LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

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Cavity Optics Suspension Subsystem Design Requirements Document

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1 Introduction

1.1 Purpose and Scope

This document sets out the design requirements and interface specifications for the Advanced LIGO cavity optics suspensions system. Most of the requirements are derived by flow-down from the Advanced LIGO Systems Design (T010075-00). [reference added]

The scope of this document is limited to the specific requirements for the suspension subsystem (SUS) for the sensitive cavity optics, namely the input and end test masses, the power- and signal-recycling mirrors, the beamsplitter, the folding mirrors (the folded interferometer only), and the mode cleaner mirrors. It includes information necessary to quantify the relationship and define the interfacing to other subsystems, in particular the seismic isolation subsystem (SEI), core optics (COC), auxiliary optics subsystem (AOS), and interferometer sensing and control (ISC). Requirements common to all types of suspensions are given in a companion document, Universal Suspension Subsystem Design Requirements Document (T000053-01). [reference added]

The requirements for all sensors and actuators, including electronics and actuator coatings on the test masses, are treated in this document, except for the photon drive actuator. In-vacuum wiring between the feedthrough and the connection block on the suspension system is not included in the assumed scope.

There are several types of suspensions for Advanced LIGO. Suspension designs for optics other than cavity optics will be detailed in other documents. The conceptual design is presented in a separate companion document, Advanced LIGO Suspension System Conceptual Design (T010103-03. [reference added]

1.2 Applicable Documents [tidied up and extended]

- LSC White Paper Baseline Design Description (LIGO-T990080-01-D).
- LIGO II Suspension Reference Design, The GEO Suspension Team, Jan 31 2000, (LIGO-T000012-00).

- Advanced LIGO Systems Design (LIGO-T010075-00).
- Generic Requirements & Standards for Detector Subsystems (LIGO-E010123-00) [added]
- LIGO Vacuum Compatibility, Cleaning Methods and Qualification Procedures (LIGO-E960022-B)
- LIGO Vacuum Compatible Materials List (LIGO-E960050-B) [added]
- Vacuum Hydrocarbon Outgassing Requirements (LIGO-T040001-00) [added]
- Advanced LIGO Suspension System Conceptual Design (LIGO-T010103-04).
- Seismic Isolation System Payload Mass Properties (LIGO-E040136-00) [added]
- Low-frequency Cutoff for Advanced LIGO (LIGO-T020034-01-D). [added]
- Universal Suspension Subsystem Design Requirements Document (LIGO-T000053-01).
- Auxiliary Suspended Optics Displacement Noise Requirements (LIGO-T010097-00).
- Interface Control Document for the Advanced LIGO Detector (LIGO-E040508-00).
- Seismic Isolation Subsystem Design Requirements Document (LIGO-E990303-03).
- Advanced LIGO Safety Stop Design Requirements (LIGO-E040457-00).
- Optical Layout for Advanced LIGO (LIGO-T010076-01) [added]
- Alignment Sensing/Control Preliminary Design (LIGO-T970060-00) [added]
- ASC Initial Alignment Procedures (LIGO-T970151-C) [added]
- Input to the OSEM selection review decision (LIGO-T040110-01) [added]
- Preliminary investigation of the effects of massive resonant elements suspended from the SEI platforms (ALUKGLA0050aAUG03) [added]
- Test Mass Material Down-select Plan (LIGO-T020103-08) [added]
- Advanced LIGO Substrate Selection Recommendation (LIGO-M040405-00) [added]

1.3 Version History

26 Jan 2001 – -00. Initial release by Phil Willems

16 Oct 2001 – -01. Change of scope from test masses to cavity optics

31 Dec 2004 – -02. Major rewrite by Mark Barton. Changes from -01 noted in [].

7 Jun 2005 – -03. Fixed error in test mass transverse noise limit. Adjusted cross-references.

2 General description

2.1 Functions of the Cavity Optics Suspensions [revised]

The suspension system for each optic must:

- Provide a mechanical and functional interface with the seismic isolation system
- Provide a mechanical and functional interface with the core optics system [deleted, restored]
- Support the optic so that it hangs freely but is constrained against damage from large motions such as those from earthquakes [added stuff]
- Provide vibration isolation in conjunction with the seismic isolation system
- Avoid increasing the thermal noise from internal modes of the optic above the minimum set by losses in the bulk material
- Keep pendulum mode thermal noise and any other thermal noise sources to a comparable level, so as to meet overall thermal noise requirements
- Provide sensors and actuators for a local control system (or some other mechanism such as eddy current damping) which can reduce the velocity of the optic relative to its structure to the range required for lock acquisition and normal operation. This must be considered in conjunction with the seismic isolation and global control systems.
- Provide suitable actuators for global control, in conjunction with the seismic isolation systems.
- Accept inputs for global control and act as part of the system for acquiring and maintaining lock of the whole interferometer, in conjunction with the LSC and ASC
- Avoid impairing the functioning of the interferometer by occulting the light, causing stray reflections, or by responding to stray light [separated out from previous]
- Accommodate (where applicable) a thermal compensation system for the optic [added]
- Accommodate (where applicable) a reaction chain for the optic

2.2 Procedure for Determining Requirements

The practical procedure for determining the requirements for the suspension is as follows; some iteration is of course performed.

1. Parameterized models for the thermal noise performance of the suspension fibers and of the target test mass materials are made.
2. Coarse mechanical (e.g., height) and electronic (e.g., damping system noise) limitations are determined.
3. Best-guess parameters are inserted and a first cut at the range of performance and trades involved are generated.
4. System trades are performed: The resulting performance curves are compared with other noise sources and with potential sources of signals, and the technical risk and cost are weighed.
5. Requirements for the thermal noise performance and test mass material and size are established by the systems group and given to the suspensions group.
6. The suspension subsystem group determines the mechanical and electrical design, and delivers the suspension isolation and actuator specification to systems where it is passed on

to seismic isolation (i.e., the suspension design takes precedence in determining the isolation available).

The process is presently roughly at step 5 above. There are several top-level system trades to be performed which have great impact on the suspension design, and the choice of fibers or ribbons, and detailed requirements or anticipated specifications will have to await their resolution:

- Choice of test mass material and dimensions
- Optical noise in the range 10-50 Hz.

[item on low frequency limit deleted]

2.3 Note on Geometrical Terminology [added]

Throughout this document, displacements of an optic are described as “longitudinal”, “transverse” or “vertical”. “Vertical” is in the direction of local gravity. “Longitudinal” is the local horizontal direction nearest the perpendicular to the HR face of the optic and “transverse” is the local horizontal direction at right angles to this.

3 General Requirements

3.1 Precedence [was 3.3]

Those requirements relating to thermal noise in the test masses have the highest priority. Compromises in the seismic isolation or the actuation can be more probably compensated in other subsystems.

3.2 Interpretation of Broadband Noise Requirements [added]

Unless otherwise specified, any broadband noise requirements given below apply from 10 Hz upwards, subject to the following exemptions:

- There may be peaks due to violin modes, provided that (i) they have a frequency of at least 400 Hz, and (ii) that are sufficiently narrow that they are easily filtered without substantial loss of detector bandwidth. [consolidated from various places such as 4.2.5, min frequency requirement added]
- There may be a peak at up to 12 Hz due to the highest frequency vertical mode of the suspension (even though this will tend to spoil a region of ±1 Hz around it). See T020034-01. A lower frequency is still desirable. [added]
- There may be a peak due to the highest frequency roll mode at approximately $\sqrt{2}$ times the highest vertical mode frequency. [added]

No other internal modes of the pendulum (e.g., internal resonances of the blade springs) may cause displacements in excess of any of the broadband requirements given below, either when excited thermally or by the seismic noise spectrum from the SEI system as given in LIGO document LIGO-E990303-03-D.

3.3 Fundamental vs Technical Noise Sources [adapted from 4.2.1]

Noise sources are classified as either fundamental or technical. Fundamental noise sources are those which are not capable of further improvement given the laws of physics and the limitations of available materials and thus have to be taken as constraints on the design. Technical noise sources are those which can in principle be reduced well below the fundamental noise sources, given enough ingenuity and resources. The noise budget given in the Advanced LIGO Systems Design (T010075-00) takes into account all anticipated fundamental noise sources. Unless otherwise specified, any technical noise sources, including any sources not explicitly considered in this document, must meet the requirement that they contribute to the gravity wave strain signal no more than 10% in amplitude (or 1% in energy) of the system requirement in T010075-00.

3.4 Control Performance [moved and adapted from 4.4]

The control performance requirements, broadly stated, are that the suspensions be capable of acquiring lock as part of a globally controlled advanced LIGO configuration, with the arm cavity powers and dynamic characteristics appropriate for the laser powers and arm cavity finesses set by the systems group, and that with the SEI subsystem it should provide sufficient dynamic range and bandwidth to control the locked interferometer during operation. The SEI will provide large actuation range at low frequency (≤100mHz).

Except as provided for below each suspension shall be operable in up to three modes as appropriate to allow for the following sets of circumstances:

- **Emergency/Installation/Pre-Alignment.** This mode must supply enough damping to bring the suspension quickly to rest if there is an earthquake, major adjustment, or inappropriate human action. The ringdown time of all body modes except the vertical bounce and roll of the bottom mass must be less than 10 seconds. There are no considerations of noise in this case. Local control should switch to this mode whenever another mode becomes inappropriate due to some disturbance. It should be the startup mode.
- **Acquisition.** This mode must reduce the velocity of the optic sufficiently such that as it sweeps through interference fringes, the ISC controllers have time to act before a fringe has passed. Since the ISC system will not be designed for some time, the only reasonable approach is to require that the suspension local damping must reduce the “average” speed of the mirrors to very close to the minimum possible given the input vibration from the SEI subsystem.
- **Detection/Science mode.** The in-band noise requirements as set out in the DRD must be met in this mode. Additionally it is necessary to restrict the required control-band feedback forces to a reasonable minimum. The latter consideration is related to the velocity requirement above but with two differences: 1) very low frequency motion is unimportant because feedback can be applied in the SEI stage rather than the suspension and 2) force (hence acceleration) is a truer measure of the problem than velocity. Sensor noise related to the local damping is a technical noise source and is discussed in section 4.2.7.

All DOF sensors and all DOF actuators are to be accessible to the suspension control system, and the controller design must allow for frequency-dependent cross-coupling terms.

The control (and entire) system must perform correctly for angles of the mounting table of up to 100 microrad (TBR).

No sensor or actuator mounting bracket shall have a resonance below 30 Hz. [added]

3.5 Installation support functions [added]

3.5.1 Alignment

In conjunction with ASC, the core optics suspensions shall support initial alignment to the positions and orientations given in Optical Layout for Advanced LIGO, T010076-01, to LIGO-I precision, as described in T970151-C, ASC Initial Alignment Procedures and reproduced in Table 1. Since alignment is sometimes using alignment marks on the structure, the error in the surveying techniques plus the positioning error of the optic in the structure (both clamped and unclamped) must be less than the indicated tolerance. (If sapphire test masses are ever resurrected, there is also a roll requirement on the ITMs set by birefringence of the sapphire.)

Table 1: Static alignment requirements

Longitudinal positioning	+/- 3 mm	T970151-C, p. 2.
Transverse/vertical[?] positioning	+/- 1 mm (ITM, ETM) +/- 5 mm (other)	T970151-C, p. 2.
Pitch/yaw positioning	+/- 0.1 mrad	T970151-C, p. 2.
Roll positioning (Sapphire ITMs only)	TBD but provisionally +/- 1 mrad	Communication from GariLynn Billingsley

The local control actuators must provide a range of +/- 1 mrad of pitch and yaw adjustment for frequencies $f < 10$ mHz.

3.5.2 Earthquake/Safety Stops

Each suspension shall have a system of earthquake/safety stops or equivalent (e.g., a "catcher") to provide the following functions:

- Facilitating assembly: the stops must hold the optic and other parts to be suspended in positions convenient for installing any wires or fibers that need to be attached in situ, and then release them to the fully suspended condition.
- Immobilizing the optic and other suspended parts during transport: the stops must be able to capture the suspended components and immobilize them securely, without perturbing the position or orientation of the optic [any others??] relative to the freely suspended by more than the tolerances in Table 1 (Section 3.5.1).
- Protecting suspended parts from damage due to earthquakes and other gross disturbances during operation
- Protecting the suspended parts from damage in the event of a wire or fiber breakage.

The first two functions may be also done in whole or in part by removable jigs as convenient. The stop design must be such as to minimize forces from static charges that might perturb the position of the suspended optic in operation, either through using non-conducting materials that minimize any buildup from pump-down and/or contact with the optic, or through using conducting materials that leave the tip grounded. See E040457-00 for elaboration of these requirements.

3.6 Structure Resonances [added]

No mode of the pendulum structure with non-trivial effective mass shall have a resonant frequency below 100 Hz. For background on this requirement, see ALUKGLA0050aAUG03.

3.7 Reaction Chains and Actuator Noise [added]

In the baseline plan, the test masses, the folding mirrors and the beamsplitters have reaction chain pendulums to serve as low noise actuation points for global control, and in some cases to hold optics for thermal compensation (see Table 2 of T010103-03). Detailed requirements for reaction pendulums will depend on the actuation scheme chosen but the general principle is that noise coupled in from the reaction chain or the structure is a technical noise source and must be held to one tenth of the fundamental noise for the associated core optic. Couplings to be considered include

- Intrinsic noise of the actuators
- Control noise from noisy local control sensors or the like
- Coupling of reaction chain noise (seismic, thermal, etc) via a non-zero rate of change of force with distance in the actuator
- Fluctuating forces from a scanning thermal compensation scheme, if used

3.8 Mass Budget

The suspensions must conform to the mass budget set out in E04136-00 or revisions thereof. This is a particularly tight constraint for the folding mirrors, which share a SEI platform with their associated input test mass.

3.9 Interfaces [moved from 8, content replaced by reference]

Interfaces to other LIGO subsystems are specified in E040508-00.

4 Test Mass Suspension Requirements

4.1 Assumptions and Dependencies

There are two variants of the test mass suspension: one for the ETM which carries potentially non-transmissive actuators behind the optic, and one for the ITM which must allow the input beam to couple into the Fabry-Perot arm cavity. The test mass suspension system is mounted (via bolts and/or clamps) to the BSC seismic isolation system by attachment beneath the BSC SEI optics table. In the folded interferometer the input test masses will share a platform with the folding mirror suspensions; the resulting weight and space constraints must be considered. See Section 3.8, E040508-00.

The internal thermal noise calculation depends upon the spot size on the mirror. The working value is a 6 cm w_0 gaussian beam for both ITM and ETM.

All thermal noise calculations depend on the test mass size and material. We assume a sapphire test mass with the following dimensions: mass, 40 kg; diameter, 31.4 cm; thickness, 13 cm. If fused silica is instead chosen for the test mass some requirements will need revision.

4.2 Noise performance

Table 2: Noise performance requirements, test mass suspensions

Parameter	Measurement Band	Discussion
Test mass internal mode longitudinal thermal noise	$5\text{x}10^{-20}$ m/√Hz at 10 Hz, as 1/f	Section 4.2.1, Figure 1.
Suspension longitudinal thermal noise	10^{-19} m/√Hz at 10 Hz, falling as $(1/f)^2$	Section 4.2.2.
Longitudinal and vertical seismic $\text{sqrt}(x^2+(10^{-3}z)^2)$	10^{-19} m/√Hz at 10 Hz, falling faster than $(1/f)^4$ except for possible bounce mode peak at up to 12 Hz	Assumes vertical to longitudinal motion coupling of 10^{-3}; section 4.2.9. [moved from Table 2, longitudinal and vertical merged,]
Pitch noise	$1\text{x}10^{-17}$ rad/√Hz at 10 Hz, falling roughly as $(1/f)^2$	Requirement driven by offset of beam from center of mirror, alignment servo gain; section 4.2.3
Yaw noise	$1\text{x}10^{-17}$ rad/√Hz at 10 Hz, falling roughly as $(1/f)^2$	Requirement driven by offset of beam from center of mirror, alignment servo gain; section 4.2.4
Vertical thermal noise	10^{-16} m/√Hz at 10 Hz, falling roughly as $(1/f)^2$ except for possible bounce mode peak at up to 12 Hz	Assumes vertical to longitudinal motion coupling of 10^{-3}; section 4.2.5.
Transverse thermal and seismic noise	$1\text{x}10^{-17}$ m/√Hz at 10 Hz, falling roughly as $(1/f)^2$	Based on 10^{-3} coupling to longitudinal motion; section 4.2.6
Longitudinal technical noise	1/10 of longitudinal pendulum thermal noise	Section 4.2.7 (and 4.2.2) [ref added]
Vertical technical noise	1/10 of vertical thermal noise [clarified]	Section 4.2.9 (and 4.2.5) [ref added]
Transverse technical [was thermal] noise	1/10 of transverse thermal/seismic noise [clarified]	Section 4.2.8 (and 4.2.6) [ref added]
Roll noise (sapphire ITM only)	$1.2\text{x}10^{-8}$ rad/√Hz	Section 4.2.10

4.2.1 Longitudinal displacement, internal thermal modes

The internal thermal noise performance can be divided into ‘intrinsic’ and ‘extrinsic’ categories. The intrinsic sources of thermal noise derive from mechanisms which are taken to be beyond experimental improvement, such as the internal losses and thermoelastic effects in the test mass material, although the size and shape of the mass and reflected beam will influence the observed thermal noise. The polish and reflective coating on the mirror, though an active field of research at present, may also prove to be intrinsic by this definition. Intrinsic noise is an input parameter to the suspension design. The extrinsic sources of noise derive from things that are done to the test masses, such as attachment to the suspension. We require that the extrinsic sources of noise not significantly increase the thermal noise set by the intrinsic sources where internal thermal noise limits interferometer sensitivity.

The following internal thermal noise spectrum is taken as a requirement. It assumes a 40 kg sapphire mass with 5×10^{-9} loss factor, and was made using Bench version 1.7 and Cagnoli’s Maple thermal noise model. It can be described as 5×10^{-20} m/√Hz at 10 Hz, falling off as 1/f, but note that only the section of the curve around 100 Hz is likely to be limiting (cf. Figure 1 in T010075-00). Coating and polishing losses are not considered in this spectrum and are not considered intrinsic noise sources for the purposes of setting these requirements.

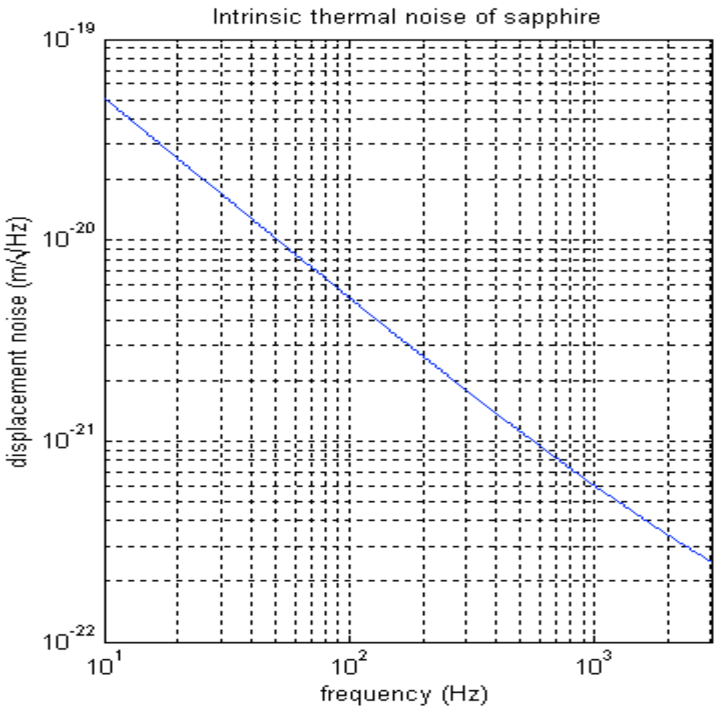

Figure 1: Intrinsic thermal noise of sapphire test mass

4.2.2 Longitudinal pendulum thermal noise

Pendulum thermal noise is not expected to dominate over optical noise, but can be comparable at low frequencies if the IFO is operated at low laser power and fibers are chosen to suspend the optic. We require 1x10^{-19} m/√Hz at 10 Hz, with the natural rolloff of $(1/f)^2$. Currently the baseline design is to use ribbons to meet the pendulum thermal noise requirement. An alternative is the use of dumbell-shaped fibers. [clarified]

4.2.3 Pitch noise

Pitch and yaw noise are special in that LIGO will use alignment sensing and control to reduce these noise sources independently of the longitudinal sensing and control. Therefore these requirements are not on the SUS alone but in combination with ISC. All sources of noise- thermal, seismic, technical- and the alignment servo together must not lead to pitch noise in excess of the quoted requirement.

The energy in this mode is stored in tension in the suspension fibers (or in the twists of a ribbon) and the losses may be large. The coupling to pitch depends on the position of the optical beam; for a specific suspension design, there is a point which will give minimum coupling (Ref: Levin). The technical noise will also have a position-dependent coupling and the two optima may not be in the same place; to be considered in the technical requirements. The value of allowed angular noise is traded against the positioning accuracy; the specification quoted in the table assumes centering within 1 mm, and gives an equivalent thermal noise power 10x lower than the longitudinal suspension [was (implicitly) internal] thermal noise. In truth, should the thermal noise in this or any other angular degree of freedom threaten the longitudinal noise requirement, then the requirement effectively restricts the positioning accuracy.

Pitch noise of the ITM will also couple into the power and signal recycling cavities. However, the pitch noise requirement listed above is more stringent than for the other mirrors in those cavities.

4.2.4 Yaw noise

The discussion of alignment servos in the section on pitch noise is also relevant here.

The energy in this mode is largely stored in the gravitational field and thus the losses can be small. Again, the positioning of the beam is important and this requirement needs to be set along with a centering precision. However, as opposed to the case for pitch the point of minimum coupling will be at middle of the mirror. The specification quoted in the table assumes centering within 1mm, and gives an equivalent thermal noise power 10x lower than the longitudinal suspension [was (implicitly) internal] thermal noise.

As with pitch noise, yaw noise of the ITM will also couple into the power and signal recycling cavities. However, the yaw noise requirement listed above is more stringent than for the other mirrors in those cavities.

4.2.5 Vertical thermal noise

Following practice in GEO we take 10^{-3} as a worst case estimate of vertical to horizontal coupling. [**could also add "Estimates by GEO (T010103-03, p6; M Husman, PhD Thesis, University of Glasgow, 2000, Husman et al., Rev. Sci. Instrum 71:2546-2551, 2000, p2550) suggest a worst-case coupling of roughly 10^{-3} from vertical to horizontal due to mechanical imperfections." However unless there's something in the thesis that not in the RSI paper, it's all irrelevant – 0.1% is a rounded up version of 0.04% which appears to be specific to the GEO optical configuration] LIGO beams are a maximum of 6x10^{-4} rad away from local vertical, making this the minimum coupling from vertical to longitudinal thermal noise. We require that the vertical contribution be equal or less than the longitudinal contribution, allowing 10^3 more noise in the vertical or ~10^6 greater loss. For the ITM, which is a transmissive optic likely to have a vertical wedge, vertical thermal noise will also couple to longitudinal noise in the short degrees of freedom (power recycling cavity, signal cavity, Michelson fringe). The requirement based on this coupling is about $2\text{x}10^{-15}$ m/√Hz at 10 Hz (assuming a coupling of vertical to horizontal motion of 0.01 outside the arm cavity due to the optic wedge) and so is less stringent by far. This noise power is not required to be smaller than the longitudinal thermal noise by a safety factor because it is expected to be an intrinsic noise source. [stuff on vertical moved to 3.1]

4.2.6 Transverse thermal and seismic noise

In the transverse direction, the losses of the pendulum are expected to be [was "should be"] comparable to those of the longitudinal direction and there is no fixed misalignment giving a minimum coupling; this requirement is based on an assumed 0.001 coupling of transverse to longitudinal motion. This requirement will require review if the ITMs have horizontal wedges due to coupling to the power and signal cavities.

4.2.7 Longitudinal technical noise

We require that this be a negligible contribution in the GW band, thus 1/10 in amplitude of the longitudinal pendulum thermal noise. Sources of technical noise include but are not restricted to: sensor and actuator noise, stray electric charges on the test mass or suspension, ambient magnetic field fluctuations at the magnetic actuators, and excess noise due to creep events in the suspension materials. It is noted that stray charge on the mass can increase pendulum thermal noise by coupling with nearby conductors.

4.2.8 Transverse technical noise

We require that this be a negligible contribution in the GW band, thus 1/10 in amplitude of the thermal/seismic noise for the given transverse to longitudinal coupling. The sources of technical noise listed in 3.2.1.1.6 are also relevant here.

4.2.9 Vertical technical noise [added]

We require that this be a negligible contribution in the GW band, thus 1/10 in amplitude of the vertical thermal noise.

4.2.10 Roll noise

Because of the birefringence of the sapphire, there is a small AC coupling from roll to longitudinal if there is a DC roll misalignment. Assuming pessimistically that the waveplate action of the ITM is uniform across the surface, and that the ITMs roll in antiphase, the coupling is

$$\frac{\lambda\phi_0}{\pi G} = 8.5\times10^{-13}\,\text{m/rad}$$

where G≈400 is the arm power gain, λ=1064 nm is the wavelength and ϕ_0=0.001 is the worst-case static roll misalignment from 3.5 (email from Bill Kells, 8/23/04). To keep this less than one tenth the longitudinal pendulum thermal noise as for pitch and yaw, requires roll to be less than $1.2\text{x}10^{-8}$

rad/√Hz, which should be trivial to achieve. Moreover because of the wedge, the waveplate action will tend to average out over some 50 fringes across the beam spot, so there should be a further factor of about 50 in hand.

4.3 Seismic isolation performance

The degree of vibration isolation required for the suspension is the system requirement less the amount supplied by the SEI subsystem. After some trades, SEI has committed to the platform noise spectrum given in the Seismic Isolation Subsystem Design Requirements Document LIGO-E990303-03-D. Since vertical motion couples to longitudinal at around the 0.001 level due to curvature of the earth and other effects, both need to be considered as fundamental noise sources. To permit the maximum design flexibility, we give a joint longitudinal/vertical requirement of $\mathrm{sqrt}(x^2+(10^{-3}z)^2) < 10^{-19}$ m/√Hz at 10 Hz, with a $1/f^4$ rolloff. Note that the value at 10 Hz is the same as that for pendulum thermal noise. The seismic noise at higher frequencies will naturally be much less than thermal noise due to the greater rolloff.

The specified frequency rolloff of the seismic noise at the suspension is conservative and should easily be achieved by the combined SEI-SUS system. It is chosen to guarantee that seismic noise falls off much more rapidly with frequency than thermal noise.

4.4 [Control performance – moved to 3.4]

5 Recycling Mirror Suspension Requirements

The recycling mirror suspension system is mounted (via bolts and/or clamps) to the HAM seismic isolation system by attachment atop the HAM SEI optics table. Available height above the optics table may prove to be a tight constraint.

The recycling mirror suspensions have much less stringent requirements than the test mass suspensions and are not expected to participate in any systems design tradeoffs. However, the requirements from systems design could change, most probably the diameter of the recycling mirror. Furthermore, though the performance requirements of the signal recycling mirror are slightly more stringent than those of the power recycling mirror, the two recycling mirrors will have identical dimensions and materials, and in the interest of common design the signal recycling mirror requirements are adopted for both mirrors.

Because these requirements are expected to be easily achievable, all sources of noise are included in this requirement, including seismic noise. Since all the requirements listed below relate to coupling to longitudinal displacement, the sum of all of them are included in this requirement. The values listed under each degree of freedom are the maximum values if that degree of freedom contributes all the noise of the suspension.

5.1 Assumptions and Dependencies

The internal thermal noise calculation depends upon the spot size on the mirror. The working value is 6 cm w_0.

All thermal noise calculations depend on the recycling mirror size and material. We assume a fused silica mirror with dimensions: m = 12.2 kg, diameter = 26.5 cm, thickness = 10 cm.

5.2 Noise performance

Table 3: Noise performance requirements, recycling mirror suspensions

Parameter	Value	Discussion
Longitudinal displacement noise due to all sources	$4\text{x}10^{-16}$ m/√Hz at 10 Hz, falling to $1.5\text{x}10^{-17}$ m/√Hz at 100 Hz	See section 5.2.1 and the seismic isolation requirements.
Pitch noise	$4.4\text{x}10^{-14}$ rad/√Hz at 10 Hz, falling to $1.7\text{x}10^{-15}$ rad/√Hz at 100 Hz	Requirement driven by optical path length through wedged ITM; see section 5.2.2.
Yaw noise	$2.7\text{x}10^{-14}$ rad/√Hz at 10 Hz, falling to $1\text{x}10^{-15}$ rad/√Hz at 100 Hz	Requirement driven by optical path length through beamsplitter; see section 5.2.3.
Vertical displacement noise	$2.2\text{x}10^{-13}$ m/√Hz at 10 Hz, falling to $8.3\text{x}10^{-15}$ m/√Hz at 100 Hz except for possible bounce mode peak at up to 12 Hz	Assumes coupling of vertical to longitudinal motion of 0.0018; see section 5.2.4.
Transverse noise	$4\text{x}10^{-13}$ m/√Hz at 10 Hz, falling to $1.5\text{x}10^{-14}$ m/√Hz at 100 Hz	See section 5.2.5.

5.2.1 Longitudinal displacement

The longitudinal displacement noise requirement for the signal recycling mirror is driven by the generation of noise sidebands directly onto the output GW signal. Assuming the RF readout scheme, which is more sensitive to the signal recycling mirror motion than the DC readout scheme, and comparing sensitivity to SRM motion to that of end mirror motion leads to the quoted specs (see document T010097-00-D).

The longitudinal displacement noise requirement for the power recycling mirror is driven by the frequency stability requirements of the laser, which uses the interferometer itself as a reference cavity. These requirements are $6\text{x}10^{-7}$ Hz/√Hz at 10 Hz and $1.9\text{x}10^{-7}$ Hz/√Hz at 100Hz. Translating these frequency noise requirements to displacement requirements for the power recycling mirror and including a safety factor so that the recycling mirror does not dominate the noise budget leads to the power recycling mirror requirements, which are nearly equal to the SRM requirements at 10 Hz and 100Hz but slightly higher in between (again, see document T010097-00-D).

5.2.2 Pitch noise

Assuming the beam will be centered on the optic only to within 5 mm, there will be a pitch to longitudinal displacement coupling of 0.005 m/rad due to motion of the reflecting surface of the recycling mirror.

Inhomogeneities in the refractive index of the material are expected to lead to optical path variations of about 10nm per mm of transverse motion of the beam through the ITM's and beamsplitter. The maximum wedge of 3 degrees in the ITM gives a larger ~$5\text{x}10^{-7}$ m optical path length change per mm of transverse motion. Given cavity lengths of ~8m, a tilt of $1.3\text{x}10^{-4}$ rad will give 1mm transverse displacement at the ITM, thus the coupling will be $4\text{x}10^{-3}$ m/rad, which is comparable to the 0.005 m/rad coupling caused by a 5mm offset of the beam from the center of the optic. These couplings are estimated without considering coupled cavity effects, which are likely to reduce them somewhat. Nevertheless, the most conservative approach would be to combine the couplings derived here, which is what we have done.

5.2.3 Yaw noise

This requirement has the same considerations as pitch noise. In addition, the first-order dependence of path length on transmission angle through the beamsplitter leads to a coupling of ~0.01 m/rad, which also might be reduced by coupled cavity effects. The sum of this coupling and that from a 5mm beam offset from optic center is adopted as setting the requirement for yaw motion.

5.2.4 Vertical noise

The ITMs are likely to have vertical wedges, which will lead to a much larger coupling of vertical motion to longitudinal motion in the recycling mirrors than in the ITM's. The requirement quoted assumes a coupling of 0.0018 as given in Table 8 of LIGO-T010076-01-D. If the ITM's instead have wedges such that the beam travels horizontally when incident on the recycling mirror, the vertical coupling can be assumed to drop to 0.001 based on practical experience with unintended vertical-to-horizontal cross-couplings.

The 12 Hz requirement on the highest vertical mode frequency does not apply to the recycling mirror. In fact the bounce mode is likely to be around 17 Hz due to height restrictions in the HAM.

5.2.5 Transverse noise

In the transverse direction, the losses of the pendulum should be comparable to those of the longitudinal direction and there is no fixed misalignment giving a minimum coupling; this requirement is based on couplings which are now assumed to be 0.001. This does not change if the wedges in the ITM's are horizontal rather than vertical.

5.3 Seismic isolation performance

Seismic noise is included in the noise requirements above. [stuff on blades moved to 3.1.2] The interchangeability of vertical and transverse motion mentioned in section 5.2.5 also applies here.

5.4 [Control performance – moved to 3.4]

5.5 Beamsplitter Suspensions

The beamsplitter suspension system is mounted (via bolts and/or clamps) to the BSC seismic isolation system by attachment below the BSC SEI optics table.

The beamsplitter suspensions have much less stringent requirements than the test mass suspensions and are not expected to participate in any systems design tradeoffs. Because these requirements are expected to be easily achievable, all sources of noise are included in this requirement, including seismic noise. Since all the requirements listed below relate to coupling to longitudinal displacement, the sum of all of them are included in this requirement. The values listed under each degree of freedom are the maximum values if that degree of freedom contributes all the noise of the suspension.

5.5.1 Assumptions and Dependencies

The internal thermal noise calculation depends upon the spot size on the mirror. The working value is 6 cm w_0.

All thermal noise calculations depend on the beamsplitter size and material. We assume a fused silica mirror with dimensions: m = 12.7 kg, diameter = 35 cm, thickness = 6 cm.

5.5.2 Noise performance

Table 4: Noise performance requirements, beamsplitter suspensions

Parameter	Value	Discussion
Longitudinal and vertical noise: $\mathrm{sqrt}(x^2+(0.000735z)^2)$	$2\mathrm{x}10^{-17}$ m/√Hz at 10 Hz, falling to $6\mathrm{x}10^{-19}$ m/√Hz at 100 Hz	See section 5.5.3
Pitch noise	$2.9\mathrm{x}10^{-15}$ rad/√Hz at 10 Hz, falling to $8.6\mathrm{x}10^{-17}$ m/√Hz at 100 Hz	Requirement driven by offset of beam from center of mirror and ITM vertical wedge; See section 5.5.4
Yaw noise	$1.3\mathrm{x}10^{-15}$ rad/√Hz at 10 Hz, falling to $4\mathrm{x}10^{-17}$ rad/√Hz at 100 Hz	Requirement driven by optical path length through beamsplitter; See section 5.5.5
Transverse noise	$2\mathrm{x}10^{-14}$ m/√Hz at 10 Hz, falling roughly as 1/f	See section 5.5.7

5.5.3 Longitudinal and vertical

The longitudinal displacement noise requirement is driven by the need to maintain the dark fringe at the output port. Since the beamsplitters are not in the arm cavities, they can be noisier than the test masses by a factor equal to the arm cavity phase gain, corrected to account for the 45° incident angle, and with another factor of 3.5 as a safety margin.

Vertical motion also needs to be limited because of a cross-coupling to longitudinal due to the wedge of the optic and the finite static pitch of the HR face, equal to $1.04\ 10^{-3}$ at LHO and slightly smaller at LLO (see Appendix 1 of LIGO-T010076-01-D, email from D. Coyne to N. Robertson, 1/27/2004). This is combined with the longitudinal to make a single joint requirement,

$$\mathrm{sqrt}(x^2+(0.000735z)^2) < 2\mathrm{x}10^{-17}\ \mathrm{m}/\sqrt{\mathrm{Hz}}\ \text{at } 10\ \mathrm{Hz}$$

(email from P. Fritschel to Norna Robertson, 1/27/2004).

These requirements are so much less stringent than the requirements for the test masses that they are expected to be easily achievable and thus not involve detailed performance tradeoffs. Therefore, all sources of noise are included in this requirement, including seismic noise.

[stuff on violin modes moved to 3.1]

5.5.4 Pitch noise

Pitch noise leads to displacement noise if the beam is offset above or below the center of the mass, so this requirement needs to be set along with a centering precision. The specification quoted in the table assumes centering within 5mm.

Additionally, the presence of a vertical wedge in the ITM (maximum value 3 degrees) causes a variation in optical path of a ~$5\mathrm{x}10^{-7}$ m optical path length change per mm of transverse motion. Given a BS/ITM separation of ~4m, a tilt of $7\mathrm{x}10^{-5}$ rad will give 1mm transverse displacement at the ITM, thus the coupling will be $2\mathrm{x}10^{-3}$ m/rad, which is comparable to the 0.005 m/rad coupling caused by a 5mm offset of the beam from the center of the optic. This coupling is estimated without considering coupled cavity effects, which are likely to reduce it somewhat. Nevertheless, the most conservative approach would be to assume the sum of these couplings in setting the pitch requirement, which is what we have done here.

5.5.5 Yaw noise

This requirement has the same considerations as pitch noise. In addition, the first-order dependence of path length on transmission angle through the beamsplitter leads to a coupling of ~0.01 m/rad, which also might be reduced by coupled cavity effects. The sum of these couplings is adopted as setting the requirement for yaw motion.

5.5.6 Vertical noise

[stuff on vertical moved to 5.5.3]

5.5.7 Transverse noise

In the transverse direction, the losses of the pendulum are expected to be [was “should be”] comparable to those of the longitudinal direction and there is no fixed misalignment giving a minimum coupling; this requirement is based on couplings which are now assumed to be 0.001. This will not change if the wedges in the ITM’s are horizontal rather than vertical. If the beamsplitter wedge is changed to horizontal, the requirement should in principle be modified to use the coupling figure of $1.04\mathrm{x}10^{-3}$ from 5.5.3. [added]

5.6 Seismic isolation performance

Because the net requirements are expected to be achieved easily with little in the way of tradeoffs, no separate seismic requirement is given. [clarified]

5.7 [Control performance – moved to 3.4]

6 Folding Mirror Suspension Requirements

The folding mirrors are suspended from the same BSC SEI platform as the ITMs of the folded interferometer. Therefore particular attention will need to be paid to meeting the mass budget specified in E040508-00. [reference added]

The folding mirror suspensions have much less stringent noise requirements than the test mass suspensions and are not expected to participate in any systems design tradeoffs. However, the requirements from systems design could change; for example, the radius is linked to that of the test mass, which may change if fused silica is chosen for the test mass material. Because these requirements are expected to be easily achievable, all sources of noise are included in this requirement, including seismic noise. Since all the requirements listed below relate to coupling to longitudinal displacement, the sum of all of them are included in this requirement. The values listed under each degree of freedom are the maximum values if that degree of freedom contributes all the noise of the suspension.

6.1 Assumptions and Dependencies

The internal thermal noise calculation depends upon the spot size on the mirror. The working value is 6 cm w_0.

All thermal noise calculations depend on the folding mirror size and material. We assume a fused silica mirror with dimensions: m = 12.7 kg, diameter = 35 cm, thickness = 6 cm.

6.2 Noise performance

Table 5: noise performance requirements, folding mirror suspensions

Parameter	Value	Discussion
Longitudinal noise, all sources	$2\text{x}10^{-17}$ m/√Hz at 10 Hz, falling to $6\text{x}10^{-19}$ m/√Hz at 100 Hz	See section 6.2.1 and the seismic isolation requirements
Pitch noise	$4\text{x}10^{-15}$ rad/√Hz at 10 Hz, falling to $1.2\text{x}10^{-16}$ rad/√Hz at 100 Hz	Requirement driven by offset of beam from center of mirror; see section 6.2.2.
Yaw noise	$1.3\text{x}10^{-15}$ rad/√Hz at 10 Hz, falling to $4\text{x}10^{-17}$ rad/√Hz at 100 Hz	Requirement driven by optical path length through beamsplitter; see section 6.2.3.
Vertical noise	$2\text{x}10^{-14}$ m/√Hz at 10 Hz, falling to $6\text{x}10^{-16}$ m/√Hz at 100 Hz	Vertical to longitudinal motion coupling 0.001 [decided]; see

	[added]	sections 6.2.4, 6.2.5.
Transverse noise	2x10^{-14} m/√Hz at 10 Hz, falling to 6x10^{-16} m/√Hz at 100 Hz	See sections 6.2.4, 6.2.5.

6.2.1 Longitudinal noise

The longitudinal displacement noise requirement for the folding mirrors, like that of the beamsplitters, is driven by the need to maintain the dark fringe at the output port. Since the folding mirrors are not in the arm cavities, they can be noisier than the test masses by a factor equal to the arm cavity phase gain, corrected to account for the 45° incident angle, and with another factor of 3.5 as a safety margin.

These requirements are so much less stringent than the requirements for the test masses that they are expected to be easily achievable and thus not involve detailed performance tradeoffs. Therefore, all sources of noise are included in this requirement, including seismic noise.

6.2.2 Pitch noise

This requirement is based on beam centering. If the beam is offset from the center of the folding mirror vertically, then small tilts of the mirror will change the path length of the laser beam from the beamsplitter to the input test mass to first order. The coupling due to the wedge in the ITM, which dominates the pitch noise coupling for the recycling mirrors and beamsplitter, is negligible for the folding mirrors since they are less than a meter away from the ITM's. The centering is assumed to be within 5mm.

6.2.3 Yaw noise

This motion couples most strongly into the displacement noise through the dependence of the optical path length through the beamsplitter on incident angle. The beam passing through the 6cm thick beamsplitter sees a coupling of ~0.01 m/rad. This coupling is added to that due to the 5mm beam offset from the mirror center.

6.2.4 Vertical noise

The vertical wedges of the ITM's limit the allowable vertical motion of the folding mirrors as well. The requirement depends upon a coupling which is TBD. If the ITM's instead have wedges such that the beam travels horizontally when incident on the folding mirrors, the vertical coupling can be assumed to drop to 0.001 based on practical experience with unintended vertical-to-horizontal cross-couplings.

[stuff on bounce mode consolidated into 3.1]

6.2.5 Transverse noise

In the transverse direction, the losses of the pendulum should be comparable to those of the longitudinal direction and there is no fixed misalignment giving a minimum coupling; this requirement is based on couplings which are now assumed to be 0.001. This does not change if the wedges in the ITM's are horizontal rather than vertical.

6.3 Seismic isolation performance

Because the net requirements are expected to be achieved easily with little in the way of tradeoffs, no separate seismic requirement is given. [clarified]

[stuff on blades moved to 3.1]

6.4 [Control performance – moved to 3.4]

7 Mode Cleaner Suspension Requirements

There will be two suspended mode cleaners within the HAM chambers: an input mode cleaner before the mode-matching telescope and an output mode cleaner after the signal recycling mirror. These requirements are specifically for the input mode cleaner mirrors. The output mode cleaner mirror suspensions are assumed to be identical pending a detailed systems review.

The input mode cleaner mirror suspension system is mounted (via bolts and/or clamps) to the HAM seismic isolation system by attachment above the HAM SEI optics table.

All sources of noise are included in this requirement, including seismic noise. Since all the requirements listed below relate to coupling to longitudinal displacement, the sum of all of them are included in this requirement. The values listed under each degree of freedom are the maximum values if that degree of freedom contributes all the noise of the suspension.

7.1 Assumptions and Dependencies

The internal thermal noise calculation depends upon the spot size on the mirror. The working value is 1 mm w_0.

All thermal noise calculations depend on the input mode cleaner mirror size and material. We assume a fused silica mirror with dimensions: m = 2.9 kg, diameter = 15 cm, thickness = 7.5 cm. [corrected mirror dimensions]

7.2 Noise performance

Table 6: Noise performance requirements, mode cleaner mirror suspensions

Parameter	Value	Discussion
Longitudinal noise, all sources	3×10^{-17} m/√Hz at 10 Hz, falling to 3×10^{-19} m/√Hz at 100 Hz	See 7.2.1
Pitch noise	3×10^{-14} rad/√Hz at 10 Hz, falling to 3×10^{-16} rad/√Hz at 100 Hz	Requirement driven by offset of beam from center of mirror; see 7.2.2
Yaw noise	3×10^{-14} rad/√Hz at 10 Hz, falling to 3×10^{-16} rad/√Hz at 100 Hz	Requirement driven by offset of beam from center of mirror; see 7.2.3
Vertical noise	3×10^{-14} m/√Hz at 10 Hz, falling	Assumes vertical to

	to 3x10^{-15} m/√Hz at 100 Hz	longitudinal motion coupling of 0.001; see 7.2.4
Transverse noise	3x10^{-14} m/√Hz at 10 Hz, falling to 3x10^{-15} m/√Hz at 100 Hz	See 7.2.5

7.2.1 Longitudinal noise

The longitudinal noise requirement is driven by the need for the mode cleaner not to introduce frequency noise into the light transmitted through it.

These requirements are less stringent than the requirements for the test masses; however, given the limited space within the HAM chambers, the required seismic isolation may be difficult to obtain, and given the small beam size on the optic, the internal thermal noise may be large.

7.2.2 Pitch noise

This requirement is based on coupling of tilt to displacement motion when the beam is not centered on the optic. Assuming the beam is centered within 1mm, the displacement noise is as specified.

7.2.3 Yaw noise

This requirement is based upon the same considerations as for pitch noise.

7.2.4 Vertical noise

The mode cleaner is short and can have the input and output beams horizontally aligned. Therefore, the requirement quoted assumes a vertical to horizontal coupling of 0.001 based upon experience with achievable levels of residual coupling.

The frequency of the vertical bounce mode is not required to be below 10 Hz, but any isolated noise peaks due to the suspension fiber resonances must be sufficiently narrow where they appear in the IFO output spectrum that they are easily filtered without substantial loss of detector bandwidth.

7.2.5 Transverse noise

In the transverse direction, the losses of the pendulum should be comparable to those of the longitudinal direction and there is no fixed misalignment giving a minimum coupling; this requirement is based on couplings which are now assumed to be 0.001.

7.3 Seismic Isolation Performance

As with the thermal noise requirements, the specified seismic noise requirements are much less stringent than for the test mass suspensions and should easily be achieved by the mode cleaner mirror suspensions. These requirements scale from the test mass requirements in the same way as the thermal noise requirements. [stuff on blades moved to3.1] The interchangeability of vertical and transverse motion mentioned in section 3.2.3.2.5 also applies here.

7.4 [Control performance – moved to 3.4]

The control performance requirements are the same as those for the test mass suspensions.

8 Interfaces [moved to 3.8 and content replaced by reference]