LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
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ASC Centering Subsystem Description

Title

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1 SCOPE

This description of the ASC Centering subsystem is designed to give more precise but informal design information about the procedure planned for the Centering subsystem, and to document the ‘choice of sensor’ for the Centering system. To summarize, a dithering sensor is used to determine the correct center of the mirrors.

2 REQUIREMENTS

The performance specification is developed using a model for the coupling from a combination of offset from center and GW-band rotational motion to length changes. Note that the centering must be maintained within prescribed limits for both static positioning and dynamic ‘beam wander’ or optic motion. See the ASC DRD Section 7.2. on page 36 for the approach to determining the requirement.

The rotational motion is estimated by assuming that the suspension’s actuators output noise increases the suspended optic’s angular motion above the seismic. If seismic noise is in fact dominant, and the motion at the optic edges to due rotational motion is no greater than that due to translation, the spot may be anywhere on the surface (i.e., other constraints, like beam fall-off, become more important).

If suspension actuators drive the edges of the mirror at four points with random noise, there will be both rotational and translational motion of the mirror. Their ratio can be calculated from the ratio of the rotational inertia to the translational inertia; this leads to

$$\frac{\theta}{x} = \frac{r}{\left(\frac{l^2}{3} + \frac{r^2}{4}\right)} = 26.1 \text{ rad/m} \qquad \text{(EQ 1)}$$

for our mirrors ($r = 0.125$ m, $l = 0.05$ half-length). Perhaps more useful is the ratio of the edge of the mirror motion due to rotation to that due to translation; this is $(\theta / x) r = 3.3$. This indicates that the net (sum) translational motion on the mirror has equal contributions from rotations and translation at about 1/3 of the mirror radius for one rotational degree of freedom (DOF). There are two DOFs of the mirror for one translational DOF, and we assume that the electronic noise from the 4 coils is uncorrelated, so that the rotational motion is $\sqrt{2}$ times larger. For the additional noise due to the angular noise to rest below that of the translation (GW-mimicking noise), the beam must be centered to within $1/((3.3)\sqrt{2}) = 0.21$ of the mirror radius or 2.7 cm. Since each mirror contributes both translational and rotational noise, no sum over the degrees of freedom for all mirrors is needed.

A different concern is fall-off of the beam from the mirror. One of the drivers for the requirement for the mirror diameters is the amount of light lost at the edges of the mirror. We have used 1 ppm/bounce as the nominal value. Around this point, a reduction of the diameter by 1 cm increases the loss to 10 ppm for our particular values (Spero93, Spero95: Diffraction losses). We make a simple model to obtain a requirement for the centering: Assume that the fall-off grows parabolically away from perfect centering, and that 1 cm deviation of the beam center from the mirror center leads to about 5 ppm loss. This leads to the approximation that the loss A in ppm is given by $A = 1 + 5\times10^{-2}y^2$, where y is the deviation in meters. If we now way that we do not want more than 2 ppm total loss (one additional ppm), we ask that y remain less than 4.5 mm. This additional 1 ppm is a very small additional loss (to put it in perspective, all modeling to date uses a loss of 100 ppm loss), and so we use this number, for the precision per optic.

No other mechanisms for conversion of translations perpendicular to the optic axis (with or without rotational motion) have been considered in detail. Ripples on the mirrors (given the stringent requirements on the surfaces) do not appear to lead to significant effects. Variations in the reflectivity might also add constraints, but probably not interferometric ones (constancy of calibration, for instance, might be affected).

We thus recommend to SYS 4.5 mm per mirror as the centering requirement.

3 OUTLINE OF METHOD

There are two steps in the process. First the correct position must be found, that is the position which couples the least angular motion of the mirror to longitudinal changes. Then the beam position on the mirror must be maintained at this spot on the mirror (to the required precision). The first step is performed using a dithered determination of the best position; the second involves a closed-loop control over the beam position based on position sensitive detectors, linked with changes in the alignment (to move the optical axis of the cavities).

A hierarchy is needed to ensure that the automatic alignment system does not cause the beam position on the mirrors to drift. Thus, one of the inputs to the computation of control signals for the closed-loop automatic alignment system must come from the centering system.

3.1. Dithering to determine correct position

The approach taken is to make an intentional periodic rotation of the optic to be centered on the beam and to analyze the interferometer output; this information is combined with alignment information to develop control signals used to minimize the observed coupling. This dither procedure is performed at intervals as needed, but not more often than once per day; the procedure is automated to make the total duration acceptable with respect to the operations scenario.

In somewhat more detail, an automated procedure applies a sinusoidal excitation at a frequency within the normal GW band (order of 100 Hz) to one of the angular degrees of freedom of the optic in question. The GW-sensing output of the interferometer is synchronously demodulated at the modulation frequency, and the resulting signal is proportional to the difference from the correct beam positioning and carries a sign which indicates the correct relative motion between the beam and the optic to bring the signal to zero. The needed translations of the optic or the beam (depending on the optic) are made, and the new position is stored for reference.

3.1.1. Check on wavefront alignment

The procedure also allows a check of the wavefront alignment system by monitoring the power in the cavities as a function of alignment dither with a simultaneous registration of the wavefront alignment signals. Our present understanding of the alignment is that the alignment which gives the maximum of power in the arm cavities is the best alignment, and this can be checked. In addition, this dithering technique offers a backup alignment system (which either functions periodically or with a low modulation amplitude to avoid significant degradation of the GW sensitivity). This leads to a requirement that the modulation frequency be variable over a range to avoid mechanical resonances and important regions of the spectrum.

3.2. Maintaining the beam position on mirror

Once the correct position is located, it must be maintained. The basic approach is to use position-sensitive detectors (nominally quadrant photodiodes or four diodes arranged to give centering information) mounted physically near the mirrors in question (not in the vacuum, and probably after relay mirrors) such that a part of the beam falling on the mirror falls on the quad detector (using wedge beams for the vertex optics, and transmitted beams for the end mirrors). The Wavefront Sensor detectors have DC readouts and can be used for some of the centering information. To within the required precision, the detector remains fixed with respect to the mirror; it suffices to keep the beam centered on the quad diode once the correct position has been found. No effort is made to image or otherwise detect the position of the mirror with respect to the detector, as relative motions are considered to be negligible.

Because the beam positions are affected by the alignment, no information on operational centering is processed unless the interferometer is locked and aligned. (An independent program of measurement is used in the initial alignment of the interferometer to get the initial beam pointing.)

Because of this coupling between alignment and pointing, the centering quadrant detector must be part of the regular data used for the alignment system.

The centering errors can be corrected with simple beam pointing changes (with alignment changes) for the far mirrors; for the near (vertex) optics, some combination of beam pointing and physical translation of the mirrors is needed. Because of the large tolerance for the centering, corrections are only anticipated which would require mm (or cm) motions of the mirrors. We do not require that the interferometer operate during these large motions.

It should be possible to place the optics within the expected tolerance using surveying techniques when first installed, and so we could imagine simply monitoring the beam position on injection into the interferometer. Later diagnostic interest motivates sensors for the other vertex masses.

4 OUTLINE OF PROCEDURE

1. Initial alignment: misalign for no resonances, get beam roughly centered on back mirror; memorize GW-sensing dog-leg position; follow rest of setup procedure; get running.
2. check for preconditions: locked, aligned, no unusual seismic activity.
3. dither direct-path back mirror, read in data; correct alignment and pointing in a coordinated way to bring signal to zero; put quad sensor in place to read zero
4. repeat for indirect-path back mirror
5. dither each of the front components (near direct, near indirect, beamsplitter, recycling)
6. calculate what translations of the input beam will minimize translations (or combinations of translations) of the near optics; calculate remaining needed translations
7. perform, realign, remeasure to ensure satisfactory correction
8. periodic recheck with modulation of each mirror and subsequent calculation of errors; resolution into physical coordinates to understand sources of drift, separate from changes in suspension behavior

5 PARAMETERS

This is a casual list of the most important parameters of the centering system, to be incorporated when refined, into the ASC interface document.

frequency (cies) of modulation: 100 Hz or 75 Hz for standard dither procedure. Desire to mimic physical motions but have good signal to noise. Higher/lower (3 Hz...1 kHz) for diagnostic/ backup alignment using dither.

amplitude of modulation: 10x larger than competing signals (ground noise), smaller than VLF ground noise and string resonances to avoid saturation of mixer etc.

duration of checking procedure: short enough to meet operations scenario requirements

frequency of checking procedure: TBD, but of the order of once per day or once per week

precision of centering: 4.5 mm

triggers for recentering other data which suggest a centering problem: e.g., change in the LF GW spectrum

6 QUESTIONS RAISED

Theses questions should be resolved as the design goes forward, and will be removed as they are answered.

Need for 100 Hz bandwidth angular control: does this present problems for output filters?

Need other frequencies as well, up to ~1 kHz; sampling limits for DC Wavefront Sensor outputs?

Dynamic range of the input beam translations? Need to be able to translate the input optics? Who is responsible for this?

Hierarchy: should we align to a given input beam position and angle? Need flexibility in program to minimize the net DC current in all coils

How to determine that dither contains negligible translational motion about the desired point? natural point is the free oscillation nodal point. Measure this? What precision is needed? Dos it matter if there is ground or coil-driven noise sources dominating for where the actual ‘center’ lies?

What precision needed to avoid coupling from length to angle? due to suspension drive imbalance.

What precision needed to avoid coupling from angle to length? due to suspension drive imbalance. Trust high gain in the length loop to suppress this?

Can we use the wavefront sensors to give unambiguous centering information?

Should we read out the length from the wavefront sensors?

Should some of these tests be built into the Wavefront R&D task?

What bandwidth of control on the 4km pointing? ---same as wavefront servo, probably.