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Performance of a 1200 m long suspended Fabry–Perot cavity

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Abstract
Using one arm of the Michelson interferometer and the power recycling mirror of the interferometric gravitational wave detector GEO 600, we created a Fabry–Perot cavity with a length of 1200 m. The main purpose of this experiment was to gather first experience with the main optics, its suspensions and the corresponding control systems. The residual displacement of a main mirror is about 150 nm rms. By stabilizing the length of the 1200 m long cavity to the pre-stabilized laser beam, we achieved an error point frequency noise of 100 μHz Hz$^{-1/2}$ at 100 Hz Fourier frequency. In addition we demonstrated the reliable performance of all included subsystems by several 10-hour-periods of continuous stable operation. Thus the full frequency stabilization scheme for GEO 600 was successfully tested.

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

1. Introduction

By the beginning of 2001 the installation of the main optics of the gravitational wave detector GEO 600 [1] was well under way. The Nd:YAG laser source and the mode cleaners were completely installed. The frequency and length control system as well as an automatic alignment system for the mode cleaners were installed. These systems are operated in a fully automated, remotely controllable fashion and provide the input beam for an interferometer in the main vacuum system. In addition, three main mirrors were suspended, the *power recycling*

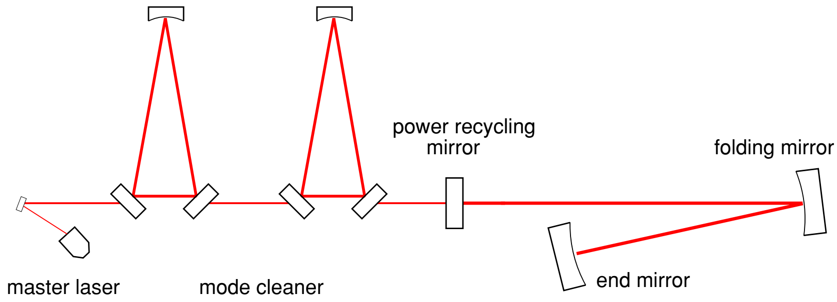

Figure 1. The 1200 m cavity in January 2001: The light of the master laser is filtered by two mode cleaners and injected into the 1200 m long cavity formed by the power recycling mirror and the two mirrors of the folded east arm of GEO 600.

Table 1. Measured optical parameters of the GEO 600 mode cleaners.

Mode cleaner	Finesse	Throughput	Visibility
MC1	2700	80%	94%
MC2	1900	72%	92%

mirror, the *folding mirror* and the *end mirror* of one arm of the Michelson interferometer (see figure 1). These mirrors form a cavity with 2400 m round trip length, which is very similar to the power recycling cavity in a recycled Michelson interferometer. This enabled us to perform a first test of the length and frequency control. The cavity is the first large-scale optical system we have operated in GEO 600 and the *first arm* of the detector.

2. Optical layout

The laser system of GEO 600 is an injection-locked master and slave system with 14 W output power at 1064 nm [2]. After leaving the laser, the light is passed through two successive mode cleaners [3]. The mode cleaners are ring cavities with 8 m round trip length and three mirrors each, which are suspended as double pendulums. The measured optical parameters of the two mode cleaners are shown in table 1. The main optical instrument in GEO 600 is a dual-recycled Michelson interferometer [4, 5]. In contrast to other interferometric gravitational wave projects [6–8], GEO 600 does not employ arm cavities but folded arms (see figure 2).

The laser light enters the main instrument from the west (W) at the *power recycling mirror* (PM) and is split into an east (E) and a north arm (N) at the beam splitter (BS). At a distance of 600 m from the beam splitter each arm has a *folding mirror* (FM) that directs the beam back (slightly tilted) towards the beam splitter. The light hits the *end mirror* (EM) located close to the beam splitter 25 cm above the axis of the injected beam. In the final optical layout the beams reflected from the two end mirrors are superimposed on the beam splitter. The Michelson interferometer is held on the so called *dark fringe*, where the tiny phase modulation sidebands containing the gravitational wave signal are directed south (S) towards the *signal recycling mirror* (SM). The major part of the light power (the carrier) is reflected back to the power recycling mirror. Thus the power recycling mirror and the Michelson interferometer form a cavity for the carrier light of 2400 m round trip length, the *power recycling cavity*.

All main mirrors are suspended as triple pendulums to give a very good seismic isolation in the direction of the optical axis [9]. By January 2001 three main mirrors were installed.

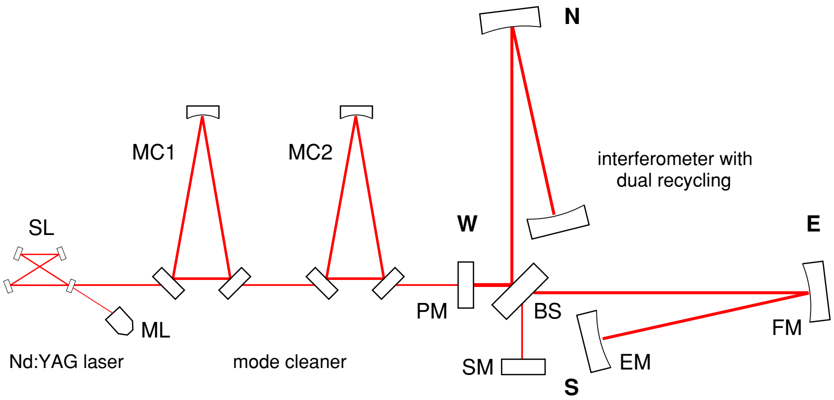

Figure 2. The optical layout of GEO 600: The laser consists of a monolithic master laser plus an injection-locked slave laser in a bowtie set-up, the two mode cleaners are suspended 8 m ring cavities, the main interferometer is a dual recycled Michelson interferometer with folded arms.

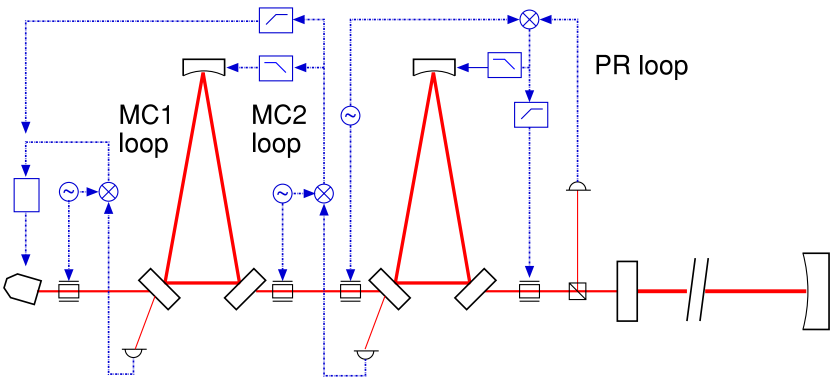

Figure 3. The frequency stabilization scheme of GEO 600: the feedback paths of the length and frequency control for the power recycling cavity, the two mode cleaners and the master laser.

The east arm was fully equipped with the end mirror and the folding mirror. Furthermore, the power recycling mirror was in place. The beam splitter was left out so that the three mirrors formed a Fabry–Perot cavity (see figure 1), which is very similar to the power recycling cavity of the final detector. For the experiment described here the master laser (ML), an 1 W non-planar ring oscillator (NPRO), was used as the light source, with the 14 W amplifier (SL) being bypassed.

3. Laser frequency stabilization

The laser frequency stabilization scheme used in GEO 600 is unique because it does not include any rigid reference cavity. Instead cavities with suspended mirrors are used. The suspended cavities provide a very good reference for frequencies above 50 Hz because of their excellent seismic isolation.

The optical systems and the feedback systems are shown in figure 3. The frequency of the laser is locked to the first mode cleaner using a standard Pound–Drever–Hall method (MC1 loop). The feedback is applied to the frequency modulation input of the master laser. The bandwidth of this control loop is 100 kHz.

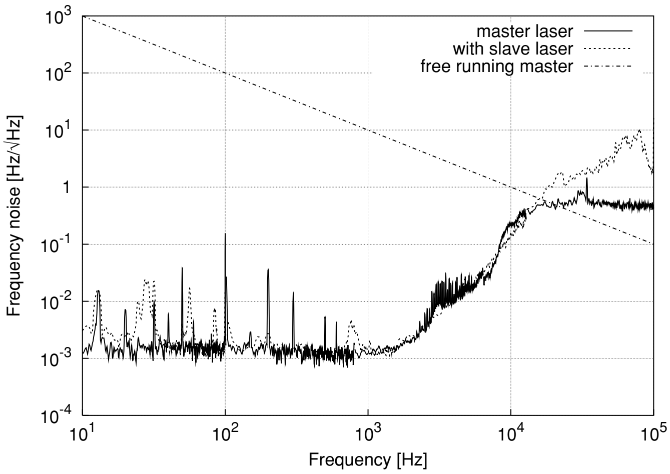

Figure 4. The frequency noise at the first mode cleaner (MC1). The in-loop frequency noise is about 1 mHz and is not degraded when the high power slave laser is added.

The next step is to pass the light through the second mode cleaner. To do so we have to bring the injected light into resonance with the second mode cleaner by changing the length of the first mode cleaner and thus the laser frequency. This is done with a feedback control system using another Pound–Drever–Hall error signal (MC2 loop). The control signal is split and fed back to two actuators: the slow Fourier components ($<$4 kHz) are applied to the length of mode cleaner MC1 via coil magnet actuators on one of its mirrors, while the fast components are injected into the error point of the MC1 loop, i.e. they directly act on the master laser frequency (see figure 3). The fast feedback path is necessary to achieve a high servo bandwidth (about 25 kHz) and thus a high gain at low Fourier frequencies.

Finally, the pre-stabilized light has to be resonant in the power recycling cavity. A third control loop (PR loop) with yet another Pound–Drever–Hall scheme is used to control the length of mode cleaner MC2 accordingly. The feedback of this loop was split into a ‘slow’ path, which acts on the length of the second mode cleaner (by moving one of its mirrors), and a ‘fast’ path. The fast signal is applied to an electro-optic modulator in front of the power recycling cavity that serves as a fast phase corrector. In the experiment described here the control bandwidth of the PR loop was 40 kHz.

In order to measure the performance of the frequency stabilization, one can perform two different experiments: (a) an in-loop measurement of the frequency noise (this is done by taking the error point spectrum of the frequency control loop) or (b) an out-of-loop measurement of the residual frequency noise of a stabilized laser with respect to an independent frequency reference. Figure 4 shows the error point spectrum of the MC1 loop that stabilizes the master laser to the first mode cleaner. The frequency noise in the error point is about 1 mHz $Hz^{-1/2}$ below 1 kHz. In comparison with the typical frequency noise of a free running NPRO one can see the gain of the servo loop, e.g. 100 dB at 100 Hz.

The master and slave laser system can be treated as a black box from the outside, in the sense that the frequency of the slave laser is following the frequency of the master laser and thus the slave inherits the frequency stability of the master. The injection locking controls the slave laser frequency with a higher bandwidth than the servo loops that apply feedback to the frequency of the master laser. Figure 4 also shows a comparison of the error signal of the MC1 loop for (a) the master laser only and (b) the master plus injection-locked slave. It

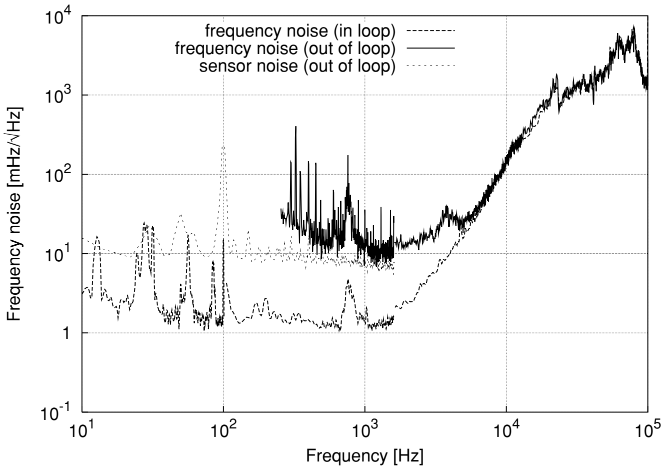

Figure 5. Comparison of in-loop and out-of-loop frequency noise at mode cleaner MC1. The sensor noise of this stabilization loop is also plotted. Please note that, with the method used here, the out-of-loop frequency noise could only be measured down to 300 Hz.

can be seen that the laser frequency noise is very similar in both cases. The servo electronics of the MC1 loop were not changed between the two measurements.

With two mode cleaner cavities, one can also use the second mode cleaner as an independent reference (apart from common-mode effects caused by suspending both mode cleaners from the same mechanical structure in their vacuum tanks) to measure the performance of the laser frequency stabilization of the first mode cleaner. This is an out-of-loop measurement of the frequency noise and the result is shown in figure 5. For this measurement the laser was locked to the first mode cleaner as usual. Then the first mode cleaner was locked to the second as described above (MC2 loop) but with a very low servo bandwidth (unity gain frequency $\approx$300 Hz). The frequency noise in the error signal of the MC2 loop then gives the residual frequency noise of the MC1 loop for Fourier frequencies above the unity gain frequency of the MC2 loop.

As can be seen in figure 5 the measured out-of-loop noise floor is about 10–30 mHz $Hz^{-1/2}$ below 1 kHz and very close to the sensor noise of the MC1 loop, i.e. the electronic noise of the photo diode. We believe that the shot noise limit can be reached by increasing the light power on the photo diode by a factor of five.

We also measured the out-of-loop frequency noise of the MC2 loop with respect to the power recycling cavity. This measurement showed that the out-of-loop frequency noise of the MC2 loop and that of the MC1 loop are very similar. As both mode cleaners are similar cavities with common noise sources, the frequency noise can only be improved a little by the second control loop. This is different for the power recycling cavity: the cavity has a much smaller bandwidth (400 Hz in this experiment) and the length of 1200 m greatly improves the relative stability. Also this cavity uses triple pendulum suspensions for its mirrors, so that the absolute motion of the mirrors is less than that of the mode cleaner mirrors with their double pendulum suspension for Fourier frequencies above 10 Hz. Thus the power recycling cavity can be used as a stable frequency reference and by stabilizing the mode cleaners and the laser light to the power recycling cavity length, the frequency noise can be further improved (see next section).

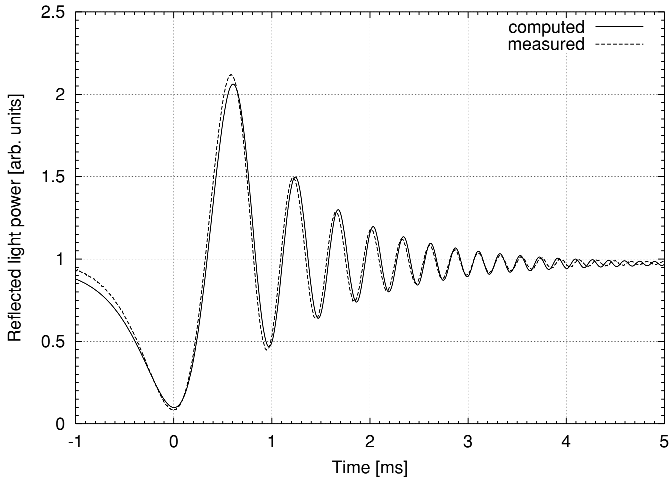

Figure 6. Simulated fringe of the power recycling cavity compared to a measured typical fringe. The simulation gives a finesse of 300 for the power recycling cavity and a velocity for the relative motion of the mode cleaner MC2 mirrors of 20 nm s^{-1}.

4. Performance of the 1200 m cavity and its length control system

The mode cleaner system was completed in December 2000. Both cavities were automatically aligned and the lock acquisition of the length control loops was fully automated. The servo systems for the length control use analogue electronic devices. They can be guided by a computer system via a digital bus [10] to automate lock acquisition of the full optical system. Therefore, in normal operation no human interaction is required. We thus had a stable input beam for the experiment with the 1200 m cavity.

The three mirrors of this cavity were without any alignment control and thus had to be aligned manually for every experiment. When a reasonably good alignment was established one could observe fringes in the light reflected from the long cavity. A numerical simulation was used to fit a model function to a measured time series of the reflected light power of the 1200 m long cavity (see figure 6). The simulation works in the time domain and calculates the dynamic changes of the light power inside a cavity after an incident laser beam comes into resonance with the cavity. In our case the cavity was assumed to be rigid while the frequency of the incoming beam is subject to a sweep (the effect is the same as for a cavity with moving mirrors that is illuminated by a light source with fixed frequency [11]). This assumption can be made because the relative stability of the 1200 m long cavity is much better than that of the mode cleaners, which function at that time as reference for the laser frequency. The particular fringe shown in figure 6 was chosen because it could be modelled with a simple linear frequency sweep.

The parameters of the fitted model function showed that the finesse of the cavity (with that particular alignment) was 300 and the speed of the mirrors of the second mode cleaner was 20 nm s^{-1}. This means that a control loop locking the incoming light to that cavity had to acquire lock in some milliseconds. The low minimum of the ringing in figure 6 shows that the mode matching is better than 90%. The finesse of 300 corresponds to a loss inside the cavity of 0.7%.

To stabilize the incoming light to the resonance of the 1200 m long cavity, another feedback control featuring the third Pound–Drever–Hall scheme was installed (PR loop).

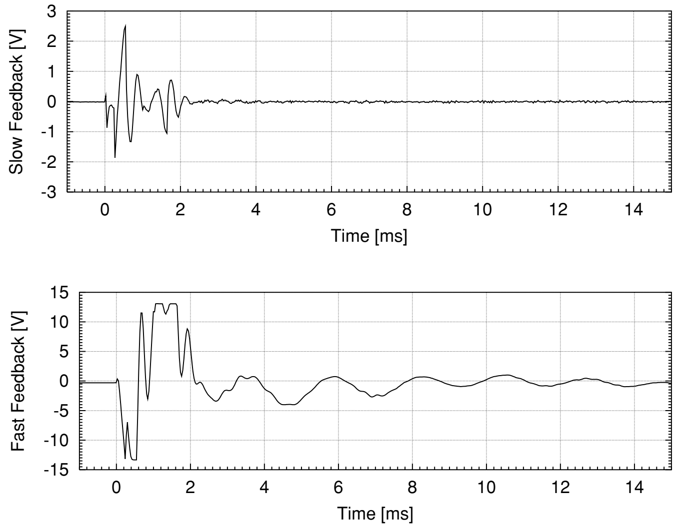

Figure 7. Time series of feedback signals of the control system for the 1200 m long cavity during lock acquisition.

Figure 7 shows these feedback signals during lock acquisition. The servo loop was closed automatically during a fringe at time zero. It can be seen that the cavity acquired lock in 2 ms and stayed in lock while a residual motion of the mirrors damped out quickly.

The automation of the lock acquisition of this control loop was installed and worked reliably. Without an alignment control of the cavity mirrors, the continuous lock durations were limited by alignment drifts. However, we still achieved continuous lock periods of up to 10 h, and the automation was able to relock the cavity over periods of up to 36 h before the mirrors had to be realigned. For comparison, the laser and mode cleaner systems, which were under automated alignment control [12], typically achieved continuous lock times of 48 h. The stable operation of the entire system over periods of 36 h showed the stability of the involved subsystems, especially of the seismic isolation and the control electronics.

For the GEO 600 detector in its final state, the required frequency stability inside the power recycling cavity is 10 μHz Hz$^{-1/2}$ at 100 Hz, which corresponds to a frequency stability of 100 μHz Hz$^{-1/2}$ at 100 Hz for the injected light. For the intermediate experiment described here, the goal was to achieve an in-loop frequency noise at this level. Figure 8 shows the in-loop noise (i.e. the error point spectrum) of the control loop for the 1200 m long cavity and the sensor noise of that loop. It can be seen that the goal mentioned above is met.

As of summer 2001, all main optics of the Michelson interferometer were installed and the power recycling cavity including a full interferometer was in place. This system has two longitudinal degrees of freedom, the Michelson interferometer operating point (differential arm length) and the power recycling length (common arm length plus the distance from the power recycling mirror to the beam splitter). The error signals for each degree of freedom depend strongly on the state of the other. In order to lock the Michelson interferometer the power recycling cavity is stabilized first. The experience with the 30 m prototype interferometer in Garching [4] showed that this locking hierarchy works reliably. To compensate for the variable reflectivity of the Michelson interferometer (when the interferomter is not yet locked to the dark fringe), an automatic gain control has been added to the servo system for the power recycling cavity. The otherwise unchanged servo system can lock the power recycling

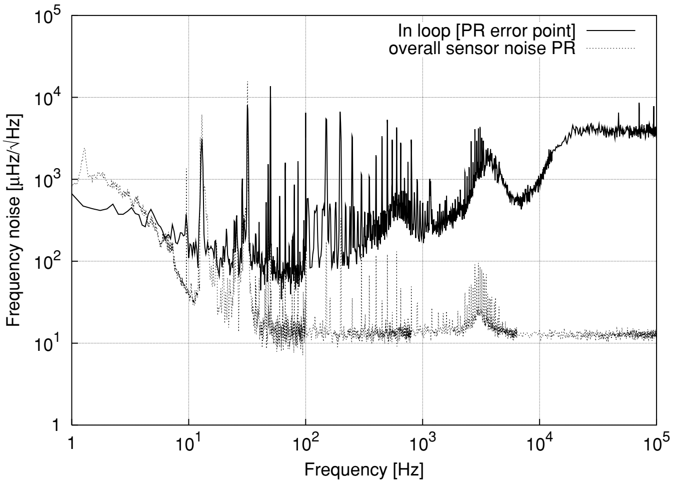

Figure 8. In-loop frequency noise of the control loop of the 1200 m long cavity (PR loop): about 100 μHz Hz$^{-1/2}$ at 100 Hz.

cavity long enough for about four or five slow fringes of the Michelson interferometer to pass. During this time the Michelson interferometer error signal allows the lock acquisition of the Michelson interferometer. Currently, the servo system for the Michelson interferometer control is being tested.

5. Conclusion

The 1200 m experiment described in this paper employed the first large-scale optical system in GEO 600. With the laser, the two mode cleaner systems and a 1200 m long cavity we could demonstrate the frequency stabilization system of GEO 600. The required frequency noise reduction was achieved by stabilizing the laser only to suspended cavities. The frequency and length control servos are automated and controlled by a computer system. The described system can acquire lock reliably and stay locked for 10 h long periods. We demonstrated that the system works as expected so that the requirement for the laser frequency noise in the GEO 600 gravitational wave detector can be met.

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