The Advanced LIGO Input Mode Cleaner

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Presentation for the Detector Characterization Group
3 February, 2014

Outline

1. What is the Input Mode Cleaner?
2. Why do we Have an Input Mode Cleaner?
   - An Optical Cavity as a Phase Discriminator
   - The Passive Purposes of the IMC
   - The Active Purpose of the IMC
3. Nuts and Bolts
   - Input Optics Layout
   - Angular Controls
   - Length/Frequency Control
   - Noise in the IMC
4. Characterizing the Input Mode Cleaner
   - Channels of Interest
   - Interesting Detector Characterization Studies

Input Mode Cleaner Fact Sheet

- 3 Mirror Impedance Matched Ring Cavity
- Mirrors:
  - Diameter: 150 mm
  - Thickness: 75 mm
  - Mass: 2.9 kg
- Seismic Isolation:
  - HSTS Triple Suspensions
  - Single Stage HAM ISI
  - HAM HEPI
- Finesse: 475
- FSR: 9.11 MHz
- Cavity Pole: 8.7 kHz

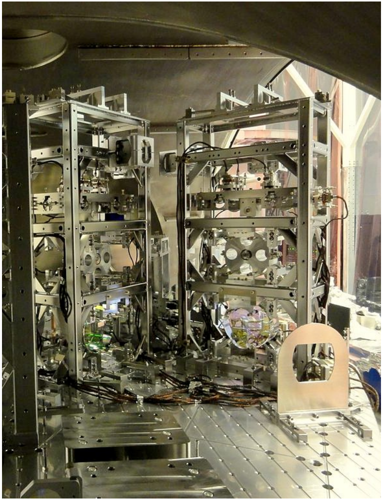
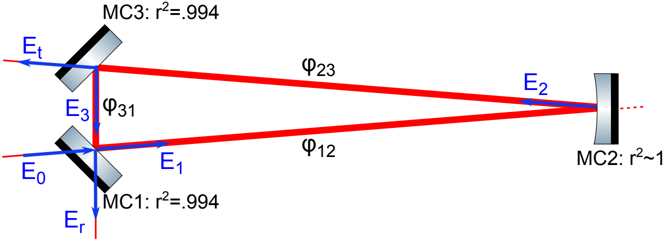


Figure: MC1 and MC3 in HAM2

The IMC as a Phase Discriminator



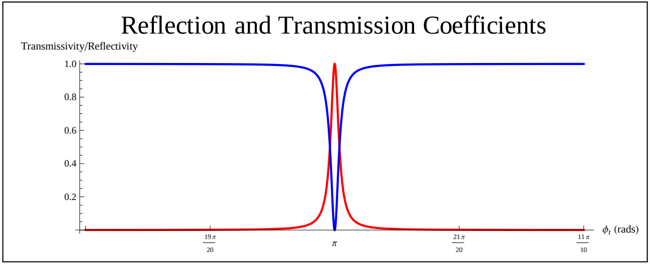
$$E_r = tE_3 e^{-i\phi_{31}} + rE_0$$
$$E_t = tE_2 e^{-i\phi_{23}}$$
$$E_1 = tE_0 - rE_3 e^{-i\phi_{31}}$$
$$E_2 = -E_1 e^{-i\phi_{12}}$$
$$E_3 = -rE_2 e^{-i\phi_{23}}$$

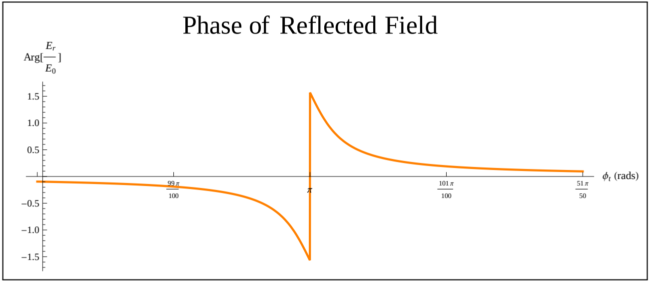
$$\Rightarrow$$

$$\frac{E_r}{E_0} = \frac{r(1 + e^{-i\phi_t})}{1 + r^2 e^{-i\phi_t}}$$

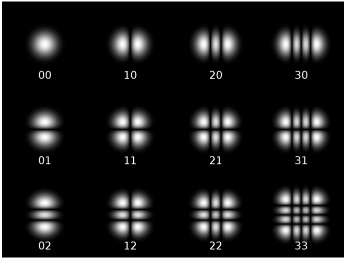
$$\frac{E_t}{E_0} = \frac{t^2 e^{-i(\phi_t - \phi_{31})}}{1 + r^2 e^{-i\phi_t}}$$
$$\phi_t = \phi_{12} + \phi_{23} + \phi_{31}$$

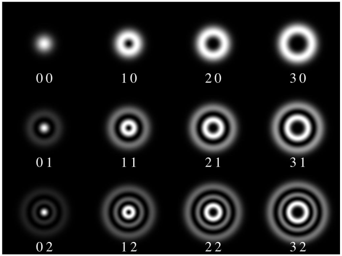
The IMC as a Phase Discriminator





The IMC as a Phase Discriminator





What determines the round trip phase?

- The dominant term is the round trip length of the cavity relative to the frequency of the laser: $\frac{2\pi}{c} f \ell$
- Equally as important is the Gouy phase of the different Gaussian modes: $(n + m + 1)\psi$

$$\phi_t = \frac{2\pi}{c} f \ell + (n + m + 1)\psi$$

The IMC as a Phase Discriminator

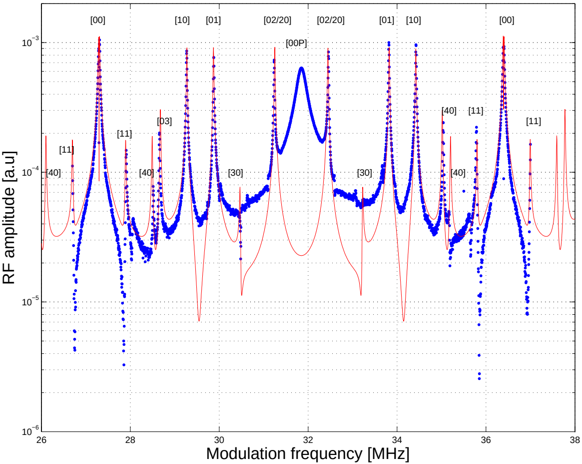
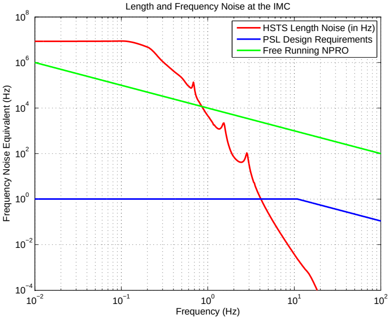


Figure: Measurement and model of the resonant modes of the L1 IMC (alog 4849)

The Passive Purposes of the IMC

- **Polarization filtering** An odd number of mirrors gives the horizontal polarization an extra π phase. Clean polarization is important for good interferometry.
- **Mode Cleaning** The cavity is locked so only the fundamental Gaussian mode is transmitted. This prevents light which will scatter and create shot noise from being injected into the interferometer.
- **Jitter Suppression** Misalignment between the beam and the cavity looks to the cavity like higher order modes, which are suppressed. Power stabilization after the IMC keeps this from coupling to intensity noise.
- **Frequency Noise Suppression at High Frequencies** The cavity line width (cavity pole) is about 9 kHz so fluctuations at higher frequencies are suppressed. This is not as important as low frequency stabilization which is done actively.

Active Frequency Noise Suppression



The IMC compares its length to the frequency of the incoming laser. For active suppression we have to choose where to send the feedback; length or frequency. Noise models suggest a crossover of ~ 5 Hz, but practical limitations from the hierarchical feedback keep it at ~ 15 Hz.

Active Frequency Noise Suppression

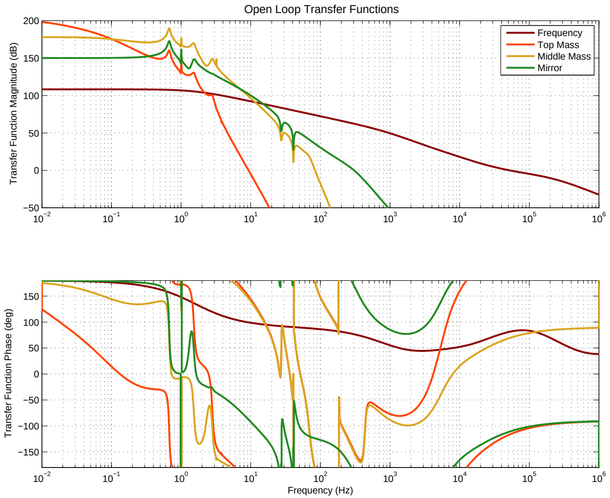


Figure: The control loops of the IMC

Input Optics Layout

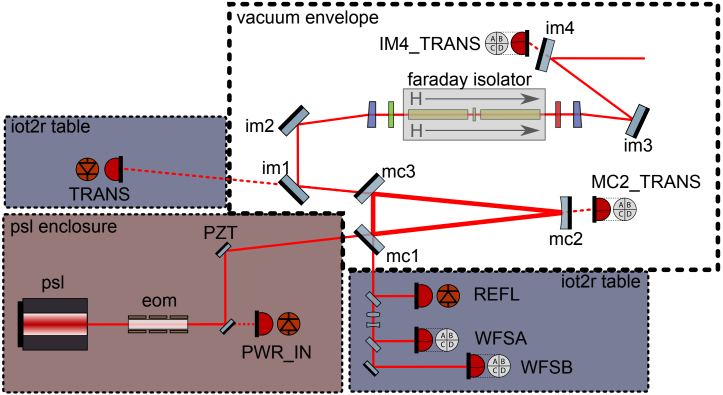


Figure: A schematic layout of the input optics. Capital letters represent channel names perepended with {ifo}:IMC-

Angular Control of the Input Mode Cleaner

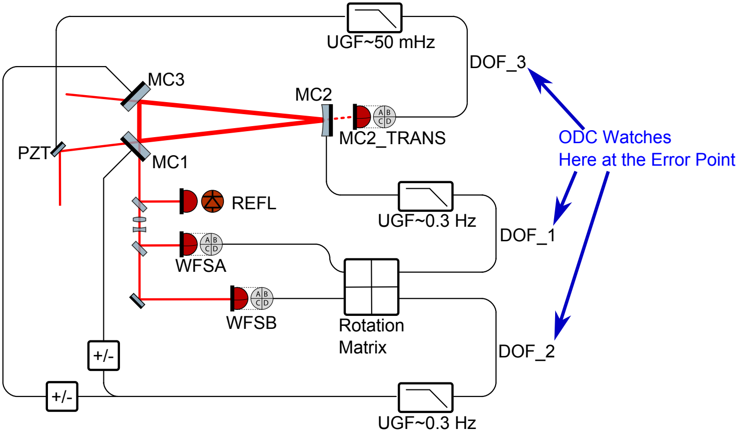


Figure: Schematic of the IMC Angular Control Scheme.

Angular Control of the Input Mode Cleaner

- **Low UGFs** The angular stability of the triple suspensions and seismic platforms is good enough at high frequency that only very low frequency angular control is required.
- **Offloading Loop** The feedback from MC2 Trans to the input PZT mirror has a significantly lower UGF than the WFS loops. The WFS loops keep the cavity resonant, and the PZT loop keeps the input beam pointing at the center of MC2.
- **Uncontrolled DOF** A three mirror cavity has three degrees of freedom, but we only have two effective sensors. This leaves one uncontrolled degree of freedom which can be though of as the spot position on MC3. This doesn't seem to be a problem yet.

Length/Frequency Control Details

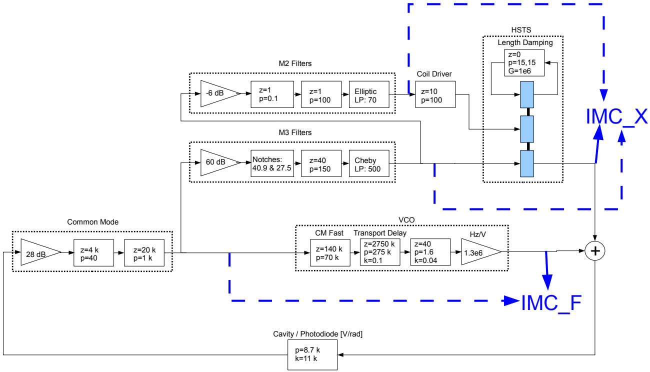
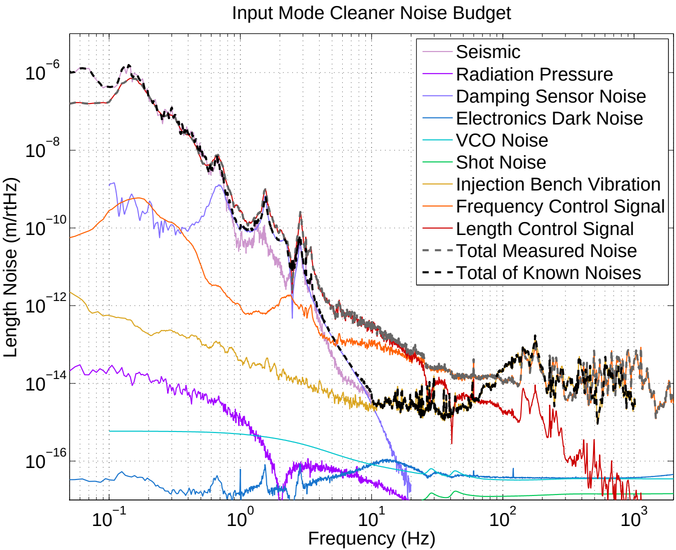


Figure: A schematic view of the length control loops. Also shown are the important DetChar channels; dashed lines show where the signals are actually taken from and solid lines show where the signals are calibrated to look like they came from.

Length/Frequency Control Details

- **IMC_F** The fast feedback to the frequency never makes it into the digital system. A monitor of the signal sent to the VCO is picked up in the digital system. This signal is calibrated by the measured VCO transfer function so that IMC_F has units of Hz.
- **IMC_X** All of the slow controls for feedback to the length of the cavity are done inside of the digital system. There are separate signals sent to each stage of the triple suspension; M1, M2, and M3. These signals are calibrated through a digital filter that replicates the suspension transfer function and summed together to make IMC_X.
- **PSL** The frequency actuation of the IMC is accomplished by driving a VCO which shifts the frequency of a pickoff of the PSL light. The PSL loop known as the frequency stabilization servo (FSS) keeps this light locked to a small cavity known as the reference cavity. The IMC frequency loop therefore runs on top of this loop which has a bandwidth of ~ 500 kHz. This is not shown in the diagram.

The IMC Noise Budget



The IMC Noise Budget

- **Low Frequency is Dominated by Seismic** Below all three suspension resonances (< 3 Hz) the noise in the IMC is dominated by seismic motion. No surprise here.
- **High Frequency is Dominated by PSL Vibration** Above ~ 80 Hz the measured noise is dominated by vibrations on the PSL table. The peaks are resonances of optic mounts and periscopes. This noise should be suppressed by the IMC feedback.
- **Noise In Between is not Understood** The noise between 5 Hz and 80 Hz is still not understood. There are some indications that it is related to the reference cavity on the PSL table, but no smoking gun yet.

Channels of Interest

PSL

- **ISS:** {ifo}:PSL-ISS_PDA_OUT_DQ, {ifo}:PSL-ISS_PDB_OUT_DQ, {ifo}:PSL-ISS_AOM_DRIVER_MON_OUT_DQ
- **FSS:** {ifo}:PSL-FSS_FAST_MON_OUT_DQ, {ifo}:PSL-FSS_PC_MON_OUT_DQ, {ifo}:PSL-FSS_TPD_OUT_DQ
- **PMC:** {ifo}:PSL-PMC_HV_MON_OUT_DQ

IMC

- **Frequency/Length:** {ifo}:IMC-F_OUT_DQ (calibrated in kHz), {ifo}:IMC_X_DQ (calibrated in μm, whitened with z=0.2Hz,0.2Hz; p=1kHz,1kHz), {ifo}:LSC-PRCL_OUT_DQ, {ifo}:IMC-X_(M2,M3)_OUT_DQ
- **Angular Stability:** {ifo}:IMC-MC2_TRANS_(PIT,YAW)_OUT_DQ, {ifo}:IMC-(MC1,MC2,MC3)_(YAW,PIT)_OUT_DQ, {ifo}:IMC-DOF_(1,2,3)_(Y,P)_IN_DQ, {ifo}:IMC-WFS_(A,B)_(I,Q)_(YAW,PIT)_OUT_DQ
- **Intensity Noise:** {ifo}:IMC-(MC2,IM4)_TRANS_SUM_OUT_DQ, {ifo}:IMC-REFL_DC_OUT_DQ, {ifo}:PSL-ISS_SECONDLOOP_(SUM14,SUM58)_OUT_DQ

SEI

- **Suspension Point Motion:** {ifo}:ISI-(HAM2,HAM3)_BLND_GS13(X,Y,Z,RX,RY,RZ)_IN1_DQ, {ifo}:ISI-(HAM2,HAM3)_MASTER_(H1,H2,H3,V1,V2,V3)_DRIVE_DQ
- **Ground Motion:** {ifo}:HPI-(HAM2,HAM3)_STSINF_(A,B,C)_(X,Y,Z)_IN1_DQ

Interesting Detector Characterization Studies

- **Noise in 5-80 Hz Band** The noise is this region is still not understood by an order of magnitude.
- **Suspension Upconversion** Low frequency seismic motion can cause slips and creaks in the suspension which would show up as periodic bursts of high frequency noise. Hopefully the IMC isn't sensitive enough to see crackle in the blade springs, but a poor joint or a slipping wire might show up.
- **Scattered Light Noise** Scattered light can recombine with the Refl beam and cause noise in the signal. This should show up as seismic upconversion noise due to fringe wrapping of the scattered light. Depending on the scatterer, it might come and go as optics move around in the chambers.

Interesting Detector Characterization Studies

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Chris Mueller

Meet the IMC
Why an IMC?
Phase Disc.
Passive
Active
Nuts & Bolts
IO Layout
Angular Control
Length Control
Noise
DetChar
Channels
Tasks

- **WFS Signals and Transmitted Intensity Noise**
  Misalignments between the input beam and the IMC cause pointing fluctuations to couple to intensity noise at first order (it is a second order effect when well aligned). It would be interesting to see the transfer function from pointing noise to intensity noise over long time periods.
- **Glitches** Glitches in IMC_X and IMC_F could cause glitches in the main interferometer. When possible glitches should be checked for correlation with PRCL signal.
- **Up Time** We run the mode cleaner 24/7 these days, rarely taking it down intentionally for commissioning. It has been in this state since ∼August. It would be nice to see some statistics about uptime.