LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
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Advanced LIGO Arm Length Stabilisation Design

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1 Introduction

This document describes the design for the Arm Length Stabilisation (ALS) system. In addition the Single Arm Test performed at LHO will be outlined.

The quadruple suspension system (quad) designed for the test masses, provide isolation of the ground motion to the test mass at frequencies above 10 Hz. Displacements at frequencies below and near the quadruple suspension resonance frequencies will not be well attenuated. Complex feedback will damp the suspension resonance modes. Even with the BSC ISI platforms, this results in the test mass displacement of $\sim 10^{-7}$ m/$\sqrt{\text{Hz}}$ below 0.5 Hz. This displacement is too much for the actuators mounted on the quad to acquire lock of the arm cavities in a deterministic manner. To make the lock acquisition more deterministic, the arm cavities are locked independently from the central recycling cavities, using auxiliary lasers. The independent arm locking scheme will provide a means to 'park' the arm cavities away from being resonant with the pre-stabilised laser (PSL). The lock acquisition of the recycling cavities will then not be hindered by the arm cavities going through resonance and breaking the acquisition process. Once the recycling cavities have been locked, the offset on the arm cavities is reduced to bring them into resonance with the PSL.

To achieve the deterministic locking procedure, the residual arm cavity length fluctuations need to be reduced to within the line-width of the cavity, the line-width equivalent displacement is 1.3 nm.

Since document version '-v2' significant change have been discussed within the ISC group. The main change has been to phase lock the green auxiliary laser to the PSL using a heterodyne beatnote measurement in the vertex. A portion of the PSL will be injected into a second harmonic generator (SHG) to generate 532 nm, which will be used to combine with the transmitted light of the arm cavities. This heterodyne signal has a much lower noise floor then the fibre noise cancellation or reference cavity method (equivalent $\ll$1 pm/$\sqrt{\text{Hz}}$). When used to feedback to the ETM quad this would not in-ping on the high frequency saturation of the quad actuators.

2 Requirements

The requirements are described in T0900095, of which the main displacement requirement and result shown in figure 1. Modelling using the Quad model in Simulink, shows sufficient suppression of the residual displacement using feedback to all the Quad stages (Top, Upper-Intermediate, Penultimate and Test mass). See section 6 for more details.

In table 1 various system requirements are repeated.

3 System Overview

The ALS system for a single arm can be divided in to four main systems: 1) test mass coating modifications, 2) in-vacuum transmon table, 3) auxiliary laser table and 4) end-station phase reference. These sections are shown in figure 2, which provides a single arm

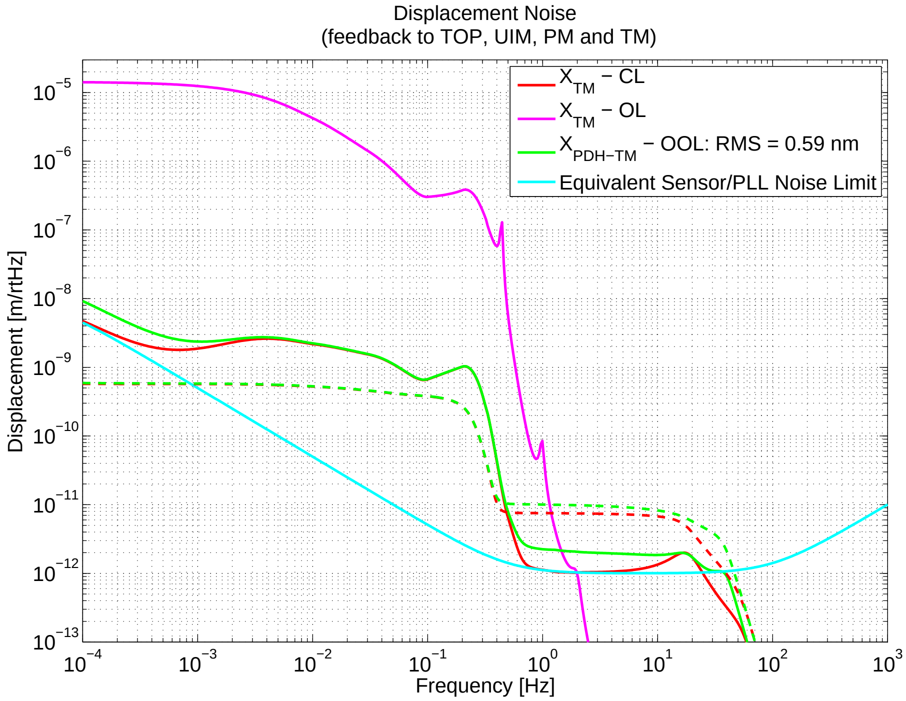

Figure 1: Open-loop and close-loop test mass RMS displacement.

Table 1: ALS system requirements and parameters.

ITM HR@532 nm	$> 99\%$
ETM HR@532 nm	95%
Arm cavity Finesse (@532 nm)	∼100
Sensor equivalent displacement noise	$\leqslant 1$ pm$\sqrt{\text{Hz}}$ (see figure 1)
Sensor Noise Limit	∼70 mHz/$\sqrt{\text{Hz}}$
Phase Noise Limit	∼70 mrad/$\sqrt{\text{Hz}}$ ($1/f$ @1 Hz)

ALS system overview. This section will provide a brief approach and overview of these systems. Although required for the ALS system items 1) test mass coating modifications, 2) in-vacuum transmon table are outside the scope of this document.

3.1 Test Mass Coating Modifications

The high performance coating for 1064 nm on the test masses will be modified to include a deterministic reflectivity at 532 nm. The ITM will have a high reflectivity of $> 99\%$, while the ETM will have a reflectivity of $\sim 95\%$. With these reflectivities, the cavity finesse will be ∼100. This has been included in the test mass coating specifications E0900068-v1 (ETM) and E09xxxxx (ITM).

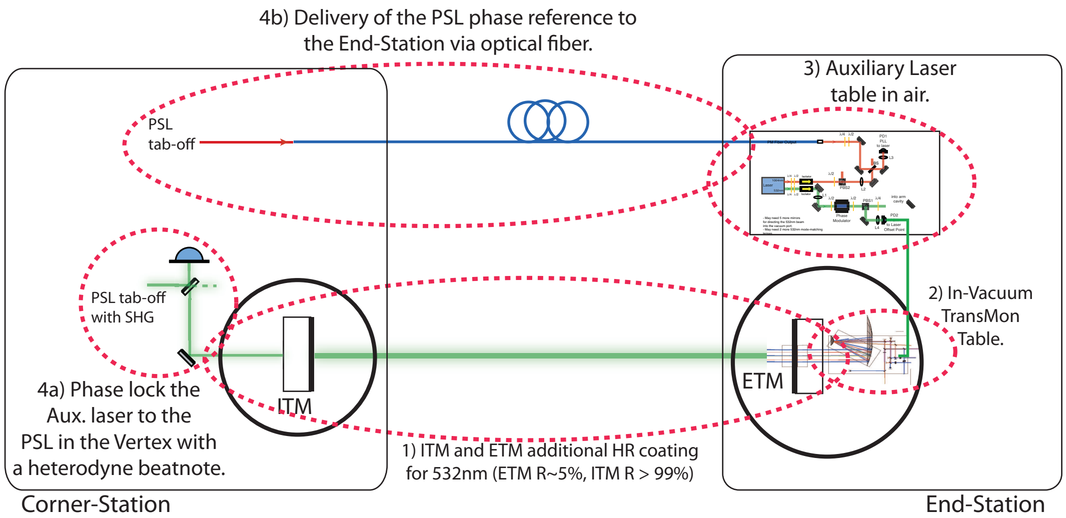

Figure 2: General overview of the Arm Length Stabilisation system.

3.2 In-Vacuum TransMon Table

The Transmon Table is a suspended table behind the ETM quad suspension and holds the ETM Transmission Monitor Telescope. The table is approximately 23” x 40” (600 mm x 1000 mm), and is suspended from the BSC ISI platform.

The ETM telescope is a 16:1 ratio beam reducing telescope, supporting both the 1064 nm and 532 nm beams. Also on the transmon table are QPDs for the transmitted 1064 nm beam. In addition there are DC alignment QPD for the 532 nm ALS beam into the arm cavity, this to aid and monitor the ALS beam injection. There is also a Hartmann beam pick-off, which directs the 532 nm reflection of the wedged AR coating of the ETM through one of the viewports. For more detail on the design and layout see [1, 2, 3].

3.3 Auxiliary Laser Table

The Auxiliary Laser Table is the hart of the ALS and is an 4ft x 8ft optical table located next to the vacuum chamber in the end-station. The auxiliary dual wavelength laser (1064/532 nm) and accompanied injection optics are located on this table. The table will be xx cm away from the chamber and the table surface will be at a height of 30 inch (760 mm). Details of the optical layout and required components will be discussed further in section 4.

3.4 End-Station Phase Reference

The auxiliary laser needs to be phase locked to the PSL in the corner station. This is required to keep the arm cavity resonance stable around its offset point, once the laser is locked to the arm cavity. This is a two step approach, initially the laser is phase locked to a fiber output in the end-station, to set the DC heterodyne frequency at ∼20 MHz. Then once the arm cavity is locked, the heterodyne beatnote in the vertex is measured and its fluctuations fed back to the ETM.

3.4.1 Vertex Heterodyne Beatnote

To phase lock the auxiliary laser with the PSL a heterodyne beatnote measurement in the vertex (on the PSL table) is made. The transmitted beam of the arm cavities is directed to and transmitted by PR2 of the power recycling cavity. The 532 nm beam is then guided to HAM1 and subsequently directed through a vacuum window to the PSL table. A small amount of power (∼1 W) from the PSL is picked off and directed into an single-pass second harmonic generator (SHG), which will provide ∼4 mW of 532 nm beam which is used to combine with the transmitted beams from the arm cavities. The generated heterodyne signal is measured and the fluctuations are fed back to the respected ETM. To distinguish between the two end-stations, each auxiliary laser has a different frequency offset from the PSL (heterodyne frequency).

3.4.2 Fiber Delivery to End-Station

A small amount of power (at 1064 nm) is picked off from the PSL (after the SHG), injected into a optical fiber (already present) and sent to the end-station. The fiber output, in the end-station, is then combined with the 1064 nm output of the auxiliary laser to generate a heterodyne beatnote, at around tens of MHz. This beatnote is then used to monitor the offset frequency and phase lock the auxiliary laser to the PSL at DC. The fiber will introduce additional phase noise at higher frequencies, which will dominate the phase locking stability but are ignored. The phase locked loop will feedback to the laser to keep the auxiliary laser frequency close to its operational heterodyne frequency in the vertex. This is required because during lock acquisition of the 532 nm beam in the arm cavity the vertex heterodyne beatnote is not available (running through cavity resonance) generating large power fluctuations at the arm cavity transmission (from 1 μW to 1 mW).

4 Auxiliary Laser Table

The laser table holds the auxiliary dual wavelength laser (532 nm/1064 nm), the 532 nm injection optics and the 1064 nm fiber optics. The 1064 nm beam is used to phase lock the laser to the phase reference delivered by the optical fiber, while the 532 nm beam is used to stabilise the arm cavity, using the standard PDH technique.

As illustrated in figure 3, the 1064 nm output has the standard beam preparation (wave plates and faraday isolator). The output has ∼1 W of optical power, so a half-wave plate and polarising beam splitter are installed to provide some control of the optical power. The unused power is directed onto a high power beam dump. The power control is adjustable so that approximately 1 mW of power is provided for the heterodyne measurement with the fiber output. The heterodyne signal is used to lock the laser frequency to the fiber output. Prior the heterodyne measurement, the beam goes through a double pass AOM to provide a means to lock the effective laser frequency to the arm cavity resonance. The PDH error signal is fed back to the VCO driving the AOM to lock the laser to the arm cavity resonance.

The 532 nm beam is also prepared with wave plates and a faraday isolator, with the addition of the phase modulator providing the modulation sidebands (∼24.5 MHz) for the PDH

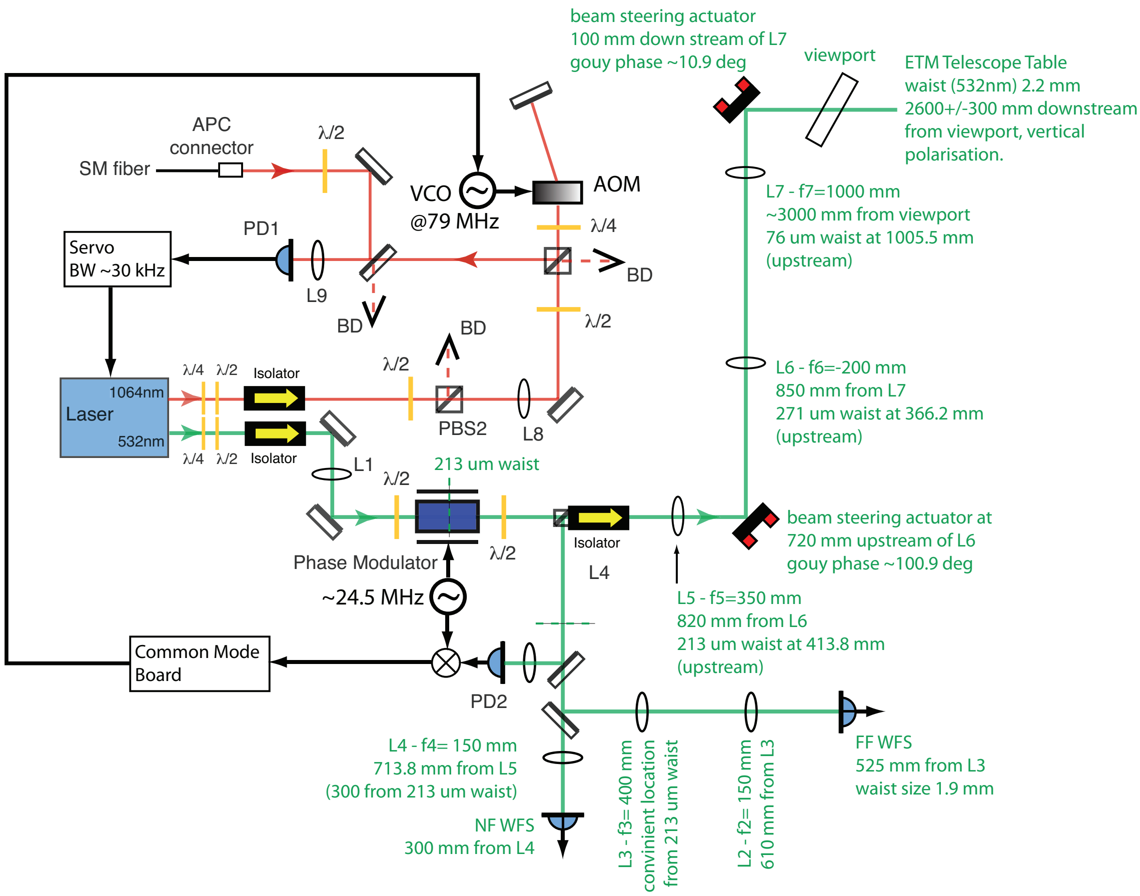

Figure 3: Layout of the end-station laser table. The laser is stabilised to the fiber output using the 1064 nm beam, and feedback is to the laser actuators (PZT and temperature). The 532 nm laser output is mode-matched and locked to the arm cavity, by feeding back to the offset point of the 1064 nm feedback servo. The high gain LSC detectors of the ETM transmitted beam used in the full IFO acquisition process are not shown.

readout. Through a mode-matching (and gouy phase telescope), the beam is injected into the arm cavity, via the ETM Transmon table. The PDH readout, via a second faraday isolator, is used to initially feedback to the laser frequency. The power incident on the ETM will be ∼10 mW, with an approximate total attenuation of 50% (due to 2x faraday isolators T∼80%, 1x Hartmann pickoff T∼90%, 1x Transmon pickoff T∼95%, 3x Transmon dichroics T∼97%), the laser will need to have an 532 nm optical power output of at least ∼20 mW.

There are three laser beams coming in/out of the vacuum chamber and onto the optical table at the end-station, see figure 10. The main 1064 nm transmitted beam through the arm cavity, which will be directed onto a high gain detector for lock acquisition. Then there is the 532 nm beam injected into the arm cavity, used for the arm length stabilisation. Another 532 nm beam, the reflection from the wedged AR surface of the ETM, is directed onto the optics table and sent into a Hartmann sensor.

The beams coming through the viewport will have an approximate angle of 20° downwards from the suspended Transmon Table. The beams will travel across the table and intercepted by a 300 mm periscope with 2" optics, to be 'levelled' at a 4" beam height above the table surface. The periscope height can be adjusted to accommodate the variations of the beam height out of the viewport.

The optical table will be enclosed with an acoustic chamber to reduce acoustic coupling into the PDH sensing.

4.1 Frequency Range

Initially the 532 nm laser output is locked to the arm cavity length. To be able to follow the arm cavity length fluctuations, the 532 nm laser needs to have a sufficient frequency dynamic range.

The dynamic range is dominated by the equivalent displacement of the test masses at low frequency, the system needs to be able to cover a 1 μm peak change in arm length. This converts to a frequency dynamic range of 140 kHz peak for the 532 nm beam.

This frequency range can easily be covered by feedback to the the VCO driving the AOM.

4.2 Laser and Mode-Matching

The main mode-matching telescope for the 532 nm beam into the arm cavity is based on a galileo telescope (together with the in-vacuum ETM TransMon). The telescope consist of a positive 1000 mm lens (L7 in figure 3) and a negative 200 mm lens (L6 in figure 3), with a set separation. The separation is optimised such that there is a gentle gouy phase slope which crossing through 90 degrees at the output. Two X/Y PZT actuator mirrors for beam steering are located on either side of the telescope, such that the differential gouy phase between the two locations is 90°.

According to [1], the 532 nm waist out of the TransMon Telescope is 2.2 mm and 2.6 ± 0.3 m from the viewport, then there is another $\sim$3 m from the viewport to the first steering mirror on the optical table (including a 10" periscope).

Figure 3 shows the mode-matching done from the phase modulator, assuming that the laser is appropriate mode-matched into the 213 μm waist. Also in the figure are both the near-field (NF) and the far-field (FF) wavefront sensor (WFS) telescopes shown. These are designed to provide 90 degrees gouy phase sensing between the near field and the far field WFS, to obtain orthogonal sensing between the beam tilt and offset. These signals will be used to feedback to the PZT actuated steering mirrors.

4.3 Beam Steering

The initial beam steering into the arm cavity will be done manual. For active wavefront sensing and feedback, two PZT actuated mirrors will be used, as shown in figure 10 (currently Nano-MTA2 from Mad City Labs are being looked at). Both the actuators are located on either side of the mode-matching telescope (and hence 90 degrees gouy phase apart), to provide orthogonal feedback to tilt and offset.

Table 2: ALS RF modulation frequencies.

IFO	X-arm	Y-arm
H1	24.407079 MHz	24.482125 MHz
L1	24.407079 MHz	24.482125 MHz
H2	24.440707 MHz	24.515730 MHz

4.4 High Gain QPD

Also on the table is a high gain QPD for the 1064 nm transmitted arm cavity power used for full IFO lock acquisition. A separate beam from the TransMon Table is directed through a viewport on to the optics table.

4.5 Hartmann Sensing

In addition to the ALS optics, the ETM Hartmann sensing optics and sensors are placed on the table. This mainly consist of optics to image the ETM onto a CCD camera. There are two beams, one is a dedicated beam which comes from the wedged AR coated surface of the ETM and is directed from the TransMon Table through a viewport on to the table. While the second is a reflection from the HR coated surface, and is a pick off in the main ALS beam. More details on the Hartmann beams and sensors can be found in LIGO-Tyyxxxxx-vz [].

4.6 RF Modulation and RF Electronics

The RF modulation frequencies for the locking of the arm cavities will be chosen so initial LIGO ISC detectors can be used. In doing so, the modulation frequency will be around 24.5 MHz. Table 2 list the modulation frequencies for each arm of the three interferometers.

Table 3: ALS RF building blocks (see figure 4).

Chassis	DCC Number	Qty/IFO
RF Oscillator Source (with T0900280-v1)	D080702-A	6
Distribution Amplifier 1U	D1000124-A	2
TTSFF	D0901897-A	2
TTSFF Interface	D0902048-C	2
4-Ch I&Q Demodulator	T1000041	4
2-Ch I&Q Demodulator	T1000181	4
LSC Photodetector (532 nm)	Dyyxxxxx	2
LSC Photodetector Interface	D0901833-B	2(?)
WFS (532 nm)	Dyyxxxxx	4
WFS Interface	Dyyxxxxx	4
Broadband Detectors	xxxxx	2

Also, the wavefront sensors will use the same RF modulation frequency, so it is perceived that the initial LIGO wavefront sensors will be used. A diagram of the RF electronics is shown in figure 4, as well as a list of RF building block in Table 3.

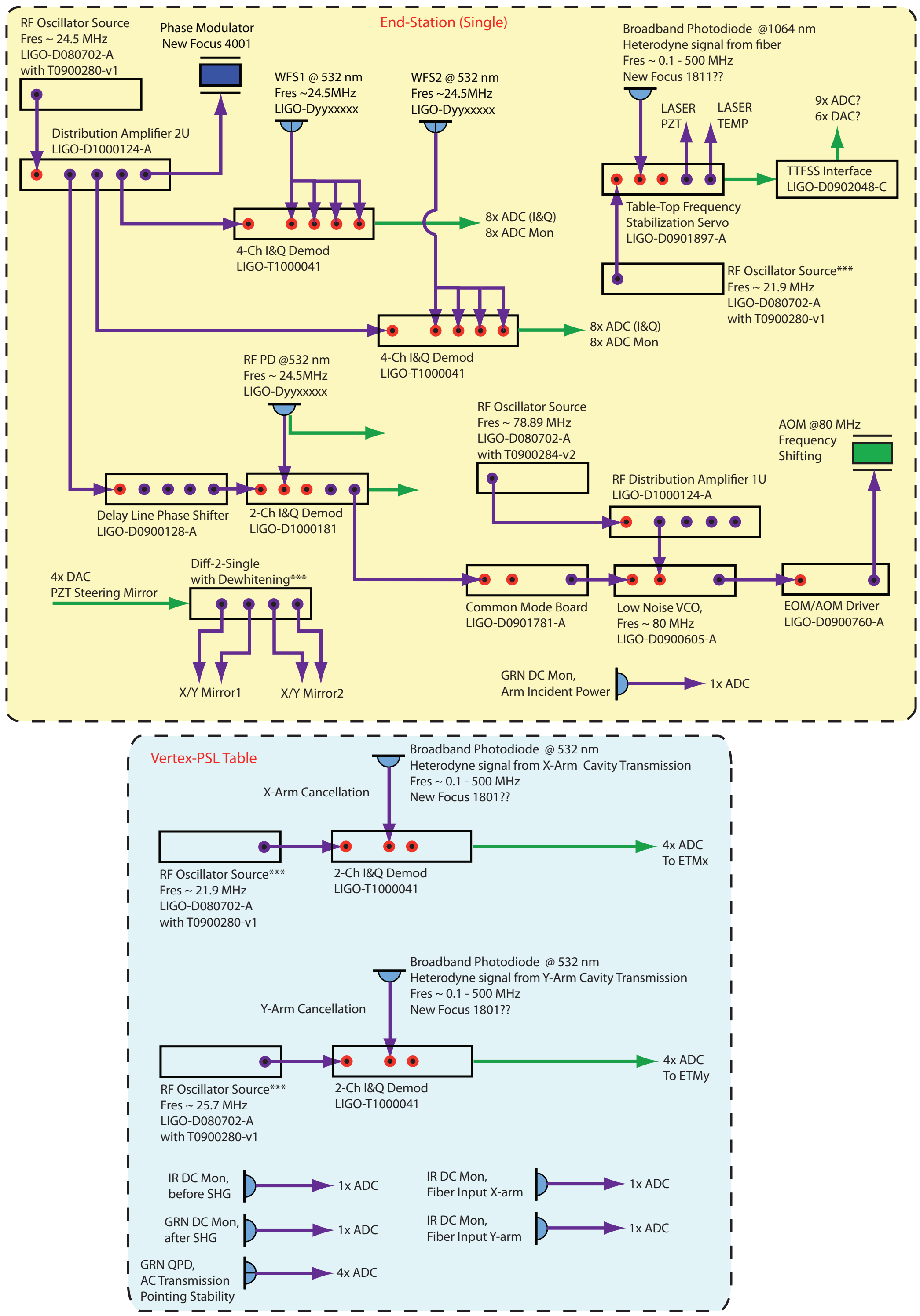

Figure 4: Diagram of the RF building blocks. Top diagram is the layout for a single end-station, while the bottom diagram shows the layout in the vertex for both arms.

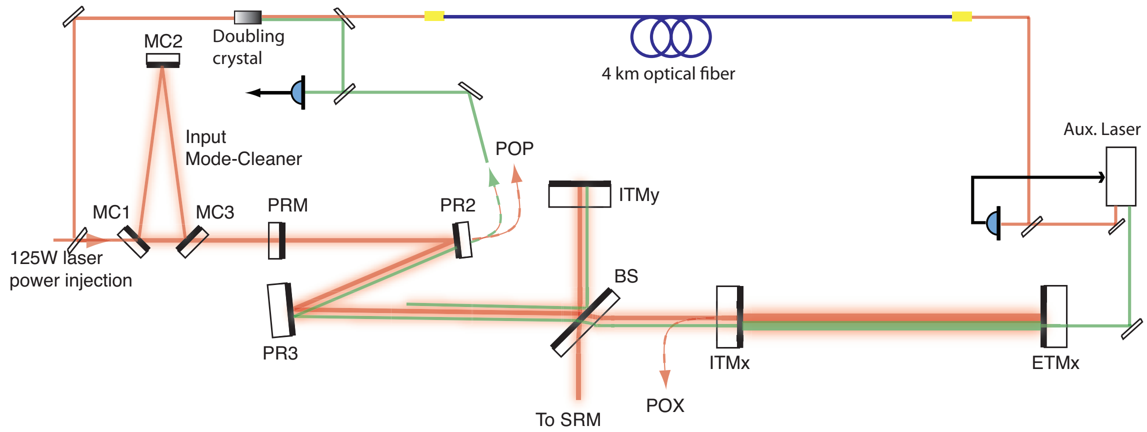

Figure 5: Schematic overview of the phase reference for the auxiliary laser in the end-stations.

5 End-Station Phase Reference

To provide a smooth transition between the independent arm cavity locking using ALS and the full IFO lock acquisition, the auxiliary laser and the PSL need to be phase locked. The required frequency stability is <70 mHz/$\sqrt{\text{Hz}}$ up to 100 Hz (see T0900095).

To do this, there is a two level control to the laser in the end-station. First the laser is phase locked to the PSL, by delivering a little bit of power from the PSL via an optical fiber to the end-station. The fiber output (at 1064 nm) will be combined with the 1064 nm output of the auxiliary laser to obtain a heterodyne beatnote at ∼20 MHz. The laser will be locked to the frequency fluctuations of the heterodyne beatnote, by feeding back to the temperature and PZT of the laser via the Table-Top Frequency Sabilization Servo (D0901897-A). Once the auxiliary laser is locked to the PSL, the laser is locked to the arm cavity using the 532 nm beam. The PDH error signal is directed to a Common Mode Board to a low noise VCO which controls the AOM frequency. Frequency adjustments to the AOM are directed to the laser which in turn locks the laser frequency to the arm cavity resonance.

On resonance, the arm cavity transmitted beam will be directed (through the beamsplitter and transmitted through PR2, see figure 5) to the PSL table. Here a 1 W pick-off from the main laser is directed onto an SHG, which in turn provides a 532 nm beam. This beam is used as a local oscillator and combined with the arm cavity transmitted light, creating another heterodyne beatnote, see figure 6. The phase fluctuations from this heterodyne signal are digitised and send to the ETM to suppress the arm length fluctuations and stabilising the arm cavity length.

The two 532 nm beams transmitted through the arm cavities on the PSL table are spatially very close together, ∼mm. To obtain either arm cavity heterodyne signal on a photodiode, the beam is split so the local oscillator can be optimally aligned to either spatial transmitted beam.

Because the laser in the end-station has already been tuned to a 20 MHz (±79 MHz AOM frequency shift) frequency offset with the PSL, the heterodyne demodulation in the vertex is done at the resultant offset frequency (100 MHz and 60 MHz) as in the end-station.

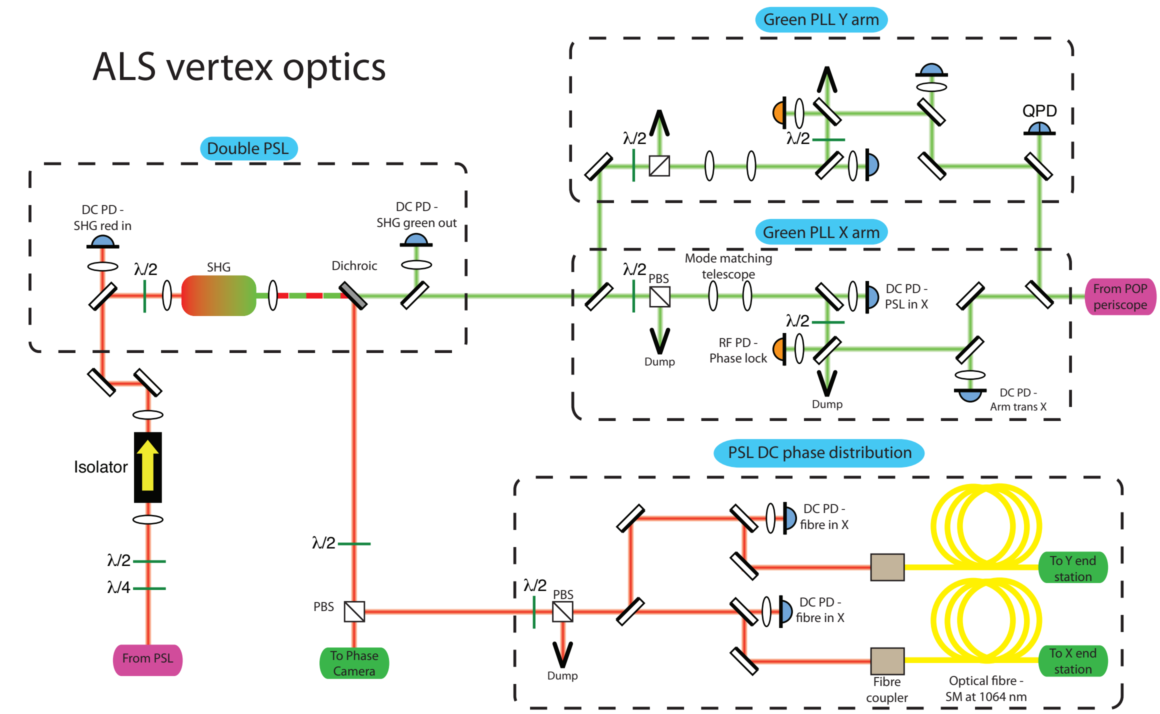

Figure 6: Layout of the heterodyne beatnote measurement in the vertex, as well as the PSL fiber injection.

5.1 Vertex Heterodyne Beatnote Stability

Figure 7 shows the equivalent phase noise limit on the local oscillator for the demodulation in the vertex. This is obtained by converting the 'Equivalent Sensor/PLL Noise Limit' displacement in figure 1 to phase noise, by using

$$\phi(f) = \frac{\delta x(f)\,\nu}{L_{arm}\,f} \qquad [\mathrm{rad}/\sqrt{\mathrm{Hz}}], \tag{1}$$

in which $\delta x(f)$ is the displacement limit from figure 1, ν laser frequency in Hz (532 nm light), L_{arm} arm cavity length in m, and f the Fourier frequency in Hz. The phase noise around the RF local oscillator is given by [],

$$S(f) = 20\log\left(\frac{\phi^2(f)}{2}\right) \qquad [\mathrm{dBc/Hz}]. \tag{2}$$

This is shown in figure 7, for the equivalent displacement noise limit along with the phase noise of the Wenzel 500-14927 (21-26 MHz-AT Streamline Crystal Oscillator) OCXO stable oscillator. The oscillator noise is a factor of ~3 below the modelled noise limit.

5.2 Fiber Delivery of Phase Reference

A pick off beam from the PSL is sent to the end station using a single mode optical fiber, as shown in figure 6. The fiber is know to be single mode for 1310/1550 nm, and may be

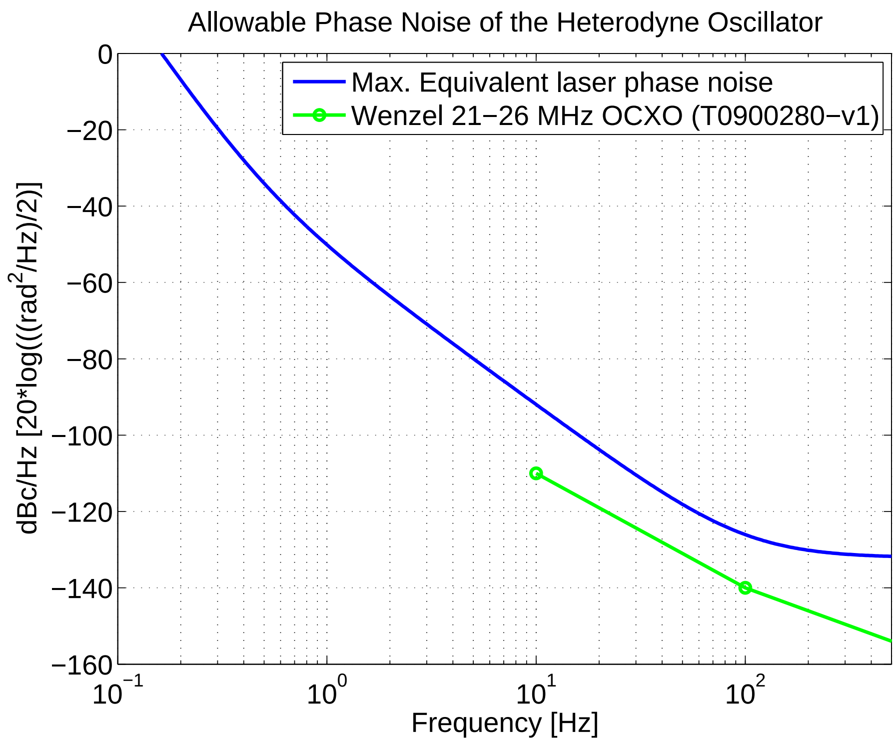

Figure 7: Allowable phase noise on the RF local oscillator in solid blue, while the green line with circles is the oscillator phase noise of the Wenzel 500-14927 OCXO oscillator used in the RF Oscillator Source (see figure 4).

single mode for 1064 nm. The output of this fiber in the end-station is then used to create a heterodyne beatnote with the 1064 nm beam from the auxiliary laser. There is no fiber phase noise cancellation system required, as the feedback from the vertex heterodyne signal is used to feedback to the ETMs.

5.3 PSL Layout modifications

Figure 8 shows the layout on the PSL table where the ALS beam is tapped off, at the beam splitter just after the PMC. Approximately 1 Watt of power is required in this beam, which is directed to an SHG to provide ∼4 mW of 532 nm light. This light is split up in two equal parts and used as the local oscillator for the two heterodyne beatnotes for either transmitted arm cavity signal. The transmitted IR light through the SHG crystal is directed into the two fibers which go towards the end-station. There is also a small amount of 1064 nm light required for the phase cameras.

6 Lock Acquisition

Initially, the auxiliary laser will be phase locked to the PSL using the beam delivered by the optical fiber. This feedback loop will have an approximate locking bandwidth of ∼35 kHz.

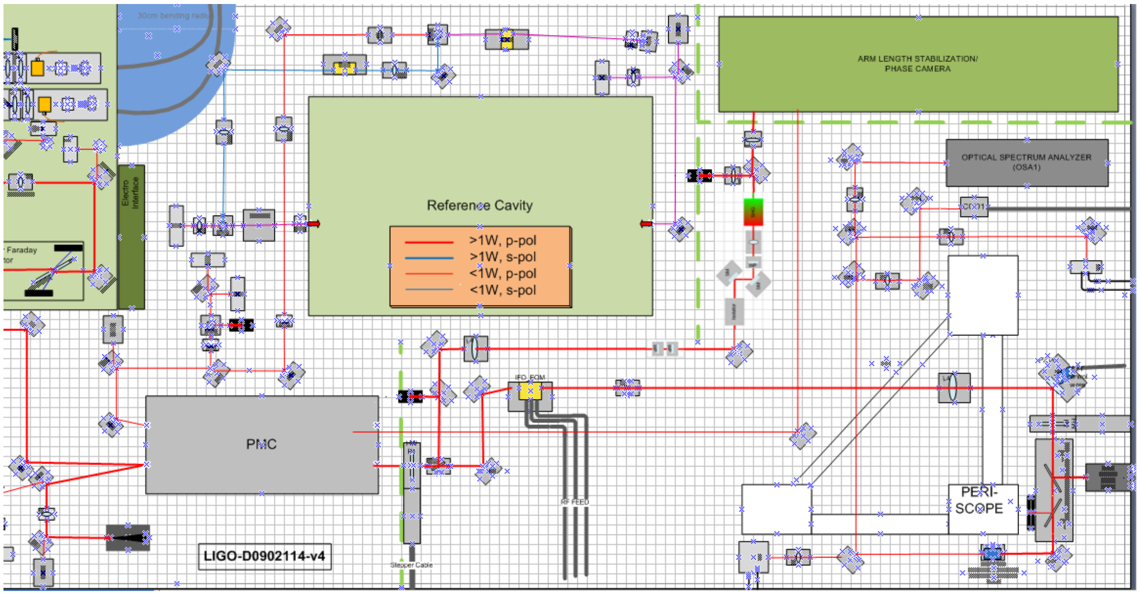

Figure 8: PSL layout with the pick off for the ALS beam (just after the PMC, bottom left). The pick off will be 1 Watt in power and is directed to the SHG to generate ∼4 mW of 532 nm. (LIGO-D0902114-v4)

The error signal from the demodulated PDH sidebands is fed back to the laser frequency to lock the laser to the arm length fluctuations. The required frequency dynamic range is ∼ 20 kHz (see T0900095), which the laser can quite easily follow but may be limited by the fiber noise cancellation servo loop. Once the laser is locked to the arm cavity length fluctuations, the PDH error signal is in its linear range and can be used to feedback to the ETM quad suspension. Feedback is provided to the penultimate mass (PM) and the test mass (TM). This has been modeled in Simulink with the results shown in figure 1.

The arm length stabilisation performance is limited by the sensor noise and the maximum feedback current and force of the quad actuators. The sensor noise is limited by the fiber phase noise cancellation performance. The sensor limit is set to the equivalent displacement of 10^{-12} m/$\sqrt{\text{Hz}}$, while the maximum PM OSEM current is set to 50 mA RMS and the ESD force to 20 μN RMS. These modeling results are shown in figure 1 with the actuator feedback signals in figure 9.

6.1 Locking Strategies

It has been noted that with the ALS system in place, there are various combination of signal recovery. Not only the individual arm length changes can be obtained from the heterodyne signals, as well as the differential arm length. This in turn can be used to start to reduce the common mode in the overall IFO lock acquisition.

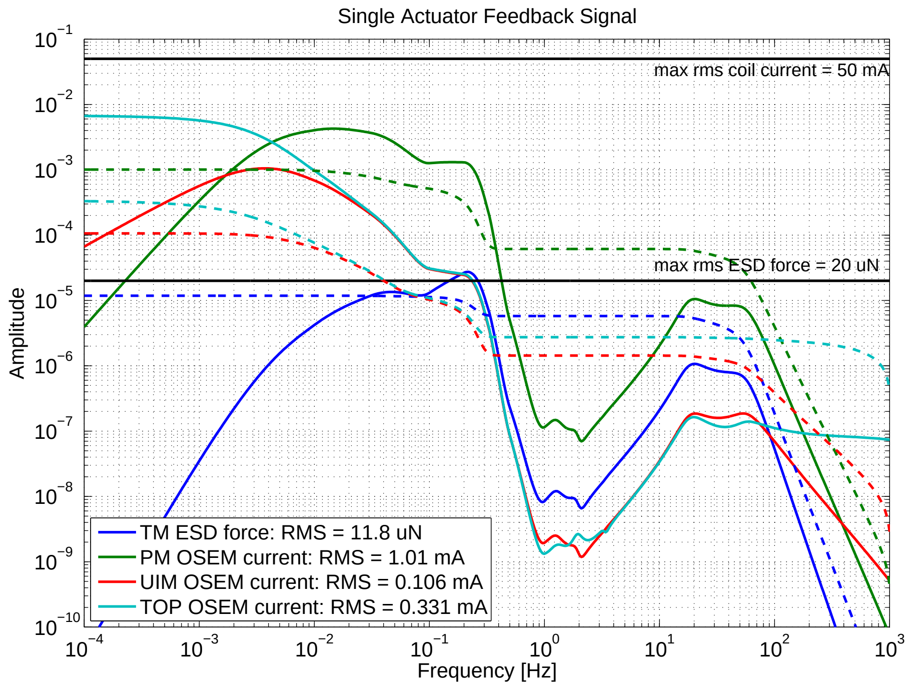

Figure 9: Feedback to the penultimate mass and test mass. The solid lines represents the amplitude spectral density [$A/\sqrt{Hz}$ or $N/\sqrt{Hz}$], and dotted lines represent the rms values [Ampere or Newton].

7 Single Arm Test at LHO

The Single Arm Test is the installation and commissioning of a single Advanced LIGO arm cavity, and testing the combined quadruple suspension and ISI system. This will investigate and implement the integrated control and feedback of the BCS ISI and the quad suspension.

The single arm test is possible because with the ALS system there is an independent laser in the end-station and so can be seen as a pre-cursor to the full ALS. The free running laser frequency will be the dominant noise contribution when the arm cavity is locked on resonance. To reduce this, the laser will be locked to a reference cavity. This is achieved using a Table-Top Frequency Stabilization Servo (TTFSS).

To lock the laser frequency to the arm cavity, an double pass AOM is wrapped around the reference cavity locking. By adjusting the AOM frequency the laser frequency is adjusted to be locked to the arm cavity, while still being locked to the reference cavity.

Figure 10 shows the opto-mechanical layout (to scale) of the in air table.

7.1 Main Hardware List

The main hardware list for the ALS/Single Arm test is given in Table 4.

Table 4: ALS and Singel Arm Test (SAT) hardware (Baseline - 1 IFO)

Item	Part	Vendor	Location	Qty	Spare	Total Qty	SAT Qty
Prometheus Laser 1W @1064 nm & 100mW @532nm		InnoLight GmbH	End	2	1	3	1
Faraday Isolator at 1064nm	IO-3-1064-HP	OFR/Thorlabs	Vertex/End	3	0	3	1
PBS@1064nm	PBS-1064-050	CVI	End	2	2	4	3
Beam splitter @1064nm (50/50 P-pol)	BS1-1064-50-1012-45-S	CVI	End	10	1	11	2
Steering Mirrors @1064nm - 1-inch	Y1-1025-45-UNP	CVI	Vertex/end	24	4	28	9
Steering Mirrors @1064nm - 2-inch	Y1-2037-45-UNP	CVI	End/Vertex	2	2	4	1
Lenses @1064nm	PLCX-25.4-178.5-C-1064 (for example)	CVI	Vertex/end	20	2	22	8
Halve Waveplate @1064nm (zero order)	QWPO-1064-05-2-R10	CVI	Vertex/end	8	2	10	5
Quarter Waveplate @1064nm (zero order)	QWPO-1064-05-4-R10	CVI	Vertex/end	4	2	6	2
Beam Dumps @1064		LIGO	End	10	5	15	5
AOM - 40 MHz @1064nm	AOM-402AF4	IntraAction Corp.	End	0	0	0	1
AOM - 80 MHz @1064nm	AOM-	IntraAction Corp.	End	0	0	0	1
Phase Modulator - 21.5 MHz @1064nm	4002	New Focus	End	0	0	0	1
Reference Cavity + Vacuum enclosure		LIGO	End	0	0	0	1
Optical Table 4ft x 8ft + enclosure + legs		Newport	End	1	0	1	1
Faraday Isolator at 532nm (5mm aperture)	I-56T-5M	ISOWAVE	End	4	0	4	2
PBS @532nm	PBS-532-050	CVI	End	6	1	7	2
Beam plitters @532nm (50/50)	BS1-532-50-1025-45-S	CVI	End/Vertex	6	2	8	3
Steering Mirrors @532nm - 1-inch	Y2-1025-45-S	CVI	End	30	4	34	6
Steering Mirrors @532nm - 2-inch	Y2-2037-45-S	CVI	End	10	0	10	5
"Lenses @532nm (1"" + 2"")"	PLCX-25.4-178.5-C-532 (for example)	CVI	End	31	4	35	10
Halve Waveplate @532nm (zero order)	QWPO-532-05-2-R10	CVI	End	14	2	16	5
Quarter Waveplate @532nm (zero order)	QWPO-532-05-4-R10	CVI	End	2	2	4	1
Phase Modulator @532nm (24 MHZ)	4001	New Focus	End	2	0	2	1
Fast Steering Mirror + Driver	Nano-MTA2	Mad City Labs	End	4	0	4	2
"Non-linear crystal (sinlge pass	LiNb/PPKTP?)"		Vertex	1	2	3	
Crystal Holder with oven/peltier element			Vertex	1	0	1	
Temp Controller			Vertex	1	0	1	
Dichroic HR@1064nm	AR@532nm"		Vertex	1	2	3	
Mount for Faraday Isolators	Block for ISOWAVE FI	ANU	End	7	0	7	3
Mount for PM	9071	New Focus	End	2	0	2	1
Mount for AOM	9071	New Focus	End/Vertex	0	0	0	2
BS/Mirror Mounts - 1-inch	SN100-F3K	Newport	Vertex/End	16	3	19	5
Mirror Mounts - 1-inch	SS100-F2K	Newport	Vertex/End	54	8	62	15
Mirror Mounts - 2-inch	SL51BM	Newport	End	8	2	10	5
Waveplate mount + 2" post	RSP1 + TR2	Thorlabs	Vertex/end	28	8	36	13
Lens Mounts - 1-inch + 2" post	LMR1 + TR2	Thorlabs	Vertex/End	51	6	57	18
PBS Mounts		Newport		8	3	11	5
Post/base for 1" mirror mount (4" beam height)	D0901749-v1-C& 0.75-inch diameter post	LIGO/ANU	Vertex/End	70	11	81	20
Post/base for 2" mirror mount	D0901749-v1 -C& 0.75-inch diameter post	LIGO/ANU	Vertex/End	10	0	10	5
Base PBS mount (variable heigth)	Q-TMS-2	Newport	End	8	3	11	5
Post PBS mount & 1-inch diameter, 2" length	PS-2E	Newport	End	8	3	11	5
Post/base for Waveplate Lens + Mounts (4")	PH2	Thorlabs	Vertex/End	79	14	93	31
Base - mounting plate	BA2	Thorlabs	Vertex/End	159	25	184	56
Clamp L-shape	CL5	Thorlabs	Vertex/End	318	50	368	112
Grub Screw	#8-32 x xx"			80	11	91	25
SHCS 1/4-20 x 0.5"				80	20	100	10
SHCS 1/4-20 x 3/8"				79	20	99	10

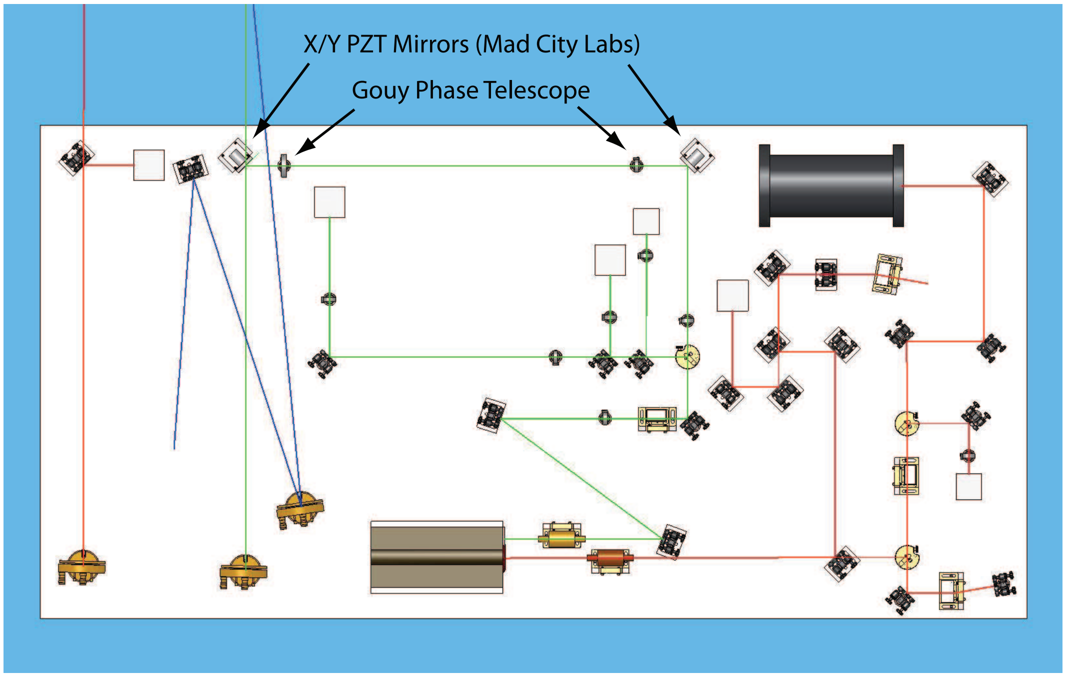

Figure 10: Drawing of the In-Air optical table.

7.2 RF Electronic Building Blocks

Figure 11 shows the wiring diagram of the RF building blocks required for the single arm test. There are two main control loops, the first one it the laser frequency stabilization control, shown in the middle 'blue' box in the figure. A Table-Top Frequency Stabilization Servo is used to lock the laser frequency to the reference cavity, which is a standard LIGO style reference cavity. The servo feeds back to the laser temperature and PZT to keep the laser locked ot the resonance of the reference cavity.

To lock the laser to the arm cavity, a double-pass AOM is wrapped around the laser frequency locking to the reference cavity. The AOM shifts the laser frequency prior it is injected into the reference cavity. When the AOM frequency is adjusted, the laser frequency is adjusted accordingly by the feedback servo to keep the laser locked to the reference cavity. This provides a means to lock the laser frequency to the arm cavity, while suppress the laser frequency noise contributions.

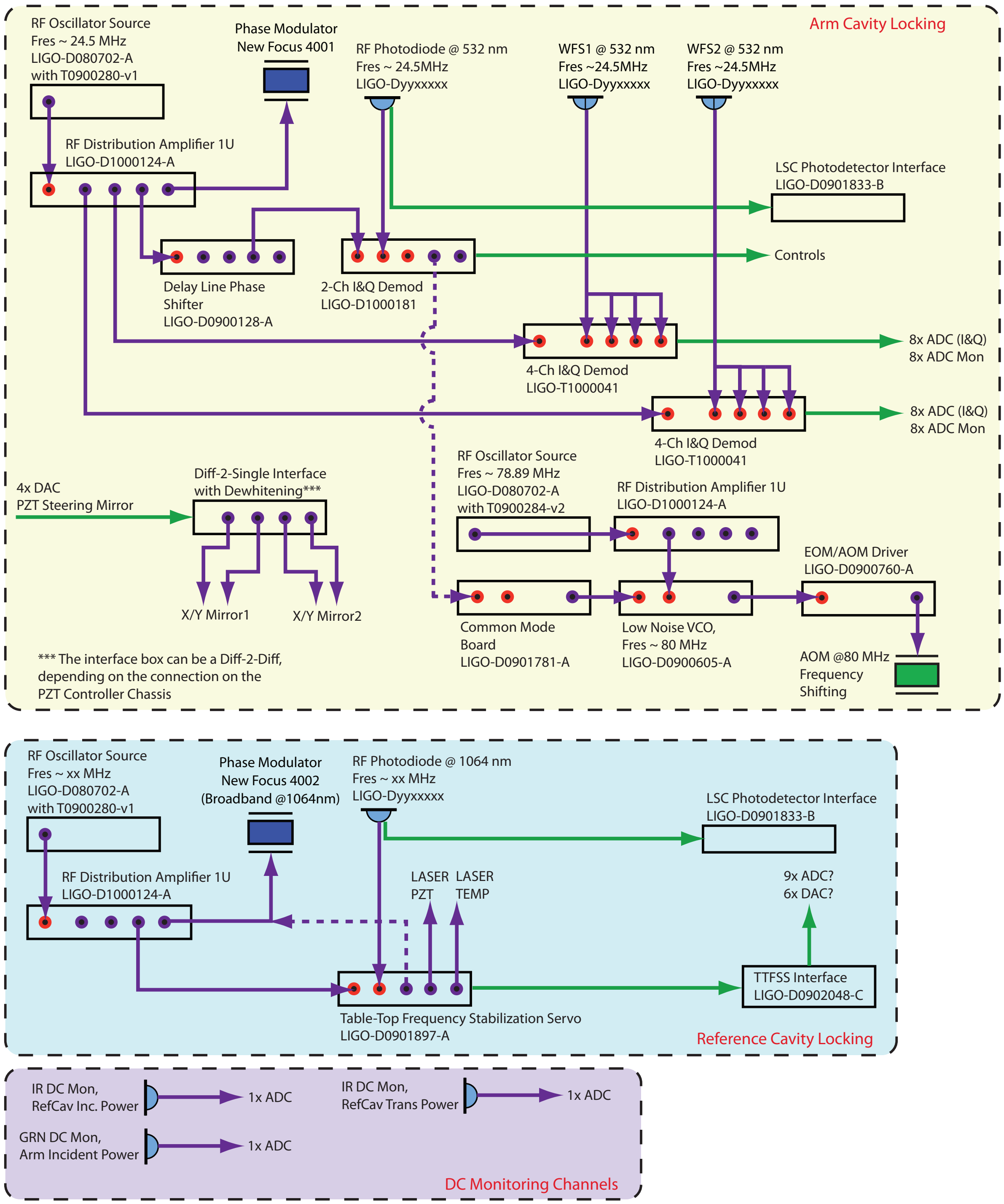

Figure 11: Diagram of the RF building blocks. Top diagram shows the RF electronics for locking the laser to the arm cavity, while the middle diagram shows the layout for locking the laser to the reference cavity, the bottom diagram shows the DC photodiode.

Table 5: Single Arm Test RF building blocks (see figure 11).

Chassis	DCC Number	Qty	Reused in ALS
RF Oscillator Source (with T0900280-v1)	D080702-A	2	yes (need 18)
RF Oscillator Source (with T0900284-v1)	D080702-A	1	no
Distribution Amplifier 1U	D1000124-A	3	yes (need 6)
TTSFF	D0901897-A	1	yes (need 6)
TTSFF Interface	D0902048-C	1	yes (need 6)
4-Ch I&Q Demodulator	T1000041	2	yes (need 12)
2-Ch I&Q Demodulator	T1000181	1	yes (need 12)
Delay Line Phase Shifter	D0900128-A	1	no
Common Mode Board	D0901781-A	1	no
Low Noise VCO (∼80 MHz)	D0900605-A	1	no
EOM/AOM Driver	D0900760-A	1	no
LSC Photodetector (532 nm)	Dyyxxxxx	2	yes (need 6)
LSC Photodetector (1064 nm)	xxxxx	2	no
LSC Photodetector Interface	D0901833-B	4(?)	(need 6)
WFS (532 nm)	Dyyxxxxx	4	yes (need 12)
WFS Interface	Dyyxxxxx	4	yes (need 12)

A Version History

A.1 -v1

Initial release

A.2 -v2

- Started appendix A 'Version History'.
- Modified section 4.1 to reflect what is mentioned in the ALS Requirements Document (T0900095-v2).
- Updated figures 1,**??**,9 with the latest fiber phase noise correction measurements.
- Updated figure 3, include the mode matching telescope for the 532 nm beam and wavefront sensors.

A.3 -v3

- Modified the introduction including the start of the discussion of using the green heterodyne beatnote signal in the vertex to phase lock the auxiliary laser to the PSL.
- Made small changes to the Approach section.
- Removed section 6 In-Vacuum-Trans-Mon-Table.

- Modified section 3.2 'In-Vacuum Transmon-Table'.
- Updated 'System Overview'.
- Removed fiber phase noise cancellation implementation and results.
- Added the Single Arm Test.
- Included the RF building blocks.

B CDS Channels

In the table below, from Excel spreadsheet *ALS_CDS_ADC_DAC.xls*, the channel account for the ADC and DACs.

References

[1] S. J. WaldmanWaldman. The Advanced LIGO ETM transmission monitor. *LIGO-T0900385-v6*, 2010.

[2] P. Fritschel and S. Waldman. Requirements and Interfaces for the ETM Transmission Monitor Suspension and Telescope. *LIGO-T0900265-v1*, 2009.

[3] S. Waldman and M. Smith. Advanced LIGO Transmon Zemax. *LIGO-D0900446-v11*, 2009.

ALS_CDS_ADC_DAC_Channels.xls

ADC/DAC Channels for the Arm Length Stabilisation System (incl. the fiber noise cancellation scheme)

Total ADC Cards (Corner and 2x End Stations) 3

Total DAC Cards (Corner and 2x End Stations) 3

ADC Channels - End Station

Item	Ch. Per item	Item Qty	Total
Tip-Tilt Actuator	**4**	**2**	**8**
Sensors	2		
Act. Mon.	2		
WFS	**8**	**2**	**16**
DC power	4		
error signal	4		
PD (green)	**1**	**2**	**2**
DC power	1		
PDH Error (green)	**1**	**1**	**1**
error signal	1		
PD (IR)	**1**	**2**	**2**
DC power	1		
PDH Error (IR)	**1**	**1**	**1**
error signal	1		
Fiber Noise PD	**1**	**2**	**2**
DC power	1		

Total ADC Channels 32
Total ADC Cards (32 ch) 1

DAC Channels - End Station

Item	Ch. Per item	Item Qty	Total
Tip-Tilt Actuator	**2**	**2**	**4**
Actuators	2		
Laser	**3**	**2**	**6**
PZT	1		
Temp	1		
Temp Offset	1		

Total DAC Channels 10
Total DAC Cards (15 ch) 1

ADC Channels - Corner Station

Item	Ch. Per item	Item Qty	Total
Fiber Noise PD	**1**	**4**	**4**
DC power	1		
Fiber Noise Error	**1**	**2**	**2**
error signal	1		

Total ADC Channels 6
Total ADC Cards (32 ch) 1

DAC Channels - Corner Station

Item	Ch. Per item	Item Qty	Total
Fiber Noise PD	**1**	**2**	**2**
VCO	1		
Fiber Noise Pol. Contro	**1**	**2**	**2**
Pol. Rotator	1		

Total DAC Channels 4
Total DAC Cards (15 ch) 1

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