LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
– LIGO –

LIGO Laboratory / LIGO Scientific Collaboration

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Seismic Isolation Subsystem Design Requirements Document

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1 General Description

Isolation of the LIGO II optics from ambient vibration is accomplished by the Seismic Isolation (SEI) Subsystem and the Suspension Subsystem. This document gives the requirements for the SEI subsystem, including requirements for interfacing to the suspension subsystem.

1.1. Product Functions

The seismic isolation system must provide the following functions:

- provide vibration isolated support for the payload(s)
- provide a mechanical and functional interface for the suspensions
- provide adequate space and flexibility for mounting of components (suspensions and auxiliary optics) and adequate space for access to components
- provide coarse positioning capability for the isolated supports/platforms
- provide external actuation suitable for use by the interferometer's global control system to maintain long-term positioning and alignment
- provide means for the transmission of power and signals from control electronics outside the vacuum chambers to the suspension systems and any other payloads requiring monitoring and/or control
- provide counter-weights to balance the payloads

1.2. General Constraints

LIGO interferometers have strict vacuum compatibility requirements which constrain the material choices to those materials compatible with LIGO Vacuum Compatibility, Cleaning Methods and Procedures (LIGO-960022-00-D). Wherever possible, material choices should be conservative with regard to vacuum compatibility. In particular, polymers and elastomers should not be exposed in the LIGO-II SEI system, with the exception of Kapton and PEEK for cabling.

All LIGO-II SEI systems must fit within the LIGO vacuum chambers as presently built.

The SEI piers around the chambers should be left in-place. The present SEI support tubes shall be re-used.

2 Environmental Inputs

The isolation systems must meet performance requirements in the presence of various environmental influences. Seismic motions are broken up into four types: average spectrum of ground noise, in the band 0.1–30 Hz; maximum peak-peak ground excursion at the microseismic peak (6–8 sec period); tidal stretching of the arms; earthquakes. Longer term thermal changes of the arm lengths may also be significant; such influences may be specified at a later date–at present there is insufficient data to go on.

2.1. Ground noise spectra

Because the average ground noise at the two observatories differ significantly, two separate ground noise models are carried for LHO and LLO; these are shown in Figure 1. The SEI isolation requirements must be met assuming the ground noise shown in the figure as input. The ground noise input is taken to be the same for all three translational degrees-of-freedom.

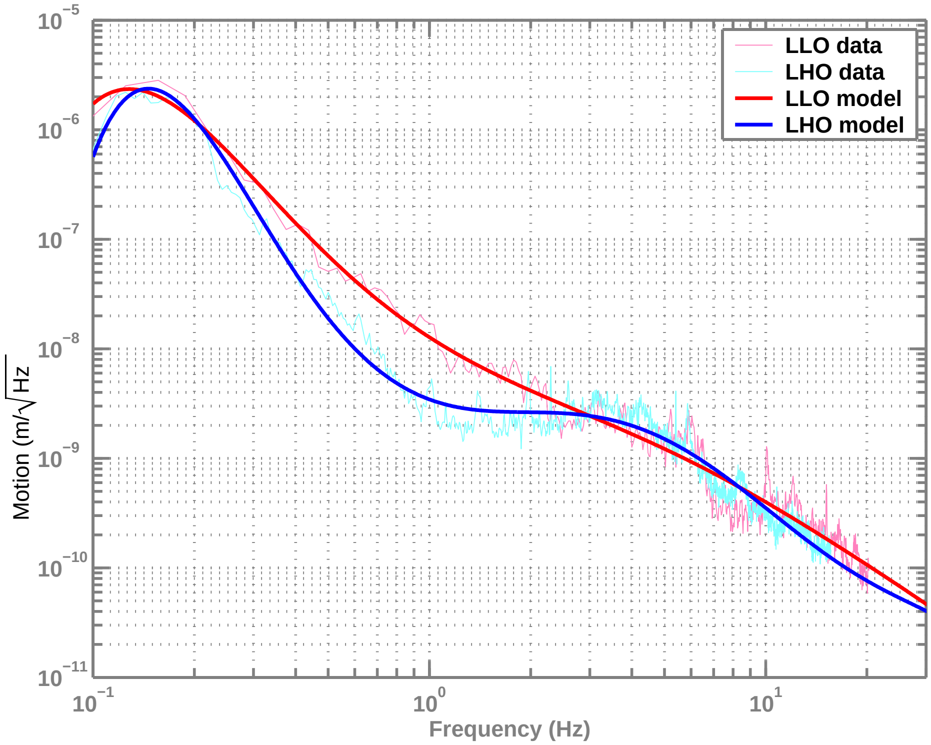

Figure 1: Ground noise model to be used as the input spectrum for the SEI design (smooth curves), shown along with the site seismometer on which the models are based. Each model is a polynomial fit to the data.

At frequencies below 0.1 Hz, the LIGO site seismometers do not reliably measure ground translations. Data from the length control signal of a locked LHO 2km arm cavity show that the relative ground motion drops from the microseismic level of $\sim 2\mu m/\sqrt{Hz}$ to $\sim 0.1\mu m/\sqrt{Hz}$ at $0.01 < f < 0.08$ Hz. For simulations of the SEI system below 0.1 Hz, the input spectrum should thus fall from the level in Figure 1 at 0.1 Hz to $\sim 0.1\mu m/\sqrt{Hz}$ by ~50 mHz, and be more-or-less flat below that.

2.2. Microseism amplitude

The level of the 6–8 second microseism varies significantly on daily through seasonal time scales at both LIGO sites. Studies to characterize the level and variation of the microseism over a year are in progress at each site. The levels indicated in Figure 1 are expected to be close to the average microseism level at each site, probably a bit higher than average for LHO. Existing data for LHO shows that it can be up to 20× lower than this average LHO curve, and up to 2× higher. LLO data indicates variation from 3× lower to 4× higher than the above curve.

As input to the design of the seismic isolation system's actuation system, it is important to identify the maximum excursion (peak-peak) of the 6–8 second microseism that the system will be required to handle. At present, there is insufficient data from the sites to set a maximum level based on actual measurement. We thus take a conservative level of 40 microns pk-pk as the maximum microseism excursion to be used as the input to the SEI design (may be revised). The SEI system must be able to function in the presence of this input with no saturation; it is not required to meet the performance level given in section 3.5. While LLO has shown larger microseismic motion than LHO, no distinction between the two sites for the purpose of defining a maximum microseismic input to SEI.

2.3. Tidal strains

As input to the design of the seismic isolation system's actuation system, it is important to identify the maximum tidal changes of the arm lengths. These maxima are shown in Table 1, for the year 2001.

Tidal component	*Maximum pk-pk stretching, microns*		*Overall maximum, multiplied by 1.2, microns*
	LHO	*LLO*	
Differential mode	100–110		130
Common mode	180	200–210	250
Single arm		260	310

Table 1: Maximum tidal 4 km arm length changes at the two sites, over the year 2001. For the overall maxima (last column), the model predictions are multiplied by 1.2, to conservatively account for a 20% systematic discrepancy between the model and measured arm length changes at LHO. These are results of calculations performed by Fred Raab.

2.4. Earthquakes

Small, frequent (few times a week) earthquakes tend to increase ground motion in the band ~0.4–3 Hz by one to two orders of magnitude; they do not significantly increase the total rms ground motion, though, as this remains dominated by the microseismic peak. The SEI design team should examine the behavior of their system in the presence of such earthquake-induce motions, through prototype measurements and modeling. The system should continue to function without saturation, though the performance levels given in section 3.5. do not apply.

Larger, rarer earthquakes tend to substantially increase the rms ground motion, with most of their energy occurring at 20-30 second time scales. Rate versus amplitude data is currently being collected from the LHO seismometers. Quantitative requirements for the SEI will be determined after examining such data; the intention is that the SEI will be required to function without saturation for all but the rarest events.

3 REQUIREMENTS

3.1. Vacuum chambers

Seismic isolation systems are required for both types of LIGO vacuum chambers, HAM and BSC. The size requirements and physical interfaces of the SEI systems depend on the chamber type. Performance requirements depend on the payload and its isolation requirements. While in principle each vacuum chamber could have unique requirements, significant physical and/or performance differences exist only between the two chamber types, and in general the requirements are given for all HAM systems and for all BSC systems.

3.2. Payloads

The payloads for the seismic isolation system consist of the following components:

- Core Optics Components (COC): Input Test Masses (ITM); End Test Masses (ETM); Folding Mirrors (FM); Power Recycling Mirror (RM); Beamsplitter (BS); Signal Recycling Mirror (SRM)
- Mode Cleaner (MC) optics: Input MC and Output MC
- Telescopes: Input and Output Beams; Pick-Off Beams; ETM Transmission
- Ancillary Optics: pick-off mirrors; beam dumps/baffles
- Photodetectors: input beam power stabilization photodetector; output photodetector
- Counter-weights used to balance the above payloads

To accommodate the various payloads, and to provide flexibility in the use of the seismic platforms, all SEI systems should be able to support a payload of up to 800 kg (TBR). This includes any counter-weights which may be required (supplied by SEI) to balance the payload for the seismic isolation or suspension systems.

In addition to supporting these optical components, the SEI system must provide a means for the support of power and signal cabling, and its transmission from chamber ports to the seismic platforms.

3.3. Optics Platform Interface Requirements

For mounting the payloads, each SEI system shall provide an optics mounting platform, with interface dimensions as given in Figure 2. The platform height specifications are subject to review,

SEI type	*Platform size*	*Platform height (LIGO global z-coordinate)*[a]		*Comments*
		Nominal height	*Potential Range*	
BSC	1.5m diam.	1540 mm	1470–1800 mm	Minimum height for quad suspension w/ beam centerline on ITMs at -213 mm
HAM	1.9m × 1.7m[b]	–315 mm	0	Must be low to accommodate triple suspension

Table 2: Interface dimensions for the SEI optics mounting platform.

a. height of the platform’s optic mounting surface
b. shorter dimension is transverse to the beam axis

pending further suspension design work. In any case, the required height will not go outside of the potential range listed in the table. The platforms for a given chamber type will all be at the same height; different optic heights are accommodated by spacers supplied with the suspensions.

The SEI platform mounting surface must be able to be placed at the nominal height to within ±0.5mm (half of the beam centering requirement on the test masses), based on optical survey direction at the time of installation (equipment and survey provided by others).

The SEI platform mounting surface shall have a matrix of 1/4"-20 threaded holes, with 5.08 cm spacing. It shall have an overall (edge to edge) flatness of ±0.102 mm (0.004"), and a flatness of ±0.051 mm (0.002") over any 0.26 m^2 region.

3.4. Operational modes & startup

It may be desirable to have different modes of operation for the SEI system, depending on the environmental excitations and the interferometer status. For example, during interferometer commissioning the system could be tuned to have a better time domain (impulse) response at the expense of some isolation. No specific requirements for different operational modes are given at this time, pending further review, but the SEI design should remain open to such possibilities.

The isolation system must start-up (go from power down to fully operational) in a reasonably short time–less than ~30 minutes. Initial start-ups, or start-ups following chamber pumpdown may take longer–a few hours.

3.5. Isolation Performance

The isolation and noise requirements for the seismic system are characterized by a maximum displacement spectrum of the optics mounting platform, in the presence of the ground noise spectra given in section 2.1. The displacement spectrum requirement is shown in Figure 2.

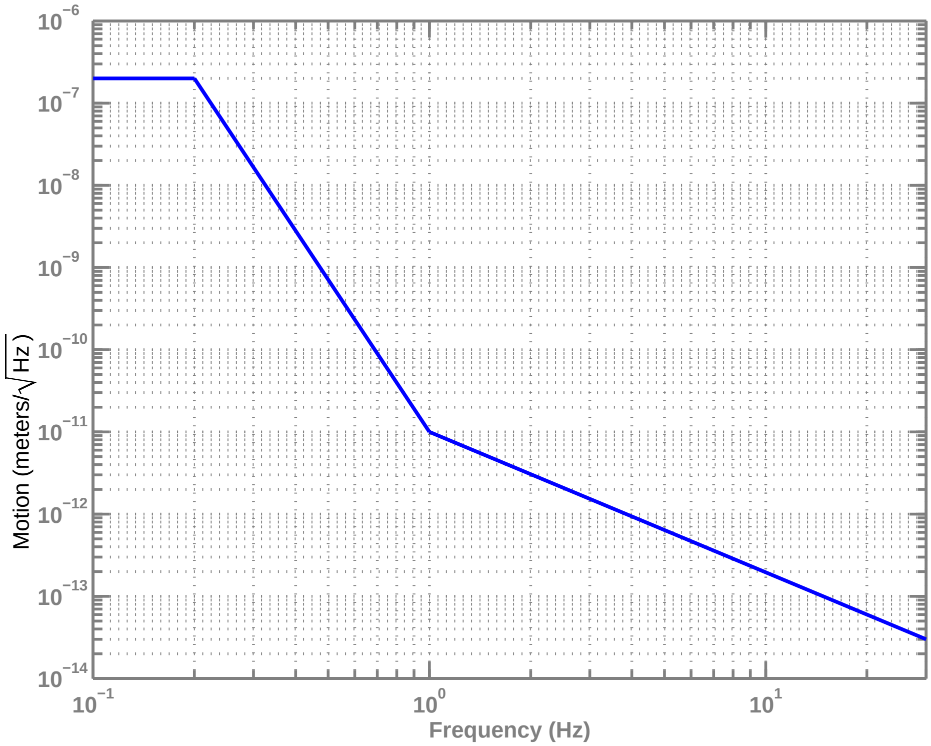

Figure 2: SEI optics platform displacement requirement, applicable to all three translational degrees-of-freedom.

Several comments on the displacement requirement must be made:

- The displacement requirements are the same in all three translational degrees-of-freedom. Vertical motion must be as low as motion along the optic axis to make up for the suspension system's weaker vertical isolation. While horizontal motion transverse to the optic axis could be allowed to be larger, such a refinement does not seem to bring any practical benefits. A less stringent vertical motion requirement at lower frequencies–below several Hz–could be considered if found that this would benefit the SEI design.
- The requirement in the microseismic band of 0.1–0.3 Hz represents a suppression of the typical 1-2 μm-rms microseismic amplitude by a factor of 5-10. Strictly speaking, the displacement requirement in this band would apply only to the interferometer arm lengths, since the optic-optic distances at the vertex (within the LVEA) are essentially unaffected by the microseismic peak. This means that the SEI design may choose to stabilize each vacuum chamber platform to the level given in Figure 2, or it may choose to stabilize only the 4km arm lengths.
- Related to the preceding bullet, all chamber platforms within the vertex station (LVEA) must be treated similarly with regard to the microseismic band. If each chamber platform is stabi-

lized, this must also include chambers which do not contain Core Optics. If only the arm lengths are stabilized, the correction must be applied to the End Station platforms. The intent is to avoid relative motions between the Core Optics and auxiliary optics (input and output telescopes, e.g.) larger than a ~half-wavelength, which would lead to upconversion effects. Thus the relative optic axis motion of all vertex chamber SEI platforms must be less than ~100 nm-rms for frequencies above 0.1 Hz.

- The nominal seismic cut-off frequency for the LIGO II detectors is 10 Hz, with a cut-off level of $10^{-19}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$ displacement noise per test mass. The SEI noise requirement at 10 Hz is $2\times10^{-13}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$. The BSC quad suspension isolation at 10 Hz is $2-5\times10^{-7}$ along the optic axis, and 3×10^{-4} vertically. With a vertical-horizontal coupling of < 0.001, the optic axis motion at 10 Hz is projected to be less than $10^{-19}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$.
- The displacement noise requirement for the critical HAM chamber suspensions (recycling mirrors, mode cleaner mirrors; all triple pendulum suspensions) is $3\times10^{-17}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$ at 10 Hz (which must be met with the suspension local controls ON). The HAM triple suspension isolation at 10 Hz is 3×10^{-5} along the optic axis, and 3×10^{-3} vertically. With a vertical-horizontal coupling of < 0.05, the optic axis motion at 10Hz is projected to be less than $3\times10^{-17}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$.
- 1–10 Hz band: The level in this band is set with consideration of the impact on the interferometer’s sensing and control system (ISC). The goal is that optic motion in this band be low enough that the auxiliary degrees-of-freedom of the interferometer can be controlled to their required level with low-bandwidth feedback, of order 1 Hz. Specific residual deviation requirements for these d.o.f. are not yet developed, but are unlikely to be much more stringent than the tightest such LIGO I requirement: 10^{-10} m-rms. The SEI requirement corresponds to an rms motion of the optics platform in the 1–10 Hz band of 6.5×10^{-12} m-rms, likely low enough to achieve the goal.
- Above 30 Hz, the broadband motion of the optics platform should not exceed the level of $3\times10^{-14}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$. Narrowband features above 30 Hz are discussed in section 3.7.
- Angular degrees-of-freedom. Noise in the angular degrees-of-freedom of the optics platform must not compromise the combined SEI-SUS displacement requirement of $10^{-19}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$ at 10 Hz. In order to allow low-bandwidth (~1 Hz) global alignment control, the rms fluctuation in angular degrees-of-freedom of the optics platform must be less than 10^{-8} rad-rms, for the band $1 < f < 30\ \mathrm{Hz}$.

3.6. Actuation requirements

3.6.1. Coarse positioning

Provision must be made for position adjustment of the SEI optics platform, relative to its nominal installed position. The required positioning range is ±1 mm in the directions transverse to the optical axis (vertical and transverse horizontal). The horizontal positioning must also be capable of making ‘yaw’ motions (rotation about the vertical axis), with an angular range of ± 0.25 mrad. Additional positioning capability (more range and/or additional degrees-of-freedom) may be desirable, but is not required.

The coarse positioning would only be used in an ‘off-line’ mode (when the interferometer is not functioning), to compensate for initial installation errors or long term drift. Motions must be made with small accelerations to protect the suspensions and optics, though no specific acceleration requirements are imposed (at this time).

3.6.2. Tidal correction

To compensate differential tidal stretching of the arms, the End Station SEI systems must include an external actuation input capable of translating the SEI optics platform along the optic axis by ±90 μm, with a time constant no longer than 10 minutes. The SEI system must be able to operate at either end of this range with no loss of isolation performance.

A larger range of actuation may be desirable to allow the possibility of full compensation of the tidal variations by SEI End Station actuation, but this is not required.

3.6.3. Microseismic correction

To allow correction signals for the microseismic band (originating from the interferometer's ISC, or global control system) to be applied as far as possible from the test masses, the End Station SEI systems must include an external actuation input capable of translating the SEI optics platform along the optic axis by ±10 μm, with a time constant no longer than 0.1 second.

The microseism and tidal actuation inputs may be combined in a single input, and in that case the range must be the sum of the specified tidal and microseismic correction ranges.

3.7. Internal resonances

All undamped, internal resonances of the SEI system must be above 100 Hz. Care must be taken that resonances above 100 Hz do not compromise the transmission of the combined SEI-SUS systems, due for example to excessive overlap of SEI modes with SUS wire/fiber resonances. The SEI team should work with the SUS team to develop limits to the $\{Q_i, f_i\}$ of SEI modes.

3.8. Field emission

Care must be taken that any magnetic fields leaked from the SEI system do not compromise the performance of the suspensions, through interaction with the suspension magnets. The SEI team should address this issue in conjunction with the suspension team.

3.9. Drift and thermal expansion

Uncompensated drift or positional changes of the optics platform, due to environmental temperature changes or mechanical creep, shall not exceed 0.1 mm in translation and 100 μradian in angle, over any 30 day period. (The LVEA is regulated to ±2 °C.)

3.10. Power and signal transmission

Means for transmission of power and signals from electronics outside the vacuum chambers to the payloads requiring them (suspensions and in-vacuum photodetectors) must be provided by the SEI system, either through in-vacuum cabling and/or wireless transmission. Further specification of cabling type/s and number is TBD.

Cabling that joins equipment mounted to the optics platform to surfaces that have less vibration isolation must satisfy the following:

- the stiffness and mass of the cable must be such that it does not compromise the SEI performance
- cabling must be firmly clamped to each successive stage of the seismic isolation system to prevent vibration conduction around the isolation system
- in the case of multi-conductor cables, each wire must be firmly fixed in place so that each wire's effective mechanical impedance at the clamped area is at least comparable to the impedance of the stage to which it is clamped
- free lengths of cable must be placed so that they cannot touch other surfaces except where they are clamped
- cabling must not 'crackle' when vibrated under operating conditions; 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 given in LIGO Vacuum Compatibility, Cleaning Methods and Procedures (LIGO-E960022)

3.11. Diagnostics

Diagnostics capability must be included in the SEI design to allow determination of the subsystem's performance. This may be done through a combination of internal SEI diagnostics and interfacing to the Global Diagnostics Subsystem.

APPENDIX 1 REFERENCES & RELATED DOCUMENTS

1. LIGO-T000024-00-U. Baseline LIGO-II implementation design description of the stiff active seismic isolation system.
2. LIGO-T000012-00-D. LIGO II Suspension: Reference Designs
3. LIGO-T000087-01-D. Available Height above the HAM Optics Table
4. LIGO-E960022-D. LIGO Vacuum Compatibility, Cleaning Methods and Procedures.
5. LIGO-T960187-01-D. The Effect of Microseismic Noise on a LIGO Interferometer.

APPENDIX 2 GROUND NOISE MODELS

The ground noise models shown in Figure 1 are polynomial fits in log-space:

$$\log x_g(f) = p_1(\log f)^n + p_2(\log f)^{n-1} + \ldots + p_n(\log f) + p_{n+1}$$

where $x_g(f)$ is the displacement spectral density at frequency f. The coefficients $p = [p_1 \ldots p_{n+1}]$ are:

LHO: [–0.2889, –0.2406, 3.3449, –2.8481, –3.5256, 3.7009, –1.1333, –8.4617]

LLO: [–0.2428, 0.9749, –0.9445, –0.8139, 1.5001, –1.9789, –7.8940]

The fit is valid over the interval $0.1 < f < 40$ Hz.