Performance of a 2400 m long suspended optical 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 cavity with an optical path length of 2400 m. The main purpose of this experiment was to gather first experience with the main optics. The residual motion of the mirrors is about 150 nm rms. Stabilising the length of this cavity to the pre-stabilised laser beam we achieved an error point noise of $100\,\mu\mathrm{Hz}/\sqrt{Hz}$ at 100 Hz. We also demonstrated the good performance of all included subsystems by 10-hour-periods of continuous stable operation. Thus the full frequency stabilisation scheme for GEO 600 was successfully tested.

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1. Introduction

In the beginning of this year the installation of the main optics of the gravitational wave detector GEO 600 [1] has been well under way. The Nd:YAG laser source and the mode cleaners were completely installed. The frequency and length control was installed as well as an automatic alignment system. These systems were in automatic operation and thus providing the input beam for an interferometer in the main vacuum system. In addition, three main mirrors were suspended, the *power recycling mirror*, the *folding mirror* as well as the *end mirror* of one arm of the Michelson interferometer (see Figure 1). These mirrors form a cavity with 2400 m optical 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.

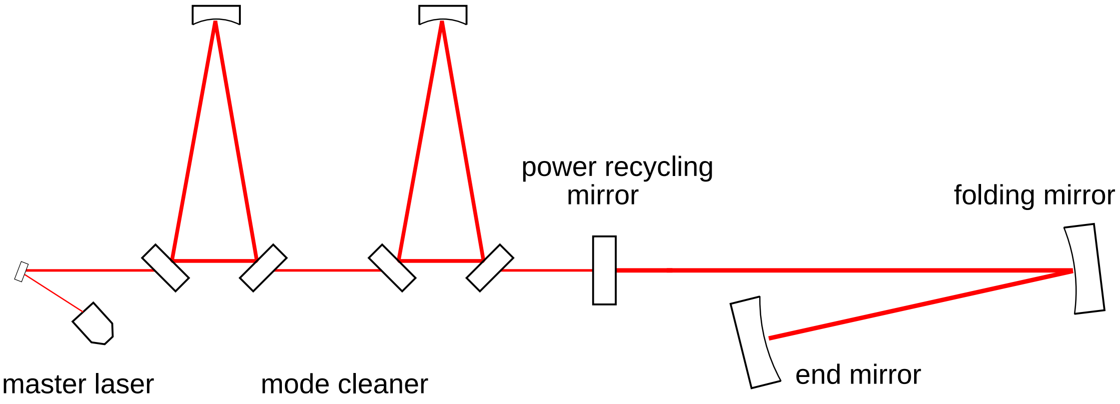

Figure 1. The 2400 m cavity in January 2001: The light of the master laser is filtered by two mode cleaners and injected into the 2400 m long cavity formed by the power recycling mirror and the two mirrors of the folded east arm of GEO 600.

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. The mode cleaners are 8 m ring cavities with three mirrors each. The mirrors are suspended as double pendulums. The optical parameters of the two mode cleaners are shown in Table 1.

Table 1. Optical parameters of the mode cleaners of GEO 600.

mode cleaner	finesse	throughput	visibility
1	2700	80%	94%
2	1900	72%	92%

The main optical instrument in GEO 600 is a dual recycled Michelson interferometer [3]. In contrast to other interferometric gravitational wave projects [4, 5, 6], GEO 600 does not employ arm cavities but folded arms (see Figure 2).

The laser light enters the main instrument from the west at the power recycling mirror and is split into an east and a north arm at the beam splitter. At a distance of 600 m from the beam splitter each arm has a *folding mirror* that directs the beam back (slightly tilted) towards the beam splitter. The light hits the *end mirror* located close to the beam splitter 25 cm above the axis of the injected beam. In the final optical layout the light reflected from both end mirrors is superimposed on the beam splitter. The Michelson interferometer will be held on the so called *dark fringe*, where the light containing the gravitational wave signal is directed south towards the *signal recycling mirror*. The major part of the light power is reflected back to the power recycling mirror. Thus the power recycling mirror and the Michelson interferometer form a cavity of 2400 m optical path length, the *power recycling cavity*.

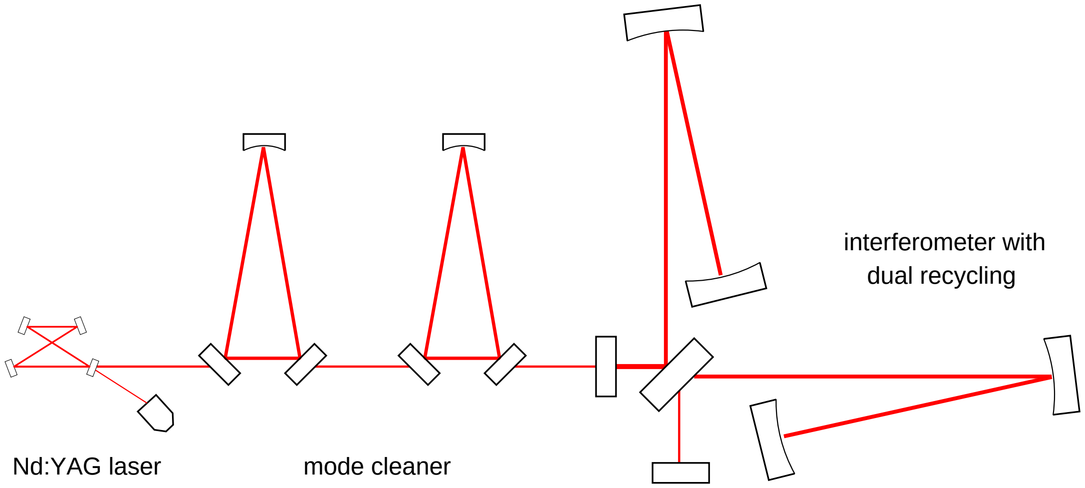

Figure 2. The optical layout of GEO 600: The laser consists of a monolithic master laser plus an injection locked slave laser in a bow tie setup, the two mode cleaners are suspended 8 m ring cavities, the main interferometer is a dual recycled Michelson interferometer with folded arms.

All main mirrors are suspended as triple pendulums to give a very good seismic isolation in the direction of the optical axis.[7] By January 2001 three main mirrors had been installed. 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 form a high finesse cavity (see Figure 1), which is very similar to the power recycling cavity of the final detector. For the experiment described here a 1 W non-planar ring oscillator (NPRO) was used as the light source.

3. Laser frequency stabilisation

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

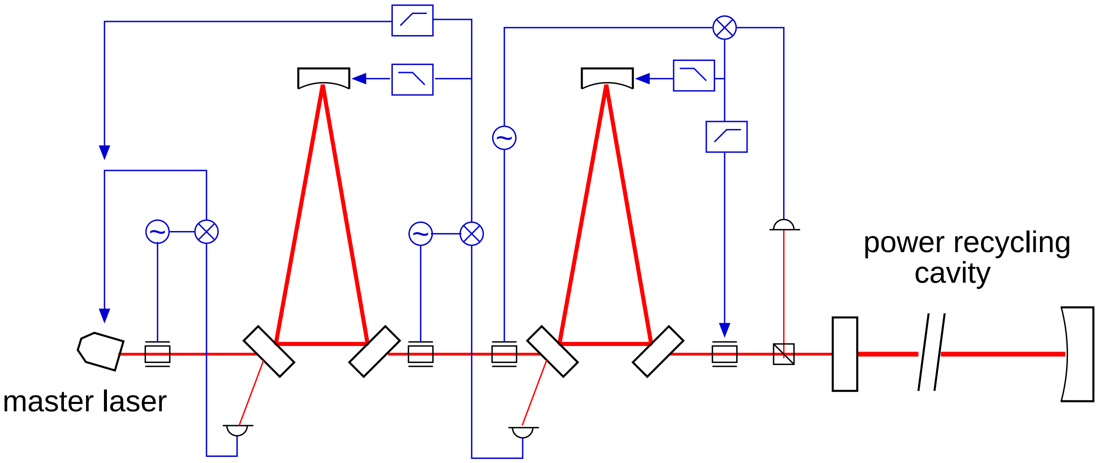

Figure 3. The frequency stabilisation scheme of GEO 600: The feedback paths of the length and frequency control for the power recycling cavity, the two mode cleaners, and the master laser.

The optical systems and the feedback systems can are shown in Figure 3. The laser light is locked to the first mode cleaner with a standard Pound-Drever-Hall method. The feedback is applied to the frequency modulation input of the master laser. The bandwidth of this control loop is 100 kHz.

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 length of the second mode cleaner by changing the laser frequency and the length of the mode cleaner one. This is done with a feedback control system using the standard Pound-Drever-Hall technique. The feedback signal is split and fed to two actuators: a ‘slow’ signal (< 4 kHz) is applied to one of the mirrors of mode cleaner one via coil magnet actuators and a ‘fast’ signal is injected into the error point of the first loop, i.e. directly acts on the master laser frequency (see Figure 3). The fast signal is necessary to achieve a high servo bandwidth of about 25 kHz and thus a high gain at low Fourier frequencies.

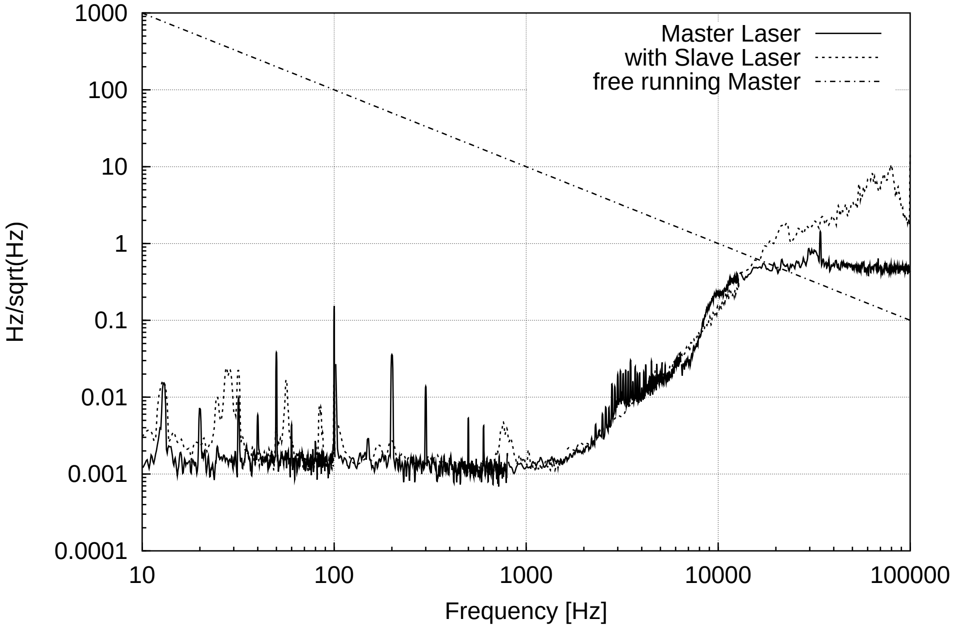

Figure 4. The frequency noise at the first mode cleaner, the in-loop frequency noise is about 1 mHz and does not degrade when the high power slave laser is added.

Finally the now pre-stabilised light has to be resonant in the power recycling cavity. A third control loop with another Pound-Drever-Hall feedback system is used to control the length of the second mode cleaner accordingly. The feedback of this loop was again split into a 'slow' path, which acts on the length of mode cleaner two (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. The bandwidth of this servo loop can be quite large because of the extra phase corrector. In the experiment described here the control bandwidth was 40 kHz.

To measure the performance of the frequency stabilisation one can perform two different experiments: a) an in-loop measurement of the frequency noise of a control loop (this is done by taking the error point spectrum) or b) an out-of loop measurement of the residual frequency noise of a control loop with an independent frequency reference.

Figure 4 shows the error point spectrum of the first control loop that stabilises the master laser to the first mode cleaner. The frequency noise in the error point is about 1 mHz/$\sqrt{Hz}$ below 1 kHz. In comparison with the estimated noise of the free running laser 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 that the slave inherits the frequency stability of the master. The injection lock used controls the slave laser frequency with a higher gain and 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 first mode cleaner stabilisation loop for a) the master laser only and b) the master plus injection locked slave. It can be seen that the laser frequency noise in both cases is very similar even though the servo was not changed at all.

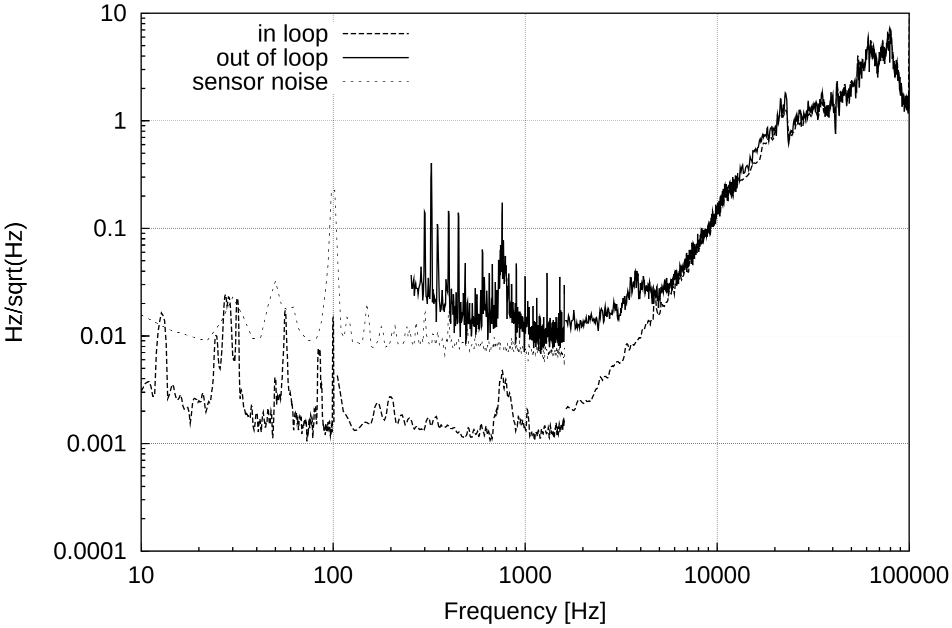

Figure 5. Comparison of the in-loop and out-of-loop frequency noise at the first mode cleaner. The noise of the sensor in the stabilisation loop is also plotted. Please note that the out-of-loop noise could only be measured down to 300 Hz with the method used here.

With two mode cleaner cavities one can also use the second mode cleaner as an independent reference (apart from common mode effects) to measure the performance of the first loop, which locks the laser to mode cleaner one. This is an out-of-loop measurement of the frequency noise of the first stabilisation loop and is shown in Figure 5. For this measurement the first mode cleaner was locked to the second as described above but with a very low servo bandwidth (unity gain frequency $\approx$ 300 Hz). The frequency noise in the error signal of the second loop then gives the residual frequency noise of the first loop for Fourier frequencies above unity gain. Since the two mode cleaners are located close to each other inside the same vacuum tanks, common mode effects have to be taken into account. The second mode cleaner cannot be a true independent reference system; some disturbances can have exactly the same effects on both mode cleaners, so that they cannot be measured with the method described above. As can be seen in Figure 5 the measured out-of-loop noise is about 10 mHz/$\sqrt{Hz}$ below

1 kHz and limited by the sensor noise of the first control 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 5.

Systems involving suspended cavity mirrors cannot stabilise the length of the cavity to the incoming laser beam at high frequencies due to the limited possibility of changing the position of a suspended mirror. In order to achieve high gain for low Fourier frequencies it is often necessary to use a servo system with a large bandwidth, i.e. which stabilises the incoming beam to the cavity for high frequencies. When the laser beam has been pre-stabilised to a rigid reference cavity this high frequency stabilisation very often suffers from Dopper shift effects from either the motion of the rigid cavity or vibrations of optics mounts with respect to the suspended cavity. Also this kind of stabilisation scheme very often involves complex cross-over designs. Without a rigid reference cavity the situation is much simpler because one does stabilise the beam onto the suspended cavity for *all* frequencies.

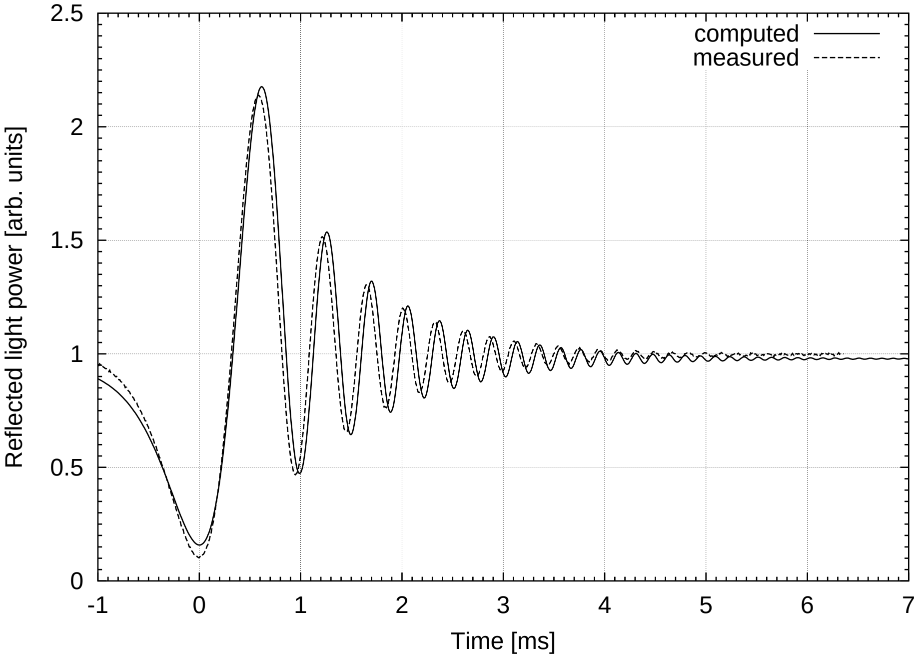

Figure 6. Simulated fringe of the power recycling cavity compared to the measured typical fringe. The simulation gives a finesse of 250 for the power recycling cavity and a mirror velocity for the mirrors of mode cleaner two of 110 nm/s.

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 optical length of 2400 m greatly improves the relative stability. Also this cavity uses triple pendulum suspensions for its mirrors, so that also the absolute motion of the mirrors is less than that of the mode cleaner mirrors (the residual motion of the main mirrors is $\approx 150\,\mathrm{nm}$ rms). Thus the power recycling cavity improves the frequency noise as a passive filter. Furthermore, by stabilising the mode cleaners and the laser light the power recycling cavity length, the frequency noise actively improved (see next section).

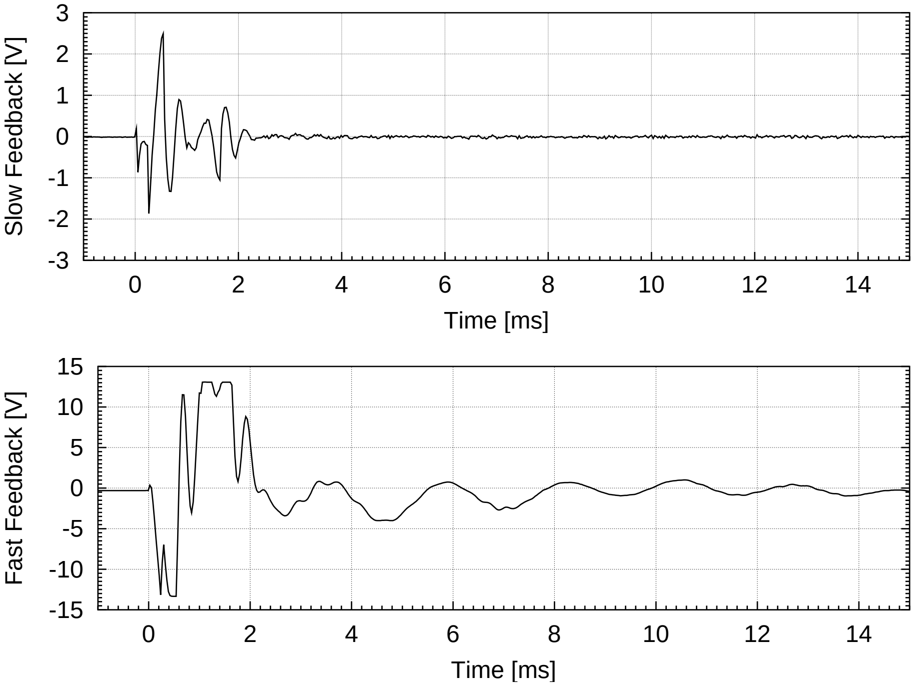

Figure 7. Time series of feedback signals of the control system for the 2400 m long cavity during lock acquisition

4. Performance of the 2400 m cavity and its length and frequency control system

The mode cleaner system was completed in December 2000. Both cavities were automatically aligned and the lock acquisition of the length and frequency control loops was fully automated. We thus had a stable input beam for the experiment with the 2400 m cavity. The three mirrors of this cavity were without any control and had to be aligned manually for every experiment. After a reasonable good alignment one could observe fringes in the light reflected from the long cavity. A numeric simulation was used to fit a model function to a measured fringe of the 2400 m long cavity (see Figure 6). The simulation works in the time domain and calculates the dynamic changes of the light power of a suspended cavity. The parameters of the fitted model function showed that the finesse of the cavity (with that particular alignment) was 250 and the speed of the mirrors of the second mode cleaner was 110 nm/s. This means that a control loop locking the incoming light to that cavity had to acquire lock in some milliseconds, which requires only a servo bandwidth of a few kHz. The large amplitude of the *ringing* indicates that the alignment and the mode matching are very good.

To stabilise the incoming light to the resonance of the 2400 m long cavity another feedback control featuring the third Pound-Drever-Hall scheme was installed. 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 times were limited by alignment drifts but we still achieved continuous lock times of up to 10 hours and the automation was able to relock the cavity over periods of up to 36 hours before the mirrors had to be realigned. For comparison, the laser and mode cleaner systems which were under automated alignment control [8] typically achieved continuous lock times of 48 hours. The stable operation of the entire system over periods of 36 hours showed the stability of the involved subsystems, especially of the seismic isolation and the control electronics.

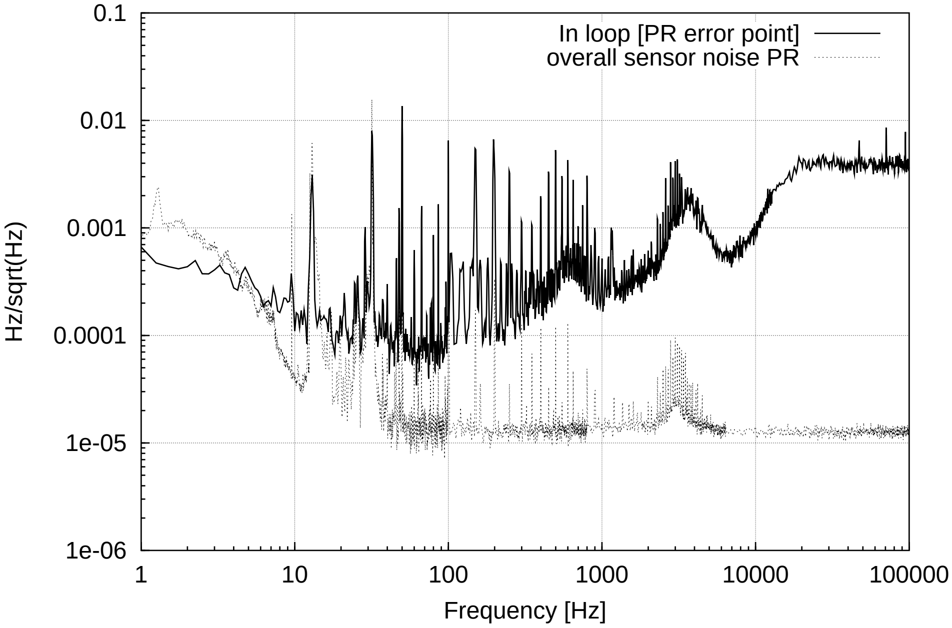

Figure 8. In-loop frequency noise of the control loop of the 2400 m long cavity: about $100\mu Hz\sqrt{Hz}$ at 100 Hz

For the GEO 600 detector in its final state the required frequency stability inside the power recycling cavity is $10\,\mu Hz/\sqrt{Hz}$ at 100 Hz, which corresponds to a frequency stability of $100\,\mu Hz/\sqrt{Hz}$ at 100 Hz for the injected light. For this intermediate experiment 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 2400 m long cavity and the sensor noise of that loop; thus the goal mentioned above is met.

At the moment all the main optics of the Michelson interferometer have been installed and the power recycling cavity including a full interferomter is in place. This system has two 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 stabilised first. 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 system long enough for about 4 or 5 slow fringes of the Michelson interferometer to pass. During this time the Michelson interferometer error signal will allow the lock acquisition of the Michelson interferometer. Currently the servo system for the Michelson interferometer control is tested and being installed. Soon we will lock the power recycled Michelson interferometer for the first time, using the frequency stabilisation described in this paper.

Acknowledgments

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