The GEO 600 status

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## Abstract

The British–German gravitational wave detector GEO 600 has concluded a long observational period called *Astrowatch*, which lasted from November 2007 to July 2009. Together with the LIGO-H2 detector, GEO 600 was kept observing, while other detectors of the world-wide network of laser-interferometers like LIGO(L1 and H1) and Virgo were upgraded. A fraction of the time during the astrowatch period was set apart for noise investigations and experiments preparing future upgrades. Even with these investigations GEO 600 reached an observation time of 86.0% of the overall time, such that a total of 522 days worth of data were collected. The average sensitivity was roughly a factor of 2 lower than that of the LIGO-H2 detector for frequencies above 500 Hz. In July 2009 GEO 600 has started an upgrade program called *GEO-HF*. Within this program we aim at improving the sensitivity by a number of sequential upgrades, like tuned signal recycling, DC readout, output mode-cleaning, injection of squeezed vacuum states and the increase of circulating light power. Tuned signal recycling and DC readout have already been implemented and can be operated robustly, due to a new technique associated with the automatic alignment system.

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

## 1. Introduction

The GEO 600 detector [1] is part of the worldwide network of laser interferometers aiming at the direct detection of gravitational waves at audio-band frequencies. While the GEO detector is shorter in arm-length by factors of 5 and 6.7 with respect to Virgo [3] and LIGO [2], it uses the so-called advanced techniques which are planned to be implemented, in future upgrades of the other detectors. These are in particular monolithic suspensions, signal recycling and

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[1] A list of members of the LIGO Scientific Collaboration can be found at the end of this issue.
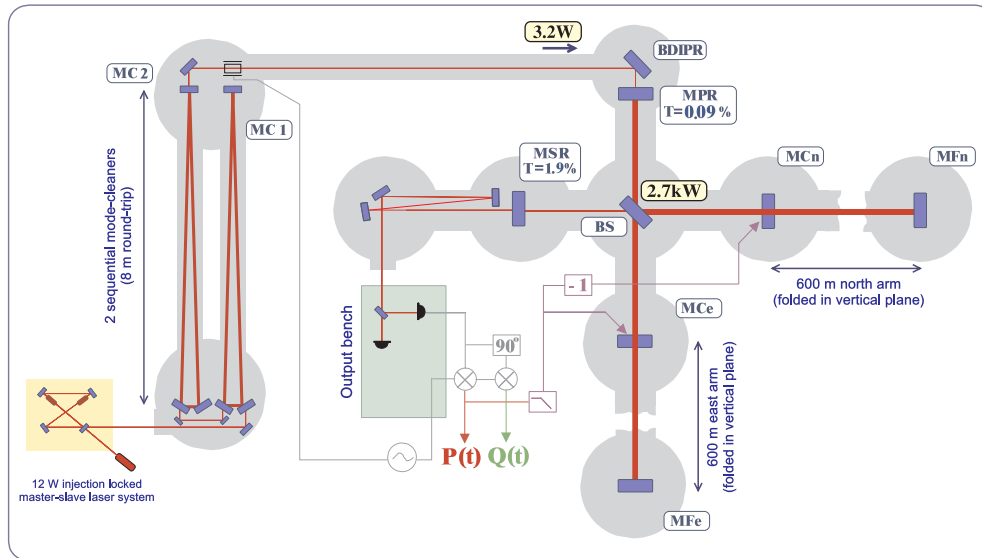
**Figure 1.** Simplified optical layout of the GEO 600 detector. GEO 600 is a power- and signal-recycled Michelson interferometer with single folded arms within 600 m long beam tubes. See more details in the text.

electrostatic test mass actuators, which have been described elsewhere. (See for example [1] and the references therein.)

In this paper, a very brief overview of GEO 600 is given in section 2, followed by a description of the data-collecting time within the *astrowatch* period in section 3. In section 4 we describe investigations during and after the astrowatch period, and in section 5 an outlook of plans and upgrades is given.

## 2. The GEO 600 detector

A simplified layout of the GEO 600 interferometer is shown in figure 1. The light of a master-slave laser system is filtered by two sequential input mode cleaners (MC1 and MC2), ring cavities of about 8 m round-trip length consisting of three mirrors each. The stabilized and filtered light leaving the mode cleaners is injected into the main part of the interferometer, consisting of a Michelson interferometer with single folded arms of 600 m length, a power recycling mirror (MPR) and a signal recycling mirror (MSR). Up till September 2009 GEO has been operating with detuned signal recycling at a detuning frequency of 530 Hz [4], and with a heterodyne readout technique, using Schnupp modulation [5], and operation of the Michelson at the dark fringe condition. In detuned signal recycling, the output of the heterodyne detector appears in two quadratures, which have to be combined in a frequency-dependent way, to yield a single data stream of strain measurement [6].

## 3. Astrowatch

From November 2007 to July 2009, GEO 600 operated in the so-called *astrowatch* mode, collecting data for most of the time. The aim of this mode was to have some interferometric
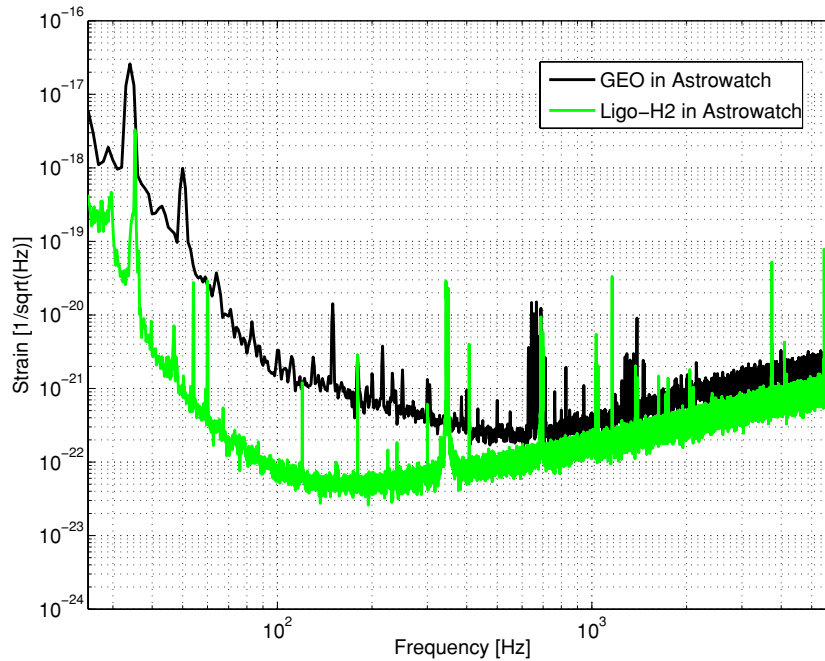
**Figure 2.** Typical strain sensitivities of the GEO 600- and the LIGO-H2 detector in astrowatch. Above 500 Hz, GEO is roughly within a factor of 2 of the LIGO-H2 sensitivity.

detectors online, while others were upgrading their instruments. The LIGO-H2 detector took part in the astrowatch program from February 2008 to the end of May 2009. While the overall sensitivity of GEO 600 and LIGO-H2 was lower than that of LIGO-L1/H1 and Virgo in 2007, the data are valuable for searches triggered by astronomical events that are detected in the electromagnetic or particle domain, as for example gamma-ray bursts and neutrinos. Typical sensitivities of the GEO 600 and the LIGO-H2 detector during astrowatch are shown in figure 2.

Figure 3 shows the daily duty factors of GEO 600 over the time from 1 November 2007 to 1 July 2009. The fraction of the total time (or *duty factor*) of the astrowatch period when GEO 600 was in the locked state is 92.4%. The locked state is characterized by properly resonating light fields in all of the optical cavities, while the science mode state needs some requirements in addition, as for example a stable on-line calibration and the absence of people from the main experimental hall. The overall fraction of science time obtained in astrowatch is 86.0%, which corresponds to a total of 522 days of well calibrated and characterized science data collected in the period between November 2007 and July 2009.

To keep GEO 600 in the data collecting mode, typically there were operators on the site on normal working hours during astrowatch, while the detector was working fully automated at night and at weekends. Over weekends, operators were on schedule to intervene, if the detector would not re-lock automatically after a loss of lock, or if any other error occurred that could be remotely sensed. We did not have operators on duty at night. Investigating the cases where the detector could not re-lock on its own at night showed that we lost about 1.5% of the total science time due to not having assigned night shifts, which seems perfectly acceptable.

The end of the atsrowatch period marks the end of about 3.5 years of predominant data taking mode in GEO 600. During the time from January 2006 to October 2007 GEO has
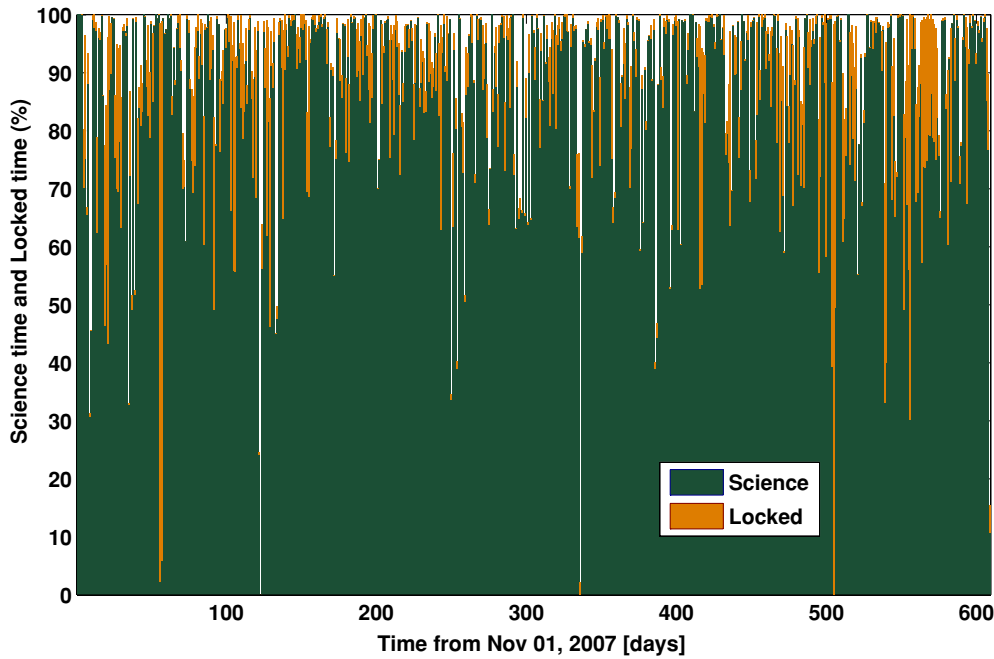
**Figure 3.** Daily fractions of locked time and science mose time (duty factors) for the astrowatch period. In the locked state, all light fields are resonating in their respective optical cavities. To qualify the data for the science mode, more conditions have to be met, like the absence of people from the main building, minimum fit quality of the calibration parameters and some others.

collected 421 days of science data within the fifth science run (S5) of the LIGO scientific collaboration. Together with the data taken in the astrowatch period, this makes up 943 days of science data.

## 4. Investigations and experiments during and after astrowatch

### 4.1. Detuned heterodyne noise budget

Investigation of the actual limiting noise sources of the interferometer sensitivity is an essential activity to facilitate further progress. While a standard set of *noise projections* can be done in a highly automated way, new noise sources have to be taken into account from time to time, in case there is unexplained noise in the sensitivity curve. Over the last years, the GEO detector has seen unexplained noise in the frequency band from about 100–600 Hz, at only slightly varying levels. In [1] we have described the investigation of laser frequency noise, oscillator phase noise and scattered light noise. Since then we have started the investigation of phase- and amplitude noise of the signal recycling modulation sidebands. To yield a control signal for the microscopic position of the signal recycling mirror, GEO uses a dedicated phase modulation of the light incident to the PR cavity at a frequency of about 9 MHz, chosen to resonate within the power recycling cavity.

While it could be shown that phase noise of this modulation signal does not limit the strain sensitivity, it turned out that amplitude noise of this modulation was coupling to the strain signal at least for a number of lines in the frequency range of 30–300 Hz. The amplitude
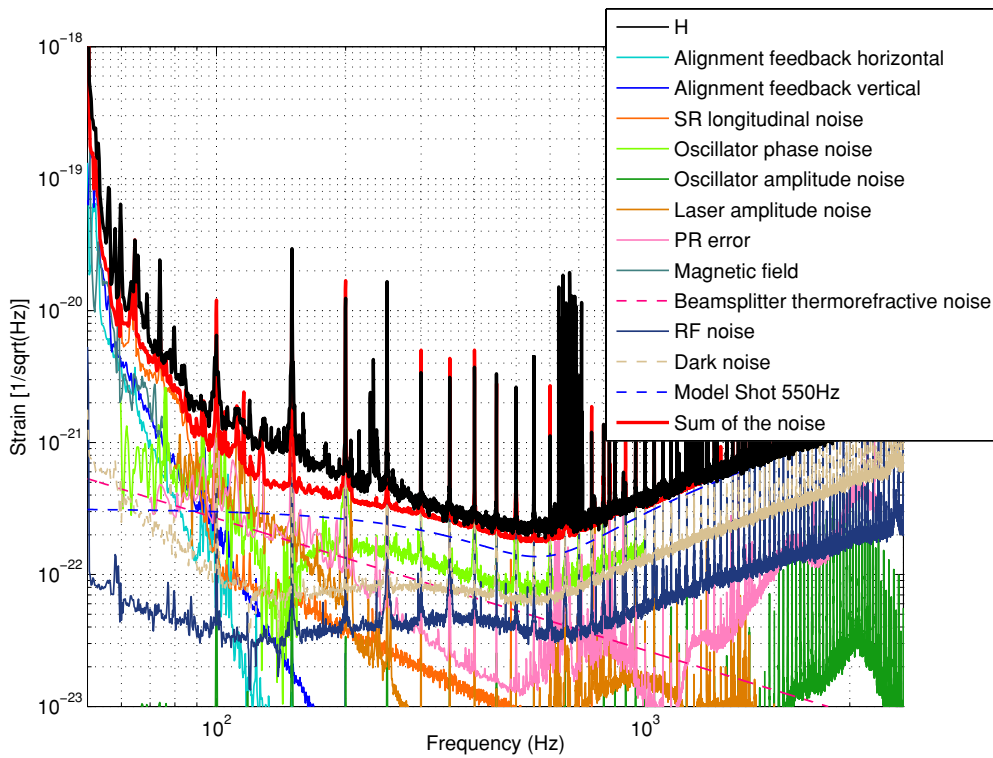
**Figure 4.** The GEO 600 noise budget in the configuration of detuned signal recycling and heterodyne readout, as used during the astrowatch period. The trace 'sum of the noise' is the uncorrelated sum of all other noise source shown in the graph. There is a gap of unexplained noise between the actual sensitivity (h) and the sum of the noises.

noise on the RF modulation was caused by GEOs digital control system, coupling to the RF modulation by electromagnetic pickup. Mitigation of this noise was possible by better electromagnetic shielding of the signal recycling modulation path against the GEO control system. Due to lack of the proper hardware, we have not yet investigated the coupling of the noise floor of the signal recycling modulation's amplitude noise. Currently, hardware is under construction to fill this gap. Besides the improvement in the signal recycling modulation path, there have also been improvements in the modulation path used for the power recycling control loop. Another field of investigation was the reduction of phase noise in the electronic demodulation path for the strain signal. Here we applied a cancellation technique, where we electrically subtract a sine wave of fixed amplitude and phase from the signal that enters the main frequency mixer. A small improvement around 10–20% of the strain noise above 1 kHz resulted from this.

Figure 4 shows the noise budget of GEO 600 after the end of astrowatch in August 2009, with GEO operating with heterodyne readout and a signal recycling detuning of 530 Hz. Compared to the noise budget shown in [1] from 2007, the unexplained noise has reduced from a factor 3 at 150 Hz to about a factor of 2, and has also been reduced at higher frequencies. Even though this is a nice improvement of the situation, the GEO sensitivity as shown in figure 4 was still not stationary over long times, and there have been times with yet additional unexplained noise, behaving like a system with two more-or-less stationary noise states.
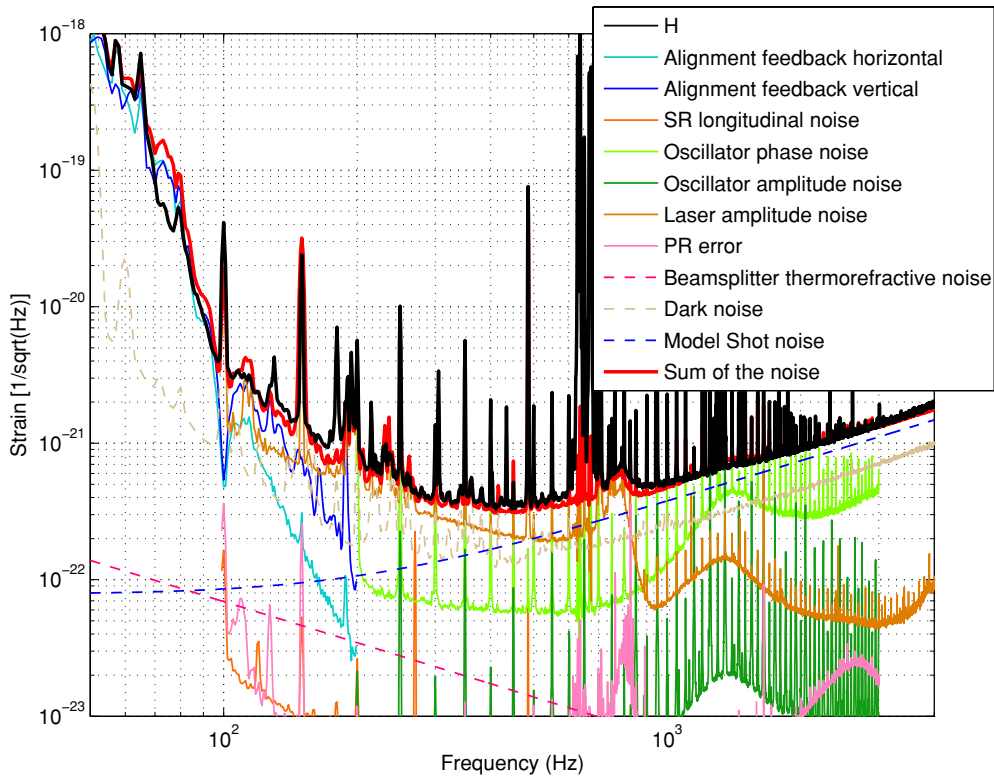
**Figure 5.** The GEO 600 noise budget in the configuration of tuned signal recycling DC readout, as of September 2009. The trace 'sum of the noise' roughly matches the observed sensitivity h. There is almost no unexplained noise.

## 4.2. Tuned signal recycling and DC readout

Tuned signal recycling and DC readout [7, 8] are two major changes in the detector configuration which are the first part of the upgrades within the program called *GEO-HF* (see also section 5). To study the implementation of tuned signal recycling and DC readout in GEO, we occasionally conducted experiments already during the astrowatch period. These experiments mainly aimed at establishing the combined operation of tuned signal recycling and DC readout (also denoted as *tuned DC readout*). Tuned signal recycling needs a modification of control loops and a dedicated acquisition technique to reach the nominal operating point. DC readout needs a change of the operating point of the Michelson interferometer and changes of readout electronics and detector calibration. Both operating conditions are incorporated in the automated locking procedure. After the stable operation of tuned DC readout was established (see also next section), we could start to study the noise budget of this configuration.

Figure 5 shows the noise budget of the detector in the tuned DC configuration, as of September 2009. Essentially there is almost no unexplained noise at all frequencies. This is an important result, in particular since the strain sensitivity obtained in tuned DC readout around 200–300 Hz is comparable to the sensitivity in the detuned heterodyne mode, while in the latter condition, the noise cannot be fully explained. Further investigations are needed to confirm this result and interpret it with respect to the unknown noise sources in the detuned heterodyne condition. It seems that the unexplained noise sources in the latter configuration

may not be present in the tuned DC readout configuration, but more quantitative analysis is pending.

*4.2.1. The 2f beam centering technique.*    While we could test the DC readout operation in GEO for a while, this configuration never was as robust as the heterodyne readout. The typical lock length in the DC readout was always clearly less than an hour, and the DC readout was hardly possible to lock under windy conditions at all. Investigation of this phenomenon led to the fact that the beam motion on the wavefront sensor at the anti-symmetric port (which is used to generate control signals for the differential alignment mode of the Michelson interferometer) was critical for the stability of the DC readout. This can be understood by the fact that in DC readout, there is a first-order coupling of the beam position on the wavefront sensor to the alignment signal (obtained on this wavefront sensor) itself. On the photodiode, the offset from the dark fringe condition of the Michelson causes a common signal at the Michelson modulation frequency across the whole area of the anti-symmetric port beam. If this beam is perfectly centered on the wavefront sensor, the common mode terms are suppressed by subtraction of the signals from each of the two half-planes of the two lateral dimensions, resulting in proper error signals for the Michelson alignment. A lateral displacement of the anti-symmetric port beam on the wavefront sensor then generates a fake alignment signal, resulting in a misalignment of the Michelson interferometer, apparently compromising its stability.

Obviously, it is difficult to predict at which level this problem would show up for any interferometer, as it depends on several factors:

- The amount of dark fringe offset determines the linear coupling coefficient of beam motion to the generated alignment signal.
- The amount of beam motion is determined to a large extent by suspension design parameters, and by the global control loops which align the mirrors.
- More external factors like the actual seismic noise level or air currents on beam paths can further increase the beam motion.

If the influence of these factors cannot be reduced, an obvious solution is the attempt to actively control the beam position on its corresponding wavefront sensor. In GEO we have always been following this strategy for almost all of the wavefront sensors, regardless of the fact that normally (i.e. non-DC-readout conditions) the beam positions only couple in *second* order terms to the corresponding alignment signals. In the detuned heterodyne configuration of GEO we have used the overall power distribution across the anti-symmetric port beam to generate a control signal for the active steering of this beam. In this configuration, the overall power is dominated by the modulation sidebands used for the heterodyne readout, and even without DC readout this increased the robustness of the lock. This strategy failed for DC readout. One obvious reason for this was that we reduced the level of the modulation sidebands, but although we experimented with large dark-fringe offsets, causing the anti-symmetric port beam to be dominated by carrier power, the lock was never very robust, and the overall power of the anti-symmetric port beam could not be used for the beam-centering. A general problem of the usage of the overall power is the presence of higher-order TEM modes (here: at the anti-symmetric port), which result from imperfections of the mirror surfaces within the interferometer and from thermal lensing effects. These higher order modes can be a function of the alignment, laser power, non-stationary heat distribution within the test-masses and dark fringe offset, just to name some.

To potentially improve the error signal for the anti-symmetric port beam centering, we now only detect the spatial distribution of the light power of the modulation sidebands present
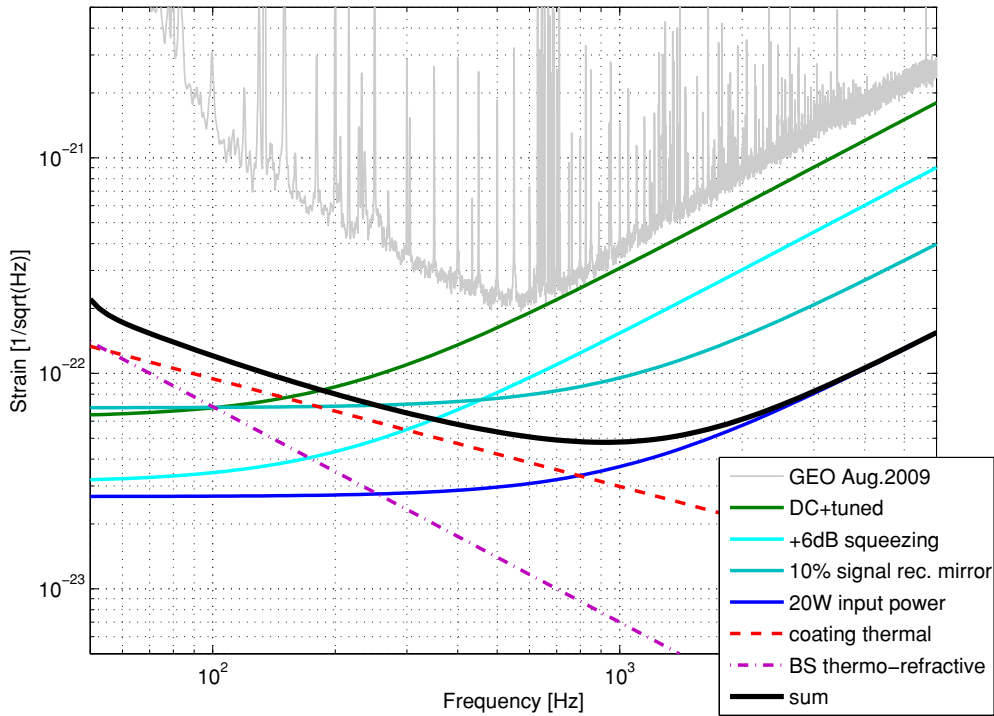
**Figure 6.** The potential strain sensitivity of GEO-HF and shot noise limited sensitivites of the individual upgrade steps of GEO-HF. Also shown are expected coating thermal noise, thermo-refractive noise of the bemsplitter of GEO, and the actual sensitivity curve as of August 2009.

at the anti-symmetric port. At least in the case of GEO, these sidebands are nice TEM00 modes, yielding the proper reference frame for the wavefront sensor, as the sidebands are used as a local oscillator for the heterodyne beat with the main carrier beam. The power of the modulation sidebands on the four quadrants of the photodiode is detected by measuring the amplitudes of the photocurrents at twice the modulation frequency. Therefore, we call this the *2f beam centering technique*.

Controlling the centering of the anti-symmetric port beam on the wavefront sensor with this signal, the DC readout extremely increased in robustness. It now can be operated in high-seismic-noise conditions and appears to be of similar stability as the heterodyne readout in GEO.

## 5. GEO-HF

With the beginning of the S6 science run within the LIGO scientific collaboration and the VSR2 science run on 7 July 2009, the upgrade program of the GEO detector has started. Within this program we aim at an increase of the strain sensitivity of GEO by a number of sequential upgrades:

- tuned signal recycling and DC readout,
- implementation of an output mode-cleaner,
- injection of squeezed vacuum into the anti-symmetric port,

- reduction of the signal recycling mirror reflectivity and
- light power increase

All of these upgrades are independent from each other, at least as far as implementation and control is concerned. Therefore, we plan to establish full locking and analysis of the actual sensitivity after each upgrade step, including data taking to gain experience with the then actual new configurations. Figure 6 shows the potential strain sensitivity of GEO 600, together with shot noise limited sensitivity curves for the individual upgrade steps of GEO, and two sources of expected thermal noise. More details about GEO-HF can be found in [9].

### 5.1. Data taking periods from 2011 to 2015

As far as it can be foreseen now, in the period from 2011 to 2015, GEO 600 will be the only interferometer in the world that can be on-line for astrophysical observations for a substantial amount of time. The three LIGO interferometers as well as Virgo will be upgrading to the *advanced* versions of their instruments. Therefore, current planning is that GEO will spend more and more time in observation mode, as all the upgrades foreseen for GEO-HF at this time are implemented, and the sensitivity would approach the planned goal.

### Acknowledgments

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