant factor, implying that the most probable rate of binary neutron star coalescences detectable

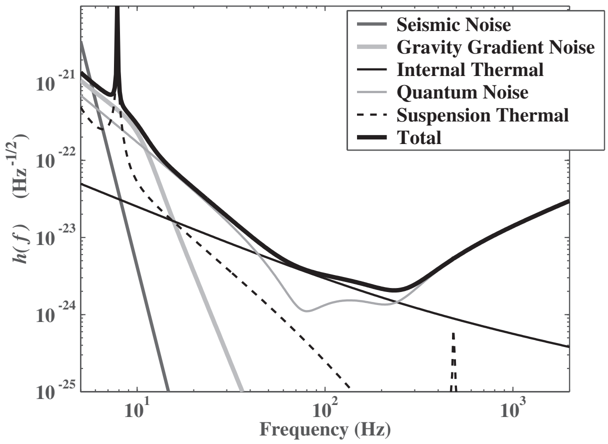

Figure 5. Sensitivity curve, showing noise anatomy, for the planned Advanced LIGO detector system.

by the LIGO system now lies between one per 10 years and one per 600 years [49]. Many people expect the rate of binary black hole coalescences to be even higher.

Detection at the level of sensitivity of the initial detectors is no way guaranteed; thus improvement of the order of a factor of ten in sensitivity of the current interferometric detectors is essential to allow compact binary coalescences to be detected at a useful rate. Indeed, plans for an upgraded LIGO, 'Advanced LIGO', are already mature and the project has recently been approved by the National Science Board in the USA. Plans are also well advanced for an underground detector with cooled test masses (LCGT) to be built in Japan [50]. The proposed design for Advanced LIGO has 40 kg silica test masses, suspended by fused silica fibres or ribbons, along with an improved seismic isolation system, increased laser power, ∼200 W, and signal recycling [51]. The upgrade is now expected to commence in 2009 and it is exciting to note that the most probable rate of detectable binary neutron star coalescences is now expected to be in the range of 10 to 500 per year [49]. The noise anatomy for Advanced LIGO is shown in figure 5.

For GEO a different upgrade strategy is being adopted. A proposed upgrade will be targeted at the observation of the oscillations of neutron stars resulting from quakes in pulsars or magnetars, situations where there is an external trigger from other branches of astronomy, and detector improvement will be in the area of enhancing narrow-band sensitivity around a few kilohertz.

4.5. The quantum limit

Future detectors require high levels of laser power to reduce photon noise and this power produces fluctuations in radiation pressure on the mirrors. It can easily be shown that in the case of a simple Michelson interferometer the resulting equivalent differential displacement sensitivity is given by

$$\delta x^2 \cong \frac{16\pi\hbar P}{\lambda m^2\omega^4 c}\Delta f$$

where m is the mass of each end mirror of the interferometer. For ease of calculation we have assumed that the beamsplitter has infinite mass.

If the photon noise fluctuations are statistically independent of the radiation pressure fluctuations—a valid assumption in the case of the simple Michelson interferometer as they have been shown [52, 53] to arise from orthogonal fluctuations of the vacuum field entering the unused port of the beamsplitter—then the two effects can be combined additively to give

$$\delta x^2 \cong \frac{\hbar c\lambda}{4\pi P}\Delta f + \frac{16\pi\hbar P}{\lambda m^2\omega^4 c}\Delta f.$$

Clearly there is a frequency-dependent optimum operating power to give minimum noise level and in this situation the minimum detectable noise spectral amplitude of displacement is

$$\delta x^2 \cong \frac{4\hbar}{m\omega^2}\Delta f.$$

This argument can be generalized for multiple beams in the arms and for Fabry–Perot cavities and essentially the same result is obtained. This is really an example of the Heisenberg microscope experiment and thus it is not surprising that the same result can be obtained by using the Heisenberg uncertainty principle to calculate the uncertainty in position of the interferometer test masses [32, 54]. This apparent limitation to sensitivity is known as the standard quantum limit (SQL), this limit and its fallacy for mechanical systems first being highlighted by Vladimir Braginsky. For a review of Braginsky's work in this field, which has spanned the last 40 years, see the review paper by Braginsky and Khalili [55] and references therein.

It is important to note that the above calculation relies on the lack of correlation between the displacement limits set by the photon noise and those set by the radiation pressure noise. There are a number of interesting corollaries to this.

Firstly if it is possible to alter the balance of the fluctuations in the two quadratures of the vacuum field it is possible to reach the SQL at lower power levels than required in the above analysis. Such an imbalance can be achieved by 'squeezing' the vacuum fluctuations entering the unused port of the beamsplitter [53]. Squeezing has been experimentally demonstrated in a number of laboratories (see for example [56–59]), but of particular note are recent results from McClelland and colleagues in Australia [60] who have demonstrated several decibels of squeezing at the frequencies relevant for ground based gravitational wave detectors. Further, if correlations are present between the displacement limits discussed above, it is possible, at least in principle, to bypass the limit set by the SQL [61]. There are at least two ways to introduce such correlations through the following.

- Using a cavity configuration where there is a strong optical spring effect coupling the optical field to the mechanical system. Such effects can be enhanced by using intra-cavity readout schemes where the motion of small internal test masses is monitored with a local transducer. Such schemes—optical bars, optical levers etc—have been devised and studied in depth by Braginsky and colleagues at the University of Moscow (see for example [62, 63]).
- Measuring the output signal after suitably designed filtering at optical frequencies. This filtering, by means of long Fabry–Perot cavities, effectively introduces correlations [64, 65].

Of course another possibility to evade the SQL is to measure a different variable, one for which the measurement operator commutes with the operator resulting from the back-action. This implies that the measurement operator at one time should commute with itself at a later time. Clearly 'x'—displacement—is not such an operator as 'x' at one time is correlated with 'x' at a later time through the HUP relationship with momentum 'p'. However, 'p' is a suitable operator as although a measurement of 'p' results in an uncertainty in 'x', this does not feed back into 'p'. Thus if a velocity measurement system—speedmeter—is devised, this allows performance below the SQL. A number of systems have been suggested for speedmeters (see for example [65–68]), the most straightforward being the implementation of a Sagnac configuration [69].

It should be noted that the signal-recycling concept as currently used in GEO 600 and planned for Advanced LIGO has the potential of allowing measurements below the SQL [70]. The asymmetry introduced by narrow-banding the sensitivity offset on one side of the optical carrier introduces a correlation between the photoelectron shot noise and the effect of the back-reaction. In this case quantum noise curves of the type included in figure 5 have been calculated. At its lowest point the quantum noise is better than would be predicted by the SQL. In principle the quantum noise limited sensitivity at different frequencies may be further improved by using squeezed light for illumination of the system and/or by using a long filtering cavity before the detection of the signal out of the system [71, 72].

While these techniques for sensitivity enhancement beyond the SQL require losses in all parts of the main optical system to be very low and the quantum efficiencies of the photo-detection systems to be very high, they have real potential for the future and there is a growing experimental community dedicated to applying them to the detection of gravitational waves.

5. The future

The next stage forward in interferometric detectors is well defined with the design for Advanced LIGO incorporating silica fibre suspensions, signal recycling and higher power lasers being well advanced. On approximately the same timescale we can expect to see a similar upgrade to VIRGO, the rebuilding of GEO as a detector aiming at high sensitivity in the kilohertz frequency region and the building of a long baseline underground detector, LCGT, in Japan. To go beyond this point, however, a number of challenges involving mechanical losses in coatings [73] and thermal loading effects will have to be overcome, the latter possibly requiring the use of non-transmissive optics [74, 75] with materials of high conductivity such as silicon [76].

Research groups in the field are already looking towards the next generation of detectors that will herald the start of gravitational wave astronomy: ground based instruments making full use of squeezed light and techniques to bypass the standard quantum limit and space borne detectors such as LISA and its extensions.

Acknowledgments

We wish to thank all colleagues in the field for useful discussions and Peter Fritschel at MIT for the Advanced LIGO noise anatomy curves. We are indebted to PPARC and the University of Glasgow for support.

References

[1] Hulse R A 1994 *Rev. Mod. Phys.* **66** 699
Taylor J H 1994 *Rev. Mod. Phys.* **66** 711
[2] Sigg D *et al* 2004 *Class. Quantum Grav.* **21** S409
Abramovici A *et al* 1992 *Science* **256** 325
[3] Acernese F *et al* 2004 *Class. Quantum Grav.* **21** S385
[4] Willke B *et al* 2004 *Class. Quantum Grav.* **21** S417
[5] Takahashi R *et al* 2004 *Class. Quantum Grav.* **21** S403
[6] Einstein A 1916 *Erster Halbband* vol 688, *Koeniglich Preussiche Akademie der Wissenshaften Berlin, Sitzungsberichte*
[7] Grishchuk L 2004 *Astrophysics Update* ed J W Mason (Berlin: Springer) p 281
[8] Weber J 1960 *Phys. Rev.* **117** 306
[9] Weber J 1961 *General Relativity and Gravitational Waves* (New York: Wiley)
[10] Weber J 1969 *Phys. Rev. Lett.* **22** 1320
[11] Weber J 1970 *Phys. Rev. Lett.* **25** 180
[12] Fafone V 2004 *Class. Quantum Grav.* **21** S377
[13] Gertsenshtein M E and Pustovoit V I 1962 *Sov. Phys.—JETP* **16** 433
[14] Moss G E, Miller L R and Forward R L 1971 *Appl. Opt.* **10** 2495b
[15] Weiss R 1972 *Q. Prog. Rep. Res. Lab. Electron.* **105** 54
[16] Billing H, Maischberger K, Ruediger A, Schilling R, Schnupp L and Winkler W 1979 *J. Phys. E: Sci. Instrum.* **12** 1043
[17] Shoemaker D, Schilling R, Schnupp L, Winkler W, Maischberger K and Ruediger A 1988 *Phys. Rev.* D **38** 423
[18] Drever R W P, Hough J, Pugh J R, Edelstein W A, Ward H, Ford G M and Robertson N A 1979 *Proc. R. Soc.* A **368** 11
[19] Hough J, Hoggan S, Kerr G A, Mangan J B, Meers B J, Newton G P, Robertson N A, Ward H and Drever R W P 1984 *Lecture Notes in Physics* vol 212 (Berlin: Springer) p 204
[20] Robertson D, Morrison E, Hough J, Killbourn S, Meers B J, Newton G P, Strain K A and Ward H 1995 *Rev. Sci. Instrum.* **66** 4447
[21] Drever R W P *et al* 1981 *Laser Spectroscopy V* ed A R W McKellar *et al* (Berlin: Springer) p 33
[22] Abramovici A *et al* 1996 *Phys. Lett.* A **218** 157
[23] Mizuno E, Kawashima N, Miyoke S, Hein E G, Wada K, Naito W, Nagano S and Arakawa K 1997 *Gravitational Waves, Sources and Detectors* (*Edoardo Amaldi Foundation Series* vol 2) ed I Ciufolini and F Fidecaro (Singapore: World Scientific) p 108
[24] Kawabe K, Nagataki S, Ando M, Tochikubo K, Mio N and Tsubono K 1996 *Appl. Phys.* B **62** 135
[25] Fidecaro F 2001 LIGO doc. G010317-00
[26] Bender P *et al* 1998 *LISA Pre-Phase A Report* 2nd edn *MPQ Report* No. 233
[27] Danzmann K and Rüdiger A 2003 *Class. Quantum Grav.* **20** S1
[28] Rowan S and Hough J 2000 *Living Rev. Relativity* **2** 3 http://www.livingreviews.org/lrr-2000-3
[29] Robertson N A 2000 *Class. Quantum Grav.* **17** 19
[30] Saulson P R 1990 *Phys. Rev.* D **42** 2437
[31] Braginsky V B, Gorodetsky M L and Vyatchanin S P 1999 *Phys. Lett.* A **264** 1
[32] Edelstein W A, Hough J, Pugh J R and Martin W 1978 *J. Phys. E: Sci. Instrum.* **11** 710

[33] Drever R W P *et al* 1983 *Proc. NATO Advanced Study Institute on Quantum Optics and Experimental General Relativity* vol B94, ed P Meystre and M O Scully (New York: Plenum) p 503
[34] Schilling R 1981 private communication
[35] Ando M *et al* 1998 *Phys. Lett.* A **248** 145
[36] Meers B J 1988 *Phys. Rev.* D **38** 2317
[37] Strain K A and Meers B J 1991 *Phys. Rev. Lett.* **66** 1391
[38] Grote H *et al* 2004 *Class. Quantum Grav.* **21** S473
[39] Pound R V 1947 *Proc. IRE* **35** 1405
[40] Drever R W P, Hall J L, Kowalski F V, Hough J, Ford G M, Munley A J and Ward H 1983 *Appl. Phys.* B **31** 97
[41] Kawashima N 1991 *Gravitational Astronomy* ed D E McClelland and H-A Bachor (Singapore: World Scientific) p 57
[42] Fujimoto M K *et al* 1995 *Gravitational Wave Experiments* ed E Coccia, G Pizzella and F Ronga (Singapore: World Scientific) p 304
[43] Whitcomb S 2004 LIGO doc G040332-00 (http://www.ligo.caltech.edu/docs/G/G040332-00.pdf)
[44] Strain K A *et al* 2004 *Gravitational Wave and Particle Astrophysics Detectors* (*Proc. SPIE* vol 5500) ed J Hough and G H Sanders (Bellingham, WA: SPIE) p 25
[45] Abbott B *et al* 2004 *Phys. Rev.* D **69** 082004
[46] Abbott B *et al* 2004 *Phys. Rev.* D **69** 122001
[47] Abbott B *et al* 2004 *Phys. Rev.* D **69** 102001
[48] Abbott B *et al* 2004 *Phys. Rev.* D **69** 122004
[49] Kalogera V *et al* 2004 *Astrophys. J.* **601** L179 (*Preprint* astro-ph/0312101v3)
[50] Uchiyama T *et al* 2004 *Class. Quantum Grav.* **21** S1161
[51] Fritschel P 2001 LIGO document number T010075-00-D available at http://www.ligo.caltech.edu/docs/T010075-00.pdf
[52] Caves C M 1980 *Phys. Rev. Lett.* **45** 75
[53] Caves C M 1981 *Phys. Rev.* D **23** 1693
[54] Braginsky V B *et al* 2003 *Phys. Rev.* D **67** 082001
[55] Braginsky V B and Khalili F Ya 1996 *Rev. Mod. Phys.* **68** 1
[56] Slusher R E, Holberg L W, Yurke B, Mertz J C and Valley J F 1985 *Phys. Rev. Lett.* **55** 2409
[57] Wu L-A, Kimble H J, Hall J L and Wu H 1986 *Phys. Rev. Lett.* **57** 2520
[58] Schneider K, Lang M, Mlynek J and Schiller S 1998 *Opt. Express* **2** 59
[59] Schnabel R, Arms J, Strain K A and Danzmann K 2004 *Class. Quantum Grav.* **21** S1045
[60] McKenzie K, Grosse N, Whitcomb S E, Gray M B, McClelland D E and Lam P K 2004 *Phys. Rev. Lett.* **93** 161105
[61] Unruh W G 1983 *Proc. NATO Advanced Study Institute on Quantum Optics and Experimental General Relativity* vol B94, ed P Meystre and M O Scully (New York: Plenum) p 647
[62] Braginsky V B and Khaliliy F Ya 1996 *Phys. Lett.* A **218** 167
[63] Braginsky V B, Gorodetsky M L and Khalili F Y 1997 *Phys. Lett.* A **232** 340
[64] Kimble H J, Levin Yu, Matsko A B, Thorne K S and Vyatchanin S P 2001 *Phys. Rev.* D **65** 022002
[65] Corbitt T and Mavalvala N 2004 *J. Opt. B: Quantum Semiclass. Opt.* **6** S675
[66] Braginsky V B and Khalily F Ya 1990 *Phys. Lett.* A **147** 251
[67] Braginsky V B, Gorodetsky M L, Khalily F Ya and Thorne K S 2000 *Phys. Rev.* D **61** 044002
[68] Purdue P and Chen Y 2002 *Phys. Rev.* D **66** 122004
[69] Chen Y 2003 *Phys. Rev.* D **67** 122004
[70] Buonanno A and Chen Y 2001 *Phys. Rev.* D **64** 042006
[71] Harms J, Chen Y, Chelkowski S, Franzen A, Vahlbruch H, Danzmann K and Schnabel R 2003 *Phys. Rev.* D **68** 042001
[72] Buonanno A and Chen Y 2004 *Phys. Rev.* D **69** 102004
[73] Crooks D R M *et al* 2004 *Class. Quantum Grav.* **21** S1059
[74] Byer R L 1990 *Gravitational Astronomy: Instrument Design and Astrophysical Prospects* ed D E McClelland and H-A Bachor (Singapore: World Scientific)
[75] Drever R 1995 *Proc. 7th Marcel Grossman Mtg on General Relativity* ed M Keiser and R T Jantzen (Singapore: World Scientific) p 1401
[76] Rowan S, Byer R L, Fejer M M, Route R K, Cagnoli G, Crooks D R M, Hough J, Sneddon P and Winker W 2003 *Gravitational-Wave Detection* (*Proc. SPIE* vol 4856) ed M Cruise and P Saulson (Bellingham, WA: SPIE) p 4856