LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

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LIGO Hanford SQZ Subsystem Report

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Table of Contents

1 Introduction

This document is an overview of what has happened so far to LHO squeezer from November 2017 to April 2019.

2 List of Acronyms

Spelling everything out can be lengthy. Here I include a list of acronyms that I will be using throughout this document.

CLF = Coherent Locking Field

LO = can refer to **1)** local oscillator used in Pound-Drever-Hall locking technique and **2)** Local Oscillator field used to lock SQZ side bands to the main IFO beam.

NLG = Non-linear gain, described by how much red is produced given a certain amount of green pump light

OPO = Optical Parametric Oscillator

SHG = Second Harmonic Generator

SQZ/ASQZ = Squeeze/Anti-squeeze, refer to quantum state of light

TTFSS = Table-top Frequency Stabilization Servo

REFL = Reflected. Normally refer to a reflected beam off a cavity.

TRANS = Transmitted. Normally refer to a transmitted beam through a cavity

LLO = LIGO Livingston Observatory

LHO = LIGO Hanford Observatory

PFD = Phase-Frequency Discriminator

3 Layout

The system was designed such that we can flip back and forth between using the homodyne for diagnostic purposes and using the OMC DCPDs when we inject squeezing into the IFO. Below is a simplified layout of how we operate.

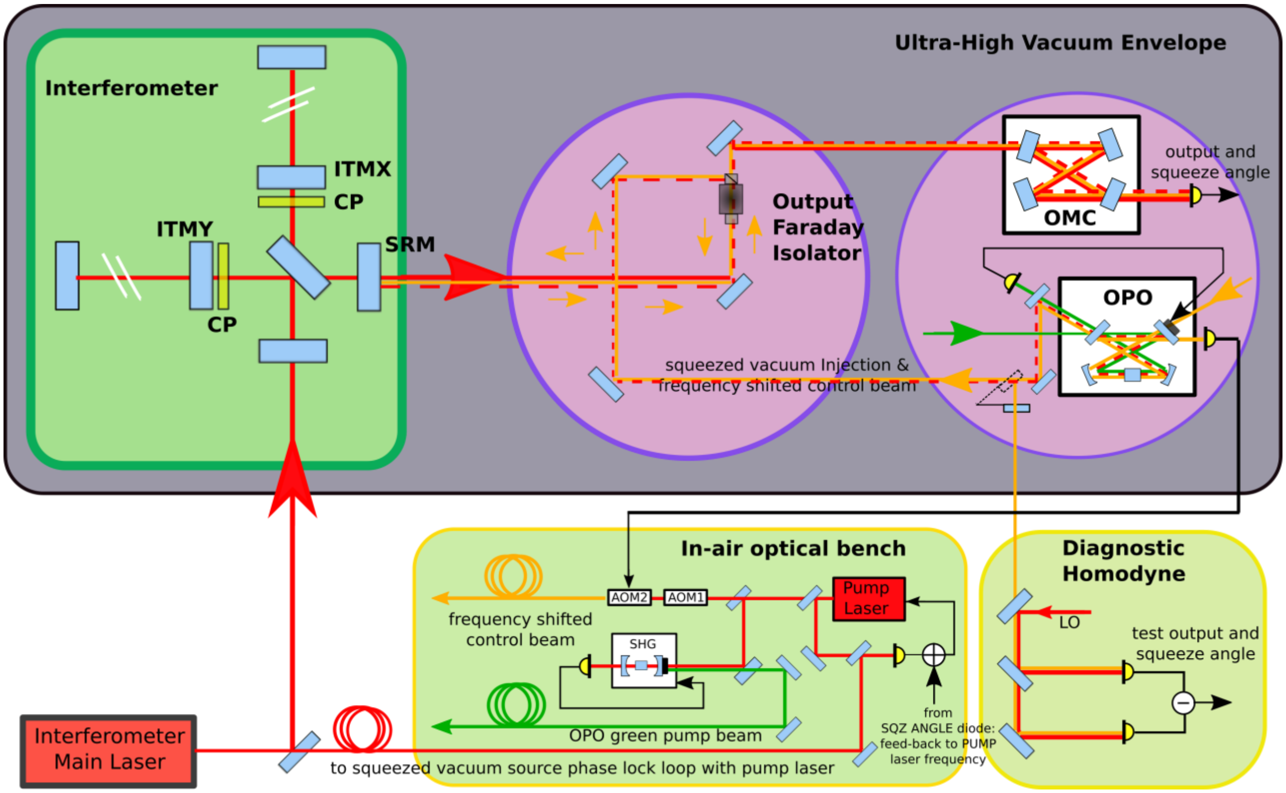


Figure 1 **I think this is Lisa's drawing. Couldn't find it on the dcc.**

Below is a somewhat more detailed layout.

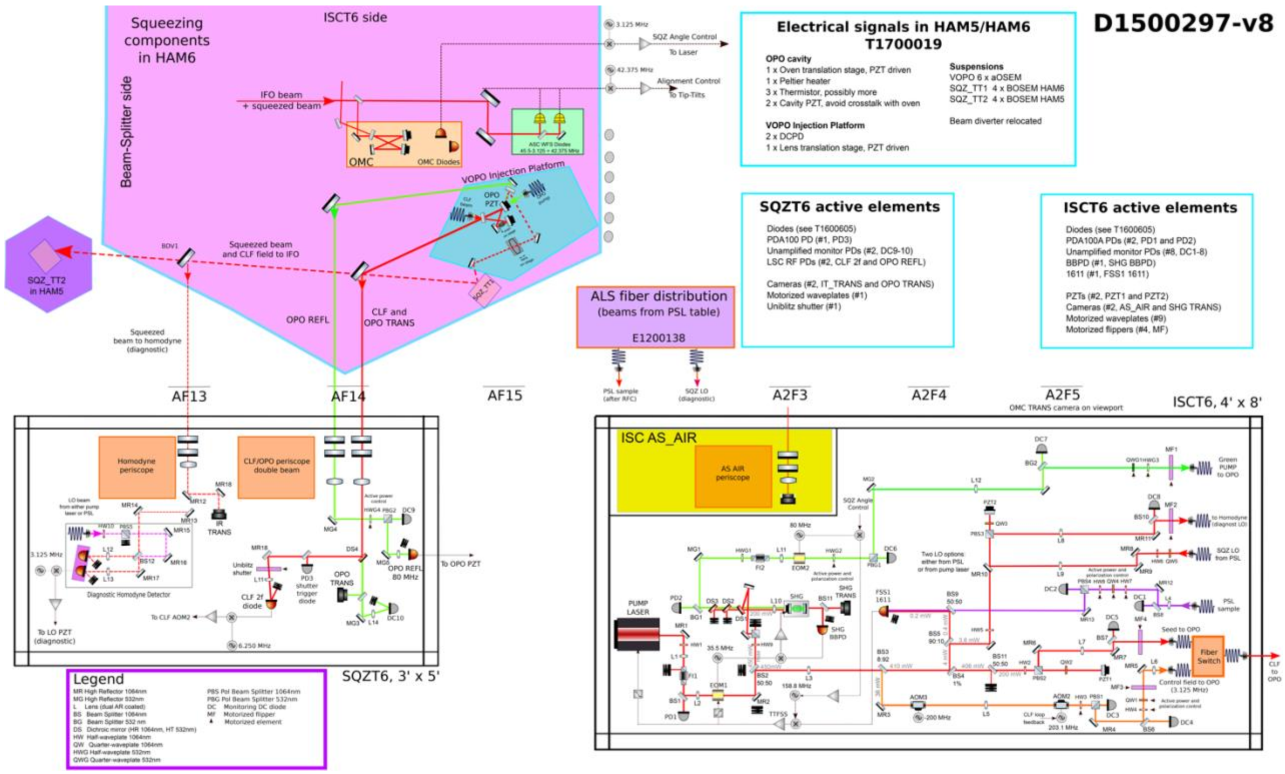


Figure 2

An even more detailed ISCT6

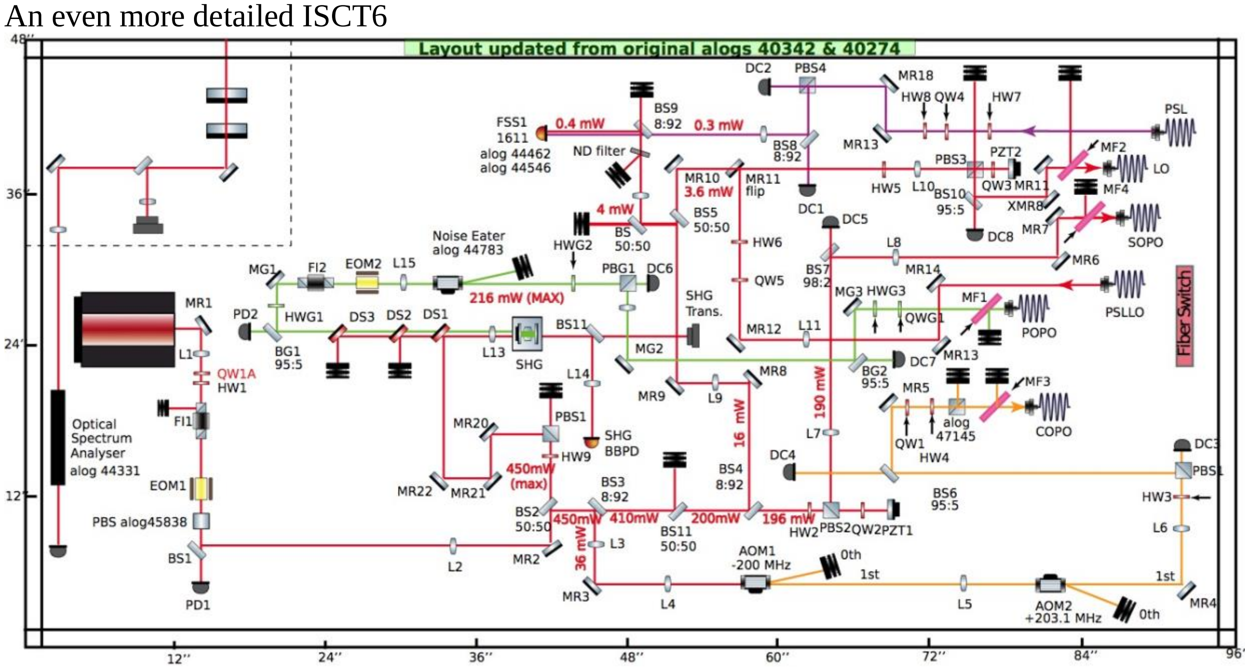


Figure 3 D1201210-v9 still missing PBS in CLF path and MR5 is now 90/10 BS + beam dump behind it.

4 Parameters, Calibrations, Characterizations (excluding noise. See CH 5)

4.1 Generic Constants

Parameter	Variable	Value
Speed of light (m/s)	c	299792458
Planck’s Constant (J.s)	h	6.626e-34
Red laser (m)		532e-9
Green laser (m)		1064e-9
KTP Crystal index of refraction (Red)	n_{KTP_1064}	1.8296
KTP Crystal index of refraction (Green)	n_{KTP_532}	1.8868

4.2 TTFSS

4.3 SHG

SHG cavity and housing: AEI design https://dcc.ligo.org/LIGO-D1300494 Same SHG used in enhanced LIGO

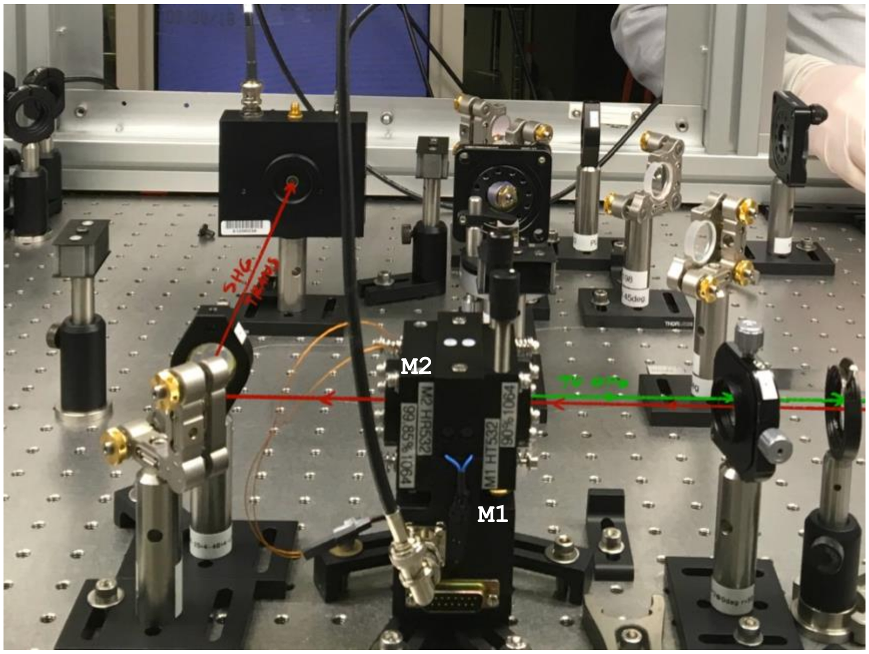


Figure 4

Mirror Reflectivity (R)	**1064**	**532**
M1	.90	<.02
M2	.9985	>.999

Table 1. https://dcc.ligo.org/DocDB/0008/E0900492/004/E0900492_v4.pdf

Photodiode:

Broad Band PD looking at SHG transmitted signal, S1200236
(Design document: https://dcc.ligo.org/LIGO-T1100467)

Responsivity (1064) = 0.1A/W
Transimpedance = 2kOhms

Parameter	**Variable**	**Formula**	**Value**
PPKTP Crystal Length (m)	$d_{crystal}$		10e-3
*Cavity Length (m)	L		50e-3 [1]
Free Spectral Range (GHz)	FSR	$\frac{c}{2L}$	2.9979
*Finesse, 1064	$\mathcal{F}$	$\frac{\pi * \sqrt{\sqrt{R1R2 \ldots R_i}}}{1 - \sqrt{R1R2 \ldots R_i}}$	58.79

Full width at half max (MHz)	FWHM	$\frac{FSR}{\mathcal{F}}$	51
**Hz to V calibration (V/Hz)		$\frac{2.9\,Vpp}{FWHM}$	5.6366e-8
PZT Hz to V calibration			60V/FSR (red)

* Cavity length can be calculated more accurately by taking crystal path length into account:

$$L_{total} = \mathrm{L} + (n_{KTP} d_{crystal})$$

** Taken Feb 23, 2018. We had 1.74 mW transmitted when locked. We have 1.9mW transmitted as of April 10, 2019.

4.3.1 SHG PZT issue and a slight modification that fixed it

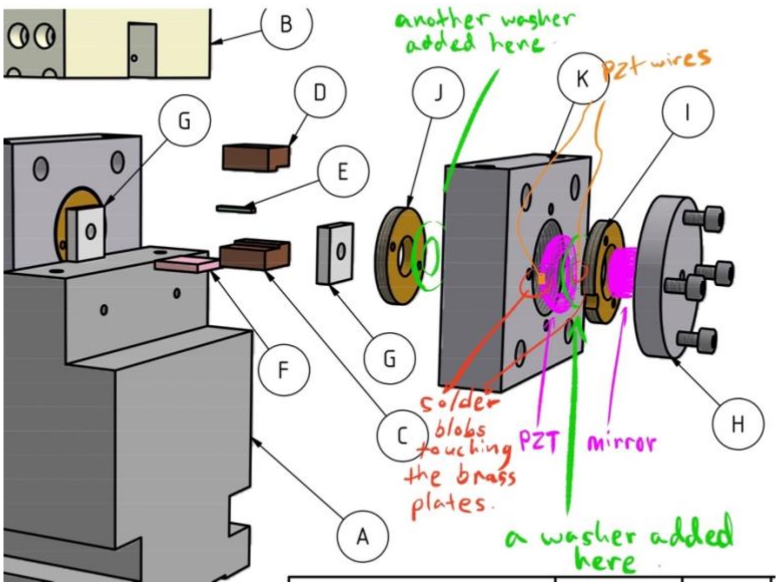


Figure 5

We had a few issues with the SHG PZT. The circuit was shorted due to the electrical contacts soldered on the edge of the PZT touching the brass plates (see SHG layout for reference, the plates mentioned are labeled I and J on page 2). Sheila put in a couple of insulating washers between the PZT and the brass (ordered from McMaster, part #95601A360). That fixed it.

4.3.2 Mode matching

The measured waist at the position of the SHG is 72.5um (before insertion of the SHG). Close to the solution at LLO (71um). With this ~99% mode matched was possible. After we tilted the first lens to avoid the back reflection into the laser we ended up with ~98% mode matched.

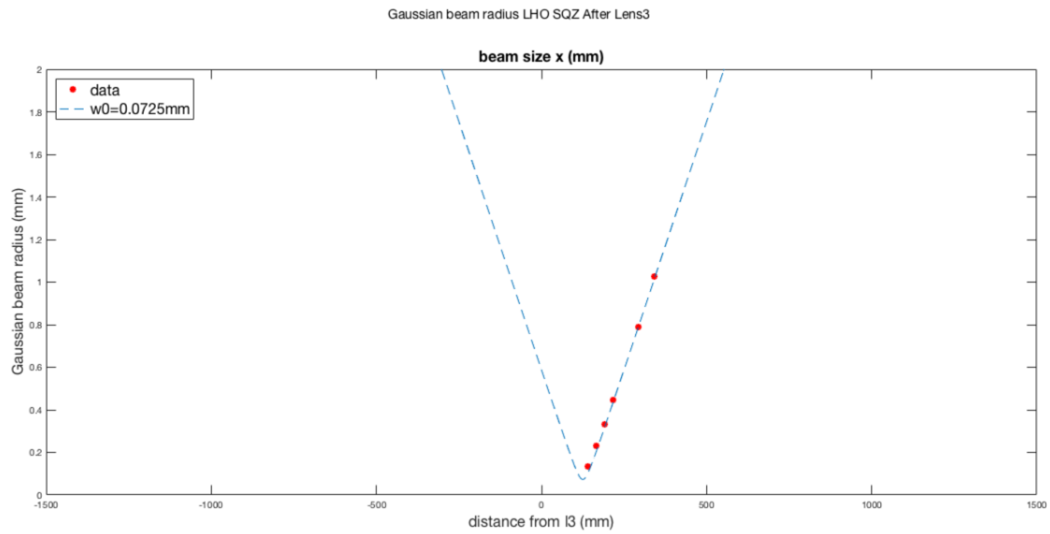


Figure 6

4.3.3 Conversion Efficiency

Polzik and Kimble 1991 eq (1)

$$\sqrt{\epsilon} = \frac{4T_1\sqrt{E_{NL}\mathrm{P}_1}}{[2-\sqrt{1-T_1}(2-\mathrm{L}-\sqrt{\epsilon E_{NL}P_1})]^2}$$

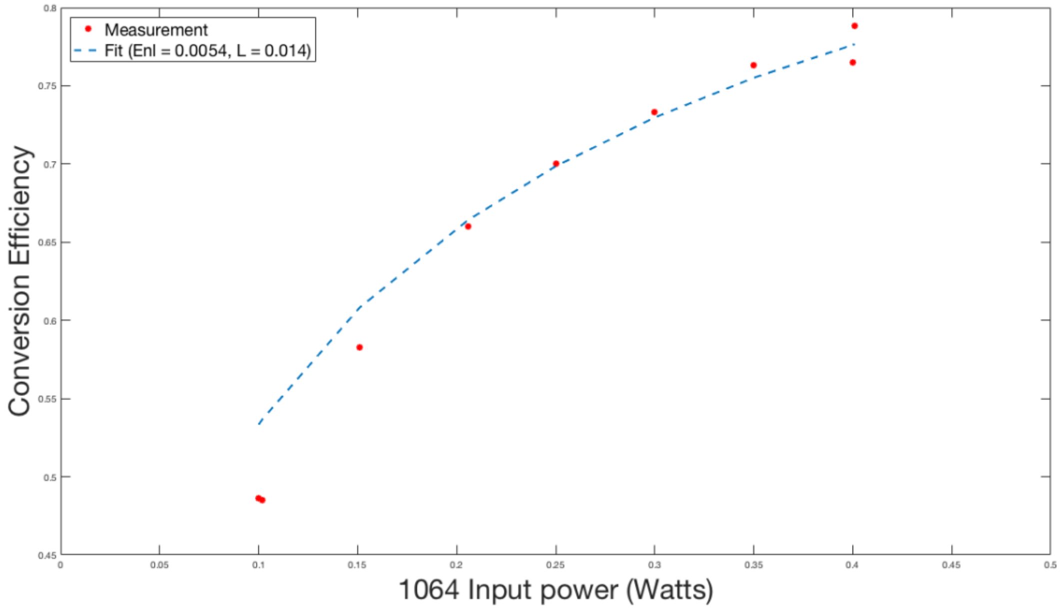


Figure 7: Conversion efficiency of LHO SHG cavity

For the fit I tweaked a couple parameters, intracavity losses (L) and the single-pass nonlinear conversion efficiency (E_{NL}).

4.4 OPO

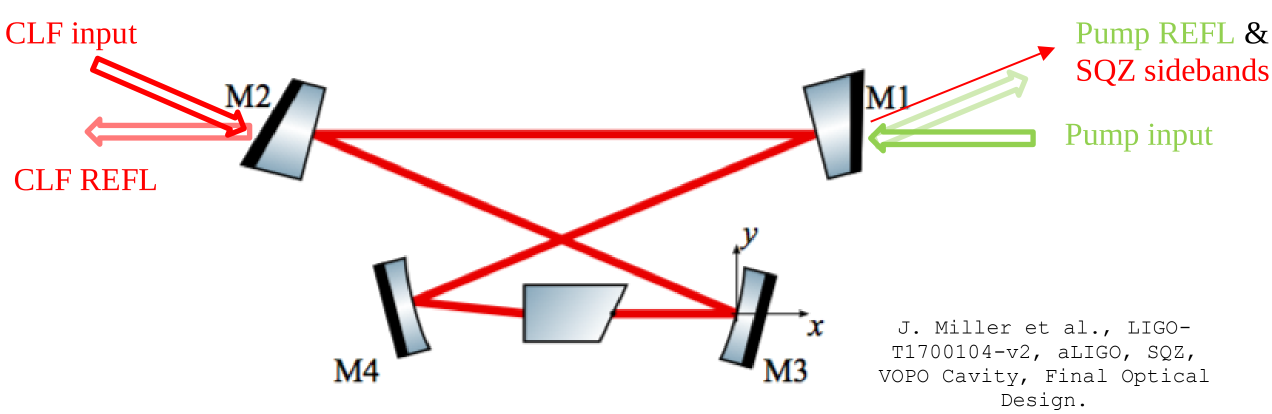


Figure 8

Mirror Reflectivity (R)	1064	532	1064/532 high finesse (both LLO and LHO are now using this design)
M1	. 87298077	. 86623711	.875/.98
M2	.99818636	.99998293	
M3	.99993587	.99998067	
M4	.99993625	.99998159	

H1 OPO before the M1 swap were serial numbers 37, 11, 6 , 8 for M1 to M4 respectively in E1800011.
For new M1 mirror (high finesse for 532) see E1700299

For more details on OPO mirror characterizations and installed optics see alog40500 and E1800011

Photodiode:

OPO REFL diode: S1200234, Broadband PD, unmodified
OPO trans diode: FEMTO LCA-S-400K-SI-FST, responds up to 400 kHz (alog47895).

Parameter	Variable	Formula	Value
PPKTP Crystal Length (m)			10e-3
Cavity Length (m)	L		0.1750
Free Spectral Range (MHz)	FSR	$\frac{c}{2L}$	856.549880
*Finesse, 1064	$\mathcal{F}$	$\frac{\pi * \sqrt{\sqrt{R1R2 \ldots R_i}}}{1-\sqrt{R1R2 \ldots R_i}}$	46.4
Finesse, 532	$\mathcal{F}$		310.16
Full width at half max, 532 (MHz)	FWHM	$\frac{FSR}{\mathcal{F}}$	3.8419
Cavity pole, 532 (MHz)		$\frac{FSR/\mathcal{F}}{2}$	1.921
**Hz to V calibration (PZT)		$\frac{40\,V}{FSR}$	4.6699e-08
***Hz to V calibration (PDH)		$\frac{.354\,Vpp}{FWHM}$	9.2142e-08

*Chua's thesis eq. 3.53
** Use scan V per (green) FSR on oscilloscope. Cavity response is not linear. Less accurate.
*** Looking at Vpp of PDH error signal when we had 0.5 mW OPO refl power. The value depends on input power to the OPO. More accurate calibration compared to scanning V/FSR.

4.4.1 Crystal position and sinc^2 fitting

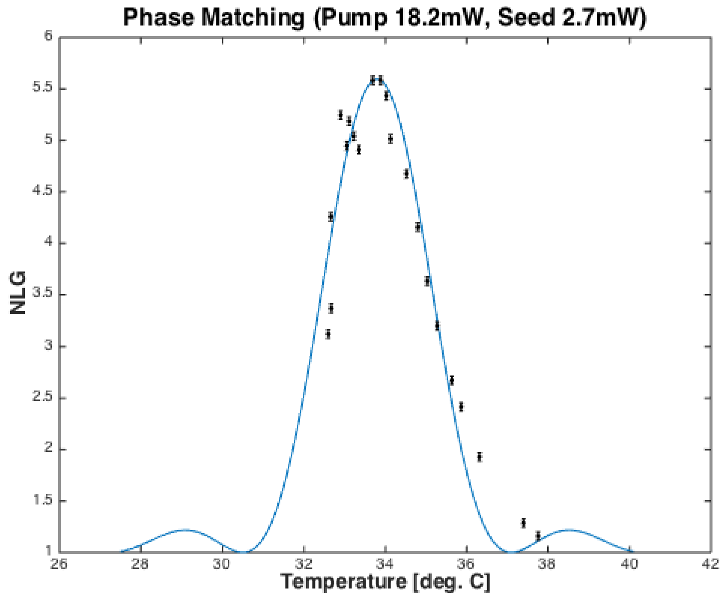


Figure 9 alog43647

"We followed the procedure in alog43292: We measure nonlinear gain by injecting a seed beam, scanning the seed phase, and measuring the de-amplification and amplification of the seed. (x=(sqrt(max./min)-1)./(1+sqrt(max./min)); gain=1./(1-x).^2;)

The plot with a sinc2 fitting is attached and with a SHG fiber launch power of 18.3 +/-0.1 mW and a seed launch power of 2.7 mW the phase matching temperature seems to be ~33.8 C. The pump power is limited by the fiber power limit.

The dual resonance position was set to within about +/- 10 clicks on the translation stage driver so the temperature accuracy is still not much better than 0.1C as in alog41150.

We left the crystal at the position where we see co-resonance for 33.8 C, because we think this is about at the peak of the phase matching curve."

4.4.2 Threshold Power

Threshold power changes over time as the KTP crystal degrades. The lowest threshold power ever observed at LHO was 7.4-8mW (alog41150) and the highest threshold power ever measured was 27-28 mW (alog52988)

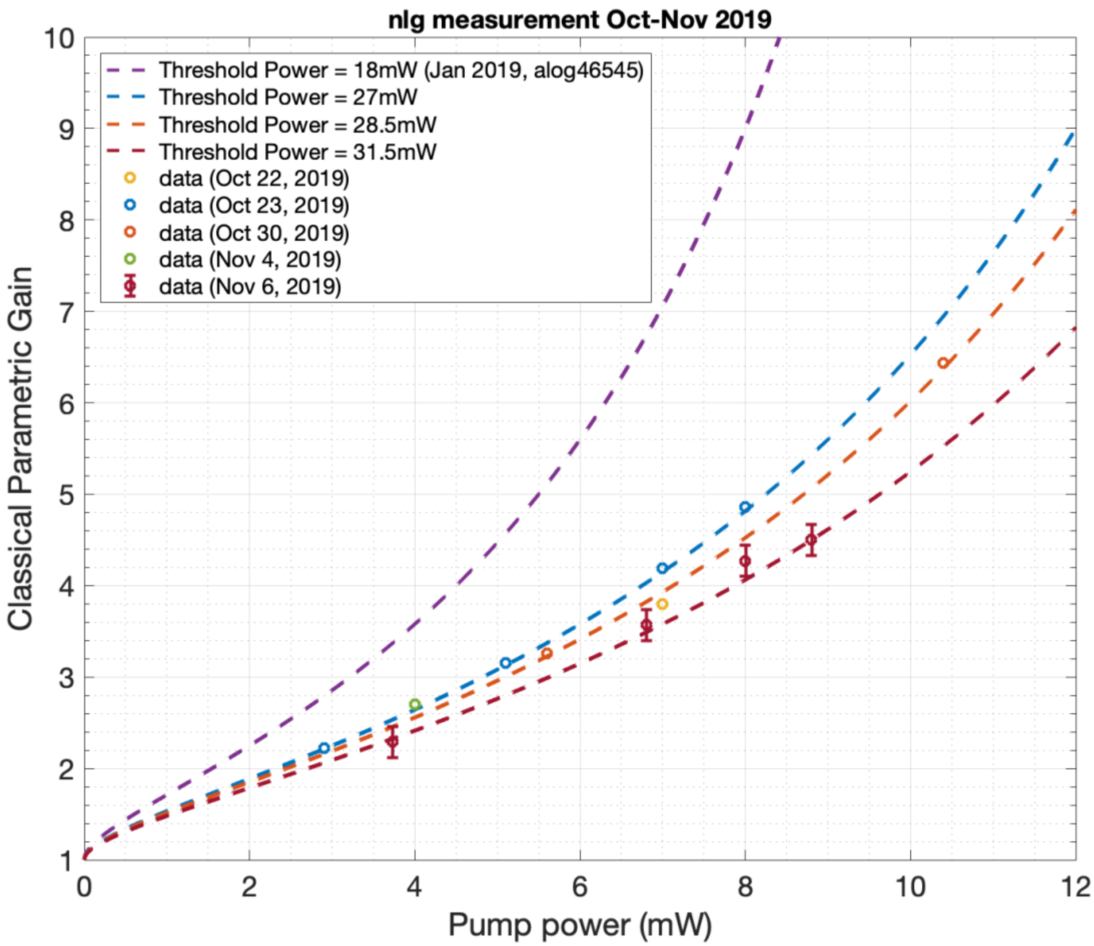


Figure 10 [alog523120]

4.5 CLF

AOMs used

	Brand	RF power in	Max RF power allowed	Diffraction Efficiency achievable
AOM1	IntraAction ATM-200	34dBm (2.5W)	2.9 W	83%
AOM2	AA Opto Electronic MT200	33 dBm (2.1W)	2.27 W	70%

See alog40698 for more details

Photodiode:

Old diode, S1300532

RF Transimpedance gain: 6.8kOhms

New diode, S1900052
Replaced March 4, 2019
alog47222 and comments therein, alog47171, alog47196
Responsivity: 0.774 A/W
RF Transimpedance gain: 18.7 kOhms

RF amplifier used: minicircuits ZFL-500LN. The amplifier is still in with the new diode.

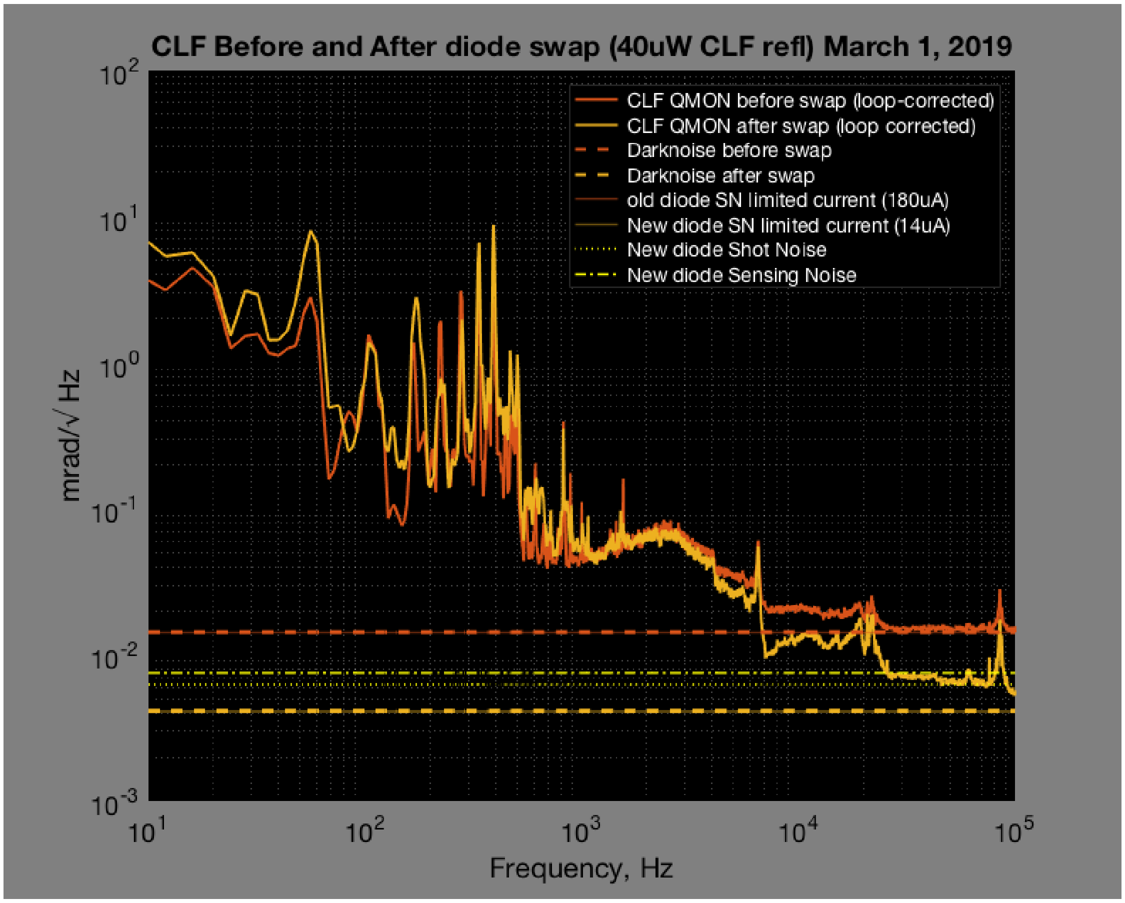


Figure 11 Noise Performance of old and new CLF diode. Never mind the shelves feature. We fixed that. See alog52755

*V per Radian calibration			$\frac{0.68\,Vpp}{Rad}$

* measured when we had -13dBm RF6 signal, loop opened

4.6 LO

Photodiode:

S1800623

V per Radian calibration			$\frac{0.218\ Vpp}{2\ Rad}$

* measured when we had -21dBm RF3 signal, -13 dBm RF6, loop opened

5 Loopology, Noise, and Transfer Functions

There have been several trials and errors with the locking configurations here at LHO. In this report I will only talk about the two final configurations that worked, refer to as the **Standard configuration** and the **OPO Reference configuration**. The information about the OPO reference configuration can be found in an appendix. For more details of our other trials and errors please see T1900048.

Table 2 shows phase noise contributions inferred from each locking loop in the squeezing control system. The Advanced LIGO table is what we currently have from the standard configuration.

Table 2 Phase noise budget for the current Advanced LIGO squeezed light source and projections for future generation detectors. For the latter we are modelling 3 cases: a simple reduction of the LO bandwidth to 1 kHz (no FC), the addition of a filter cavity with IR sensing (FC IR) using 10 kHz bandwidth for the laser feedback, and the addition of a filter cavity with green sensing (FC green) using 100 kHz bandwidth. Contributions are given in mrad rms.

Contribution (value in mrad)	Advanced LIGO	Future Generation no FC	Future Generation FC IR	Future Generation FC green
Laser locking	0.73	0.73	0.73	0.73
SHG	0.12	0.36	0.066	0.017
OPO	0.10	0.20	0.079	0.035
CLF	1.72	1.89	<0.1	<0.02
FC length noise	–	–	0.003	0.003
FC sensing noise	–	–	0.26	0.005
Fiber/acoustic noise	0.48	3.55	0.18	0.017
LO sensing noise	0.18	0.11	0.044	0.044
RF sidebands (CLF)	1.2	2.1	1.1	0.7
RF sidebands (interferometer sensing)	15	4.2	–	–
Total	15	6.2	1.4	1.0

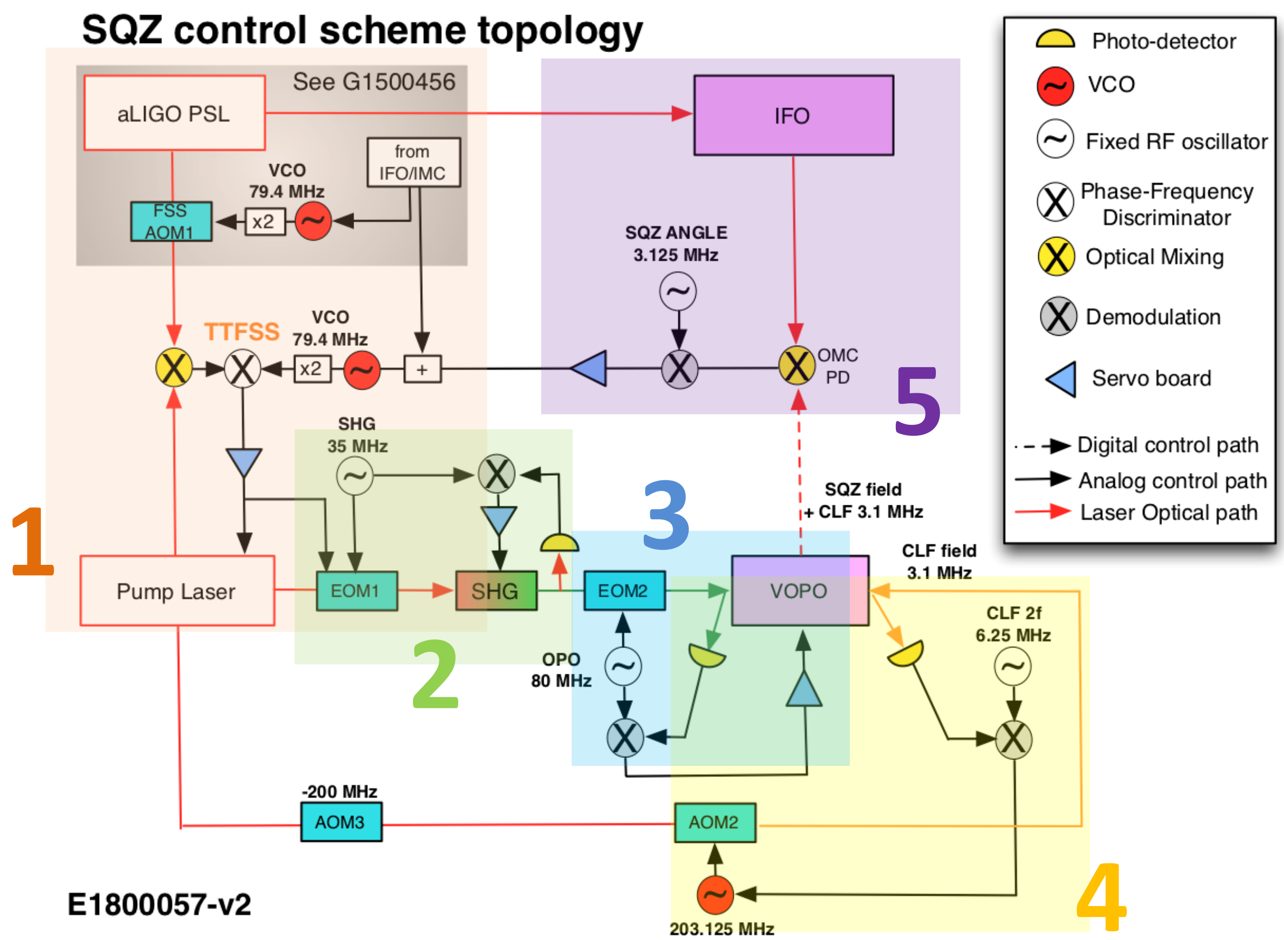


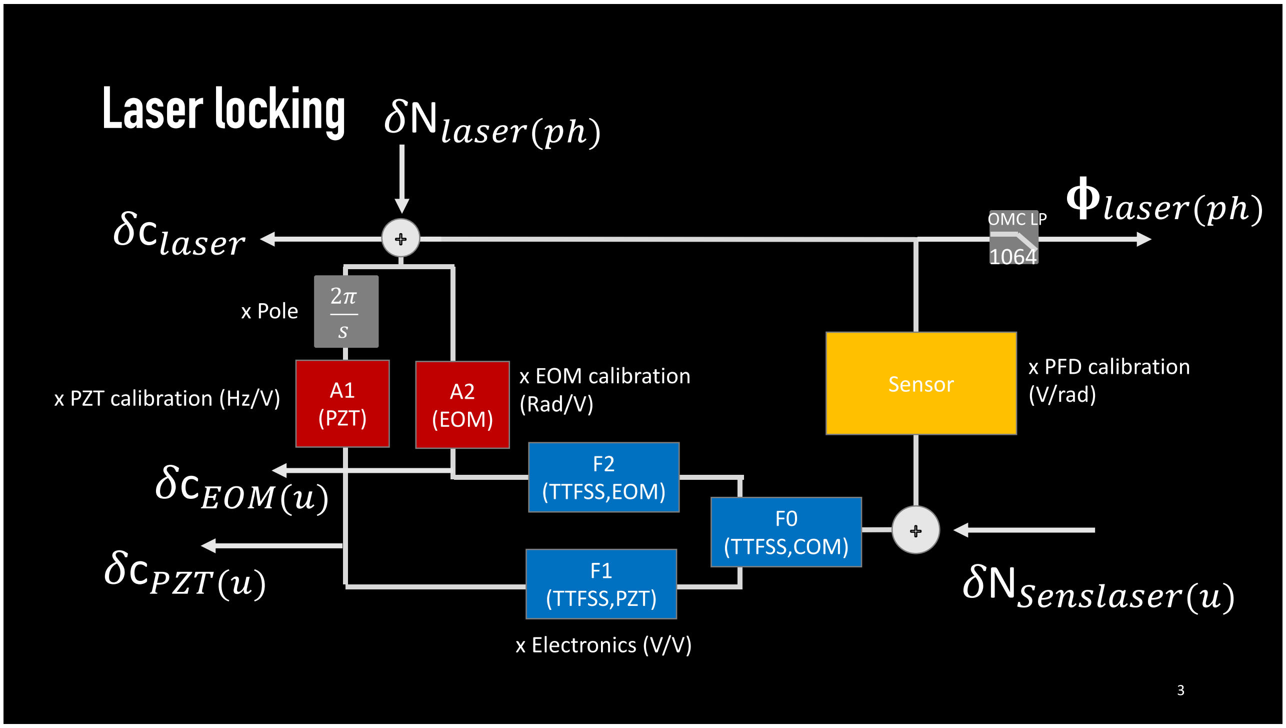
Figure 12. Block diagram – Standard configuration (currently used)

There are 5 locking loops in this configuration: **1) Laser Locking** 2) **SHG** **3) OPO** 4) **CLF** and **5) LO.** This is the configuration that both LLO and LHO now using (LHO swapped back to this configuration in January 2019). CLF and LO uses heterodyne locking (generic sidebands locking where the sidebands may or may not be equals) while SHG and OPO uses PDH locking (heterodyne with symmetric sidebands generated by bouncing signals off cavities). The modulated frequencies are: 158.8MHz, 35MHz, 79.4MHz, 6.25 MHz, and 3.125 MHz respectively

To fully understand how noise from each loop gets projected onto SQZ angle phase noise we need to start with equations for all open loop transfer functions and understand where noise enters. There are five open loops that we need to consider: TTFSS, SHG, OPO, CLF, and LO.

$\boldsymbol{e}$ depicts error signal
$\emptyset_{\_}$ depicts the residual noise we care about for each system
$\boldsymbol{\delta N_{\_}}$ depicts noise entering each system. Subscript **f** implies frequency noise $\frac{Hz}{\sqrt{Hz}}$, subscript **ph** implies phase noise $\frac{rad}{\sqrt{Hz}}$, **l** implies length noise $\frac{m}{\sqrt{Hz}}$, and **u** implies voltage noise $\frac{V}{\sqrt{Hz}}$.
$\boldsymbol{\delta c_{\_}}$ depicts control signal

5.1 Laser Locking (1)



The **1064 pump laser** on ISCT6 is locked to a 158MHz beat note that is a result of pump laser beating with PSL sample picked off after the reference cavity. The laser is now picked off BEFORE the reference cavity. See alog52381.

The disadvantage of picking the squeezer reference after the reference cavity is that if the reference cavity loses lock, we've got no light. But no matter where you pick your reference it's going to follow the IMC, which is what we want. We want the squeezer laser to follow the main IFO light. The PSL sample light is delivered via a 30m long optical fiber routed across the LVEA.

The pump laser frequency has to be 158MHz BELOW (alog52399) the PSL because SQZ laser needs to be at the same frequency as the main IFO beam.

When the loop is not closed (when IFO freshly dropped out of lock, for instant), the beat note error signal is used and only the slow control part of TTFSS is working. The slow signal is sent to actuate laser crystal temperature. Once the beat note between pump and PSL sample is at ~158MHz, the fast path closes follows by the EOM path. TTFSS fast path sends signal to laser PZT taking care of suppressing noise up to 30kHz while EOM does the rest, suppressing noise at 30kHz – 300kHz region.

Fun fact: There is a curve mirror that sends the beam back to 80MHz AOM after it comes through once. This was done in order to get rid of the beam diverging affect as the frequency offset is being sent to the AOM. This is why we get 158MHz coming from inside the PSL.

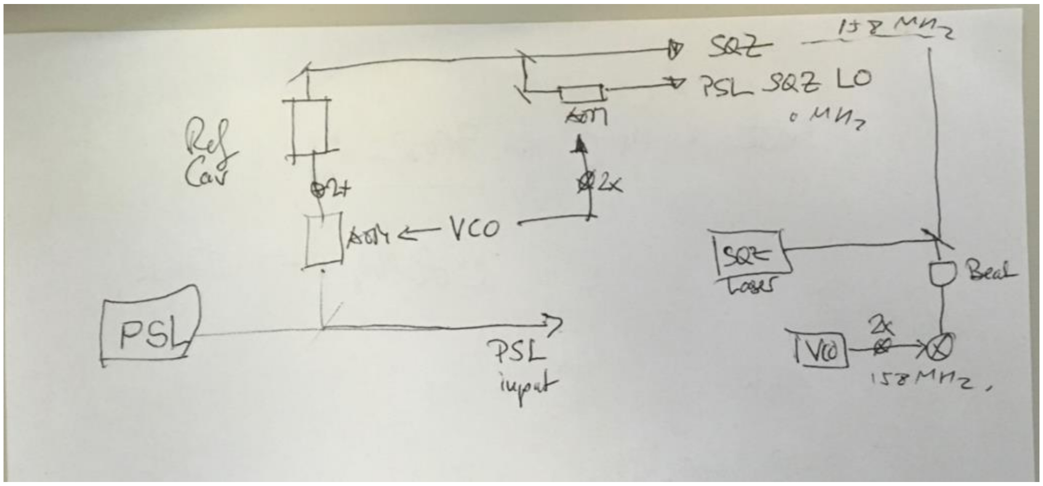


Figure 13. Inside the PSL. The diagram shows how each of the PSL sample gets picked off from inside the PSL with a sample for pump laser locking coming in at 158MHz and a sample from LO coming in at 0Hz relative to the interferometer carrier. This is an old diagram. We no longer pick off our reference after the reference cavity but somewhere before.

TTFSS rms is dominated by noise structure between 100kHz-5MHz. I wish I have an RF spectrum of the old configuration to compare. Instead we could compare this to PSL noise measured at mixer output. The details of the calibration can be found in alog46503.

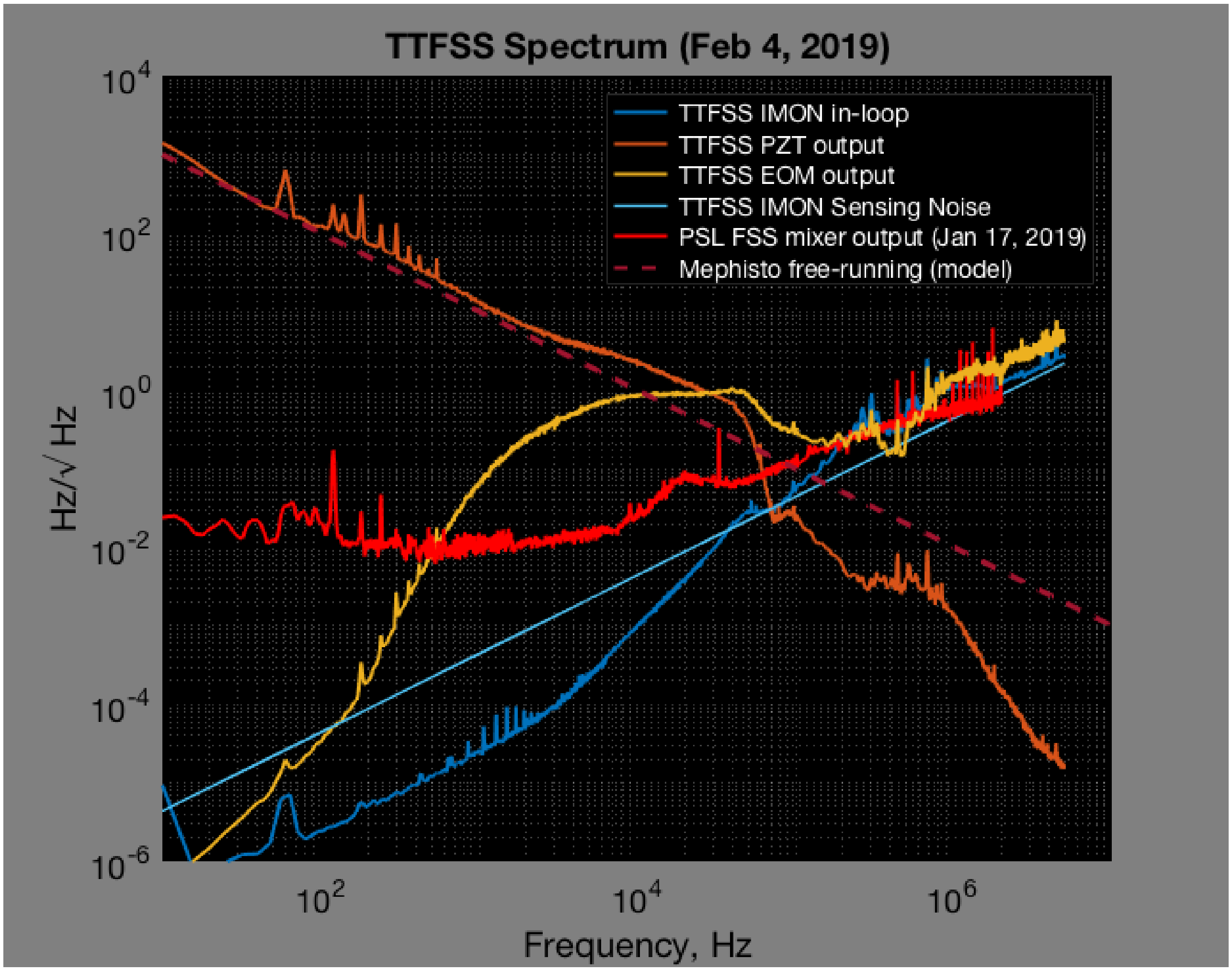


Figure 14. TTFSS suppressed error signal and control signal. TTFSS error signal is currently suppressed below sensing noise. PSL frequency noise from FSS mixer is also plotted in comparison to show that the noise around MHz region does not come from the PSL. 70kHz zero is included in the PSL FSS plot.

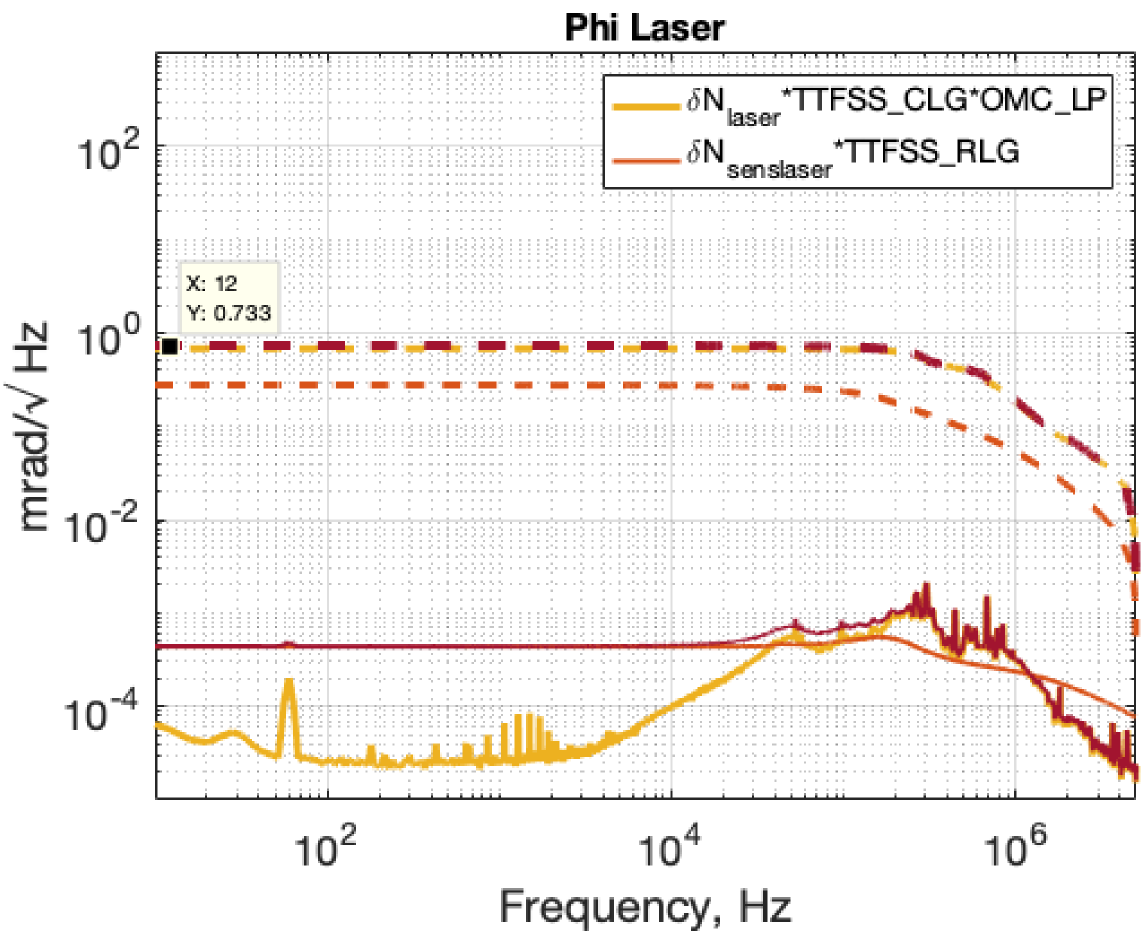


Figure 15. Laser phase noise contribution to squeeze angle. Most rms comes from f>100kHz. No future loop will have a bandwidth up to MHz. So rms contribution from Phi laser doesn't change.

```
FASTpath = F1magzpk.*PZTcalib.*pole0Lmagzpk1;
EOMpath = F2magzpk.*EOMcalib;

dNsensTTFSS = ones(size(TTFSS_IMON_xall)).*700e-9; %V
dNlaser = sqrt( (TTFSS_IMON_yall./TTFSS_CLG).^2 - dNsensTTFSS.^2)./TTFSS_S;; %.*(TTFSSoneplusGonG);
senslaser = dNsensTTFSS.*(TTFSS_CLG).*TTFSSG./TTFSS_S;

philaser = sqrt( abs(dNlaser.*(TTFSS_CLG)).^2 + abs(senslaser).^2).*OMCcavLPOLmagzpk;
```

To be rewritten

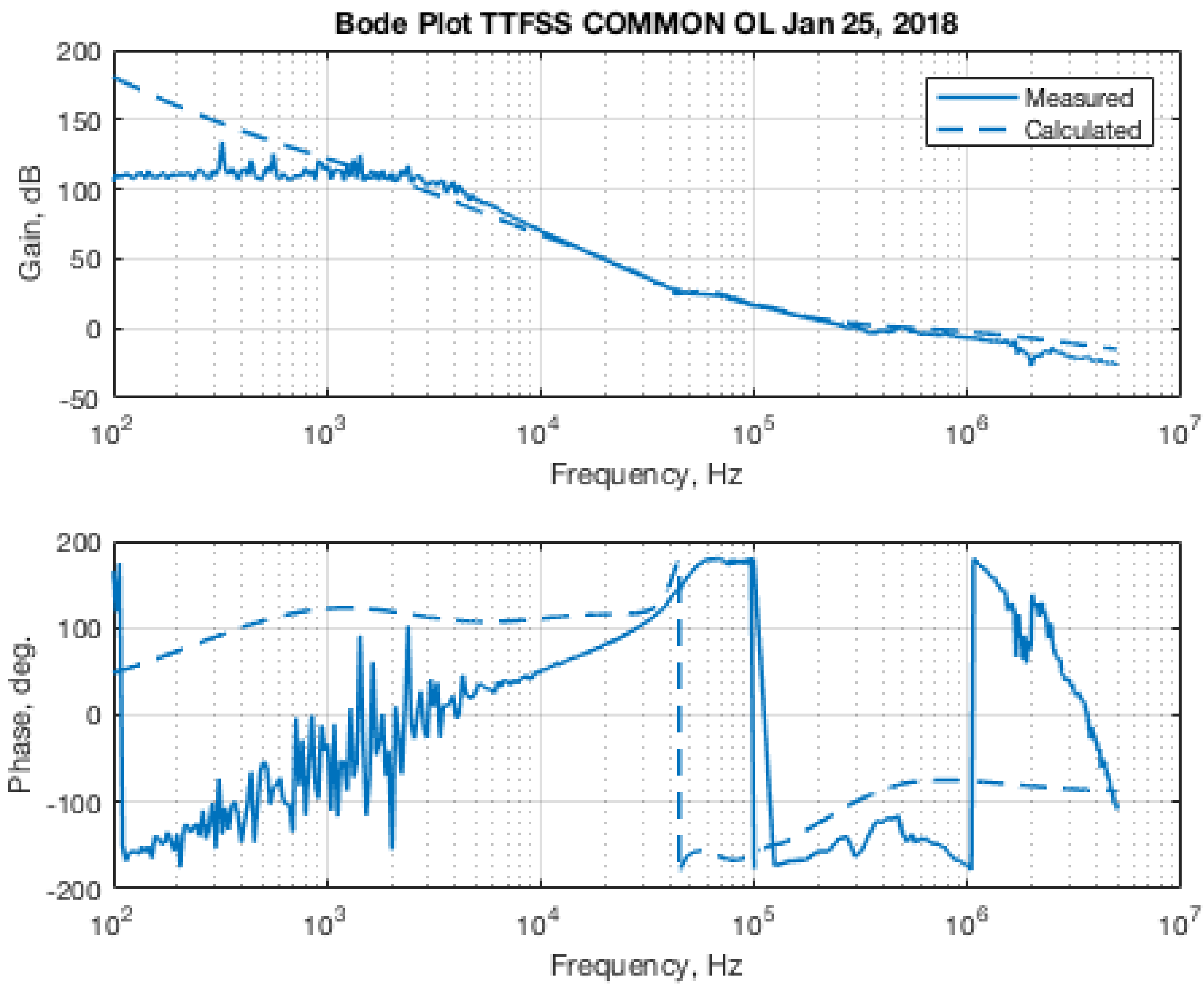


Figure 16 Laser locking closer loop gain, measurement and model

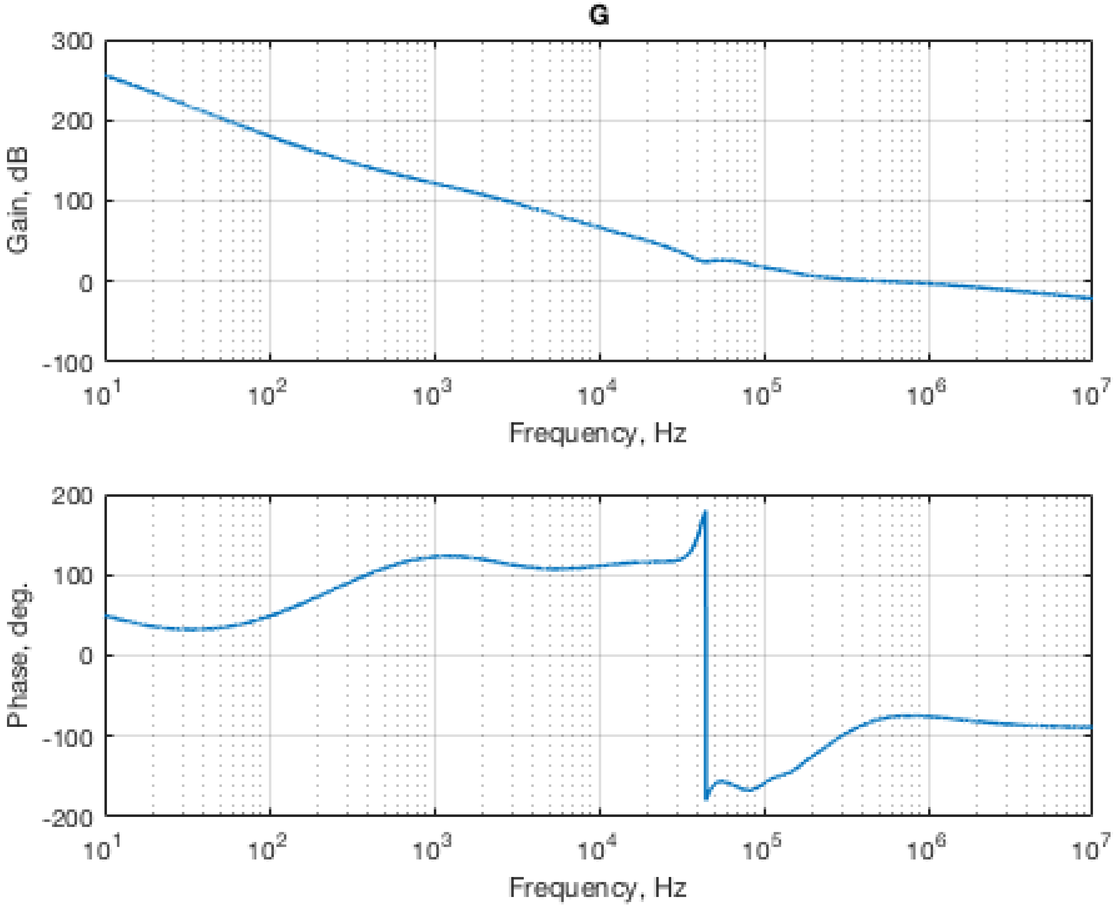


Figure 17 Lasre locking open loop G

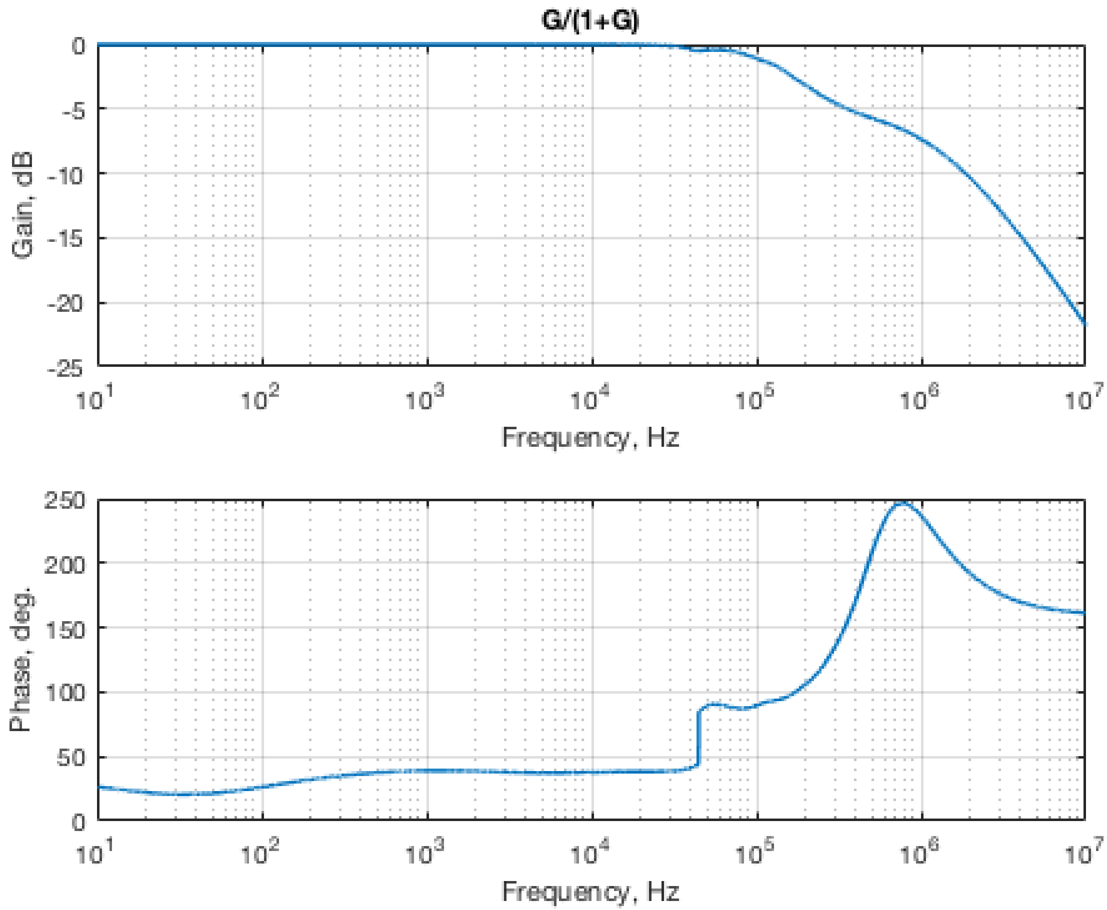


Figure 18 Laser locking round trip loop gain

5.2 SHG (2)

SHG uses 1064 transmitted light as its PDH error signal and sends the control signal back its own PZT.

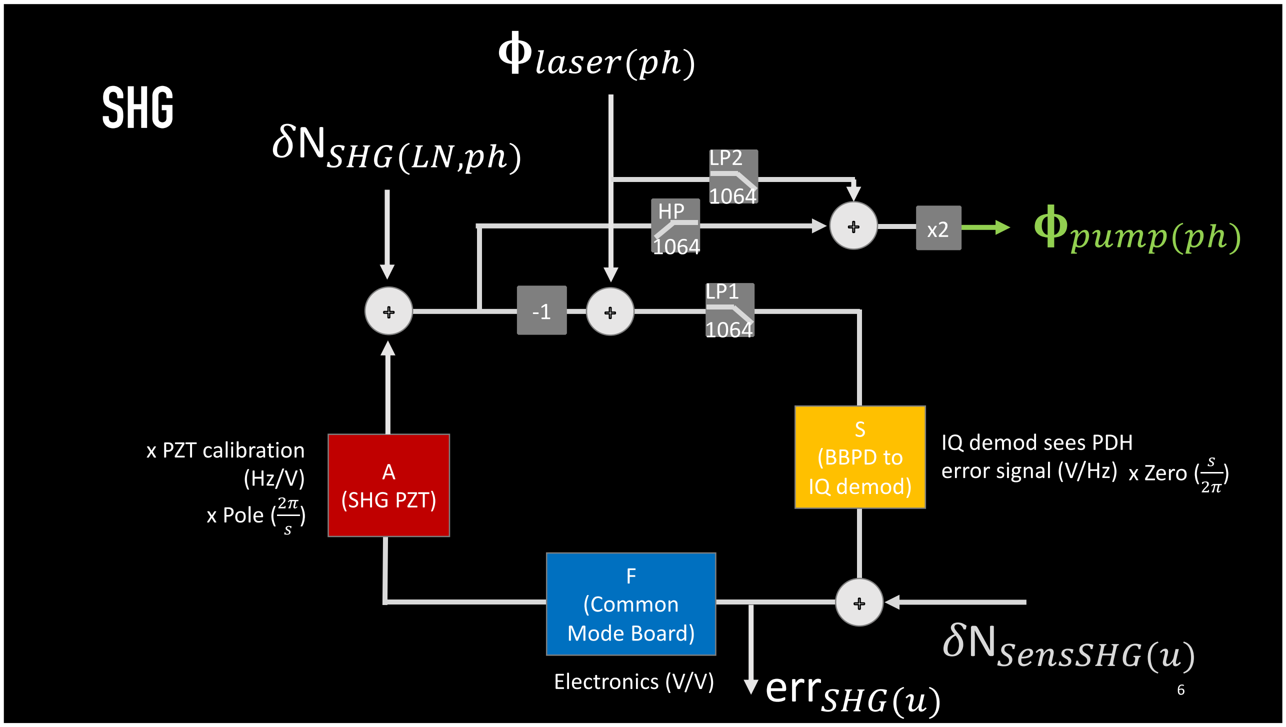


Figure 19: SHG loop in terms of phase. Some of the Phi_laser goes straight to Phi_Pump due to the conversion. Some goes through the transmission which then enters the loop. Both path sees the cavity low pass filter (1064). Length noise occur from inside the cavity, which couples into the loop via a different path.

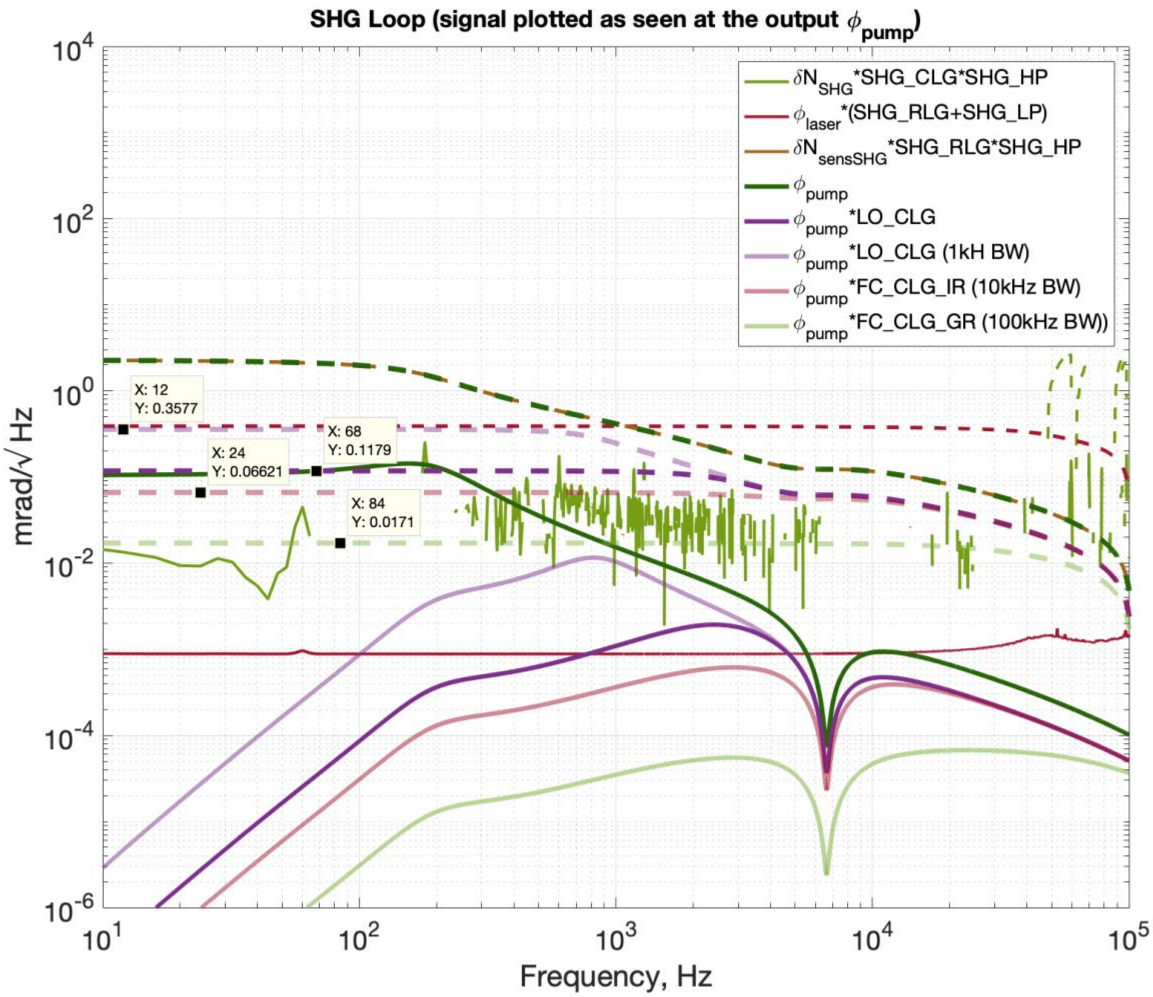


Figure 20 SHG phase noise contribution to the squeezer phase noise. There's no evidence that we measured SHG length noise. The only number report as sqz phase noise contribution from SHG is sensing noise. The projection includes possible future filter cavity reference scheme. See https://iopscience.iop.org/article/10.1088/1361-6382/aba4bb. The topic won't be covered in this version of the document. Perhaps in the future.

```
%% phi SHG

dNSHGsens = ones(size(SHG_x)).*SHGsens; %V/sqrt(Hz)
dNSHG =sqrt((SHG_y./SHG_CLG).^2-dNSHGsens.^2)./(SHG_LP.*SHG_S);
dNSHGinloop = dNSHG.*SHG_CLG.*HPOLmagzpk;
philaserinSHG =  sqrt((philaser.*SHG_HP.*SHG_RLG).^2 + (philaser.*SHG_LP).^2) ; %philaser comes in rad
SHGsensinloop = dNSHGsens.*(SHG_RLG).*SHG_HP./(SHG_LP.*SHG_S);

%philaserinSHG shouldn't be included if we're after the noise contribution to phi_sqz. It's already included in LO_IMON
%dNSHG is not included because we can't say for sure we measured any length
%noise.
phipump = sqrt( (2.*SHGsensinloop).^2 );

phipump_LOCLG = phipump.*LO_CLG./2;
phipump_LOCLG1k = phipump.*LO_1kCLG./2;

%% call FC TF

FC_TF_foraLIGO

phipump_FCCLG_IR = phipump.*FC_CLG./2;
phipump_FCCLG_GR = phipump.*FC_CLG_GR./2;
```

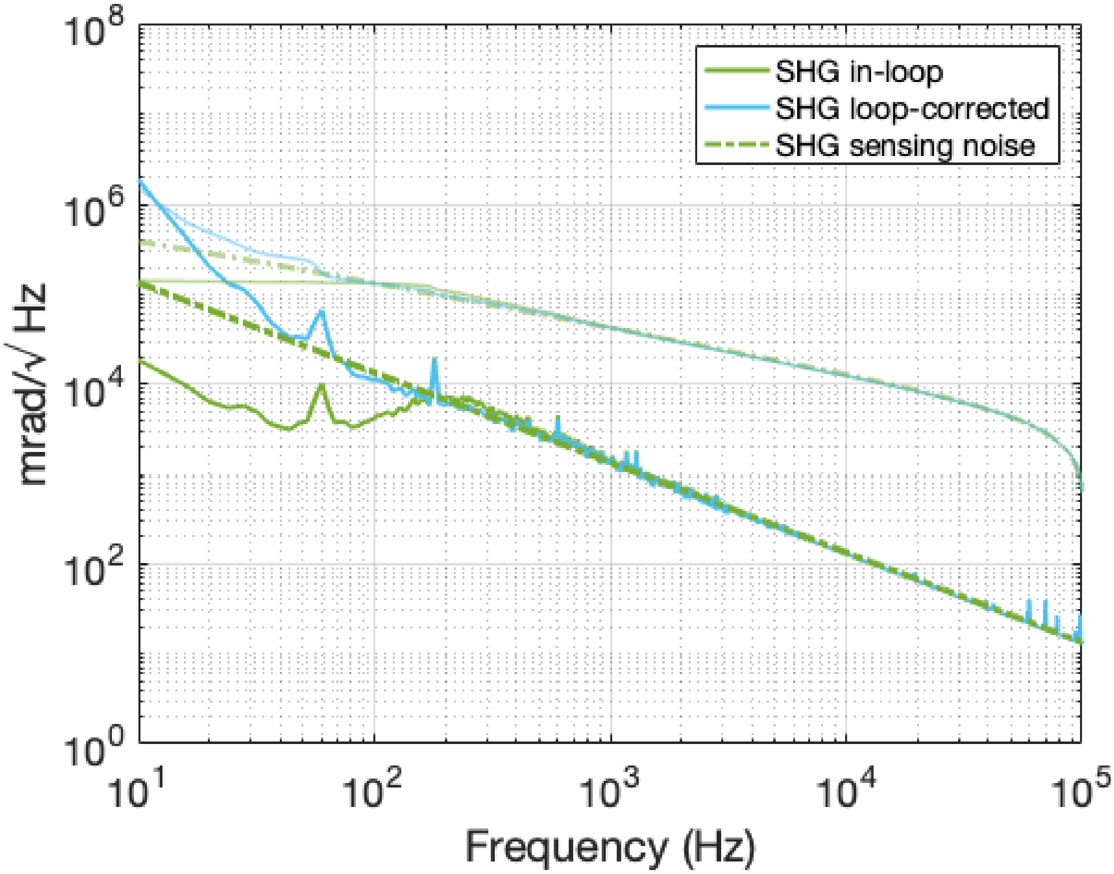


Figure 21 SHG IMON. Not much is there except for a sensing noise.

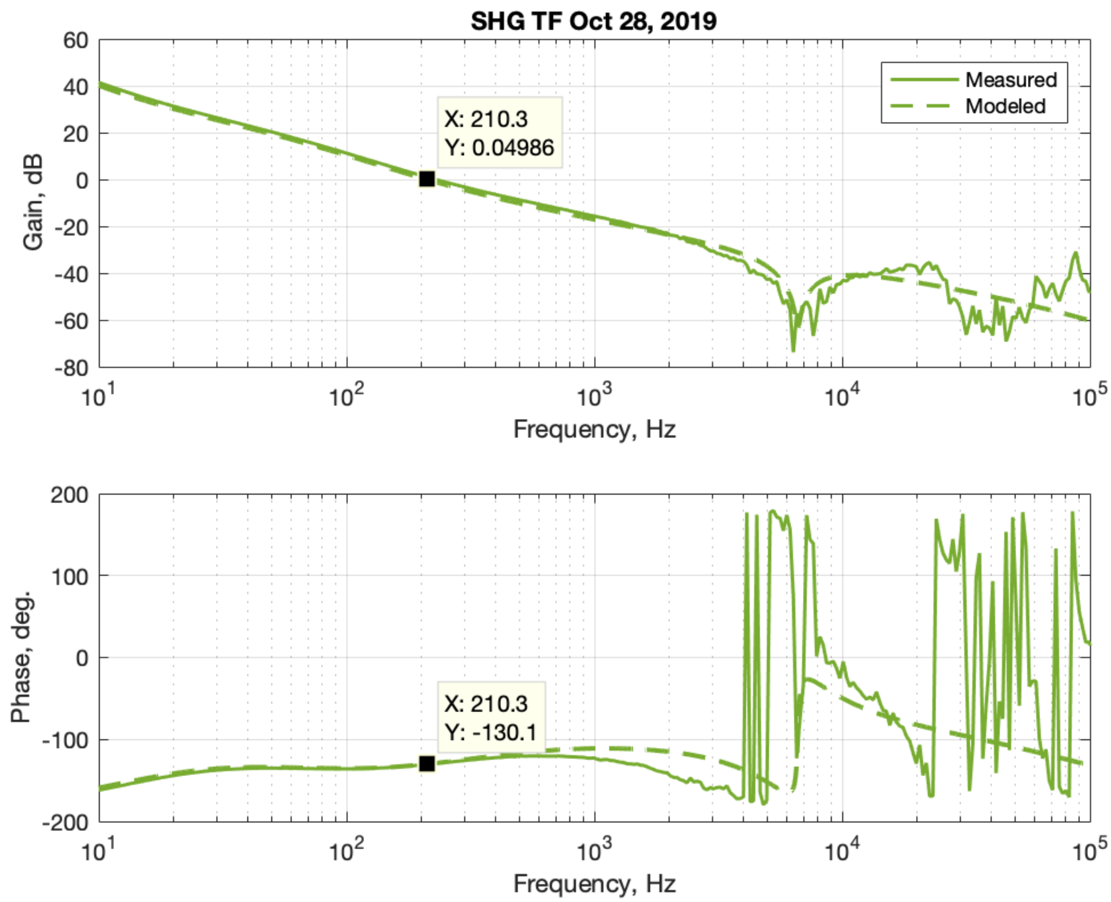
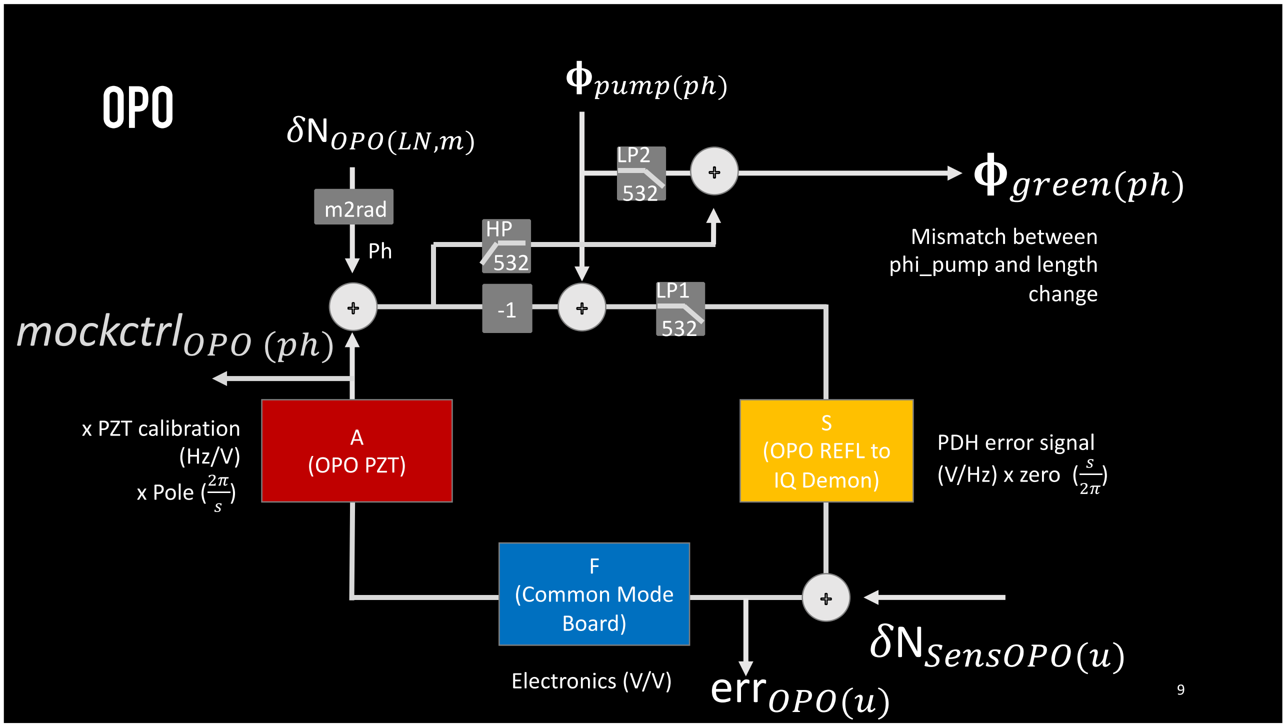


Figure 22 SHG transfer function. The model does not include PZT resonance around 6kHz, which is where the measurement loses phase faster than the model. The UGF is as we are operating it. See alog530099

5.3 OPO (3)

The **OPO** uses the reflected signal as its PDH error signal and sends the control signal back to the OPO PZT.


OPO
$\Phi_{pump(ph)}$
$\delta N_{OPO(LN,m)}$
m2rad
Ph
LP2 532
HP 532
-1
LP1 532
$\Phi_{green(ph)}$
Mismatch between phi_pump and length change
$mockctrl_{OPO\ (ph)}$
x PZT calibration (Hz/V)
x Pole $(\frac{2\pi}{s})$
A (OPO PZT)
S (OPO REFL to IQ Demon)
PDH error signal (V/Hz) x zero $(\frac{s}{2\pi})$
F (Common Mode Board)
Electronics (V/V)
$err_{OPO(u)}$
$\delta N_{SensOPO(u)}$
9

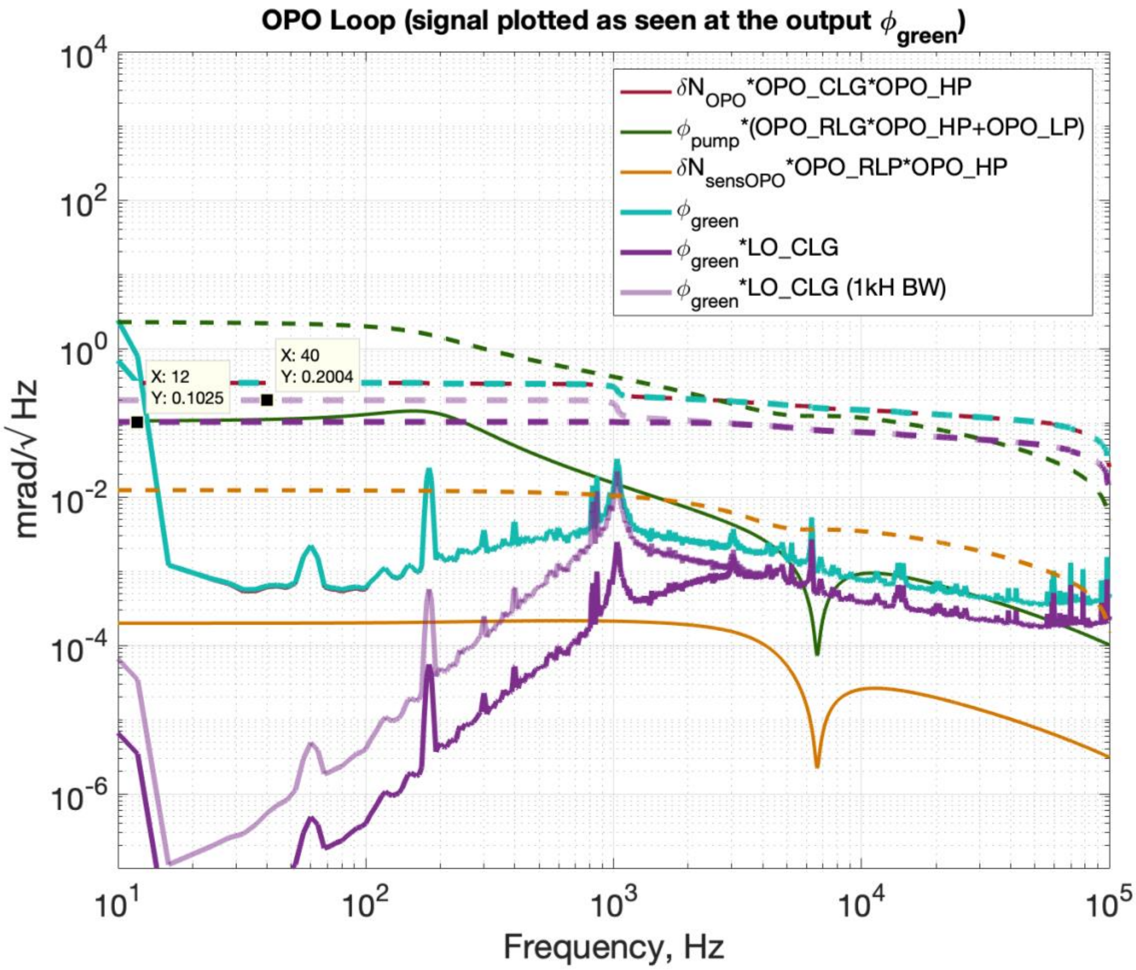


Figure 23 It's true that phi_pump propagate forward, but we are only counting noise from each loop. What would you see on phi sqz if you actuate on this loop? Propagating phi_pump forward and including it here would be over counting. In OPO loop, breadboard bendy

```
dNOPOsens = ones(size(OPOIMONlowpower_x)).*OPOsens;
dNOPO = sqrt((OPOIMONlowpower_y./OPO_CLG).^2-dNOPOsens.^2)./(OPOLP.*OPOS);
dNOPOinloop = dNOPO.*OPO_CLG.*OPOHP;
phipumpinOPO = sqrt( (phipump.*OPO_RLG.*OPOHP).^2 + (phipump.*OPOLP).^2);
dNOPOsensinloop = dNOPOsens.*OPO_RLG.*OPOHP./(OPOS.*OPOLP);

%Do not include phipump. We only want noise contributino from OPO alone.
%phi_green = sqrt( (dNOPOinloop).^2 + (phipumpinOPO).^2 + (dNOPOsensinloop).^2 );
phi_green = sqrt( (dNOPOinloop).^2 + (dNOPOsensinloop).^2 );

phi_green_LOCLG = phi_green.*LO_CLG./2;
phi_green_LOCLG1k = phi_green.*LO_1kCLG./2;
```

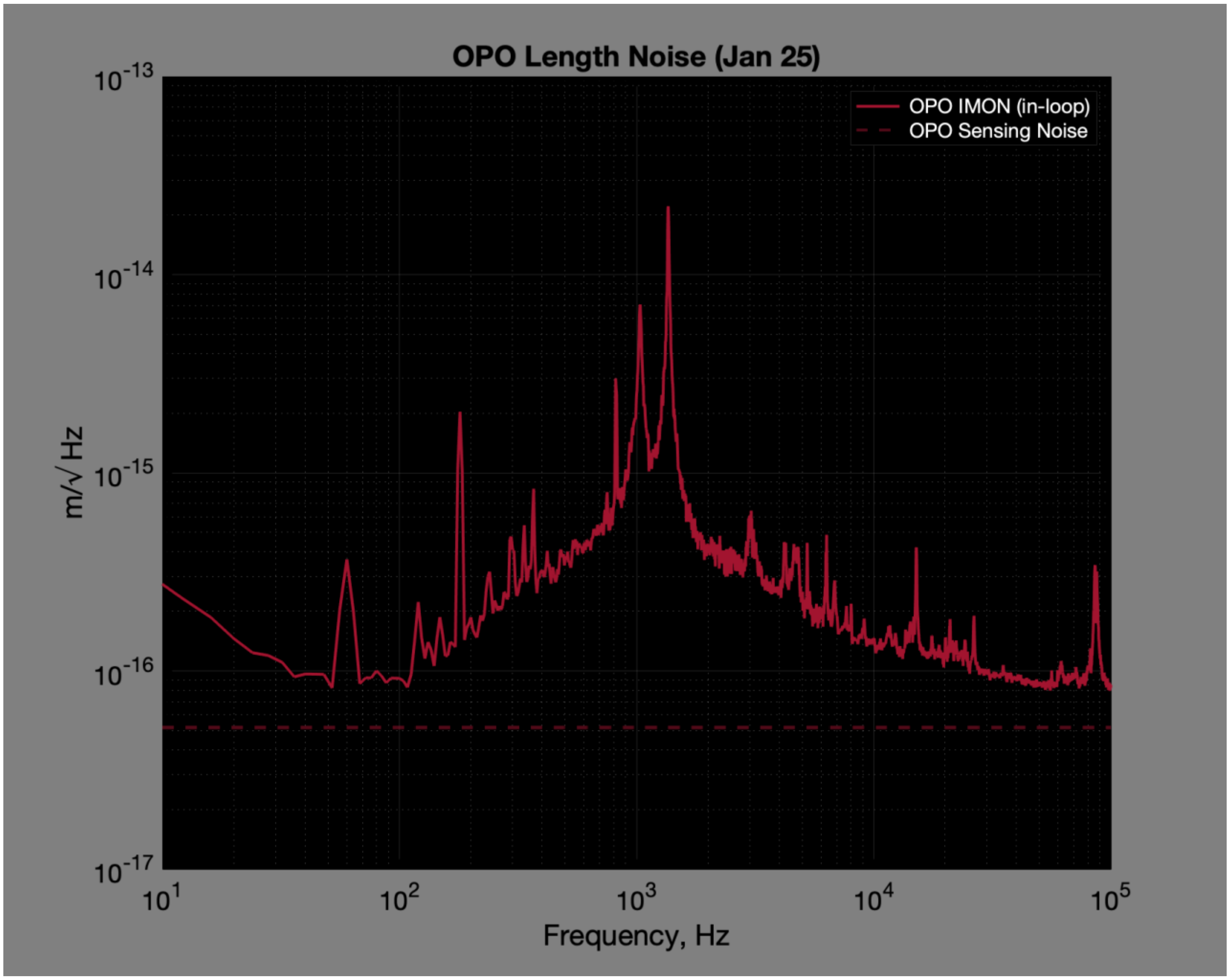


Figure 24 OPO length noise in m/sqrt(Hz)

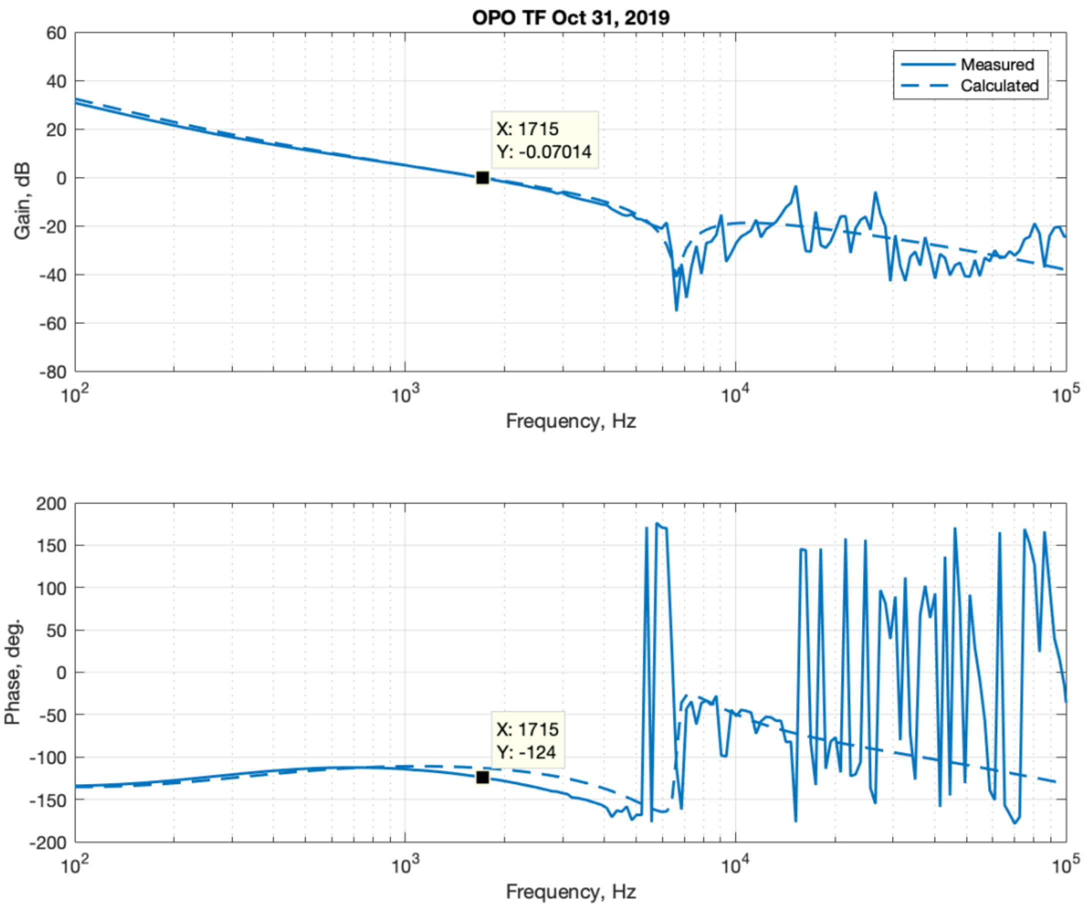


Figure 25 UGF 1.7kHz. See alog530099 for calibration and boosts used.

5.4 CLF Loop (4)

CLF gets error signal from reflected light off the OPO modulated at 6.25MHz . The control signal gets sent to the +203MHz AOM. The point of the CLF loop is to keep CLF phase constant relative to the pump phase.

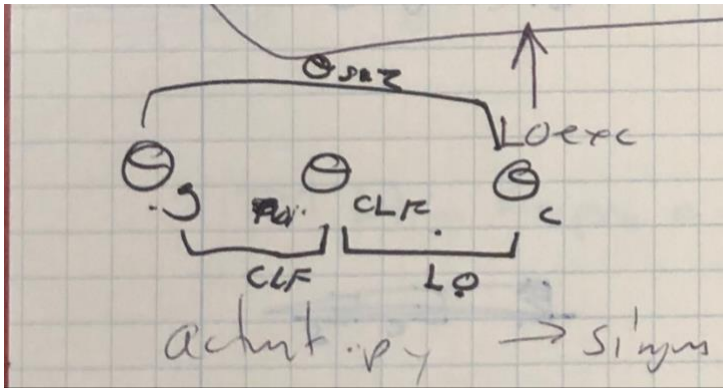


Figure 26

Inferring CLF noise contribution to squeezer phase noise is probably the most complicated one of all 5 loops.

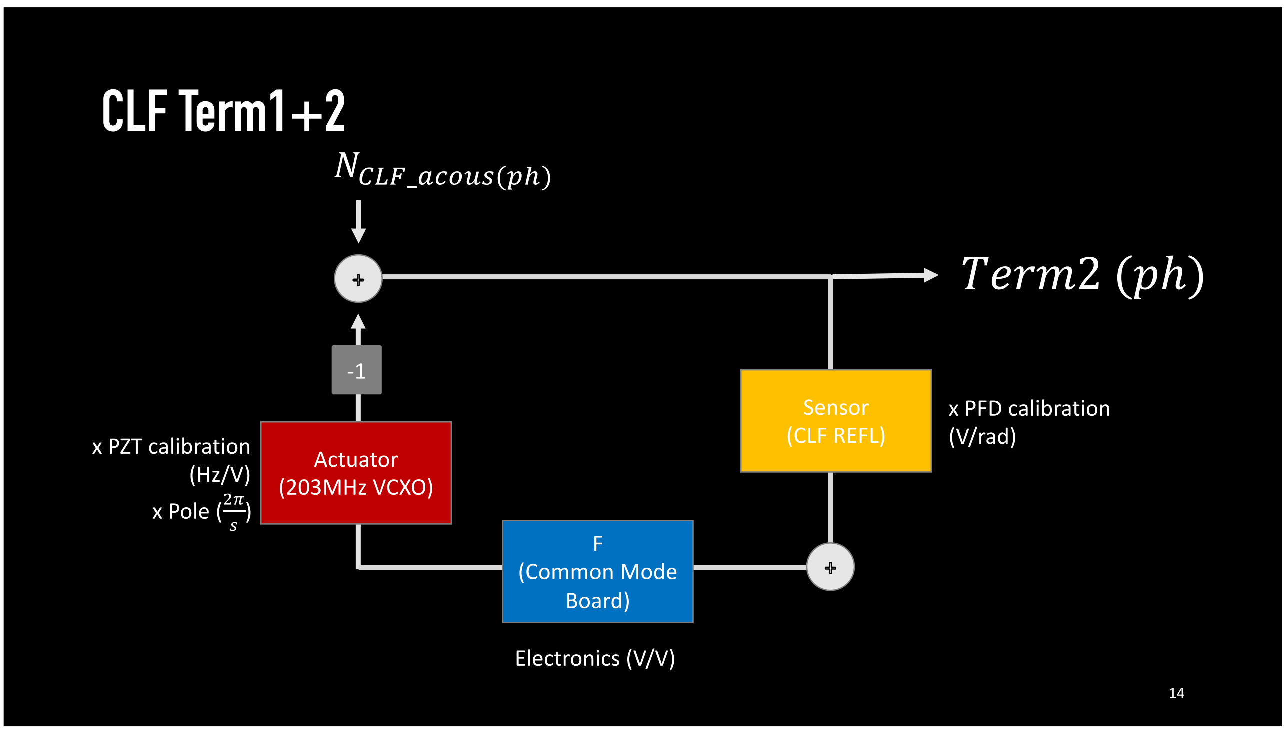


Figure 27

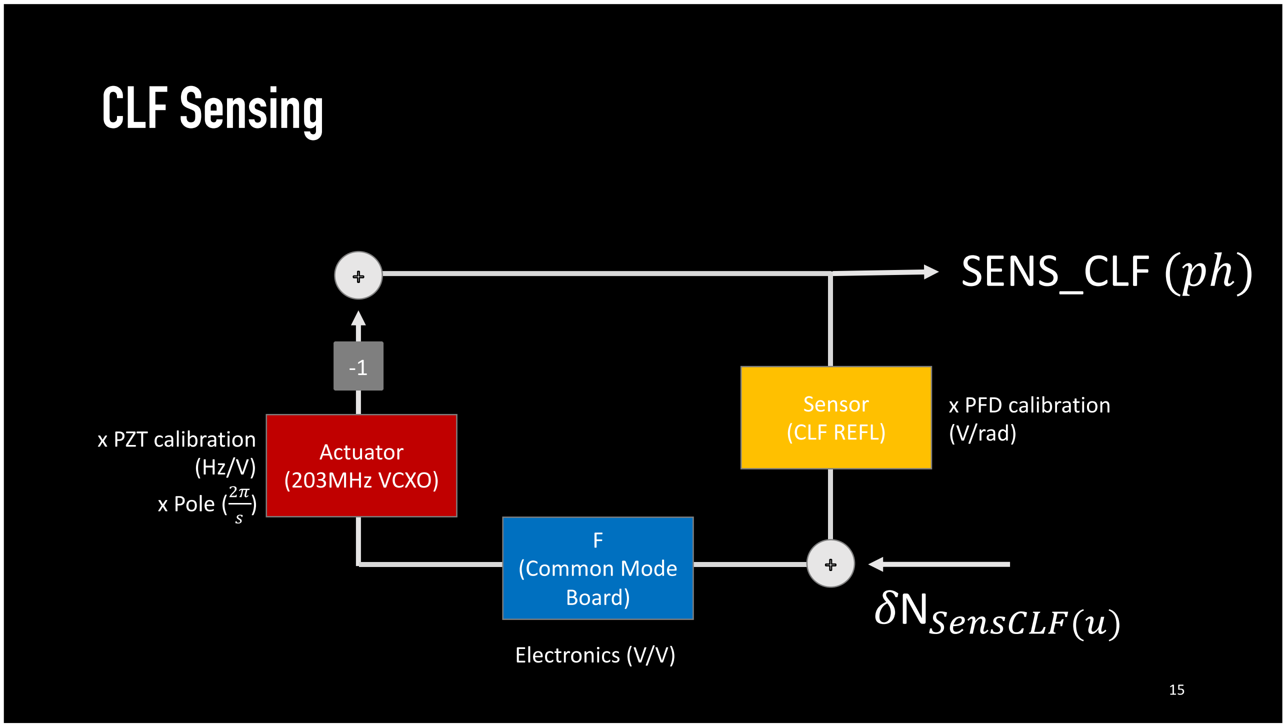


Figure 28

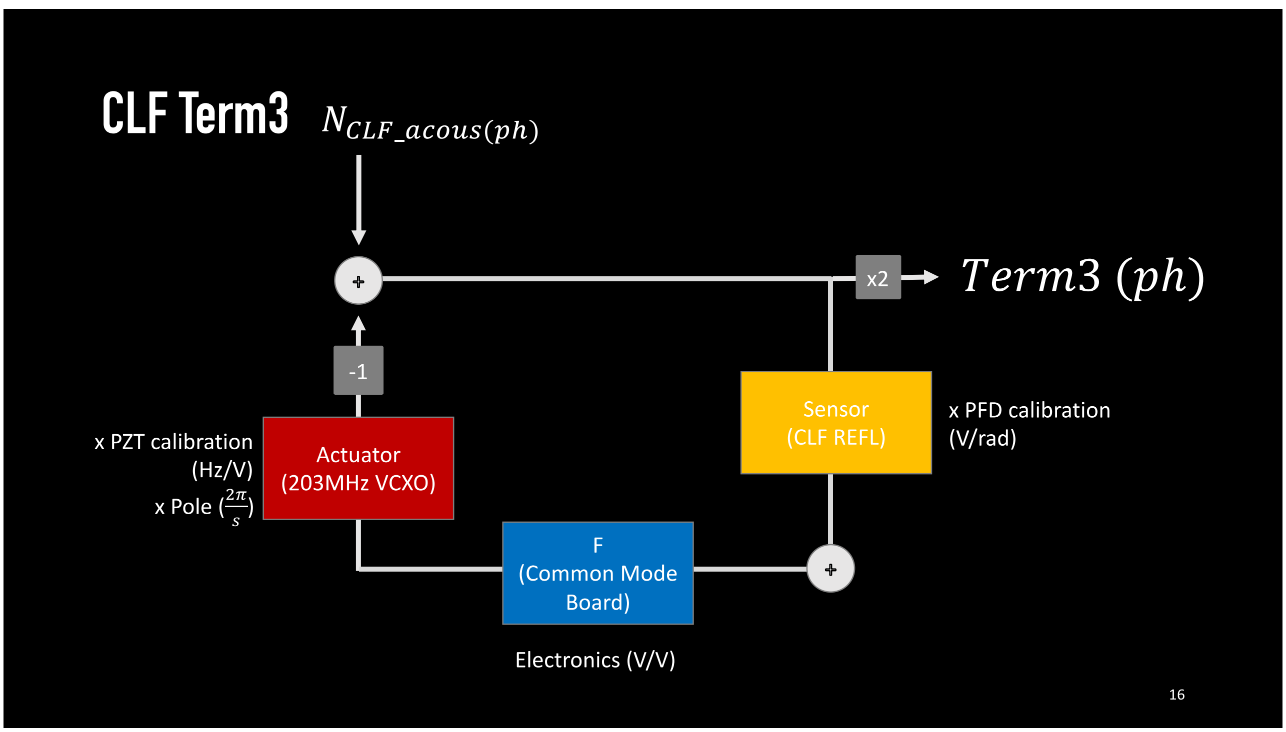


Figure 29

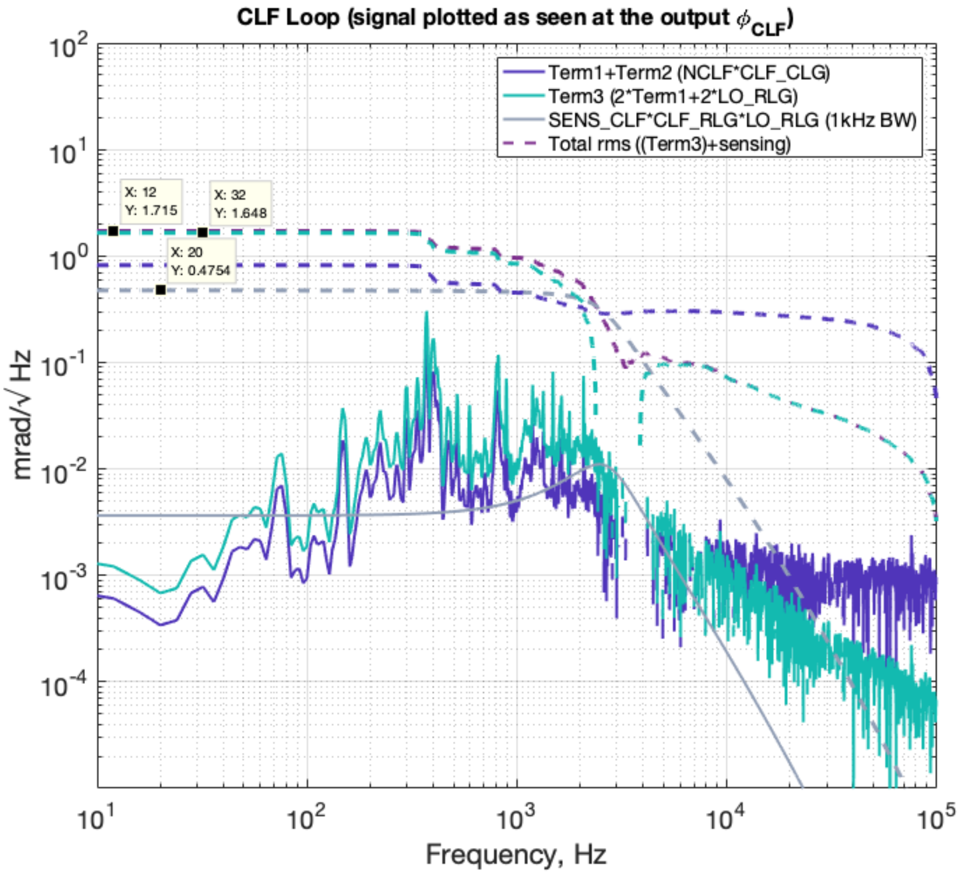


Figure 30 The most complicated one of all. The noise is divided into 3 terms.

```
dNsensCLF = CLFsens.*CLF_CLG.*CLFG./CLFS.*CLFsenspole.*LO_RLG;
NCLF = sqrt( (CLFhighpwr_y.*oneplusCLFG).^2-(CLFsens.*ones(size(CLFhighpwr_x)).*CLFsenspole).^2 )./CLFS;

%for aLIGO case
phiCLF1 = (NCLF.*CLF_CLG);  %FC_CLG comes from FC_TF_foraLIGO
phiCLF3 = 2.*phiCLF1.*LO_RLG; %multiply by LO_1kRLG_long for no FC case, multiply by LO_RLG for aLIGO cas

phiCLFtotal = sqrt(phiCLF3.^2 + (dNsensCLF).^2);
```

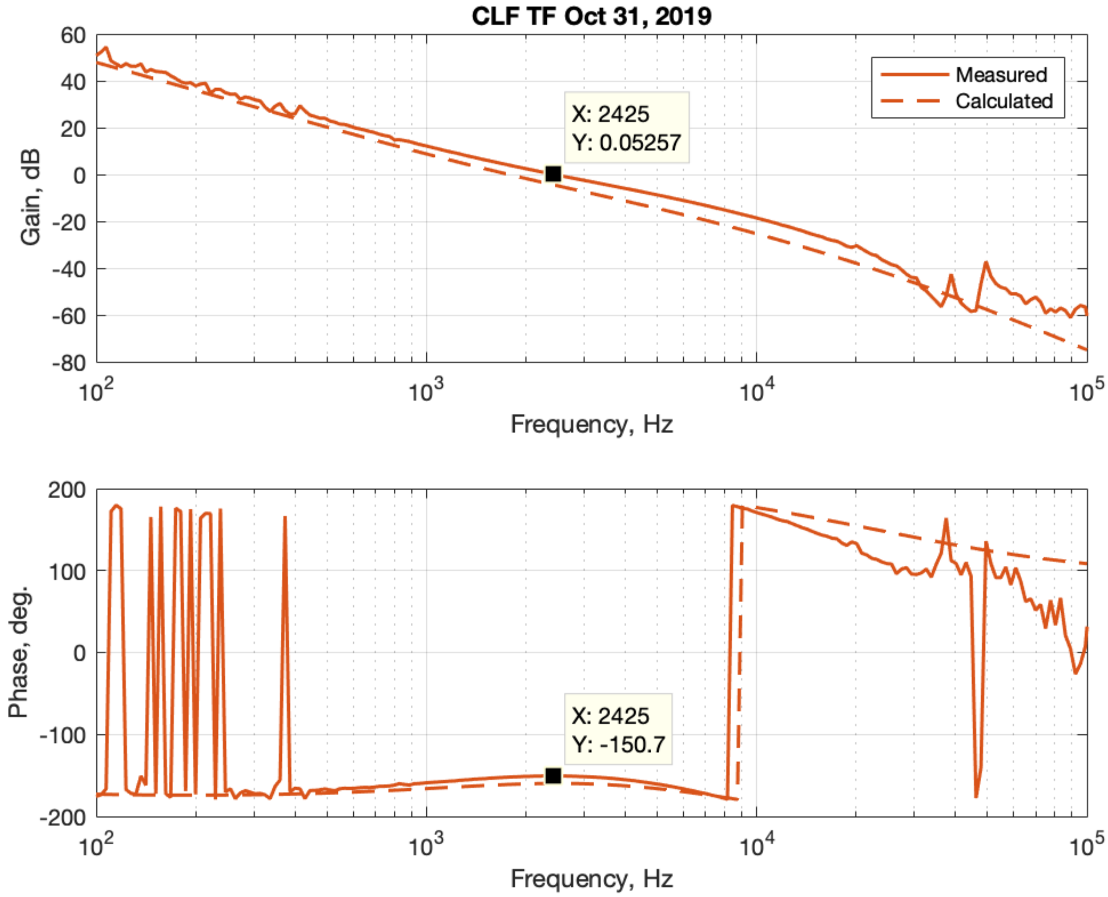


Figure 31 See alog530099 for calibration and boosts used.

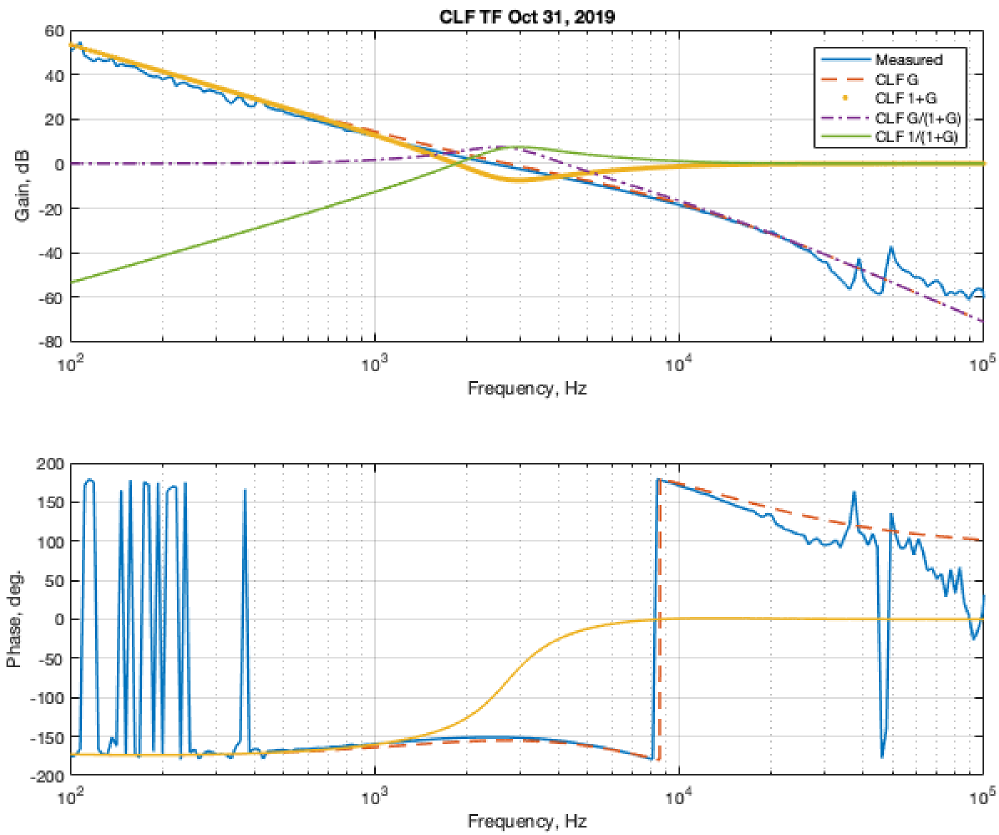
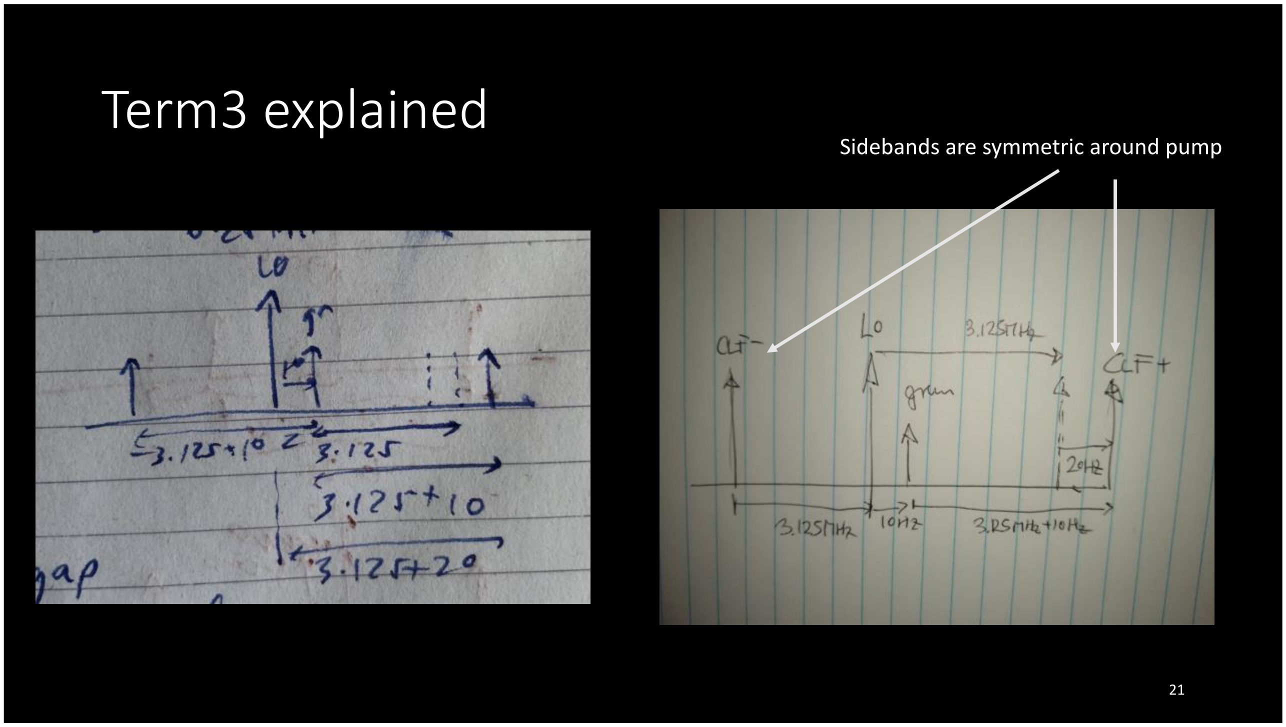


Figure 32

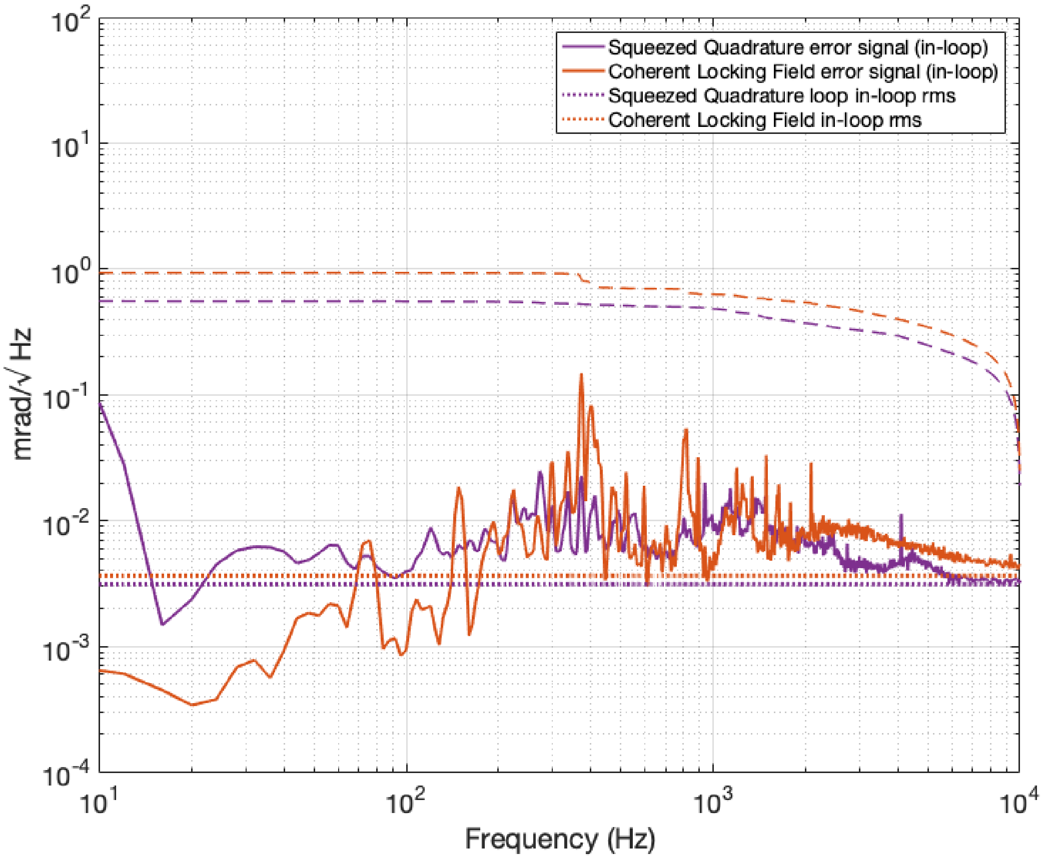
Noise contribution from CLF loop explained:

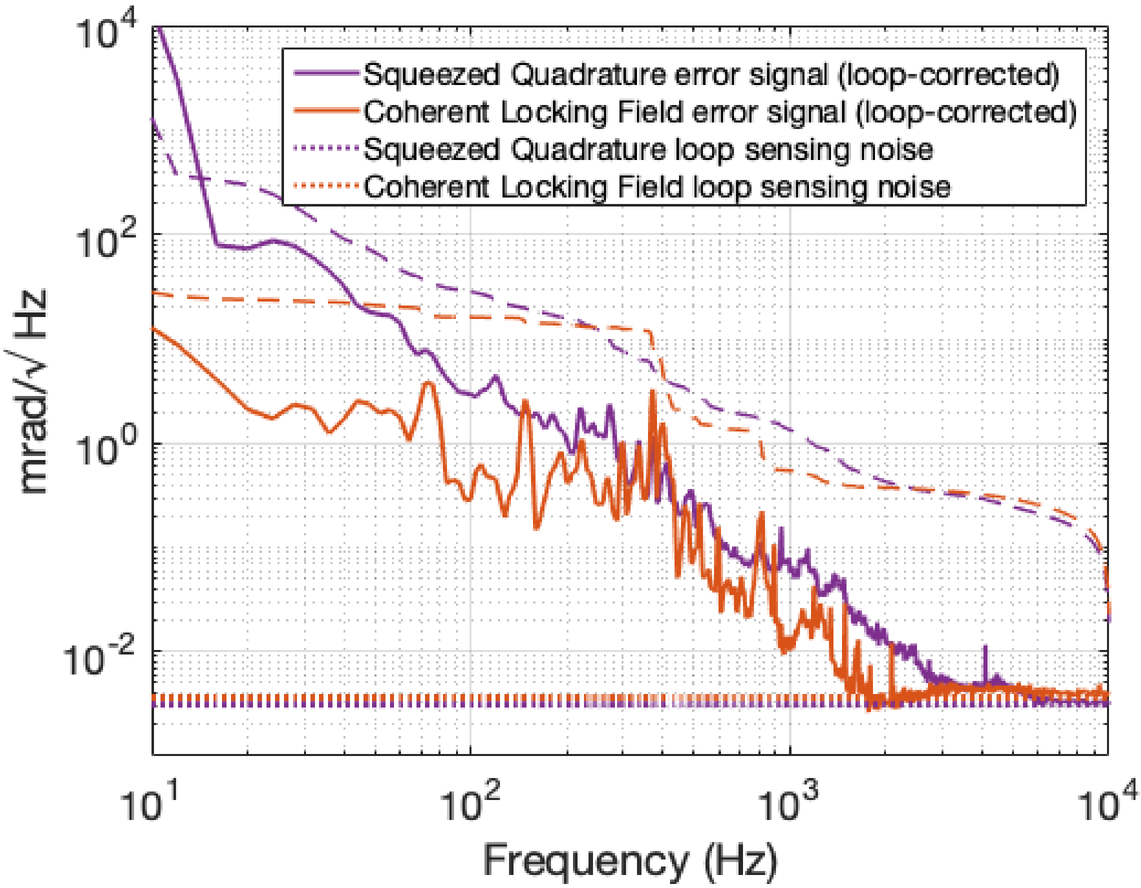
- **Term1 = NCLF_IR*CLF_CLG*LO_RLG**
    - This is IR acoustic noise introduced in CLF path.
    - Does not representation of what's sqz sidebands are doing
- **Term2 = NCLF_GR*CLF_CLG**
    - This is GR acoustic noise introduced by pump
    - Represents sqz sidebands
- Because we don't know which is the cause of NCLF (as measured at IMON). We assume the worse case where everything comes from pump and it's not seen by LO loop (above the UGF, assuming sqz sidebands see this noise, so what ever is left from CLF_CLG is not seen by LO)
    - **Term1+2 = NCLF*CLF_CLG**
- Term3 is when the pump noise occur above CLF ugf but below LO ugf. If pump moves 10 Hz. CLF idler moves 10 but CLF signal doesn't. It appears to LO as 20Hz signal when beat +3MHz with carrier.
    - **Term3 = m*2*NCLF*CLF_CLG*LO_RLG** (factor of 2 is the 10Hz to 20Hz picture. m depends on the sidebands position <=1 let be 1 for now.



The difference between term1+2 and term 3:

- Term1+2 is when LO does nothing (above both CLF and LO ugf)
- Term3 is when LO does the wrong thing (above CLG ugf but below LO ugf)
- Total CLF estimate contribution to sqz phase noise = 2*NCLF*CLF_CLG*LO_RLG (last term makes little different)


Squeezed Quadrature error signal (in-loop)
Coherent Locking Field error signal (in-loop)
Squeezed Quadrature loop in-loop rms
Coherent Locking Field in-loop rms
mrad/√ Hz
Frequency (Hz)
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^1
10^2
10^3
10^4



5.5 LO Loop (5)

LO gets error signal from either the Homodyne on the diagnostic table or the OMC when squeezed vacuum is being injected into the interferometer. The signal is modulated at 3.125MHz and the control signal is then fed back to the 79.4 MHz VCO which goes through a frequency doubler and then to TTFSS local oscillator input (158.8MHz). To summarize, LO loop keeps LO phase constant relative to CLF. Remember that CLF phase is now locked to pump, which means LO phase now follows the pump phase. And because pump phase follows IFO carrier phase, this means in theory LO phase should now follow the IFO carrier phase. **The difference between LO phase and IFO carrier phase is squeeze angle phase noise.**

The squeeze ellipse angle is then optimized by either adjusting CLF or LO phase. At LHO we hooked up four phase delay line boxes in series to CLF because we found that changing CLF phase gives us more change in squeeze angle than changing the LO phase.

Fun fact: LLO also injects an audio sideband to its 203MHz AOM for squeeze level monitoring. We won't be going into detail about this in this report. For more information please see T1800475. I think they're no longer doing this.

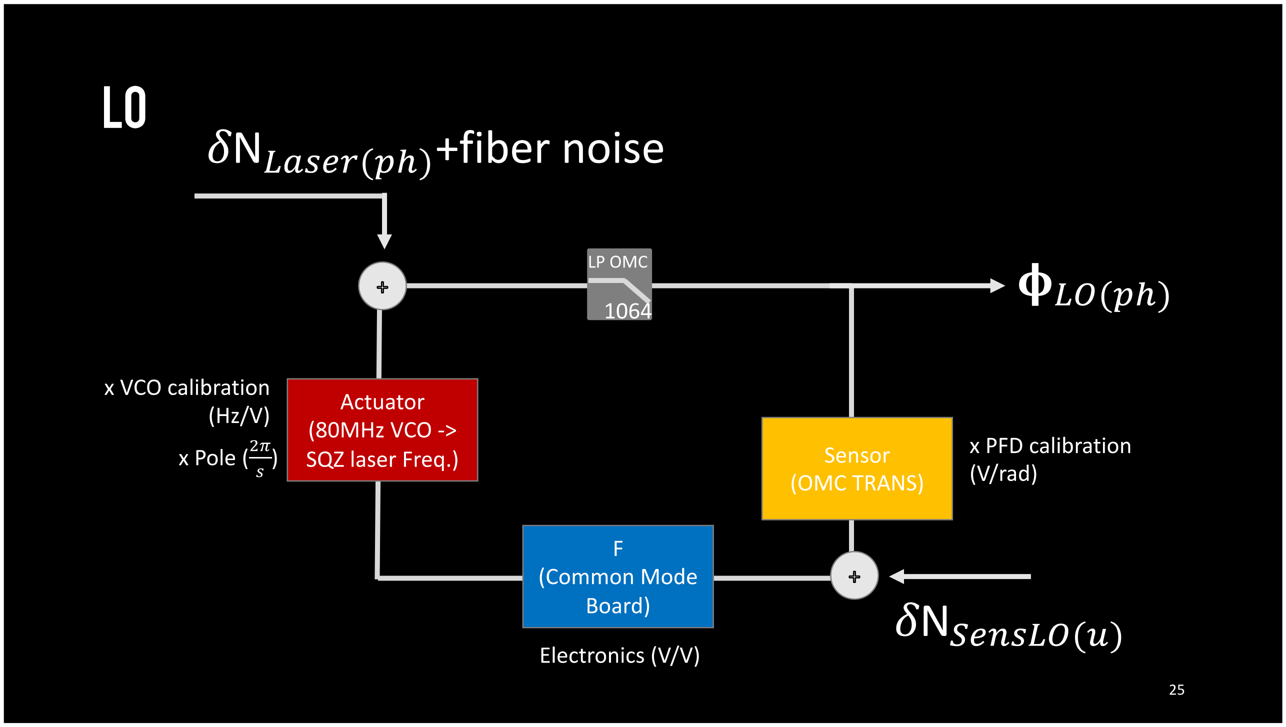

LO
δN_Laser(ph) +fiber noise
LP OMC
1064
Φ_LO(ph)
x VCO calibration (Hz/V)
x Pole (2π/s)
Actuator (80MHz VCO -> SQZ laser Freq.)
Sensor (OMC TRANS)
x PFD calibration (V/rad)
F (Common Mode Board)
Electronics (V/V)
δN_SensLO(u)
25

Figure 33

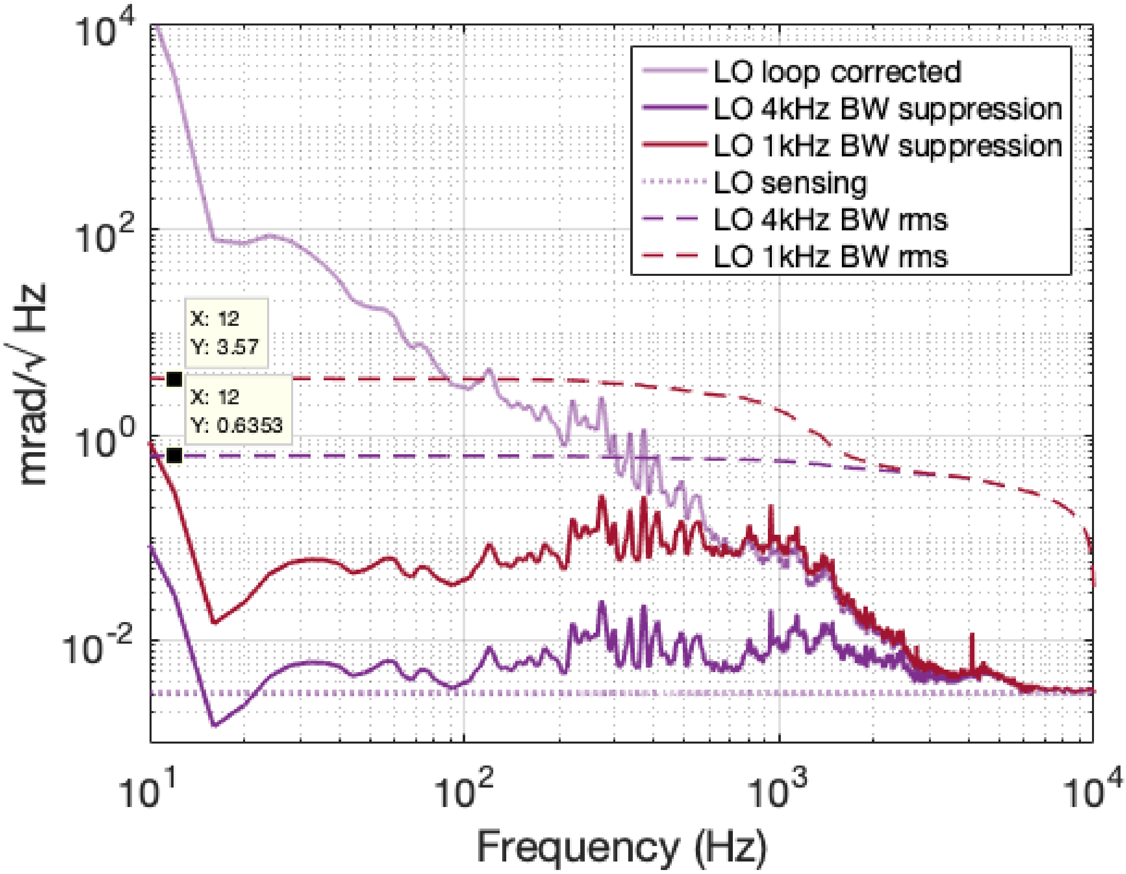


Figure 34 Noise contribution from the LO loop

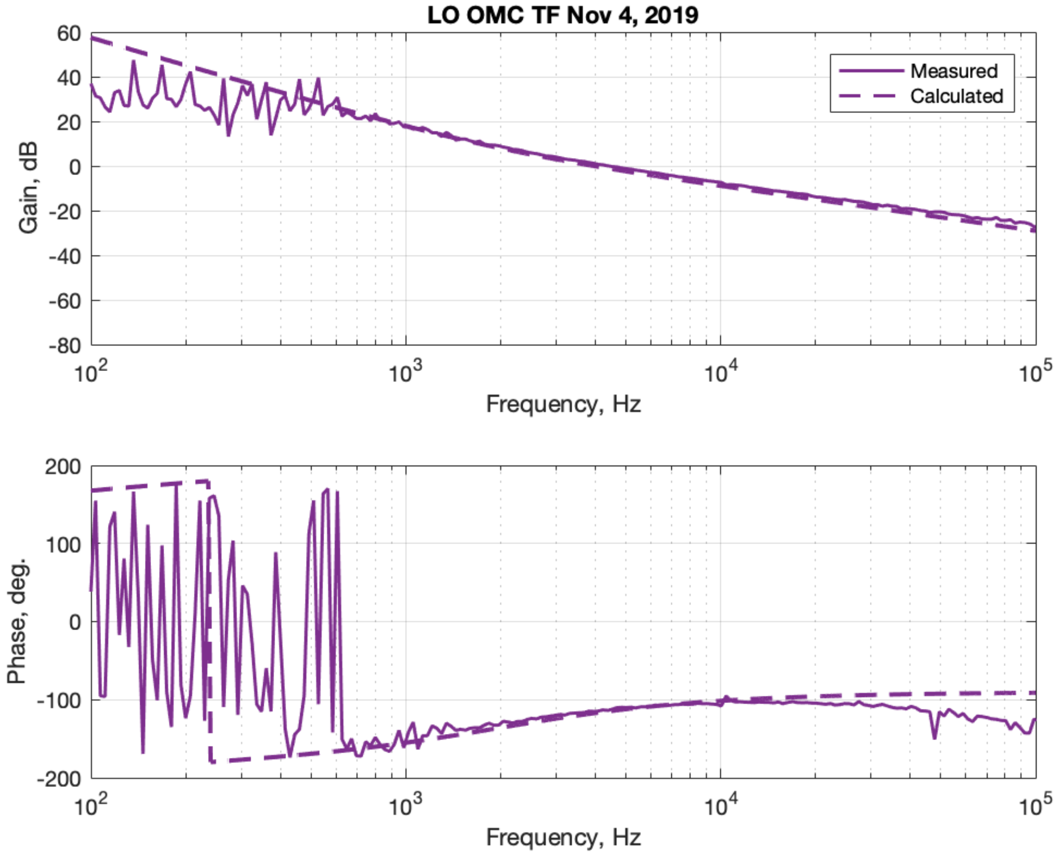


Figure 35 LO loop UGF cannot be pushed much further because then we start adding sensing noise. IFO FSR is 37kHz so in theory this UGF could max out at about half the FSR. See alog530099 for calibration and boosts used.

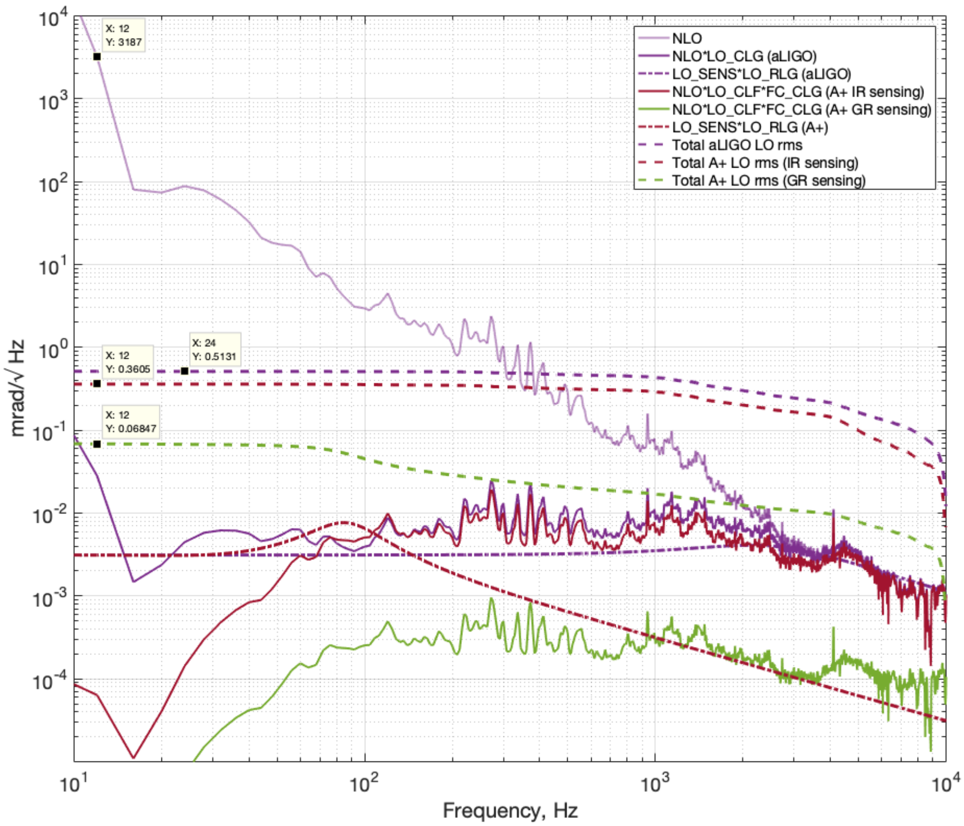


Figure 36 LO noise contribution to sqz phase noise projection if we were to make use of the filter cavity. We won't be going into details in this dcc version.

```
%% aLIGO case
% OMCLO makes no different. Cavity pole too far out
LOIMON = LOshort_y;
NLO = sqrt( (LOIMON./LO_CLG).^2 - OMCsens.^2)./(OMCLP.*LOS);
NLO_inloop = NLO.*LO_CLG.*OMCLP;
LOsens_inloop = OMCsens.*LO_RLG./LOS;

LOtotal = sqrt(NLO_inloop.^2+LOsens_inloop.^2);
```

```
%% FC case

NLO_inloop_FCIR = NLO.*FC_CLG.*LOFC_CLG;
NLO_inloop_FCGR = NLO.*FC_CLG_GR.*LOFC_CLG;

LOsens_inloop_FC = OMCsens.*LOFC_RLG./LOS;

LOtotal_FC_IR = sqrt(NLO_inloop_FCIR.^2+LOsens_inloop_FC.^2);
LOtotal_FC_GR = sqrt(NLO_inloop_FCGR.^2+LOsens_inloop_FC.^2);
```

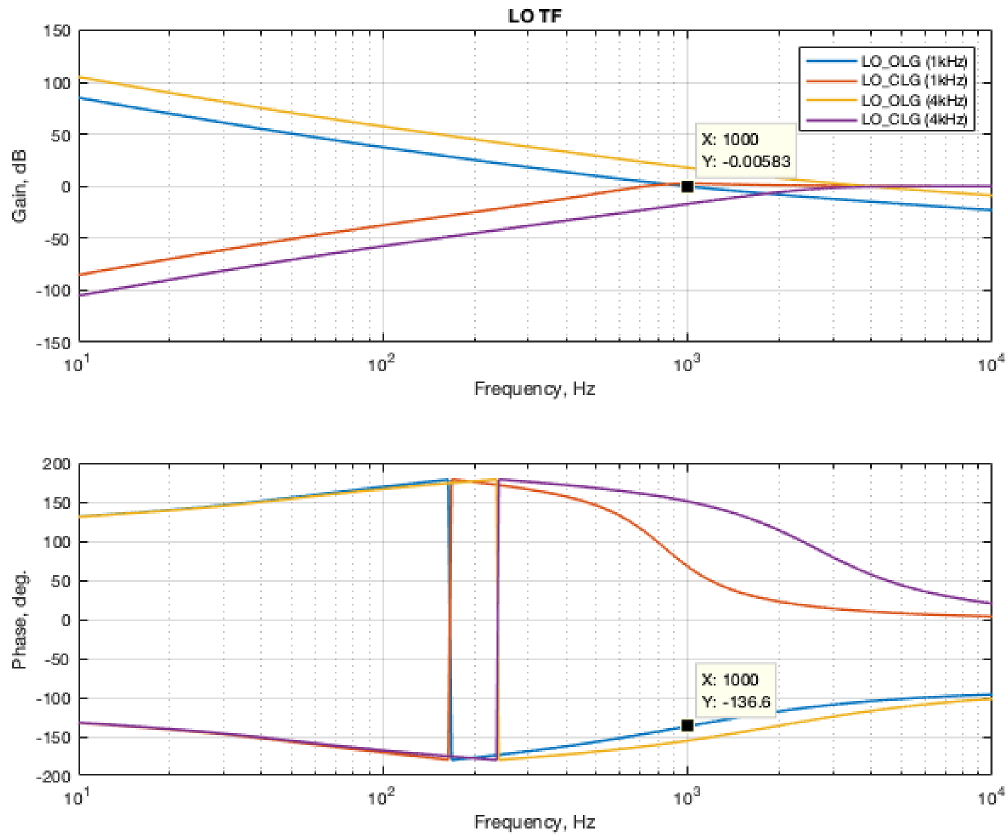


Figure 37 LO loop gain at various UGF. Only 4kHz is relevant to the current aLIGO set up.

5.6 Extra: Intensity Stabilization Servo

I'd like to talk about this one separately because the servo is used in both the standard and OPO Reference Configuration. When the OPO common mode board was available when we were using the OPO Reference Configuration we feed OPO REFL diode DC readout to OPO common mode board input. The inverse output is then sent to an AOM in the green path which we installed for this purpose (alog45871). As of today, everything is done digitally (alog46730) as we claimed back the OPO common mode board for the Standard Configuration. The UGF of the loop is 100Hz and with a better OPO TRANS diode installed (alog47895), we now use OPO TRANS as our error signal.

Using OPO REFL was not ideal as it kept the pump power going into the OPO constant but it weren't necessary true that the transmission was kept constant, which is what we care more.

As our laser has tendency to run multimode Pump laser has been replaced on August 13th, 2019 (LHOalog51238), the intensity stabilization servo is needed as the intensity change in 532 pump light can induce OPO cavity length change (via crystal heating, dn/dT) and impose noise on SQZ angle. Slow drift of pump power also changes the optimum squeeze angle and the level of squeezing. In addition, our pump fiber on ISCT6 shouldn't see more than 20mW input. See section 5.1.5 for transfer function and noise plots.

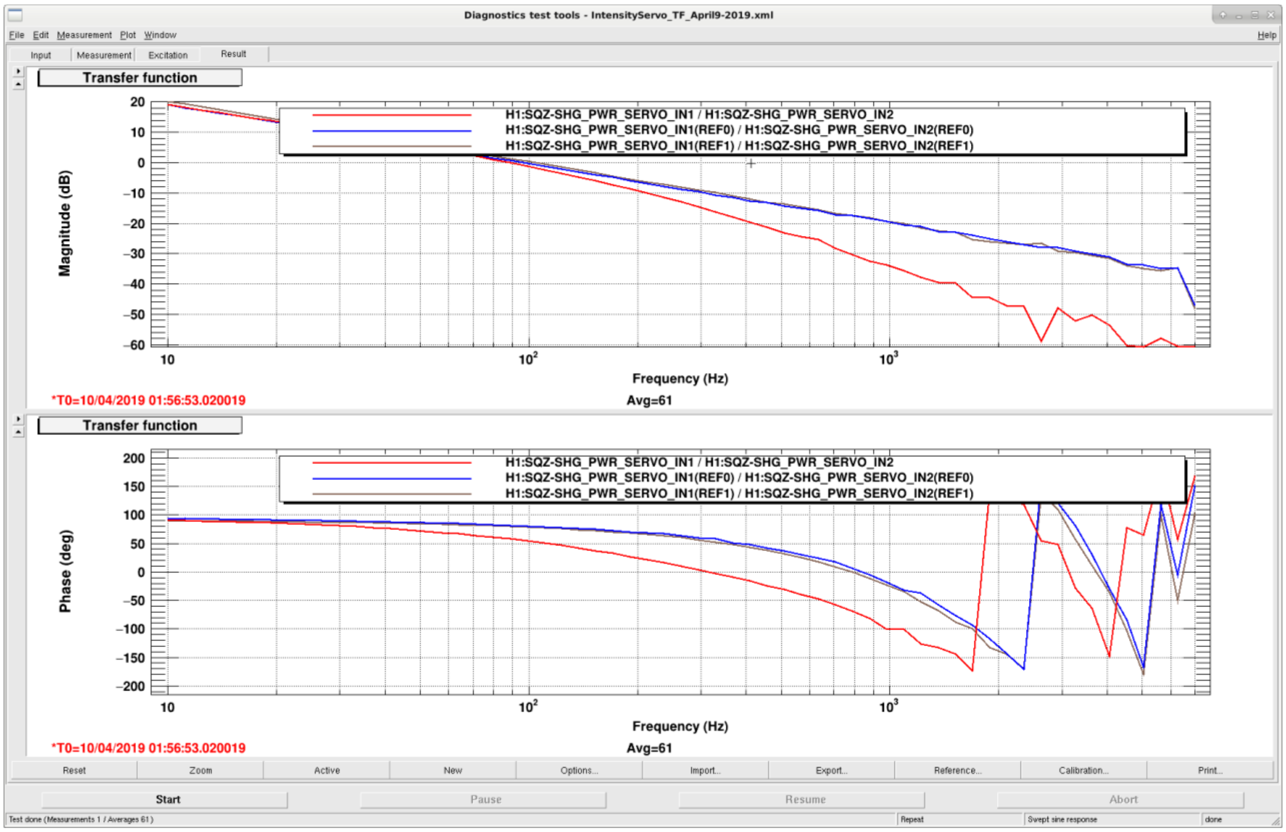


Figure 38 The open loop gain of the intensity stabilization servo. Blue and brown represent the original transfer functions using the OPO TRANS and REFL as error signals, respectively. UGF is 100 Hz. The red curve is after we added a 200 Hz low pass filter to reduce high frequency noise (alog48363).

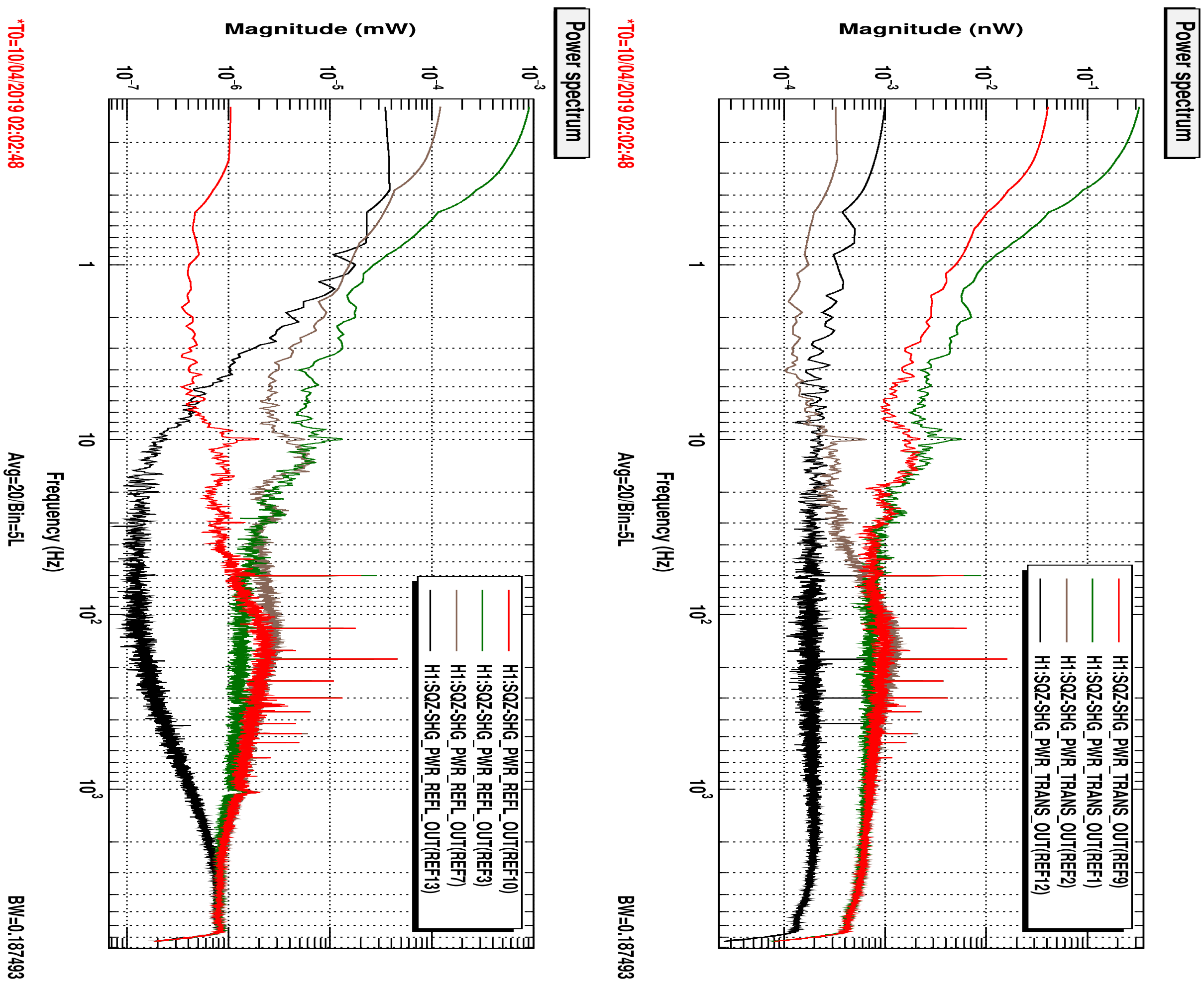


Figure 39 The noise of the OPO TRANS and REFL photodetectors: the green curve shows the noise with the servo off, the red curve is with REFL as the error signal, the brown curve with TRANS as the error signal, and black represents the dark noise (alog48363).

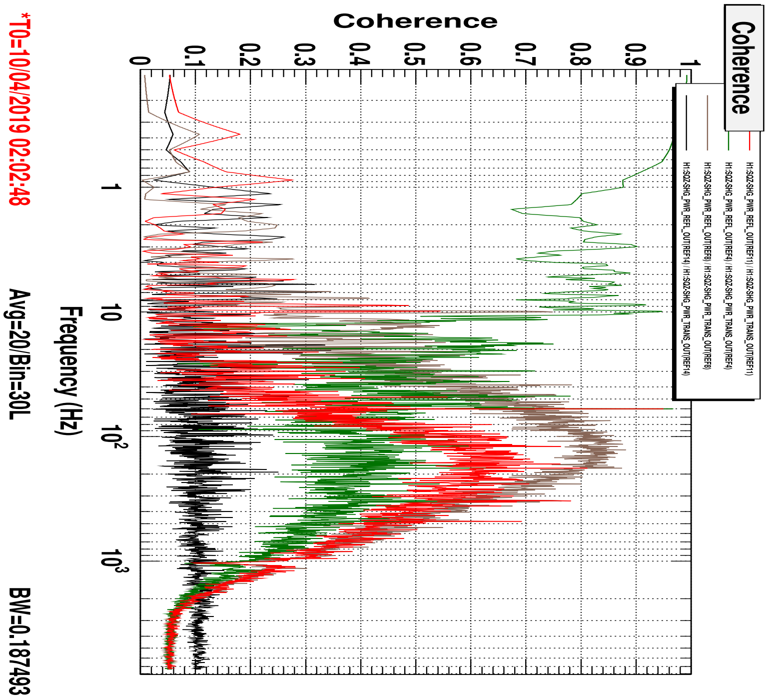


Figure 40 There is a lot of uncorrelated noise below ~10 Hz (alog48363).

5.7 SQZ system Noise projection onto DARM

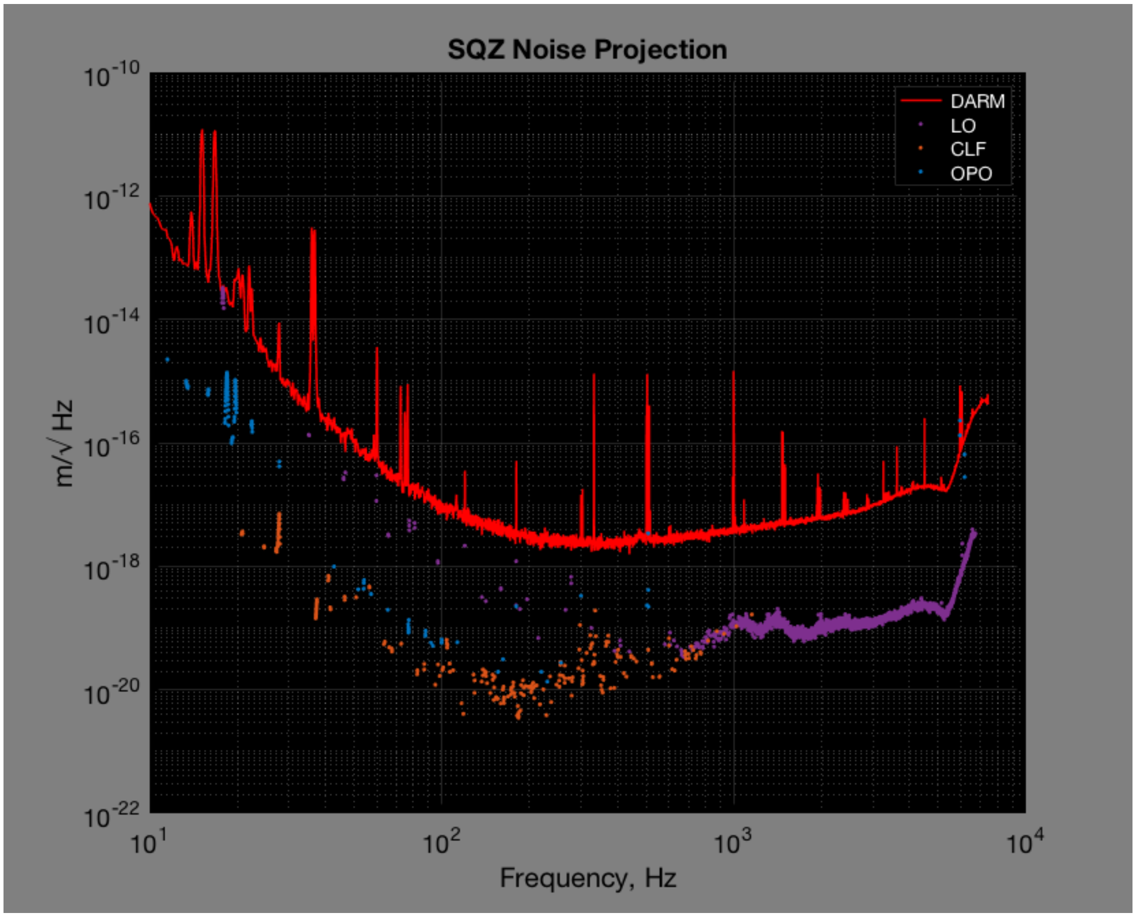


Figure 41. Overall SQZ noise projection onto DARM. DARM cavity pole removed.

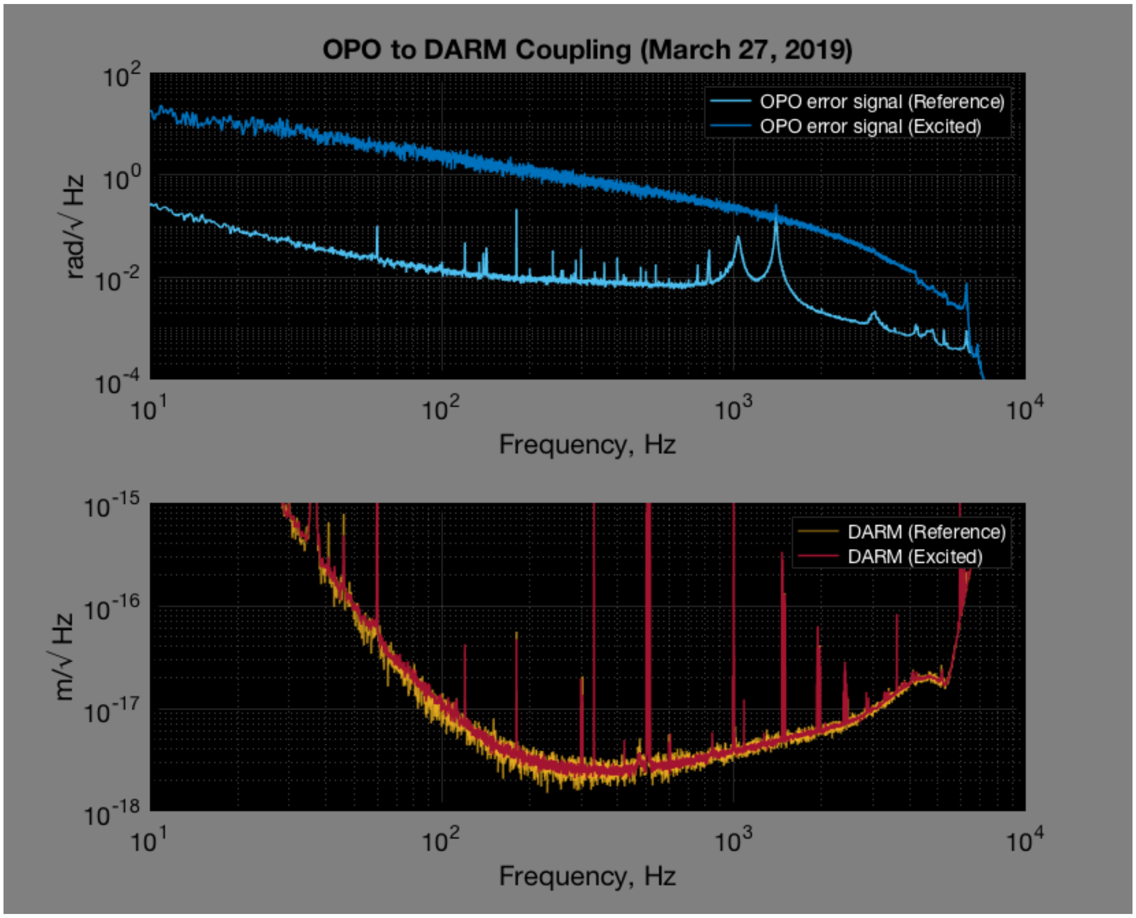


Figure 42. OPO excitation – no coupling.

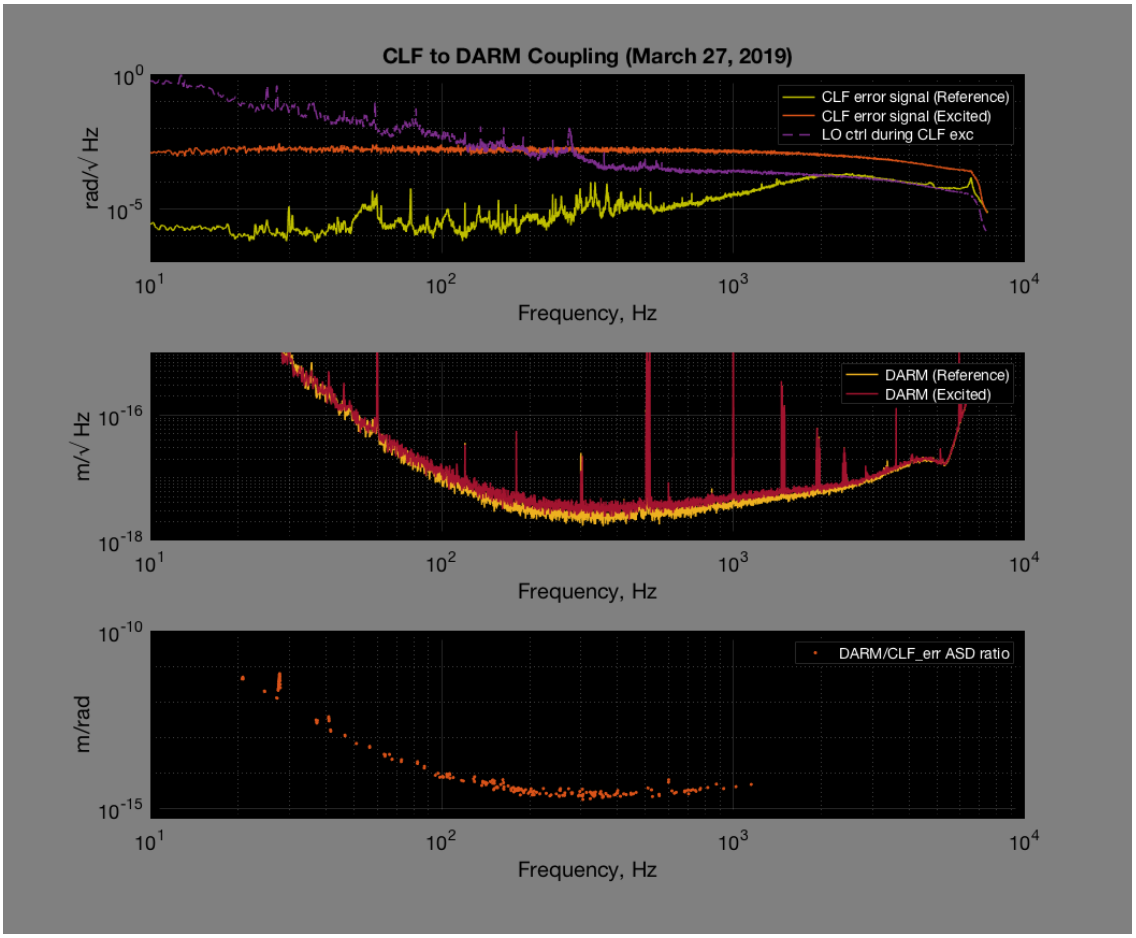


Figure 43. CLF excitation – Coupling below 1kHz.

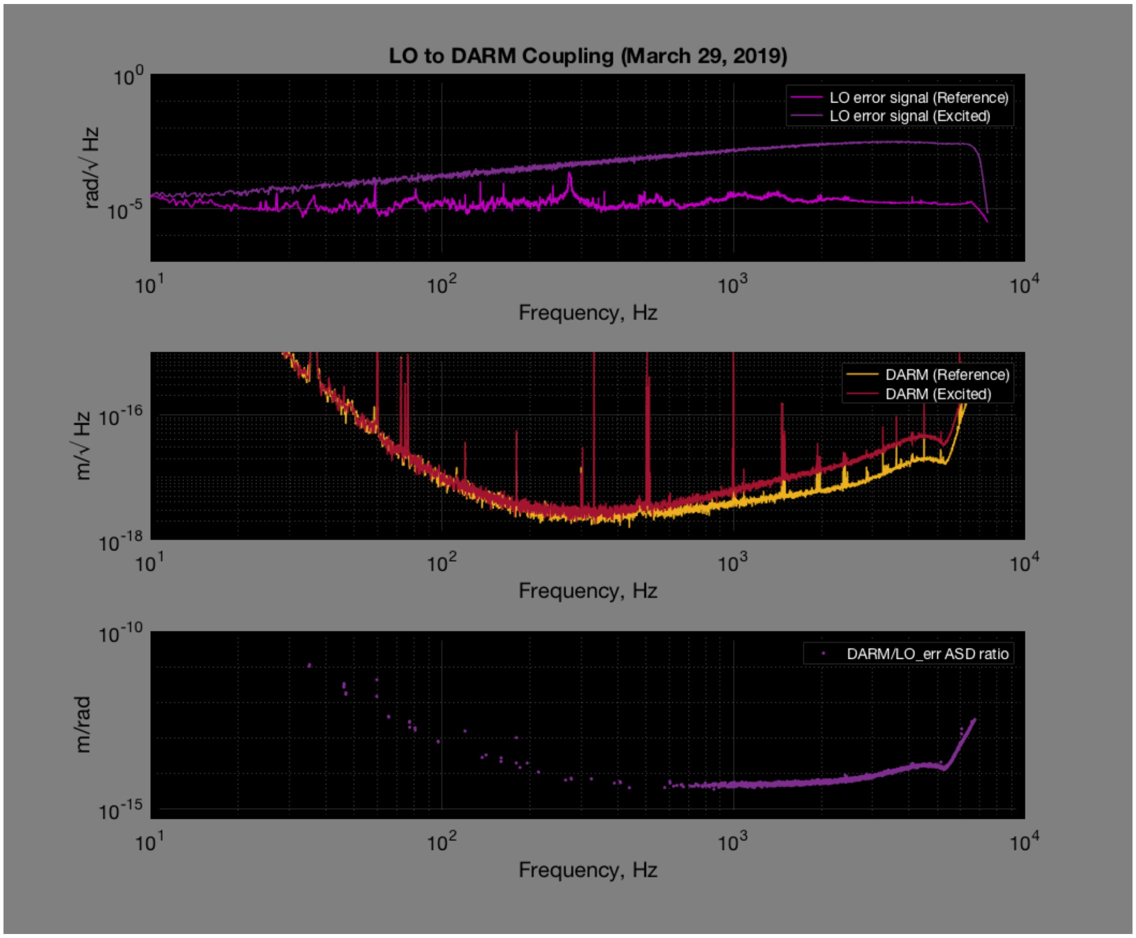


Figure 44. LO excitation – coupling above 1kHz.

5.7.1 SQZ angle phase noise (projection)

Borrowing this table again

Contribution (value in mrad)	Advanced LIGO	Future Generation		
		no FC	FC IR	FC green
Laser locking	0.73	0.73	0.73	0.73
SHG	0.12	0.36	0.066	0.017
OPO	0.10	0.20	0.079	0.035
CLF	1.72	1.89	<0.1	<0.02
FC length noise	–	–	0.003	0.003
FC sensing noise	–	–	0.26	0.005
Fiber/acoustic noise	0.48	3.55	0.18	0.017
LO sensing noise	0.18	0.11	0.044	0.044
RF sidebands (CLF)	1.2	2.1	1.1	0.7
RF sidebands (interferometer sensing)	15	4.2	–	–
Total	15	6.2	1.4	1.0

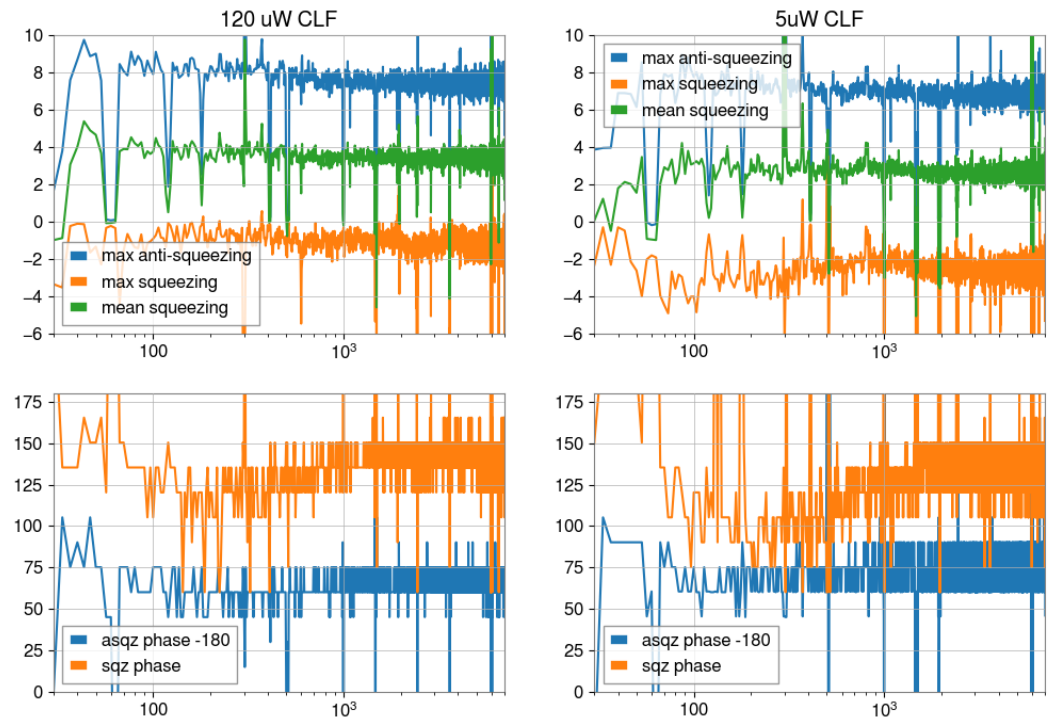
ϕ_{SQZ} = All the noise sources added in quadrature

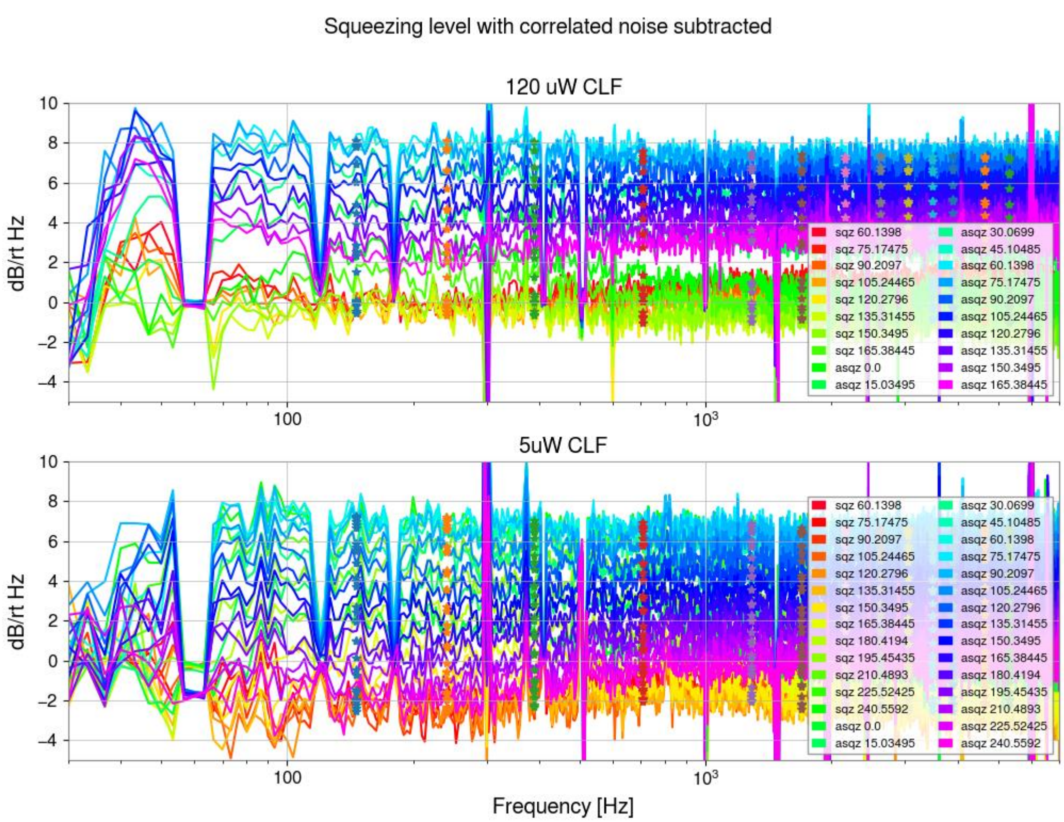
6 Loss, and phase noise inferred from IFO SQZ measurements

This section isn't as straight forward as I thought it was going to be. Here I included some of the detail analysis by Sheila and Lee that I found (not in chronical order). We are limited by the nonlinear gain so we are not at the point where we can measure sqz/asqz plot until we see the turn around to reliably determine the phase noise.

It's frequency dependent, and can be up to 4 dB

https://alog.ligo-wa.caltech.edu/aLOG/index.php?callRep=56068
https://alog.ligo-wa.caltech.edu/aLOG/index.php?callRep=56156
https://alog.ligo-wa.caltech.edu/aLOG/index.php?callRep=55760
https://alog.ligo-wa.caltech.edu/aLOG/index.php?callRep=53443
https://alog.ligo-wa.caltech.edu/aLOG/index.php?callRep=51981


120 uW CLF
5uW CLF
max anti-squeezing
max squeezing
mean squeezing
asqz phase -180
sqz phase


Squeezing level with correlated noise subtracted
120 uW CLF
5uW CLF
dB/rt Hz
Frequency [Hz]
sqz 60.1398
sqz 75.17475
sqz 90.2097
sqz 105.24465
sqz 120.2796
sqz 135.31455
sqz 150.3495
sqz 165.38445
sqz 180.4194
sqz 195.45435
sqz 210.4893
sqz 225.52425
sqz 240.5592
asqz 0.0
asqz 15.03495
asqz 30.0699
asqz 45.10485
asqz 60.1398
asqz 75.17475
asqz 90.2097
asqz 105.24465
asqz 120.2796
asqz 135.31455
asqz 150.3495
asqz 165.38445
asqz 180.4194
asqz 195.45435
asqz 210.4893
asqz 225.52425
asqz 240.5592

7 Operations

In this chapter we will go through the steps of how squeezer operates at Hanford. (LHO) SQZ subsystem is controlled by both Guardian (mostly) and Beckhoff. This chapter is written assuming you have already read Loopology chapter (chapter 5).

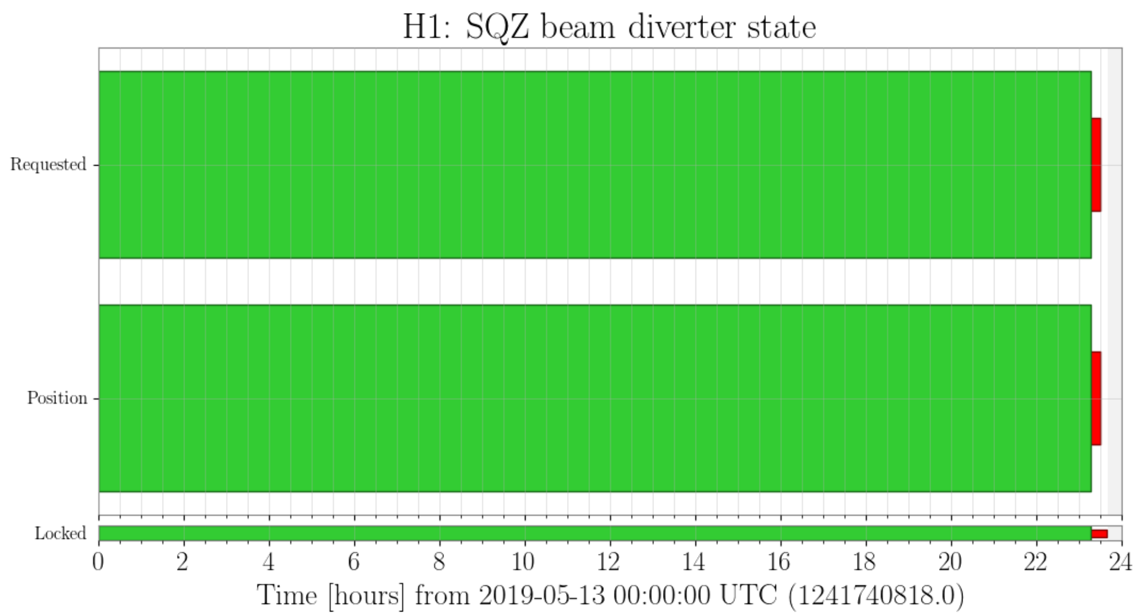
7.1 Locking Sequence

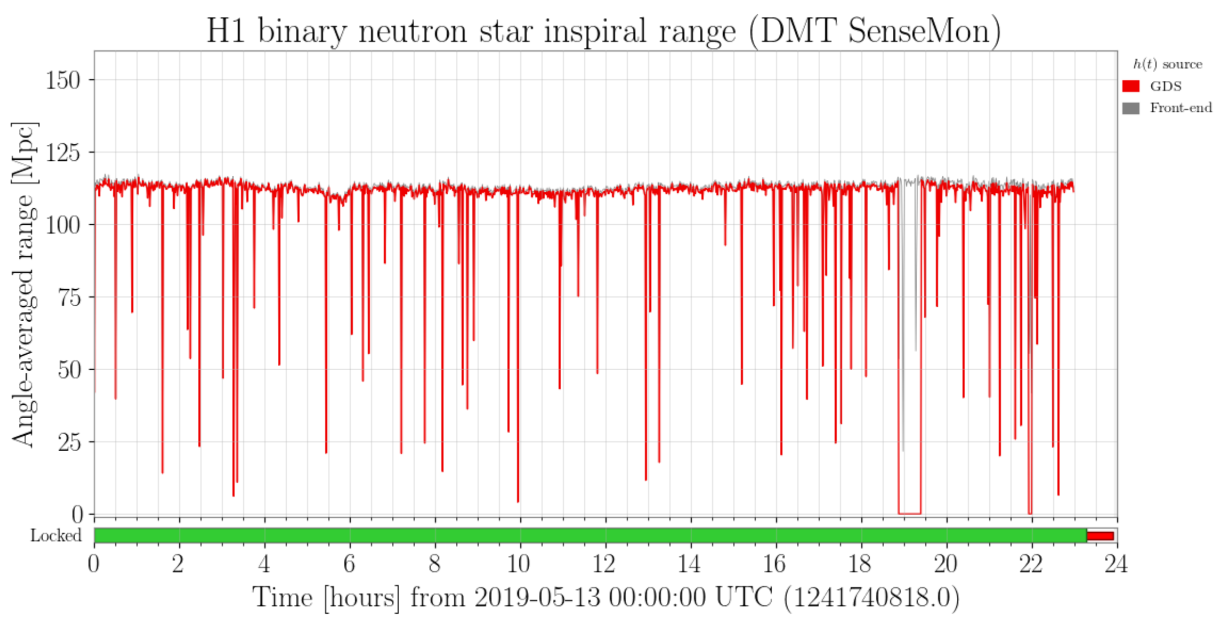
Let's start from the beginning. Imagine the interferometer has just lost lock:

1) Generally SQZ pump laser locks to PSL when the IFO have IMC back. This means the PSL reference cavity is undisturbed. Unless the reference cavity itself has issues, it will pose a problem on pump laser locking and the interferometer locking as a whole.
2) Once the SQZ pump laser is locked, SHG will automatically acquire lock but OPO remains down in order to save the life time of the green fiber (pump path flipper remains down). From this step onward including the SHG all the locking logics are controlled by guardian.
3) The realignment of squeeze optics (ZM1 and ZM2) is optional can be done during initial alignment. Generally the system is well aligned enough such that the alignment doesn't have to be performed often. If 3MHz signal during the previous lock segment appeared to be low (nominally > -25dBm), that might be a sign that you should perform a realignment of squeezer optics during the initial alignment. As the alignment loop relies on the squeezer seed beam it can only be performed during the initial alignment.
4) Once the IFO locking sequence starts (beyond DOWN state), the pump path beam diverter will be opened, letting green pump light through. At this point OPO and CLF should be locked and the intensity servo should be engaged.
5) Once the IFO locking sequence reaches INJECT_SQUEEEZING (guardian state as of May 16, 2019) the IFO_LOCK guardian will talk to SQZ_MANAGER guardian. If the SQZ pump frequency and 2xIMC VCO frequency differs no more than 50kHz, squeezer beam diverter will be open and LO loop will engage:
    a. If LO successfully locked, AS centering loop will kick in and keep ZM1 ZM2 aligned throughout the lock.
    b. If LO lock fails, the beam diverter closes and the guardian will not move on.
6) If squeezer fails to lock, ISC_LOCK guardian will move on without injecting squeezing. NLN state can still be achieved (This might have changed since this section was written.). At this point it is up to the operator on shift to make the IFO state into Observe, which has been a tricky bit as some of the squeezer guardian won't be in the nominal states and there will be SDF differences.

7.2 Performance

LHO squeezer has been running reliably at ~2dB of squeezing. At Hanford 2.2dB of squeezing corresponds to 14.5Mpc of range improvement, or 50.1% increase in search volume. On March 12, 2019 the BNS range before squeezing was 100Mpc, with 2.2dB of squeezing the range was 114.5 Mpc. This section was written more than a year ago. There could have been an improvement since.





8 Issues

Below I listed some of the SQZ issues we run into at LHO:

8.1 Pump fiber

Bad.

8.2 Laser

Kept running multimode. Fixed. See alog51244

8.3 OPO Length Noise

Not quiet enough for the OPO Ref configuration. But not an issue for the standard configuration.

8.4 Noisy CLF

The higher power we operate, the noisier it becomes. We also have seen CLF degrade squeezing level in the IFO broad band. We also observed this in the homodyne. The reason remains unknown.

9 Conclusion

It works. For now.

10 Appendix

10.1 OPO Reference Configuration (LHO trial configuration)

10.1.1 Loopology, Noise Budget, and Results

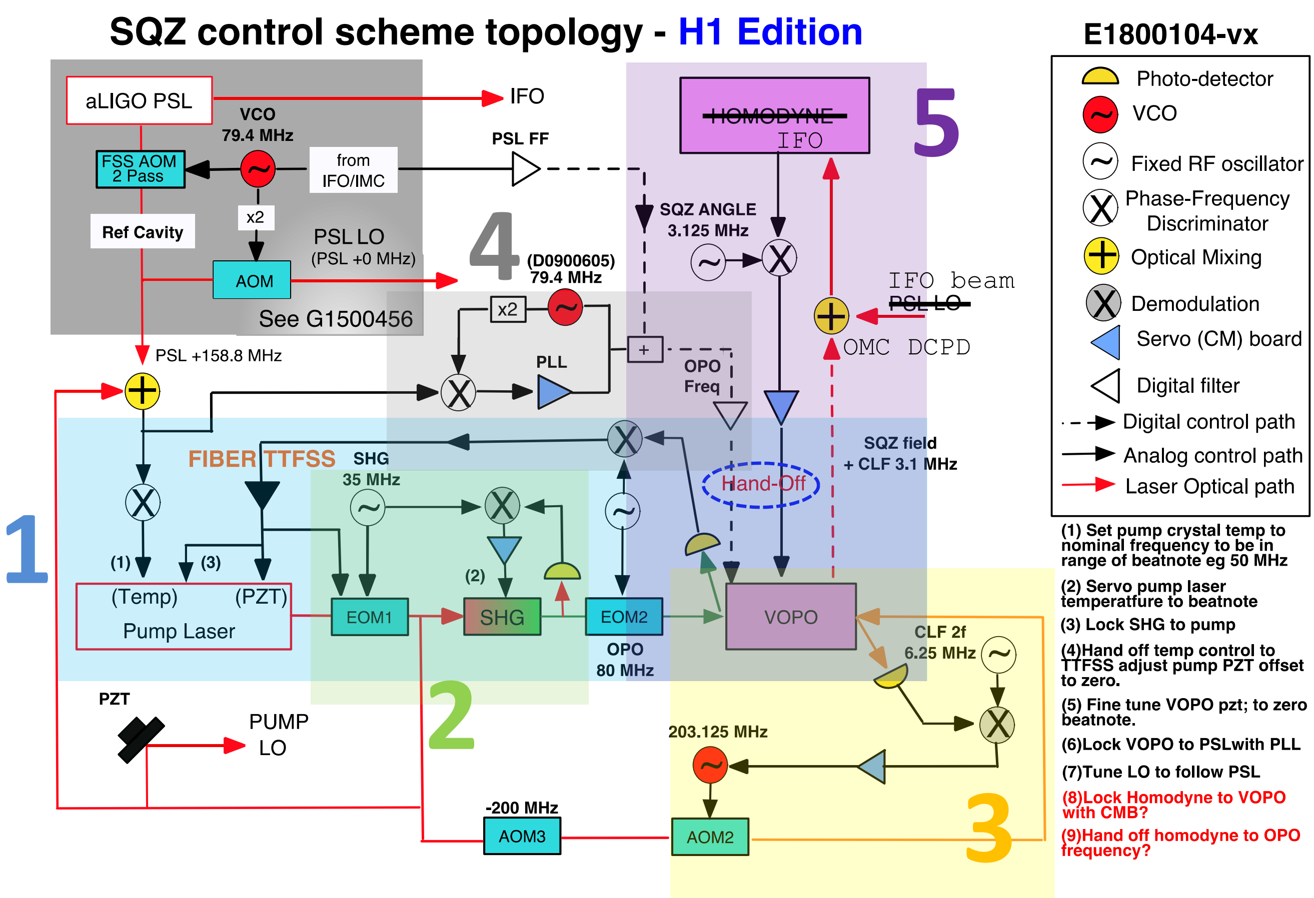


Figure 45 Block diagram – OPO Reference Configuration (aka H1 configuration)

At Hanford we experimented with an alternative configuration that would give us more suppression of SQZ phase noise using the OPO cavity as a reference. The original idea of this configuration was we thought OPO was going to be an excellent reference cavity (suspended in vacuum and all that). By locking our laser to the OPO we would be taking advantage of the OPO high cavity pole and suppress more noise that would eventually become SQZ angle phase noise with TTFSS. This is beyond what LO loop itself is capable of (OMC sensing bandwidth is limited by DARM FSR at 37kHz). However, due to thermal heating of the PPKTP crystal this configuration is useless without an intensity servo on the OPO input pump light. Heating of the crystal introduces OPO length noise via dn/dT. We originally changed our OPO cavity finesse to give us higher signal to noise ratio. Although we thought we didn't need this for the Standard configuration, it turned out that high finesse cavity was necessary due to low 532nm fiber transmission.

There are still 5 loops in this locking configuration: **1) Laser frequency 2) SHG 3) CLF 4) Adjust frequency** and **5) LO.** Notice that there is no more OPO loop because OPO is now acting as a reference cavity in which pump laser follows. So this leaves one common mode board open (OPO common mode board) which we then used temporary for the intensity stabilization servo when we were running with this OPO Reference Configuration (I will talk about the intensity stabilization servo separately to avoid making the control configuration section more complicated than it already is).

Laser frequency (1)

Instead of locking the pump laser to the 158 MHz beat note all the time in this configuration we make the pump laser follow the OPO. The 79.8MHz (green) pump reflected off the OPO is used as an error signal which feeds into TTFSS. 158 MHz is only used (for slow control) if the TTFSS loop is not closed to keep the pump frequency roughly at the carrier frequency. The advantage of this set up is that whenever the IFO loses lock, kicks the IMC and the PSL reference cavity out of lock, pump laser won't be as susceptible to that erupt change in the IFO configuration compared to the standard configuration.

SHG (2)

SHG in OPO Reference Configuration works the same as the Standard Configuration.

CLF (3)

CLF in OPO Reference Configuration works the same as the Standard Configuration.

Adjustment Frequency and LO

Because our pump laser no longer follows IFO carrier frequency, before LO loop can be engaged the frequency has to be brought within a certain range with OPO PZT.

LO loop gets error signal from either the Homodyne on the diagnostic table or the OMC just like the other configuration. However, the control signal no longer feeds back to TTFSS. Instead LO sends its slow control signal to OPO PZT, and its fast control signal to TTFSS additive offset. This was needed because OPO PZT alone doesn't have enough bandwidth to lock the pump laser to the main IFO beam.

OPO PZT can send 3MHz signal flying when it loses lock, this can also cause a lock loss of the whole IFO. Not good.

Noise Budget

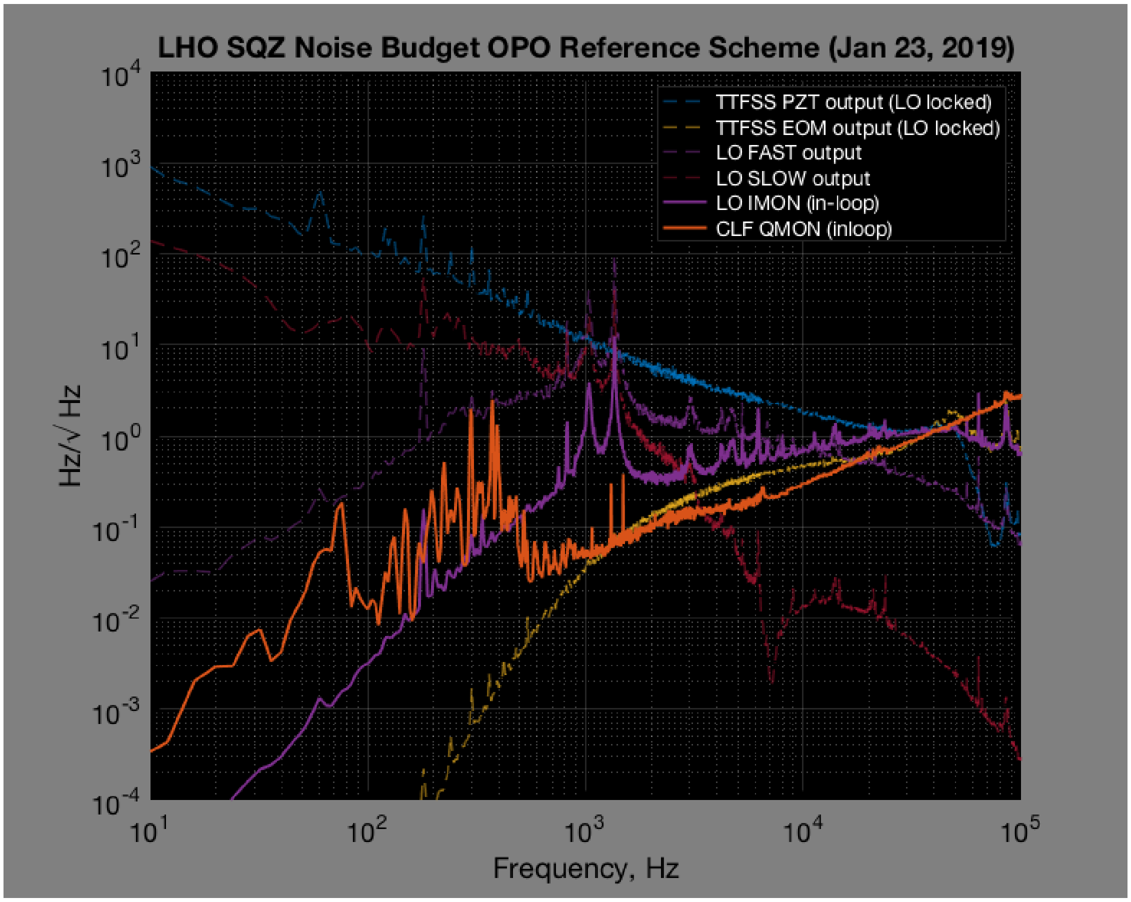


Figure 46 OPO Reference Configuration Noise budget, calibrated in red Hz/$\sqrt{Hz}$

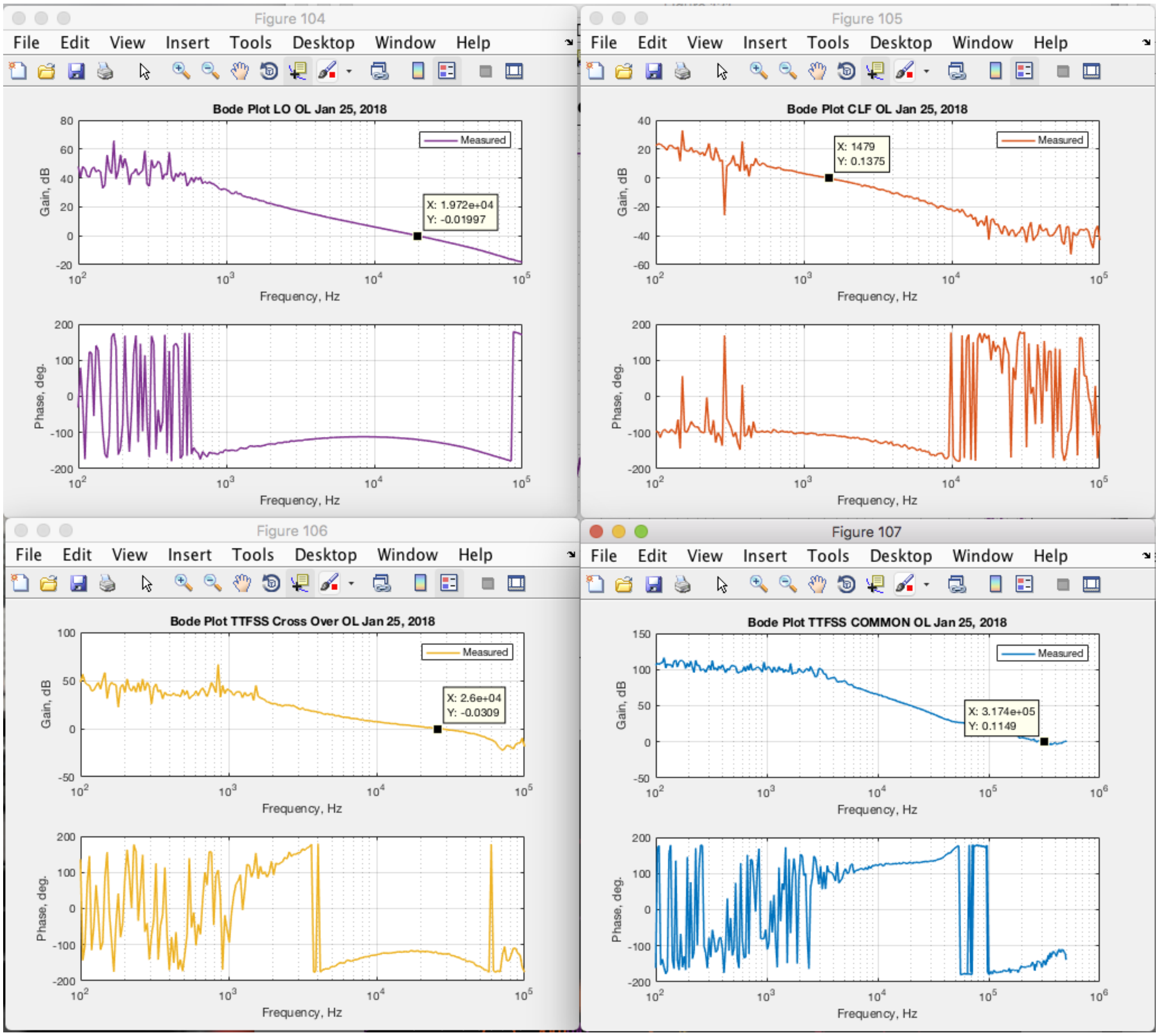
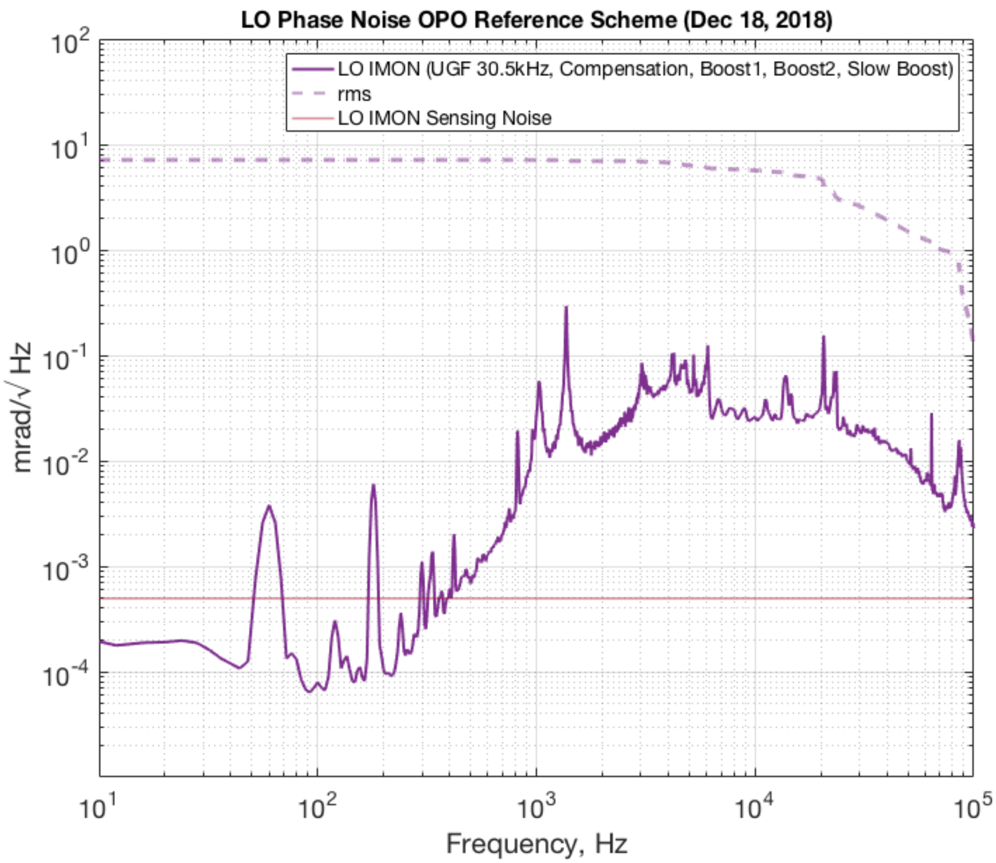


Figure 47 Transfer functions during the time of Jan23 measurement

The only difference between OPO Reference configuration and the standard configuration noise budget was that OPO length noise (two largest peaks near 1kHz) showed up on LO error signal as it used OPO PZT as an actuator. This poses two problems: 1) OPO length noise was visible in DARM and 2) IFO was kicked out of lock when LO loses lock because OPO PZT had enough range to push 3MHz signal too far. The offsetted 3MHz field could have overlapped with the carrier at the OMC DCPDs. What could have mitigated the problem here was to put a voltage divider at the output of the common mode board to limited the amount of voltage sent to OPO PZT.

The OPO length noise peaks also dominated the LO rms noise. We believe the peaks around 1kHz comes from the bending mode of the OPO breadboard. This is where a more rigid glass OPO would have been useful. Unlike the standard configuration, these peaks showed up in LO noise spectrum and thus showed up in DARM.


LO Phase Noise OPO Reference Scheme (Dec 18, 2018)
LO IMON (UGF 30.5kHz, Compensation, Boost1, Boost2, Slow Boost)
rms
LO IMON Sensing Noise
mrad/√ Hz
Frequency, Hz

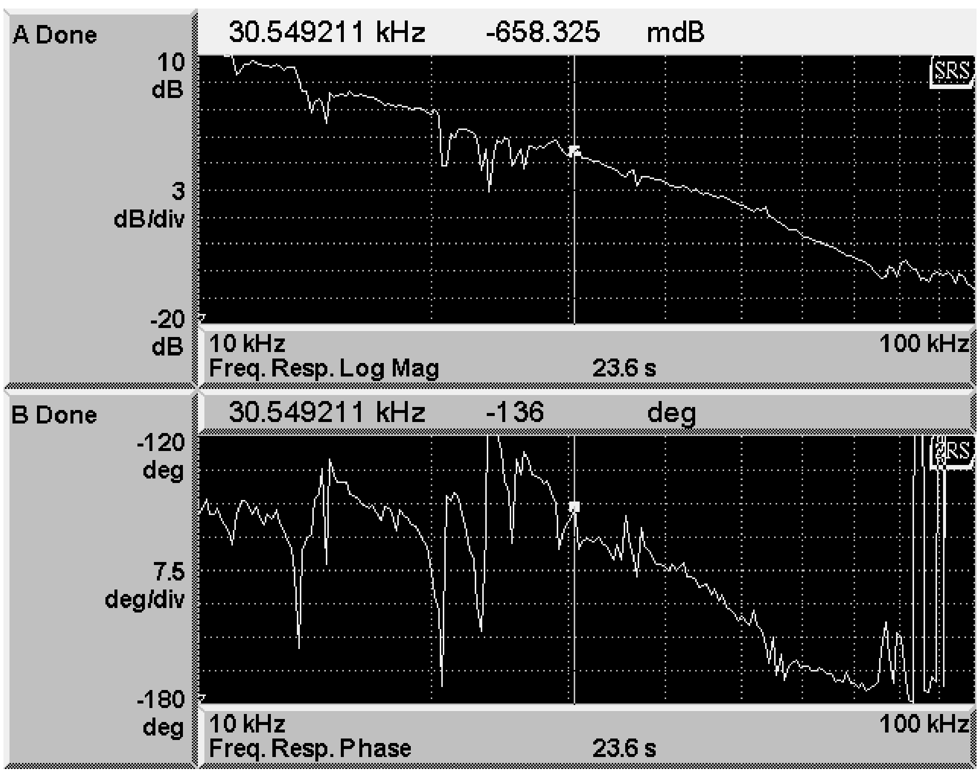

A Done
30.549211 kHz -658.325 mdB
10 dB
3 dB/div
-20 dB
10 kHz
100 kHz
Freq. Resp. Log Mag
23.6 s
B Done
30.549211 kHz -136 deg
-120 deg
7.5 deg/div
-180 deg
10 kHz
100 kHz
Freq. Resp. Phase
23.6 s

Figure 48 LO noise measured off the homodyne. Compensation is a boost at 40Hz/4kHz pole/zero, Boost1 is 0Hz/10Hz, Boost2 is 20Hz/2kHz, and Slow Boost is 4Hz/400Hz. The common gain was 14dB and fast gain was 6dB. Slow option were on to notch 6kHz PZT resonance (E1700420).

We didn't analyze loss and phase noise when we injected squeezing using this configuration because loc the lock loss issue. But what we measured with the homodyne proved that the configuration can perform equally well and has a potential of being better given lower the OPO length noise and higher UGF.

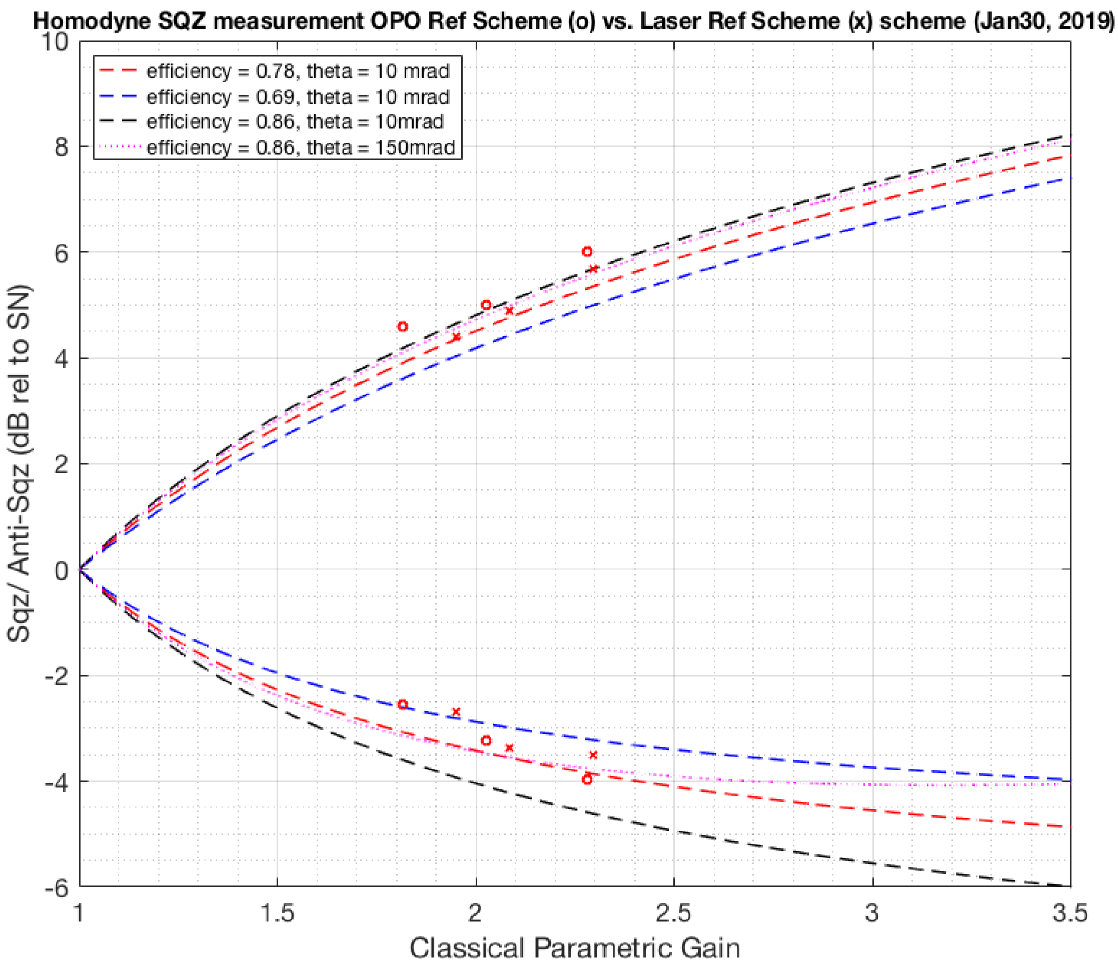


Figure 49

10.1.2 When will this configuration matter?

Future. We won't talk about this in this dcc version.

References

[1] Nathan Z. Zhao. LIGO SURF: Enhancement of Second Harmonic Generation for Squeezing in aLIGO, September 2014. DCC#

[2] Fabrice Matichard, Lee McCuller, Lisa Barsotti: LHO Cavity test report, January 2018. E1700420