LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
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CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Document Type **LIGO-T970000-00-D** Oct. 25, 1997

IOO Mode Cleaner Wavefront Sensing Telescopes

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Distribution of this draft:

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Introduction

The purpose of this document is to specify the design of the Guoy phase telescopes which are part of the wavefront sensing alignment scheme for the Input Optics Mode Cleaner (IOOMC). The design entails calculation of the Guoy phase corresponding to maximum sensitivity to each degree of freedom and then determining the focal lengths and positions of lenses and the positions of the detectors which give this Guoy phase shift.

Alignment sensitivity matrix

The mode cleaner alignment sensitivity matrix is calculated using the Modal Model [1]. A convenient basis in which the alignment degrees of freedom can be expressed is common-mode and differential tilts of the input and output mirrors. It should be noted that because the mode cleaner is a three-mirror ring cavity, the antisymmetric spatial modes of the cavity have an additional Guoy phase shift in the horizontal plane (due “spatial flips” upon reflection from the odd number of mirrors), which leads to a different Guoy phase shift for detection of horizontal and vertical misalignments. For the mode cleaner parameters listed in the Appendix, the alignment sensitivity matrix is given in Table 1:

Port	Degree of Freedom			
	ΔIO_x		$\overline{IO}_x$	
reflection	3.53 (3.52)		−2.25 (−2.25)	
	I (I)	90˚ (90˚)	I (I)	0˚ (0˚)
	ΔIO_y		$\overline{IO}_y$	
reflection	−2.25 (−2.25)		−1.44 (−144)	
	I (I)	0˚ (0˚)	I (I)	90˚ (90˚)

Table 1: Alignment sensitivity for the 4 km and 2 km (in parentheses) configurations. The upper entry is the signal strength per divergence angle, the lower left entry is the RF phase and the lower right entry is the Guoy phase shift for maximal detection of the signal.

Telescope layout and definitions

A schematic of the layout for the mode cleaner photodetection is given in Figure 1.

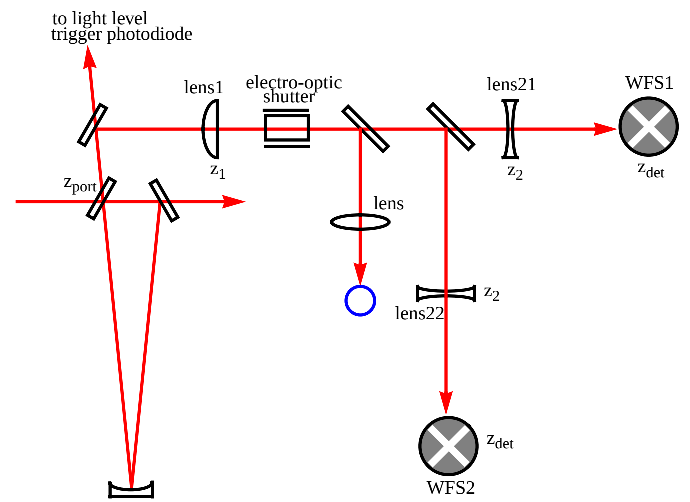

Figure 1: Schematic layout of mode cleaner photodetection. z_{port} is the location of the mode cleaner input mirror, which is also the reflection port. Since the beam waist occurs at z_{port}, we set $z = 0$ there. z_1 is the position of the first lens, with focal length, f_1; z_2 is the position of the second lens, with focal length, f_2; and z_{det} is the position of the detector.

Design constraints

The following practical considerations have driven the design choices:

- The nearest accessible position to the reflection port is about 4 m away, so $z_1 \geq 4.0$ m.
- Separation between lenses must be large enough to accommodate the electro-optic shutter and two beamsplitters, so $z_2 - z_1 \geq 0.5$ m.
- The total distance between the telescopes and the detector should not exceed 2.5 m, so $z_{det} - z_1 \leq 2.5$ m.
- The electro-optic shutter has a clear aperture of 8 mm so the spot size on it should not exceed 5 mm in diameter.
- The optimum spot size on the detector is determined by the size of the quadrant photodiodes [2]. The EG&G YAG 444-4 have an active area of 1 cm^2, which gives detector radius,

$R = 5.64$ mm .The ratio of the spot size on the detector, *w*, to the detector radius, *R*, which ensures that less than 1% of the signal is lost due to the finite detector size is $w/R \le 0.6$. This corresponds to $w \le 3.4$ mm . **We use $w = 3.0$ mm**.

- We use commercial off-the-shelf lenses; their focal lengths must be accordingly chosen.

Lens selection

To minimize spherical aberrations, we use a plano-convex lens for lens 1 and a bi-concave lens for lens2. The CVI lenses we choose have good surface quality and figure, with a small error in the focal length. Specifically, for CVI lenses

- Surface quality: 10-5 scratch-dig (cf. 40-20 for same Newport lens)
- Surface figure: l/10 at 633 nm (cf. λ/4 to λ/2 at 546 nm for Newport)
- Focal length tolerance: ±0.5% (cf. ±2% for Newport)

The part numbers for the lenses used in the design of the Guoy phase telescopes (below) are:

CVI PLCX-25.4-515.1-C with *f*(1064 nm) = +1016.7 mm

CVI BICC-25.4-77.6-C with *f*(1064 nm) = –76.3 mm

Telescope design

The focal lengths and positions of the lenses and the position of the detector head for the Guoy phase telescopes is given in Table 2.

Detector Guoy phase	Configura-tion	f_1 (mm)	z_1 (mm)	f_2 (mm)	z_2 (mm)	z_{det} (mm)
180˚	4 km	+1016.7	4000.0	–76.3	5299.4	5637.5
90˚	4 km	+1016.7	4000.0	–76.3	4945.8	5951.7
180˚	2 km	+1016.7	4000.0	–76.3	5300.6	5595.9
90˚	2 km	+1016.7	4000.0	–76.3	4945.2	6077.4

Table 2: The Guoy phase telescopes for two wavefront sensors for the 4 km and 2 km configurations.

The Gaussian beam propagation, along with Guoy phase shift along the telescope train is give in Figure 2 for the 4 km and in Figure 3 for the 2 km configuration.

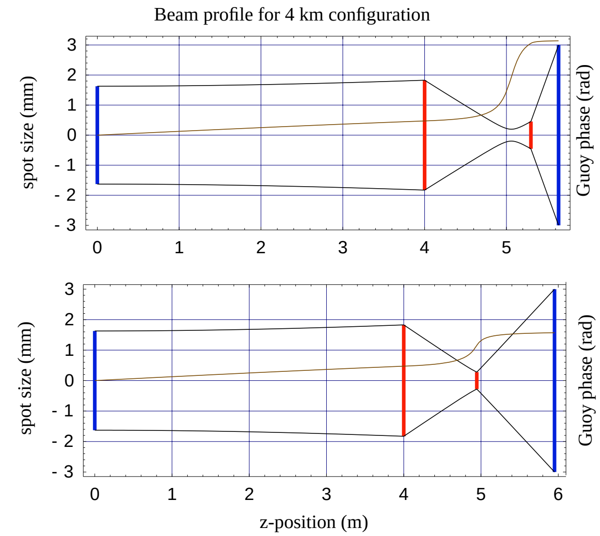

Figure 2: Beam profiles for the 4 km configuration for detectors at 0˚ (180˚) and 90˚ Guoy phase shift.

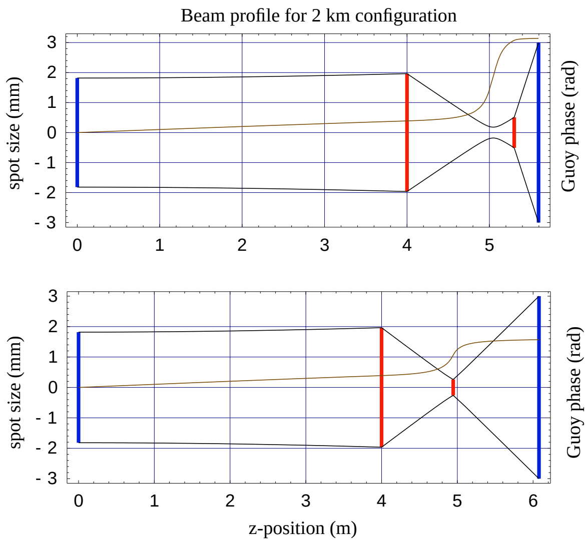

Figure 3: Beam profiles for the 2 km configuration for detectors at 0˚ (180˚) and 90˚ Guoy phase shift.

Error propagation

The dominant source of Guoy phase error in this two-lens design is error in the position of the second lens. In fact, for an error of ±10 mm in the placement of the second lens corresponds to a Guoy phase error of ±6˚ for both detectors at 90˚, and a guoy phase error of less than ±1˚ for both detectors at 0˚. All other errors contribute less than ±0.5˚ to the Guoy phase error and less than 0.1 mm to the spot size on the detector.

References

[1] LIGO-T960118-00-DModal Model Update 6: Mode Cleaner (Dec. 1996).

[2] LIGO-T960111-A -DWavefront Sensor (July 1996).

[3] LIGO-T970144-00-DInput Optics Preliminary Design (Aug. 1997).

[4] LIGO-T970068-00-DRecycling Cavity and Mode Cleaner Baseline Dimensions (Feb. 1997).

Appendix

The relevant parameters for the mode cleaner for the 4 km and 2 km configuration are given in Table 3. These parameters are derived from references [3] and [4].

Parameter	Unit	input mirror	output mirror	third mirror
length (round-trip)	m			24.510 (30.540)
power transmission		0.002	0.002	10^{-5}
power reflectivity		0.998	0.998	$1–10^{-5}$
radius of curvature	m	∞	∞	17.25 (21.50)
beam waist	mm			1.628 (1.818)
modulation frequencies	MHz			33.289 (27.717)
modulation depths	G			0.015
wave length	µm			1.064
refractive index				1.44968

Table 3: Mode cleaner parameters for the 4 km and 2 km configurations. Values for the 2 km configuration are given in parentheses, unless same for both.