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Proposal for Consideration by LIGO Project

Experimental Study of Phase Noise for the Initial LIGO Interferometer

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ABSTRACT

The document contains the rational for and the outline of an experimental program to study the phase noise spectral density at frequencies within the LIGO gravitational wave detection band in a suspended interferometer. A two year program is proposed which builds up the interferometer in 3 stages to the full complexity of the initial LIGO interferometer. The initial stage is a simple Michelson interferometer with a single pass per arm. The second stage adds a power recycling cavity and is designed to achieve the phase noise performance required of the initial LIGO interferometer. The final stage is the complete power recycled Fabry-Perot/Michelson interferometer with 5 meter cavities. Technical developments and studies directly applicable to the LIGO initial interferometer include: photodetector and RF preamplifier systems designed for high power, control of photodetector non-linearity and intermodulation distortion, photodetector uniformity and operation at LIGO RF modulation frequencies, measurement of intermodulation products, studies of scattered light and stray beams and methods for handling them.

INTRODUCTION

The project has made good progress in approaching the displacement sensitivity of 10^{-19} m$\sqrt{\text{Hz}}$ in the band between 500 to 100 Hz. At 500 Hz we have a factor of 10 to go while at 100 Hz it is a factor of 1000. The expectation is that improved ground noise isolation will make a dramatic improvement at 100 Hz. There is, however, still a large factor needed in improving our ability to split a fringe through the reduction of the optical phase noise. The storage times of the current 40 meter system and the proposed LIGO arm cavities are comparable so that the straightforward division by the length, the correct procedure for noise due to random forces applied to the test masses, does not apply. The LIGO initial interferometer design assumes an optical phase noise at the detector of 10^{-10} radians/$\sqrt{\text{Hz}}$. The current value in the unrecombined 40 meter system is approximately 10^{-8} radians/$\sqrt{\text{Hz}}$, a factor of about 100. We intend to make this up by increasing the effective optical power in the interferometer by optical recombination, improved optical efficiency, and finally power recycling. The expectation is that the Mark II 40 meter system will initially concentrate on improving the displacement noise sensitivity and that experience with improving the phase noise performance will occur later in the Mark II program. It therefore seems timely and necessary to carry out an experimental study of phase noise concurrently.

A basic assumption made in formulating this proposal is that displacement noise and phase noise are separable. In a highly idealized system they are. Phase noise would be that component of the noise that remains when the test masses are immobilized in inertial space and held at a temperature of absolute zero. It is the fringe sensing noise. A well known contributor to the phase noise is the photon shot noise. There are in addition a host of other technical sources of phase noise, including amplitude and frequency noise in the laser, beam spatial instabilities, fluctuations in the forward scattering by the residual gas, stray light from moving sources (other than the principal optical components), and instrumentation noise. These noise sources can be investigated in a special purpose interferometer designed to have low sensitivity to the test mass motions. Such an interferometer is proposed as the initial step in the program and should be able to measure phase noise at the level and in the frequency band of the initial LIGO interferometer. In the course of these measurements the technology will be developed for the high power photodetection and electronics as well as the means for dealing with stray beams to be encountered in the LIGO.

A test of the phase noise in the initial LIGO interferometer configuration follows. The separation of phase noise from displacement noise is more difficult in such a system, but the step before will help to separate the different noise terms. The interferometer will be designed to have a short arm storage time (low displacement sensitivity) and should be complementary to the Mark II 40 meter system which will have a high displacement sensitivity. The new phase noise producing terms to investigate are parasitic interferometers formed by the additional optical components, new sensitivities to beam geometry instabilities, and an enhanced sensitivity to the conversion of frequency noise into phase noise.

Relationship to Mark II 40m: The experimental plan for the Mark II will evolve with the research results. In general, though, it has concentrated on obtaining very high displacement sensitivity. This is vital to understanding mechanical sources of noise: seismic, thermal, and (perhaps the most important) 'none of the above' like controller noise or suspension performance. A likely sequence for the Mark II is as follows (MEZ): 1) Installation of the Mark I suspensions and optical layout with the new stacks; 2) installation and characterization of the triangular mode cleaner; 3) installation and research with a second-generation suspension design and monolithic test masses; 4) recombination, without recycling; and 5) recycling. MEZ gives 3 to 6 months as a very rough estimate of the time required for each of the steps. It is clear that steps 1) and 3) would be best performed with high displacement sensitivity, since it is mechanical sources of noise that are being investigated. Step 2) will yield the most data if a clear comparison can be made with the preceeding steps, and tests of frequency noise will be more sensitive with long-storage time cavities. Step 4) could be performed with short or long storage times, but 5) will require short storage times to give a sufficiently large reflectivity from the cavities on resonance. Thus the Mark II will probably not be free to start the phase noise measurement until step 4) or 5), which could be between 1 and 2.5 years.

Previous experiments: The Mark I 40m prototytpe obtained its high displacement sensitivity via long storage times in the cavities, not large circulating powers. The typical light power for a shot-noise limited measurement on the 40m was 60 to 80 mW (inferred from a photocurrent of 16 mA), with a resulting phase sensitivity of 10^{-8} rad$\cdot$Hz$^{-\frac{1}{2}}$, or a factor of 100 from the LIGO goal.

The Garching interferometer, when configured as a simple single-bounce Michelson with 30 cm long arms, has shown shot noise for 233 mA of photodiode current, or about 1 W of circulating power. The measured, and calculated, phase sensitivity was 1.5×10^{-9} rad·Hz$^{-\frac{1}{2}}$, or a factor of 15 greater than the initial LIGO goal. (Note that for the case of perfect contrast and vanishing modulation depth, the ideal shot-noise limited sensitivity that could be obtained from 233 mA of photocurrent is $\phi_{\text{ideal}}(f) = \sqrt{2e/I} = 1.2\times10^{-9}$ rad·Hz$^{-\frac{1}{2}}$; the disrepancy is due to the finite contrast of the Garching interferometer.) This sensitivity was maintained down to 300 Hz, where low-frequency seismic noise transmitted through the simple pendulum isolation (no stack was used) started to dominate. Attempts to make shot-noise limited measurements at higher powers in Garching were not successful, due to heating of the Pockels cells in the in-line modulation scheme employed.

The Fixed Mass Interferometer (FMI) using in-line modulation was close to shot-noise limited in a very limited frequency band near 80 kHz for 8 mA of photocurrent. Because of the cancellation of the modulation, the resulting phase sensitivity was some 4×10^{-8} rad·Hz$^{-\frac{1}{2}}$, a factor of 400 greater than the LIGO goal.

Inapplicability of a fixed mass interferometer: The intrinsic mechanical construction of a fixed mass interferometer (FMI) prevents a measurement of phase noise at LIGO sensitivity. The mirrors of an FMI, mounted on ordinary mirror mounts, are excited by a combination of external mechanical sources and thermal noise. Assuming that such an interferometer could be seismically isolated and placed entirely in a vacuum, the thermal motion of the mirrors would still be prohibitively large. As an example, a typical resonance in the FMI spectrum is at 65 kHz with a FWHM of 1 kHz, or $Q = 65$. Assuming an effective moving mass of 10 gr, the resulting thermally driven peak motion is 4×10^{-17} m/$\sqrt{\text{Hz}}$; the FMI spectrum shows many such resonances up to 100 kHz (and presumably beyond). The limit from our experience to the displacement noise sensitivity of an FMI is $\approx 2\times10^{-17}$ m/$\sqrt{\text{Hz}}$ at 80 kHz (much worse at lower frequencies), which is a factor of 5 greater than the displacement noise associated with the LIGO phase noise sensitivity in a simple 1-bounce Michelson.

A separate question is whether the measurement must be made at frequencies in the GW band. Many of the potential noise sources (frequency noise, amplitude noise, beam jitter, mechanical excitation and consequent parasitic interferometer noise) could be investigated at, say, 10 kHz via artificial modulations. This would reduce the demands on the seismic isolation. However, until a measurement is made at LIGO frequencies, we will not be sure that there are no unexpected noise sources lurking at lower frequencies.

These two facts—the ultimate displacement noise, and the necessary frequency regime—make the FMI a poor choice. The additional drawback that the servo and transducer techniques would be irrelevant to LIGO rule out an FMI for the phase noise measurement.

Experimental plan; key milestones

The objective is to obtain as much relevant information as quickly as possible, we propose the following staged approach:

1) Suspended single-bounce Michelson. This will give us the experience of dealing with an interferometer made of suspended mirrors using the current LIGO project technology. We are presently installing two suspended mirrors, which will be used to demonstrate the single-cavity Main Alignment scheme, so will have already had some contact with the technology. The interferometer will be servo-controlled in difference (to maintain the dark fringe) and common-mode (to eliminate the common 'breathing' motion of the two arm mirrors). With the simple Michelson, we will demonstrate shot-noise limited detection at the power directly available from our existing laser (150 mW).

2) Recycled suspended single-bounce Michelson. With the addition of a recycling mirror, it will be possible to increase the circulating power in the Michelson interferometer to levels similar to the initial LIGO goal. We expect to be able to obtain recycling factors on the order of 100 in this simplified system (thus 15 W of circulating power); we already know that the limiting factor will not be power lost due to finite contrast in the interferometer (the FMI simple Michelson lost only 2×10^{-4} of the power due to an imperfect dark fringe). Note that a modest recycling factor of 30 would already allow new territory to be explored.

Because there will not be cavities in the arms, the position sensitivity of the interferometer will be much less than LIGO—the LIGO phase noise sensitivity will be reached with a position sensitivity of 4×10^{-18} m/$\sqrt{\text{Hz}}$. This is a factor of 4 less sensitive than the best Mark I sensitivity, so we are confident that no unforseen displacement noise sources (e.g., thermal noise) will limit the measurement. With the MIT ground noise, the mixed RTV-Viton stack, and a single pendulum suspension, seismic noise should not dominate above about 150 Hz.

In this system, we expect to be able to make the phase noise measurement but without the complexity or position sensitivity of a full FP (Fabry-Perot) LIGO layout. We will encounter most of the problems entailed in making a LIGO photodiode-RF detection system (power handling and large currents; uniformity of response; intermodulation distortion; dynamic range), and effects of scattered light (especially parasitic interferometers). Beam dumps can be tested (and will be needed!). Diagnostic tests of the phase noise dependence on laser frequency and amplitude noise, interferometer contrast, and beam position instability will be carried out. In addition, we will gain experience in the locking and servo problems of a hanging recycled Michelson. Initially we will use our current laser to achieve $\approx$ 15 W of circulating power incident on the beam splitter. At the end of this step we intend to install a main frame laser to increase the power to $\approx$ 70 W, comparable to the power circulating in the recycling cavity of the initial LIGO interferometer.

3) Recycled Suspended Fabry-Perot Michelson. This last step will involve an optical layout closely resembling the initial LIGO interferometer. The locking and servo systems will be tested on a realistic, hanging interferometer. The addition of the arm cavities will allow (and necessitate) the understanding of the way the cavity mode structure influences parasitic interferometers. The cavities will sustain the same circulating power as LIGO, and any resulting distortion of the wavefronts will be seen in the character of the interferometer dark fringe.

The increased displacement sensitivity with the addition of the LIGO-like cavities (10^{-19} m/$\sqrt{\mathrm{Hz}}$) will be beyond our current experience on the Mark I ($\approx 10^{-18}$ m/$\sqrt{\mathrm{Hz}}$); however, the Mark II may well have arrived at this sensitivity when we are ready for this step. The additional power from the large frame laser will be needed in this phase of the program to make up for the loss in the arm cavities. With the seismic ground noise spectrum at MIT, we expect to be able to make shot-noise limited measurements down to $\approx$ 270 Hz in this system.

Detailed experiment description

laser: We plan to start with our present small frame Coherent laser, which delivers 0.6 W single mode dependably without intracavity Pockels cell. We will convert the frequency stabilization to the now standard fast pzt and external phase-corrector. In the later stages of the work, a large-frame laser will be necessary.

input optics: To start, a fiber will carry the power from the laser table into the vacuum system. This has been demonstrated with the FMI to be workable up to 150 mW of power (limited by the laser with Pockels cell); in Garching, the fiber routinely delivers 1 W of power. The output end of the fiber will be suspended on a table bearing matching lenses, isolators, and modulators. Again, in the final stages of the experiment, simple relay mirrors may be used to transport the light through a viewport into the vacuum system if necessary.

For the initial experiments (steps 1) and 2) above) no mode cleaning cavity will be used (the fiber will serve this function). Sufficient space will be left for a two- or three-mirror suspended mode cleaning cavity, which can run parallel to the 6 m-long arm cavity.

The recycling cavity (starting in step 2) will be folded along one of the 6 m arms to allow modulation sidebands to be resonant.

vacuum system: The existing MIT vacuum system will be used. The 5m long connecting tubes give a path length from tank center to tank center of 6 m. The connecting tubes are 0.74 m in diameter, which will allow mode-cleaner and recycling cavity beams to run parallel to the arm cavities. The central tank stack top plate is 1.5 m in diameter, which will allow the relatively complicated optical layout needed there. Some additional electrical and optical feedthroughs are necessary. The pumping system (which has had quite a workout from the stack research) may need some attention. The system is basically clean, and can be ion-pumped when necessary.

seismic isolation: The stack as engineered for the Mark II will be used, probably with mixed RTV and Viton elastomers.

mirror suspension: We will use the suspensions jointly designed for the hanging mode cleaner (Caltech) and the Main Alignment (MIT). Initial experiments with these suspensions are underway now at both MIT and Caltech. If there are any modifications as a result of these experiments, they will be incorporated.

pointing system: The two-mirror tests now underway will show definitively if the shorter arm length of the 5m interferometer will allow the use of the OSEMS incorporated in the mirror suspensions as both local and global pointing. If not, or if it becomes a project priority, we will take on the development of the next generation of pointing systems, which will be a prototype for the LIGO pointing.

optics: We plan to use 3" diameter by 1/2" thickness monolithic substrates for all optical elements. If necessary, larger substrates could be accommodated at a later time.

topology: The ideal situation would be to use the topology chosen for the LIGO. We believe that the FMI experiments presently underway will yield the information we need for the project to choose an initial LIGO layout by the end of '92. The central question is whether an imbalance in the near-mirror Michelson, or a Mach-Zehnder, will be used to interrogate the fringe for GW signals. Either can be accommodated in the vacuum system.

Noise Sources

The optical phase noise at the photodetector of the interferometer can be decomposed into a sum of terms from specific phenomena. When the sources of the phase noise are uncorrelated, the total phase noise power spectral density in radians^2/Hz is given by the sum

$$\phi^2(f) = \sum_1^n \phi_n^2(f)$$

Known contributors to the sum include the following.

Photon shot noise (Poisson noise)

This is the fundamental limiting noise in the sensing of an optical fringe and in the limit of perfect contrast at the output of the interferometer is given by

$$\phi^2(f) = \frac{2hc}{\lambda\eta P_{\mathrm{mbs}}}$$

η is the quantum efficiency of the photodetector and P_{mbs} is the optical power on the main beam splitter. For initial LIGO parameters: $P_{\mathrm{mbs}} = 70$ watts, $\lambda = 5.145 \times 10^{-5}$ cm, $\eta = 0.8$, $\phi(f) = 1.2 \times 10^{-10}$.

Residual gas forward scattering fluctuations

The phase noise due to the forward scattering of the residual gas in the interferometer beam is given by

$$\phi^2(f) = \frac{(2\pi)^4\alpha^2\rho l}{\lambda^2 wv} e^{-\pi f w/v}$$

when the minimum beam size is used, $w \approx \sqrt{\lambda l/\pi}$, the phase noise at low frequencies becomes

$$\phi^2(f) = \frac{16\pi^{9/2}\alpha^2\rho l^{1/2}}{\lambda^{5/2}v}$$

Using $\alpha = 1.6 \times 10^{-24}$ cm^2, the polarizability of molecular nitrogen, $v = 4.2 \times 10^4$ cm/sec, the thermal speed of nitrogen and a path length, l of 1000 cm; the phase noise due to the residual gas in a simple Michelson interferometer becomes equal to that of the shot noise at a pressure $\approx$ 0.1 torr (a pressure so high that the given formulation no longer applies).

Displacement noise

The phase noise associated with differential motions of the interferometer arm mirrors is

$$\phi^2(f) = \left(\frac{\delta\phi}{\delta x}\right)^2 x^2(f)$$

For a simple Michelson interferometer

$$\frac{\delta\phi}{\delta x} = \frac{4\pi}{\lambda}$$

which implies that to keep the displacement noise contribution to the phase noise below the shot noise, we must have $x(f) \leq 5 \times 10^{-18}$ m/$\sqrt{\mathrm{Hz}}$. The ground noise spectrum at MIT is approximately 100 times larger than at a LIGO site so that with the current stack performance of 120db isolation, it should be possible to measure the phase noise at LIGO levels to $\approx$ 150 Hz. The experience on the Mark 1 interferometer is that the maximum thermal noise from the substrates could be as large as 10^{-18} m/$\sqrt{\mathrm{Hz}}$ when projected to 100 Hz and it is unlikely (though not ruled out) that the thermal noise from the pendulum suspension is as large as 5×10^{-18} cm/$\sqrt{\mathrm{Hz}}$ at 100 Hz.

Laser frequency noise

The phase noise from frequency noise in the residual light hitting the photodetector is

$$\phi^2(f) = 16\pi^2\nu^2(f)\sum_{\mathrm{j}=1}^{n} \alpha_{\mathrm{j}}\tau_j^2$$

$\nu(f)$ is the laser frequency noise in Hz/$\sqrt{\mathrm{Hz}}$, τ_{j} is the time delay associated with the fraction α_{j} of the intensity incident on the photodetector that has experienced this delay. The largest contribution will arise from unbalance in the Michelson arms if asymmetric arms are employed to develop the fringe modulation sidebands. With a 50 cm unbalance in the interferometer arms, the frequency noise must be less than 5×10^{-3} Hz/$\sqrt{\mathrm{Hz}}$ to cause a phase noise smaller than that from shot noise. Stray laser light experiencing larger delays could cause difficulties and this phenomena is one of the first to investigate if the system does not perform at the shot noise limit.

Scattered light from moving sources

The phase noise from light incident on the detector scattered by moving sources not directly in the beam (not making parasitic interferometers) has been analyzed for the LIGO and is given by

$$\phi^2_{\text{scat}}(f) = \int\limits_{\Omega,A} \Big(P_{\text{rec}}(\theta)\Big)\left(\frac{dp_{sc}(\theta)\big/dAd\Omega}{p_{in}}\right)\Big(\Phi^2(f,\theta)\Big)\, d\Omega dA$$

The limits of the integration are taken over the solid angle subtended by the main beam mode, $\approx \lambda/L$, and the area of this mode at the detector, $\approx \lambda L$. The expressions in the three parentheses of the integrand have the following meanings.

$P_{\text{rec}}(\theta)$ is the probability that a scattered wavefront incident at an angle θ to the normal of the detector will *recombine* with the main field mode (overlap with it). The probability depends on the spatial distribution of the main beam multiplied by the spatial distribution of the photodetector sensitivity. If the photodetector is uniform or a mode filter is used between the interferometer output and a nonuniform photodetector

$$P_{\text{rec}}(\theta) = \frac{2\alpha}{\theta^2}\,\frac{\lambda}{L}$$

The probability for recombination with a model nonuniform detector is

$$P_{\text{rec}}(\theta) = \frac{(1-\eta)^2}{2\theta}\left[\frac{\lambda}{L}\right]^{1/2}$$

The term in the middle pair of parentheses is the scattered light power, p_{sc}, brightness distribution, evaluated at the detector as a function of θ and normalized to the power hitting the beam splitter

$\Phi^2(f)$ is the phase modulation of the stray light by the motion of the scatterer and depends on the path history.

No specific estimate is made for this noise contribution; however, it must be considered in the experiment and could play a role if the system does not exhibit shot noise limited phase noise. The experimental procedures to evaluate the contribution of modulated stray light will include blackening beam stops, direct measurements of the stray light, and correlation studies with two detectors.

Laser amplitude noise

Laser amplitude noise contributes phase noise through several mechanisms and depends on the fringe interrogation technique. The relation between the amplitude spectral density of intensity fluctuation, $I(f)$, and the inferred optical phase amplitude density is given generically as

$$\frac{\phi(f)}{I(f)} = \frac{1}{I_0 J_{\text{equiv}}}$$

where I_0 is the intensity at the beam splitter and J_{equiv} is the amplitude of the RF sideband used in the fringe interrogation. Some examples: In an inline phase modulated system, $J_{\mathrm{equiv}} = J_1(\Gamma)$, while in the asymmetric arm externally modulated interferometer, $J_{\mathrm{equiv}} = \sin(2\pi\Delta l/\lambda_{\mathrm{mod}})J_1(\Gamma)$, and in the externally modulated system with a Mach Zehnder interferometer at the output, $J_{\mathrm{equiv}} = rJ_1(\Gamma)$, where r is the amplitude reflection at the pickoff.

Direct coupling of laser amplitude noise to inferred phase noise occurs when there is excess amplitude noise (above shot noise) in the laser output in the region around the modulation frequency. This is then given by

$$\phi(f) = \frac{I(f_m \pm f)}{I_0 J_{\mathrm{equiv}}}$$

This noise source is characterized as being directly proportional to the laser intensity rather than as the square root of the intensity as is the case with shot noise. This contribution, as well as many others, is also directly proportional to the contrast defect at the antisymmetric port of the interferometer. The shot noise from unmodulated light would be handled in a similar manner; in this case, $I^2(f) = 2h\nu I_{\mathrm{dc}}/\eta$.

Indirect coupling of laser amplitude noise in the gravitational wave band may come about through a dc phase offset, $\Delta\phi$, in the fringe locking servo system

$$\phi(f) = \frac{I(f)}{I_0}\Delta\phi$$

or from the frequency components of the phase offset $\phi(f')$ that multiply with the intensity noise, $I(f'')$ when $f'' \pm f' = f$.

With the high light levels involved in gaining the LIGO phase noise sensitivity, nonlinearities in both the photodetector and in the photo detector amplifiers and demodulator electronics may become important. An often discussed but never measured noise term is the intermodulation noise that would occur in a non-linear photodetector where the photocurrent has both a linear and quadratic response.

$$i = \alpha I + \beta I^2$$

The nonlinearity causes mixing in the intensity noise at frequency f' with that at frequency f'' so that all beat pairs with $f' \pm f'' = f$ will contribute noise at f. Relevant values of f are those directly in the gravity wave detection band or in the band embracing the RF modulation frequency. The intermodulation noise is heuristically represented as

$$\phi(f) = \sqrt{\Delta f}\frac{\beta I(f'') * I(f')}{\alpha I_0 J_{\mathrm{equiv}}}$$

where Δf is the bandwidth of the detector. Similar convolutions of the intensity noise amplitude spectrum may occur after photodetection in the nonlinearities of the photodetector preamplifiers and mixer electronics.

Another known source of conversion of amplitude noise to phase noise is due to radiation pressure fluctuations on the mirror masses. In the limiting case of a completely balanced interferometer and equal mirror masses this reduces to one term making up the "naive" quantum limit of the interferometer. In an imperfect interferometer with a mass unbalance $\Delta m/m$ or a beam division unbalance of $\Delta I/I$, amplitude noise will drive a differential motion in the interferometer arms given by

$$x(f) = \frac{I(f)}{2\pi^2 mcf^2}(\Delta I/I \pm \Delta m/m) \ .$$

For a single pass interferometer with a power $I_0 = 70$ watts on the beam splitter, $m = 1$ kg and a 10 % unbalance in mass or beam splitter division, the displacement noise becomes

$$x(f) \approx \frac{\gamma(f)10^{-19}}{f^2} \quad \mathrm{m}/\sqrt{\mathrm{Hz}}$$

where $\gamma(f)$ is the amplitude of the intensity fluctuation spectrum normalized to the amplitude of the shot noise spectrum. Although we hope that this is not a problem in the Michelson phase noise measurements, it should be considered in the LIGO where the effect is multipled by the cavity finesse. It may necessitate amplitude stabilization of the laser in the gravitational wave frequency band.

Beam position instability

Beam position instabilities at the input to the interferometer will produce first order phase noise due to offsets in the alignment of the interferometer. The largest terms will arise from beam angular fluctuations, $\theta(f)$, coupled to angular misalignment of the mirror normals, α. The phase noise is then

$$\phi(f) = \frac{4\pi\alpha l\theta(f)}{\lambda}$$

where l is the length of the Michelson arm. The experience at Garching is that a fiber coupler reduced the beam position and angular noise to $s(f) \leq 3\times10^{-12}$ $\mathrm{m}/\sqrt{\mathrm{Hz}}$ and $\theta(f) \leq 3\times10^{-12}$ $\mathrm{rad}\cdot\mathrm{Hz}^{-\frac{1}{2}}$ at 100 Hz and greater. Using these values, the alignment precision required to reach the LIGO phase noise goal in the one pass Michelson will require that $\alpha \leq 3 \times 10^{-4}$ radians. This precision of alignment is easy to achieve. If beam instability proves to be a dominant noise source, we will include a mode cleaner to suppress beam jitter by an additional factor of the finesse. Higher order sensitivity to beam motion, and the sensitivity of the complete FPMI, have yet to be determined, but will be in the research program for either or both of the 40m and the 5m prototypes.