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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).

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 (PRM and SRM), the intra-recycling-cavity optics (PR2, PR3, SR2, SR3) [new], 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).

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 (T010103-05.

1.2 Applicable Documents

- 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).
- Generic Requirements & Standards for Detector Subsystems (LIGO-E010123)
- LIGO Vacuum Compatibility, Cleaning Methods and Qualification Procedures (LIGO-E960022)
- LIGO Vacuum Compatible Materials List (LIGO-E960050)

- Vacuum Hydrocarbon Outgassing Requirements (LIGO-T040001)
- Advanced LIGO Suspension System Conceptual Design (LIGO-T010103-05).
- Seismic Isolation System Payload Mass Properties (LIGO-E040136)
- Low-frequency Cutoff for Advanced LIGO (LIGO-T020034-01-D).
- 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)
- Alignment Sensing/Control Preliminary Design (LIGO-T970060-00)
- ASC Initial Alignment Procedures (LIGO-T970151-C)
- Input to the OSEM selection review decision (LIGO-T040110-01)
- Preliminary investigation of the effects of massive resonant elements suspended from the SEI platforms (ALUKGLA0050aAUG03)
- Design Requirements for the In-Vacuum Mechanical Elements of the Advanced LIGO Seismic Isolation System for the HAM Chamber (E030180-02)
- Design Requirements for the In-Vacuum Mechanical Elements of the Advanced LIGO Seismic Isolation System for the BSC Chamber (E030179-A)
- Interface Control Document (ICD): Seismic Isolation (SEI) – Suspension, UK Scope (SUS/UK) (E050159-00, chapter of E030647)
- Test Mass Material Down-select Plan (LIGO-T020103-08)
- Advanced LIGO Substrate Selection Recommendation (LIGO-M040405-00)
- Responsibilities for Elements of the Stable Recycling Cavities (M080038-03)
- Displacement Noise in Advanced LIGO Triple Suspensions (LIGO-T080192-01)
- Conceptual Design of Beamsplitter Suspension for Advanced LIGO (LIGO-T040027-03) [added]
- Initial Alignment System (IAS) Design Requirements Document, T080307

  (Note that the version number for various documents above may not be the latest. The latest version should always be referred to).

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.

12 Sep 2008 – -04. Revised BS, FM sections. Added mental health warnings for ETM/ITM and RM sections. Changes from -03 noted in [].

10 Nov 2008 -05 Revised structure resonance, RM, IMC sections. (Note: version-05 became -v1).

Oct 2009: -v2 This contains updated info on version number of Optical Layout for Advanced LIGO, T010076-02, (currently at version 2). Also sentence added noting that T010076-02 contains information on the beam heights above/below the optical tables.

7 Nov 2011: -v3 Transverse technical noise level set at 1/10 of the longitudinal seismic noise, bringing it into line with other technical noise sources. Previously it was set at 1/100 of the longitudinal seismic noise.

6 July 2012: -v4. Removed info regarding sapphire and update with silica. Removed references to ribbons and updated with dumbbell fibres. Added reference to Initial Alignment System (IAS) Design Requirements Document. Other minor updates.

15 May 2013: -v5. Corrected typos in BS yaw and pitch requirements in table 4 page 18. Yaw now reads "…falling to 4×10^{-17} rad/√Hz at *40* Hz.." and pitch has m/rt Hz changed to rad/rt Hz in one place.

2 General description

2.1 Functions of the Cavity Optics Suspensions

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
- Support the optic so that it hangs freely but is constrained against damage from large motions such as those from earthquakes
- 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
- Accommodate (where applicable) a thermal compensation system for the optic
- Accommodate (where applicable) a reaction chain for the optic

2.2 Procedure for Determining Requirements [deleted as of historical interest only]

2.3 Note on Geometrical Terminology

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

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

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.
- For the test mass suspensions 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. For other suspensions there may be a vertical mode peak at a higher frequency.
- There may be a peak due to the highest frequency roll mode at approximately $\sqrt{2}$ times the highest vertical mode frequency.

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

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) 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.

3.4 Control Performance

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. See Section 3.6 for requirements on resonances of the structure as a whole.

3.5 Installation support functions

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, T010076-02, to LIGO-I precision, as described in T970151-C, ASC Initial Alignment Procedures and reproduced in Table 1. Note that T010076-02 also contains information on the beam heights above/below the optical tables (see table 2 of T010076-02). 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.) **With regard to alignment requirements for optics, this document is superceded by T080307 "Initial Alignment System (IAS) Design Requirements Document".**

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 relative to the freely suspended masses 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. The chosen design for all suspended optics is a stop with a silica tip embedded in fluorel. See T060139 and D060544.

3.6 Structure Resonances

The suspension structures need to be stiff to avoid resonances at frequencies that may interfere with the control system of the active seismic platforms (ALUKGLA0050aAUG03). The original requirement for structures in both the BSC and HAM chambers was that no mode of the pendulum structure with non-trivial effective mass shall have a resonant frequency below 150 Hz assuming an infinitely rigid attachment surface (E030179-A, E030180-02). This requirement stands for the HAM suspensions. However as design proceeded on the ETM/ITM and BS/FM structures it became clear that 150 Hz was not achievable without struts and a partial exemption has been granted as follows (E050159-00, chapter of E030647; email from D. Coyne to N. Robertson, 11/5/08):

- > 200 Hz first resonance for the upper structure
- > 100 Hz lower structure
- > 100 Hz combined upper and lower structure

3.7 Reaction Chains and Actuator Noise

In the baseline plan, the test masses 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

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. The chosen material is silica with dimensions mass, 40 kg; diameter, 34 cm; thickness, 20 cm.

4.2 Noise performance

Table 2: Noise performance requirements, test mass suspensions

Parameter	Measurement Band	Discussion
Test mass internal mode longitudinal thermal noise	5×10^{-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 $\mathrm{sqrt}(x^2+(10^{-3}z)^2)$	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.
Pitch noise	1×10^{-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	1×10^{-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	1×10^{-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	1/10 of longitudinal	Section 4.2.7 (and 4.2.2)

technical noise	pendulum thermal noise	
Vertical technical noise	1/10 of vertical thermal noise	Section 4.2.9 (and 4.2.5)
Transverse technical noise	1x10^{-17} m/√Hz at 10 Hz, falling roughly as $(1/f)^2$	Based on 10^{-3} coupling to longitudinal motion; Section 4.2.8 (and 4.2.6)
Roll noise (sapphire ITM only)	1.2x10^{-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.

Silica was chosen over sapphire as the test mass material after a downselection process (see M040405). The following graph (taken from, G040321) shows the expected internal thermal noise spectra. Coating and polishing losses are not considered in the spectra and are not considered intrinsic noise sources for the purposes of setting these requirements.

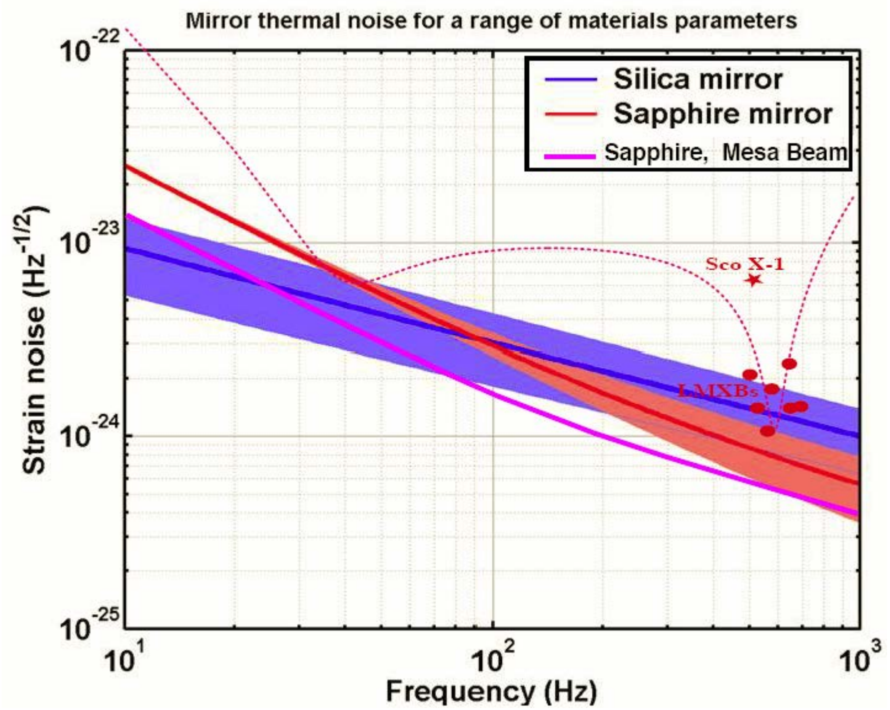

Figure 1: Intrinsic thermal noise of silica and sapphire test masses. Strain noise assumes noise from four test masses added in quadrature, dived by arm length. To turn the y axis into displacement of one mass, multiply by 4000/2 = 2000. Thus 10^-23 becomes 2 x 10^-20.

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 $1\text{x}10^{-19}$ m/√Hz at 10 Hz, with the natural rolloff of $(1/f)^2$. We will use dumbbell fibres to meet the pendulum thermal noise requirement. See T080091.

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 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 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 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. LIGO beams are a maximum of 6×10^{-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 $\sim 10^{6}$ 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 2×10^{-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.

4.2.6 Transverse thermal and seismic noise

In the transverse direction, the losses of the pendulum are expected to 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 longitudinal pendulum thermal noise. The requirement is based on an assumed 0.001 coupling of transverse to longitudinal motion.

4.2.9 Vertical technical noise

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

If we ever return to using sapphire then a requirement on roll noise is required. 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

Error! Bookmark not defined. $$\frac{\lambda\phi_0}{\pi G} = 8.5 \times 10^{-13}\,\mathrm{m/rad}$$

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.

5 HLTS and HSTS (formerly RM Suspension) Requirements

Early designs for AdvLIGO and earlier revisions of this document assumed arrangements for the power and signal recycling cavities similar to that of the (power) recycling mirror in Initial LIGO: the recycling mirror proper being suspended, relatively large and nearest the beamsplitter, with a number of non-suspended mode-matching optics outboard of it, i.e., IMMT1, IMMT2, IMMT3, PRM, BS, SRM, OMMT3, OMMT2, OMMT1. However the design has been revised to have the power and signal recycling mirrors still suspended, but rather smaller, and with two suspended mode matching optics nearer the BS in each cavity: PRM, PR2, PR3, BS, SR3, SR2, SRM.

PR3 and SR3 will have the same size optic as was planned for the PRM and SRM in the earlier design so that the R&D effort for what was the RM suspension can be salvaged. This will now be known as the HLTS (HAM Large Triple Suspension). The PRM, SRM and PR2 and SR2 will use the design developed for the input mode cleaner, now called the HSTS (HAM Small Triple Suspension).

All these suspensions mount (via bolts and/or clamps) on top of various HAM seismic isolation systems. Available height above the optics table is a tight constraint.

5.1 Assumptions and Dependencies

Peter Fritschel has analysed the longitudinal requirements for the HLTS and HSTS in T080192-01. The signal recycling cavity drives the requirements – the power recycling cavity requirement is taken to be the same. The requirement is binding on the three mirrors (PRM/PR2/PR3 or SRM/SR2/SR3) as a set.

5.2 Noise performance

Table 3: Noise performance requirements, recycling mirror suspensions

Parameter	Value	Discussion
Longitudinal + 0.001 vertical displacement noise due to all sources for set of three optics [was just longitudinal]	3×10^{-17} m/√Hz at 10 Hz, falling as $f^{-5/2}$ to 2×10^{-18} m/√Hz at 30 Hz [was 4×10^{-16} m/√Hz at 10 Hz, falling to 1.5×10^{-17} m/√Hz at 100 Hz]	See section 5.2.1 and the seismic isolation requirements.
Pitch noise	TBD	Previous requirement superceded by new layout and new wedge angles - see section 5.2.2.
Yaw noise	TBD	Previous requirement superceded by new layout and new wedge angles - see section 5.2.3.
Vertical displacement noise	Incorporated in longitudinal	See section 5.2.4.
Transverse noise	TBD	Previous requirement superceded by new layout and new wedge angles - see section 5.2.5.

5.2.1 Longitudinal + 0.001 vertical displacement

The coupling of SRCL noise to DARM falls off as f^{-2}, and the limiting noise source at higher frequencies is thermal noise, which will fall off as approximately $f^{-5/2}$, so only noise up to about 30 Hz is important. As a technical noise source, the net effect on DARM should be less than 10% of fundamental noise. This gives a recommended limit for all three optics (weighted $1^2 + 2^2 + 2^2$ for SRM/SR2/SR3) of $3\text{x}10^{-17}$ m/√Hz at 10 Hz, falling as $f^{-5/2}$ to $2\text{x}10^{-18}$ m/√Hz at 30 Hz, with an exception for a bounce mode peak for each suspension in the 20-30 Hz range. In fact as Peter Fritschel notes in T080192-01, this is somewhat unrealistic due to large seismic excitations of the HAM optics tables in the 10-20 Hz range together with limited height of the suspensions (which constrains the horizontal isolation) but is left in place as aspirational.

5.2.2 Pitch noise

TBD.

5.2.3 Yaw noise

TBD.

5.2.4 Vertical noise

This is now incorporated in the longitudinal per T080192-01 with an assumed coupling of 0.001.

5.2.5 Transverse noise

TBD.

5.3 Seismic isolation performance

Seismic noise is included in the noise requirements above. The interchangeability of vertical and transverse motion mentioned in section 5.2.5 also applies here.

6 Beamsplitter Suspensions [revised with reference to T080192-01]

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.

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 beamsplitter size and material. We assume a fused silica mirror with dimensions: m = 13.5 kg, diameter = 37 cm [was 35 cm], thickness = 6 cm.

6.2 Noise performance

Table 4: Noise performance requirements, beamsplitter suspensions

Parameter	Value	Discussion
Longitudinal and vertical noise: sqrt(x^2+$(0.001z)^2$) [was sqrt(x^2+$(0.000735z)^2$)]	6.4x10^{-18} m/√Hz [] at 10 Hz, falling to 2x10^{-19} m/√Hz at 40 Hz [was 2x10^{-17} m/√Hz at 10 Hz falling to 6x10^{-19} m/√Hz at 100 Hz] except for a bounce mode peak (around 16 Hz)	See section 6.2.1
Pitch noise	1.3x10^{-15} rad/√Hz at 10 Hz, falling to 4x10^{-17} rad/√Hz at 40 Hz [was 2.9x10^{-15} rad/√Hz at 10 Hz, falling to 8.6x10^{-17} m/√Hz at 100 Hz]	Requirement driven by offset of beam from center of mirror; see section 6.2.2
Yaw noise	1.3x10^{-15} rad/√Hz at 10 Hz, falling to 4x10^{-17} rad/√Hz at 40 Hz [was 2.7x10^{-14} rad/√Hz at 10 Hz, falling to 1x10^{-15} rad/√Hz at 100 Hz]	Requirement driven by offset of beam from center of mirror; See section 6.2.3
Transverse noise	2x10^{-14} m/√Hz at 10 Hz, falling roughly as 1/f	See section 6.2.5

6.2.1 Longitudinal and vertical [revised with reference to T080192-01]

The longitudinal displacement noise requirement is driven by the need to maintain the dark fringe at the output port. As described in T080192-01, the coupling factor from BS displacement to DARM is

$$x_{DARM} / x_{BS} = \pi / \sqrt{2}F \,,$$

where F is the arm cavity finesse and x is normal to the HR face of each optic. Because the cross-coupling from vertical is expected to be significant and because thermal and seismic are expected to be comparable in the 10-20 Hz range, the requirement is placed on a mixture of all longitudinal and vertical noise assuming a cross coupling of 0.001 from vertical to horizontal and is taken to be slightly above the expected pendulum thermal noise for a loss of 2x10^{-4} in the final wires:

sqrt(x^2+$(0.001z)^2$) < 6.4x10^{-18} m/√Hz at 10 Hz rolling off at $f^{-5/2}$ to 2x10^{-19} at 40 Hz

A narrow bounce mode peak is allowed (expected at around 16 Hz). (The above cross-coupling factor is more conservative than the 0.000735 used in earlier versions of the document.)

6.2.2 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 5 mm. [Stuff on ITM vertical wedge deleted as outdated.]

6.2.3 Yaw noise

This requirement has the same considerations as pitch noise. [Stuff on BS wedge deleted as outdated.]

6.2.4 Vertical noise [merged with 6.2.1]

6.2.5 Transverse noise

In the transverse direction, the losses of the pendulum are expected to 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 1.04×10^{-3} from 6.2.1.

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.

7 Folding Mirror Suspensions [revised with reference to T080192-01]

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.

The FM is governed by the most of the same considerations as the BS, so we take the joint longitudinal/vertical requirement from T080192-01.

7.1 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 = 13.5 kg, diameter = 37 cm, thickness = 6 cm.

7.2 Noise performance

Table 5: noise performance requirements, folding mirror suspensions

Parameter	Value	Discussion

Longitudinal and vertical noise: sqrt($x^2+(0.001z)^2$) [was sqrt($x^2+(0.000735z)^2$)]	6.4×10^{-18} m/√Hz [] at 10 Hz, falling to 2×10^{-19} m/√Hz at 40 Hz [was 2×10^{-17} m/√Hz at 10 Hz falling to 6×10^{-19} m/√Hz at 100 Hz] except for a bounce mode peak (around 16 Hz)	See section 7.2.1.
Pitch noise	1.3×10^{-15} rad/√Hz at 10 Hz, falling to 4×10^{-17} m/√Hz at 40 Hz [was 2.9×10^{-15} rad/√Hz at 10 Hz, falling to 8.6×10^{-17} m/√Hz at 100 Hz]	Requirement driven by offset of beam from center of mirror; see section 7.2.2.
Yaw noise	1.3×10^{-15} rad/√Hz at 10 Hz, falling to 4×10^{-17} rad/√Hz at 100 Hz [was 2.7×10^{-14} rad/√Hz at 10 Hz, falling to 1×10^{-15} rad/√Hz at 100 Hz]	Requirement driven by offset of beam from center of mirror; see section 7.2.3.
Transverse noise	2×10^{-14} m/√Hz at 10 Hz, falling roughly as 1/f	See sections 7.2.4, 7.2.5.

7.2.1 Longitudinal/vertical noise

As for the beamsplitter.

7.2.2 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.

7.2.3 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.

7.2.4 Vertical noise

[Merged with 7.2.1].

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. This does not change if the wedges in the ITM's are horizontal rather than vertical.

7.3 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.

8 Input 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 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.

8.1 Assumptions and Dependencies

Since the previous revision of this document there have been two major developments:

1. The IMC suspension design has been adopted (under the name HSTS) for the PRM, the SRM and PR2 and SR2, which have somewhat more stringent requirements.
2. The requirements for the IMC itself have become rather less stringent.

Therefore for reference, this section gives the requirements for the IMC itself, but in practice a suspension meeting the requirements of Section 5 will be used.

8.2 Noise performance

Table 6: Noise performance requirements, mode cleaner mirror suspensions

Parameter	Value	Discussion
Longitudinal noise + 0.001 vertical, all sources	$3x10^{-15}$ m/rtHz at 10 Hz falling to $2x10^{-17}$ m/rtHz at 100 Hz [was $3x10^{-17}$ m/√Hz at 10 Hz, falling to $3x10^{-19}$ m/√Hz at 100 Hz	See 8.2.1.
Pitch noise	TBD	See 8.2.2.
Yaw noise	TBD	See 8.2.3.

Vertical noise	Incorporated in vertical	Assumes vertical to longitudinal motion coupling of 0.001; see 8.2.4.
Transverse noise	TBD	See 8.2.5.

8.2.1 Longitudinal noise

Peter Fritschel (email to N. Robertson, 11/29/07) estimates a requirement on the total longitudinal noise (including cross coupling from vertical at 0.001) of 3×10^{-15} m/rtHz at 10 Hz falling to 2×10^{-17} m/rtHz at 100 Hz.

8.2.2 Pitch noise

TBD.

8.2.3 Yaw noise

TBD.

8.2.4 Vertical noise

Incorporated in longitudinal requirement assuming cross-coupling of 0.001.

8.2.5 Transverse noise

TBD.

8.3 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. The interchangeability of vertical and transverse motion mentioned in section 3.2.3.2.5 also applies here.