LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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aLIGO DRMI Noise Budget Modeling for Best Sensitivity

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1 Introduction

1.1 Purpose

In the L1 Dual-Recycled Michelson Interferometer (DRMI) test we are interested not only in the ability to lock the corner as a step of the full interferometer locking procedure, but also in the performance of the DRMI as a sensitive test of the individual components of the interferometer. Unfortunately the two tests require different configurations (PRC locked on sideband or carrier respectively) [1].

From calculations of sensing matrices [2], we can see that the sideband-locked DRMI has better sensing, and so we expect it to be an easier configuration to lock than the carrier-locked DRMI. However, it is the carrier-locked DRMI that gives best noise performance at the AS port (in the

MICH DoF) and so we concentrate on a noise budget calculation for the MICH DoF in the carrier-locked configuration of the DRMI and PRMI (power-recycled michelson interferometer - SRM mis-aligned), with two readout configurations, RF and DC, and two input powers, 5W and 25W. Other configurations will also be used as necessary [3] [4] and we would also like to test angular control performance [5].

1.2 Modeling

The modeling has been done in Optickle and Lentickle, and the scripts can be found in the emvogil3 mit cvs repository under: *iscmodeling/LentickleAligo/DRMI/*. See section 6 for details.

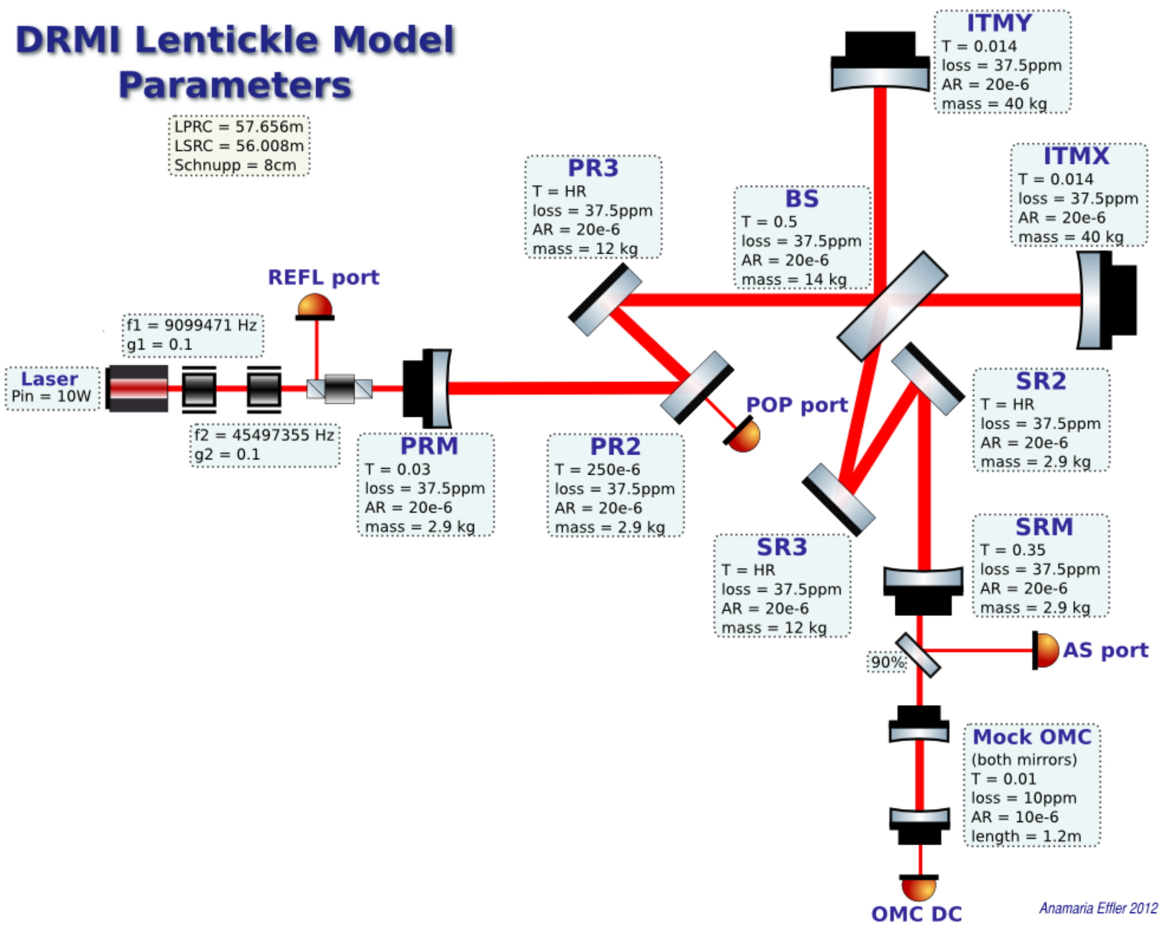

Figure 1: *Diagram of DRMI Model Parameters (not to scale)*

Fig. 1 shows the optical parameters used in this calculation. Table 1 shows the common parameters used for all the calculations. We use 5W input power as a reasonable starting point for DRMI commissioning. At each port, there may be RFPDs both in air and in vacuum looking at the same signal, comparable in size.

The modeling doesn't take into account mode matching or contrast defect, so there will be inaccuracies associated with that, especially an underestimate of the DC powers and signal strength at the AS port.

Input Power	REFL PO	POP PO	AS PO	OMC/AS Split	$\gamma_1 = \gamma_2$
5W	1.25%	12.5%	1.25%	90/10	0.1

Table 1: *Common parameters for all calculations*

The loops used for the controls of each of the three DoFs are shown in the figure below. The probes are named by port, then quadrature (I or Q) and then 1 or 2, depending whether they are demodulated at 9MHz or 45MHz respectively. If they contain a number (2 or 3) before the quadrature, then it is a probe for a multiple of the demodulation frequency (e.g. REFL_3I2 is the signal demodulated at 135MHz, at the REFL port, in the I quadrature).

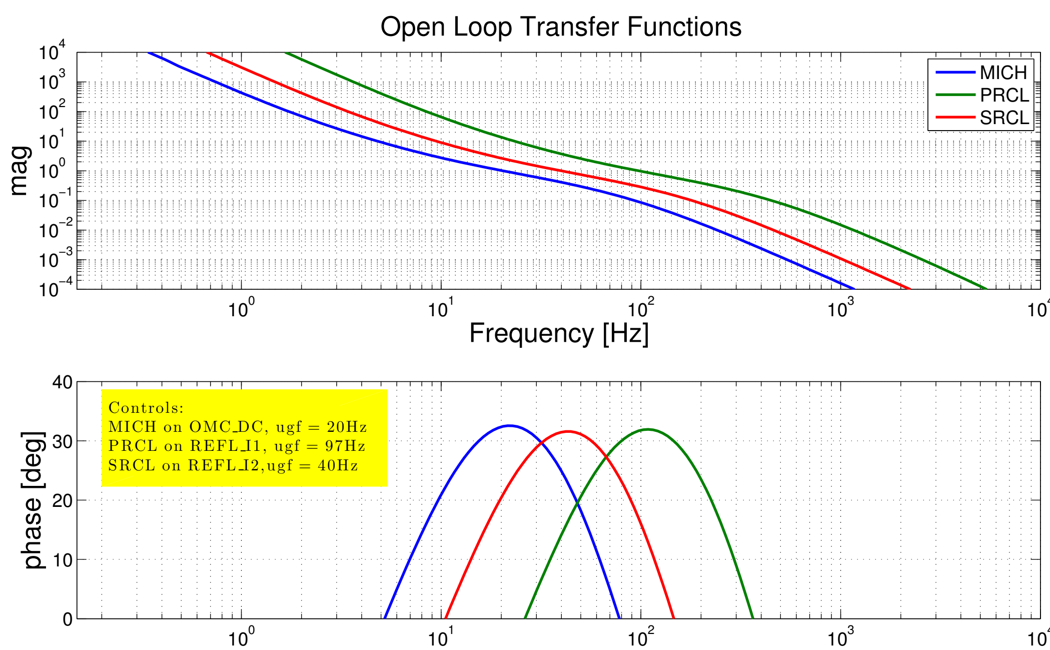

Figure 2: *Control loop shapes, not especially optimized. The phase was made to be above 30 deg, but otherwise are simple 1/f at UGF filters, with some boosting at low frequency and high frequency.*

2 Noise Calculations

2.1 Shot noise

The shot noise curve is calculated by using the Optickle quantum noise output at the PD (of those used in the control) and then propagated by the closed loop transfer function to the error point of MICH.

2.2 Control noise

This calculation is like the shot noise above, but includes the control loops as well, to show which loop may be problematic. Coupling exists due to the optical coupling of PRCL and SRCL to the MICH sensing (moving SRM and PRM affects MICH by varying the powers in the PRC and SRC, which shows up at the AS port sensors). It is not added to the total noise curve.

2.3 Intensity noise

Intensity noise is propagated through the closed loop transfer function from an AM modulator at the laser, and assuming some input noise, in this case a RIN of 1e-8.

2.4 Frequency noise

Frequency noise is propagated through the closed loop transfer function from an FM modulator at the laser, assuming as input noise the sensing noise of the IMC (measured electronics noise).

2.5 Electronics noise

Electronics noise represents the dark current PD noise effect, and is propagated just like shot noise, using shot noise equivalent numbers for the PDs we use. For the OMC PDs, this is 0.2mA, for 9MHz PDs it is 1.35mA and for 445MHz PDs it is 1.98mA (refs).

2.6 Seismic noise

Seismic noise input is data taken during the IMC test at LLO for HAM-ISI and during OAT at LHO for BSC-ISI. We may have better seismic noise than this. The noises are applied at each optic propagated through the relevant suspension transfer function, then added incoherently. While we expect some common mode rejection from the slab at low frequencies, we do not expect it above some 5 Hz, and hence the calculation is relevant above these frequencies. Only suspension length DoF is considered.

2.7 BOSEM noise

BOSEM noise is taken from measurements performed at Birmingham and propagated through the suspension transfer function including damping loops. The noise couples exactly because we are using them as sensors for damping the suspensions.

2.8 Thermal Noise

In the DRMI configuration, for MICH, the largest thermal noise term is the wire suspension of the BS, we include it separately from ITMs. The calculations were done by MarkB (T040027 for BS) and the data can be found in the Sus svn. The thermal noise in m/$\sqrt(Hz)$ is then propagated through the closed loop transfer function of the corresponding optic to MICH.

3 DRMI Configuration

3.1 DRMI DC Readout with 5W Input Power

Sensing Matrix [W/m]			
Dof/PD	MICH	PRCL	SRCL
REFL_I1	-1.5e3	4.3e6	-49
REFL_3I2	2	-140	80
OMC_DC	1.9e7	-42	81
Input Matrix			
PD/Dof	REFL_I1	REFL_3I2	OMC_DC
MICH	0	0	1
PRCL	1	0.616	0
SRCL	3.3e-5	1	0

Table 2: *Sensing matrix and resulting input matrix for DRMI DC readout, 5W input power. SRCL sensing is very poor due to PRC being in carrier lock and rejecting most of the sideband power.*

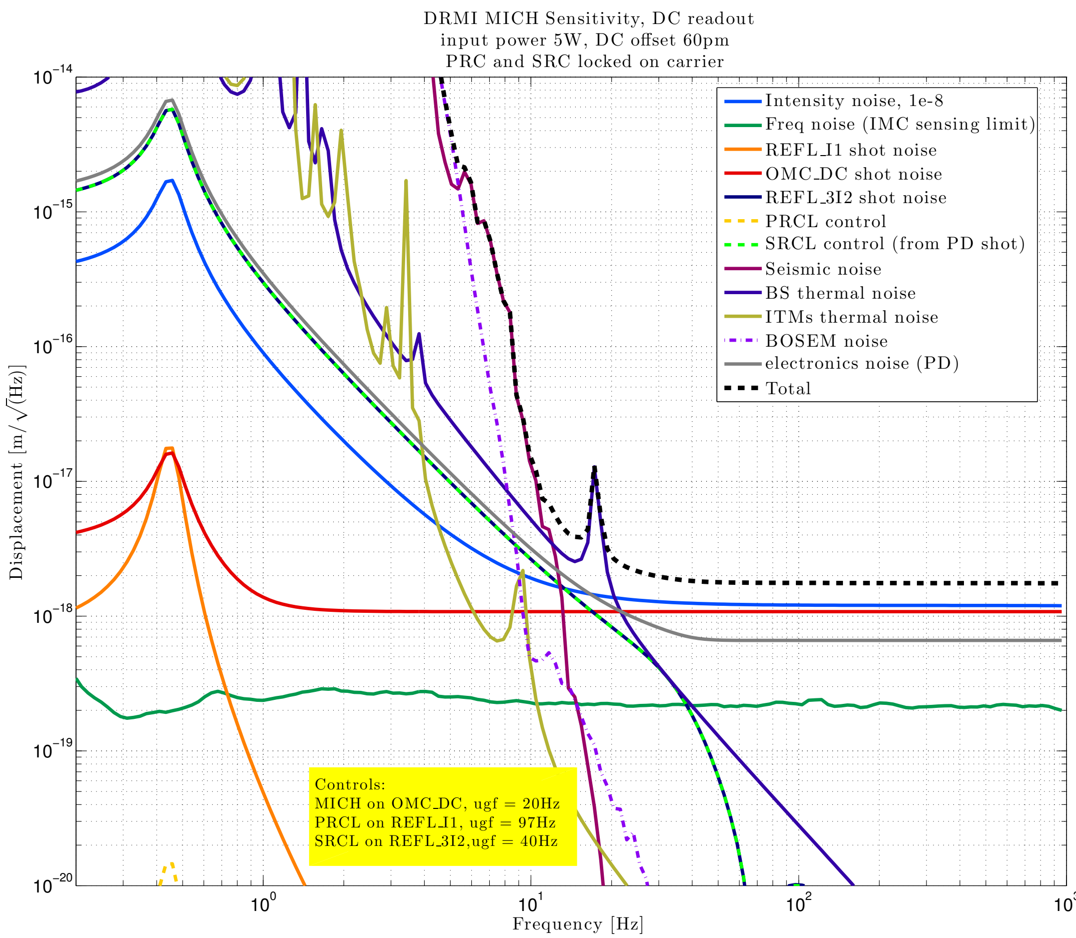

Figure 3: *DRMI DC readout, 5W input power. DC offset applied to ITMs, chosen such that the intensity noise is approximately equal to the shot noise at high frequency. SRCL/PRCL control noise is not added into the total, it is just a propagation to show which loop is responsible for this coupling.*

3.2 DRMI DC Readout with 25W Input Power

Sensing Matrix [W/m]			
Dof/PD	MICH	PRCL	SRCL
REFL_I1	-1.6e4	2.1e7	-200
REFL_3I2	9	-720	200
OMC_DC	4e7	-88	-230
Input Matrix			
PD/Dof	REFL_I1	REFL_3I2	OMC_DC
MICH	0	0	1
PRCL	1	0.514	0
SRCL	3.3e-5	1	0

Table 3: *Sensing matrix and resulting input matrix for DRMI DC readout, 25W input power. SRCL sensing is very poor due to PRC being in carrier lock and rejecting most of the sideband power.*

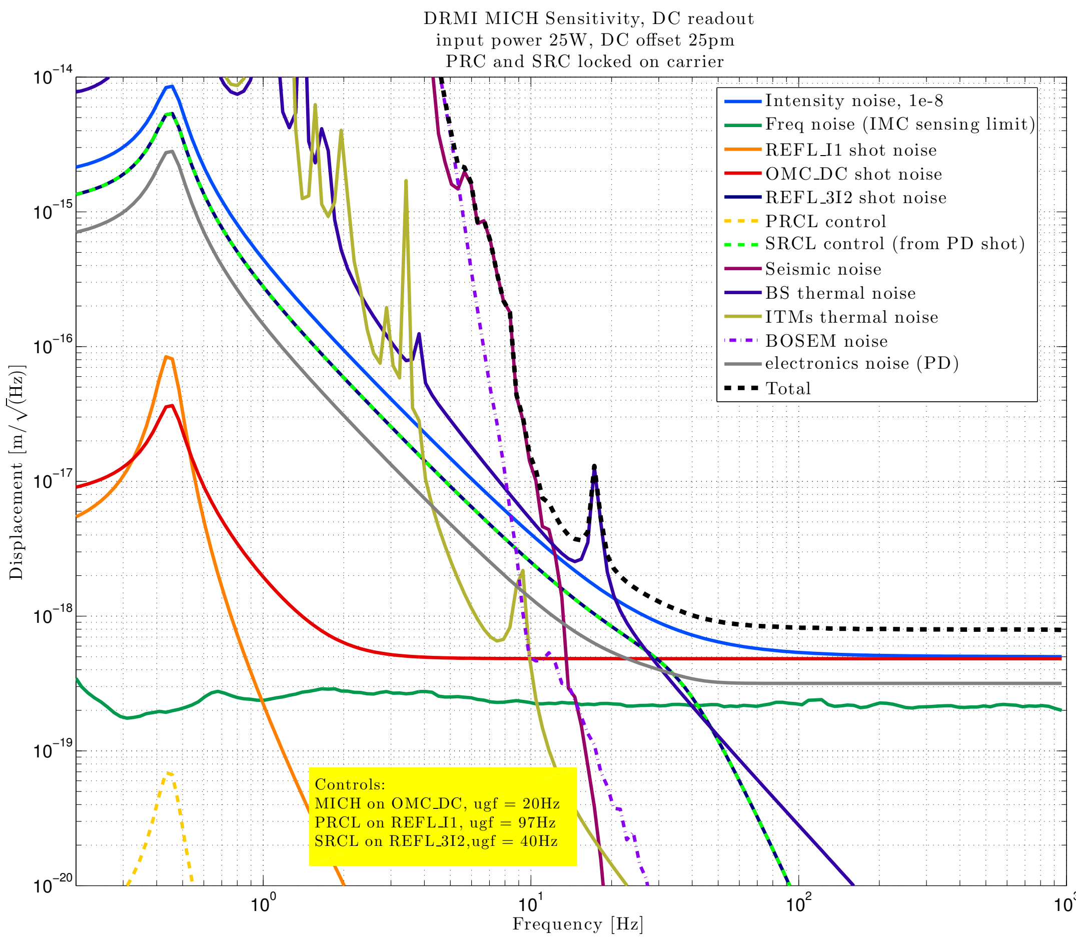

Figure 4: *DRMI DC readout, 25W input power. DC offset applied to ITMs, chosen such that the intensity noise is approximately equal to the shot noise at high frequency. SRCL/PRCL control noise is not added into the total, it is just a propagation to show which loop is responsible for this coupling.*

3.3 DRMI RF Readout with 5W Input Power

Sensing Matrix [W/m]			
Dof/PD	MICH	PRCL	SRCL
REFL_I1	120	4.3e6	-38
REFL_3I2	2	-140	80
AS_Q2	3.3e4	14	0
Input Matrix			
PD/Dof	REFL_I1	REFL_3I2	AS_Q2
MICH	0	0	1
PRCL	1	0.467	0
SRCL	3.3e-5	1	0

Table 4: *Sensing matrix and resulting input matrix for DRMI RF readout, 5W input power. SRCL sensing is very poor due to PRC being in carrier lock and rejecting most of the sideband power.*

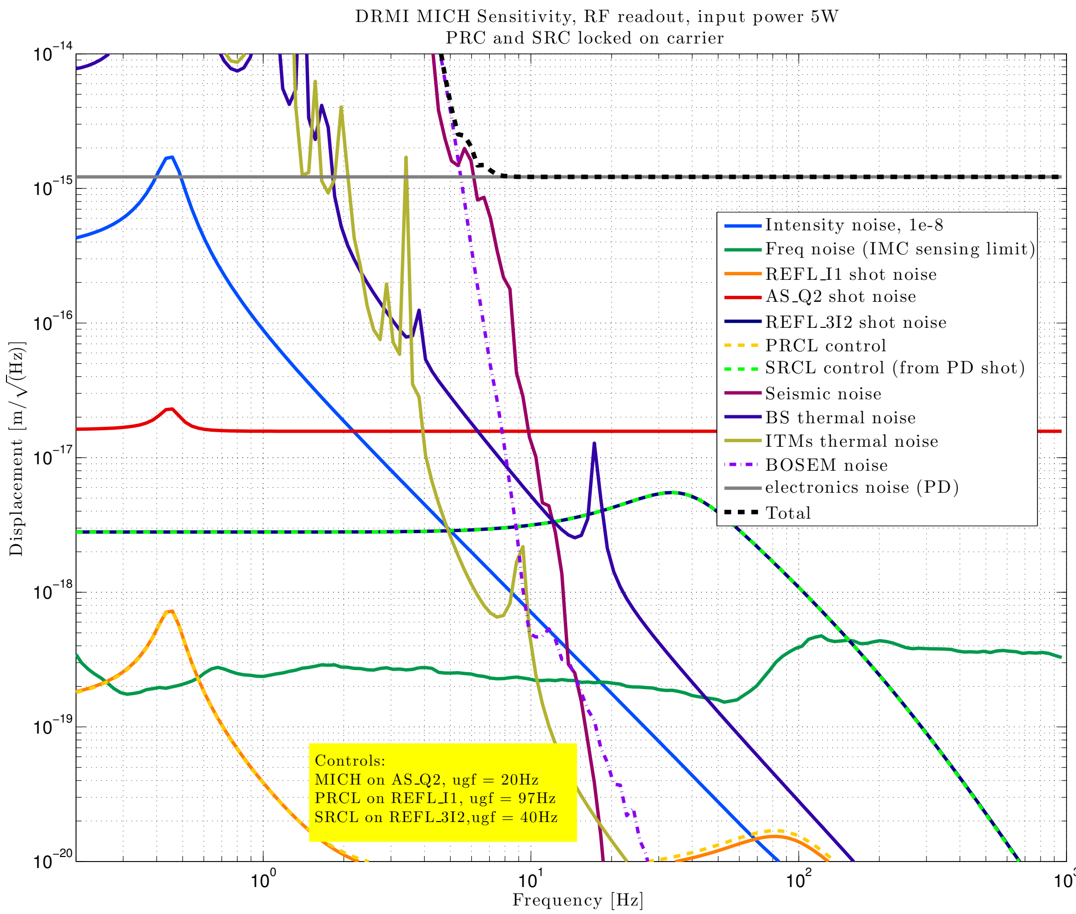

Figure 5: *DRMI RF readout, 5W input power. SRCL/PRCL control noise is not added into the total, it is just a propagation to show which loop is responsible for this coupling.*

3.4 DRMI RF Readout with 25W Input Power

Sensing Matrix [W/m]			
Dof/PD	MICH	PRCL	SRCL
REFL_I1	570	2.1e7	-190
REFL_3I2	9	-720	400
AS_Q2	1.6e5	71	0
Input Matrix			
PD/Dof	REFL_I1	REFL_3I2	AS_Q2
MICH	0	0	1
PRCL	1	0.467	0
SRCL	3.3e-5	1	0

Table 5: *Sensing matrix and resulting input matrix for DRMI RF readout, 25W input power. SRCL sensing is very poor due to PRC being in carrier lock and rejecting most of the sideband power.*

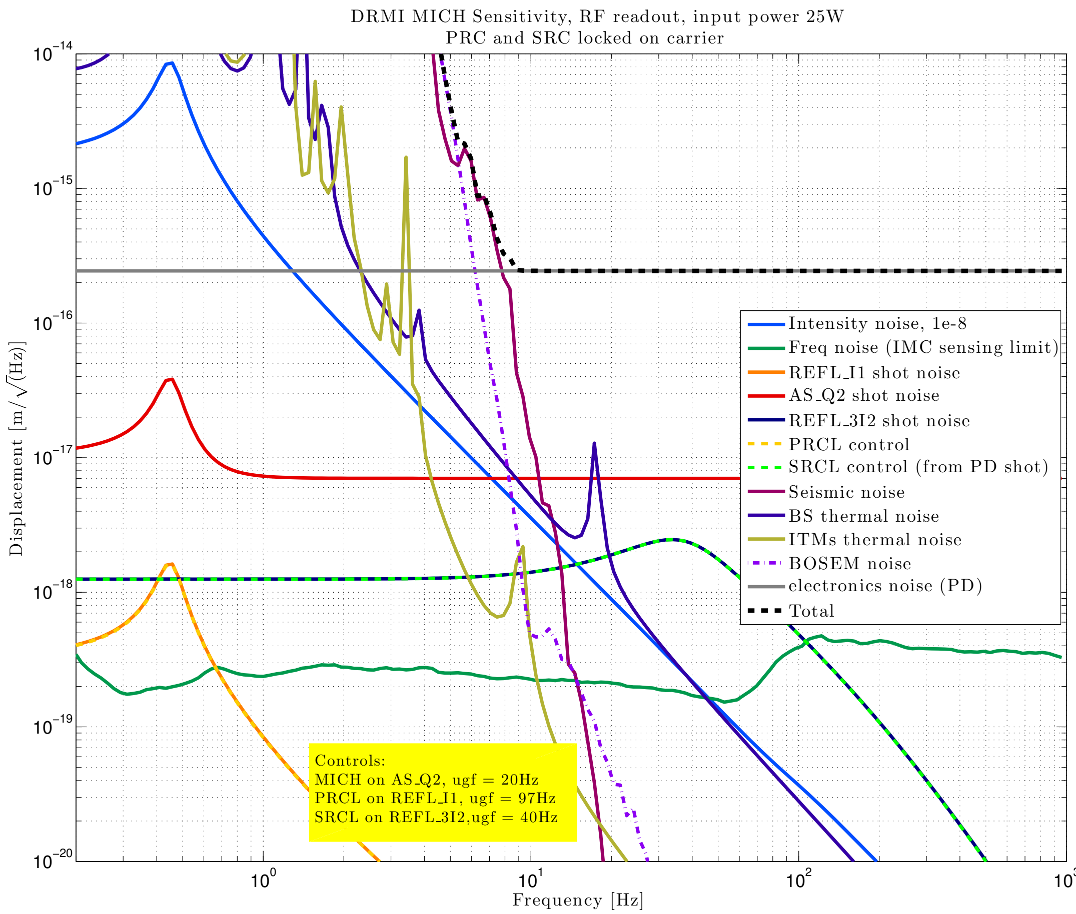

Figure 6: *DRMI RF readout, 5W input power. SRCL/PRCL control noise is not added into the total, it is just a propagation to show which loop is responsible for this coupling.*

4 PRMI Configuration

4.1 PRMI DC Readout with 5W Input Power

Sensing Matrix [W/m]		
Dof/PD	MICH	PRCL
REFL_I1	-960	4.3e6
OMC_DC	3.8e6	8
Input Matrix		
PD/Dof	REFL_I1	OMC_DC
MICH	0	1
PRCL	1	0

Table 6: *Sensing matrix and resulting input matrix for PRMI DC readout, 5W input power.*

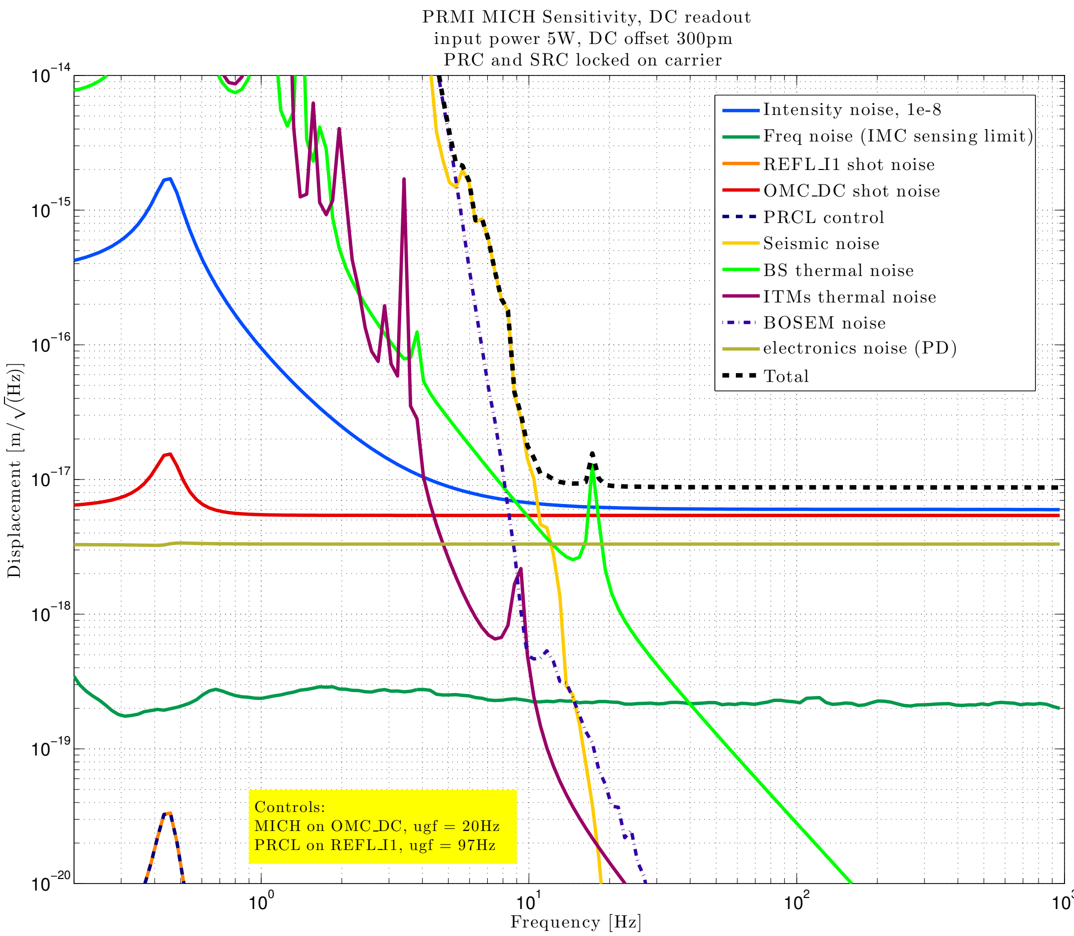

Figure 7: *PRMI DC readout, 5W input power. PRCL control noise is not added into the total.*

4.2 PRMI DC Readout with 25W Input Power

Sensing Matrix [W/m]		
Dof/PD	MICH	PRCL
REFL_I1	-9.7e3	2.1e7
OMC_DC	8e6	170
Input Matrix		
PD/Dof	REFL_I1	OMC_DC
MICH	0	1
PRCL	1	0

Table 7: *Sensing matrix and resulting input matrix for PRMI DC readout, 5W input power.*

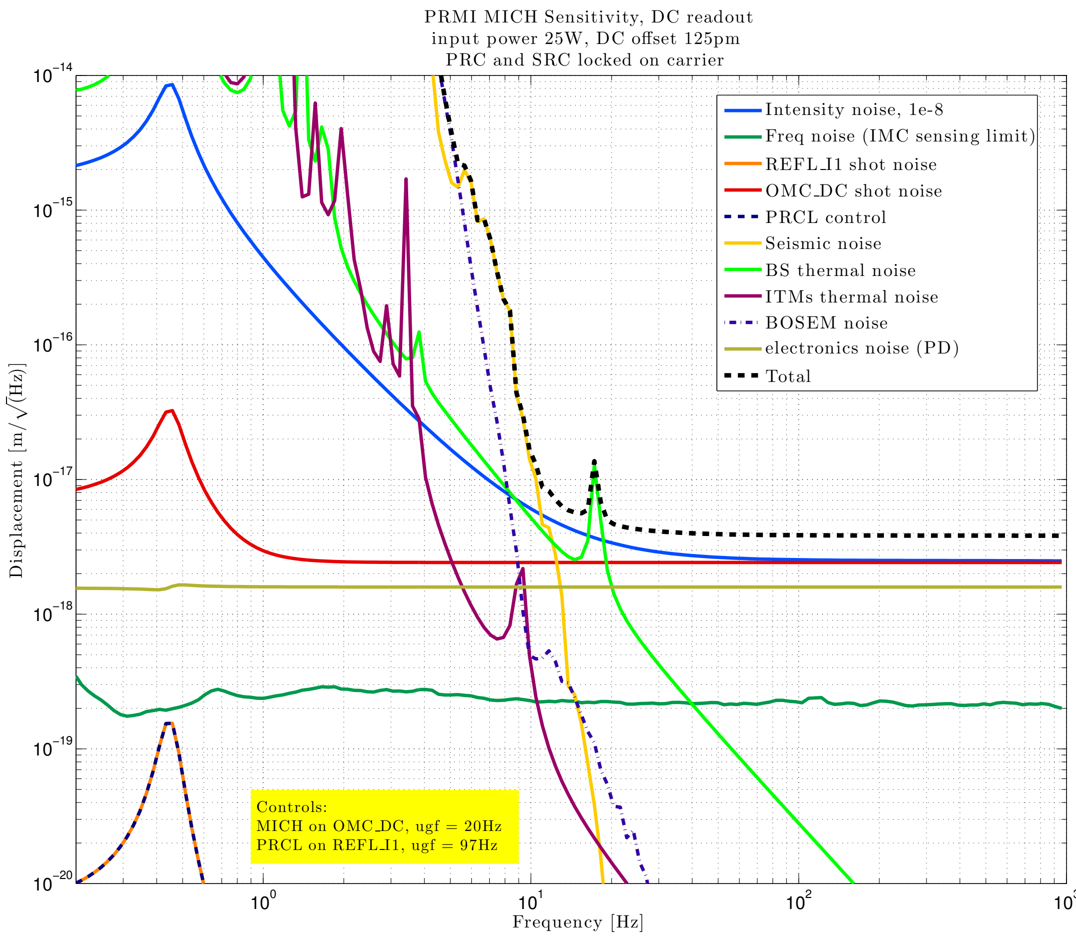

Figure 8: *PRMI DC readout, 25W input power. PRCL control noise is not added into the total.*

4.3 PRMI RF Readout with 5W Input Power

Sensing Matrix [W/m]		
Dof/PD	MICH	PRCL
REFL_I1	-68	4.3e6
AS_Q2	1.3e3	0
Input Matrix		
PD/Dof	REFL_I1	AS_Q2
MICH	0	1
PRCL	1	0

Table 8: *Sensing matrix and resulting input matrix for PRMI DC readout, 5W input power.*

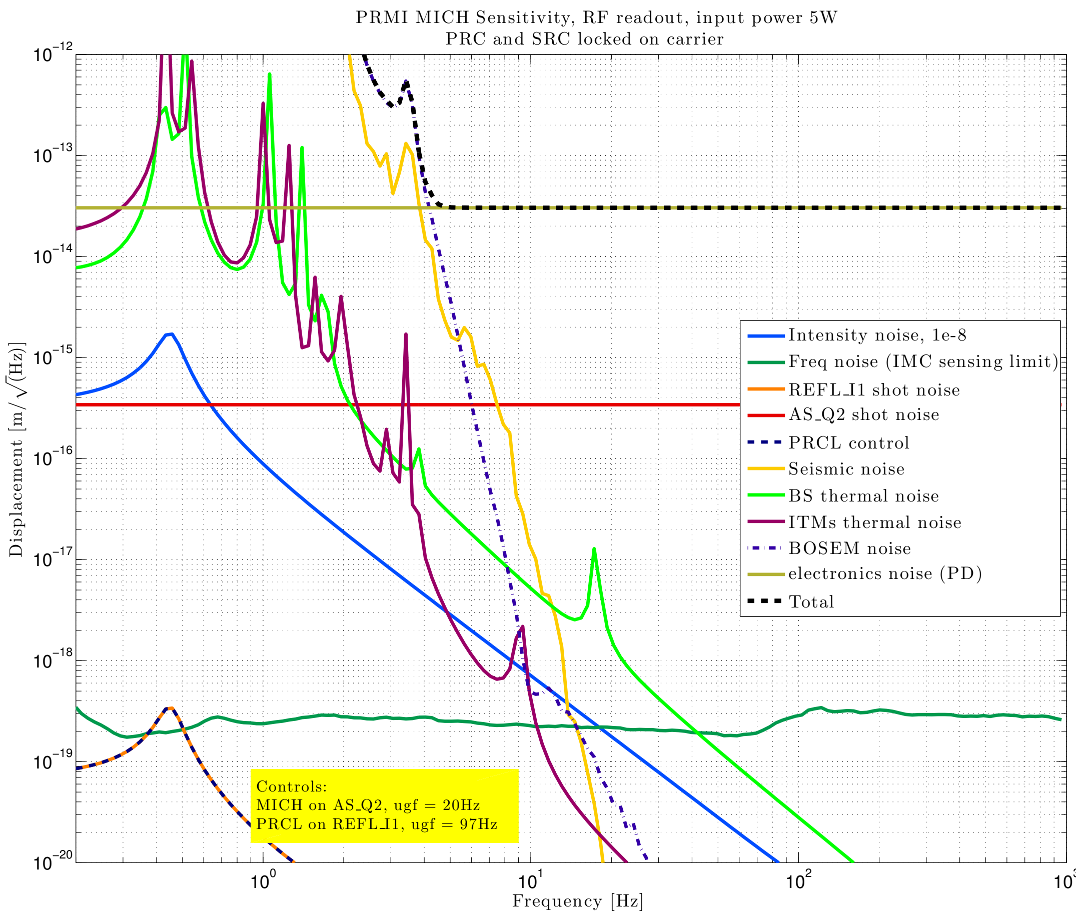

Figure 9: *PRMI RF readout, 5W input power. PRCL control noise is not added into the total.*

4.4 PRMI RF Readout with 25W Input Power

Sensing Matrix [W/m]		
Dof/PD	MICH	PRCL
REFL_I1	-340	2.1e7
AS_Q2	6.5e3	1
Input Matrix		
PD/Dof	REFL_I1	AS_Q2
MICH	0	1
PRCL	1	0

Table 9: *Sensing matrix and resulting input matrix for PRMI DC readout, 25W input power.*

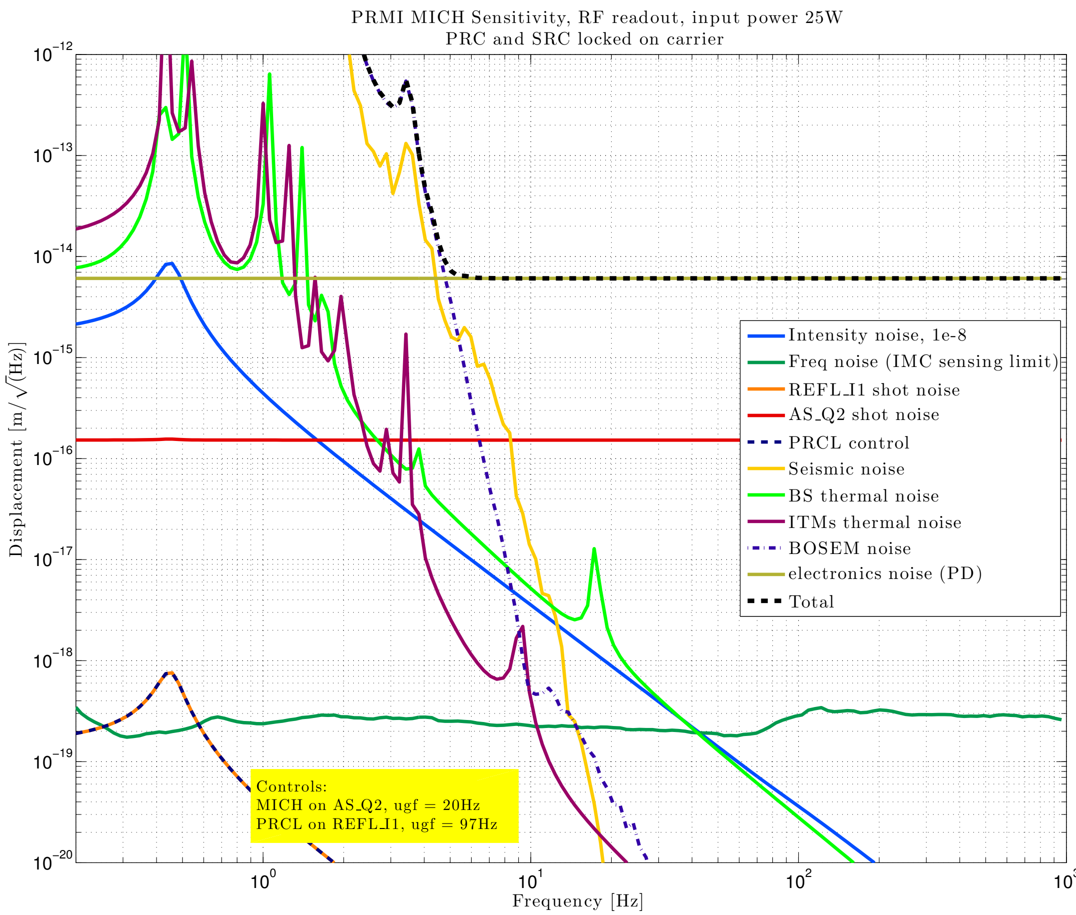

Figure 10: *PRMI RF readout, 25W input power. PRCL control noise is not added into the total.*

5 Some Conclusions

We can obtain reasonably low noise both in the DRMI and PRMI configurations with DC readout, differing only in a factor of a few, having to do with the SRM having 35% transmission.

Since the most sensitive configuration of the DRMI is with the PRC locked on carrier, the SRC sees very low sideband power and has bad sensing. This is not an issue in the full interferometer configuration because then both carrier and sidebands are resonant in the PRC. However, we have to account for this effect in the DRMI test.

In RF readout, the DRMI is heavily dominated by electronics noise because the contrast defect is idealized (on the order of a few parts in 10^{-9}), and the only imbalance in this calculation comes from the BS AR coating loss (20ppm in the code). This also couples intensity noise and frequency noise to the AS port, while in a perfectly dark Michelson this coupling should be zero.

BOSEM damping noise - noise coming from BOSEMs and coupling in due to damping loops using them as sensors at the top stage of each suspension - may be a troubling point at low frequency.

6 Further Code Details

The code can be found and run from the *emvogil-3.mit.edu* cvs repository in the `iscmodeling/LentickleAligo/DRMI/` directory.

The main files to run are `runLentickleDRM.m` and `runLenticklePRM.m`, for DRMI and PRMI respectively. The only file to edit for correct paths on different computers should be `ParamFiles/setPaths.m`. Inside each `runLentickle*` one can set either RF or DC readout. For now, the DC readout is only optimized (intensity noise versus shot noise) for 5W and 25W input powers (on the PRM).

The optical parameters used can be seen in the `ParamFiles/` directory. The relevant ones are:

- `paramL1DRM.m` - contains optics, lengths, modulation frequencies, etc.
- `optL1DRM.m` - links optics together into an Optickle system.
- `probesL1DRM_00.m` - adds carrier probes such as REFL, POP and AS, DC and RF.
- `DRMI_ns.m` - names the probes so they can be easily called.

The scripts also use other information, such as the seismic noise and suspension transfer functions in the `../SeismicIsolation/` directory. The seismic noise input comes from an IMC HAM-ISI measurement at LLO and an OAT BSC-ISI measurement at LHO, considered to be average seismic conditions with ISI performance we can expect to achieve. The relevant functions here are `seisHAM2.m, seisBSC2.m, seisSUS2.m` and the suspension transfer function ss objects denoted as `<type>_SS2.mat`. These contain the latest BSFM and QUAD damping filters as of May 2013, designed by JeffK. (The scripts and data structures without a `2` on the end use older seismic noise and suspension transfer functions).

In the main directory, the most important scripts called are:

- `makeCucumber*RM.m` - designs the loop for Lentickle, sets input/ouput matrices, UGFs, etc.
- `showSensing*RM.m` - shows sensing matrices and OLTFs
- `showNoise*RM.m` - calculates and plots the full noise budget.

References

[1] T1000294 - Lock Acquisition Study for aLIGO

[2] T1300328 - DRMI Sensing Matrices

[3] T1200289 - Simple Configurations for Early aLIGO Commissioning

[4] T1300009 - A Simple Measurement of PRC Length

[5] T1300155 - ASC Control Signals for DRMI