LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

LIGO- T020033 -02-D | *Initial LIGO* | 26 March 2002

Initial LIGO Seismic Isolation Upgrade Design Requirements Document

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Table of Contents

Appendices

Table of Tables

Table of Figures

1 Introduction

1.1 Purpose

This document defines the requirements for the Initial LIGO Seismic Isolation upgrades planned for reductions in the low-frequency (sub-GW band, <40 Hz) motion of the test masses.

1.2 Scope

The scope of the document covers the functional and performance requirements for the additions and changes to the seismic isolation system, inside and outside of the vacuum system. Seismic upgrade modifications are required on all chambers with suspended optics.

In addition, there is the potential need to minimize path length fluctuations between the suspended optics and the PSL/IO table, and the path length fluctuations between the suspended optics and the antisymmetric port detection table. The motivation is to prevent up-conversion from parasitic interferometer paths which could be significant if the LVEA optics are held stationary in inertial space (by the pre-isolator system) while the laser and photodiode tables move with the LVEA floor. This may involve active seismic isolation systems for the PSL/IO table and the antisymmetric port detection table, and/or additional motion sensing. The DRD will be updated when further definition of the need to address this risk is available.

Not included in this document are any complementary changes in the suspension or length control system. It is anticipated that the performance of these other subsystems can be relaxed after the installation of the upgrade(s).

1.3 Definitions

1.4 Acronyms

See http://www.ligo.caltech.edu/LIGO_web/docs/acronyms.html

EPI: External Pre-isolator

ISD: Internal Stack Damping

1.5 Applicable Documents

1.5.1 LIGO Documents

T000024-00-U pdf 03/08/2000 Baseline LIGO-II Implementation Design Description of the Stiff Active Seismic Isolation System

G010325-00.pdf Weiss talk on seismic conditions at LLO

LLO Ilog entry 2002:01:16:20:56:44-RaiW with noise histograms

T010074-03-D 07/17/2001 The LIGO Observatory Environment

T980084-00-D 10/09/1998 Transfer Function and Drift Measurements on First Article HAM

T000101-00-D 10/07/1999 Transfer Function Measurement on the BSC Seismic Isolation Stack

T960065 SEI DRD

T950011 SUS DRD

T000073-00 Digital LOS and SOS Control Systems for LIGO

T970059-01-D The Effect of Earth Tides on LIGO Interferometers

T010140-00 Digital Suspension Filter Design

1.5.2 Non-LIGO Documents

2 General description

2.1 Specification Tree

This document should be considered as an update to the initial LIGO seismic isolation system documentation.

2.2 Product Perspective

The requirements address two complementary approaches to reducing the motion in the control frequency band (frequencies less than 40 Hz) for initial LIGO and systems issues associated with their implementation.

2.2.1 External pre-isolator (EPI)

An external pre-isolator would be placed between the support piers and the horizontal crossbeams of the existing initial LIGO isolation system, replacing the present coarse (and in the case of the BSC chambers, fine) actuators. The pre-isolator allows the crossbeams to be moved relative to the piers, in all six degrees of freedom, with the general objective of reducing the motion of the test masses at frequencies below 40 Hz. This could be done by independently inertially sensing the motion and reducing to a minimum at each isolation system, and/or by reducing the relative motion of all optical systems in the LVEA and causing the end station isolation systems to track optical axis motion.

2.2.2 Internal damping system (ISD)

An internal (in the vacuum) damping system would allow forces to be applied to the initial LIGO isolation system optics platform. These forces might be applied via reaction masses or by generating forces between the optics platform and a point mechanically before the isolation system (e.g., the crossbeams). The objective would be to reduce the motion at the isolation system solid-body mode frequencies by reducing the mechanical Q of the motion. Optionally, sensors and high-gain servo systems may further reduce the motion.

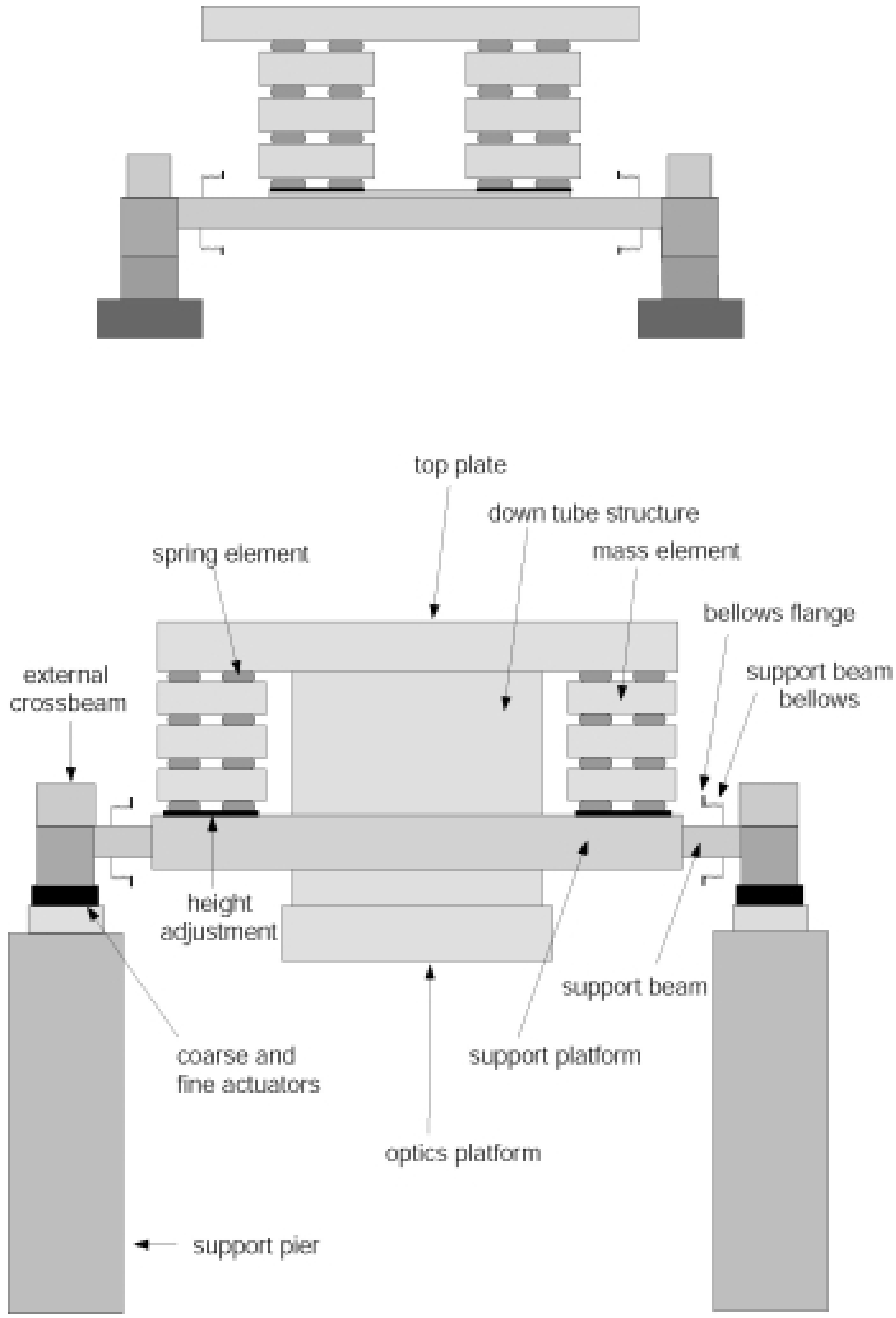

Figure 1 Block Diagram: Initial LIGO isolation system and nomenclature. A possible implementation of the pre-isolator is as a replacement of the coarse and fine actuators. The internal damping system may consist of a means to exert forces between the optics platform and the support platform, or may contain masses which exert inertial forces on the optics platform.

2.3 Product Functions

2.3.1 External pre-isolator

The external pre-isolator will

- Provide coarse positioning of the seismic load
- Compensate for tidal motions (6 and 12 hour periods) and quasi-static alignment offsets (replacing this function of the original initial LIGO PZT fine actuator)
- Compensate for the ~6 second period microseismic motion (replacing this function of the original initial LIGO PZT fine actuator)
- Reduce the input seismic motion in the region of the stack solid-body resonances, especially 1-3 Hz to a level permitting performance according to the SRD

Feedback to the pre-isolator actuators (from pre actuator sensors or elsewhere) may as a goal (but not a requirement) be used to damp the initial LIGO solid-body resonances. An additional goal of the pre-isolator system is to provide additional long-period dynamic range so that the IFO can be kept locked for long (weeks or months) periods of time.

2.3.2 Internal damping system

The internal damping system will

- Damp the solid-body resonances of the initial LIGO seismic isolation system, in particular from1-3 Hz

Internal sensing and feedback may be used to reduce the motion to levels smaller than the seismic input.

2.4 General Constraints

The point of departure is that the external pre-isolator will replace the initial LIGO coarse and fine actuator assemblies (including scissors tables, air bearings, linear stages, etc). An internal stack damper is expected to be attached to existing seismic isolation system components in the vacuum chamber. The HAM piers may be replaced or modified if advantageous; any other changes to the existing equipment of the seismic isolation system or other internal components of the initial LIGO detector (suspensions, optics, core optic support equipment, etc.) is nominally forbidden.

Installation of either pre-isolator or internal damping must not require removal of the existing interferometer components and must not disturb the alignment beyond recovery through alignment to local references. Installation may require that suspended mirrors be clamped *in situ* with the existing safety stops.

No appreciable degradation in the noise performance in the GW band (40 Hz to 10 kHz) is allowed, through additional mechanical resonances, acoustic sensitivity, self generated noise, etc.

The system must be controlled and monitored via the observatory DAQ/EPICS system, and must interface seamlessly with the ISC controls system

Materials used inside the LIGO vacuum chambers 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 vacuum system, with the exception of Kapton and PEEK for cabling.

Safety of personnel and of the installed interferometer components, during installation and operation, must be assured.

2.5 Assumptions and Dependencies

2.5.1 Environment

We assume that the seismic environment, in particular around LLO, is well described by observations in late 2001 and January-February 2002, as documented in T010074-03. The baseline input seismic noise is as described in E990303, reproduced below. This curve is useful to establish the RMS motion, and not necessarily the peak motion (see Section 6, Notes: background information on requirements). Figure 2 is also used to determine the requirements for performance in the GW band.

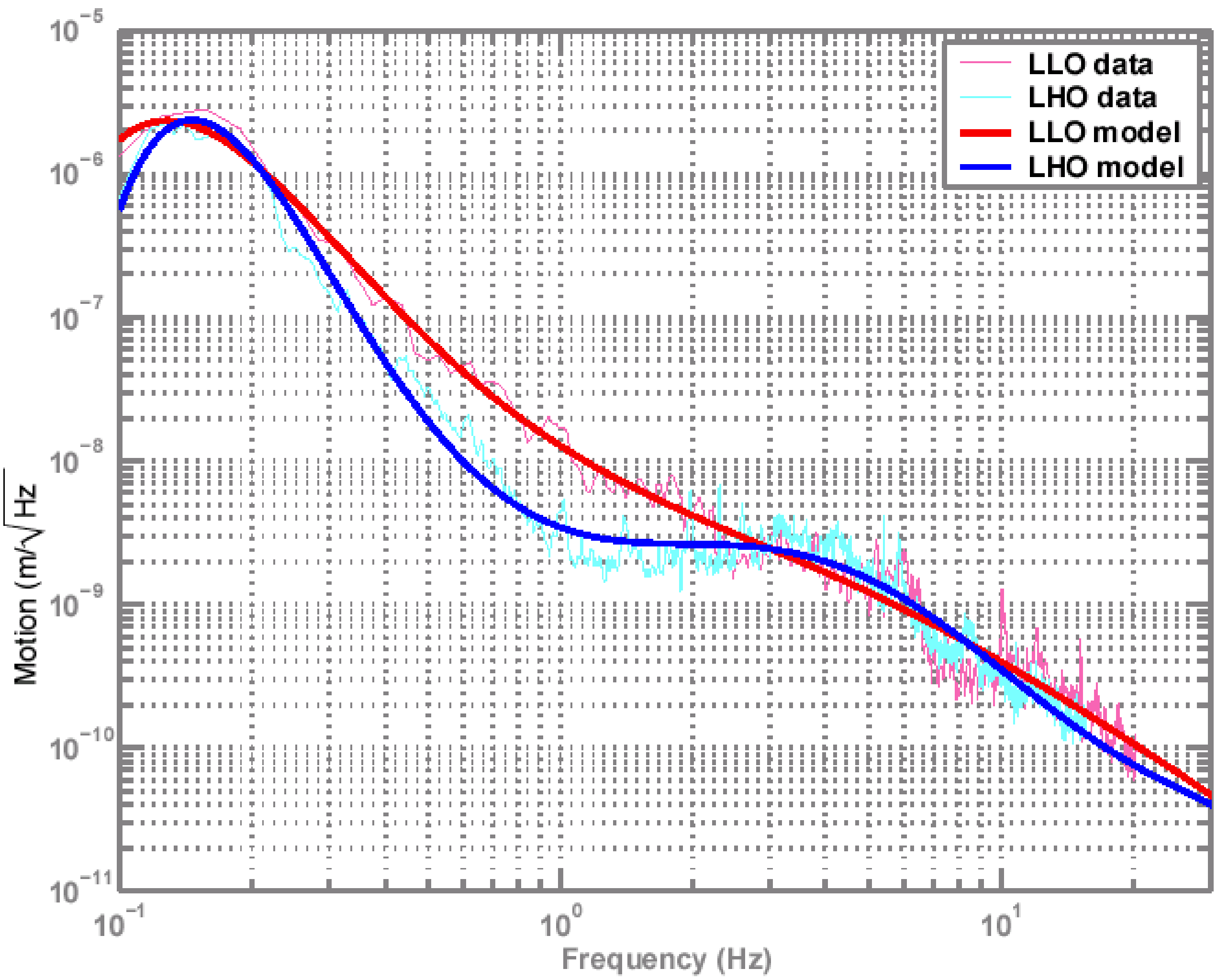

Figure 2: Baseline seismic input. We assume that the trend at high frequencies continues, following 5e-8/f^2 m/rHz, for $5 < f < 50$ Hz. (or higher).

2.5.2 Isolation systems

We assume that the isolation systems are as installed as of February 2002.

2.5.3 Suspensions

We assume that the suspension actuators and driving circuits will provide the authority and noise performance described in T000073-00 Digital LOS and SOS Control Systems For LIGO. This document indicates a 100 micron pk-pk range in “acquisition mode”; in “run mode” 20 micron pk-pk authority below the pendulum resonant frequency; and 5e-20 m/√Hz noise performance at 40 Hz on the optical axis (local longitudinal damping turned off).

3 Requirements

3.1 Introduction

The top-level performance of the initial LIGO interferometers is dictated by the Science Requirements Document E950018. The requirements are flowed down to the subsystems in E960112; the relevant subsystems for this upgrade are SEI DRD T960065 and SUS DRD T950011.

The basic purpose of this upgrade is to reach the performance required by the Science Requirements Document, given unanticipated seismic noise (in level and character) in conjunction with mechanical resonances in the seismic isolation system. This dictates locking times of 40 hours or more, and the sensitivity indicated in the SRD. A goal is to reduce the motion further to yield smaller RMS motion (with reduced risk of upconversion) and reduced needed actuator authority in the suspension actuators (improving noise performance in-band). The SRD sensitivity curve is reproduced below (from T960065) in Figure 3.

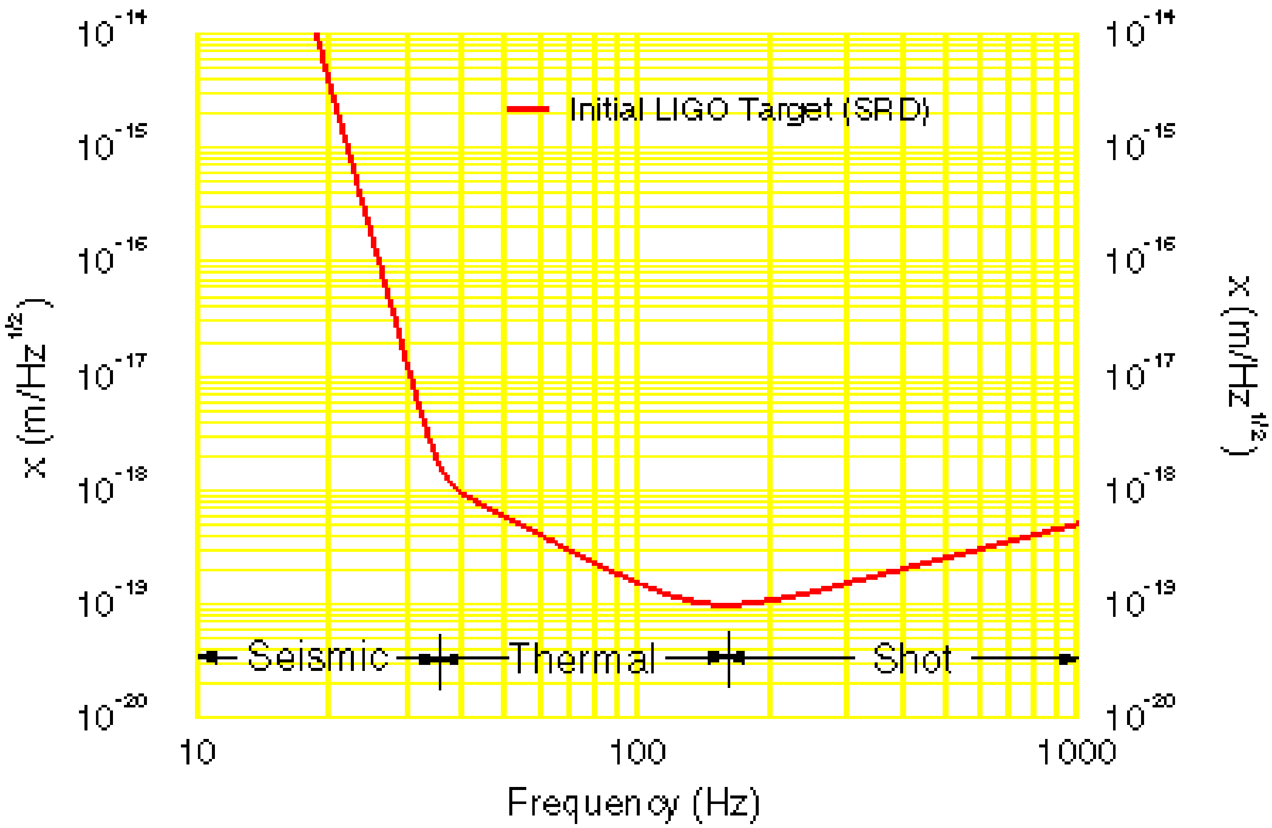

Figure 3: Science Requirements Document (SRD) sensitivity curve.

The principal constraints in forming requirements for the EPI and ISD are

- The seismic noise, which is greater in RMS and in peak value than originally thought. Characterization is still under way, but Section 6 shows some indicative plots. There is a strong variation with time of day. We use, given our present knowledge, the night-time low-wind Hanford spectrum and impulsive character as our reference for the desired input spectrum to the crossbeams and support tubes.

- The resonant character of the initial LIGO seismic isolation system. The high-Q solid-body resonances amplify the ground motion. It appears that cross-coupling from translations or tilts to a 'yaw' motion within the stack is also a key problem. Reducing the resonance Qs is a complementary approach to reducing the RMS motion of the optics platform which we pursue in parallel with an external additional isolation.
- The pendulum transfer function, which has not been carefully characterized. We assume at present that both horizontal (~1 Hz) and vertical (~15 Hz) modes attenuate as 1/*f*^2 above the resonance, and that the transfer function from vertical motion to optic axis motion is 10^-3.
- The limited dynamic range of the suspension controller coil drivers. Large forces are required at low frequencies to deal with the seismic motion, but very low noise is required in the GW band. With the present seismic noise input, the controllers must be at least a factor of 10 too noisy at 100 Hz to maintain lock.

3.2 Characteristics

3.2.1 Performance Characteristics

The performance requirements apply to both the BSC and the HAM unless otherwise noted.

3.2.1.1 External pre-isolator (EPI)

3.2.1.1.1 Net noise performance

We give a requirement for the noise, measured at the support beams (or 'tubes'), in translation in each of the 3 DOF. It represents the net motion at that point, due to (filtered) ground noise and any self-generated noise in the EPI. All six degrees of freedom (DOF) are to be actively sensed and controlled.

1 month	10 microns pk-pk
100 seconds	1 micron pk-pk
0.16 Hz	4e-7 m/√Hz
1 Hz	1e-9 m/√Hz
10 Hz	4e-10 m/√Hz
15 Hz	2e-10 m/√Hz
30 Hz	6e-11 m/√Hz
50 Hz and higher	2e-11 m/√Hz

To clarify the origin of these requirements:

- The presently observed drift in the pointing of the optics at Hanford is of the order of 10 microns pkpk over month time scales. We do not wish to degrade the existing stability. This small level of drift helps diagnose the sources of other changes in the installation over time, and aids in recovery from catastrophes.

- The sensing plant requires alignment precision of the order of 1 micron presently for some optics to allow lock. We wish for this precision to be held long enough to achieve lock, thus ~100 seconds.
- Reduction in the microseismic peak at ~0.16 Hz will allow a smaller actuator authority, and will reduce the physical motion of the stack (reducing the likelihood of internal upconversion and 'creaking'). The requirement is intended to be compatible with the technologies available and yet give a noticeable reduction from the ambient value.
- At 1-10 Hz, the level is intended to give an integrated RMS which is similar to the night Hanford noise and to be compatible with the technologies available. There will be exceptional seismic events which will cause the motion to exceed this level; the objective is to meet the requirement 'most' of the time, with a more precise definition to come with more study of the statistical properties of the noise. The working goal is to meet the requirement 95% of the time.
- The vertical 'bounce modes' of the suspensions are around 15 Hz, and their excitation stresses the control system design and risks upconversion. We require that the noise with the pre-isolator not be greater than the present noise. Any reduction here would be valuable.
- At 30 and 50 Hz, we require that the noise with the pre-isolator not be greater than the present noise. Current projections indicate that the measured seismic noise (lower than the initial 'LIGO Standard Spectrum', times the measured and extrapolated SEI transfer function, times a simple pendulum, would lead to a crossing of seismic and thermal noise a bit lower than in the SRD. This would be very desirable, and so we require that the present noise not be exceeded.
- At frequencies greater than 50 Hz, we do not know the transmission of the isolation system. It may be possible to allow greater noise than the present noise (or even noise greater than the level at 50 Hz) above 50 Hz, and narrowband exceptions can be allowed, but we wish to have exceptions examined carefully because of our lack of knowledge of the transmission at high frequencies. So we start by requiring that the system not become more noisy at higher frequencies.

Exceptions for narrow features may be granted if they do not effectively impact either the control systems or the GW band (in the spirit of exceptions for small $n\times60$ Hz peaks).

An alternative formulation of the performance requirements is under study which would specify an RMS velocity, over a prescribed band, observed at the optics platform, not to be exceeded more than (say) 5% of the time. The two means of setting the requirements for the system are intended to result in similar performance; the approach under development relates more directly to the interferometer behavior and would be helpful in the actual design of the isolators.

3.2.1.1.2 Acoustic noise

See 3.2.6.2.2. The requirement is motivated by the desire that the acoustic pressure not lead to excess noise or narrowband features via transmission through the isolation system or through the air (e.g., to the PSL/IO table).

3.2.1.1.3 Back-action on environment

The noise induced in the floor of the VEA by the EPI in normal operation must not increase the level of seismic noise by more than 1/10 of the ambient. This requirement is intended to avoid a degradation of the installation for other equipment in the vacuum or elsewhere (e.g., the PSL/IO table).

3.2.1.1.4 Dynamic range

3.2.1.1.4.1 Static alignment

The EPI must allow for coarse positioning (as presently enabled by the scissors table and air bearing) over the ±5 mm range (in *x,y,z*) permitted by the support tubes and bellows. This positioning may require external setups (cranes or bolt-on temporary lifting mechanisms) and shimming.

3.2.1.1.4.2 Quasi-static alignment

The EPI must allow quasi-static alignment in 6 degrees-of-freedom. Settling time for the maximum motion is 10 minutes. The range of adjustment is to be determined by the tidal requirements below. If we break lock and want to reset the actuators to where we think they should optimally be, to allow a long subsequent locked section, the time to reset the position should be comparable to the time to relock and have the machine settle down.

3.2.1.1.4.3 Tidal and microseismic motions

The EPI is required to be able to correct for the differential mode tidal strains and microseismic motion through actuation at one end of the 4km-long arm (allowing all optics in the LVEA to remain stationary with respect to the vacuum equipment over microseismic and longer time scales). (The common mode tidal forces will be accommodated through laser frequency changes.) The actual implementation (actuators/sensors/controls) must allow this approach, or the approach of minimizing inertial motion for each chamber’s isolation system, or for any grouping of isolation systems.

This leads to requirements for the horizontal dynamic range of 260 microns pk-pk, 6 and 12 hour periods; 40 microns pk-pk, ~6 second periods, for a total maximum dynamic range of 300 microns pk-pk.

In the vertical direction, no tidal correction is needed, but we assume that the correct microseismic correction may well require vertical actuation (to achieve ‘pitch’ angular compensation) with an amplitude equal to the horizontal microseismic peak, so 40 microns pk-pk.

The magnitude of these dynamic range requirements are based on observed amplitudes at the two observatories.

It is a goal to provide a larger plus/minus 1 mm range on the optical axis to accommodate possible long-term drifts in the length of the 4km arms, enabling locking during month-scale periods.

3.2.1.1.4.4 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 EPI must be well-behaved in the presence of such earthquake-induce motions. The system should continue to function without saturation, though the performance requirements do not apply.

Larger, rarer earthquakes can substantially increase the RMS ground motion, with most of their energy occurring at 20-30 second time scales. The EPI will be required to fail gracefully for all but the rarest events, and in under no foreseeable circumstances should the system amplify the motion or the risk to components through e.g., saturation transients.

Safety stops, if needed, should protect the EPI components from earthquake damage; an Olympia-class earthquake should damage neither the EPI nor the in-vacuum interferometer components. Note that the interferometer components before the installation of the EPI are expected to be able to withstand an Olympia-class earthquake.

Quantitative requirements associated with earthquakes are forthcoming.

3.2.1.1.5 Diagnostics, states, and modes

3.2.1.1.5.1 Power up and power down

The EPI system should be able to transition from power down to normal operation in no more than 1 hour. This requirement is motivated by the desire to minimize the time to return to normal operation after a power failure. The specific value is a guess of the time it would take to prepare the remainder of the infrastructure to the point where one would want to start damping masses and establishing crude pointing with optical levers, which would require that the platform be in its nominal starting position and pitch/yaw.

The system on power-up and power-down will not cause motions which exceed the ability of the suspension controllers to maintain local damping in acquisition mode. A numerical requirement is TBD, to be estimated for the final suspension controller authority, as represented by the 'digital controller' design. This requirement is designed to protect the optics from running into their safety stops, thus reducing the risk of changes in suspension angle and charge generation.

The EPI system must become gracefully inactive upon (accidental or intentional) loss of power to any part of the EPI system or its environment, meeting the requirement for intentional power-down. The objective is to reduce the risk to the suspended optics

3.2.1.1.5.2 Optics Installation

The net change in alignment of the optics tables in pitch and yaw, from before the start of installation to after completion of installation, must not be greater than 20 microradians. This requirement is based on a desire not to require any mechanical alignment changes to the installed optics in the process of installation.

During installation and manual ‘initial alignment’ of components on the optics platform of the isolation system, the EPI should not require any difference in tooling or procedures than would be required with the current (or a rigid) connection between the piers and the crossbeams. Manual mechanical stops may be used as long as the alignment is not affected more than 20 microradians.

Note that during installation, it is possible for there to be significant actual excitation of the optics platform from installation activities, in contrast to the normal operational scenario where all excitation comes from the outside.

3.2.1.1.5.3 Earthquake

Within the operational dynamic range requirements, the earthquake mode should minimize accelerations of the optical platform during earthquakes. Alternative proposals which would better protect the optics during earthquakes are welcome.

3.2.1.1.5.4 Inactive

It must be possible to render the EPI system inactive, allowing tests of with/without, and troubleshooting (e.g., to ensure that the EPI is not contributing to a phenomenon). Manual mechanical stops may be used.

3.2.1.1.5.5 Excitation

Within the normal operational force and dynamic range requirements, the EPI system should allow coordinated excitation of the optics platform in 6 degrees of freedom for diagnostic purposes.

3.2.1.1.5.6 Self test

The system should be able to be tested for basic functionality remotely, using only signals to and from the EPI, for nominal functionality.

3.2.1.2 Internal stack damping (ISD)

It should be possible by the basic design principle adopted to damp all six DOF of the optics platform. Characterization and *in-situ* tests will be used to determine a specific implementation. All requirements hold for both the BSC and HAM isolation systems unless otherwise noted.

3.2.1.2.1 Self-generated noise

In the GW band (40 Hz and greater) the ISD must not contribute significant additional noise (sensor or actuator electronic or mechanically generated noise, creep, etc.). Specifically, any noise motion from the ISD must make a net contribution of $\leq$1/10 the level of the SRD sensitivity. Assuming that the pendulum delivers $1/f^2$ isolation above the resonant frequency (~1 Hz horizontal, ~15 Hz vertical), this leads to the following requirements for the motion of the optics platform:

BSC:

Horizontal: 1.2e-13 m/√Hz at 20 Hz, 2.5e-17 m/√Hz at 50 Hz and higher

Vertical: 5e-13 m/√Hz at 20 Hz, 1e-16 m/√Hz at 50 Hz and higher

HAM:

Horizontal: 4e-12 m/√Hz at 20 Hz, 2.5e-16 m/√Hz at 50 Hz and higher

Vertical: 2e-11 m/√Hz at 20 Hz, 1e-15 m/√Hz at 50 Hz and higher

3.2.1.2.2 Damping performance

The ISD system should damp the targeted modes such that the resulting amplification of motion at the resonant peak is a factor of 3 or less. As a minimum the 1.2 and 2.1 Hz modes of the BSC passive isolation stack and the analogous TBD? modes of the HAM stack will require damping. The numerical value of the requirement is motivated by the desire to place a threshold for installation of an in-vacuum remedial system. The initial LIGO stacks show resonances of 30 and greater; seeing a reduction to a factor of three would correspond to a 'significant change' of a factor of ~10 in the motion due to these resonances.

None of the other modes of the stacks should be excited above their pre-existing levels (i.e., prior to implementation of the ISD) by more than that which would increase the resulting total RMS by more than a factor of 1.5 (for example by control spillover). Additional modes or modal splitting induced by the addition of the ISD may not result in an RMS motion which is more than 1.5x greater than the value it would have with no additional resonances.

Parasitic excitation of other preexisting stack modes, or of new resonant modes introduced by the ISD itself, shall not increase the total RMS payload velocity by more than a factor of 1.5 over the contribution from the damped principal modes alone.

3.2.1.2.3 Dynamic range

No mechanical interference or significant change in performance of the ISD should result from motion (translations, rotations, tilts) of the isolation system via the crossbeams over the ±5 mm range of adjustment of the crossbeams

3.2.1.2.3.1 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 ISD must be well-behaved and functional in the presence of such small earthquake-induce motions, though the performance requirements do not apply.

Larger, rarer earthquakes can substantially increase the RMS ground motion, with most of their energy occurring at 20-30 second time scales. The ISD will be required to fail gracefully for all but the rarest events, and in under no foreseeable circumstances should the system amplify the motion or risk to components through e.g., saturation transients.

An Olympia-class earthquake should damage neither the ISD nor the in-vacuum interferometer components as a consequence of the ISD. Note that the interferometer components before the installation of the ISD are expected to be able to withstand an Olympia-class earthquake.

3.2.1.2.4 Diagnostics, states, and modes

3.2.1.2.4.1 Power up and power down

The system on power-up and power-down will not cause motions which exceed the ability of the suspension controllers to maintain local damping in acquisition mode. A numerical requirement is TBD, to be estimated for the final suspension controller authority, as represented by the 'digital controller' design. This requirement is designed to protect the optics from running into their safety stops, thus reducing the risk of changes in suspension angle and charge generation.

The ISD system must become gracefully inactive upon (accidental or intentional) loss of power to any part of the ISD system or its environment, meeting the requirement for intentional power-down. The objective is to reduce the risk to the suspended optics.

3.2.1.2.4.2 Optics Installation

The net change in alignment of the optics tables in pitch and yaw, from before the start of installation to after completion of installation, must not be greater than 20 microradians. This requirement is based on a desire not to require any mechanical alignment changes to the installed optics in the process of installation.

During installation, manual ‘initial alignment’, etc. of components on the optics platform of the isolation system, the ISD must be well behaved and not induce motions of the platform in excess of the original installation. (Note that during installation, it is possible for there to be significant real excitation of the optics platform from installation activities, in contrast to the normal operational scenario where all excitation comes from the outside.)

3.2.1.2.4.3 Inactive

If the approach for the ISD is ‘active’, using sensors, actuators, and amplifiers, it must be possible to render the ISD system inactive, effectively returning to the state of the initial LIGO design.

If the approach for the ISD is passive, e.g., a resonant tuned damper, it is TBD if a means to render the system inactive (e.g., locking the mass) is required.

3.2.1.2.4.4 Self test

If active, the system should be able to be tested remotely, using only ISD inputs and outputs, for nominal functionality.

3.2.2 Physical Characteristics

3.2.2.1 External Pre-isolator (EPI)

3.2.2.1.1 Cleanliness

The design must assure that that no oils or lubricants will be released in the vicinity of the Vacuum equipment. Installation, repair, maintenance, and removal procedures must address this issue explicitly.

3.2.2.2 Internal Stack Damping (ISD)

3.2.2.2.1 In-vacuum components

As noted elsewhere, all components used in-vacuum must meet the requirements called out in LIGO Vacuum Compatibility, Cleaning Methods and Procedures (LIGO-960022-00-D). Explicit protection against overheating (and consequent outgassing) of in-vacuum components must be integrated into the design.

3.2.3 Interface Definitions

3.2.3.1 External pre-isolator (EPI)

3.2.3.1.1 Mechanical Interfaces

The BSC EPI is to fit into the space between the support piers and the spherical knuckle attached to the crossbeam, or the existing mounting surface and bolt hole patterns on the crossbeam. No net misalignment greater than 20 microradians of the existing optical system is allowed.

3.2.3.1.2 Electrical Interfaces

The production version of the EPI must interface via the observatory installed data acquisition system and control system. Control signals from the real-time length and alignment servosystems must be available as inputs. State control and slow monitoring is to be provided using the EPICS protocol. Buffered analog test points for the sensor signals and for the actuator signals should be available.

3.2.3.1.3 Optical Interfaces

The EPI must not impact any of the optical systems.

3.2.3.1.4 Stay Clear Zones

Rack space for the control electronics will need to be assigned to the EPI, and cabling to/from the EPI will need to be routed. No interference with the operation or servicing of presently installed equipment is allowed.

3.2.3.2 Internal Stack Damping (ISD)

3.2.3.2.1 Mechanical Interfaces

The ISD must use existing points of attachment on the in-vacuum SEI components. The resonant frequencies, *Q*s and changes in the moment of inertia of the resulting construction of the optics platform must not cause objectionable resonances (from a controls point of view) or excessive thermal noise of the optics platform. The requirement for thermally induced noise amplitude impressed on the SEI platform is that it shall not exceed the SRD test mass noise requirement in the frequency band 30-1000Hz (see LIGO Science Requirements Document, LIGO-E950018-02-E). See Appendix C, page 41, of T960065 SEI DRD for calculations of the thermal noise.

Counterbalancing of the optics platform to recover the pre-installation alignment is required. No net misalignment greater than 20 microradians of the existing equipment is permitted.

3.2.3.2.2 Electrical Interfaces

The production version of the ISD must interface via the observatory installed data acquisition system and control system. Control signals from the real-time length and alignment servosystems must be available as inputs. State control and slow monitoring is to be provided using the EPICS protocol. Buffered analog test points for the sensor signals and for the actuator signals should be available.

Feedthroughs at the vacuum to be installed as needed.

3.2.3.2.3 Optical Interfaces

Because of the in-vacuum installation, interference with the existing interferometer installation is a particular concern. The ISD must not adversely impact any of the optical systems:

- principal interferometer beams
- auxiliary beams
- 'ghost' beams
- optical levers
- illuminators
- video camera ports

If any parts or cabling for the ISD are on or on the beam side of the optics platform, a review of scattered light paths and beam clearance must be performed by the COS and COC subsystems.

3.2.3.2.4 Stay Clear Zones

Rack space for the control electronics will need to be assigned to the ISD if active, and cabling to/from the ISD will need to be routed. No interference with the operation or servicing of presently installed equipment is allowed.

3.2.4 Reliability

3.2.4.1 External pre-isolator (EPI)

The EPI system must operate continuously and must (almost) never need repair. The MTBF should be greater than 5 years.

3.2.4.2 Internal Stack Damping (ISD)

The ISD system must operate continuously and must (almost) never need repair. The penalty for failure in the vacuum system is severe, as there is risk for damage to the optical system or its alignment any time the system is opened, and there are significant delays in recovering from a venting of the vacuum system.

The MTBF for in-vacuum components should be greater than 10 years, and external components should have a MTBF greater than 5 years.

An installation plan which gives significant indications of the health of the components and cabling at each stage of the installation up to the moment of closing the vacuum system must be developed and explicitly reviewed.

3.2.5 Maintainability

Must have a really short Mean Time To Repair (MTTR); be accessible, use modular construction, provide test points, etc.

3.2.5.1 External pre-isolator (EPI)

Any required scheduled maintenance (cleaning/replacing filters, motor maintenance, etc.) must be communicated to the Observatory Site Manager in a written plan. Maintenance must not impact the availability of the overall interferometer (must be possible to plan for it to be timed to coincide with other maintenance of the existing infrastructure).

3.2.5.2 Internal Stack Damping (ISD)

Installation and removal must be possible. No routine maintenance should be required for any in-vacuum components. We require as complete external diagnostics as possible of all in-vacuo active components to aid in determining the nature of problems from outside the vacuum; possible failure modes should be listed along with external diagnostics.

3.2.6 Environmental Conditions

The packing and shipping plan for in-vacuum components must be reviewed in advance.

3.2.6.1 Natural Environment

3.2.6.1.1 Temperature and Humidity

Table 1 Environmental Performance Characteristics

Operating as specified	Operating, without damage	Transport/Storage
+18 C to +22 C, 0–50 % RH	+10 C to +40 C, 0–90 % RH	-10 C to +70 C, 0–90 % RH

3.2.6.1.2 Atmospheric Pressure

Normal atmospheric pressure

3.2.6.1.3 Seismic Disturbance:

Restraint against seismically induced large motion is required.

The system shall be designed to resist the static equivalent lateral forces defined in the Uniform Building Code (UBC), 1994 edition, for a seismic zone factor Z = 0.15 (i.e. zone 2B, Hanford) and a structure importance factor I = 1. The support structure shall resist the seismic loads without damage. The seismic stack shall sustain the base shear motion of the support structure without collapse or release of any of the stack layers. At a minimum, failure of the actuators under these loads should not cause failure of the bellows or cause the seismic stack to “drop”; ideally the actuators would survive these loads with no damage.

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

Interpretation of the requirement: If there is no damping or plastic deformation to absorb the seismic loading (Rw = 1), and the SEI first frequency is between 2.5 Hz and 10 Hz (i.e. at the peak), then the base shear, Vb = (Z I C/Rw) W = (0.15 (1) 2.75/1) W = 0.4 W

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

3.2.6.2 Induced Environment

3.2.6.2.1 Electromagnetic Radiation

Fluctuating magnetic fields from in-vacuum or extra-vacuum electromagnets must be characterized and documented (DCC); explicit calculation and/or tests are required to ensure that coupling to the test mass magnets will not cause the test mass to experience forces greater than 1/10 those already present.

3.2.6.2.2 Acoustic

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

3.2.6.2.3 Mechanical Vibration

See main specifications.

In addition to the principal system, cooling fans, valve operation, liquid flow should be checked that they do not contribute significantly ($\leq$1/10 ambient) to the vibrational background.

3.2.7 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 for forklift. All items over 100 lbs. which must be moved into place within LIGO buildings shall have appropriate lifting eyes and mechanical strength to be lifted by cranes.

3.3 Design and Construction

3.3.1 Materials and Processes

3.3.1.1 Finishes

Ambient Environment: Surface-to-surface contact between dissimilar metals shall be controlled in accordance with the best available practices for corrosion prevention and control.

External surfaces: External surfaces requiring protection shall be painted purple or otherwise protected in a manner to be approved.

- Metal components shall have quality finishes on all surfaces, suitable for vacuum finishes. All corners shall be rounded to TBD radius.
- All materials shall have non-shedding surfaces.

- Aluminum components used in the vacuum shall not have anodized surfaces.
- Optical platform surface roughness shall be within 32 micro-inch.

3.3.1.2 Materials

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

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

3.3.1.3 Processes

1.1.1.1.1 Welding

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

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

1.1.1.1.2 Cleaning

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

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.

1.1.1.2 Component Naming

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

3.3.2 Workmanship

All components shall respect high standards of workmanship with general appearance, freedom from defects, and edge and surface treatments compatible with sensitive scientific instrumentation intended for Class 100 clean room usage.

3.3.3 Interchangeability

All elements of the systems shall be interchangeable, replaceable, units insofar as possible. Any field customizations, characterizations or adjustments required for a specific application instance must be accomplished within constraints of the allowable MTTR.

3.3.4 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.

3.3.5 Human Engineering

Not applicable

1.2 Assembly and Maintenance, Installation

3.3.6 External Active Isolator (EPI)

A detailed installation plan with separate review is required which does not disturb the existing optical alignment. The in-vacuum optics may be constrained by the safety stops if required during installation.

3.3.7 Internal Stack Damping (ISD)

A detailed installation plan with separate review is required which does not disturb the existing optical alignment. The in-vacuum optics may be constrained by the safety stops if required during installation.

3.4 Documentation

3.4.1 Specifications

This document

3.4.2 Design Documents

- EPI/ISD Preliminary Design Document (including supporting technical design and analysis documentation)
- EPI/ISD Final Design Document (including supporting technical design and analysis documentation)

- EPI/ISD Prototype/Test Plans
- EPI/ISD Commissioning Plans and Procedures

3.4.3 Engineering Drawings and Associated Lists

A complete set of drawings suitable for fabrication must be provided along with Bill of Material (BOM) and drawing tree lists. The drawings must comply with LIGO standard formats and must be provided in electronic format. All documents shall use the 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

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

3.4.4.2 Manuals

Manuals for commercial products are to be entered into the DCC and referenced in Final Design Documentation.

3.4.5 Documentation Numbering

All documents shall be numbered according to the DCC standards; all documents to be placed in source and pdf format in the DCC

3.4.6 Test Plans and Procedures

All test plans and procedures shall be documented, and reviewed at the Design Requirements Review, the Preliminary Design Review, and the Final Design Review (with updates and refinements as needed)

3.5 Logistics

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

3.6 Precedence

Not relevant.

3.7 Qualification

Not relevant.

4 Quality Assurance Provisions

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

4.1 General

This should outline the general test and inspection philosophy, including all phases of development.

4.1.1 Responsibility for Tests

Who is responsible for testing.

4.1.2 Special Tests

4.1.2.1 Engineering Tests

List any special engineering tests which are required to be performed. Engineering tests are those which are used primarily for the purpose of acquiring data to support the design and development.

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.

4.1.3 Configuration Management

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

4.2 Quality conformance inspections

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

4.2.1 Inspections

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

4.2.2 Analysis

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

4.2.3 Demonstration

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

4.2.4 Similarity

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

4.2.5 Test

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

5 Preparation for Delivery

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

5.1 Preparation

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

5.2 Packaging

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

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

5.3 Marking

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

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

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

6 Notes: background information on requirements

Motivation for the performance requirements

The level of ground motion experienced at the LLO facility with the initial LIGO seismic isolation system makes it impossible to hold the interferometers locked reliably during the day (February 2002). Retrofits to the instrument are necessary to allow both reliable locking and to allow better noise performance while locked. The science requirements document calls for 90% duty cycle of each interferometer and the ability to keep the interferometer locked continuously for at least 40 hours. In addition, a reduction in the noise in the control band (frequencies less than 40 Hz, especially in the range of several Hz) will allow a smaller actuator authority in suspension controllers; this is necessary to permit performance at the level of the Science Requirements Document. Lastly, upconversion of large, low frequency motions to the GW band can occur through 'wrapping of fringes' of scattered light paths (see, e.g., LHO 2k ilog 1 mar 2002), through electronics non-linearities, or through bi-linear processes (laser intensity noise times offset from the dark fringe).

There are several other measures of performance one could consider: making the daytime LLO performance as good as the nighttime performance, making the performance of the LLO facility as good as that of the LHO facility, and making the performance of the LLO facility as good as the "LIGO Standard Spectrum." These performance criteria all impact the required rms performance in the 1-3 Hz band, based on measured ground motion, the stack resonances, and observations of locking robustness during recent interferometer runs.

To keep the interferometer locked for long periods a day also requires displacements at each chamber on the order of 40 microns pkpk to accommodate the microseismic motion (6 second periods), and ~120 microns to accommodate the 6- and 12-hour tidal strains. These are currently addressed via the PZT 'fine actuators', but if these are removed to install a pre-isolator, that pre-isolator must also deliver this motion. It may be advantageous to hold all of the optics in the vertex building stationary with respect to eachother (to avoid upconversion from scattered light paths between the optics). In this case, all of the microseismic and tidal motion must be accommodated at the end stations, increasing the requirement to ~240+40 microns.

Although the Science Requirements Document only requires 40 hour lock segments, we would like to be able to keep the interferometer locked for substantially longer periods of time. Currently, no reliable data exist upon which to set the monthly displacement requirement, as these are strongly influenced by local temperature, temperature gradients, soil mechanics, and hydrology.

Observations of the seismic environment at LLO and of the interferometer locking

Experience at the Observatories (as of February 2002) indicates that for interferometer locking, the threshold ground velocity is 2.5 microns/sec peak (or 0.5 microns/sec rms) in the 1-3 Hz band (where amplification of the motion due to stack modes occurs). A histogram of the peak velocity at the Livingston site (figure 1), indicates that ground velocities of up to 15 microns/sec peak occur once per 40 hr. period. A minimum ground isolation reduction of 15 times in the 1-3 Hz band would be required in order to reduce these high velocity events to below the locking threshold (taken to be 1 micron/sec or the original LIGO design guidance).

As a complement to a reduction in the seismic excitation through a pre-isolator, reduction of the motion of the payload could be accomplished by increasing the effective damping of the problematic stack modes in the 1-3 Hz band. The stack modes have typical *Q*s of ~30, and damping to say *Q*~3 would give a factor of 10 reduction in the motion for a given seismic excitation. It appears that coupling to a stack mode at 1.3 Hz cause large 'yaw' motions from a given seismic excitation, and that the present state of the alignment system (combination of optical levers and wavefront sensing) is ill-equipped to reduce the misalignment to an acceptable value; damping this one mode might significantly change the usability of the system.

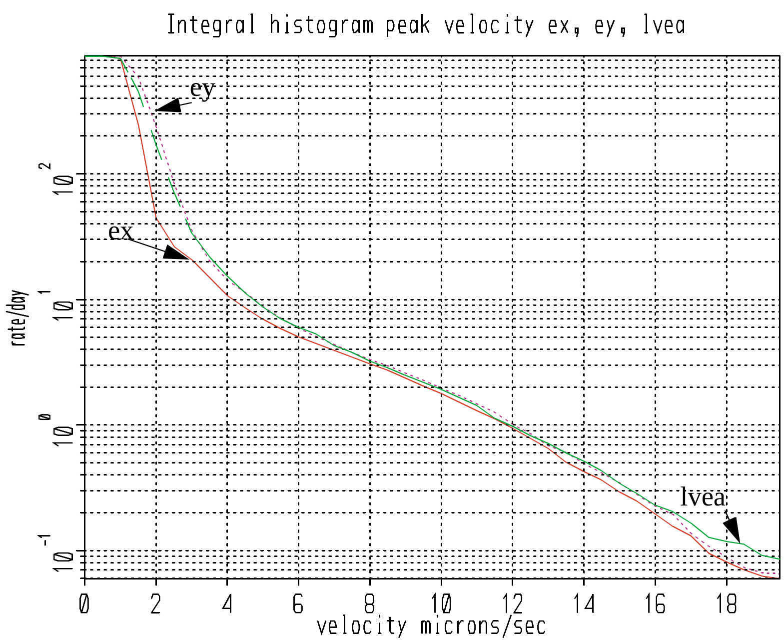

Figure 1: Integral of the pulse height distribution of vertical seismic velocity at the x-end, y end, and the LVEA between November 15, 2001 and January 11, 2002. The histogram uses the peak data from the dataviewer (v(+) – v(-))/2. This eliminates the low frequency drift in the seismometer but does not distinguish between the microseism and the higher frequency seismic noise. Typically the peak is about 5 times larger than the rms. As of Jan 2002, the interferometer would remain locked at peak velocities below 2.5 microns/ sec (rms velocities of 0.5 microns/sec). (Rai Weiss.)

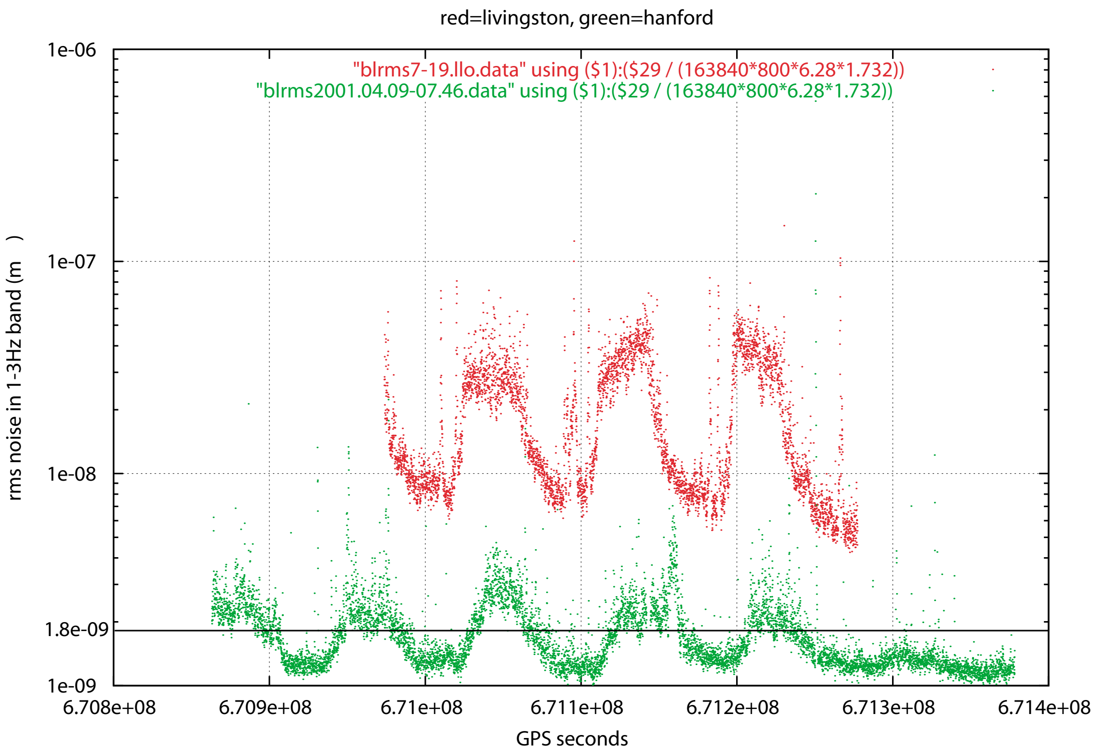

Figure 2: Time history for several days of the 1-3 Hz band limited ground motion at LLO and LHO. The noise floor requirement of 2e-9 m/rtHz at 1 Hz and 3e-10m/rtHz at 10 Hz gives an rms motion between 1 and 3 Hz of 1.8e-9 m/rtHz. This level has been added to the figure. (Figure from Rai Weiss's Aug 2001 talk at LSC, generated by Ed Daw's BLRMS monitor)

Appendix A Quality Conformance Inspections

This appendix should contain a table which lists the requirements and the method of testing requirements. An example table follows.

Table 2 Quality Conformance Inspections

Paragraph	Title	I	A	D	S	T
3.2.1	Performance Characteristics					X
3.2.1.1	Controls Performance		X			
3.2.1.2	Timing Performance‘		X			X