Classical and Quantum Gravity

DC-readout of a signal-recycled gravitational wave detector

To cite this article: S Hild *et al* 2009 *Class. Quantum Grav.* **26** 055012

Class. Quantum Grav. **26** (2009) 055012 (10pp) doi:10.1088/0264-9381/26/5/055012

DC-readout of a signal-recycled gravitational wave detector

S Hild[1], H Grote[2], J Degallaix[2], S Chelkowski[1], K Danzmann[2], A Freise[1], M Hewitson[2], J Hough[3], H Lück[2], M Prijatelj[2], K A Strain[3], J R Smith[4] and B Willke[2]

[1] School of Physics and Astronomy, University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK
[2] Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut) and Leibniz Universität Hannover, Callinstr. 38, D–30167 Hannover, Germany
[3] SUPA, Physics & Astronomy, University of Glasgow, Glasgow G12 8QQ, UK
[4] Syracuse University, Department of Physics, 201 Physics Building, Syracuse, NY 13244-1130, USA

E-mail: hild@star.sr.bham.ac.uk

Received 19 November 2008, in final form 8 January 2009
Published 17 February 2009
Online at stacks.iop.org/CQG/26/055012

Abstract
All first-generation large-scale gravitational wave detectors are operated at the dark fringe and use a heterodyne readout employing radio frequency (RF) modulation–demodulation techniques. However, the experience in the currently running interferometers reveals several problems connected with a heterodyne readout, of which phase noise of the RF modulation is the most serious one. A homodyne detection scheme (DC-readout), using the highly stabilized and filtered carrier light as a local oscillator for the readout, is considered to be a favourable alternative. Recently a DC-readout scheme has been implemented on the GEO 600 detector. We describe the results of first measurements and give a comparison of the performance achieved with homodyne and heterodyne readout. The implications of the combined use of DC-readout and signal recycling are considered.

PACS numbers: 04.80.Nn, 95.75.Kk

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

1. Introduction

Currently, all of the large-scale gravitational wave detectors LIGO [1], Virgo [2], TAMA300 [3] and GEO 600 [4] operate at the dark fringe using a heterodyne readout technique. However, the operation of the currently running interferometers reveals several problems being connected

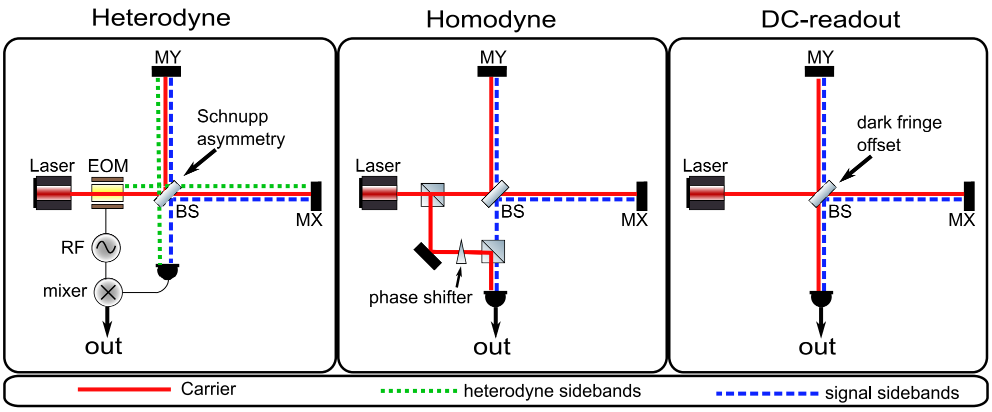

Figure 1. Illustration of three different readout methods of a Michelson interferometer: heterodyne, homodyne and DC-readout. (A detailed explanation is given in the text.)

with heterodyne readout. Changing the readout system to DC-readout, which is a special case of homodyne detection, can be beneficial for future gravitational wave detectors. Therefore it is planned to implement DC-readout in Enhanced LIGO [5] and Virgo+ [6] as well as in Advanced LIGO [7] and Advanced Virgo.

In this paper we give an overview of work related to DC-readout carried out at the GEO 600 gravitational wave detector. We begin, in section 2, with a brief description of the principles of heterodyne, homodyne and DC-readout applied to a simple Michelson interferometer as an illustrative example. In section 3, we give a brief summary of the expected advantages and disadvantages of DC-readout over heterodyne detection. We compare the simulated shot-noise limited sensitivity of GEO 600 with heterodyne and homodyne readout in section 4. It is found that in the case of detuned signal recycling not only is the overall level of the shot noise different for homodyne and heterodyne readout, but also the shape of the optical response. The actual experimental scheme for realization of DC-readout in the GEO 600 interferometer is described in detail in section 5. As we show in section 6 the simulated shape change of the optical response is accurately confirmed by experimental observations. A comparison of the actual sensitivity of the GEO 600 detector for homodyne and the nominal heterodyne detection scheme is given in section 7. Finally, section 8 provides a summary of this paper and an outlook.

2. Definitions: heterodyne, homodyne and DC-readout

Figure 1 shows simplified schematics of three different readout methods applied to a basic Michelson interferometer. Usually Michelson interferometers used for gravitational wave detection are operated at a dark fringe[5]: the differential arm-length is controlled to give destructive interference at the output port, i.e. ideally no carrier light (f_c, red solid line) reaches the photodetector. The interaction of a gravitational wave with the Michelson interferometer can be considered as shortening of one interferometer arm, whilst the perpendicular one is elongated. This change of the differential arm length causes phase modulation sidebands, i.e. gravitational wave signal sidebands (blue dashed line). In contrast to the carrier light the gravitational wave signal sidebands interfere constructively at the beam splitter, exit the

[5] Operating at the dark fringe has the advantage of providing good suppression of common mode noise and allows for the use of power recycling.

interferometer at its output port and finally reach the photodetector. The absolute frequency of the gravitational signal sidebands is given by $f_{\mathrm{sig}} = f_{\mathrm{c}} \pm f_{\mathrm{gw}}$, where f_{gw} is the frequency of the gravitational wave (usually in the audio-band) and f_{c} is the frequency of the main laser light (carrier). Since f_{sig} is a few hundred terahertz, the photodiode cannot directly detect the gravitational wave signal, unless the presence of an optical local oscillator is provided. Heterodyne, homodyne and DC-readout use different concepts to ensure the presence of a low-noise optical local oscillator at the output port photodiode.

In the heterodyne schemes, commonly used by the first generation gravitational wave detectors, radio frequency (RF) sidebands (f_{het}, green dotted lines) are modulated onto the light at the input of the Michelson interferometer (Schnupp modulation [10]). Introducing a macroscopic arm length difference of several centimetre (so-called Schnupp asymmetry) allows the modulation sidebands to be transferred through the interferometer to the output port, where they serve as optical local oscillator for the gravitational wave signal. The photo current produced by the beat between the different optical field components (optical demodulation) contains a radio frequency component at $f_{\mathrm{het}} \pm f_{\mathrm{gw}}$. In a second demodulation process the photo current is then electronically demodulated at f_{het} (using a mixer) in order to finally derive a signal stream at f_{gw}.

In the homodyne readout scheme (the centre plot of figure 1) a small fraction of the carrier light is split off in front of the interferometer and guided directly to the output photodetector without passing through the interferometer. The big advantage of this form of homodyne readout is that a phase shifter, placed in the local oscillator path, allows an easy change of the optical demodulation phase, i.e. the readout quadrature, without any hardware changes. On the other hand, homodyne readout has the disadvantage that the length and the alignment of the local-oscillator path needs to be highly stable. In practice this usually implies that the local-oscillator path length as well as its alignment need to be actively stabilized by a low-noise control system, and all components of the local-oscillator path must be seismically isolated inside a vacuum system. Due to these demanding noise and hardware requirements, so far there have been no serious plans to change the readout scheme of the currently operating gravitational wave detectors from heterodyne to homodyne readout.

DC-readout is a special case of homodyne readout which is much easier to combine with the existing elements of currently used gravitational wave detectors. In a DC-readout scheme the operating point of the Michelson interferometer is slightly shifted off the dark fringe, by introducing a so-called *dark-fringe offset*, thus a certain amount of carrier light leaves the interferometer at the output port and can serve as a local oscillator. Compared with the previously described homodyne readout, DC-readout has the advantage that no additional local oscillator path outside the main interferometer is required. On the other hand, DC-readout offers no easy way to vary the phase of the optical demodulation.

DC-readout was already used in the first 'Michelson' interferometer ever by Michelson and Morley in 1887 [17]. It is probably the simplest way to read out a Michelson interferometer, but was considered to be unsuitable for the first generation of gravitational wave detectors due to the strong coupling of laser power noise. However, increased stability of the laser power inside future instruments gives hope for a renaissance of DC-readout for gravitational wave detectors, which was first proposed by Fritschel 2000 [11, 12]. A demonstration of a DC-readout in a suspended prototype interferometer (without signal recycling) has recently been performed [21].

The following section briefly summarizes the general advantages and disadvantages of DC-readout compared with heterodyne readout, especially taking into account the implications for an interferometer with tuned or detuned signal recycling [15].

3. Motivation for the use of DC-readout

DC-readout has many advantages over the commonly used heterodyne readout which are summarized in the following list:

(i) When going from the currently-used heterodyne readout scheme to a DC-readout scheme the ratio of signal to shot noise will increase [13]. This effect is due to the fact that in the homodyne detection the shot noise contribution from frequencies twice the heterodyne frequency does not exist (please see section 4 for more details).

(ii) A reduced number of beating light fields at the detection port potentially reduces and simplifies the couplings of technical noise [15]. Most notably the coupling of amplitude and phase noise of the heterodyne modulation is strongly reduced in a DC-readout scheme. In addition the frequency noise coupling to the gravitational wave channel is also expected to be reduced in DC-readout.

(iii) A simpler calibration procedure can be applied, because the GW-signal is present in a single data-stream even for detuned signal recycling (and not spread over the two heterodyne quadratures as described in [14]).

(iv) As the main photodiode(s) and electronics for the detection do not need to be capable of handling RF signals, they can be simplified.

(v) Large-area photodiodes[6] may be used. These should offer reduced coupling of beam-pointing noise, due to decreased beam clipping and decreased influence of photodiode inhomogeneity (by averaging over a larger area).

(vi) As in the homodyne readout the local oscillator and the GW-signal pass the same optical system an optimal spatial overlap is guaranteed. (Due to thermal distortion current GW detectors employing arm cavities encountered the problem of imperfect spatial overlap of the carrier light (GW signal) and the heterodyne sidebands (local oscillator) [16].)

(vii) Finally, the realization of a squeezed light enhanced interferometer is simpler using DC-readout rather than heterodyne readout. DC-readout requires squeezed light to be present only at frequencies in the GW signal bandwidth compared to heterodyne readout which requires squeezed light around twice the heterodyne frequency as well [22].[7]

This long list of advantages has to be compared with the drawbacks of DC-readout. Even though power fluctuations of the carrier light (i.e. the local oscillator) are strongly filtered by the cavity poles of the power recycling cavity and the high-finesse arm cavities, the major disadvantage of DC-readout is (at least for GEO 600) an increased coupling of laser power noise (see section 7)[8]. In addition there is the potential problem that the response from DC-readout is not completely linear, due to the operating point sitting on the near-quadratic slope close to the dark fringe. However, this should not be a significant problem as long as the mean deviation from the differential arm length operation point is not too large.

[6] RF photodiodes are required to have a low electrical capacitance.

[7] A squeezed light source working only in the GW signal bandwidth would result in the DC-readout case in a sensitivity enhancement limited by the squeezing strength generated, whereas the same source would act in a heterodyne-readout based interferometer as if 50% of the squeezing was reduced due to losses. Hence, a sensitivity improvement by a factor of 6 dB in the DC-readout case would result in the heterodyne case in an improvement factor of only 2 dB.

[8] The relatively strong coupling of laser power noise in DC-readout was the reason to use heterodyne techniques instead for the first generation of gravitational wave detectors. However, with improved stabilization techniques in recent times, the relative stability of the light inside the interferometer is better than the relative phase noise achievable with excellent RF techniques.

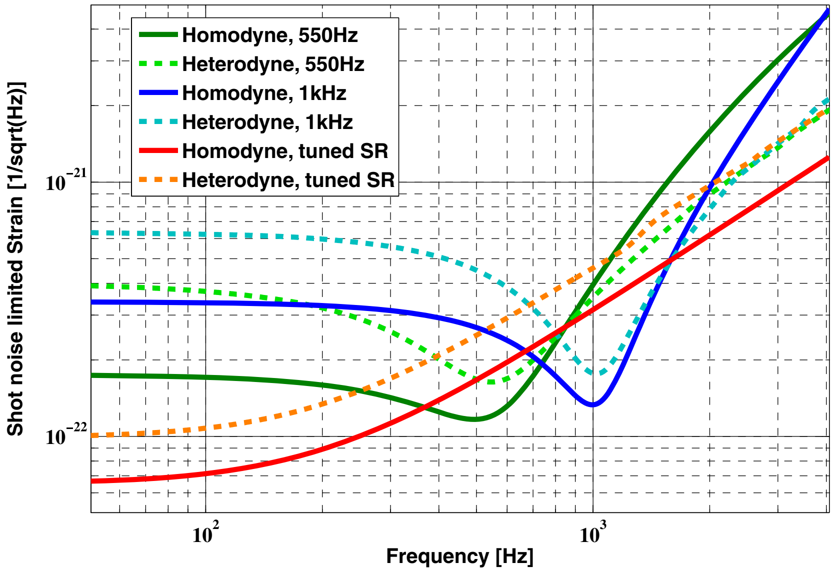

Figure 2. Simulated shot noise limited sensitivities of GEO 600 for three different SR tuning frequencies, each for heterodyne and DC-readout.

4. Simulated shot noise limited sensitivities of GEO 600 for homodyne and heterodyne readout

Figure 2 displays the shot noise limited sensitivity of the GEO 600 interferometer for heterodyne readout (dashed lines) and DC-readout (solid lines), including plots of three different signal recycling tunings for each of the readout methods. These simulations, carried out with the interferometer simulation software Finesse [19] show two major differences between the two different readout methods:

(i) For each signal recycling tuning the peak sensitivity achieved with DC-readout is better than that from heterodyne readout.

(ii) For detuned signal recycling the shape of the sensitivity differs for the two readout methods.

4.1. Overall shot noise level

The first point can be explained by a change of the overall shot noise level. When going from heterodyne readout to DC-readout the amplitude spectral density of the overall shot noise level decreases by a factor between $\sqrt{1.5}$ and $\sqrt{2}$ [13, 18, 23, 24]. The exact factor depends on the balancing of the two heterodyne sidebands at the dark-port. The sensitivity will be increased by between a factor of $\sqrt{1.5}$ for balanced sidebands and a factor of $\sqrt{2}$ for completely unbalanced sidebands. This effect can be understood by looking at the individual shot noise contributions at the dark-port. In the heterodyne case there is an additional shot noise contribution from harmonics of the heterodyne frequency. With standard sinusoidal modulation the significant contribution is twice the modulation frequency.

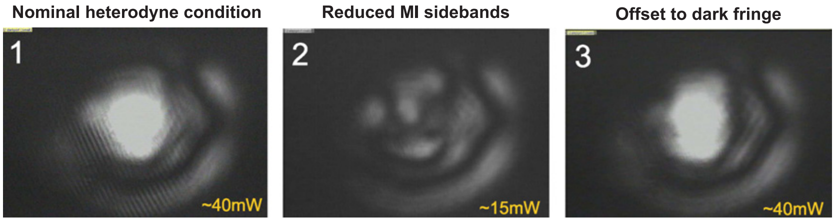

Figure 3. Realization of DC-readout in GEO 600. Starting from a fully locked interferometer in the heterodyne condition (image 1), we first turn down the RF modulation sidebands by a factor of 10 (image 2) and finally introduce a dark-fringe offset that couples TEM_{00} carrier light into the output port, serving as a new local oscillator (image 3).

4.2. Shape of the detector response

The second point can be explained by a change of the optical readout quadrature, which determines the shape of optical gain of the interferometer. The optical gain (or the optical transfer function) is defined as the transfer function from differential arm length fluctuations to the error signal of the Michelson differential arm length servo [20].

As one can see in figure 2 for detuned signal recycling, the shot noise limited sensitivity increases for frequencies below the signal recycling tuning frequency and decreases for high frequencies, when going from heterodyne readout to DC-readout. This shift corresponds to an increase of the optical gain for frequencies below the signal recycling tuning frequency and a decrease for high frequencies. In section 6 we present measurements confirming this simulated shape-change of the optical response.

5. Realization of DC-readout in GEO 600

Figure 3 (image 1) shows an image of the output mode of GEO 600, when operated in the normal heterodyne configuration. In the centre there is a strong TEM_{00} light field of about 25–30 mW consisting of the RF modulation sidebands (14.9 MHz) that are transmitted to the output via the Schnupp asymmetry and serve as a local oscillator for the differential arm length control system and the gravitational wave readout. In addition one can see some higher order mode structure, which is mostly made of carrier light originating from asymmetric optical imperfections, such as for instance thermal lensing, inside the main interferometer.

In order to realize DC-readout of the differential arm length degree of freedom, the main task is to replace TEM_{00} RF modulation sidebands as local oscillator by TEM_{00} carrier light. We start from the interferometer locked in the nominal heterodyne condition and, in a first step, reduce the amplitude of the RF modulation sidebands by a factor of 10 by turning down the modulation index in lock, while compensating the gain of all control loops that are affected. In this condition the optical power at the dark port is reduced to about 15 mW and dominated by higher-order tmodes (see figure 3 (image 2)). In a second step, we introduce an offset into the servo electronics controlling the arm length difference in order to dominate the GEO 600 output port with TEM_{00} carrier light (see figure 3 (image 3)). Finally, the readout as well as the control of the differential arm length of the Michelson is switched from the heterodyne signal

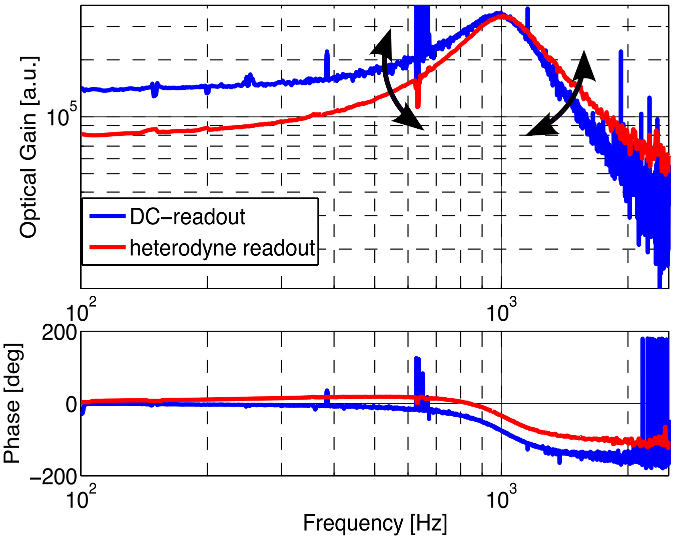

Figure 4. Measurement of the optical response of GEO 600 with detuned signal recycling (1 kHz) for DC-readout and heterodyne readout. The change of the optical transfer function predicted by simulations (see figure 2) is nicely confirmed by experimental results.

to the DC-readout signal. The whole procedure of changing from heterodyne to DC-readout has been automated, and it takes just a few tens of seconds[9].

A big advantage of our method is that no hardware changes are required. In particular it allows us to establish a DC-readout scheme without making use of an output mode cleaner which is usually required for removing the heterodyne sidebands from the light impinging on the main photodiode. The use of an output mode cleaner would allow the heterodyne sidebands to be kept at a high level inside the interferometer. An additional benefit of an output mode cleaner is the potential reduction of higher order optical modes. However, an output mode cleaner is found to be unnecessary in the particular case of GEO 600, which has good mode-healing [25], but is likely to be required for GEO-HF [26], which will encounter much stronger higher order optical modes due to operating at much higher optical power than GEO 600. An output mode cleaner has the drawback of requiring new hardware together with a low-noise control system as well as introducing additional noise sources and noise couplings.

6. Comparison of simulated and measured optical response functions

In order to confirm the simulated shape change of the optical response function for GEO 600 in detuned signal recycling mode when changing the readout from heterodyne to homodyne (see section 4.2) we have to measure the optical transfer function for the two different cases. The result of such a measurement for a signal recycling tuning frequency of 1 kHz is shown in figure 4. The shape change of the optical response predicted by simulations is well confirmed by this measurement.

[9] It has to be noted that only the readout method of the differential arm length degree of freedom is changed to DC-readout, while most of the auxiliary length and angular degrees of freedom are still controlled using radio frequency heterodyne readout.

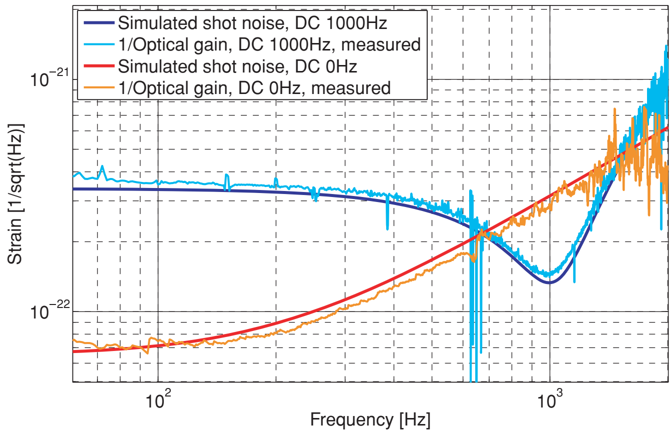

Figure 5. Comparison of measured and simulated optical transfer functions of the GEO 600 detector with DC-readout for tuned and detuned signal recycling. The simulation parameters were changed in a predefined way reflecting the experimental changes. No fitting was applied. A good agreement of simulated and measured data is found.

In a next set of measurements we compared the optical transfer function of GEO 600 with DC-readout for tuned and detuned signal recycling. As shown in figure 5 [10] the measured optical responses for both detector configurations, detuned (light blue trace) and tuned signal recycling (orange trace) agree accurately with the Finesse [19] simulations (dark blue and red trace). Please note that this good agreement is achieved using the standard GEO 600 parameter set as input for the simulations and no additional fitting or corrections have been applied.

7. Current sensitivity achieved with DC-readout

Figure 6 shows a comparison of the nominal GEO 600 sensitivity from the fifth LSC science run (blue solid trace) and the sensitivity that was achieved during first tests of DC-readout (red solid trace) for a signal recycling detuning of 550 Hz. With DC-readout a peak strain sensitivity of about 4×10^{-22} Hz$^{-1/2}$ at frequencies around 500 Hz is obtained which corresponds to a displacement sensitivity of about 2.5×10^{-19} m Hz$^{-1/2}$.

The solid green and the dashed green traces in figure 6 represent the simulated shot noise limited sensitivity of GEO 600 for DC-readout and heterodyne readout, respectively. As expected from the simulations, at high frequencies the sensitivity with DC-readout is worse compared to heterodyne readout. However, the expected benefit from DC-readout, i.e. the improved shot noise limited sensitivity for frequencies below 700 Hz is found to be covered by excess noises. Noise projections [27] revealed that the DC-readout sensitivity is at least partly limited by laser power noise for frequencies below 300 Hz [28]. In addition it has to be noted that the gap between the simulated shot-noise limited sensitivity and the measured sensitivity for DC-readout at high frequencies is partly explained by electronic noise originating from (so far) not optimized detection electronics. The noise sources limiting the peak sensitivity with both, heterodyne and DC-readout, in the frequency band between 300 Hz and 1 kHz, are so far unexplained. The different frequency dependence of the unexplained noise in the two

[10] Due to limited strength of the electro-static actuators the measurement of the optical transfer function can only be performed for frequencies up to 2 kHz.

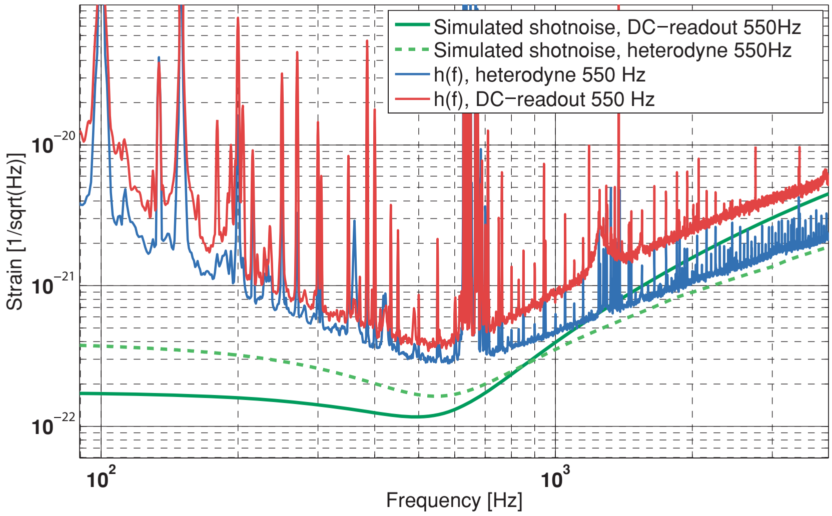

Figure 6. Sensitivities achieved with heterodyne readout and DC-readout (solid lines) and the corresponding simulated shot noise limited sensitivities. All traces represent a signal recycling detuning of 550 Hz.

measurements, might provide valuable information about the origin of the excess noise, which is subject of intense investigation.

8. Summary and outlook

We have developed and implemented a DC-readout scheme at the GEO 600 gravitational wave detector. This scheme only requires very minor hardware changes, i.e. in particular no output mode cleaner is required for removing the heterodyne sidebands from the main output port. We compared the optical response function of GEO 600 for heterodyne readout and DC-readout as well as for tuned and detuned signal recycling. The change of the optical response for detuned signal recycling when going from heterodyne to DC-readout, predicted by simulations, was well confirmed by experimental data. With DC-readout we obtained a strain sensitivity only slightly worse than the nominal GEO 600 sensitivity with heterodyne readout. At frequencies around 500 Hz a peak strain sensitivity of 4×10^{-22} Hz$^{-1/2}$ is achieved which corresponds to a displacement sensitivity of about 2.5×10^{-19} m Hz$^{-1/2}$.

These encouraging results have led to the decision to change the nominal readout scheme of GEO 600 from heterodyne to DC-readout in spring 2009. Amongst other hardware changes these upgrades which will mark the transition from GEO 600 to GEO-HF [26], will include the installation of a suspended in-vacuum output mode cleaner, whose main purpose is to remove the light from higher order optical modes. In the near future it is planned to operate the GEO detector with tuned signal recycling and DC-readout in combination with the injection of squeezed light.

Acknowledgments

We would like to thank A Rüdiger, R Schilling and S Waldman for many helpful discussions and comments. The authors are grateful for support from the Science and Technology Facilities

Council (STFC) in the UK, the BMBF, Max Planck Society (MPG) and the state of Lower Saxony in Germany and the European Gravitational Observatory (EGO). This work was partly supported by DFG grant SFB/Transregio 7 'Gravitational Wave Astronomy'. This document has been assigned LIGO Laboratory document number LIGO-P080105-00-Z.

References

[1] Sigg D *et al* 2008 Status of the LIGO detectors *Class. Quantum Grav.* **25** 114041
[2] Acernese F *et al* 2008 Status of VIRGO *Class. Quantum Grav.* **25** 114045
[3] Takahashi R (the TAMA Collaboration) 2004 Status of TAMA300 *Class. Quantum Grav.* **21** S403–8
[4] Grote H (for the LSC) 2008 The Status of GEO 600 *Class. Quantum Grav.* **25** 114043
[5] Adhikari R *et al* 2006 Enhanced LIGO, *LIGO Technical Note* LIGO-T060156-01-I
[6] Marque J (on behalf of the Virgo collaboration) 2007 Future Virgo upgrades, presentation at the 42nd Moriond meeting (La Thnile, Italy, March 2007)
[7] Fritschel P 2003 Gravitational wave detection *Proc. SPIE* **4856** 282–91
[8] Advanced LIGO reference design (LIGO Tech. Rep. M060056, 2007; http://www.ligo.caltech.edu/docs/M/M060056-08/M060056-08.pdf).
[9] http://wwwcascina.virgo.infn.it/advirgo/
[10] Schnupp L 1988 Presentation at European Collaboration Meeting on Interferometric Detection of Gravitational Waves, (Sorrent, Italy, Oct 1988)
[11] Fritschel P 2008 private communication
[12] Fritschel P 2003 Talk at Technical Plenary Session of the LSC meeting 2003, Hannover, LIGO-G030460-00 R
[13] Buonanno A *et al* 2003 Quantum noise in laser-interferometer gravitational-wave detectors with a heterodyne readout scheme *Phys. Rev.* D **67** 122005
[14] Hewitson M *et al* 2005 Optimal time-domain combination of the two calibrated output quadratures of GEO 600 *Class. Quantum Grav.* **22** 4253–61
[15] Hild S *et al* 2007 Demonstration and comparison of tuned and detuned signal recycling in a large-scale gravitational wave detector *Class. Quantum Grav.* **24** 1513–23
[16] Lawrence R *et al* 2002 Adaptive thermal compensation of test masses in advanced LIGO *Class. Quantum Grav.* **19** 18031
[17] Michelson A A and Morley E W 1887 On the relative motion of the Earth and the luminiferous ether *Am. J. Sci. (3rd series)* **34** 333–45
[18] Harms J 2006 Shot noise and heterodyne detectors, internal document
[19] Freise A *et al* 2003 Frequency-domain interferometer simulation with higher-order spatial modes *Class. Quantum Grav.* **21** 1067–74
[20] Hild S (for the LSC) 2006 The status of GEO 600 *Class. Quantum Grav.* **23** S643–51
[21] Ward R L *et al* 2008 DC readout experiment at the Caltech 40m prototype interferometer *Class. Quantum Grav.* **25** 114030
[22] Chickarmane V *et al* 1998 Squeezed light in a frontal-phase-modulated signal-recycled interferometer *Phys. Rev.* A **57** 3898–912
[23] Niebauer T M *et al* 1991 Nonstationary shot noise and its effect on the sensitivity of interferometers *Phys. Rev.* A **43** 5022–9
[24] Meers B J and Strain K A 1991 Modulation, signal, and quantum noise in interferometers *Phys. Rev.* A **44** 4693–703
[25] Hild S 2006 Experience with signal recycling in GEO 600, Presentation at GWDAW, Elba, LIGO-G060342-00-Z
[26] Willke B *et al* 2006 The GEO-HF project *Class. Quantum Grav.* **23** S207–14
[27] Smith J R *et al* 2006 Linear projection of technical noise for interferometric gravitational-wave detectors *Class. Quantum Grav.* **23** 527–37
[28] Hild S *et al* 2007 Homodyne and heterodyne readout of a signal-recycled GW detector, presentation at 7th Edoardo Amaldi Conference on Gravitational Waves, Sydney, LIGO-G070443-00-Z