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Transfer function and drift measurements on the first-article HAM

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1 ABSTRACT

The transfer function and the long-term dimensional stability of the HAM first article seismic isolation stack were measured.

2 KEYWORDS

HAM, stack, vibration isolation, transfer functions

3 OVERVIEW

The seismic vibration stacks for LIGO were designed by Hytec Inc. of Los Alamos, NM, in conjunction with LIGO. There are two rather different designs, to suit the BSC and HAM vacuum chambers. First article testing of the two designs commenced in April 1998, in parallel at Hytec and Hanford. This document addresses only the HAM stack, which was installed in a HAM in a spare corner of the LVEA at Hanford. The scope of the tests was to confirm that the stack performed sufficiently well that the design could be put into construction. A fuller characterization will be done by the PEM group at a later time. Transfer function measurements using both shakers and natural seismic motion were performed to check that the performance of the stack matched the analytical model that had been used to design it. Concurrently, the long term drift performance of the stack was measured.

4 TRANSFER FUNCTION MEASUREMENTS

4.1. Overview

This section describes the transfer function measurements using shakers as input.

4.2. Details of system tested

Due to schedule and cost constraints, the system actually tested was not entirely identical to a production version. The following minor differences should be kept in mind when interpreting the results:

- The piers supporting the system were not grouted (to avoid having to remove the grout later, a very dusty operation). The bases of the piers were supported at the design height (several inches off the ground) only by nuts on the threaded rod anchoring them in place.
- There were dummy components in place of the vertical actuator and air bearings. (Since the HAM and BSC actuation components were identical, only one first article set was produced and this was tested on the BSC stack at Hytec.)
- The V-blocks attaching the support tubes to the cross beams were clamped 0.5” from the design position on the support tubes because it had been found necessary to place the piers an extra 1” further apart to cope with an interference. The production support tubes will be 1” longer.
- Only two of the four bellows making the seal between the support tubes and the chamber

were in place. (The remaining two were used for vacuum testing.)

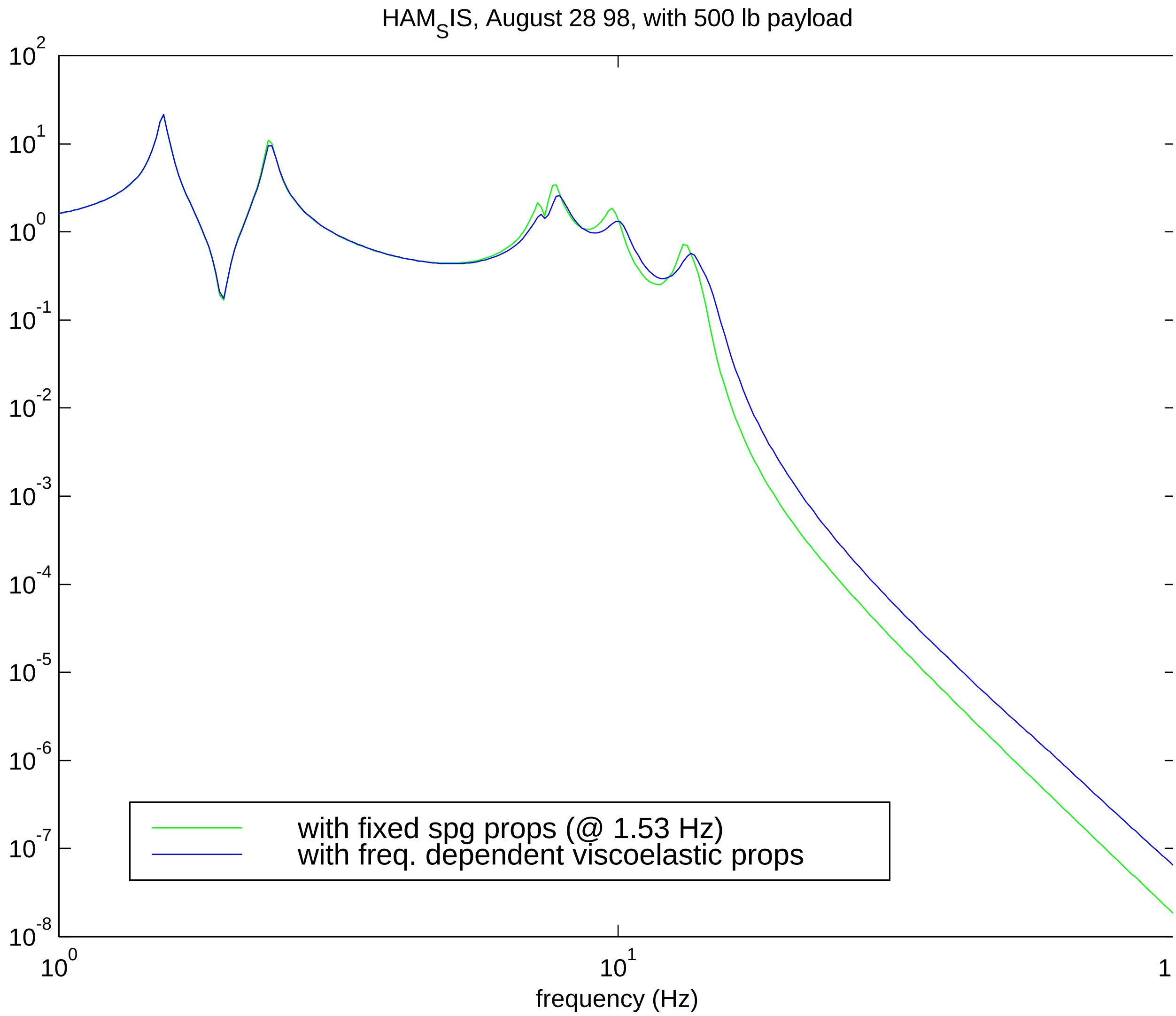
- In consequence, the chamber as a whole was not evacuated for testing.
- The support table had been machined to create a bevel on two of the lower edges to eliminate an interference. The bevel cut into the honeycomb structure and may have reduced the strength.
- The support table was only loosely attached to the support tubes. Due to problems of galling with the TiN-coated stainless bolts, brass bolts were used and these were not very many and only finger-tightened.

The stack was designed to be sufficiently compliant (and the supporting structure to be sufficiently rigid) that there was no overlap (by about a factor of 2) between stack modes and high frequence support modes. The above differences from the production system will mainly affect the modes of the support structure, not the stack itself.

4.3. Analytic model

The model used as a reference ("HAM_SIS") is a subset of a fuller one created by Eric Ponslet of Hytec for use in the design of the stack. The coordinate system used has position coordinates u, v and w, with u transverse to the HAM cylinder axis (the beam direction for most HAMs) and w vertical. The corresponding angle coordinates are α, β, and γ.The full model contains information on the frequency dependence of the elastic constant of the springs, but the subset uses a snapshot of the elasticity matrices at 1.53 Hz. Thus the eigenmodes near 1.53 Hz should be well predicted but there is a slight error at higher frequencies. The extent of the error (minor) can be seen in Fig. 1. The model included the as-assembled distribution of counterweights (used as ballast to keep the stack load constant as detector components are added and removed).

Figure 1:



4.4. Measurement procedure

4.4.1. Overview

The transfer functions were measured from the support table to the optical table. Because nearly all the compliance is in the stack rather than the support structure, this is a satisfactory approximation to the performance of the system as a whole.

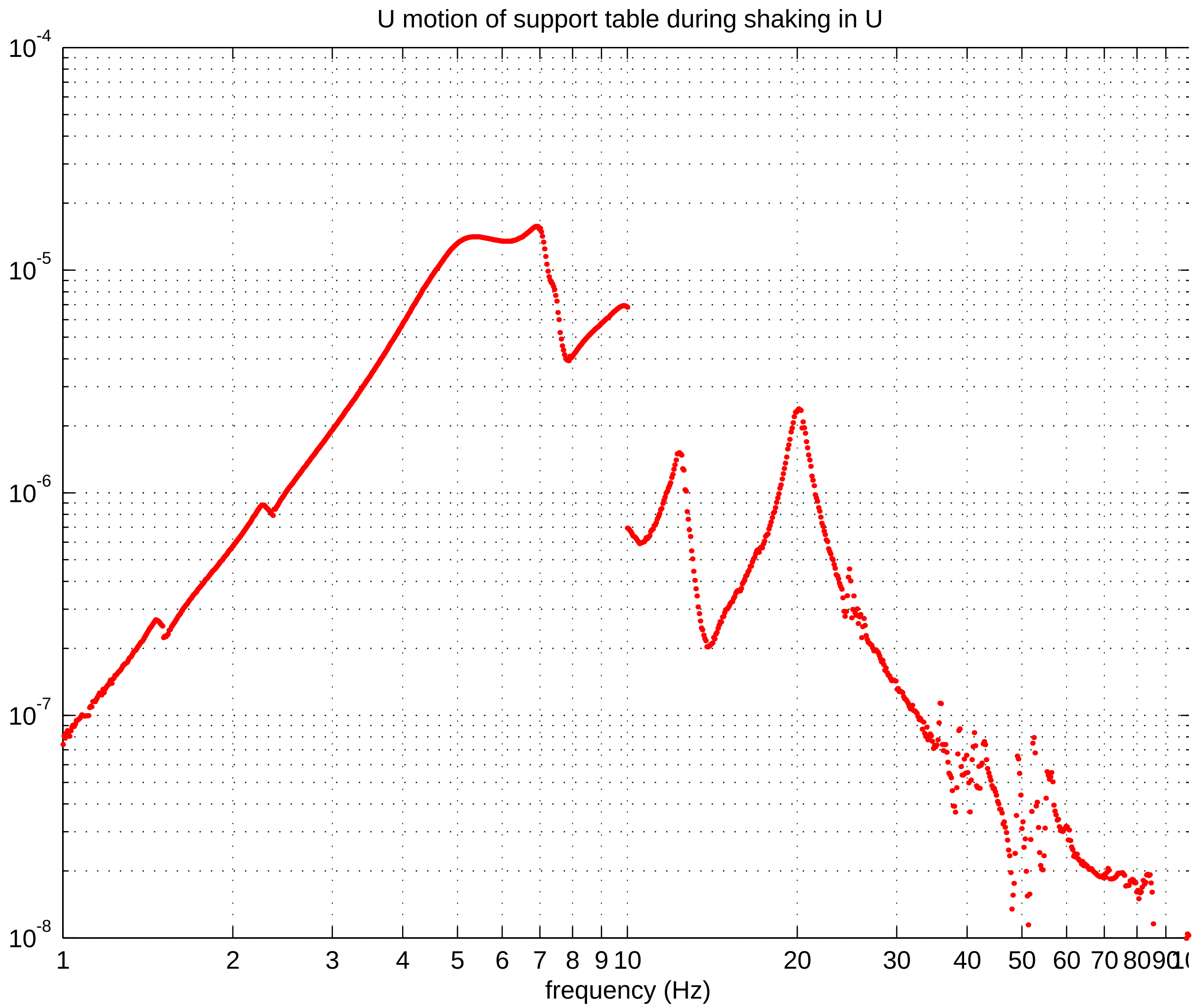
The measurements were done using the swept sine mode of an SRS 785 signal analyzer. Because of the complex geometry of the support structure and the difficulty of adjusting the shakers to give the same force, it could not be assumed that, for the shakers in the “u” configuration, say, that the support table motion was purely in the u direction. Thus the motion of the support and optics tables had to be characterized in all six degrees of freedom. This required multiple runs with the analyzer, which is a two channel instrument. Provided the source auto-level function is not used, the SRS guarantees a stable (if arbitrary) relationship phase relationship between source and input across runs. Thus the source did not need to be monitored but appears as a common factor in all raw data and cancels out in all transfer functions.

4.4.2. Actuation

Actuation was provided by four Bruel and Kjaer 4809 electromagnetic shakers made available by the PEM group. Each shaker was placed in a frame and coupled to an 8.3 kg reaction mass. With a little reconfiguration, the shaker could be made to act either horizontally or vertically. The shaker units were attached to the ends of the support tubes, outside the vacuum chamber. By adjusting the phase and orientation of the four shakers the support table could be driven in all six degrees of freedom. The force that could be applied was limited by three factors: (i) the maximum displacement of the shaker (at low frequencies), (ii) the resonance of the reaction mass with the spring of the shaker at 6 Hz and (iii) various high-Q resonances in the support structure which might have overloaded the sensors (especially at 20 Hz). It was found convenient to break the frequency range of interest into two bands, 1-10 Hz and 10-100 Hz, and to use 10 times as much source voltage for the lower band. The resulting amplitudes were comfortably above ground noise at all frequencies from 1 to 100 Hz, except very near 1 Hz (Figure 2).

Figure 2: Typical displacement of the support table induced by the shakers. The source level

was reduced by a factor of 10 above 10 Hz to cope with the support resonance at 20 Hz.



4.4.3. Sensing

The vibration was sensed by a pair of Integrated Dynamics TAS 3000 3-axis geophones, also provided by the PEM group. These are electromagnetic velocity sensors with a bandwidth of 0.08 Hz to 100 Hz with a sensitivity (on the low gain setting, as used) of 1.088×10^4 V/(m/s). The geophones were easily able to detect the motion of the support table up to 100 Hz, and and were able to follow the “wall” in the transfer function as far as around 25 Hz. Because of the steepness of the wall, only enormous increases in sensitivity would have sufficed to track it further.

4.4.4. Procedure

To get angular displacement information, the geophones were placed at the edges of the table, first on the u axis and then on the v axis. For each position, the horizontal displacement transverse to the line joining the sensors, plus the vertical displacement were logged. From these 8 displacement vs frequency curves the six degrees of freedom could be extracted with two redundancies (w and γ). These was done for both support and optic tables for each shaker configuration (“u”, “v”, “w”, “α”, “β”, “γ”). The measurement time for each run was approximately 45 minutes and the total number of runs was 48.

4.4.5. Results

Figures 3-5 show the transfer functions of principal interest: the u->u, v->v and w->w. The tilt of the support table in the “u” and “v” shaker configurations has been corrected for in the u->u and v->v functions (although the correction is barely visible). The rising trend at high frequency is due to the sensors on the optical table reaching their noise floor before those on the support table. Below this, the agreement is generally excellent. All the predicted peaks occur, and nearly all of them are within 10% or better of the predicted frequencies. The biggest discrepancy is the lowest v mode which is about 40% off. The cause of this has not been identified. The vibration isolation is actually about one order of magnitude worse than predicted in the “wall” region for both u and v, but this is not a large error considering the large gradient there. In any case the requirement of 10^{-2} isolation by 40 Hz is comfortably met.

Figure 6 gives the w->γ transfer function. Because the model is perfectly symmetric, the prediction here is identically zero, but this is obviously unrealistic. Since all the springs used were right-handed, there was obviously the possibility of a strong cross-coupling here, and this was observed. Partly as a result of this (but mostly because of long-term yaw drift; see below) it was decided to use a mixture of left and right-handed springs. The w->γ transfer function was repeated towards the end of the measurements after the stack had been reassembled with a different spring clocking procedure in the expectation that the coupling would decrease. Unfortunately a different signal analyser (an HP3563A) had to be used. It turned out to have a higher noise floor so that it was not clear whether there had been any improvement at low frequencies.

Figure 3: Beam-line displacement transfer function

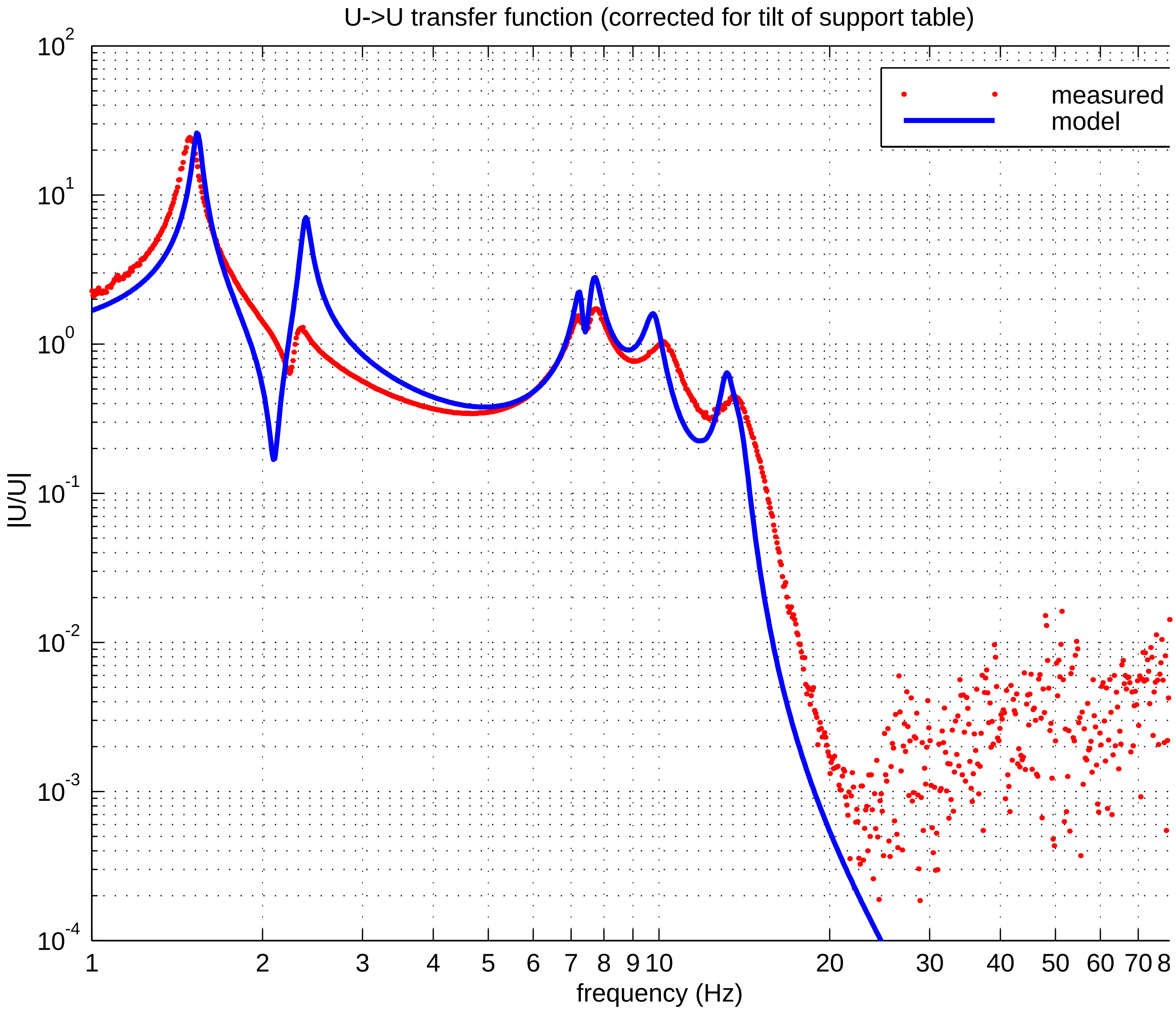


Figure 4: Transverse horizontal transfer function

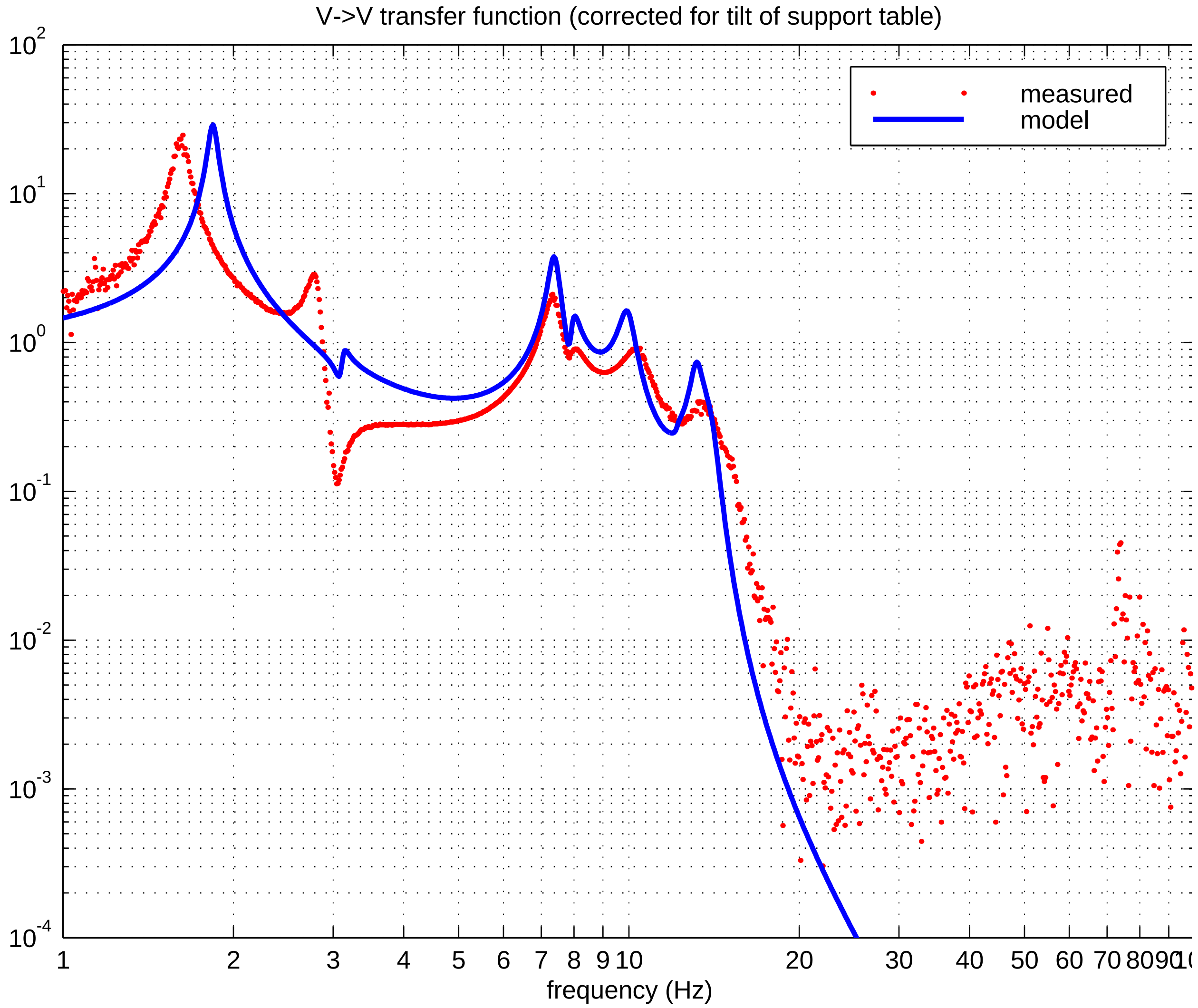


Figure 5: Vertical transfer function

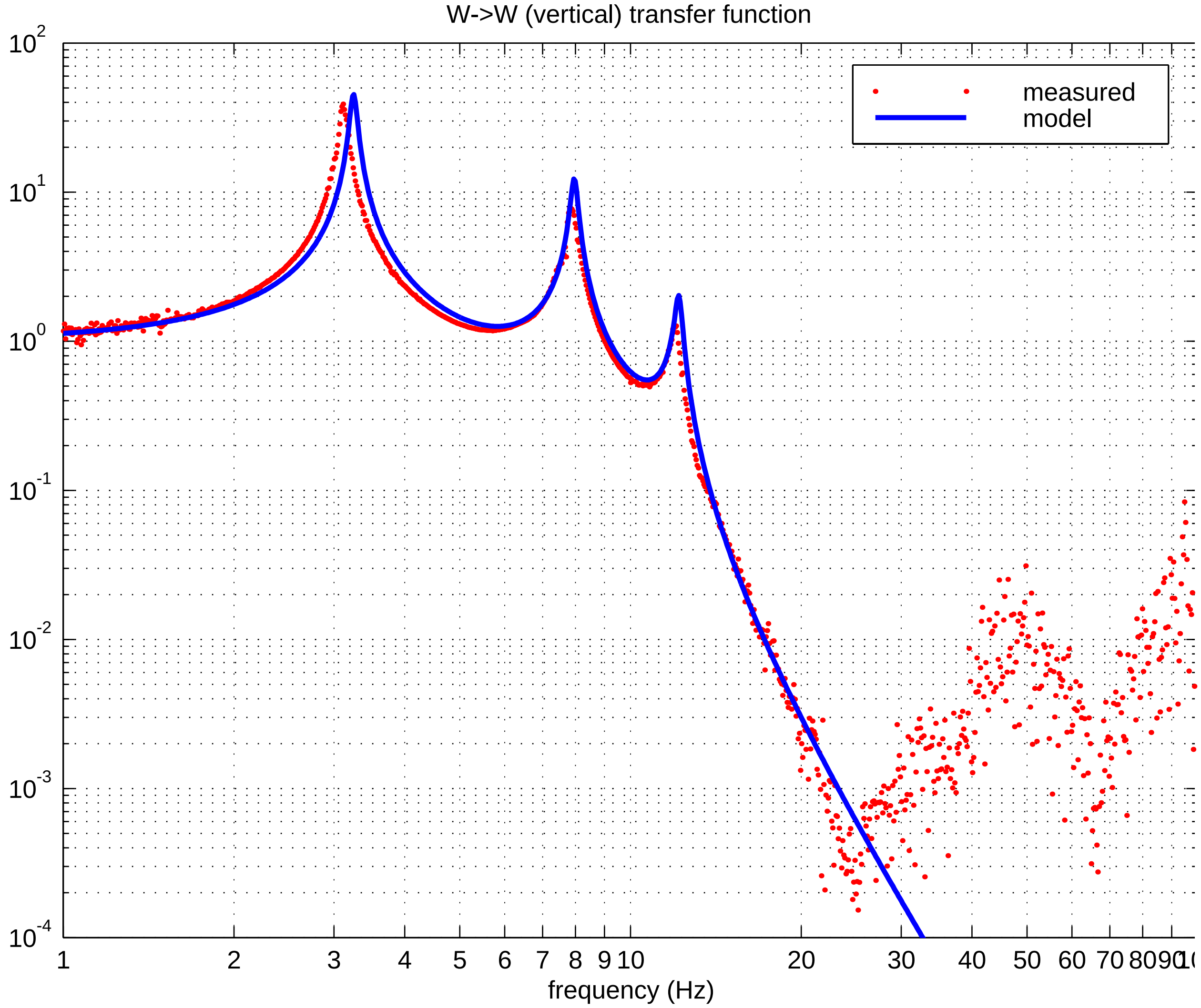
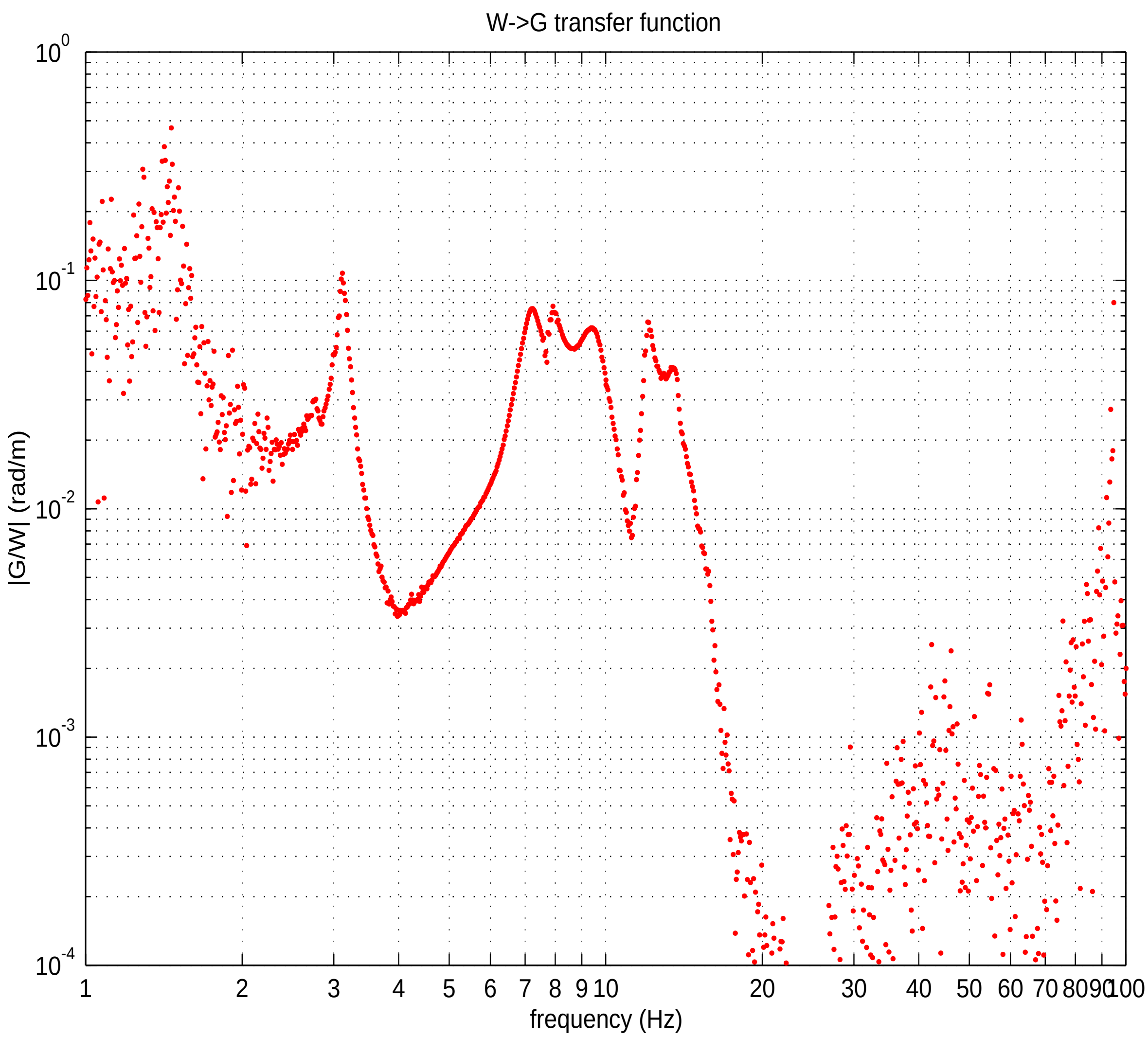


Figure 6: Vertical to yaw transfer function



5 PASSIVE ISOLATION TESTS

5.1. Overview

Although the support structure was not entirely faithful to the production version, it needed to be tested to some extent. Since the above active transfer function measurements bypassed the piers and crossbeams, a second measurement was done using the natural seismic motion of the ground as input. While not especially accurate, this could at least show that there were no catastrophic short-circuits in the vibration isolation. Most of the work in this section was done by Gabriela Gonzalez.

5.2. Sensing

In total 12 channels of data were logged as follows:

1. A 3-axis Guralp low-frequency seismometer on the ground
2. Another Guralp seismometer at the centre of the optic table (2 horizontal channels only)
3. 2 Wilcoxon low-frequency accelerometers oriented vertically at the edges of the table on the v axis (east-west in crane coordinate system).
4. 2 Geophones at the edges of the table along the u axis (north-south in crane coordinate system). 5 channels: 2 vertical, 2 v-direction, 1 u-direction.

Note that the geophones were operated on a gain setting 10 times higher for these measurements.

5.2.1. Results

The power spectra for the three directions, u, v and w are given in Figures 7, 8 and 9 respectively. The horizontal vibration isolation appears to fall short of the target at 40 Hz by about an order of magnitude but this is probably limited by acoustic coupling. Note that there are no peaks in the displacement spectra at the optic table that are not present in either the ground noise or the previously measured transfer functions. This points to acoustic coupling because although the support structure has high-Q resonances that could defeat isolation at specific frequencies, a broad-band amplification of noise is very implausible (However in Figure 9, the limiting factor for the accelerometers is clearly their own noise floor.) The HAM cleanroom air filters were shut down for the measurement but there was still a very high level of ambient noise. In the setup phase when the sensor output was directed to a CRO, audible noises could be seen to correlate with noise in the signal.

Figure 7: Vibration isolation performance in u direction with real seismic input

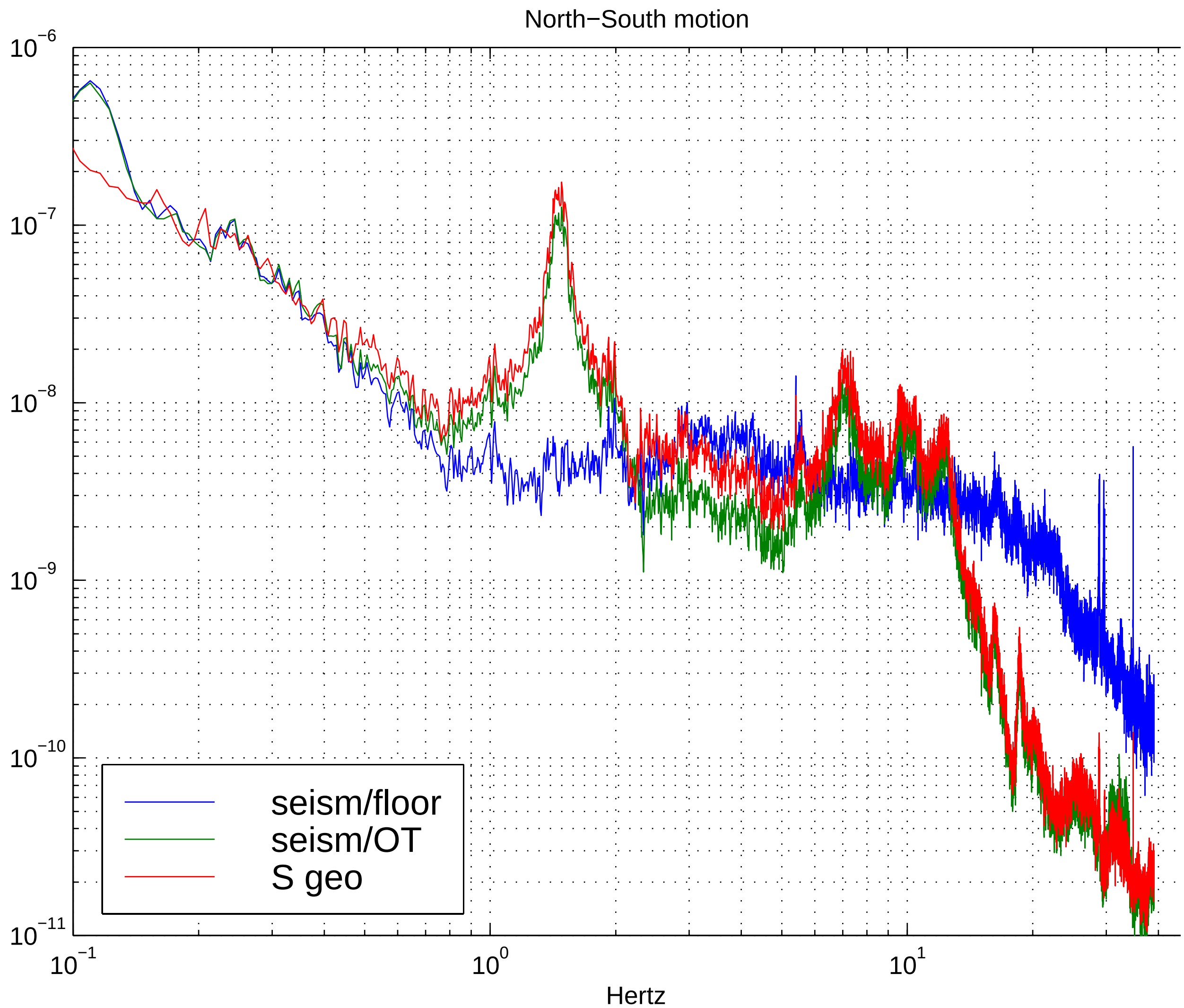


Figure 8: Vibration isolation performance in v direction with real seismic input

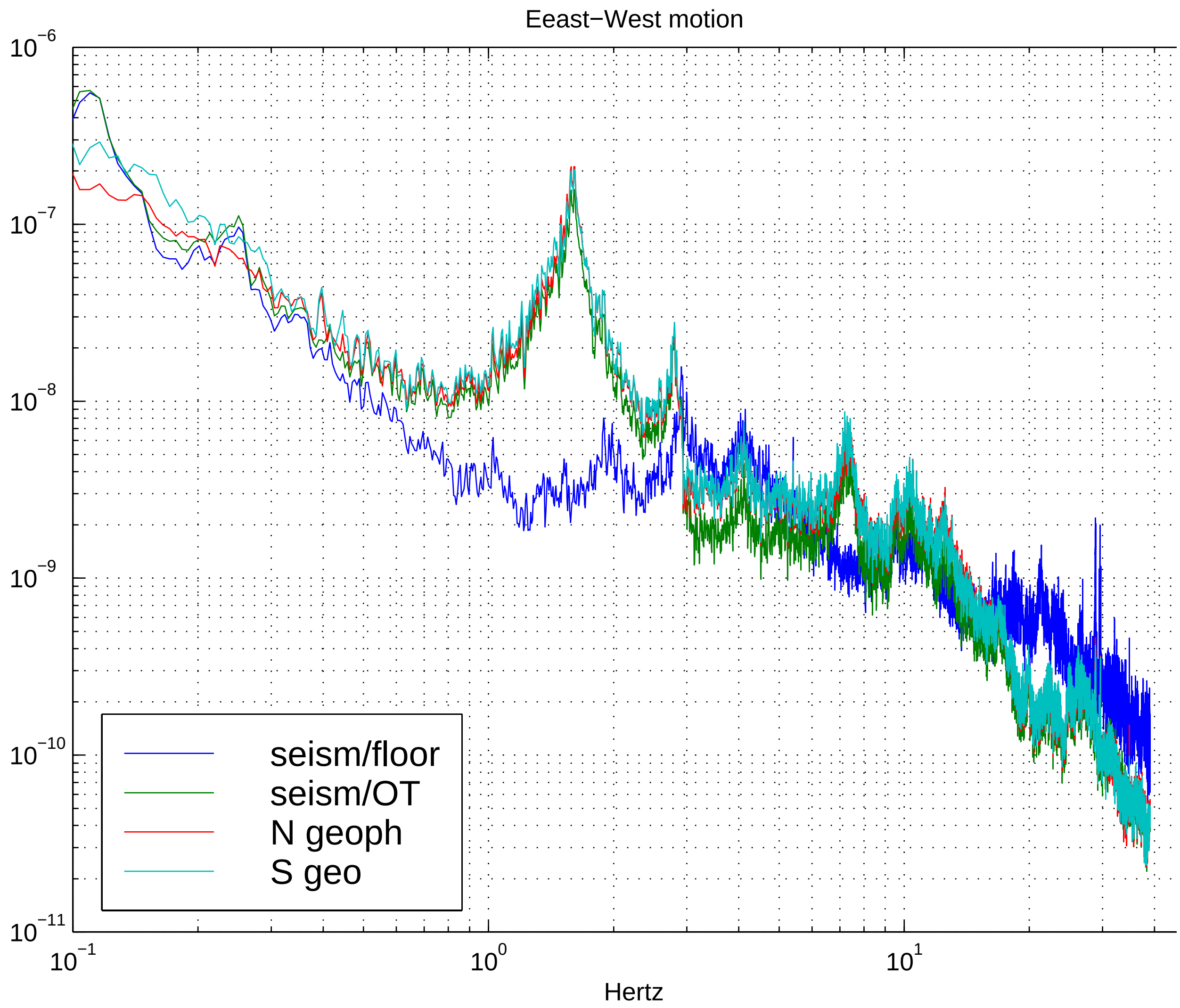
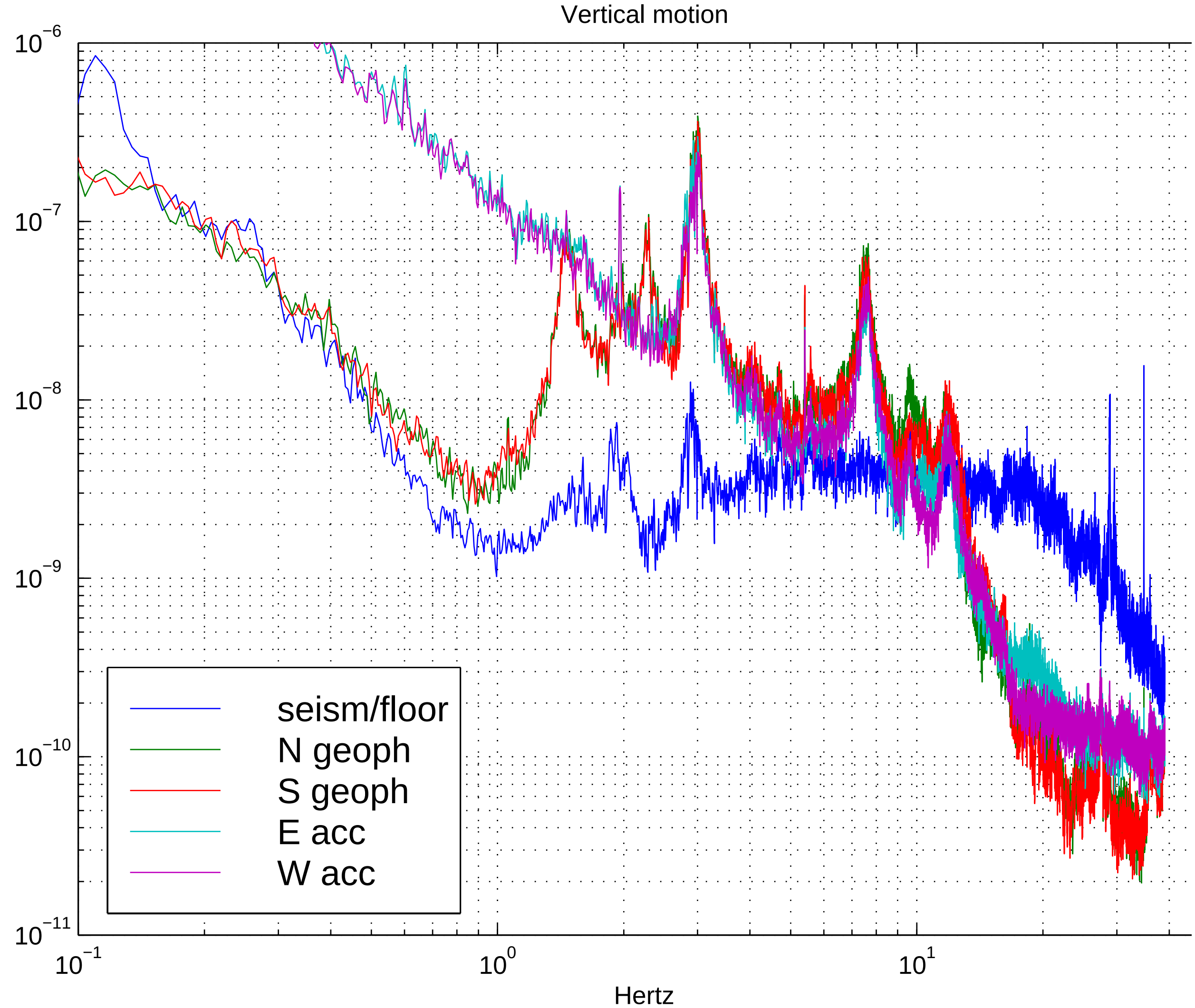


Figure 9: Vibration isolation performance in vertical with real seismic input



6 DRIFT MEASUREMENTS

6.1. Theory and requirements

Elastic elements with approximately anelastic (as opposed to velocity-proportional) damping are prone to long term drift as a consequence of the Kramers-Kronig relations. Drift in the stack is taken up by the mirror actuators in the first instance and actuators powerful enough to accomodate moderately large drift would have unacceptable noise levels.

If a step-function in stress is applied to an ideal anelastic spring, the creep velocity is inversely proportional to time, or equivalently, the strain is logarithmic:

$$x = x_0 + v_0 \ln(t - t_0)$$

Here, the parameter v_0 is dimensionally a position but conceptually a velocity, being numerically equal to the velocity at unit time after the initial step (for any consistent choice of time unit).

The measured drift performance of the MIT stacks was adopted as the requirement for LIGO. The downward drift at day 20 should be less than 50 μm/day (i.e., $v_0/20<50\mu m$). No horizontal requirement was specified.

6.2. Instrumentation

The position of the optic table relative to the support table was measured using eddy current displacement sensors with a range of 1 mm and a precision of around 0.3 μm (Non-contacting sensors were used to allow transfer function measurements to be done simultaneously without interference.) Six sensors were mounted on three brackets clamped to the support table - three in the centre, two at the middle of one edge and one at the middle of an edge at right angles so as to allow all six degrees of freedom to be monitored.

The output of the position sensors and a temperature probe were sampled at 10 Hz by a PC by a PC and 10 s averages were written to disk. A total of 14 days of data were taken, although the later part is degraded by glitches due to moving the geophones used for the transfer function measurements.

6.3. Results

The data was fit to a logarithm by first fitting the successive differences to $v_0/(t-t_0)$. The fit was very good, especially for the degrees of freedom with large displacements, w (vertical) and γ (yaw). The values of $v_0/20$ (i.e., drift per day at day 20) obtained were

u: 0.024 μm
v: 0.24 μm
w: 6.5 μm
α: 0.65 μrad
β: 0.79 μrad
γ: 1.9 μrad

The vertical drift is within the requirement by nearly an order of magnitude. A horizontal requirement had not been set, because previous stacks had not been close to causing a problem. However for the coil-spring stack, the drift in yaw is surprisingly large and could overwhelm the actuators over the first year of operation for optics not positioned centrally.

In retrospect it is clear that this large drift is due to having all right-handed springs. Another manifestation of the problem is that the optical table twisted out of alignment as it was lowered onto the stack during assembly, by approximately the same amount as the twist in drift (0.1 rad/m). It was decided to change to a mixture of left- and right-handed springs.

Supplementary experiments with a number of small test stacks showed that about 2/3 of the twist is due to shear of the springs on compression. This probably arises from a slight difference in compliance between the spring and the Viton rubber seat. The original radially symmetric "clocking" of the springs allowed the shear to accumulate around the circle of springs supporting each element, thus converting it to a twist. A better clocking arrangement can remove this component of the twist but the balance is apparently intrinsic, which vindicates the decision to order the left-handed springs.

7 CONCLUSION

7.1. Hints for people making similar measurements (PEM, Hytec)

1. Signal analysers vary markedly in their effectiveness at swept sine measurements. The SRS785 signal analyser had nearly an order of magnitude lower noise floor than the HP3563A for comparable integration times. This is very important because for swept sine measurements of functions with high-Q peaks near 1 Hz, integration times of more than a cycle or so give prohibitive total measurement times. A commercial system with a very large number of channels could be an alternative.
2. The limiting factor in shaker measurements at low frequencies is interference from ground noise. Therefore the shakers need large reaction masses but the sensors do not have to be especially sensitive there. Sensitivity is the limiting factor at high frequencies. Since the limiting noise source in an inertial sensor tends to be electronic and white, a sensor whose natural output is velocity (a geophone) or acceleration (an accelerometer) rather than a position sensor is indicated, to take advantage of the factor of ω or ω^2.
3. Better results could be obtained (at the expense of a lot more record-keeping) by breaking the total frequency band of interest into more pieces to better work around the shaker (6 Hz) and support structure resonances (20 Hz for the HAM first article). Alternatively one could just tolerate saturation of the sensors there.

7.2. Compliance with requirements

The stack comfortably meets the vertical drift requirement. Although the yaw with all right-handed springs (as designed) is surprisingly high and a potential problem, there is good reason to suppose that this will be completely cured by going to a mix of left- and right-handed springs. Both left-hand spring and matching seats are already being produced.

According to the shaker tests, the stack conforms quite closely to the model that was used to design it and comfortably meets the vibration isolation requirements. There is an inconsistency between these results and the passive measurements which is probably due to acoustic coupling of ambient noise. As a doublecheck, the passive measurements should be repeated in vacuum with a very sensitive accelerometer as soon as an evacuatable HAM becomes available, but there is reason to be confident that the design is sound.

8 REFERENCES

Seismic Isolation Requirements Design Document (LIGO-T960065-03D).