

**LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
--LIGO--**

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**Characterization and commissioning of
digital suspensions for the 40m Mode
Cleaner**

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of the LIGO Laboratory.**

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Characterization and commissioning of digital
suspensions for the 40m Mode Cleaner.

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LIGO SURF program

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Abstract

The 40m LIGO prototype at Caltech has recently acquired a new input mode cleaner, an optical system which serves to stabilize the input laser beam in frequency, position, angle and transverse profile before it enters into the arms of the main interferometer. A core component of the mode cleaner is three suspended optics, each controlled by a separate digital suspension controller. The goal of this summer was to characterize and commission these controllers. I measured noise characteristics and transfer functions of the controllers, diagonalized them to maximally decouple the optics' degrees of freedom, and calibrated the readout of the motion of the mirrors.

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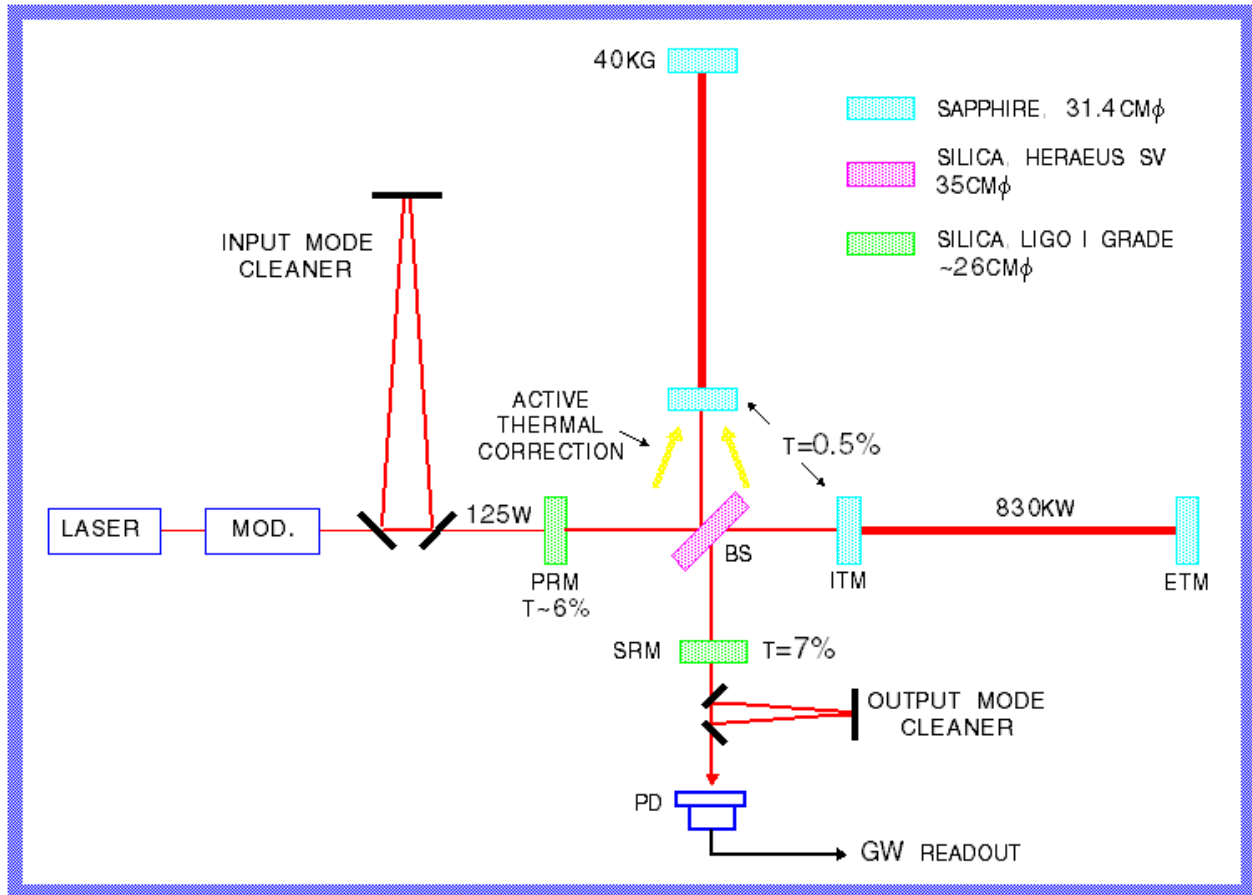


Figure 1: Advanced LIGO design

1 Background

1.1 LIGO 40m Lab

LIGO (Laser Interferometer Gravitational-Wave Observatory) is a project that aims to detect gravitational waves from astronomical sources. In principle, the apparatus is a Michelson interferometer with Fabry-Perot cavities in the two arms, where the laser, which monitors the distance between the test masses, resonates. Currently there are two LIGO sites, one in Hanford, Washington and one in Livingston, Louisiana. Both will come online within days for the first concurrent science run together with GEO in Germany and TAMA in Japan. This will mark the beginning of the LIGO scientific duty-cycle. However, gravitational-wave detection is a long-term process, so the LIGO 40 meter lab at Caltech (40m) is currently prototyping the Advanced LIGO layout (Figure 1) that will be installed at the sites in a few years. So far, the laser and the input optics have been installed and the mode cleaner (MC) has been the most recent acquisition.

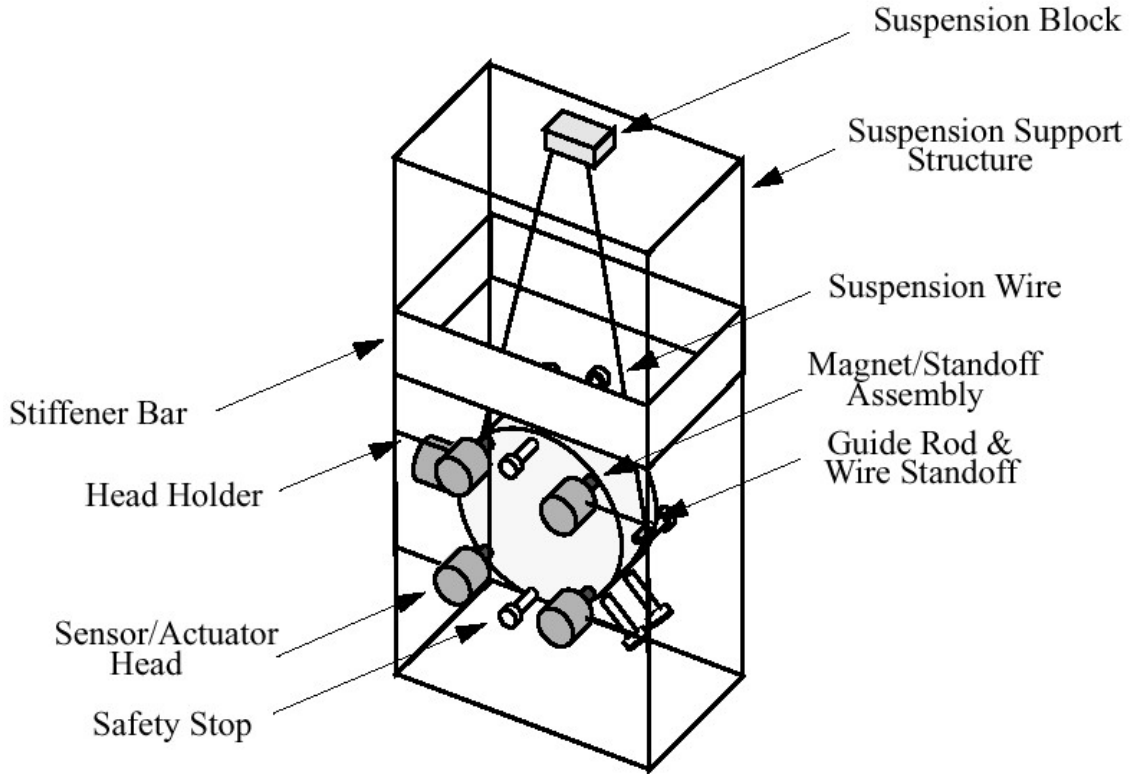


Figure 2: Suspension

1.2 Mode Cleaner

The mode cleaner is a triangular cavity, which performs several tasks: it stabilizes the laser beam in frequency, power, and transverse profile. As a result, the output beam is much more stable, and random fluctuations in it are less likely to be mistaken for gravitational waves. In order for this to happen, the laser beam needs to resonate in the mode cleaner, that is the length of the light path in the cavity must be an integral multiple of the laser wavelength, which in this case is $1064nm$. Moreover, the mode cleaner must remain locked (in resonance) for indefinite periods of time, so frequency stabilization requires a mode cleaner length which is very stable above 40Hz (gravitational-wave band). The pendulum suspensions reduce high frequency length noise dramatically, so this design was chosen.

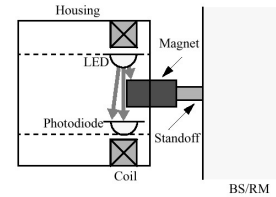


Figure 3: OSEM

1.3 Digital Suspension Controllers

To isolate the optics from seismic noise, which dominates at low frequencies, they are suspended, effectively swinging on a pendulum with natural frequency of 1Hz. To steer the mirrors in the right place and damp them enough to stay in that spot an actuation system

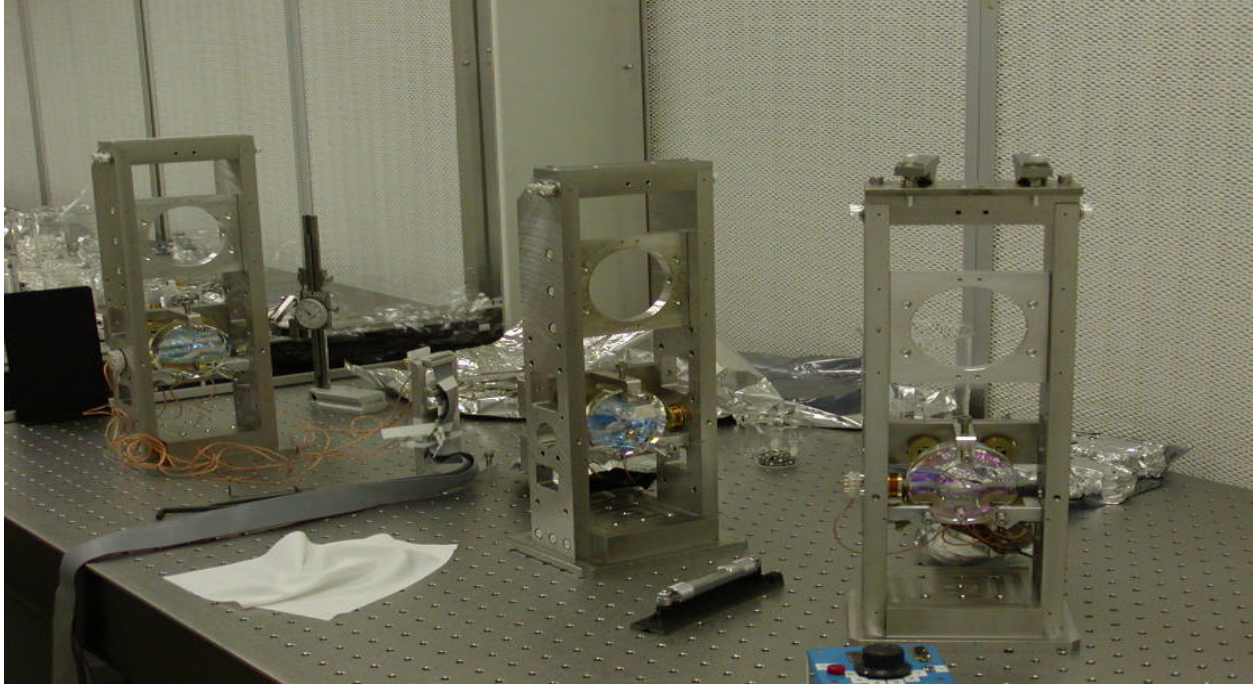


Figure 4: Suspensions

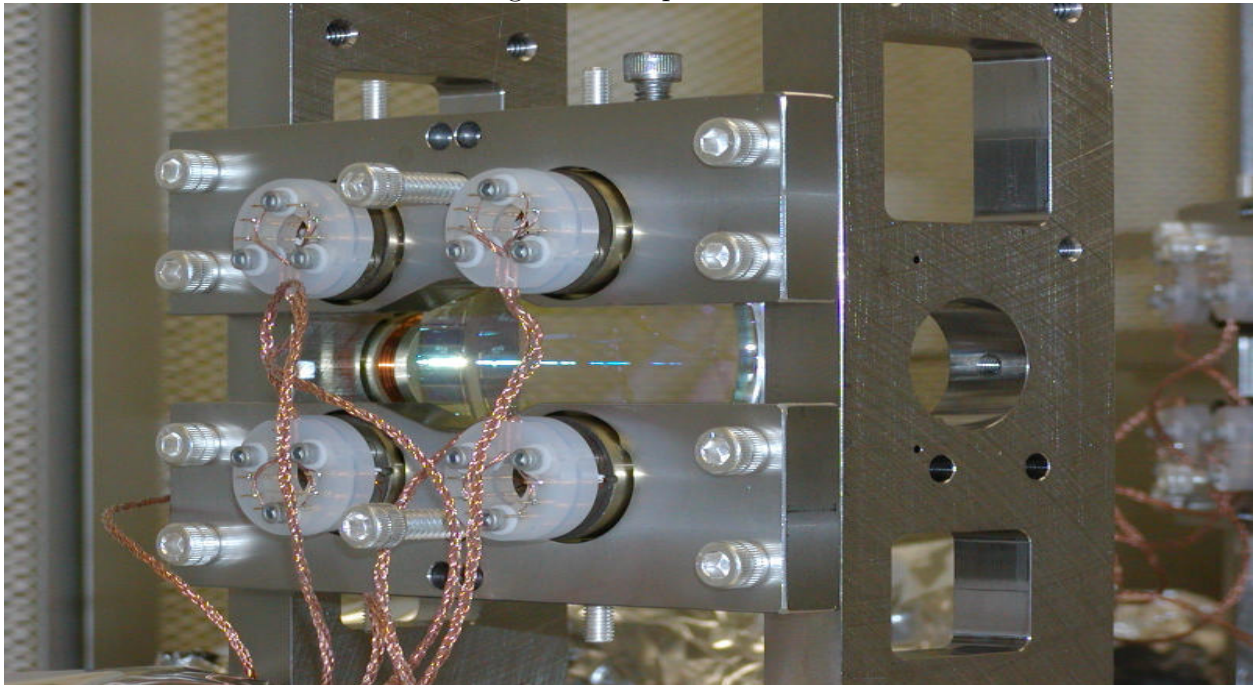


Figure 5: OSEMs

2 The Mode Cleaner 2 (MC2) stack transfer function.

In order to have the optics isolated from seismic noise, the suspension cages are mounted on seismic isolation stacks. Each stack is a multi-layer sandwich of massive metal plates and springs between them. MC1 and MC3 optics sit on top of the same table, and this stack has been commissioned before. The MC2 seismic stack, however, is new to the 40m lab, and to check whether it performs its duties, a transfer function for the ambient seismic noise was taken.

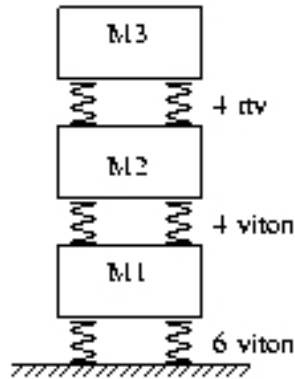


Figure 7: MC2 seismic stack

For this purpose one accelerometer (Wilcoxon Research 731A Seismic Accelerometer, sensitivity: $10V/g$) was placed on the floor near the MC2 chamber, while another one was bolted to the top of the MC2 stack. The outputs of the accelerometers were connected to a Hewlett-Packard Control Systems analyzer, which then performed a transfer function measurement. The vertical, horizontal transfer functions and power spectra of stack motion were recorded using the ambient seismic motion to excite all frequencies.

In addition the stack was modeled in MATLAB using the layout in Figure 7. The spring-mass “sandwich” uses two different types of springs – ‘viton’ and ‘rtv’, each with its own spring constant. The number and type of springs in each layer is indicated on the diagram. The model for the vertical stack motion assumed that the stack moves only in one dimension, which is rather far from the truth, since the plates have an extended geometry, and the springs are laid out in a non-trivial fashion. The graph of the transfer function and its model appear in Figure 10. The calculated resonant frequencies are 11.72Hz, 33.15Hz, and 52.53Hz. Moreover, the falloff of the measured transfer function was measured by fitting a line to it on a logarithmic plot, the resulting exponent was determined to be -2.0851 . The model predicts fall-off rate of f^{-6} for $f > 50\text{Hz}$, but this was not measurable using ambient seismic noise. This steep fall-off, however, is the reason for employing such a system, and the performance of the mode cleaner depends on it. The actual power spectra of ambient noise measured at the top of the stack are shown in Figures 8 and 9.

The ambient transfer function for horizontal stack displacement was also measured, but due to the nature of seismic vibrations in the lab, the transfer function in Figure 11 has rather poor coherence for most of the spectrum. In addition, the lateral modes of vibration are rather complicated to calculate (a finite element analysis is required), so no model of them was built.

3 Diagonalization of Mode Cleaner suspensions with respect to position.

The mode cleaner optics are suspended on wire, and any motion in the position degree of freedom is automatically coupled to the pitch degree of freedom (Figure 12). In addition, since the OSEMs are not exactly identical, the yaw degree of freedom could also be coupled in,

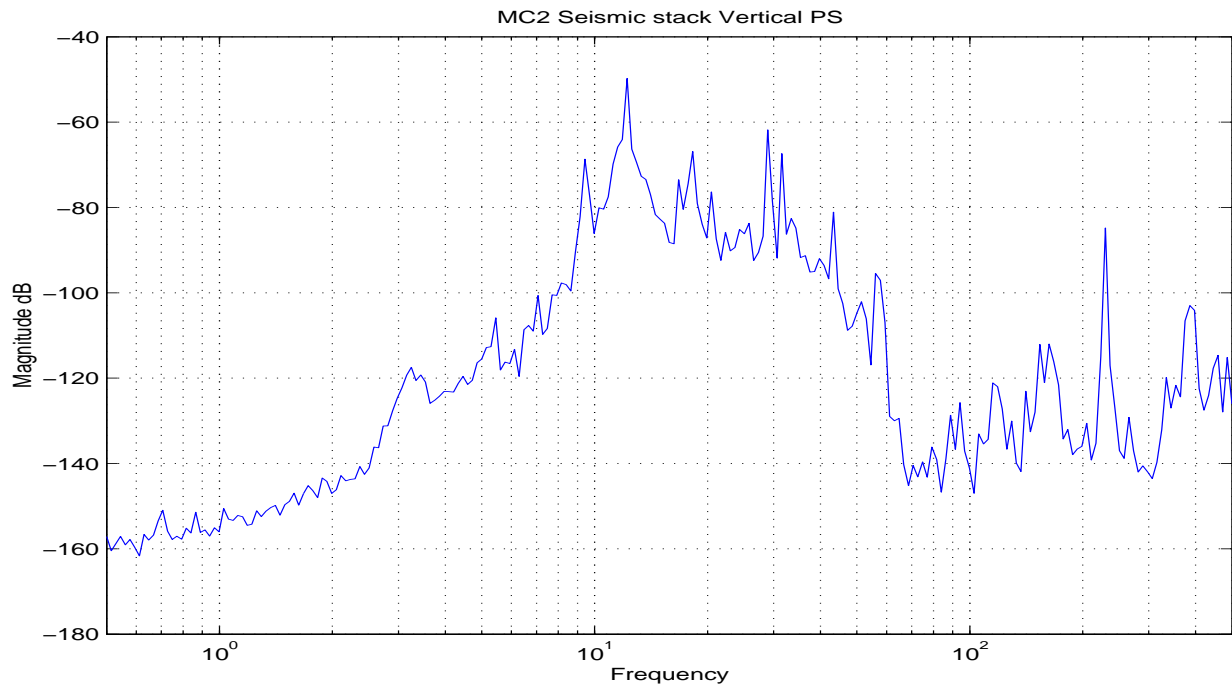


Figure 8: MC2 Vertical Power Spectrum

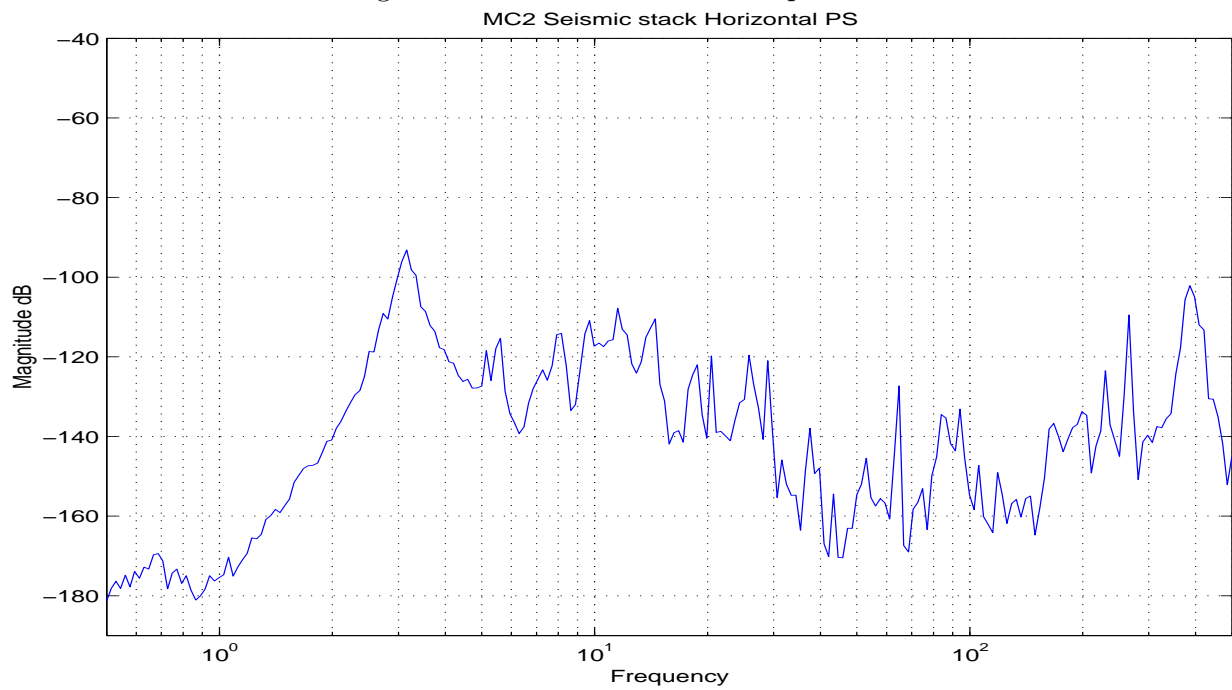


Figure 9: MC2 Horizontal Power Spectrum

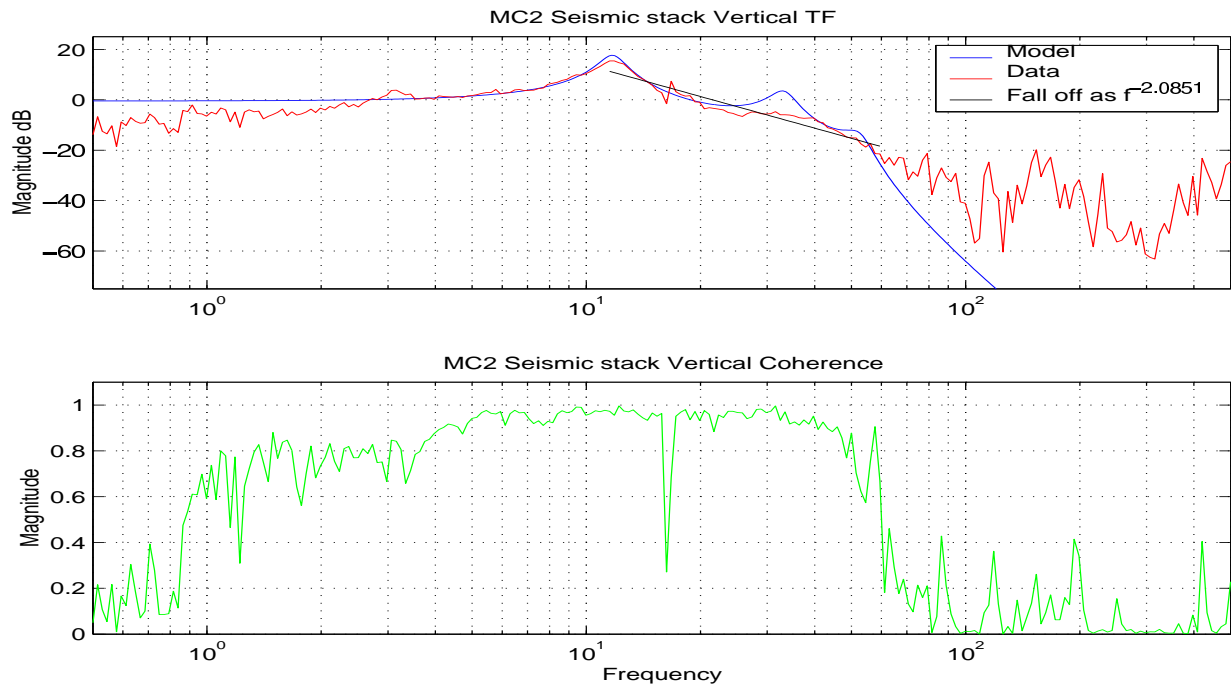


Figure 10: MC2 Vertical Transfer Function

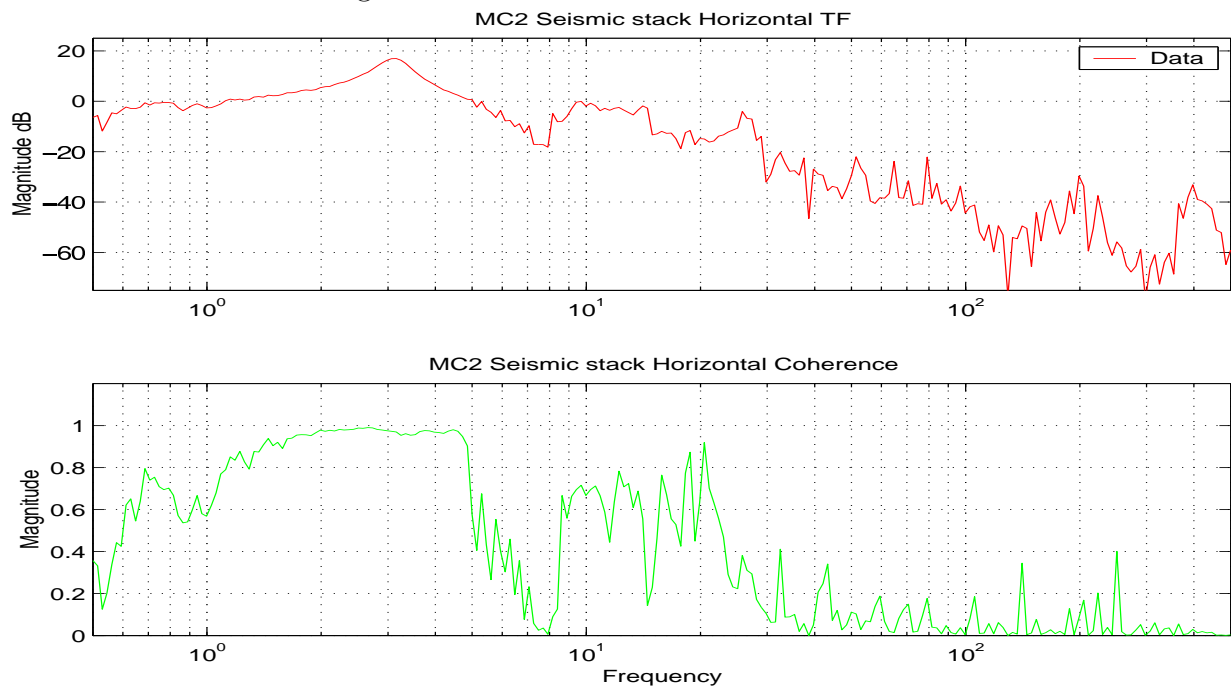


Figure 11: MC2 Horizontal Transfer Function

due to imperfections in construction. Thus, by adjusting the output matrix these couplings can be significantly reduced.

However, before doing this, it must be ascertained that the sensor inputs are correctly converted into the position, pitch and yaw motion. To do that, a set of `MATLAB` routines is used to analyze the motion of undamped optic and produce the correct sensing matrix, which decouples the sensors (see [1]).

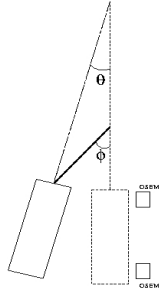


Figure 12:
Position
couples
with pitch.

In order to protect the interferometer controls (EPIC screens) from unauthorized access the several operator work stations in the 40m lab were isolated in a “Martian” network. These computers have access to the raw data from the frame builder, but not to the `MATLAB` license server at Caltech ITS, therefore the diagonalization routines had to be modified to read data from frame files on disk, rather than from the frame builder directly. Now, in order to use the code, data from the OSEMs of the optic being diagonalized need to be collected into a single frame file using `FrCopy` from `ligotools`, transferred to the General Computing machine used for calculations and then extracted into `MATLAB` using `frextract`. The first part is performed manually on the frame builder machine, the second part is easily integrated into the `getimatdataRDO.m` script provided by the diagonalization software.

Using an initial guess for the sensing matrix the software first computes appropriate angles to transform sensor signals to normal coordinates (motion along the arc of the suspension pendulum, and angular motion in the pitch angle relative to pendulum motion). Then power spectra are computed, and resonance peaks for position (around 1Hz), pitch (around 0.7Hz), and yaw (around 0.85Hz) are located. Cross-correlations between the signals are minimized, and the sensing matrix is adjusted so that only the appropriate peak is seen in the resulting noise spectrum for that degree of freedom (Figure 13).

To tune the input matrix, first remove any offsets it might have, then, when the optic settles down, undamp it (refer to yellow rectangle in Figure 14). Set both the sensing and the output matrices (red and blue rectangles) to initial values (± 1), then add an offset of about 2000 DAQ counts on the UL coil (green rectangle). When the sensors display oscillations of a thousand or so DAQ counts in `dataviewer` and complicated envelopes on all channels, record the optic’s sensor channels for the next two minutes using `FrCopy` and feed the resulting file into the provided script. The script might need adjustment for it to properly locate the resonance peaks for each degree of freedom. Once that has been done the resulting matrix should have proper signs in each field. Otherwise, a better set of data should be gathered by starting over. Further information can be found from authors of [1]. Results are shown in tables 1 and 3.

Next, to tune the position component of the output matrix, attach a function generator to the LSC cable, and enable the LSC IN switch for the appropriate optic. Set the function generator to output 0.1Vpp and 0.2Hz. Then, watching the `POS_CORR`, `PIT_CORR` and `YAW_CORR` signals in `dataviewer` (Figure 15) vary the LL and LR components of the matrix by equal amounts to minimize the pitch correction with respect to the position input. Then adjust UL and LL by equal amounts to minimize the yaw-pitch coupling.

The results of diagonalizing MC2 output matrix are as follows: for 900 DAQ counts

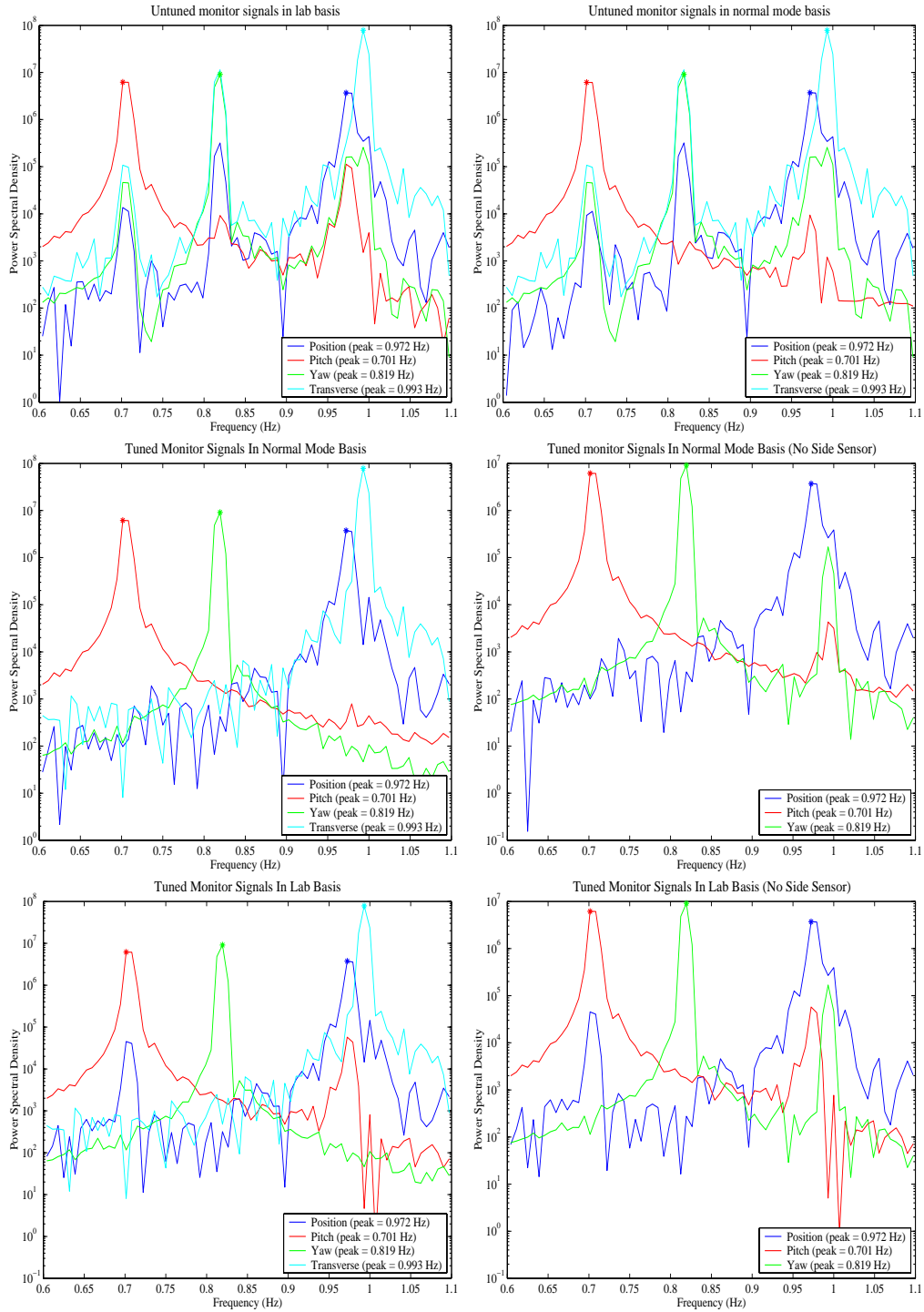


Figure 13: Plots made by the diagonalization routines showing their progress and identifying the resonance peaks for pitch, position and yaw at each step.

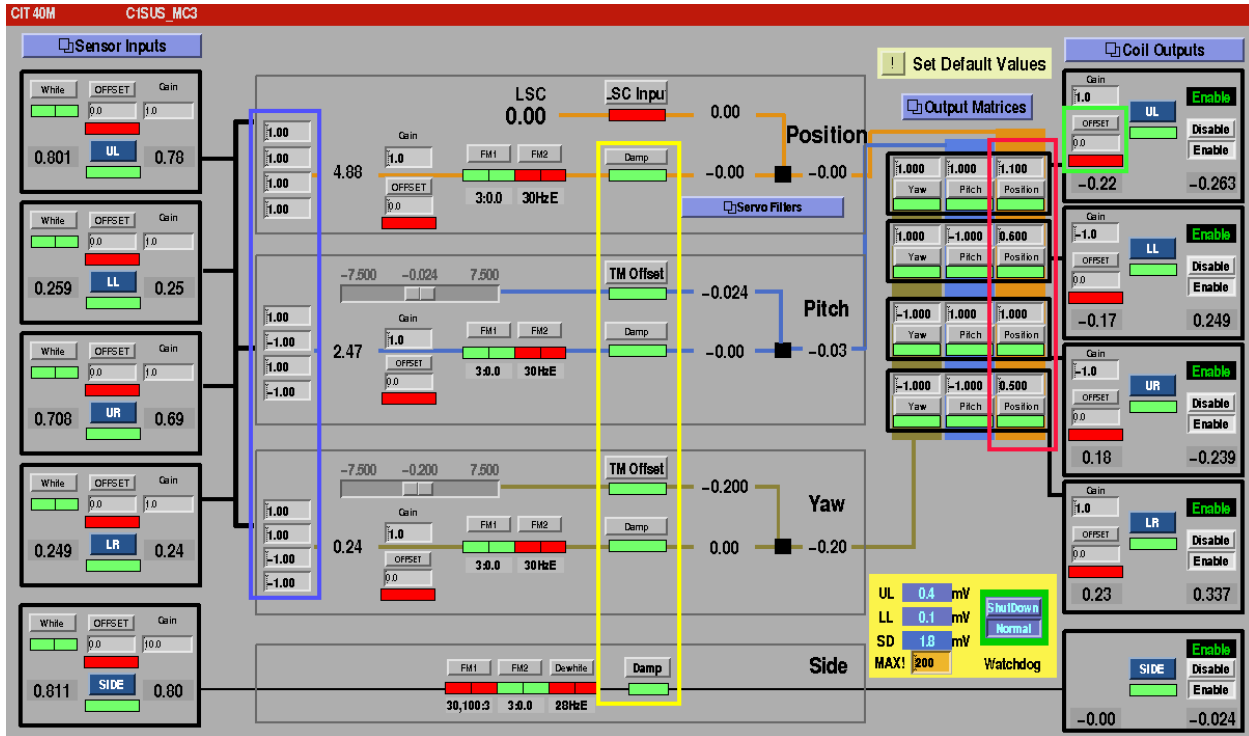


Figure 14: EPIC's digital suspension control screen

peak-to-peak motion in position the resulting output is 2 DAQ counts peak-to-peak in pitch, and 0.4 DAQ counts in yaw, which is less than 1% coupling. Final values are in table 2.

The MC3 output matrix is diagonalized the same way, and the results are shown in table 4. For 1200 DAQ counts peak-to-peak motion in position MC3 outputs less than 1.5 DAQ counts peak-to-peak in Pitch, and less than 1.5 DAQ counts in Yaw. This is much less than 1% coupling, which is quite good.

Unfortunately, the same procedure could not be repeated for MC1. The diagonalization software cannot correctly decouple the oscillations of different normal modes. This is probably due to the problems with the lower OSEMs on the MC1 suspension. Fixing them, however, requires venting the vacuum system, which could not happen during the summer, since SURF projects required a locked mode cleaner under vacuum. So, once the OSEMs are fixed, MC1 should be diagonalized, although, since the mode cleaner can hold lock for hours at a time in its current state this is probably not a pressing problem.

There's probably some merit to diagonalizing the output matrix at around 0.7Hz, the pitch mode. This would help in lock acquisition mode, since then the optic swing wildly, and pitch couples in tighter, however, since most of the time the optic will spend in lock, it's probably best to diagonalize it at or about DC. Checking the performed diagonalization at 0.7Hz produces 5% pitch coupling, 1.2% of yaw coupling in MC3 (50 counts and 12 counts per 1000 counts of input respectively) and 0.5% pitch coupling, 0.2% yaw coupling in MC2 (5 counts and 2 counts per 1000 counts of input respectively).

	UL	LL	UR	LR
Pos	0.79	0.83	1.17	1.21
Pitch	0.88	-1.01	0.94	-0.96
Yaw	0.70	0.89	-1.28	-1.10

Table 1: MC2 Sensing matrix

	UL	LL	UR	LR
Pos	0.95	1.02	0.98	1.05
Pitch	0.75	-1.17	0.79	-1.13
Yaw	0.90	1.03	-1.05	-0.92

Table 3: MC3 Sensing matrix

	UL	LL	UR	LR
Pos	1.02	0.91	1.00	0.89
Pitch	1.00	-1.00	1.00	-1.00
Yaw	1.00	1.00	-1.00	-1.00

Table 2: MC2 Output matrix

	UL	LL	UR	LR
Pos	0.96	0.77	1.00	0.81
Pitch	1.00	-1.00	1.00	-1.00
Yaw	1.00	1.00	-1.00	-1.00

Table 4: MC3 Output matrix

4 Install optical levers on MC2 and MC3.

Once a coarse alignment is performed in air it is desirable to have a reference for this position during and after pump-down, in order to check whether the suspended optics have moved. Also, for absolute diagonalization it is required to have optical levers on the optics in question.

Thus, an auxiliary optical table was set up with two low power red lasers, steering mirrors and quad photo-diodes (Figure 16 shows the setup with metal targets in place of the QPDs.) The laser beams are steered onto MC2 and MC3 independently, and the reflected light from these optics is pointed at the quad photo-diodes.

5 Figure out the problem in MC1 and MC3 damping.

A few weeks ago it was noticed that one of the three optics (MC3) is damped much worse than the other two. However, since MC1 was mounted on the same stack and yet appeared to have none of these problems a comparison between the two signal paths were performed. It was determined that when hardware whitening board was switched off in favor of its software equivalent damping improved significantly. In addition, it was conjectured, that modifications made to satellite amplifiers could have been incorrect. Thus, to check, whether the problem is with the whitening board, the satellite amplifier or the suspension itself, power spectra of the signal paths were measured in three schemes (Figure 17).

Results of these measurements are shown in Figures 18, 19 and 20.

These measurements implied that the peak stayed with the MC3 optic itself. However, upon inspection it turned out that the satellite amplifiers for MC1 and MC2 were not modified correctly, and the amplifier for MC3 had one mis-soldered resistor, which incorrectly scaled down one of the readouts.

Also, the cause of disappearance of the 23.71Hz peak (the “roll” mode of the suspended optics, which is anomalously large in many of the noise spectra taken with the MC1 and MC3 optics) between the measurements of Figures 19 and 20 was not noticed at first, but was later attributed to time-dependence of the peak. This particular hypothesis was tested for both Figure 17(2) and 17(3) setups. Results of these measurements can be seen in Figures 21 and 22. As nothing else was changed between the successive measurements, the peak

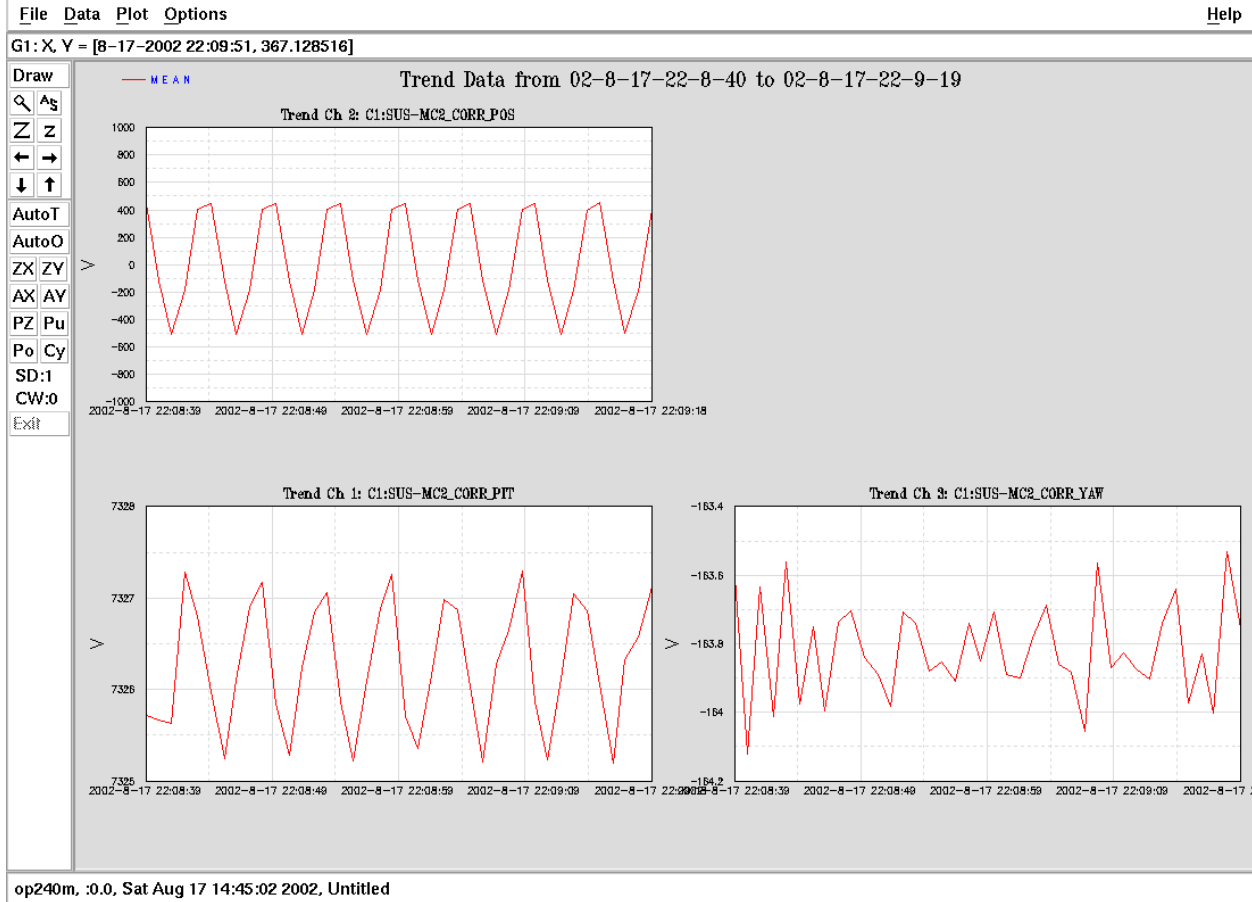


Figure 15: dataviewer showing input and output error signals

is clearly time-dependent. Moreover, turning SIDE damping on and off on the MC3 optic controls the presence of the 23.71Hz peak. However, since the above changes to the MC3 satellite amplifier and to the tilting of the optical table on which MC3 rests its damping problem disappeared.

Upon pumping down to vacuum, however, it turned out that MC1 now had the peak. Since there was no way of fixing it, a digital notch filter for this frequency was created and inserted into the MC1 damping path. Figures 23 and 24 show the effect of turning on the filter.

Since the mode cleaner can sustain lock for hours at a time, it would seem that the modifications made to the suspensions had a positive effect, and that, indeed, further modifications might not be needed. However, measurements of the beam quality on the mode cleaner's output are required to provide the definitive answer.

6 Q of the Mode Cleaner suspensions.

To see how well suspensions damp the optics their Q must be known. To measure the Q , the optics were excited on the EPICS screens, their ring-up was watched in `dataviewer`, and

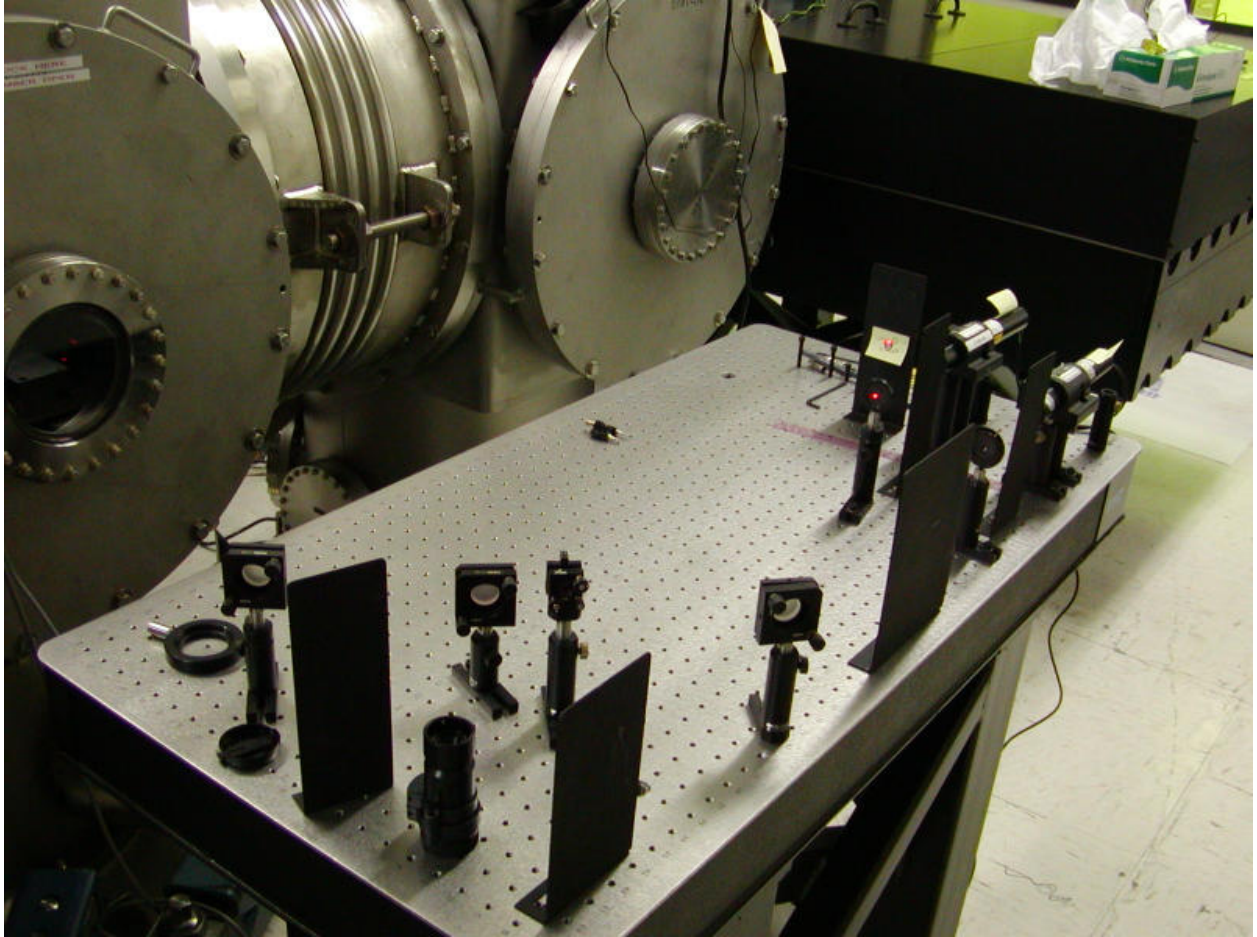


Figure 16: Optical Levers, metal targets are in place of the QPDs.

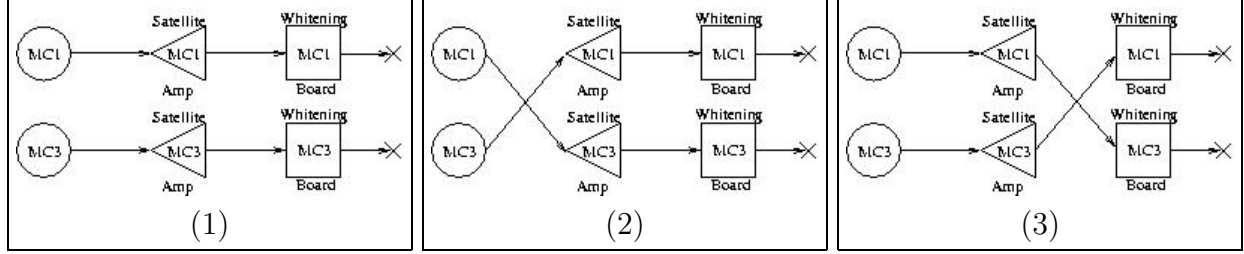


Figure 17: Measurement setups for MC1 & MC3 noise diagnostic. Power spectra taken at X – UL sensor on the appropriate whitening board.

then damping was turned on. The approximate GPS time of the ring down was noted, and the data pertaining to the optic’s OSEMs sensor channels was extracted using `FrCopy` and `frextract` into `MATLAB`. There the plots were made, damped sinusoids ($A \sin(2\pi ft + \phi)e^{-\frac{t}{\tau}}$, where A , f , ϕ , τ are fit parameters) were fit to data, recovering the frequencies of oscillation f and the time constants τ of the ring down, and then $Q = \pi f\tau$. Results are shown in figures 25, 26 and 27. The fits with frequencies other than around $1.00 \pm 0.02 \text{ Hz}$ were rejected, because these oscillations are not the position mode, which is of the greatest interest. Alternative measurements could be of the Q for pitch and yaw degrees of freedom, unfortunately until excitation could be supplied to those channels this is rather impractical. In addition, the lower OSEMs on MC1 do not seem to work correctly, for that reason the calculated Q is not very believable, however, because stable lock can be achieved, it seems that the optic is damped well enough.

7 Calibration of sensors and coils.

It is important to know how the voltage readings on suspensions sensors and coils correspond to actual motion of the mirrors. For this purpose, it is enough to drive the mirror to swing through one free spectral range (FSR) of the mode cleaner cavity, and then, knowing the value of FSR and the driving voltage calibrate the appropriate readouts.

Figure 28 shows the setup used for locking the mode cleaner, and performing the calibration. The two variable gain SR560 pre-amplifiers (G1 and G2) were used to lock the mode cleaner, with the MCA path driving one of the three mirrors. Once lock was acquired the sensor and coil voltages were noted (Figure 14). The DC Offset was slowly varied until the mode cleaner lost lock, and gained it again with new sensor voltages. Slow offset variation guarantees that the new lock will be exactly one FSR away. This part was repeated a num-

	MC1 Sensors	MC1 Coils	MC2 Sensors	MC2 Coils	MC3 Sensors	MC3 Coils
UL	70.93	5.22	78.81	3.28	36.69	2.31
LL	212.80	6.11	88.67	3.62	56.00	2.69
UR	56.00	4.36	133.00	3.41	56.00	2.42
LR	106.40	5.17	112.00	3.77	59.11	2.32

Table 5: Calibration constants, all values are in $\frac{\mu\text{m}}{\text{V}}$.

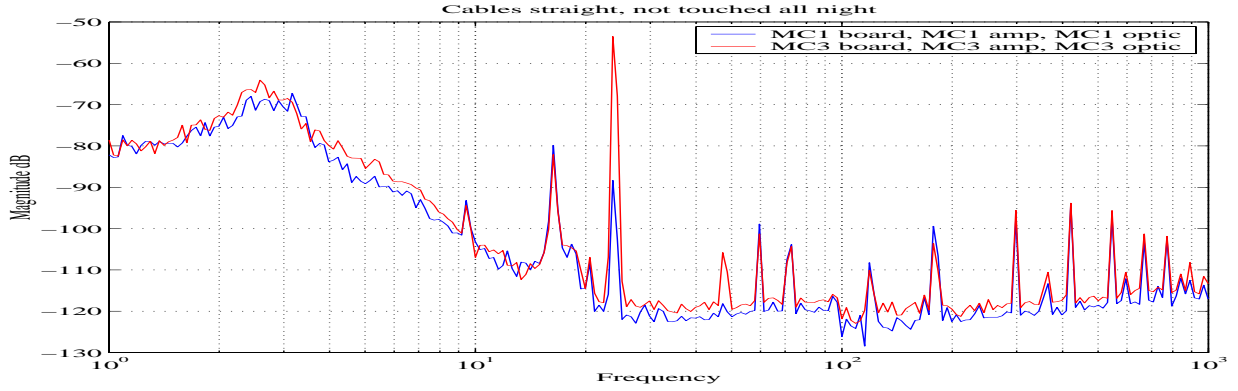


Figure 18: Cables straight

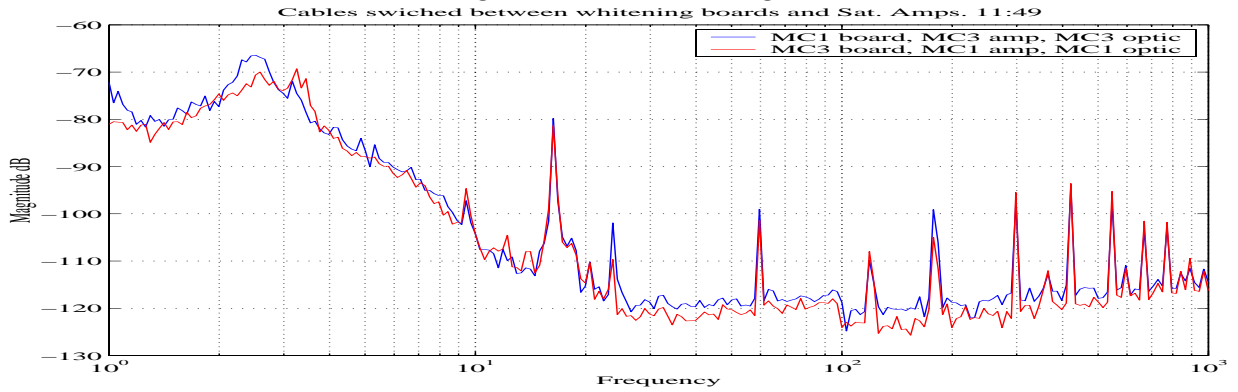


Figure 19: Cables switched between satellite amps and whitening boards.

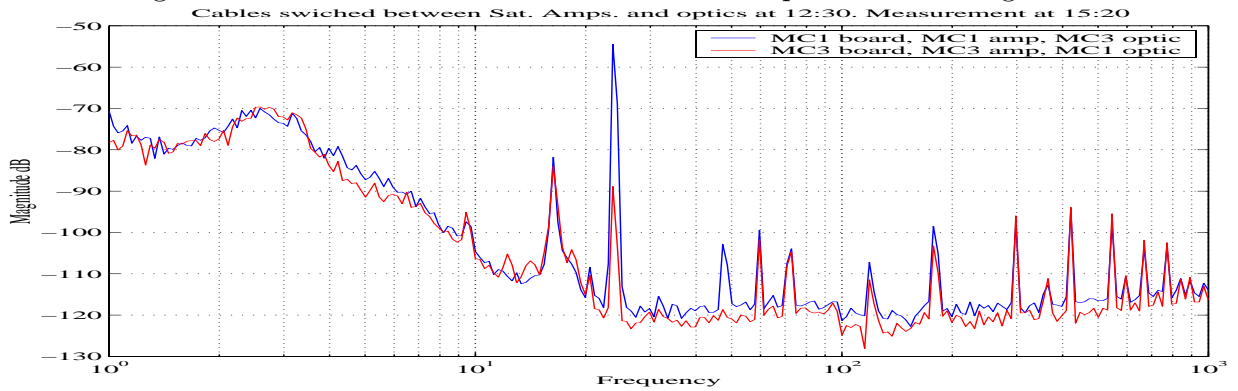
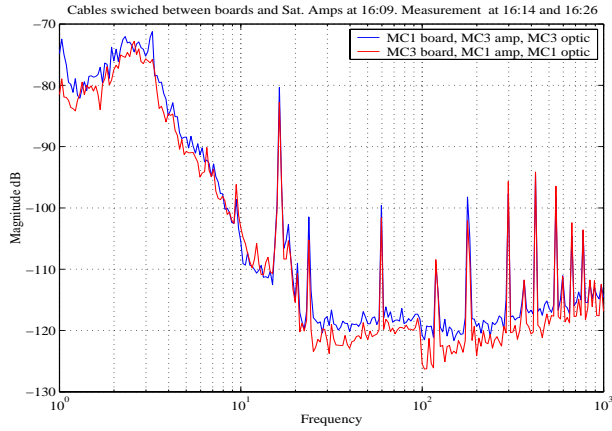


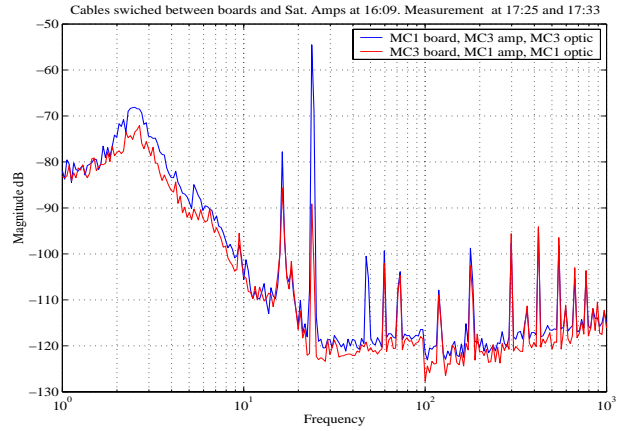
Figure 20: Cables switched between optics and satellite amps.

ber of times to make sure, that on separate occasions lock is acquired for the same OSEM voltages. After this verification the new voltages were recorded and conversion factors were computed by dividing the voltage difference by the half-wavelength. The measured values are shown in table 5.

This method in its current implementation, however, has a major downside. Due to the nature of the setup, the laser frequency follows the slow fluctuations in the mode cleaner. The changes are a few megahertz, and yet the change in the wavelength is large. If locking

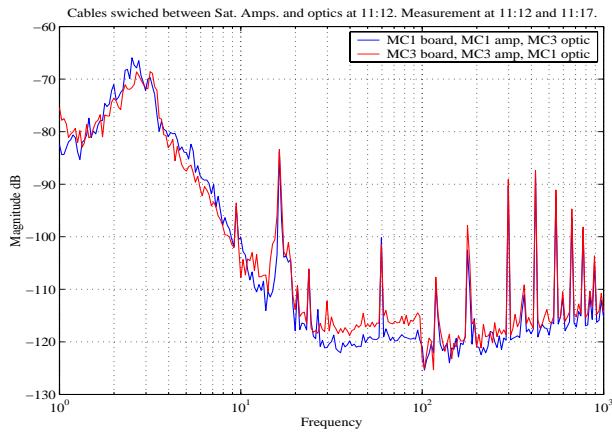


Cables switched at: 16:09.
Time of measurement: 16:14.

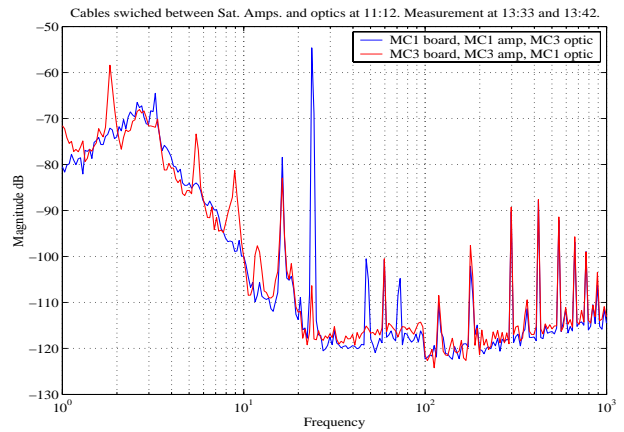


Cables switched at: 16:09.
Time of measurement: 17:25.

Figure 21: Cables switched between satellite amps and whitening boards.



Cables switched at: 11:12.
Time of measurement: 11:12.



Cables switched at: 11:12.
Time of measurement: 13:33.

Figure 22: Cables switched between the optics and satellite amps.

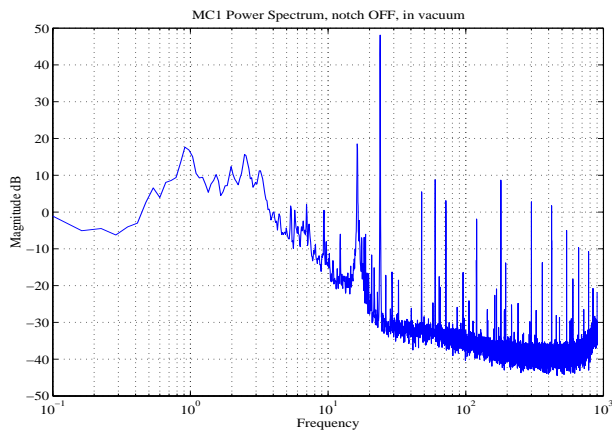


Figure 23: MC1 without notch filter

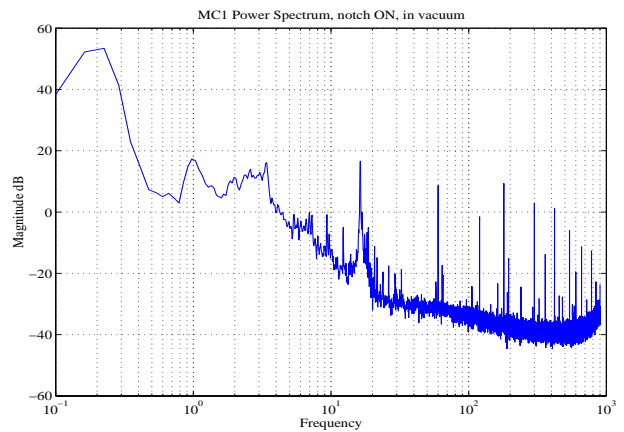


Figure 24: MC1 with notch filter

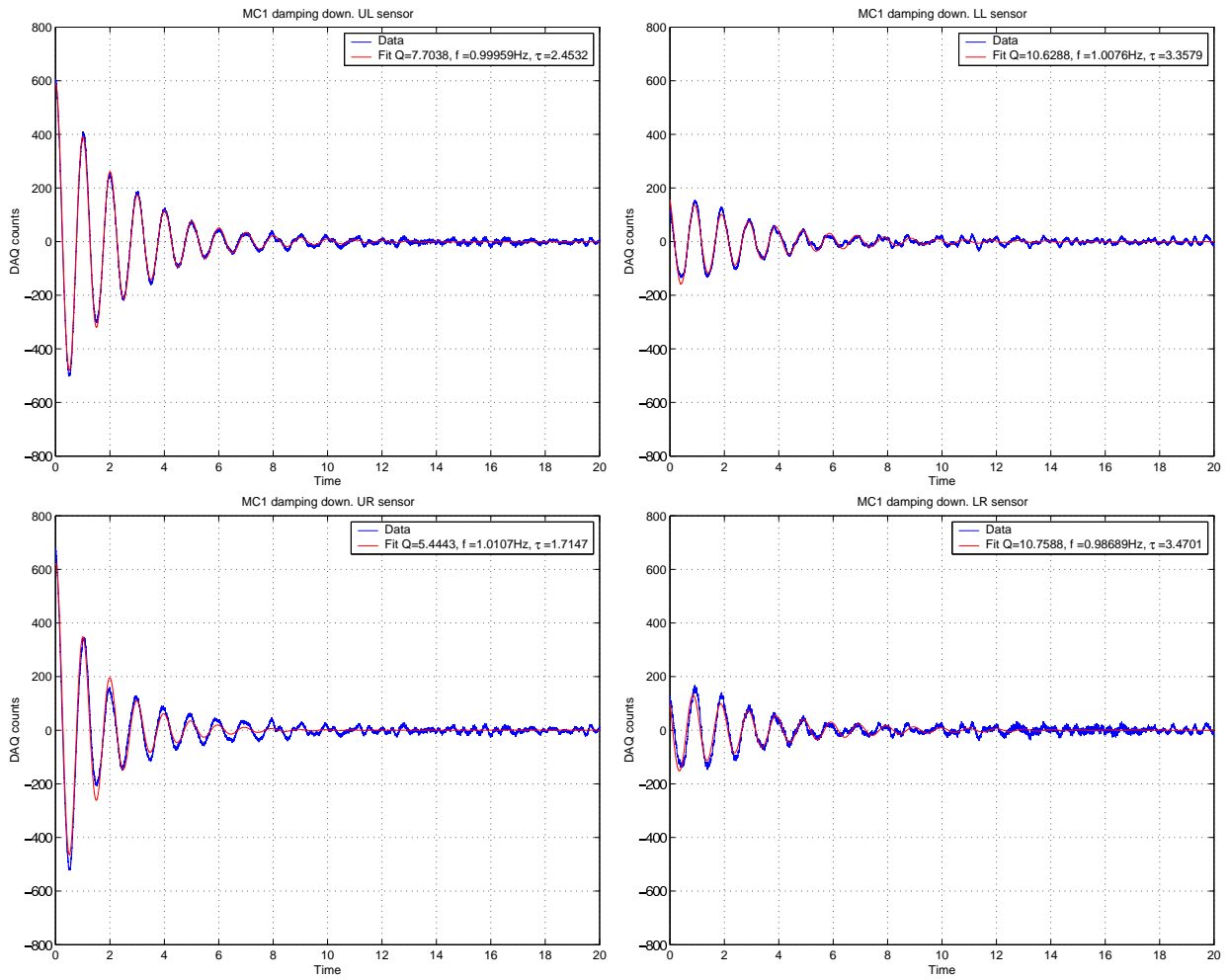


Figure 25: MC1 UL, LL, UR, LR sensors. Mean $Q \simeq 6.5740$, only of UL and UR.

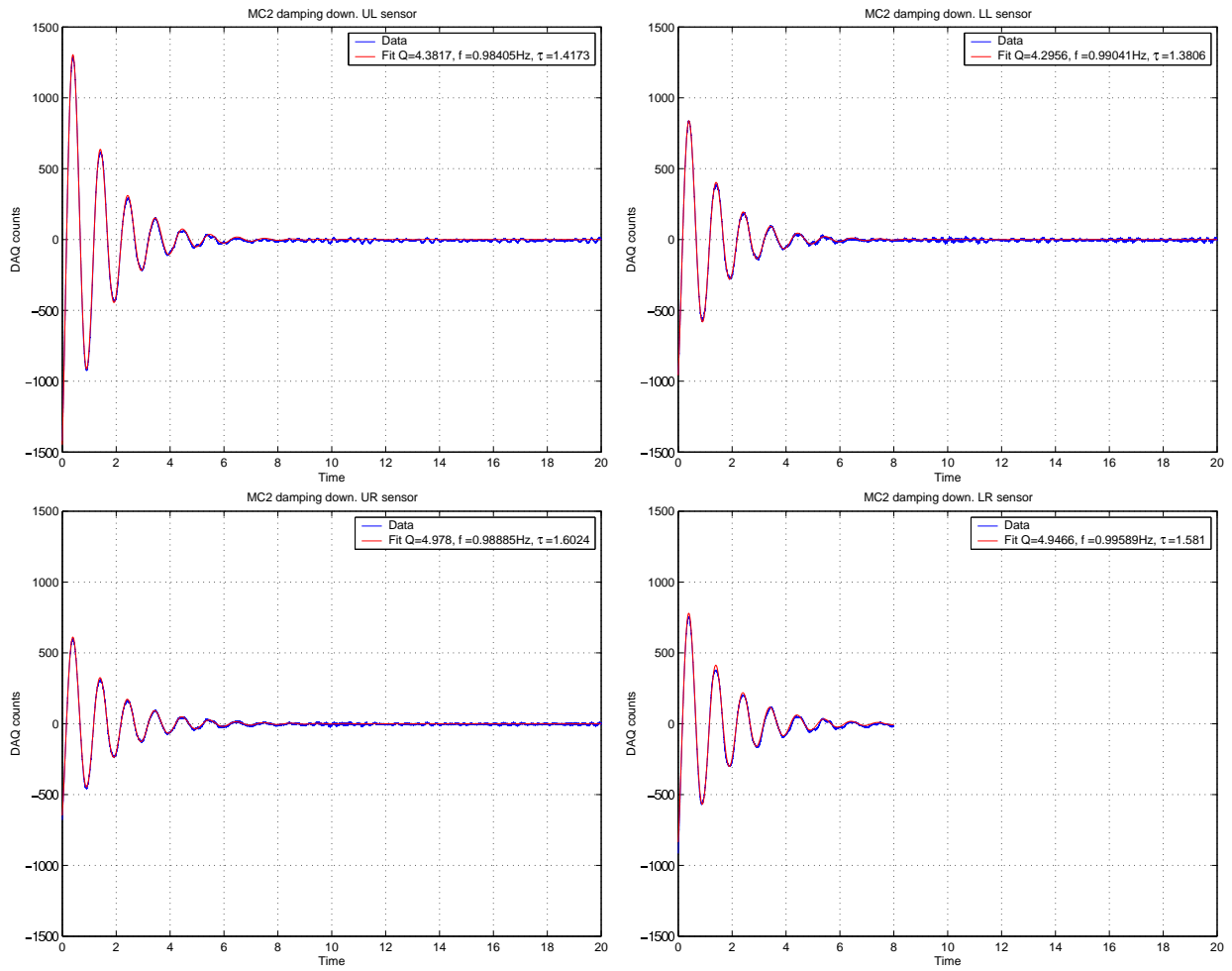


Figure 26: MC2 UL, LL, UR, LR sensors. Mean $Q \simeq 4.6506$

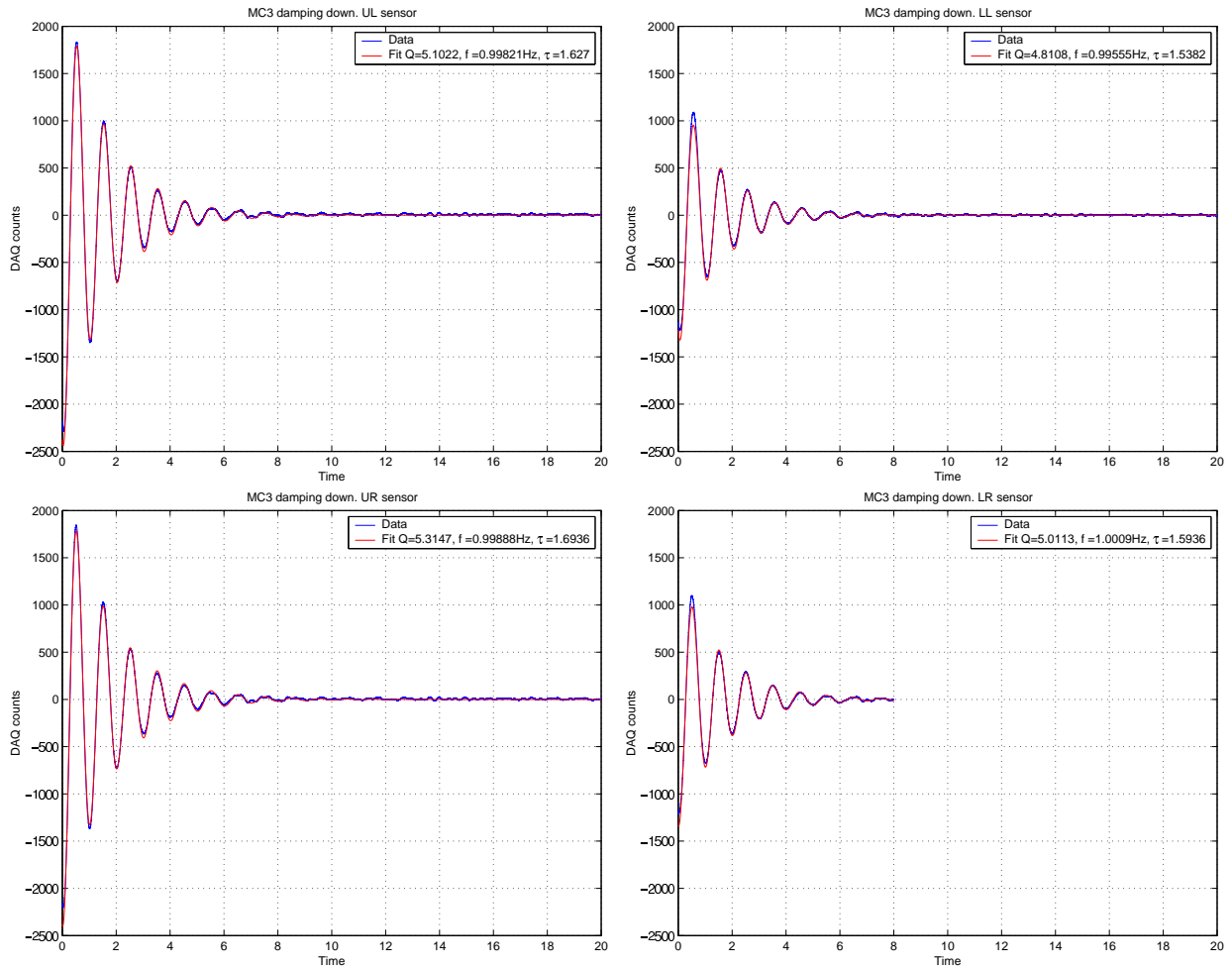


Figure 27: MC3 UL, LL, UR, LR sensors. Mean $Q \simeq 5.0598$

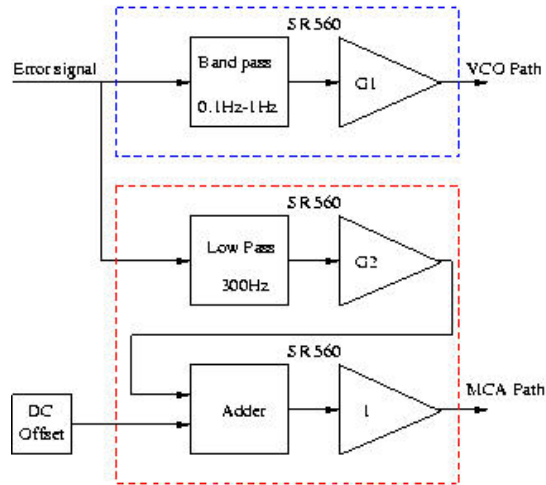


Figure 28: Calibration

was not engaged in order to remove the effect of the VCO on the laser at low frequencies, it was hard to get reproducible measurements from a freely swinging mirror. Once the mode cleaner servo card works, the VCO won't follow the optics at low frequencies, and these measurements should be rechecked, as the current numbers are probably wrong.

8 Power spectra of position noise

When the mode cleaner is locked, the noise spectrum is dominated at low frequencies by length noise, and laser frequency noise at high frequencies. To get the best quality beam on the interferometer input, the beam is actuated on at high frequencies to follow the stable mode cleaner, and at low frequencies the less stable mode cleaner is locked to the laser. Knowing the position noise in the mode cleaner suspensions allows for full characterization. The measured noise spectra appear in figures 29, 30, and 31. The design specifies noise requirements for frequencies above 40Hz as per equation 1.

$$3.8 \times 10^{-18} \left(\frac{f}{40} \right)^{-2} \frac{m}{\sqrt{Hz}} \quad (1)$$

However, the measured position noise at the sensors is given in $\frac{V}{\sqrt{Hz}}$, so the conversion factors from the previous section must be used. Unfortunately, comparing the measured noise spectra to this requirement produces a result that is off by several orders of magnitude. The reason is probably that there's some gain in the signal path from the OSEM shadow sensors to the DAQ. Once that is obtained, the measured noise spectra could be referred back to the optic motion noise and a comparison between the design requirement and the actual noise can take place. However, above approximately 20Hz sensor noise dominates these measurements, so one must extrapolate to 40Hz with the $\frac{1}{f^2}$ fall-off. Nonetheless the peaks at 2 – 4Hz have to be understood (most likely the MC2 seismic stack vibrations), and the 16.25Hz bounce mode needs to be notched out.

9 Build and install GDS.

Many aspects of digital suspensions on the 40m Mode Cleaner are controlled by the EPICS system, and various embedded software running in the lab. To ease diagnose problems with the interferometer LIGO has a package called the Global Diagnostic System (GDS). This package is extremely useful for studying the performance of a LIGO interferometer. In fact, data for many plots in this paper (Figures 23, 24 29, 30, 31) were collected using GDS.

In order to perform certain tasks for the suspensions, GDS had to be installed on the computers in the lab. Thus, after enlisting help of the General Computing staff, this problem reduced to following the installation instructions provided with the software. GDS is now built and functions well. For the exact building instructions refer to Appendix A.

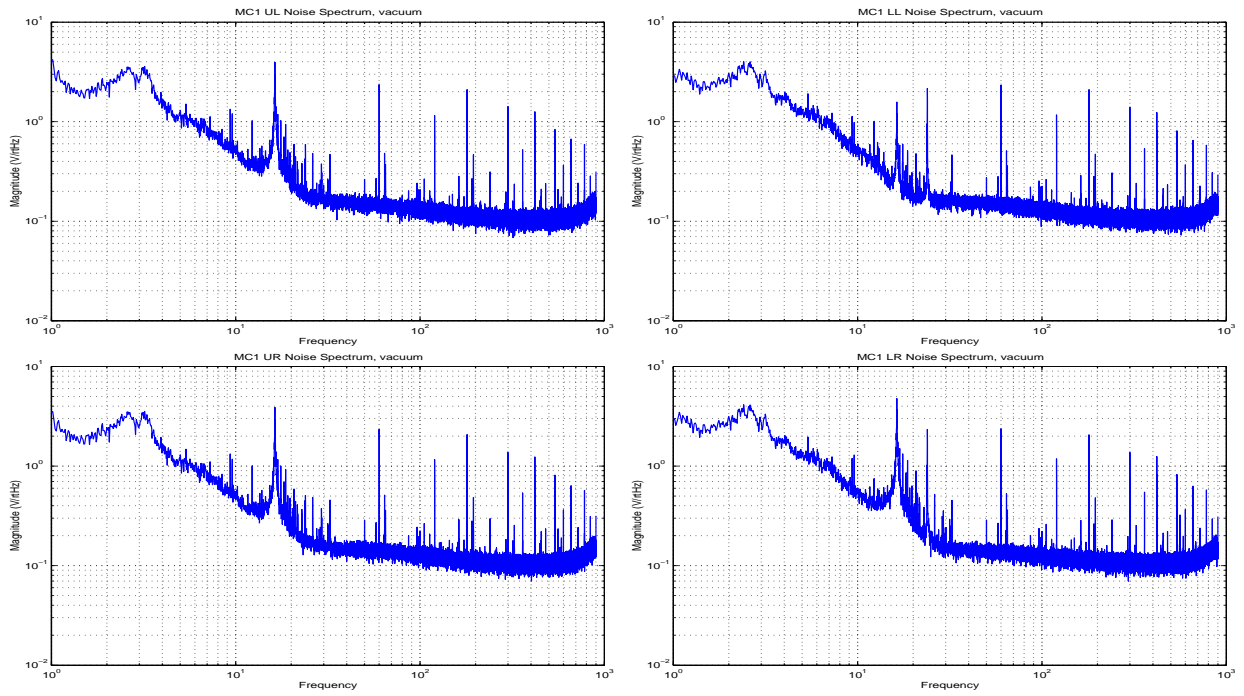


Figure 29: MC1 UL, LL, UR, LR sensor noise.

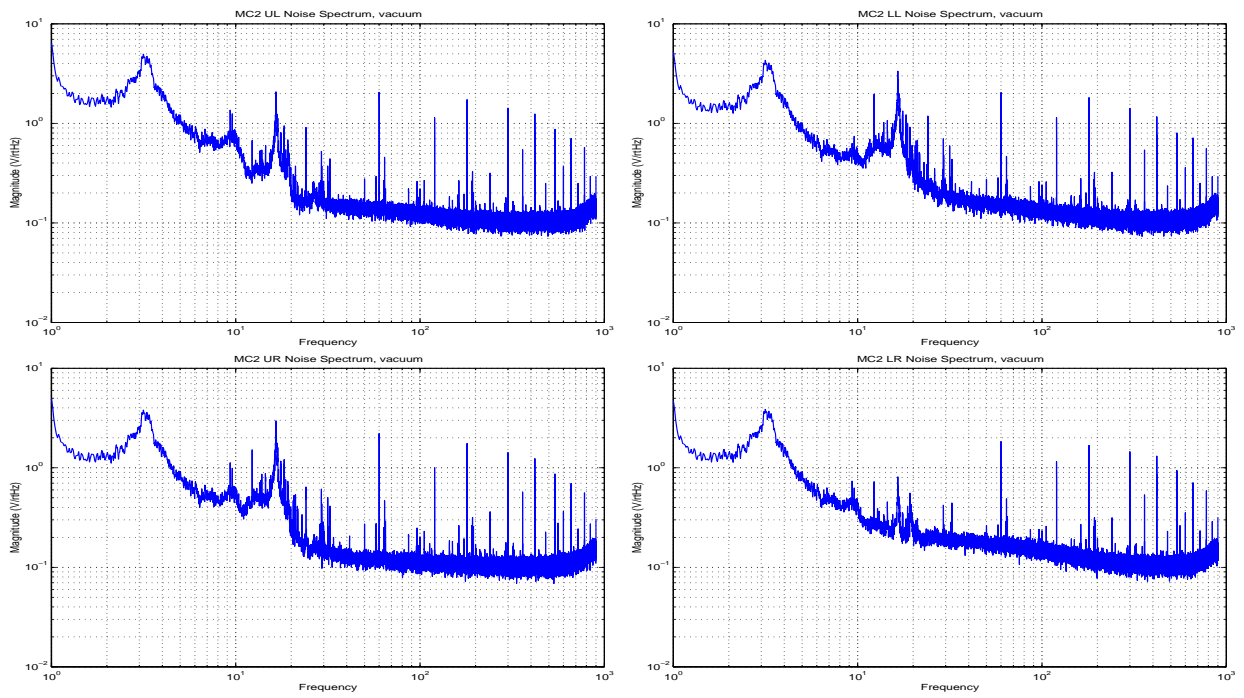


Figure 30: MC2 UL, LL, UR, LR sensor noise.

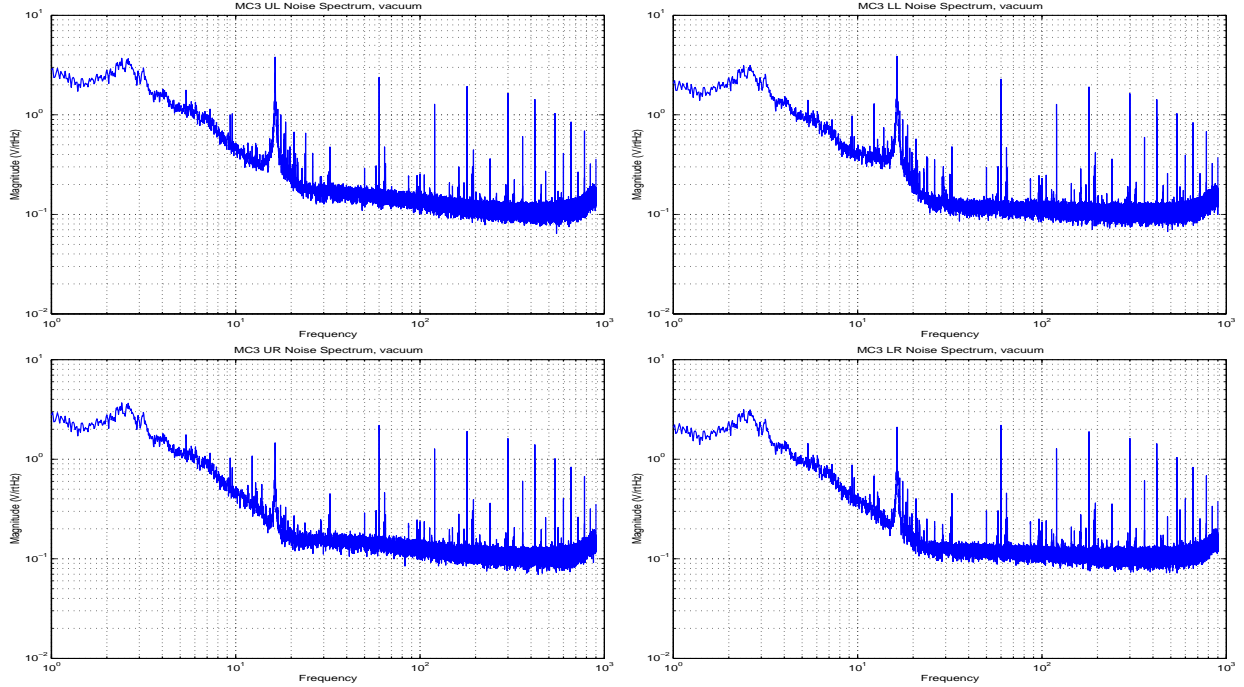


Figure 31: MC3 UL, LL, UR, LR sensor noise.

10 Conclusions and future work

The chief results of the project were the diagonalization of the mode cleaner optics and the measurement of Q for the suspensions. In the process the GDS package was installed in the 40m lab, which will help once the core optics are installed. Unfortunately diagonalization of MC1 couldn't happen this summer, so this will have to be performed once the interferometer is vented.

Also once the digital suspension controller software is upgraded by the CDS staff, diagonalization of pitch and yaw components of the output matrices can take place. It would be interesting to see how well that works, and how well the diagonalization procedure works for the core optics. Moreover, all of the measurements made of the mode cleaner suspensions will have to be repeated for the core optics.

The absolute calibration of the sensors and coils needs to be repeated more carefully. The satellite amplifier resistors need to be changed back to their correct values, after which, much of this work might need to be repeated. The damping gains will need to be optimized to minimize MC frequency noise. The noise spectra remain to be understood quantitatively.

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And finally, thanks to LIGO for its great hospitality.

A Building GDS

Building gds according to

<http://www.ligo.caltech.edu/~jzweizig/DMT-Download.html> and
http://www.ligo.caltech.edu/~jzweizig/install_sparc_solaris-2.0.0.txt

Get Lisa Bogue to install the required development software on
dmt140m, list of software is on

<http://www.ligo.caltech.edu/~jzweizig/DMT-Download.html>.

On dmt140m make a directory where all will be built:

```
> mkdir /cvs/cds/caltech/build
```

On sirius as iberdnik:

```
> setenv CVSROOT :pserver:readonly@ldas-sw.ligo.caltech.edu:/ldcg_server\  
/common/repository_gds  
> cvs login  
Password: m0n1t0r  
> cvs co gds  
> tar cvf gds-cvs.tar.gz gds  
  
> getUrl http://www.ldas-sw.caltech.edu/packages/framecpp-0.0.23.tar.gz .
```

Get the ROOT package as follows : <http://root.cern.ch/root/Install.html>

```
> ftp root.cern.ch  
User: ftp  
Password: ilya@  
ftp> cd root  
ftp> bin  
ftp> get root_v3.02.07.source.tar.gz  
ftp> get xpm-3.4j.tar.gz  
ftp> quit
```

Get the ligotools package from LIGO:

<http://www.ldas-sw.ligo.caltech.edu/ligotools>

```
> getUrl http://www.ldas-sw.ligo.caltech.edu/ligotools/  
ligotools_init/ligotools_init_1.5.tar .  
> getUrl http://www.ldas-sw.ligo.caltech.edu/ligotools/  
Fr/v4r52/Fr_v4r52_SOURCE.tar.gz .
```

```
> getUrl http://www.ldas-sw.ligo.caltech.edu/ligotools/\
  dataflow/4.8/dataflow_4.8_SOURCE.tar.gz .
```

Transfer the files to rana: (do this for each of gds-cvs.tar.gz, framecpp-0.0.23.tar.gz, root_v3.02.07.source.tar.gz, xpm-3.4j.tar.gz, ligotools_init_1.5.tar,Fr_v4r52_SOURCE.tar.gz, dataflow_4.8_SOURCE.tar.gz)

```
> scp <FILENAME>.tar.gz controls@rana:
```

Then on rana, transfer the files to dmt140m (simply copying files into /cvs/cds/caltech/build on rana gives a "can't write to the filesystem" error)

```
> scp <FILENAME>.tar.gz dmt140:/cvs/cds/caltech/build
```

NOW, get to building on dmt140m: from /cvs/cds/caltech/build

First, install the ligotools:

(http://www.ldas-sw.ligo.caltech.edu/ligotools/setup_info.html)

```
> tar xf ligotools_init_1.5.tar.gz
> ./ligotools_init
```

Follow the directions there, call the install directory <LTdir>. Afterwards, insert "eval '<LTdir>/bin/use_ligotools'" into the ~/.tcshrc file, and rerun ~/.tcshrc or just run "eval '<LTdir>/bin/use_ligotools'" on the command line to have the environment properly setup.

Then, install the packages:

```
> ligotools_install Fr_v4r52_SOURCE.tar.gz
> ligotools_install dataflow_4.8_SOURCE.tar.gz
```

Now you should be done with ligotools.

Proceed onto building ROOT (<http://root.cern.ch/root/Install.html>)

First, build libXpm (to be installed into <XPMdir>/lib and <XPMdir>/include):

```
> gunzip -c xpm-3.4j.tar.gz | tar xf -
> cd xpm-3.4j
> setenv PATH /usr/openwin/bin:\$PATH
> rehash
```

```
> xmkmf -a
> make CC=gcc CCOPTIONS= PICFLAGS=-fpic LD=/usr/local/bin/ld\
  SHLIBLDFLAGS='-G -z text' REQUIREDLIBS='-lX11 -lXext'
> make install DESTDIR=<XPMdir>
```

Now, build root itself:

```
>gunzip -c root_v3.02.07.source.tar.gz | tar xf -
> cd root/
> setenv ROOTSYS <ROOTdir>
> ./configure solarisgcc --with-xplibdir=<XPMdir>/lib
> make
> make install
```

Insert the following lines into ~/.tcshrc after the ligotools line:

```
setenv ROOTSYS <ROOTdir>
setenv PATH $ROOTSYS/bin:$PATH
setenv LD_LIBRARY_PATH $ROOTSYS/lib:$LD_LIBRARY_PATH
```

Rerun ~/.tcshrc or just run these lines in the shell.

Build gds:

```
> gunzip -c gds-cvs.tar.gz | tar xf -
> mv framecpp-0.0.23.tar.gz gds/External
> cd gds
> setenv GDSBUILD framecpp
> ./configure solarisgcc
> make -C External >& make_external_`date +%m%d%y`.log &
> make >& make_`date +%m%d%y`.log &
> make install prefix="<GDSdir>/pro"
```

Add the following lines into ~/.tcshrc:

```
setenv DMTHOME <GDSdir>
setenv DMTVERSION pro
```

That's all folks!

References

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