

# Control and automatic alignment of the output mode cleaner of GEO 600

M. Prijatelj<sup>1</sup>, H. Grote<sup>1</sup>, J. Degallaix<sup>1</sup>, M. Hewitson<sup>1</sup>, S. Hild<sup>2,3</sup>, C. Affeldt<sup>1</sup>, A. Freise<sup>2</sup>, J. Leong<sup>1</sup>, H. Lück<sup>1</sup>, K. A. Strain<sup>1,3</sup>, H. Wittel<sup>1</sup>, B. Willke<sup>1</sup> and K. Danzmann<sup>1</sup>

<sup>1</sup> Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut) and Leibniz Universität Hannover, Callinstr. 38, 30167 Hannover, Germany

<sup>2</sup> School of Physics and Astronomy, The University of Birmingham, Edgbaston, Birmingham, B15 2TT, United Kingdom

<sup>3</sup> Institute for Gravitational Research, University of Glasgow, Glasgow, G12 8QQ, United Kingdom, United Kingdom

E-mail: mirko.prijatelj@aei.mpg.de

**Abstract.** The implementation of a mode cleaner at the output port of the GEO 600 gravitational wave detector will be part of the upcoming transition from GEO 600 to GEO-HF. Part of the transition will be the move from a heterodyne readout to a DC readout scheme.

DC readout performance will be limited by higher order optical modes and control sidebands present at the output port. For optimum performance of DC readout an output mode cleaner (OMC) will clean the output beam of these contributions.

Inclusion of an OMC will introduce new noise sources whose magnitudes needed to be estimated and for which new control systems will be needed.

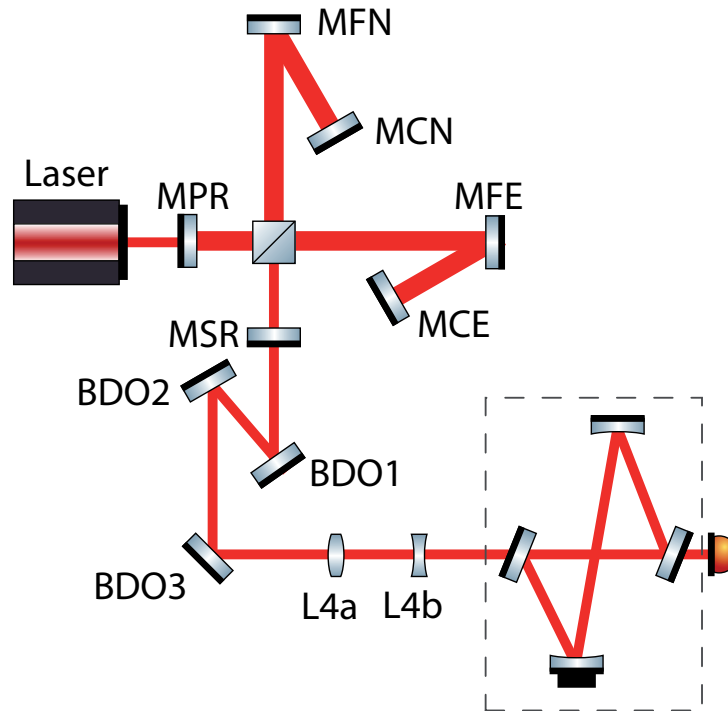
In this article we set requirements on the performance of these control systems and investigate the simulated performance of different designs.

## 1. Introduction

The upcoming GEO-HF [1] upgrade to GEO 600 [2] consists among other things in the change from the current heterodyne readout scheme to a DC readout scheme [3]. DC readout performance will be limited by higher order optical modes (HOMs) and modulation sidebands present in the output beam of GEO 600.

HOMs and sidebands contribute to shot noise but no gravitation wave signal will be extracted from them. In combination with the planned upgrade of the laser power by a factor of 10 the presence of HOMs and sidebands would require multiple photo diodes to accommodate for the increased light power. To reject sidebands and HOMs from the output beam an output mode cleaner (OMC) will be installed. The OMC will be located on a suspended bench. For more details see [3]. Transmissivity of the OMC for the TEM<sub>00</sub> carrier will depend on the frequency mismatch  $\Delta f$  between the GEO 600 output beam and the OMC resonance frequency. It will also depend on the alignment of the output beam onto the OMC.

Fluctuations in  $\Delta f$  and the alignment will create fluctuations in the power transmitted through the OMC. In DC readout these fluctuations couple directly to the GEO 600 strain measurement. The impact of these two new noise sources are investigated and compared to other



**Figure 1.** Simplified optical layout of the GEO-HF gravitational wave detector. The interferometer is formed by the mirrors MPR, MCN, MCE, MFN, MFE and MSR. BDO1 to BDO3 steer the output beam. L4a and L4b are used to mode match the output beam to the OMC. The output mode cleaner is shown in the lower right corner inside the dashed box.

noise sources in section 2. These investigations lead to requirements onto the control systems that minimize  $\Delta f$  and misalignment. In section 3 different designs for control systems are presented and expected performances are compared to the requirements derived in the previous section. In section 4 the current status of the preliminary experiments with the OMC under air are layed out and a outlook is given.

## 2. Investigations regarding noise sources introduced by the OMC

The magnitude of the noise sources introduced by the OMC are investigated. Requirements are formulated to ensure that they are below shot noise for the frequencies of interest.

The frequency of the GEO 600 laser is locked to the GEO 600 power recycling cavity (PRC) [4]. The PRC is formed by the mirrors MPR, MCE and MCN (see fig. 1). These mirrors are seismically isolated by multiple pendulum stages with a resonance frequency around 1 Hz [5]. If we omit frequencies below 0.3 Hz their residual motion is dominated by frequencies around 1 Hz. This is well below the GEO-HF measurement band. The amplitude of these low frequency fluctuations can be assumed to be  $\pm 2 \mu\text{m}$ . Given the length of the PRC of 1200 m this results in a frequency change of the laser of  $\pm 470 \text{ kHz}$ . Since fluctuations in the OMC length around 1 Hz are negligible due to its monolithic design this introduces a frequency mismatch  $\Delta f_{\text{LF}}$  between the output beam of GEO 600 and the OMC resonance frequency of the same amount. At higher frequencies in the GEO-HF measurement band length fluctuations of the PRC can be neglected due to the elaborate seismic isolation system of the mirrors forming the PRC.

In addition to  $\Delta f_{\text{LF}}$  there are higher frequency fluctuations  $\Delta f_{\text{audio}}$  in the frequency mismatch dominated by length changes of the OMC. The actual value of  $\Delta f_{\text{LF}}$  defines the coupling coefficient for  $\Delta f_{\text{audio}}$  into the power transmitted through the OMC. Since fluctuations in the

length of the OMC at  $\Delta f_{\text{audio}}$  happen in the measurement band of GEO-HF they contribute to noise in the strain signal. It is therefore important to minimize the low frequency frequency mismatch to minimize the coupling coefficient. Coupling coefficients were calculated using FINESSE software [6]. We want the fluctuations in the power transmitted through the OMC due to  $\Delta f_{\text{audio}}$  to be less than 1/10 shot noise. The resulting requirement for  $\Delta f_{\text{audio}}$  was calculated:

$$\Delta f_{\text{audio}} \leq 10.79 \frac{\text{Hz}}{\sqrt{\text{Hz}}} \frac{470 \text{ kHz}}{\Delta f_{\text{LF}}}. \quad (1)$$

The OMC length will be 65.8 cm. The required stability in the measurement band was calculated as

$$\text{OMC length stability} \leq 7.69 \cdot 10^{-16} \frac{\text{m}}{\sqrt{\text{Hz}}} \frac{470 \text{ kHz}}{\Delta f_{\text{LF}}}. \quad (2)$$

The OMC will be located on a suspended bench. We assume that the OMC will achieve a length stability of  $1 \cdot 10^{-15} \text{m}/\sqrt{\text{Hz}}$ . This requires  $\Delta f_{\text{LF}}$  to be less than 100 kHz. This requires the closed loop suppression at the dominant frequencies around 1 Hz to be at least 5. This should be achievable without great difficulty.

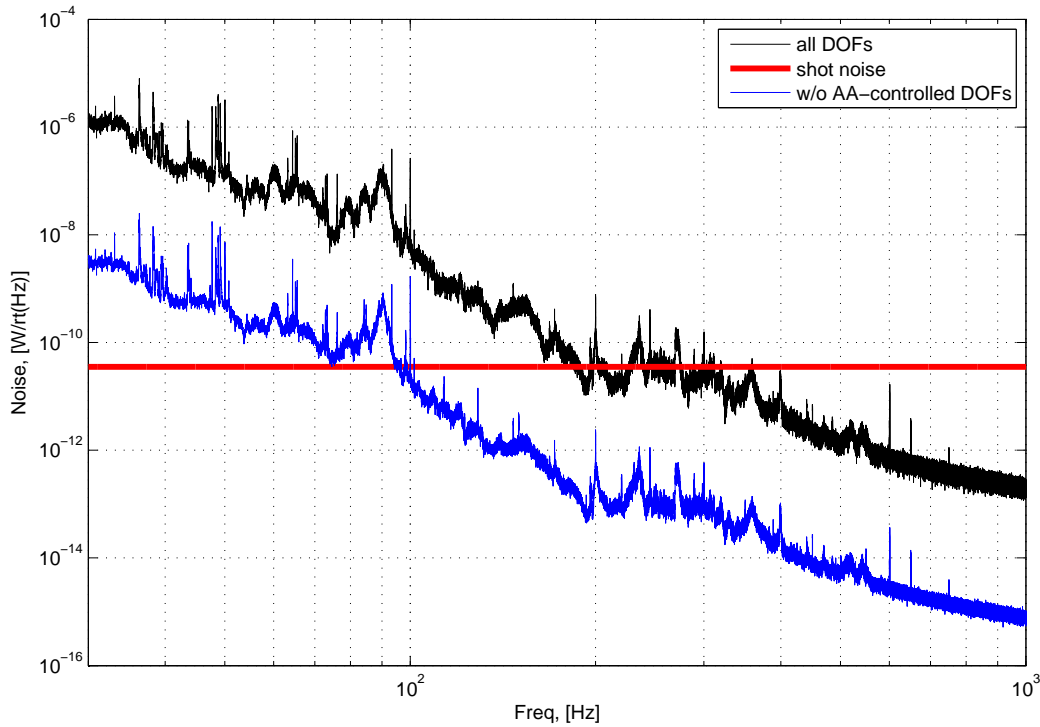
### 2.1. Alignment requirements

Determination of alignment requirements follows the same structure as the determination of the frequency mismatch requirements. Again the margin of allowed fluctuations in the measurement band is determined by lower frequency fluctuations. Alignment fluctuations in and below the measurement band are both caused by fluctuations in the rotation and tilt of the GEO 600 mirrors MPR, MCE, MCN, MSR, BDO1, BDO3 and translation of the OMC itself. Due to the GEO 600 configuration it is useful to investigate motions of the mirrors MCE and MCN as the degrees of freedom (DOFs) MCE-MCN and MCE+MCN. MCE-MCN is the differential misalignment. Low frequency rotations of the mirrors are assumed to be  $\pm 250$  nrad. Mirror fluctuations in the measurement band were estimated by multiplying seismometer data from the GEO site with the respective pendulum transfer functions. Pendulum transfer functions were assumed to be of magnitude 1 up to the pendulum resonance frequency at 1 Hz and  $f^{-2n}$  with n the number of pendulum stages for higher frequencies. The number of pendulum stages for the different mirrors can be seen in table 1. The suspension points of the pendulums are isolated by stack isolators consisting of layers of metal and rubber. These stack isolators provide additional isolation above approximately 10 Hz.

Coupling of alignment fluctuations in the measurement band in any DOF into the power transmitted through the OMC is determined by the current misalignments of all other DOFs. To simulate the coupling coefficients of a DOF the other DOFs were assumed to be misaligned by discrete values in steps of 50 nrad between -250 nrad and 250 nrad. This leads to 23716 possible configurations: (7 DOFs times 11 misalignment values times 2 axes)<sup>2</sup>. To reduce the computational needs only 2 DOFs at a time were evaluated yielding less than 1000 configurations. For each DOF the biggest coupling coefficient was recorded and the misalignment fluctuations in the measurement band were multiplied by it. The resulting fluctuations in the power transmitted through the OMC were summed coherently. The resulting noise is shown in figure 2. It can be seen that noise due to misalignments falls below shot noise at 300 Hz (see 'all DOFs' trace). This is for a power transmitted through the OMC of 40 mW. It should be noted that this noise estimation is very conservative. The DOFs of the MPR mirror and MCE-MCN are controlled by automatic alignment (AA) systems that reduce their misalignments. If perfect alignment for these DOFs is assumed this results in a alignment noise as shown in trace 'w/o AA-controlled DOFs' in figure 2. Noise introduced by the OMC will fall below shot noise above frequencies of 100 Hz to 300 Hz. Therefore only a drift control is needed.

**Table 1.** Number of pendulum seismic isolation stages of different GEO 600 mirrors.

	MPR	MCE	MCN	MSR	BDO1	BDO3
# of pendulum stages	2	3	3	3	1	1

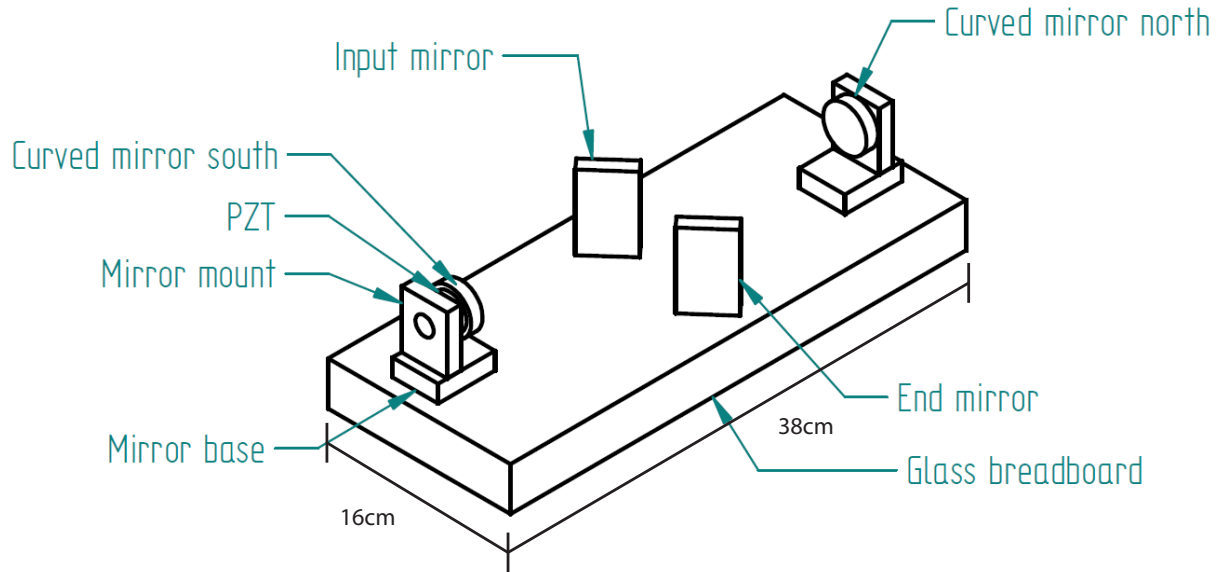


**Figure 2.** Noise in the power transmitted through the OMC induced by misalignments. Uncalibrated spectrum at the detector behind the OMC. Transmitted power 40 mW.

### 3. Potential output mode cleaner control systems

#### 3.1. Longitudinal control

As has been stated in the previous section the frequency mismatch between the OMC and the PRC resonance frequencies needs to be controlled and minimized. The error signal for this control system is generated via dither locking. The OMC length is dithered (modulated) at  $f_{\text{dither}}$ . At zero frequency mismatch this leads to a modulation of the power transmitted through the OMC at  $2 \cdot f_{\text{dither}}$ . With increasing frequency mismatch, a modulation at  $f_{\text{dither}}$  appears. It is possible to either make the OMC follow the PRC or to make the PRC follow the OMC. We will first make the OMC follow the PRC. This has the benefit of avoiding adding additional feedback into the complex control loops controlling the suspended GEO 600 mirrors. If it should prove necessary to extend the actuation range actuation on the PRC length will however be possible. Tuning the length of the OMC is done with a piezo actuator (Physik Instrumente S-303) attached to one of the OMC mirrors (see fig. 3). Actuation range of the PZT is  $3 \mu\text{m}$



**Figure 3.** Schematic view of the output mode cleaner. Modified from [3].

corresponding to a change in resonance frequency of the OMC of 1.3 MHz. We do not expect length-to-angle coupling to be a problem.

### 3.2. Alignment control

All possible alignment configurations can be represented as points in a 4D parameter space. Misalignments in one plane can be represented as a transversal shift and a rotation. For two planes this results in a 4D parameter space. A requirement for the automatic alignment system is to have actuators available that can cover the whole 4D alignment parameter space. Promising actuators in our case are BDO1 and BDO3. Actuators can be represented by vectors in the alignment parameter space. These vectors are the rows of the control matrix. The angle between the two actuator vectors in the alignment space is a measure the controllability of the system. As a rule of thumb a bigger angle leads to a more robust control system. This separation angle is influenced by the optical configuration of the output optics. Several configurations for the output optics are possible: keep the existing BDO mirrors and add two lenses or change the BDOs ROCs and add either one or no lens. For simplicity we have decided to keep the existing BDOs and accept the non-optimal separation angle. Separation angles for several configurations are compared in table 2. The benefit of keeping the existing BDO mirrors convinced us to choose the two lens configuration.

Several designs for the automatic alignment system were investigated:

1. Dither lock with four frequencies. Dithering is applied to BDO1 and BDO3: Both tilt (pitch) and rotation (yaw) degrees of freedom for BDO1 and BDO3 respectively are dithered at separate frequencies  $f_1$  to  $f_4$ . At perfect alignment the power transmitted through the OMC will be modulated at frequencies  $(2 \cdot f_1)$  to  $(2 \cdot f_4)$ . Proportionally to misalignment modulations at  $f_1$  to  $f_4$  appear. In the current coil driver design, the maximum possible dither amplitude is limited to

$$\text{Dither amplitude} \leq 1.14 \cdot 10^{-7} \text{ rad} \frac{100 \text{ Hz}^2}{f_{\text{dither}}^2} \quad (3)$$

**Table 2.** Comparison of optical configurations of the output optics and resulting separation angles for the actuators BDO1 and BDO3.  $R_{\text{BDO1}}$  and  $R_{\text{BDO2}}$  are the radii of curvature of BDO1 and BDO2.  $f_{\text{L4a}}$  and  $f_{\text{L4b}}$  are the focal lengths of L4a and L4b.

Configuration	$R_{\text{BDO1}}$ [m]	$R_{\text{BDO2}}$ [m]	$f_{\text{L4a}}$ [m]	$f_{\text{L4b}}$ [m]	Sep. angle [°]
Two lens	6.27	$\infty$	0.25	-0.052	17.44
One lens	6.27	-6.86	-0.50	$\infty$	9.47
Zero lens	4.12	-1.14	$\infty$	$\infty$	64.69

**Table 3.** Shot noise limited sensitivity of different designs for the output mode cleaner automatic alignment system in terms of BDO1 and BDO3 misalignments.

	Design 1	Design 2	Design 3
BDO1 rotation [rad]	$4.88 \cdot 10^{-12}$	$9.00 \cdot 10^{-3}$	$2.04 \cdot 10^{-9}$
BDO1 tilt [rad]	$1.95 \cdot 10^{-10}$	$9.30 \cdot 10^{-4}$	$1.48 \cdot 10^{-9}$
BDO3 rotation [rad]	$1.05 \cdot 10^{-9}$	$7.26 \cdot 10^{-2}$	$2.70 \cdot 10^{-8}$
BDO3 tilt [rad]	$9.78 \cdot 10^{-8}$	$1.19 \cdot 10^{-1}$	$3.15 \cdot 10^{-8}$

In the simulation we assumed a dither amplitude of  $1 \cdot 10^{-7}$  rad which corresponds to a dither frequency of about 105 Hz. A lower dither frequency can also be implemented.

2. Dither lock with a common frequency. Dithering is applied to BDO1 and BDO3:

Again the BDO mirrors are dithered. This time with a common frequency. The light reflected off of the OMC is split 50:50 and detected by two quadrant photo detectors. The Gouy phase shift between them is  $\pi/2$ . Essentially this is differential wavefront sensing [7] with sidebands created by dithering the BDO mirrors instead of by an electro-optic modulator. HOM-content of the GEO 600 output beam was assumed to be 1.4 mW. Ideal mode matching was assumed.

3. Dither lock with a common frequency. Dithering is applied to the OMC length:

In this configuration the OMC length is dithered. The same OMC length dither can be used for longitudinal and alignment control. The full width at half maximum of the OMC resonance is about 7 nm. A realistic dither amplitude can be assumed to be 1 nm. Just as in design 2 the light reflected off of the OMC is split 50:50 and detected by two quadrant photo detectors.

The shot noise limited sensitivities of designs 1 to 3 were estimated using the FINESSE simulation software for a power of 40 mW transmitted through the OMC. Their sensitivities are presented in table 3. Since the sensitivities of design 1 and 3 are considerably better than the requirements we derived on mirror movements in section 2, both designs seem promising. Sensitivities and requirements should scale proportionally for different noise levels. We intend to test designs 1 and 3 in GEO-HF.

#### 4. Preliminary tests of the output mode cleaner

The output mode cleaner has been assembled in a clean room. The frequency locking scheme has been successfully tested by locking the OMC to a laser (Innolight Mephisto 500 NE). The frequency mismatch has been minimized in this test setup by actuating on the laser frequency. The dithering, demodulation and the control loop filter were implemented with a real-time computer control system identical to the one developed for the Advanced LIGO detector. The unity gain frequency of this control loop was 145 Hz and closed loop suppression at 1 Hz was above 30 dB.

It has become obvious that the OMC can easily lock onto HOMs instead of the  $\text{TEM}_{00}$  mode. Since HOMs do not contain an easily usable gravitational wave signal the OMC must not lock

onto HOMs when integrated into GEO 600. Future investigations will show if this will pose a problem in the GEO 600 implementation.

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### References

- [1] Lück H, Affeldt C, Degallaix J, Freise A, Grote H, Hewitson M, Hild S, Leong J, Prijatelj M, Strain K A, Willke B, Wittel H, Danzmann K 2009 Commissioning of the tuned DC readout at GEO 600 *J. Phys.: Conf. Series* published in this issue
- [2] Grote H (for the LIGO Scientific Collaboration) 2008 *Class. and Quantum Grav.* B **25** 114043
- [3] Degallaix J, Grote H, Prijatelj M, Hewitson M, Hild S, Affeldt C, Freise A, Leong J, Lück H, Strain K A, Wittel H, Willke B and Danzmann K 2009 *J. Phys.: Conf. Series* published in this issue
- [4] Wilke B et al 2002 *Class. and Quantum Grav.* **19** 1377
- [5] Goßler S 2004 Phd thesis <http://edok01.tib.uni-hannover.de/edoks/e01dh04/389559768.pdf>
- [6] Freise A <http://www.rzg.mpg.de/adf/>
- [7] Morrison E et al 1994 *Appl. Opt.* **33** 5041-5049
- [8] Risk W P, Gosnell T R, Nurmikko A V 2003 *Compact blue-green lasers* (Cambridge: Cambridge University Press)