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Thermal correction of astigmatism in the gravitational wave observatory GEO 600

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Abstract

The output port of GEO 600 is dominated by unwanted higher order modes (HOMs). The current thermal actuation system, a ring heater behind one of the folding mirrors, causes a significant amount of astigmatism, which produces HOMs. We have built and installed an astigmatism correction system, based on heating this folding mirror at the sides (laterally). With these side heaters and the ring heater behind the mirror, it is possible to tune its radius of curvature in the horizontal and the vertical degree of freedom. We use this system to match the mirrors in the two arms of GEO 600 to each other, thereby reducing the contrast defect. The use of the side heaters reduces the power of the HOMs at the output of GEO 600 by approximately 37%.

Keywords: GEO 600, thermal compensation, astigmatism, high order modes

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(Some figures may appear in colour only in the online journal)

1. Introduction

The gravitational wave (GW) observatory GEO 600 is a 600 m long dual-recycled [1] Michelson interferometer with folded arms. GEO 600 is operated close to the dark fringe, such that most of the light is reflected towards the input port. The output port is therefore called the dark port. For the dual-recycled operation, GEO 600 has two mirrors added to the basic Michelson topology. A highly reflecting mirror at the input port forms a high finesse cavity, called the power recycling cavity (PRC). The other recycling mirror is located at

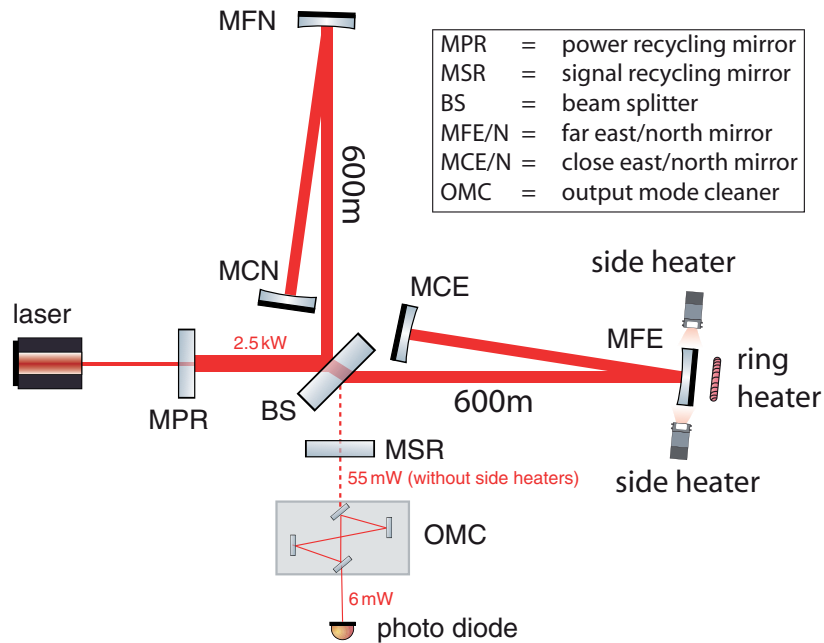


Figure 1. A simplified layout of GEO 600. The power of the laser field at different points in the interferometer is given in red numbers.

the output port of the interferometer and forms the signal recycling cavity. A simplified layout of GEO 600 including the heaters is shown in figure 1. Mirror imperfections convert light from the TEM_{00} mode to higher order modes (HOMs), which are not resonant in the PRC and leave the interferometer. The power at the dark port of GEO 600 is dominated by HOMs, which do not carry a useful GW signal for GEO 600, and only contribute to shot noise. The TEM_{00} light at the darkport is composed of about 6 mW of carrier light for the dc readout [2], and RF sidebands to this carrier light. These sidebands are used for controlling the interferometer. Their power is very low compared to the carrier, thus they will be neglected for this work. A small cavity, the output mode cleaner (OMC) [3], is installed in front of the main photodiode to filter out the HOMs and RF sidebands. HOMs can cause problems, however. When the OMC is not optimally aligned, HOMs can overlap with the TEM_{00} eigenmode of the OMC and decrease the signal to noise ratio for GWs on the main dc readout photodiode. A detailed study of this effect can be found in [4]. HOMs have led to complications in the operation of GEO 600. For example right after the installation of the OMC, we observed a significant amount of noise in the GW-channel of GEO 600 in the frequency band of 100–300 Hz. It turned out that it was caused by beam jitter, which caused HOMs in the interferometer basis to overlap with the TEM_{00} eigenmode of the OMC and reach the main photodiode. The beam jitter was caused by beam steering mirrors at the output of GEO 600. This problem has been fixed by a change of the suspension of said steering mirrors [5]. In 2010 we observed another issue with HOMs: The signal recycling mirror was changed as part of the GEO-HF upgrade program. Since the new mirror had a higher transmission, there was a higher amount of HOMs in the dark port beam. This caused the OMC alignment control system, which was based on maximizing the transmitted power through the OMC, to malfunction, leading to worse sensitivity and stability; The reason was that the alignment control system maximized

in this case the overlap of HOMs with the TEM_{00} eigenmode of the OMC. A different OMC alignment system had to be implemented to work with the increased amount of HOMs [6].

In the signal recycling cavity HOMs are partially converted back to the TEM_{00} mode [1]* (this effect is called ‘mode healing’). In the case of GEO 600, it has been observed that this process depends strongly on the alignment of the signal recycling mirror. Therefore, in the presence of HOMs, small fluctuations of the signal recycling cavity can lead to power fluctuations in the interferometer. The largest source of HOMs in GEO 600 is astigmatism.

2. The ring heater and astigmatism

All large scale GW detectors require very high quality optics. Since the specifications for the optics are very demanding, some mirrors deviate from the specified radius of curvature (RoC). Both GEO 600 [7, 8] and recently Virgo [9], the Italian–French GW observatory, have developed and used systems to correct the curvature of a mirror in one degree of freedom by application of thermal radiation. Ring heaters are also planned to be used in advanced LIGO [10]. Additionally, LIGO and Virgo have also used CO_2 laser based heating [11, 12].

GEO 600 has been using a ring heater to match the RoC of the far east mirror to the RoC of the far north mirror since 2004. The ring heater sits behind the mirror. It consists of a metal ribbon that is wrapped around a glass ring. When a current is sent through the metal ribbon, its temperature increases. The thermal radiation from the ribbon is absorbed by the mirror, and due to the thermal gradient from back to front, the mirror deforms and changes its RoC. Without the ring heater, we cannot lock the PRC of GEO 600. For a detailed description of the problem, see [7].

We have studied a finite elements model (FEM) of the ring heater setup and found that it causes a significant astigmatism in the far east mirror. This is due to the fact that the thermal radiation of the ring heater is not completely directed towards the mirror, but also reaches structures underneath the mirror, which in turn heat the bottom of the mirror.

In addition to the prediction of the astigmatism by the FEM model, we simulated the dark port beam shape (using the software FINESSE [13]) for different RoCs of the far east mirror. Then we compared the simulations with measured dark port beam images. This way we can estimate the RoC of this mirror (shown in figure 2). We find a RoC of the far east mirror of $665.5(\pm 2)$ m in the horizontal direction and $658(\pm 2)$ m in the vertical direction. This was done with the ring heater at the setting that gave the lowest power at the dark port (34.7 W). The ring heaters powers given in this work are very different from the numbers given in [7]. The reason is that we installed a reflector, which increases the efficiency of the ring heater.

Ideally, the curvature would be identical in both directions. We decided to design and install additional heaters at the sides of the far east mirror which would cause a local thermal expansion of the mirror at the sides and as a result, decrease the RoC in the horizontal direction. This way we can adjust the mirror RoC in two degrees of freedom (horizontal and vertical).

3. Side heater design

Each of the two side heaters consists of a curved, ceramic-coated, stainless steel rod with grooves for a NiCr heating wire with a diameter of 0.5 mm. The wire is wound onto the rod with a bifilar winding, to minimize the magnetic field that it produces. This is important, because the main mirrors of GEO 600 are suspended as triple pendulums and the upper stage

* This can be seen by the power build up in the PRC. With signal recycling it is about 30% higher than in the case of just using GEO as power recycled Michelson interferometer.

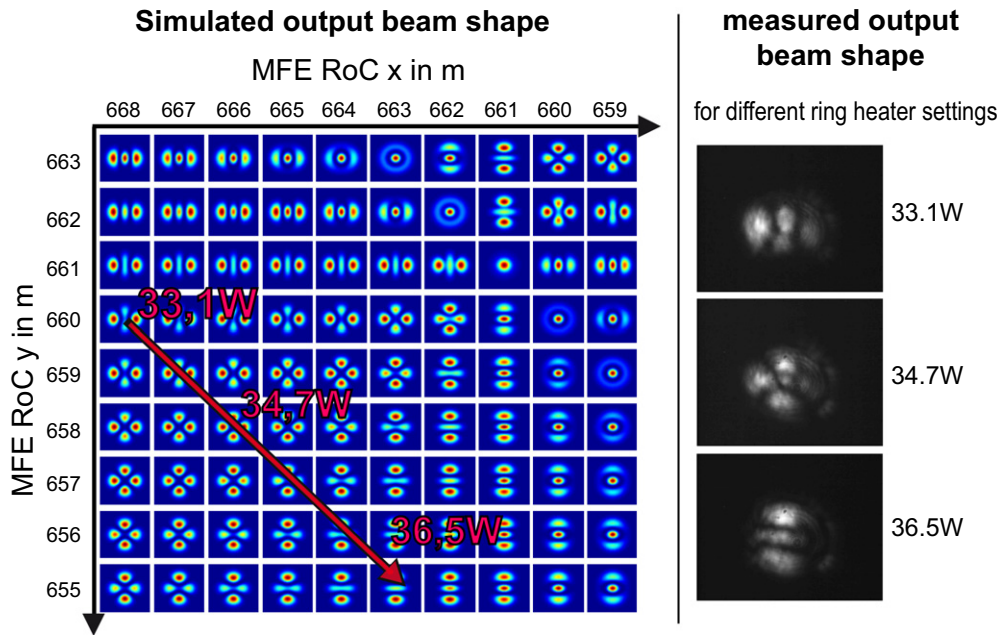


Figure 2. This figure shows simulated output beam shapes of GEO 600 when used as power recycled Michelson interferometer (left) for different ring heater powers. The measured output beam shapes (right) have been used to determine the RoC of MFE by matching them to the simulated ones. The arrow on the left shows the result, the MFE RoCs that can be accomplished by (only) using the ring heater.

uses coil magnet actuators for damping and alignment. Magnetic fields may couple into those actuators.

In addition to the direct radiation, the side heaters also use a polished aluminium reflector. Figure 3 shows a drawing of one of the side heaters. The side heaters have been installed at a distance of about 10 cm from the mirror.

4. Side heater performance

We find that the side heaters are a good tool to reduce the HOM content at the dark port of GEO 600. For a circulating light power of about 2.5 kW in the PRC and a ring heater power giving the lowest power at the output, the optimal power of the side heaters is 2.5 W each. Subsequent optimization of the ring heater power shows that this is the optimum setting. We can reduce the total power at the output of GEO 600, which is dominated by HOMs, from 55 to 37 mW. Since the TEM₀₀ light has a power of 6 mW at the dark port of GEO 600, the side heaters reduce the power of HOMs in GEO 600 by about 37%.

In order to exclude any effect that the side heaters may have on the amount of circulating light power, we also look at the total output power normalized by the circulating power. This normalized output power decreases by 30% with the side heaters. A plot of the normalized total output power is provided in figure 4, while figure 5 shows CCD camera images of the output beam without and with side heaters, respectively. The time constant of the side heaters can be fitted with a first order lowpass filter with a cutoff frequency of $f = 10^{-4}$ Hz, which gives the time constant of $t = 1/f \approx 2.8$ h.

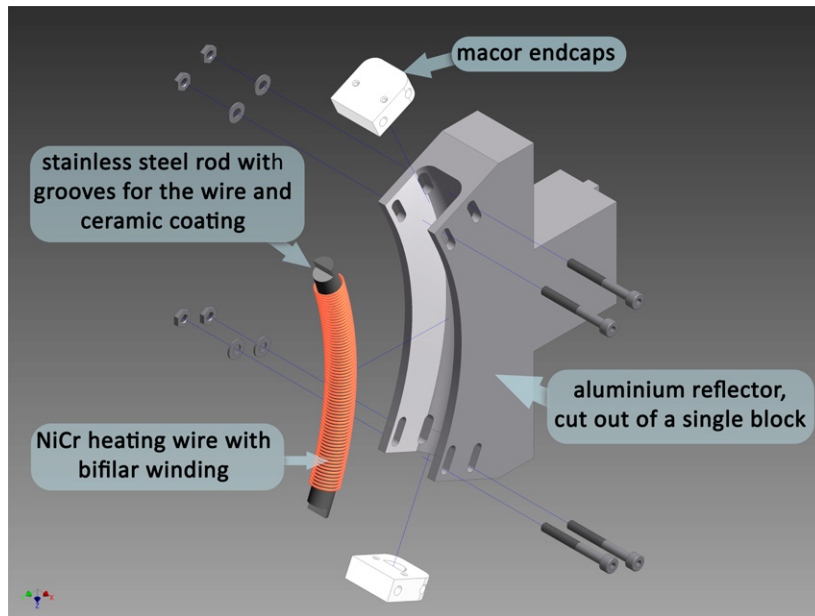


Figure 3. CAD drawing of one of the side heaters.

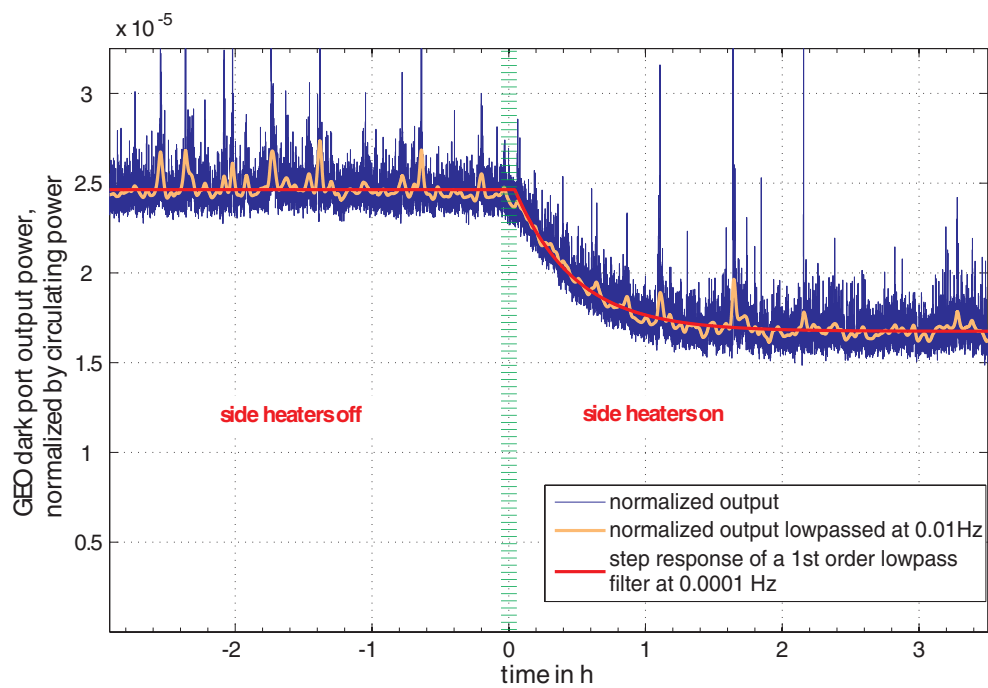


Figure 4. Time series of the normalized power leaving the dark port of GEO 600. At the start of the experiment the side heaters are off. They are turned on at the time marked as zero hours on the time axis.

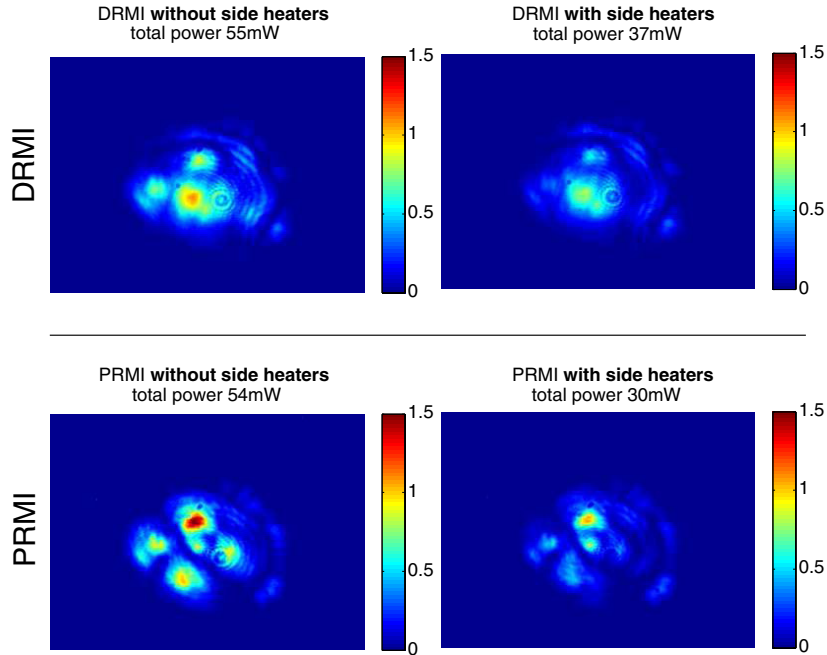


Figure 5. This figure shows calibrated (to Watt per total image area) CCD images of the dark port output of GEO 600. The top row shows the dark port image in normal (DRMI) operation, with and without the side heaters. The bottom row shows the situation in PRMI mode. Especially in PRMI mode, but also in DRMI mode, the lower power in HOMs is apparent.

GEO 600 can also be operated without signal recycling, as a power recycled Michelson interferometer (PRMI). In that operating mode, the effect of the side heaters is even more pronounced because there is no mode healing effect of the signal recycling cavity. In PRMI mode, the side heaters reduce the power at the dark port from 54 to 30 mW. When normalized to the circulating light power, this corresponds to a reduction of 50%. In fact, when using the side heaters, the normalized output power of GEO 600 in PRMI mode is the same as in the normal, dual-recycled, operating mode at 1.7×10^{-5} normalized units. This demonstrates that we can ideally match the east mirror to the north mirror in two degrees of freedom. This is equal to a curvature change of the mirror from $(665.5/658 \pm 2)$ m without the side heaters to $(661/661 \pm 2)$ m with the side heaters at the ideal setting of 2.5 W.

5. Summary and outlook

GEO 600 uses a ring heater behind the far east mirror to correct its RoC in one degree of freedom. We find that this ring heater induces astigmatism at that mirror, which leads to an increase in higher order mode content at the output of the interferometer. We designed and installed additional heaters laterally at the same mirror to correct the astigmatism, and reduce the power in unwanted HOMs at the darkport by 37%. Since their installation in November 2012, the side heaters have been running nearly continuously, with GEO 600 taking astrophysical data. The remaining higher order modes at the output are most likely a result of microscopic imperfections in the mirror surfaces. These may originate from the polishing or

the coating of the mirrors. If found to be a problem, those residual higher order modes could be further reduced by localized heating of the mirror surfaces. This could be done with a scanning CO₂ laser system, as proposed in [14]. Another way would be to use an array of many hot black body emitters, and project it onto the optics (as described in [15]).

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