Class. Quantum Grav. **24** (2007) S389–S397 doi:10.1088/0264-9381/24/19/S02

GEO600: status and plans

B Willke (for the LIGO Scientific Collaboration)

Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut) und Leibniz Universität Hannover, Callinstr. 38, D-30167 Hannover, Germany

E-mail: benno.willke@aei.mpg.de

Received 27 April 2007, in final form 28 June 2007
Published 19 September 2007
Online at stacks.iop.org/CQG/24/S389

Abstract
The GEO600 gravitational wave detector located near Hannover in Germany is one of the four detectors of the LIGO Scientific Collaboration (LSC). For almost the entire year of 2006, GEO600 participated in the S5 science run of the LSC. Overall an equivalent of about 270 days of science data with an average peak sensitivity of better than 3×10^{-22} $\mathrm{Hz}^{-1/2}$ have been acquired so far. In this paper, we describe the status of the GEO600 project during the period between January 2006 and February 2007. In addition, plans for the near-term and medium-term future are discussed.

PACS numbers: 04.80.Nn, 95.75.Kk

1. Introduction

A search for gravitational waves is currently being performed by an international network of large-scale laser-interferometric gravitational wave detectors (LIGO [1], TAMA300 [2], Virgo [3] and GEO600 [4]). Over the last few years, GEO600 has been operated in a mode of alternating periods of short to medium duration science runs (S3 and S4 LSC Science run) and long stretches of intensive detector commissioning. In 2006, GEO600 joined the LIGO detectors for a long S5 science run which was anticipated to last for more than 1 year.

A simplified layout of the GEO600 interferometer is shown in figure 1. The light from a master-slave laser system is filtered by two sequential input mode cleaners (MC1 and MC2), each consisting of a three-mirror ring-cavity of about 8 m round-trip length. In addition to their spatial filtering, these cavities serve as a first set of frequency references to which the laser light is stabilized. The stabilized and filtered light is then injected through the power-recycling mirror (MPR) into the Michelson interferometer with folded arms and an optical round trip length of 2400 m. The operating point of the Michelson interferometer is chosen to be at the dark fringe such that, ideally, only signal sidebands and control sidebands leave the interferometer towards the output port, which hosts the signal-recycling mirror (MSR). The gravitational wave (GW) signal is derived by using a radio frequency heterodyne technique.

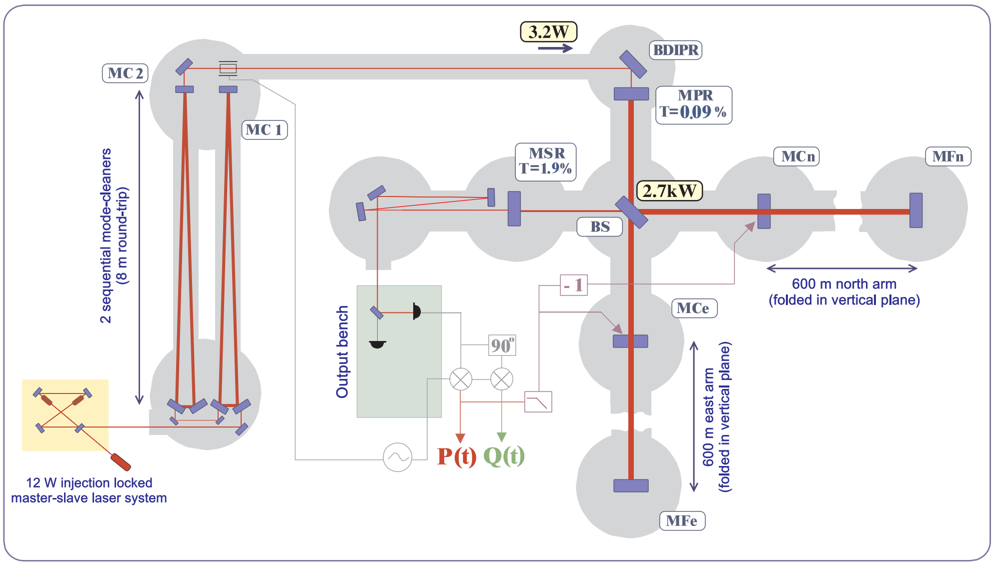

Figure 1. Simplified optical layout of the GEO600 detector. A more detailed description is given in the text.

A feature of a detector employing detuned signal-recycling is the fact that a GW signal has frequency-dependent components in both output quadratures $P(t)$ and $Q(t)$. In GEO600, these two signals are optimally combined, using a maximum likelihood method, resulting in a single GW channel, $H(t)$, with optimal signal-to-noise ratio at all frequencies within the defined observation band [5].

2. Commissioning challenges and advanced technology applications

During the commissioning of GEO600, many challenges were encountered. In this section, we briefly describe some of them which are related to triple suspensions with monolithic stages, signal-recycling and electro-static actuators.

In order to minimize thermal noise in the suspensions, the core optics of GEO600 are suspended from triple cascaded pendulums with quasi-monolithic last stages made of thin fused silica fibres [7]. These have low dissipation in flexure and their attachment to the test mass eliminates friction at that point. Loss angles of various test mass internal modes have been measured to be as low as 2.5×10^{-7} [9]. To avoid an instability of the control system, the mechanical quality factor Q of transversal fibre eigenmodes (violin modes) of the fused silica fibres had to be reduced without affecting the pendulum Q. This was realized by a novel technique employing damping, mainly of the first- and second-order violin modes, via a coating of amorphous Teflon at the relevant fibre sections [8]. The presence of actuators at each of the three pendulum stages allows the longitudinal feedback to be hierarchically split among them according to the range and the frequency band of the individual actuators [10, 11]. In summary: short-range fast corrections are applied directly to the mirror, with progressively longer range and lower frequency components being applied at the stages further up the suspension. Moreover, the passive filtering of the individual pendulum stages significantly reduces the feedback noise contributions.

While standard coil–magnet combinations are used for actuation at the top and the intermediate pendulum stages, electro-static drives (ESD) are used as fast actuators directly acting onto the test masses. By using ESDs instead of a standard coil–magnet system, it can be avoided to attach magnets to the test masses, which could degrade the thermal noise properties of the mirror. A fringing field design is employed with the curved field-lines from interleaving combs of electrodes at different voltages penetrating the dielectric test mass. At the design operating point, where the gap between the drive and test mass is about the same as the gap between the fingers of the alternating electrode combs, the force F acting on the test mass is unidirectional given by

$$F = U^2 \cdot \varepsilon \cdot \varepsilon_r \cdot d^{3/2} \cdot a, \tag{1}$$

where U is the voltage difference, ε and ε_r are the dielectric constant and the relative dielectric constant of the test mass substrate, d is the distance between the test mass and the ESD, and a is a constant geometry factor depending on the electrode pattern design [12]. In order to make the force linearly proportional to the applied voltage, the square-root of the feedback signal is generated by an electronic circuit before application to the actuator. The use of the square root circuits has the drawback of introducing additional electronic noise, but it is indispensable in providing the wide linear range needed for lock acquisition. Once the Michelson loop is locked, the required actuator range is small enough to allow the switching off of the noisy square-root circuits, and adequate linearity is obtained by use of a bias voltage. The ratio of the linear to the nonlinear term in (1) increases with the dc voltage applied to the ESDs. Hence a bias voltage of 630 V is used as the normal operation point at which nonlinearities in the ESD can be neglected [15].

GEO600 is the first large-scale GW detector to take advantage of dual-recycling, which is the combination of power-recycling and signal-recycling. While power-recycling increases the storage time of the carrier light, signal-recycling allows a shaping of the detector response and increases the sensitivity in a certain frequency band. Signal-recycling provides a variety of operation modes such that the detector response can be adjusted to match astrophysical targets. In order to maximize the science contribution of GEO600 within the network of the LSC detectors, it is operated with detuned signal-recycling, i.e. the signal recycling cavity is chosen to be off resonance for the carrier light. In the LSC S4 science run GEO600 was operated with a detuning of 1 kHz and for the S5 run a detuning of 550 Hz was established. Two measured sensitivity curves with different detunings of the signal-recycling cavity are shown in figure 2.

In the detuned signal-recycling configuration, the signal-recycling cavity is not resonant for the carrier light and has asymmetric response functions for the signal-recycling sidebands. This is the cause of a strong imbalance of the detected control and signal sidebands which leads to several potential disadvantages compared to tuned signal-recycling, including increased coupling of technical noise [6] to the detector output. Recently the operation of tuned signal-recycling was demonstrated in GEO600 and is considered as an optional configuration for the medium-term future.

Figure 3 shows the noise budget of GEO600 for the S5 run. While at high frequencies, the sensitivity is limited by shot noise, at low frequencies (below 100 Hz) feedback noise, mainly from the automatic alignment system, is the dominant noise contribution. In the region between 100 Hz and 500 Hz, a discrepancy between the uncorrelated sum of all noise projections and the actual noise level is found; this is suspected to originate from scattered light.

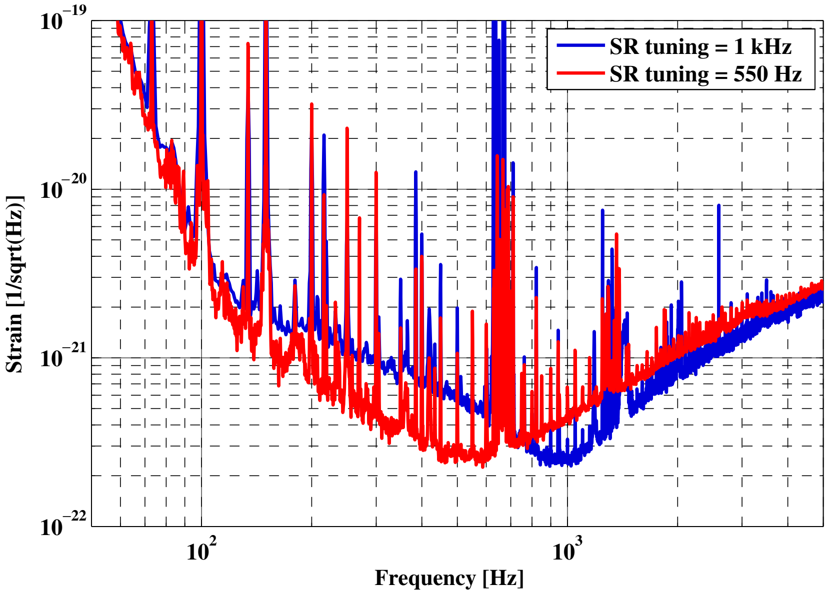

Figure 2. The usage of signal-recycling allows us to shape the sensitivity of GEO600 in a frequency-dependent way. Shown is the strain amplitude spectral density of the GEO600 detector for two different tuning frequencies of the signal-recycling cavity.

3. The S5 LSC science run

At the end of the year 2005, the three LIGO detectors started the S5 LSC science run. In contrast to previous science runs which had durations of up to a few months, S5 is intended to last about 2 years. From 21 January 2006, the GEO600 detector has participated in this notable data taking activity. The participation of GEO600 in S5 can be split up into three different periods.

- Night- and weekend-mode, period 1: 21/01/2006 to 01/05/2006.
- 24/7-mode: 01/05/2006 to 16/10/2006.
- Night- and weekend-mode, period 2: 16/10/2006 to present.

Each of these periods is briefly described in the following subsections.

The strain sensitivities of the four LSC detectors in the network are shown in the upper subplot of figure 4. The lower subplot shows the corresponding displacement sensitivities. For the GEO600 detector, a displacement of the far mirror couples twice as much into $h(t)$ as a displacement of the near mirror. In this plot the sensitivity to a displacement of one of the folding mirrors is given (MFn, MFe in figure 1).

3.1. Night- and weekend-mode, period 1

In the first section of the S5 science run, data has been taken during nights and at weekends, while the day time was dedicated for commissioning work, with care being taken to avoid disrupting the science periods. This commissioning work was mainly focussed on gaining a better understanding of the instrument performance and increasing the data quality. Strong efforts were put towards investigating glitches, to identify them and achieve their reduction

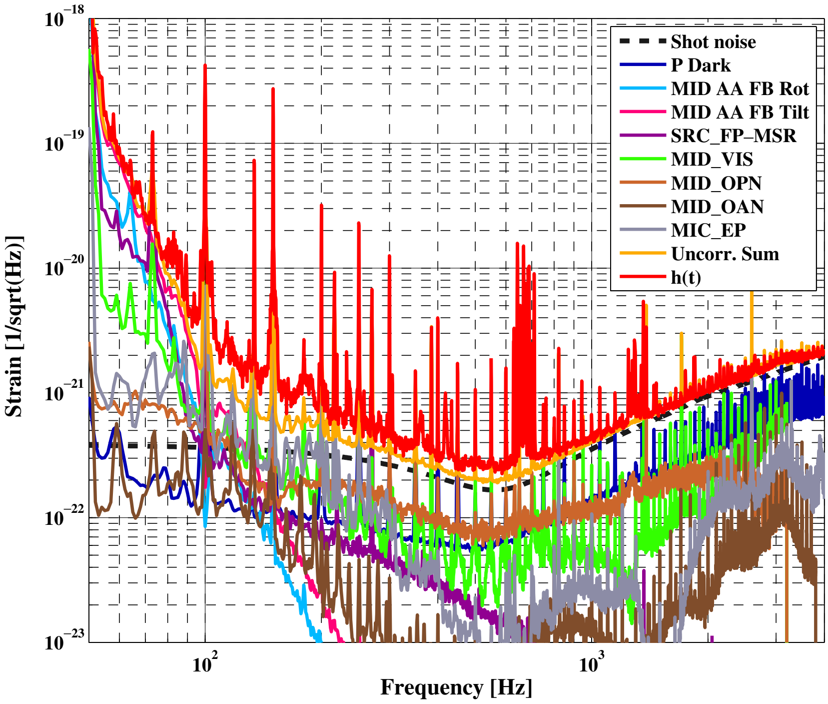

Figure 3. Noise projection of various signals for a time of the S5 LSC science run. At high frequencies, the sensitivity is limited by shot noise, while at low frequencies (below 100 Hz) feedback noise is dominating. In the region between 100 Hz and 500 Hz, a discrepancy between the uncorrelated sum of all noise projections and the actual observed sensitivity is found, that is suspected to originate from scattered light contributions.

in several interferometer channels. The highest priorities were to maintain a good calibration and characterize the science data taken during nights and weekends.

3.2. 24/7-mode

In the period from 1 May 2006 to 16 October 2006, GEO600 was operated in the so-called 24/7-mode, meaning that we tried to collect science data 24 h per day, 7 days a week, seeking a science time duty cycle as high as possible. Only very short maintenance periods took place for remeasuring noise transfer functions. Overall in 24/7-mode, an instrumental duty cycle of about 95% and a science time duty cycle of greater 90% were achieved.

An average peak sensitivity of better than 3×10^{-22} Hz$^{-1/2}$ was obtained. Figure 5 shows histograms of the rms of the GEO600 strain sensitivity in a frequency band around 560 Hz. Detailed information about the performance of GEO600 is generated automatically and stored in the GEO-reports, which contain comprehensive information about sensitivity, data quality, calibration and glitchiness of the instrument.

A main focus in the 24/7 mode was set to develop vetoes to exclude glitch events in $h(t)$, which did not originate from gravitational wave events. Four different categories of vetoes are available for S5 data of GEO600:

- *Nullstream veto.* The two calibrated output quadrature signals $P(t)$ and $Q(t)$ contain (within the calibration accuracy) the same gravitational wave information. By subtraction

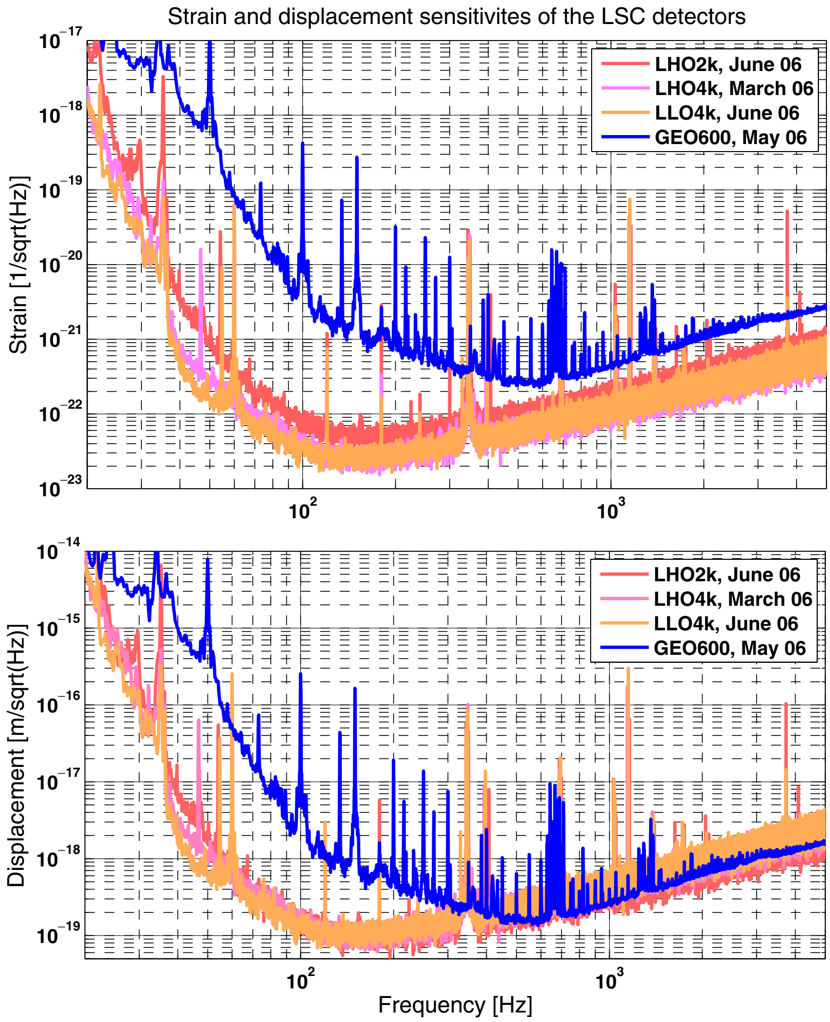

Figure 4. Strain and displacement sensitivities of the LSC detectors during the S5 science run. Shown are the LIGO interferometers (LHO2k = Hanford 2 km, LHO4k = 4 km, LLO4k = Livingston 4 km) and the GEO600 detector.

of these two signals it is possible to create a data stream, h_{null} containing no gravitational wave information. This nullstream serves as a reliable veto channel. The details of this method are described in [17].

- χ^2 *veto*. The χ^2 value is a byproduct of the calibration process [16] and indicates, first of all, the calibration accuracy, and second, the stationarity of the instrumental noise (at frequencies close to calibration lines). In case the χ^2 value points to bad detector performance for a time interval longer than a few seconds, the corresponding data are flagged out. Based on hardware injections, the time interval is chosen to be a few seconds in order to not flag out short duration potential GW events.
- *Statistical veto with amplitude consistency check*. This technique allows the derivation of safe statistical vetoes from interferometer channels which can contain traces of GW signal. Using this novel technique, we were able to develop a veto for glitches originating

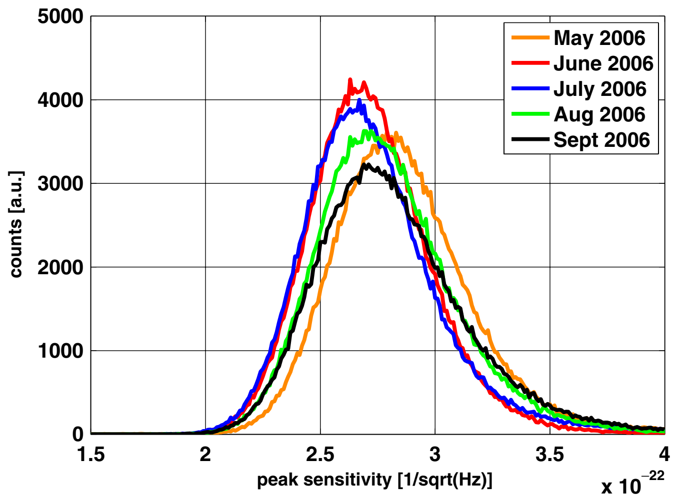

Figure 5. Histograms of the bandlimited rms of the GEO600 strain sensitivity in a bandwidth of 10 Hz around 560 Hz. For all months during the S5 24/7 period an average peak sensitivity of better than 3×10^{-22} $Hz^{-1/2}$ was achieved.

from dust particles falling through the main output beam (referred to as *dust veto*). More details about this method and its application to S5 data can be found in [13].

- *Noise projection vetoes.* This method makes use of phenomenological understanding of the coupling of different detector sub-systems to the main detector output. The main idea behind this method is that the noise at the detector output (channel H) can be projected into two orthogonal directions in the Fourier space along, and orthogonal to, the direction in which the noise in an instrumental channel X would couple to H. If a noise transient in the detector output originates from channel X, it leaves the statistics of the noise component of H orthogonal to X unchanged, which can be verified by a statistical hypothesis testing. Details of this method are presented in [18] while the application to S5 data of GEO600 is described in [19].

Figure 6 indicates the performance of the nullstream, χ^2 and the dust veto exemplarily for a 24 h data stretch from September 2006. Shown is the time–frequency-map containing all burst triggers (black dots). Events that are vetoed by the χ^2-veto, the nullstream veto and the dust veto are marked with crosses (green), diamonds (blue) and squares (orange), respectively. For the full month of September 2006, out of the roughly 115 000 burst triggers about 1000 are vetoed by the χ^2 veto, about 16 000 by the nullstream veto and about 6000 by the dust veto.

3.3. Night- and weekend-mode, period 2

In a trade-off-decision in October 2006 the following three points were taken into account:

- the necessity for maintenance of the infrastructure,
- the chance to improve the sensitivity with further commissioning work, in order to maximize the science impact of GEO600 during off-line times of the other detectors in the network,
- the acquisition of science data at the current sensitivity in coincidence with the LIGO detectors.

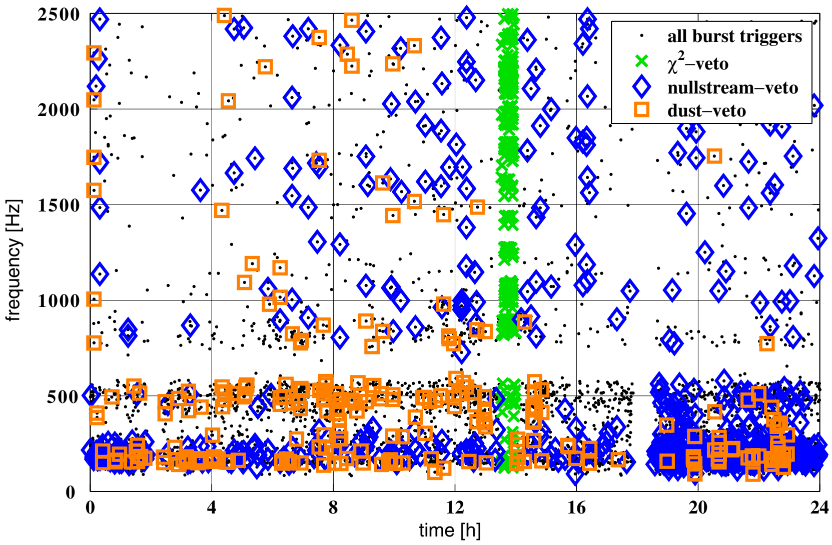

Figure 6. Performance of nullstream, χ^2 and the dust veto exemplarily for a 24 h data stretch from September 2006. Shown is a time–frequency-map containing all burst triggers (black dots). Events that are vetoed by the χ^2-veto, the nullstream veto and the dust veto are marked with crosses (green), diamonds (blue) and squares (orange), respectively. For the full month of September, out of the roughly 115 000 burst triggers about 1000 are vetoed by the χ^2 veto, about 16 000 by the nullstream veto and about 6000 by the dust veto.

Table 1. A summary of the accumulated science time and the science time duty cycle of the GEO600 detector during the S5 LSC science run so far (21 January 2006 to 18 February 2007).

Period	Duration (days)	Accumulated science time (days)	Science time duty cycle (%)
N&W-mode 1	100	46.5	46.5
24/7-mode	168	152.4	90.7
N&W-mode 2	125	70.1	56.1
Total	393	269	68.4

With input from the LSC data analysis groups, the LSC operations committee and based on a detailed benefit/risk analysis of the GEO600 commissioning team, the strategic decision was made to take the GEO detector out of the 24/7 mode (see also section 4). On 16 October 2006, GEO600 started a second period of night- and weekend-mode. The beginning of this period was dedicated mainly to non-invasive investigations necessary for future planning of the detector operation. Then in 2007 the work shifted towards invasive hardware changes in order to maintain the reliability of the instrument, increase its sensitivity and reduce its glitch rate.

3.4. Summary of S5

Overall, GEO600 collected about 270 days of well calibrated and characterized science data in the period between January 2006 and February 2007. Table 1 gives an overview of the accumulated science time and duty cycle for the three different periods of S5.

4. Future plans

Since the three LIGO detectors and VIRGO are going to shut down their interferometers for installation and commissioning of enhanced LIGO and Virgo+ in 2008, it was decided that GEO600 will have a long science data taking to cover this period. The year 2007 will be dedicated to maintenance work necessary to allow reliable operation in 2008 with a high duty cycle and an improved sensitivity. The upcoming intensive commissioning period will concentrate on increasing the circulating light power, reducing scattered light noise and improving the performance of several control loops (aiming for more stability and less noise contribution in the detection band).

Furthermore, investigations will be performed to check whether changing the readout system from the currently used heterodyne scheme to a dc-readout scheme might be beneficial. In addition we will test tuned signal-recycling operation, especially in combination with dc-readout. This configuration also seems to be promising for the application of squeezed light [20], which is considered to be part of the long term future of GEO600, namely GEO-HF.

Acknowledgments

The authors are grateful for support from the Science and Technology Facilities Council (STFC) and the University of Glasgow in the UK, and the Bundesministerium für Bildung und Forschung (BMBF) and the state of Lower Saxony in Germany.

References

[1] Sigg D *et al* 2004 Commissioning of LIGO detectors *Class. Quantum Grav.* **21** S409–S415
[2] Takahashi R and the TAMA Collaboration 2004 Status of TAMA300 *Class. Quantum Grav.* **21** S403–8
[3] Acernese F *et al* 2004 Status of VIRGO *Class. Quantum Grav.* **21** S385–4
[4] Willke B *et al* 2004 Status of GEO600 *Class. Quantum Grav.* **21** S417–23
[5] Hewitson M *et al* 2005 Optimal time–domain combination of the two calibrated output quadratures of GEO600 *Class. Quantum Grav.* **22** 4253–61
[6] 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
[7] Plissi M *et al* 2000 GEO600 triple pendulum suspension system: seismic isolation and control *Rev. Sci. Instrum.* **71** 2539–45
[8] Gossler S *et al* 2004 Damping and tuning of the fibre violin modes in monolithic silica suspension *Class. Quantum Grav.* **21** 923–33
[9] Smith J R *et al* 2004 Mechanical quality factor measurements of monolithically suspended fused silica test masses of the GEO600 gravitational-wave detector *Class. Quantum Grav.* **21** S1091–8
[10] Grote H *et al* 2004 Alignment control of GEO600 *Class. Quantum Grav.* **21** S441–9
[11] Grote H *et al* 2005 The status of GEO600 *Class. Quantum Grav.* **22** S193–8
[12] Grote H 2003 Making it work: second generation interferometry in GEO600! *PhD Thesis* Hannover
[13] Hild S *et al* 2007 A statistical veto employing an amplitude consistency check *Class. Quantum Grav.* **24** 3783–98
[14] Smith J R *et al* 2006 Projection of technical noise for interferometric gravitational-wave detectors *Class. Quantum Grav.* **23** 527–37
[15] Hild S *et al* 2006 Towards gravitational wave astronomy: commissioning and characterization of GEO600 *J. Phys.: Conf. Ser.* **32** 66–73
[16] Hewitson M *et al* 2004 Principles of calibrating the dual-recycled GEO600 *Rev. Sci. Instrum.* **75** 4702
[17] Hewitson M and Ajith P 2005 Using the null-stream of GEO600 to veto transient events in the detector output *Class. Quantum Grav.* **22** 4903–12
[18] Ajith P *et al* 2006 Robust vetoes for gravitational-wave burst triggers using known instrumental couplings *Class. Quantum Grav.* **23** 5825–37
[19] Ajith P *et al* Physical instrumental vetoes for gravitational-wave burst triggers, in preparation
[20] Chelkowski S *et al* 2007 Coherent control of broadband vacuum squeezing *Phys. Rev.* A **75** 043814