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External Pre-Isolation (EPI) Evaluation

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1 Introduction

The External Pre-Isolator (EPI) design effort was initiated in response to the need to provide better seismic isolation for the LIGO Livingston Observatory (LLO) environment. The concept was to accelerate the pre-isolation design effort already underway as part of the advanced LIGO seismic development. The advanced LIGO EPI system, as originally conceived, was to employ a quiet hydraulic actuator. Since the hydraulic actuator required considerable development risk, a commercial-off-the-shelf electro-magnetic actuator was chosen for a parallel effort to reduce the overall development risk. The EPI version using a hydraulic actuator is known as HEPI (Hydraulic EPI) and the EPI version using an electro-Magnetic actuator is known as MEPI (electro-Magnetic EPI).

In the interim period the Fine Actuation System (FAS) was used for active damping of the seismic support structure with feedback from sensitive (GS-13) geophones placed on the crossbeams near the piers. This Piezo-electric EPI (or PEPI) has control in the x-direction (optical axis direction) and yaw (rotation about the vertical axis) degrees of freedom.

Although MEPI was originally planned to be a fallback option only to be used if the HEPI development ran into problems, we have since found that the costs for the HEPI system are considerably higher than for the MEPI system. There are also positive and negative aspects for both systems. In addition, the PEPI system has been able to afford reasonable performance.

The purpose of this note is to (i) define appropriate evaluation factors, (ii) provide input to the design review committee on an evaluation of the relative importance and ratings for each system. The evaluation is not intended to be binary, but rather defines the pluses and minuses with some narrative response to each evaluation factor. We then leave it to the review committee to review/critique the evaluation and make their recommendation. This is not designed to lead the committee, but rather to make their job easier. Ultimately it will be a management decision. At the very least by way of a CCB review to allocate the funds.

This report is not considered complete as a few significant unaddressed (or insufficiently addressed) issues remain. Conclusions are therefore with caveats and may change as more information is gathered. Nonetheless it was felt important to define what we know (and don't know) now as input to a project level evaluation of the correct course(s) of action.

2 Evaluation Factors

2.1 Isolation Performance

The isolation performance is addressed by frequency band for steady-state performance, in accordance with the requirements[1]. There is also an added evaluation factor for the isolation performance for a transient event. In the appendix an alternative set of isolation performance criteria are also discussed. The absolute noise performance is basically dictated by the choice of low noise instrumentation, which are basically common to all of the EPI concepts. Consequently the focus of this evaluation is on the gain limited performance of the systems. The latest

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[1] B. Lantz, et. al., "Initial LIGO Seismic Isolation Upgrade Design Requirements Document", LIGO-T020033-02, 26 Mar 2002

performance estimates/measurements and system identification measurements are reported in the design review presentations[2,3] and not here.

2.1.1 Drift

As far as we know both HEPI, MEPI and PEPI can meet the long term drift (1 month) requirement of less than 10 microns pk-pk, although this has not been verified experimentally. There is no reason to believe that either system is superior with regard to this requirement.

2.1.2 Tidal

Since the EPI system replaces the current piezo-electric Fine Actuation System (FAS), it must also perform tidal correction at the End Test Mass (ETM) chambers (2 BSC chambers). The feedback signal for tidal correction is derived from the interferometricly sensed cavity length and is common to all EPI instantiations. All EPI systems are inherently capable of performing this function and none is thought to be superior with regard to this requirement. HEPI has the most actuation range (+/-1 mm), but the MEPI range (+/- 300 microns) is adequate. The PEPI range (+/- 90 microns) is adequate as compared to an original requirement of +/- 60 microns[4] and inadequate (or marginal at best) against the revised requirement of +/- 130 microns[5].

It should be noted that the isolation performance of the PEPI system while providing tidal correction has been tested at LLO. There is no noticeable degradation in performance when the PEPI actuators are operating at an offset from the null position. (should confirm with Joe Giaime.)

The HEPI system has been operated off of the null position to investigate a bilinear noise coupling with source pressure noise. The supply pressure fluctuations were found to be low enough that this bilinear coupling mechanism is not a limiting noise source.

The isolation performance of the MEPI/HAM system when the actuation has a significant DC position offset has not been tested as yet. Since the maximum change in actuator response with a maximum offset (on axis or transverse to the actuation axis) is only 15%, it is not expected to be a problem.

2.1.3 Microseismic

Since the EPI system replaces the current piezo-electric Fine Actuation System (FAS), it must also perform microseismic feedforward correction. All derive the sensor correction, or feedforward, signal from a floor mounted STS-2 seismometer. All EPI systems are inherently capable of performing this function and none is superior with regard to this requirement. Are the HEPI & MEPI systems better than PEPI because we can sensor correct the Kaman eddy current position sensor, rather than the internal strain gauge sensor in the piezoelectric actuator?

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[2] B. Lantz, et. al., HEPI/BSC System Controls and Performance, LIGO-G03xxxx

[3] R. Mittleman, et. al., MEPI/HAM System Controls and Performance, LIGO-G03xxxx

[4] LIGO-T960065-03, section 3.2.1.7.1, pg. 20.

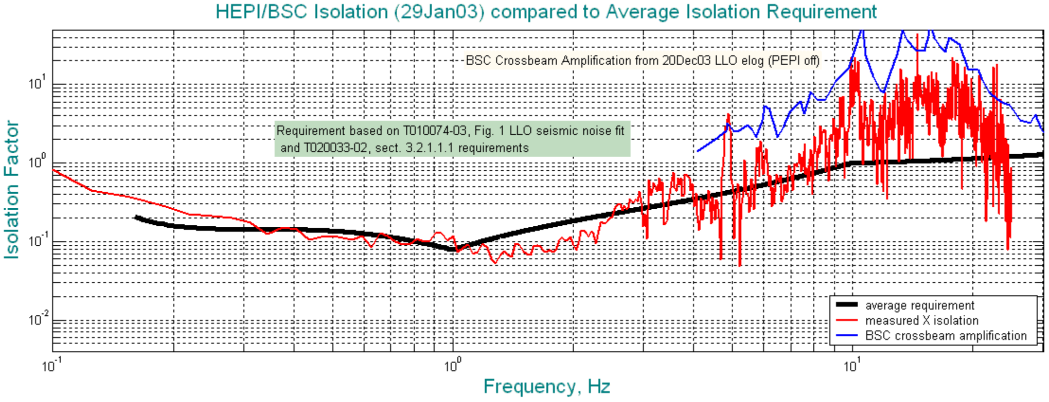
[5] LIGO-T020033-02, section 3.2.1.1.4.3, pg. 15.

2.1.4 Stack Modes (1 to 3+ Hz)

At the LIGO Advanced Systems Test Interferometer (LASTI) facility, the HEPI isolation on a BSC platform and the MEPI isolation on a HAM platform have both basically met the gain limited performance implied by the requirements, in the 1 to 3 Hz band. Both systems can achieve a factor of ~15 reduction[6] across the 1 to 3 Hz band and more isolation at stack modes when resonant gain stages are added at the two lower stack mode frequencies. The PEPI system has demonstrated a factor of ~7 reduction in the rms, by use of resonant gain stages at the two lower BSC stack modes (1.2 Hz and 2.1 Hz). The measured MEPI/HAM isolation and the HEPI/BSC isolation are compared to the requirements in the following two figures (figures 2.1, 2.2 and 2.3; also see the HEPI/BSC and MEPI/HAM Control and Performance presentations which are part of the 18 April 2003 EPI review). See also the appendix for noted on isolation requirements.

[Note: Should overlay requirement curve and crossbeam amplification on figures 2.2 through 2.4]

Figure 2.1: HEPI/BSC X-direction Isolation Performance vs Requirements
Note that more recent HEPI/BSC performance includes the addition of resonant gain at the lower stack modes.


HEPI/BSC Isolation (29Jan03) compared to Average Isolation Requirement

BSC Crossbeam Amplification from 20Dec03 LLO elog (PEPI off)

Requirement based on T010074-03, Fig. 1 LLO seismic noise fit and T020033-02, sect. 3.2.1.1.1 requirements

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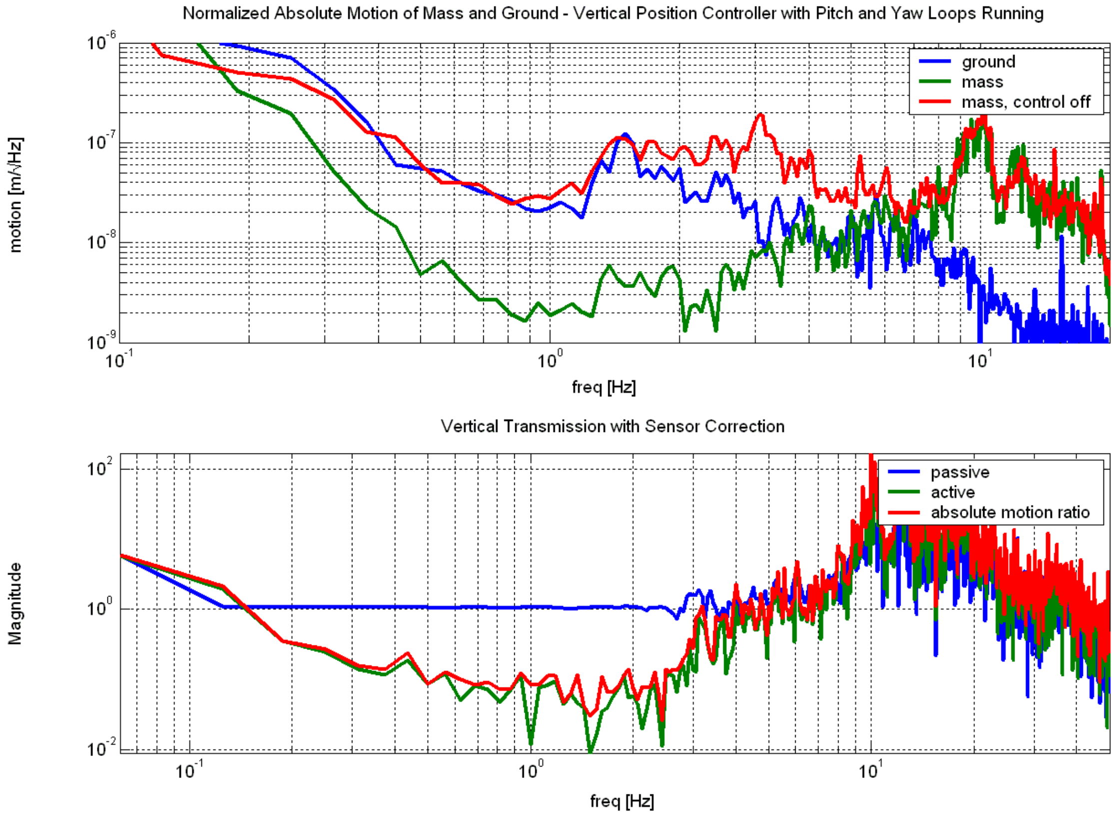
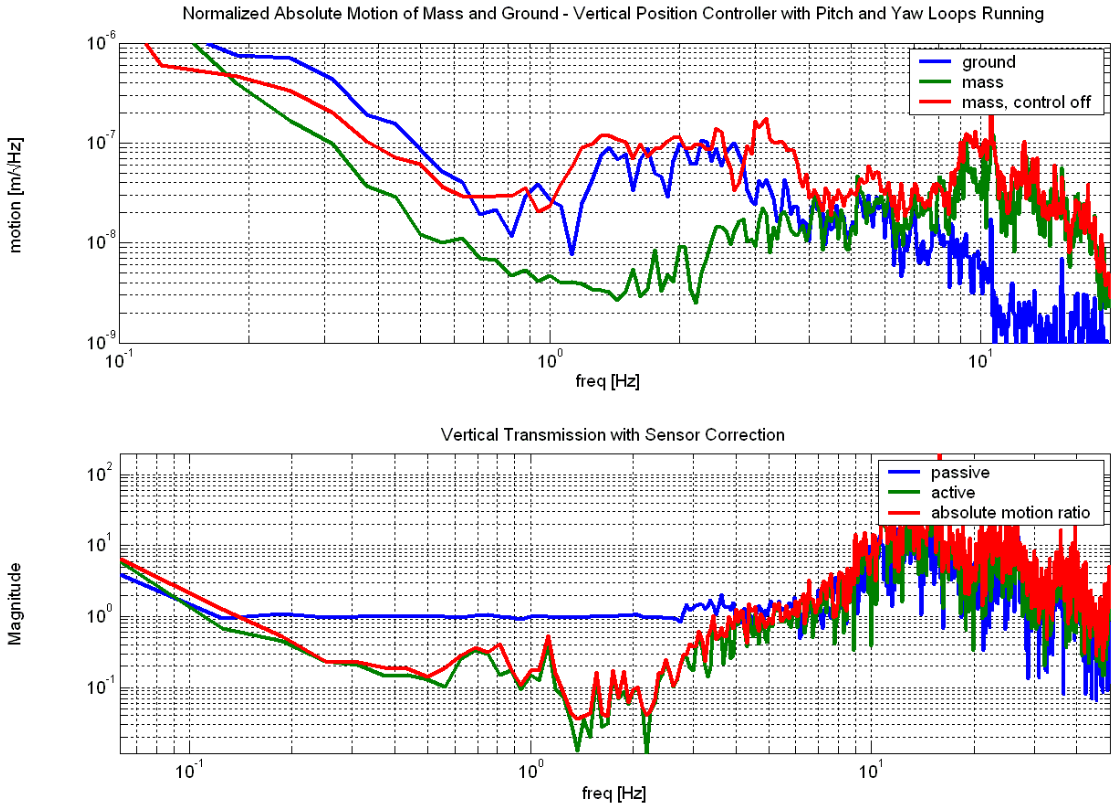
[6] The factor of 15 reduction in the 1 to 3 Hz band limited rms is motivated in section 6 of T020033-02

Figure 2.2 HEPI/BSC X-direction Isolation ASD (control on and off) at LASTI


Normalized Absolute Motion of Mass and Ground - Vertical Position Controller with Pitch and Yaw Loops Running

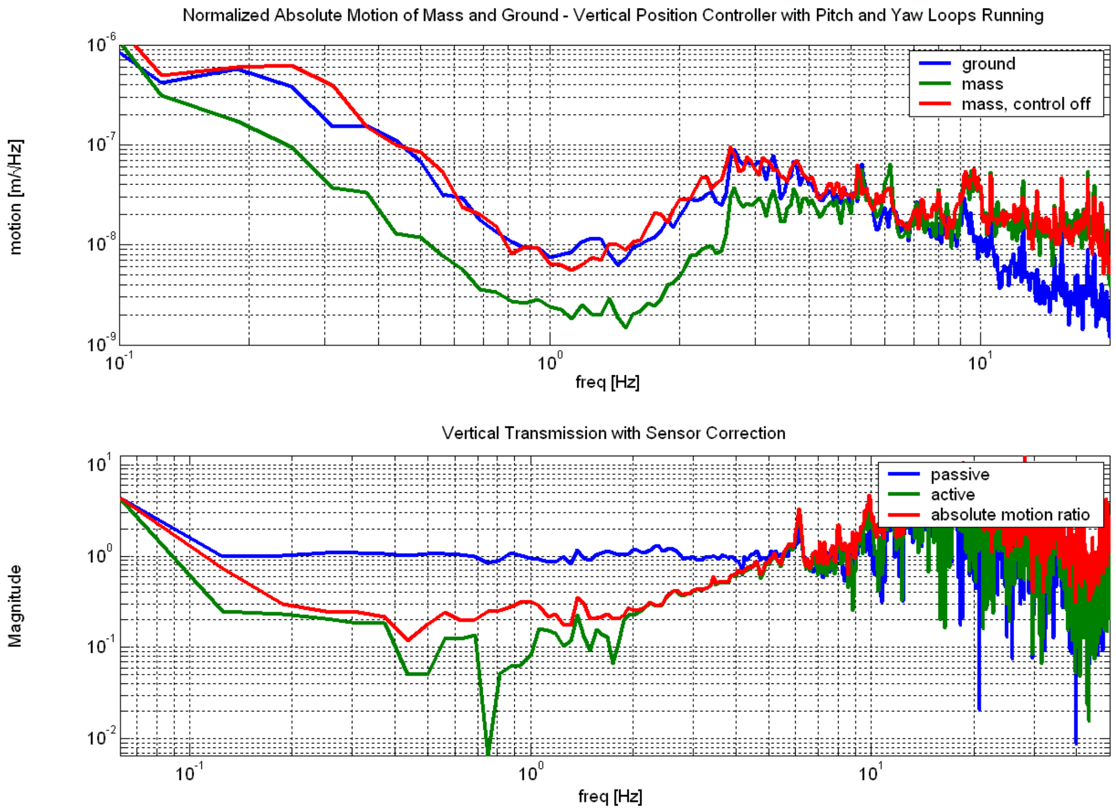
Vertical Transmission with Sensor Correction

Figure 2.3 HEPI/BSC Y-direction Isolation ASD (control on and off) at LASTI


Normalized Absolute Motion of Mass and Ground - Vertical Position Controller with Pitch and Yaw Loops Running

Vertical Transmission with Sensor Correction

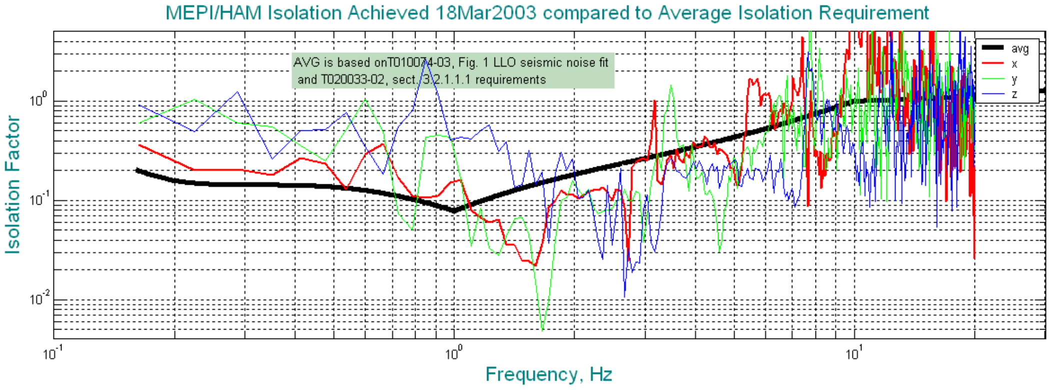
Figure 2.4 HEPI/BSC Z-direction Isolation ASD (control on and off) at LASTI


Normalized Absolute Motion of Mass and Ground - Vertical Position Controller with Pitch and Yaw Loops Running

Vertical Transmission with Sensor Correction

Figure 2.5: MEPI/HAM X-Direction Isolation Performance vs Requirements

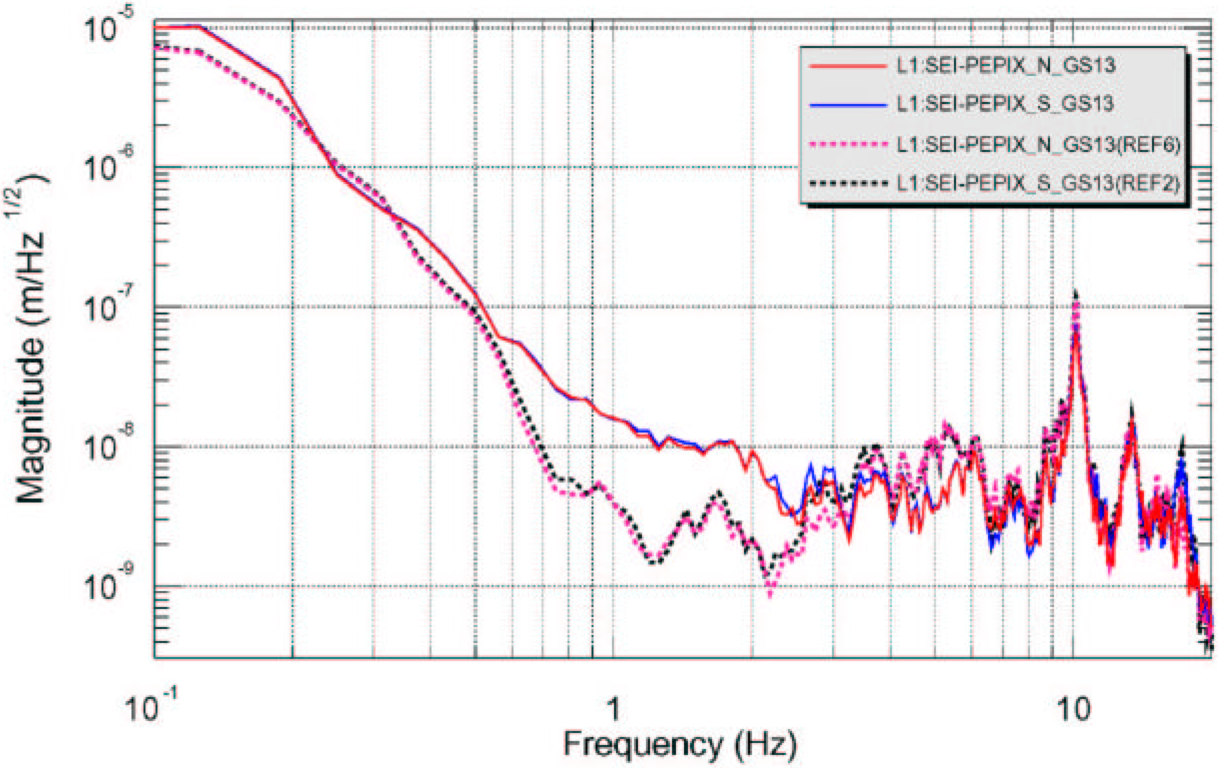
Note that it is expected that the performance of the MEPI/HAM system below 1 Hz is can be improved through more optimal filtering and setting of the sensor correction gain.


MEPI/HAM Isolation Achieved 18Mar2003 compared to Average Isolation Requirement

AVG is based onT010074-03, Fig. 1 LLO seismic noise fit and T020033-02, sect. 3.2.1.1.1 requirements

[Note: Should include MEPI/HAM ASD, not just attenuation.]

Figure 2.3: PEPI/BSC X-Direction Isolation Performance



2.1.5 "High" Frequency Noise (>4 Hz)

Considerable amplification of ground motion from ~4 Hz to ~25 Hz (up to a factor ~40) is apparent in both the HAM and BSC isolation responses. In fact this amplification is observed in the BSC crossbeams with the currently installed PEPI structures (with the PEPI system open loop), as shown in the appendix. Apparently this amplification is due to the dynamics of the piers and crossbeams. If one considers the transfer function of the passive isolation stack and the LOS pendulum, the amplification of ground noise above 4 Hz does not appear to be significant. This is addressed further in the form of revised, or alternative, requirements in the appendix of this document. As a minimum some allowance seems appropriate for amplification of ground noise above the control bandwidth. As noted in the appendix, this amplification of the ground noise does not add to the rms motion of the optics significantly. None of the EPI systems seem superior with regard to this evaluation factor.

2.1.6 Suspension Vertical Bounce Modes (~15 Hz)

It would be helpful if the EPI system could reduce the ground motion at the vertical bounce frequency of the suspensions (since this vertical bounce motion then couples into cavity length due to wedge angles (transmission) and non-vertical reflective surfaces). The Large Optics Suspensions (LOS) have bounce modes at ~12 Hz, while the Small Optics Suspensions (SOS) have bounce modes at ~15 Hz (steel wires) and ~19 Hz (Mo wire). The PEPI system has no actuation in the vertical direction. One can imagine that a resonant gain stages in the feedback controller, for either HEPI or MEPI, might be able to afford some noise reduction at these bounce mode frequencies. This seems possible for MEPI on the HAM where the upper unity gain points in the vertical mode is ~30 Hz (check this). HEPI should likewise be able to get a high upper unity gain in the vertical mode. [To date this has not been tried on either HEPI or MEPI, either by simulation or by test.]

2.1.7 Transients

Transient noise events can cause the interferometer to break lock. All testing and modeling to date has been on quasi-stationary ground noise. This is clearly the usual condition even during periods of elevated noise (such as when the train passes at LLO). However, sudden sharp transitions in ground velocity may not be as well attenuated as the steady-state performance. [Can we make relative/qualitative statements about the systems on the basis of maximum slew rate?]

2.2 Form, Fit, Function

Mechanical interferences, thermal control, electronics packaging, etc. all seem to be within acceptable limits for all of the EPI systems on all of the platforms. This does not appear to be a discriminator.

2.3 Contamination

Neither the PEPI not the MEPI systems present contamination risks to the LIGO Ultra-High Vacuum (UHV) systems. The hydraulic fluid used in the HEPI system presents a small risk of contamination:

- Exposure tests[7] in the LIGO high irradiance optical exposure cavities, of the hydraulic fluid used in the LASTI prototype, indicates no observable effect on optical absorption (0.2 +/- 0.4 ppm/year compared to a requirement of < 2 ppm/year) or optical scattering (-8 +/- 2 ppm/year compared to a requirement of <10 ppm/year).
- There have been no leaks in the system after about 3 months of operation.
- We have replaced one servo-control valve in situ with no problems or fluid contamination.
- The fluid used is a clear, water soluble, non-toxic, non-flamable fluid with bio and corrosion inhibitors. No biological growth has been observed after 18 weeks of exposure to air and after seeding. Lubricity is adequate according to the manufacturer and there isn't evidence of any problems after running for ? months.
- The HEPI application is low pressure (< 100 psi) and all fittings are face sealed o-rings or hermetic (with the possible exception of some isolation valves which can be double sealed).
- The design of the pump station controller has incorporated monitoring of a fluid level sensors which can be used to trigger a shut down in the event of loss of a small amount of fluid
- The pump station can be enclosed in an outer box with air exchange to the outside environment if concern about integrated exposure of possible small leaks over long periods remains; We do not think that this is needed.

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[7] LIGO-T030023-00

2.4 Environmental Disturbances

2.4.1 Magnetic Field and RFI

The RFI and EM field emissions by the control electronics and power supplies common to all the EPI systems are not any more significant than other LIGO control electronics now in the high bay (Vacuum Equipment Area (VEA) spaces). However the MEPI system presents a potential hazard for (i) elevated magnetic fields leaking from the electro-magnetic actuator and (ii) possibly increased RFI emissions (radiated and conducted) due to the (likely) need for a switching supply for the 10A coil drivers. Analytical modeling[8] on the basis of measurements on the radiated magnetic field coupling to the test mass magnets indicate that shielding would be required to ensure that the effect of magnetic field coupling to the test masses is well below the Science Requirements Document (SRD) performance requirements. The shielding would require a 2.5 mm thick inner steel box surrounding by a thin mu-metal foil. This magnetic shielding has not been designed or built to date, but does not present any significant problems.

The 10A coil drivers are sized for peak advanced LIGO needs. For initial LIGO, the ETMs in the X-direction only, would require about 3A continuously (at the peak range of the tide). The vertical direction should need only about 1A peak under normal operating conditions. If one considers the power supply used in the tidal servo (HP6267B; 40 volt, 10A) or similar HP units, they require about 5U of rack space and cost a few $1K. These supplies almost universally use a circuit called a pre-regulator. The pre-regulator uses a thyristor or scr to chop the input AC waveform to limit the power dissipation on the series pass transistor bank, thus improving the efficiency and size of internal elements in the supply. The "chopping" may rival a switching supply so far as dV/dT, and dI/dT, which might be a problem for RF emission. Perhaps it is best to consider putting the supplies (or at least the supply for the ETM horizontal actuators) far away from the loads (e.g. in the mechanical rooms) and running cables to the chambers. At ay rate this is not an insurmountable problem.

2.4.2 Acoustic and Seismic Noise

The acoustic and seismic noise generated by the control electronics and power supplies common to all the EPI systems are not any more significant than other LIGO control electronics now in the high bay (Vacuum Equipment Area (VEA) spaces). The HEPI system requires a hydraulic fluid pump stations (one for every two chambers in the current design) which would reside in the mechanical room slab. The motor and pump rotate at ? rpm. Both the motor and pump are balanced and have some mechanical isolation from the slab. These are small, but additional, noise sources added to the mechanical room. No measurements on the floor induced motion from the prototype pump station have been made to date. [...or did Ken Mailand do this at CIT?]

2.5 Reliability

This reliability assessment is based upon engineering judgment and no data on mean between failure (MTBF) or for repair (MTBR). The MTBF for the electronics should be about the same for all EPI systems and not significantly different than for other LIGO control electronics.

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[8] LIGO-T030072-00

- The MEPI actuator is over-rated for its application and should run cool[9] and does not present a significant repair/replacement risk.
- The position sensors of both the MEPI and HEPI systems (Kaman eddy current transducer) are fragile and represent a risk for initial installation. However, once installed should not represent an increased risk for failure or repair.
- The PEPI system does not have any low MTBF/MTBR components either. Although piezo-electric actuators are sensitive to lateral loads and so there is a risk of failure during installation or coarse re-alignment, we have had no failures to date in LIGO.
- The HEPI actuator though a complex system has no parts which should fail or wear, with the exception of the servo-control valve. One unit had an intermittent failure after relatively few test hours on the LASTI BSC system (the flapper apparently went into a flutter oscillation; cause still as yet unknown). Replacement with a new unit (approx. $700 hardware cost) was done in about 1 hour.
- The HEPI pump station should have long mean time between servicing/inspection and possible replacement of filters (order of 4 to 12 months). Pump and motor life should be years. Although the pump station represents an added complexity, as compared to the MEPI power supply, the reduction in system reliability should be small.

2.6 Robustness

2.6.1 Control

2.6.1.1 Position Sensor Correction

All of the isolation provided by the HEPI system, except for the additional isolation afforded by resonant gain stages at the two lower BSC stack modes, is obtained from sensor correction (feed forward, inertial correction to the position sensor used in position feedback control). All of the low frequency isolation (lower than the blending frequency of the position and geophone sensors, or ~1 Hz) on the MEPI system is due to sensor correction. The same is true for the PEPI system. The sensor correction control concept common to all EPIs is to use a sensitive, low noise, low frequency response seismometer (the Streikhausen STS-2) mounted on the slab "near" the chambers. Mechanical interaction from the actuators to the seismometer has not been observed in the thick slab at LLO with PEPI and can be controlled at LASTI (with a much thinner slab) by appropriate placement of the seismometer. Mechanical interaction of one chamber with the next chamber (through reaction forces/torques in the slab) has not been tested or analyzed to date, but is not likely to be a problem.

Although there is some evidence in the HEPI/BSC testing that the optimal sensor correction gain may not be stationary, this has not been confirmed and is hard to understand, if real. One would expect that baring aging of the sensors, the transfer functions from the ground motion to seismometer, and from the ground motion to the position sensor response, should be quite stable on any of the EPI platforms. The variation might be due to changes in the directionality (or mode of coupling) of ground noise sources in the LASTI environment. If real, based on rather limited

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[9] LIGO-T030072-00

experience to date, this effect might limit broad band isolation performance (0.1 to 3 Hz) to a factor of about 5 instead of 10, or better, if sensor correction gain was not adaptively re-tuned.

The sensor correction concept relies upon good correlation between the seismometer and the displacement sensor; The correlated frequency range is typically from < 0.1 Hz to ~3 Hz (and occasionally higher at LASTI) for the HEPI/BSC system.

Since we plan to use the PEM STS-2 seismometers as feedforward sensors to the EPI systems, we will not have independent PEM seismometer sensors, unless additional units are purchased (at $14K each).

2.6.1.2 Velocity Feedback Control

In order to extend the control bandwidth, geophones were designed into the EPI systems collocated, and co-axial with, the actuators. These geophones are intended for use in inertial velocity feedback to the actuators.

2.6.1.2.1 HEPI on the BSC Platform

With the high Q pier resonance at about 23 Hz and the bellows breathing mode resonance (in the hydraulic actuator) at about 30 Hz (Figure x), it is not practical to get any significant control authority by feeding back the geophone signal to the hydraulic actuator.

How has HEPI achieved resonant gain at the stack modes? With the geophones in feedback or the positions sensors, or a blending?

Figure X: HEPI/BSC Actuator to Horizontal Geophone Transfer Function

2.6.1.2.2 HEPI on the HAM Platform

Simulation results are pending. We expect a much better behaved plant since the quasi-rigid body modes will be much higher (out of the control band) and they will be well damped (passively) by the HEPI actuator. The bellows breathing mode resonance at 30 Hz will still be a limitation.

2.6.1.2.3 MEPI on the BSC Platform

Simulation results are pending. We expect that the pier resonance will be less of a problem for the MEPI system than for the HEPI system. The pier resonance will couple to the geophones through the offload springs, but no longer through the actuator. The actuator reaction mass will be much less at the pier resonance, but it should still be possible to invert the response and push the bandwidth above the pier resonance.

2.6.1.2.4 MEPI on the HAM Platform

Modal control of the MEPI/HAM system at LASTI has been successful after stiffening the HAM crossbeams with the addition of the stiffening beam. The control objective (in response to the requirements as posited in T020033-02) has been broadband control with > 10 Hz upper unity gain and significant gain in the 1 to 3 Hz band. To this is added resonant gain stages at the two lower HAM stack modes (1.7 Hz and ? Hz). In order to achieve this control with the quasi-rigid body modes (from 3.0 to 9.3 Hz by modal survey[10] prior to the stiffening beam attachment), it has been necessary to implement partial plant inversion to recover phase; By partial plant inversion we mean

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[10] LIGO-G030187-00

not a precise inversion of the phase loss for in-line resonance, but rather a broad gain and phase bump (with a zero-pole pair) which very approximately recovers the phase loss and should be fairly robust to shifts in the precise frequency or narrowness of the transfer function features. Either 2nd order notch filters and/or elliptic low pass filters are used to suppress the 'forest' of high Q modes just beyond the upper unity gain point. The resulting control laws, for each of the eight global modes, typically employ ~8 pole-zero pairs for loop shaping, ~3 pole-zero pairs for partial plant inversion, ~3 second order resonant gain stages for stack mode suppression or high Q, high frequency support structure suppression and a second order elliptic filter. Although plant inversion is generally to be avoided because it is not robust to plant variation, in the LIGO application the plant should not change - at all; The entire system is in a temperature controlled environment, the payload is not varying, the alignment is not varying - it is as stable a plant as one might imagine. The bottom line is that the control is not overly complex and should be robust.

2.6.2 Alignment (angular and translational)

There is no requirement for active (dynamic or DC) alignment (angular or positional) other than tidal correction (which is covered above). However there is a "goal" of +/- 1 mm range to (i) permit month long continuous locking and (ii) (presumably) to allow for translation of an optic (optics table) to effect an intentional de-centering of the beam (either vertically or horizontally) with the intent of finding the optimal position with respect to minimizing sensing noise, and (iii) (presumably) to correct aperture clipping in the optical port relay optic chains within the vaccum system. Only the HEPI system can achieve the goal of +/- 1 mm of positional range.

Since de-centering on the test mass optics can be accomplished by 'walking the beam' in the input optics section with suspension system controllers, the need for de-centering capability in the seismic isolation system is not significant.

2.6.3 Passive performance

In the event of a failure of the active controls, the EPI systems behave differently. The HEPI system provides significant passive damping (?% or Q?) to the rigid body modes of the support structure, which are created by the addition of the offload springs. The PEPI system provides a similarly stiff connection between the support structure and the pier. In contrast, when uncontrolled, the MEPI system has quasi-rigid body modes (six modes between 3.0 to 9.3 Hz) and elastic bending/torsion modes (9 modes from 9.9 to 20 Hz) which amplify the ground motion. It is not clear that this graceful degradation to a state of approximately "no worse than not present" when uncontrolled merits much value, but it is a comforting feature in the HEPI and PEPI systems.

2.6.4 Earthquake Response

No analysis has been performed to determine the effect of any of the systems in an earthquake. This is not a significant factor for the LLO location, but would be if the EPI systems are fielded in the LHO facility.

2.7 Compatibility with Advanced LIGO

The PEPI system is not in accord with the advanced LIGO design, which calls for a 6 degree of freedom pre-isolator system. Both the MEPI and HEPI systems are compatible with the advanced LIGO system as presently designed.

2.8 Applicability to LHO Wind Noise

The applicability of the EPI systems to the wind induced seismic noise at LHO has not been studied; This is a significant open issue. The current (technically unsupported) planning baseline is to move the four PEPI systems at LLO to LHO, when either HEPI or MEPI are installed at LLO. To these four PEPI systems we would add the sensor and electronics systems required to complement the four Fine Actuation Systems (FAS) currently on the ETMs at LHO, resulting in PEPI systems on all test mass chambers for the two LHO interferometers. It is unclear at this time if pre-isolation systems are required on the HAM chambers at LHO.

Recently it has been observed[11] that the control signals in MICH and PRC are completely dominated by the 12 Hz LOS vertical bounce modes, at the level of 1000 counts p-p during 20 mph winds. If the vertical bounce modes require isolation then PEPI systems will not be sufficient. Furthermore, as indicated in section 2.1.6, the capability of the HEPI and MEPI system to effect significant isolation at the vertical bounce modes is as yet unproven.

2.9 Cost

The costs for the systems are roughly:

- \$125K/chamber for a PEPI system (with GS-13 geophones). The cost of the PEPI system could be reduced from it's current implementation (with GS-13 geophones borrowed from the advanced LIGO effort) by use of L4-C geophones, which would bring the total down to \$98K/chamber.
- \$130K/chamber for a MEPI system, and
- \$235K/chamber for a HEPI system.

These costs do not include:

- any structural modifications (stiffening or damping) which might be required (or desired) on the seismic support structures (and are presumed to be common to any EPI system).
- Seismic isolation of the ISC tables with optical readouts, which are likely to be required to prevent fringe wrapping. This might be accomplished with commercial-off-the-shelf units such as TMC's Statis system (at ~\$35K per table for a set of three - should check this estimate)
- There is no contingency in the above estimates and a healthy (often 30%) reduction in unit costs over the prototype unit costs have been assumed for production

2.10 Extensibility

The requirements were motivated by the coincidence of what seems achievable and a vibration level which does not currently limit interferometer noise performance. However, we have not yet achieved the design noise floor of the LIGO interferometers. As the interferometer improves, we may yet reveal a nonlinear coupling which up-converts the at low frequency residual motion into in-band noise. Consequently it would be good to know if there are ways to extend the performance of the EPI systems in the future.

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[11] N. Mavalvala, LHO elog, 15 Apr 2003.

HEPI could be augmented with a reaction mass actuator mounted on the crossbeam with higher frequency control authority to complement the low frequency (sensor correction) compensation by the hydraulic actuator. One could also add optical levers to sense the bending modes of the crossbeams and use this to correct the tilt coupling to the geophones. Low frequency performance is not likely to be significantly improved over the current performance.

MEPI low frequency performance is also not likely to be significantly improved over the current performance. Stiffening

3 Summary

The state of the evaluation of the HEPI and MEPI systems against each of the factors described above is summarized in the table below. In summary PEPI does not quite meet performance requirements, nor does it allow for future extensibility and improvement. Both HEPI/BSC and MEPI/HAM will meet requirements.[12] However further simulation and testing is needed to be absolutely sure that either system will perform on either the BSC or HAM chamber. Given the large cost differential between the HEPI and MEPI systems, I recommend that the following steps be taken:

1) Complete the simulation of the performance of a MEPI system on a BSC plant to verify assumptions that the MEPI/BSC system will meet requirements,
2) Move the MEPI system from the HAM to the BSC at the LASTI facility and verify the performance by test,
3) Order all long lead items common to HEPI and MEPI designs,
4) Migrate the control from dSpace to VME compatible hardware (in parallel with continued prototyping in the dSpace environment)

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[12] Will meet requirements with allowance for amplification of ground noise, at the support structure, in the 4 to 40 Hz region, when accompanied by attenuation at the vertical bounce mode of the suspension systems. As indicated in the appendix this does not significantly effect the total rms motion.

Table: Summary Evaluation of HEPI and MEPI

	HEPI		MEPI		PEPI	
	BSC	**HAM**	**BSC**	**HAM**	**BSC**	**HAM**
Isolation Performance						
drift	OK	OK	OK	OK	OK	OK
tidal	OK	OK	OK	OK	OK	OK
microseismic	OK	OK	OK	OK	OK	OK
stack modes (1 - 3+ Hz)	>15 iso	TBD	TBD	>15 iso	~7 iso	?
vertical bounce mode (~15Hz)	TBD	TBD	TBD	TBD	No	No
low noise at high freq (>10 Hz)	housing & crossbeam modes damped?	housing & crossbeam modes damped?	housing, RB & crossbeam modes amplify	housing, RB & crossbeam modes amplify	crossbeam modes amplify	crossbeam modes amplify
Transient	?	?	?	?	?	?
Form, Fit, Function	OK	OK	OK	OK	OK	?
Contamination	low risk	low risk	none	none	none	none
Environmental Disturbance						
Magnetic Field	NA	NA	need mu-shield	need mu-shield	none	none
RFI	OK	OK	remote PS?	remote PS?	OK	OK
Acoustic, seismic	minimal, pump in mech rm	minimal, pump in mech rm	none	none	none	none
Reliability	lower	lower	higher	higher	highest	highest
Control Robustness						
Control	OK < 3Hz complex > 3Hz	best	don't know yet	OK	OK	?
alignment	OK	OK	OK	OK	OK	?
passive performance	OK	OK	poor	poor	OK	OK
Earthquake response **Note: not a factor for LLO**	?	?	?	?	?	?
Comaptibility with Adv. LIGO	OK	OK	OK	OK	No	No
Applicability LHO Wind Noise	?	?	?	?	?	?
Cost	1.8x	1.8x	1x	1x	0.8x	0.8x

4 Appendix: Revised Isolation Requirements

The isolation requirements in LIGO-T020033-02 (section 3.2.1.1.1) are stated in terms of absolute displacement noise performance at the support structure. These requirements do not take into account the amplification of the noise by the passive isolation stack. A better, or at least alternate set of requirements, which allows for meeting performance objectives by reducing support structure vibration at the stack resonances is needed. Furthermore, since our testing is performed in the noisy Cambridge environment (LASTI) we need requirements stated in terms of gain limited isolation performance.

Recently it was pointed out that the presence of the pier and support structure dynamics causes an amplification of the ground noise in the ~10 to ~50 Hz range, as shown in Figure 4.1. This additional noise is common to any EPI system and cannot be significantly reduced (the upper unit gain point for MEPI is about 30 Hz).

If a fit to the crossbeam ground noise is then multiplied by the BSC stack transfer function and the horizontal transfer function of the LOS, the velocity amplitude spectral density shown in Figure 4.2 results, for the horizontal (optical axis) motion of an LOS mounted on the BSC optics table without the benefit of any pre-isolation. It is apparent from figure 4.2 that the largest contributions to the rms motion of the optic along the optical axis is from the microseismic peak at ~0.15 Hz and the first two stack resonances (at 1.2 Hz and 2.1 Hz), even when one includes the amplified ground noise due to the presence of the support structure. Using the locked interferometer control signals to infer the relative motion of the ITM and ETM (Figure 4.3) one reaches a similar conclusion. However, from this measurement one observes that (i) there is a large contribution from a ~0.75 Hz mode (LOS yaw?), (ii) there is a much larger relative contribution to the total rms from the stack modes at 2.1 Hz and ~7.5 Hz.

[More work needed here to complete a crisp restatement of the requirement for the X-direction and to state a requirement for the Z-direction.]

Figure 4.1: Ground Noise Amplification at the BSC Crossbeam

In this graph, ground noise measured by the STS-2 located in the PEM area (near ITMY) is compared with vibration seen by a crossbeam-mounted GS-13 on the ITMX BSC SEI frame. The two signals track well, with good coherence, below about 2 Hz (apart from a slight calibration difference that I have not yet resolved). Above 2 Hz, though, the crossbeam moves a lot more, showing the resonant peaks in the external SEI structure, and without much coherence with the slab motion in the same direction. PEPI is off for this measurement. (LLO 20Dec2002 elog)

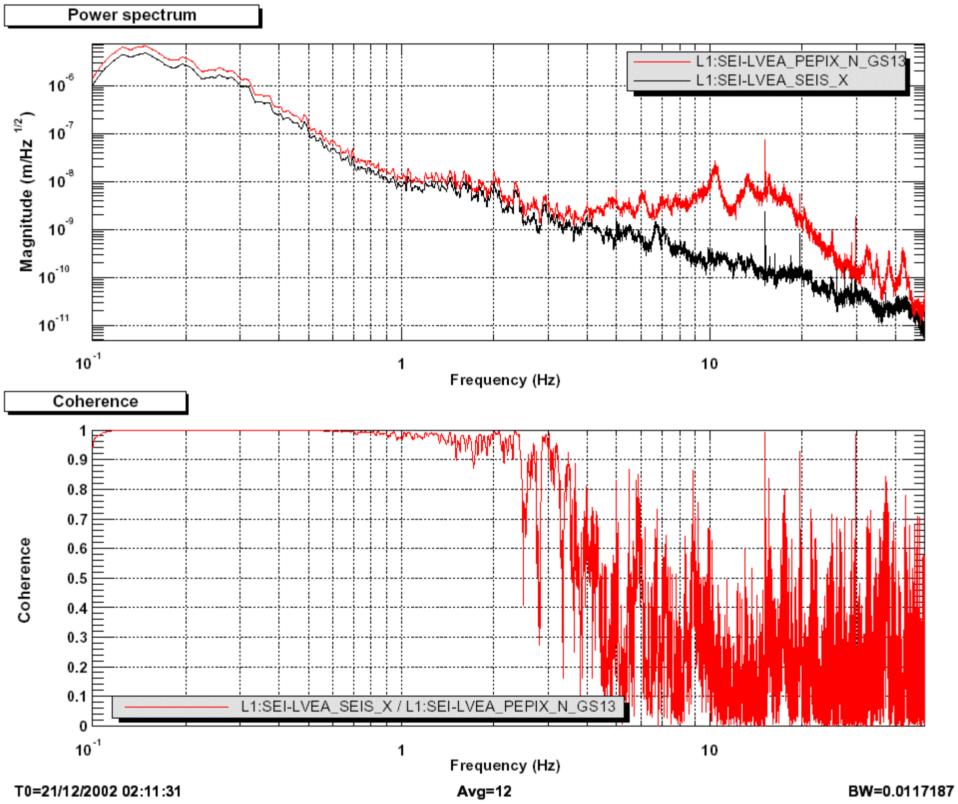

Figure 4.2: Predicted Velocity ASD for an LOS Optic on a BSC optics table
(Using a fit to the crossbeam vibration spectrum, the BSC stack transfer function and the LOS transfer function)

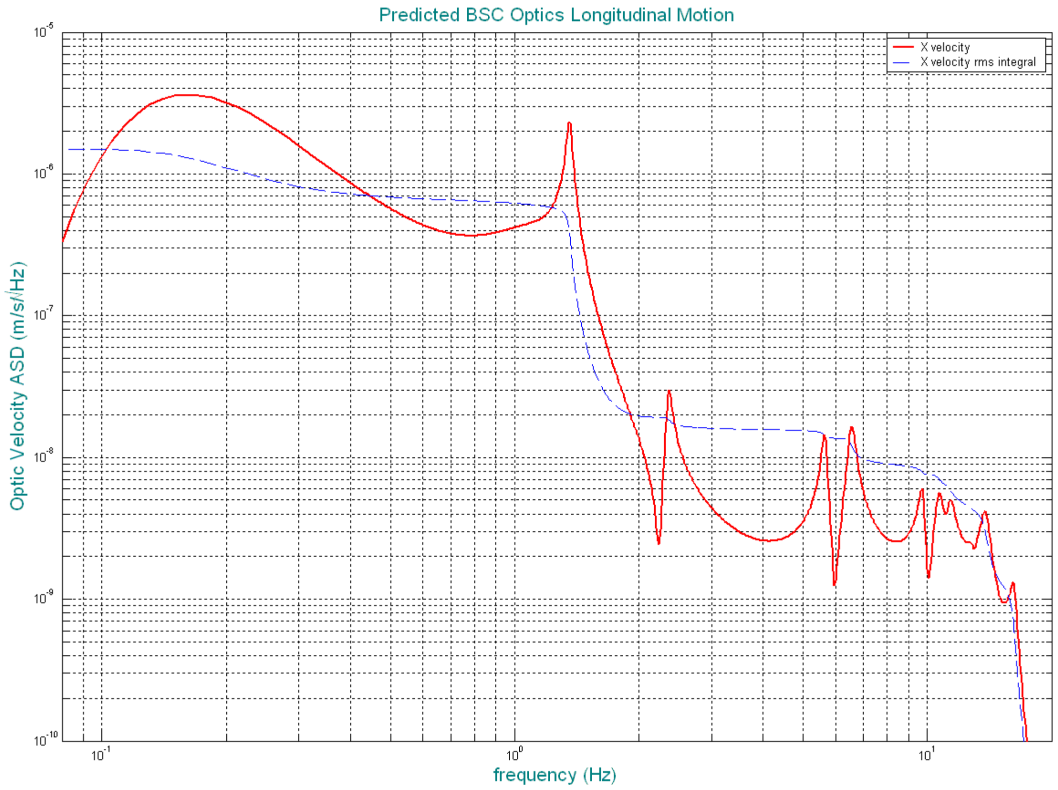

Figure 4.3: Velocity between ITM and ETM inferred from locked control signals