The status of GEO 600

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ABSTRACT

The GEO 600 laser interferometer with 600 m armlength is part of a worldwide network of gravitational wave detectors. GEO 600 is unique in having advanced multiple pendulum suspensions with a monolithic last stage and in employing a signal recycled optical design. This paper describes the recent commissioning of the interferometer and its operation in signal recycled mode.

1. INTRODUCTION

The first world-wide network of ground based kilometer-scale laser-interferometric gravitational wave detectors is currently in the final stages of commissioning, and within a year scientific data taking should become routine. These detectors are designed to search for audio-frequency gravitational waves from a wide variety of astrophysical sources with the highest probability of detection being for inspiralling binary neutron stars or black holes,

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core collapse in supernovae, and non-symmetric spinning neutron stars (whether already observed as pulsars, low mass X-ray binaries, or not yet observed in the electromagnetic spectrum). Reference[1] presents a review of gravitational wave sources and requirements for their detection.

The network consists of five detectors at various stages of commissioning. The three LIGO detectors are located in the USA.[2] Two of these detectors share a common site (and vacuum system) at Hanford, Washington. These each have two orthogonal arms extending from a shared central building, in one case the arms are 2 km long and in the other 4 km long. The third LIGO detector is at Livingston, Louisiana, where there is a single 4 km system. In order of decreasing length, the French-Italian VIRGO detector comes next with a 3 km system under construction near Pisa, Italy,[3] followed by the German-British GEO 600,[4] near Hannover, Germany, the main subject of the present work. The Japanese TAMA 300 m detector is in operation in Tokyo,[5] and there is also an Australian prototype being built by the ACIGA project in Western Australia which could be extended to km-scale in the future.[6]

All of the systems listed use laser interferometry developed from Michelson's orginal interferometer,[7] but with a number of important differences which bring advantages to individual detectors. In particular, GEO 600 is the only detector thus far to employ signal recycling[8,9] in its optical configuration and fused-silica suspension technology[10] to support the interferometer mirrors. The remainder of this work will address these distinctive technologies and show how they interact with the process of commissioning the interferometer.

2. THE MONOLITHIC SILICA SUSPENSIONS

In order to limit thermal noise in the observing band it is necessary to mimimise dissipation within the mechanical components and to design systems with as few as possible resonant modes within the band.[11] This, combined with the need to isolate the optical components from external sources of vibration (seismic and cultural noise) led to the decision in GEO 600 to suspend each of the main optical components as the lowest element in a three-stage cascaded suspension system. A schematic is given in figure 1. To enhance the rejection of ground vibrations active and passive vibration isolation stages are built into the three 'legs' that support the platform from which the suspension hangs. These legs or stacks are described in detail in.[12]

To maintain the required resonance conditions in the optical cavities forming the interferometer, the control system must maintain the alignment of the optics to nanoradian accuracy and hold their relative positions to sub-nanometre accuracy. Correction signals are applied to the suspension *via* the reaction pendulum hanging immediately behind the mirror suspension. The weak forces required to make short term corrections are applied directly to the optic, while the larger forces necessary to correct slow drifts are applied further up the suspension chain. Each stage of the suspension provides considerable isolation within the observing band allowing stronger but noisier actuators to be employed higher up the suspension chain. The necessity to control pitch and yaw of the optic forces the use of multiple connections (wires or fibres) between neighbouring suspension stages (four connections in GEO 600). Another part of the control system must ensure that, when the interferometer falls out of operation and the control signals vanish, the low loss and hence high Q-factor resonances of the suspension are not excited so much that regaining control becomes impossible. This is achieved by active, cold damping applied in six degrees of freedom at the top stage of the suspension. The masses, moments of inertia and geometry of the connections between the stages were chosen to ensure that all, low frequency, rigid-body modes of the suspension were visible at the top stage, and hence controllable from there. (The higher frequency vertical and roll modes associated with the extension of the connections between the two lowest stages do not require to be damped.)

Due to curvature of the Earth and the folding of the arms in GEO 600 (done in a vertical plane), vertical motion of the optics inevitably couples to motion along the beam with a coupling factor of up to 10^{-3}. Two layers of cantilever mounted, maraging steel springs are incorporated one above and one below the top mass of the suspension to enhance vertical isolation.[13]

The most significant, original design feature of the GEO 600 suspensions is the use of fused-silica fibres to connect the two lower stages to reduce mechanical dissipation. Reference[14] provides full detail of this technique. Apart from one very minor problem due to tapering fibres causing the effective connection points not to match those in the suspension model (see below) there have been no operational difficulties with the suspensions.

Photographs of the lower stages of suspensions immediately prior to installation are shown in figure 2.

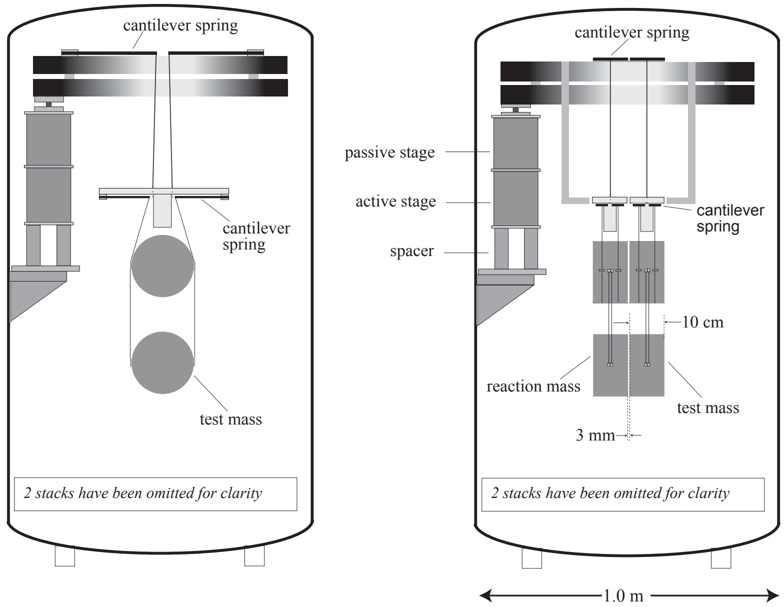

Figure 1. Face view (left panel) and front view (right panel) of the GEO 600 triple pendulum suspensions for the main interferometer optics (or 'test masses'). The top stage is metal supported by steel wires while the two lower stages are fused silica, connected by fused silica fibres for low dissipation. There are two stages of cantilever-mounted maraging steel springs included to enhance vertical isolation. In some cases a second 'reaction pendulum' suspension hangs immediately behind the main suspension and is used as a quiet platform from which to generate the forces needed to position and align the optic. The entire suspension hangs from a support platform which sits on 3 isolation legs or stacks. Each stack has an active and passive isolation stage enclosed in steel bellows. Further detail is given in the text.

3. THE DUAL RECYCLED OPTICAL SYSTEM OF GEO 600

A simplified diagram showing the most important optical components of GEO 600 is given in figure 3. This represents the situation in May 2004, and is very close to the final configuration of the instrument.

One of the key problems in laser interferometry is suppression of the effects of laser amplitude, frequency and beam geometry noise. The first step was to construct the interferometer with enough symmetry to reject any noise (as an example, if the arms of the interferometer were perfectly equal in length there would be no sensitivity to frequency noise). The second approach is to make the laser as quiet as possible, to clean and stabilise its output and finally to attempt to sense any residual noise and use negative feedback to suppress it.

The Nd:YAG laser consists of an injection locked system of monolithic low noise, low power 'master' laser and a higher power 'slave', both are diode pumped. The 12 to 14 W output of the slave acquires the frequency-noise of the master. The amplitude stability of the output is improved by negative feedback from a power sensor near the laser to control the pump power of the slave.

Beam geometry noise (position, pointing, and fluctuations in beam size) are improved by spatial filtering of the beam from the laser.[15] In GEO 600 it was chosen to do this using a pair of stable, high finesse, ring cavities: the 'mode cleaners' shown in figure 3. When the fundamental mode is on resonance, as required to transmit the beam from the laser, the higher order spatial modes are (for the most part) far off resonance in these cavities. (Non-degeneracy of higher order modes in a cavity is equivalent to stability.) Any tendency for the beam to change position, direction, or size leads to light being injected into higher order spatial modes, but since these are not resonant, their transmission through the cavity is very small. Each cavity, with finesse ~ 2000, provides at least 3 orders of magnitude filtering of beam geometry fluctuations, and two together are sufficient. The mode cleaning process leads to some increase in amplitude noise, which can be corrected by monitoring the light power emerging from the second mode cleaner and feeding back to adjust the operating point of the stabilisation system mentioned above.

Figure 2. Side view (left panel) and oblique view (centre panel) of a GEO 600 mirror, showing the attachment of fused-silica fibres. A fused silica ear is bonded to the substrate and the fibres are subsequently welded to the ear using an oxy-hydrogen flame. The welding is done in a jig (right panel) which is then used to support the suspension as it is installed in the vacuum tank and hung from the top suspension mass on a pair of loops of steel wire which pass round the upper of the two masses shown.

An additional benefit of the use of cavities as mode cleaners is that they also provide temporal filtering. The GEO 600 mode cleaners are 8 m and 8.1 m round trip length, respectively, and have storage times of about $30\,\mu s$. The gravitational wave signal is to be detected by using a heterodyne scheme operating at about 15 MHz (see below), and the effect of the low-pass action provided by the mode cleaners is to suppress strongly the laser noise at such a high frequency.

The most significant imperfection of the laser is its frequency noise. Even a small imbalance of the arms of the interferometer makes the fringe pattern at the photo detector sensitive to changes in light frequency. Modelling has shown that the frequency noise must be reduced by about 6 orders of magnitude at Fourier frequencies around 100 Hz, from an initial, measured, level of $\sim 100\,\mathrm{Hz}/\sqrt{\mathrm{Hz}}$. This is accomplished using a relatively complex hierarchical control method,[16] the overall effect of which is to maintain the laser wavelength in proportion to the average length of the two interferometer arms, assumed to be sufficiently stable on the short term.

In the initial operation of GEO 600 the output from the laser has been attenuated to about 2 W before being directed to the first mode cleaner, mainly to avoid damage to components − such as photo detectors − until experience was gained in the operation of the detector. The injection optics (mode cleaners and associated components) transmit half of the light, leaving 1 W to be injected into the core interferometer.

The core of the GEO 600 detector is based on a simple Michelson interferometer, but with a number of variations and enhancements. A key component is the beamsplitter, which must divide the light into two equal beams, and provide recombination, with very little loss of power. Inevitably some of the light must pass through the substrate of the transmissive beamsplitter. To obtain the desired sensitivity a circulating power of 7 kW must be achieved in GEO 600, so considerable care is needed to avoid thermal effects in the substrate. To this end the beamsplitter was fabricated on a substrate of ultra-low absorption fused silica (a type of Suprasil, by Heraeus, developed especially for VIRGO[17]). The 9 cm thick substrate is expected to absorb less than 18 parts per million (ppm) of the light power passing through it. It also has extremely low optical inhomogeneities as required to preserve the interference quality.

All laser interferometric gravitational wave detectors employ low-loss coated optics fabricated using ion-beam-sputtering deposition of multi-layer dielectric stacks. Such mirrors typically have total optical loss in the

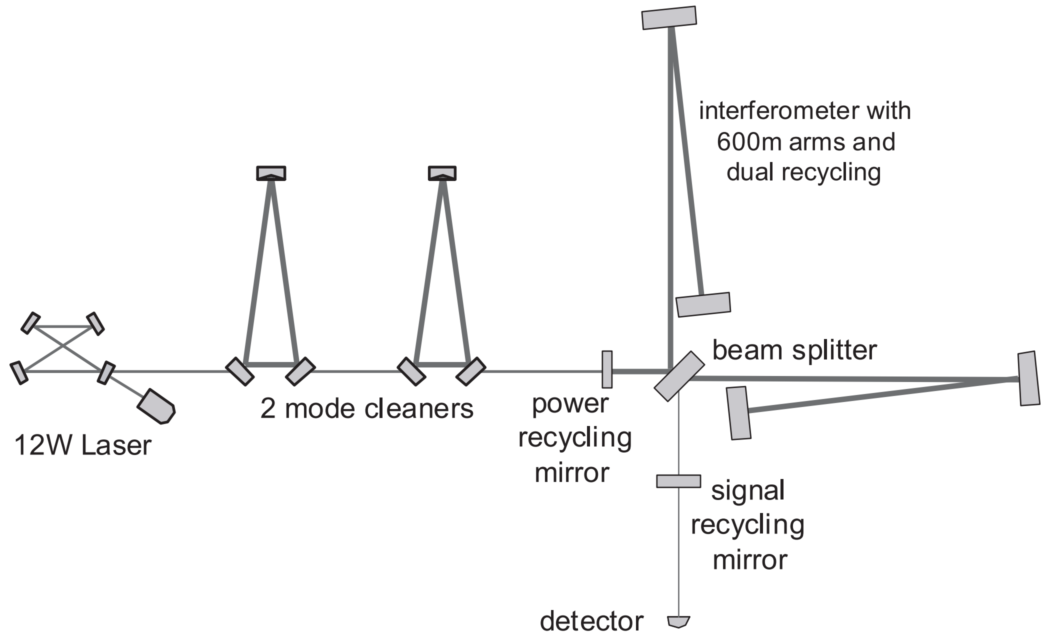

Figure 3. A simplified schematic showing the layout of the most significant optical components of GEO 600. The light from the laser, shown left, passes through 2 ring cavity mode cleaners before being injected into the interferometer. The beam splitter divides the light equally so that half passes along each of the folded 600 m arms, for a total round trip of 2400 m. The power and signal recycling mirrors, the latter unique to GEO 600 are shown. Light emerging through the signal recycling mirror is focussed in an output telescope (not shown) before reaching the main photo detector, an InGaAs photodiode.

10 ppm to 100 ppm range. The detectors are operated with the laser light shone into one port and the other (output or detection) port maintained at an interference minimum by delicate control of the relative positions of the mirrors and beamsplitter. In this situation most of the light would be reflected from the interferometer back in the direction of the laser, and wasted. This inefficiency is avoided by adding a 'power recycling mirror' to form an optical cavity with the rest of the interferometer (termed the power recycling cavity). The maximum possible photon count can be achieved in the arms of the interferometer when the transmittance of this mirror is equal to the total optical loss in the interferometer, enhancing the sensitivity.[18]

In GEO 600 the initial power recycling mirror has a transmittance of $T = 1.5\%$, larger than optimum, but designed to tolerate imperfections such as minor misalignment of the interferometer, and to allow simplified operation until experience is gained. The optical loss in the interferometer is small compared to the transmittance of the power recycling mirror, and so the power build up factor within the power recycling cavity is $4/T \approx 270$. Since approximately 1 W enters the interferometer the circulating power is currently about 270 W.

All interferometric gravitational wave detectors, except GEO 600, employ two Fabry-Perot cavities, of finesse of order 100, one in each arm of the interferometer. The action of these is to store the photons for a longer time than they would require just to double-pass the arm length, increasing the phase change accumulated during the passage of a gravitational wave, at the expense of detection bandwidth.

A simple Michelson interferometer of 600 m arm length would have a bandwidth (up to the first null in the response) of about 250 kHz, far wider than is optimum for gravitational wave detection. In GEO 600 the arms are folded to an effective round trip length of 2400 m, giving a first null at about 125 kHz, still too large. Instead of cavities in each, a similar signal enhancement and bandwidth reduction is achieved in GEO 600 by adding a cavity to enclose the entire interferometer. This technique is called signal recycling, by close analogy to power recycling described above. When used together these are often called dual recycling.

Power recycling operates on the components of the light field that are in-phase in the two arms. Any light components that are out of phase between the two arms (such as the differential fluctuations caused by a passing gravitational wave) are directed to the detection port. If instead of allowing these signal components to reach a photo detector, a partially transmitting 'signal recycling' mirror is placed in their path, they are reflected back into the interferometer in superposition with other signal components (optical sidebands) from earlier and later times. The signal components behave just like any light fields in an optical cavity, and so the transmittance of the signal recycling mirror determines the bandwidth of the interferometer, and its microscopic position determines the signal frequency that is maximally enhanced. At present the signal recycling mirror of GEO 600 has a transmittance of $\approx 2\,\%$ yielding a signal bandwidth of 430 Hz. The centre frequency of the response can be adjusted over the band of interest by adjusting the parameters of the control system that maintains the position of the signal recycling mirror with respect to the rest of the interferometer. Up to now GEO 600 has been tuned to give maximum performance for signal frequencies around 1 kHz, where other, non-optical, noise contributions are best understood and have been minimised.

Another significant feature of dual recycling is its capacity for 'mode-healing', i.e. compensation of defects such as figure errors or minor misalignment of the interferometer components.[19] In a power recycled (but not dual recycled) interferometer, a defect in one arm will lead to power leaving the dark port. The simplest way to analyse this effect is to consider the defect as scattering some power from the fundamental spatial mode of the power recycling cavity into higher order modes.[20] Unless these modes are generated with precisely the same amplitude and phase, in both arms, there will be some light that leaves the output port of the interferometer, reducing the power recycling gain and increasing the measurement noise. The power recycling cavity of GEO 600 was designed to be stable, ensuring that the most important higher order spatial modes are far off resonance. This was achieved using a combination of curved mirrors to form the arms and a plane power recycling mirror. The signal recycling mirror is also plane, and so also forms a stable cavity in conjunction with the interferometer. In a stable cavity (most of) the higher order spatial modes are off resonance, and are suppressed. This is exactly the same behaviour that is observed in any Fabry-Perot cavity where imperfectly shaped and aligned mirrors can still lead to a stable mode that is very close in shape to the perfect Gaussian profile.

4. CONTROL OF THE DUAL RECYCLED INTERFEROMETER

The control system for the interferometer has two main functions: firstly it must sense the relative positions and alignments of all of the suspended optical components, and by feeding back appropriate control forces maintain the components close to the ideal alignment. The second function is to read out signals that represent the variations in the average length of the arms and in their difference. As mentioned above, the average length (common mode) signal is taken as a measure of laser frequency variations (noise) and used to compensate them. The differential mode signal contains any gravitational wave signal and must be read out with the highest possible fidelity. References[21] and[22] describe the GEO 600 control schemes in detail.

Every signal representing relative positional or angular information in GEO 600 is obtained by using a variant (or generalisation) of the RF-reflection schemes first used for laser stabilisation.[23] The basic principle is to add additional frequency components (usually phase-modulation sidebands) on to the light illuminating the complex optical system. The additional components are chosen so that they resonate differently from the carrier light in the complex coupled-cavity system (i.e. the interferometer). Each signal is then obtained by detecting a light field either reflected from the system or transmitted through it, and analysing the beats between the components using coherent demodulation at the modulation frequency. In GEO 600 three pairs of modulation sidebands are applied to the light travelling towards the interferometer to allow control of the core interferometer and to read out the gravitational wave signal.

The common mode signal, required to control power recycling and laser frequency noise, is obtained using the original RF-reflection method: the sidebands are non-resonant in the interferometer, and the light reflected from the interferometer is analysed to reveal the phase shift picked up by the carrier as it resonates in the power recycling cavity. The signal is derived by square law detection on a photodiode followed by demodulation of the resultant electrical signal at the modulation frequency to measure the amplitude and phase of the beat signal. In GEO 600 the modulation frequency for this purpose is carefully adjusted to match the resonance of the second mode cleaner at 37.19685 MHz. The phase modulation sidebands are passed through the second mode cleaner and the modulation frequency is adjusted to match the free spectral range of the cavity. This is done to provide some spatial filtering of the modulated beam.

The position of the signal recycling mirror determines the tuning of the interferometer. A control signal for the signal recycling mirror is obtained by applying sidebands which resonate in the signal recycling cavity, where there is very little carrier light. The signal is obtained by detecting and demodulating a sample of the light from one arm of the interferometer, picked off by the anti-reflection coating on the 'rear' surface of the beamsplitter substrate. In this case the roles of sidebands and carrier are reversed from the normal RF-reflection method since the carrier is the phase reference and the sidebands, incident on the signal recycling mirror, acquire the appropriate phase change when resonant.

In order to obtain the desired control signal (with a zero crossing at the chosen operating point) it was necessary to adjust the frequency of the phase modulation quite precisely and also to suitably arrange the macroscopic positions of beamsplitter, power recycling and signal recycling mirrors. The correct parameters were found by modelling using a specially written numerical tool,[24] and are given in.[21] The modulation frequency was selected from a large number of possibilities (one near each free spectral range of the signal recycling cavity) to be about 9.0122 MHz, the particular multiple of the free spectral range being chosen largely for convenience. The precise frequency chosen depends on the desired tuning frequency for the interferometer.

The gravitational wave signals are expected to be very weak, and the path length changes caused by them expected to produce tiny phase modulation sidebands on the light in the arms of the interferometer (nanoradian modulation indices or less). These sidebands could, in principle, be detected by mixing them with a sample of the carrier light, e.g. by adjusting the relative arm lengths to slightly offset the interference from the dark fringe, and direct measurement of the beat using a photodiode at the base-band frequency. In GEO 600, however, the light is relatively noisy at the baseband frequencies but extremely quiet at MHz frequencies due to the filtering provided by the mode cleaners. An RF heterodyne system is, therefore, employed. A strong local oscillator at 14.904855 MHz is added to the field at the output port and mixed with any signal sidebands on a fast photo detector there. This frequency is chosen to maximise transmission of sideband power through the interferometer. The modulation frequency was chosen (from a large set corresponding to free spectral ranges of the power recycling cavity) to be high enough to minimise any residual excess noise without making design of the relatively high power photo detector too difficult. In selecting the various modulation frequencies used in GEO 600 care was taken to ensure that low-order harmonics of the various frequencies were not co-incidental, to avoid spurious signal products appearing at mixers.

The local oscillator in GEO 600 is generated by phase modulating the light on the path to the interferometer following the method of Schnupp.[25] If the two arms of the interferometer were of exactly equal length, and the carrier were to be held at a dark fringe, the local oscillator would not reach the detection port. For this reason an asymmetry of about 10 cm was introduced into GEO 600. With this small change it becomes possible to transmit the local oscillator power relatively efficiently to the output port of the interferometer.

Efficiency is important as it is impractical to divert more than a few percent of the power into the local oscillator sidebands at the modulator, and yet the local oscillator must strongly dominate the optical field at the output port to allow a near-ideal measurement of any signals; the signal size is proportional to the local oscillator amplitude, while the shot-noise in the detection of a coherent field is proportional to the modulus of the total light amplitude, see.[26]

In GEO 600, with 1 W of light injected into the interferometer, about 50 mW of local oscillator is generated in each sideband by an electro-optic phase modulator suspended between the second mode cleaner and the power recycling mirror. In the dual recycled system one sideband is transmitted more efficiently than the other, and so the modulation waveform at the output is a mixture of amplitude and phase modulation. When the interferometer is operating correctly the additional unmodulated light at the output port is estimated to be < 1 mW (in fact the best fit to the experimental measurement of this is consistent with zero). This unwanted power reaching the photo detector represents only a few ppm of the power incident on the beamsplitter: signal recycling is key to achieving such high 'fringe contrast'.

The control signals for length and angular alignment are filtered and applied to the feedback actuators on the mirror suspensions. Most of the actuators are linear electromagnetic motors (coil-magnet systems) which produce forces up to a few mN, but the sub-micro newton corrections required to keep the interferometer at the dark fringe on short timescales (less than 250 ms) are applied directly to one mirror in each arm using electrostatic actuators.

The electrostatic actuators consist of patterned gold electrodes forming interleaving fingers on a dielectric mass suspended parallel to and 3 mm behind one mirror of each arm. Voltages are applied to the electrodes which produce a fringing field penetrating the fused silica mirror substrate. The substrate experiences an attractive force proportional to the square of the voltage. To avoid damping the suspended mirror, and thus in that way introducing thermal noise, the resistance of the electrodes, wiring and drive amplifiers is kept to $< 10\,\Omega$. The square law non-linearity of the drive is corrected by operating with a bias large compared to the typical dynamic forces and by pre-processing the correction signal through an amplifier that approximates a square root law. The actuator is also non-linear with respect to changes in the spacing between the plate carrying the electrodes and the interferometer mirror. This is not problematic, however, as the electrostatic drive hangs on a suspension essentially identical to that supporting the mirror. A photograph of an electrostatic actuator ready to be installed in GEO 600 is shown in figure 4.

Figure 4. Face view of an electrostatic actuator for GEO 600. Four pairs of electrodes, when driven in combination, allow longitudinal, pitch and yaw adjustment of the mirror. Each actuator pad consists of two gold patterns deposited on fused silica, with a chromium intermediate layer to increase reliability. The gaps between the electrode-strips average about 4 mm.

5. COMMISSIONING THE DUAL RECYCLED INTERFEROMETER

The control systems required to operate the dual recycled interferometer, as described above, have been extremely reliable in normal steady state operating conditions. It was, however, a considerable challenge to discover a reliable approach to bringing all three length control systems to their operating condition from an arbitrary starting point in the face of various environmental perturbations (seismic noise, motion of buildings due to wind and so forth) which lead to initial relative mirror velocities of up to around $1\,\mu$m/s in poor weather.

If the three systems were just switched on and left, locking (achieving the desired operation) would probably never occur, because the locking condition represents a tiny part of the 3-dimensional parameter space and the freely-swinging mirrors would cause the state of the interferometer to pass through this point in a fraction of a millisecond, too fast for the control system to react. A number of techniques have been invented and employed to minimise the time taken to lock the system.

The first important step was the realisation (during preparatory experiments[27]) that it was possible to keep the common-mode control of the laser frequency at or very close to its operating point irrespective of the condition of the other parameters. This is possible because the laser and mode cleaners can track the frequency shifts of around 100 kHz/s required to keep the carrier resonant in the interferometer. When the interferometer output passes through a bright fringe the common mode signal disappears transiently, but careful design of the common mode feedback electronics allows the system to pass through this singularity without too much of a perturbation.

By this method the control problem is reduced to a two-dimensional one and the probability of success in a given time increased substantially. The second important realisation was obtained by close inspection of the two-dimensional parameter space during detailed modelling of the GEO 600 system. The region immediately surrounding the desired locking point was seen to be very complicated, with steep gradients and sign reversals, any attempt to bring the system straight to the final operating point was seen to be unlikely to work. It was quickly realised, however, that for sufficiently large detuning of the signal recycling cavity (making the system resonant above about 5 kHz, rather than the desired few hundred Hz) would allow initial locking in a relatively benign region of parameter space.

The detuning frequency is determined by the microscopic position of the signal recycling mirror relative to the rest of the interferometer. Modelling showed that small changes (by just a few kHz) of the RF modulation frequency would allow the detuning frequency to be swept from that appropriate for initial locking to that required for gravitational wave searches. Later, when initial locking was made more reliable, a computer control system was set up to monitor the condition of the interferometer. After initial locking with large detuning the modulation frequency for control of signal recycling was changed step by step to the final value, allowing a fraction of a second for the control system to relax at each step.

It was found that the system could only lock when the relative velocity of the mirrors was unusually small, otherwise the control system lacked the authority to halt the mirrors before the interferometer had left the, still quite small, region of parameter space in which locking is possible. It was realised that less critical signals, in the detuned state, could be obtained by measuring the power in the RF sidebands at $\sim 15\,\mathrm{MHz}$ by demodulating the output from the main photo detector at twice this frequency. This so called '2f' system produces a signal which, when a DC-offset is subtracted, indicates the tuning of the signal recycling cavity well enough to allow initial locking. After lock is acquired a micro-controller recognises this and switches over to the original phase sensing method. This method worked immediately and has proven extremely reliable.

At first there were a number of problems associated with locking dual recycling in poor weather. These were traced to some unmodelled defects of the mirror suspension systems. It was noted that initial lock acquisition was frequently followed by loss of lock after only a fraction of a second, accompanied by evidence of angular misalignment of the mirrors. The problem was traced to excitation of the suspensions by seismic, wind-related and cultural noise, in the frequency range from about 0.5 to 3 Hz. After some analysis it was recognised that horizontal motion of the ground at one or other of the interferometer mirrors was leading to excessive pitching of the mirrors (and in an L-shaped interferometer of 600 m length the motions are almost guaranteed to be out of phase at the various mirrors most of the time). This effect had been expected, but was exaggerated by a minor constructional error in the suspensions: the fused-silica fibres were tapered rather than cylindrical as had been modelled, this led to slight changes in the rigid-body motion of the suspension, and in particular increased longitudinal-pitch coupling.

A first step in correcting this problem was to implement feed-forward active compensation of the micro-seismic motion.[28] Piezo-electric actuators had been built into the support structure of the mirror suspensions for precisely this eventuality. Sensitive seismometers (Streckeisen STS-2[29]) were mounted on the floor of each building to determine the motion and a digital signal processor based feedforward system implemented to cancel the motion by adjusting the voltage applied to the piezo-electric actuators. Implementing this system brought a significant improvement, but there was still some observed coupling of longitudinal adjustment of the interferometer to pitching of the mirrors in response to longitudinal control forces applied further up the suspension chain. The same digital signal processor system was used to generate a pitch correction to cancel the pitch error in the suspension, again using a feedforward technique. This proved highly satisfactory.

Shortly after all of these corrective measures were put in place GEO 600 participated in an observing run ('S3') with LIGO. The duty cycles achieved during a little over two weeks of that run are shown in figure 5.

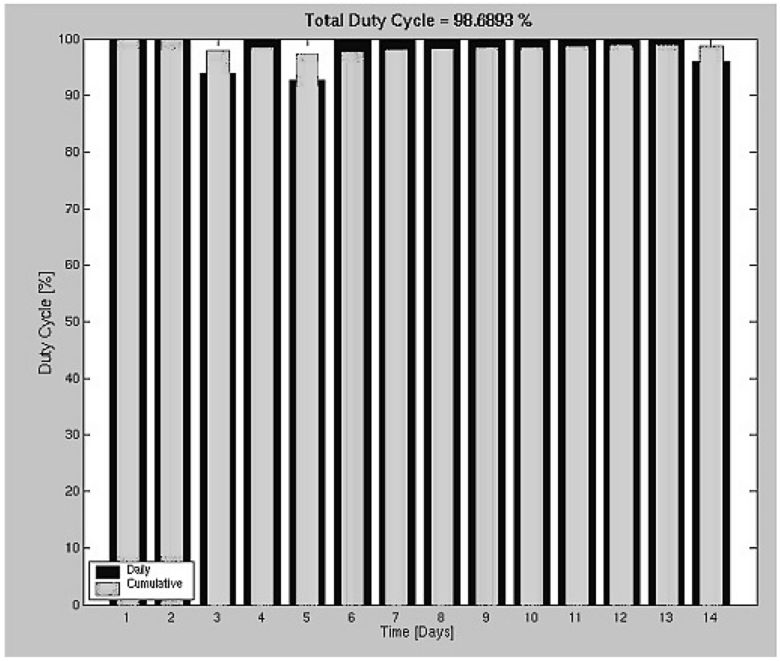

Figure 5. Duty cycles of GEO 600 over two weeks of observing early this year. The percentage of time the interferometer was operating in a fully correct and calibrated manner is shown by the black bars (daily) and grey bars (cumulative). The final cumulative figure, over 98.5% is extremely satisfactory.

6. FUTURE STEPS

The commissioning of GEO 600 is not complete as there are still a few minor adjustments required to the optical system. In particular, the optics between the signal recycling mirror and the detection port are not yet in final form.

The diffraction-limited beam leaving the signal recycling mirror is, at over 2 cm diameter, too large to be directed onto the final photo detector (which must have a frequency response extending beyond 15 MHz). A two mirror 'telescope' is used to focus the beam to the required $\approx$ 1 mm size. Initially this telescope was built on an optical bench outside the vacuum system. It was, however, noted that seismically and acoustically induced motions of the output telescope components were generating noise far in excess of that which could be tolerated. Improved components and changes to the configuration of the interferometer have allowed the noise to be reduced to tolerable levels, but at present the output telescope is being relocated into the vacuum system to provide improved isolation from acoustic and seismic vibration.

At the same time the attenuator that restricts the laser power from its full 12 to 14 W to just 2 W is being removed. This should increase the effective light power circulating in the power recycling cavity from about 270 W at present to over 1.5 kW. At some point, when all other noise contributions have been reduced sufficiently, it will be necessary to change the power recycling mirror to allow the design value of 7 kW to be achieved.

As mentioned above, the fringe contrast of GEO 600 is extremely high. As the laser power is turned up to the full 14 W, and, especially, when the power recycling mirror is replaced, it is expected that a thermally induced, astigmatic 'lens' or refractive index profile will be produced in the substrate of the beamsplitter.[30] This can be dealt with in several ways: a compensation plate could be used, and one of sufficiently low loss has been obtained and is held in reserve; but another approach is to fit a mode cleaning cavity on the output of the interferometer, which has the advantage of also correcting defects other than those arising at the beamsplitter. With dual recycling the system will tolerate considerable internal distortions without large changes to the shape of the optical mode which will remain close to the ideal Gaussian shape. The gravitational wave signal will still, therefore, be found in Gaussian shaped phase modulation sidebands at the output port. Most of the extra light reaching the output due to defects will be in other spatial modes, and so a mode cleaner can reject the unwanted light while transmitting most of the signal.

Such an 'output mode cleaner' has been designed for GEO 600, roughly following the design of one for the VIRGO interferometer.[31] It is a triangular ring cavity of 10 cm round trip and finesse about 30 designed to be placed just in front of the photo detector. Its resonant bandwidth (~ 50 MHz) is such that it can transmit carrier, signal sidebands and local oscillator efficiently through one longitudinal resonance. This component will be implemented in GEO 600 as soon as it is clear that its use will bring advantage. The optical system will then be complete, although it would always be possible to change the signal recycling mirror for one of lower or higher transmittance to allow observation with smaller or larger bandwidth in the search for particular classes of astrophysical signal.

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