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Calibration of the LIGO detectors for S2

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Abstract

We describe the methods used to calibrate the LIGO interferometer responses for the S2 run. An analysis of uncertainties in the calibration is also presented. These uncertainties are summarized in Table 5.

1 Introduction

The second LIGO Scientific Run, S2, consisted of 62 days of data taking from February 14th 2003 to April 14th 2003. This document is intended as a summary of the techniques used to calibrate the response of the interferometers and an estimate of associated uncertainties. Those readers wishing to skip the details can find a convenient summary in Table 5.

2 Calibration Procedure

We consider the response of the interferometer to an external disturbance (e.g. a gravitational wave) to be that of a simple feedback loop with a gain $\mathrm{G(f)}$ (see Figure 1). This loop can be parameterized by three functions: a “cavity response” or “sensing” function $\mathrm{C(f)}$ which describes the response of the optical cavities, a “Digital Filter” function $\mathrm{D(f)}$ which describes the digital filtering used in the loop and an “Actuation” function $\mathrm{A(f)}$ which describes the mechanical response of the suspended test masses[1]. These functions are related by

$$\mathrm{G(f) = C(f).A(f).D(f).} \tag{1}$$

The strain sensitivity of the interferometer at a time $\mathrm{t_0}$, $\mathrm{h(f, t_0)}$ is related to $\mathrm{AS\_Q}$ by:

$$\mathrm{h(f, t_0)} = \left[\frac{\mathrm{1 + G(f, t_0)}}{\mathrm{C(f, t_0)}}\right] \mathrm{AS\_Q(f, t_0)} \tag{2}$$

or:

$$\mathrm{h(f, t_0) = R(f, t_0) AS\_Q(f, t_0).} \tag{3}$$

We call $\mathrm{R(f, t_0)}$ the response function for the interferometer. In practice we can obtain direct measurements of all of the above functions with the exception of the sensing function $\mathrm{C(f, t_0)}$. This function depends on the optical gain of the arm cavities and is very sensitive to fluctuations in the alignment. We use Equation 1 to find $\mathrm{C(f, t_0)}$ from our measurements of $\mathrm{G(f, t_0)}$, $\mathrm{A(f, t_0)}$ and $\mathrm{D(f, t_0)}$.

We assume that the time evolution of the interferometer calibration manifests itself as a linear change in the optical gain of the instrument $i.e.$ $\mathrm{C(f, t)} = \alpha\mathrm{(t)C(f, t_0)}$, and an occasional change in the digital gain tracked by a parameter $\beta(t)$ such that $\mathrm{D(f, t)} = \beta\mathrm{(t)D(f, t_0)}$. During S2 $\beta(t)$ changes on the L1 interferometer were caused by occasional changes in the Input Matrix. These changes were tracked by the CONLOG[2] tool. At H1 there were several different epochs with

[1] This is a change of notation from that used in reference [1]

[2] Written and maintained by P. Shawhan.

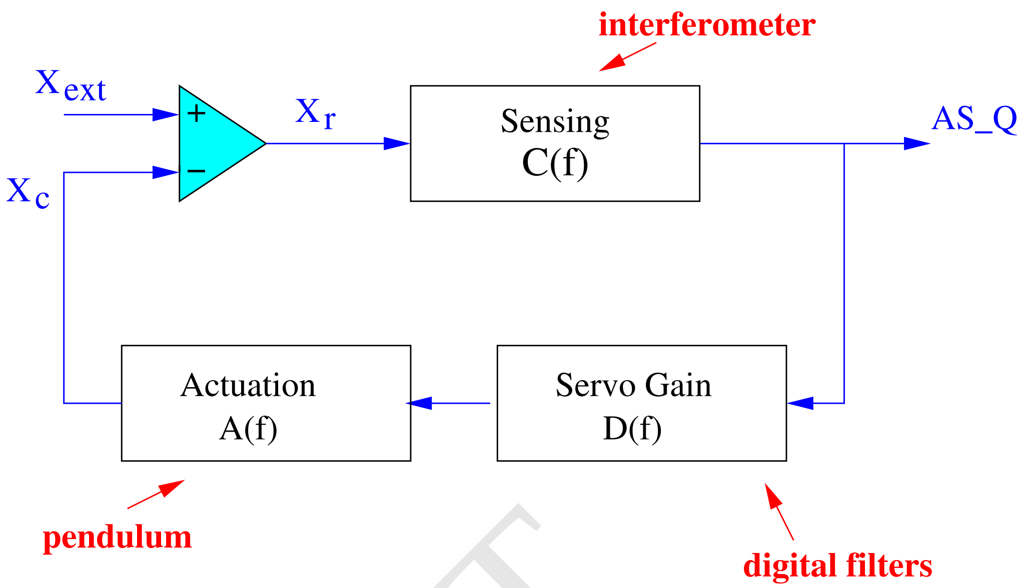

Figure 1: Block diagram of the interferometer

different $\beta(t)$ corresponding to different H1:LSC-DARM_GAIN values. For more information on α and β behaviour during S2 see reference [2]. For any given time the strain response is given by:

$$h(f,t) = \left[\frac{1+\alpha(t)\beta(t)G(f,t_0)}{\alpha(t)C(f,t_0)}\right] AS\_Q(f,t) \tag{4}$$

and so,

$$R(f,t) = \left[\frac{1+\alpha(t)\beta(t)G(f,t_0)}{\alpha(t)C(f,t_0)}\right]. \tag{5}$$

The variation in the optical gain is measured by applying sinusoidal excitations (calibration lines) to one of the end test masses and monitoring its amplitude as a function of time. This approach has been shown to yield consistent results when propagating between calibration functions which were determined at different times.

In order to obtain the S2 reference functions and α factors, we followed the following procedure:

- Measure the open loop gain function $G(f,t_0)$ at a chosen 'reference time'.
- Measure the DC gain of the test mass actuation functions and construct $A(f,t_0)$ assuming a simple pendulum response.
- A combination of measurements of the electronics and known digital filter parameters is used to construct $D(f,t_0)$.
- The unity gain frequency measured in the first step is used in a MATLAB model [3], to find $C(f,t_0)$ ($= G(f,t_0)/A(f,t_0)D(f,t_0)$) at the time of the measurement.

[3] Written by R. Adhikari and P.Fritschel. The main MATLAB script, and the parameter files used for each interferometer are attached at Appendices to this document.

- Values of $\alpha(t_0)$ and $\beta(t_0)$ are obtained from **SenseMonitor** [3] and determine the normalization for $\alpha(t)$ and $\beta(t)$.
- The response at any given time, $\mathrm{R(f,t)}$, can be calculated from equation 5. The quantities $\alpha(t)$ and $\beta(t)$ are obtained from **SenseMonitor**.

2.1 The Open Loop Gain G

The open loop function is measured by injecting a swept sine excitation into the loop at the IFO:LSC-DARM_EXC point and recording the ratio IFO:LSC-DARM_IN1/IFO:LSC-DARM_IN2. The measurement is taken with the instrument set for normal data taking (but not in Science mode).

2.2 The Actuation Function A

The frequency dependent response of the end test masses (ETMs) to an excitation is the most time consuming and, at least at Livingston, the largest source of uncertainty in the calibration process. Most of the measurement techniques rely on a determination of the actuation functions of the input test masses (ITMs) and propagating these measurements to the ETMs using a single arm lock. The procedure can be summarized as follows:

- Obtain the relationship between counts in AS_Q to meters of displacement of an ITM by either:
  - Measuring the peak to peak excursions of AS_Q with an unlocked Michelson. Then $\mathrm{AS\_Q(counts/meter)} = 2\pi \mathrm{AS\_Q_{p2p}}/\lambda$, so the wavelength of the laser calibrates AS_Q.
  - Perform a swept sine excitation of an ITM with a locked Michelson and measure the AS_Q response. This calibrates the ITM response in meters.

  or,

  - Use the sign toggling or fringe fitting techniques described in reference [4]. These techniques were used on the Hanford interferometers during S2 and resulted in a better determination of the actuation function.
- Lock a single arm and measure the transfer function of both the ITM and the ETM w.r.t. AS_I (the single-arm error signal). A ratio of the transfer functions then gives the ETM response relative to the previously measured ITM response.

There are problems with the methods for calibrating the ITM response. The first technique assumes that the response of the ITM is well described by a simple pendulum. In practice (probably due to a poor understanding of the electronic actuation path) this is not true and the extrapolation of the high frequency response to DC reflects this. This technique does have the advantage of measuring the response in the frequency range where the instruments are most sensitive. The techniques described in [4] have the disadvantage of measuring the response at or close to DC while the response we really care about is at higher frequencies. Care must be taken that the extrapolation from DC to AC is done properly.

The DC actuation function measurements are summarized in Table 1.

IFO	ETMX (nm/ct)	ETMY (nm/ct)
L1	0.40	0.37
H1	0.72	0.83
H2	0.87	0.92

Table 1: Summary of measurements of the DC values of the actuation functions for all three interferometers.

2.3 Calibration using the Fine Actuator Piezo-electric Transducers

The LIGO seismic isolation (SEI) subsystem provides for actuation along the interferometer beamline allowing correction of the tidal strain due to the Moon and Sun. These strains far exceed the suspension optic control range. Keeping the suspension positioning and damping loops at their optimal operating point allows sustained locking through tidal cycles as well as providing the best noise performance operation.

The SEI Fine Actuators are stainless steel weldments positioned atop the SEI piers between the Coarse Actuation System (CAS) Scissor Table and the CAS Airbearing Assembly (See Figure 2. The CAS were designed to provide offline movement of the SEI platform for long term drift compensation. The weldment consists of a bottom frame which is essentially attached to the ground and a top frame to which the CAS Airbearing Assembly (horizontal motion stage), CrossBeam, Support Tube and eventually the in-vacuum optic suspension are attached. The top frame is connected to the Bottom Frame by a mechanical flexure which effectively limits displacement to a single axis. Displacement between the frames is controlled by a linear piezo-electric device with strain gauge closed-loop control.

The fine actuator piezo-electric transducers (PZTs) have ¡1.5μm relative error comparing any two units. The Physik Instrumente provided performance sheets show that they mantain this accuracy except when nearing the limit of their +-90μm range. Because four PZTs work in unison to effect the desired movement (one on each SEI Pier), adverse yawing of the optical table is not expected.

Each Fine Actuator is equiped with a +-100μm range dial indicator (DI) with 1μm unit resolution. With care the DI can be read to +-1/4μm. The controller was stepped through its full range while reading the DI at each step. The average of the four DI readings less the requested displacement (+-5Volts/+-90μm) are plotted in Figure 3. The result is a linear error of about 2% throughout the range.

2.3.1 Calibration

To perform the near-DC calibration of the end test masses using the PZTs, a single arm of the IFO is held in resonance and the fine actuator PZT position is driven with a slow sine wave having a

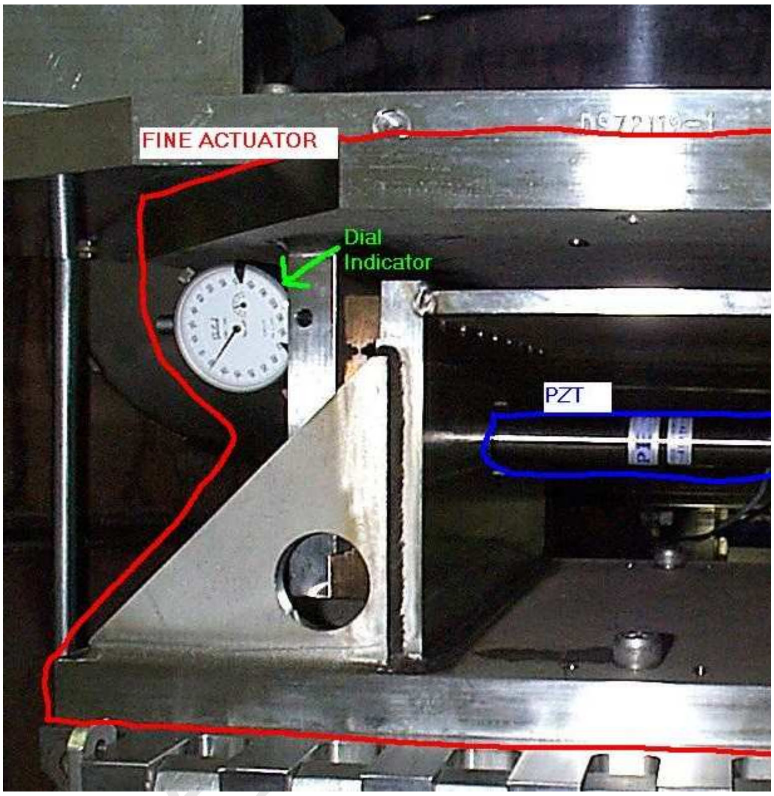

Figure 2: Fine Actuator Weldment Image

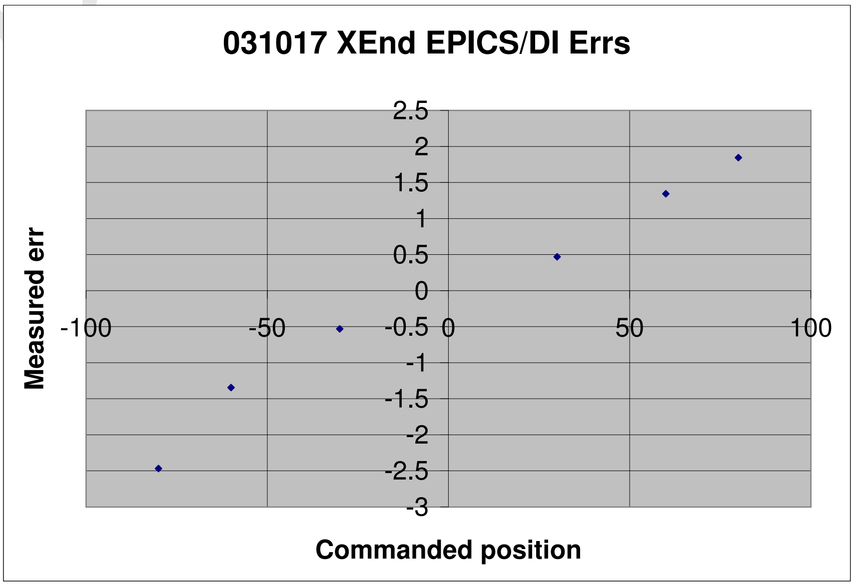

Figure 3: Fine Actuator commanded versus measured errors

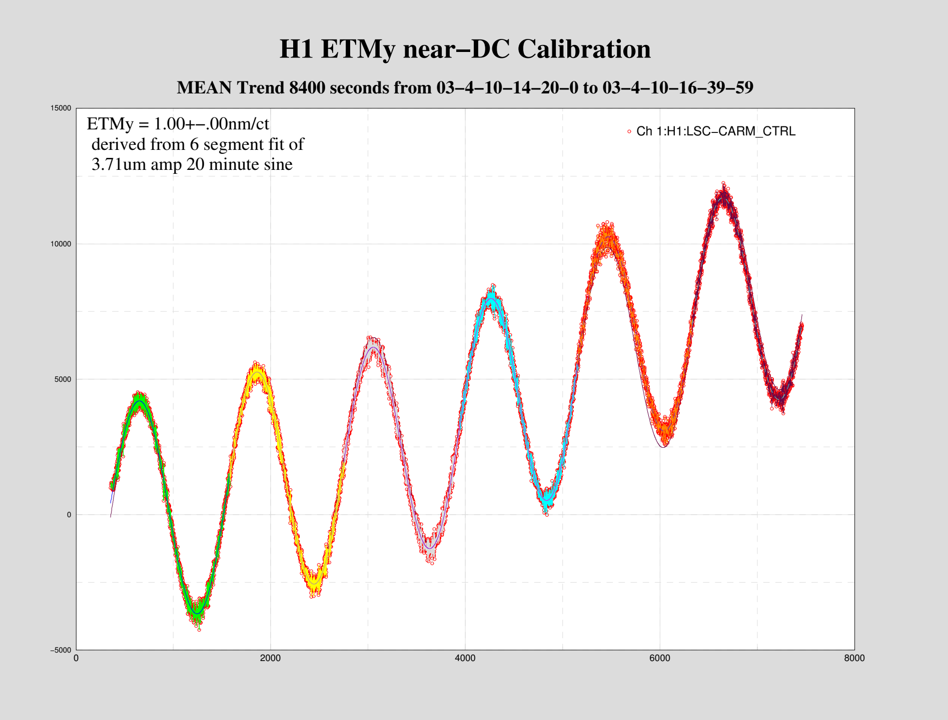

Figure 4: PZT induced motion of the Y-arm of H1 fit to a sine wave.

period of between 5 and 20 minutes period [4]. The near-DC relief of the control signal is disabled allowing it to accumulate a DC offset relative to the Fine Actuator displacement. The control signal is then fit to a sine of fixed period but free phase and amplitude, along with a quadratic term to allow for other drifts, giving a drive to control signal calibration. Figure 4 shows the control signal trend for the Hanford 4 km interferometer with several sine wave fit superimposed.

This technique has uncertainties of $\simeq 7\%$ which are comparable to those coming from the methods described in section 2.2, but completely independent systematics. This agreement gives us confidence that no large source of systematic uncertainty had been overlooked[5].

2.4 The Digital Filter function D

This part of the loop is modeled using the actual filter files loaded in the LSC during S2. In general any analog whitening and dewhitening filters in the loop are compensated digitally and should have no effect. This compensation was checked by direct measurement. Uncompensated filters are modeled using information from the parameter files (digital) or from measurement (analog).

[4]Typical interferometer control signals have amplitudes of order 1x10^{-11}m; our near-DC calibration amplitudes are 2 to 4x10^{-6}m.

[5]For example the DC values obtained for H2 using the fine actuators had an average of 0.88(0.93) nm/ct for ETMX(ETMY) compared to 0.87(0.92) nm/ct from our swept sine measurement

3 Calibration coefficients α and β

We generate a time series of calibration coefficients α , β that can be used for generating the calibration function at any point in time during S2, from a reference calibration at a given time, following Eq. 5.

The coefficient α measures the gain of the sensing function, determined by fluctuating optical gains, light attenuation into the antisymmetric photodiode, photodiode and demodulator electronic gains, digital gains, etc. The coefficient α is expected to change during a locked segment, due to changing alignment affecting optical gains.

The coefficient β measures possible differences of the digital loop filter $D(f)$ =DARM_CTRL/AS_Q. The only changes to this filter function during science mode is a global gain coefficient, and $\beta(t)$ is the ratio of this gain at time t compared to the gain at the reference time. Unlike S3, in which β was dynamic, in S2 this factor changed only a few times during S2, and it did not change during any given science segment. The value of β is determined from gains recorded as an EPICS value, and thus perfectly known.

The open loop gain $G(f)$ has always the same functional form, but changes a function of time as $G(f, t) = \alpha(t)\beta(t)G_0(f)$, where $G_0(f)$ is the open loop gain measured at a reference time t_0, when $\alpha(t) = \beta(t) = 1$.

The method we use to calculate the coefficients α ,β is as follows:

1. We inject a calibration line at a frequency f_0 adding a single ETM mirror excitation to the control signals.During S2, we used several different excitation amplitudes; we find the times when these amplitudes changed, and store them in a function $E(t)$=ETM_EXC(t)/ETM_EXC(t_0). This function has only a few discrete values.

2. The amplitude of the line appearing in the spectrum of ASQ is measured by SenseMon, in counts, as $ASQ(f_0, t)$.

3. A reference time t_0 is chosen, when the open loop gain of the DARM loop $G_0 = G(f)$ is measured, and a model is found that provides a good fit to the data. The model for $G(f)$, and corresponding models for the actuation function $A(f)$, sensing function $C(f)$ and digital filters $D(f)$ are provided as a frequency series. We interpolate a value of the open loop gain function at the calibration frequency $g_0 = G_0(f_0)$.

4. We calculate the ratio of the amplitude of the calibration line to the reference amplitude, taking into account possible differences in the excitation amplitude: $r(t) = ASQ(f_0, t)/(ASQ(f_0, t_0)E(t))$

5. We find the coefficient β , from EPICS values used as gains of digital filters in the path from AS_Q to DARM_CTRL.

6. We solve the following quadratic equation for the product α β :

$$(r^2|g_0|^2 - |1 + g_0|^2/\beta^2)(\alpha\beta)^2 + 2r^2\Re(g_0)(\alpha\beta) + r^2 = 0 \quad (6)$$

   We choose the solution to the equation that results in α β =1 when $r = 1$. We calculate α dividing the solution to the previous equation by the known coefficient β .

3.1 Excitation Amplitudes

- L1 used several different excitation amplitudes for its 927.7 Hz calibration line. We identified the transition times from minute trends of max/min values of L1:LSC-ETMX_EXC_DAQ. Then we got the starting time of changing amplitudes within a second, from the raw data of the excitation channel. The peak amplitude in the table below was measured demodulating the signal at 927.7 Hz, and is the actual amplitude injected by the command line version of Diagnostic Test Tools (DTT) Arbitrary Waveform Generator (AWG), the awg command (i.e., "awg set sine 52.3 0.02 0 0; sine 166.7 0.003 0 0; sine 927.7 0.4 0 0" generated the L1 calibration lines with the initial amplitude).

begin GPS	AMP
729273600	0.4
731486442	0.8
731486587	4.0
731486757	12.0
731576428	0.4
731714478	4.0

  The actuation function at 927.7 Hz is 1.38×10^{-15} meters/count; digital gains from DARM to ETMX and ETMY are the same (2.5), and DC calibrations for the mirrors are 0.40 nm/ct and 0.37 nm/ct respectively. Thus, 12 counts in ETMX produce a displacement of $12 \times 0.40/(2.5*(.40+0.37)) \times 1.4 \times 10^{-15} = 3.5 \times 10^{-15}$ meters. This large excitation, although present at the time taken as reference, was short lived, and was soon reduced by a factor of 3 to the final amplitude of 1.2×10^{15} m.

- H1 used only two different line amplitudes for its calibration line at 973.3 Hz. It started S2 with an ETMX excitation of 0.07 counts; at GPS time 730793022 (as seen in H1:LSC-ETMX_EXC_DAQ) it increased by a factor of 3 to 0.21 counts. At 973.3 Hz, the actuation function is 9.9×10^{-16} meters/count; digital gains for ETMX and ETMY are 1.04 and 0.90, respectively; and DC gains are 0.81 nm/ct and 0.93 nm/ct, respectively. Thus, 0.21 counts in ETMX produce $0.21 \times 0.81/(1.04*0.81+0.90*0.93) \times 9.9 \times 10^{-16} = 1.0 \times 10^{-16}$ meters.

- H2 used the same excitation amplitude for all of S2, 0.08 counts at 973.8 Hz. The actuation function at 973.8 Hz is 6.1×10^{-16} m/count, digital gains for ETMX and ETMY are 0.53 and 0.50, respectively; and DC gains are 0.87 nm/ct and 0.95 nm/ct, respectively. Thus, 0.08 counts in ETMX produce $0.08 \times 0.87/(0.53*0.87+0.50*0.95) \times 6.1 \times 10^{-16} = 4.5 \times 10^{-17}$ meters.

3.2 Calibration Line Amplitude

We use the following data files produced by Patrick Sutton with results from SenseMon (we used the values produce by the v2 version of the S2 SenseMon results):

- **L1**: L1.729273600.734367600.dat

IFO	OLG Filename	fcal (Hz)	g_0, mag	g_0, phase
L1	S02-L1-CAL-OLOOP_GAIN-731488397.txt	927.7	0.248	72 deg
H1	S02-H1-CAL-OLOOP_GAIN-734073939.txt	973.3	0.193	48 deg
H2	S02-H2-CAL-OLOOP_GAIN-734234127.txt	973.8	0.237	86 deg

Table 2: Open Loop gains at calibration frequencies

- **H1**: H1.729273600.734367600.dat
- **H2**: H2.729273600.734367600.dat

These files have seven columns with the following information: 1. GPS time (beginning of a measurement minute); 2. SenseMon measured range to binary neutron stars, in kpc; 3. SenseMon volume, in kpc^3; 4. Ratio of line amplitude to reference amplitude; 5. Measured amplitude of calibration line in ASQ spectrum, in counts; 6. Coefficient α calculated by SenseMon; 7. Coefficient β .

For the generation of the "official" α , β coefficients, we only use the measurement of the line amplitude (column 5), since we are using different reference functions than the ones used by SenseMon to generate the α , β values stored in the files.

3.3 Reference time t_0

3.3.1 Open Loop Gain at reference time

The reference times (when the coefficients α , β are equal to one by definition) are the GPS times of the reference open loop transfer function $G_0(f)$.

The open loop gains at the calibration frequencies were interpolated from the final models for the open loop gains. The results are shown in Table 2.

3.3.2 Range of possible $\alpha\,\beta$ values

We find the interval of possible products $\alpha\,\beta$, or scales of the open loop gain relative to the reference one, that are possible; we then make a map of unity gain frequency and phase margin corresponding to each value of $\alpha\,\beta$. The possible values for $\alpha\,\beta$ are:

- **L1**: 0.469 - 2.20
- **H1**: 0.411 - 2.48
- **H2**: 0.463 - 1.63

For L1, the magnitude of the open loop gain function is not monotonic between 30 and 60 Hz, so for values of $\alpha\,\beta$ in the interval (0.469, 0.541) there are other frequencies where the magnitude of G_0 is unity. These low gains do not make the loop necessarily unstable, but they may produce increased noise at frequencies between 30 and 60 Hz, which may be upconverted into the gravitational wave band.

3.4 Reference amplitude of the Calibration line

We find times near the measurement times of the reference open loop gain, when the calibration line was turned on and stable.

- For L1, the reference time is 731488397, when we were injecting 12 counts into the excitation line. The line was on during the open loop gain measurement, and was considered stable from 10 minutes before to 5 minutes after the reference time, as indicated in Fig. 5. The standard deviation in the 15 points around the reference was only 0.2%. The reference amplitude of the line as measured by SenseMon is 0.0187 counts. Using the reference response function at the calibration frequency $R-0(927.7\text{Hz}) = 1.73\times10^{-13}$ m/ct, we get 3.2×10^{-15} meters. A more precise demodulation of the line for the same time interval results in 0.0192 counts (3% higher than measured by SenseMon), corresponding to 3.3×10^{-15} meters, still a bit short (6%) of what we estimated from the excitation line (3.5×10^{-15}m).

- For H1, the line was turned not on during the open loop measurement at 734073939. It was turned on 7 minutes later; the interferometer broke lock 25 minutes later, and the line seemed to be drifting down during those 25 minutes, as shown in Fig. 5. We chose the time interval to use for calculating the reference line amplitude between 8 and 16 minutes after the reference time for the open loop gain measurement. The standard deviation in these 8 minutes was 1.5%. The reference response function at 973.3 Hz is 6.1×10^{-14} m/ct, and the reference value for the line is 0.00159 counts, so the calibrated amplitude of the excitation is 0.97×10^{-17} meters. Again, a demodulation of the line in ASQ results in a larger amplitude, 0.00165 counts (4% higher than measured by SenseMon), which corresponds to 1.0×10^{-16} meters, just as calculated from the injected excitation.

- For H2, the reference time is 734234127, and the line was on during the open loop measurement. We took as reference time an interval starting 4 minutes before the reference time, during 24 minutes, as shown in Fig. 5. There seemed to be a drift down in the locked segment, but the reference segment seemed stable. The standard deviation in these 24 minutes was 2.4%. The reference response function at 973.8 Hz is 4.5×10^{-14} m/ct, and the reference value for the line is 0.000926 counts, so the calibrated amplitude of the excitation is 4.2×10^{-17} meters. Again a demodulation of the line results in 0.000961 counts (4% higher than SenseMon), which corresponds to 4.3×10^{-17} m, close but 5% smaller than the amplitude estimated from the injected excitation.

3.5 Amplitude of calibration line, scaled to reference time

Now that we have the functions $E(t)$ for the amplitude of the excitation line, and the measured amplitude of the calibration line observed in ASQ, we can produce a scaled amplitude of the line $r(t)$, with respect to the reference time. We show the original measured amplitude lines and the scaled ones, during science modes, in Figs.6. The large changes in amplitude in the original measurements (upper panels in the figures), correspond to changes in excitation line for L1, H1. The changes in excitation line is reflected in less scatter in the scaled amplitudes (bottom panels).

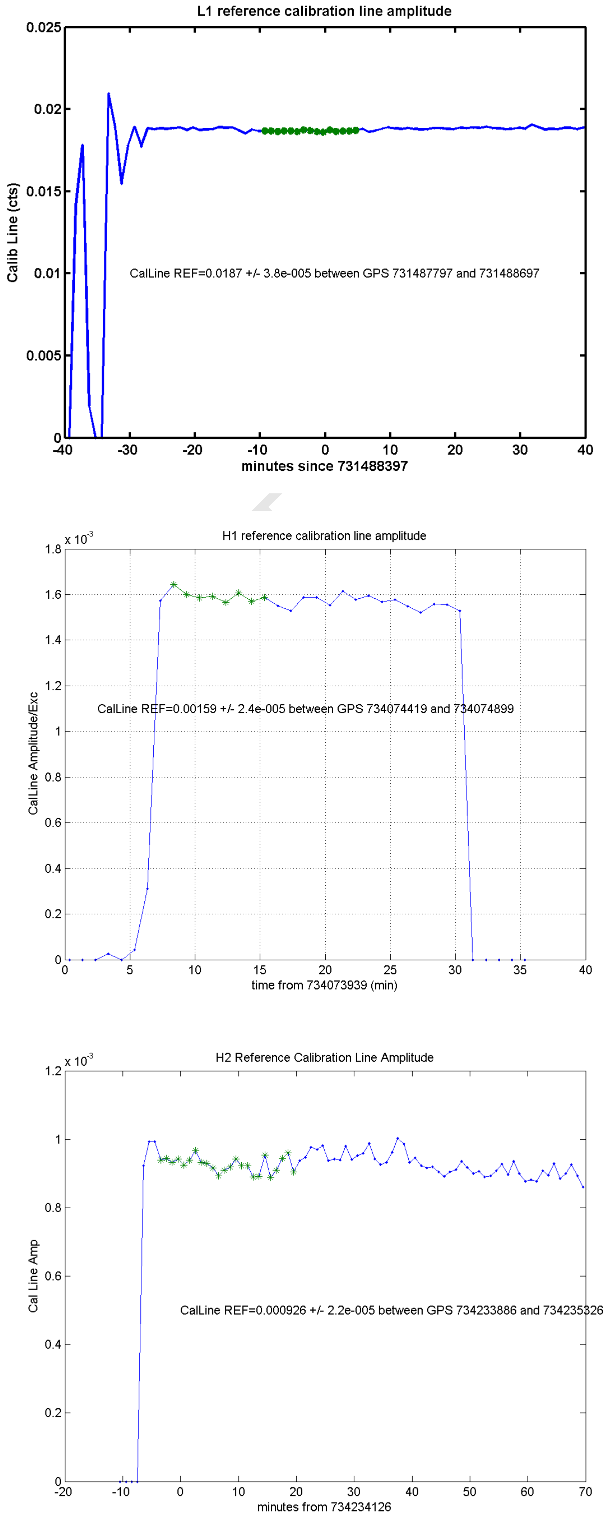

Figure 5: Calibration Line amplitude near the reference time. The points used to get the reference value are indicated with green stars.

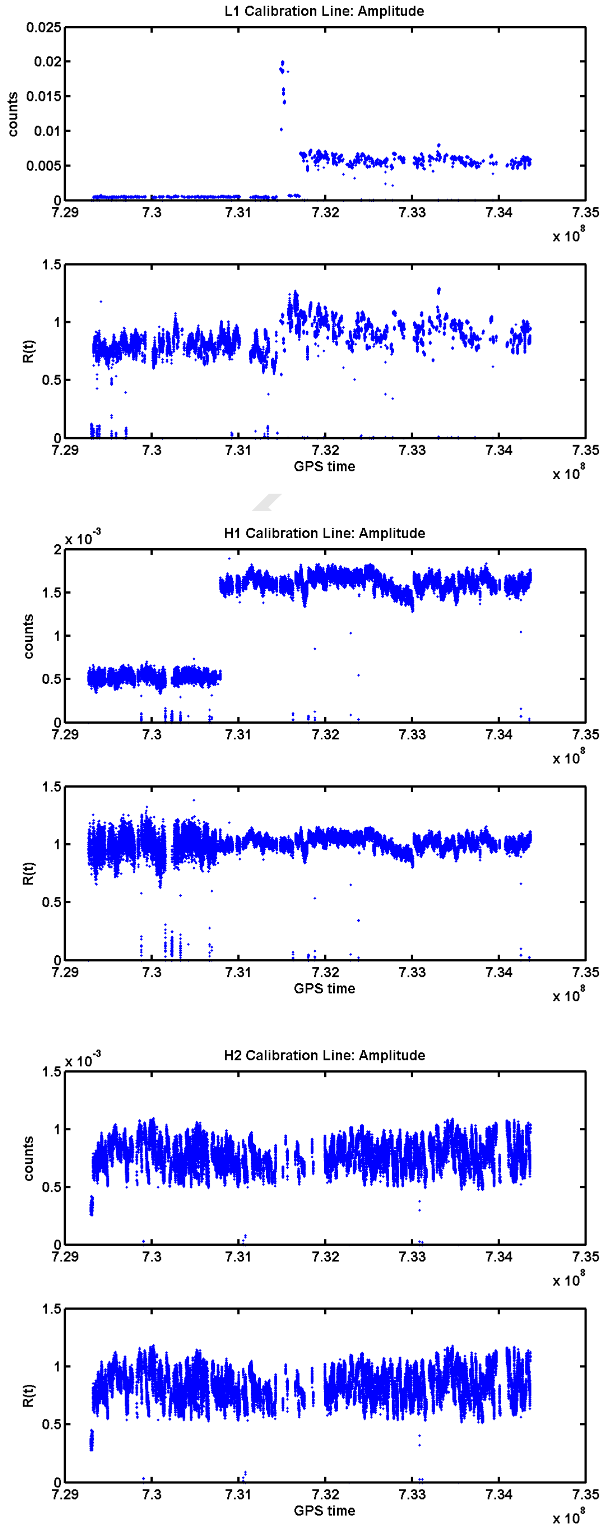

Figure 6: Amplitude of calibration lines in S2, in counts (upper panels) and relative to the reference time (lower panels).

3.6 Beta coefficients

- For L1, the only changes in β were due to changes in the input matrix element ITMTRX01 (from L1:LSC-AS_Q to L1:LSC-DARM_IN1). We found out the times for changes in this matrix element during S2 using Peter Shawhan's conlog tool, and took those into account in the beta coefficient, to make sure we have the right calibrations during injections, calibration runs, etc. The conlog results are documented in

  `http://www.phys.lsu.edu/faculty/gonzalez/S2Calibration/L1/ConlogITMTR`

  During science segments, β was always the same (0.012) except in segment # 1, but this segment did not have the calibration line on.

- For H1, there were some changes in the DARM_GAIN element, as shown below. We changed the beta coefficient correspondingly.

```
Begin GPS H1:LSC-DARM\_GAIN
729273600  -3.0
729879386 -2.5
729912552 -3.0
730376684 -2.8
730380422 -3.0
```

- From Pater Shawhan's notes on epics changes in science segments for H2, DARM_GAIN changed from -0.82 to -0.60 in segment 3, starting at 729309908. We then set the beta coefficient equal to .60/.82 before that time, and 1 afterwards.

3.7 Calculation of α , β coefficients

Finally, with the scaled values of line amplitude in ASQ $r(t)$, the beta coefficients $\beta(t)$, and the value of the open loop gain function at the calibration frequency $g_0 = G_0(f_{cal}$, we can find the coefficients $\alpha(t)$ solving the quadratic equation $A(\alpha\beta)^2 + B(\alpha\beta) + C = 0$; with $A = (r|g_0|)^2 - (|1+g_0|/\beta)^2$, $B = 2r^2\Re(g_0)$, and $C = r^2$. We set to zero any imaginary value, or values outside the allowed possible range (mostly obtained when integrating over a minute that had the line absent, or the interferometer out of lock for a fraction of the minute).

All the steps described in this procedure are done with a Matlab script "GenerateXXABs.m" with XX=L1, H1 or H2. The scripts used, input files, results, and plots of the results can be found in

`http://www.phys.lsu.edu/faculty/gonzalez/S2Calibration/`.

4 Calibration Coefficients: Error Estimates

Since the coefficient β is a digital gain from an epics channel with only a few discrete values, we presume it has no associated error. In what follows for the error analysis in α , let me assume for simplicity that $\beta = 1$.

In order to estimate the errors in the calibration coefficients α , we trace the effect of errors in the parameters used in their calculation, as described in section 3. The quadratic equation 6 we solve for α depends on two parameters: the ratio of the calibration line to its reference amplitude, $r(t)$, and the complex open loop gain at the calibration frequency, $g_0 = G_0(f_{cal})$. Since the open loop gain at the calibration frequency is small, and the ratio of the calibration line to this reference is close to one, we can use an approximate formula for the solution:

$$\alpha \approx r\,(1 - (r-1)\Re g_0)\,.$$

The relative error in g_0 is 2% in magnitude and 2 deg in phase. The mean value of r is 0.87 (L1), 1.01 (H1), and 0.83 (H2). Thus, the error in loop gain contributes at most 0.5% to the error in α . Notice that although g_0 does not depend on time, the error introduced in α by the error in g_0 will not be a systematic error (i.e., a systematic over-estimate or under-estimate of the true value) because it is weighted by $(r-1)$.

Most of the error is then due to the function $r(t)$, or the measurement of the line amplitude. The amplitude of the line is measured once a minute, in fact assuming the line is constant in each minute. We thus have two kinds of errors: the error arising from the measurement error of the calibration averaged over a minute; and the error in the assumption that the line is constant for time scales smaller than a minute. We tackle these two sources of errors separately in the following subsections.

4.1 Error in α from measurement of the line amplitude

The function $r(t)$ is calculated as the ratio of the amplitude of the calibration line at time t, to the amplitude of the line measured at reference time t_0. We estimate the error in the reference point value as the standard deviation of the points taken for the measurement, as described in 3.4, as 0.2% (L1), and 2% (H1, H2). The error in the reference value for the calibration line will translate into a systematic error in α : the values for the whole science run will be systematically over-estimated if the true value at the reference time is smaller than the assumed value. This may be particularly important for H1, since the line was not turned on during the measurement of the reference open loop gain, and a drift was observed during the later time when the measurement was taken.

Finally, we are left with the estimation of the error in the measurement of the line amplitude by SenseMon. The algorithm estimates the amplitude of the line using an average power spectral density (psd) of ASQ using 60 seconds of data, and then subtracts an average background estimated from neighboring points to the peak. The psd estimate of a random variable (as we assume ASQ is) has a Rayleigh distribution in each frequency bin, with standard deviation equal to the mean. Assume that in the absence of the line, the spectral density at such points is P_0 (P_i has units of $\mathrm{counts}^2/\mathrm{Hz}$). In the frequency bins spanned by the line, the power density will be significantly larger than P_0, but the error in each bin will always be P_0: the relative error will go down as the line gets larger[6].

Lacking an analytical formula for the error in the algorithm used in SenseMon, we estimate the error by looking at the distribution of differences in consecutive estimates, and the standard deviation of values in 2048 second-long "chunks" (a time unit used in some of the data analysis

[6] If we used an optimal demodulation of the line, the error would be $\sqrt{2P_0 f_d}$, where f_d is the sampling frequency of the demodulated line, in this case $1/f_d = 60$ sec.

	(Width α)/(Mean α)	Width ($\Delta\alpha/\alpha$)	(Width α_N)/(Mean α_N)	Mean ($\delta\alpha_N/\alpha_N$)
Random variable	0.10	$0.14 = 0.10\sqrt{2}$	$0.018 = 0.10/\sqrt{33}$	0.10
L1 (exc=0.4)	0.10	$0.03 = 0.02\sqrt{2}$	0.11	0.02
L1 (exc=12)	0.10	$0.007 = 0.005\sqrt{2}$	0.11	0.007
H1 (exc=0.07)	0.09	$0.098 = 0.07\sqrt{2}$	0.09	0.06
H1 (exc=0.21)	0.05	$0.03 = 0.02\sqrt{2}$	0.05	0.02
H2	0.15	$0.035 = 0.025\sqrt{2}$	0.14	0.03

Table 3:

algorithms). We have done this analysis on α , rather than the raw line amplitude, but as we have proven above, the error in α is dominated by the error in the line measurement.

Let us assume that the time series of α , sampled once a minute, is a constant plus a random variable with zero mean and standard deviation σ. The distribution of the difference of consecutive values of alpha (what we use for the estimate of σ) has also a zero mean and a width $\sigma/\sqrt{2}$. We now create a time series α_N, sampled once every N minutes, with each value α_N being the average of N-values of α (i.w., we have a downsampled time series of α).

The distribution of α_N has the same mean value than the distribution of α , but it has a smaller width, or standard deviation, $\sigma_N = \sigma/\sqrt{(N)}$. For 2048 seconds, N=33 and $\sigma_{2048} = 0.17\sigma$. The distribution of the standard deviations in each chunk, $\delta\alpha_N$ has a mean value of σ.

Of course, the true value of $\alpha(t)$ is not constant, but it is assumed to have time variations mostly due to fluctuations in optical gain, which have many different time scales. It has been observed that time scales slower than a minute are typically hours, due to drifting alignment, tidal motions, etc. In principle, we cannot distinguish between random fluctuations of the true value, and a constant true value with a random measurement error. However, the fluctuations due to measurement error scale with the amplitude of the calibration line relative to the noise in ASQ, while the true fluctuations do not. Since in L1 and H1 we have two epochs with different line amplitudes, we can test the distributions in each epoch. In the following table, we present the values for means and widths of the different distributions, compared with an example of a constant plus a random variable.

There are many conclusions that can be drawn from these numbers. Let us first focus on L1:

- The overall width of the distribution (first column) does not scale with the line amplitude, and is much larger than the corresponding width of difference of consecutive values (second column). This means that there is a true scatter of the values of α during the science run, with an overall width of 10%.
- The widths of the distributions of α (first column) and α_N (third column) are the same (10%, 11%). This is not consistent with a constant true value during the run (since the width should have decreased by $\sqrt{33}$, but rather with the 10% fluctuations of α having time scales longer than 33 minutes.
- The width of the distribution of differences of consecutive values (second column), and the mean standard deviation of sets of 33 consecutive values (last column), are consistent with

α being a constant value (for times shorter than 33 minutes) plus a random variable, adding 2% fluctuations with the lower line amplitude, and 0.6% with the higher line amplitude.

- The fluctuations at times shorter than 33 minutes decreased significantly, from 2% to 0.6% when the amplitude of the line was increased. This means that the 2% fluctuations observed when the line had a low amplitude was due to measurement error, and were not true fluctuations. Since we expect the error to scale inversely proportional to the amplitude of the line, and the line was increased by a factor of 10, the 0.6% fluctuations observed when the line was high are probably true fluctuations of $\alpha(t)$ with a time scale of 60 seconds.

We then conclude that for L1, the error in α , arising from the measurement error in the amplitude of the calibration line, was 2% before 731714478, and 0.2% afterwards.

With H1, we can draw the same conclusions than for L1: the fluctuations for times shorter than 33 minutes (second and last columns) are 6% with the lower line amplitude, and 2% afterwards. Since the line was increased by a factor of 3, and the error decreased by the same factor, we can assume that both are measurement errors: **for H1, the error in α , arising from the measurement error in the amplitude of the calibration line, was 6% before 730793022, and 2% afterwards.** There is a 5% scatter of the values of α during the run (from the width of α and α_N, first and third columns). Notice that the scatter of α is larger in the low line epoch (9%), because the measurement error (6%) adds in quadrature to the true scatter (5%).

For H2, we have a consistent estimate of 3% fluctuations from differences in consecutive α values and from standard deviations in 33 minute chunks. We do not have the change in line amplitude to test whether these fluctuations are in the true value or due to measurement error. However, we can use two arguments to say these are measurement errors: (i) we expect the true fluctuations in LHO to be smaller than in L1 (since they are due to seismic noise and to alignment, and both are less significant at LHO than LLO), and we have 0.6% fluctuations in L1; and (ii) the amplitude of the line, relative to the noise floor, was similar in H1 and H2, and we know the 2% error in H1 is measurement error. Thus, we conclude that **for H2, the error in α , arising from the measurement error in the amplitude of the calibration line, was 3%**. The scatter of the values during the run is 15%, with time scales longer than 33 minutes (from the width of α and α_N distributions).

4.2 Calibration Fluctuations with time scales faster than 60 seconds

Fluctuations in the value of α represent varying optical gains in the instrument; optical gains change because the alignment of the instrument is changing, due to the motion of suspended mirrors. We expect the alignment fluctuations to have some of the typical frequencies we have observed in mirror motion: microseismic peak, pendulum modes, seismic isolation stack resonances, etc, all with frequencies between 0.1 Hz and 20 Hz. The question to answer is about the magnitude of these fluctuations, relative to the mean value of α in a given minute.

The straightforward method to answer this question is to use a heterodyne modulation of the calibration line, with sampling frequencies higher than 1/60s. If we define demodulated signals

$$S_I(t) = ASQ(t)\sin(2\pi f_0 t)$$

and

$$S_Q(t) = ASQ(t)\cos(2\pi f_0 t),$$

and then downsample the resulting time series to a sampling frequency f_s (equivalent to averaging the results over times $1/f_s$), the peak amplitude of the line can be estimated[7] as

$$A(t) = 2\sqrt{S_I(t)^2 + S_Q(t)^2}$$

In practice, we need to bandpass ASQ to avoid aliasing of low frequencies, and take care of gains and phases introduced by filters used, but the method is relatively straightforward. We wrote a Matlab script to do this demodulation on data selected for a few segments in each detector.

If we estimate the amplitude of the calibration line using an integration time T, we obtain a time series $A(t)$ for the estimates, with sampling frequency $f_s = 1/T$. We could then estimate fluctuations in amplitude at frequencies smaller than $fs/2$. If we assume the background noise in ASQ near the line is white, with a power spectral density S_0 (in rms counts/$\sqrt{Hz}$, the error introduced by the background noise is equal to $\Delta A = \sqrt{2S_0 f_s}$. To help the test and interpretation of this method, we tried the Matlab script on data built as a sine wave plus a random variable with white noise. We obtained a standard deviation in the estimated peak amplitude equal to $1.27\sqrt{S_0 f_s}$, a bit smaller than expected (!), but consistent with our estimate. If we use an arbitrary 1 Hz bandwidth, we define a "signal to noise" ratio $\mathrm{SNR} = A_0/\sqrt{2S_0 1\mathrm{Hz}}$. The relative error in the measurement of the line amplitude, if sampled at a frequency f_s, is then

$$\frac{\Delta A}{A_0} = \frac{\sqrt{2S_0 f_s}}{A_0} = \frac{\sqrt{f_s/\mathrm{Hz}}}{\mathrm{SNR}}$$

The SNR figure depends not only in the amplitude of the injected line, but also on the optical gain (determining the amplitude of the calibration line in ASQ) and the background noise in ASQ, both quantities that change somewhat during the run, it is however a useful figure to estimate the frequencies we may use.

We looked at some selected segments, one hour long each, scattered during the run, in each detector. For L1 and H1, we looked at times when the injected line was higher. We estimated the mean amplitude of the line, the background noise and the SNR in each of these segments, as shown in Table4.

L1 has an SNR between 47 and 92, but we can take a rough average of 70; H1 and H2 are less variable, and we can assign them an SNR of 8.5 and 7. For a sampling frequency of 1/60 seconds, as used in SenseMon, estimates of α using an optimal demodulation method, would have errors in L1, H1 and H2 of 0.2%, 1.5% and 2%, respectively: these are remarkably similar to the errors estimated in the previous section (0.2%, 2% and 3%). We have 10% errors at sampling frequencies of 50 Hz, 0.7 Hz and 0.5 respectively. This means we cannot measure fluctuations in LHO faster than 0.3 Hz unless they are significantly larger than 10%.

If the noise in ASQ near the line is not white, the spectral features (like harmonics of 60 Hz power lines) will appear in the demodulated line just as fluctuations of true line amplitude would. True line amplitude fluctuations, however, appear as symmetric sidebands of the line. We show

[7]We can also estimate a phase for the calibration line, which are expected to result in a real coefficient α , or be constant for a constant optical gain

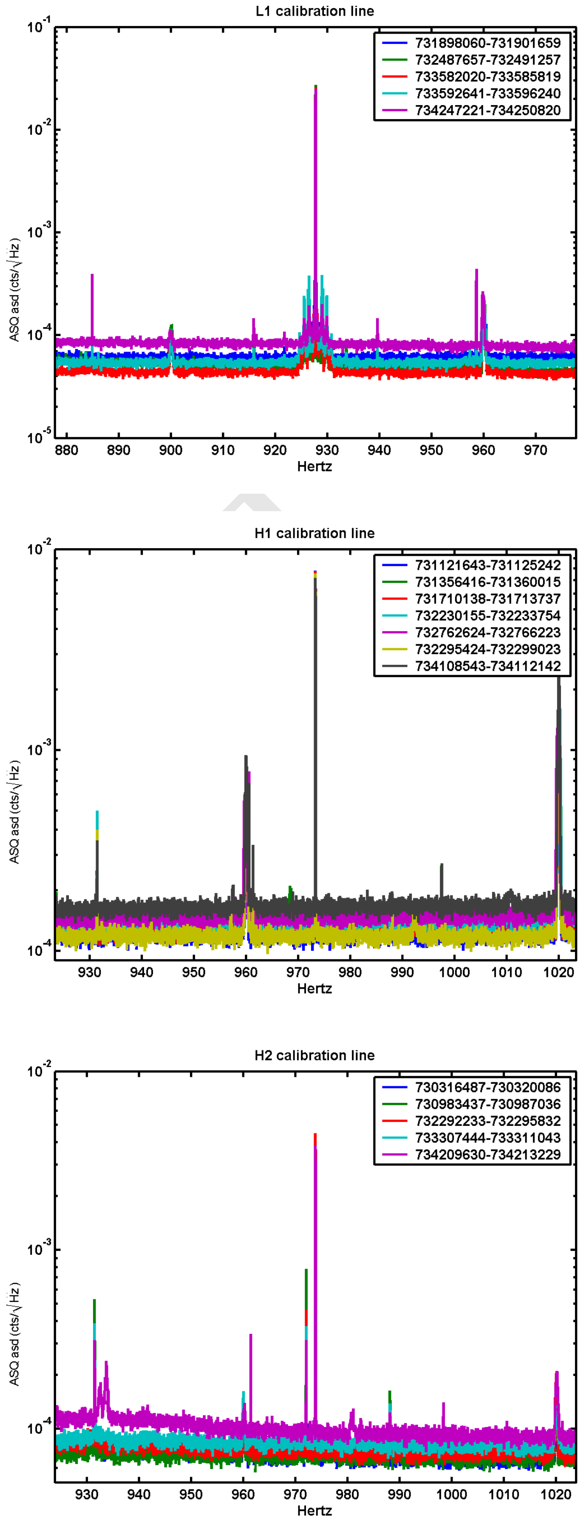

Figure 7: Amplitude spectral density near the calibration lines.

Detector	GPS time	Line Amp (10^{-3} cts)	$S_0(10^{-9}\mathrm{cts}^2/\mathrm{Hz})$	SNR	Range (kpc)
L1	731898060-731901659	5.72	3.78	66	852
	732487657-732491257	6.04	2.54	85	956
	733582020-733585819	5.71	1.94	92	1045
	733592641-733596240	5.38	2.96	70	898
	734247221-734250820	5.58	6.94	47	895
H1	731121643-731125242	1.73	14.4	10	428
	731356416-731360015	1.64	22.0	8	371
	731710138-731713737	1.73	17.0	9	369
	732230155-732233754	1.67	19.2	8	382
	732762624-732766223	1.57	21.3	8	437
	732295424-732299023	1.67	13.9	10	404
	734108543-734112142	1.60	27.6	7	391
H2	730316487-730320086	0.71	4.9	7	278
	730983437-730987036	0.64	4.8	6	292
	732292233-732295832	1.00	5.6	9	339
	733307444-733311043	0.79	6.9	7	248
	734209630-734213229	0.85	9.2	6	242

Table 4: Times analyzed for estimating fast fluctuations in calibration.

in Figure 7 the amplitude spectral density of ASQ for a band of 100 Hz around the calibration line. We see obvious sidebands at the usual frequencies in L1, but we don't see any sidebands in H1 or H2[8]: the sidebands produced by fluctuations of the line are smaller than the background noise. We do see the power lines in the ASQ spectral density, as expected, but also several other narrow features that would limit the ability to resolve the calibration as a function of time for higher sampling rates.

We show in Fig.8 the power spectral density of the L1 calibration line, in the frequency band 0.01-12.5 Hz, where all the features correspond to known sources: the microseismic (sometimes double) peak at 0.1-0.3 Hz, pendulum frequencies in the 0.7-1 Hz, resolved stack resonances at 1.2 Hz, 1.4 Hz, 2.1 Hz, some smaller stack resonances (not always present) near 3 Hz and 6 Hz, and a narrow vertical mode at 11.8 Hz. The magnitude of power at the different frequencies changes significantly in the different segments considered, but the total integrated power in this band is quite similar, between 7% and 12% of the mean peak amplitude. Fluctuations above the background are smaller, 6%-9% of the mean. Thus, **we estimate that in L1, α fluctuations at time scales shorter than 60 seconds have a 10% relative amplitude.** However, the fluctuations cannot be resolved in the time domain, since the error due to the background is comparable to the magnitude of the fluctuation itself.

For H1 and H2, there is little we can say, since the background noise produces a 50% error in a 12.5 Hz band, which is larger than plausible fluctuations in calibrations. Since the source of alignment fluctuations is seismic, we can assume the fluctuations in LHO are equal or (likely) smaller than at LLO, and **we then take the LLO estimates, 10% fluctuations, as appropriate**

[8]Another possible source of sidebands is upconversion of the low frequency spectrum in ASQ: we checked this is not the case.

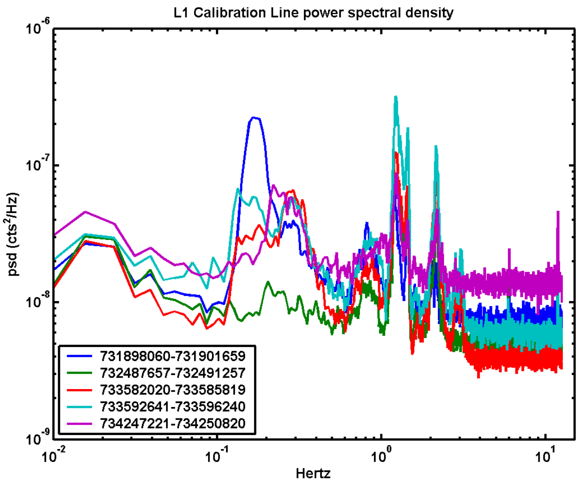

Figure 8: Amplitude spectral density near the calibration lines.

estimates in LHO. The only hard estimate we can have for LHO is that in the band 0.01-0.3Hz, the fluctuations are smaller than 10% (in this band, the measured fluctuations above background for L1 are 1-3%).

4.3 Summary

We collect here the estimates for errors in calibration coefficients α .

- **Statistical errors** in the estimates of α averaged over a minute arise from errors in the measurement of the line amplitude, and errors in the open loop gain at the calibration frequency. All errors except L1 after GPS 731714478 are dominated by line amplitude errors.
  - L1: 2% before 731714478, and 0.5% afterwards.
  - H1: 6% before 730793022, and 2% afterwards.
  - H2: 3%.
- **Systematic errors** arising from the estimate of the calibration line at the reference time are 0.2% in L1, and 2% in H1, H2.
- Estimates of calibration fluctuations at times shorter than 60 seconds are:
  - L1: 10% of the mean, at frequencies corresponding to microseismic peak, pendulum frequencies, seismic resonance peaks, and vertical modes.
  - H1, H2: equal or less than at LLO (10%). An upper limit for fluctuations at frequency f is given by 10% $\times(f/0.3\mathrm{Hz})$.

5 The sign of the calibration

5.1 Definition

The sign of the calibration is defined in the following sense. There are two signs we are concerned with, an actuation sign and a sensing sign. Both signs are defined relative to the lengthening of an X-arm, i.e. what is the observed effect at DC in the event of the translation of the X-end (or X-mid, in the case of H2) station away from the corner station? Recall that $h = \Delta L/L = (L_x - L_y)/L$.

The actuation sign is obtained by translating the X-end (or mid) station away from the corner-station and monitoring the effect on the ETMX control signal (or equivalently, the DARM_CTRL signal, connected to the ETMX control signal via the known, static output matrix element). The sensing sign is obtained by taking a transfer function down to (near) DC between AS_Q and DARM_CTRL, and assessing whether or not there is a sensing sign flip (AS_Q) relative to the actuation (ETMX_CTRL, or equivalently, DARM_CTRL).

Sign measurements are described in some detail in two separate log entries, one for LHO during S1 [7], and another for LLO during S2 [8].

5.2 Actuation sign

To determine the actuation sign, the tidal fine-actuation system wass employed to translate an ETMX mass away from the corner station. Two of us (Radkins/Landry) visited the Mid and End stations at LHO, confirming that a positive signal sent to the fine-actuator control signal H(1or2):TID-DMXARM_CALIBOUT translated the optic table (and ETMX) away from the corner station. We did this by sending large positive control signals, corresponding to many tens of microns of motion, and using calipers to see that the fine-actuator split-gap had opened or closed appropriately, i.e. the optics table had moved a measurable amount away from the corner station. All signs follow relative to this physical measurement.

We then sent sinusoids with 2 minute periods into the CALIBOUT control signal, lengthening and shortening the arm with a known sign. Fig. 9 (H1) and Fig. 10 (H2) show the CALIBOUT signal (the injected amplitude was $1\mu m$ for both H1 and H2, however an arbitrary scale factor is applied the CALIBOUT trace), and the response seen in DARM_CTRL and ETMX_CTRL (H2 only). As DARM_CTRL is π out of phase with the CALIBOUT tidal actuation control signal, *we assign a negative sign to the actuation for the LHO IFOs*.

A similar process was performed at LLO. The CALIBOUT excitation and L1:LSC-DARM_CTRL are shown in Fig. 11.

5.3 Sensing signs

As ETMX_CTRL and DARM_CTRL have the same sign at DC, we can compare the sign of AS_Q and DARM_CTRL to obtain the sensing sign from the actuation sign. The sensing sign can thus be measured via the digital filter D(f), a transfer function of AS_Q to DARM_CTRL, and inspecting the phase of the function as it goes towards DC. One has to rely on an understanding of the hardware in order to ensure the phase is inspected at a sufficiently low frequency, e.g. well below the 0.75Hz pendulum resonances). If the phase tends to zero at DC, the sensing and actuation signs are the same. If the phase tends to $\pm\pi$ at DC, then the sensing and actuation signs are flipped. Digital

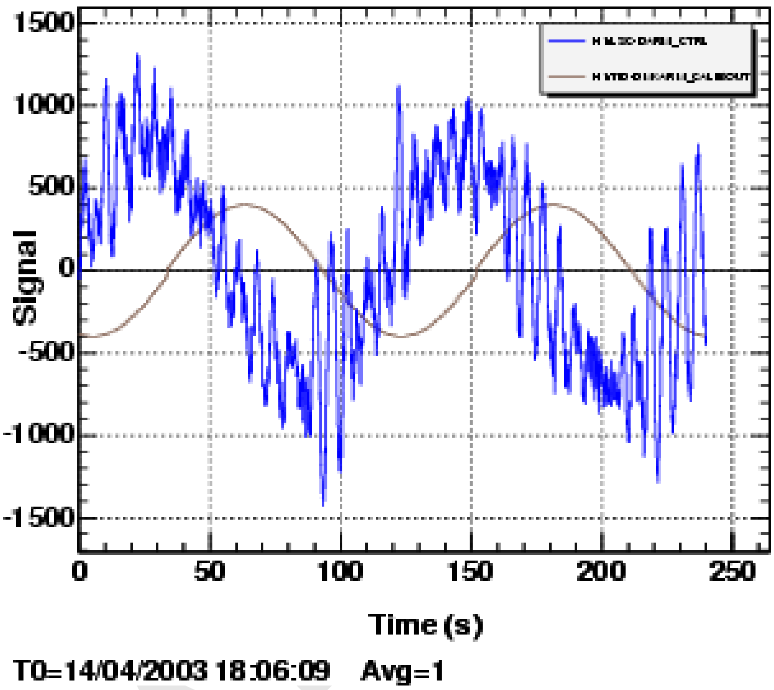

Figure 9: H1 Actuation Sign.

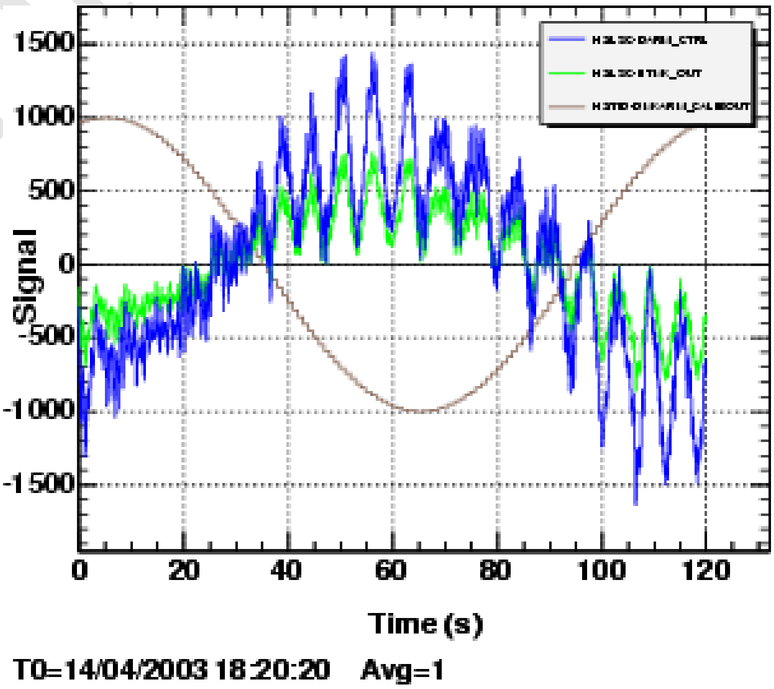

Figure 10: H2 actuation sign.

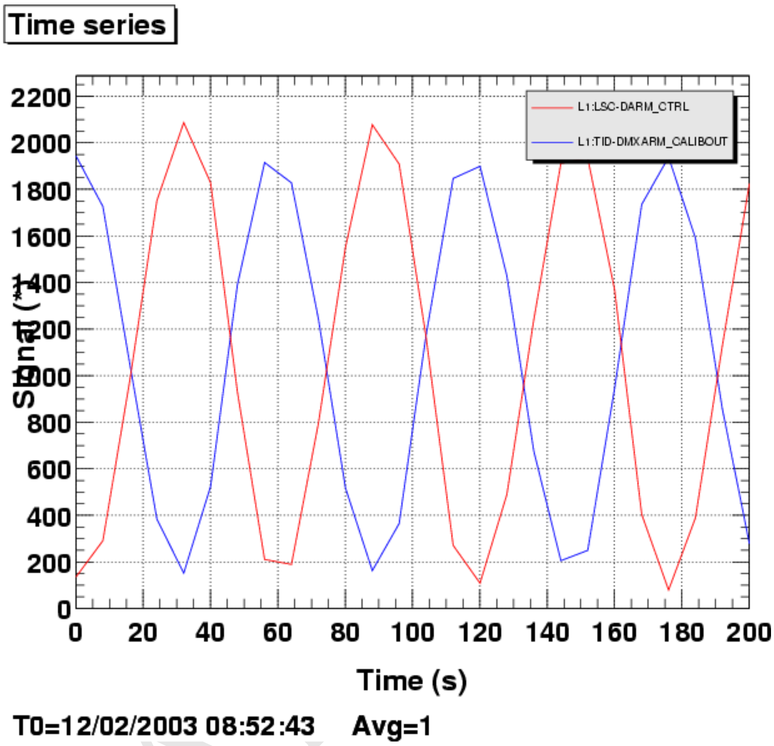

Figure 11: L1 actuation sign.

transfer functions D(f) formed in Diagnostic Test Tool for LHO IFOs are shown in Fig. 12 and Fig. 13 (magnitude and phase, respectively). We see that for the Hanford instruments, the phase tends to $-\pi$ so that the sensing sign is flipped relative to the actuation. As the actuation has been shown to be negative for LHO, the sensing sign is thus *positive*.

A similar transfer function for L1 is shown in Fig 14 (magnitude) and Fig. 15 (phase); the phase tends to zero at DC so that the *L1 sensing sign is negative*, like the L1 actuation sign.

One can check the sensing sign by first obtaining the actuation sign, then propogating backwards through the DARM loop to AS_Q, and comparing the two methods for agreement. For example, the actuation sign for LHO was found above to be negative. Propogating backwards, the

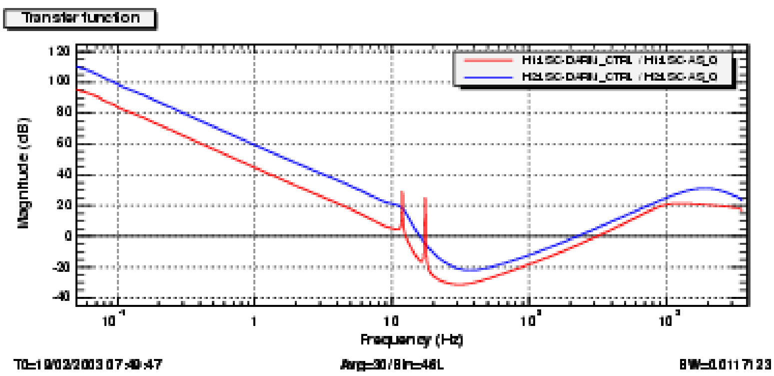

Figure 12: H1 and H2 digital filters D, magnitude.

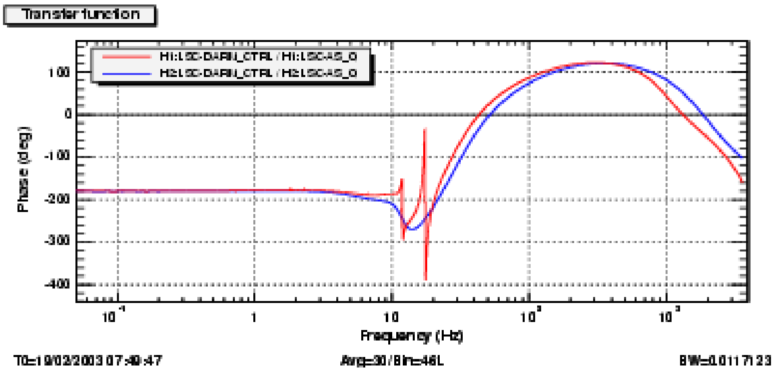

Figure 13: H1 and H2 digital filters D, phase.

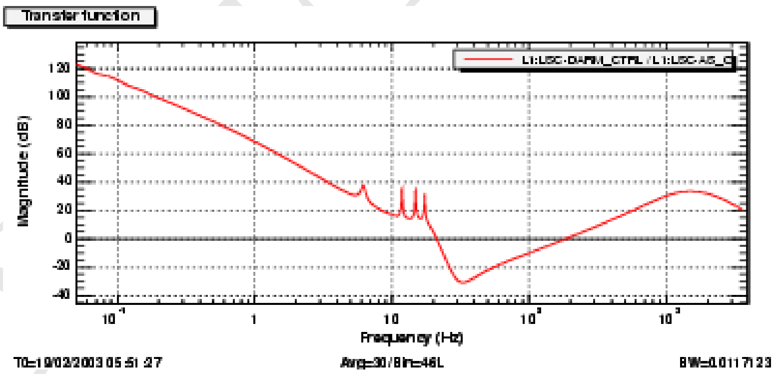

Figure 14: L1 digital filter D, magnitude.

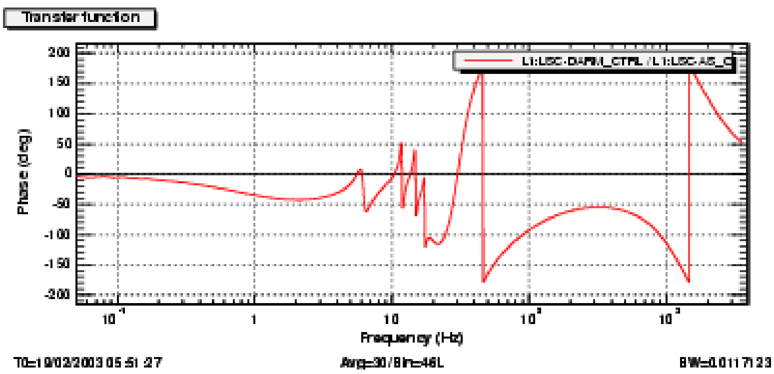

Figure 15: L1 digital filter D, phase.

sensing sign is:

$$sensing\_sign = actuation\_sign \times DARM\_gain\_sign \times BOOST\_filter\_sign \times Input\_matrix\_sign$$

Here, $DARM\_gain\_sign$ is the sign of the main DARM filter gain (negative for all three IFOs), $BOOST\_filter\_sign$ is the negative sign that comes from the low-frequency boost (FM1) filter in the LSC DARM bank (negative, all IFOs), and the $Input\_matrix\_sign$ is *negative for H1 and H2, positive for L1*. Plugging in the known signs on the RHS, we obtain a postive sensing sign for H1 and H2, and a negative sensing sign for L1, in agreement with D(f).

Note the sensing sign divergence between the sites. This was first noted by the S1 analysis of hardware injections by the Stochastic Search group, and is evident in the sign flip between sites in the input matrix element. The physical origin of the sign flip is unknown, but may be due to flipped magnets or pc board asymmetries between sites. It has been suggested that the calibration group produce sign-corrected response functions (comparing the phase of response functions for the interferometers, we see that the phase tends to zero for LHO, and π for L1). This has not been done to date (as of S3 V2 calibrations), but could be part of future calibration releases.

6 Calibration Errors

The fractional uncertainty on the magnitude of the response function can be written as:

$$\left(\frac{\Delta|\mathrm{R}|}{|\mathrm{R}|}\right)^2 = \left(\frac{\Delta|\mathrm{A}|}{|\mathrm{A}|}\right)^2 + \left(\frac{\Delta|\mathrm{D}|}{|\mathrm{D}|}\right)^2 + \mathrm{C_R}\left(\frac{\Delta|\mathrm{G}|}{|\mathrm{G}|}\right)^2 + \mathrm{C_R}\left(\frac{\Delta\alpha}{\alpha}\right)^2 + \mathrm{C_I}\Delta\phi_\mathrm{G}^2 \qquad (7)$$

and on the phase:

$$\Delta\phi_\mathrm{R}^2 = \Delta\phi_\mathrm{A}^2 + \Delta\phi_\mathrm{D}^2 + \mathrm{C_I}(\alpha^2\Delta|\mathrm{G}|^2 + |\mathrm{G}|^2\Delta\alpha^2) + \mathrm{C_R}\Delta\phi_\mathrm{G}^2 \qquad (8)$$

where

$$\mathrm{C_R} = \frac{\Re(1+\alpha\mathrm{G})^2}{|1+\alpha\mathrm{G}|^2} \qquad (9)$$

and

$$\mathrm{C_I} = \frac{\Im(1+\alpha\mathrm{G})^2}{|1+\alpha\mathrm{G}|^2} \qquad (10)$$

and we have taken α to be real. The coefficients C_R and C_I are plotted in Figure 16 using values from L1. Obviously they enhance or reduce the effect of some contributions depending on the frequency.

In our treatment of the uncertainties we combine different sources in quadrature, regardless of whether they cause a systematic shift in the 'true' value of the measured quantity or a random variation in that value. When the calibration accuracy improves and we implement other methods with independent systematics it will be desirable to make such a distinction.

6.1 $\Delta|A|$

The uncertainty has contributions from:

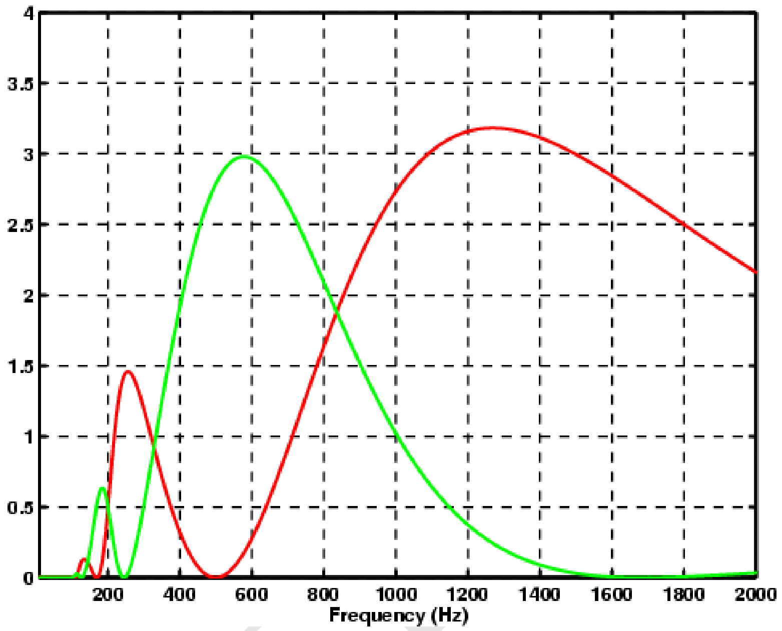

Figure 16: Co-efficients C_R(red) and C_I(green) for the L1 interferometer.

- The peak-to-peak measurement of AS_Q obtained with the free swinging Michelson. This was estimated from the standard deviation of ten separate measurements and was found to be of order 0.1% *i.e.* negligible.

- The deviation from a simple pendulum response of the ITM/AS_Q transfer function. This is illustrated in Figure (17). The uncertainty is estimated by taking the standard deviation of the values between 100 and 800 Hz. This gives a contribution of around 5% to the total uncertainty for L1.

- H1 and H2 used a different calibration technique[9], which gave smaller uncertainties, on the order of 1.5% for the ITM calibrations.

- The uncertainty on a transfer function measurement is given by [5]:

$$\frac{\sqrt{1-\gamma^2(f)}}{|\gamma(f)|\sqrt{2\mathrm{N_d}}} \tag{11}$$

  where $\gamma(f)$ is the coherence of the measurement and $\mathrm{N_d}$ is the number of averages. The three transfer function measurements used in the calibration *i.e.* ITM/AS_Q, ITM/AS_I and ETM/AS_I, all contribute an uncertainty calculated using the above equation. Since care is taken to keep the coherence high these contributions are small.

- Finally the ratio of the ITM/AS_I and ETM/AS_I transfer functions should ideally be flat. As shown in Figure 18 this is not the case for L1, probably due to a mismatch between the run and acquire filter paths in the coil driver module. This gives a contribution to the uncertainty of $\simeq 6\%$ for L1. The Hanford interferometers can be calibrated in run mode and so this

[9] This is the 'Sign Toggling' method described in reference [4]

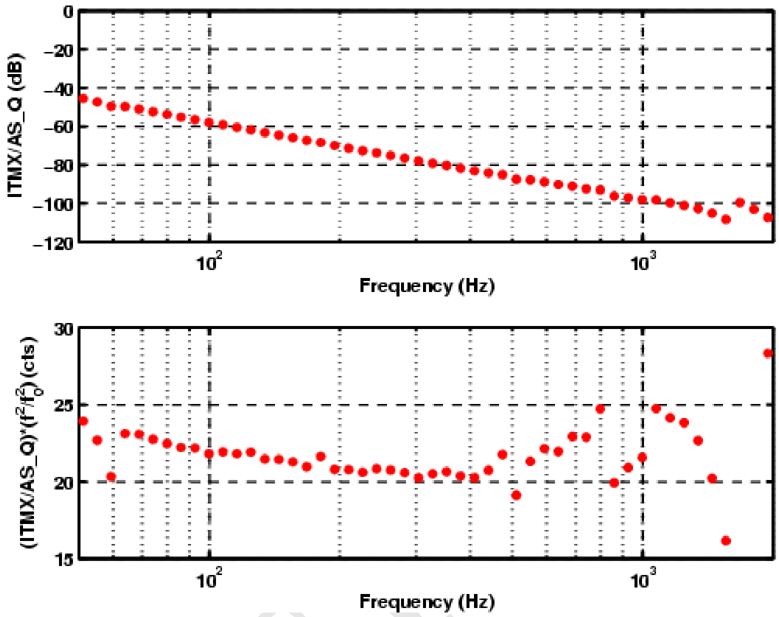

Figure 17: Transfer function of ITMX to AS_Q obtained with a locked simple Michelson. The lower figure shows the response corrected for the simple pendulum. Ideally this should be flat.

mismatch is not a problem. The transfer function ratios for H1 and H2 are shown in Figures 19 and 20.

- Since the actuation function measurement is an extrapolation to DC we do not quote a frequency dependent uncertainty. Instead we use the mean uncertainty calculated in the range 80-2000 Hz. The different sources of uncertainty from transfer function measurements described above are combined in quadrature.

6.2 $\Delta|D|$

Because of the careful work that was done to match the modeled and measured electronics this uncertainty was negligible for all interferometers. A comparison of the model with the measurement for L1 is shown in Figure 21, for H1 in Figure 22 and for H2 in Figure 23.

6.3 $\Delta|G|$

This uncertainty is obtained from the coherence of the measurement using equation (11). Our measurements typically have very high coherence and so this contribution is typically 2% or less for all three interferometers.

6.4 $\Delta\alpha$

For details on how this uncertainty is estimated see reference [2]. The uncertainty is estimated from the difference in values of α obtained in consecutive minutes. These differences are histogrammed

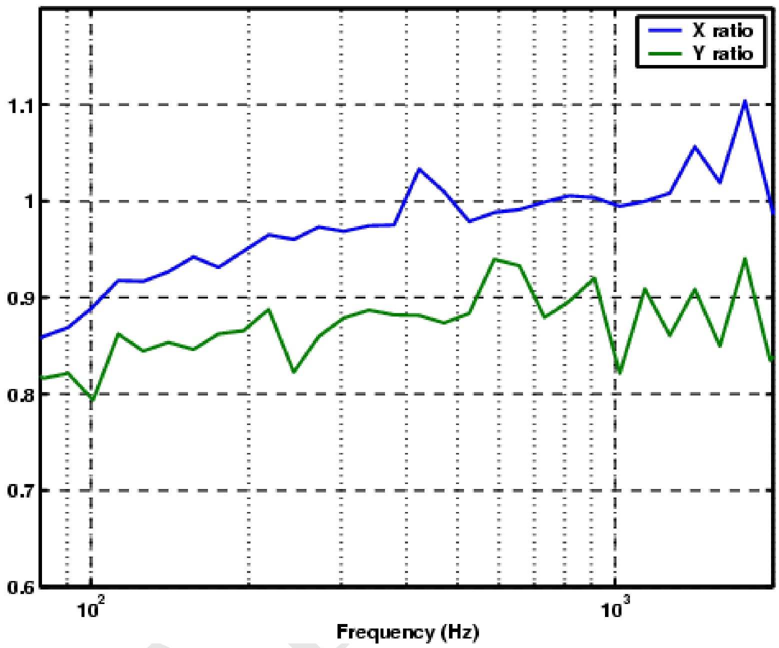

Figure 18: Ratio of the transfer functions of ITM/AS_I and ETM/AS_I for L1.

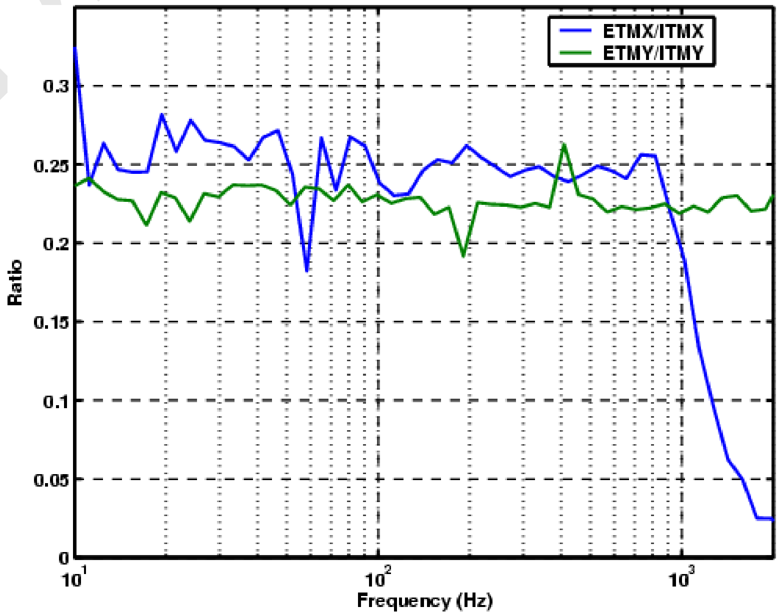

Figure 19: Ratio of the transfer functions of ITM/AS_I and ETM/AS_I for H1.

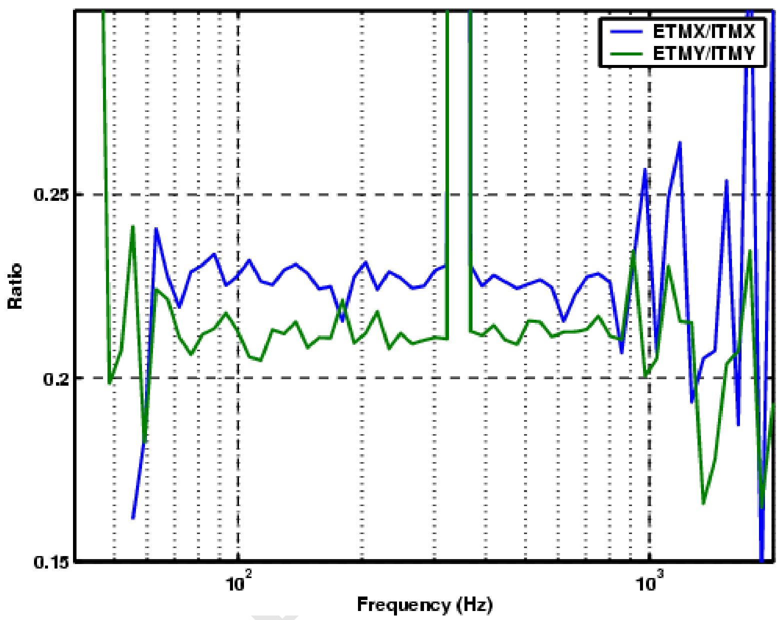

Figure 20: Ratio of the transfer functions of ITM/AS_I and ETM/AS_I for H2. The large spike is due to the violin modes.

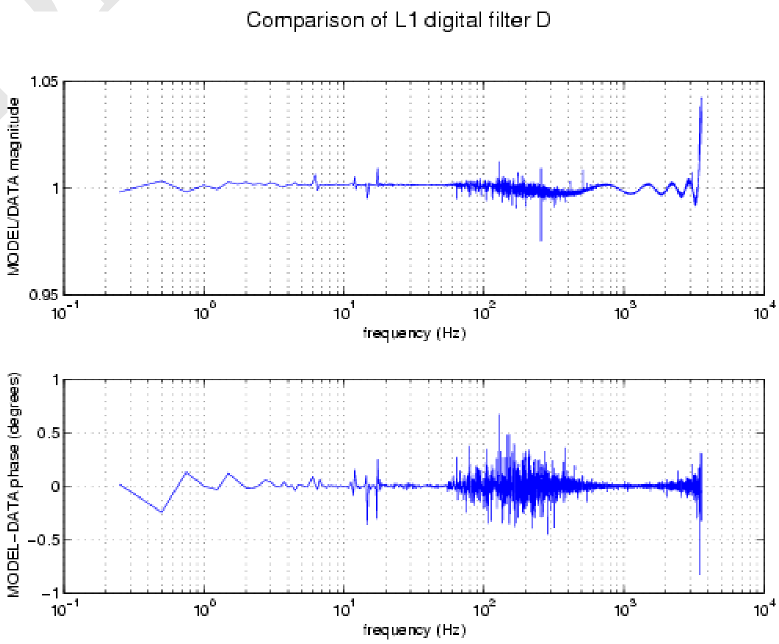

Figure 21: Comparison of model to measurement for the L1 digital transfer function.

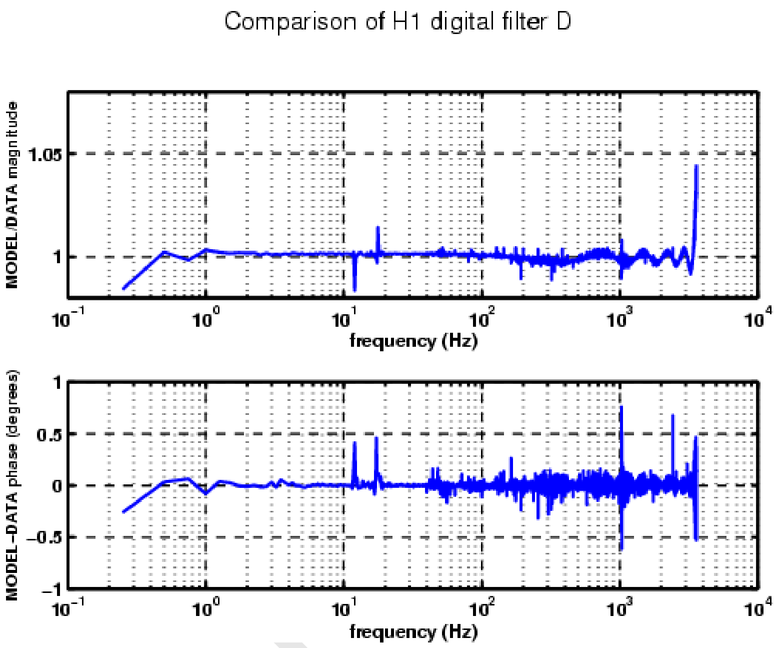

Figure 22: Comparison of model to measurement for the H1 digital transfer function.

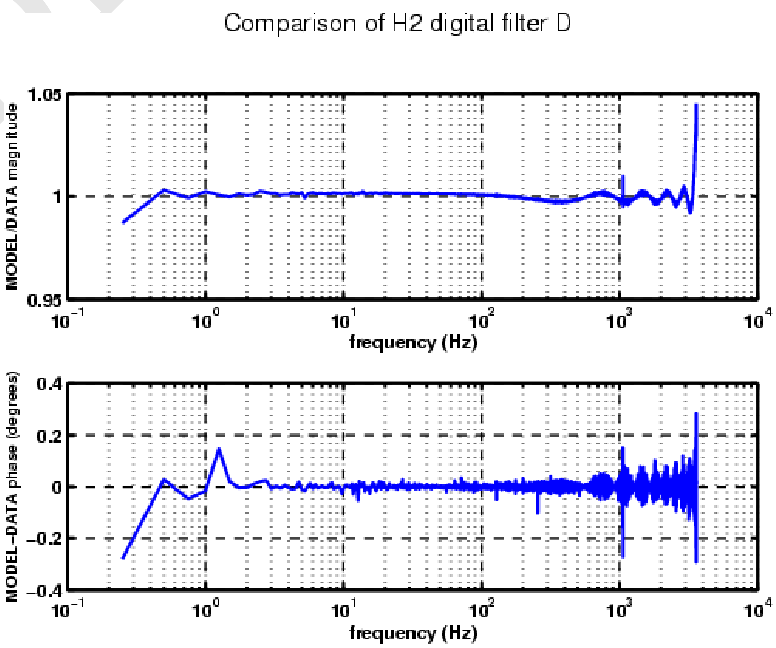

Figure 23: Comparison of model to measurement for the H2 digital transfer function.

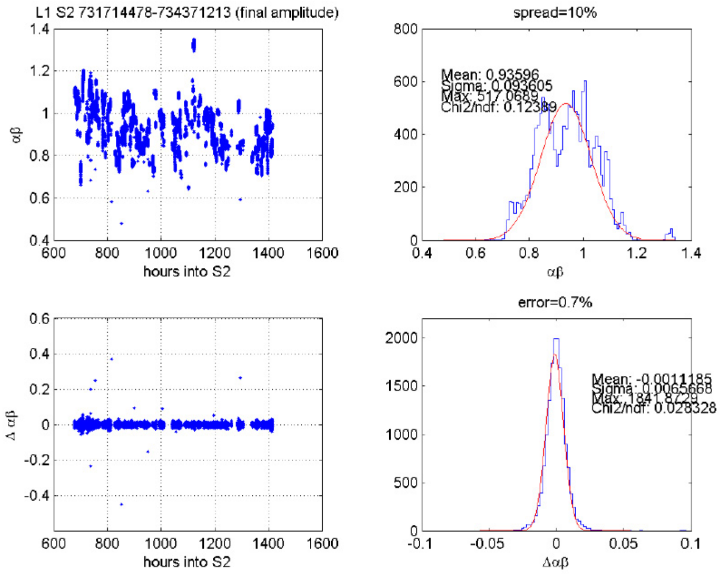

Figure 24: Plot of $\alpha\beta$ for L1 used to estimate the uncertainty.

and the mean of the histogram is taken to be $\Delta\alpha$ (see Figure 24).

This value is strongly dependent on the amplitude of the high frequency calibration line. During S2 the initial injected amplitude of this line was too low and so the contribution to the uncertainty is higher. For L1 we have (see Figure 25) $\Delta\alpha$ values of 3.4% before GPS time 731714478 and 0.7% afterwards for H1 (figure 26) the values are 9.8% before 730793022, 2.9% afterward; for H2 the initial amplitude of the calibration line was large enough giving value of 3.5% for the entire run.

6.5 $\Delta\phi_A$

Our treatment of the uncertainty in $\Delta|A|$ does not lead easily to a method for estimating $\Delta\phi_A$. However, we would expect any such phase uncertainties to show up in the reconstruction of hardware injections. These injections assume a similar simple pendulum transfer function for the actuation. From analysis of periodic injections we estimate a phase uncertainty of 10° for L1 and 2° for H1 and H2[10]. The reason for the larger uncertainty on L1 is unknown.

6.6 $\Delta\phi_D$

As for $|D|$ we have no appreciable uncertainty in ϕ_D.

6.7 $\Delta\phi_G$

$\Delta\phi_G$ is also found from the coherence of the transfer function measurement. The equation is the same as equation (11), but now the interpretation is as the standard deviation of ϕ_G and not as

[10] From work by X. Siemens.

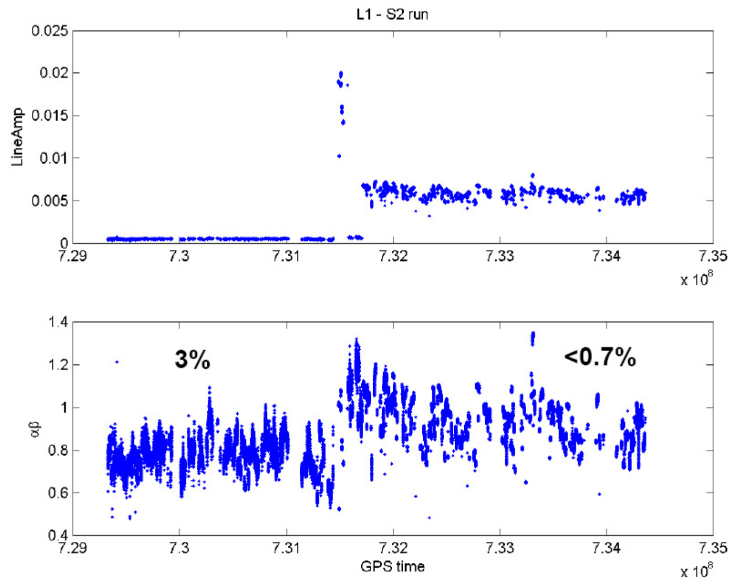

Figure 25: Plot of $\alpha\beta$ for L1 showing the different line amplitudes.

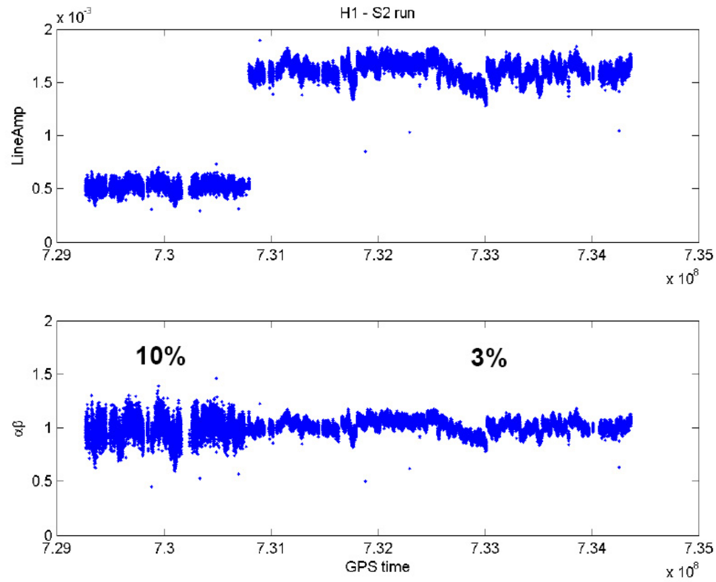

Figure 26: Plot of $\alpha\beta$ for H1 showing the different line amplitudes.

a fractional error. Again, because the coherence is high the contribution is typically less than 2 degrees for each interferometer.

The above contributions to the uncertainty in magnitude and phase are plotted for each interferometer in Figures 27 to 36.

7 Results

For most analyses an overall, non-frequency dependent estimate of the uncertainty is sufficient. Table 5 summarizes this information for each interferometer. There are two sets of numbers for L1 and H1 corresponding to the two periods of different calibration line amplitude. Frequency dependent uncertainties are available at the Calibration Home Page [6] for those who require them. These correspond to the "total" curves in Figures 27 to 36.

	Magnitude Uncertainty %	Phase Uncertainty °
L1 before GPS time 731714478	10	11
L1 after GPS time 731714478	9	10
H1 before GPS time 730793022	19	10
H1 after GPS time 730793022	6	4
H2	7	5

Table 5: Summary of uncertainties for the LIGO interferometers during S2. The numbers are a conservative estimate based on Figures 27 to 36.

8 Conclusion

This detailed look at the S2 calibration highlights the contributions of different parts of the process to the final uncertainty. Clearly better actuation function measurements (especially at LLO), and stronger calibration lines would have resulted in a more accurate calibration of the S2 data. However, at some stage we will become systematics limited and it may be that considerably more rigor in assessing and combining sources of uncertainty will be necessary. Having other techniques available for the calibration, (for example a photon calibrator), should help greatly in assessing systematics. Of course at some stage our level of precision will be adequate to the task at hand and further refinements will be driven by inaccuracies in our observations of real sources.

References

[1] Adhikari R., Fritschel P., González G., Landry M., Matone L., O'Reilly B.,Radkins H., Takamori A. *Calibration of the LIGO detectors for the First LIGO Scientific Run* `T030097-00-D`

[2] González, G. *LIGO S2 Calibration: Alpha, Beta coefficients* available in `http://www.phys.lsu.edu/faculty/gonzalez/S2Calibration/`

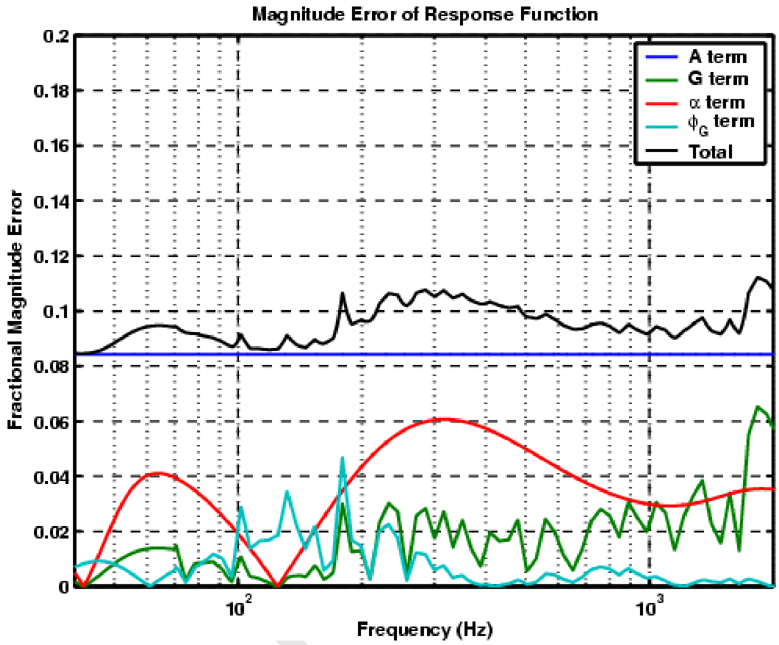

Figure 27: Contributions to the magnitude uncertainty for L1 before GPS time 731714478.

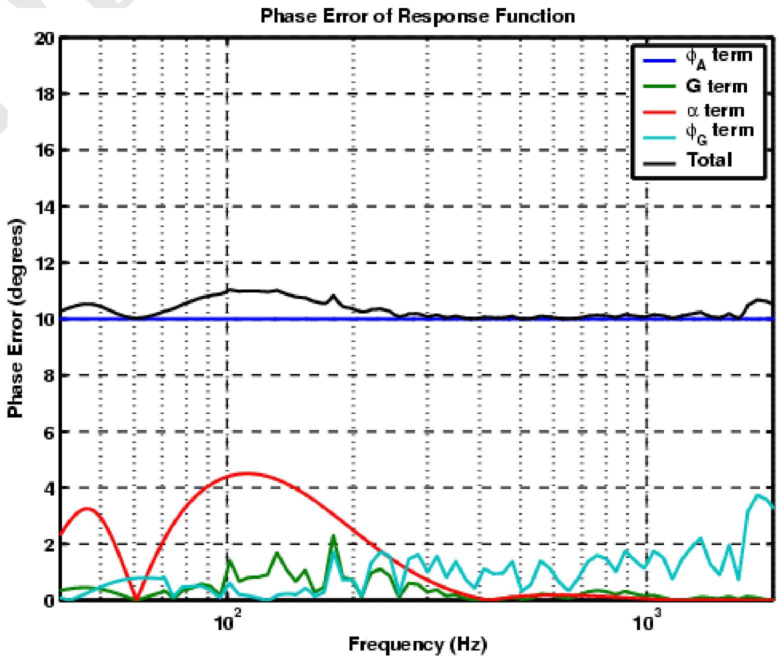

Figure 28: Contributions to the phase uncertainty for L1 before GPS time 731714478.

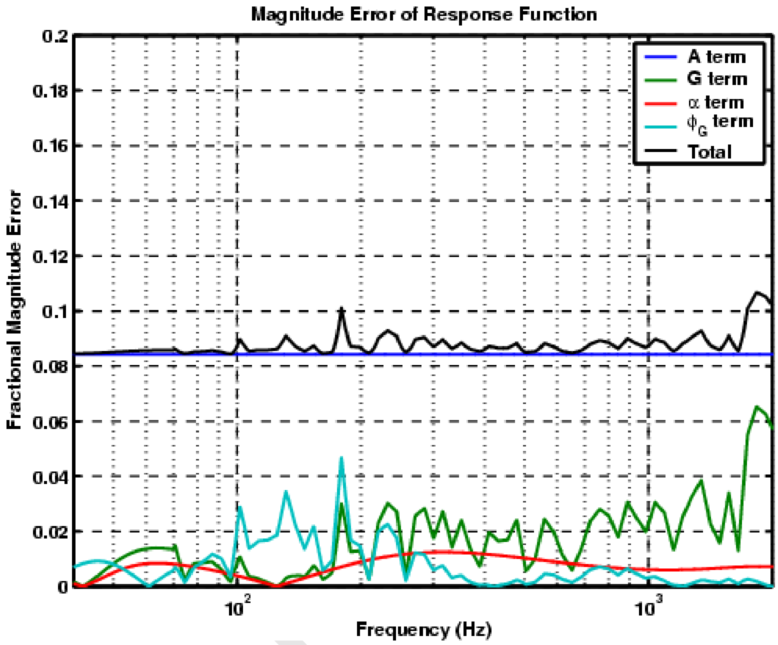

Figure 29: Contributions to the magnitude uncertainty for L1 after GPS time 731714478.

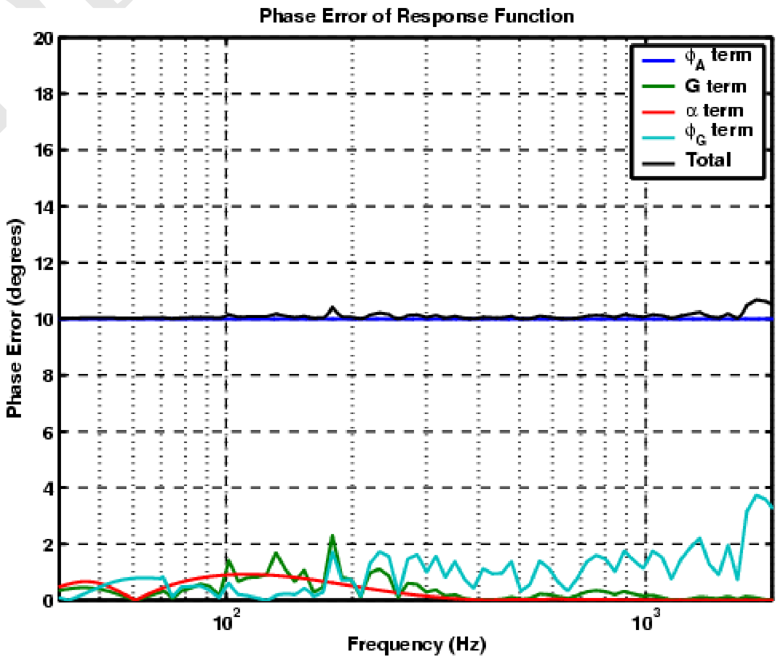

Figure 30: Contributions to the phase uncertainty for L1 after GPS time 731714478.

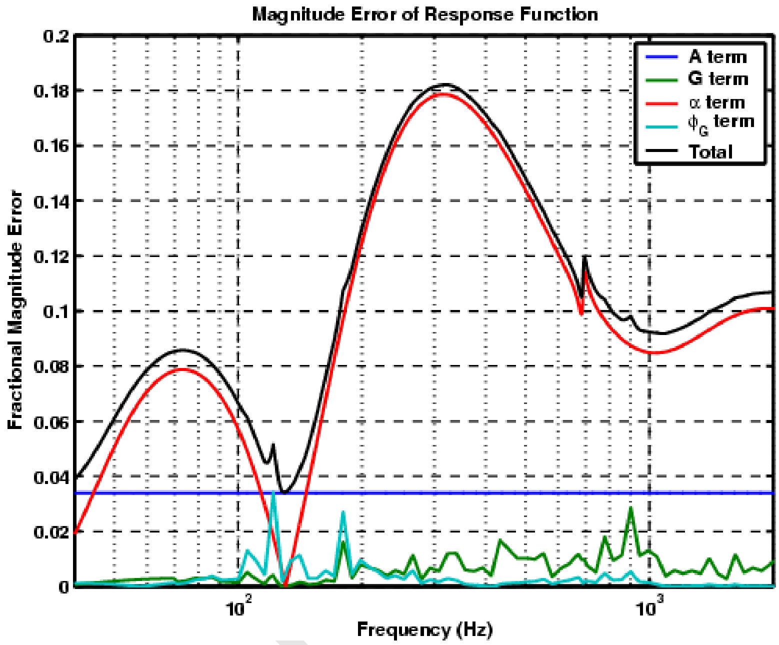

Figure 31: Contributions to the magnitude uncertainty for H1 before GPS time 730793022.

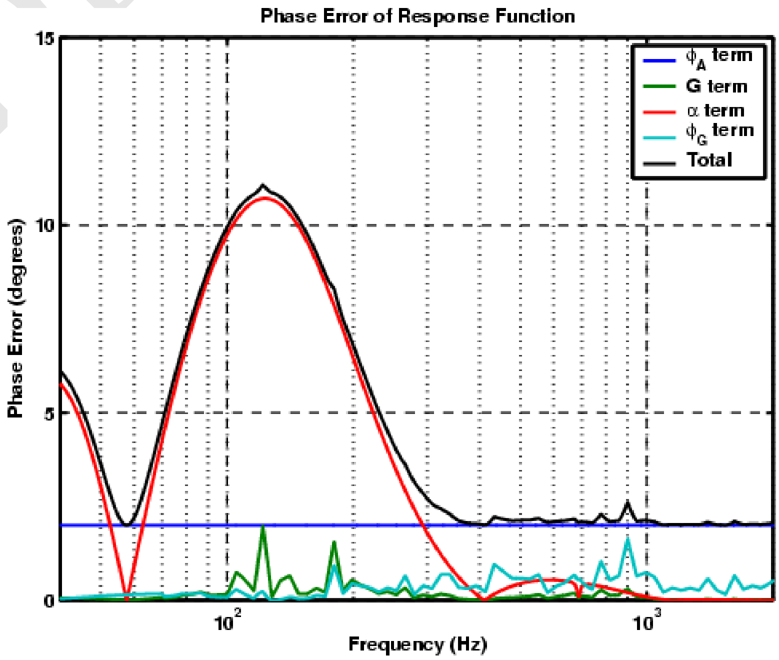

Figure 32: Contributions to the phase uncertainty for H1 before GPS time 730793022.

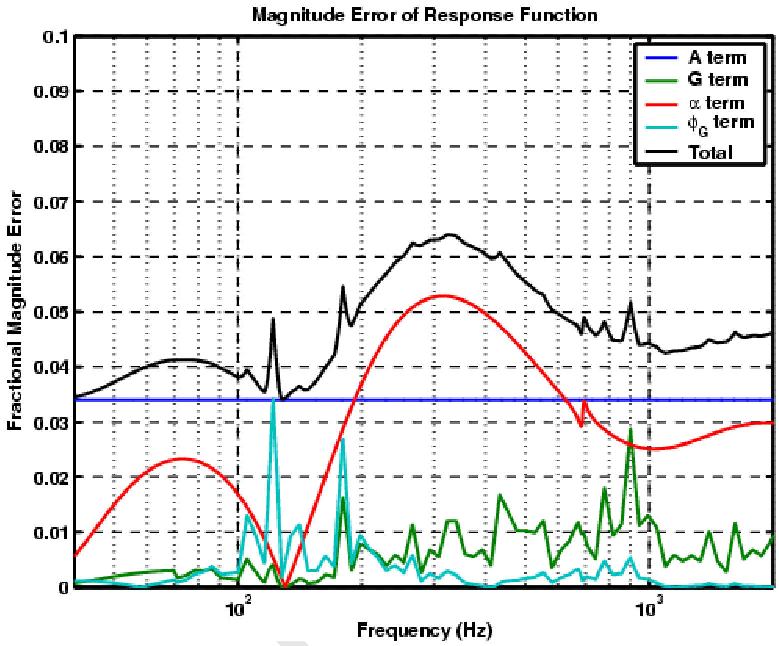

Figure 33: Contributions to the magnitude uncertainty for H1 after GPS time 730793022.

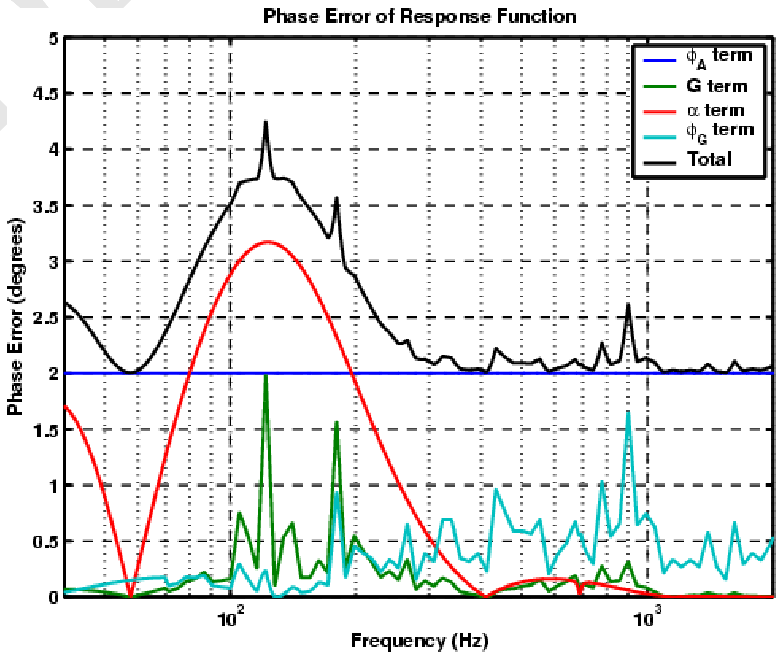

Figure 34: Contributions to the phase uncertainty for H1 after GPS time 730793022.

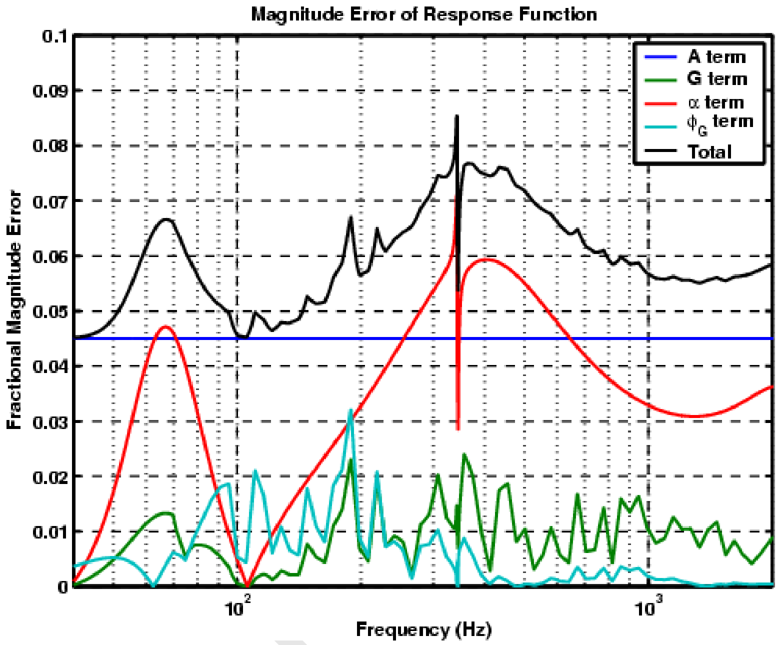

Figure 35: Contributions to the magnitude uncertainty for H2.

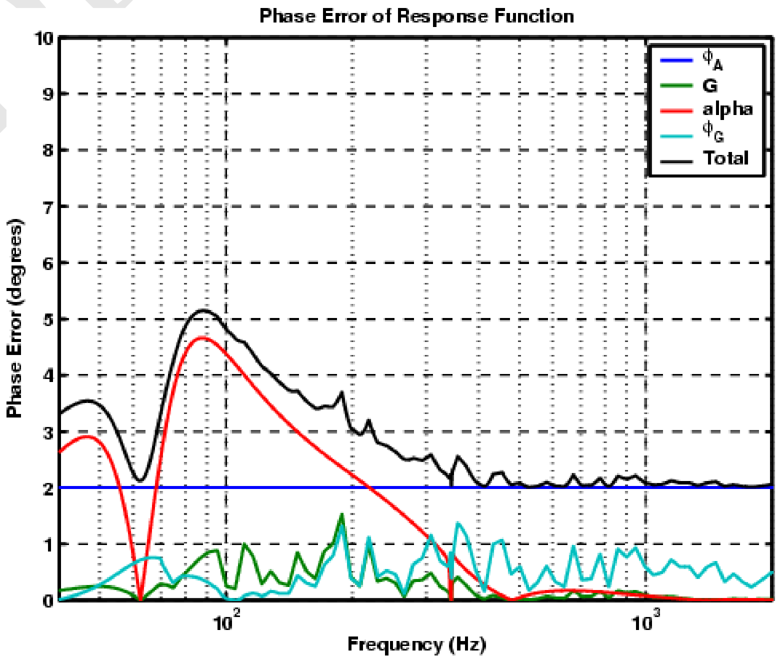

Figure 36: Contributions to the phase uncertainty for H2.

[3] Sutton P., *SenseMonitor: An Inspiral Sensitivity Monitor for the DMT* T040065-00-Z

[4] Adhikari R, Evans M, Landry M, Marka S, Matone L and Yamamoto H, *Input Test Mass (ITM) Absolute Calibrations: Fringe Counting, Fringe Fitting, and Sign Toggling Methods* T020141-00-D

[5] Bendat J. S., Piersol A. G. *Random Data Analysis and Measurement Procedures* Third Edition

[6] LIGO Amplitude Calibration Homepage
http://blue.ligo-wa.caltech.edu/engrun/Calib_Home/

[7] The stochastic search group elog, Nov 25, 02, entry by M. Landry
http://http://ldas-sw.ligo.caltech.edu/ilog/pub/ilog.cgi

[8] The LLO detector group elog, Feb 12 03, entry by B. O'Reilly
http://http://www.ligo-la.caltech.edu/ilog/pub/ilog.cgi

A MATLAB model of the interferometers

```
function [varargout] = LSCmodel(varargin)
% LSCmodel   ------------------------------------------------------%%%
% Evaluates a model of one of the interferometers LSC feedback loops %%
% Usage:                                                             %%
%        [openloopgain, sensing, actuation, response]                %%
%        = LSCmodel(IFOin,'darm',f,ugf)                              %%
%                                                                    %%
%                                                                    %%
%      Returns the open loop gain (OLG, unitless),                   %%
%      Sensing function (SENSE, in counts/meter), etc.               %%
%       each in a 2 column array, where                              %%
%         the first column is the frequency vector (real) and        %%
%         the second column is the response vector (complex)         %%
%                                                                    %%
%     the response function R is in strain/count                     %%
%        i.e.  h(f) = AS_Q(f) * R(f)                                 %%
% - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -- - - - -
%  v 1.1.0   Aug  4th, 2003
%  v 1.1.1   Aug 14th, 2003  - Some comments added
%  v 1.2.2   Aug 17th, 2003  - Added SUS LSC filters
%  v 1.2.3   Aug 25th, 2003  - added ugf as 4th varargin
%                              + fixed x2 bug in 'hd' calculation
%-------------------------------------------------------------------%%%

global lsc


%----- Parse input arguments ----------------------------%%%%
if nargin < 1
  error('Not enough inputs: specify IFO params!')

elseif nargin > 0
  IFOin = varargin{1};
  loop_name = 'darm';       % default loop is DARM
  lsc = eval(strcat('IFOin.',loop_name));
  ff = logspace(log10(lsc.fl),log10(lsc.fu),lsc.npt);

  if nargin > 1
    loop_name = varargin{2};

    if nargin > 2
      ff = varargin{3};
      fdim = size(ff);
      if fdim(1) > 1 & fdim(2) == 1
        ff = ff';
      end

        if nargin > 3               % 4th argument is UGF
          lsc.ugf = varargin{4};
        end
    end
  end

else
  error('%s','Invalid Number of Input Arguments')
end
%---------------------------------------------------------%%%%%



switch upper(loop_name)
 case 'CM'
  module_name = 'LSC';
 otherwise
  module_name = loop_name;
  mcld = zeros(size(ff))';
  aod = zeros(size(ff))';
end

n = 1:length(ff);

if max(ff) < lsc.ugf
   warning('Specified frequencies are below the UGF')
   ff_low = log10(max(ff)+1);
   ff_higher = log10(lsc.ugf*3);
   ff_plus = logspace(ff_low,ff_higher,301);
   ff = [ff ff_plus];
   quack = 1;
end



ugf = lsc.ugf;
iugf = min(find(ff>ugf));

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%     Analog portion of loop               %%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
lscpend = pendulum(lsc);
```

```
fc = lsc.cavpole;          % cavity pole
cavpole = zpk([], -2*pi*fc, 2*pi*fc);

aa = IFOin.misc.aa;
ai = IFOin.misc.ai;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%% Time Delay  %%%%%%%%%%
[num,den] = pade(lsc.tdelay,4);
tdelay = tf(num,den);

%%%%%%%%%% DAC sample-and-hold  %%%%%%%%%%%%%%%%%%%%
fs = lsc.fs;
d2a = (sin(pi*ff/fs)./(pi*ff/fs)).*exp(-i*pi*ff/fs);

%%%%%%%%%% Coil Driver Snubber Circuit  %%%%%%%%%%%%%%%%%%%
snub = snubber(lsc);

%%%%%%%%%%%%  Sensing function   %%%%%%%%%%%%%%%%%%%
sense = cavpole * lsc.hflowpass * aa * lsc.electronics_gain;
%%%%%%%%%%% Actuation function   %%%%%%%%%%%%%%%%%%%
actuation = lscpend * ai * tdelay * snub;
dcgain(actuation)
%%%%%%%%%  compute freq response vectors  %%%%%%%%%%
hsense = squeeze(freqresp(sense,2*pi*ff));
hact = d2a’ .* squeeze(freqresp(actuation,2*pi*ff));
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%             Digital portion of loop                %%%
%                                                          %%
% First filter file is for the LSC loop (e.g. DARM)        %%
% The 2nd & 3rd are for the SUS modules (e.g. ETMX & ETMY) %%
% It still works even there’s just one mass (e.g. RM)      %%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
filtnums = lsc.digitalfilters;
file = lsc.filterfile;
[sos,dgain,filtname] = ...
    readfilters(file,upper(module_name),filtnums);
clear h
for ii = 1:size(sos,1),
    [b,a] = sos2tf(sos(ii,:));
    h(ii,:) = freqz(b,a,ff,fs);
end
hd = prod(h,1);
hd = shiftdim(hd,1);
hd = dgain * lsc.lsc_gain * lsc.itmtrx * hd;

if ischar(lsc.susfilterfile1)
  filtnums = lsc.susdigitalfilters1;
  file = lsc.susfilterfile1;
  [sos,dgain,filtname] = ...
    readfilters(file,upper(’LSC’),filtnums);
  clear h
  for ii = 1:size(sos,1),
    [b,a] = sos2tf(sos(ii,:));
    h(ii,:) = freqz(b,a,ff,fs);
  end
  hd1 = prod(h,1);
  hd1 = shiftdim(hd1,1);
  if ~ischar(lsc.susfilterfile2)
    hact = hact .* hd1;
  end
end

if ischar(lsc.susfilterfile2)
  filtnums = lsc.susdigitalfilters2;
  file = lsc.susfilterfile2;
  [sos,dgain,filtname] = ...
    readfilters(file,upper(’LSC’),filtnums);
  clear h
  for ii = 1:size(sos,1),
    [b,a] = sos2tf(sos(ii,:));
    h(ii,:) = freqz(b,a,ff,fs);
  end
  hd2 = prod(h,1);
  hd2 = shiftdim(hd2,1);
  if ischar(lsc.susfilterfile1)
    hact = hact .* (hd1 + hd2)/2;
  else
    hact = hact .* hd2;
  end
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%       Total loop gain                    %%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
lscolg = hsense .* hact .* hd;
gtemp = abs(lscolg(iugf));
lscolg = lscolg / gtemp;                   % Sensing gain fudged to
hsense = hsense / gtemp;                   % get the UGF right
response = 1./hsense .* (1 + lscolg);

%%%%%%%%%%%%%%%%% Put returned data into arrays %%%%%%%%%%%
openloopgain = [ff(n)’ lscolg(n)];
sensing = [ff(n)’ hsense(n)];
```

```
actuating = [ff(n)' hact(n)];
response = [ff(n)' response(n)];
%%%%%%  optional AO loop gain for CM servo %%%%%%%%%%%%%%
switch upper(loop_name)
 case 'CM'
  mcl2f = squeeze(freqresp(lsc.mcl2f,2*pi*ff));
  mcld = lscolg .* mcl2f;
  hact = hact .* mcl2f;

  ao = zpk(cavpole * lsc.hflowpass * lsc.ao_c);
  aod = squeeze(freqresp(ao,2*pi*ff));
  nn = min(find(ff>ugf));
  ao_fudge = abs(aod(nn));                 % Fudges AO to set the UGF
  aod = aod / ao_fudge;

  nn = min(find(ff>lsc.xover));
  mcl_fudge = abs(mcld(nn)/aod(nn));      % Fudges MCL to set xover freq
  mcld = mcld / mcl_fudge;

  hsense = hsense / mcl_fudge;

  lscolg = mcld + aod;

  response = 1./hsense .* (1 + lscolg);
  %%%%%%%%%% Put returned data into arrays %%%%%
  openloopgain = [ff(n)' lscolg(n) mcld(n) aod(n)];
  sensing = [ff(n)' hsense(n)];
  actuating = [ff(n)' hact(n)];
  response = [ff(n)' response(n)];

end
%%%%%%%%%%%%%%%%% Output Argument Assignments %%%%%%%%%%%
if nargout < 1
    mybodeplot(openloopgain)
elseif nargout > 0
  varargout(1) = {openloopgain};
  if nargout > 1
    varargout(2) = {sensing};
    if nargout > 2
      varargout(3) = {actuating};
      if nargout == 4
        varargout(4) = {response};
      end
    end
  end
elseif nargout > 4
  error('Too Many Output Arguments')
end

return

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% ------------------------------------------------------
% Sub-functions of LSCmodel  -----------------------
% \/\/\/\/\/\/\/\/\/\/\/\/\/\/\/\/\/\/\/\/\/\/\/\
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function lscpend = pendulum(lsc)

wp = 2 * pi * lsc.pendf0;
Qp = lsc.pendQ;
sys = tf(wp^2, [1 wp/Qp wp^2]);
DCcal = lsc.DCcal;
lscpend = DCcal * sys;

return
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function snub = snubber(lsc)

R_ser = lsc.R_ser;
R_snub = lsc.R_snub;
C_snub = lsc.C_snub;
C_cabl = lsc.C_cabl;
R_coil = lsc.R_coil;
H_coil = lsc.H_coil;

A_snub = R_snub * C_snub;
den_s3 = A_snub*C_cabl*H_coil*R_ser;
den_s2 = R_ser*A_snub*R_coil*C_cabl+R_ser*C_cabl*H_coil+ ...
              R_ser*C_snub*H_coil+A_snub*H_coil;
den_s1 = R_ser*A_snub+C_cabl*R_coil+C_snub*R_coil+...
              A_snub*R_coil+H_coil;
den_s0 = R_coil+R_ser;
TF_gain= R_coil + R_ser;
snub = TF_gain * tf([A_snub 1],[den_s3 den_s2 den_s1 den_s0]);
return
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [sos,gain,name] = readfilters(file,module,varargin)

ret = 1;
fm = [varargin{:}];
```

```
fid = fopen(file);
firstflag = 1;
mlen = length(module);

while 1

  tline = fgetl(fid);

  if ~ischar(tline), break, end

  if strncmp(tline,module,mlen)

    arr = strread(tline,'%s','delimiter',' ');
    rfm = str2double(arr(2));

    if ismember(rfm,fm)
      if firstflag
        name = arr(7);
        gain = str2double(arr(8));
        coef = str2double([arr(9) arr(10) arr(11) arr(12)]);
firstflag = 0;
      else
        name = strcat(name,'/',arr(7));
        gain = gain*str2double(arr(8));
        coef = [coef str2double([arr(9) arr(10) arr(11) arr(12)])];
      end

      nsos = str2double(arr(4));

      if nsos > 1
        for ksos=1:nsos-1
       tline = fgetl(fid);
       arr = strread(tline,'%s','delimiter',' ');
       coef = [coef str2double([arr(1) arr(2) arr(3) arr(4)])];
    end;
      end
    end;
  end
end
fclose(fid);
g = coef;
dim = length(g);
n2b = dim/4;
soscoef = [];

for i = 1:n2b,
   a = [1, g(1+(i-1)*4), g(2+(i-1)*4)];
   b = [1, g(3+(i-1)*4), g(4+(i-1)*4)];
   soscoef = [soscoef; b(1) b(2) b(3) a(1) a(2) a(3)];
end
sos = soscoef;
return
%%%%%% ***************************************************************
```

B Parameter file for L1

```
function L1 = L1IFOparams;
% Parameter file for Interferometer LSC loop model
%
% version 1.0.1      Updated AA & AI filter to match board measurements
% version 1.2.3      Cavity pole -> 82.6  Andri elog ~August
%%%%%%%%   frequencies of interest   %%%%%%%%%%%%%%%%
darm.fl  = 9;                                    % lower frequency of band, Hz
darm.fu  = 8000;                                 % upper frequency of band, Hz
darm.npt = 301;                                  % number of points in band
darm.fs  = 16384;                                % sampling frequency, Hz
darm.ugf = 175;                                  % unity gain frequency of loop, Hz

%%%%%%%%%  parameters of the plant    %%%%%%%%%%%%%%%
darm.cavpole = 82.6;                             % cavity pole, Hz
darm.pendf0  = 0.76;                             % pendulum eigenfrequency, Hz
darm.pendQ   = 10;                               % pendulum Q
darm.ETMXcal = 0.40e-9;                          % DC calibration of ETMX, m/count
darm.ETMYcal = 0.37e-9;                          % DC calibration of ETMY, m/count
darm.tdelay  = 160e-6;                           % time delay in loop, sec
darm.armlength = 3995.15;                        % arm length in meters
darm.hflowpass = ...
    zpk([],-2*pi*[33e3 33e3 33e3],...
        (2*pi*33e3)^3);                          % RC lowpass in L1 after mixer

%%%%%%%%%%% digital filters  %%%%%%%%%%%%%%%%%%%%%%%%
%% specify vector of DARM digital filters engaged %%%
%% Note: FM1 = 0, FM2 = 1, etc                    %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
darm.filterfile = '/home/irish/FOTON/L1/L1LSC.txt';
darm.digitalfilters = [0,1,2,3,4];

darm.susfilterfile1 = '/home/irish/FOTON/L1/L1SUS_ETMX.txt';
darm.susdigitalfilters1 = [3,4];

darm.susfilterfile2 = '/home/irish/FOTON/L1/L1SUS_ETMY.txt';
darm.susdigitalfilters2 = [3,4];

%%%%%%%%%%% digital gains  %%%%%%%%%%%%%%%%%%%%%%%%%%
darm.darm2etmx =  2.5;                           % Output matrix: DARM to ETMX
darm.darm2etmy = -2.5;                           % Output matrix: DARM to ETMY
darm.itmtrx = 0.012;                            % Input matrix: AS_Q to DARM
darm.lsc_gain = -1.0;                           % DARM filter module gain

darm.DCcal = darm.ETMYcal * darm.darm2etmy -...  % DARM_CTRL cal
             darm.ETMXcal * darm.darm2etmx;

%%%%%%%%%%% snubber component values  %%%%%%%%%%%%%%%
%% snubber is a series RC (R_snub & C_snub), in  %%%%
%% parallel with the coil                        %%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
darm.R_ser  = 3000;                              % Coil Driver series resistor
darm.R_snub = 680;                               % snubber series resistor
darm.C_snub = 0.022e-6;                          % snubber series cap
darm.C_cabl = 800e-12;                           % ribbon cable capacitance
darm.R_coil = 22;                                % OSEM coil resistance
darm.H_coil = 3.3e-3;                            % OSEM coil inductance


% Misc Info (mostly unused) --------------------------------------------------------
darm.opgain = 1.2e9;                          % Calculated watts/meter
darm.efficiency = 0.9;                        % PO fraction * 90/10 split
darm.eta = 0.8;                               % Amps / Volt
darm.Zrf = 140;                               % Tank circuit impedance
darm.Grf = 10;                                % Pre-amp gain
darm.Cable = 0.67;                            % 3.5 dB of loss in 100' of RG-405
darm.PS = 0.707;                              % 3 dB loss in power splitter
darm.Mixer = 0.5;                             % 6 dB loss in mixer
darm.WG = 10^(24/20);                         % 24 dB of whitening gain
darm.AA = 2;                                  % Gain of 2 in single-diff conv
darm.ADC = 32768/10;                          % 16-bit Analog to Digital conversion
darm.AS1_Q_GAIN = 0.005;                      % Compensates some whitening gain

darm.electronics_gain = darm.eta *...        % Counts / Watt
                        darm.Zrf *...
                        darm.Grf *...
                        darm.Cable *...
                        darm.PS *...
                        darm.Mixer *...
                        darm.WG *...
                        darm.AA *...
                        darm.ADC *...
                        darm.AS1_Q_GAIN;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%



%-----------------------------------------------------------------------------------
% Parameter file for MICH loop model
%
```

```
%%%%%%%%   frequencies of interest   %%%%%%%%%%%%%%%%
mich.fl  = 0.9;                                 % lower frequency of band, Hz
mich.fu  = 1000;                                % upper frequency of band, Hz
mich.npt = 301;                                 % number of points in band
mich.fs  = 16384;                               % sampling frequency, Hz
mich.ugf = 10;                                  % unity gain frequency of loop, Hz

%%%%%%%%%  parameters of the plant    %%%%%%%%%%%%%%%
mich.cavpole = 1e6;                             % Something must happen here
mich.pendf0  = 0.75;                            % pendulum eigenfrequency, Hz
mich.pendQ   = 10;                              % pendulum Q
mich.RMcal = 0.38e-9;                           % DC calibration of RM, m/count
mich.BScal = 0.8e-9;
mich.tdelay  = 150e-6;                          % time delay in loop, sec
mich.schnupp = 0.31;                            % (ly-lx)
mich.hflowpass = ...
    zpk([],-2*pi*[100e3],...
        (2*pi*100e3));                         % RC lowpass in L1 after mixer

%%%%%%%%%%% digital filters  %%%%%%%%%%%%%%%%%%%%%%%%
%% specify vector of MICH digital filters engaged %%%
%% Note: FM1 = 0, FM2 = 1, etc                     %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
mich.filterfile = '/home/irish/FOTON/L1/L1LSC.txt';
mich.digitalfilters = [0,1,2,3,5];

%%%%%%%%%%% digital gains  %%%%%%%%%%%%%%%%%%%%%%%%%%
mich.mich2rm = -10.5;                           % Output matrix: MICH to RM
mich.mich2bs = 7.4;                             % Output matrix: MICH to BS
mich.itmtrx = -0.666;                           % Input matrix: POB_Q to MICH
mich.lsc_gain = -0.08;                         % MICH filter module gain

mich.DCcal = (sqrt(2) * mich.BScal * mich.mich2bs +...
                        mich.RMcal * mich.mich2rm) -...
                        mich.RMcal * mich.mich2rm;       % MICH_CTRL cal

%%%%%%%%%%% snubber component values  %%%%%%%%%%%%%%%
%% snubber is a series RC (R_snub & C_snub), in  %%%%
%% parallel with the coil                        %%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
mich.R_ser  = 3000;                             % series resistor
mich.R_snub = 680;                              % snubber series resistor
mich.C_snub = 0.022e-6;                         % snubber series cap
mich.C_cabl = 800e-12;                          % cable capacitance
mich.R_coil = 22;                               % coil resistance
mich.H_coil = 3.3e-3;                           % coil inductance

% Misc Info (mostly unused) --------------------------------------------------------
mich.opgain = 2;                               % Calculated watts/meter
mich.efficiency = 0.9 * 80e-6;                 % EO Shutter, clipping, etc.
mich.eta = 0.8;                                % Amps / Volt
mich.Zrf = 380;                                % Tank circuit impedance
mich.Grf = 10;                                 % Pre-amp gain
mich.Cable = 0.67;                             % 3.5 dB of loss in 100' of RG-405
mich.PS = 0.707;                               % 3 dB loss in power splitter
mich.Mixer = 0.5;                              % 6 dB loss in mixer
mich.WG = 10^(36/20);                          % 24 dB of whitening gain
mich.AA = 2;                                   % Gain of 2 in single-diff conv
mich.ADC = 32768/10;                           % 16-bit Analog to Digital conversion
mich.POB_Q_GAIN = 0.125;                       % Compensates some whitening gain

mich.electronics_gain = mich.eta *...       % Counts / Watt
                        mich.Zrf *...
                        mich.Grf *...
                        mich.Cable *...
                        mich.PS *...
                        mich.Mixer *...
                        mich.WG *...
                        mich.AA *...
                        mich.ADC *...
                        mich.POB_Q_GAIN;
%--------------------------------------------------------------------------------


%********************************************************************************
% Parameter file for PRC loop model
%
%%%%%%%%   frequencies of interest   %%%%%%%%%%%%%%%%
prc.fl  = 9;                                    % lower frequency of band, Hz
prc.fu  = 1000;                                 % upper frequency of band, Hz
prc.npt = 301;                                  % number of points in band
prc.fs  = 16384;                                % sampling frequency, Hz
prc.ugf = 30;                                   % unity gain frequency of loop, Hz

%%%%%%%%%  parameters of the plant    %%%%%%%%%%%%%%%
prc.cavpole = 100e3;                            % PRC pole??
prc.pendf0  = 0.75;                             % pendulum eigenfrequency, Hz
prc.pendQ   = 10;                               % pendulum Q
prc.RMcal = 0.38e-9;                            % DC calibration of RM, m/count

prc.tdelay  = 170e-6;                           % time delay in loop, sec
```

```
prc.rclength = 9.204;                           % (l1+l2)/2
prc.hflowpass = ...
    zpk([],-2*pi*[100e3],...
        (2*pi*100e3));                         % RC lowpass in L1 after
                                               % mixer

%%%%%%%%%%% digital filters  %%%%%%%%%%%%%%%%%%%%%%%%
%% specify vector of PRC digital filters engaged %%%
%% Note: FM1 = 0, FM2 = 1, etc                    %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
prc.filterfile = '/home/irish/FOTON/L1/L1LSC.txt';
prc.digitalfilters = [0,1,2,3,4,5];

%%%%%%%%%%% digital gains  %%%%%%%%%%%%%%%%%%%%%%%%%%
prc.prc2rm = 7.4;                               % Output matrix: PRC to RM
prc.itmtrx = 0.17;                              % Input matrix: POB_I to PRC
prc.lsc_gain = -0.125;                          % PRC filter module gain

prc.DCcal = -prc.RMcal * prc.prc2rm;            % PRC_CTRL cal

%%%%%%%%%%% snubber component values  %%%%%%%%%%%%%%%
%% snubber is a series RC (R_snub & C_snub), in  %%%%
%% parallel with the coil                         %%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
prc.R_ser  = 3000;                              % series resistor
prc.R_snub = 680;                               % snubber series resistor
prc.C_snub = 0.022e-6;                          % snubber series cap
prc.C_cabl = 800e-12;                           % cable capacitance
prc.R_coil = 22;                                % coil resistance
prc.H_coil = 3.3e-3;                            % coil inductance

% Misc Info (mostly unused) -----------------------------------------------------
prc.opgain = 1.2e9;                             % Calculated watts/meter
prc.efficiency = mich.efficiency;               % PO fraction * 90/10 split
prc.eta = mich.eta;                             % Amps / Volt
prc.Zrf = mich.Zrf;                             % Tank circuit impedance
prc.Grf = mich.Grf;                             % Pre-amp gain
prc.Cable = mich.Cable;                         % 3.5 dB of loss in 100' of RG-405
prc.PS = mich.PS;                               % 3 dB loss in power splitter
prc.Mixer = mich.Mixer;                         % 6 dB loss in mixer
prc.WG = 10^(36/20);                            % 36 dB of whitening gain
prc.AA = mich.AA;                               % Gain of 2 in single-diff conv
prc.ADC = mich.ADC;                             % 16-bit Analog to Digital conversion
prc.POB_I_GAIN = 0.125;                         % Compensates some whitening gain

prc.electronics_gain = prc.eta *...       % Counts / Watt
                         prc.Zrf *...
                         prc.Grf *...
                         prc.Cable *...
                         prc.PS *...
                         prc.Mixer *...
                         prc.WG *...
                         prc.AA *...
                         prc.ADC *...
                         prc.POB_I_GAIN;
%*******************************************************************************


% Parameter file for CARM loop model
%
%%%%%%%%   frequencies of interest   %%%%%%%%%%%%%%%%
carm.fl  = 9;                                   % lower frequency of band, Hz
carm.fu  = 8000;                                % upper frequency of band, Hz
carm.npt = 301;                                 % number of points in band
carm.fs  = 16384;                               % sampling frequency, Hz
carm.ugf = 150;                                 % unity gain frequency of loop, Hz

%%%%%%%%%  parameters of the plant    %%%%%%%%%%%%%%%
carm.cavpole = 1;                               % cavity pole, Hz
carm.pendf0  = 0.75;                            % pendulum eigenfrequency, Hz
carm.pendQ   = 10;                              % pendulum Q
carm.ETMXcal = 0.38e-9;                         % DC calibration of ETMX, m/count
carm.ETMYcal = 0.38e-9;                         % DC calibration of ETMY, m/count
carm.tdelay  = 100e-6;                          % time delay in loop, sec
carm.armlength = 3995.15;                       % arm length in meters
carm.hflowpass = ...
    zpk([],-2*pi*[33e3 33e3 33e3],...
        (2*pi*33e3)^3);                         % RC lowpass in L1 after mixer


%%%%%%%%%%% digital filters  %%%%%%%%%%%%%%%%%%%%%%%%
%% specify vector of CARM digital filters engaged %%%
%% Note: FM1 = 0, FM2 = 1, etc                     %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
carm.filterfile = '/home/irish/FOTON/L1/L1LSC.txt';
carm.digitalfilters = [0,1,2];

%%%%%%%%%%% digital gains  %%%%%%%%%%%%%%%%%%%%%%%%%%
carm.carm2etmx = -2.5;                          % Output matrix: CARM to ETMX
carm.carm2etmy = -2.5;                          % Output matrix: CARM to ETMY
carm.itmtrx = 0.05;                             % Input matrix: REFL_I to CARM
```

```
carm.lsc_gain = -1.5;                           % CARM filter module gain

carm.DCcal = carm.ETMXcal * carm.carm2etmx +...
             carm.ETMYcal * carm.carm2etmy;

%%%%%%%%%%% snubber component values  %%%%%%%%%%%%%%%
%% snubber is a series RC (R_snub & C_snub), in  %%%%
%% parallel with the coil                        %%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
carm.R_ser  = 3000;                             % series resistor
carm.R_snub = 680;                              % snubber series resistor
carm.C_snub = 0.022e-6;                         % snubber series cap
carm.C_cabl = 800e-12;                          % cable capacitance
carm.R_coil = 22;                               % coil resistance
carm.H_coil = 3.3e-3;                           % coil inductance

% Misc Info (mostly unused) --------------------------------------------------------
carm.opgain = 1.2e9;                         % Calculated watts/meter
carm.efficiency = 0.125;               % PO fraction * 90/10 split
carm.eta = 0.8;                              % Amps / Volt
carm.Zrf = 320;                              % Tank circuit impedance
carm.Grf = 10;                               % Pre-amp gain
carm.Cable = 0.67;                           % 3.5 dB of loss in 100' of RG-405
carm.PS = 0.707;                             % 3 dB loss in power splitter
carm.Mixer = 0.5;                            % 6 dB loss in mixer
carm.WG = 10ˆ(30/20);                        % 36 dB of whitening gain
carm.AA = 2;                                 % Gain of 2 in single-diff conv
carm.ADC = 32768/10;                         % 16-bit Analog to Digital conversion
carm.REFL_I_GAIN = -1.0;                      % Compensates some whitening gain

carm.electronics_gain = carm.eta *...       % Counts / Watt
                          carm.Zrf *...
                          carm.Grf *...
                          carm.Cable *...
                          carm.PS *...
                          carm.Mixer *...
                          carm.WG *...
                          carm.AA *...
                          carm.ADC *...
                          carm.REFL_I_GAIN;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


%~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
% - - - Miscellaneous Parameters - - -
%_____________________________________________________________________________

mc.Lmc = 12.243;                                % MC round trip L = 25 m
mc.Tmc1 = 2000e-6;                              % Power transmission
mc.Tmc2 = 10e-6;
mc.Tmc3 = 2000e-6;
mc.m_sos = 0.25;                                % SOS mass in kg
mc.sys = load('/home/irish/mat/cm/mcob.mat');
mc.ao = -zpk(mc.sys.mcsys(7,8));
mc.mcl = -zpk(mc.sys.mcsys(7,11));

los.m = 10.5;                                   % LOS mass in kg
los.phi = 1e-3;                                 % Loss angle of steel wire
los.wirelength = 0.442;                         % LOS wire length
los.fp = 0.75;                                  % LOS pend freq


%%%%%%%%%%%     AA & AI filtering   %%%%%%%%%%%%%%%
[z,p,k] = ellip(4,4,60,2*pi*7570,'s');
misc.ai = zpk(z,p,k*10ˆ(4/20)) * zpk([],-2*pi*13e3,2*pi*13e3);

% Fudged Anti-Imaging Filter
[z,p,k] = ellip(8,0.001,80,2*pi*7570,'s');
misc.aa = zpk(z,p,k*10ˆ(0.001/20)) *...
          zpk([],-2*pi*32768,2*pi*32768);

% Schematic AA Filter
%[z,p,k] = ellip(8,.035,80,2*pi*7570,'s');
%misc.aa = zpk(z,p,k*10ˆ(0.035/20));

misc.c = 299792458;
misc.ec = 1.6022e-19;
misc.lambda = 1064e-9;
misc.nu = misc.c / misc.lambda;
misc.alpha = 1/137.0360;
%____________________________________________________________________________



% Parameter file for Common Mode Servo loop model
%
%%%%%%%%   frequencies of interest   %%%%%%%%%%%%%%%%
cm.fl  = 9;                                   % lower frequency of band, Hz
```

```
cm.fu  = 100e3;                                 % upper frequency of band, Hz
cm.npt = 901;                                  % number of points in band
cm.fs  = 16384;                                % sampling frequency, Hz
cm.ugf = 25000;                                % unity gain frequency of loop, Hz
cm.xover = 250;                                % MCL / AO crossover freq, Hz

%%%%%%%%%%  parameters of the plant    %%%%%%%%%%%%%%%
cm.cavpole = 1;                                % cavity pole, Hz
cm.pendf0  = 1.0;                              % pendulum eigenfrequency, Hz
cm.pendQ   = 10;                               % pendulum Q
cm.MC2cal = 0.44e-9;                           % DC calibration of MC2, m/count
cm.tdelay  = 60e-6;                           % time delay in loop, sec
cm.armlength = 3995.15;                        % arm length in meters

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
cm.U9 = zpk(-2*pi*1,-2*pi*50,1);                       % Additive Offset
cm.AO_Gain = 10^(4/20);                                % path on the
cm.U15 = zpk(0,-2*pi*5,1);                             % CM board
cm.U16 = zpk(0,-2*pi*5,1);
cm.Bounce_Notch = zpk(twint(16.25,100));               % External Twin-T

cm.AOtf = cm.U9 * cm.U15 * cm.U16 * cm.Bounce_Notch * cm.AO_Gain;
cm.ao_c = cm.AOtf * mc.ao;

cm.mcl2f = mc.mcl;


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%% digital filters  %%%%%%%%%%%%%%%%%%%%%%%%
%% specify vector of CM digital filters engaged %%%
%% Note: FM1 = 0, FM2 = 1, etc                   %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
cm.filterfile = '/home/irish/FOTON/L1/L1SUS_MC2.txt';
cm.digitalfilters = [0,3,4,5,6,8,9];

%%%%%%%%%%%% digital gains  %%%%%%%%%%%%%%%%%%%%%%%%%%
cm.itmtrx = 0.05;                              % Input matrix: REFL_I to CM
cm.lsc_gain = -0.0012;                         % MC2_LSC filter module gain

cm.DCcal = cm.MC2cal;

%%%%%%%%%%%% snubber component values  %%%%%%%%%%%%%%%
%% snubber is a series RC (R_snub & C_snub), in  %%%%
%% parallel with the coil                        %%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
cm.R_ser  = 7200;                              % series resistor
cm.R_snub = 10;                               % snubber series resistor
cm.C_snub = 1e-12;                                % snubber series cap
cm.C_cabl = 800e-12;                           % cable capacitance
cm.R_coil = 22;                                % coil resistance
cm.H_coil = 3.3e-3;                            % coil inductance

% Misc Info (mostly unused) --------------------------------------------------------
cm.opgain = 1.2e9;                          % Calculated watts/meter
cm.efficiency = 0.125;                       % PO fraction * 90/10 split
cm.eta = 0.8;                               % Amps / Volt
cm.Zrf = 320;                               % Tank circuit impedance
cm.Grf = 10;                                % Pre-amp gain
cm.Cable = 0.84;                            % 1.5 dB of loss in 100' of RG-405
cm.PS = 0.707;                              % 3 dB loss in power splitter
cm.Mixer = 0.5;                             % 6 dB loss in mixer

cm.cmboost = zpk(-2*pi*3000,-2*pi*30,1);

cm.cmgain = 10^(9/20);

cm.hflowpass = cm.cmgain * cm.cmboost;

cm.WG = 10^(18/20);                         % 18 dB of whitening gain
cm.AA = 2;                                  % Gain of 2 in single-diff conv
cm.ADC = 32768/10;                          % 16-bit Analog to Digital conversion
cm.REFL_I_GAIN = -1.0;                       % Compensates some whitening gain

cm.electronics_gain =     cm.eta *...        % Counts / Watt
                          cm.Zrf *...
                          cm.Grf *...
                          cm.Cable *...
                          cm.PS *...
                          cm.Mixer *...
                          cm.WG *...
                          cm.AA *...
                          cm.ADC *...
                          cm.REFL_I_GAIN;


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%



L1.darm = darm;
```

```
L1.mich = mich;
L1.prc = prc;
L1.carm = carm;
L1.cm = cm;
L1.mc = mc;
L1.los = los;
L1.misc = misc;

return
```

C Parameter file for H1

```
function H1 = H1IFOparams;
% Parameter file for LSCmodel loop
%
% includes DARM, MICH, PRC, CM, MC
%
%%%%%%%%   frequencies of interest   %%%%%%%%%%%%%%%%
darm.fl  = 9;                                % lower frequency of band, Hz
darm.fu  = 8000;                             % upper frequency of band, Hz
darm.npt = 301;                              % number of points in band
darm.fs  = 16384;                            % sampling frequency, Hz
darm.ugf = 152;                              % unity gain frequency of loop, Hz

%%%%%%%%%  parameters of the plant    %%%%%%%%%%%%%%%
darm.cavpole = 84.8;                         % cavity pole, Hz
darm.pendf0  = 0.764;                        % pendulum eigenfrequency, Hz
darm.pendQ   = 10;                           % pendulum Q
darm.ETMXcal = 0.72e-9/0.891;                % DC calibration of ETMX, m/count
darm.ETMYcal = 0.83e-9/0.891;                % DC calibration of ETMY, m/count
darm.tdelay  = 140e-6;                       % time delay in loop, sec
darm.armlength = 3995.064;                   % mean arm length in meters
darm.hflowpass = ...
    zpk([],-2*pi*[100e3],...
        (-2*pi*100e3));                      % RC lowpass in H1 after mixer

%%%%%%%%%%% digital filters  %%%%%%%%%%%%%%%%%%%%%%%%%
%% specify vector of DARM digital filters engaged %%%
%% Note: FM1 = 0, FM2 = 1, etc                   %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
darm.filterfile = 'H1LSC.txt.030214';
%darm.filterfile = '/home/ldas-dev/calibration/s2/model/rana/ranaTF/aug17/H1LSC.txt.030214';
%darm.filterfile = '/home/rana/FOTON/H1/H1LSC.txt';
darm.digitalfilters = [0,1,2,3,7];

%% LSC ETMX
%% 0 = TMNotch
%% 3 = TM6622
%% 6 = violin2
darm.susfilterfile1 = 'H1SUS_ETMX.txt';
%darm.susdigitalfilters1 = [0,6];
darm.susdigitalfilters1 = [0,3,6];

%% LSC ETMY
%% 0 = TMNotch
%% 5 = TM6622
darm.susfilterfile2 = 'H1SUS_ETMY.txt';
%darm.susdigitalfilters2 = [0,6];
darm.susdigitalfilters2 = [0,5];

%%%%%%%%%%% digital gains  %%%%%%%%%%%%%%%%%%%%%%%%%%%
darm.darm2etmx =  1.04;                     % Output matrix: DARM to ETMX
darm.darm2etmy = -0.90;                     % Output matrix: DARM to ETMY
darm.itmtrx = -0.003;                       % Input matrix: AS_Q to DARM
darm.lsc_gain = -3.0;                       % DARM filter module gain

darm.DCcal = darm.ETMYcal * darm.darm2etmy -...  % DARM_CTRL cal
             darm.ETMXcal * darm.darm2etmx;

%%%%%%%%%%% snubber component values  %%%%%%%%%%%%%%%
%% snubber is a series RC (R_snub & C_snub), in  %%%%
%% parallel with the coil                        %%%%
%% except that for LHO, R_snub is not present    %%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
darm.R_ser  = 1010;                             % series resistor
darm.R_snub = 10;                           % snubber series resistor
darm.C_snub = 0.1e-6;                      % snubber series cap
darm.C_cabl = 800e-12;                          % cable capacitance
darm.R_coil = 25;                               % coil resistance
darm.H_coil = 3.3e-3;                           % coil inductance


% Misc Info (mostly unused) --------------------------------------------------------
darm.opgain = 1.2e9;                      % Calculated watts/meter
darm.efficiency = 0.9;                    % PO fraction * 90/10 split
darm.eta = 0.8;                              % Amps / Volt
darm.Zrf = 400;                           % Tank circuit impedance
darm.Grf = 10;                               % Pre-amp gain
```

```
darm.Cable = 0.67;                              % 3.5 dB of loss in 100' of RG-405
darm.PS = 0.707;                                % 3 dB loss in power splitter
darm.Mixer = 0.5;                               % 6 dB loss in mixer
darm.WG = 10^(18/20);                        % 18 dB of whitening gain
darm.AA = 2;                                    % Gain of 2 in single-diff conv
darm.ADC = 32768/10;                            % 16-bit Analog to Digital conversion
darm.AS1_Q_GAIN = 0.005;                     % Compensates some whitening gain

darm.electronics_gain = darm.efficiency * ...
                        darm.eta *...        % Counts / Watt
                        darm.Zrf *...
                        darm.Grf *...
                        darm.Cable *...
                        darm.PS *...
                        darm.Mixer *...
                        darm.WG *...
                        darm.AA *...
                        darm.ADC *...
                        darm.AS1_Q_GAIN;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%



%-----------------------------------------------------------------------------------
% Parameter file for MICH loop model
%
%%%%%%%   frequencies of interest   %%%%%%%%%%%%%%%
mich.fl  = 0.9;                                    % lower frequency of band, Hz
mich.fu  = 1000;                                   % upper frequency of band, Hz
mich.npt = 301;                                    % number of points in band
mich.fs  = 16384;                                  % sampling frequency, Hz
mich.ugf = 10;                                     % unity gain frequency of loop, Hz

%%%%%%%%  parameters of the plant    %%%%%%%%%%%%%%
mich.cavpole = 1e6;                                % Something must happen here
mich.pendf0  = 0.75;                               % pendulum eigenfrequency, Hz
mich.pendQ   = 10;                                 % pendulum Q
mich.RMcal = 3*0.38e-9;                              % DC calibration of RM, m/count
mich.BScal = 3*0.8e-9;
mich.tdelay  = 150e-6;                             % time delay in loop, sec
mich.schnupp = 0.31;                               % (ly-lx)
mich.hflowpass = ...
    zpk([],-2*pi*[100e3],...
        (2*pi*100e3));                            % RC lowpass in H1 after mixer

%%%%%%%%%%% digital filters  %%%%%%%%%%%%%%%%%%%%%%%%
%% specify vector of MICH digital filters engaged %%%
%% Note: FM1 = 0, FM2 = 1, etc                    %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
mich.filterfile = '/home/rana/FOTON/H1/H1LSC.txt';
mich.digitalfilters = [0,1,2,3,5];

%%%%%%%%%%% digital gains  %%%%%%%%%%%%%%%%%%%%%%%%%%
mich.mich2rm = -10.5;                              % Output matrix: MICH to RM
mich.mich2bs = 7.4;                                % Output matrix: MICH to BS
mich.itmtrx = -0.666;                              % Input matrix: POB_Q to MICH
mich.lsc_gain = -0.08;                            % MICH filter module gain

mich.DCcal = (sqrt(2) * mich.BScal * mich.mich2bs +...
                        mich.RMcal * mich.mich2rm) -...
                        mich.RMcal * mich.mich2rm;       % MICH_CTRL cal

%%%%%%%%%%% snubber component values  %%%%%%%%%%%%%%%
%% snubber is a series RC (R_snub & C_snub), in  %%%%
%% parallel with the coil                        %%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
mich.R_ser  = 3000;                                % series resistor
mich.R_snub = 680;                                 % snubber series resistor
mich.C_snub = 0.022e-6;                            % snubber series cap
mich.C_cabl = 800e-12;                             % cable capacitance
mich.R_coil = 22;                                  % coil resistance
mich.H_coil = 3.3e-3;                              % coil inductance

% Misc Info (mostly unused) --------------------------------------------------------
mich.opgain = 1e14;                             % Calculated watts/meter
mich.efficiency = 0.85;                         % EO Shutter, clipping, etc.
mich.eta = 0.8;                                 % Amps / Volt
mich.Zrf = 125;                                 % Tank circuit impedance
mich.Grf = 10;                                  % Pre-amp gain
mich.Cable = 0.67;                              % 3.5 dB of loss in 100' of RG-405
mich.PS = 0.707;                                % 3 dB loss in power splitter
mich.Mixer = 0.5;                               % 6 dB loss in mixer
mich.WG = 10^(36/20);                           % 24 dB of whitening gain
mich.AA = 2;                                    % Gain of 2 in single-diff conv
mich.ADC = 32768/10;                            % 16-bit Analog to Digital conversion
mich.POB_Q_GAIN = 0.125;                        % Compensates some whitening gain

mich.electronics_gain = mich.eta *...       % Counts / Watt
                          mich.Zrf *...
                          mich.Grf *...
                          mich.Cable *...
```

```
                         mich.PS *...
                         mich.Mixer *...
                         mich.WG *...
                         mich.AA *...
                         mich.ADC *...
                         mich.POB_Q_GAIN;
%----------------------------------------------------------------------------


%****************************************************************************
% Parameter file for PRC loop model
%
%%%%%%%%   frequencies of interest   %%%%%%%%%%%%%%%%
prc.fl  = 9;                                 % lower frequency of band, Hz
prc.fu  = 1000;                              % upper frequency of band, Hz
prc.npt = 301;                               % number of points in band
prc.fs  = 16384;                             % sampling frequency, Hz
prc.ugf = 70;                                % unity gain frequency of loop, Hz

%%%%%%%%%  parameters of the plant    %%%%%%%%%%%%%%%
prc.cavpole = 100e3;                         % PRC pole??
prc.pendf0  = 0.75;                          % pendulum eigenfrequency, Hz
prc.pendQ   = 10;                            % pendulum Q
prc.RMcal = 3*0.38e-9;                         % DC calibration of RM, m/count

prc.tdelay  = 170e-6;                        % time delay in loop, sec
prc.rclength = 9.204;                        % (l1+l2)/2
prc.hflowpass = ...
    zpk([],-2*pi*[100e3],...
        (2*pi*100e3));                      % RC lowpass in H1 after
                                            % mixer

%%%%%%%%%%% digital filters  %%%%%%%%%%%%%%%%%%%%%%%%
%% specify vector of PRC digital filters engaged %%%
%% Note: FM1 = 0, FM2 = 1, etc                    %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
prc.filterfile = '/home/rana/FOTON/H1/H1LSC.txt';
prc.digitalfilters = [0,1,2,3,4,5];

%%%%%%%%%%% digital gains  %%%%%%%%%%%%%%%%%%%%%%%%%%
prc.prc2rm = 7.4;                            % Output matrix: PRC to RM
prc.itmtrx = 0.17;                           % Input matrix: POB_I to PRC
prc.lsc_gain = -0.125;                       % PRC filter module gain

prc.DCcal = -prc.RMcal * prc.prc2rm;         % PRC_CTRL cal

%%%%%%%%%%% snubber component values  %%%%%%%%%%%%%%%
%% snubber is a series RC (R_snub & C_snub), in  %%%%
%% parallel with the coil                        %%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
prc.R_ser  = 3000;                           % series resistor
prc.R_snub = 680;                            % snubber series resistor
prc.C_snub = 0.022e-6;                       % snubber series cap
prc.C_cabl = 800e-12;                        % cable capacitance
prc.R_coil = 22;                             % coil resistance
prc.H_coil = 3.3e-3;                         % coil inductance

% Misc Info (mostly unused) -------------------------------------------------------
prc.opgain = 1.2e9;                      % Calculated watts/meter
prc.efficiency = 0.9 * 80e-6;            % PO fraction * 90/10 split
prc.eta = 0.8;                           % Amps / Volt
prc.Zrf = 380;                           % Tank circuit impedance
prc.Grf = 10;                            % Pre-amp gain
prc.Cable = 0.67;                        % 3.5 dB of loss in 100' of RG-405
prc.PS = 0.707;                          % 3 dB loss in power splitter
prc.Mixer = 0.5;                         % 6 dB loss in mixer
prc.WG = 10^(36/20);                     % 36 dB of whitening gain
prc.AA = 2;                              % Gain of 2 in single-diff conv
prc.ADC = 32768/10;                      % 16-bit Analog to Digital conversion
prc.POB_I_GAIN = 0.125;                  % Compensates some whitening gain

prc.electronics_gain = prc.eta *...        % Counts / Watt
                         prc.Zrf *...
                         prc.Grf *...
                         prc.Cable *...
                         prc.PS *...
                         prc.Mixer *...
                         prc.WG *...
                         prc.AA *...
                         prc.ADC *...
                         prc.POB_I_GAIN;
%*******************************************************************************


% Parameter file for CARM loop model
%
%%%%%%%%   frequencies of interest   %%%%%%%%%%%%%%%%
carm.fl  = 9;                                % lower frequency of band, Hz
carm.fu  = 8000;                             % upper frequency of band, Hz
carm.npt = 301;                              % number of points in band
```

```
carm.fs  = 16384;                           % sampling frequency, Hz
carm.ugf = 150;                             % unity gain frequency of loop, Hz

%%%%%%%%%  parameters of the plant    %%%%%%%%%%%%%%%
carm.cavpole = 1;                           % cavity pole, Hz
carm.pendf0  = 0.75;                        % pendulum eigenfrequency, Hz
carm.pendQ   = 10;                          % pendulum Q
carm.ETMXcal = 0.38e-9;                     % DC calibration of ETMX, m/count
carm.ETMYcal = 0.38e-9;                     % DC calibration of ETMY, m/count
carm.tdelay  = 100e-6;                      % time delay in loop, sec
carm.armlength = 3995.15;                   % arm length in meters
carm.hflowpass = ...
    zpk([],-2*pi*[33e3 33e3 33e3],...
        (2*pi*33e3)^3);                     % RC lowpass in H1 after mixer


%%%%%%%%%%% digital filters  %%%%%%%%%%%%%%%%%%%%%%%%%
%% specify vector of CARM digital filters engaged %%%
%% Note: FM1 = 0, FM2 = 1, etc                    %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
carm.filterfile = '/home/rana/FOTON/H1/H1LSC.txt';
carm.digitalfilters = [0,1,2];

%%%%%%%%%%% digital gains  %%%%%%%%%%%%%%%%%%%%%%%%%%%
carm.carm2etmx = -2.5;                      % Output matrix: CARM to ETMX
carm.carm2etmy = -2.5;                      % Output matrix: CARM to ETMY
carm.itmtrx = 0.05;                         % Input matrix: REFL_I to CARM
carm.lsc_gain = -1.5;                       % CARM filter module gain

carm.DCcal = carm.ETMXcal * carm.carm2etmx +...
             carm.ETMYcal * carm.carm2etmy;

%%%%%%%%%%% snubber component values  %%%%%%%%%%%%%%%
%% snubber is a series RC (R_snub & C_snub), in  %%%%
%% parallel with the coil                        %%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
carm.R_ser  = 3000;                         % series resistor
carm.R_snub = 680;                          % snubber series resistor
carm.C_snub = 0.022e-6;                     % snubber series cap
carm.C_cabl = 800e-12;                      % cable capacitance
carm.R_coil = 22;                           % coil resistance
carm.H_coil = 3.3e-3;                       % coil inductance

% Misc Info (mostly unused) --------------------------------------------------------
carm.opgain = 1.2e9;                     % Calculated watts/meter
carm.efficiency = 0.125;           % PO fraction * 90/10 split
carm.eta = 0.8;                          % Amps / Volt
carm.Zrf = 320;                          % Tank circuit impedance
carm.Grf = 10;                           % Pre-amp gain
carm.Cable = 0.67;                       % 3.5 dB of loss in 100' of RG-405
carm.PS = 0.707;                         % 3 dB loss in power splitter
carm.Mixer = 0.5;                        % 6 dB loss in mixer
carm.WG = 10^(30/20);                    % 36 dB of whitening gain
carm.AA = 2;                             % Gain of 2 in single-diff conv
carm.ADC = 32768/10;                     % 16-bit Analog to Digital conversion
carm.REFL_I_GAIN = -1.0;                  % Compensates some whitening gain

carm.electronics_gain = carm.eta *...       % Counts / Watt
                          carm.Zrf *...
                          carm.Grf *...
                          carm.Cable *...
                          carm.PS *...
                          carm.Mixer *...
                          carm.WG *...
                          carm.AA *...
                          carm.ADC *...
                          carm.REFL_I_GAIN;


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%



%~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
% - - - Miscellaneous Parameters - - -
%_____________________________________________________________________________

mc.Lmc = 12.243;                            % MC round trip L = 25 m
mc.Tmc1 = 2000e-6;                          % Power transmission
mc.Tmc2 = 10e-6;
mc.Tmc3 = 2000e-6;
mc.m_sos = 0.25;                            % SOS mass in kg
mc.sys = load('/home/ldas-dev/calibration/s2/model/rana/ranaTF/aug17/mcob.mat');
mc.ao = -zpk(mc.sys.mcsys(7,8));
mc.mcl = -zpk(mc.sys.mcsys(7,11));

los.m = 10.5;                               % LOS mass in kg
los.phi = 1e-3;                             % Loss angle of steel wire
los.wirelength = 0.442;                     % LOS wire length
los.fp = 0.75;                              % LOS pend freq
```

```
%%%%%%%%%%%     AA & AI filtering   %%%%%%%%%%%%%%%
[z,p,k] = ellip(4,4,60,2*pi*7570,'s');
misc.ai = zpk(z,p,k*10^(4/20)) * zpk([],-2*pi*13e3,2*pi*13e3);

[z,p,k] = ellip(8,.035,80,2*pi*7570,'s');
misc.aa = zpk(z,p,k*10^(0.035/20));

misc.c = 299792458;
misc.ec = 1.6022e-19;
misc.lambda = 1064e-9;
misc.nu = misc.c / misc.lambda;

%_____________________________________________________________________________



% Parameter file for Common Mode Servo loop model
%
%%%%%%%%   frequencies of interest   %%%%%%%%%%%%%%%%
cm.fl  = 9;                                % lower frequency of band, Hz
cm.fu  = 100e3;                             % upper frequency of band, Hz
cm.npt = 901;                              % number of points in band
cm.fs  = 16384;                            % sampling frequency, Hz
cm.ugf = 25000;                            % unity gain frequency of loop, Hz
cm.xover = 250;                            % MCL / AO crossover freq, Hz

%%%%%%%%%  parameters of the plant    %%%%%%%%%%%%%%%
cm.cavpole = 1;                            % cavity pole, Hz
cm.pendf0  = 1.0;                          % pendulum eigenfrequency, Hz
cm.pendQ   = 10;                           % pendulum Q
cm.MC2cal = 0.44e-9;                       % DC calibration of MC2, m/count
cm.tdelay  = 180e-6;                       % time delay in loop, sec
cm.armlength = 3995.15;                    % arm length in meters

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
cm.U9 = zpk(-2*pi*1,-2*pi*50,1);                   % Additive Offset
cm.AO_Gain = 10^(4/20);                            % path on the
cm.U15 = zpk(0,-2*pi*5,1);                         % CM board
cm.U16 = zpk(0,-2*pi*5,1);
cm.Bounce_Notch = zpk(twint(16.25,100));           % External Twin-T

cm.AOtf = cm.U9 * cm.U15 * cm.U16 * cm.Bounce_Notch * cm.AO_Gain;
cm.ao_c = cm.AOtf * mc.ao;



%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%% digital filters  %%%%%%%%%%%%%%%%%%%%%%%%
%% specify vector of CM digital filters engaged %%%
%% Note: FM1 = 0, FM2 = 1, etc                  %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
cm.filterfile = '/home/rana/FOTON/H1/H1SUS_MC2.txt';
cm.digitalfilters = [0,3,4,5,6,8,9];

%%%%%%%%%%%% digital gains  %%%%%%%%%%%%%%%%%%%%%%%%%%
cm.itmtrx = 0.05;                          % Input matrix: REFL_I to CM
cm.lsc_gain = -0.0012;                     % MC2_LSC filter module gain

cm.DCcal = cm.MC2cal;

%%%%%%%%%%%% snubber component values  %%%%%%%%%%%%%%%
%% snubber is a series RC (R_snub & C_snub), in  %%%%
%% parallel with the coil                        %%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
cm.R_ser  = 7200;                          % series resistor
cm.R_snub = 0;                           % snubber series resistor
cm.C_snub = 10e-12;                           % snubber series cap
cm.C_cabl = 800e-12;                       % cable capacitance
cm.R_coil = 22;                            % coil resistance
cm.H_coil = 3.3e-3;                        % coil inductance

% Misc Info (mostly unused) --------------------------------------------------------
cm.opgain = 1.2e9;                      % Calculated watts/meter
cm.efficiency = 0.125;                   % PO fraction * 90/10 split
cm.eta = 0.8;                           % Amps / Volt
cm.Zrf = 320;                           % Tank circuit impedance
cm.Grf = 10;                            % Pre-amp gain
cm.Cable = 0.67;                        % 3.5 dB of loss in 100' of RG-405
cm.PS = 0.707;                          % 3 dB loss in power splitter
cm.Mixer = 0.5;                         % 6 dB loss in mixer

cm.cmboost = zpk(-2*pi*3000,-2*pi*30,1);

cm.cmgain = 10^(9/20);

cm.hflowpass = cm.cmgain * cm.cmboost;

cm.WG = 10^(30/20);                     % 36 dB of whitening gain
cm.AA = 2;                              % Gain of 2 in single-diff conv
```

```
cm.ADC = 32768/10;                         % 16-bit Analog to Digital conversion
cm.REFL_I_GAIN = -1.0;                      % Compensates some whitening gain

cm.electronics_gain = cm.eta *...        % Counts / Watt
                          cm.Zrf *...
                          cm.Grf *...
                          cm.Cable *...
                          cm.PS *...
                          cm.Mixer *...
                          cm.WG *...
                          cm.AA *...
                          cm.ADC *...
                          cm.REFL_I_GAIN;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%



H1.darm = darm;
H1.mich = mich;
H1.prc = prc;
H1.carm = carm;
H1.cm = cm;
H1.mc = mc;
H1.los = los;
H1.misc = misc;


return
```

D Parameter file for H2

```
function H2 = H2IFOparams;
% Parameter file for DARM loop model
%
%%%%%%%%   frequencies of interest   %%%%%%%%%%%%%%%%
%darm.fl  = 9;                                    % lower frequency of band, Hz
%darm.fu  = 8000;                                 % upper frequency of band, Hz
%darm.npt = 301;                                  % number of points in band
darm.fl  = 0;                            % lower frequency of band, Hz
darm.fu  = 7000;                         % upper frequency of band, Hz
darm.npt = 448001;                       % number of points in band
darm.fs  = 16384;                        % sampling frequency, Hz
darm.ugf = 185;                          % UGF on 030412, nominal point cal date
%darm.ugf = 180;                         % UGF on 030317, mid run cal date
%darm.ugf = 113;                         % UGF on 030412, start run cal date


%%%%%%%%%  parameters of the plant    %%%%%%%%%%%%%%%
darm.cavpole = 170;                           % cavity pole, Hz
darm.pendf0  = 0.757;                         % mean pendulum eigenfrequency, Hz
darm.pendQ   = 10;                            % pendulum Q
darm.ETMXcal = 0.87e-9;                       % DC calibration of ETMX, m/count
darm.ETMYcal = 0.92e-9*1.032;                 % DC calibration of ETMY, m/count
%                                               times the increase in the POS matrices
darm.tdelay  = 145e-6;                        % time delay in loop, sec
darm.armlength = 2009.12;                     % arm length in meters
darm.hflowpass = ...
    zpk([],-2*pi*[100e3],...
        (-2*pi*100e3));                       % RC lowpass in H2 after mixer

%%%%%%%%%%% digital filters  %%%%%%%%%%%%%%%%%%%%%%%%
%% specify vector of DARM digital filters engaged %%%
%% Note: FM1 = 0, FM2 = 1, etc                    %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
darm.filterfile = 'H2LSC.txt.030210';
darm.digitalfilters = [0,1,2,3];

%darm.susfilterfile1 = 'H2SUS_ETMX.txt.030212';
darm.susfilterfile1 = 'H2SUS_ETMX.txt.030315';
darm.susdigitalfilters1 = [0,2];
%darm.susdigitalfilters1 = [0];

%darm.susfilterfile2 = 'H2SUS_ETMY.txt.030212';
darm.susfilterfile2 = 'H2SUS_ETMY.txt.030331';
darm.susdigitalfilters2 = [0,2];
%darm.susdigitalfilters2 = [0];

%%%%%%%%%%% digital gains  %%%%%%%%%%%%%%%%%%%%%%%%%%
darm.darm2etmx =  0.53;                       % Output matrix: DARM to ETMX
darm.darm2etmy = -0.50;                       % Output matrix: DARM to ETMY
darm.itmtrx = -0.015;                         % Input matrix: AS_Q to DARM
darm.lsc_gain = -0.6;                        % DARM filter module gain

darm.DCcal = darm.ETMYcal * darm.darm2etmy -...  % DARM_CTRL cal
             darm.ETMXcal * darm.darm2etmx;
```

```
%%%%%%%%%%% snubber component values  %%%%%%%%%%%%%%%
%% snubber is a series RC (R_snub & C_snub), in  %%%%
%% parallel with the coil                        %%%%
%% except that for LHO, R_snub is not present    %%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
darm.R_ser  = 1010;                              % series resistor
darm.R_snub = 10;                            % snubber series resistor
darm.C_snub = 0.1e-6;                       % snubber series cap
darm.C_cabl = 800e-12;                           % cable capacitance
darm.R_coil = 25;                                % coil resistance
darm.H_coil = 3.3e-3;                            % coil inductance


% Misc Info (mostly unused) ---------------------------------------------------------
darm.opgain = 1.2e9;                       % Calculated watts/meter
darm.efficiency = 0.9;                     % PO fraction * 90/10 split
darm.eta = 0.8;                               % Amps / Volt
darm.Zrf = 400;                            % Tank circuit impedance
darm.Grf = 10;                                % Pre-amp gain
darm.Cable = 0.67;                            % 3.5 dB of loss in 100' of RG-405
darm.PS = 0.707;                              % 3 dB loss in power splitter
darm.Mixer = 0.5;                             % 6 dB loss in mixer
darm.WG = 10^(18/20);                      % 18 dB of whitening gain
darm.AA = 2;                                  % Gain of 2 in single-diff conv
darm.ADC = 32768/10;                          % 16-bit Analog to Digital conversion
darm.AS1_Q_GAIN = 0.005;                   % Compensates some whitening gain

darm.electronics_gain = darm.efficiency * ...
                        darm.eta *...        % Counts / Watt
                        darm.Zrf *...
                        darm.Grf *...
                        darm.Cable *...
                        darm.PS *...
                        darm.Mixer *...
                        darm.WG *...
                        darm.AA *...
                        darm.ADC *...
                        darm.AS1_Q_GAIN;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%



%-----------------------------------------------------------------------------------
% Parameter file for MICH loop model
%
%%%%%%%%   frequencies of interest   %%%%%%%%%%%%%%%%
mich.fl  = 0.9;                                  % lower frequency of band, Hz
mich.fu  = 1000;                                 % upper frequency of band, Hz
mich.npt = 301;                                  % number of points in band
mich.fs  = 16384;                                % sampling frequency, Hz
mich.ugf = 10;                                   % unity gain frequency of loop, Hz

%%%%%%%%%  parameters of the plant    %%%%%%%%%%%%%%%
mich.cavpole = 1e6;                              % Something must happen here
mich.pendf0  = 0.75;                             % pendulum eigenfrequency, Hz
mich.pendQ   = 10;                               % pendulum Q
mich.RMcal = 3*0.38e-9;                            % DC calibration of RM, m/count
mich.BScal = 3*0.8e-9;
mich.tdelay  = 150e-6;                           % time delay in loop, sec
mich.schnupp = 0.31;                             % (ly-lx)
mich.hflowpass = ...
    zpk([],-2*pi*[100e3],...
        (2*pi*100e3));                          % RC lowpass in H2 after mixer

%%%%%%%%%%% digital filters  %%%%%%%%%%%%%%%%%%%%%%%%
%% specify vector of MICH digital filters engaged %%%
%% Note: FM1 = 0, FM2 = 1, etc                     %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
mich.filterfile = '/home/rana/FOTON/H2/H2LSC.txt';
mich.digitalfilters = [0,1,2,3,5];

%%%%%%%%%%% digital gains  %%%%%%%%%%%%%%%%%%%%%%%%%%
mich.mich2rm = -10.5;                            % Output matrix: MICH to RM
mich.mich2bs = 7.4;                              % Output matrix: MICH to BS
mich.itmtrx = -0.666;                            % Input matrix: POB_Q to MICH
mich.lsc_gain = -0.08;                          % MICH filter module gain

mich.DCcal = (sqrt(2) * mich.BScal * mich.mich2bs +...
                        mich.RMcal * mich.mich2rm) -...
                        mich.RMcal * mich.mich2rm;       % MICH_CTRL cal

%%%%%%%%%%% snubber component values  %%%%%%%%%%%%%%%
%% snubber is a series RC (R_snub & C_snub), in  %%%%
%% parallel with the coil                        %%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
mich.R_ser  = 3000;                              % series resistor
mich.R_snub = 680;                               % snubber series resistor
mich.C_snub = 0.022e-6;                          % snubber series cap
mich.C_cabl = 800e-12;                           % cable capacitance
mich.R_coil = 22;                                % coil resistance
mich.H_coil = 3.3e-3;                            % coil inductance
```

```
% Misc Info (mostly unused) -------------------------------------------------------
mich.opgain = 1e14;                          % Calculated watts/meter
mich.efficiency = 0.85;                      % EO Shutter, clipping, etc.
mich.eta = 0.8;                              % Amps / Volt
mich.Zrf = 125;                              % Tank circuit impedance
mich.Grf = 10;                               % Pre-amp gain
mich.Cable = 0.67;                           % 3.5 dB of loss in 100' of RG-405
mich.PS = 0.707;                             % 3 dB loss in power splitter
mich.Mixer = 0.5;                            % 6 dB loss in mixer
mich.WG = 10^(36/20);                        % 24 dB of whitening gain
mich.AA = 2;                                 % Gain of 2 in single-diff conv
mich.ADC = 32768/10;                         % 16-bit Analog to Digital conversion
mich.POB_Q_GAIN = 0.125;                     % Compensates some whitening gain

mich.electronics_gain = mich.eta *...      % Counts / Watt
                          mich.Zrf *...
                          mich.Grf *...
                          mich.Cable *...
                          mich.PS *...
                          mich.Mixer *...
                          mich.WG *...
                          mich.AA *...
                          mich.ADC *...
                          mich.POB_Q_GAIN;
%--------------------------------------------------------------------------------



%********************************************************************************
% Parameter file for PRC loop model
%
%%%%%%%%   frequencies of interest   %%%%%%%%%%%%%%%%
prc.fl  = 9;                                    % lower frequency of band, Hz
prc.fu  = 1000;                                 % upper frequency of band, Hz
prc.npt = 301;                                  % number of points in band
prc.fs  = 16384;                                % sampling frequency, Hz
prc.ugf = 70;                                   % unity gain frequency of loop, Hz

%%%%%%%%%  parameters of the plant    %%%%%%%%%%%%%%%
prc.cavpole = 100e3;                            % PRC pole??
prc.pendf0  = 0.75;                             % pendulum eigenfrequency, Hz
prc.pendQ   = 10;                               % pendulum Q
prc.RMcal = 3*0.38e-9;                            % DC calibration of RM, m/count

prc.tdelay  = 170e-6;                           % time delay in loop, sec
prc.rclength = 9.204;                           % (l1+l2)/2
prc.hflowpass = ...
    zpk([],-2*pi*[100e3],...
        (2*pi*100e3));                         % RC lowpass in H2 after
                                               % mixer

%%%%%%%%%%% digital filters  %%%%%%%%%%%%%%%%%%%%%%%%
%% specify vector of PRC digital filters engaged %%%
%% Note: FM1 = 0, FM2 = 1, etc                    %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
prc.filterfile = '/home/rana/FOTON/H2/H2LSC.txt';
prc.digitalfilters = [0,1,2,3,4,5];

%%%%%%%%%%% digital gains  %%%%%%%%%%%%%%%%%%%%%%%%%%
prc.prc2rm = 7.4;                               % Output matrix: PRC to RM
prc.itmtrx = 0.17;                              % Input matrix: POB_I to PRC
prc.lsc_gain = -0.125;                          % PRC filter module gain

prc.DCcal = -prc.RMcal * prc.prc2rm;            % PRC_CTRL cal

%%%%%%%%%%%% snubber component values  %%%%%%%%%%%%%%%
%% snubber is a series RC (R_snub & C_snub), in  %%%%
%% parallel with the coil                        %%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
prc.R_ser  = 3000;                              % series resistor
prc.R_snub = 680;                               % snubber series resistor
prc.C_snub = 0.022e-6;                          % snubber series cap
prc.C_cabl = 800e-12;                           % cable capacitance
prc.R_coil = 22;                                % coil resistance
prc.H_coil = 3.3e-3;                            % coil inductance

% Misc Info (mostly unused) -------------------------------------------------------
prc.opgain = 1.2e9;                         % Calculated watts/meter
prc.efficiency = 0.9 * 80e-6;               % PO fraction * 90/10 split
prc.eta = 0.8;                              % Amps / Volt
prc.Zrf = 380;                              % Tank circuit impedance
prc.Grf = 10;                               % Pre-amp gain
prc.Cable = 0.67;                           % 3.5 dB of loss in 100' of RG-405
prc.PS = 0.707;                             % 3 dB loss in power splitter
prc.Mixer = 0.5;                            % 6 dB loss in mixer
prc.WG = 10^(36/20);                        % 36 dB of whitening gain
prc.AA = 2;                                 % Gain of 2 in single-diff conv
prc.ADC = 32768/10;                         % 16-bit Analog to Digital conversion
prc.POB_I_GAIN = 0.125;                     % Compensates some whitening gain

prc.electronics_gain = prc.eta *...        % Counts / Watt
```

```
                         prc.Zrf *...
                         prc.Grf *...
                         prc.Cable *...
                         prc.PS *...
                         prc.Mixer *...
                         prc.WG *...
                         prc.AA *...
                         prc.ADC *...
                         prc.POB_I_GAIN;
%*********************************************************************************



% Parameter file for CARM loop model
%
%%%%%%%%   frequencies of interest   %%%%%%%%%%%%%%%%
carm.fl  = 9;                                    % lower frequency of band, Hz
carm.fu  = 8000;                                 % upper frequency of band, Hz
carm.npt = 301;                                  % number of points in band
carm.fs  = 16384;                                % sampling frequency, Hz
carm.ugf = 150;                                  % unity gain frequency of loop, Hz

%%%%%%%%%  parameters of the plant    %%%%%%%%%%%%%%%
carm.cavpole = 1;                                % cavity pole, Hz
carm.pendf0  = 0.75;                             % pendulum eigenfrequency, Hz
carm.pendQ   = 10;                               % pendulum Q
carm.ETMXcal = 0.38e-9;                          % DC calibration of ETMX, m/count
carm.ETMYcal = 0.38e-9;                          % DC calibration of ETMY, m/count
carm.tdelay  = 100e-6;                           % time delay in loop, sec
carm.armlength = 3995.15;                        % arm length in meters
carm.hflowpass = ...
    zpk([],-2*pi*[33e3 33e3 33e3],...
        (2*pi*33e3)^3);                          % RC lowpass in H2 after mixer


%%%%%%%%%%% digital filters  %%%%%%%%%%%%%%%%%%%%%%%%
%% specify vector of CARM digital filters engaged %%%
%% Note: FM1 = 0, FM2 = 1, etc                    %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
carm.filterfile = '/home/rana/FOTON/H2/H2LSC.txt';
carm.digitalfilters = [0,1,2];

%%%%%%%%%%% digital gains  %%%%%%%%%%%%%%%%%%%%%%%%%%
carm.carm2etmx = -2.5;                           % Output matrix: CARM to ETMX
carm.carm2etmy = -2.5;                           % Output matrix: CARM to ETMY
carm.itmtrx = 0.05;                              % Input matrix: REFL_I to CARM
carm.lsc_gain = -1.5;                            % CARM filter module gain

carm.DCcal = carm.ETMXcal * carm.carm2etmx +...
             carm.ETMYcal * carm.carm2etmy;

%%%%%%%%%%% snubber component values  %%%%%%%%%%%%%%%
%% snubber is a series RC (R_snub & C_snub), in  %%%%
%% parallel with the coil                        %%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
carm.R_ser  = 3000;                              % series resistor
carm.R_snub = 680;                               % snubber series resistor
carm.C_snub = 0.022e-6;                          % snubber series cap
carm.C_cabl = 800e-12;                           % cable capacitance
carm.R_coil = 22;                                % coil resistance
carm.H_coil = 3.3e-3;                            % coil inductance

% Misc Info (mostly unused) -----------------------------------------------------
carm.opgain = 1.2e9;                          % Calculated watts/meter
carm.efficiency = 0.125;                % PO fraction * 90/10 split
carm.eta = 0.8;                               % Amps / Volt
carm.Zrf = 320;                               % Tank circuit impedance
carm.Grf = 10;                                % Pre-amp gain
carm.Cable = 0.67;                            % 3.5 dB of loss in 100' of RG-405
carm.PS = 0.707;                              % 3 dB loss in power splitter
carm.Mixer = 0.5;                             % 6 dB loss in mixer
carm.WG = 10^(30/20);                         % 36 dB of whitening gain
carm.AA = 2;                                  % Gain of 2 in single-diff conv
carm.ADC = 32768/10;                          % 16-bit Analog to Digital conversion
carm.REFL_I_GAIN = -1.0;                       % Compensates some whitening gain

carm.electronics_gain = carm.eta *...        % Counts / Watt
                          carm.Zrf *...
                          carm.Grf *...
                          carm.Cable *...
                          carm.PS *...
                          carm.Mixer *...
                          carm.WG *...
                          carm.AA *...
                          carm.ADC *...
                          carm.REFL_I_GAIN;


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
%~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
% - - - Miscellaneous Parameters - - -
%______________________________________________________________________________

mc.Lmc = 12.243;                                % MC round trip L = 25 m
mc.Tmc1 = 2000e-6;                              % Power transmission
mc.Tmc2 = 10e-6;
mc.Tmc3 = 2000e-6;
mc.m_sos = 0.25;                                % SOS mass in kg
mc.sys = load('mcob.mat');
mc.ao = -zpk(mc.sys.mcsys(7,8));
mc.mcl = -zpk(mc.sys.mcsys(7,11));

los.m = 10.5;                                   % LOS mass in kg
los.phi = 1e-3;                                 % Loss angle of steel wire
los.wirelength = 0.442;                         % LOS wire length
los.fp = 0.75;                                  % LOS pend freq


%%%%%%%%%%%     AA & AI filtering   %%%%%%%%%%%%%%%
[z,p,k] = ellip(4,4,60,2*pi*7570,'s');
misc.ai = zpk(z,p,k*10^(4/20)) * zpk([],-2*pi*13e3,2*pi*13e3);

[z,p,k] = ellip(8,.035,80,2*pi*7570,'s');
misc.aa = zpk(z,p,k*10^(0.035/20));

misc.c = 299792458;
misc.ec = 1.6022e-19;
misc.lambda = 1064e-9;
misc.nu = misc.c / misc.lambda;

%_____________________________________________________________________________



% Parameter file for Common Mode Servo loop model
%
%%%%%%%%   frequencies of interest   %%%%%%%%%%%%%%%%
cm.fl  = 9;                                   % lower frequency of band, Hz
cm.fu  = 100e3;                                % upper frequency of band, Hz
cm.npt = 901;                                 % number of points in band
cm.fs  = 16384;                               % sampling frequency, Hz
cm.ugf = 25000;                               % unity gain frequency of loop, Hz
cm.xover = 250;                               % MCL / AO crossover freq, Hz

%%%%%%%%%  parameters of the plant    %%%%%%%%%%%%%%%
cm.cavpole = 1;                               % cavity pole, Hz
cm.pendf0  = 1.0;                             % pendulum eigenfrequency, Hz
cm.pendQ   = 10;                              % pendulum Q
cm.MC2cal = 0.44e-9;                          % DC calibration of MC2, m/count
cm.tdelay  = 180e-6;                          % time delay in loop, sec
cm.armlength = 3995.15;                       % arm length in meters

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
cm.U9 = zpk(-2*pi*1,-2*pi*50,1);                      % Additive Offset
cm.AO_Gain = 10^(4/20);                               % path on the
cm.U15 = zpk(0,-2*pi*5,1);                            % CM board
cm.U16 = zpk(0,-2*pi*5,1);
cm.Bounce_Notch = zpk(twint(16.25,100));              % External Twin-T

cm.AOtf = cm.U9 * cm.U15 * cm.U16 * cm.Bounce_Notch * cm.AO_Gain;
cm.ao_c = cm.AOtf * mc.ao;



%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%% digital filters  %%%%%%%%%%%%%%%%%%%%%%%%
%% specify vector of CM digital filters engaged %%%
%% Note: FM1 = 0, FM2 = 1, etc                   %%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
cm.filterfile = '/home/rana/FOTON/H2/H2SUS_MC2.txt';
cm.digitalfilters = [0,3,4,5,6,8,9];

%%%%%%%%%%% digital gains  %%%%%%%%%%%%%%%%%%%%%%%%%%
cm.itmtrx = 0.05;                             % Input matrix: REFL_I to CM
cm.lsc_gain = -0.0012;                        % MC2_LSC filter module gain

cm.DCcal = cm.MC2cal;

%%%%%%%%%%% snubber component values  %%%%%%%%%%%%%%%
%% snubber is a series RC (R_snub & C_snub), in  %%%%
%% parallel with the coil                        %%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
cm.R_ser  = 7200;                             % series resistor
cm.R_snub = 0;                              % snubber series resistor
cm.C_snub = 10e-12;                                % snubber series cap
cm.C_cabl = 800e-12;                         % cable capacitance
cm.R_coil = 22;                               % coil resistance
cm.H_coil = 3.3e-3;                           % coil inductance
```

```
% Misc Info (mostly unused) --------------------------------------------------------
cm.opgain = 1.2e9;                          % Calculated watts/meter
cm.efficiency = 0.125;                       % PO fraction * 90/10 split
cm.eta = 0.8;                               % Amps / Volt
cm.Zrf = 320;                               % Tank circuit impedance
cm.Grf = 10;                                % Pre-amp gain
cm.Cable = 0.67;                            % 3.5 dB of loss in 100' of RG-405
cm.PS = 0.707;                              % 3 dB loss in power splitter
cm.Mixer = 0.5;                             % 6 dB loss in mixer

cm.cmboost = zpk(-2*pi*3000,-2*pi*30,1);

cm.cmgain = 10^(9/20);

cm.hflowpass = cm.cmgain * cm.cmboost;

cm.WG = 10^(30/20);                         % 36 dB of whitening gain
cm.AA = 2;                                  % Gain of 2 in single-diff conv
cm.ADC = 32768/10;                          % 16-bit Analog to Digital conversion
cm.REFL_I_GAIN = -1.0;                       % Compensates some whitening gain

cm.electronics_gain = cm.eta *...        % Counts / Watt
                          cm.Zrf *...
                          cm.Grf *...
                          cm.Cable *...
                          cm.PS *...
                          cm.Mixer *...
                          cm.WG *...
                          cm.AA *...
                          cm.ADC *...
                          cm.REFL_I_GAIN;


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%



H2.darm = darm;
H2.mich = mich;
H2.prc = prc;
H2.carm = carm;
H2.cm = cm;
H2.mc = mc;
H2.los = los;
H2.misc = misc;


return
```