LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

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LHO Control Scheme Summary

Terry McRae, Nutsinee Kijbunchoo , Daniel Sigg, Haocun Yu

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1 Introduction - Two Control Schemes

There are two control schemes that have been proposed and tested to lock the phase of the squeezed light to the interferometer. One scheme uses the PSL reference cavity as a reference for the squeezed light and the other uses the VOPO as the reference cavity for the squeezed light. We will briefly discuss the advantages and disadvantages of each scheme [1] before focusing on the scheme that uses the VOPO as the reference cavity. This note is an attempt to give the alogs some perspective with reference to the methodology for choosing the squeezed light control scheme at LHO.

1.1 The Control Scheme with the PSL reference

The vacuum squeezed light needs to be phase locked to the IFO. One approach is to use the PSL as the reference (Fig. 1). This scheme locks the VOPO to the SHG and the SHG to the pump laser with their respective PZT's and PDH phase sensors. The pump laser is then locked to the PSL reference cavity via a long optical fiber using the 3.125 MHz signal from the CLF and IFO beat-note detected by the squeeze angle phase sensor and sent to the VCO and the TTFSS to control the pump laser frequency. In this scheme as the VOPO follows the PSL it is sensitive to PSL fiber noise and we rely on the closed loop gain of the TTFSS to suppress this noise. This loop suppression is complicated because the squeeze angle phase sensor is offset by 3.125 MHz from the fiber noise and so the amount of suppression of fiber noise will be compromised by this offset. A similar issue exists for the CLF fiber noise, however the fiber length is much shorter and should be controlled by the CLF loop gain. However if the squeeze angle needs to be high bandwidth the interferometer arm cavity notches may also be a problem.

1.2 The Control Scheme with the VOPO reference

An alternative scheme has been proposed to use the VOPO as the reference for the squeezed light control scheme in an attempt to address the above issues (Fig. 2). In this scheme the VOPO does not see the fiber noise directly as the VOPO-PDH frequency sensor is connected to the VCO frequency actuator and the pump laser is locked to the VOPO with the large BW of the TTFSS. If the VOPO is stable enough the larger BW has the potential to suppress fiber noise. The Squeeze angle loop phase sensor is then used to control the VOPO-PZT that behaves as a phase actuator. However there are two issues that need to be addressed that could compromise this locking scheme.

1) Excessive length noise in the VOPO

2) Instability in the path length between the OPO and the IFO

Here we give a detailed overview of the work done at LHO to develop the VOPO reference control scheme.

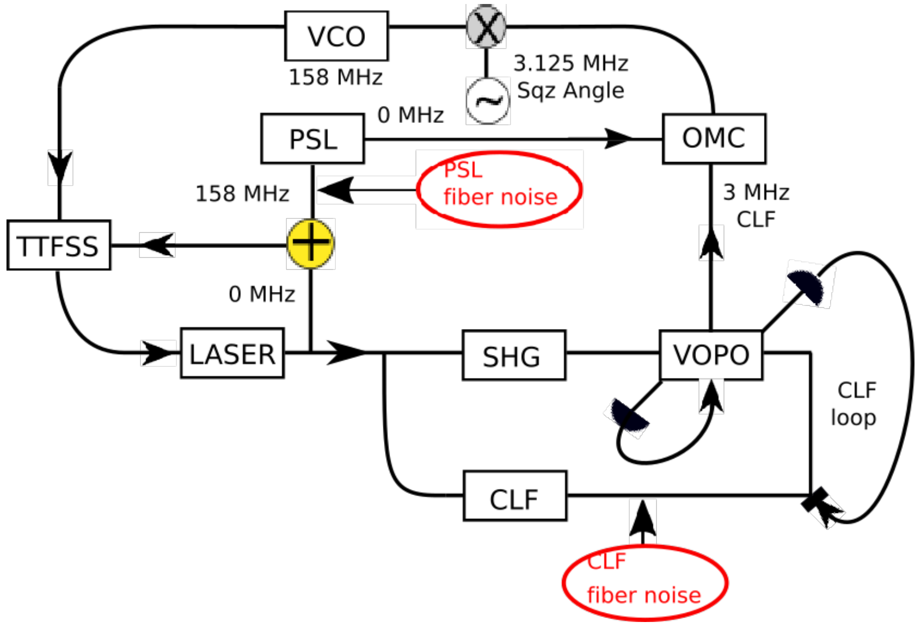

Figure 1: Control scheme for squeezed light using PSL as a reference (TTFSS has PFD)

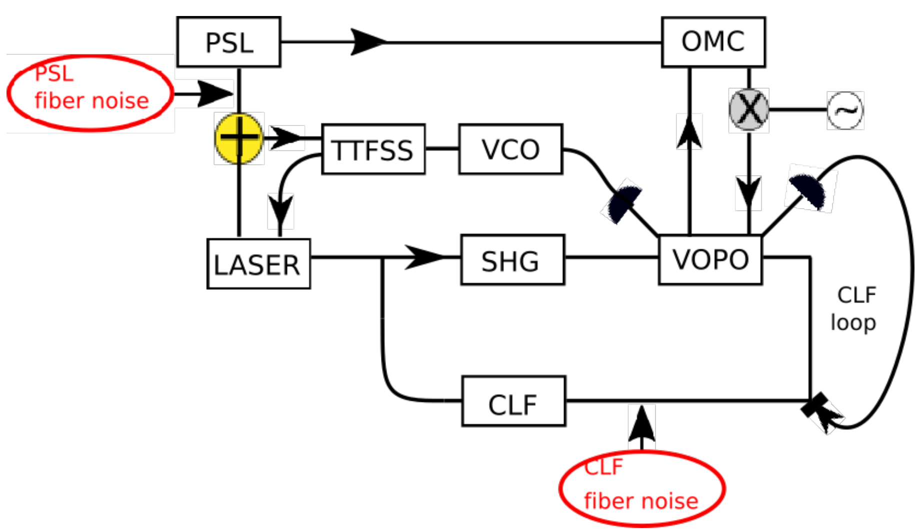

Figure 2: Control scheme for squeezed light using the OPO as a reference (TTFSS has DeMod)

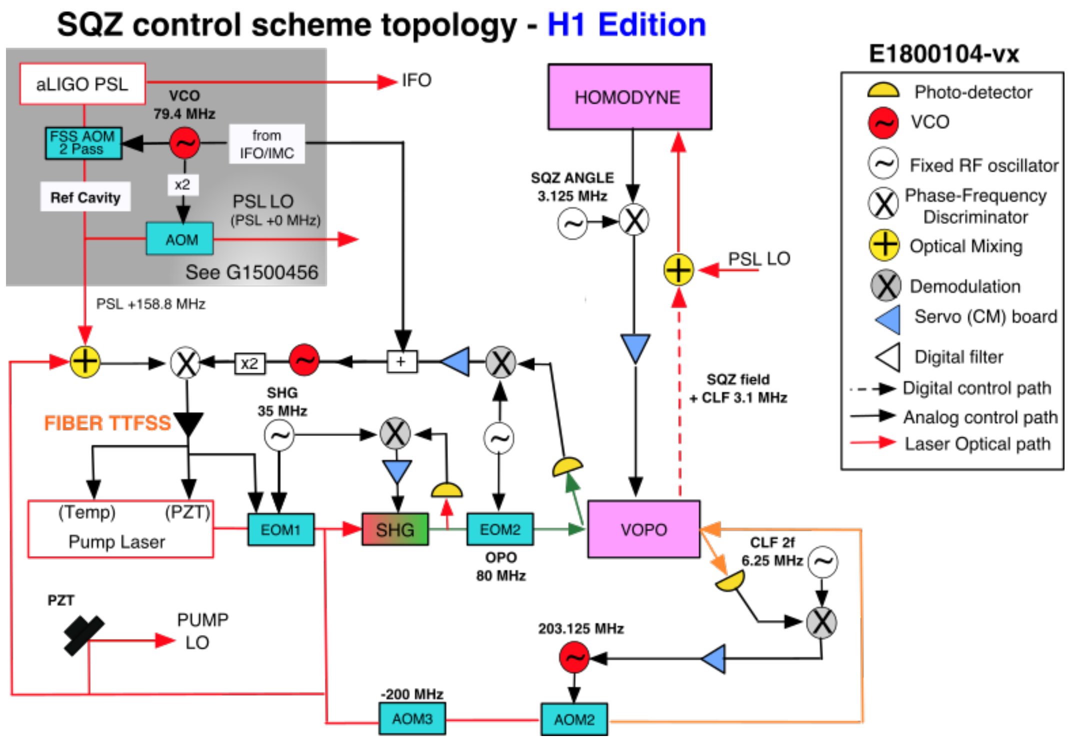

Figure 3: The Original proposal for using the VOPO as a reference.

2 Control Scheme with VOPO reference

The practical implementation of the VOPO reference control scheme as it was first proposed is shown in (Fig. 3). There were a number of issues with this implementation which will be covered in the following sections.

2.1 The SHG Loop

The SHG is mode-matched (39544) and PDH locked with 35 MHz sidebands (40094) to the Mephisto pump laser on the IR transmitted beam with a UGF of about 3 kHz 40129). SHG crystal temperature optimized to 35.9°C (40406) with a nominal input power of 100 mW with 48% conversion efficiency (40199). The BBPD used for SHG control has been amplified.

2.2 The Laser Beat-note

The TTFSS V4 was installed (40346). First the pump laser was locked **to the PSL** using the (**laser**) PZT only (40178). It became necessary to increase the beat note strength so the first directional coupler in the TTFSS preamplifier was replaced by a splitter which resulted in 8dB more gain (40282, 40346, (40367)).

The modifications are described in E1700364. The UGF is around 500kHz with a crossover around 30kHz.

2.3 The OPO Loop in Air

The pump laser is locked to the OPO with the green Refl diode (BBPD) 40944. The RF signal is quite large and we ended up installing a 20dB attenuator in the green EOM modulation path. As expected the green transmitted power is tiny, about 70nA when locked with 1.3mW. We suffered from red contamination and a second dichroic beamsplitter was installed in this path. We **first tried to lock the laser to the OPO, but soon realized that this won't work with 1MHz of VCO range** (Fig. 3). We switched to the OPO PZT and were able to keep it "locked" near resonance to within about the full line-width (Fig. 4). What remains looks like a 1kHz feature that we can't suppress, since at higher gain setting we see an instability around 5kHz. The dip in reflection seems to be about 0.7. **We were finally able to lock the OPO in air with the output of the common mode board sent to the laser PZT via a Thorlabs PZT driver** (gain of 15) (Fig. 5). The UGF we achieved was 10kHz (41017). The noise spectrum indicates a strong acoustic peak around 1.1kHz that is consistent with the need for a large driving range. The transfer function from the OPO PZT to the laser PZT has the first resonance is at 6.0 kHz as expected—confirming that the 1.1kHz peak is not an inline resonance. Note there was 4kHz low pass filter in the CMB common path is flawed by design and was operating as a voltage follower. With the ISI no longer locked the 1kHz acoustic peak is a factor of a few lower and the OPO locking needs correspondingly less range. The lock also looks much better now (41045). HAM6 was then closed and the squeezed light control system was largely untouched for 6 months while work continued with the rest of the interferometer.

2.4 The OPO Loop in Vacuum

HAM6 was closed early in May 2018 and the reduced acoustic noise enabled better diagnostics of control system problems. **Work on the squeezed light control subsystem, now under vacuum, resumed on August 3rd 43257. We fed the signal from fast path out of the common mode board to a VCO that's connected to LO input of the TTFSS. The signal from slow path now goes to OPO PZT1 (Fig. 6).** We were afraid that VCO may not have enough range (it probably would have done just fine without). We added the boost/notch filters, (D1000798-v2), to the slow path of all squeezer common mode boards. The measured transfer function is pretty close to the theoretical one, see (T1800112-v1).

2.4.1 The CLF and Pump LO loops

The CLF loop was installed 43453,43531. The UGF for the CLF loop was 6kHz with a phase margin of 30deg. Note here we start with the pump LO (not

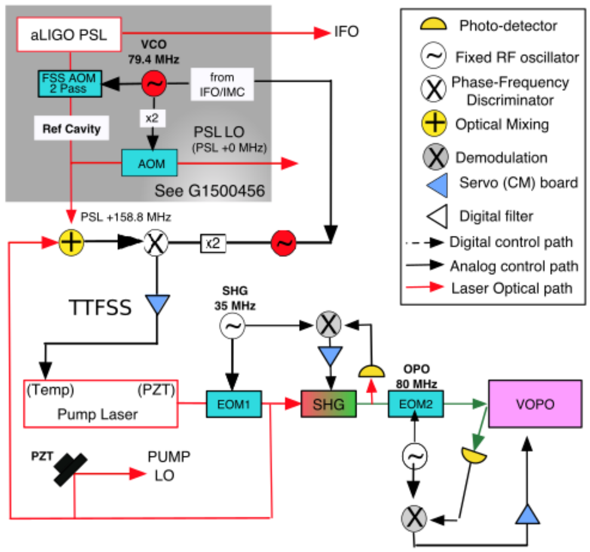

Figure 4: Control flow in air with feedback to OPO PZT

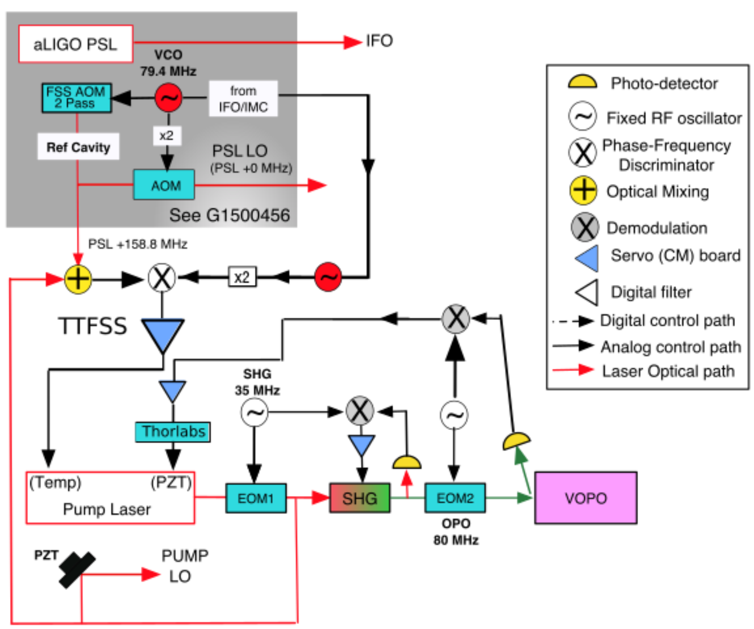

Figure 5: Control flow in air with feedback to Laser PZT

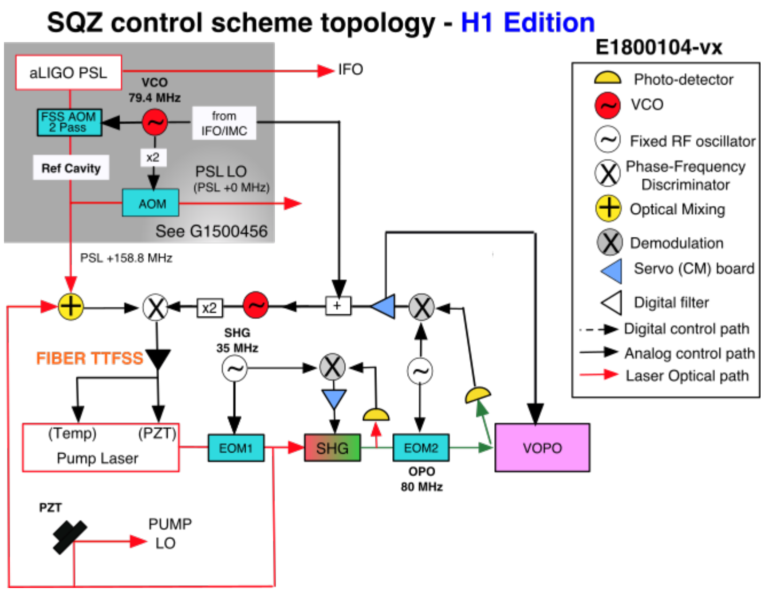

Figure 6: Control flow in vacuum with feedback to Laser PZT

PSL LO) (43453, 43531). The UGF for the pump LO was around 2kHz with 40deg phase margin. This cannot be pushed further because of the large peak around 34kHz that's believed to be LO PZT. However this control scheme was good enough to see initial squeezing of -1.3 dB on the homodyne. Note for this squeezing measurement the pump was not locked to the PSL (43738). With lower CLF power, extra CLF phase adjustment and improved visibility this squeezing measurement was improved to -3.6 dB (43740). A 34 kHz notch filter was installed on the slow path of the LO CMB to suppress the pzt resonance (43783) and with 4 mw of pump power into the VOPO we got a nonlinear gain of 3.6 and 4 dB of squeezing (43782). There was a further issue with the green Refl diode in this control system with RF saturation. An ND1 filter was added (43924,43930) however this left the TTFSS with too little common mode gain. The correct solution was to expand the beam onto the detector surface to distribute the power over more charge carriers. For this control scheme that uses the VOPO as a reference the TTFSS required the PFD to be changed for an IQ demodulation board (43988). These modifications gave an initial UGF of 100kHz (44007).

2.4.2 The PSL LO loop and the PLL

To lock the OPO to the pump laser/PSL beat note, the beat note error signal and LO is sent to an IQ de-mod board and the output of the IQ de-mod board went to the OPO common mode board This configuration is the same as illustrated in Fig. 7 except that at this point an I/Q

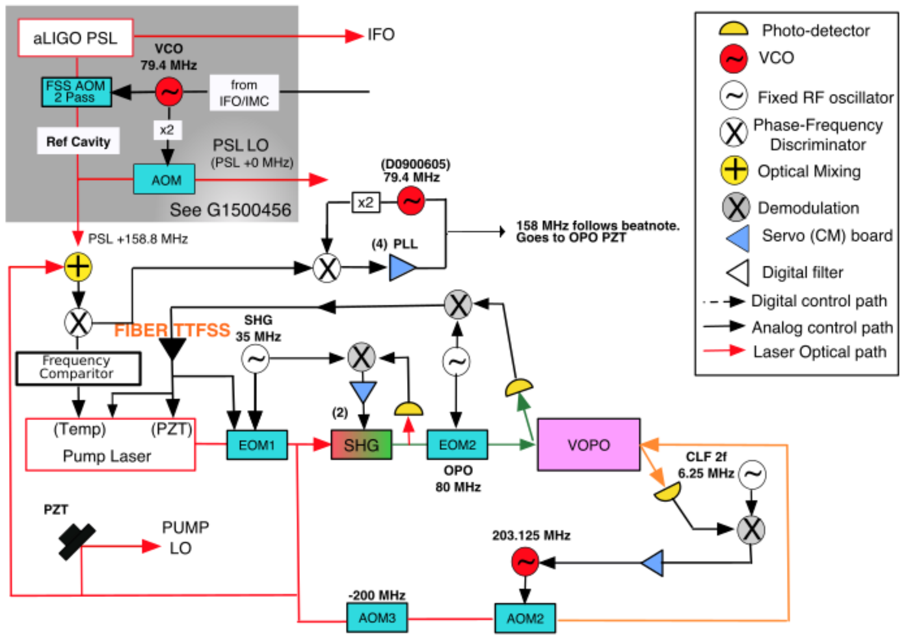

Figure 7: Control scheme with PLL

de-mod is used in the phase locked loop (PLL) instead of the PFD illustrated in Fig. 7. We bypassed the PZT driver box completely to reduce the gain to the OPO PZT (PZT driver box has a gain of x22, and a pole at 400Hz). A 10Hz low pass filter was added (not shown) between OPO common mode board output and in-vac PZT driver to give it a low frequency roll-off, which (according to the writing on the box) attenuated the signal by a gain of 10 (44102).

2.4.3 The Feed-Forward

We installed a phase frequency discriminator chassis (U7 on SQZ rack near ISCT6) to phase lock our 158MHz VCO with the beat note. The pump/PSL beat note RF signal and 158MHz LO went in and the output went to OPO common mode board. **We unplugged the output to the PZT and only used the fast path error signal to feed into the 158MHz VCO. The 158MHz VCO now follows the beat note frequency.** The control signal is here 44135. As the result we now have a frequency correction signal to send to OPO PZT (Fig. 7), 44160. This signal goes through a 10Hz lowpass blue box (with gain of -10), and into the in-vac PZT driver. In addition the fibers from the PSL at ISCT6 feed through were swapped after realizing they were plugged in wrong so that the PSL that's used for beat note is 158MHz shifted coming in and the PSL LO has been down shifted (0Hz) coming in (which would be the same as what goes into the IFO). We also put back the motorized half

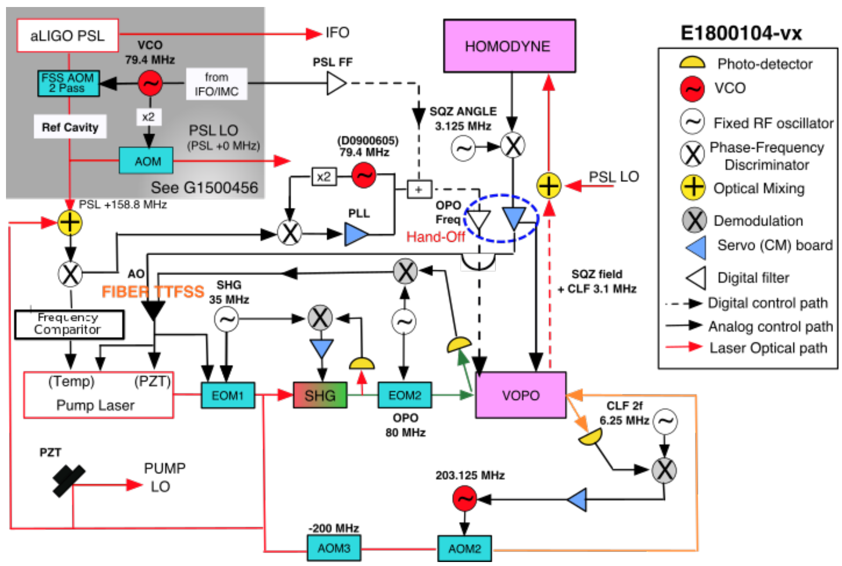

Figure 8: Control scheme with PLL and feed-forward

wave-plate we borrowed from the PSL beat note path. Next thing to do is to include feed forward from IMC VCO in the frequency locking loop. Once that's done we should be ready for 3MHz hand-off.

We had some trouble to lock the laser to the OPO using the full TTFSS. It worked fine with just the fast (PZT) path only, but as soon as we engaged the EOM path, the lock became unstable. Furthermore, the fast/EOM crossover had a crazy shape with 3 unity gain crossings. We traced this to slew rate limitations and saturation. There was just too much noise in the 50-300 kHz region which the EOM couldn't handle. This resulted in a low UGF with high fast gain. We re-allocated some high frequency gain in the TTFSS fast path, but it wasn't enough. Finally, we increase the modulation depth by about a factor of 10, and voilà, it worked! (44195, 44200).

We introduced a PSL feed forward summing point so that it happens before the OPO frequency servo filter bank The lock at 3MHz with PSL LO was still unsuccessful. The plan at this point was to loosely lock the 3MHz with signal out of PFD and hand off the locking to the signal that comes out of IQ demod by changing the relative gain 44317. A 10Hz/60Hz pole/zero Pomona box added to LO slow output 44446.

2.4.4 The Addative Offset (AO)

We temporarily locked LO loop (with PSL LO) using additive offset on TTFSS just so we can figure out why is it so noisy; slow path **still** output to OPO PZT, fast goes to TTFSS AO (Fig. 8). We saw 3MHz leaking out of PFD IMON and it also shows up in LO common mode board fast control signal. Some filters need fixing, (44484). LO loop OLG transfer function shows UFG at 63kHz (without 4Hz/400Hz slow path compensation). Transfer function at fast path shows crossover 700Hz (with 4Hz/400Hz). Within a factor of 2 of what we calculated. With the original Pomona box (44446) we would've needed a gain of 36dB on the fast path for a reasonable cross over. Daniel doodly clipped a 220 Ohm resister in parallel to the existing 1kHz to give us 14dB less gain in the slow output to PZT. This allow fast gain to be within +32dB slide bar range. One of the issues we discovered was that the TTFSS was modified to have a pole/zero and more gain in the sensing path. This was done to make the OPO look more like a reference cavity with a 70kHz pole. However, this reduced the AO path gain by 20. To get this gain back we need to move the compensation to the next OpAmp, after the AO is added; (see E1800283). The second issue is with the PFD and the 3.125 MHz LO. The PFD filter is designed for LO frequencies >9MHz. At 3.125 MHz there is only 12dB of attenuation which results in a 1V LO signal leaking into the servo board. We can add a notch filter by stuffing C14 and C19 with 260pF on D1002471.

A number of tests were then performed in this (temporary) configuration including a measurement of phase noise (44575), OPO loop sensor noise (44964) and a measurement of pump intensity noise transferred to the OPO loop (45019). HAM6 was vented to swap out the degrading fiber (44663). This vent also provided an opportunity to optimize the linearity of the polarization onto OPO Refl by rotating an in chamber waveplate, improve the modematching of the pump path into the OPO and flip the dichroic over to its proper orientation to reduce the losses on the squeezed light path 45372 (also 45150, 45405, 45423).

After the HAM6 vent further tests were carried out regarding the intensity noise (45745,45787, 45774, 45846, 45838, 45903, 45902) this will be covered in more detail in a separate document regarding the stability and noise of the OPO and how it contributes to the locking scheme. We will note here however, that an AOM was added to the green pump path after "EOM2" with feedback from OPO Refl to control the intensity noise (45871, 45883) Fig. 9.

We made another squeezing attempt with PSL LO on Homodyne (45956) and a 20dB attenuator was taken out of 80MHz LO (46011) We attached a LO IMON (in-loop) before set up (going from ADC through a Pomona box to in-vac PZT driver) introduced a lot of OPO length noise. The rms at low frequency came down from 100 mrad to 10 mrad after the cable was unplugged. Daniel reconfigured the loop shape that puts us below 10 mrad (3rd attachment, 30kHz UGF). The 1.4kHz peak now dropped by a factor of 6. The 1.4kHz wasn't improved after we unplugged the feed forward cable. It disappeared from TTFSS PZT mon when LO loop was engaged and came back when LO loop was disengaged (our LO loop feeds back to the OPO PZT). This suggests that 1.4kHz may have come from the OPO itself. An RF amplifier was added to the CLF photodetector (44633) [2].

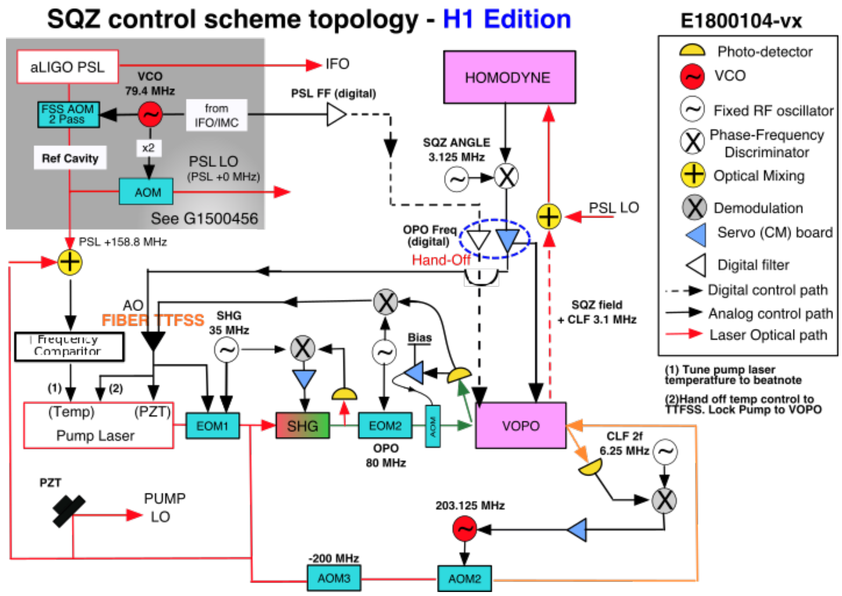

Figure 9: Control scheme with digital feed-forward (and "noise-eater" for pump intensity.)

3 Control Scheme with PSL reference

There were issues with the OPO reference scheme knocking the interferometer out of lock when we did squeezing injection tests 4605645767. This severely limited the number of tests we could do. As we could not see antisqueezing there were clearly a number of further tests required and with time to O3 running out a decision was made to go with the PSL reference scheme as there is more experience with this scheme. The control scheme was changed on Janurary 25 to using the PSL reference cavity as the reference for the squeezer (instead of the VOPO) see 46630, 46651 and Fig. 10. Nutsinee took a squeezed light measurement with this scheme 46706, and associated noise budgets and transfer functions 46724. Note the intensity noise eater on the pump for the VOPO is now operated as a digital servo 46730 as this locking scheme did not leave us with a spare common mode board.

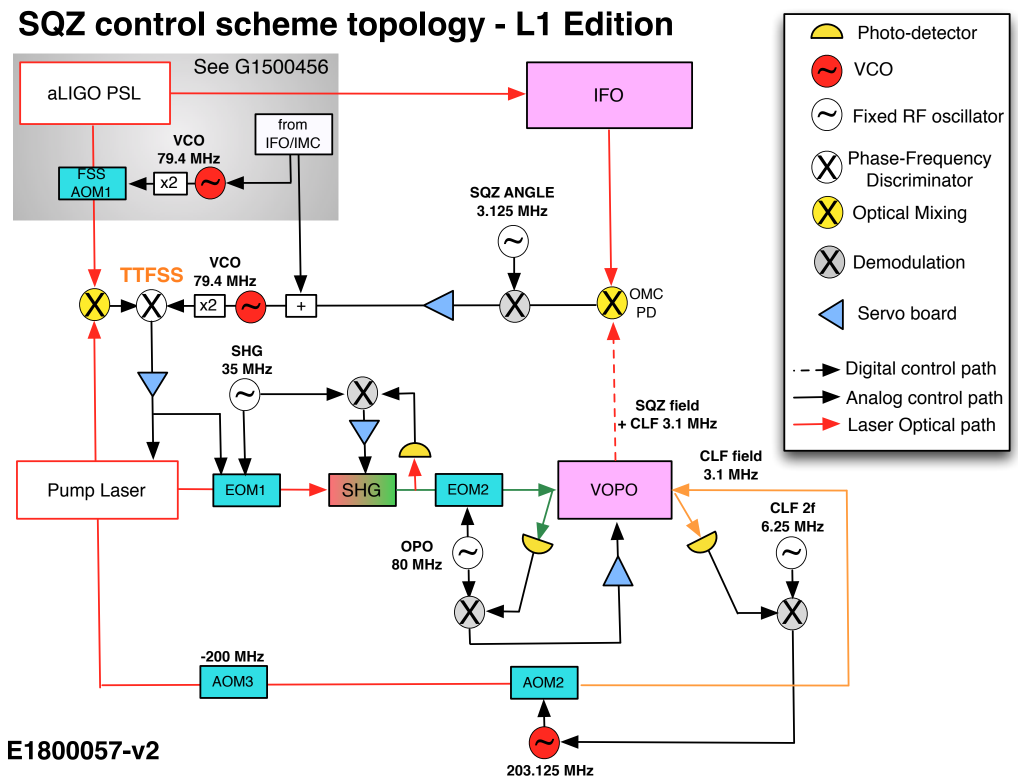

Figure 10: PSL reference Control scheme to be used as a backup for LHO, spare TTFSS with PFD

4 Appendix

Some useful LHO Squeezer Parameters			
Devcice	Callibration	Parameters	alog()
80 MHz EOM	.98 rad/V	532 nm	(41622)
4004 EOM	15 mrad/V	1064 nm	(manual)
SHG Modematch	98.5 %	nominal	(40698)
Mephisto (25 Feb 18)	2.182A, 25.98C, 20.22C	I, Xtal T, Diode T	(40698)
Mephisto (27 Nov 18)	2.122A, 27.63C,	I, Xtal T, Diode T	(45519)
Mephisto (29 Nov 18)	2.116A, 29.57C,	I, Xtal T, Diode T	(45564)
Mephisto (22 Jan 19)	2.016A, 33.67C,	I, Xtal T, Diode T	(46587)
SHG LOCK		.	(40094)
ISCT6 Isolator	T=91%, I -26 dB	532 nm	(40478)
ISCT6 Isolator	T=95%, I=-30.5 dB	1064 nm	(40507)
VOPO PZT	20V/FSR	532 nm	(41581)
VOPO M1, M2	98%, 99.9%	532 nm	(41581)
VOPO M2	4%	1064 nm (CLF)	(45826)
VOPO L Noise (1)			(43401)
VOPO Threshold	18 mW		(43606,43740)
VOPO Intracavity loss	1.06% (power)	532 nm	(43601)
VOPO loss*	$> 0.3\%$	532 nm (Air)	(41581)
VOPO Refl PD (1)	TIG=1550, R=0.3A/W		(44964)
OPORefl Shot noise			(41637,40944)
SQZ CMB's		notch added	(43323)
CLF AOM1	2.68 W	1064 nm	(40698)
CLF AOM2	1.9 W	1064 nm	(40698)
CLF detector + amp		1064 nm	(44633)
Ham 6 Photos			(41868)
Ham 6 Photos			(Cory)

*Imprecision due to HAM6 exposed to air.

References

[1] Lee McCuller Notes on squeezed loop configuration LIGO - T1800065.

[2] LLO CLF measurements quoted before OPO (45767)