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- LIGO -
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Seismic Isolation Design Requirements Document		
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1	Introduction	1
1.1.	Purpose	1
1.2.	Scope	1
1.3.	Definitions	1
1.3.1.	Names of Components	1
1.3.2.	Definitions of Terms	4
1.4.	Acronyms	5
1.5.	Applicable Documents	5
1.5.1.	LIGO Documents	5
1.5.2.	Non-LIGO Documents	6
2	General description	7
2.1.	Specification Tree	7
2.2.	Product Perspective	8
2.3.	Product Functions	8
2.4.	General Constraints	8
2.5.	Assumptions and Dependencies	9
2.5.1.	Assumed System-Level Parameters	9
2.5.2.	Ground Noise	11
2.5.3.	Assumed Suspension Parameters	12
2.5.3.1	Mass of Test Masses	12
2.5.3.2	Suspension Resonances	13
2.5.3.3	Sensor range	13
2.5.3.4	Suspension actuator range	13
2.5.4.	Assumed Requirement on Optical-Beam Centering	14
2.5.5.	Assumed Worst-Case Drift of Seismic-Isolation Components	14
3	Requirements	15
3.1.	Requirements Flowdown From Detector	16
3.2.	Characteristics	17
3.2.1.	BSC-SEI Performance Characteristics	17
3.2.1.1	Optics-Table Vibration (Above 10 Hz)	17
3.2.1.2	Internal Resonances in Top Structure, Down Structure and Optical Platform	17
3.2.1.3	Internal Resonances in Mass Elements	18
3.2.1.4	Internal Resonances in Support Beam/Structure/Piers	18
3.2.1.5	Optics-Platform Low-Frequency Motion (From 0.1 Hz to 10 Hz)	18
3.2.1.6	Optics-Platform Drift (Below 0.1 Hz)	19
3.2.1.7	Stack-Actuator Requirements	20
3.2.1.8	Requirements on In-Vacuo Cabling	24
3.2.1.9	Required Size of Optical Platform	25
3.2.1.10	Requirements on Support-Beam Bellows	25
3.2.2.	HAM-SEI Performance Characteristics	25
3.2.2.1	Optics-Platform Vibration (Above 10 Hz)	25
3.2.2.2	Optics-Platform Low-Frequency Motion (From 0.1 Hz to 10 Hz)	26
3.2.2.3	Optics-Platform Drift (Below 0.1 Hz)	27
3.2.2.4	Actuation Requirements	27
3.2.2.5	Requirements on In-Vacuo Cabling	27
3.2.2.6	Required Size of Optical Platform	27

3.2.2.7	Requirements on Support-Beam Bellows	27
3.2.3.	Physical Characteristics	27
3.2.4.	Interface Definitions	27
3.2.5.	Reliability	27
3.2.6.	Maintainability	28
3.2.7.	Environmental Conditions	28
3.2.7.1	Natural Environment.....	28
3.2.7.2	Induced Environment.....	29
3.2.8.	Transportability.	29
3.3.	Design and Construction.	30
3.3.1.	Materials and Processes	30
3.3.1.1	Finishes	30
3.3.1.2	Materials	30
3.3.1.3	Processes.....	30
3.3.2.	Component Naming	31
3.3.3.	Workmanship	31
3.3.4.	Interchangeability	31
3.3.5.	Safety	31
3.3.6.	Human Engineering	31
3.3.7.	Assembly and Maintenance	31
3.4.	Documentation	32
3.4.1.	Specifications	32
3.4.2.	Design Documents	32
3.4.3.	Engineering Drawings and Associated Lists	32
3.4.4.	Technical Manuals and Procedures	32
3.4.4.1	Procedures.....	32
3.4.4.2	Manuals.....	32
3.4.5.	Documentation Numbering.....	32
3.4.6.	Test Plans and Procedures	33
3.5.	Logistics	33
3.6.	Precedence	33
3.7.	Qualification	33
4	Quality Assurance Provisions.....	33
4.1.	General	33
4.1.1.	Responsibility for Tests	33
4.1.2.	Special Tests	33
4.1.2.1	Engineering Tests.....	33
4.1.2.2	Reliability Testing.....	34
4.1.3.	Configuration Management	34
4.2.	Quality conformance inspections	34
4.2.1.	Inspections	34
4.2.2.	Analysis.	34
4.2.3.	Demonstration.....	34
4.2.4.	Similarity	35
4.2.5.	Test	35
5	Preparation for Delivery	35

5.1.	Preparation	35
5.2.	Packaging	35
5.3.	Marking	36
6	Notes	36
Appendix A	Anticipated Drift of a Four-Layer Stack With Viton Springs	36
Appendix B	Basis for Vibration Requirement on the BSC Seismic-Isolation Transfer Functions	38
Appendix C	Basis For Vibration Requirement related to thermal Noise Affecting the Optics Platform	41
Appendix D	Basis for Low-Frequency Motion Requirement	42
Appendix E	Effect of Daily Thermal Fluctuations	44
Appendix F	Basis for the cabling Requirements	45
Appendix G	Basis for Vibration Requirement on the HAM Seismic-Isolation Transfer Functions	46

1 INTRODUCTION

1.1. Purpose

This Design Requirements Document (DRD) for the Seismic Isolation subsystem (SEI) identifies the information necessary to define the SEI subsystem and to quantify its relationship to other subsystems. This includes:

- Objective and scope of the SEI subsystem
- Subsystem definition
- Requirements flowdown
- Design Requirements
- References to interface control documentations
- References to testing criteria

1.2. Scope

The Seismic Isolation subsystem provides a vibrationally quiet platform for interferometer components inside the vacuum system. The requirements defined herein relate to the stability, the level of vibration of the isolated surfaces and the actuators needed for the seismic isolation subsystem. The seismic isolation subsystem starts with support piers that rest on the facility floor and end at the optical platforms inside the vacuum chambers, to which other optical components and support equipment are attached. Seismic isolation of components external to the vacuum system (such as laser/optical tables) is outside the scope of SEI.

This DRD covers the requirements for this subsystem as they flow down from its interactions with other detector subsystems. There are two different seismic isolation designs, one for HAM chambers and one for BSC chambers, that are both covered in this document. The conceptual design of the SEI is the subject of another document, so that conceptual design information only appears herein to clarify the requirements.

1.3. Definitions

1.3.1. Names of Components

The Seismic isolation subsystem consists of assemblies in, and surrounding, the HAM and BSC chambers that are composed of the following elements:

- The *Optics Platform* is the table-like surface that has been isolated from vibration and has provisions for mounting optical components (both fixed and suspended), stray-light shields and

cabling.

- *Spring Elements* are the compliant elements of the seismic isolation system.
- *Mass Elements* are inertial elements that separate the spring elements.
- A *Stage* refers to a mass-element/spring-element pair, that comprises a tuned filter to block transmission of seismic noise and vibration.
- The *Support Platform* provides a flat surface onto which the cascaded stages are mounted.
- The *Support Beam* provides support for the support plate and transfers the weight of the isolation components and payload from within the vacuum chamber to supporting structures outside the vacuum chamber.
- The *Support-Beam Bellows* provide a flexible vacuum connection between the support beam and the vacuum chamber.
- *Actuators* allow the position and orientation of the seismic isolation and payload to be adjusted. These provide for both coarse and fine adjustment. Coarse and fine actuation may be accommodated in either a single modular unit or in separate modular units, to be decided as an outcome of the preliminary SEI design.
- *Coarse* adjustments have a larger range and are not intended to be used while maintaining interferometer lock.
- *Fine* adjustments have a more limited range than coarse adjustments and may be used without disrupting a locked state of the interferometer.
- *Active Isolators* are modules that incorporate local sensing and feedback actuation to achieve enhanced low-frequency vibration isolation.

Figures 1 through 4 below illustrate the relationships among these parts.

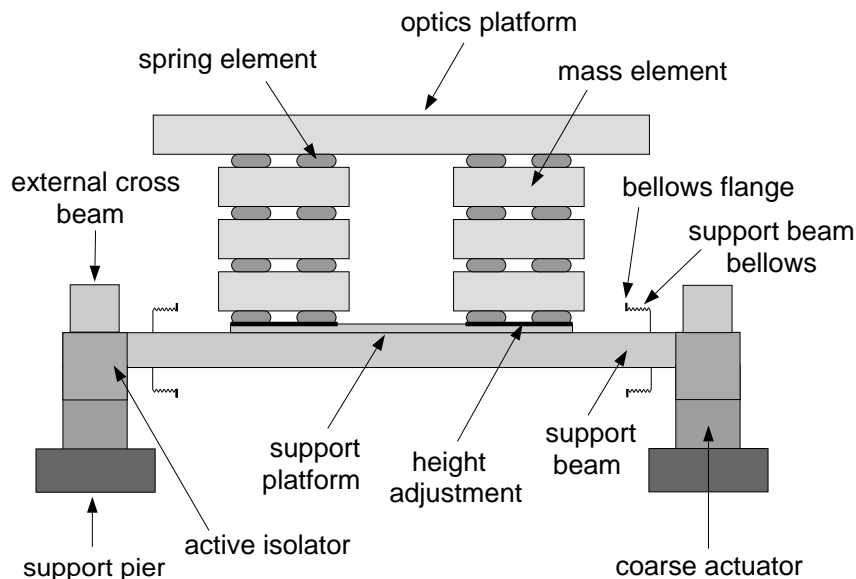


Figure 1: Naming convention for conceptual HAM-SEI design

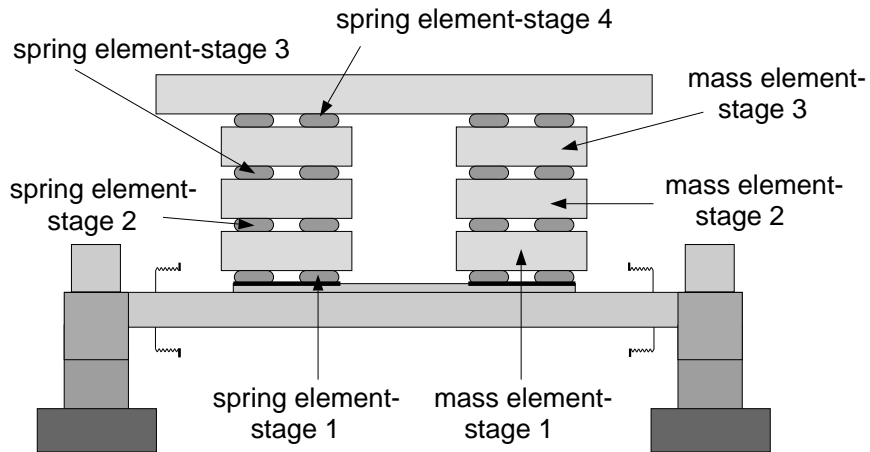


Figure 2: Naming convention for conceptual HAM-SEI design

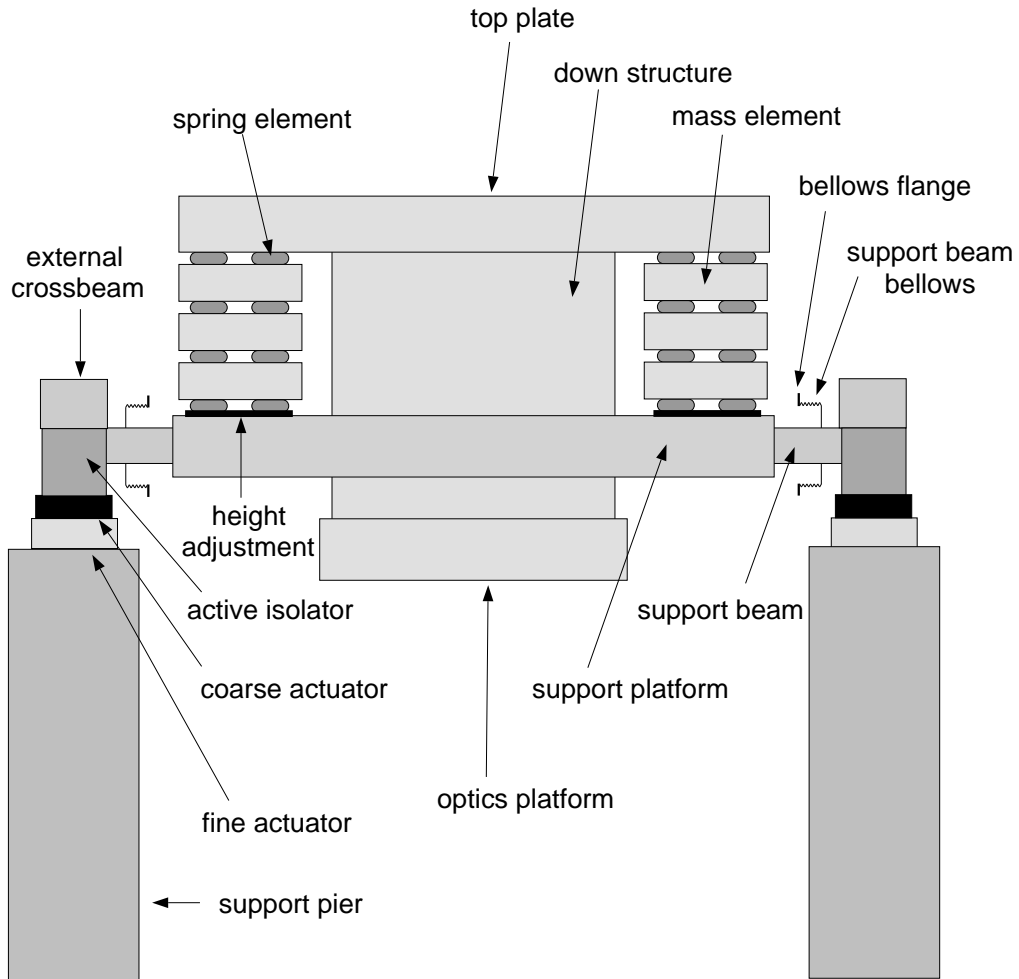


Figure 3: Naming convention for conceptual BSC-SEI design

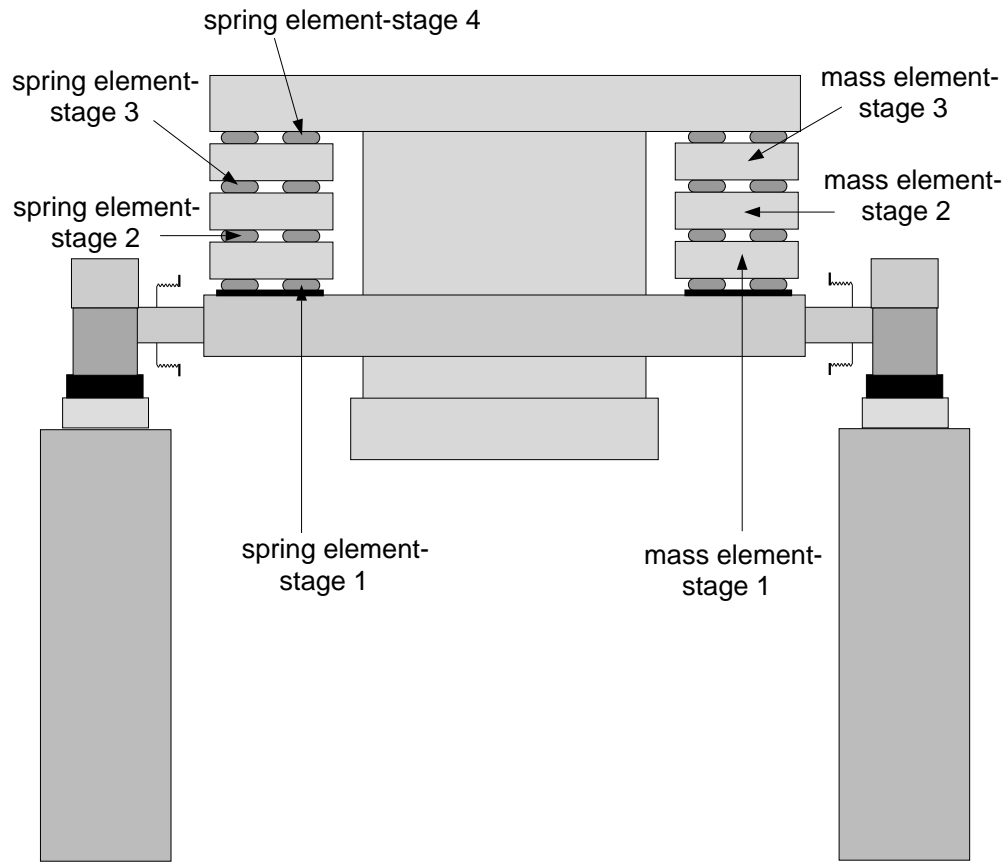


Figure 4: Naming convention for conceptual BSC-SEI design

1.3.2. Definitions of Terms

- *lock* indicates the state of the interferometer when all optical cavities are resonating stably with the light
- *lock acquisition* indicates the process of bringing the interferometer into resonance
- *lock maintenance* indicates the process of maintaining resonance in all optical cavities of the interferometer
- *amplitude spectral density* (sometimes referred to as *amplitude spectrum*) indicates the square root of the power spectral density

1.4. Acronyms

- IFO indicates Interferometer
- SEI indicates Seismic Isolation subsystem
- SUS indicates Suspension subsystem
- IOO indicates Input/Output Optics subsystem
- COC indicates Core-Optics Components subsystem
- COS indicates Core Optics Support subsystem
- ASC indicates Alignment Sensing and Control subsystem
- LSC indicates Length Sensing and Control subsystem
- HAM indicates horizontal-access, vacuum chamber used for input/output optics
- BSC indicates vacuum chamber type used for beam splitters and test masses
- RMS indicates root-mean-square as in “RMS motion”

1.5. Applicable Documents

1.5.1. LIGO Documents

The following documents are applicable:

- *LIGO Science Requirements Document* (LIGO-E950018-02-E)
- *Detector Construction Phase Implementation Plan* (LIGO-140151 Rev. B)
- *LIGO Vacuum Compatibility, Cleaning Methods and Procedures* (LIGO-E960022-00-D)
- *LIGO Project System Safety Management Plan*
- *Suspension Design Requirements Document* (LIGO-T950011-06-D)
- *Measurement of Ambient Relative Test Mass Motion in the 40 M Prototype* (LIGO-T950038-R)
- *Response of Pendulum to Motion of Suspension Point* (LIGO-T960040-00-D)
- *DRAFT Detector Alignment Sensing/Control Design Requirements Document* (LIGO-T952007-00-I)
- *ASC Optical Lever Design Requirement Document* (LIGO-T950106-01-D)
- *SYS Design Requirements Document* (TBD)
- *Effect of Microseismic Noise on a LIGO Interferometer* (LIGO-T960187-01-D)
- *Effect of Earth Tide on LIGO Interferometers* (LIGO-T970059-01-D)
- *SEI Interface Control Document* (LIGO-T970064-01-D)
- *Specification Guidance for Seismic Component Cleaning, Baking, and Shipping Preparation*

(LIGO-L970061-00-D)

- *LIGO Naming Convention* (E950111-A-E)
- *Thermal Noise Requirements for HAM Seismic Isolation* (LIGO-T960188-00-D)

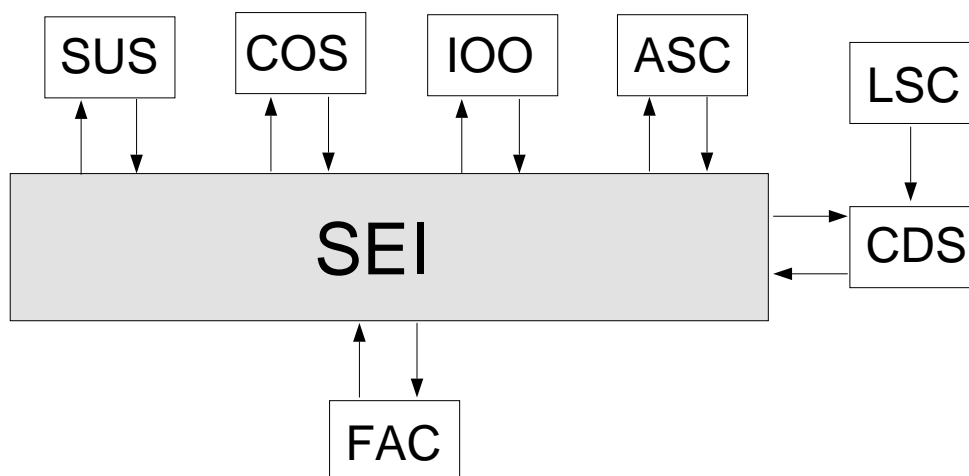
1.5.2. Non-LIGO Documents

The Tides of Planet Earth by Paul Melchior (Pergamon Press, Oxford, 1978)

Figure 5: Document location in LIGO specification tree.

2.2. Product Perspective

The relation of the SEI subsystem to other detector subsystems and the facilities (FAC) is shown below. The seismic isolation is supported by the facility floor and will support equipment belonging to the SUS, COS, IOO and ASC subsystems. CDS cabling will be attached to the seismic isolation and CDS will monitor and provide signals to seismic isolation equipment.

**Figure 6: Relationship of SEI to other subsystems.**

2.3. Product Functions

The seismic isolation system must fulfill the following general requirements:

- Provide stable support for the payload.
- Maintain the total motion of the test mass within a range suitable for lock acquisition and maintenance, using the suspension actuators.
- Minimize vibration of the optical-table surface to which optical components are mounted.
- Provide adequate space for mounting of components and adequate space for access to components.

2.4. General Constraints

- LIGO must operate continuously, with a minimum of disruptions due to loss of lock events. This constrains the allowable drift rates for the seismic isolation components, particularly the spring elements.
- LIGO interferometers have strict vacuum-compatibility requirements which constrain the material choices for spring elements to those materials compatible with *LIGO Vacuum Compatibility, Cleaning Methods and Procedures* (LIGO-E960022-00-D). Wherever possible,

material choices should be conservative with regard to vacuum compatibility.

- Most of the critical LIGO interferometer components are supported, either directly or indirectly, by the seismic isolation. Thus the seismic isolation will be required to be installed in the earliest stages of the detector integration process. This constrains the design to be conservative, so as to guarantee readiness at the beginning of integration, but readily upgradeable to higher performance without major replacement of equipment.

2.5. Assumptions and Dependencies

2.5.1. Assumed System-Level Parameters

The following factors affect the SEI requirements and, if these change, then the requirements will have to be changed:

Stack payload (including all suspended or fixed-mount optics, auxiliary components, and counterweights) for both HAM and BSC chambers is assumed to be 225 kg.

Stack payload is balanced.

Optical beam height in the HAM chamber is nominally¹ 20 cm above the optics table mounting surface. Consequently the optics table mounting surface is 10 cm below the HAM aperture centerline.

The nominal optical beam height is 10 cm below the beam tube centerline and 70 cm below the BSC optics table mounting surface. Consequently the BSC optics table mounting surface is 60 cm above the BSC aperture centerline.

Ambient temperature variations in the vicinity of vacuum chambers (in the LVEA and VEAs) are less than 3.9K peak-to-peak including seasonal changes, and can reasonably be expected to vary daily by less than 1.1 K.

1. The optical path deviates from horizontal due to refraction through wedged optics so that beam height above the optic table mounting surface is chamber dependent. Specific locations (deviations from nominal position) are dependent upon the Detector Systems optical and physical layouts.

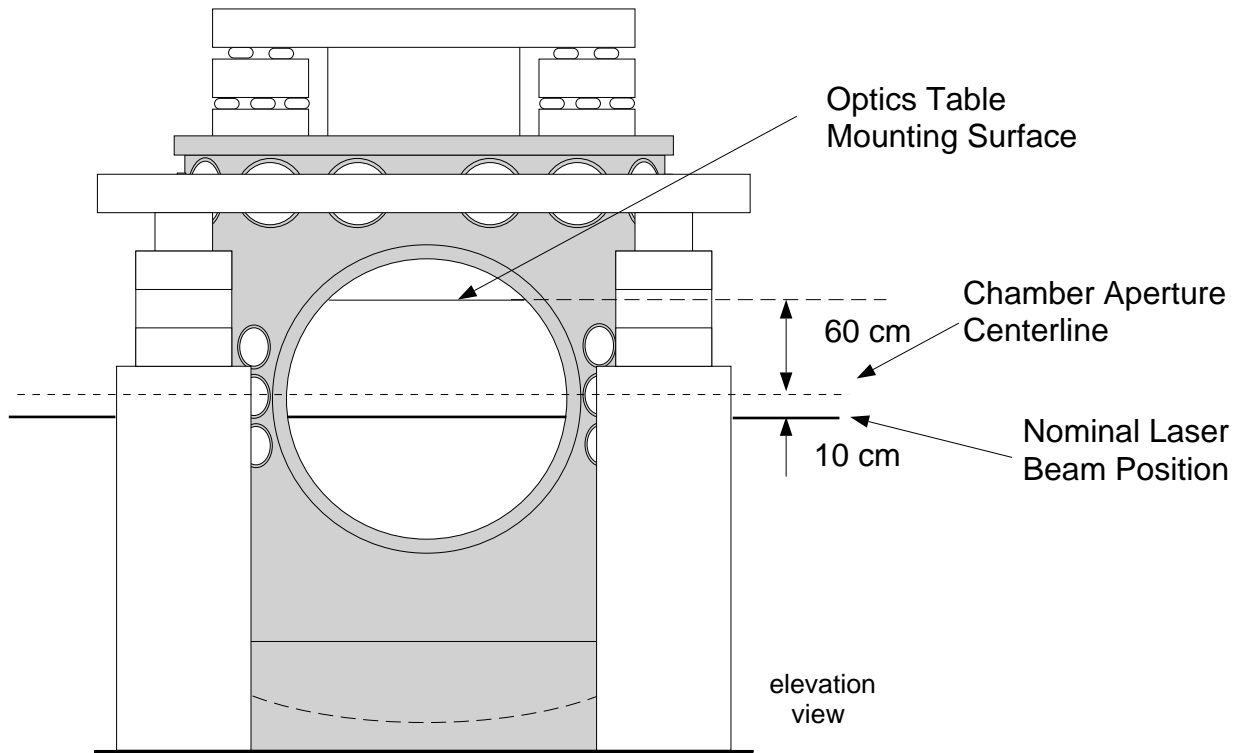


Figure 7: BSC-SEI Optics Table Mounting Surface Location Relative to the Nominal Laser Beam Plane

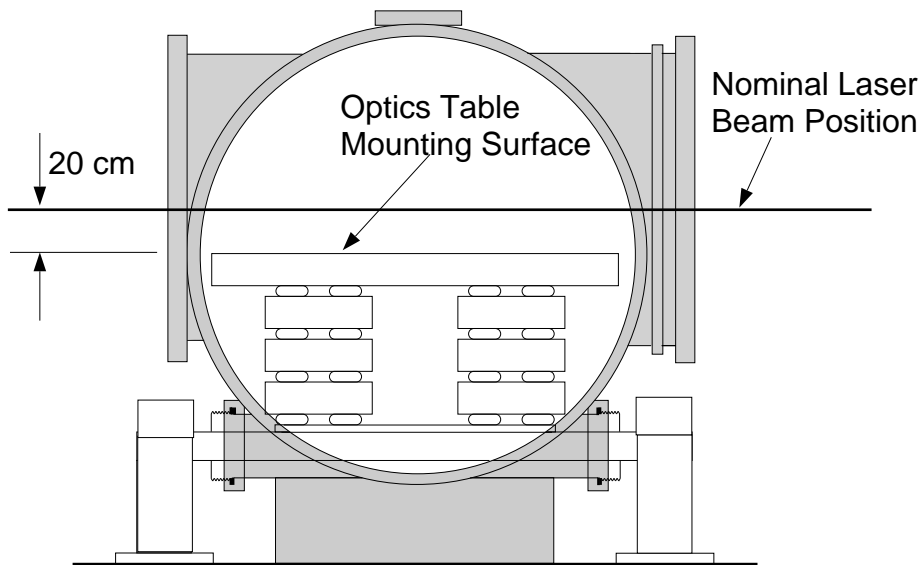


Figure 8: HAM-SEI Optics Table Mounting Surface Location Relative to the Nominal Laser Beam Plane

2.5.2. Ground Noise

Vibration of the floor in the LVEA and VEA's is estimated based on seismic measurements at the sites prior to erection of the buildings and support equipment. Approximate power-law fits to the ground noise at Livingston and Hanford were prepared by L. Sievers, based on measurements by A. Rohay¹. Results for both sites are given in Figure 9.

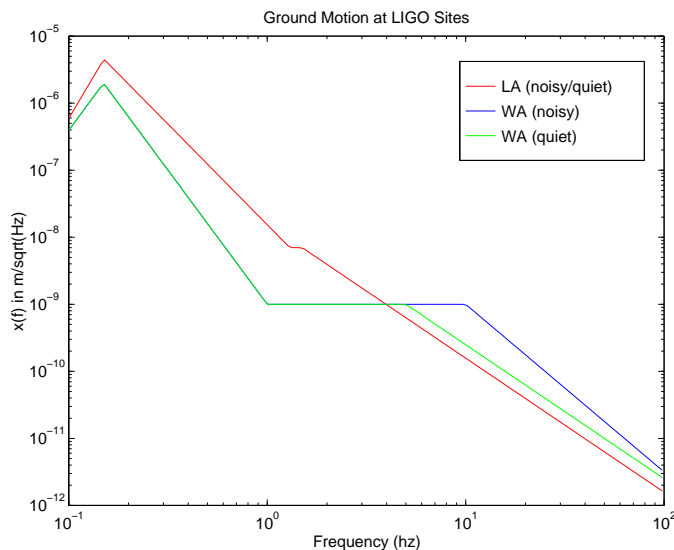


Figure 9: Characteristic ground noise at the observatory sites.

The Livingston noise spectrum places the most stringent requirements on total (RMS) motion, but the measured noise at the Hanford site was greater at higher frequencies. A composite ground-noise spectrum $G(s)$ was compiled to serve as the basis for deriving the requirements on transmission of vibration for the seismic isolation. This composite curve was obtained by concatenat-

1. A. Rohay, *Ambient Ground Vibration Measurements at the Hanford, Washington LIGO Site* (LIGO-C950572-02-D1); A Rohay, *Ambient Ground Vibration Measurements at the Livingston, Louisiana LIGO Site* (LIGO-C961022-A)

ing the Livingston noise at frequencies below 4 Hz with the LIGO Standard Spectrum above 4 Hz. The composite curve is shown in Figure 10. Recently data on the seasonal variation of the

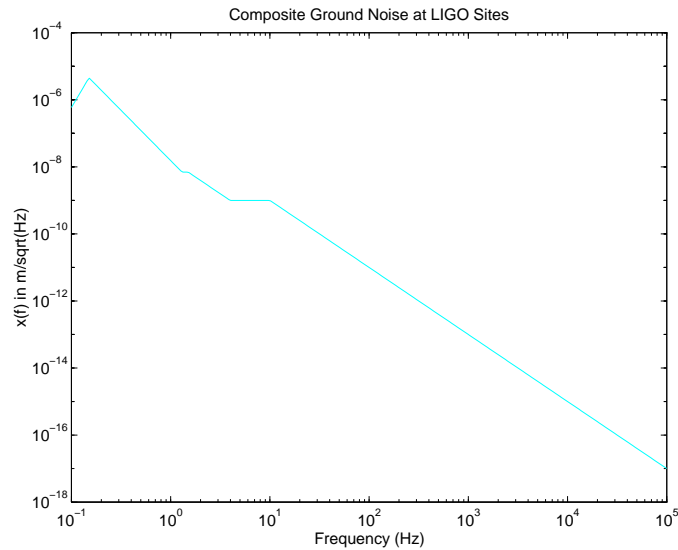


Figure 10: Ground noise spectrum assumed for SEI design.

microseismic peak has been obtained and reviewed by LIGO (LIGO-T960187-01-D). Performance analyses related to suppression of the microseismic peak should use this reference for the disturbance environment.

The ground noise is assumed to be isotropic, i.e., the same for translation along three orthogonal axes. There is no data available for fluctuating ground tilt and any such tilt is assumed to have negligible effect on the seismic isolation¹. If the ground noise exceeds this spectrum, then the required seismic-isolation transfer functions will need revision.

2.5.3. Assumed Suspension Parameters

2.5.3.1 Mass of Test Masses

The test masses are assumed to have a mass of 10.7 kg, based on 25-cm-diameter by 10-cm-thick dimensions. This principally affects the estimates of test-mass kinetic energy used here, which are used to estimate the maximum allowable test-mass velocity. The use of larger test masses could change the consideration of actuation requirements for handling the microseismic peak.²

-
1. Translations at the base of support piers could give rise to rotations of the support structure, which are non-negligible in their effect on the optical platform.
 2. SUS actuator-force limitations and their relation to SEI are described in Appendix D. Larger test masses could require a redesign of either the SUS or SEI actuators.

2.5.3.2 Suspension Resonances

2.5.3.2.1 Mode-Cleaner-Mirror Suspensions

Transfer functions for the suspension of mode-cleaner mirrors have been assumed in the derivation of the transmission requirements for the BSC seismic isolation. These had the following properties¹:

- A single-stage pendulum transfer function with resonant frequency of 0.74 Hz
- A vertical spring transfer function with resonant frequency of 11 Hz.
- A pitch-mode transfer function with resonant frequency of 0.60 Hz.
- A yaw-mode transfer function with resonant frequency of 0.50 Hz.

2.5.3.2.2 Test-Mass Suspensions

Transfer functions for the test-mass suspension have been assumed in the derivation of the transmission requirements for the BSC seismic isolation. These had the following properties²:

- A single-stage pendulum transfer function with resonant frequency of 0.74 Hz
- A vertical spring transfer function with resonant frequency of 11 Hz.
- A pitch-mode transfer function with resonant frequency of 0.60 Hz.
- A yaw-mode transfer function with resonant frequency of 0.50 Hz.

2.5.3.3 Sensor range

The range of the suspension's sensor is of order 1mm. The required positioning accuracy for the sensor relative to the suspended optic's magnet is of order 0.2 mm.

2.5.3.4 Suspension actuator range

The following ranges have been assumed for suspension actuators³ (see Figure 14 on page 20 for coordinate definitions):

- The test mass actuator's range is $8 \times 10^{-5} m_{pp}$ in the x direction and 2 mrad_{pp} about the y and z axes.
- The beam splitter actuator's range is at least $8 \times 10^{-5} m_{pp}$ in the x direction and 2 mrad_{pp} about y and z axes.
- The mode cleaner actuator's range is at least $8 \times 10^{-5} m_{pp}$ in the x direction and 2 mrad_{pp} about the y and z axes.

It has been assumed that the microseismic peak places no requirement for actuation on the seismic isolation. This is based on the fact that estimates of the kinetic energy of 40-Meter-IFO test masses, based on measurements of relative motion in the 40-Meter Interferometer, are within a factor of two of the estimated kinetic energy for the LIGO test masses in Livingston. It is currently believed that this small difference in test-mass kinetic energies can be readily accommo-

1. *Suspension Design Requirements Document* (LIGO-T950011-07-D)

2. *Suspension Design Requirements Document* (LIGO-T950011-07-D)

3. S. Kawamura private communication, 4/6/96.

dated in the design of the suspension actuators.

2.5.4. Assumed Requirement on Optical-Beam Centering

The centering requirement for the beam on the core optics and on the input optics is ~1 mm. Beam centering to within this range will be done manually through a combination of suspension and stack adjustments.

2.5.5. Assumed Worst-Case Drift of Seismic-Isolation Components

The spring elements of the seismic isolation system can be subject to drift over time. A worst-case assumption (see Table 1, below and Appendix A) was made for this drift and used to evaluate actuator requirements for both HAM and BSC isolation, based on the viton spring elements that were evaluated at MIT and which were installed into the 40-meter interferometer.

Table 1: Estimated drift in a 4 layer isolation stack with viton springs

category	yearly drift	thermal drift	drift rate at day 20
x translation	3 mm	$<1 \times 10^{-5}$ m/day	6×10^{-10} m/sec
y translation	3 mm	$<1 \times 10^{-5}$ m/day	6×10^{-10} m/sec
z translation	3 mm	$<1 \times 10^{-5}$ m/day	6×10^{-10} m/sec
x rotation	0.4 mrad	2×10^{-6} rad/day	8×10^{-11} rad/s
y rotation	0.4 mrad	2×10^{-6} rad/day	8×10^{-11} rad/s
z rotation	4 mrad	2×10^{-5} rad/day	8×10^{-10} rad/s

If larger amounts of drift are anticipated, based on future considerations, this may change the actuator requirements.

3 REQUIREMENTS

The isolation subsystems, namely seismic isolation and suspension, affect the interferometer sensitivity principally in terms of minimizing background motion of the test masses - referred to as displacement noise. The displacement noise target for the initial LIGO interferometer is shown below in Figure 9.

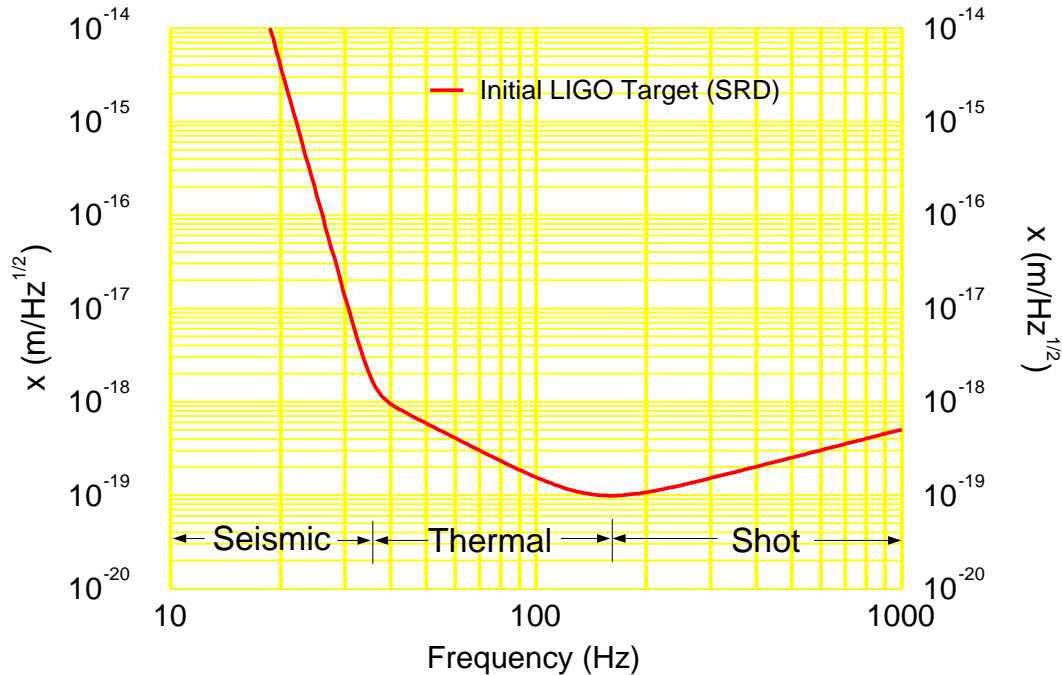


Figure 11: Displacement noise target for the initial LIGO interferometer.

Low vibration is required above 40 Hz. Below 40 Hz, transmitted seismic noise and thermal noise arising from the seismic-isolation components is expected to be the main contributor to interferometer noise. Above 40 Hz, transmitted seismic noise and thermal noise from the seismic-isolation components must be a factor of ten below the interferometer noise curve of Figure 11. The interferometer must be capable of acquiring lock and maintaining stable resonance with the light, which places a requirement on the allowable root-mean-square (RMS) motion of the optics platform and on the allowable drift of the optics platform. Drift due to the seismic-isolation components is minimized by making appropriate choices of materials and acceptable stresses. However there are additional drifts, due to motion of the earth's surface.

There will be two types of actuators incorporated into the SEI designs to remove drifts. One must operate while the interferometer is fully operational (lock maintenance mode) without causing disturbance. It will compensate for daily drifts in the arm lengths of the IFO, controlled by signals sent from the LSC subsystem. The other will provide coarse adjustment over a larger range. It will be used only when the IFO is not in operation and will be manually controlled. It will be used to correct for long term stack drifts that take place over the course of many months or years.

In addition to these requirements, there is a design goal to minimize the total weight of the passive seismic isolation components, in order to facilitate the introduction of active seismic isolation as an upgrade.

3.1. Requirements Flowdown From Detector

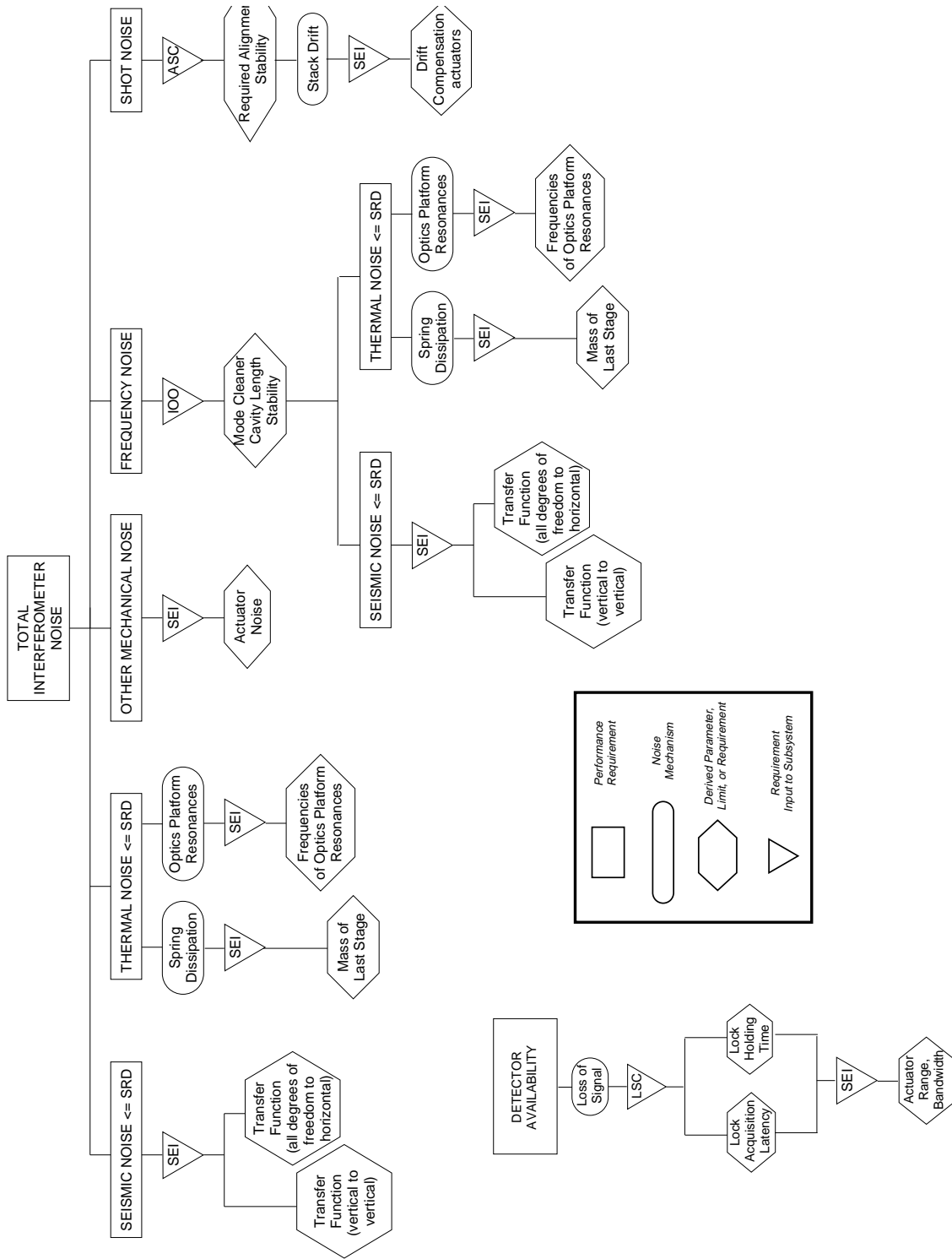


Figure 12: SEI Requirements Flowdown from Detector.

3.2. Characteristics

3.2.1. BSC-SEI Performance Characteristics

3.2.1.1 Optics-Table Vibration (Above 10 Hz)

The optical components in the BSC chambers with the greatest sensitivity to vibration are the test masses which were used as the basis for BSC-SEI vibration requirements. The estimate for the vibration requirements is discussed in the Appendix B. There are no requirements for the transfer function of each individual component in the SEI subsystem. However, the end-to-end (from ground to suspended mass) model of the isolation system must meet the seismic noise transmission requirements shown in Figure 13, assuming the ground motion shown in Figure 10.

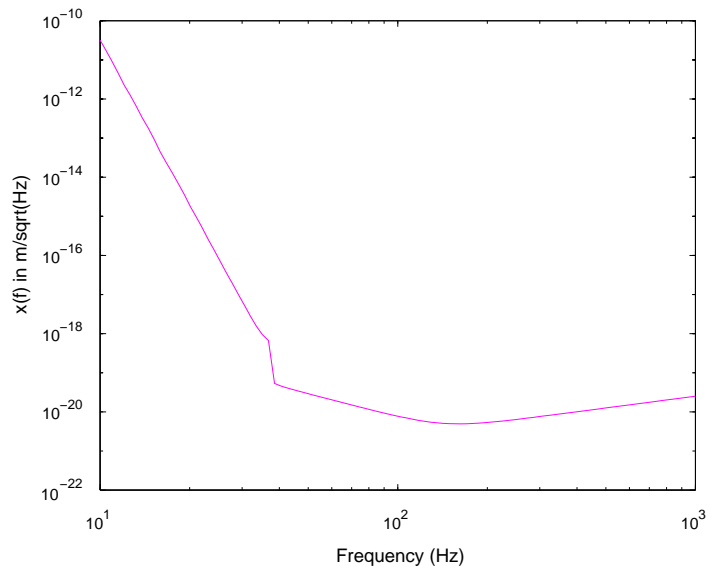


Figure 13: Requirement for seismic noise transmitted to suspended test mass.

3.2.1.2 Internal Resonances in Top Structure, Down Structure and Optical Platform

The resonant frequencies and Q's of internal resonances in the top structure, down structure and optical platform shall be set so that the seismic noise transmission and thermal noise fluctuation of the optical platform do not exceed the required values given in Figure 13. Modes with resonant frequencies above 600 Hz, effective masses above 230 kg and structural damping losses above 0.00025 will generally meet the thermal noise criteria. Alternatively the criteria given in Appendix C can be used to test resonances that do not meet these parameters.

3.2.1.3 Internal Resonances in Mass Elements

The resonant frequencies and Q's of internal resonances in the mass elements shall be set so that the seismic noise transmission does not exceed the required values given in Figure 13. Thermal noise from these resonances is not an issue.

3.2.1.4 Internal Resonances in Support Beam/Structure/Piers

The resonances in the supporting structure, consisting of the support beams and the support structure, shall have frequencies that are above 20 Hz¹, while still maintaining adequate clearance between the support beams and the support-beam bellows-ports (34-cm ID, nominal) to allow the full range of motion for the stack actuators. The dynamics of the support beam/structure/piers should be so designed that the end-to-end (ground to suspended mass) seismic noise transmission shall not exceed the requirements shown in Figure 13.

3.2.1.5 Optics-Platform Low-Frequency Motion (From 0.1 Hz to 10 Hz)

The two criteria for low-frequency motion are:

- that a stable resonant configuration can be acquired for the interferometer (lock acquisition)
- that this resonance condition can be maintained (lock maintenance)

In the absence of a lock-acquisition model for the LSC subsystem, we adopt the requirement that the RMS velocity of a test mass that is damped by the SUS sensor/actuators (pendulum Q = 3) but not controlled by LSC shall be less than or comparable to 1 micron/sec.

The lock-maintenance condition (based on the maximum force available from the SUS actuators before the output drivers saturate) requires that the RMS value of

$$\chi(s) = F^{-1}(s) \cdot T_{sus,xx}^{-1}(s) \cdot \left\{ [T^{sei+sus}(s)] \cdot \begin{bmatrix} G_{xx}^2(s) & 0 & 0 \\ 0 & G_{zz}^2(s) & 0 \\ 0 & 0 & G_{pitch}^2(s) \end{bmatrix} \cdot [T^{sei+sus}(s)]^* \right\}^{\frac{1}{2}}$$

where

1. The 20-Hz limit is based on the desire to limit total motion of the optical platform caused by resonances in the seismic isolation. This requirement may be relaxed to save weight in the support structure if modeling shows that a particular SEI design can meet total-motion requirements with a lower frequency.

$$[T^{sei + sus}] = \begin{bmatrix} T_{x,x}^{sus} & T_{x,z}^{sus} & T_{x,pitch}^{sus} \\ T_{z,x}^{sei} & T_{z,z}^{sei} & T_{z,pitch}^{sei} \\ T_{pitch,x}^{sei} & T_{pitch,z}^{sei} & T_{pitch,pitch}^{sei} \end{bmatrix} \cdot \begin{bmatrix} T_{x,x}^{sei} & T_{x,z}^{sei} & T_{x,pitch}^{sei} \\ T_{z,x}^{sei} & T_{z,z}^{sei} & T_{z,pitch}^{sei} \\ T_{pitch,x}^{sei} & T_{pitch,z}^{sei} & T_{pitch,pitch}^{sei} \end{bmatrix}$$

be less than 2.7 microns. Here $G(s)$ is the composite ground-noise spectrum, $T_{i,j}^{sei}(s)$ is the appropriate transfer function of the seismic isolation (where i refers to x or y), $T_{i,j}^{sus}(s)$ is the appropriate transfer function of the suspension, $*$ denotes the conjugate transpose of the matrix $[]$ and $F^{-1}(s)$ is the inverse of the saturated force limit of the SUS actuators, normalized to unity at DC. (See Appendix D for further information.)

3.2.1.6 Optics-Platform Drift (Below 0.1 Hz)

The optical platform shall not exceed the assumed drift values given in Table 1.

A related requirement is on the levelness on the optical platform. Figure 14 depicts the angular interplay between the optical platform, suspension/actuator heads, test mass, and laser beam. After initial alignment is achieved, drift in the optics platform angle must not move the suspension sensor out of range (~ 0.2 mm). This sets a maximum deviation from level for the optical platform of $0.2\text{mm}/45\text{cm} \sim 0.4$ mrad. According to table 1, this magnitude of tilt could occur only over a time period of order 1 year. (This is within the range of the SUS actuators.)

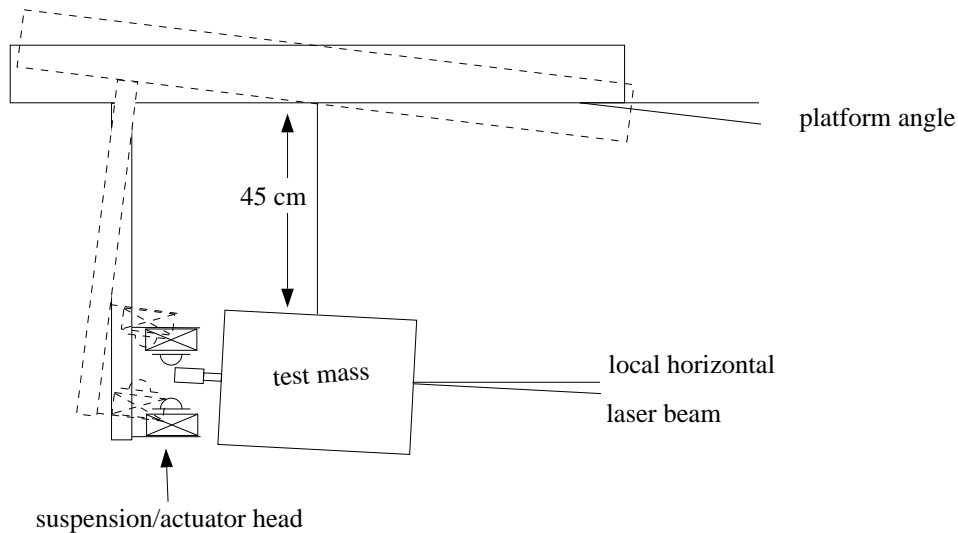


Figure 14: Dependence of suspension/actuator head position on optical platform pitch.

Daily fluctuations in the optical platform height must be less than 1 mm. Daily fluctuations in optical platform position along the optical beam axis must be less than 10 microns.

Counterweights shall be provided so that levelness can be achieved after the optical-platform and payload is installed or altered. The number and size of counterweights will vary from chamber to chamber, depending on the nature of the payload.

3.2.1.7 Stack-Actuator Requirements

The interferometer arm lengths vary over 6 and 12 hour periods due to earth tides. The differential displacement between two arms is approximately $10^{-4} m_{pp}$ and will require fine adjustment during interferometer lock maintenance mode. (See LIGO-T970059-01-D for details.) Temperature fluctuations in the slab of the facility are expected to be smaller than the air temperature fluctuations and to occur over much longer time scales. There is no requirement for fine actuators associated with BSC chambers in the LVEA. (The effect of daily temperature cycles is treated in Appendix E.)

3.2.1.7.1 Fine Actuator Requirements:

The fine actuators providing translation along the beam tube axis will be required on the BSC chambers at the mid and end stations to provide compensation for tidal and thermal drifts and microseismic peak motion ($\sim 1/6$ Hz). These fine actuators will be controlled by the LSC subsystem. The requirements for fine adjustment of stack translation during lock maintenance mode of the IFO are listed in the following:

1. Loads:

X-Direction:

bellows: 77 lb., 4 bellows 12.9 mm excursion

friction: 0 lb.

acceleration: 0 lb. diurnal, 0.2 lb. @ 1/6 Hz, 3350 lb. @ 20 Hz

2. Move Profile: Externally controlled

3. Motion:

Travel:

X: +/- 60 μm (120 μm P-P)

Cycle over life of actuator:

X: 30,000 diurnal, $1.05e8$ @ 1/6 Hz, $1.26e10$ @ 20 Hz

Velocity:

X: 0.01 $\mu\text{m/s}$, 25 $\mu\text{m/s}$ @ 1/6 Hz, 6000 $\mu\text{m/s}$ @ 20 Hz

Acceleration:

X*: 0 diurnal, 25 $\mu\text{m/s}^2$ @ 1/6 Hz, 360 mm/s^2 @ 20 Hz

*not to exceed the background ambient noise level into the stack

4. Accuracy: $\leq 1 \mu\text{m}$

5. Repeatability: $\leq 1 \mu\text{m}$

6. Resolution: $\leq 1 \mu\text{m}$

7. Backlash: None
8. Mechanical Vibration Limit:
 - 1/1000 of LIGO cultural input spectrum if an active isolation system(e.g. STACIS™ or similar) is mounted above the fine actuator,
 - or,
 - 1/10 of the LIGO cultural input spectrum if an active isolation system(e.g. STACIS™ or similar) is mounted below the fine actuator or no active isolation is used.
9. Duty Cycle: 100%
10. Life expectancy: 20 years
11. Environment:
 - Temperature: 22°C +/-2°C
 - Humidity: 20~70 %
 - Contaminants (cleanliness): Clean environment
 - Radiation: none
 - Electromagnetic Radiation: Shall satisfy the requirements of VDE 0871 Class A
12. Interfaces:
 - Mechanical: coarse actuator, support cross-member
 - Electrical: 110 V
 - Controls: Standard RS232 controls interface
 - Absolute position monitoring: Absolute encoders are required to monitor the position of the actuators at all time. This information will be incorporated into the device controller.
13. Smoothness:
 - Stiction, creak, and friction shall cause no motion greater than the level of seismic noise measured at the fine actuator location.
14. Transmitted Seismic Noise:
 - Above 40 Hz transmitted seismic noise from the seismic isolation system must be a factor of 10 below interferometer noise curve.
15. System Stiffness:
 - The overall stiffness of the components used for the fine actuator system must meet the stack attenuation goals.

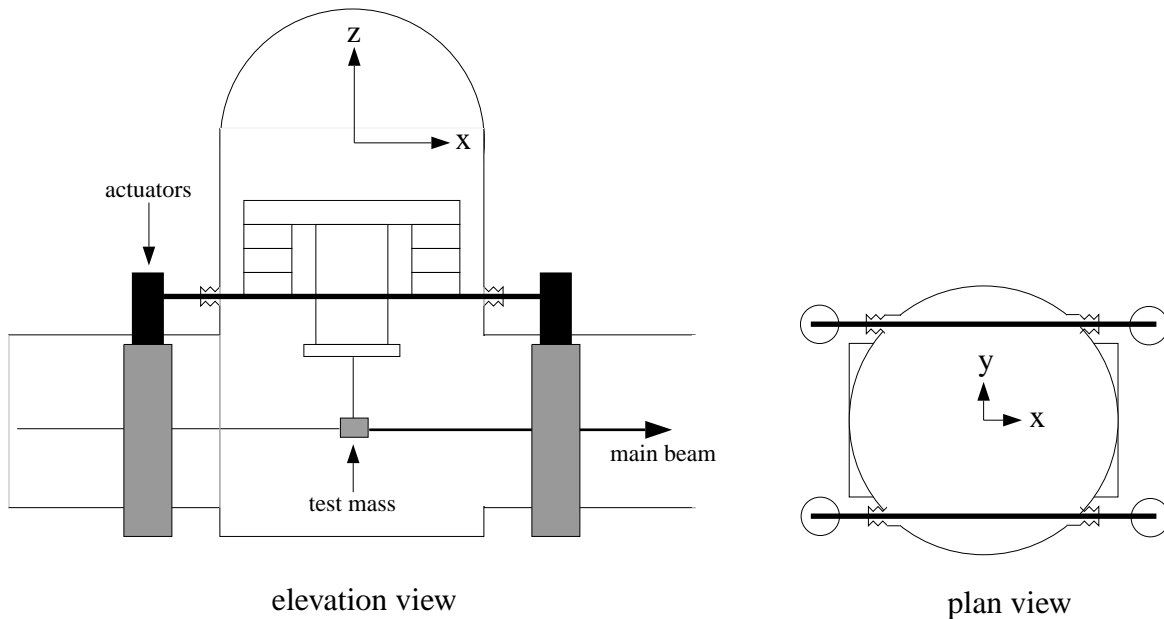


Figure 15: SEI, bellows and beam tube orientation for the BSC chambers in the mid- and end-station buildings.

3.2.1.7.2 Coarse Actuator Requirements

Coarse actuators are used to compensate for long term stack drift for a time of order 1 year. The range requirement of ± 5 mm is specified to maintain centering on optics. The requirements for coarse actuator are:

1. Loads (total for 1 platform):

X- Direction (along beam path):

Bellows: 77 lb., 4 bellows 12.9 mm excursion

Friction: $\text{Weight} * m_s = 8.81$ lb. ($m_s = 0.001$ for roller bearings)

Acceleration: .036 lb. (assumes a 50 second period for load movement)

Y- Direction:

Bellows: 369 lb., 4 bellows 17 mm excursion Y-Z plane

Friction: $\text{Weight} * m_s = 9.32$ ($m_s = 0.001$ for roller bearings)

Acceleration: .036 lb. (assumes a 50 second period for load movement)

Z - Direction:

Bellows: 369 lb., 4 bellows 17 mm excursion Y-Z plane

Friction: Could be the same or higher depending on whether or not we use roller screw or acme screws

Applied load: BSC weight = 9319 lb.. (weight of components supported by the actuator system)

Acceleration: 0.036 lb. (assumes a 50 second period for load movement)

2. Move Profile: Trapezoidal (see max velocity and acceleration requirements)

3. Motion (assume a 50 second excursion period):

Travel:

X, Y, Z: +/- 5 mm

Rotation Z: +/-4 mrad (approximately 6 mm of travel in X and/or Y)

Travel over life of actuator (240 months, 1 reset/month):

X, Y, Z < 240 m, the number will probably be smaller since the maximum travel is only 5mm, and platform movement occurs only one time per month (i.e. design is not limited by bearing fatigue).

Velocity:

X, Y, Z: 0.01 cm/s max

Acceleration:

X, Y, Z: 0.001 cm/ s² max

4. Accuracy:

Linear motions: 50 mm

Parasitic Roll (Rotation X): <0.05 mrad

5. Repeatability: 25 mm

6. Resolution: 100 mm (suggest 1 mm)

7. Backlash: Should be able to be locked out of the system while the fine actuator is moving.

8. Duty Cycle: < 1%

9. Life expectancy: 20 years

10. Nominal Operating Environment:

Temperature: 22°C +/-2°C

Humidity: 20~70 %

Contaminants (cleanliness): clean environment

Radiation: none

Earthquakes: Designed to resist the static equivalent lateral forces defined in the UBC for seismic force factor $Z = 0.15$, and a structure importance factor $I = 1$.

11. Interfaces:

Mechanical: STACIS active isolation, fine actuator

Electrical: 110 V

Controls: Standard RS232 controls interface.

12. Absolute position monitoring: absolute encoders are required to monitor the position of the actuators at all times. This information will be incorporated into the device controller and will be also read out over the serial RS 232 interface.

13. Smoothness:

Stiction - TBD

Creak - should not cause motion greater than the level of seismic noise measured at the fine actuator location.

Friction - TBD

14. System Stiffness: The overall stiffness of the components used for the coarse actuator system must meet the stack attenuation goals.

15. Safety Stops: The system will incorporate both limit switches and mechanical safety stops to prevent any damage to the system caused by an errant actuator system. The stops will be configured to allow for the full range of mobility.

16. Motion during power up or power down: The system is required to remain in the same absolute position while being powered on or during voluntary or accidental shut down.

3.2.1.8 Requirements on In-Vacuo Cabling

Cabling that joins equipment mounted to the optics platform to surfaces that have less vibration isolation must satisfy the following conditions (details are in Appendix F):

- Cabling shall be firmly clamped to each successive stage of the seismic isolation to prevent this cabling from conducting vibration around the isolation system.
- In the case of multiconductor cables, each wire must be firmly fixed in place so that its effective mass at the clamped area is comparable to the mass of the stage to which it is clamped.
- The strain rate (stiffness of the cable) for free lengths of cable¹ clamped to isolation stages must be less than 10 N/m.
- The mass of the free lengths of cable must be less than $10/Q$ kg, where Q is the mechanical quality for oscillation of the free cable length.
- Free lengths of cable must be placed so that they cannot possibly touch other surfaces except where they are clamped.
- Cabling must not “crackle” when vibrated under operating conditions². This may be ensured

1. “Free length” indicates the length of cable that is between clamps connecting two stages or connecting the lowest stage to any non-isolated surface.

2. “Crackle” refers to the sound made by upconversion when a low-frequency (inaudible) motion of the cable is made. (Thin plastic wrap often crackles when subjected to large slow flexing.)

either by choice of material or by the method in which the material is mounted.

- Cabling must satisfy the requirements for vacuum compatibility listed in *LIGO Vacuum Compatibility, Cleaning Methods and Procedures* (LIGO-E960022-00-D)

3.2.1.9 Required Size of Optical Platform

The optical platform diameter shall not exceed 1.5 m, to allow sufficient access inside the BSC chamber¹, which has an inside diameter of 2.64 m. The platform shall not be less than 1.2 m in order to provide sufficient space for detector components which mount to the platform. The platform shall be centered in the chamber.

3.2.1.10 Requirements on Support-Beam Bellows

- Absolute maximum rotation about bellows axis should be greater than 1.77 mrad.
- Absolute maximum axial displacement should be greater than 35.4 mm.
- Absolute maximum shear displacement should be greater than 16.95 mm.

3.2.2. HAM-SEI Performance Characteristics

3.2.2.1 Optics-Platform Vibration (Above 10 Hz)

The optical components in the HAM chambers with the greatest sensitivity to vibration are the mode-cleaner mirrors, which were used as a basis for the HAM-SEI vibration requirement. The estimate for the vibration requirements is discussed in Appendix B. There are no requirements for the transfer function of each individual component in the SEI subsystem. However, the end-to-end (from ground to suspended mass) model of the isolation system must meet the seismic noise transmission requirements shown in Figure 16, assuming the ground motion shown in Figure 10.

1. It is desirable to have the maximum useful surface area with minimal mass, which may favor an oblong table for test-mass chambers.

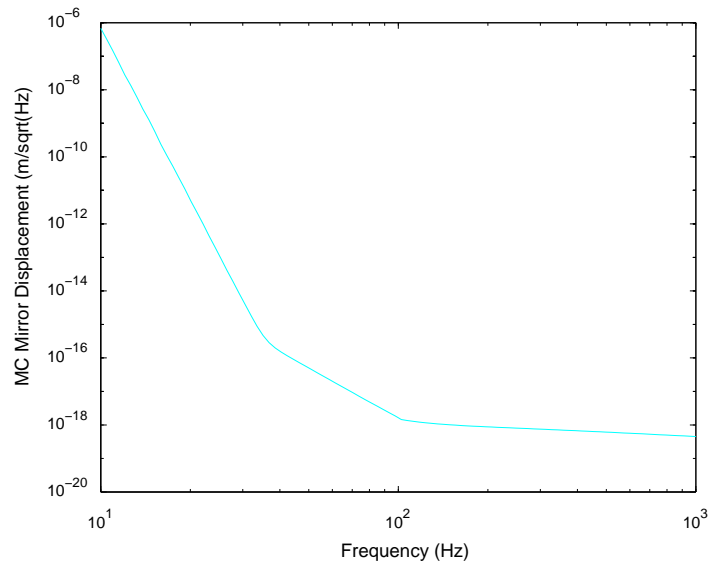


Figure 16: Seismic noise allowance for mode cleaner mirrors.

3.2.2.1.1 *Internal Resonances in Optics Platform*

The resonant frequencies and Q's of internal resonances in the optics platform shall be set so that the seismic noise transmission and thermal-noise fluctuations of the optical platform do not exceed the required values given in Figure 16. Thermal-noise requirements are given in *Thermal Noise Requirements for HAM Seismic Isolation* (LIGO-T960188-00-D).

3.2.2.1.2 *Internal Resonances in Mass Elements*

The resonant frequencies and Q's of internal resonances in the mass elements shall be set so that the seismic noise transmission does not exceed the required values given in Figure 16. Thermal noise from these resonances is not an issue.

3.2.2.1.3 *Internal Resonances in Support Beam/Structure/Piers*

The resonant frequencies and Q's of internal resonances in the support beam/structure/piers shall be set so that the seismic noise transmission does not exceed the required values given in Figure 16.

3.2.2.2 **Optics-Platform Low-Frequency Motion (From 0.1 Hz to 10 Hz)**

The mode-cleaner suspensions have the same actuator range as the test masses, so the requirements for low frequency motion of the optics platforms are the same as for the BSC-SEI.

3.2.2.3 Optics-Platform Drift (Below 0.1 Hz)

The optical platform shall not exceed the assumed drift values given in Table 1. The levelness requirement the HAM-SEI is the same as for the BSC-SEI.

3.2.2.4 Actuation Requirements

The HAM-chamber seismic isolation has no requirement for fine actuation (i.e., actuation that can be active when the interferometer is in its resonant state). Only coarse actuators are required for the HAM stacks. The requirements for coarse actuator are the same as for BSC-SEI.

3.2.2.5 Requirements on In-Vacuo Cabling

Requirements are the same as for the BSC-SEI.

3.2.2.6 Required Size of Optical Platform

The HAM optical platform shall be at least 1.9-m long and 1.7-m wide. Design and fabrication must accommodate insertion of the optical platform into the HAM-chamber through the 2.13-m (ID) opening with features to prevent damage to the vacuum-chamber flange or the optical platform.

3.2.2.7 Requirements on Support-Beam Bellows

- Absolute maximum rotation about bellows axis should be greater than 0.5 mrad.
- Absolute maximum axial displacement should be greater than 11.31 mm.
- Absolute maximum shear displacement should be greater than 15.46 mm.

3.2.3. Physical Characteristics

The seismic isolation components must be assembled inside the installed vacuum chambers. This requires that all components of the seismic isolation be handled by the craneage available in the part of the LVEA or VEA where the chamber is located (limited to 5 ton capacity and a 26 ft. 6 in. hook height), or that an independent means of lifting, moving and fine-positioning of the component must be made available. Provisions for attaching lifting and positioning equipment must be provided. These provisions must accommodate the high-vacuum compatibility of the cleaned, seismic-isolation components, including fitting within the portable clean room facilities provided as part of the Vacuum Equipment. Optical platforms shall have a matrix of 1/4-20 threaded holes, with 5.08 cm center spacing. Optical platform surfaces to which optical components are mounted shall have overall (edge to edge) flatness of $\pm 102 \mu\text{m}$ (0.004 inch) and over any 0.26 m^2 region, $\pm 51 \mu\text{m}$ (0.002 inch).

3.2.4. Interface Definitions

SEI interface with other sub-systems is defined in LIGO-T970064-00-D.

3.2.5. Reliability

Mean Time Between Failures (MTBF) and Availability requirements are TBD.

3.2.6. Maintainability

The Mean Time To Repair (MTTR) is TBD.

3.2.7. Environmental Conditions

Under normal operating conditions the seismic-isolation equipment shall be isolated in a temperature and humidity controlled environment. However the equipment must be safe from damage and harm to other equipment or personnel during exceptional circumstances such as a power failure, earthquake, etc.

3.2.7.1 Natural Environment

3.2.7.1.1 Temperature and Humidity

See Table 2 for ranges during normal operations, shipping and storage.

Table 2: Environmental Performance Characteristics

<i>Components</i>	<i>Operating</i>	<i>Non-operating (storage)</i>	<i>Transport</i>
metal parts	+15 C to +30 C 0-90%RH	-40 C to +70 C 0-90% RH	-40 C to +70 C 0-90% RH
spring elements	+15 C to +30 C vacuum	+5 C to +70 C 0-90% RH	+5 C to +70 C 0-90% RH
electronics	+0 C to +30 C 0-90%RH	-40 C to +70 C 0-90% RH	-40 C to +70 C 0-90% RH

Additionally, all components and parts which are exposed to the vacuum shall be capable of sustaining the bake requirements of the LIGO Vacuum Compatibility, Cleaning Methods and Qualification Procedures (LIGO-E960022, or by another procedure approved by the LIGO vacuum review board, per the requirements of this document). All components exposed to the vacuum shall be capable of sustaining an in situ vacuum bake of 150C with the exception of the stack springs which can be removed prior to a vacuum chamber bake if required.

3.2.7.1.2 Atmospheric Pressure

N/A

3.2.7.1.3 Seismic Disturbance

Restraint against seismically induced large motion of the stacks is required.

The SEI shall be designed to resist the static equivalent lateral forces defined in the Uniform Building Code (UBC), 1994 edition, for a seismic zone factor $Z = 0.15$ (i.e. zone 2B, Hanford) and a structure importance factor $I = 1$. The support structure shall resist the seismic loads without damage. The seismic stack shall sustain the base shear motion of the support structure without collapse or release of any of the stack layers. At a minimum, failure of the actuators under these

loads should not cause failure of the bellows or cause the seismic stack to “drop”; ideally the actuators would survive these loads with no damage.

As an alternative to this static equivalent load, an acceleration design spectrum for use in dynamic analysis could be used.

Interpretation of the requirement: If there is no damping or plastic deformation to absorb the seismic loading ($R_w = 1$), and the SEI first frequency is between 2.5 Hz and 10 Hz (i.e. at the peak), then the base shear,

$$V_b = \left(\frac{ZIC}{R_w} \right) W = \left(\frac{0.15(1)2.75}{1} \right) W = 0.4W$$

or the SEI must sustain a 0.4 g lateral load. If, as in the case of the Corner Station building, $R_w = 6$, then, then SEI must sustain a 0.1 g lateral load.

3.2.7.2 Induced Environment

3.2.7.2.1 Electromagnetic Radiation

Electrical equipment associated with stack actuators shall meet the EMI and EMC requirements of VDE 0871 Class A or equivalent.¹ The SEI system shall also comply with the LIGO EMI Control Plan and Procedures (LIGO-E960036).

3.2.7.2.2 Acoustic

SEI equipment shall be designed to produce the lowest levels of acoustic noise as possible and practical. As a minimum, SEI equipment shall not produce acoustic noise levels greater than specified in *Derivation of CDS Rack Acoustic Noise Specifications, LIGO-T960083*.

3.2.7.2.3 Mechanical Vibration

Mechanical vibration from SEI actuators on a chamber shall not increase the vibration amplitude of the facility floor within 1 m of any other vacuum chambers and equipment tables by more than 1 dB at any frequency between 0.1 Hz and 10 kHz.² Limited narrowband exemptions may be permitted subject to LIGO review and approval.

3.2.8. Transportability

All items shall be transportable by commercial carrier without degradation in performance. As necessary, provisions shall be made for measuring and controlling environmental conditions (temperature and accelerations) during transport and handling. Special shipping containers, shipping and handling mechanical restraints, and shock isolation shall be utilized to prevent damage and maintain cleanliness. All containers shall be movable by forklift. All items over 100 lbs. which

-
1. SEI fine-adjustment actuators shall be operable without electromagnetically interfering with neighboring interferometers.
 2. SEI fine-adjustment actuators shall be operable without interfering acoustically with neighboring interferometers.

must be moved into place within LIGO buildings shall have appropriate lifting eyes and mechanical strength to be lifted by cranes.

3.3. Design and Construction

3.3.1. Materials and Processes

3.3.1.1 Finishes

- Metal components shall have quality finishes on all surfaces, suitable for vacuum finishes. All corners shall be rounded to TBD radius.
- All materials shall have non-shedding surfaces.
- Aluminum components used in the vacuum shall not have anodized surfaces.
- Optical table surface roughness shall be within 32 μ inch.

3.3.1.2 Materials

A list of currently approved materials for use inside the LIGO vacuum envelope can be found in LIGO Vacuum Compatible Materials List (LIGO-E960022). All fabricated metal components exposed to vacuum shall be made from stainless steel, copper, or aluminum. Other metals are subject to LIGO approval. Prebaked viton (or fluorel) may be used subject to LIGO approval. All materials used inside the vacuum chamber must comply with *LIGO Vacuum Compatibility, Cleaning Methods and Procedures* (LIGO-E960022-00-D).

The only lubricating films permitted within the vacuum are dry platings of vacuum compatible materials such as silver and gold.

3.3.1.3 Processes

3.3.1.3.1 Welding

Before welding the surfaces should be cleaned (but baking is not necessary at this stage) according to the UHV cleaning procedure(s). All welding exposed to vacuum shall be done by the tungsten-arc-inert-gas (TIG) process. Welding techniques for components operated in vacuum shall deviate from the ASME Code in accordance with the best ultra high vacuum practice to eliminate any “virtual leaks” in welds; i. e. all vacuum welds shall be continuous wherever possible to eliminate trapped volumes. All weld procedures for components operated in vacuum shall include steps to avoid contamination of the heat affected zone with air, hydrogen or water, by use of an inert purge gas that floods all sides of heated portions.

Materials shall be joined in such a way as to facilitate cleaning and vacuum preparation procedures; i. e. internal volumes shall be provided with adequate openings to allow for wetting, agitation and draining of cleaning fluids and for subsequent drying.

The welds should not be subsequently ground (in order to avoid embedding particles from the grinding wheel).

3.3.1.3.2 Cleaning

All materials used inside the vacuum chambers must be cleaned in accordance with *Specification Guidance for Seismic Component Cleaning, Baking, and Shipping Preparation* (LIGO-L970061-00-D). To facilitate final cleaning procedures, parts should be cleaned after any processes that result in visible contamination from dust, sand or hydrocarbon films.

3.3.2. Component Naming

All components shall be identified using the LIGO Naming Convention (LIGO-E950111-A-E). This shall include identification physically stamped on components, in all drawings and in all related documentation.

3.3.3. Workmanship

TBD

3.3.4. Interchangeability

All HAM-SEI components shall be interchangeable between Ham chambers and all BSC-SEI components shall be interchangeable between BSC chambers. Standard cabling clamps shall be used to attach in-vacuo cabling to the mass elements, down structures and optical platforms.

3.3.5. Safety

This item shall meet all applicable NSF and other Federal safety regulations, plus those applicable State, Local and LIGO safety requirements. A hazard/risk analysis shall be conducted in accordance with guidelines set forth in the LIGO Project System Safety Management Plan LIGO-M950046-F, section 3.3.2.

3.3.6. Human Engineering

Optics platforms must accommodate addition, removal and adjustment of equipment with a minimum of force or torque applied to the platforms. This requires that adequate space be provided surrounding the optics platform for an individual to move into proper position for the work intended. Equipment mounted to the optics platform should be provided with fasteners that can accommodate these force/torque requirements.

3.3.7. Assembly and Maintenance

Assembly fixtures and installation/replacement procedures shall be developed in conjunction with the SEI hardware design. These shall include (but not be limited to) fixtures and procedures for:

- SEI component insertion and assembly into the vacuum chambers without load support from

the chambers

- assembly of the in vacuo components in a clean room (class 100) environment
- initial alignment of the SEI components
- installation/removal/replacement of the bellows
- installation/removal/replacement of the actuator components
- installation/removal/replacement of the stack spring elements

3.4. Documentation

3.4.1. Specifications

TBD

3.4.2. Design Documents

- *LIGO SEI System Final Design Document (including supporting technical design and analysis documentation)*
- *LIGO SEI Prototype/Test Plans*
- *LIGO SEI Installation and Commissioning Plans*

3.4.3. Engineering Drawings and Associated Lists

Any drawings to be provided and any standard formats that they must comply with, such as shall use LIGO drawing numbering system, be drawn using LIGO Drawing Preparation Standards, etc.

3.4.4. Technical Manuals and Procedures

3.4.4.1 Procedures

Procedures shall be provided for, at minimum,

- Initial installation and setup of SEI equipment
- Normal operation of SEI equipment
- Normal and/or preventative maintenance
- Installation of new equipment onto SEI platforms
- Troubleshooting guide for any anticipated potential malfunctions

3.4.4.2 Manuals

Procedures listed in section 3.4.4.1 and applicable as-built documentation shall be collected into an Operator's Manual for the HAM-SEI and BSC SEI subsystems.

3.4.5. Documentation Numbering

All documents shall be numbered and identified in accordance with the LIGO documentation control numbering system LIGO document TBD

3.4.6. Test Plans and Procedures

All test plans and procedures shall be developed in accordance with the LIGO Test Plan Guidelines, LIGO document TBD.

3.5. Logistics

The design shall include a list of all recommended spare parts and special test equipment required.

3.6. Precedence

3.7. Qualification

4 QUALITY ASSURANCE PROVISIONS

This section includes all of the examinations and tests to be performed in order to ascertain the product, material or process to be developed or offered for acceptance conforms to the requirements in section 3.

4.1. General

4.1.1. Responsibility for Tests

TBD

4.1.2. Special Tests

4.1.2.1 Engineering Tests

- actuator prototype/test
- drift tests of spring elements (average drift rates and statistical variations)
- tests for “crackle” noise in spring elements and cabling
- outgassing/optical qualification of spring elements (not needed for encapsulated elastomer springs)
- verification that resonant frequencies and Q’s of mass elements, down structure and optical platforms are within specifications
- performance measurement of single-stage isolation parameters, including characterization of

linearity of response linearity of response

- design checks (form, fit and function)

4.1.2.2 Reliability Testing

Reliability evaluation/development tests shall be conducted on items with limited reliability history that will have a significant impact upon the operational availability of the system. This includes:

- dimensions and spring parameters (e.g. loss factor)
- outgassing certification of spring elements and bellows
- tests of actuator elements and electronics

4.1.3. Configuration Management

Configuration control of specifications and designs shall be in accordance with the LIGO Detector Implementation Plan.

4.2. Quality conformance inspections

Design and performance requirements identified in this specification and referenced specifications shall be verified by inspection, analysis, demonstration, similarity, test or a combination thereof per the Verification Matrix, Appendix 1 (See example in Appendix). Verification method selection shall be specified by individual specifications, and documented by appropriate test and evaluation plans and procedures. Verification of compliance to the requirements of this and subsequent specifications may be accomplished by the following methods or combination of methods:

4.2.1. Inspections

Inspection shall be used to determine conformity with requirements that are neither functional nor qualitative; for example, identification marks.

4.2.2. Analysis

Analysis may be used for determination of qualitative and quantitative properties and performance of an item by study, calculation and modeling.

4.2.3. Demonstration

Demonstration may be used for determination of qualitative properties and performance of an item and is accomplished by observation. Verification of an item by this method would be accomplished by using the item for the designated design purpose and would require no special test for final proof of performance.

4.2.4. Similarity

Similarity analysis may be used in lieu of tests when a determination can be made that an item is similar or identical in design to another item that has been previously certified to equivalent or more stringent criteria. Qualification by similarity is subject to Detector management approval.

4.2.5. Test

Test may be used for the determination of quantitative properties and performance of an item by technical means, such as, the use of external resources, such as voltmeters, recorders, and any test equipment necessary for measuring performance. Test equipment used shall be calibrated to the manufacture's specifications and shall have a calibration sticker showing the current calibration status.

5 PREPARATION FOR DELIVERY

Packaging and marking of equipment for delivery shall be in accordance with the Packaging and Marking procedures specified herein.

5.1. Preparation

- Vacuum preparation procedures as outlined in *LIGO Vacuum Compatibility, Cleaning Methods and Procedures* (LIGO-E960022-00-D) shall be followed for all components intended for use in vacuum. After wrapping vacuum parts as specified in this document, an additional, protective outer wrapping and provisions for lifting shall be provided.
- Electronic components shall be wrapped according to standard procedures for such parts.

5.2. Packaging

Procedures for packaging shall ensure cleaning, drying, and preservation methods adequate to prevent deterioration, appropriate protective wrapping, adequate package cushioning, and proper containers. Proper protection shall be provided for shipping loads and environmental stress during transportation, hauling and storage. The shipping crates used for large items should be built to military specification MIL-C-104B, Crates, Wood; Lumber and Plywood Sheathed, Nailed and Bolted. Passive shock witness gauges should accompany the crates during all transits.

For all components which are intended for exposure in the vacuum system, the shipping preparation shall include double bagging with Ameristat 1.5TM plastic film (heat sealed seams as practical, or tied off, or taped with care taken to insure that the tape does not touch the cleaned part). Purge the bag with dry nitrogen before sealing.

5.3. Marking

Appropriate identification of the product, both on packages and shipping containers; all markings necessary for delivery and for storage, if applicable; all markings required by regulations, statutes, and common carriers; and all markings necessary for safety and safe delivery shall be provided.

Identification of the material shall be maintained through all manufacturing processes. Each component shall be uniquely identified. The identification shall enable the complete history of each component to be maintained (in association with Documentation “travelers”). A record for each component shall indicate all weld repairs and fabrication abnormalities.

For components and parts which are exposed to the vacuum environment, marking the finished materials with marking fluids, die stamps and/or electro-etching is not permitted. A vibratory tool with a minimum tip radius of 0.005" is acceptable for marking on surfaces which are not hidden from view. Engraving is also permitted.

6 NOTES

APPENDIX A ANTICIPATED DRIFT OF A FOUR-LAYER STACK WITH VITON SPRINGS

At MIT measurements were taken on a 4 layer prototype stack made with viton spring elements. The following was reported.¹ The vertical stack drift rate twenty days after initial construction of the stack was $\sim 6 \times 10^{-10}$ m/sec. The change in the height of the stack due to temperature variation was $\sim 3 \times 10^{-5}$ m/C. The strain in the springs was less than 20% and the drift over time displayed a logarithmic behavior. Angular and horizontal creep was not reported. Estimates for drifts in LIGO stacks are made based on these measurements.

A.1. vertical and translational drift

The time between construction of the stacks and initial alignment of the optical components for the interferometer was assumed to be 20 days. (Approximately 3 months were used to install the optics on the 40 meter interferometer.) The twenty day assumption may be too ambitious but it gives an upper estimate for the expected stack drifts and drift rates.

LIGO stacks will have four spring mass layers with spring elements that are loaded at levels similar to the prototype stacks. Therefore, the vertical stack drift rate twenty days after construction of stack would be $\sim 6 \times 10^{-10}$ m/sec ($\sim 5 \times 10^{-5}$ m/day). The total drift one year beyond this time would be ~ 3 mm assuming the drift decreases logarithmically over time. The daily facility temperature fluctuation is approximately 1.1 K peak-to-peak, but daily temperature fluctuations inside the vacuum chambers are expected to be at least an order of magnitude smaller due to poor thermal transport and large thermal masses of the stack elements². Therefore, the maximum daily excursion in response to temperature variation would be $< 1 \times 10^{-5}$ m.

1. J. Giaime, Ph.D. thesis, June 1995, p. 29.

2. See Appendix F for estimates.

A worst case assumption for horizontal drift is the following. Vertical drift is accompanied by an equal amount of sideways translation. In this case, drift in x or y would equal that in z.

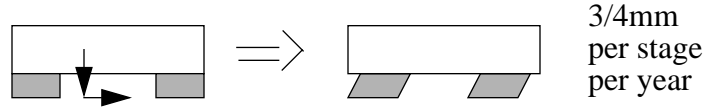


Figure 2. Compression accompanied by sideways translation in viton springs

A.2. angular drift

A 20% variation in the drift rate between opposite legs of the stack was assumed for purposes of estimating angular drift rates. This can lead to a tilt angle of ~ 0.4 mrad after 1 year (see figure 3). The rate of change of tilt angle on day 20 would be 8×10^{-11} rad/s. Daily temperature fluctuations produce $\sim 2 \times 10^{-6}$ rad. If sideways translation of the stack leg elements work in concert to produce a corkscrew rotation of the stack, then we can expect the following rotations about z: 4 mrad after 1 year, $\sim 2 \times 10^{-5}$ rad thermal response, and $\sim 8 \times 10^{-10}$ rad/s initial rate.

There is no data to support the 20% variation assumption. However, as part of the stack construction procedure, spring elements fabricated in batches will be grouped together. Each group will be vacuum baked together and only springs from the same group will be used to make up an individual layer of the isolation stack. Under these conditions it seems reasonable to expect no more than a 20% variation.

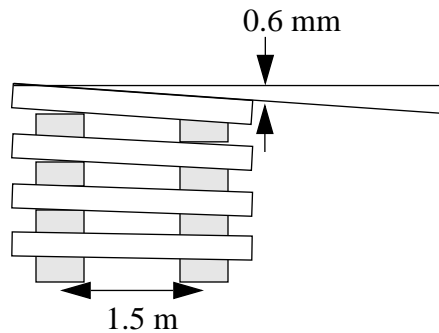


Figure 3. Tilt due to variation in spring constants

A summary of the estimated translational and angular stack drift is given in table 1.

A.3. stack drift during pump down

The seismic isolation stacks in the 40 meter interferometer occasionally drift during pump down. The cause of this drift has not been determined. The magnitude and direction of the drift is seen to vary. However, the drift never exceeds the range of the external stack adjustment which is ~5 mm.

APPENDIX B BASIS FOR VIBRATION REQUIREMENT ON THE BSC SEISMIC-ISOLATION TRANSFER FUNCTIONS

The LIGO displacement-noise target for the initial LIGO interferometer serves as the basis for the vibration requirement on the seismic-isolation transfer functions. The most sensitive optics contained in BSC chambers are the four test masses belonging to each interferometer. The interferometer requirement is first divided by two to get the displacement noise requirement for a single test mass. Seismic noise can account for all of the test mass' displacement noise at frequencies below 35 Hz, the region labelled "Seismic" in Figure 8.

Seismic noise should not be the primary noise contribution in the regions labelled "Thermal" and "Shot" in Figure 8, so the requirement on test-mass displacement noise over this frequency range is divided by a factor of ten. The resulting curve is the seismic allowance for test-mass displacement. This curve is then divided by the magnitude of the appropriate transfer function for the SUS and the amplitude power spectrum of the composite ground noise to give the required transfer for the seismic isolation.

The assumed transfer function for test-mass displacement along the optic axis generated by horizontal motion of the optics platform in the same direction is the simple-pendulum transfer function

$$T_{xx} = \frac{\omega_0^2}{[(\omega_0^2 - \omega^2)^2 + \omega_0^4 \phi^2]^{1/2}}$$

where $\omega_0 = 2\pi f_0$ is the resonant angular frequency of the pendulum mode and ϕ_0 is the loss factor for that mode. The transfer function from vertical motion of the optical platform to test-mass displacement along the optical beam is given by

$$T_{xy} = \frac{\omega_v^2}{[(\omega_v^2 - \omega^2)^2 + \omega_v^4 \phi_v^2]^{1/2}} \bullet 3.1 \times 10^{-4}$$

where $\omega_v = 2\pi f_v$ is the resonant angular frequency of the vertical-spring mode of the suspension, ϕ_v is the loss factor for that mode and the numerical factor is due to the effect of the earth's curvature over a 4-km baseline. Optics-Table Vibration (Above 10 Hz)

The optical components in the BSC chambers with the greatest sensitivity to vibration are the test masses which were used as the basis for BSC-SEI vibration requirements. The criteria for the vibration requirements is discussed in the preceding paragraph. These transfer functions apply from ground translations, measured at the base of the support piers to motion of the optics platform. The transfer function requirements must be met over the range of displacements expected at each isolation stage in actual operation. Additionally, upconversion of motion from the excitation frequency to higher frequencies must not permit excessive motion to be transmitted at some other frequencies.

B.1. BSC Horizontal Ground Motion to Horizontal Motion of Optics Platform

The required transfer function magnitude for transmission of horizontal ground noise to the optics platform for the BSC seismic isolation is given in Figure 15.

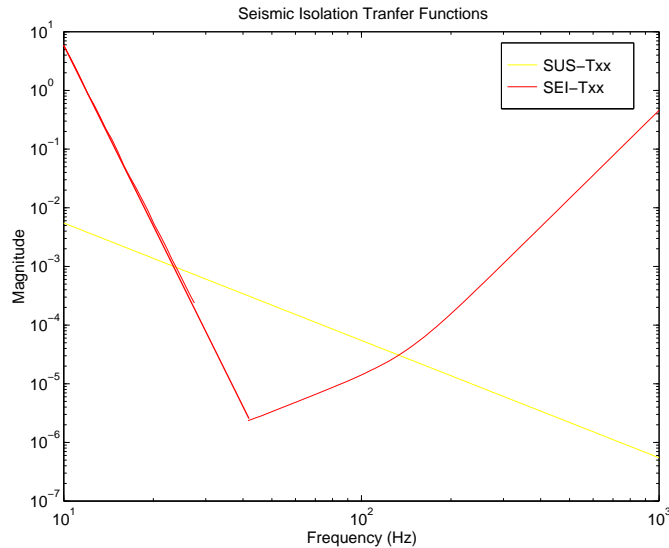


Figure 17: Horizontal-to-horizontal transfer function (SEI- T_{zz}) requirement for BSC-SEI. The assumed transfer function for the single-stage pendulum (SUS- T_{xz}) is also shown

B.2. BSC Vertical Ground Motion to Vertical Motion of Optics Platform

The required transfer function magnitude for transmission of vertical ground noise to the optics platform for the BSC seismic isolation is given in Figure 16.

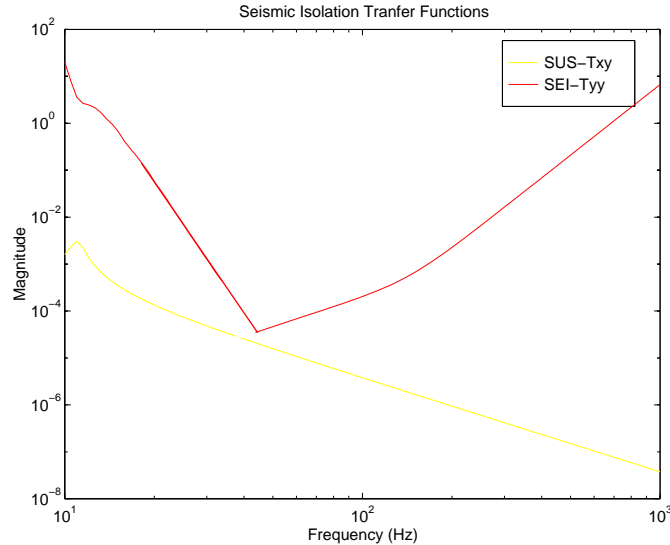


Figure 18: Vertical-to-vertical transfer function (SEI-T_{yy}) requirement for BSC-SEI. The assumed transfer function for the single-stage pendulum (SUS-T_{xy}) is also shown. HAM Optics-Platform Vibration (Above 10 Hz)

The optical components in the HAM chambers with the greatest sensitivity to vibration are the mode-cleaner mirrors, which were used as a basis for the HAM-SEI vibration requirement. The criteria for the vibration requirements is discussed in Appendix B. Other components of the IOO subsystem may set the most stringent requirements on certain transfer functions for the HAM-SEI; setting requirements on these transfer functions requires further definition of the IOO design.

B.3. HAM Horizontal Ground Motion to Horizontal Motion of Optics

Platform

The required transfer function magnitude for transmission of horizontal ground noise to the optics platform for the HAM seismic isolation is given in Figure 15.

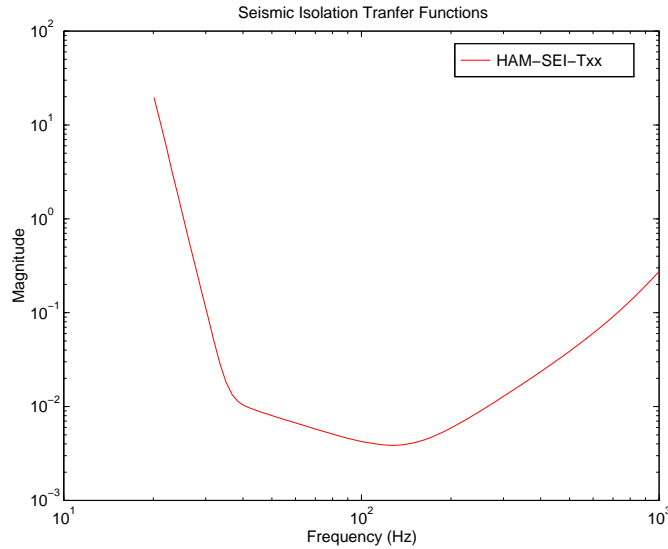


Figure 19: Horizontal-to-horizontal transfer function requirement for HAM-SEI.

B.4. HAM Vertical Ground Motion to Vertical Motion of Optics Platform

The required transfer function magnitude for transmission of vertical ground noise to the optics platform for the HAM seismic isolation does not arise from the mode-cleaner mirrors, but is likely to be set by the mode-matching components of the IOO. This requirement is TBD, pending further definition of IOO design.

APPENDIX C BASIS FOR VIBRATION REQUIREMENT RELATED TO THERMAL NOISE AFFECTING THE OPTICS PLATFORM

The natural vibrations of the optical-platform/down-structure/top-plate assembly in thermal equilibrium with its surroundings (thermal noise) can excite the suspension near these resonances. The thermal component of optical-platform motion near these resonances is independent of the level of isolation of ground motion afforded by the seismic-isolation system and is given by

$$\tilde{x}_{platform}(f) = \left(\frac{4k_B T Q}{m \omega_r^3} \right)^{1/2}$$

where k_B is Boltzmann's constant, ω_r is the resonant angular frequency of the mode, Q is its quality factor and m is its effective mass. This is then multiplied by the transfer of the pendulum to obtain the test-mass displacement, which is then compared to the science requirement. Table 14 was generated based on an effective mass of 112.5 kg. Acceptable limits can be scaled to other cases using the relation

$$Q \leq m\omega_r^7 \bullet \text{constant}$$

Table 3:

<i>Frequency</i> (Hz)	<i>Q</i>	$\frac{x(f)}{10^{-20} \text{ m}/\sqrt{\text{Hz}}}$	<i>Acceptable?</i>
600	4000	1.0	yes
500	2000	1.4	yes
400	500	1.5	yes
300	40	1.2	yes
200	no acceptable value for Q at this frequency		

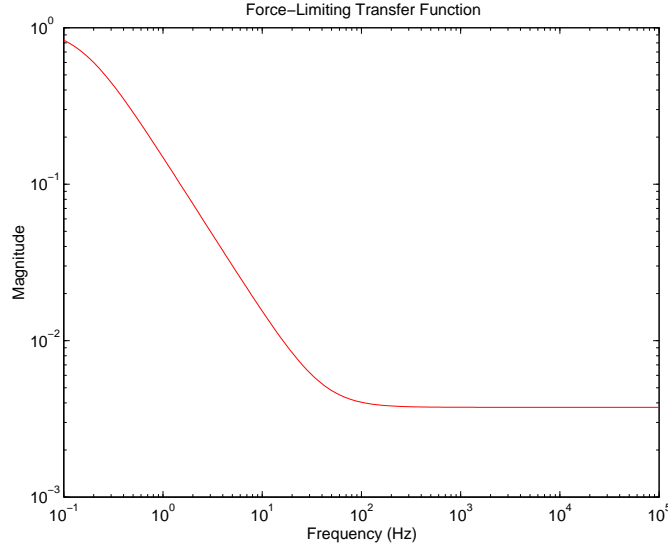
APPENDIX D BASIS FOR LOW-FREQUENCY MOTION REQUIREMENT

The lock-acquisition criteria is based on measurements in the 40-meter interferometer in November 1994 by L.Sievers¹, when the interferometer showed reasonable lock-acquisition behavior with applied forces comparable to those available from the SUS actuators in LIGO. At an RMS velocity of 1 micron/sec, the LIGO test mass will have a similar kinetic energy to that exhibited by the 40-meter-interferometer test masses in that study.

The lock-maintenance criteria is based on the maximum force that can be applied by the SUS actuators. The available force can cause test-mass displacements of 80 microns peak-to-peak at

1. L. Sievers, *Relative Test-Mass Motion in the 40-Meter Interferometer* (LIGO-T950038-00-R)

DC and is attenuated by the filter function $F(s)$ shown in Figure D1, which has a pole at 0.15 Hz and a zero at 40 Hz. The Laplace transform of the inverse filter function is given by



$$F^{-1}(s) = \frac{\omega_2}{\omega_1} \cdot \frac{s + \omega_1}{s + \omega_2}$$

where ω_1 is the pole angular frequency and ω_2 is the zero angular frequency. The figure of merit for the amount of broad band motion at the optical platform, taking into consideration the force limiting characteristics of the SUS actuator, is given by

$$\chi(s) = F^{-1}(s) \cdot T_{sus,xx}^{-1}(s) \cdot \left\{ [T^{sei+sus}(s)] \cdot \begin{bmatrix} G_{xx}^2(s) & 0 & 0 \\ 0 & G_{zz}^2(s) & 0 \\ 0 & 0 & G_{pitch}^2(s) \end{bmatrix} \cdot [T^{sei+sus}(s)]^* \right\}^{\frac{1}{2}}$$

and

$$[T^{sei + sus}] = \begin{bmatrix} T_{x,x}^{sus} & T_{x,z}^{sus} & T_{x,pitch}^{sus} \\ T_{z,x}^{sei} & T_{z,z}^{sei} & T_{z,pitch}^{sei} \\ T_{pitch,x}^{sei} & T_{pitch,z}^{sei} & T_{pitch,pitch}^{sei} \end{bmatrix} \cdot \begin{bmatrix} T_{x,x}^{sei} & T_{x,z}^{sei} & T_{x,pitch}^{sei} \\ T_{z,x}^{sei} & T_{z,z}^{sei} & T_{z,pitch}^{sei} \\ T_{pitch,x}^{sei} & T_{pitch,z}^{sei} & T_{pitch,pitch}^{sei} \end{bmatrix}$$

where $G(s)$ is the composite ground-noise spectrum, $T_{ij}^{sei}(s)$ is the appropriate transfer function of the seismic isolation, $T_{ij}^{sus}(s)$ is the appropriate transfer function of the suspension, and $*$ denotes the conjugate transpose of matrix $[]$. $\chi(s)$ has been weighted properly for a direct comparison with the DC range of the actuator.¹ The condition for acceptable maintenance of lock by the interferometer, namely that the actuators be able to supply the necessary control forces is that

$$[\chi(s)]_{\text{RMS}} \leq \frac{80\text{microns}}{30}$$

The factor of thirty is the standard multiplier/divisor adopted in the SUS DRD for conversions between RMS and maximum peak-to-peak specifications. This factor includes a factor of three to convert RMS to peak-to-peak motion, a statistical factor of three and a further safety factor of three.

APPENDIX E EFFECT OF DAILY THERMAL FLUCTUATIONS

B.1. Thermal Expansion of Optical Platforms

The thermal expansion of the optical platforms is not expected to cause stability problems for the interferometer (i.e., loss of lock). The vacuum-chamber areas are expected to have ambient temperature variations of approximately 1.1 K peak-to-peak on a daily basis, but the optical platforms are isolated from these fluctuations by the vacuum. Assuming that radiative coupling dominates the heat exchange to the optical platform, and modeling the optical platform and payload as having a typical area of 2-3 m² and a typical mass of about 500 kg, we expect a typical thermal transport time of order several hundred hours. The motion of any optic on the platform due thermal expansion of the platform will be small compared to the range of the SUS actuators.

1. S. Kawamura, *Framework of Range Requirement of Suspension Actuator* (LIGO-T960070-D).

B.2. Thermal expansion of LVEA Floor

Thermal expansion of the LVEA floor is not expected to cause stability problems for the interferometer. The applicable thermal expansion coefficient for concrete at uniform temperature is $5.5 \times 10^{-6} \text{ K}^{-1}$, but the effective temperature changes in the concrete will likely be 30 times smaller than fluctuations in air temperature.¹ This results in about 2 μm peak-to-peak daily variation over a 10-m baseline, well within suspension-actuator range.

APPENDIX F BASIS FOR THE CABLING REQUIREMENTS

The strategy for vibration isolation of the cabling is that the cabling should not affect the restoring force on any layer of the seismic isolation and that the vibration that can be coupled acoustically through any free cable length must be less than the vibration requirement per stage of the isolation system.

A typical strain rate for a layer of springs in the seismic isolation will be of order 1000 N/m. To ensure that the cabling has negligible stiffness, a strain rate for the cable of 10 N/m has been chosen to satisfy the criterion with an adequate safety factor to cover uncertainties in the strain rate of the spring elements at this time.

A sound wave of amplitude x traveling along a free length of cabling with mechanical impedance $Z_1 = \mu v$, where v is the sound-wave velocity and μ is the mass per unit length of the cable, will shake a mass M with impedance $Z_2 = M\omega$, where ω is the angular frequency of the sound wave by an amount X such that

$$\frac{X}{x} = \frac{2Z_1}{Z_1 + Z_2} = \frac{\mu\lambda}{\pi M}$$

where λ is the wavelength of sound in the cable. An upper bound on $\mu\lambda$ is the total mass m of the free cable length. Assuming that the cable length is shaken on one end by an amount x and that the sound wave may resonate in the free length with quality factor Q , we get the condition

$m < \pi \frac{M}{Q} \cdot T_{\text{stage}}$, where T_{stage} is the required transfer function per stage. The most stringent

requirement on T_{stage} is $T_{\text{stage}} \approx 3 \times 10^{-2}$, set by the BSC horizontal transfer function. Typical masses for a single mass element are 100 kg. Setting $m < 10/Q$ kg satisfies this relation with an

1. P. MacCalden, R. M. Parsons Co., April 1996.

adequate safety margin to cover uncertainties in the parameters at this time. As these uncertainties become resolved, a more relaxed requirement can be set using the equations above.

APPENDIX G BASIS FOR VIBRATION REQUIREMENT ON THE HAM SEISMIC-ISOLATION TRANSFER FUNCTIONS

The most vibration-sensitive optics contained in HAM chambers are the mode-cleaner mirrors. Motion of these mirrors can affect the frequency of the light entering the main interferometer. The frequency noise will be equal to the mode-cleaner strain induced by vibration times the average frequency of the light $\Delta\nu = (\Delta l/l) \cdot \nu_0$. Frequency noise on the light should not limit interferometer sensitivity at any frequency, so the requirement is divided by a factor of ten. The effect of frequency noise on the interferometer sensitivity is given by the product of a common-mode rejection factor β (that depends on how accurately the optics are matched in the two interferometer arms) and the open-loop gain $A_{CM}(f)$ of the common-mode servo that suppresses frequency noise. This gives for the required deviation in mode cleaner length

$$(\Delta l/l) = \frac{1}{10} \cdot \left(\frac{\Delta x_{TM}}{L} \right) \cdot \beta \cdot A_{CM}(f)$$

The common-mode servo gain, not available at the time of this version, was conservatively set to be¹

$$A_{CM}(f) = 1 + \left(\frac{1000\text{Hz}}{f} \right)^3$$

which should be replaced by the actual loop shape of this servo, when it is known.

The limit for Δl is then divided by the magnitude of the appropriate transfer function for the SUS and the amplitude power spectrum of the composite ground noise to give the required transfer for the seismic isolation. The assumed transfer function for mode-cleaner-mirror displacement along the optic axis generated by horizontal motion of the optics platform in the same direction is the same simple-pendulum transfer function used in Appendix B for the test masses. However the coupling of mode-cleaner length to vertical motion of the mirrors is so weak that this effect has little influence on the vertical-to-vertical transfer function of the HAM seismic isolation. It is more likely that this transfer function will depend on the vibration sensitivity of the mode-matching optics contained in IOO.

1. The gain factor given is an approximation that probably underestimates the actual gain. It also has an instability near the unity gain point. The properly tailored loop will likely have greater gain at the relevant frequencies and thus greater suppression of vibration-driven frequency noise.

