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- LIGO -
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Seismic Isolation Design Requirements Document

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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
- Interfaces
- 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 to 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 desing 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 accomodated 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.

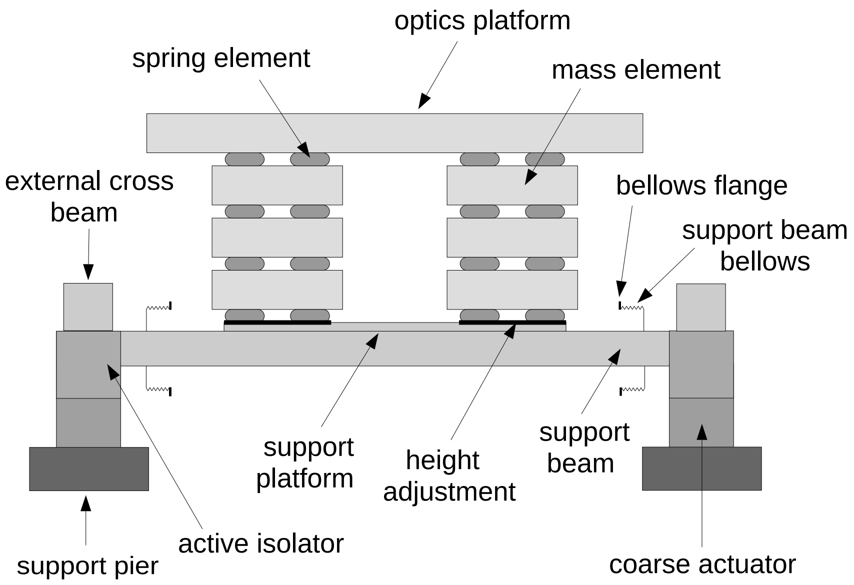

Figure 1: Naming convention for HAM-SEI parts

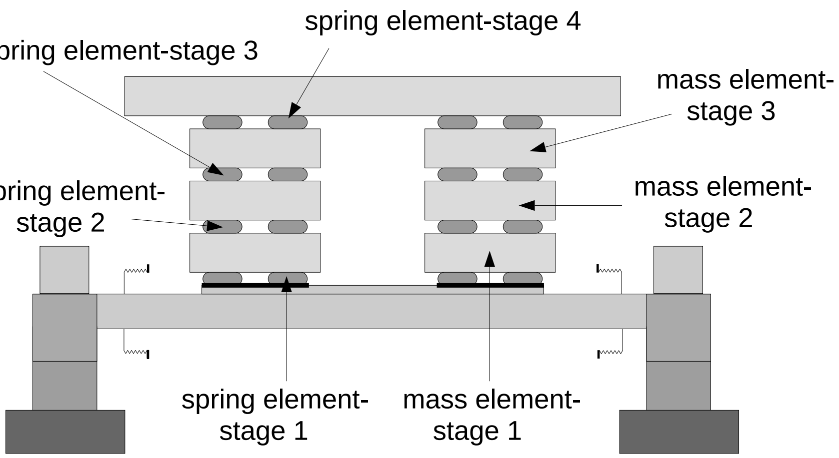

Figure 2: Naming convention for HAM-SEI parts

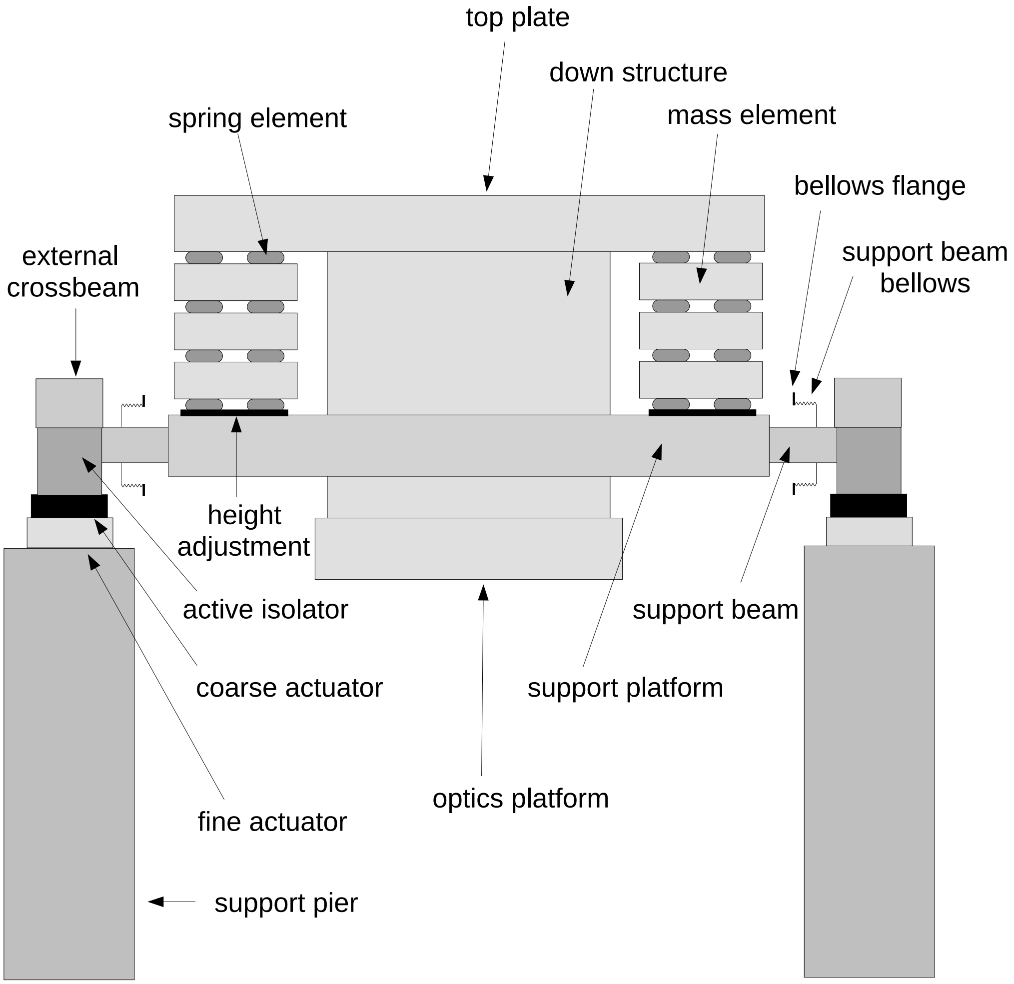

Figure 3: Naming convention for BSC-SEI parts

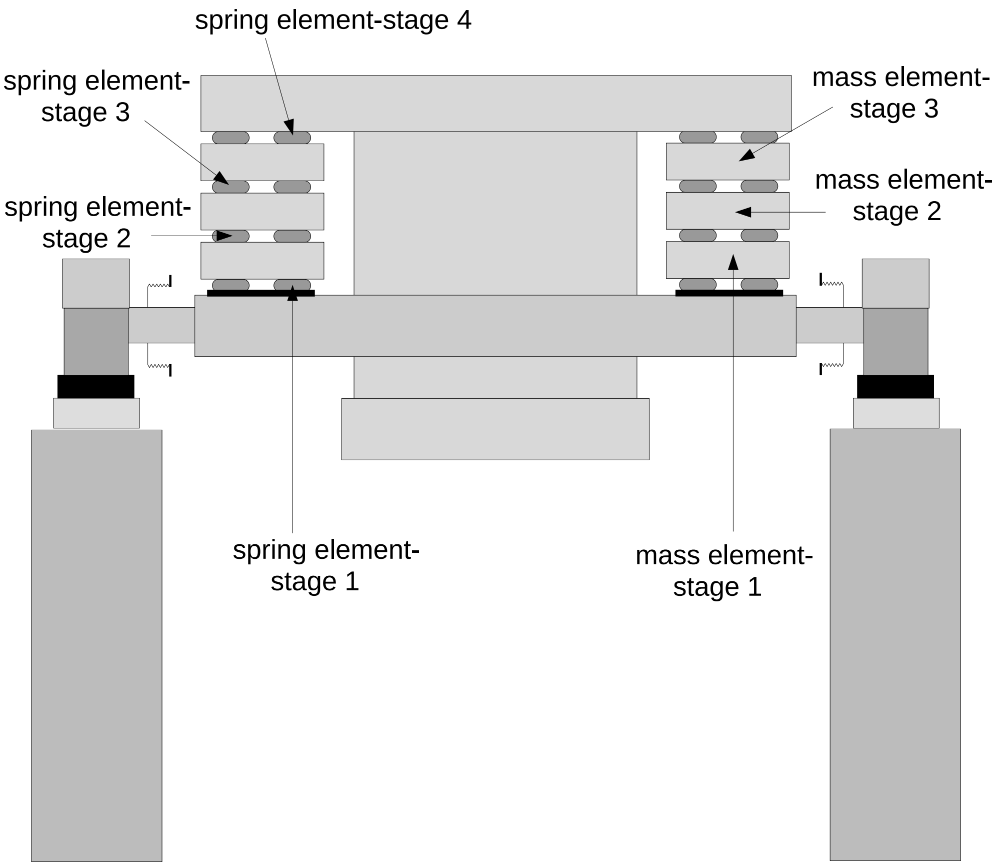

Figure 4: Naming convention for BSC-SEI parts

1.3.2. Definitions of Terms

- *lock* indicates the state of the interferometer when all optical cavities are resonating satbly 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
- *on-line actuators* indicates actuators that operate when the interferometer is fully operational without causing disturbance as opposed to *off-line actuators* which are not used when the interferometer is operational

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 susbsystem
- 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)

1.5.2. Non-LIGO Documents

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

2 GENERAL DESCRIPTION

2.1. Specification Tree

This document is part of an overall LIGO detector requirement specification tree. This particular document is highlighted in the following figure.

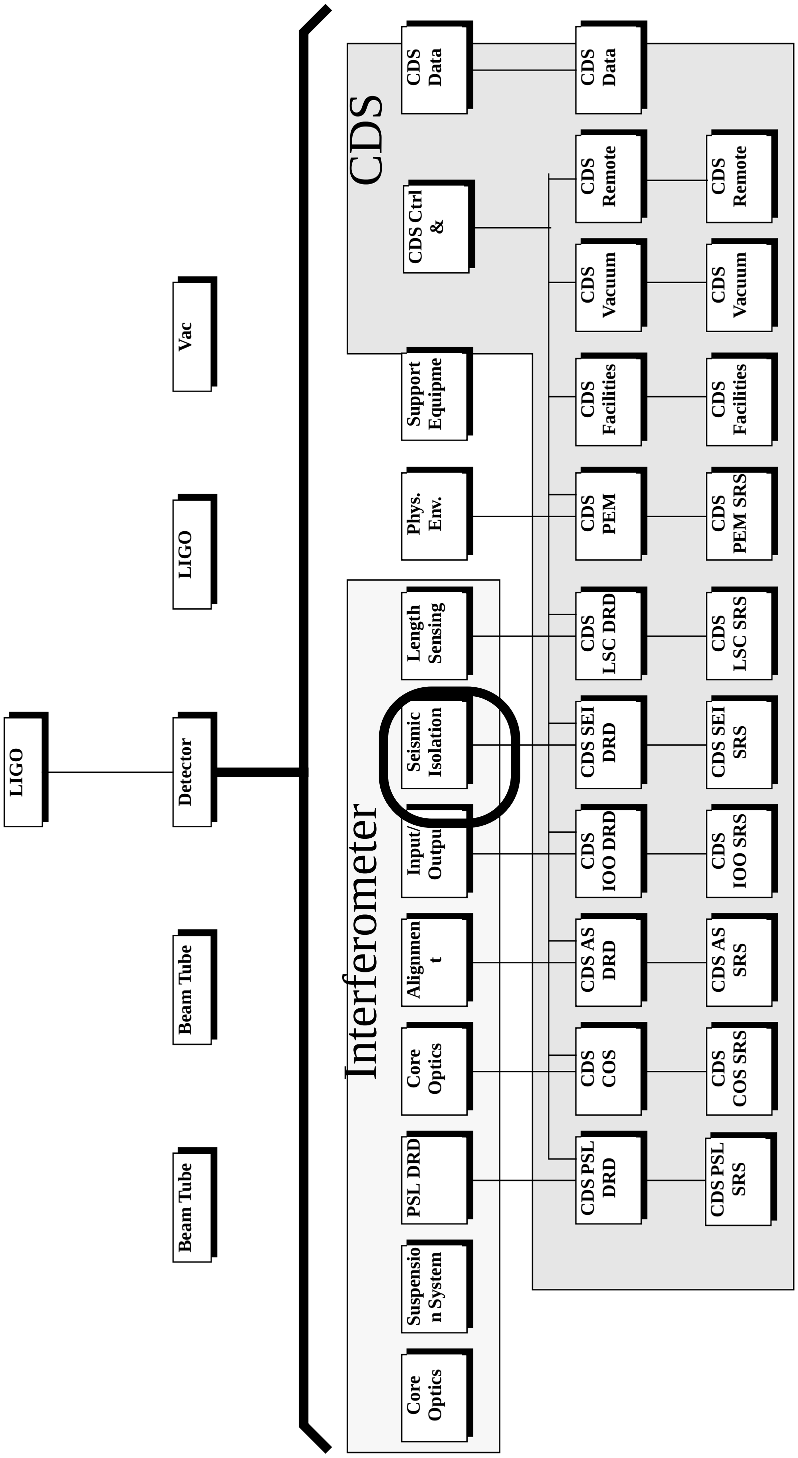

Figure 5: Document location in LIGO specification tree.

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 COC, COS, IOO and ASC subsystems. CDS cabling will attached to the seismic isolation and CDS will monitor and provide signals to seismic isolation equipment.

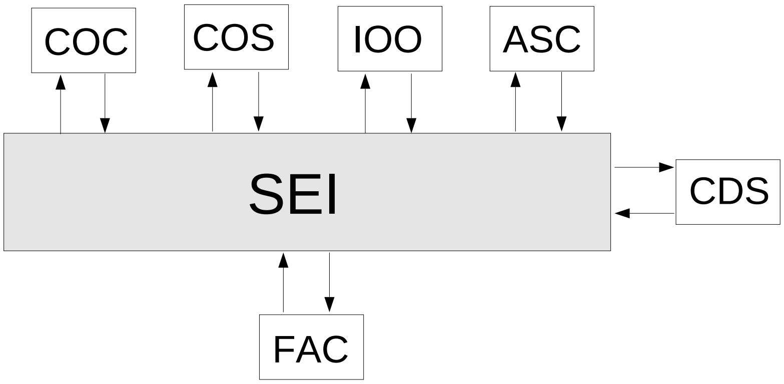

Figure 6: Relationship of SEI to other subsystems.

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 maintainence, 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 conser-

vative, 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 nominally[1] 20 cm above the optical table mounting surface, which is TBD cm below the access-door centerline.
- Optical beam height in the BSC chamber is nominally[1] 60 cm below the optical table mounting surface, which is at the same height as the beam tube centerline. However, the optical specifications and beam heights are only loosely defined at this time, so variations (of order +/- 20 cm) between component heights may occur in future.
- Ambient temperature variations in the vicinity of vacuum chambers (in the LVEA and VEAs) are less than 3.9K peak-to-peak icluding seasonal changes, and can reasonably be expected to vary daily by less than 1.1 K.

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

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[1] Precise definitions will be provided by SYS.

ground noise at Livingston and Hanford were prepared by L. Sievers, based on measurements by A. Rohay[1]. Results for both sites are given in Figure 7.

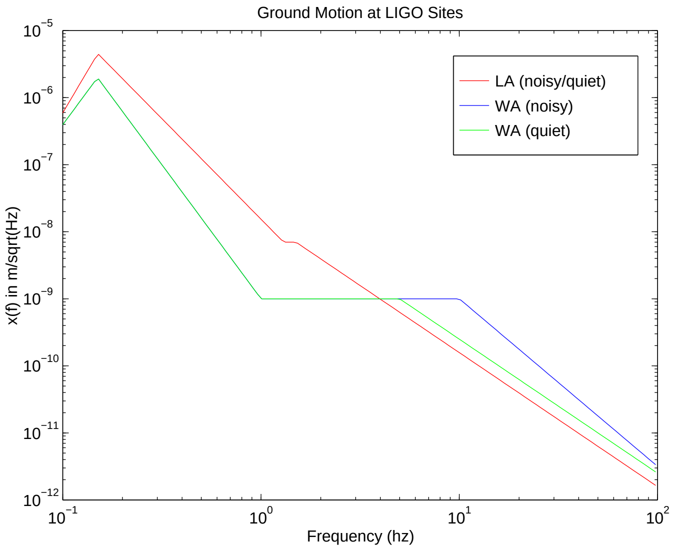

Figure 7: Characteristic ground noise at the observatory sites.

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 fequencies. 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 concatenating the Livingston noise at frequencies below 4 Hz with the LIGO Standard Spectrum above 4 Hz. The composite curve is shown in Figure 8.

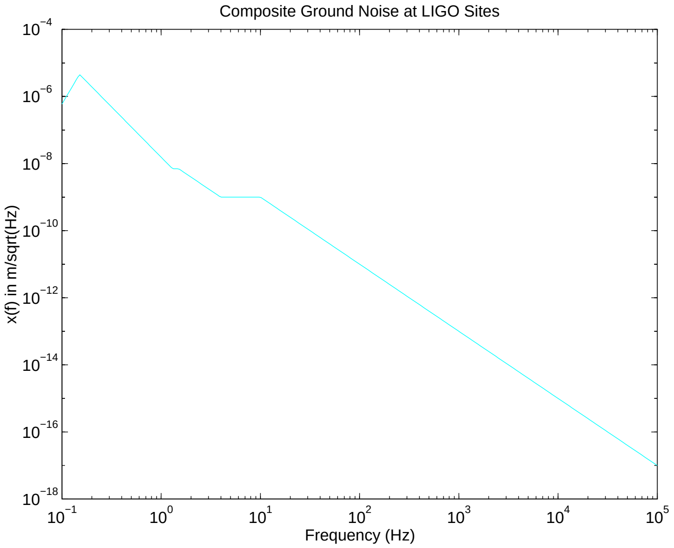

Figure 8: Ground noise spectrum assumed for SEI design.

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[1] A. Rohay, *Ambient Ground Vibration Measurements at the Hanford, Washington LIGO Site* (LIGO-C950572-02-D1). Livingston-site report not yet available.

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 isolation[1]. 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 11 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]

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 properties[3]:

- 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 properties[4]:

- 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.

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[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.

[3] *Suspension Design Requirements Document* (LIGO-T950011-06-D)

[4] *Suspension Design Requirements Document* (LIGO-T950011-06-D)

2.5.3.4 Suspension actuator range

The following ranges have been assumed for suspension actuators[1] (see Figure 14 on page 20 for coordinate definitions):

- The test mass actuator's range is $8\text{x}10^{-5}$ 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 $8\text{x}10^{-5}$ m_{pp} in the x direction and 2 mrad_{pp} about y and z axes.
- The mode cleaner actuator's range is at least $8\text{x}10^{-5}$ 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 isolaton. 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 accomodated 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 is ~1 cm[2]. A strict centering requirements 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	$<1\text{x}10^{-5}$ m/day	$6\text{x}10^{-10}$ m/sec
y translation	3 mm	$<1\text{x}10^{-5}$ m/day	$6\text{x}10^{-10}$ m/sec
z translation	3 mm	$<1\text{x}10^{-5}$ m/day	$6\text{x}10^{-10}$ m/sec
x rotation	0.4 mrad	$2\text{x}10^{-6}$ rad/day	$8\text{x}10^{-11}$ rad/s
y rotation	0.4 mrad	$2\text{x}10^{-6}$ rad/day	$8\text{x}10^{-11}$ rad/s
z rotation	4 mrad	$2\text{x}10^{-5}$ rad/day	$8\text{x}10^{-10}$ rad/s

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[1] S. Kawamura private communication, 4/6/96.

[2] D. Shoemaker, DRD draft p.2, April 9, 1995.

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 diplacement noise target for the initial LIGO interferometer is shown below in Figure 8.

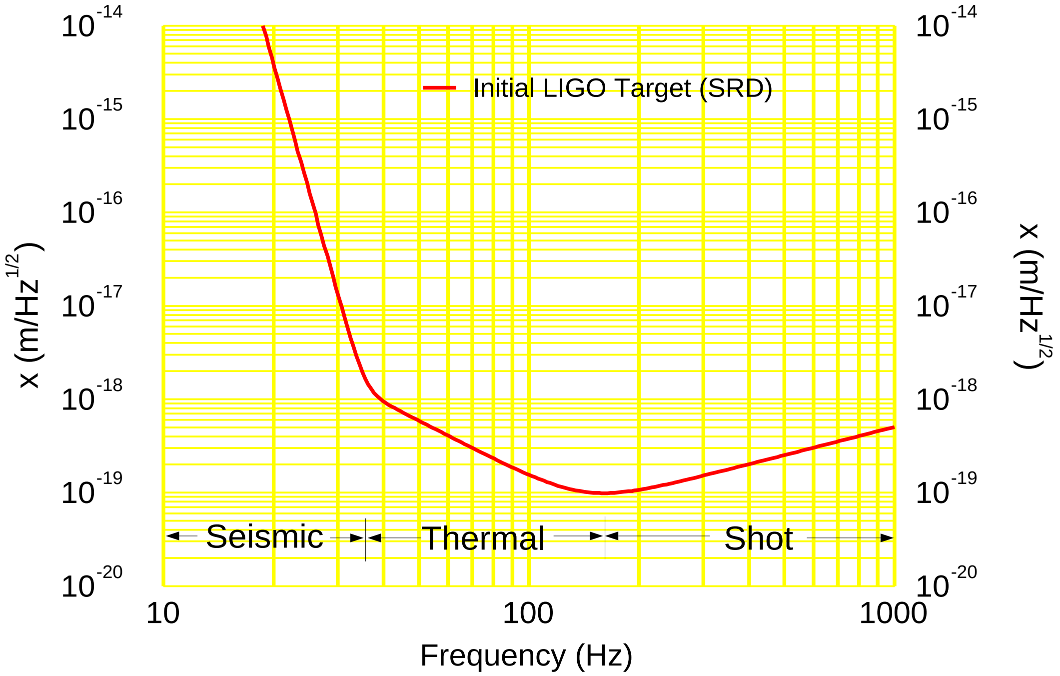

Figure 9: Displacement noise target for the initial LIGO interferometer.

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 8.

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 paltform. 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 (“on-line” actuator) 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 course adjustment over a larger range. It will be used only when the IFO is “off-line” 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

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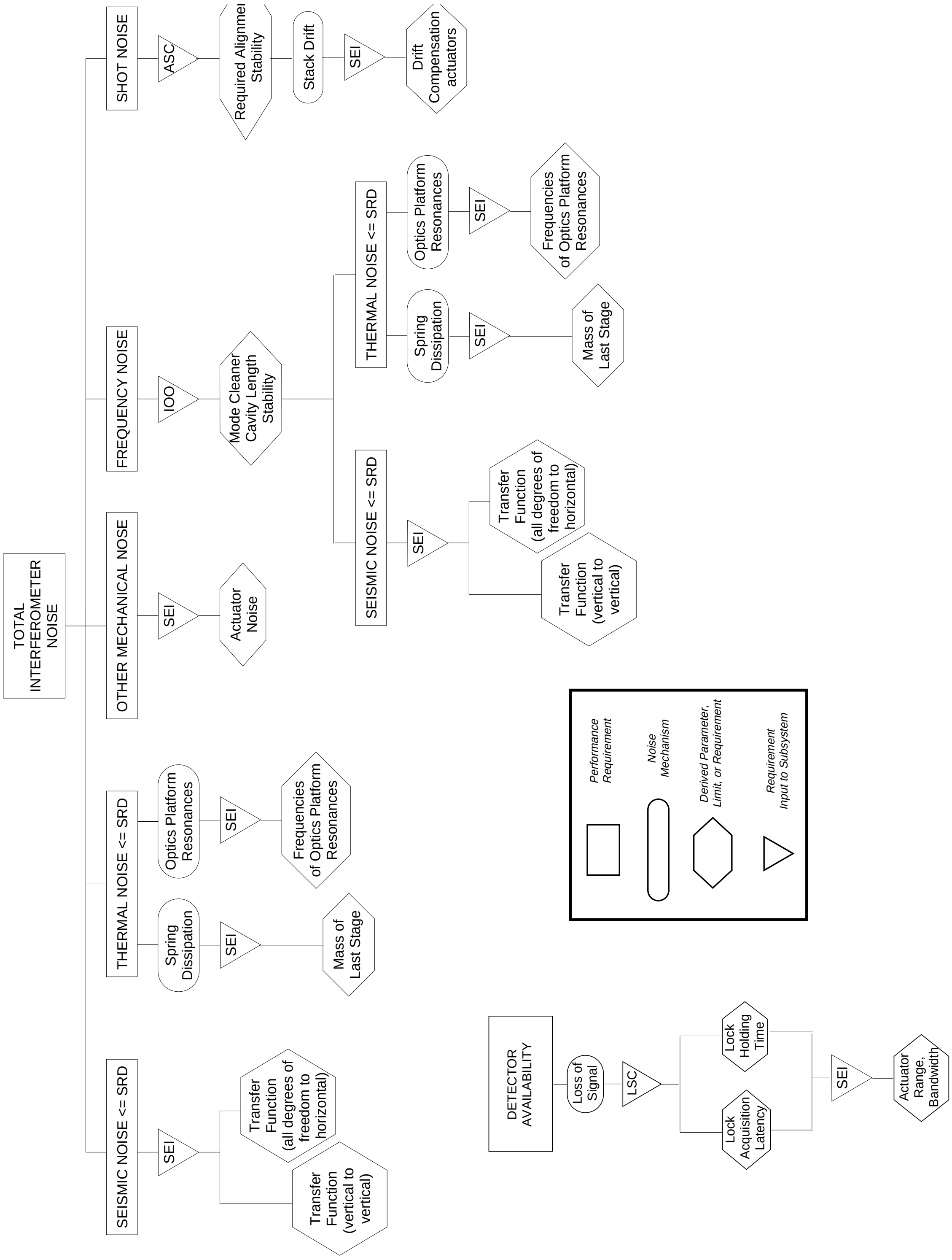

Figure 10: SEI Requirements Flowdown from Detector.

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 criteria for the vibration requirements is discussed in Appendix B. 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 dispalcements 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 frequency.

3.2.1.1.1 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 sesmic isolation is given in Figure 11.

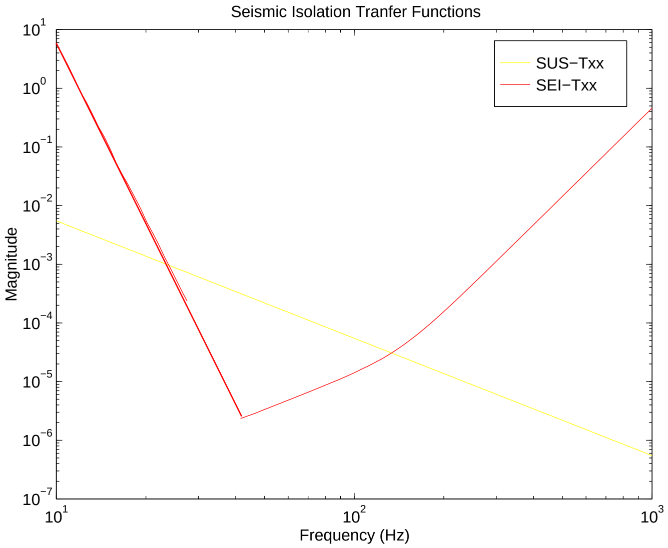

Figure 11: Horizontal-to-horizontal transfer function (SEI-T_{xx}) requirement for BSC-SEI. The assumed transfer function for the single-stage pendulum (SUS-T_{xx}) is also shown.

3.2.1.1.2 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 sesmic isolation is given in Figure 12.

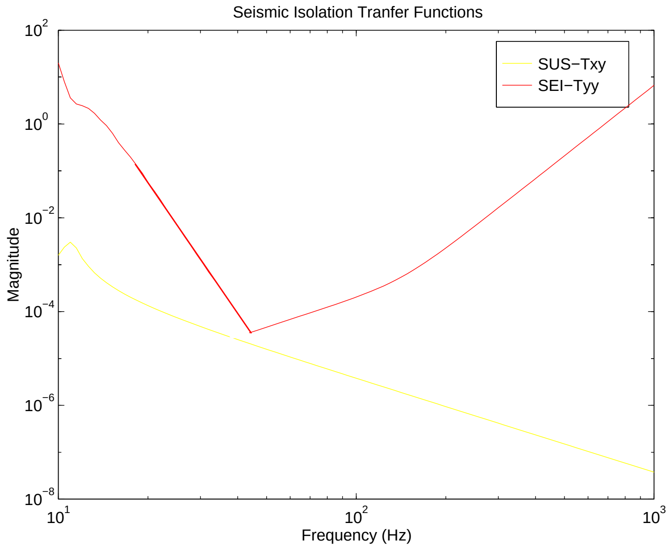

Figure 12: Vertical-to-vertical transfer function (SEI-T_{yy}) requirement for BSC-SEI. The assumed transfer function for the single-stage pendulum (SUS-T_{xy}) is also shown.

3.2.1.1.3 Horizontal Ground Motion to Yaw Motion of Optics Platform

TBD

3.2.1.1.4 Vertical Ground Motion to Pitch Motion of Optics Platform

TBD

3.2.1.1.5 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-isolation transfer functions do not exceed the required values given in Figures 11 and 12 and so that the thermal-noise fluctuations of the optical platform position does not cause excessive test-mass motion. 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 criteria.

3.2.1.1.6 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-isolation transfer functions do not exceed the required values given in Figures 11 and 12. Thermal noise from these resonances is not an issue.

3.2.1.1.7 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 Hz[1], 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 (Table 3, below).

3.2.1.2 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 subsystm, 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

$$\chi(s) = F^{-1}(s) T^{-1}_{\mathrm{SEI},xx}(s) \cdot [T_{\mathrm{SUS},xx}(s) T_{\mathrm{SEI},xx}(s) + T_{\mathrm{SUS},xy}(s) T_{\mathrm{SEI,yy}}(s)] \cdot G(s)$$

be less than 2.7 microns. Here *G(s)* is the composite ground-noise spectrum, $T_{\mathrm{SEI,ii}}(s)$ is the appropriate transer function of the seismic isolation (where i refers to x or y), $T_{\mathrm{SUS,ii}}(s)$ is the appropriate transfer function of the suspension, 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.)

3.2.1.3 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 12 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

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[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.

of 0.2mm/45cm ~ 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.)

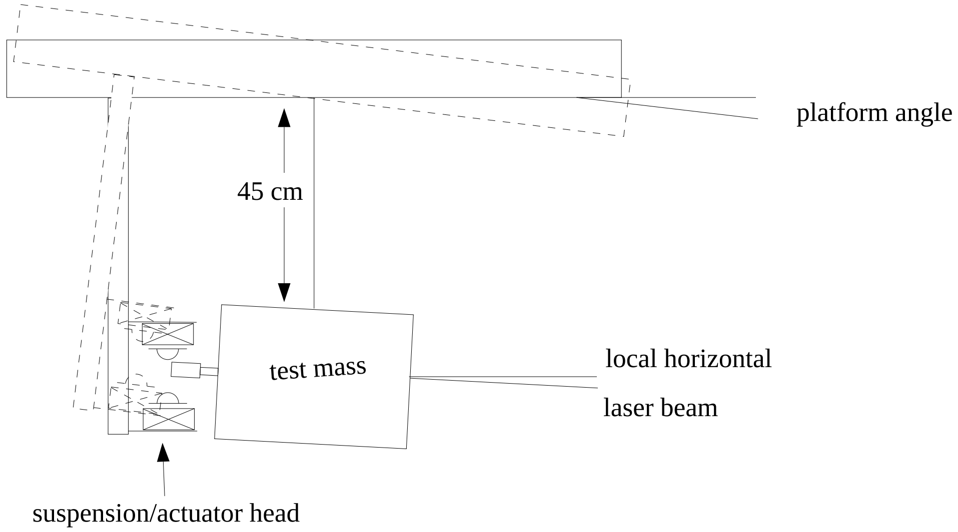

Figure 13: Dependence of suspension/actuator head position on optical platform pitch.

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.

3.2.1.4 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 using on-line actuators. (See Appendix E 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 F.) On-line 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. These rest on top of the off-line actuators and will be controlled by the LSC subsystem. The requirements for fine adjustment of stack translation and rotation during on-line mode of the IFO are listed in table 2. Actuator requirements are:

- a response of ~$3x10^{-7}$ m/minute and a maximum range of order 10^{-4} m
- no vibrations at the support beams in excess of the facilities vibration requirements
- tolerable stick-slip or impulsive response on the stack support beam is **TBD**
- total driven mass is **TBD**[1]

There are no requirements for on-line rotation adjustments[1]. A limitation for rotation about x of order 0.5 mrad is set by the allowable shear stress in the support beam bellows due to torsion.

Table 2: Fine actuator requirements during on-line mode for BSC

item	range	resolution
x translation	+/- 10^{-4} m	~1×10^{-6} m
y translation	N/R	N/R
z translation	N/R	N/R
x rotation	< 0.5 mrad	N/R
y rotation	N/R	N/R
z rotation	N/R	N/R

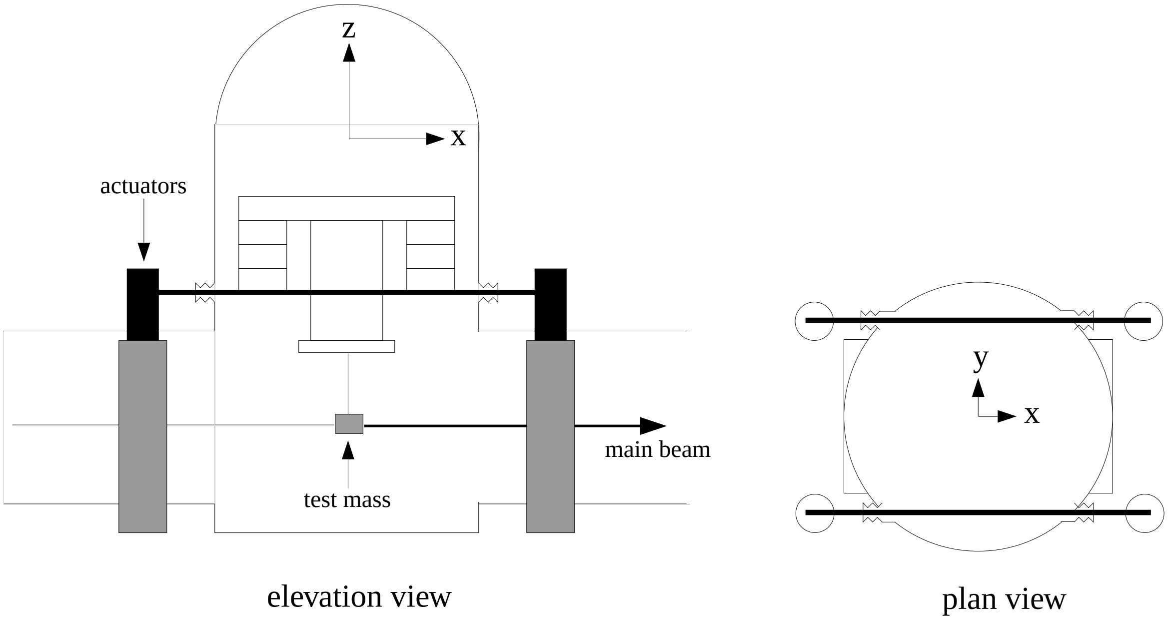

Figure 14: SEI, bellows and beam tube orientation for the BSC chambers in the mid- and end-station buildings.

The requirements for stack translation and rotation during off-line mode are listed in table 3. In this mode, actuators are used to compensate for long term stack drift for a time of order 1 year. A range requirement of +/- 5 mm will be specified to maintain centering on any small optics that might be placed in a BSC. The resolution in x, y and z must equal 1/10 of the beam centering requirement, ~1×10^{-4} m. A rotation range of +/- 4 mrad is required to compensate for stack rotational drift about the z axis. The resolution is 1/10 of the suspension actuator range, 0.1 mrad.

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1. Consists of mass of SEI from support beams to optical platform, inclusive.
1. The suspension sensor/actuators have sufficient range to compensate for daily drifts.

Rotation about x is limited to 0.5 mrad to restrict stress in the bellows. (Stack tilt drift about x and y is small enough to remain within the suspension sensor/actuator's range for more than one year.) Vibrations during translation are limited to a level **TBD**.

Any drift beyond these ranges will require venting the chamber and adjusting the individual optics. This is expected to be infrequent and could be done during scheduled shut down of the IFO as required for routine maintenance or repair.

Table 3: Coarse actuator requirements during off-line mode for BSC

item	range	resolution
x translation	1 cm	1×10^{-4} m
y translation	1 cm	1×10^{-4} m
z translation	1 cm	1×10^{-4} m
x rotation	< 0.5 mrad	N/R
y rotation	N/R	N/R
z rotation	+/- 4 mrad	+/- 0.1 mrad

3.2.1.5 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 G):

- 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 cable[1] clamped to isolation stages must be less than 10 N/m.
- The mass of the free lengths of cable must be less than $3 \bullet Q$ 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 possible touch other surfaces except where they are clamped.
- Cabling must not "crackle" when vibrated under operating conditions[2]. This may be ensured 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)

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[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.)

3.2.1.6 Required Size of Optical Platform

The optical platform diameter shall not exceed 1.5 m, to allow sufficient access inside the BSC chamber[1], which has an inside diameter of 2.64 m.

3.2.1.7 Requirements on Support-Beam Bellows

- Absolute maximum rotation about bellows axis should be greater than 0.5 mrad.
- TBD

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 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.

3.2.2.1.1 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. Details

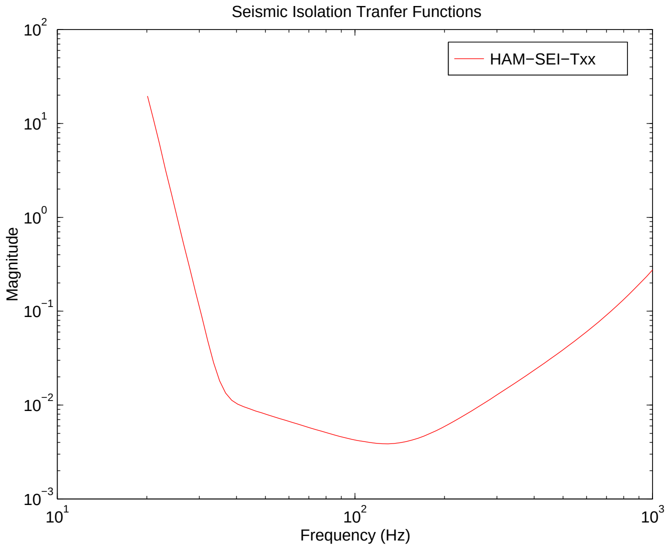

Figure 15: Horizontal-to-horizontal transfer function requirement for HAM-SEI.

3.2.2.1.2 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 sesmic isolation does not arise from the mode-cleaner mirrors, but is likely

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

to be set by the mode-matching components of the IOO. This requirement is TBD, pending further definition of IOO design.

3.2.2.1.3 Horizontal Ground Motion to Yaw Motion of Optics Platform

TBD

3.2.2.1.4 Vertical Ground Motion to Pitch Motion of Optics Platform

TBD

3.2.2.1.5 Internal Resonances in Optics Platform

TBD

3.2.2.1.6 Internal Resonances in Mass Elements

TBD

3.2.2.1.7 Internal Resonances in Support Beam/Structure/Pier

The resonances in the supporting structure, consisting of the support beams and the support structure, shall have frequencies that are above 20 Hz[1], while still maintaining adequate clearance between the support beams and the support-beam bellows-ports (29-cm ID, nominal) to allow the full range of motion for the stack actuators (Table 4, below).

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 is 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.

Table 4 gives the off-line actuator requirements for the HAM stacks. A range requirement of +/- 5 mm will be specified to maintain centering on the small optics. Resolution in x, y and z equals 1/10 of the beam centering requirement, $\sim 1\times 10^{-4}$ m. The requirements for rotation are the same as for BSC-SEI. To prevent damage to the bellows, position sensors or actuator stops must be pro-

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[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.

vided at each stack support beam port. No actuator shall operate at frequencies coincident with the modal frequencies of the stack and stack support structure.

Table 4: Actuator requirements during off-line mode for HAM

item	range	resolution
x translation	1 cm	1×10^{-4} m
y translation	1 cm	1×10^{-4} m
z translation	1 cm	1×10^{-4} m
x rotation	< 0.5 mrad	N/R
y rotation	N/R	N/R
z rotation	+/- 4 mrad	+/- 0.1 mrad

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 accomodate 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.
- TBD

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, 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 accomodate the high-vacuum compatibility of the cleaned, seismic-isolation components.

3.2.4. Interface Definitions

3.2.4.1 Interfaces Between BSC-SEI and other LIGO detector subsystems

3.2.4.1.1 Mechanical Interfaces

The mechanical interfaces to be specified are shown schematically in Figure 16. Note that for counterweights, SYS will provide information on the optical layout from which SEI and SYS can plan for counterweights.

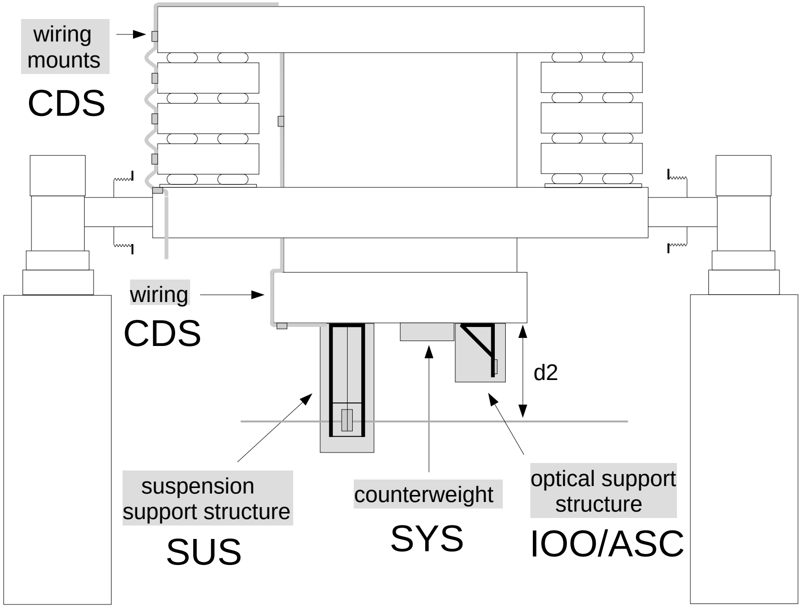

Figure 16: Mechanical interfaces between BSC-SEI and other Detector subsystems

Table 5: Mechanical interfaces between BSC-SEI and other Detector subsystems

Mechanical Mounting Interfaces			Drawing/ Doc #
SEI Mounting Surface	Other Subsystem-Mounting Surface	Interface and its Characteristics	
BSC optics platform	Top Plate of suspension support structure (SUS)	Bolts/screws • bolt hole pattern • bolt hole thread size	
BSC optics platform	Optical support structures (IOO/ASC)	Bolts/screws • bolt hole pattern • bolt hole thread size	
BSC optics platform	Counter weight (SYS)	Bolts/screws • bolt hole pattern • bolt hole thread size	
BSC support platform, mass elements, down structure and top plate	Wiring mounts (CDS)	Bolts/screws • screw hole pattern • screw hole thread size • location and number of wiring mounts	
Critical Dimensions/Size			Drawing/ Doc #
d2= 60 cm (nom.): Distance of main laser beam below optics platform Total mass load on optics platform Moments of inertia about center of optics platform surface Wiring mass and stiffness			

3.2.4.1.2 Electrical Interface

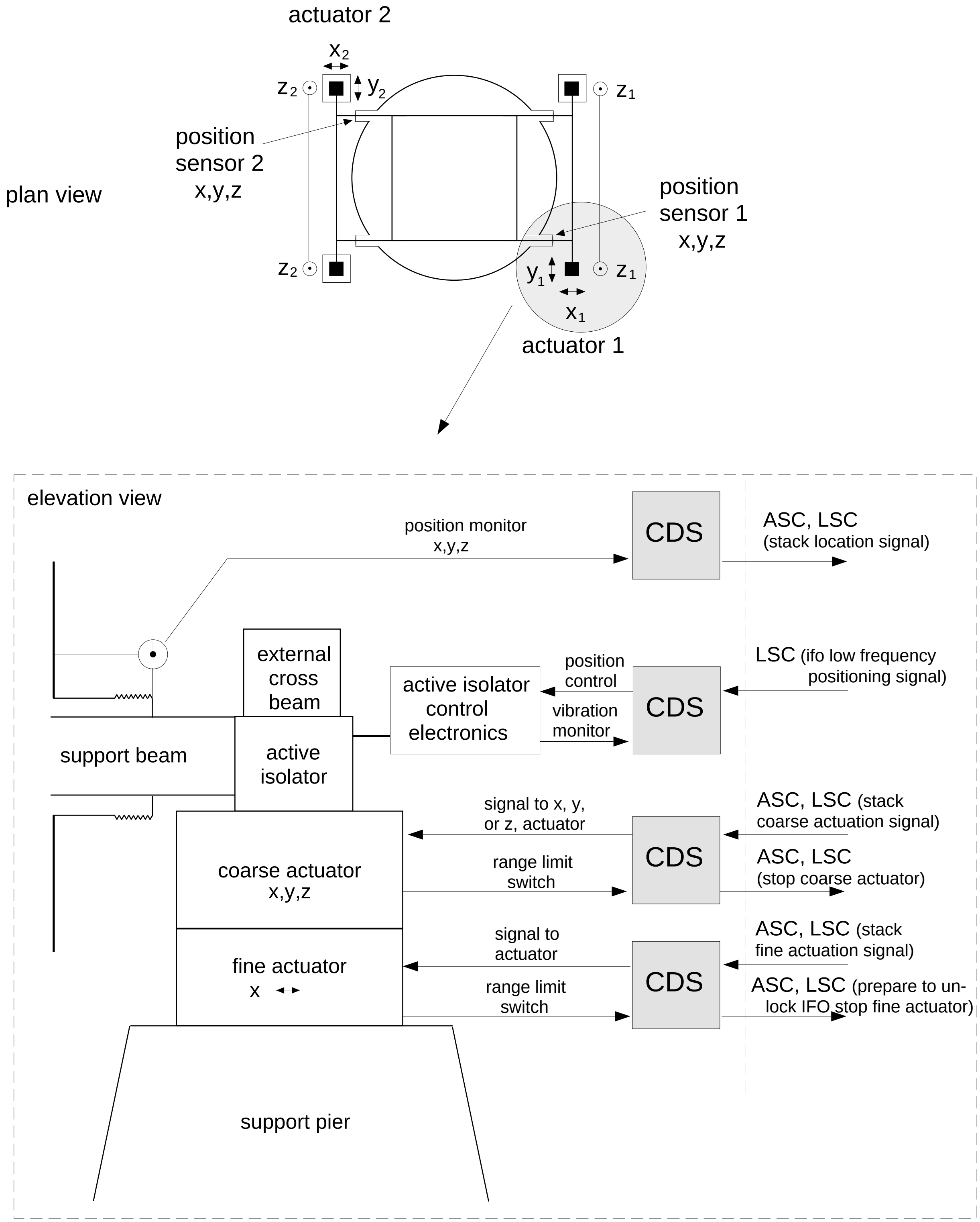

Figure 17: Diagram showing signal interfaces between BSC-SEI and other Detector subsystems

BSC-SEI Control Signals
Inputs • Interferometer low frequency positioning signal (LSC) • Stack coarse actuation signal (ASC, LSC) • Stack fine actuation signal (ASC, LSC) Outputs • Stop coarse actuator (ASC, LSC) • Stop fine actuator (ASC, LSC)
HAM-SEI Monitor Signals
Outputs • Stack location signal (ASC, LSC)

Table 6: Control Signal interfaces between BSC-SEI and other Detector subsystems

3.2.4.1.3 Optical Interfaces

There are no optical interfaces.

3.2.4.1.4 Stay Clear Zones

3.2.4.2 Interfaces Between HAM-SEI and other LIGO detector subsystems

3.2.4.2.1 Mechanical Interfaces

The mechanical interfaces to be specified are shown schematically in Figure 18. Note that for counterweights, SYS will provide information on the optical layout from which SEI and SYS can plan for counterweights.

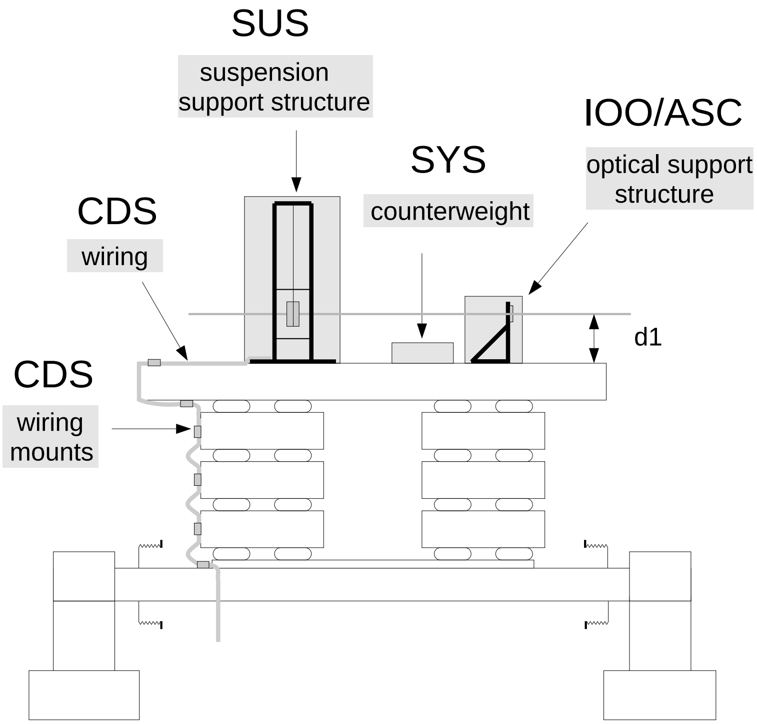

Figure 18: Mechanical interfaces between HAM-SEI and other detector subsystems.

Table 7: Mechanical interfaces between HAM-SEI and other Detector subsystems

Mechanical Mounting Interfaces			Drawing/ Doc #
SEI Mounting Surface	Other Subsystem Mounting Surface	Interface and its Characteristics	
Ham optics platform	Bottom plate of suspension support structure (SUS)	Bolts/screws • bolt hole pattern • bolt hole thread size	
HAM optics platform	Optical support structures (IOO/ASC)	Bolts/screws • bolt hole pattern • bolt hole thread size	
HAM optics platform	Counter weight (SYS)	Bolts/screws • bolt hole pattern • bolt hole thread size	
HAM support platform, mass elements and optics platform	Wiring mounts (CDS)	Bolts/screws • bolt hole pattern • bolt hole thread size • location and number of wiring mounts	

Critical Dimensions/Size	Drawing/ Doc #
d1= 20 cm (nom): Height of main laser beam above optics platform Total mass load on optics platform Moments of inertia about center of optics platform surface Wiring mass and stiffness	

3.2.4.2.2 Electrical Interface

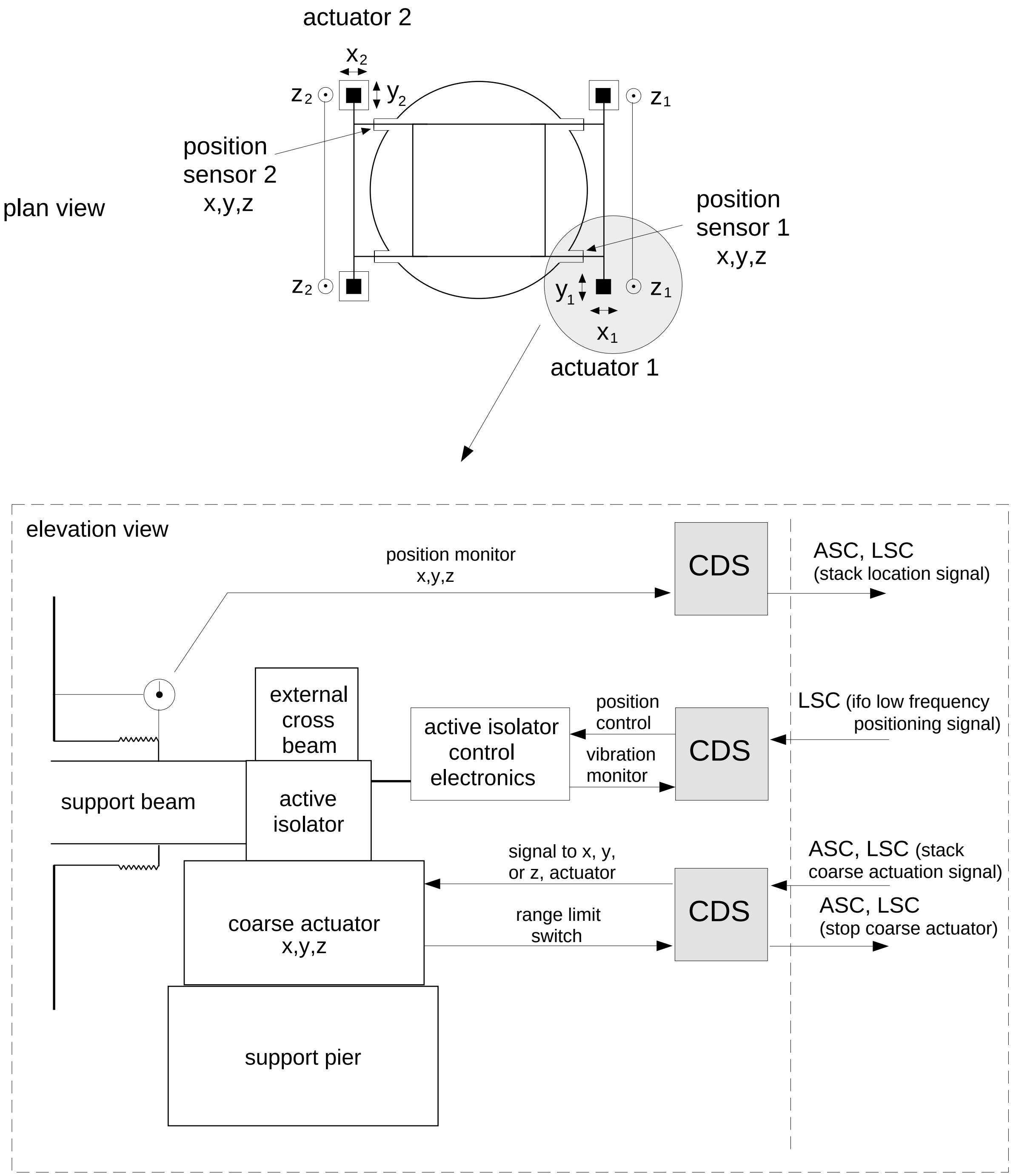

Figure 19: Diagram showing signal interfaces between HAM-SEI and other Detector subsystems

HAM-SEI Control Signals
Inputs • Interferometer low frequency positioning position (LSC) • Stack coarse actuation signal (ASC, LSC) Outputs • Stop coarse actuator (ASC, LSC)
HAM-SEI Monitor Signals
Outputs • Stack location signal (ASC, LSC)

Table 8: Control Signal interfaces between HAM-SEI and other Detector subsystems

3.2.4.2.3 Optical Interfaces

There are no optical interfaces.

3.2.4.2.4 Stay Clear Zones

3.2.4.3 Interfaces of BSC-SEI external to LIGO detector subsystems

3.2.4.3.1 Mechanical Interfaces

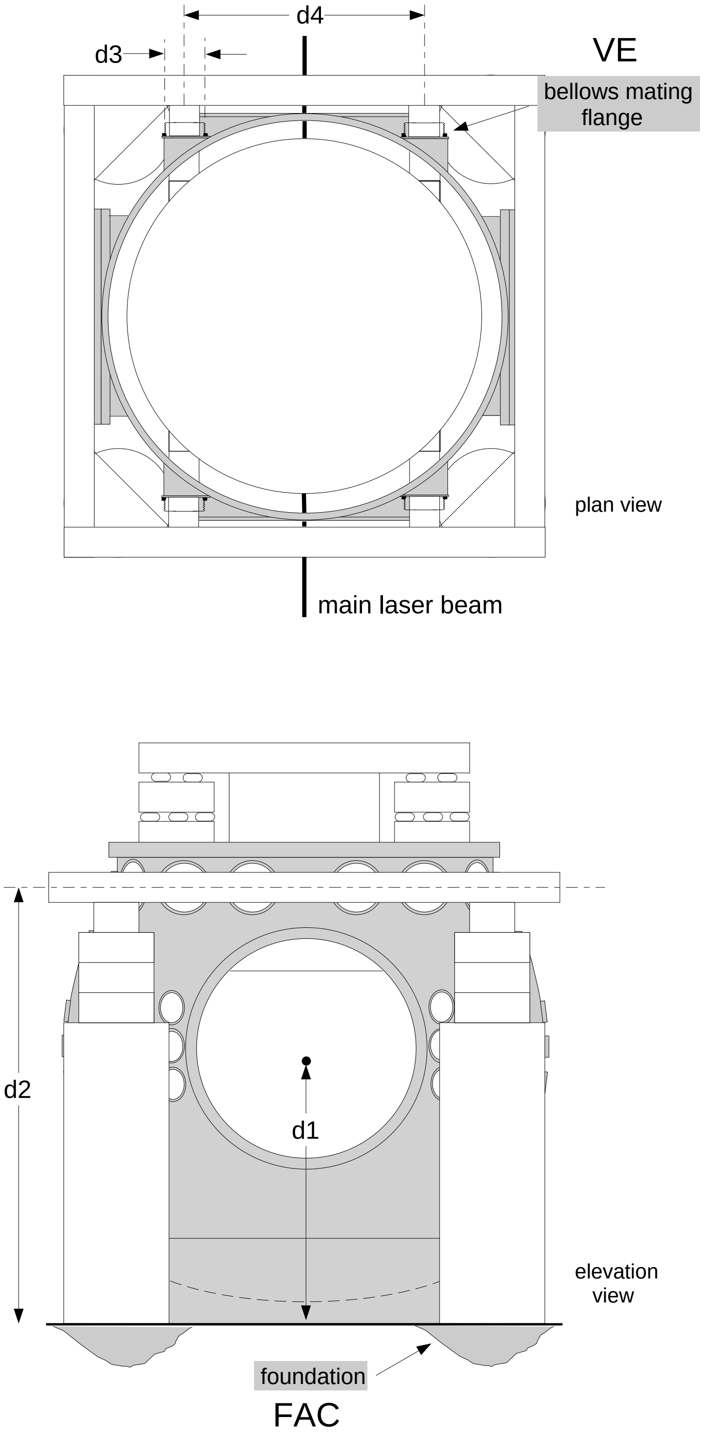

Figure 20: Mechanical interfaces between BSC-SEI and systems external to the detector

Mechanical Mounting Interfaces			*Drawing/ Doc #*
BSC-SEI Mounting Surface	*FAC/VE Mounting Surface*	*Interface and its characteristics*	
Support pier	Foundation slab (FAC)	Anchoring must secure pier to foundation rigidly so that actuator forces applied between pier and support structure do not tilt or displace piers	
Bellows flange	Bellows mating flange (VE)	Flange size and type Bolt hole pattern Bolt size	

Critical Dimensions	*Drawing/ Doc #*
d1 +/- tol. = distance from main laser beam to the facility floor d2 +/- tol. = distance from centerline of support beam port to the facility floor d3 +/- tol. = inner diameter of VE support beam port d4 +/- tol. = 1.676 m (nom) distance between centerlines of the 2 parallel support beam tube ports	

Stay Clear Zones	*Drawing/ Doc #*
Piers require ~ 3 ft diameter footprint on the facility floor. This must extend vertically to the height of the support beam ports. A stay clear zone for the external support structure and actuators requires a 3 ft wide ring surrounding the BSC in the plane defined by the support beam ports.	

Table 9: Mechanical interfaces between BSC-SEI and systems external to the detector

3.2.4.3.2 Electrical Interfaces

BSC-SEI Component Interface	*Utility Interface*	*Characteristics*	*Drawing/ Doc #*
fine actuators	power	voltage/power requirements	
Coarse actuators	power	voltage/power requirements	
active isolators	power	voltage/power requirements	

Table 10: Electrical interfaces between BSC-SEI and facility

3.2.4.3.3 Stay Clear Zones

3.2.4.4 Interfaces of HAM-SEI external to LIGO detector subsystems

3.2.4.4.1 Mechanical Interfaces

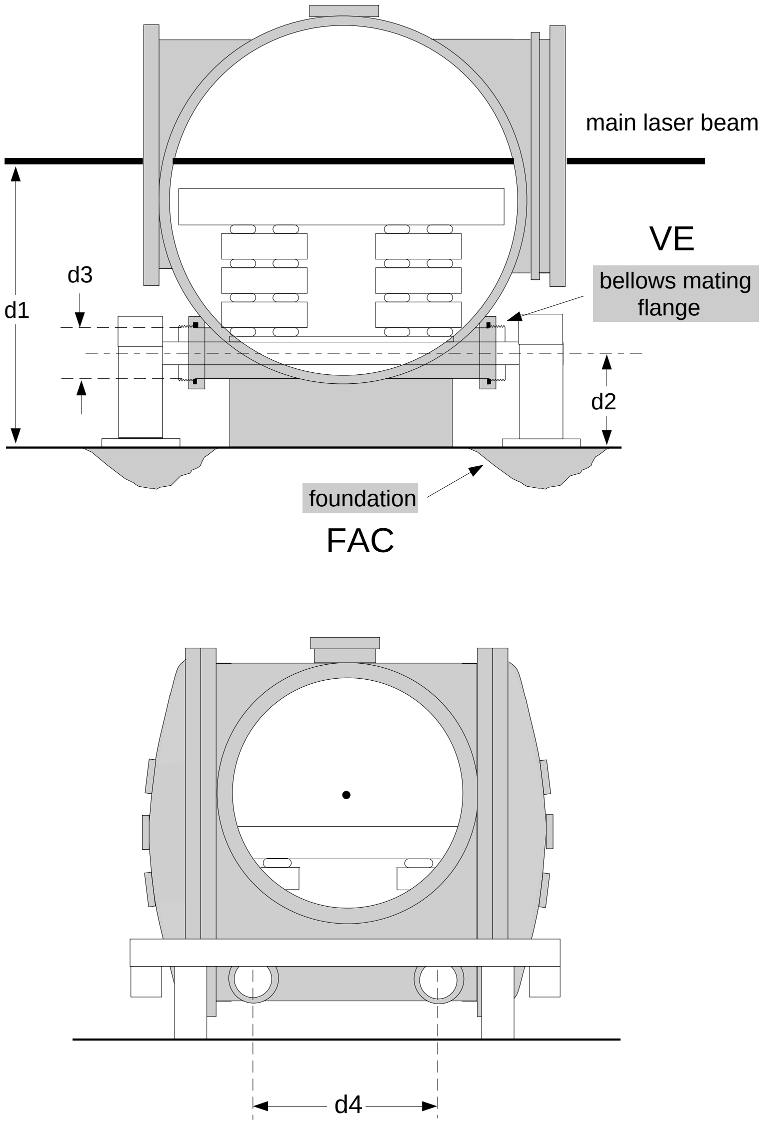

Figure 21: Mechanical interfaces between HAM-SEI and systems external to the detector

Mechanical Mounting Interfaces			*Drawing/ Doc #*
HAM-SEI Mounting Surface	*FAC/VE Mounting Surface*	*Interface and its characteristics*	
Support pier	Foundation slab (FAC)	Anchoring must secure pier to foundation rigidly so that actuator forces applied between pier and support structure do not tilt or displace piers	
Bellows flange	Bellows mating flange (VE)	Flange size and type Bolt hole pattern Bolt size	

Critical Dimensions	*Drawing/ Doc #*
d1 +/- tol. = distance from main laser beam to the facility floor d2 +/- tol. = distance from centerline of support beam port to the facility floor d3 +/- tol. = inner diameter of VE support beam port d4 +/- tol. = 1.37 m (nom) distance between centerlines of the 2 parallel support beam tube ports	

Stay Clear Zones	*Drawing/ Doc #*
Installation of optics platform requires ~9 ft of clearance on one side and ~4 ft of clearance on the opposite side of the large access ports of the HAM ~ 3 ft of clearance surrounding the base of the HAM is required for external support framework and actuators and piers.	

Table 11: Mechanical interfaces between HAM-SEI and systems external to the detector

3.2.4.4.2 Electrical Interfaces

HAM-SEI Component Interface	*Utility Interface*	*Characteristics*	*Drawing/ Doc #*
Coarse actuators	power	voltage/power requirement	
active isolators	power	voltage/power requirement	

Table 12: Electrical interfaces between HAM-SEI and facility

3.2.4.4.3 Stay Clear Zones

3.2.5. Reliability

Mean Time Between Failures (MTBF), Availability

3.2.6. Maintainability

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 13 for ranges during normal operations, shipping and storage. Additionally, the spring and mass elements and vacuum cabling (including associated cable harnesses) shall be compatible with vacuum baking at temperatures up to 180 C.

3.2.7.1.2 Atmospheric Pressure

TBD

Table 13: Environmental Performance Characteristics

Components	*Operating*	*Non-operating (storage)*	*Transport*
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

3.2.7.1.3 Seismic Disturbance

The seismic-isolation subsystem shall have provisions to withstand accelerations of 0.1 g without significant damage.

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]

3.2.7.2.2 Acoustic

Acoustic noise from actuators at any vacuum chamber shall not exceed PNC-40 (Preferred Noise Criterion 40) within 1 m of any other vacuum chambers or equipment tables.[2]

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 oof any other vacuum chambers and equipment tables by more than 1 dB at any frequency between 0.1 Hz and 10 kHz.[3] 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. All containers shall be movable by forklift. All items over 100 lbs. which must be moved into place

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[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.

[3] SEI fine-adjustment actuators shall be operable without interfering acoustically with neighboring interferometers.

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.
- Optical platforms shall have a matrix of 1/4-20 threaded holes, with 2.54 cm center spacing.
- BSC optical platforms shall have an additional matrix of TBD-diameter through holes on a TBD pattern. (Intended to allow passage of suspension fibers that are part of a multiple-stage suspension system to be passed through the optical platform.
- Optical platform surfaces to which optical components are mounted shall be flat to within TBD.
- All materials shall have non-shedding surfaces.

3.3.1.2 Materials

All fabricated metal components exposed to vacuum shall be made from type 304L or 316L stainless steel, copper, or aluminum. Other metals may be used 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).

3.3.1.3 Processes

3.3.1.3.1 Welding

All welding exposed to vacuum shall be done by the tungsten-arc-inert-gas (TIG) process. Welding techniques for components operated in vaccum 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.

3.3.1.3.2 Cleaning

All materials used inside the vacuum chambers must be cleaned in accordance with *LIGO Vacuum Compatibility, Cleaning Methods and Procedures* (LIGO-E960022-00-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 Detector Naming Convention (document TBD). 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 accomodate 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 accomodate these force/torque requirements.

3.4. Documentation

Requirements for documentation of the design, including types of documents, such as operator manuals, etc.

3.4.1. Specifications

TBD

3.4.2. Design Documents

- *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 precess 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

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 constants (i.e., strain rates under static load) of spring elements
- outgassing certification of spring elements
- 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 Meth-*

ods 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.

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.

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 ~6x10^{-10} m/sec. The change in the height of the stack due to temperature variation was ~3x10^{-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 ~6x10^{-10} m/sec (~5x10^{-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

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

fluctuation is approximately1.1 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 elements[1]. Therefore, the maximum daily excursion in response to temperature variation would be <1x10^{-5} m.
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.

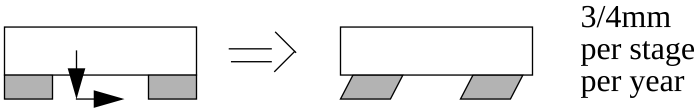

Figure 2. Compression accompanied by sideways translation in viton springs

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 8x10^{-11} rad/s. Daily temperature fluctuations produce ~2x10^{-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, ~2x10^{-5} rad thermal response, and ~8x10^{-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.

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[1] See Appendix F for estimates.

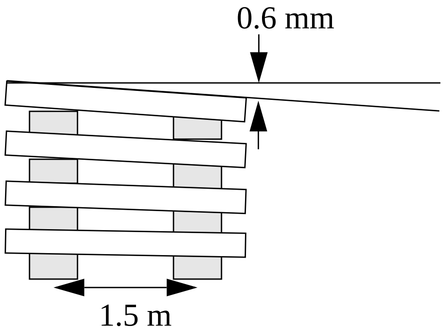

Figure 3. Tilt due to variation in spring constants

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

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

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

$$T_{xy} = \frac{\omega_v^2}{\left[(\omega_v^2 - \omega^2)^2 + \omega_v^4 \phi_v^2\right]^{1/2}} \bullet 3.1\times10^{-4}$$

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.

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 14:

Frequency (Hz)	Q	$\frac{x(f)}{10^{-20}\text{m}/\sqrt{\text{Hz}}}$	*Acceptable?*
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 measurments in the 40-meter interferometer in November 1994 by L.Sievers [1], 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

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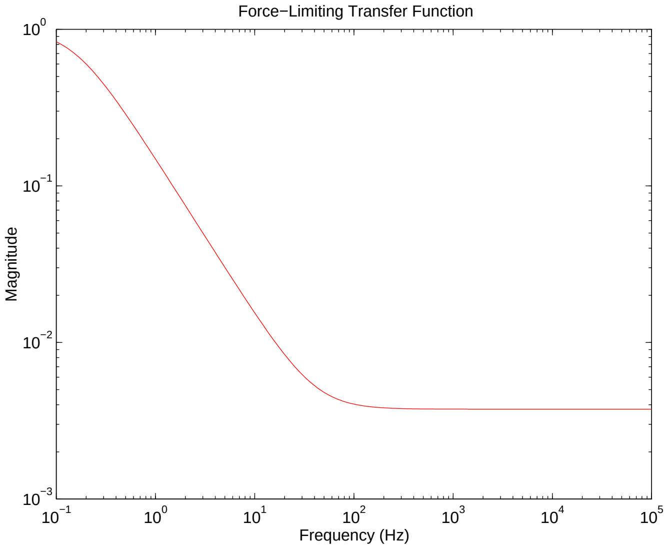
[1] L. Sievers, *Relative Test-Mass Motion in the 40-Meter Interferometer* (LIGO-T950038-00-R)

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 frquency. The figure of merit for the amount of broad band motion at the optical platform, taking into consideration the force limitng characteristics of the SUS actuator, is given by

$$\chi(s) = F^{-1}(s) T^{-1}_{\mathrm{SEI},xx}(s) \cdot [T_{\mathrm{SUS},xx}(s) T_{\mathrm{SEI},xx}(s) + T_{\mathrm{SUS},xy}(s) T_{\mathrm{SEI,yy}}(s)] \cdot G(s)$$

where *G(s)* is the composite ground-noise spectrum, $T_{\mathrm{SEI,ii}}(s)$ is the appropriate transer function of the seismic isolation (where i refers to x or y), $T_{\mathrm{SUS,ii}}(s)$ is the appropriate transfer function of the suspension. $\chi(s)$ 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

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

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 DRIFT IN IFO ARM LENGTHS DUE TO EARTH TIDES

Earth tides cause a significant drift in the separations between test masses in the long arms of the LIGO interferometer. Other drifts, due to thermal and soil conditions are expected to be smaller than the tidal effect. [2]Earth-tide effects were estimated using data and formulae from The Tides of Planet Earth by Paul Melchior (Pergamon Press, Oxford, 1978), and the applicable site coordinates and arm bearings. The maximum possible contribution from alignment of the moon and sun was included to obtain the maximum possible peak tide. The appropriate angular factors were then used to derive common-mode and differential mode arm-length changes for the two sites. The results are shown in Tables 14 and 15, below.

Table 15: Earth-Tide Effects for Hanford

Quantity	*Value*	*Units*
Site Properties:		
Site Longitude	119 24 27.1 W	deg, min, sec, E/W
Site Latitude	46 27 18.5 N	deg, min, sec, N/S
Bearing of Arm 1	N 36.8 W	N/S, deg, E/W
Bearing of Arm 2	S 53.2 W	N/S, deg, E/W
Diurnal (Tesseral) Wave:		
Common-Mode Amplitude	113.6	microns peak-max
Differential-Mode Amplitude	22.0	microns peak-max

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

[2] R. Weiss, memo on thermal considerations for LIGO beam tubes, December, 1988.

Table 15: Earth-Tide Effects for Hanford

Quantity	*Value*	*Units*
Semi-Diurnal (Sectoral) Wave		
Common-Mode Amplitude	71.0	microns peak-max
Differential-Mode Amplitude	31.1	microns peak-max

The maximum common-mode drifts are approximately 370 microns(p-p) at Hanford and 440 microns(p-p) at Livingston. This corresponds to a peak-to-peak strain of $\sim 10^{-7}$, which can be removed by a slight adjustment of the laser frequency (equivalent to changing the temperature of the reference cavity by 0.2 K). The differential-mode drifts are approximately 106 microns(p-p) at Hanford and 90 microns(p-p) at Livingston. These require a differential change in arm lengths that exceeds the range of the suspension actuators. Providing the end- and mid-station BSC-SEI

Table 16: Earth-Tide Effects for Livingston

Quantity	*Value*	*Units*
Site Properties:		
Site Longitude	90 46 27.3 W	deg, min, sec, E/W
Site Latitude	30 33 46.0 N	deg, min, sec, N/S
Bearing of Arm 1	S 18 E	N/S, deg, E/W
Bearing of Arm 2	S 72 W	N/S, deg, E/W
Diurnal (Tesseral) Wave:		
Common-Mode Amplitude	99.4	microns peak-max
Differential-Mode Amplitude	20.0	microns peak-max
Semi-Diurnal (Sectoral) Wave		
Common-Mode Amplitude	110.7	microns peak-max
Differential-Mode Amplitude	30.4	microns peak-max

with actuators capable of 100 microns(p-p) motion will allow differential earth-tide motion to be handled with adequate margin.

APPENDIX F 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 m^2 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.

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 $5.5 \times 10^{-6} \mathrm{K}^{-1}$, 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 $\mu\mathrm{m}$ peak-to-peak daily variation over a 10-m baseline, well within suspension-actuator range.

APPENDIX G 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

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

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 $m < \pi MQ \bullet T_{\text{stage}}$, where T_{stage} is the required transfer function per stage. The most stringent requirement on T_{stage} is $T_{\text{stage}} \approx 3\times10^{-2}$, set by the BSC horizontal transfer function. A typical mass for a single mass element is approximately 300 kg. Setting $m < 3Q$ kg satisifes this relation with an 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 H 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 $\Delta\nu = (\Delta l/l) \bullet \nu_0$. 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

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

The common-mode servo gain, not available at the time of this version, was conservatively set to be[1]

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

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.

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[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.