LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
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CALIFORNIA INSTITUTE OF TECHNOLOGY
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Adv. LIGO Arm Length Stabilisation Requirements

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1 Introduction

The quadruple suspension system (quads), designed for the test masses, has an impressive isolation performance at frequencies above 10 Hz. However any displacement at frequencies below or near the quadruple suspension resonance frequencies will not be attenuated as well. Even with the BSC ISI platforms, this results in the test mass displacement of $\sim 10^{-7}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$ below 0.5 Hz. This displacement is too much for the quadruple actuators to acquire lock of the arm cavities in a deterministic manner. The residual arm cavity length fluctuations need to be reduced to within the line-width of the cavity, after which the acquisition of the full interferometer can be done in a deterministic approach.

This document described the requirements for the arm length stabilisation system. This system will stabilise the arm length by locking the arm cavity to an auxiliary laser from the end-station and then damped the test mass motion.

2 Approach

The approach for stabilising the arm length fluctuations is to use an auxiliary laser at 532 nm and inject it at the back of the arm cavity through the ETM, then lock the laser to the cavity by feeding back to the laser frequency. This will keep the error signal within its linear range, so once locked, the error signal can be fed back to the ITM/ETM to reduce the test mass displacement fluctuations.

3 Requirements

3.1 Test Mass Coating Reflectivities

The arm cavity test masses will have high performance reflection coatings for 1064 nm. The coating layers will be optimised to have the optimum performance at 1064 nm, e.g. low Brownian noise. In addition, the coatings will be slightly modified to have a determined reflectivity at 532 nm. It is important that with the coating modifications, the Brownian noise performance at 1064 nm is not degraded. It has been shown that this is possible [1]. In the end-test mass coating specifications E0900068-v1 the transmission for 532 nm is specified to be in the range of 3% to 15%, with a preference of 5%. The input-test mass has a transmission specification of $< 1\%$. This will provide an over-coupled cavity with a finesse of $\mathcal{F}_{532nm} \sim 100$ (seen from the end-station by the 532 nm laser with R_{ETM}=95% and R_{ITM}=99%).

There is no real optimum value for the finesse, but to high a finesse will make it hard to acquire lock, while a lower finesse will make the locking more susceptible to cavity misalignments. With the provided coating specifications for the ITM and the preferred ETM transmission, the cavity finesse will range between 100 and 120.

3.2 Test Mass RMS Displacement Noise

The rms cavity length fluctuations must be reduced to be within the equivalent arm cavity linewidth ($FWHM_{ARM}$) of the 1064 nm field,

$$FWHM_{ARM} = \frac{FSR_{ARM}}{\mathcal{F}_{1064nm}} = \frac{37.5 \times 10^3}{400} = 93 \text{ Hz} \tag{1}$$

where FSR_{ARM} is the arm cavity free spectral range and $\mathcal{F}_{1064nm}$ the finesse at 1064 nm. The equivalent length fluctuation requirement is

$$\frac{\delta x}{L_{ARM}} = \frac{\delta \nu}{\nu_0} \rightarrow \delta x < \frac{FWHM_{ARM} \cdot \lambda \cdot L_{ARM}}{c} < \frac{93 \cdot 1 \times 10^{-6} \cdot 4 \times 10^3}{3 \times 10^8} < 1.3 \times 10^{-9} \text{ m} \tag{2}$$

in which ν_0 is the frequency of the light, $\delta\nu = FWHM_{ARM}$ the arm cavity linewidth, L_{ARM} the arm cavity length, λ the wavelength and c the speed of light.

The quads actuators have a finite amount of feedback force. With a modeled feedback system and gain in the feedback servo, the maximum sensor noise level is set to an equivalent displacement of ~1 pm/$\sqrt{\text{Hz}}$. Noise at frequencies below 0.5 Hz typically rises with a $1/f$ dependency. The modeling results are shown in figure 1. Of course the lower the sensor noise the lower the strain on the actuators.

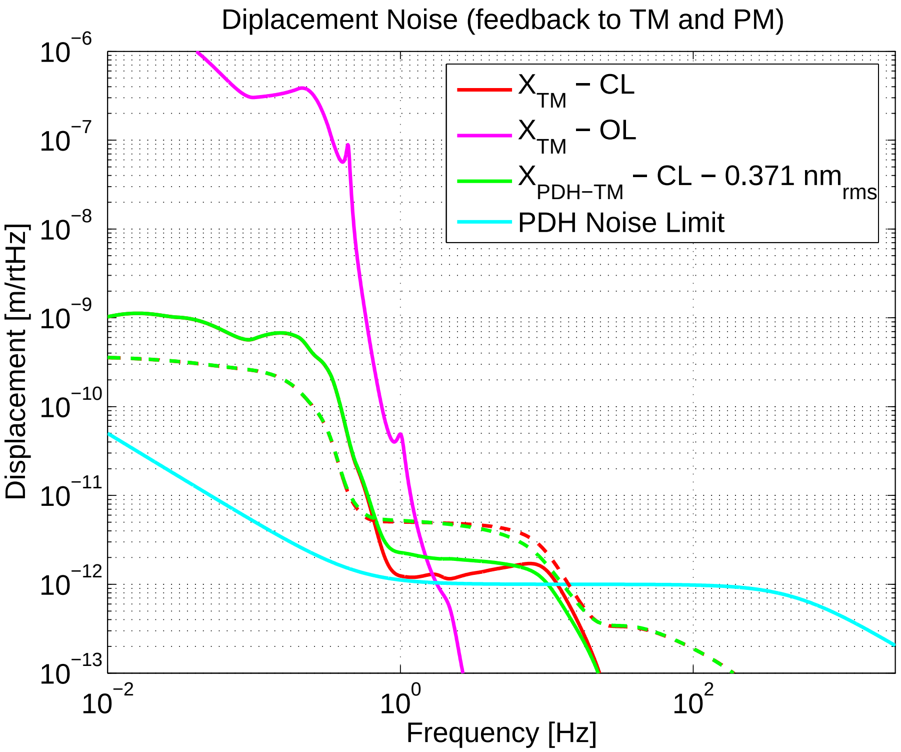

Figure 1: Test mass RMS displacement

Figure 1 shows the test mass displacement with ($X_{TM} - CL$) and without ($X_{TM} - OL$) feedback. The *PDH Noise Limit* trace indicates the maximum sensor noise which will still provide adequate displacement suppression, without saturating the actuators on the quad suspension.

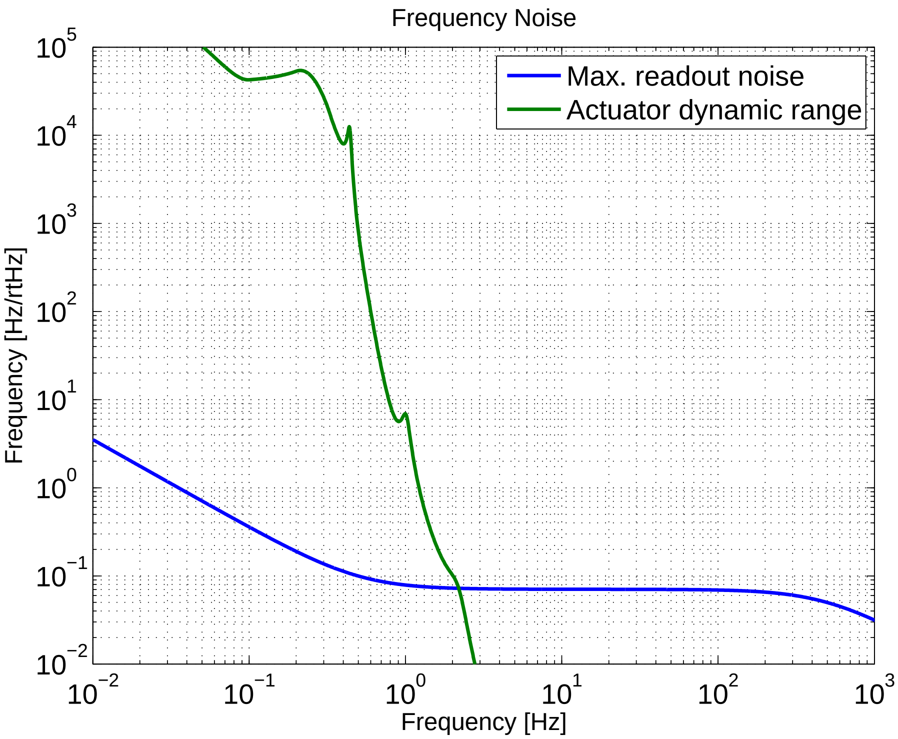

Figure 2: Dynamic range of the frequency actuator and the equivalent sensor noise.

3.3 Frequency Range

Initially the 532 nm laser output is locked to the arm cavity length. To be able to follow the arm cavity length fluctuations, the 532 nm laser needs to have a sufficient frequency range.

The dynamic range is dominated by the equivalent displacement at low frequency, the system needs to be able to cover a 1 μm peak change in arm length. This converts to a frequency dynamic range of 140 Hz/$\sqrt{\mathrm{Hz}}$ peak.

This frequency range can easily be covered by feedback to the laser frequency (PZT and temperature), as shown in figure 2.

3.4 Shot noise Sensitivity

With a cavity finesse of 100, and 10 mW of optical power incident on the arm cavity, the PDH shot noise sensitivity for the 532 nm beam is:

$$\delta x = \frac{1}{8\,\mathcal{F}}\sqrt{\frac{h\,c\,\lambda}{P_{pd}}} = 5 \times 10^{-18}\ \mathrm{m}/\sqrt{\mathrm{Hz}} \tag{3}$$

This indicates that there is enough head room in respect to the shot noise. What may be of concern is the phase reference delivered by the fiber from the corner station.

3.5 Phase Noise Limit

The sensor frequency noise limit is shown in figure 2. The equivalent phase noise requirement can be obtained by using

$$\phi(\omega) = \frac{\nu(\omega)}{i\omega} \qquad [\text{cycles}/\sqrt{\text{Hz}}] \tag{4}$$

$$\widetilde{\phi}(f) = \frac{\widetilde{\nu}(f)}{f} \qquad [\text{rad}/\sqrt{\text{Hz}}] \tag{5}$$

where $\widetilde{\nu}(f)$ is the maximum readout noise from figure 2 and f the Fourier frequencies. The maximum phase noise is shown in figure 3.

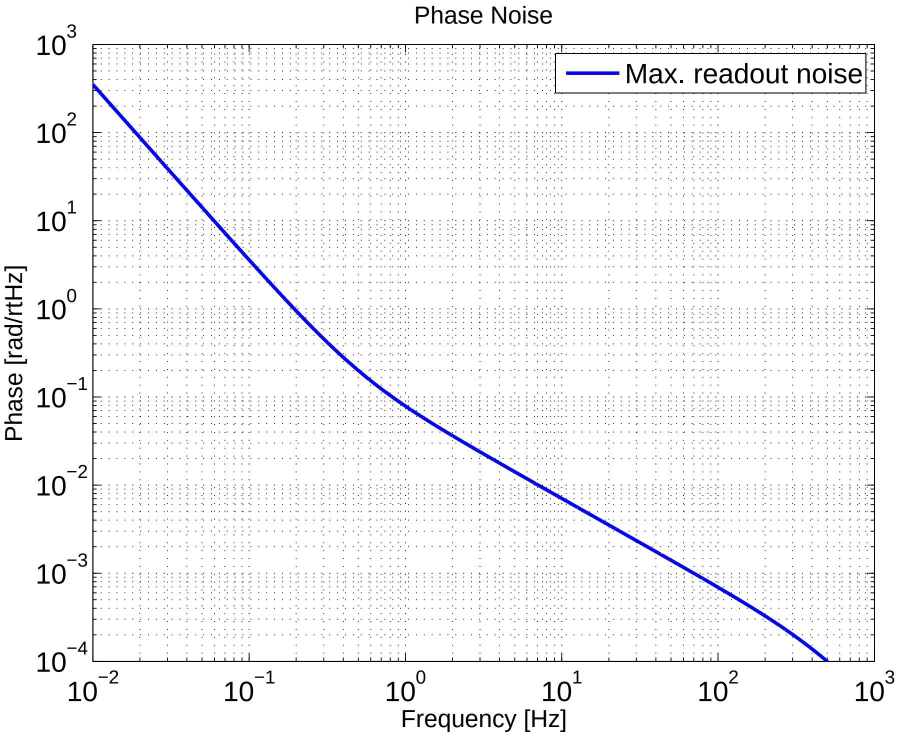

Figure 3: Maximum phase noise of the phase reference delivered at the end-station

3.6 Optical Power

The optical power incident on the ETM is aimed to be ∼10 mW. Table 1 shows the attenuation by the various optical components to estimate the required laser power. The table anticipate a minimal 532 nm laser power of in the order of 45 mW.

3.7 RF Sidebands

The RF phase modulation can use modulation frequencies similar to the main LSC sidebands (9 MHz).

Table 1: Optical Transmission of the optical components (at 532 nm).

Faraday Isolator	80%
RF Modulator	95%
Viewport	90%
ETM Transmon Table	85%
Overall optical train	80%
Hartmann Beam	50%
Total	23%

References

[1] Maria Principe, Innocenzo Pinto, Vincenzo Pierro, and Riccardo DeSalvo. Minimum brownin noise dichroic dielectric mirror coating for AdLIGO. *LIGO-T0803366-00-D*, November 2008.