LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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Interferometer Sensing and Control Design Requirements

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1 Overview

The purpose of this document is to define the content of the Interferometer Sensing and Control (ISC) subsystem, to give the design requirements for the ISC, and to identify the interfaces of the ISC with the other Detector subsystems and Facilities. For many purposes the ISC can be split into two components: the Length Sensing and Control (LSC) component, and the Alignment Sensing and Control (ASC) component.

2 Scope

The ISC subsystem includes:

- design of the interferometer sensing scheme (modulation frequencies, macroscopic lengths, pick-off beam requirements)
- sensors and controls for maintaining the interferometer lengths and alignment during operation, including optics, mounting provisions, and control electronics and software
- sensors and controls for stabilizing the length and alignment of the input mode cleaner
- interferometer lock acquisition: hardware and/or algorithms for achieving the operating point of the interferometer
- signal sources for modulation frequencies used in the sensing scheme
- the in-vacuum optics platform and any seismic isolation of the platform for the input HAM chamber (HAM1/HAM7)
- any outside-the-vacuum mounting platforms for ISC hardware
- sensors and controls for the length and alignment stabilization of the input mode cleaner

The ISC specifically does not include:

- in-vacuum relay optics or vacuum viewports for extracting the 1064 nm interferometer beams from the vacuum system
- any alignment functions for the Pre-Stabilized Laser (PSL) subsystem
- any hardware and/or algorithms for determining the axial positions or initial alignment of the IOO or COC optics; i.e., the cavity lengths and optic installation orientations are not determined by ISC
- angular stabilization of the IOO launch beam on the PSL table
- cameras for viewing the COC surfaces (these are part of AOS)
- optical levers (these are part of AOS)

3 General Information

3.1 Interferometer Parameters

The interferometer parameters that are relevant to determining ISC requirements are given in Appendix A. The strain noise spectrum that is used to determine technical noise limits is given in Appendix B.

3.2 Acquisition Mode

Acquisition mode is the mode in which the Input Mode Cleaner (IMC) is locked and the COC are within the Acquisition Alignment tolerance.

The primary function of the LSC in this mode is to lock the interferometer. After lock, a settling period is required. Wire and mirror resonances are permitted to settle down (or are actively damped), filters allowed to equilibrate, control ranges are adjusted, and diagnostics are completed to verify that residual excitations do not exceed Detection mode limits. The Lock Acquisition System (LAS) must reliably bring the interferometer to the end of the Acquisition mode within less than 3 minutes from the beginning of the Acquisition sequence.

In the Acquisition mode the ASC must:

- sense and control alignment of the IMC
- maintain the COC alignment within the Acquisition tolerance
- maintain availability 95% of the time

ASC is not required to maintain alignment through the output mode cleaner (OMC) during acquisition.

3.3 Detection Mode

In this mode the interferometer lengths are maintained at a level of stability which allows detection of strain signals within the Advanced LIGO sensitivity specifications. The functions in this mode are:

- sense and control the four interferometer lengths and the input light frequency
- provide a measure of the residual deviations of the four lengths and the light frequency
- provide a calibrated readout of the interferometer strain

In Detection mode the ASC must maintain the RMS angular fluctuations to within the Detection mode requirement. The gravitational wave (GW) band (> 10 Hz) noise caused by GW band angular noise must be kept below the technical noise requirement.

3.4 Diagnostic/Calibration Mode

ISC/GDS must have capability for making automated measurements of all ISC related noise couplings. Coupling measurements must take into account time varying coupling factors (wandering spot positions, thermal changes). ISC must also be able to do multiple simultaneous tests: different combinations of offsets to test for mystery noise sources.

In addition ISC/GDS are responsible for keeping an up to date noise budget of the interferometer during all phases of commissioning similar to what was done for Enhanced LIGO.

3.5 Definition of Degrees-of-Freedom

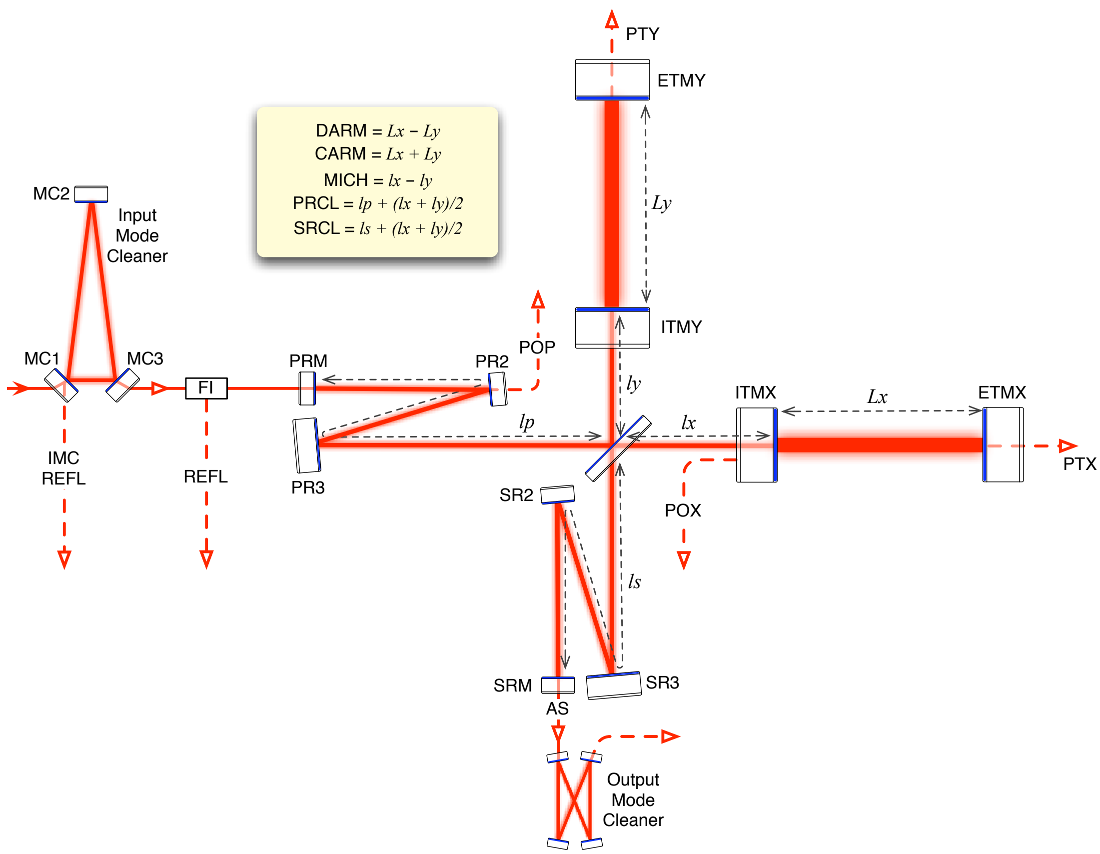

Figure 1: Def of LSC DOFs

3.6 Assumptions and Dependencies

This section should list the assumptions being made about the parameters and noise of the other subsystems:

3.6.1 Overall Requirements

The following requirements form the basis of all the ISC requirements:

1. Sensitivity: The Advanced LIGO strain sensitivity goal is given in Figure 6. The displacement requirement, x, is defined such that the strain sensitivity is h(f) = x(f)/ L , where L = 4 km; i.e., x(f) is the differential arm length sensitivity (Ly - Lx)

2. Availability goals: 90% for single interferometer operations; 85% for double coincidence; 75% for triple coincidence.

3.6.2 Noise Budget Allocation

Each noise mechanism originating within ISC or through an interaction between ISC and another Detector subsystem(s) is to be controlled so that its equivalent strain noise is no larger than 10% of the target strain noise spectrum, in the gravity wave band of 10 Hz – 10 kHz. The specific noise mechanisms which fall in this category, preceded by the subsystem(s) which contribute, are:

1. **ISC & IOO & COC**. Laser frequency noise, coupling through asymmetries in the COC, and ISC sensing and control loops.

2. **ISC &IOO**. Laser Amplitude noise, coupling through asymmetries in the COC, and ISC sensing and control loops.

3. **ISC & IOO**. RF Oscillator Amplitude noise, coupling through asymmetries in the COC, and ISC sensing and control loops.

4. **ISC & IOO**. RF Oscillator Phase noise, coupling through asymmetries in the COC, and ISC sensing and control loops.

5. **ISC & IOO**. Angular and translation jitter on the beam delivered from the input mode cleaner, coupling with residual misalignments in the COC.

6. **ISC**. Angular fluctuations of the test masses in the GW band, appearing as longitudinal motion through an offset from the center of rotation of the test masses.

7. **ISC**. Sensing and control noise in the auxiliary length degrees-of-freedom, feeding into the GW readout.

8. **ISC**. Electronics noise in the GW readout system.

9. **ISC & AOS**. Back-scattered light from the ISC detection ports, propagating back through the interferometer to the anti-symmetric port to produce noise.

There are also a couple of noise mechanisms that are not specifically the responsibility of the ISC to control, but are influenced in large part by ISC requirements. For reference, these are listed here also:

1. **ISC & SUS**. Electronics noise in the global feedback drives to the test masses. These actuation electronics are part of SUS, but the range and frequency response are determined by ISC controls demands.

2. **ISC & SUS & PEM**. Magnetic field induced motions of the test masses. Magnets on suspended optics are part of SUS, but their strengths are determined partly by ISC actuation demands.

4 Performance Requirements

4.1 Modes of Operation

The ISC design must be capable of operating the interferometer with high sensitivity in different configurations. These configurations include:

- a DC-tuned signal recycling cavity (aka broad-band mode), at input power levels of 5 – 125 Watts.
- NS-NS inspiral detection mode: full input power and small SRC de-tuning
- BH-BH inspiral detection mode: low input power (5 – 10 W), and larger SRC de-tuning
- Narrowband (pulsar) mode: detuned with the SR resonance tunable from 500 – 1500 Hz (the rotation frequency of the fastest millisecond pulsar, PSR J1748 – 2446ad, is 716 Hz)

In each case, ISC sensing and control noise must be kept small compared to the quantum and thermal noise over the relevant frequency band.

4.2 Lock Acquisition

The duration of the lock acquisition process should be short enough to not significantly impact the Detector availability for science mode operation. In Acquisition mode there are no requirements on the noise in the sensing systems (length or angle) in the GW band other than what is required to prevent saturations during acquisition.

The low frequency (control band) angular fluctuations must be consistent with small gain fluctuations in all LSC and ISC loops.

4.3 Residual Length Deviations

In Detection mode, the interferometer lengths must be controlled so that their residual deviations from the operating point do not impact the detection band performance. These limits are given in Table 1.

Readout non-linearity. The DC readout scheme presents an inherently non-linear error signal. At the operating point – with an offset from the dark fringe – the dominant signal is of course linear in the differential arm length, but there is a term that is quadratic in the readout

Degree of freedom	*Residual deviation limit*	*Notes*
Differential arm length	10^{-15} m rms	non-linearity in readout
Michelson length	10^{-12} m rms	photodetector saturation limit
Power recycling cavity length	10^{-12} m rms	photodetector saturation limit
Signal recycling cavity length	10^{-12} m rms	photodetector saturation limit
Common arm phase, $\Phi_+ = kL_+$	$\Phi_+ < 10^{-6}$ rad rms	maintain power buildup

Table 1: Maximum residual deviations of the interferometer lengths in detection mode. These limits must be maintained by the LSC servos. The limit on the common arm phase deviations keeps the power buildup no less than 99.9% of the maximum.

variable. This non-linearity could upconvert residual control band motion into the GW band (e.g. by intermodulation with strong line features such as mains harmonics and violin modes). The differential arm servo must keep the residual fluctations small enough that the upconversion noise is negligible. The effect of fringe non-linearity has been analyzed for Enhanced LIGO in Ref [4], where it is concluded that with i/eLIGO's DARM residual of 10^{-14} m rms, non-linear upconversion is not significant. To be conservative we set the AdLIGO residual requirement 10 times below the iLIGO level. Note that it is also possible to reduce this effect by linearizing the error signal digitally.

Photodetector saturation. In initial LIGO[5, 10], it was found by experience that photodetector non-linearities determined the allowed residual deviations of the auxiliary lengths (Michelson and power recycling cavity). The residual motion of these DOF needed to be suppressed to a few picometers to avoid upconversion noise in the photodetectors used to sense them. Assuming the detection power levels, optical gains, and photodetector non-linearity for these DOF will be similar in Advanced LIGO, we thus adopt a conservative residual requirement of 1 picometer.

4.4 Residual Alignment Deviations

In Detection mode, the interferometer angles must be controlled so that their residual deviations from the operating point do not impact the detection band performance.

Beam jitter coupling. Deviations from perfect alignment allow jitter of the input beam direction to couple to the output signal. This effect is analyzed in LIGO-T020022, *Pointing Requirements in Advanced LIGO, Part I*, G. Mueller, et al. It is a trade-off between the interferometer alignment stability and the level of beam jitter. The alignment stability requirement for the test masses is 10 times smaller (more stringent) than the initial LIGO level.

Beam position stability. In order to achieve a high degree of decoupling of angular control signals from the output (GW) signal, the beam positions on the optics must be stable. Our goal for the angle-to-length decoupling is 10^{-4} m/rad for the test masses, so the beam position stability on these optics should be better than 100 μm. The beam position shift for

Degree of freedom	*Residual deviation limit*	*Notes*
Test Mass angles	10^{-9} rad rms	beam jitter coupling, beam position stability
Beamsplitter and recycling mirrors	10^{-8} rad rms	
MC mirrors	$1\,\mu$rad rms	power stability

Table 2: Maximum residual deviations of the interferometer optic angles, from the optimally aligned point, in detection mode. These limits must be maintained by the ASC servos.

1 nrad of test mass misalignment is about $30\,\mu$m.

Power stability. For the input mode cleaner alignment stability, we need to control IMC transmitted beam power fluctuations due to misalignments. The IMC beam divergence angle is $160\,\mu$rad, so the alignment stability requirement ($1\,\mu$rad) corresponds to relative power fluctuations less than 10^{-4}.

4.5 Sensing and Control System Noise

4.5.1 Gravitational Wave Readout

Electronics noise in the GW readout chain (photodetectors, preamps, filters, ADCs) must be less than 1/10-th of the target strain noise spectrum at all points in the chain.

4.5.2 Auxiliary Length Degrees-of-freedom

The sensing and control of each auxiliary length degree-of-freedom must be done in such a way that limits the coupling of their sensing noise into the GW readout. The total sensing noise infiltration of these DOF into the GW readout must be less than 1/10-th of the target strain noise spectrum.

4.5.3 Angular Degrees-of-freedom

The sensing and control of the angular degrees-of-freedom must be done in such a way that limits the coupling of their sensing noises into the GW readout. The total sensing noise infiltration of these DOF into the GW readout must be less than 1/10-th of the target strain noise spectrum.

4.6 Frequency Stabilization

The ISC implements the secondary and tertiary levels of laser frequency stabilization, beyond that provided by the PSL pre-stabilization. The ISC frequency stabilization is achieved through the input mode cleaner and interferometer common mode servo loops. The required level of frequency stabilization is calculated with the Optickle [12] model, and is shown in Fig. 2.

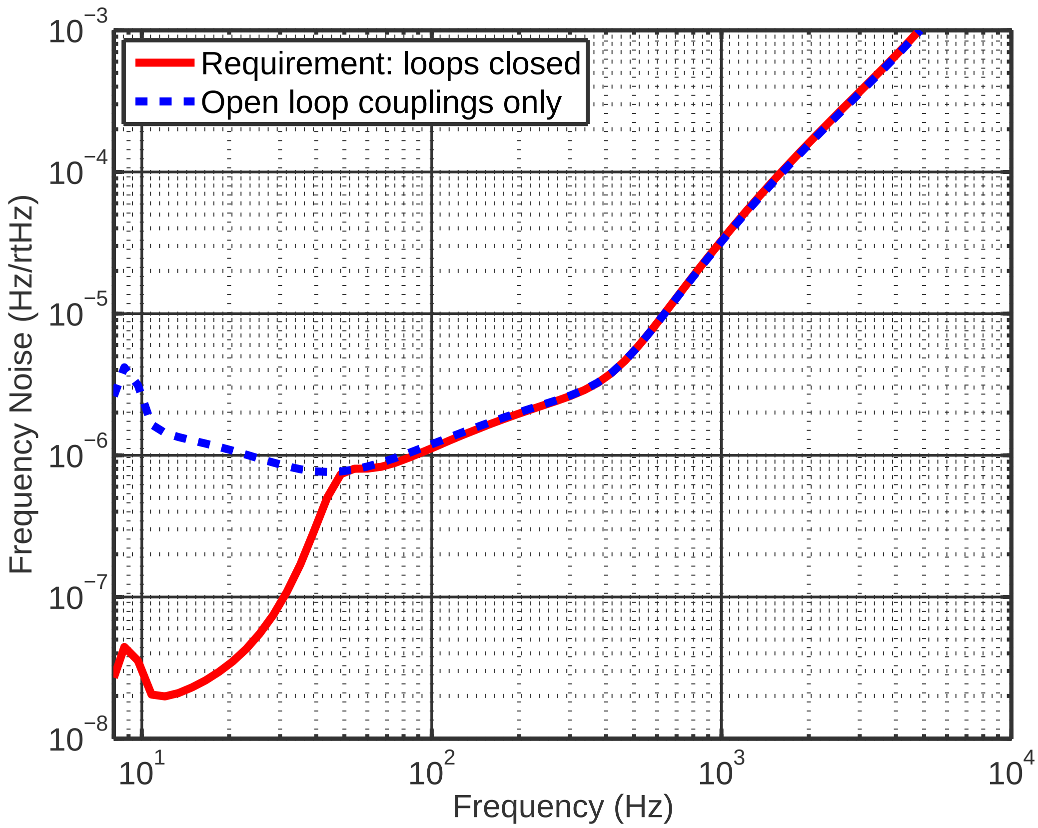

Figure 2: Frequency noise requirements for the light incident on the power recycling mirror (red curve). The curve is calculated with Optickle, using the parameters given in Appendix A. For the red curve, all length control loops are closed, except for the common mode loop. The requirement spectrum corresponds to an equivalent strain noise spectrum this is 10 times below the spectrum given in Appendix B. For reference, the dashed blue curve is the same calculation, but with all length loops open. This shows that below 50 Hz, frequency noise couples most strongly through auxiliary loops. Specifically, the coupling is through the signal recycling cavity loop, and the removal of SRC sensing noise from the strain channel is set to 10% accuracy for this plot.

4.7 Laser Amplitude Noise

Even though stabilization of the laser amplitude (or intensity) is the responsibility of the PSL subsystem, the level of stability required can depend on the sensing scheme. So for reference we include here the laser amplitude noise requirements as determined by the Optickle interferometer model.

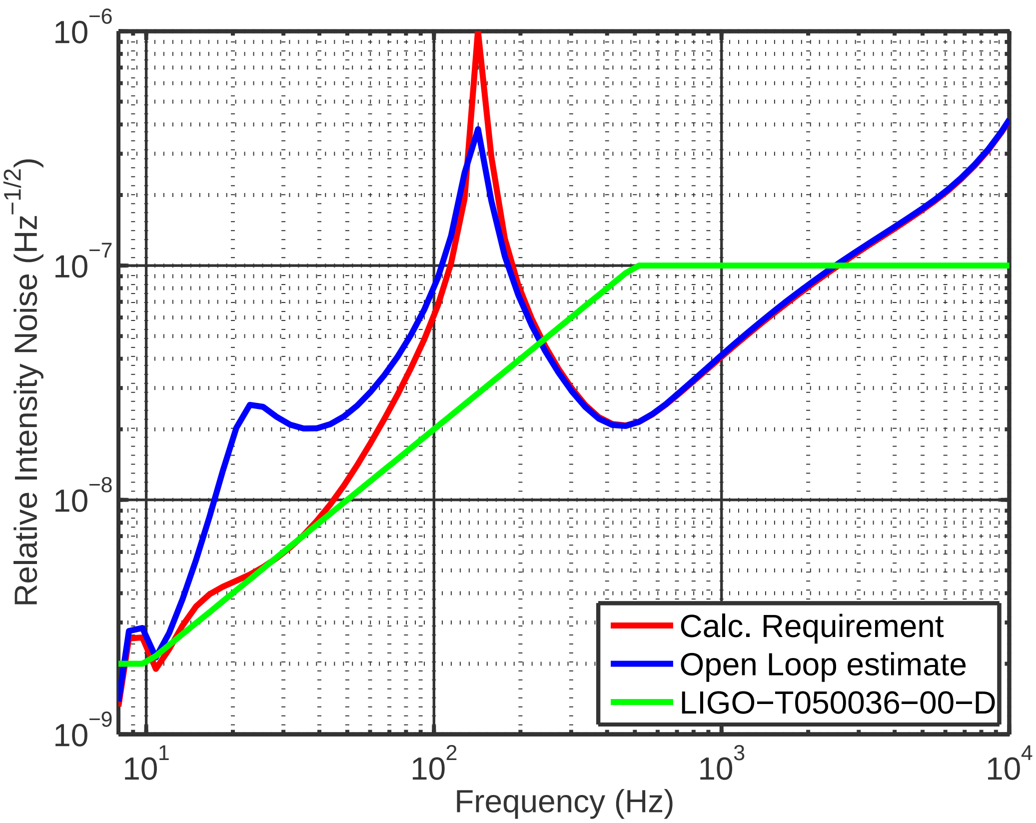

Figure 3: Amplitiude noise requirement for the light incident on the power recycling mirror (red curve). The curve is calculated with Optickle, using the parameters given in Appendix A. For the red curve, all length control loops are closed. The requirement spectrum corresponds to an equivalent strain noise spectrum this is 10 times below the spectrum given in Appendix B. For reference, the blue curve is the same calculation, but with all length loops open. This shows that below 100 Hz, amplitude noise couples most strongly through auxiliary loops. Specifically, the coupling is through the signal recycling cavity loop, and the removal of SRC sensing noise from the strain channel is set to 10% accuracy for this plot. As a reference the green curve shows the PSL requirement from LIGO-T050036-00.

4.8 Modulation Source Noise

The ISC supplies and distributes the RF modulation and demodulation sources. The AM and PM noise on the modulation signals must be small enough that they don't impact the strain noise floor. Even though a DC readout of the arm strain will be used, the RF modulation can couple into it, either by transmission through the finite finesse output mode cleaner, or coupling through the RF readout of auxiliary length degrees of freedom. The modulation noise limits are calculated with the Optickle model, again limiting their strain noise contribution to 1/10-th of the target spectrum.

The Optickle model results are shown in Figs. 4 and 5. For the phase noise requirement, we want to put in more margin, based on the experience in iLIGO where the oscillator phase coupling was found to be larger than expected from single-mode calculations. Therefore, we set the requirement below the level shown in Fig. 4, namely:

$$\begin{aligned}\phi_{osc} &< (10^{-4}/f)\,\mathrm{rad}/\sqrt{\mathrm{Hz}}\,, \quad 10 < f < 100\,\mathrm{Hz}\\ &< 10^{-6}\,\mathrm{rad}/\sqrt{\mathrm{Hz}}\,, \quad f > 100\,\mathrm{Hz}\end{aligned}$$

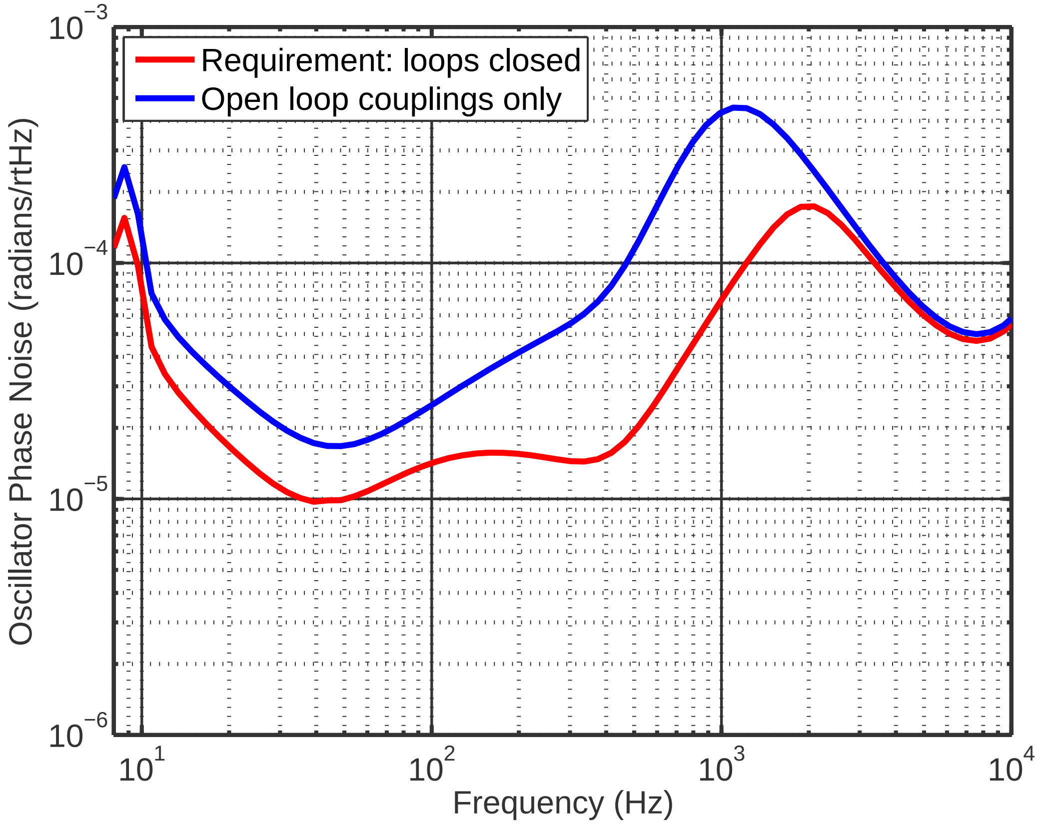

Figure 4: Phase noise requirement for the oscillator that supplies the higher RF modulation frequency (red curve). The curve is calculated with Optickle, using the parameters given in Appendix A. For the red curve, all length control loops are closed. The requirement spectrum corresponds to an equivalent strain noise spectrum this is 10 times below the spectrum given in Appendix B. For reference, the blue curve is the same calculation, but with all length loops open. This shows that below a few kHz, oscillator phase noise couples most strongly through auxiliary loops. It is worth noting that the oscillator phase noise coupling in iLIGO was much larger than expected from single mode calculations [6]. So, to be conservative, we are setting a phase noise target that is below the red curve, as specified in the text.

4.9 GW Detection Efficiency

The optical and optoelectronic efficiency of the GW detection chain must be high to preserve the quantum noise limited performance of the interferometer. We adopt the following efficiency requirements:

- Photodiode quantum efficiency: > 90%

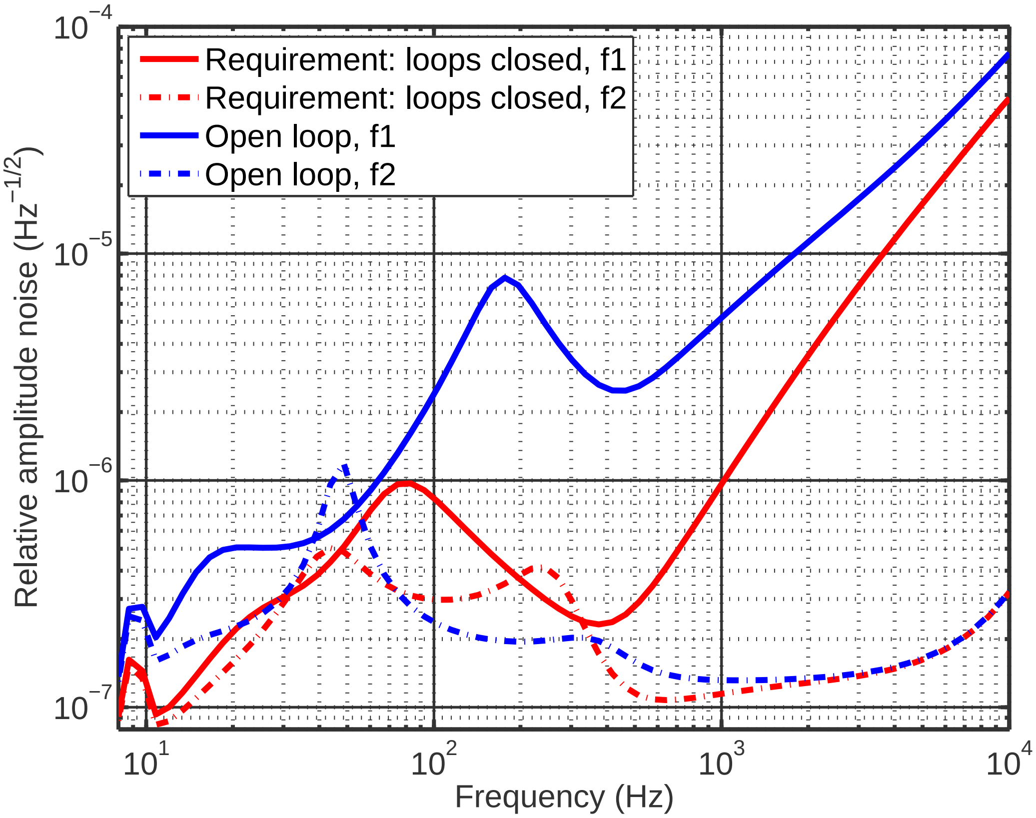

Figure 5: Amplitude noise requirement for the oscillators that supply the RF modulation frequencies (red curve). The curve is calculated with Optickle, using the parameters given in Appendix A. For the red curve, all length control loops are closed. The requirement spectrum corresponds to an equivalent strain noise spectrum this is 10 times below the spectrum given in Appendix B. For reference, the blue curve is the same calculation, but with all length loops open.

- Optical transmission of the arm cavity mode, from the AOS beam handoff point to the GW readout photodiode(s): $> 90\%$

4.10 Scattered Light

Noise due to all scattered light paths in the interferometer must be controlled so that the total scattered light noise is no greater than 1/10-th of the target strain noise spectrum (in amplitude). Many of the scattered light paths are handled by AOS, but ISC is responsible for controlling scattered light in the ISC detection ports. The total scattered light noise budget is divided equally between those sources handled by AOS and the ISC detection beams. Therefore, the total scattered light noise from all ISC detection beams must be no greater than 1/14-th of the target strain noise spectrum (in amplitude). 1/15-th is OK, but 1/13-th would be entirely too large.

A detailed analysis of the allowable scattered light injecton from all of the interferometer ports will be carried out before the preliminary design.

4.11 Squeezed Light Injection

The ISC design must be compatible with a future upgrade adding some sort of squeezed light/vacuum injection from the dark port. It is not necessary to include this feature explicitly in the initial setup but the modifications required for squeezing should not be too onerous.

References

[1] LIGO, "Advanced LIGO Wiki", http://ilog.ligo-wa.caltech.edu:7285/advligo/AdvLigo

[2] A. Lazzarini and R. Weiss, "LIGO Science Requirements Document", http://www.ligo.caltech.edu/docs/E/E950018-02.pdf

[3] P. Fritschel, "DC Readout for Advanced LIGO", http://ilog.ligo-wa.caltech.edu:7285/advligo/AdvLigo

[4] http://lhocds.ligo-wa.caltech.edu:8000/mLIGO/Nonlinearity_of_the_DC_readout_signal

[5] R. Adhikari, "Sensitivity and Noise", http://www.ligo.caltech.edu/docs/P/P040032-00.pdf

[6] S. Ballmer, "LIGO Interferometer Operating as a Radiometer", http://www.ligo.caltech.edu/docs/P/P060043-00.pdf

[7] D. Sigg and J. Sidles, "Optical Torques in Suspended Fabry-Perot Cavities", http://www.ligo.caltech.edu/docs/P/P030055-C/

[8] ISC Group, "Length Sensing and Control Final Design", http://www.ligo.caltech.edu/docs/T/T980068-00.pdf

[9] ISC Group, "Interferometer Sensing and Control Conceptual Design", http://www.ligo.caltech.edu/docs/T/T070068-00.pdf

[10] P. Fritschel, "LIGO", http://arxiv.org/abs/0711.3041

[11] M. Evans, "Optickle", http://www.ligo.caltech.edu/docs/T/T070260-00.pdf

[12] M. Evans, "Optickle (LSC talk)", http://www.ligo.caltech.edu/docs/G/G070728-00

A Interferometer Parameters

ITM Transmission	0.01
ITM imbalance ($T_{ITMX} - T_{ITMY}$)	$T_{ITM}/50$
Average round trip arm loss	75 ppm
Differential arm loss	30 ppm
Beamsplitter R/T imbalance	$\pm 5 \times 10^{-3}$
Differential arm offset from dark fringe	12 pm
Output mode cleaner finesse	500

Table 3: Parameters used in the Optickle modeling. Shown are those parameters that determine the laser and modulation source noise couplings.

B Interferometer Strain Noise Spectrum

Each ISC technical noise source (such as laser frequency noise) must be controlled to be no greater than 1/10-th of the interferometer target strain noise spectrum, at all frequencies. The target strain noise is calculated with Bench, v6.2, and is shown in Fig. 6. The Bench output for this curve is:

Laser Power:	125.00 Watt
SRM Detuning:	8.30 degree
SRM transmission:	0.12
ITM transmission:	0.010
PRM transmission:	0.0318
Finesse:	623.64
Power Recycling Factor:	33.03
Arm power:	819.57 kW
Power on beam splitter:	4128.59 W
BNS Inspiral Range:	173.61 Mpc
BBH Inspiral Range:	1032.03 Mpc
Stochastic Omega:	2.13e-009

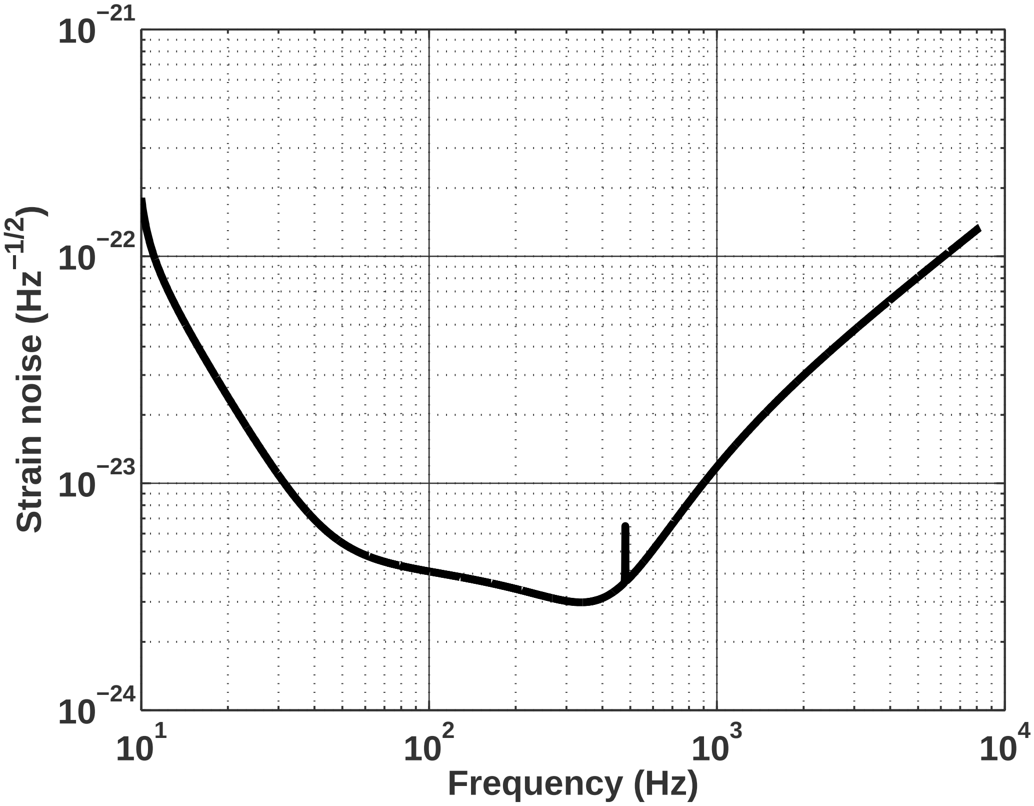

Figure 6: Interferometer strain noise spectrum used for calculating the maximum noise levels of the ISC technical noise sources. Computed with Bench, v6.2.