Temperature Increase of the Actuators in the Advanced LIGO seismic isolation system LIGO-T060076-00-R

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1 Introduction

If the actuators in the BSCs in Advanced LIGO gave off enough heat when powered to change the temperature inside the vacuum chamber noticeably, they could cause various problems, such as out gassing of the epoxy used to pot the actuator coils and distortion of material due to thermal gradients. In order to establish whether this issue warranted concern, several thermal sensors were constructed and placed on the Technology Demonstrator in the vacuum chamber of the ETF at Stanford University. One of the actuators was powered on and off while the resulting temperature increase was measured. By relating the temperature increase of the actuator to the recorded drive signal and taking various differences between the proposed Advanced LIGO isolation sytstem and the prototype at Stanford into account, the equilibrium temperature increase for normal ground motion was calculated to be approximately $1.9 \cdot 10^{-6} K$. This would mean the heat given off by the actuators for the isolation system in Advanced LIGO does not warrant concern.

2 Thermal probe setup

The thermal probes used for this experiment consisted of small blocks of aluminum with a Wheatstone bridge glued on top with thermally-conductive epoxy. Three of the resistors in the bridge were fixed while the fourth was a glass bead thermistor [1]. The probes were calibrated to each other and to read out in units approximately equal to degrees Celsius (or Kelvin since only the temperature increase mattered)[2]. Four sensors were used: 1 was attached to the stage 0-1 V1 actuator; 2 was attached to the aluminum post under the actuator; 3 was attached to the stage 0 table; 4 contained four fixed resistors (no thermistor) and was also placed on the stage 0 table. The first three sensors were fixed in

[1] see Appendix 1 Fig. 9 for circuit diagram
[2] see Appendix 2 for details

place with thermally-conductive epoxy. Figure 3 shows the temperature readout from the probes when a finger was placed next to each sensor in succession for several seconds and then from when a finger was placed on each sensor in succession for several seconds.

3 Data Collection and Analysis

In order to try to establish a correlation between the stage 0-1 actuator being powered and an increase in temperature in the chamber, for each run in which temperature data was taken, the isolation loops involving this actuator were switched off at the beginning, turned on for a period of time in the middle, and switched off for a period at the end of the run (the damping loops were kept on throughout the experiment). Initially, the actuator was driven by the control loops to cancel out ground motion (see for example Fig. 4). Since the temperature increase measured on sensor 1 for these levels of power to the actuator was too small to be reliably measured, later runs were performed where the actuator was given a constant drive signal at higher levels than that of typical ground motion. Figure 5 shows that when the actuator was given a DC drive signal for approximately 8 minutes the temperature measured by sensor 1 increased in roughly linear fashion and when the actuator was given no drive signal the temperature began to decrease. During an even longer run (Fig. 7) where the actuator was powered for approximately 70 minutes, the temperature increase measured by sensor 1 was no longer linear, it appeared to approach an equilibrium. Figure 8 shows the temperature of sensor 1 from this run during the period when it was increasing along with a fit of this data to a curve of the form $\Delta T = \Delta T_f(1 - e^{-\alpha t})$. The data was found to be a good fit for $\frac{1}{\alpha} = 1.4 \cdot 10^3 s$ and $\Delta T_f = 3.18 \cdot 10^{-2} K$.
In general, the fluctuations measured by sensor 2 indicated that the temperature of the support column was stable within a few millidegrees, while the fluctuations measured by sensor 3 (attached to stage 0 table) fluctuated 50-100 millidegrees over the course of approximately 15 minutes. The table temperatures do not seem correlated to the drive signal.

4 Estimate of thermal time constant

When the temperature increase with time of the number V1 actuator for stage 0-1 while it was being driven was recorded, the data was found to be a good fit for the curve $\Delta T = \Delta T_f(1 - e^{-\alpha t})$ where $\frac{1}{\alpha} = 1.4 \cdot 10^3 s$. This order of magnitude calculation models the actuator as a thermal resistor and capacitor to establish the reasonableness of this value.

The heat path from the actuator to the thermal probe is taken to be 4 cylindrical steel bolts with length $L = 10cm$ and base area of $A = \pi(0.5cm)^2$. Steel has a thermal conductivity $\lambda = 43Wm^{-1}K^{-1}$ so the thermal resistance of the

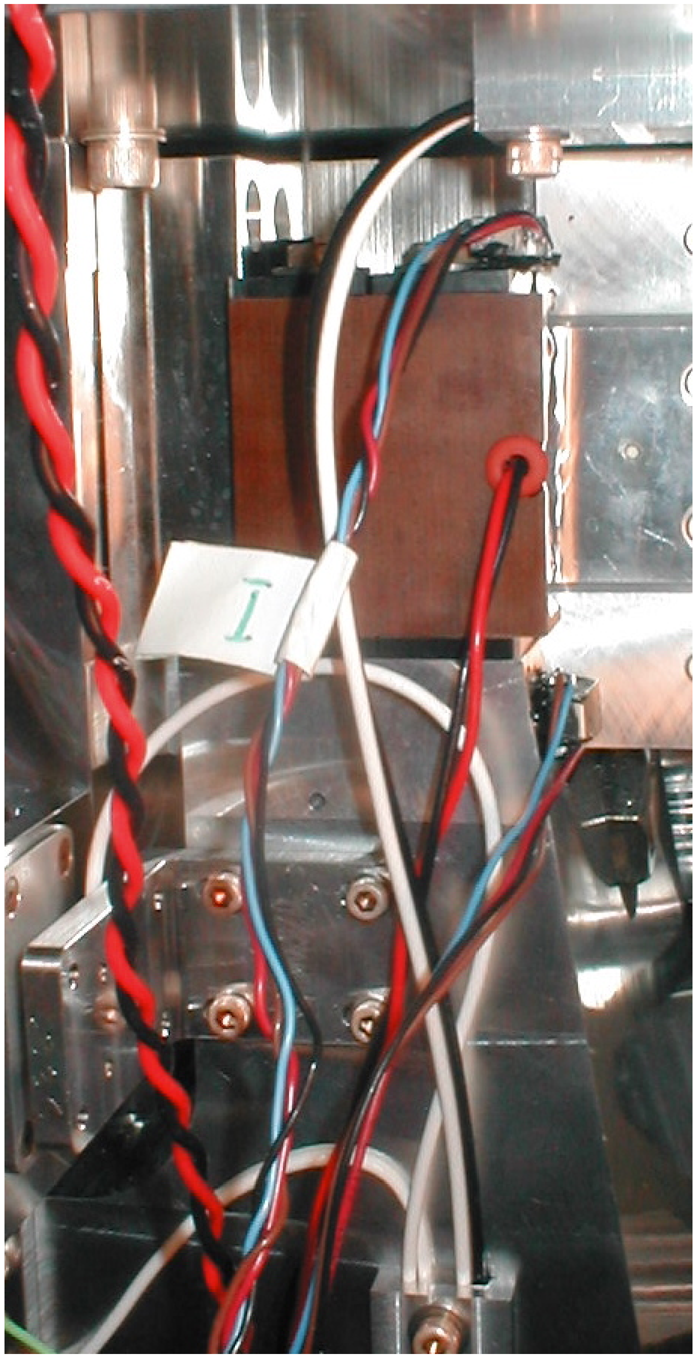

Figure 1: Thermal sensor 1 attached to the stage 0-1 V1 actuator and thermal sensor 2 below.

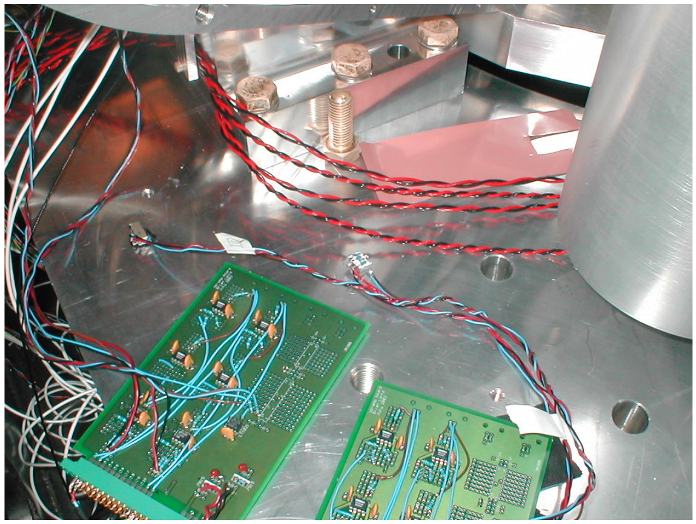

Figure 2: Thermal sensor 3 and 4.

bolts is:

$$R = \frac{L}{4\lambda A} \approx 7KW^{-1}.$$

The heat capacitor for the actuator is taken to be a block of copper with volume $V = 2 \cdot 10^{-4} m^3$. The density of copper is: $\rho = 8920 kgm^{-3}$ and the the heat capacity is $c_p = 380 Jkg^{-1}K^{-1}$. Therefore the thermal capacitance is:

$$C = c_p \rho V \approx 7 \cdot 10^2 JK^{-1}.$$

These two values can be combined to arrive at an estimate for the thermal time constant

$$RC = 5 \cdot 10^3 s,$$

which is the same order of magnitude as the measured time constant.

5 Estimate of expected temperature increase

For an experiment where the V1 actuator for stage 0-1 was given a constant drive signal of $0.06arb$ (units are arbitrary dSpace units proportional to voltage) the temperature increase with time was found to be a close fit to the curve $\Delta T = \Delta T_f(1 - e^{-\alpha t})$ where $\Delta T_f = 3.18 \cdot 10^{-2} K$. Based on the assumption that this equilibrium temperature increase is proportional to the power given

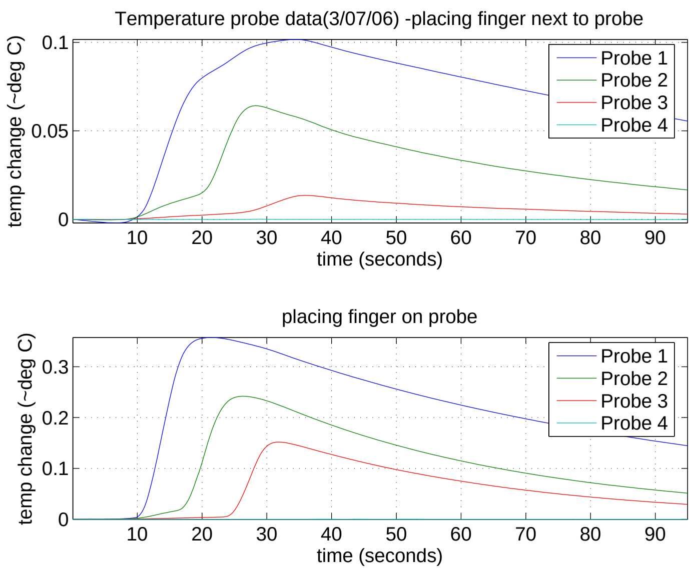

Figure 3: Temperature readout from the probes when a finger was placed next to each sensor in succession for several seconds and then from when a finger was placed on each sensor in succession for several seconds.

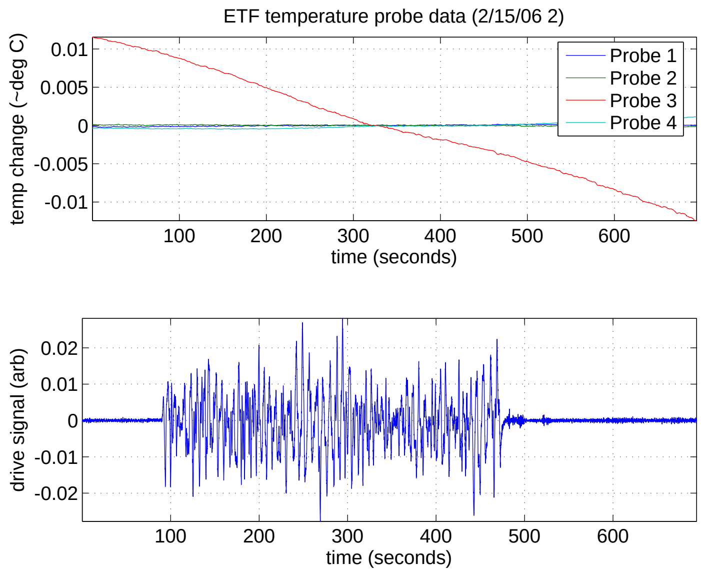

Figure 4: Temperature data from 2/15/06

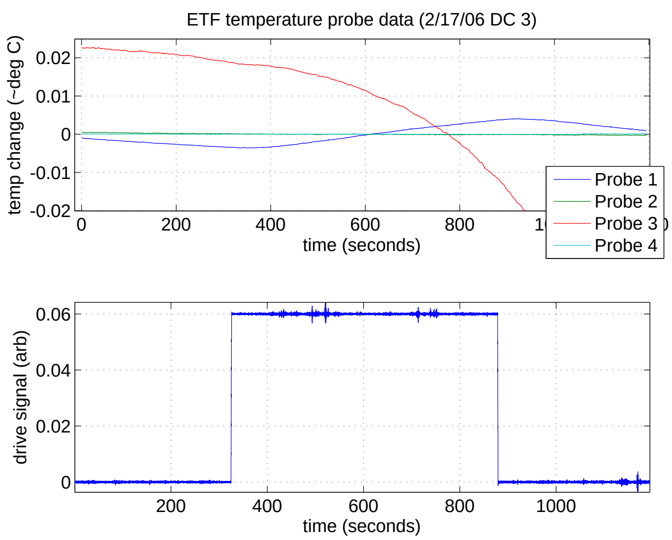

Figure 5: Temperature data from 2/17/06

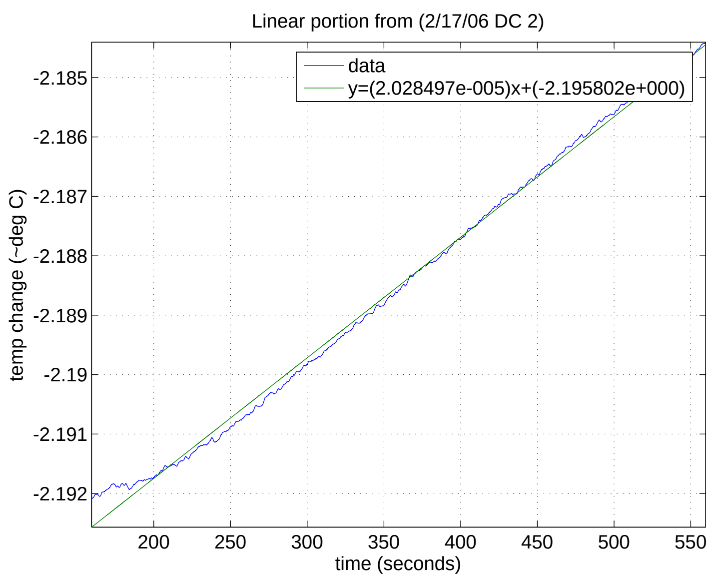

Figure 6: The portion of the sensor 1 data from the previous figure where the temperature is increasing along with a linear fit.

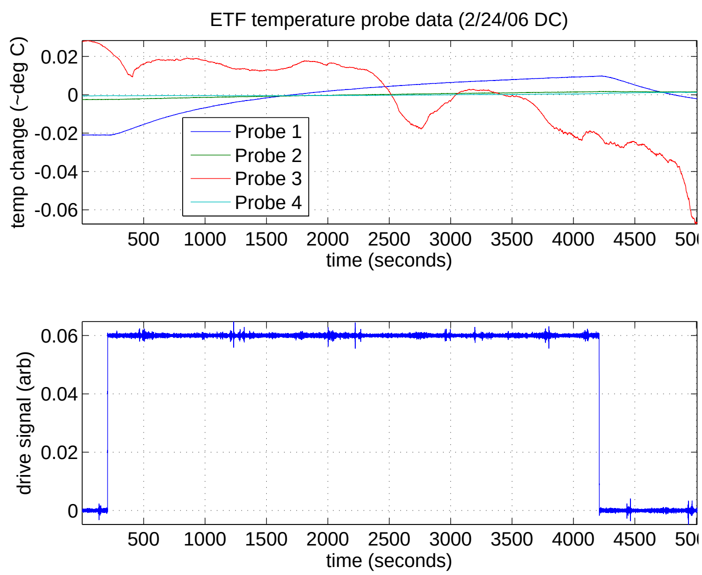

Figure 7: Temperature data from 2/24/06. The temperature rise on probe 1 corresponds to the large DC signal given to the drive. The small fluctuations in the drive signal result from the damping loops, which were left on through the course of the measurement.

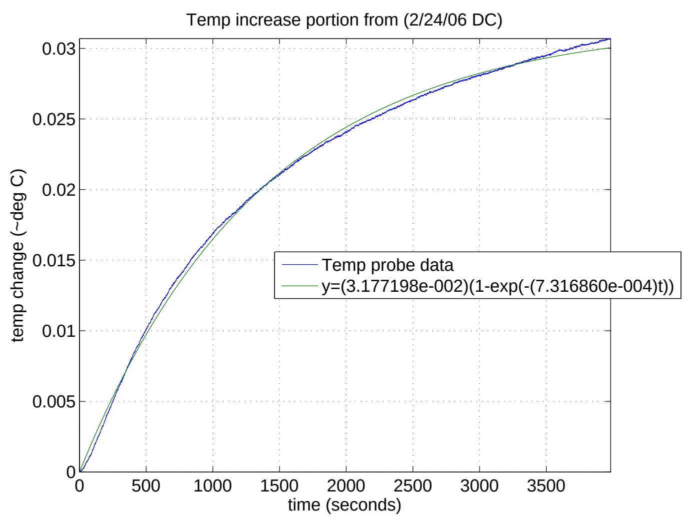

Figure 8: The portion of the sensor 1 data from the previous figure where the temperature is increasing along with a fit to a curve of the form $\Delta T = \Delta T_f(1 - e^{-\alpha t})$. The fit implies that the large DC signal caused a steady state rise of 32 millidegrees.

to the actuator, the temperature increase for Advanced LIGO can be estimated.

Since the power of the actuator is proportional to the square of the drive signal, we expect the ratio of the temperature increase to the average of the drive signal squared to be constant. Based on the numbers from the experiment this value is:

$$r = 8.83 K arb^{-2}.$$

For a typical day a Stanford (the nonzero portion of the drive signal from Fig. 4 was used), the average drive signal squared to the actuator with the isolation loops running was measured to be be approximately $P = 6.62 \cdot 10^{-5} arb^2$. This would give an expected temperature increase of:

$$\Delta T_{stanford} = rP = 5.85 \cdot 10^{-4} K$$

which is consistent with our inability to measure such a temperature rise.

Also, it needs to be taken into account that the spring stiffness of the proposed Advanced LIGO isolation system is smaller than that of the prototype at Stanford. The stage 1 vertical stiffness of the Stanford prototype is $k_1 = 1.98 \cdot 10^6 N m^{-1}$ compared to $k_2 = 6.84 \cdot 10^5 N m^{-1}$ for the proposed system.
In addition, the z-direction ground motion at Stanford is greater than that on top of LLO HEPI. For the run at Stanford where the above average drive signal was measured, the rms ground motion between $0.3 Hz$ and $1 Hz$ was $g_1 = 2.5 \cdot 10^{-7} m$. For LLO HEPI, this value is estimated to be $g_2 = 4.1 \cdot 10^{-8} m$ [3]. Since the power used by the actuator is proportional to the spring constant squared and to the ground motion squared, for Advanced LIGO the estimated temperature increase is:

$$\Delta T = (\frac{k_2}{k_1})^2 (\frac{g_2}{g_1})^2 \Delta T_{stanford} = 1.9 \cdot 10^{-6} K.$$

6 Conclusion

Based on temperature measurements made at the Stanford ETF, the expected temperature increase from the actuators in Advanced LIGO isolation system reacting to normal ground motion was estimated to be $1.9 \cdot 10^{-6} K$. This would mean that heat from the actuators would have negligible impact on the other components within the vacuum chamber.

[3]See Appendix 3

Appendix 1: Temperature Sensor Circuit Diagram

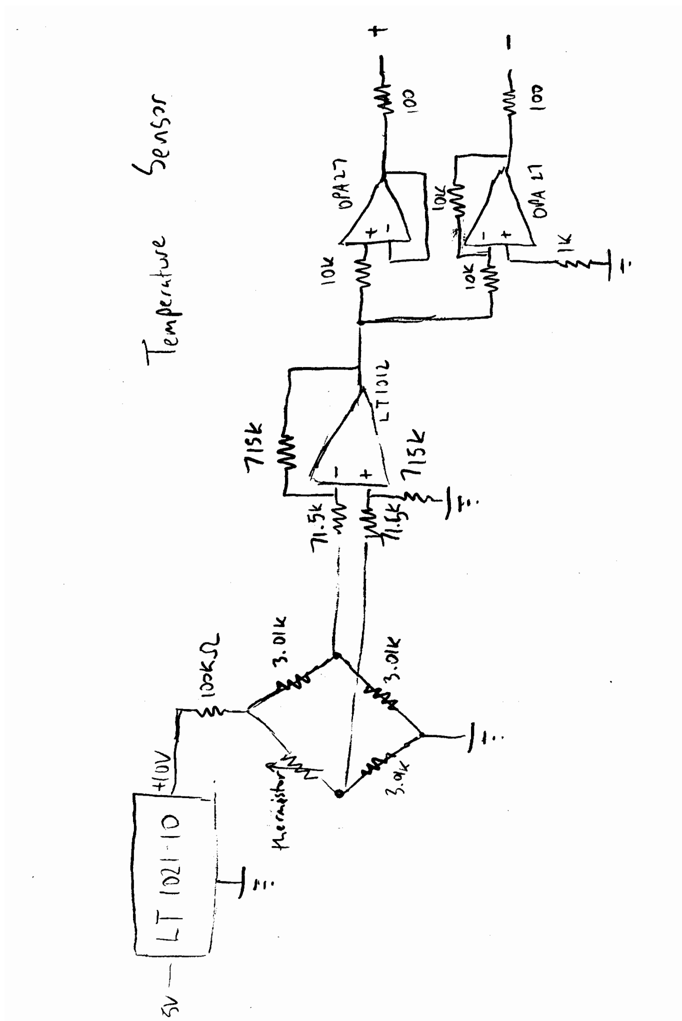

Figure 9: Circuit diagram for the temperature sensors

Appendix 2: Temperature Sensors Calibration

The temperature sensors were calibrated in the following manner. The four probes were covered in thermal grease and clamped to a single piece of aluminum to which a thermometer was also attached. This was placed in an insulated styrofoam box along with a box around with a long, resistive wire had been wrapped. The styrofoam box was closed and current was run through the wire for a short period of time to add heat to the system. The outputs of the probes were monitored until they became constant (i.e. thermal equilibrium had been reached) and then the output voltages of the probes were recorded along with the temperature reading on the thermometer. This was done for several temperatures, and the data was used to linearly fit the output voltages on the temperature sensors to each other, and then to a scale where 0 corresponded to 25 deg C and each unit corresponded to one deg C. The following equations relate the digital signal V (equal to $\frac{1}{10}$ the analog voltage in volts) of the three functioning temperature sensors to temperature T on this scale.

$$T = -4.1325V_I - 1.5791$$

$$T = -4.3782V_{II} - 1.3447$$

$$T = -4.3702V_{III} - 1.47319$$

Appendix 3: Estimate of Ground Motion

For the run at Stanford, the frequency response of the seismometer (in meters) was inverted and multiplied with a band pass filter from 0.3 to 10 Hz to obtain the filter in Figure 10 This filtered ground motion in the z-direction from the

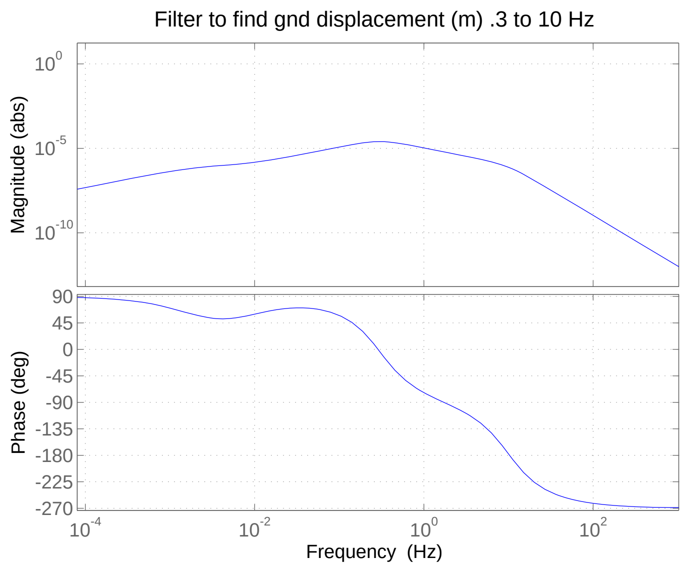

Figure 10: Bode plot of the filter used to find the ground motion in the z direction between 0.3 and 10 Hz

2/15/06 run was then squared and the average calculated and square-rooted to obtain $2.5 \cdot 10^{-7}m$.

For the LLO HEPI ground motion value, the model displayed in Figure 11 for z ground motion versus frequency was used. Using these values, the ground motion was reverse integrated from 10 Hz to 0.3 Hz to obtain the $4.1 \cdot 10^{-8}m$ value.

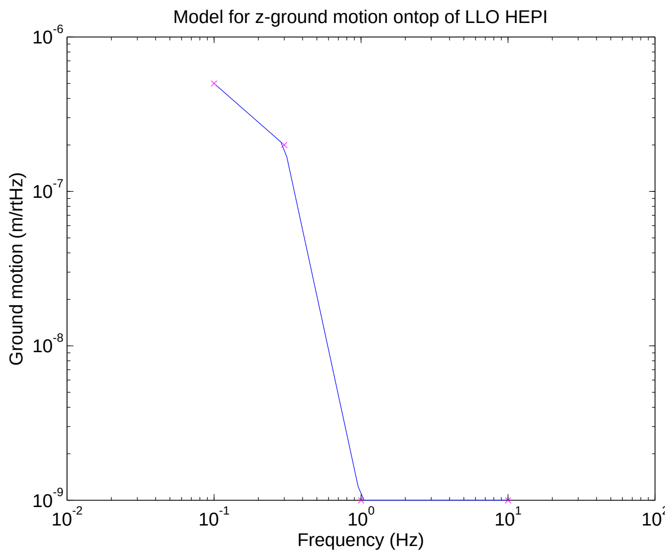

Figure 11: Plot of estimated values for the ground motion in the z direction on top of LLO HEPI for different frequencies.