# The Automatic Alignment System of GEO 600

**H Grote†§, G Heinzel‡, A Freise†, S Gossler†, B Willke†‡ H Lück†‡, H Ward¶, M Casey¶, K A Strain¶, D Robertson¶, J Hough¶ and K Danzmann†‡**

† Institut für Atom- und Molekülphysik, Universität Hannover, Callinstrasse 38, D-30167 Hannover
‡ Albert Einstein Institut für Gravitationsphysik, Aussenstelle Hannover, Callinstrasse 38, D-30167 Hannover
¶ Department of Physics and Astronomy, University of Glasgow G128QQ, Scotland, UK

**Abstract.** The article gives an overview of the automatic mirror alignment system of the modecleaner- and main interferometer of the GEO 600 gravitational wave detector.

In order to achieve the required sensitivity of the detector, the eigenmodes of all optical cavities have to be aligned with respect to the incoming beams (or vice versa) and kept aligned for long measuring periods. Moreover the beam spots have to be centered on the mirrors to minimize coupling of residual angular mirror motion into changes of the optical path length.

An overview of the principles and setup for the automatic alignment is given, and first results of the modecleaner- and 2400 m cavity alignment system are presented, including the error-point spectra of mirror angular motions, which are smaller than $10^{-8}\mathrm{rad}/\sqrt{\mathrm{Hz}}$ below 10 Hz.

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## 1. Introduction

In laser interferometric gravitational wave detectors, all cavity- and beam steering mirrors within the vacuum system are suspended as pendulums for the purpose of seismic isolation. While this gives good isolation in the gravitational wave measurement band (e.g. above 40 Hz), the mirror motions are increased around the pendulums main resonances (around 1 Hz) and the mirrors are subjected to enhanced drifts.

To enable an optimized sensitivity as well as long term stable operation of the detector, an automatic [||] angular alignment in 2 degrees of freedom for each suspended mirror is required.

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[§] To whom correspondence should be addressed (`hrg@mpq.mpg.de`)

[||] The term "automatic" has two meanings here: A feedback system which optimizes the alignment is called "automatic alignment". Furthermore "automatic alignment" describes a computer controlled system, which switches the alignment feedback loops on and off, depending on the detector status.

Within the GEO 600 [1] gravitational wave detector, there are two suspended ring-type modecleaners, the power recycling cavity and the michelson interferometer to be aligned with such a system.

The goal of the automatic alignment system is to keep the optical eigenmode of a cavity superimposed with the axes of the respective incoming beam and center all beam spots on the corresponding mirrors.

## 2. Differential Wavefront Sensing

To align a cavitys eigenmode with the incoming beam, their relative orientation has to be detected. Errorsignals providing this information are obtained with the *differential wavefront sensing* technique (see e.g. [2]), which is similar to the *Pound - Drever - Hall* [3] sensing.

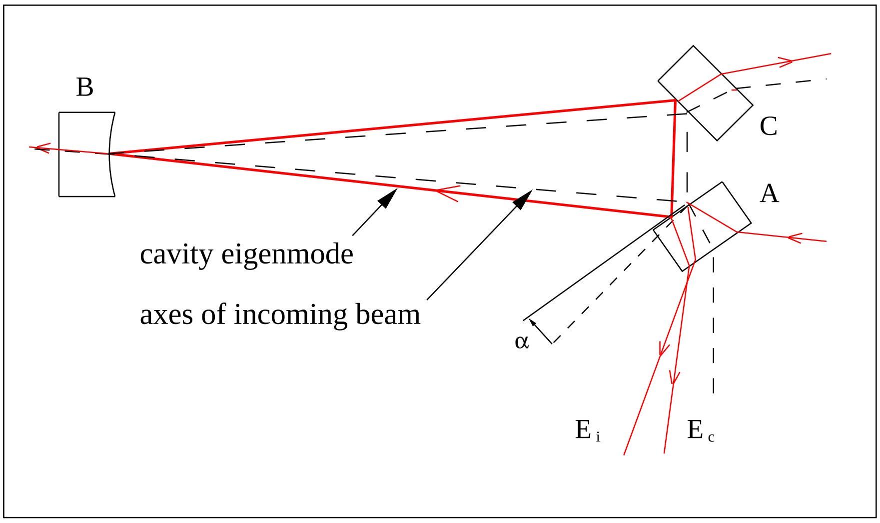

**Figure 1.** schematic triangular ring cavity, consisting of two flat mirrors A, C and a curved mirror B. Mirror A is misaligned by an angle $\alpha$.

Figure 1 shows a triangular ring cavity consisting of two flat mirrors A, C and a curved mirror B. An incident laser light impinging on mirror A is partly reflected as an electric field $E_i$ and partly enters the cavity. The light circulating inside the cavity leakes out at mirror A as field $E_c$.

The figure shows a misalignment of mirror A, resulting in an angle between $E_i$ and $E_c$. While here the misalignment is largely exaggerated, in a real situation the 2 beams cannot be separated, but their interference pattern can be detected with photodiodes.

Using Pound-Drever-Hall sensing, the phase difference between the wavefronts of $E_i$ and $E_c$ is read out over the whole cross section of the interference pattern. For this method, the incident light is being phase modulated at an appropriate radio frequency with an electro-optic modulator (EOM). The photocurrent of a diode illuminated with $E_i$ and $E_c$ is then coherently demodulated. The resulting signal is a measure for the match between the incident laser frequency and one of the cavitys resonant frequencies.

Usually an appropriate feedback loop is used to keep the difference of these frequencies close to zero, what is referred to as "locking" of a cavity.

If a cavity is locked (which is assumed for all following discussions), the *differential wavefront sensing* method can measure the *angle* between the wavefronts of $E_i$ and $E_c$ by using a split photodiode and calculating the difference between the 2 demodulated photocurrents of the different photodiode sections. ¶ With a quadrant diode this can be done for the horizontal *and* vertical direction simultaneously.

The angle between the wavefronts is generally not identical with the angle between the beams $E_i$ and $E_c$. But if the wavefront angles are measured at 2 different distances from the beam waist (which is located between mirrors A and C in the configuration of Figure 1), 4 different quantities can be obtained, giving full information about angular and parallel displacement of the cavitys axes against the axis of the incoming beam.

Any other linear combination of the 4 detected wavefront angles may be chosen to match the coordinate system of experimentally available independent actuators, enabling feedback controlled alignment. As a feature of the ring cavity in Figure 1, any misalignment of mirror A cannot be distinguished from misalignments of mirror C with the described method, but both mirrors can be chosen as actuators in a common mode. Further the linear combinations chosen for the horizontal plane are generally different from those in the vertical plane. (For details see [4].)

## 3. Automatic Alignment of a GEO 600 Modecleaner

Figure 2 shows the setup for the automatic alignment system of the first GEO 600 - modecleaner.

The laser beam directed to mirror A is phase-modulated with a frequency of 25.2 MHz by EOM1, enabling the use of *Pound Drever Hall* locking, and *differential wavefront sensing.* Steering mirror BD1 points the beam towards the cavity, constituted by the flat mirrors A and C, and curved mirror B. (For details on the GEO 600 modecleaners see [5]).

The beam consisting of the interfering fields $E_i+E_c$ (see Figure 1 for correspondence) is split into 2 paths by the power beamsplitter BS1 with a reflectivity of about 50%. In each path the light is directed to the quadrant diodes D1 and D2. A lens system (L1 and L2) in the light path to D2 provides a projection into the far field of $E_i + E_c$. With the proper adjustment of L1 and L2 the detected wavefront angles on D1 and D2 can be made as independent as possible.

The components G1 and G2 are beam pointing devices and have the purpose to center the beams on the respective quadrant diodes D1 and D2. G1 and G2 consist of 2 commercial galvanometer scanners each, carrying small (10x15 mm) mirrors on their

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¶ In principle it is also possible to obtain differential wavefront signals *without* a *locked* cavity. To do this, the photodiode signals have to be read out each time the cavity is in resonance with the incident light. A computer controlled system could provide an errorsignal then, which might be useful for an automated or manual coarse alignment of complex interferometers.

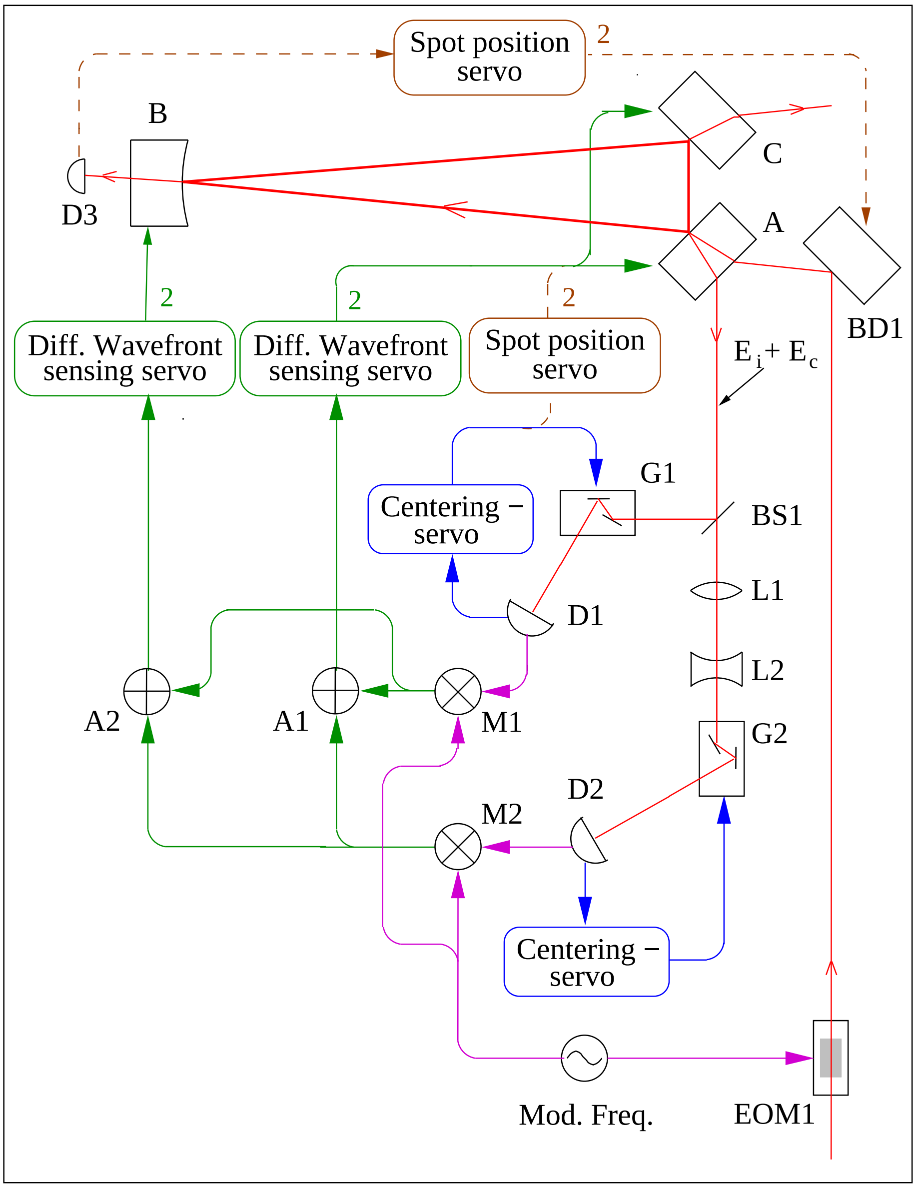

**Figure 2.** Automatic alignment system layout for one modecleaner. The numbers at the servo boxes count the degrees of freedom controlled by each path.

axis that can be rotated in 1 degree of freedom. With a perpendicular mounting of 2 scanners, one unit can point a reflected beam in 2 degrees of freedom. The "centering servo" loops control the spot position on the diodes with a bandwith of around 1kHz. We use this concept to ensure that the angle between the interfering wavefronts $E_i$ and $E_c$ is detected correctly by the quadrant photodiodes. If beam $E_i + E_c$ is not centered on the diodes, the differential wavefront signal size decreases and also includes not wanted information from higher order modes. With these additional beam steering loops the acquisition performance- and dynamic range of the automatic alignment system is largely increased.

Each quadrant photodiode D1 and D2 of the type CENTRONICS QD50-3T has

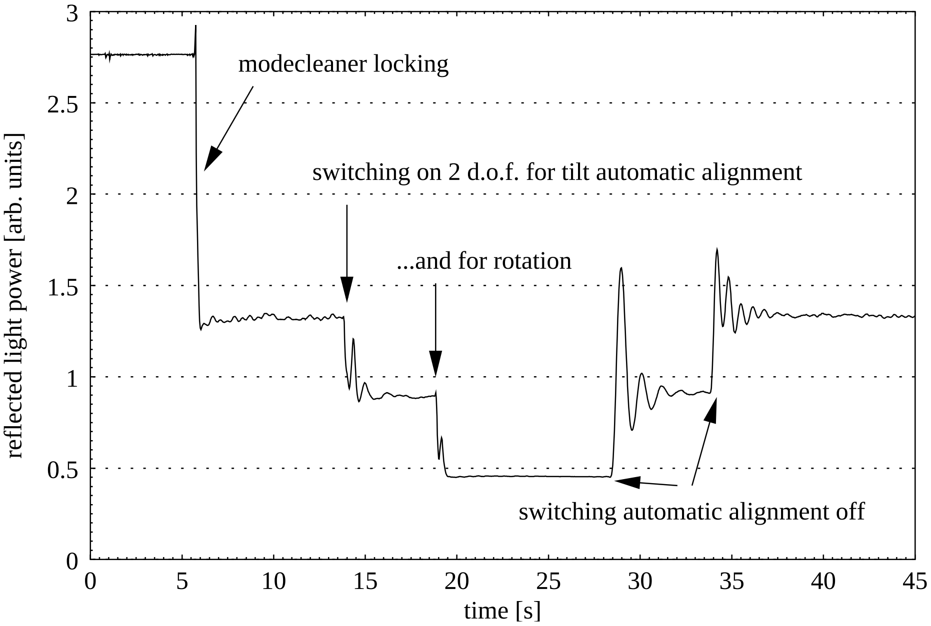

**Figure 3.** Switching on and off the modecleaner automatic alignment

a resonant electronic circuit (tuned at the modulation frequency of EOM1) for each of its quadrants to increase the signal to noise ratio. After demodulation, the differences of the quadrants of 1 photodiode give the information about the angles between the wavefronts in 2 degrees of freedom. This electronics is symbolized by M1 and M2 for each photodiode.

To generate signals that correspond to the motion of individual mirrors of the ring cavity, the according linear combinations of the outputs of M1 and M2 are processed by analog electronic circuits A1 and A2. The experimental result of this orthogonalisation is better than 1 / 10 (meaning that if e.g. mirror B rotates out of its nominal position, this signal shows up with less than 1/10 in the misalignment signal for mirrors A and C).

The error signals for the mirror orientations are then amplified with the appropriate gain and frequency response and fed back to mirror B as well as mirrors A + C in common mode.

As feedback actuator for the modecleaner alignment we use coils with magnets attached to the intermediate mass of each mirrors double pendulum. The transfer function from the input of the coil drivers to the mirrors angular motion has a phase delay of 360° at frequencies above the pendulums main resonances (around 1 Hz), which makes it difficult to achieve unity gain frequencies of the alignment system above 1 Hz. Nevertheless two different feedback filters were successfully tried, one with a bandwith of 6 Hz (using several differentiator stages to provide an electronic phase lead of 210° around 6 Hz), another one using only integrator stages yielding a bandwith of 0.2 Hz.

Figure 3 shows a timeseries of the light power reflected from the first modecleaner of GEO 600 for different operating conditions of the automatic alignment system.

Up to second 6 the cavity is not in lock and almost all light is reflected. Then the cavity is locked to an intentionally misaligned state with only around 65 % of the possible power entering the cavity. At second 14 the differential wavefront control is switched on for the 2 tilt degrees of freedom; at second 19 feedback for the 2 rotational degrees of freedom is switched on. A maximum of light is now entering the cavity, limited by not perfect annular modematching at the time of measurement. It can be seen that the power fluctuations are significantly smaller than in the misaligned case, due to reduced coupling of beam geometry fluctuations. Finally the graph shows the switching off in reverse order, with the pendulums swinging back to their equilibrium positions.

We obtain information about 4 degrees of freedom for the cavity alignment with the differential wavefront sensing, but there are 2 remaining degrees of freedom of the cavity (which consists of 3 mirrors and thus has 6 angular degrees of freedom) to be controlled. These are the differential modes of mirrors A and C, which can be detected by the direction of the beam $\mathrm{E_i} + \mathrm{E_c}$ propagation. As we have the quadrant photodiode D1 in place already, we can read out the spot position on the diode by reading out the quadrant photocurrents at low frequencies (in contrast to the RF - readout described above). The galvanometer scanners use these signals to center the beam on the photodiode, thus the propagation direction information of the beam $\mathrm{E_i} + \mathrm{E_c}$ is contained in the feedback signals applied to the scanners (at least within the scanners loop bandwith of 1 kHz). Figure 2 shows the feedback loop using these signals which are fed back to the differential modes of mirrors A and C with a digital control loop. To avoid oscillations, this loop has to be slower than the differential wavefront sensing loop.

A similar type of feedback is the spot position control with D3, detecting the transmitted light of cavity mirror B. A digital feedback loop then aligns mirror BD1, which determines the spot position on D3, as long as the cavity axes follows the axes of the incoming beam. Thus care has to be taken that this spot position control is only active (again with a low enough bandwith) when the differential wavefront feedback is working.

## 4. Main Interferometer Automatic Alignment

Figure 4 gives a brief overview of the alignment system for the power recycled michelson interferometer (signal recycling not included).

The light leaving the modecleaners is directed with BD2 and BD3 to the power recycling cavity. The light reflected from MPR is detected by D4, which symbolizes a differential wavefront sensing unit for 4 degrees of freedom like the one described for the modecleaner section. In the current configuration feedback is applied to BD3 and MPR to align the power recycling cavitys axes with the axes of the incoming beam. Both mirrors have magnets attached to the mirrors on which forces are applied with coils.

Alignment information for the Michelson interferometer is obtained by D5, which symbolizes a unit for differential wavefront sensing for 2 degrees of freedom. Feedback

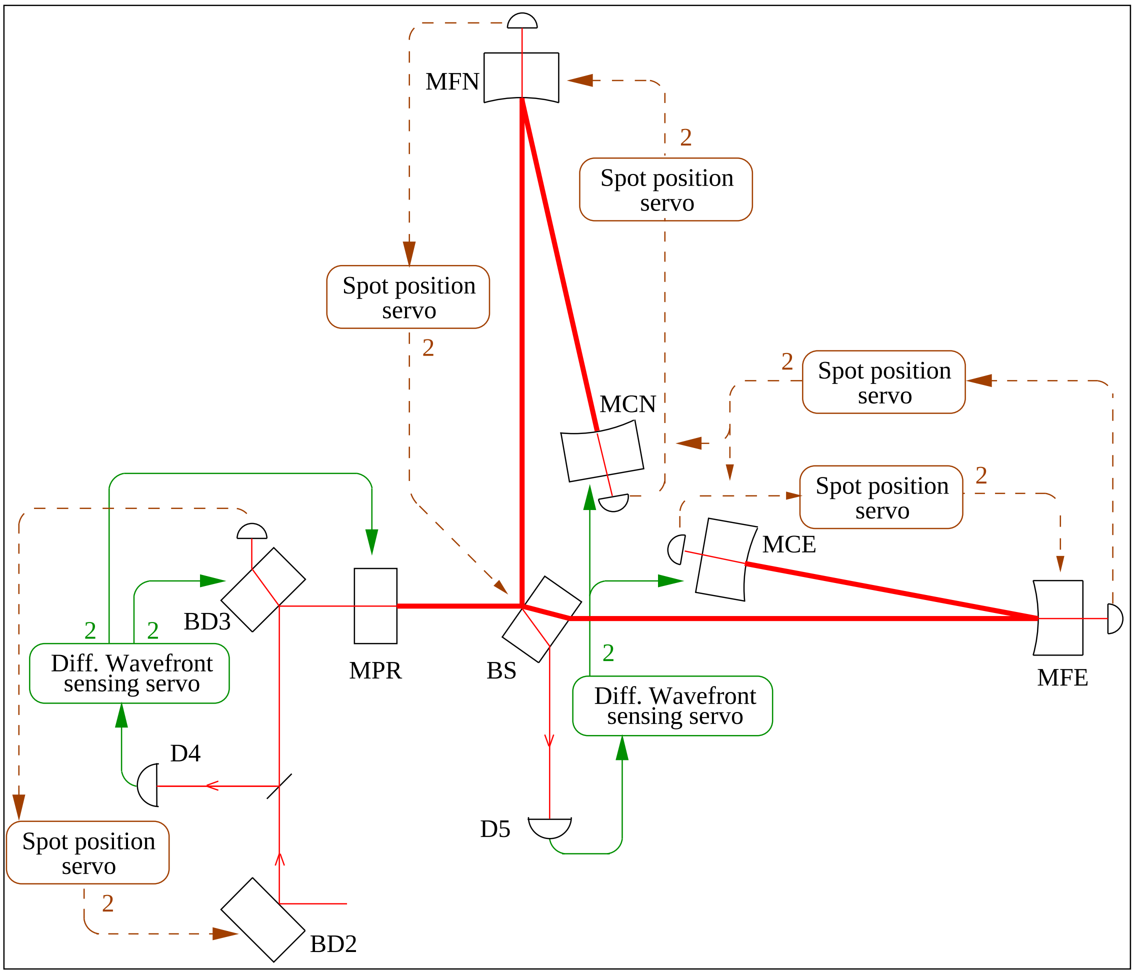

**Figure 4.** Automatic alignment system layout for the power recycled michelson interferometer

in this case is applied to the cavity folding mirrors MCE and MCN differentially. The common mode of these 2 mirrors is used for spot position control. One simplified possible topology of the spot position control for all remaining mirrors is shown, but others are possible.

Figure 5 shows the error point spectrum of the power recycling mirrors horizontal alignment degree of freedom.

At the time of this measurement in January 2001 the beamsplitter BS was not installed, and the mirrors PR, MFE and MCE formed a 2400 m long folded Fabry-Perot cavity, described in [6]. The measurement shows the angular motion of mirror PR against the incoming beam without automatic alignment and with automatic alignment for 4 degrees of freedom switched on. With a bandwith of the alignment feedback loops around 10 Hz, the rms value of the angular motion is damped to 0.02 $\mu$rad compared to 1.0 $\mu$rad without automatic alignment. The electronic noise of the differential wavefront sensor is as low as $10^{-11}\text{rad}/\sqrt{\text{Hz}}$.

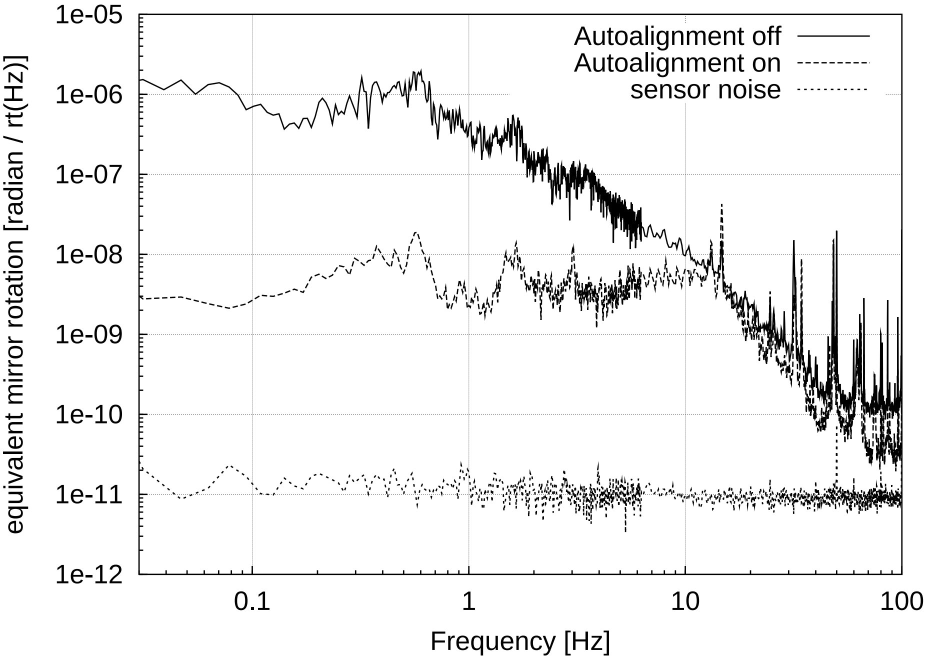

**Figure 5.** Horizontal alignment spectrum of mirror MPR with and without automatic alignment

## 5. Conclusion

The complete automatic alignment system for the two GEO 600 suspended ring type modecleaners is installed and in continuous operation. The automatic alignment of a large-scale interferometer with differential wavefront sensing in 4 degrees of freedom was succesfully demonstrated as a major part of the complete automatic alignment of GEO 600.

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