*LIGO Laboratory / LIGO Scientific Collaboration*

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# Initial LIGO Seismic Isolation Upgrade: Conceptual Design Document

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LIGO Scientific Collaboration

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# 1 Introduction

Experience in commissioning the interferometers has revealed problems in acquiring and maintaining lock in periods of high seismic activity. The steady-state seismic noise spectrum and the amplitude of non-stationary noise far exceeds the original design levels, particularly at the Livingston Observatory. The level of daytime seismic noise, due to anthropomorphic activity especially logging, at the Livingston Observatory prevents locking the interferometer. At Hanford moderately windy periods cause loss of lock. Even if we were to achieve lock, the forces currently required to hold lock combined with the necessarily limited dynamic range of the suspension coil drivers lead to excess noise in the gravitational wave band. Lastly, up-conversion of low frequency noise due to bi-linear coupling is a significant concern. The principal problem is excitation of the first two passive isolation stack modes by seismic ground motion in the 1 to 3 Hz band, causing a significant increase in the rms velocity of the suspended optics.

The LIGO Laboratory has initiated a project to retrofit the current seismic isolation system to reduce the rms motion of the suspended optics. Several approaches to the problem are being pursued through full scale prototype testing in the LASTI facilty. In this report the design alternatives which were considered are described, the basic design approaches and options are defined (with reference to more detailed, separate design reports) and the implementation plan is defined.

## 1.1 Purpose

The conceptual design approach for retrofitting the existing initial LIGO seismic isolation systems is described in this document and the documents referenced herein. The purpose is to get technical and programmatic input from the Lab in order to guide the balance of the design and testing phases leading up to installation and commissioning at the observatory(ies).

## 1.2 Scope

The scope of this design effort includes a revised look at isolation for all elements of the detector and application to both observatories.

## 1.3 Acronyms

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

AID: Active Internal Damping

EPI: External Pre-Isolator

ISD: Internal Stack Damping

MEPI: electro**M**agnetic actuator **E**xternal **P**re-**I**solator

HEPI: Hydraulic actuator External Pre-Isolator

EM: electromagnetic

## 1.4 Applicable Documents

At this conceptual design level (prior to results from subsystem level testing), the supporting documents for the design review are given in section 1.4.1.2.

### 1.4.1 LIGO Documents

| | |
|---|---|
| E950018-02 | LIGO Science Requirements Document |
| T010074-03 | The LIGO Observatory Environment |
| M950090-A | Guidelines for Detector Construction Activities |
| T950011-19 | SUS DRD |
| T000073-00 | Digital LOS and SOS Control Systems for LIGO |
| T010140-00 | Digital Suspension Filter Design |
| T000024-00 | Baseline LIGO-II Implementation Design Description of the Stiff Active Seismic Isolation System |
| T000029-00 | SAS Baseline Design and Prototypes Test Program Plan |
| M000154-A | Technical Evaluation of Alternate Design Concepts for the LIGO-II Seismic Isolation System |
| M000170-00 | Selection of the Technical Approach for Upgraded LIGO Seismic Isolation |
| T020039-01 | Passive External Pre-Isolation and Stack Damping |
| P010035-00 | The Linear Variable Differential Transformer (LVDT) position sensor for Gravitational Wave Interferometer Low-frequency |
| P010026-02 | Constant Force Actuator for Gravitational Wave Detector's Seismic Attenuation Systems (SAS) |

#### 1.4.1.1 Initial LIGO Seismic Isolation System

| | |
|---|---|
| T960065-03 | SEI DRD |
| C970257-00 | SEI Design Document |
| T980129-00 | Transfer Function and Drift Measurements on the BSC First Article Stack |
| T000101-00 | Transfer Function Measurement on the BSC Seismic Isolation Stack |
| T980084-00 | Transfer Function and Drift Measurements on the First-Article HAM |
| T020046-00 | Vibrational Modes of the BSC Seismic Isolation System |
| T020045-00 | Vibrational Modes of the HAM Seismic Isolation System |
| D972001-B | BSC SEI Top Assembly Drawing |
| D972501-B | HAM SEI Top Assembly Drawing |

#### 1.4.1.2 Seismic Retrofit System

| | |
|---|---|
| T020033-02 | Initial LIGO Seismic Isolation System Upgrade: Design Requirements Document |
| T020040-00 | External Seismic Pre-Isolation Retrofit Design |
| T020047-00 | Quiet Hydraulic Actuators for Initial LIGO |
| T020041-01 | Pre-Isolator with Electromagnetic Actuator |
| T020038-01 | Active Internal Stack Damping |
| D020124-02 | Hydraulic External Pre-Isolator (HEPI) Top Assembly Drawing |
| D020124-02 | Spring/Hydraulic Actuator Assembly Drawing |
| D020182-00 | Electro-Magnetic External Pre-Isolator (MEPI) Top Assembly Drawing |
| D020183-00 | Spring/Electro-Magnetic Actuator Assembly Drawing |
| M020142-01 | Seismic Retrofit Project Schedule |

### 1.4.2 Non-LIGO Documents

S. Peirce, H. Tran, M. Wiedemann, D. DeBra, “Quiet Hydraulics for Ultraprecision Actuation”, Stanford University, circa 1993.

## 2 Problem Statement

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.

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 ~30 times in the 1-3 Hz band would be required in order to reduce these high velocity events to below the locking threshold.

There are several other measures of performance worth consideration: making the daytime LLO performance as good as the nighttime performance (see Figure 2), making the performance of the LLO facility as good as that of the LHO facility (at times when the winds are not high), 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. Up-conversion of large, low frequency motions to the GW band can occur through ‘wrapping of fringes’ of scattered light paths, through electronics non-linearities, or through bi-linear processes (laser intensity noise times offset from the dark fringe). Significant noise due to up-conversion may occur well below seismic isolation levels which permit locking the interferometer. We have set the required performance such that the rms level in the 1-3 Hz band should be < 1.8 nm. This level (indicated in Figure 3) is comparable to the night time level at Hanford (in low wind conditions). The problem is defined in more detail, and the requirements derived, in T020033.

**Figure 1 Integral of the pulse height distribution of vertical seismic velocity, LLO**

At the LLO 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 LLO interferometer would remain locked at peak velocities below 2.5 microns/ sec (rms velocities of 0.5 microns/sec). (Rai Weiss.)

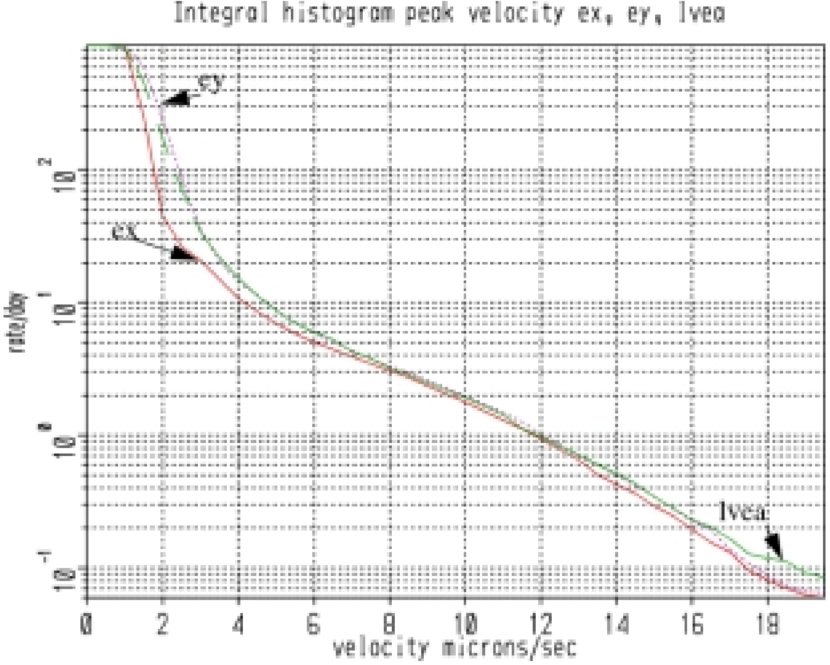
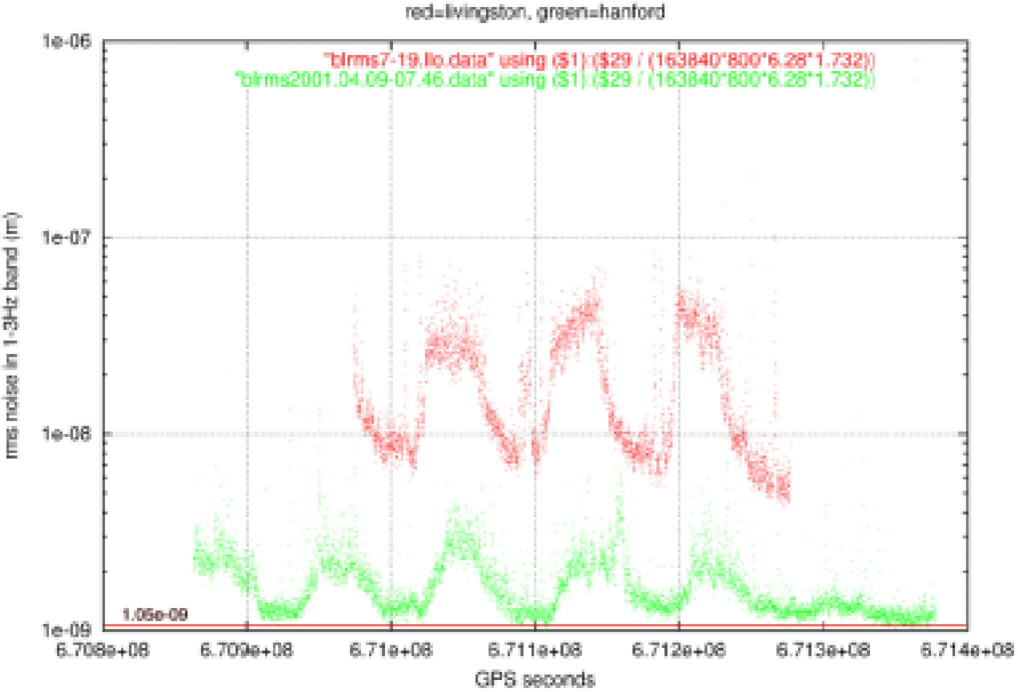


**Figure 2 Several day time history of the 1-3 Hz band limited ground motion at LLO & LHO.**

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. 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)



# 3 Design description

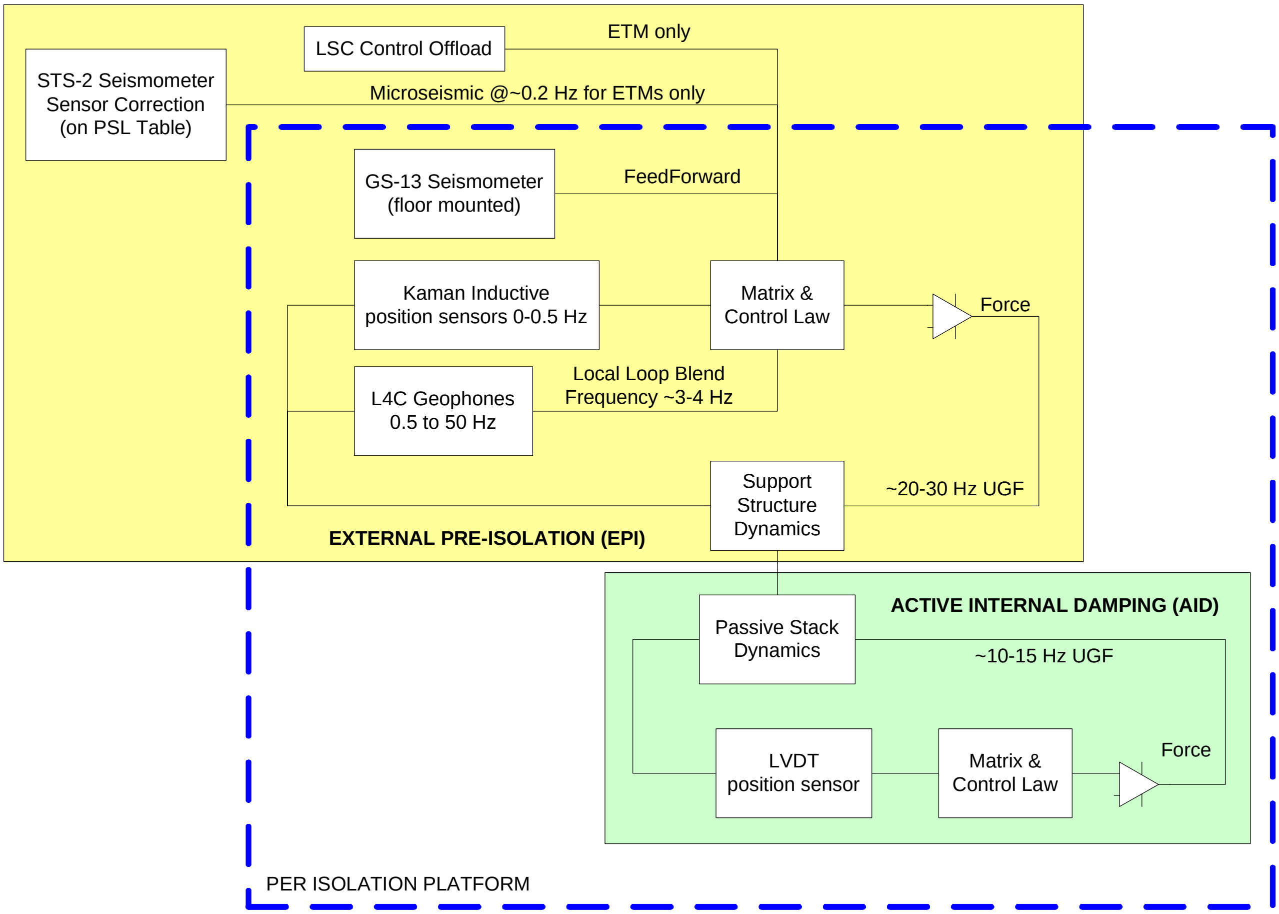
Ideally all elements of the optical system should be stationary relative to one another (in the absence of a gravitational wave). One way to accomplish this is to inertially stabilize all optics. However, given the spatial separation of the corner station optics and the considerable cost of low noise, low frequency seismometers, a more practical approach is to use a single seismometer as a reference at low frequency in each of the three buildings. Each seismically isolated platform is then servo controlled to follow the seismometer at low frequency. The DC reference for each isolated platform is initially derived locally from low noise, inductive sensors. Ultimately the DC reference for the end station platforms is determined by feedforward differential tidal and differential microseismic inputs corrected by offloading the integrated length control signal.

Presently the PSL system is not seismically isolated. In order to prevent up-conversion due to fringe wrapping of the input beam, the relative velocity between the PSL and the suspended optics must be less than about 2 microns/sec. This problem could be solved by providing seismic isolation for the PSL table (perhaps with a commercial solution like the TMC PEPS-VX™ system). Our present baseline is to locate the corner station reference seismometer on the PSL table and slave the corner station isolated platforms to follow the PSL motion; the components and system are also compatible with the alternate arrangement of isolating the PSL table. The chosen reference seismometers are STS-2 units, which are presently used at the observatories for microseismic feedforward compensation at the end test mass chambers.

We have chosen a two approaches (see Figure 4). First an External Pre-Isolation (EPI) system placed between the passive isolation stack and its support piers serves to reduce the spectrum of base motion into the stack. The control law for the pre-isolator will also include resonant gain at the troublesome stack modes in order to reduce the excitation to these modes. We think it likely that at least in the case of the test mass chambers and possibly the HAM chambers we will be able to profit from further suppression of the residual velocity of the optics. The second stage is an Active Internal Damping (AID) system placed in the vacuum chamber. The motion of the optics table is sensed and damped with feedback to a voice coil actuator which reacts against the stack support structure. Both systems employ collocated, co-axial sensing and actuation in the feedback paths. At present both are full 6 degree-of-freedom (DOF) control systems. However, it is possible that the AID system may be able to damp the most problematic stack modes with fewer DOFs.

Details for the EPI approach are given in T020040. This subsystem has two options for the actuation, either a quiet hydraulic actuator (described in T020047) or an electro-magnetic actuator (described in T020041). The AID subsystem is described in T020038.

**Figure 3 Isolation System Block Diagram**



## 3.1 Design Approach Trade Study

A number of alternative approaches to solving the problem have been considered and are listed in Table 1. Some comments on each of the approaches listed are given in the following subsections.

## Table 1 Seismic Retrofit Approaches Considered

| # | Approach | Description/comments | Options | Isolation | Stack Damping |
|---|---|---|---|---|---|
| 1a | External pre-isolation | 6 DOF isolation with collocated sensing & actuation at the base of the passive stack; feedback & feedforward control to be explored including use of OSEM sensing | Hydraulic actuator | Y | possibly |
| 1b | | | EM actuator | Y | possibly |
| 2 | Internal active damping | Collocated sensing and actuation on the internal optics table (e.g. LVDT and voice coil) to sense & damp from support structure to optics table. The addition of inertial sensing on the optics table may permit isolation. | Voice Coil or EM linear motor<br>LVDT or geophone | possibly | Y |
| 3 | Existing fine actuators | Longitudinal & yaw velocity feedback with collocated geophones. Being pursued as an interim measure. | | Y | N |
| 4 | COTS isolation systems | Piezo isolation systems like Stacis; minus-k compact low frequency spring, etc. which can perform the external pre-isolation task. | Various | Y | unlikely |
| 5 | SAS-like Implementation | A hybrid passive/active "soft" alternative approach to the stiff external pre-isolation approach. | | Y | N |
| 6 | Tuned Mass Dampers | With existing payload mass limits the optimum reduction in stack mode resonance is ~4. This does not meet requirements and requires in-vacuum hardware | Viscous fluid, eletro-restrictive or eddy current | N | Y |
| 7 | Multiple pendulum or longer period suspensions | Too invasive, too large a schedule & cost impact; not clearly a solution either | | Y | N |
| 8 | Cooled suspension coil drive electronics with larger dynamic range | Does not preclude increased noise due to bi-linear coupling mechanisms & large amplitude of real motion; might be a last ditch effort after other measures are taken | | Y | N |
| 9 | Short across 1 layer of the HAM Stack | Compromise the better-than-needed high freq. HAM isolation performance; shift stack modes; not clear this works; seems wrong to compromise performance | | N | Y |
| 10 | Replace some or all springs with lower Q springs | Too invasive & marginal improvement in Q without complete replacement | | N | Y |
| 11 | Add eddy current damping between stages | Too invasive & marginal improvement in Q without the addition of many components | | N | Y |

## 3.2 External Pre-Isolation (EPI)

The requirements address two complementary approaches to reducing the motion in the control frequency band (frequencies less than 40 Hz) for initial LIGO. The pre-isolation system can probably achieve not more than a factor of ~20 reduction in displacement spectrum amplitude (integrated from 0.1 to 10 Hz), though with resonant gain stages for targeting problematic modes, further suppression of the rms motion of the optics platform is possible.

**Figure 4 The external pre-isolation system replaces the coarse and fine actuation systems (CAS & FAS) at between the piers and the cross-beams**

An external pre-isolator would be placed between the vertical (blue) piers and the horizontal support tubes of the existing initial LIGO isolation system, replacing the present coarse actuators (and in the case of the BSC chambers, fine actuators). The pre-isolator allows the support tubes 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, 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. The later is our baseline assumption, but the system can accommodate either scheme.

## 3.3 Active Internal Damping (AID)

The residual motion at the base of the passive stack, after suppression from the external pre-isolator (EPI), will excite stack modes. Further reduction in test mass motion is possible if the stack can be damped. An internal (in the vacuum) damping system would allow forces to be applied to the initial LIGO isolation system optics table. These forces might be applied via reaction masses or by generating forces between the optics table and a point mechanically before the isolation system (e.g., the support tubes). 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.

The active internal damping (AID) system complements the pre-isolation system by using optics table motion sensing in a velocity feedback arrangement to damp the optics table motion. The sensing and actuation are collocated. The actuation is accomplished with voice coils which bridge across the passive stack from the base (support tubes) to the optics table, as depicted in Figures 1 and 2. Sensing can be either inertial (e.g., with accelerometers on the table) or relative displacement (e.g., with an LVDT between the optics table and its support frame, as is the baseline approach). In this configuration, the AID system benefits from the isolation performance of the pre-isolator. The vacuum compatible component technology for the AID system is derived from the SAS (T000029) program.

In order to prevent the AID from shorting out the high frequency isolation performance of the stack, it is essential that the electronics and sensing noise be rolled off quickly beyond the servo control band.

**Figure 5 Layout drawing of the Active Internal Damping (AID) system: plan view**

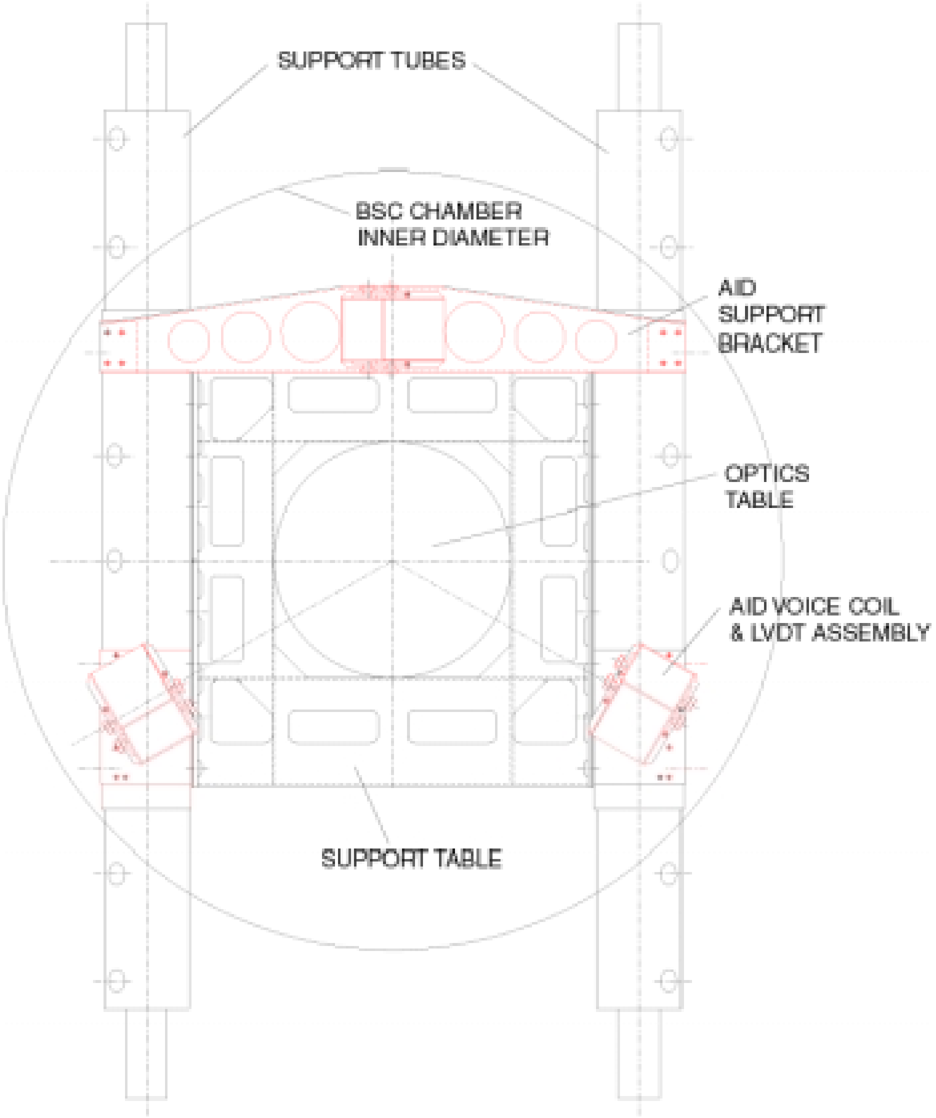
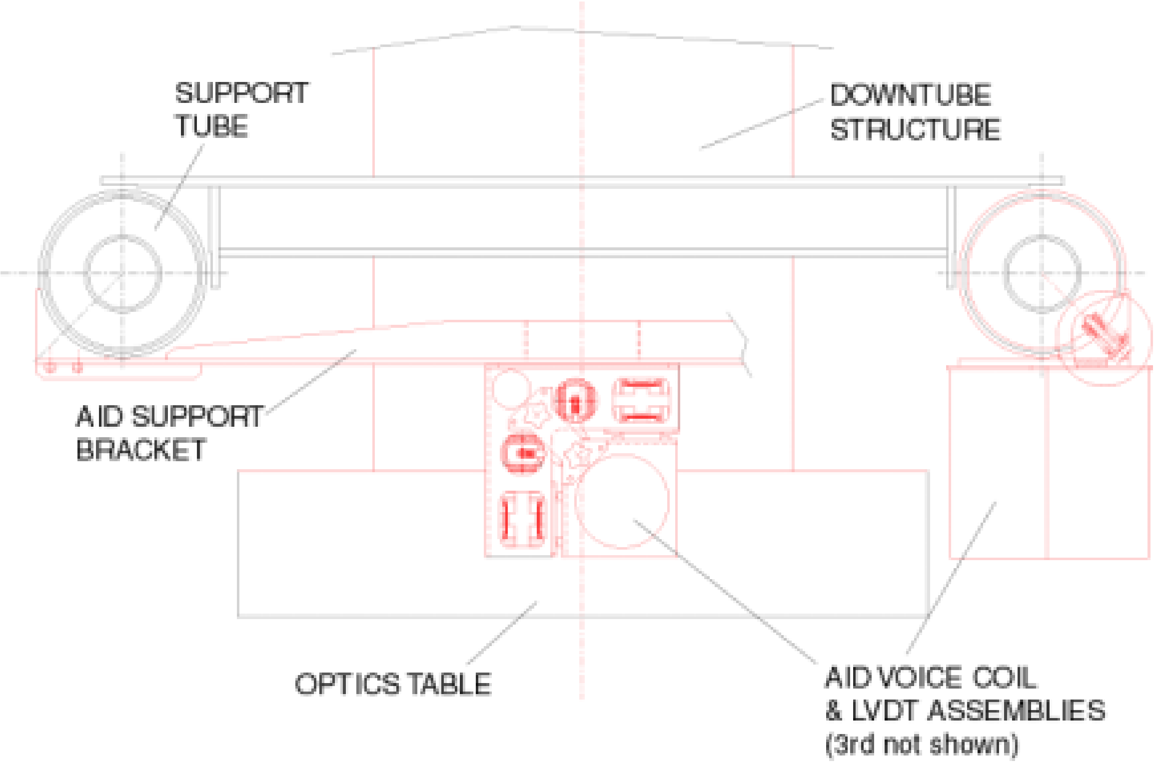


**Figure 6 Layout drawing of the Active Internal Damping (AID) system: elevation view**

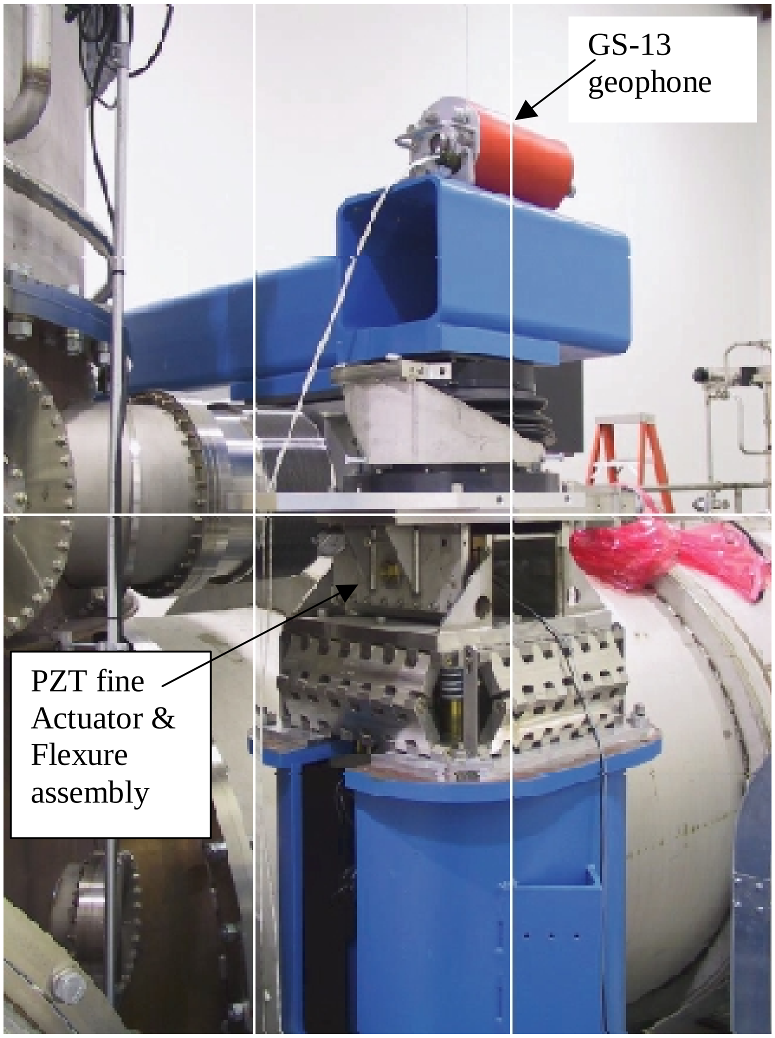


## 3.4 Existing Fine Actuators (PEPI)

Using the existing ETMy fine actuation system (Figure 2), the rms amplitude of the residual motion at the base of the passive seismic was reduced by a factor of 7 (T020040). The servo control loop employs velocity feedback from collocated geophones and resonant gain stages for the first two BSC stack resonances (at 1.2 and 2.1 Hz). With geophones on both sides of the chamber it should be possible to damp both the longitudinal and yaw degrees of freedom. To date only the longitudinal degree or freedom has been damped. Damping performance as measured at the test mass is likely to be limited by stack mode cross-coupling. It is estimated that it is possible to achieve a factor of ~10 reduction in the interferometer length signal when implemented on all test mass chambers. This is sufficient to effectively reduce the LLO daytime seismic environment to a level comparable with the nighttime, when routine locking can be achieved. Since this has the potential to significantly increase the efficiency of commissioning efforts, it is well worth the investment. Use of the Piezo-electric actuator External Pre-Isolation (PEPI) system is being pursued as an interim measure at LLO, before the seismic upgrade is available.

Once the seismic retrofit is underway at LLO, the fine actuation systems on the four test mass chambers at LLO will be made available for possible installation on the LHO to help mitigate wind induced seismic noise. These units can be directly installed on the ITM chambers and, with modification, on the HAM mode cleaner chambers. If this is insufficient to meet performance goals at LHO, or if other benefits to the pre-isolator and/or internal stack damping are perceived, they can be implemented at LHO in a second stage of retrofit.

**Figure 7 External Pre-Isolation with the PZT Fine Actuator System (PEPI)**



## 3.5 Alternatives Considered

The alternatives described in the following subsections were also briefly considered. A description and the reasoning for not pursuing these further are given below.

### 3.5.1 COTS isolation systems

If we could find a company whose product line, experience and product development and market interests were aligned with the nature and performance goals of our needed seismic retrofit, then outsourcing the problem would be a sensible approach. A cursory survey of the companies and products was made and considered. Possibilities included:

- Von Flotow's consulting firm (the Stacis designer), together with another manufacturer(s)
- TMC which bought the Stacis product line from Barry Isolators, but has been poor in answering technical questions on the Stacis units purchased for the 40m lab. STACIS is claimed, by TMC, to be unstable when supported with the compliance of the pier.

- IDE, who markets active isolation systems but failed to produce an acceptable option for a pre-isolator for the LASTI/LIGO chambers under a recent contract
- Minus-k, which markets a negative stiffness column isolator which would require modifications (including likely the addition of active servo controls) to mitigate drift problems

While we could have issued a request for proposal to the isolation industry to see what they would propose (technical approach, cost, schedule), it would consume a fair amount of time and key personnel to evaluate proposals and visit the vendors. In the end it was judged to be better to own the problem in house.

### 3.5.2 SAS-like Implementation

Variants of the super-attenuator system (SAS) have been installed on Virgo and a 3m system at TAMA. This system is a hybrid passive and active system, but the principal isolation is achieved passively. Horizontal isolation is achieved with an inverted pendulum. Vertical isolation is achieved with geometric anti-springs (negative stiffness springs). The SAS structure has very low natural resonant frequency, on the order of 0.1 – 0.3 Hz. The SAS systems to date have all been designed for in-vacuum application; The exo-vacuum use in the upgrade allows design simplifications. A conceptual study of the application of the SAS approach and technology to the initial LIGO seismic retrofit, as an external pre-isolation stage, is documented in T020039. This low frequency, or 'soft', approach is an alternative to the 'stiff' or active external pre-isolation options described above.

Since the 'stiff' approach was chosen for advanced LIGO (M000154 and M000170), and the pre-isolator is an element of that approach (thus a step toward the Advanced LIGO implementation), we have baselined the 'stiff' pre-isolation design approach. If the hydraulic or electromagnetic external pre-isolator approaches fail because of problems not likely to arise in the soft approach, and if the soft approach is in a situation to be applied, then it would be considered. Thus, this is fallback option and not part of the baseline design approach.

### 3.5.3 Tuned Mass Dampers

Tuned mass dampers (TMD) are excellent at reducing the motion of a resonance when the excitation is at a relatively narrow frequency(ies). The response suppression at the excitation frequency occurs by splitting the structural resonance into two (one slightly above and one slightly below the original frequency). However, when the excitation is broadband (at least in the vicinity of the problematic mode), then an optimal tuned mass damper must keep the Qs of the split resonances low. To be effective it is best to add a TMD reaction mass that is a sizable fraction of the modal mass being suppressed. Given the modest available payload mass, the maximum TMD reaction mass (~68 kg), is only about 8% of the BSC optics table (downtube) mass (which may be an under estimate of the effective modal mass). The optimal suppression for this mass ratio is only about a factor of 4 to 5. Given that this requires developing a vacuum compatible device and intrusion into the vacuum system to install, it does not appear to be a promising approach. (Details are in T020049).

### 3.5.4 Multiple pendulum or longer period suspensions

Both of these options involve building all new suspensions (for at least the test masses and the mode cleaner optics) and a long and complex de-installation of the optics, assembly into the new suspensions, re-installation and re-alignment. These approaches seem far too invasive, time consuming and costly.

### 3.5.5 Cooled suspension coil drive electronics with larger dynamic range

If we set the dynamic range of the coil driver high enough to accommodate the residual motion at the test mass, then the thermal (Johnson) noise is too high to meet the science requirements. We might be able to recover in-band noise performance by cooling critical components in the coil driver electronics to reduce the thermal noise. However, this does not preclude increased noise due to bi-linear coupling mechanisms and the large amplitude of residual motion of the optics table and suspension point. The implementation would be difficult.

### 3.5.6 Short across 1 layer of the HAM Stack

The isolation performance of the HAM system happens to be better than required in the sensing band (> 40 Hz). It has been proposed that if we short across one of the HAM isolation stack layers (e.g. put in some solid links) to shift the stack modes, we might use some of the isolation margin in the sensing band but reduce the overall rms motion of the optics table. No analysis of the performance of this proposed change has been made to date. It seems sensible to pursue a design change for the BSC system that can also be applied to the HAM system. Even if this is shown to work, we would prefer not to compromise existing performance. A cost/benefit decision on whether to install onto the HAM, or to perform a perturbation as described above, can be made later when more is known.

### 3.5.7 Replace some or all springs with lower Q springs

If the springs in the existing seismic isolation stacks had higher loss, the problem would be mitigated. Replacing just a few springs with higher loss (lower Q) springs will not make a significant reduction in the Q of the overall stack modes. Most of the springs would need to be replaced. The only vacuum compatible, lower loss springs that are available are solid Viton (Flourel) springs. This would aggravate the already significant moisture absorption problem. This approach is also very invasive since it requires lifting the seismic platform (losing all alignment in the process), which includes removing the top dome in the BSC systems.

### 3.5.8 Add eddy current damping between stages

Rather than replace the springs, one could imagine adding non-contacting eddy current absorbers in parallel with the springs between each stage of the passive stack. This would nominally require three dampers per layer per leg or a total of about 40 dampers for the BSC. For the BSC stack this solution would require removal of the upper dome, which is fairly invasive. In addition, to get significant damping, one would need very strong magnets and intimate coupling from the magnets to the eddy-current carrying sheets, requiring small mechanical clearances. No quantified estimate has been made for the design.

# 4 Development Plan & Schedule

The plan for development and testing plans for the seismic upgrade system described above (and in the referenced documents) are presented in this section. Somewhat more detailed test plans are described in the design documentation for each of the approaches being pursued in parallel. In this section we concentrate on system level issues, testing and development. The subsystem level testing is described in the design documentation for the three major approaches (T020040, T020047, T020041, and T020038).

## 4.1 System Level Issues

The following are system level issues that remain to be resolved in the next design phase:

- Since the level of vibration is so high, it raises concerns that fringe wrapping can occur for the input laser beam and that backscattered light from the output PD may inject too much noise. The relative motion of the PSL and ISCT and the COC may need to be reduced. The conceptual design currently only addresses BSC and HAM chamber isolation. This should not be a significant technology challenge, and can be addressed later and incrementally, but would be added complexity and cost.
- The reduction in motion must be complemented with a change in the suspension coil driver authority and possibly filter shapes to optimize the overall interferometer performance. This should in general reduce the stress on the suspension driver design.
- The additional control degrees-of-freedom must be integrated into the length and angle control systems, and the locking/unlocking procedures. The ‘slow’ nature of these additional loops will probably not lead to any new computational thresholds.
- The overall pre-isolator/stack damper system must be integrated into the existing EPICS and real-time control system. This is planned as a second phase in the LASTI system testing. The initial implementation will be with dSpace controllers.
- It has been assumed that external 2 DOF isolation with the fine (piezo) actuation system, on the test mass and mode cleaner platforms, is adequate for improved isolation during wind storms at Hanford. This requires further study.

## 4.2 Baseline Implementation Scope and Plan

The baseline plan for system implementation is as follows:

For the Livingston Observatory:

- Interim addition of the 2 DOF, Piezo-electric actuator External Pre-Isolation (PEPI) to the Test Mass platforms immediately after the Science Run No. 1 [7/2002]. This may permit routine locking of the interferometer during the day with the high force suspension coil drivers.
- Installation of the 6 DOF, External Pre-Isolation (HEPI or MEPI) and the Active Internal Damping (AID) system to all platforms with suspended optics (i.e. 3 HAMs and 5 BSCs), soon after the Science Run 2 [1/2003]

- No isolation to be added to the PSL table or the ISC tables.

For the Hanford Observatory:

- After the seismic retrofit at Livingston, move the PEPI systems to Hanford and install onto the Test Mass and Mode Cleaner platforms (6 systems). [2/2003]
- No isolation to be added to the RM platform, BS platform, PSL table or ISC tables.

## 4.3 System Integration & Testing

After component level and proof-of-concept testing has been completed, each of the three approaches (HEPI, MEPI and AID) are integrated in the LASTI laboratory for system level testing. The purpose of the LASTI testing is to:

- Demonstrate reliable, safe, clean and documented procedures for assembly and installation In particular, we hope to install the EPI system without perturbing the alignment of the optics. The LASTI optics tables will be monitored to determine the effect of the external isolation.
- Perform fit and interface checks for the equipment in and around the LIGO chambers.
- Verify function and robustness (within the limits of time and the LASTI facility).
- Verify performance (within the limits of the LASTI facility).

## 4.4 Milestones and Decision Points

The following are (success-oriented) program major milestones and decision points. More detail can be found in the schedule (M020142).

- PEPI performance review: Based on experience at Livingston, a decision on the suitability of the PEPI system for mitigation of the wind-storm induced seismic noise will be made. [8/2002]
- Preliminary Design Review/ Long-Lead Procurement Review: Once the prototypes have been installed in/on the LASTI chambers, and some preliminary experience has been obtained, we will make a decision on whether to go forward with the hydraulic actuator or fall back to the electro-magnetic actuator. This decision point is driven by the need to start long-lead procurement and to focus the team. Generally all quantity decisions (implementation scope) should be made by this time. [9/2002]
- Final Design Review: After characterization testing has been completed and drawings updated, a brief, final review of the design and test results will be held. [10/2002]
- Installation Readiness Review: A brief review of the readiness of equipment, personnel, procedures, supplies to initiate installation. [1/2003]