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A report on the status of the GEO 600 gravitational wave detector

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Abstract
GEO 600 is an interferometric gravitational wave detector with 600 m arms, which will employ a novel, dual-recycled optical scheme allowing its optical response to be tuned over a range of frequencies (from ∼100 Hz to a few kHz). Additional advanced technologies, such as multiple pendulum suspensions with monolithic bottom stages, make the anticipated sensitivity of GEO 600 comparable to initial detectors with kilometre arm lengths. This paper discusses briefly the design of GEO, reports on the status of the detector up to the end of 2002 with particular focus on participation in coincident engineering and

science runs with LIGO detectors. The plans leading to a fully optimized detector and participation in future coincident science runs are briefly outlined.

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

1. Introduction

Throughout the world, a number of laser interferometric gravitational wave detectors are all entering the final stages of commissioning and optimization. These detectors together form an international network that will search for gravitational waves from various astrophysical sources such as supernovae explosions, pulsars, inspiralling binary systems of neutron star and black-hole combinations and gravitational background radiation from the big bang. In addition to these known potential sources, the detectors will be sensitive to any unknown sources that are sufficiently bright. The current understanding of astrophysical sources of gravitational waves, together with predicted event rates, is summarized in [1]. Although the target sensitivities of the current laser interferometric detectors may be sufficient to make the first detection of gravitational waves, it will be the future generations of detectors that build upon the technologies developed to date which provide event rates high enough to do gravitational wave astronomy.

GEO 600 is one of six detectors currently being constructed in the world. The LIGO project [2] in the USA comprises three detectors (two with 4 km armlength and one with 2 km armlength); in Italy, the French-Italian VIRGO project [3] is constructing a 3 km baseline detector; the TAMA detector [4] (300 m baseline) has been operational since 2000 and took part briefly in the first worldwide coincident science run together with LIGO and GEO.

At the end of 2001, GEO held its first extended engineering run. This run was conducted in coincidence with the seventh engineering run (E7) of the LIGO interferometers and lasted for 17 days. In August–September 2002, GEO took part in the first coincident science run (S1). The run lasted a total of 17 days and was attended by GEO, the three LIGO interferometers and, for some time, TAMA. In the period between these two data runs, great improvements were made in the long-term locking stability and the strain sensitivity of GEO 600.

2. The design of GEO 600

Due to constraints in arm length (600 m), it is necessary that the design of GEO incorporates an advanced optical layout (including signal-recycling) and an advanced suspension system in order to make it comparable in sensitivity to the initial kilometre-scale interferometers. These advanced technologies help to reduce the coupling of fundamental noise sources into the interferometer output. A detailed description of the design of GEO is given in [5] and a brief description of some of the design aspects is given below.

2.1. Optical layout

The optical layout of GEO can be considered in three parts: the laser system, the mode cleaners and the dual-recycled Michelson interferometer. Figure 1 shows a simplified schematic of the optical layout. Except for the laser system and the output photodiode, all optical

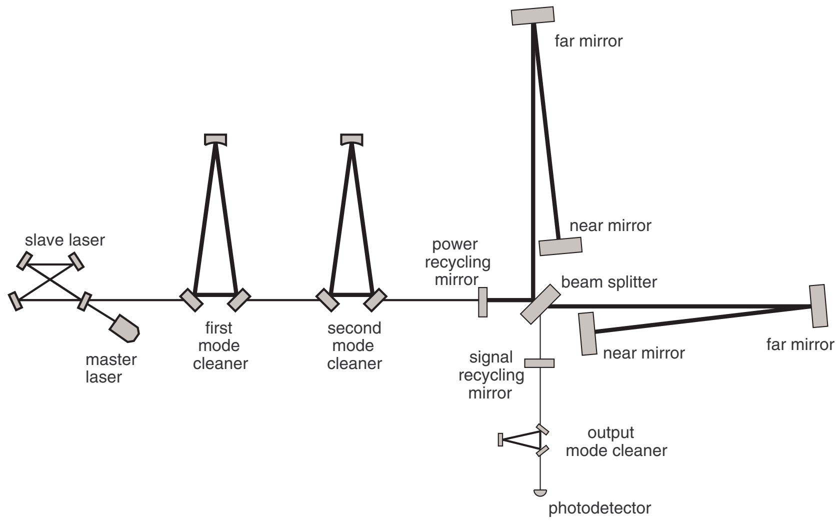

Figure 1. A schematic of the optical layout of GEO 600 showing the input laser system, the two sequential mode cleaners followed by the dual-recycled Michelson interferometer and an output mode cleaner. The output photodiode is mounted outside the vacuum system.

components are suspended inside the vacuum system. The 12 W injection-locked slave-laser is spatially filtered by two sequential mode cleaners before being injected into the interferometer. The laser frequency is stabilized to the resonant frequency of the first mode cleaner (MC1) by feeding back to the master laser. Once this loop is closed, a second loop is used to lock the laser/MC1 system to the resonant frequency of the second mode cleaner (MC2) by feeding back to the length control actuator of MC1. A third control loop is then used to lock the laser/MC1/MC2 system to the power-recycling cavity (PR). A more detailed description of the frequency control scheme used in GEO can be found in [7].

For the E7 engineering run, the two near mirrors, as well as the beamsplitter, were still test optics suspended on steel wires. This was also the case for the S1 science run. It was not until after the S1 science run that these three optical components were changed to monolithic suspensions (see section 7). For both the E7 and the S1 run, the signal-recycling mirror was not installed.

2.2. *Mirror suspensions*

In the low-frequency region (<40 Hz), the sensitivity of GEO is expected to be limited by seismic noise. The spectral density of the seismic noise in the vicinity of GEO is approximately eight orders of magnitude higher than the target displacement measurement. Two different suspension types are employed in GEO to reduce the coupling of this seismic noise to the optical components: a double pendulum system is used to suspend the mode cleaner mirrors and a triple pendulum system suspends the main test masses. A detailed description of the pendulum suspension designs can be found in [6]. To reduce the seismic coupling further, an active layer is included in the three support legs of the platform from which the main suspensions hang. This active layer contains three accelerometers which are used to sense the motion of the intermediate stage of the stacks with respect to the ground and a piezo which can be used to apply small horizontal and vertical displacements. A feedforward control system

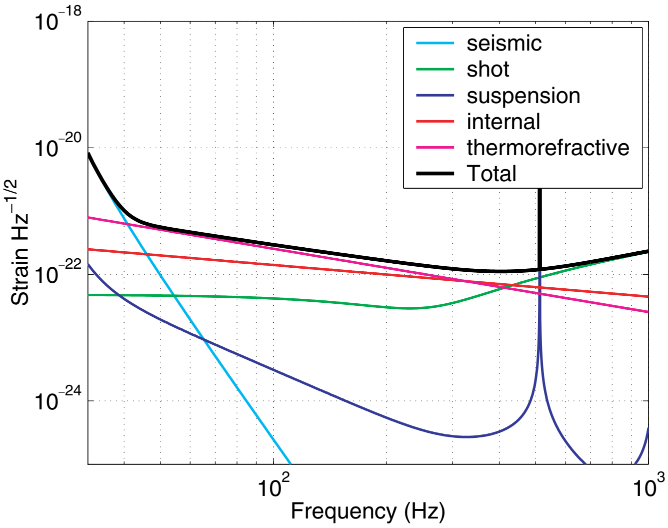

Figure 2. Modelled noise sources present in GEO 600 that contribute to the shown design sensitivity curve (total). The internal noise curve represents the thermal noise present in the test masses. The suspension noise curve consists mainly of the thermal noise present in the silica fibres of the monolithic suspensions.

is used to reduce any horizontal displacements while a feedback control scheme is used to reduce vertical displacements.

At intermediate frequencies, from 40 Hz to a few hundred Hz, thermo-refractive noise [8] is expected to dominate the detector sensitivity. At higher frequencies, it is expected that GEO will be limited by the shot-noise in the detected light.

Figure 2 shows the modelled noise sources that are present in GEO. Also shown in the figure is the total of the displayed noise sources; this curve represents the design sensitivity of GEO 600.

2.3. Detector control

Each of the four suspended cavities within GEO 600 needs both its alignment and length to be controlled. In total, 25 pendulums are locally damped in at least four degrees of freedom. In addition, eight of the vacuum tanks contain active seismic isolation systems in each of the three legs of the suspension systems. The majority of the control loops are implemented in analogue electronics and are supervised by a LabVIEW computer control environment. A full description of the LabVIEW control system can be found in [9] while an overview of the auto-alignment system can be found in [10]. The length control of the Michelson interferometer is achieved using two different actuators that act differentially on the two near mirrors using actuators mounted on a reaction pendulum chain that hangs behind the test-mass pendulum chain. At low frequencies (below 10 Hz), a coil magnet arrangement acts on the intermediate mass; at higher frequencies (between 10 Hz and 100 Hz), an electrostatic drive acts on the test mass.

3. Data acquisition and data flow

Although only the main detector output signal contains the majority of the gravitational wave information, it is also necessary to record a large range of environmental, length control and alignment signals. To do this, GEO uses a multi-channel data acquisition (DAQ) system. Three data collecting units (DCUs) are present in GEO: one in the central station, and one in each end station. Data are recorded at two possible maximum sample rates: so-called fast channels at up to 16384 Hz and slow channels at up to 512 Hz. The central station has 32 fast channels and 64 slow channels whereas each end station has only 16 fast channels. In addition to this, an interface between the detector LabVIEW control system and the DAQ system allows all the control signals ($\sim$1000) to be recorded at 1 Hz. Each DCU is locked to a GPS frequency standard to ensure accurate sampling and time-stamping of the data. A more comprehensive description of the DAQ system is contained in [11].

A central computer collects the data from the three DCUs and the LabVIEW system and writes one-second data files in a GEO internal format. These data are then transferred from the detector site to the Max Planck Institute in Hannover where it is converted into the standard gravitational wave frame format. The resulting frame files are archived on tape in Hannover and are transferred to Albert-Einstein-Institut, Golm for additional archiving and distribution to the analysis centres.

4. Coincident engineering run, January 2002 (E7)

At the end of 2001, GEO 600 started its first extensive engineering run. The run lasted about two weeks from 28 December 2001 to 14 January 2002 and was carried out in coincidence with the seventh engineering run (E7) of the LIGO detectors in the USA. The detector was operated continuously throughout this period except for maintenance periods. The purpose of the run was to gain experience in operating the detector continuously over many days. Detector improvements and repairs were not excluded. Manned shifts were conducted 24 h a day for the entire period. At the beginning of the run, operator interaction was required on an hourly basis, mostly to re-align the detector after loss of lock. As more improvements were made to the detector stability, the operator interaction became less necessary.

4.1. Detector status

At the start of this data-taking period, GEO was configured as a power-recycled Michelson interferometer with auto-alignment of the mode cleaners [10] and some slow drift control actuation implemented. Over the course of the run, more of the auto-alignment system was implemented resulting in a continuous increase in performance and duty cycle (see figure 3). From this time onward, the two far test masses were suspended via fused silica fibres from the intermediate mass, forming a monolithic bottom stage. The inboard mirrors and beamsplitter were still test optics suspended on steel wires. Only one of the electrostatic actuators was used in the longitudinal Michelson control servo. The laser power started at 1.6 W and was increased to 2.0 W during the run. The power-recycling factor was measured to be around 13 near the end of the run.

4.2. Data acquisition, data storage and calibration

The data acquisition system [11] was in a very stable condition at this time, having been extensively improved and tested in the months leading up to the engineering run. A total of 42 channels was recorded: 30 in the central station comprising all the interferometer channels and some environmental monitors, and 12 in the north station consisting entirely of environmental monitors. The total data rate was of the order of 600 kbyte s^{-1} resulting in a total storage requirement of about 800 GB. Each day, the data for that day were recorded to tape and

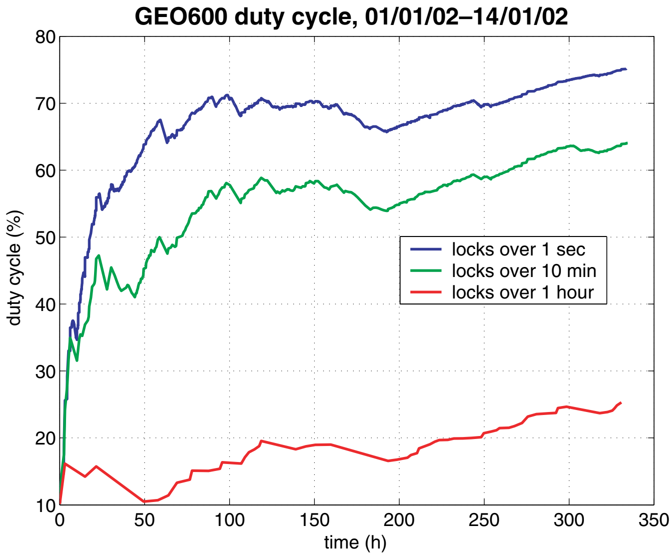

Figure 3. The cumulative duty cycle of GEO calculated between 1 and 14 January 2002.

shipped to the Albert-Einstein-Institut, Golm for archiving. In addition, data were gathered at a sample rate close to 1 Hz from approximately 800 channels of the LabVIEW control system.

The calibration of the detector for the whole run was done once about 4 days into the run. Only signals at frequencies well above the unity-gain point (∼100 Hz) of the Michelson servo were calibrated. This was done by injecting a signal at 43 Hz into one of the intermediate mass drives and looking at the signal in the detector error-point. Using a model of the intermediate mass pendulum response and by estimating the loop gain at 43 Hz, we were able to determine a high-frequency calibration (where the action of loop gain of the Michelson servo was negligible). This calibration was assumed to be constant throughout the whole run. The calibration was checked and confirmed to be still valid after the run.

4.3. Summary

At this time, the noise spectral density expressed as a strain was approximately $7 \times 10^{-19}\,\mathrm{Hz}^{-1}$ above 1500 Hz; at lower frequencies the noise increased to around $2 \times 10^{-16}\,\mathrm{Hz}^{-1}$ at 100 Hz (see figure 5). The overall duty cycle was about 70% with the longest lock being 3 h 38 min.

5. Post E7 improvements

During the months following the E7 run, extensive work was done in the following four areas: lock stability, sensitivity improvement, signal quality and calibration. The main points from each of these areas of work are briefly discussed below.

5.1. Lock stability

Work done towards improving the locking stability of the interferometer was concentrated in the following areas:

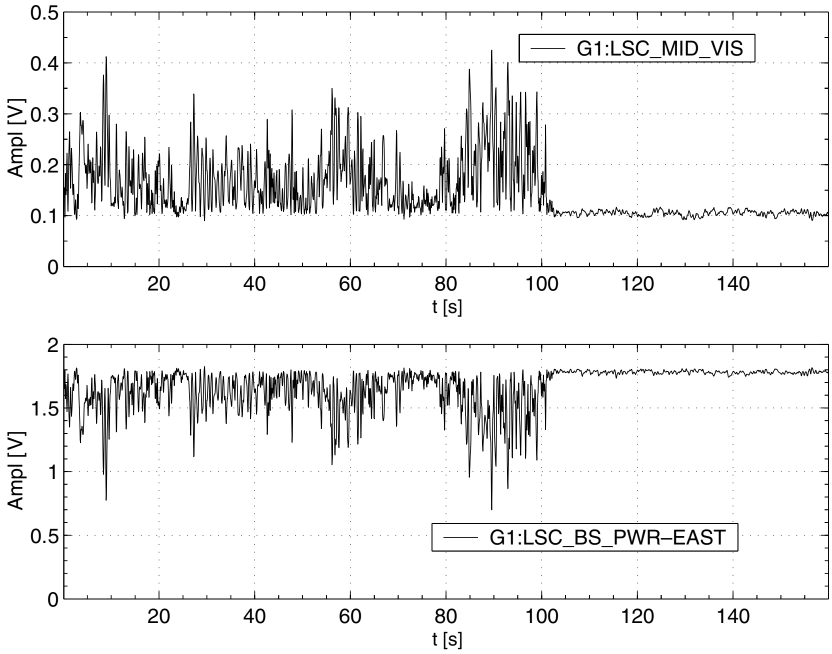

Figure 4. Time-series plots of the dark fringe power (upper trace) and power in the PR cavity (lower trace) with and without Michelson auto-alignment switched on.

- auto-alignment;
- the addition of a second electrostatic drive;
- improvements in the laser system.

Towards the end of the E7 run, most of the auto-alignment had been installed. In the period shortly after the data run, work on the auto-alignment system was completed, including all long-term drift controls. With this full alignment system in place it is possible to keep the interferometer locked for extended periods (many days). Figure 4 shows the time-series of the dark fringe light power (upper trace) and the circulating power in the power-recycling cavity (lower trace). At $t = 100$ s on these plots, the Michelson auto-alignment system is switched on. This resulted in the deviations from the dark fringe state being significantly reduced which in turn stabilized the intra-cavity power markedly.

Some time before the E7, it was noted that one of the electrostatic drives was not functioning properly. This results in only half of the design actuation force being available for acquisition and for control of the Michelson longitudinal motion. After the run, the vacuum tank of the inboard east mirror was opened and this actuator was repaired. This gave a substantial performance increase in lock acquisition.

5.2. Improving sensitivity

One of the main goals of the post E7 period was to improve the sensitivity of the detector. Looking at the noise spectrum of GEO from E7 (see figure 5), one can see a bulge in the spectrum between 50 Hz and 1 kHz. A likely source of this noise was scattered light on the

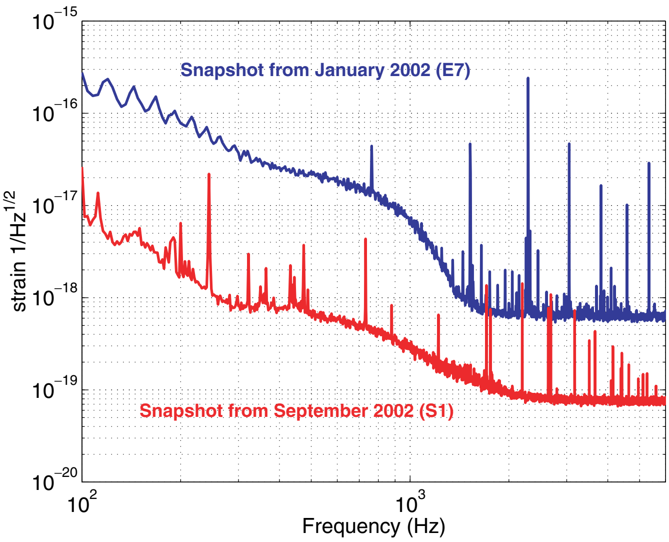

Figure 5. Snapshots of calibrated error-point spectra from GEO at two different times in 2002.

output bench mainly due to poor quality output optics. Various steps were taken to resolve this problem, including a full rearrangement of the optics on the output bench. In order to reduce the scattering to negligible levels it was necessary to attenuate the output light immediately after it left the vacuum system. This results in a poorer shot-noise performance at higher frequencies and so before starting the S1 run, a trade-off was agreed upon between good low-frequency sensitivity and better high-frequency sensitivity. With the installation of the signal-recycling mirror after the S1 run, and later the installation of an output mode cleaner, it is expected that this problem will be eliminated.

An overall improvement in the high-frequency sensitivity was due to increased circulating power in the power-recycling cavity combined with the use of a high-power photodiode to sense the output light. A change of beamsplitter for one with an improved anti-reflective coating reduced the losses in the power-recycling cavity and hence increased the circulating power. The addition of the high-power photodiode improved the shot-noise performance of the detector. For the E7 run, the output light was only sensed using the low-power quadrant photodiode that is part of the Michelson control servo. The output light had to be attenuated before hitting this diode which resulted in poor shot-noise performance. In addition to these broadband noise improvements, significant effort was put into removing line sources from the error-point spectrum. A significant fraction of the lines present during E7 was tracked down and their source removed such that for almost all of S1, the lines visible in the error-point spectrum are lines injected for calibration purposes (see section 5.4).

5.3. Signal quality

In the weeks leading up to the S1 science run, considerable effort was spent in improving the quality of the signals connected to the DAQ system. This included the installation of whitening filters for many channels and the removal of hum loops caused through incorrect shielding of signal cables and other electrical wiring problems.

5.4. Calibration

The calibration of GEO was developed further with the aim that a calibrated strain channel could be derived on-line. During the detector improvement phase leading up to S1 and throughout the run itself, a set of calibration lines was injected into the electrostatic drive feedback path. The injected signal was recorded by the DAQ system, along with the detector error-point signal. These two signals allow the optical gain of the detector to be determined using a relatively simple technique since the calibration lines were injected above the unity-gain frequency of the Michelson control servo. A time-domain model of the Michelson servo was developed using IIR filters based on measurements of the servo electronics and feedback actuators. Using this model it is possible to calibrate, at all frequencies of the detection band (50 Hz–6 kHz) and in real-time, the detector error-point to produce an on-line $h(t)$ signal. The associated software to do the on-line calibration was developed and integrated into the data acquisition such that the $h(t)$ signal would appear early in the DAQ chain. A complete record of the calibration scheme implemented for the power-recycled GEO can be found in [12].

6. Coincident science run, August–September 2002 (S1)

On 23 August 2002, GEO 600 began taking data as part of a worldwide coincident science run. The run was attended by the three LIGO detectors and for some of the time by TAMA. The run lasted 17 days and ended on 9 September 2002 GEO ran in a science mode: all operation of the detector was under the supervision of the automatic alignment and control system. Operators were on site throughout daytime hours but access to the detector buildings was restricted to 1 h per day that was defined in advance as a maintenance period. Remote intervention was possible should it be necessary (e.g., if automatic re-lock failed). An early-warning alert system was implemented consisting of a suite of software to monitor lock status, DAQ system status and file transfer status. On alert, SMS (short messaging system) messages were sent to key operators who could then attend to the problem. This kept detector down-time to a minimum during the run.

Data were recorded and archived continuously throughout the run. A total of 47 fast channels was recorded along with the many LabVIEW control channels giving a total data rate of 577 kbytes s^{-1} and resulting in a total data volume for the entire run of approximately 800 GB. A similar archiving scheme to the one used in E7 was employed.

6.1. Detector status and performance

The detector was run again as a power-recycled Michelson with full auto-alignment and slow drift control resulting in a very high duty cycle. The detector started the run locked and stayed locked for around 98% of the run—a total of about 400 h in lock. The longest lock section was close to 122 h. Figure 6 shows a record of the duty cycle. Maintenance time-slots that were actually used for maintenance are shown along with times when the DAQ system recorded poor quality data on some of the environmental channels.

The on-line calibration system was in place and various by-products of the process were recorded in the data stream. Figure 5 shows a snapshot of a calibrated strain spectrum from some time during S1. Due to the increase in the circulating power and the addition of the high-power photodiode, the strain sensitivity of GEO was significantly increased. In particular, the reduction of scattered light on the output bench led to an improvement in sensitivity of greater than one order of magnitude in the low-frequency region (a few hundred Hz). The removal of hum loops and other sources of contamination in the central building gave rise to the much

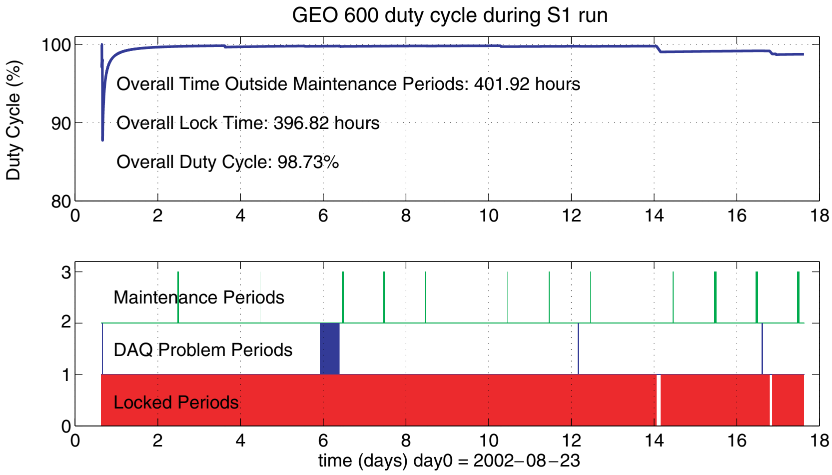

Figure 6. The duty cycle of GEO over the S1 run. In the calculation of the duty cycle, maintenance periods that were used are counted as dead time, DAQ down-time is counted as out-of-lock, and the DAQ error period is included as lock-time.

cleaner spectrum shown for S1. Most of the lines in the S1 spectrum shown in figure 5 are injected calibration lines.

6.2. Signal injection

Hardware was developed to allow artificial gravitational wave signal injection into the Michelson feedback actuators of the detector. This hardware, intended also for injecting calibration lines, allows arbitrary waveforms of a restricted length to be downloaded to onboard RAM. Towards the end of S1, this hardware was used during maintenance periods to inject inspiral waveforms with semi-random parameters. The controlling software would generate at arbitrary intervals an inspiral waveform with masses and distance chosen randomly from specified ranges. Each generated waveform was then downloaded to the injection hardware and injected into the electrostatic drive feedback path. A period of a few hours, directly after the run ended, was set aside to do more signal injection.

Data from the inspiral injection period were analysed using two distinct methods: GEO inspiral search software employing a template bank together with a chi-square veto and time-frequency transform and identification of curvilinear features in the time-frequency image. Both of these methods have been very successful in identifying the injected chirps; the instant of coalescence reported by the two algorithms agrees and is confirmed by looking at the (high-pass filtered) time-domain strain data. Currently, we are in the process of validating the results of the search algorithms with the actual parameters used during the process of injection.

6.3. Summary

Although the sensitivity of GEO during S1 still does not match the target sensitivity, it should be noted that the detector configuration is an intermediate configuration, employing only power-recycling, not dual-recycling, and using only a fraction of the final optics and monolithic suspensions. In addition, the circulating power is lower than for the final configuration and so the sensitivity achieved is consistent with what is expected of the detector at this stage in the commissioning. Exceptionally reliable locking performance was achieved during S1, indicating that GEO will be able to run automatically when it is fully commissioned.

7. Current status and future plans

After the S1 run, work began on the installation of the final optics. The two inboard mirrors were replaced with the final optics and were suspended as monolithic pendulums. The same was done for the beamsplitter. In addition, a signal-recycling (SR) mirror with 1% transmission was installed. With the exception of different SR mirror installations, the output mode cleaner and the possible replacement of the PR mirror, the complete set of final optics is now in place.

After the installation of the SR mirror but before the installation of the final monolithic inboard mirrors and beamsplitter, work started on locking the dual-recycled (DR) interferometer. Due to complexities in the locking scheme, the first attempts were made to lock the DR interferometer in a largely detuned state. A small amount of progress was made with this work before stopping to allow installation of the remaining final optics. A number of short locks (a few seconds) of the DR interferometer were achieved. Work on locking and optimizing the dual-recycling interferometer will continue after the mirror installation.

More long-term plans include installation of an output mode cleaner, an increase in circulating power and a move towards more continuous operation in science mode.

References

[1] Schutz B F 1999 *Class. Quantum Grav.* **16** A131
[2] Sigg D 2002 *Class. Quantum Grav.* **19** 1429–35
[3] Di Fiore L 2002 *Class. Quantum Grav.* **19** 1421–8
[4] Ando M 2002 *Class. Quantum Grav.* **19** 1409–19
[5] Willke B *et al* 2002 *Class. Quantum Grav.* **19** 1377–87
[6] Plissi M V *et al* 2000 *Rev. Sci. Instrum.* **71** 2539
[7] Freise A *et al* 2002 *Class. Quantum Grav.* **19** 1389–97
[8] Wanser K H 1992 *Electron. Lett.* **28** 53
[9] Casey M M *et al* 2000 *Rev. Sci. Instrum.* **71** 3910
[10] Grote H *et al* 2002 *Class. Quantum Grav.* **19** 1849–55
[11] Kötter K *et al* 2002 *Class. Quantum Grav.* **19** 1399–407
[12] Hewitson M *et al* 2003 *Rev. Sci. Instrum.* at press