Length Sensing and Control Subsystem Preliminary Design Review

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LSC Requirements: Significant Changes & Updates

- Updated parameters & dependencies (mostly COC)
- Length & Frequency Deviations
  - Recast residual length deviations into basis of true readout degrees of freedom (previously used “idealized” $L_{+/-}$, $l_{+/-}$)
  - Tightened up DM (was L_-) and dm (was l_-), relieving laser AM (PSL) and RF modulation (LSC) requirements
  - Frequency noise; basis revised (COC specs, loss vs. trans. imbalance)
- Sensing & Control Noise
  - Allocated “10%” contributions in accord with DSR guidelines (fewer)
  - Aux. DOF contributions included; referred to SRD (not their own shot noise)
  - New requirement added on PD backscattering

DRR Action Items

REQUIREMENTS

1. Consider expressing RMS deviation requirements in a different basis which is more natural for the servo problem: i.e., instead of L and l separately, specify in terms of a linear combination of L and l corresponding to the sensed coordinates. *@ PDR, done.*
2. Express requirements when appropriate by a continuous curve (instead of several points); a specific example is laser frequency noise. Analytical expressions are helpful. *SYS, done*
3. GW photodetector noise should be allowed to contribute up to 10% of the SRD shot noise, but noise for other photodiodes are taken care of by the requirements in Table 1. Remove 3.2.1.2.3 and 3.2.1.2.7 to be consistent with this approach. *SYS, done*
4. The GW sensitivity calibration requirements should explicitly address absolute and relative (frequency-dependent) terms. *SYS, no longer req'd; satisfactory absolute req. now applies over entire band.*
5. Develop calibration requirements for the auxiliary degrees of freedom to meet LSC top-level performance requirements. *@PDR, done*
6. Include the unbalanced radiation pressure contribution in the determination of the influence of AM noise on the interferometer and requirements derived from it. *SYS, considered; not a driver*
7. The strong requirement on the parent intensity noise (10^{-8}) means that small additional intensity modulations in the interferometer can be significant. Consider other mechanisms to create baseband intensity noise; query 40m/PNI scientists for practical problems. *SYS; investigated & no new mechanisms uncovered, but tightened residual deviation allowance provides general relief for AM*

DRR Actions (cont'd)

INTERFACES/INTER-SYSTEM ISSUES

8. Determine the LSC use of wedge and transmitted beams from the optical components for diagnostic purposes to enable the detailed optical layout of the interferometer. *9/96, done (ASC PDD)*
9. Adopt a new LIGO ground noise spectrum for designs, including min/max for both design and noise modeling purposes *SYS, done*
10. Call out SUS actuator range for acquisition specifically as an dependency. *@PDR, done*
11. A contamination requirement and flowdown to mirror performance must be developed (common mode as well as asymmetric losses); LSC should then develop a compatible design. *SYS*
12. Apportion the light power at output ports between ASC and LSC to accommodate separate detectors, or require a common sensor for the two systems if indicated. *@PDR, done (ASC DRD)*
13. The ASC <--> LSC interaction needed during lock acquisition needs definition. Determine if this is an ISC or Detector Systems issue; if EPICS can support the required timing; and pursue the design with an eye to testing/ validation. *@PDR, done to appropriate extent for ASC and LSC prelim. designs (still an active area of study)*
14. The interface to ASC should be included in the 'RF reference' conceptual design and the associated figures. *@PDR, done*

DRR Actions (Cont'd)

CONCEPTUAL DESIGN

15. Make initial testing plans (pre-FDR) relatively independent of perceived resources (e.g., 40m) to ensure that priorities can be set correctly; include test of the sequencer, and digital loop components (if called for). *@PDR, done*
16. Consider, for the absolute calibration, the use of the beamsplitter plus the two input test masses as a Michelson, possibly locked at a mid-fringe. *@PDR, suggestion has been adopted*
17. A more complete servo model should be developed and used to test the design, including propagation time delays in the servo design and digitization noise (if relevant) *@PDR; digital artifacts discussed in LSC CDS Conceptual Design*
18. The sensitivity to mixer demodulation phase error needs to considered due to the presence of in-phase and out-phase signals at individual photodetectors; develop a model for this effect and if necessary modify the design to accommodate it. *@PDR, done; see Freq. Response of LIGO Interferometer*
19. Integrate saturation effects (time to recover from saturation; effects on control loop robustness) into the model for the conceptual design to ensure performance requirements (loop stability, locking time) are met. *@PDR, SMAC so modified*
20. Retain the Si Photodiode detector as an option pending more experience with InGaAs photodiodes. *@PDR, REJECTED.*
21. Clarify the contributions from intrinsic shot noise and those due to thermal, seismic, technical, and electronic in the noise and servo gain calculations. It would be helpful to see them shown on a single graph and added in quadrature. *@PDR, done*
22. Assess the sensitivity of the control system plant matrix to optical plant parameters (e.g., symmetric/asymmetric optical losses, contrast defect, alignment); modify if needed to ensure robustness and flexibility. *@PDR, done*
23. Develop comparisons of the plant transfer functions used for the servo designs with the actual transfer functions to show that the fits being used are appropriate. *@PDR, 'actual' transfer functions are now used*
24. An analysis is needed of the impact of the J_2 modulation sidebands; develop a strategy to deal with any consequent problems. *@PDR, done*
25. Consider addition of a direct monitor of modulation depth for calibration, diagnostics, etc. ("Tropel" or equivalent) to the LSC system at useful ports. *@PDR, done (ASC and IO each supply ~ 2 optical spectrum analyzers)*

DRR Actions (Cont'd)

DOCUMENTATION

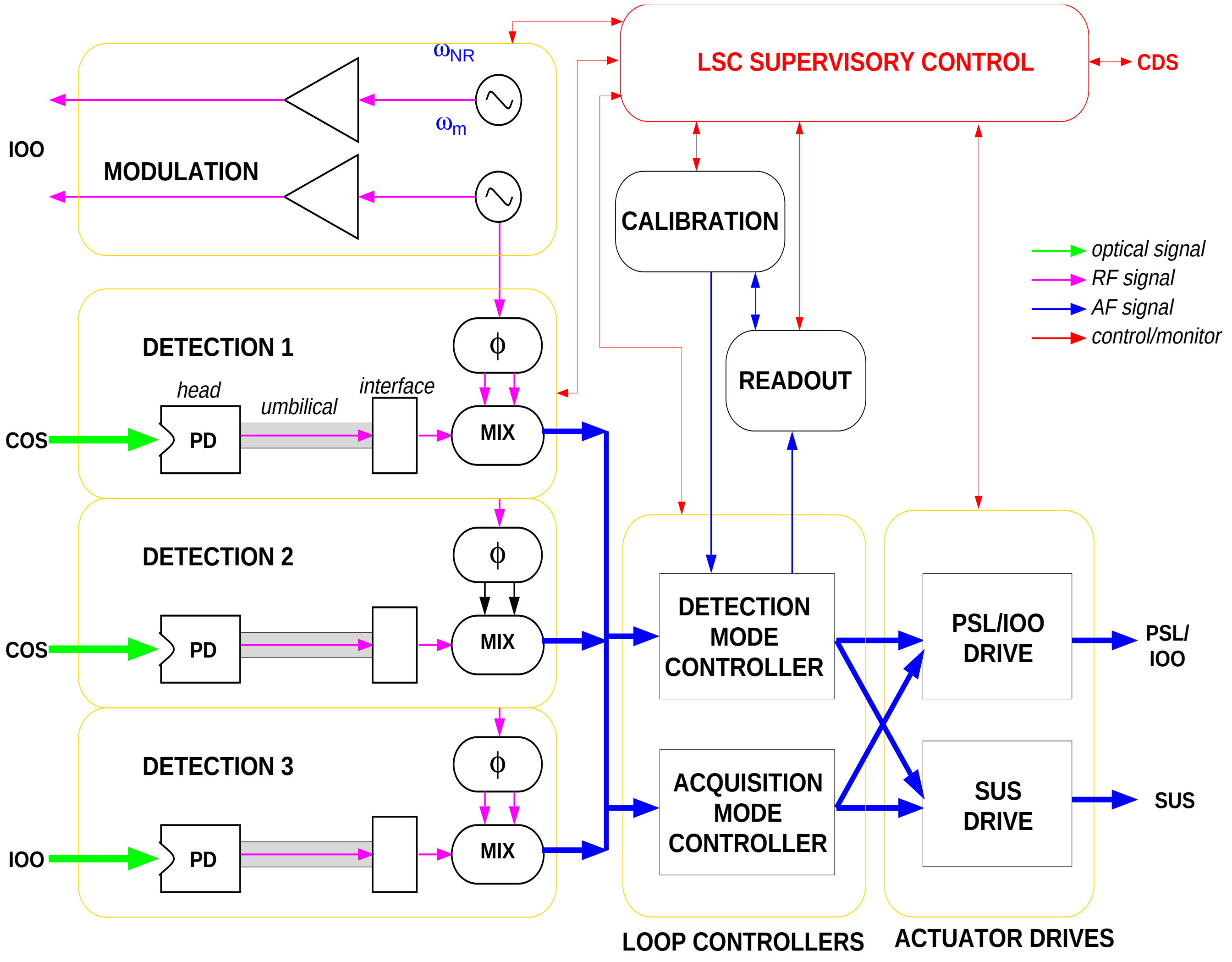
26. Document that the shot noise sensitivity of interferometer frequency noise detection suffices to meet the requirements. *@PDR, done*
27. Summarize the modeled optical system (Calflat surfaces and degradation thereof, losses, asymmetries etc.) in one place in the LSC DRR. *@PDR, superceded by DSR*
28. Include calculations or a pointer to a detailed document describing the calculation of the photocurrents used for noise calculations. *@PDR, done*
29. A more complete explanation and references to other documents are needed for the photodiode uniformity requirement. *@PDR, still pending*

LSC Design Overview

- Modes of operation:
  - Detection
  - Acquisition
  - Diagnostic
- Services:
  - Linear, calibrated readout signal of adequate sensitivity
  - Support diagnostics on other subsystems
- Parts:
  - Sensing (Modulation source, Photodetectors)
  - Controls (for each mode)

LSC FUNCTIONAL DESCRIPTION

- **LSC subsystem functional block with principal interfaces**



LSC SUPERVISORY CONTROL

CDS

ω_{NR}

ω_m

IOO

MODULATION

CALIBRATION

READOUT

DETECTION 1

DETECTION 2

DETECTION 3

head

umbilical

interface

COS

COS

IOO

PD

PD

PD

ϕ

ϕ

ϕ

MIX

MIX

MIX

DETECTION MODE CONTROLLER

ACQUISITION MODE CONTROLLER

PSL/IOO DRIVE

SUS DRIVE

PSL/ IOO

SUS

LOOP CONTROLLERS

ACTUATOR DRIVES

optical signal

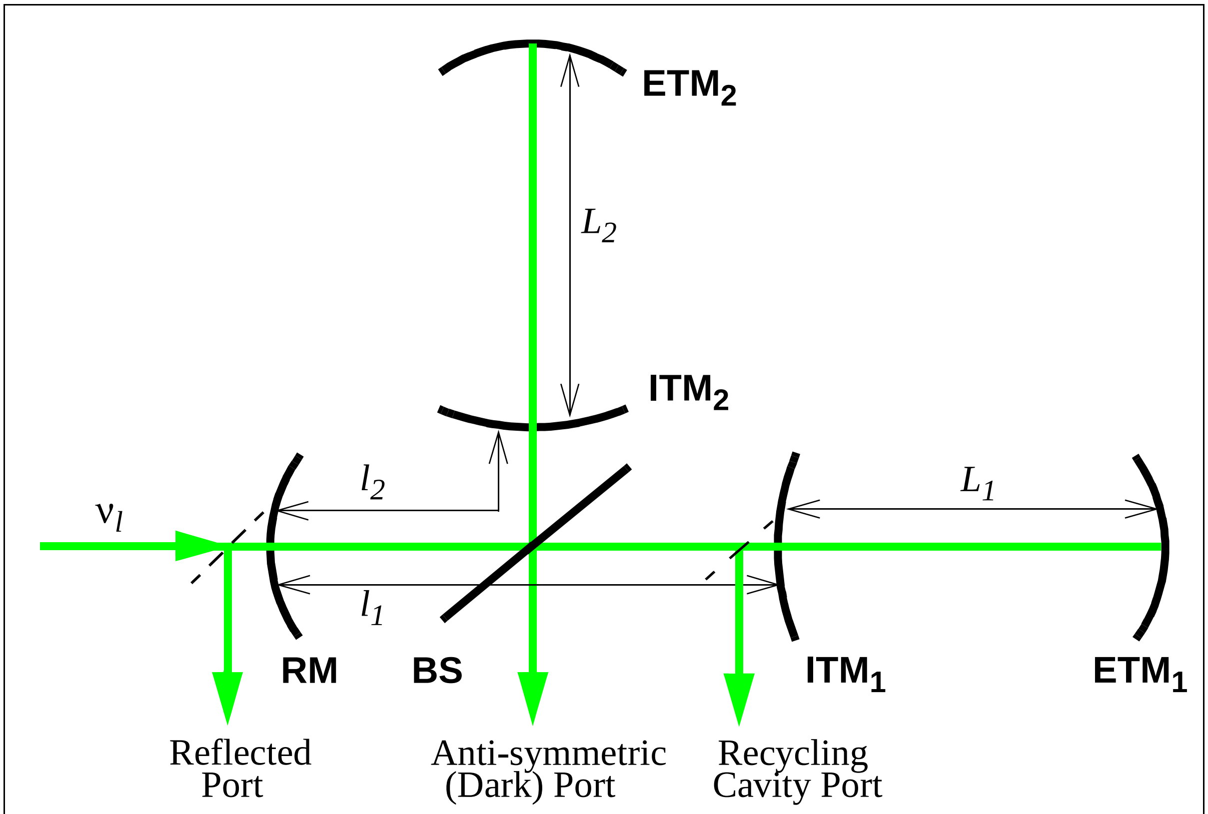
RF signal

AF signal

control/monitor

LSC FUNCTIONAL DESCRIPTION

❑ Interferometer configuration and definitions



Name	*Symbol*	*Definition*	*Deviation*
Differential Arm Length	L_-	$L_1 - L_2$	δL_-
Common Arm Length	L_+	$L_1 + L_2$	δL_+
Michelson Length	l_-	$l_1 - l_2$	δl_-
Recycling Cavity Length	l_+	$l_1 + l_2$	δl_+
Michelson Asymmetry	Δl	$(l_1 - l_2)/2$	N.A.

LSC FUNCTIONAL DESCRIPTION

❑ Sensor signals

- **Differential-mode sensors**
  - ❍ δL_- ➪ S_{AQ}
  - ❍ δl_- ➪ S_{PQ} **or** S_{RQ}
  - ❍ S_{RQ}
    - has better shot noise limited sensitivity, BUT
    - depends on amount of carrier reflected from interferometer, so very sensitive to interferometer losses
  - ❍ S_{PQ} **is robust against small changes in optical parameters**
- **Common-mode sensors**
  - ❍ δL_+ ➪ S_{PI} **or** S_{RI}
  - ❍ S_{RI}
    - has better shot noise sensitivity, necessary to meet residual frequency noise requirement in **Detection Mode**
    - no signal during **Acquisition Mode** pseudo-state
  - ❍ δl_+ ➪ S_{PI} **or** S_{RI}
    - S_{RI} and S_{PI} both more sensitive to δL_+, so enforce gain hierarchy

LSC FUNCTIONAL DESCRIPTION

- **Baseline plant sensitivity matrix**
  - **base loss per mirror surface: 50 ppm**
  - **carrier coupling can be optimized for GW signal (we overcouple carrier such that 1% carrier power reflected from interferometer)**

Signal port	ϕ_{RF}	*Sym bol*	*Degree of Freedom*			
			L_+	l_+	L_-	l_-
Reflection	I	S_{RI}	–62000	–560	0	0
Rec. cav. PO	I	S_{PI}	5200000	17000	0	0
Anti-symm.	Q	S_{AQ}	0	0	23000	180
Reflection	Q	S_{RQ}	0	0	0	19
Rec. cav. PO	Q	S_{PQ}	0	0	0	4900

DC plant matrix in units of wavelength for baseline interferometer parameters

LSC FUNCTIONAL DESCRIPTION

❑ Plant matrix variations

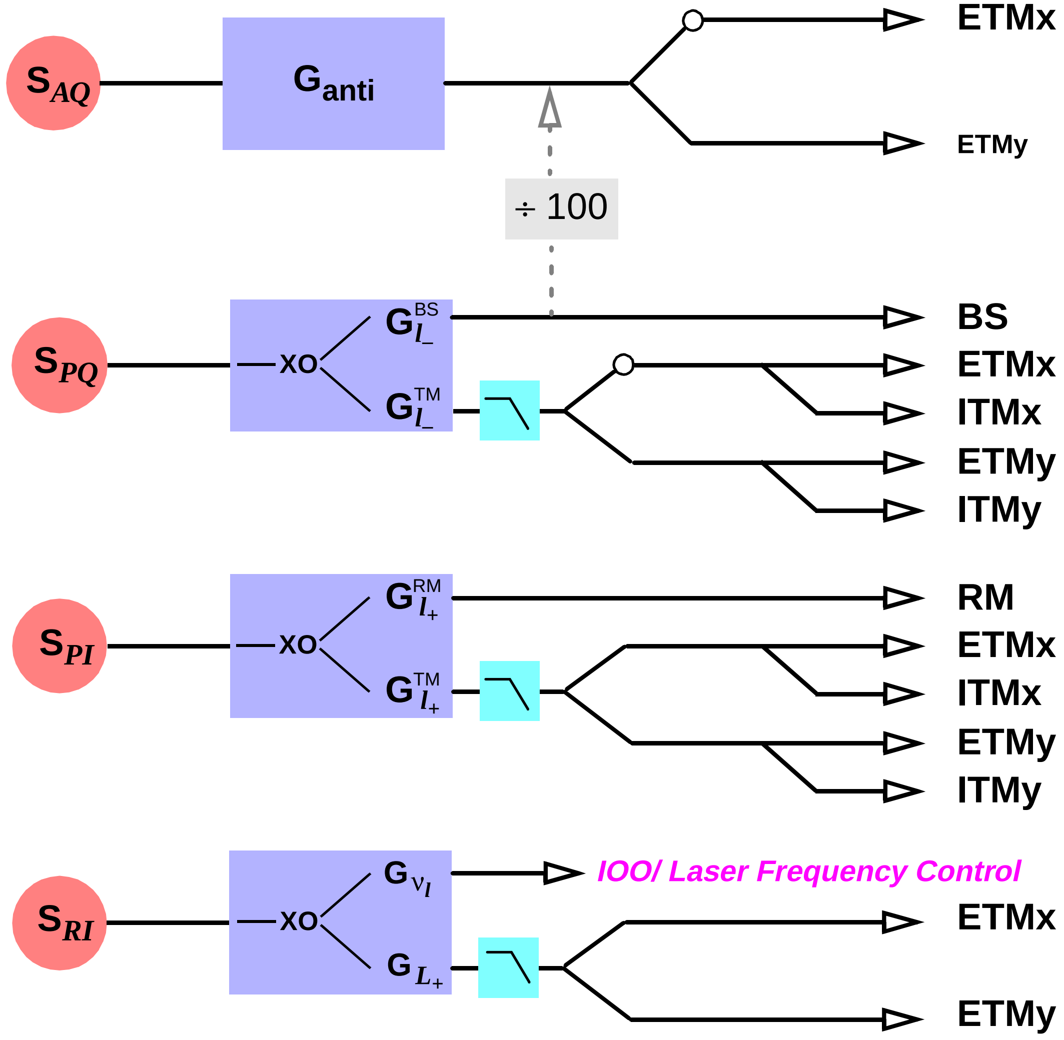
- **Exact value of base losses uncertain at present**
- **Loss accumulation due to contamination**
- **DC plant variations (negligible effect on frequency response)**

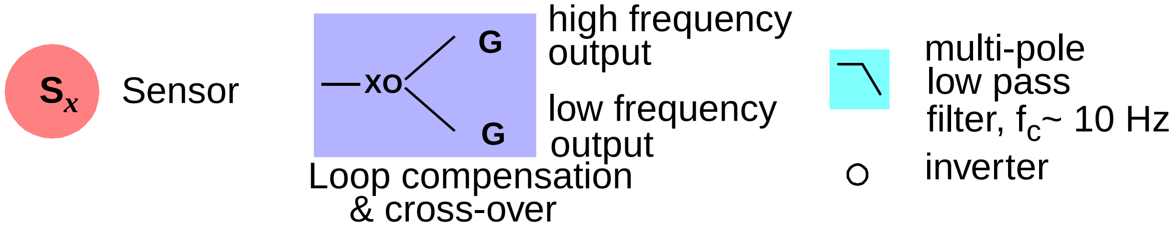
Loss *(ppm)*	$\frac{\delta S_{RI}}{\delta L_+}$	$\frac{\delta S_{RI}}{\delta l_+}$	$\frac{\delta S_{PI}}{\delta L_+}$	$\frac{\delta S_{PI}}{\delta l_+}$	$\frac{\delta S_{AQ}}{\delta L_-}$	$\frac{\delta S_{RQ}}{\delta l_-}$	$\frac{\delta S_{PQ}}{\delta l_-}$
10	**1.8**	2.0	1.8	**2.5**	**1.3**	3.2	**1.3**
100	**0.6**	0.4	0.6	**0.3**	**0.7**	–0.5	**0.8**
200	**0.3**	–0.1	0.3	**0.1**	**0.5**	–2.1	**0.5**

Fractional change in DC plant matrix scaled to baseline plant

LSC FUNCTIONAL DESCRIPTION

❑ Sensing and control topology





Sensor

high frequency output

low frequency output

Loop compensation & cross-over

multi-pole low pass filter, f_c~ 10 Hz

○ inverter

RF MODULATION/DEMODULATION

❑ Oscillator requirements summary

- **for signal sensitivity**
  - ❍ **Modulation index:** $\Gamma_R \approx$ **0.5 and** $\Gamma_{NR} \approx$ **0.05**
  - ❍ **Amplitude noise:** $\delta\Gamma_R(f)/\Gamma_R \le$ **4.5 x** 10^{-8} /√Hz **at** $f >$ **200** Hz
  - ❍ **Phase noise:** $\delta\phi_R \le$ **4 x** 10^{-5} rad/√Hz **and falling as** $1/f$ **at** $f >$ **200** Hz
- **for system diagnostic capabilities**
  - ❍ **amplitude modulation**
  - ❍ **fine frequency tuning ~ 10** Hz

❑ Oscillator prototype

- ❍ **built by Vectronics Corp.**
- ❍ **bench test:**
  - **phase noise meets specs**
  - **amplitude noise within 10 dB of spec (limited by noise floor of measuring instrument)**
- ❍ **Installed in 40 m lab**

LIGO RF Photodetectors

- Introduction and physical locations
  - ››LSC will provide RF PhotoDetector (PD) Assemblies (PDA)
    - –detect the modulated output beam intensities corresponding to length and frequency changes in the IFO
    - –PhotoDetector Assemblies (PDA) are integrated with ASC Wavefront Sensing equipment on external ISC platforms located in the LVEA.
  - ››four locations for PDA:
    - –reflected port (R),
    - – anti-symmetric or dark port (A) and
    - – recycling cavity pickoff port (P).
    - –Additional location (TBD) will be used for another detector monitoring the recycling cavity pickoff on the opposite arm (P').

Figure 1 PDA sample locations (LA IFO)

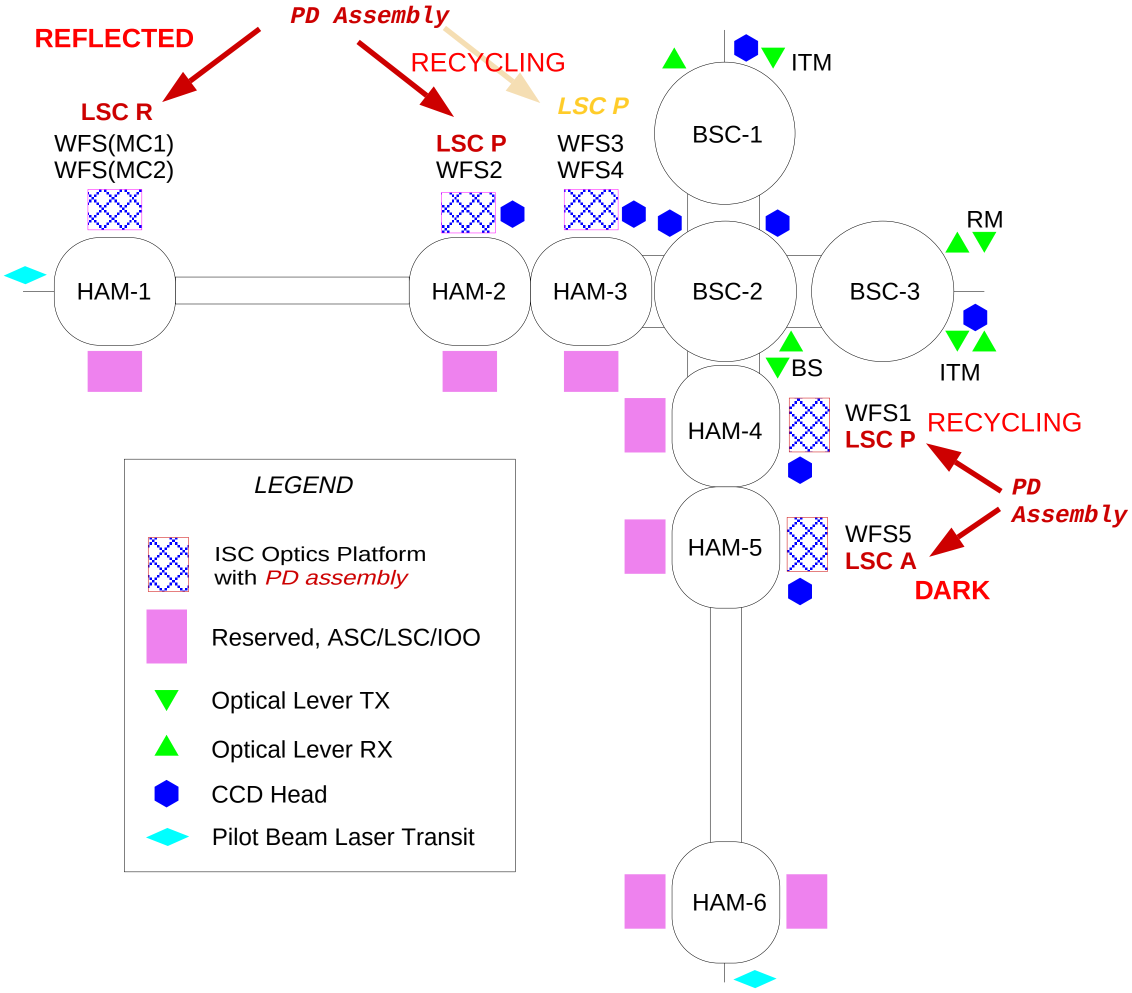
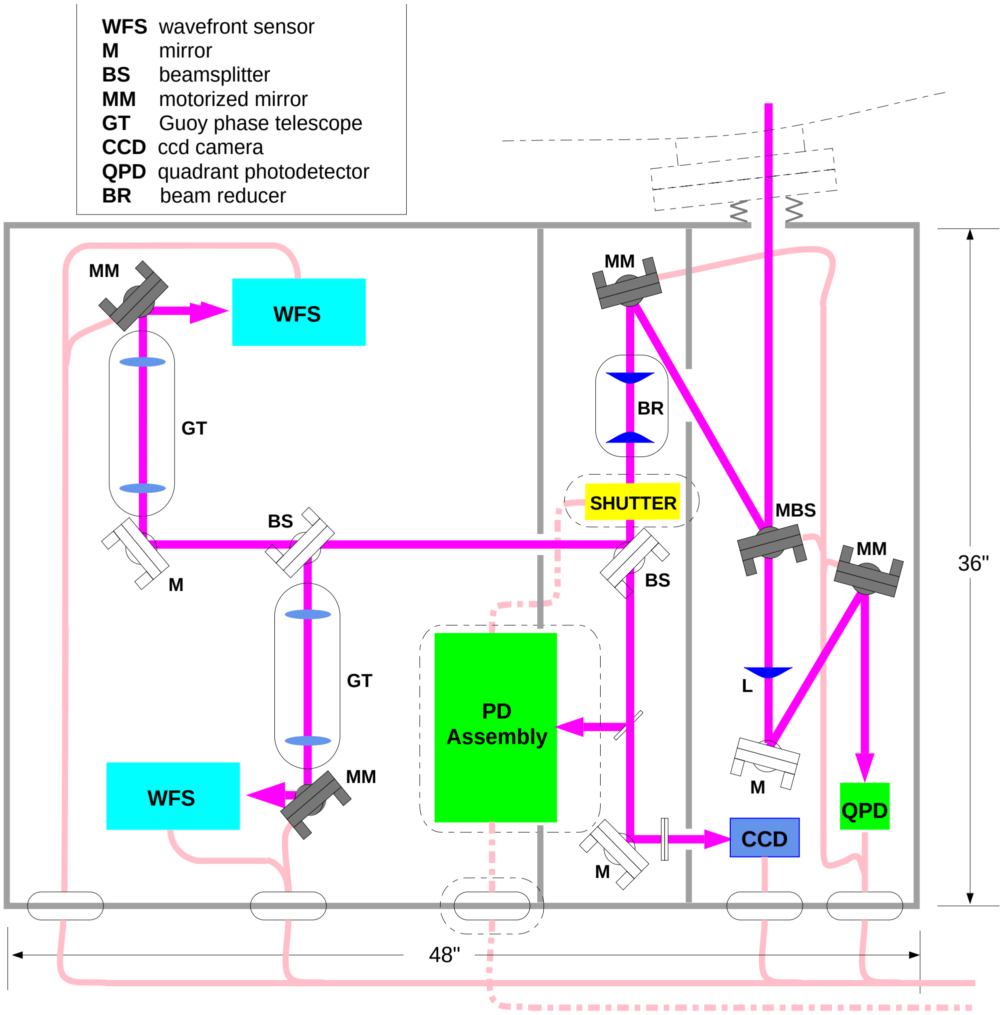


Figure 1: ISC Tables with PD Assembly Location

Figure 2 ISC table with PDA



WFS	wavefront sensor
M	mirror
BS	beamsplitter
MM	motorized mirror
GT	Guoy phase telescope
CCD	ccd camera
QPD	quadrant photodetector
BR	beam reducer

Figure 2: Preliminary ISC table layout with PD Assembly

Requirements summary and basic design features (1)

- FFT model studies of LIGO IFO

1. with realistic mirror deformations
2. with nominal input power of 6 W incident on the recycling mirror
3. other parameters optimized for minimum shot noise,

›› The antisymmetric port will emit up to ***600 mW*** of power in normal steady-state operation. This power level demands

– division of the beam among multiple discrete photodiode devices.

– number of devices combined with the additional minimum requirement of 80% total quantum efficiency at 1064 nm wavelength ***rules out use of silicon photodiodes***.

›› Transients at much higher powers.

– Preliminary modeling indicates: on sudden loss of lock, the entire stored circulating energy in the IFO, of order ***2 J***, is dumped out the antisymmetric port (depends on the rate of mirror motion associated with unlocking).

– The two cases shown in LSC PD can be regarded as very extreme cases. Also, when the IFO has unlocked or is waiting to acquire lock, the entire incident power of 6W returns from the reflected port onto the common-mode detector.

– An electromechanical ***shutter*** might be used to block ASC and LSC detectors for safety and diagnostics.

Requirements summary and basic design features (2)

- Additional detector requirements derive from

  ››The requirement to limit phase noise contamination due to ***backscatter*** from the detector surface. (see LSC DRD and COS DRD).

  ››Detect the photocurrent without contamination from ***electronic or thermal noise***

  ›› PhotoDetector Assembly Signal-to-Noise Requirement:

    – The ***shot noise*** in the detected antisymmetric port photocurrent is required to be ***10 times greater*** than the ***total electronic noise*** of the PDA, which includes both thermal (Johnson) and amplifier noise contributions (as for example, for the Hamamatsu 2mm PD the minimum current should be 95mA).

Photodiode device selection (1)

- VIRGO:
  - »research to characterize candidate PD
  - »design an PD assembly capable of satisfying VIRGO requirements
- LIGO
  - »extended the testing of the Hamamatsu 1,2,3 mm InGaAs PDs
  - »focussed on particular LIGO requirements.
    - **Figure 3: Optical setup**. The Lightwave 126 laser maximum power is ~ 800mW.

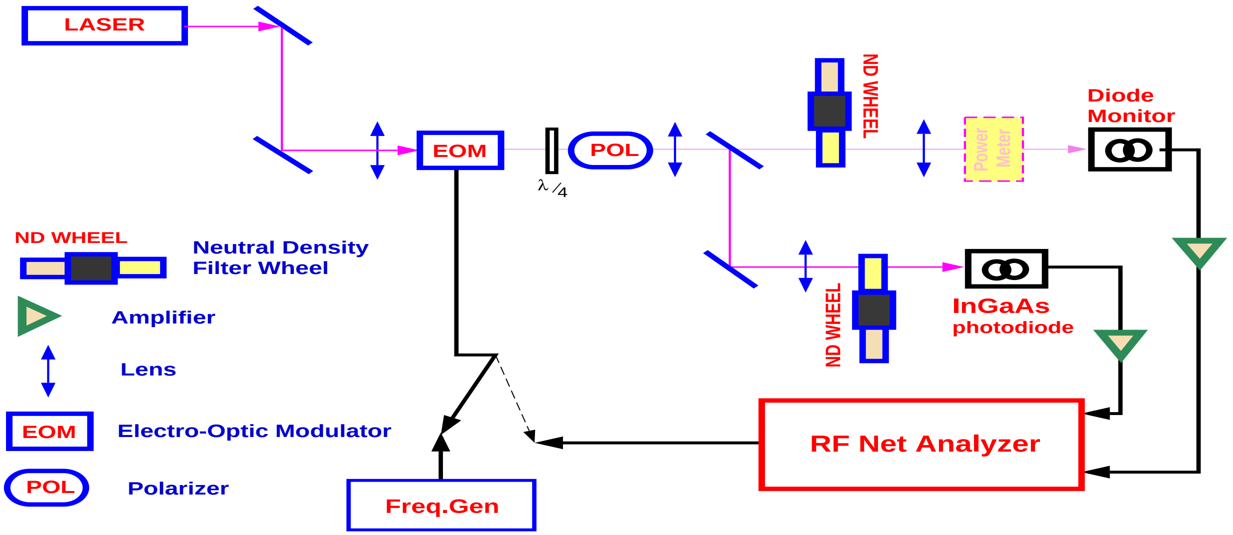


Figure 3: Experimental setup for PD evaluation

Photodiode device selection (2)

- Photodetector selection

1. The High ***QE*** requirement narrowed the candidates for the LIGO PD to ***InGaAs*** PDs
2. But the **InGaAs PDs have high Capacitance**. SeeTable 1

Table 1: Standard Hamamatsu PD: Typical Capacitance and Serial Resistance at 10V reverse Bias Voltage

PD Diameter	*Capacitance (Cd)*	*Serial Resistance(Rd)*
G5832-1 (1mm)	68pF	12.8 ohm
G5832-2 (2mm)	**250pF**	**8 ohm**
G5832-3 (3mm)	500pF	8.8 ohm
G5114-3 (VIRGO 3mm)	330pF	12 ohm

3. **Increased light power levels ---> increased capacitance** (in part due to temperature effects). From the characteristics described,
4. The ***choices are dictated by the equivalent PD impedance,*** which count for the tuned amplifier design, and the PD area. In order to have reasonable
   - **Increased power density,** -----> **larger area** PD,
   - ***Impedance considerations*** (tuned amplifier characteristics) ------> ***small area*** PD.

Photodiode device selection: RESULTS (1)

- ***Intensity dependence***: beams as small as 0.02 mm^2 --->no significant density limitations at intensities ~ 5 W/mm^2. This admits solutions involving ***relatively small detector areas and focussed beams.*** **Linearity limits appear more related to total power than power per unit area*.***

- ***Spatial uniformity***: Both the RF and DC response appears to be ***adequate***. (Figure 4).

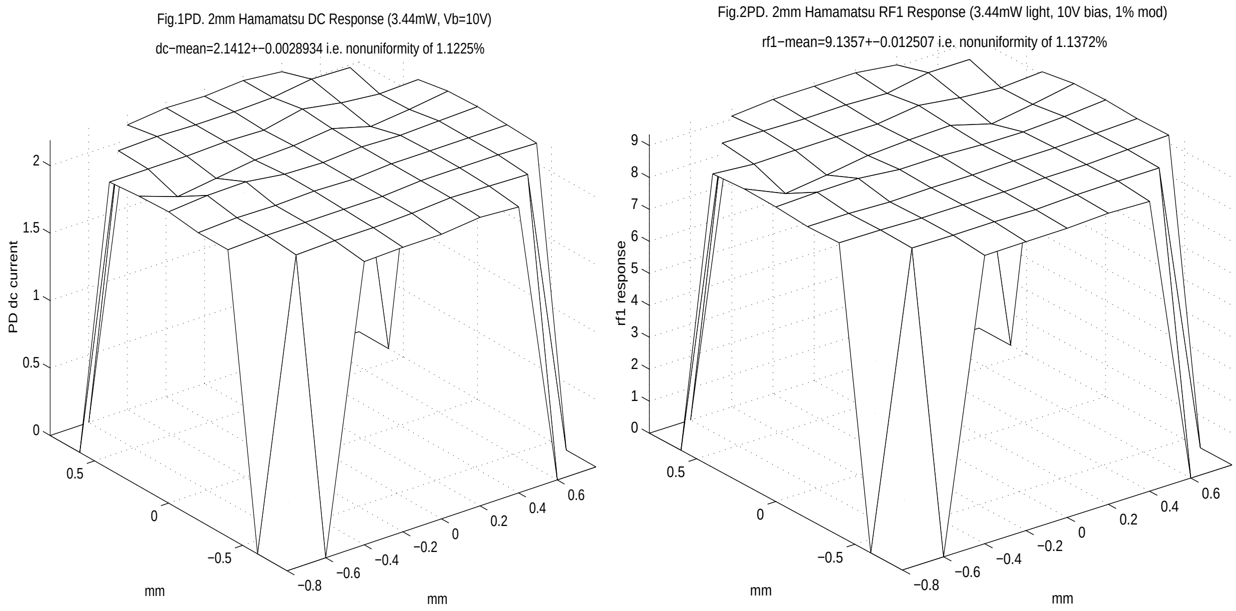


Figure 4: DC(left) and RF(right) spatial uniformity of the G5832-2 PD

- ***RF impedance***: The high C per unit area of InGaAs PDs ---> formidable problem due to SNR concerns. Fortunately, the ***2 mm*** candidate devices selected are ***acceptable*** (81 Ohm at 25MHz).

- ***Thermal properties***: Thermal impedance + measured variation in impedance + optical properties with junction T = ***consistent with continuous operation within LIGO specs***.

Photodiode device selection: RESULTS (2)

- ***The DC and RF response*** of the 2mm PD has been studied for ***various bias voltages and modulation depth***. A reverse bias of ***10V*** is adequate for RF linear responses at high light power levels and LIGO type of modulation. Maximum Continuous Power Capability: Figure 5.

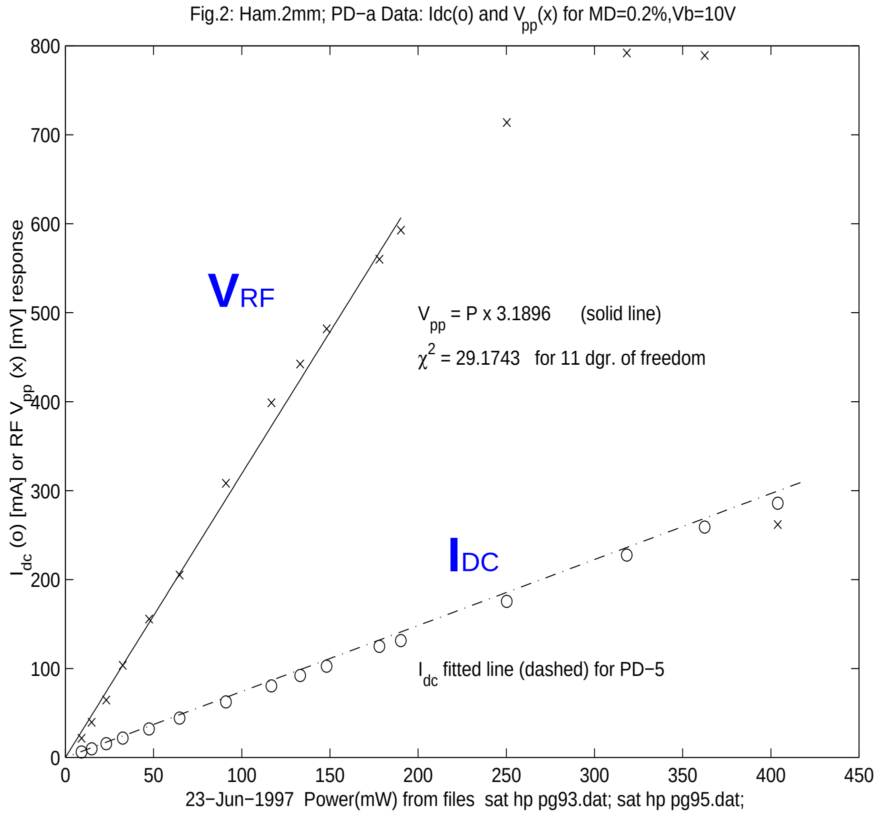


Figure 5: High Power Response of the G5832-2 (2mm) PD.The DC(o) and the RF(x) data are obtained with PD number "a". The dashed line is the fit of DC data from another PD DC response

Photodiode device selection: RESULTS (3)

›› ***Stability under operating conditions***: A 2 mm PD exposed over 500 hours to ~ 225 mW incident power (on bare PD), with no perceptible changes in properties at a test sensitivity of few percent (designed power is 150mW).

- The PD current was about 170mA at 10V bias voltage
- The PD was continuously cooled using the heat sink and a fan.

›› Transient Peak Power Capability

- The 2mm Hamamatsu PD may handle ~ ***500mW*** of light power **for few seconds,** even with the **bias voltage on**.
- An **increase in dark current** was observed after exposure to higher power (**~** ***700 mW***), the duration of this exposure and junction temperature during the test were not logged, and the full bias voltage was maintained; as a result it is not possible to extrapolate this measurement to a limit in actual practice. Further tests are planned.

›› PD to PD response variation:

- Using a very limited sample of 2mm Hamamatsu PDs, we have been able to conclude that the C and R have about ***20% variance.*** For the final design, the nominal C should be less than 250pF and the R of about maximum 8 ohm at 10V bias voltage. A 10% spread limit will be imposed Preliminary, we may require a maximum capacitance of 270pF. TBD.

Photodiode device selection: RESULTS (4)

››Photodetector Quantum Efficiency (QE), Reflections and Backscatter

– The advertised ***Radiant Sensitivity S*** is for the PD assembly (***with window***). At 200mW of light power, we measured $\mathbf{S} = \mathbf{0.70} \pm \mathbf{0.02}$ A/W. So the $\mathbf{QE} = (\mathbf{82} \pm \mathbf{2})$% for the PD with window.

– ***PD reflections***: ~ 8% of the incident power is reflected by the two window surfaces; less than 1% is reflected by the coated crystal surface (at small angles). After removing windows, the reflected light from the PD coated surface was measured to be about ***0.7%*** at small angles (below $\mathbf{15^o}$).

– QE with ***windows removed***, the bare PD devices are able to achieve ***at least 86% internal QE*** at the design wavelength. The PD face reflectance is less than 0.7% near normal incidence.

– Backscatter from Individual PD: The crystal surface does not have a special optical polish. Initial measurements, indicate that the backscattering is less than $\mathbf{10^{-3}}/(\mathbf{sterad})$. Further tests are necessary.

››Total Optical Component Losses, Reflections and Backscatter

– For the PhotoDetector Assembly, as presented in Figure 6, the ***total relative optical losses***, which includes PDs, beamsplitters and input collimator, can be ***< 6%***

Photodiode device selection: SUMMARY

- The 2 mm ***Hamamatsu G5832-2*** affords the best compromise between complexity (number of discrete devices), power density and SNR margin.

- ***Four such devices in parallel is the basis of our preliminary design***.

It is worth noting that, with some relaxation of SNR requirements,

  - the VIRGO custom 3 mm diode might be acceptable[1]

- The ***8-diode 1mm*** design will be carried as a ***backup option***

The results of this evaluation for three Hamamatsu parts tested by LIGO, and a variant tested by VIRGO, are shown in the Table 2 on page 13.

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[1] Several factors permit VIRGO to tolerate the higher capacitance of this diode while LIGO cannot; the most important difference is the choice of a lower modulation frequency in VIRGO.

Table 2: Optimized RF transimpedance and minimum DC current per device to fulfill LIGO SNR requirements

Description	*Z [ohm] at 25MHz, 10 V bias*	I_{PD}^{min} *[mA]*	*# PDs req'd*	*Power per PD [mW]*	*Central Intensity*[a] *[mW/mm²]*	*DC Current per PD [mA]*
G5832-1 (1mm)	**682**	**6**	**8**	**75**	**765**	**57**
G5832-2 (2mm)	**81**	**95**	**4**	**150**	**382**	**114**
G5832-3 (3mm)	**18**	**1100**	**< 1**[b]	**N/A**	**N/A**	**N/A**
G5114-3[c] (3mm)	31	454	1	600	678	456

a. Assuming $1/e^2$ beam diameter is chosen to be half the physical diameter of the diode; this is conservative from the standpoint of collection efficiency, but may be necessary to reduce backscattering from the device edges.

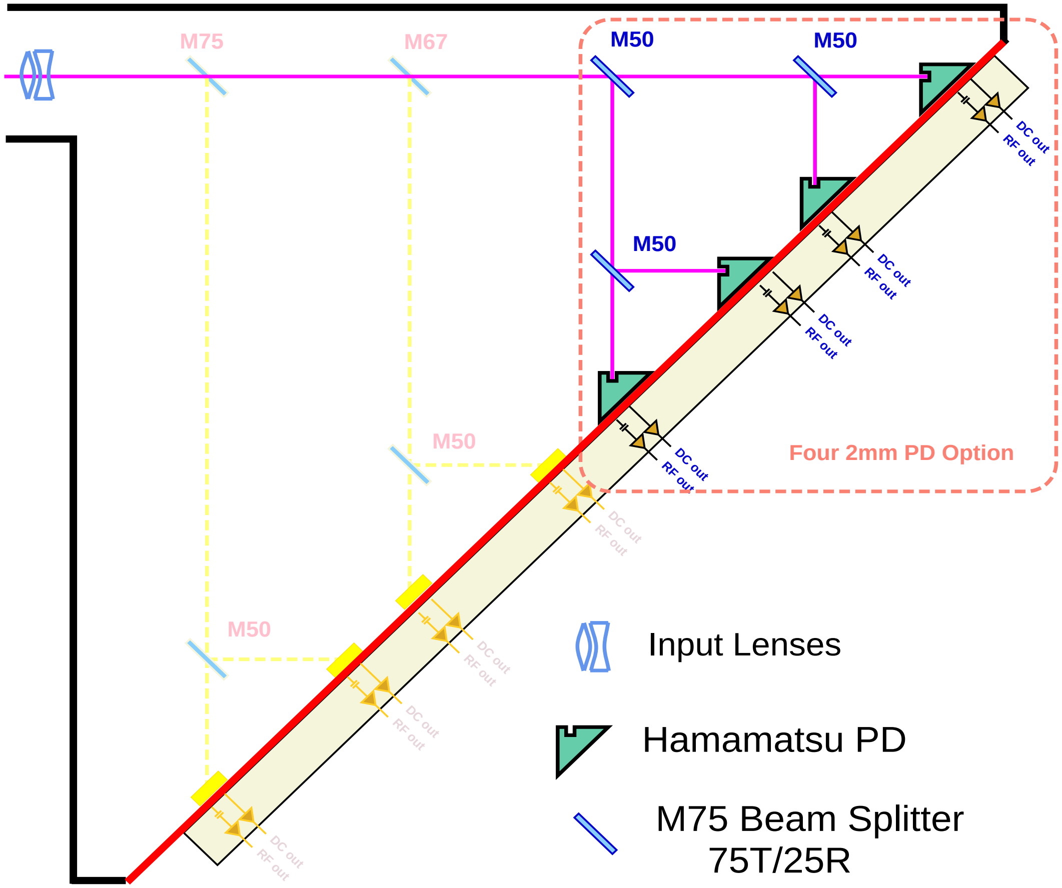
b. The RF impedance of the stock 3 mm diode is too low to realize LIGO SNR constraints (with room-temperature electronics).

c. VIRGO custom diode, modified for low capacitance (RF impedance parameters communicated by R. Flaminio).

Baseline PDA Design and Projected Performance

- **Basic optical parameters** for the PDA with ***Hamamatsu G5832-2***:
  - The beam diameter ($1/e^2$ intensity) at each detector surface will be ***1.0 mm*** (TBR).
  - All diodes will be placed at ***equal optical path distances*** from the IFO
  - The PDs will be ***canted at a 10 degree angle*** (upward) to divert the specularly reflected beam out of Rayleigh cone. A beam dump will be integrated into the cover.
  - ***Incoherent light*** will be introduced to each PD (as from an incandescent lamp), at a level to induce shot noise equal to the dark noise of the RF readout. (TBD)
- **Basic electronic design parameters**:
  - Each diode will be ***back-biased at 10V***
  - ***Heatsinking*** will maintain the case T< **45^{o}C** under operating conditions (junction T ~ **80^{o}C**).
  - The nominal operating photocurrent will be ***114 mA per diode***.
  - For the expected RF transimpedance of **81**Ω, a pre-mixer RF *voltage gain of 20 dB* will be used in the preamplifier in Detection mode.
  - With this gain, ***preamplifier noise of 1.2 nV/Hz1/2*** (input) will be adequate to guarantee that electronic noise from this and subsequent RF and baseband stages remains < the sig/noise ratio.
  - For protection, the ***bias voltage across each diode will be cut off under overload conditions*** (reduce the internal dissipation 7.7). The triggering threshold, reset criteria and response time interval necessary are TBD, pending testing on damage levels, modeling of IFO power transients.

Figure 6   PD Assembly



Photodiode Assembly

Figure 6: Photodiode Assembly Layout with full implementation (8 photodiodes). The 4-diode option is shown in the dashed box.

PD Assembly: Specifications

- The design is proposed to be ***modular***,
- Accommodate as many as 8 diodes and their optics and electronics.
- RF tank circuits and front ends will be mounted close to the diode terminals to minimize stray inductance and capacitance.
- ***Thermocouples*** mounted near one or more diode cases may be used to monitor heat sink temperature during operation.
- Within the optics housing (upper left), a system for introducing ***incoherent light*** onto each diode for testing purposes will also be integrated. This requirement has proven difficult to realize in practice; incandescent lamps which produce the required photocurrent (of order 10 mA) are too large and introduce too much heat. A system using fiberoptic light guides and a remote lamp is under consideration.
- The optics housing also acts as an ***RFI shield***, and will be gasketed for shielding purposes.

The light entry (upper left) is designed as a waveguide with the modulation frequency below cutoff for further RFI rejection. The lid of the optics housing will also house low-backscatter light traps to absorb the specular reflections.

- ***Total optical losses*** in all PD Assembly optical of ***less than 6%*** are reachable.
- ***Backscattering*** concerns may also argue for ultralow surface microroughness; this will be investigated during the final design phase.
- In some cases (e.g., lock acquisition of the common-mode control, where the PD will be exposed to 6W power until lock is acquired) a linear signal is still required during overload conditions. Either the PDA will maintain some well-defined nonzero sensitivity in its “overload protected” state, or a separate low-sensitivity detector (perhaps receiving a small light sample, of order 1%) will be provided to augment the dynamic range.
- LSC will provide a ***shutter*** for dark tests and for overload protection of LSC and ASC components. Requirements are TBD pending as above.

Detection Mode Controls

Philosophy: use realistic noise inputs and drive topologies and see how hard it is to satisfy requirements.

“Realistic” noise inputs:

- length noise
- frequency noise
- shot noise

“Realistic” drive topologies (not quite done):

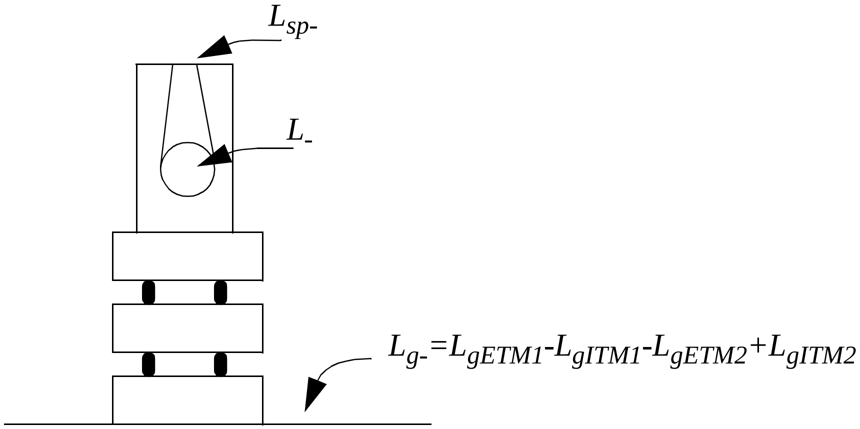
- sensing noise, dynamic ranges
- non diagonal MIMO systems
- cross couplings, imbalances, etc...

Result: We identified (some of) the issues that drive the loop design: *“preliminary”* is not *“final”*!

Noise inputs

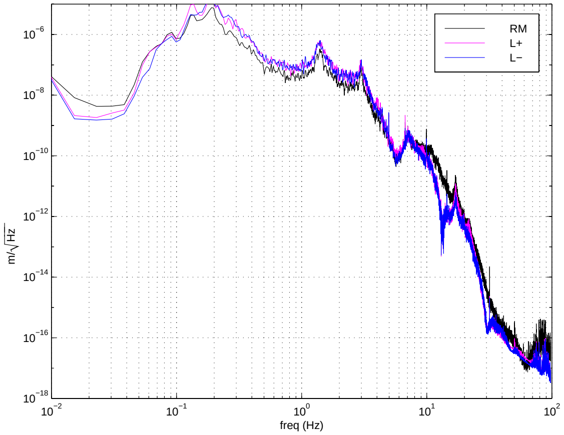
››**Frequency noise** (after PSL and mode cleaner): assume a thermal noise spectrum above 100 Hz, $1/f^2$ below 100 Hz, $10^{-4}\,\mathrm{Hz}/\sqrt{\mathrm{Hz}}$ at 100 Hz.

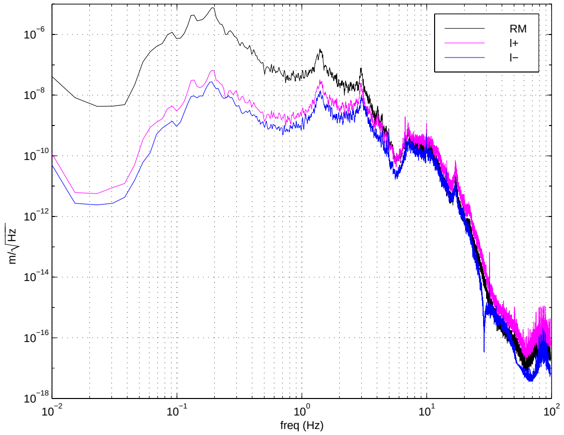
››**Length noise:** assume there are four “pendulums”: L_+, L_-, l_+, l_-, each on a SEI stack, being moved by the “common “and “differential” ground noise.



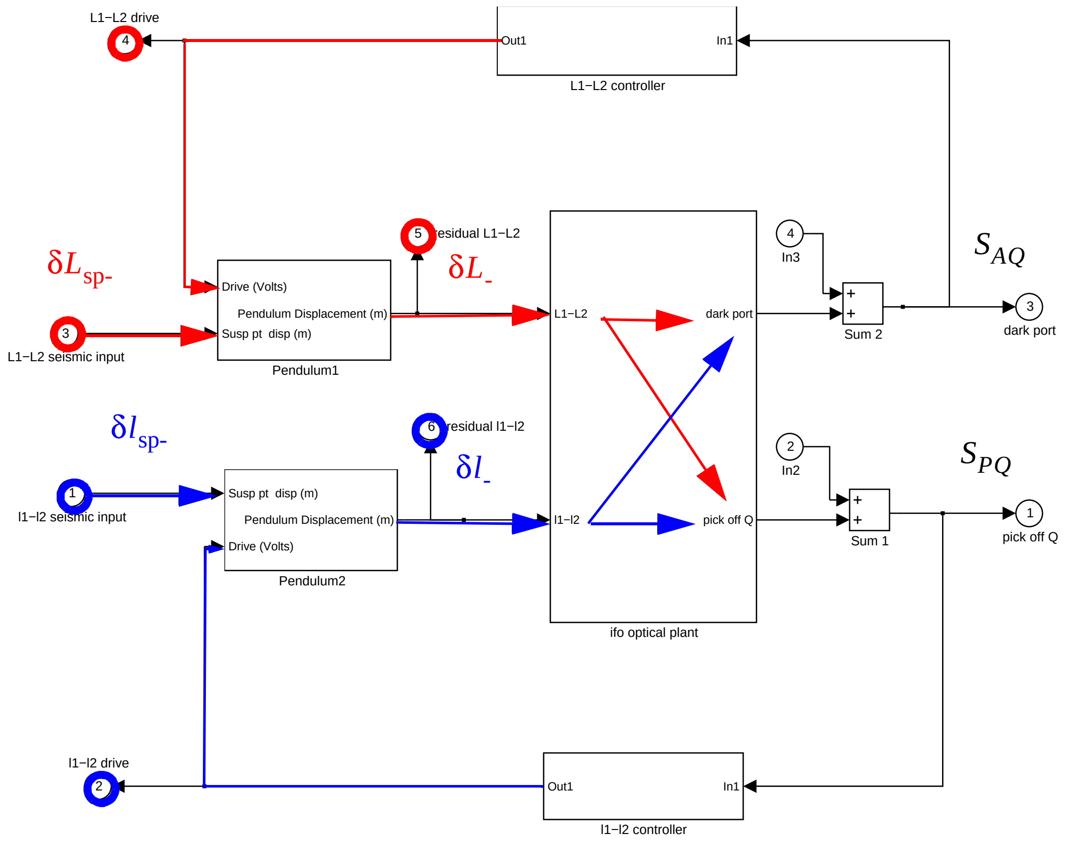
Noise Inputs

- We have measurements at the sites for L_+, L_- ground noise: worse than added uncorrelated, similar to being added correlated through a seismic wave model.
- We don’t have measurements of l_+, l_-, but we do expect less than measured noise at a particular point (low frequency seismic noise has long wavelengths): use a seismic wave model to predict these.





Servo Model: Differential Loops



Differential Mode Control Issues

›› GW signal is taken at the antisymmetric port: we see how the assumed main sources (shot noise, seismic noise) show up compared with SRD.

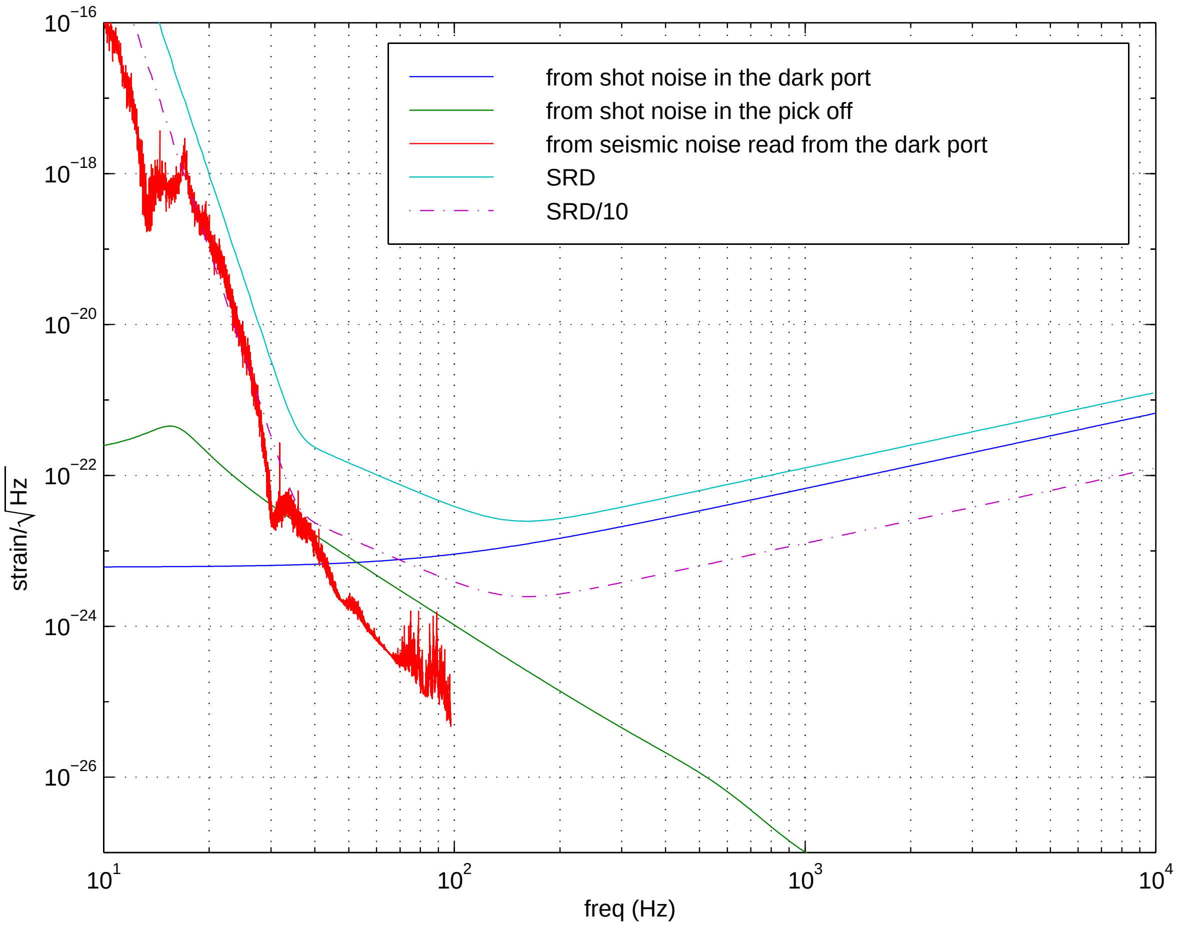
›› Requirements:

- we have to keep cavities at zero point with maximum rms deviations bounded by amplitude noise coupling: high loop gains at microseismic peak and stacks resonances.
- we have to keep shot noise in Michelson differential port away from GW signal (“SRD/10” allowance): low loop gain in l_- servo: less than unity gain at 30 Hz, 0.1 at 47 Hz.

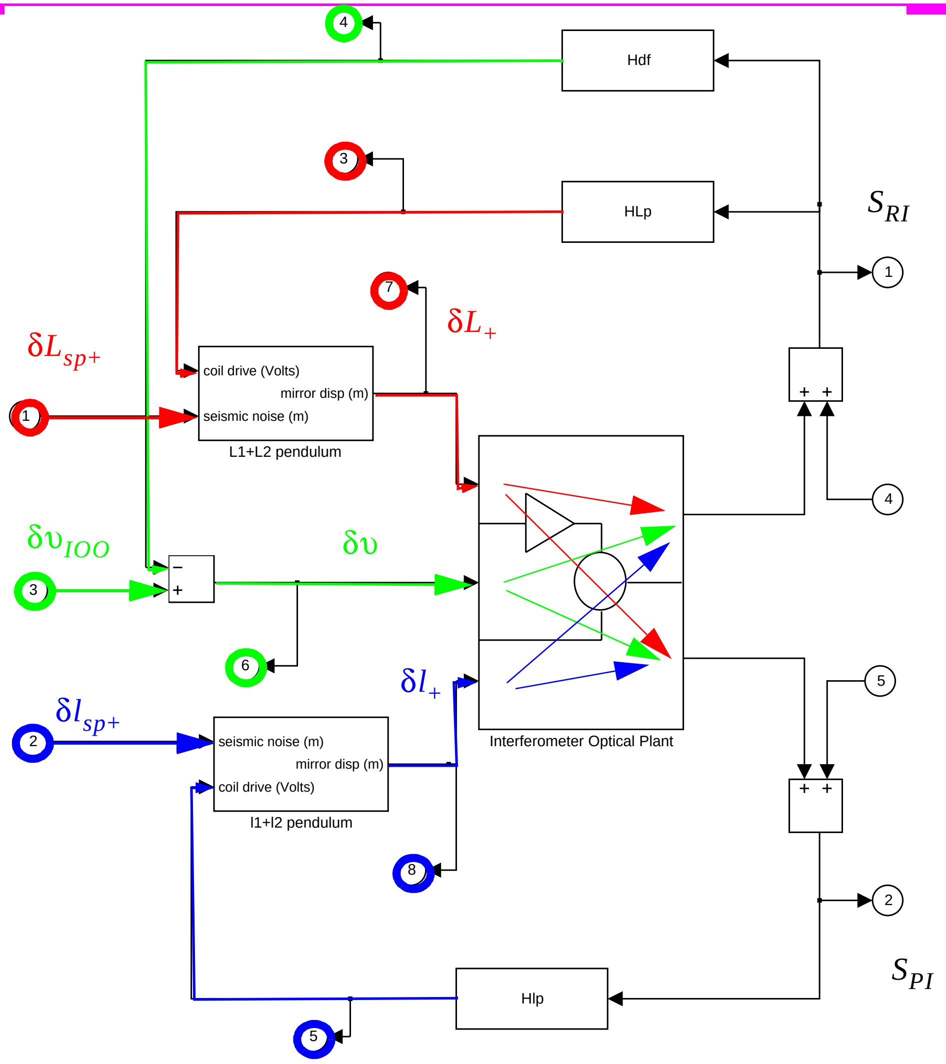
›› We have a loop satisfying the requirements, but Michelson loop has scaringly low bandwidth and low phase margin.
==>> **First problem identified:** shot noise in Michelson port from appearing in GW band vs. keeping RFAM coupling in the Michelson port below its (poor) shot noise (that then couples into GW signal).

›› **Possible solution:** use a non diagonal controller.

Servo Model: Differential mode loops



Servo Model: Common mode loops



Common Mode Control Issues

›› Requirements:

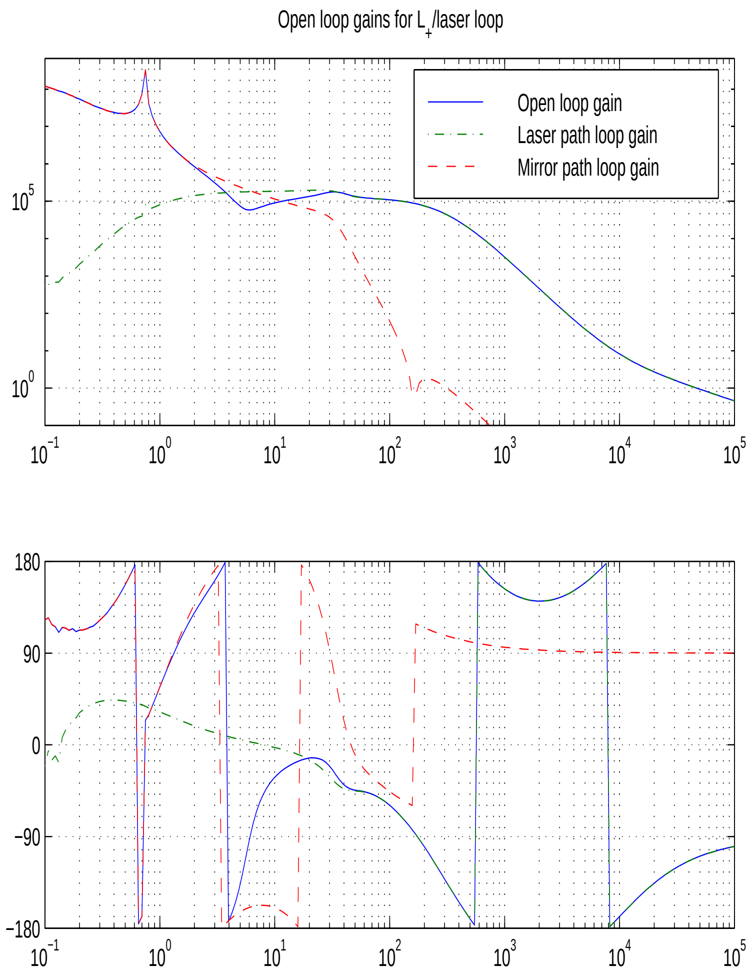
- use L+ to drive laser frequency noise below SRD/10 level
- keep cavities locked with small rms phase noise so power doesn’t drop below 99.5% level.

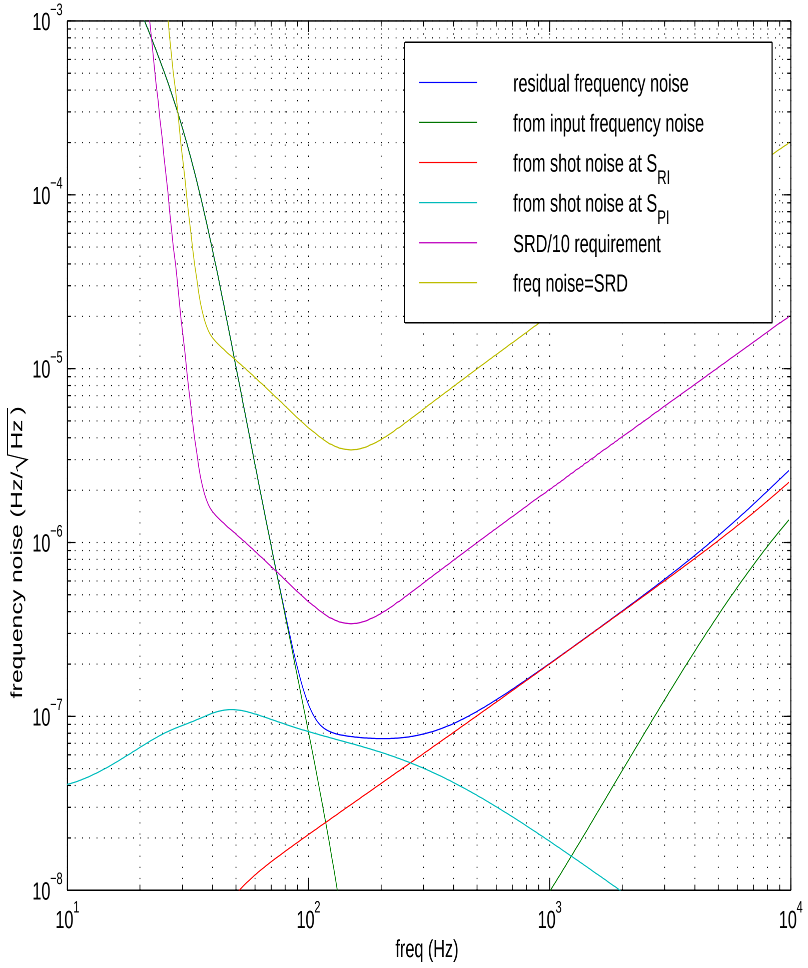
›› Problems:

- since the plant is non diagonal, and both ports are mostly sensitive to L+, not l+, relative gains in the loops are important.
- we lower frequency noise driving the laser more than the mirrors, but we lower the rms phase noise driving the mirrors, not the laser: these are too strict requirements on L+ loop: We need ~10^5 length suppression at 3 Hz and ~10^3 frequency noise suppression at 40 Hz, crossing the gains with slope shallower than $1/f^2$.
- Design in PDD “satisfies” requirements, but *it is not stable* to length excitations (!). A “preliminary” stable design does not satisfy requirements.

›› Possible Solution: diagonalize the plant using a non-diagonal (digital) controller.

Common Mode Control Issues


Open loop gains for L_+/laser loop



Summary

››Some design problems (surely not all!) were made obvious when using better models and realistic noise inputs.

››We may want to have loops that are robust even if they lead to noise couplings, and having a linear system to measure plant functions and actual noise inputs, tune the loops with necessary filters.

››We will try modeling non-diagonal controllers: although the topology may look more complicated, more robust loops may be designed that satisfy the requirements. If we consider the actual drive topology to individual test masses, a non diagonal controller does not look so different from a diagonal one.

››We haven’t succeeded at using mathematical tools that makes possible to study design changes in an automated way, but Matlab/Simulink make the design work easier (up to nuemrical precision problems).

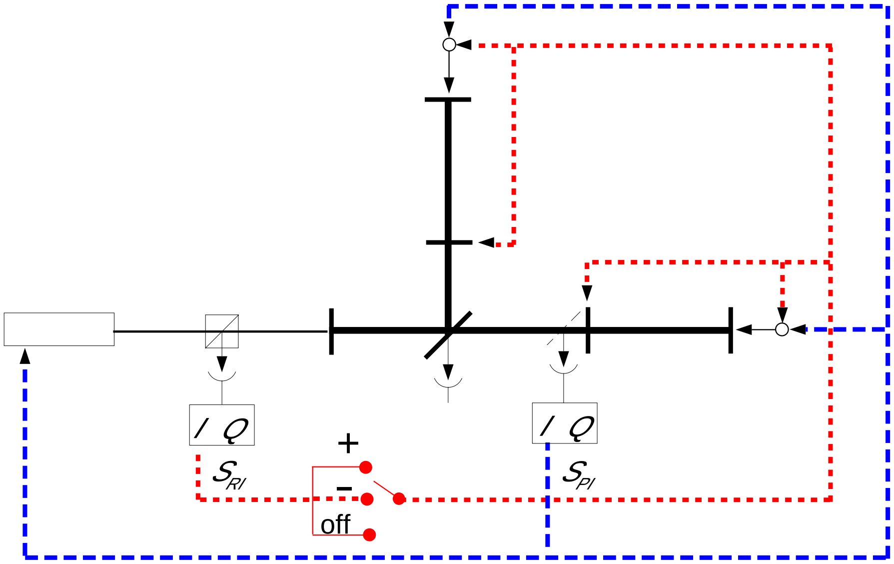
››Lots of work ahead, but “design philosophy” looks right....

VI. Acquisition Mode Conceptual Design

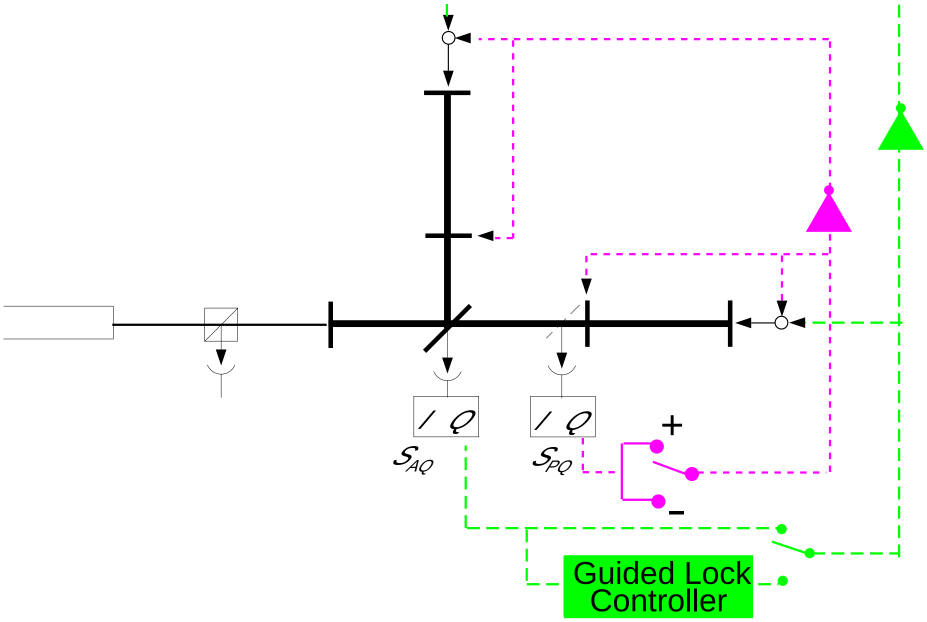
- ACQUISITION MODE: cavity lengths transition from uncontrolled state to state where lengths controlled with high precision
- Control Design Strategy
  - Make as similar as possible to Detection Mode
  - Reasons to deviate from design strategy:
    - Ability to transition successfully from unlocked state to fully locked state
    - Acceptable speed of acquisition
    - Signal to noise considerations

Servo Configuration

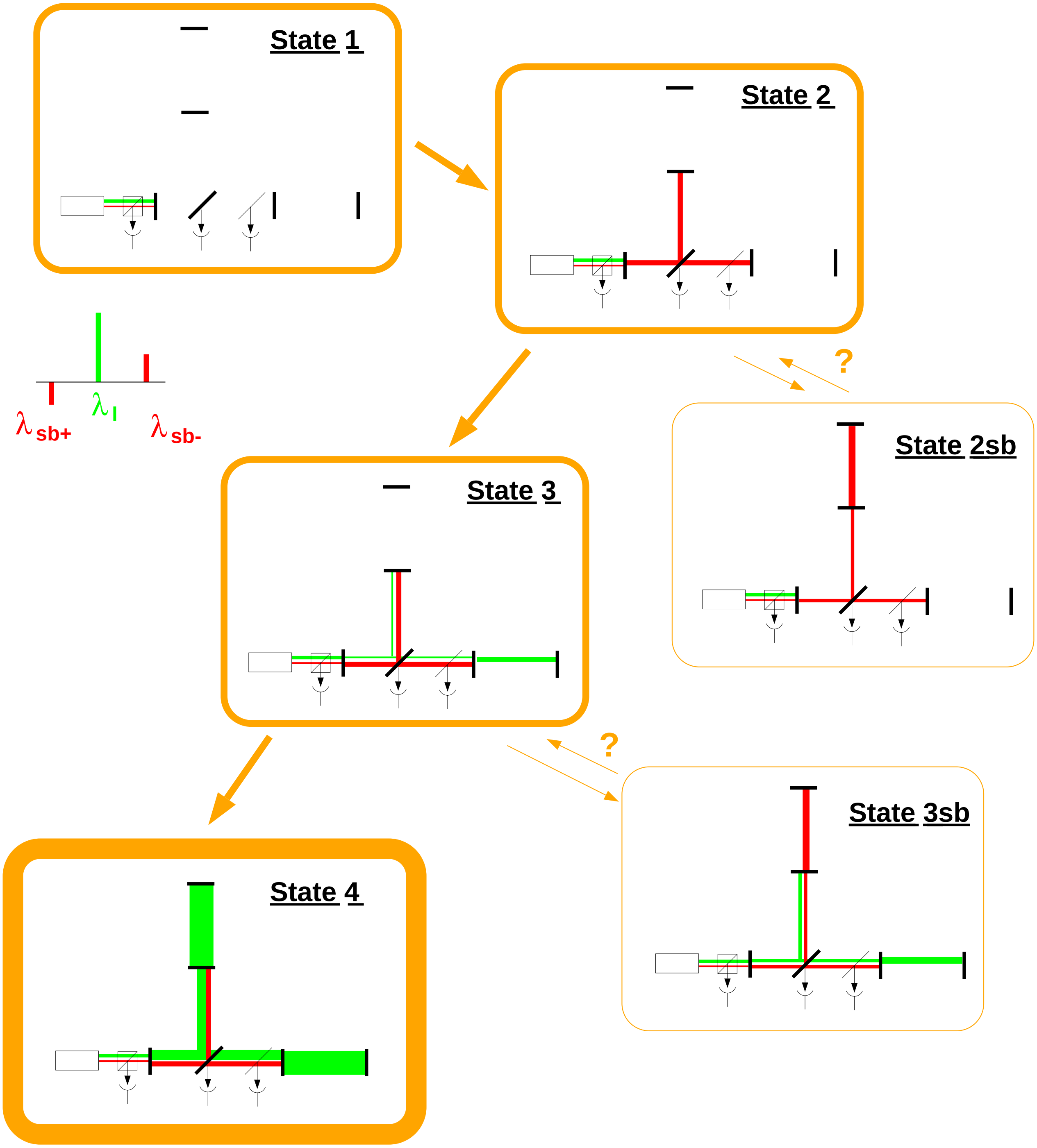
Common Mode Signal Paths



Differential Mode Signal Paths



Locking Sequence



Loop Shape Design

- Constraints
  - Gain < 10^{-6} at 6.79 kHz in all states (mirror actuated loops)
- Rules of Thumb
  - Maximize bandwidth in order to increase v_{th}
    - v_{th} = maximum velocity of optic and it still acquires
    - Because of v_{th}, bandwidth much more important than DC gain
  - Design *L+* servo with much higher bandwidth than *l+* servo in order to diagonalize loops
  - Design loops assuming they are uncoupled
- Design Procedure

1. Design stable/robust servos for all loops in State 4
2. Test to see if *L+*, *l+*, and *l-* designs are also stable/robust in State 3 and have sufficient bandwidth to maximize v_{th}
3. If not stable/robust, iterate design of each loop until stable/robust in both states 3 and 4 (get stability in State 2 of *l+* and *l-* loops for free)

Acquisition Procedure

1. State 1 Initialization

- Laser locked to mode cleaner
- Interferometer masses damped with local control
- Acquisition controllers on but not locked

2. Acquiring State 2

- Sidebands start resonating in recycling cavity as *l+* and *l-* controllers lock simultaneously
- Time to lock ~ few seconds
- v_{th} ~ 10 µm/sec (background rms < 2 µm/sec)

3. Acquiring State 3

- Carrier starts resonating in recycling cavity and one arm as *L+* controller locks
- Time to lock ~ few seconds.
- v_{th} ~ 10 µm/sec (background rms < 2 µm/sec)

Acquisition Procedure (contd. 2)

4. Acquiring State 4 (most complicated part of acquisition process)

- Guided Lock Controller triggered ($v_{th} < .1\ \mu m/sec$ (?))
  - Trigger from transmitted light in arm
  - Controller calculates relative velocity of arm cavity and kicks end test mass back into fringe at reduced velocity.
  - Guided lock controller switched out of loop and linear controller switched in.
- Linear controller locks onto fringe when velocity sufficiently small
- As arm cavity transitions into locked state, *l+* and *l-* servos switch polarity---trigger from transmitted light in arm

5. Stable Transition Through Pseudo-States

- Possibly ramp *l+* servo to off-state for a few tens of milliseconds while arm transitions through pseudo-state

Acquisition Procedure (contd. 3)

6. Transition into Detection Mode

- *l+* and *L+* sensing signals swapped
- Wavefront sensing becomes fully functional
- Wire resonances and other transients ring down

7. Integration of Alignment/Length Control Acquisition

- Plan presented at the ASC Preliminary Design Review

DIAGNOSTICS

❑ Requirements

- Digital part (primary)
  - The LSC diagnostics subsystem must be able to extract and display any (digital) LSC signal, including internal servo signals.
  - It must be able to add a stimulus to every LSC error and/or control signal using predefined waveforms (in band and out of band, up to several kHz).
  - It has the ability to store all important LSC signals plus a number of auxiliary signals simultaneously on disk for a duration up to 1 h.
  - It is able to correlate the LSC diagnostics read-outs with PEM signals (off-line).
- Digital part (secondary)
  - A high bandwidth digital link is necessary between LSC and diagnostics.
  - The storage hardware of the diagnostics system has to be able to sustain this data rate for about 1 h.
  - To support the PEM cross correlation the ISC sampling frequencies are integer multiples (or integer fractions) of the basic DAQ rate of 16384 Hz.
  - Timing accuracy of the data written by the diagnostics systems is half a DAQ tick, i.e. ~30 µs.
  - The data formats of DAQ and diagnostics are identical, i.e. the FRAME format is also used for the diagnostics data stream.

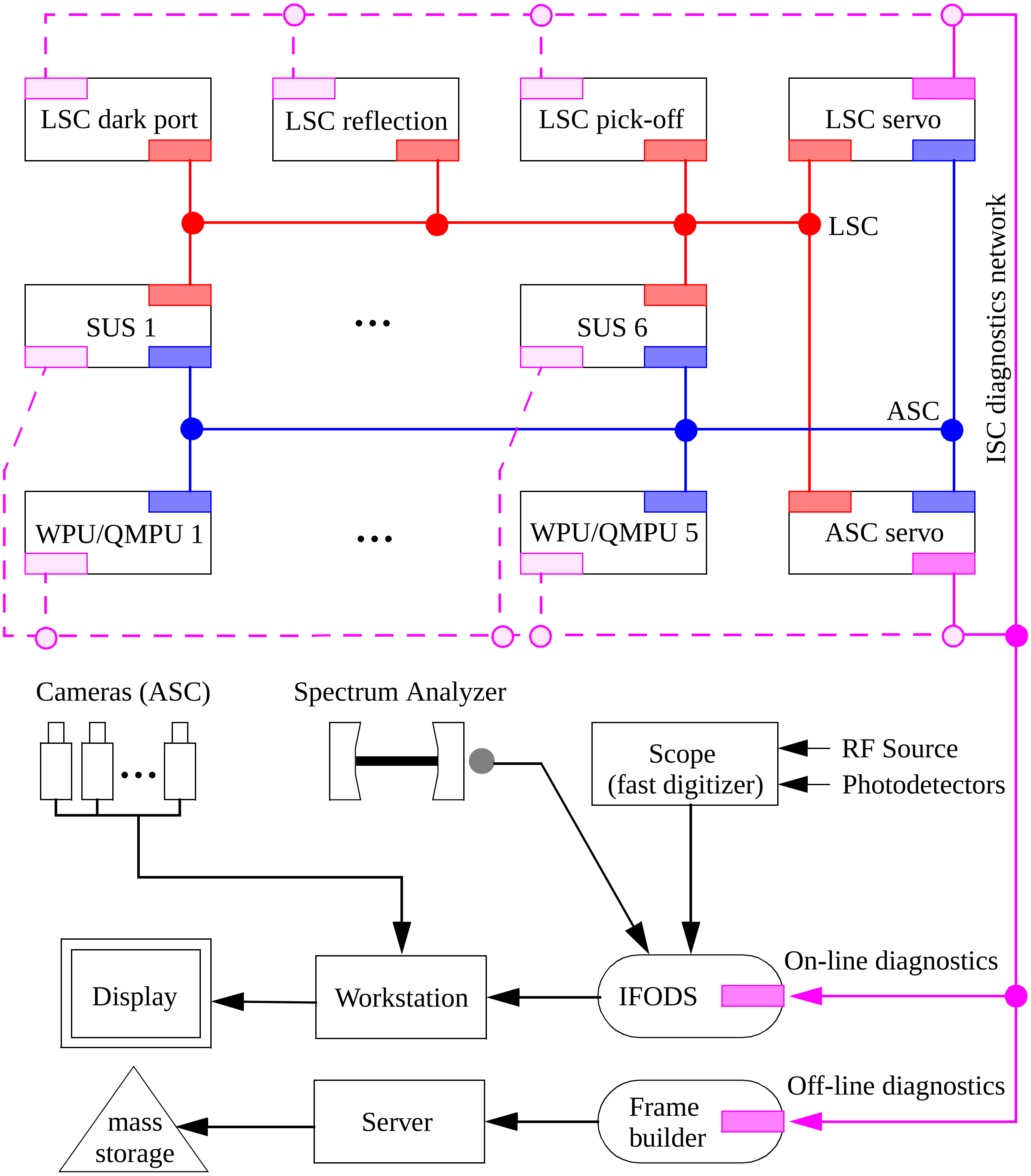
DIAGNOSTICS (2)

- Low frequency analog part
  - Crucial LSC signals which exist in analog form only (a candidate is the laser loop feedback) have to be digitized for the diagnostics system.
  - The remaining analog circuits (mainly amplifiers and filters) do not have be tested on the system level, nor have the tests to be computer controlled. For instance, anti-aliasing filters can be tested channel by channel by applying a test signal at the input and watching the output.
- RF part
  - The rf signals of each LSC length sensor signal can be monitored by taking snapshots (scope function).
  - To be able to reconstruct the full information carried by the modulation signal the down-conversion is performed in both phases.
  - The rf phase of the down-converted length signals can be adjusted remotely.
  - It can be verified that the RF sources supplies a local oscillator signal of the desired frequency and amplitude
  - Special purpose RF test equipment (e.g., spectrum and network analyzers TBD) can be interfaced, controlled as part of test procedures, and have their data integrated with other diagnostic information.

DIAGNOSTICS (3)

- Miscellaneous
  - At each port the intensity ratio between carrier and sidebands can be determined by a spectrum analyzer.
  - Video cameras monitor the beam at each port and can be used to as visual ‘lock’ indicators.
  - Single images of the beam can be stored for off-line analysis to investigate the higher order mode contents.

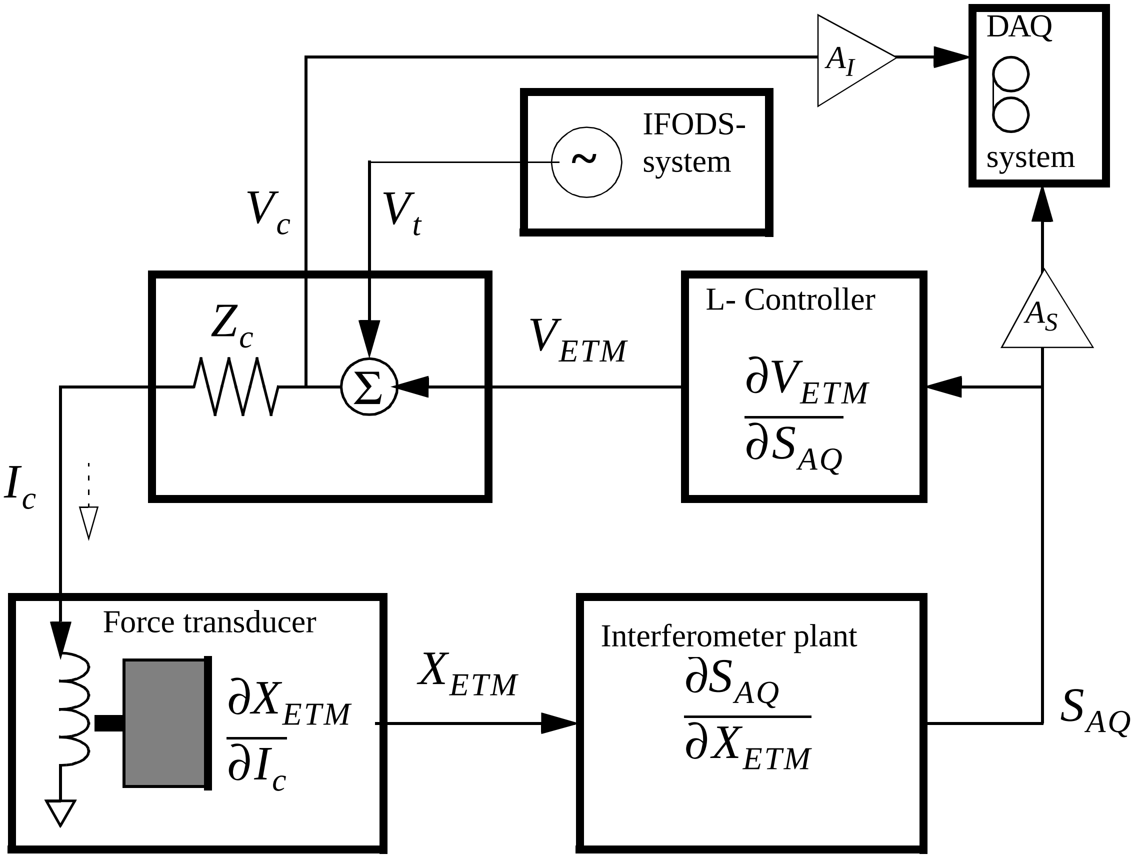
OVERVIEW


LSC dark port
LSC reflection
LSC pick-off
LSC servo
LSC
SUS 1
• • •
SUS 6
ASC
ISC diagnostics network
WPU/QMPU 1
• • •
WPU/QMPU 5
ASC servo
Cameras (ASC)
Spectrum Analyzer
Scope
(fast digitizer)
RF Source
Photodetectors
Display
Workstation
IFODS
On-line diagnostics
mass
storage
Server
Frame
builder
Off-line diagnostics

CALIBRATION

- ❑ Requirements
  - ❍ Absolute strain amplitude: 5%
  - ❍ Timing of incident GW: ±50 μsec relative to world time

COIL DRIVER



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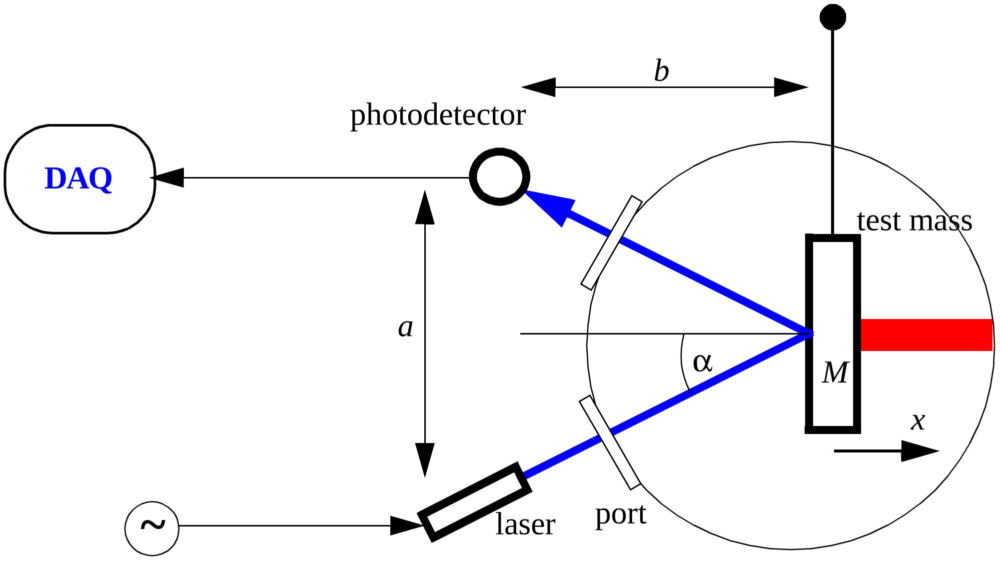
Description	**variable**	**init. error**	**est. drift (1 hr)**	**est. drift (40 hr)**
Coil current readout impedance	Z_c	.05%	.1%	.5%
Coil readout conversion gain	A_I	.05%	.1%	.5%
ETM mass	M	.1%	N/A	N/A
Coil/magnet force coefficient	dX_{ETM}/dI_c	1%	.5%	2%

PHOTON ACTUATOR



Description	**variable**	**nom. value**	**est. error + drift**	**unit**
Laser power	P	1 – 100	2%	mW
Laser wavelength	λ	980	0.5%	nm
ETM mass	M	10.70	0.1%[a]	kg
Incident angle cosine	$\cos\alpha$	.7	0.1%	~
Vacuum viewport transmission	T	.99	0.2%	
Monitor photodiode responsivity	R	100	0.2%	V/W

[a] Air buoyancy correction is of order 8 g.

LSC CDS Design Requirements

- RF Modulation and Demodulation
- RF Photodiodes
- Servo Electronics
- Diagnostics and Calibration
- Related Subsystems and Interfaces

RF Modulation and Demodulation

- The Resonant Sideband frequency used for all length sensing functions; 29.449 MHz for the 2 Km and 24.463 MHz for the 4 Km.
- The Nonresonant Sideband frequency used for ASC wavefront sensing purposes; 19.62 MHz (TBR) for the 2 Km and 36.79 MHz (TBR) for the 4 Km.
- The Mode Cleaner Length Sensing frequency which (if used) will be for the sensing and controlling of the mode cleaner cavity; 9.816 MHz for the 2 Km and 12.231 MHz for the 4 Km.
- Demodulator requirements are TBD

RF Photodiodes

- The photodiodes require a 10 volt bias voltage.
- The bias supply must provide 200 ma of continuous DC current at 10 volts and 400 ma transients for more than 1 msec
- The bias supply must have a current interrupt for DC current 20% above the steady DC current for about 1 msec.
- Each photodiode must have an independent DC and RF amplifier and DC current limiter.
- Each channel will have an active electronic bias voltage cutoff for transient currents of more than 20% of the nominal power and durations of more than 1 msec.
- The input referred electronic noise of the RF amplifier should be less than $1.2 nV\sqrt{Hz}$.
- The gain of the RF amplifier should nominally be 10.
- The gain must be linear for RF input voltages up to 100mV.

RF Photodiodes

- The circuit must be tuned to resonate at 25 MHz with a Q of (TBD).
- The circuit will have a frequency trap tuned to twice the resonant frequency such that the second harmonic is attenuated more than (TBD) dB down from the modulation frequency.
- The DC amplifier should provide a linear output for up to 200 ma of continuous DC input current.

Servo Electronics

- Arm cavity differential mode loop (driven by intensity noise specification)
- $|L_1 - L_2| < 10^{-13}\ \mathrm{m_{rms}}$
- Loop gain $< 10^{-7}$ (at 6.79 KHz (first test mass resonance)
- Electronic noise contributed by this loop must be at or below the LIGO strain requirement at all frequencies.
- Recycling cavity differential mode loop (driven by specification for dark asymmetric port)
- $|l_1 - l_2| < 10^{-9}\ \mathrm{m_{rms}}$
- Loop gain $< 10^{-7}$ at 3.58 KHz (first test mass resonance)
- Electronic noise in this loop must be at least a factor of 10 below the shot noise in the L_1-L_2 loop at frequencies above 200 Hz.

Servo Electronics

- Arm cavity common mode loop (driven by specification to maximize power in the cavity)

- $(k_l \cdot l_+) \leq 9 \times 10^{-6} radians$

- Gain at 1 Hz must be at least a factor of 130 greater than the gain at 1 Hz in the Michelson interferometer common mode loop.

- Electronic noise contributed by this loop must be at least a factor 10 below the shot noise in the L_1-L_2 loop at frequencies above 200 Hz.

- Recycling cavity common mode loop (driven by specification to maximize power in the Michelson interferometer).

- $|l_1+l_2| < 1.25\text{x}10^{-10}\ \text{m}_{rms}$

- Loop gain < 10^{-7} at 6.79 KHz (first test mass resonance)

- Electronic noise contributed by this loop must be at least a factor 10 below the shot noise in the L_1-L_2 loop at frequencies above 200 Hz.

Diagnostics and Calibration

- The following requirements apply to the accuracy of the calibration of the gravity wave readout channel in the band of 40 Hz - 10 KHz:
    - ››Amplitude: better than ± 5%
    - ››Timing: better than ± 50 µsec
- The readout of the three auxiliary lengths must be accurate to within ± 10% in amplitude and ± 100 µsec in timing in the 40 Hz - 10 KHz band.

Diagnostics and Calibration

- The LSC must be able to perform diagnostics to determine the proper functioning of the LSC in Detection Mode, and to support the operation of the interferometer in a subset of alternate optical configurations (single cavity, etc.). The following functions must be provided for:
    - Determination of closed loop transfer functions of the control loops.
    - Determination of offsets in the lock-points.
    - Determination of gravity wave detection band noise produced by the LSC.
    - Monitoring of feedback forces applied to the controlled optics.

Related Subsystems and Interfaces

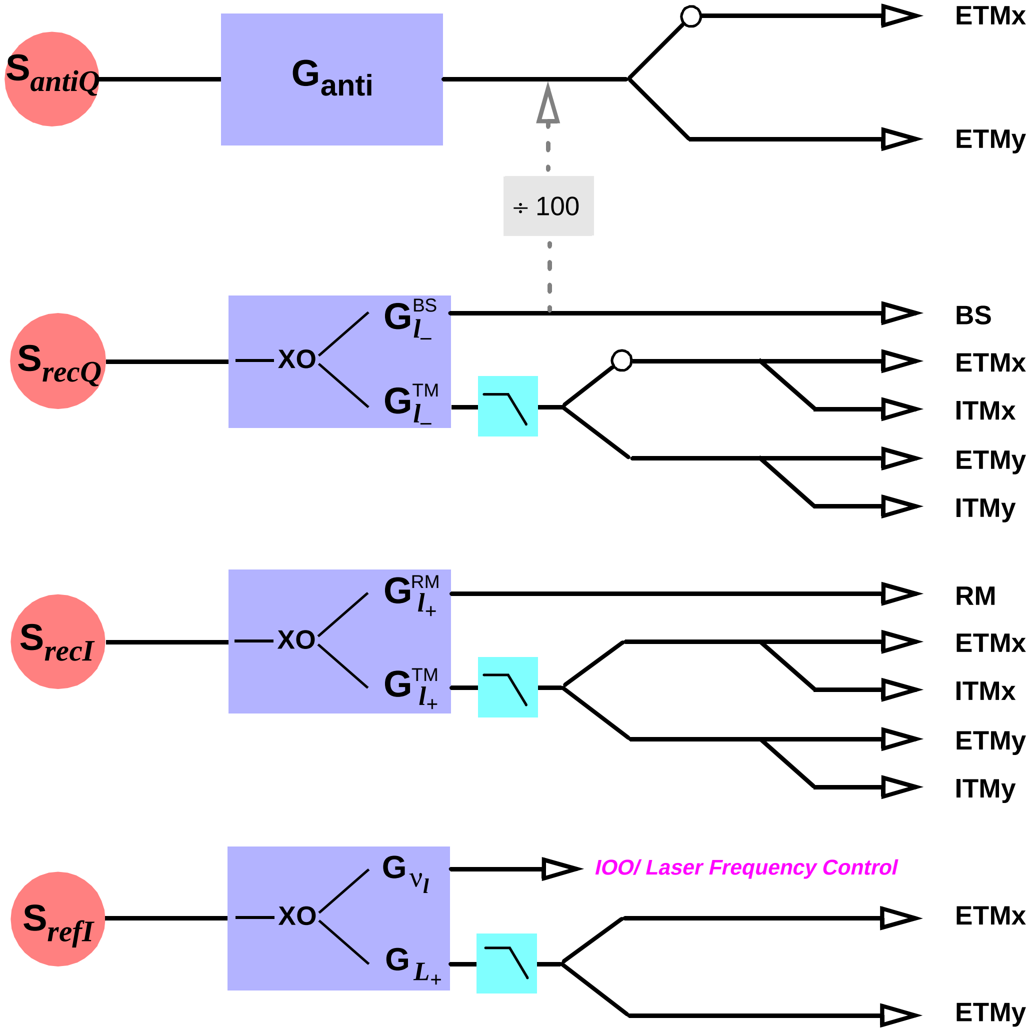
- Suspension System (SUS) Interface
  - Each suspended optic controlled by the LSC electronics has a suspension controller between the LSC servo controller output and the suspended optic. Each of these suspension controllers will have a single input from the LSC. This interface has the following characteristics (TBD).
- Input Optics and Prestabilized Laser Interface
  - The LSC makes the final corrections to the laser frequency through frequency actuators in the IOO subsystem. Specifically, there are two inputs to the IOO for frequency actuation: one for control of the mode cleaner length, and a second that is a summing input to the IOO frequency stabilization loop after the mode cleaner demodulator (i.e., the additive offset).
- Alignment Sensing and Control Interface
  - The LSC must provide lock status information to the ASC subsystem (TBD).

Related Subsystems and Interfaces

- Data Acquisition Interface
  - The interface to the Data Acquisition system is TBD.

LSC CDS Conceptual Design

- RF Modulation and Demodulation
  - f_R noise requirements were confronted with a prototype system on the 40 meter
- RF Photodiodes
  - Current plan is to modify the design of the photodiode circuit used in 40 meter
- Servo Electronics
  - Most of CDS effort was spent studying digital servo issues
- Related Subsystems and Interfaces
  - Suspension system
  - Input Optics and Prestabilized Laser
  - Alignment Sensing and Control
  - Data Acquisition



Sensing and Control Configuration Diagram

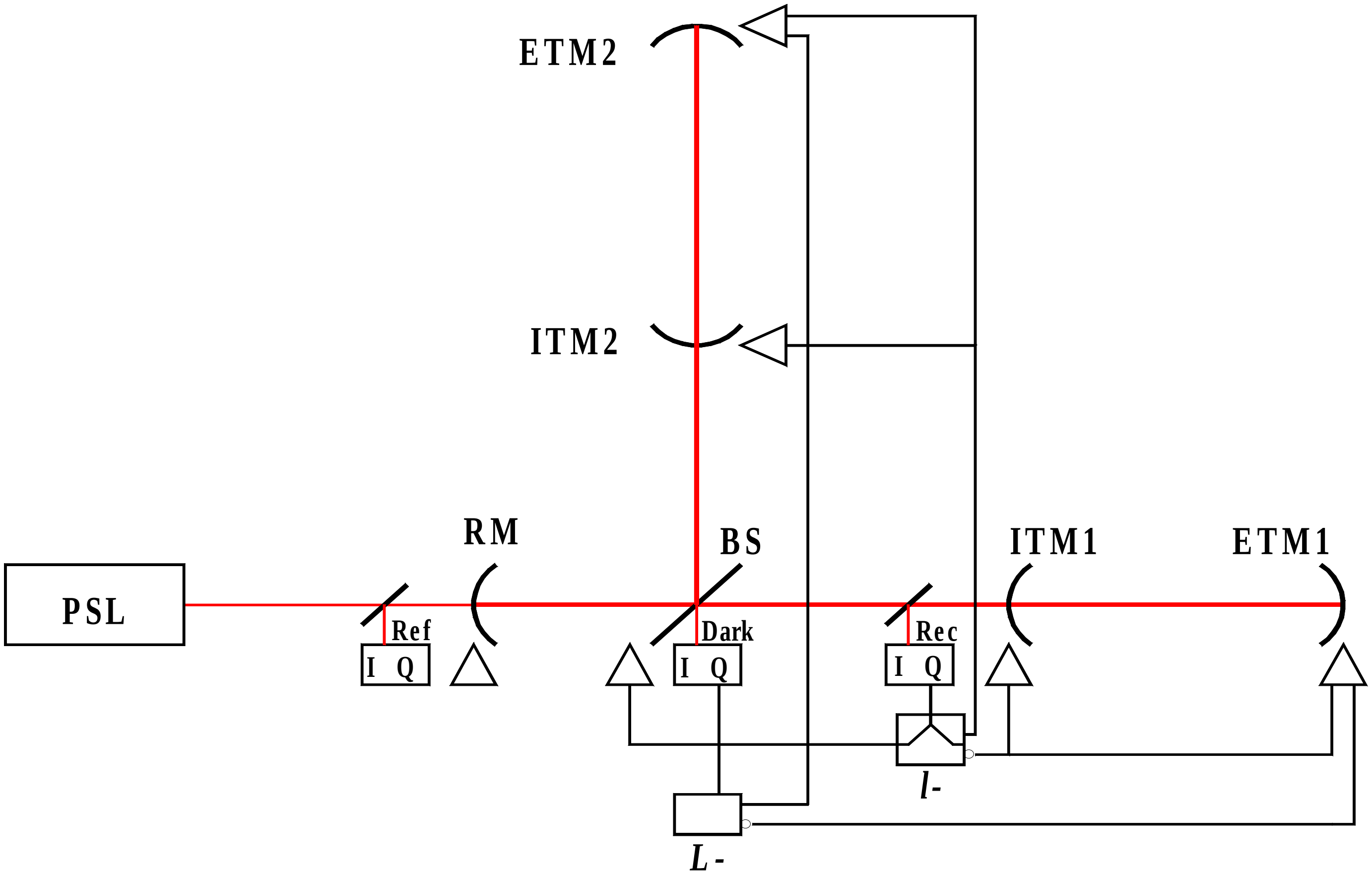


Figure 2: *L1-L2* and *l1-l2* servos in Detection Mode. *l-* crossover frequency ~ 1 to 2 Hz

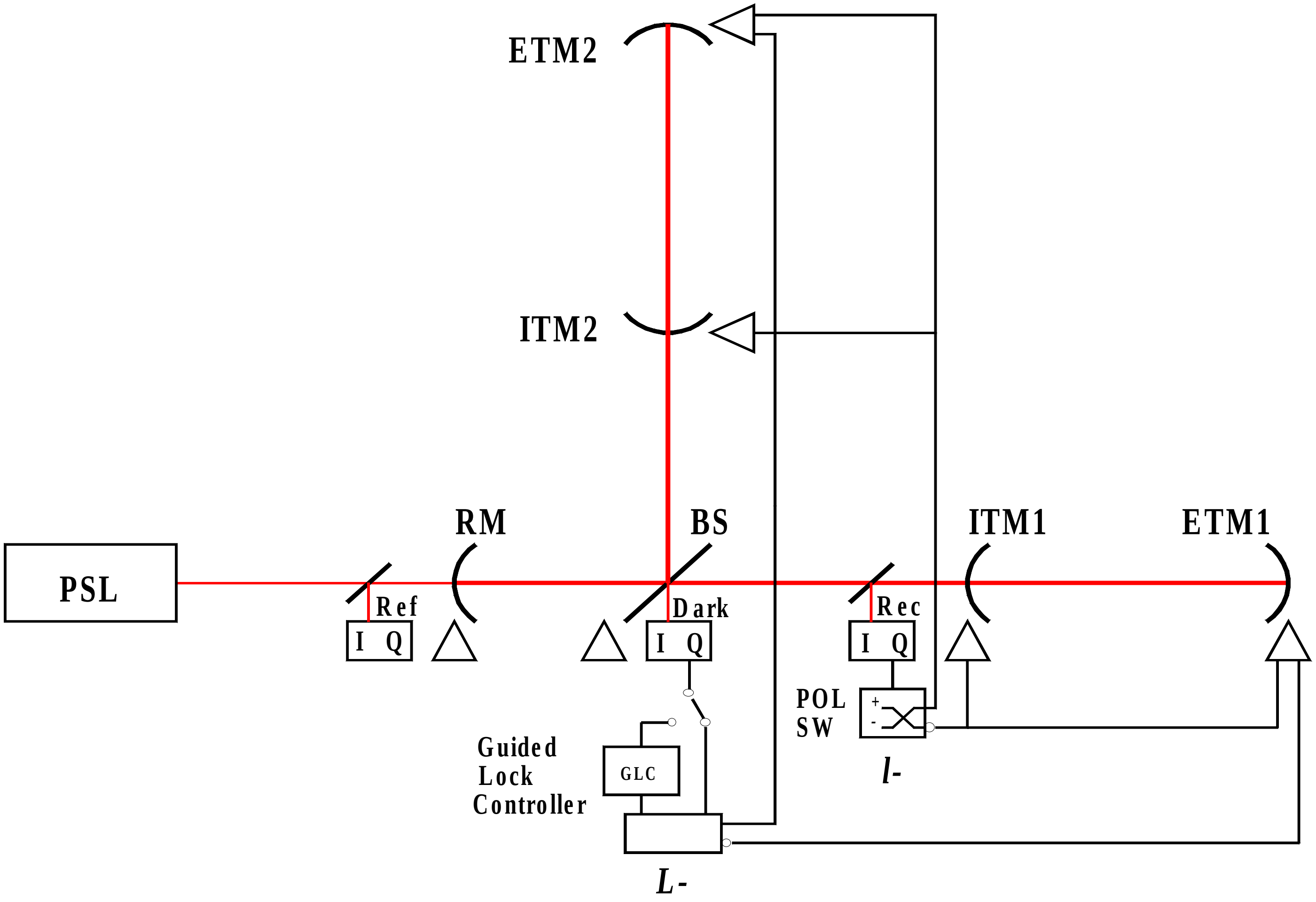


Figure 3: *L1-L2* and *l1-l2* servos in Acquisition Mode

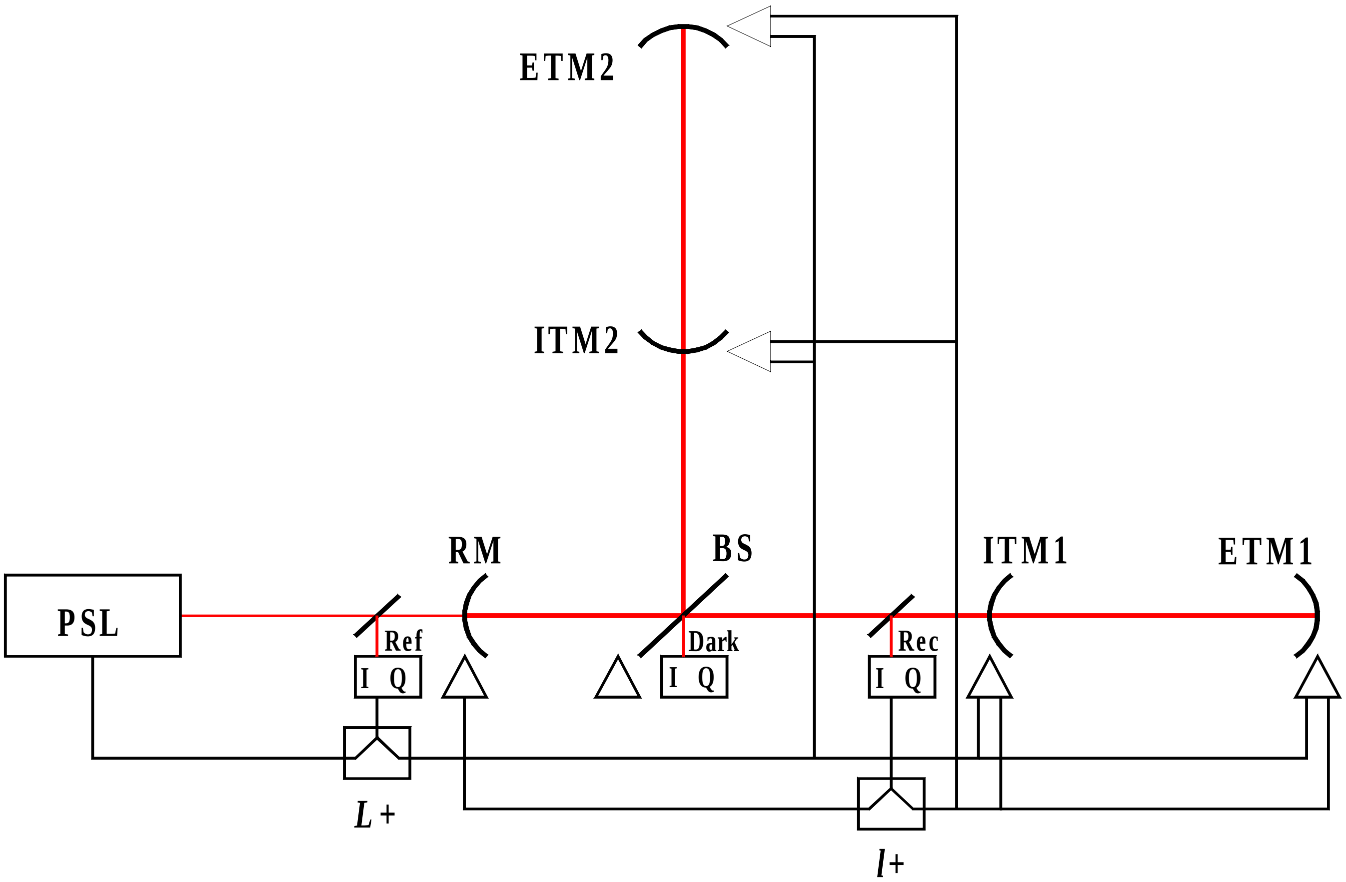


Figure 4: *L1+L2* and *l1+l2* servos in Detection Mode. *l+* crossover frequency ~ 1 to 2 Hz

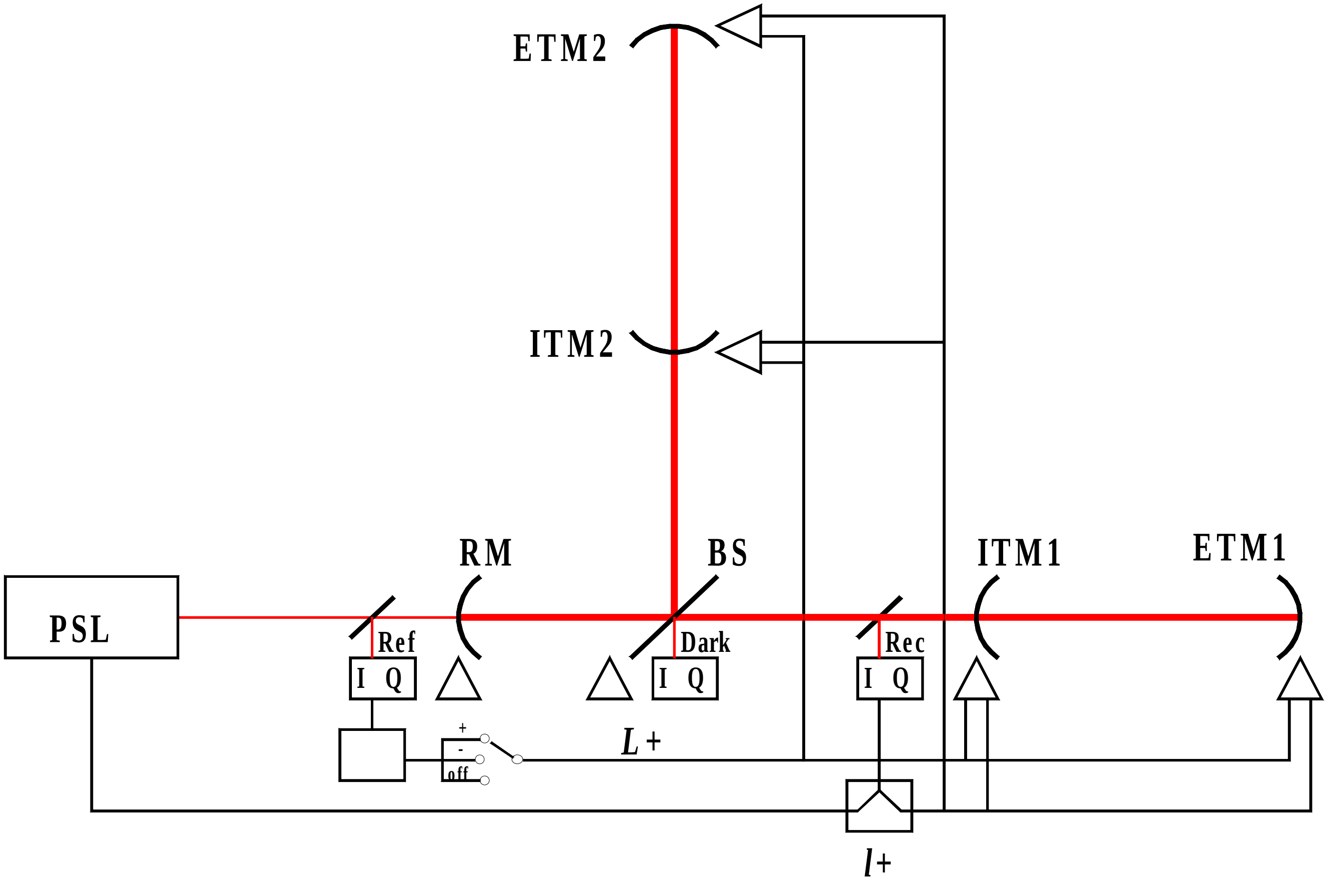


Figure 5: *L1+L2* and *l1+l2* servos in Acquisition Mode

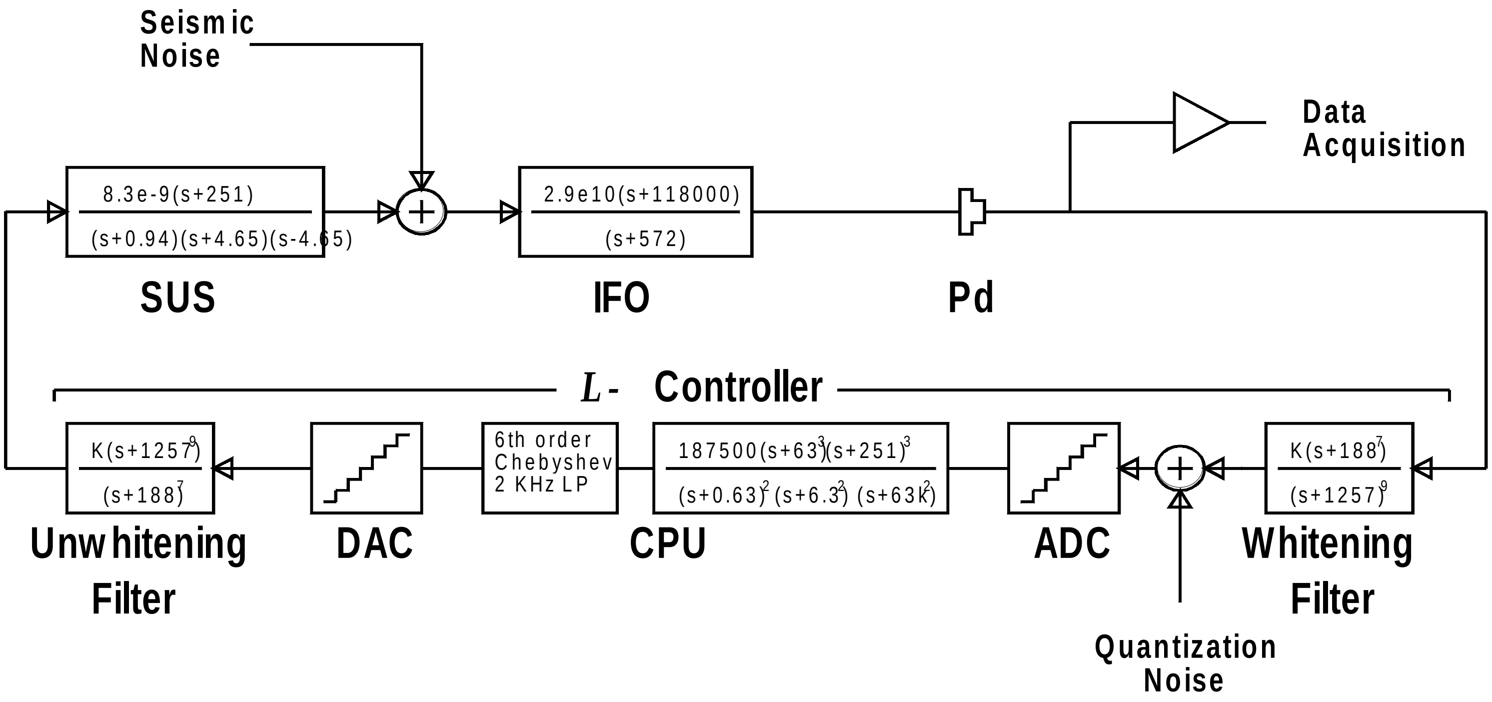
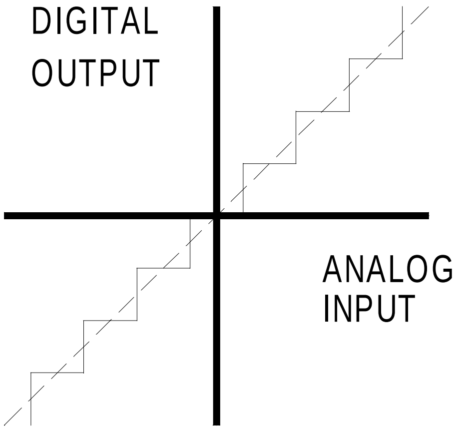
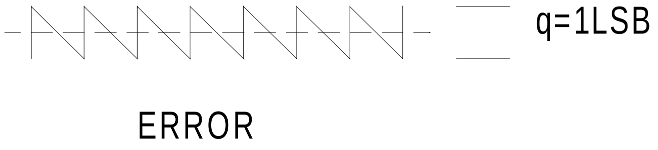


Figure 6: Block diagram of the *L1-L2* servo loop.

$$n_{qpd} = \frac{n_q \cdot Cont \cdot SUS \cdot IFO}{1 + wf \cdot Cont \cdot SUS \cdot IFO} \cong \frac{n_q}{wf}$$



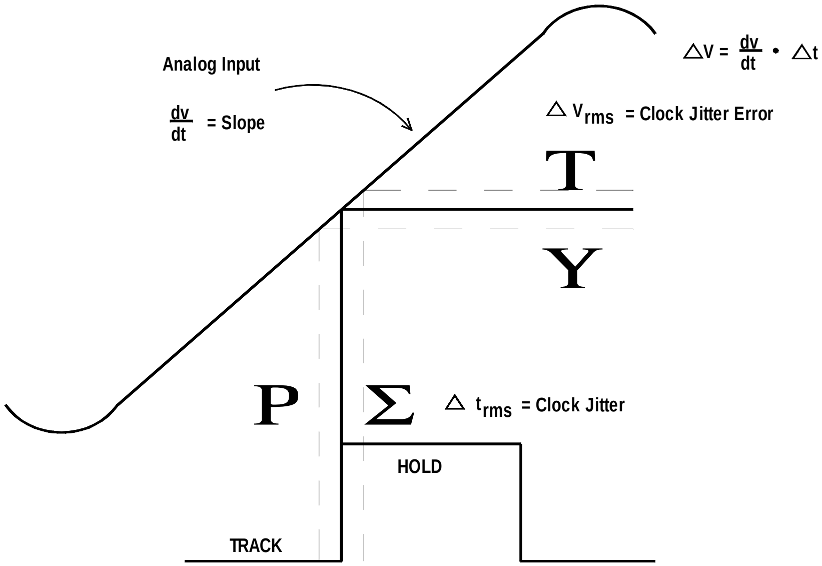


SNR due to Quantization Noise

$$SNR_q = 6.02n + 1.76 + 10\log\left(\frac{f_s}{2f_a}\right)[dB]$$

Quantization noise in V/rtHz

$$N_q = \frac{V_{fullscale}}{2^n\sqrt{3f_s}}[V/\sqrt{Hz}]$$



SNR due to Aperture/clock Jitter

$$SNR_j = 20\log\left(\frac{1}{2\pi f_a t_j}\right)[dB]$$

Noise due to Aperture/clock jitter

$$N_j = S(f)\cdot\frac{\pi f t_j}{\sqrt{2}}[V/\sqrt{Hz}]$$

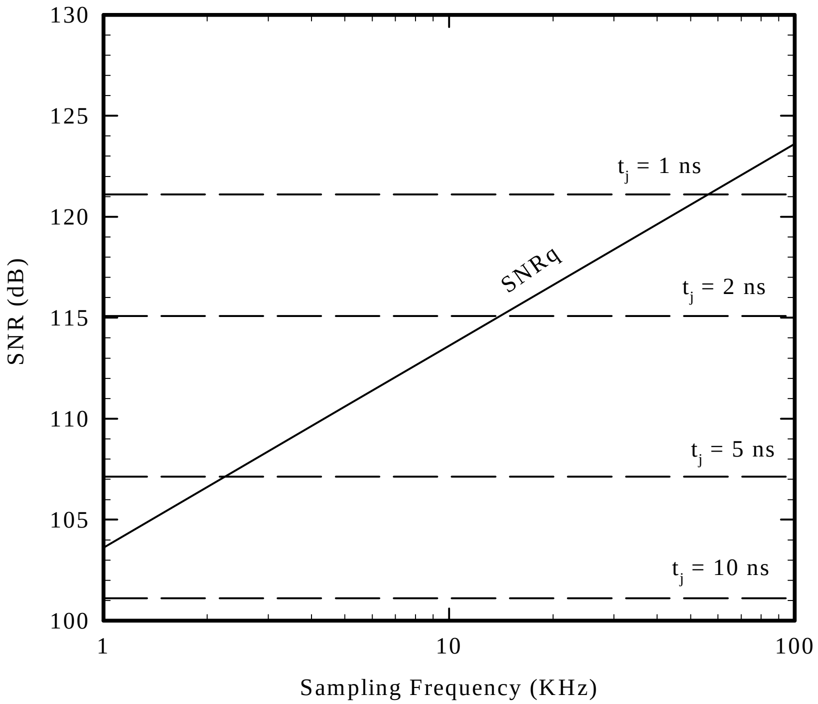


Figure 7: Signal-to-Noise ratio from quantization noise (SNR_q) and clock jitter (t_j) as a function of frequency at a bandwidth of 140 Hz.

$$\mathrm{Lminus}(s) := \frac{K\cdot(s+40\cdot\tau)^2\cdot(s+50\cdot\tau)\cdot(s+10\cdot\tau)\cdot(s+18800\cdot\tau)}{(s+0.1\cdot\tau)^2\cdot(s+500\cdot\tau)\cdot(s+1000\cdot\tau)^2\cdot(s+91\cdot\tau)\cdot(s+j\cdot0.74\cdot\tau)\cdot(s-j\cdot0.74\cdot\tau)}$$

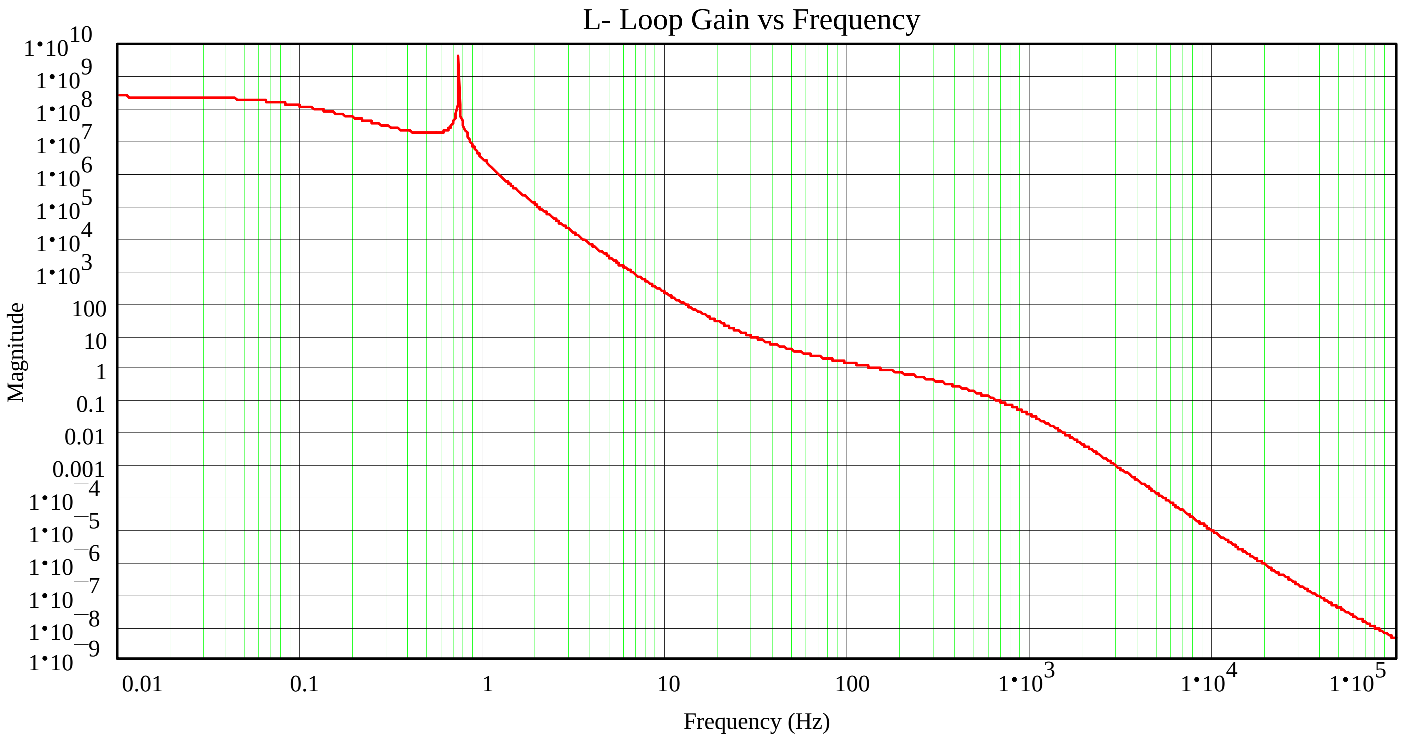


Figure 9: *L-* Loop Gain

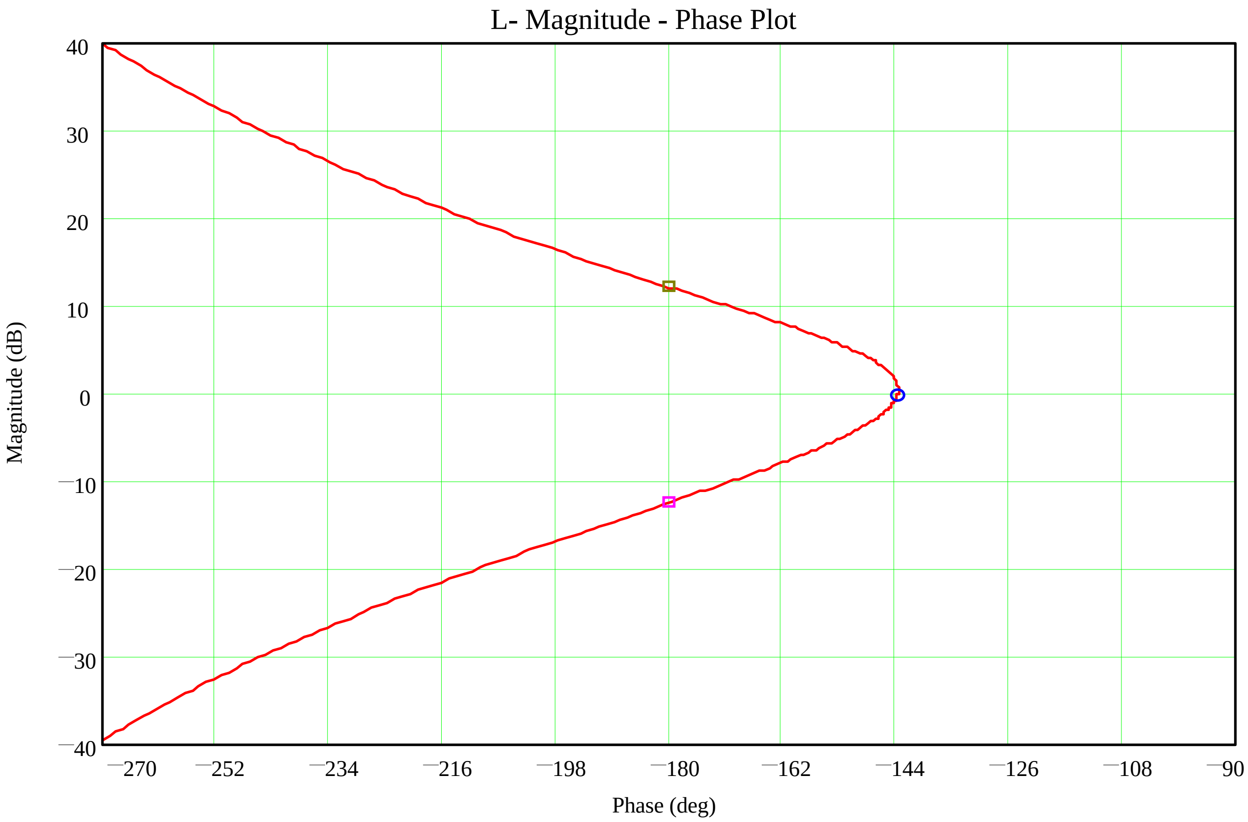


Figure 10: *L*- Magnitude - Phase plot. This shows a conditionally stable loop gain with a gain margin of ± 12 dB and a phase margin of 36°.

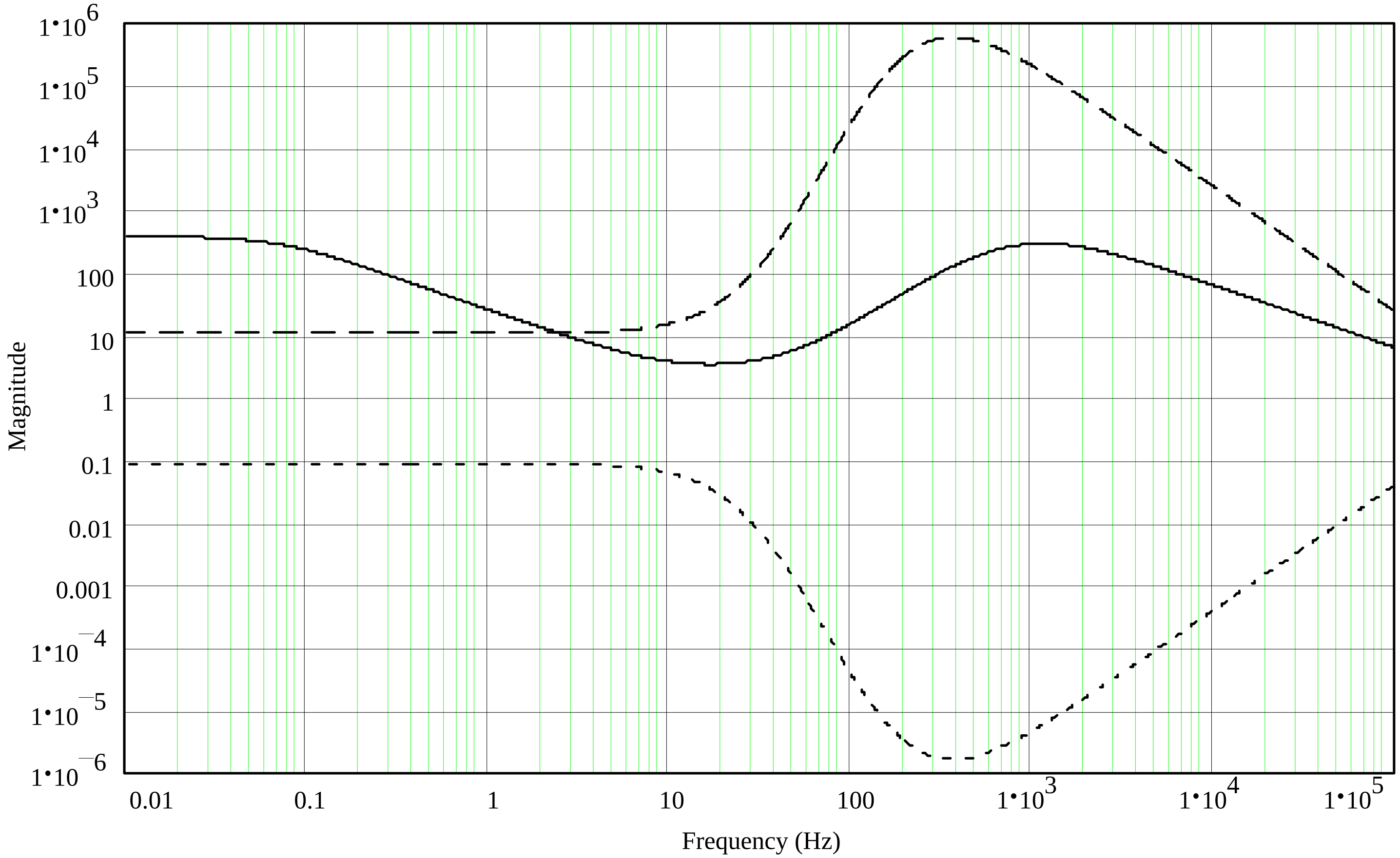


Figure 11: ***L*****- controller transfer function (solid line), example whitening filter (dashed line), example unwhitening filter (dotted line). The whitening filter has 7 zeros at 30 Hz and 9 poles at 200 Hz.**

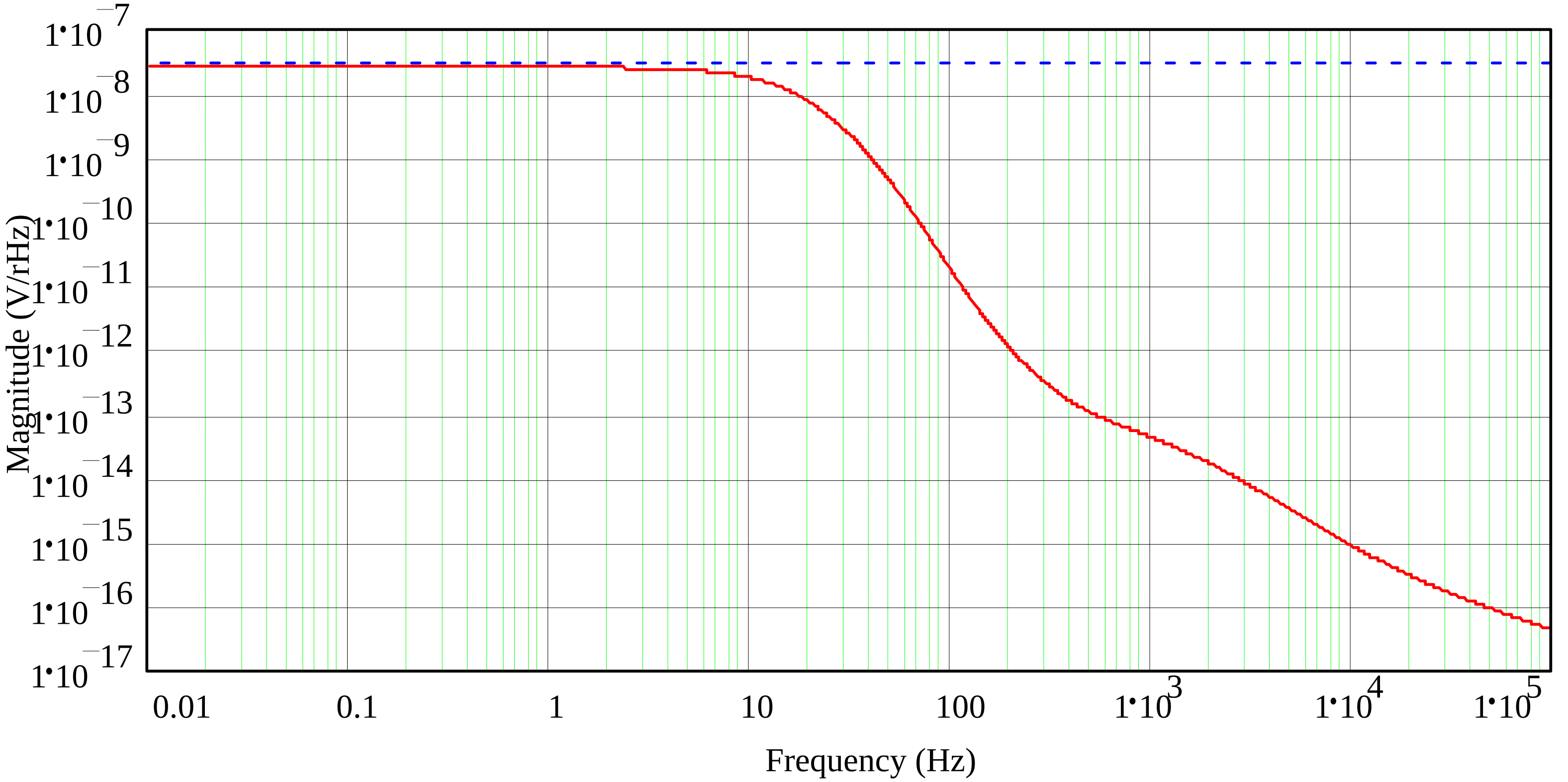


Figure 12: ADC quantization noise (solid line) at the photodiode. ***L-*** **electronic noise requirement at the photodiode.**

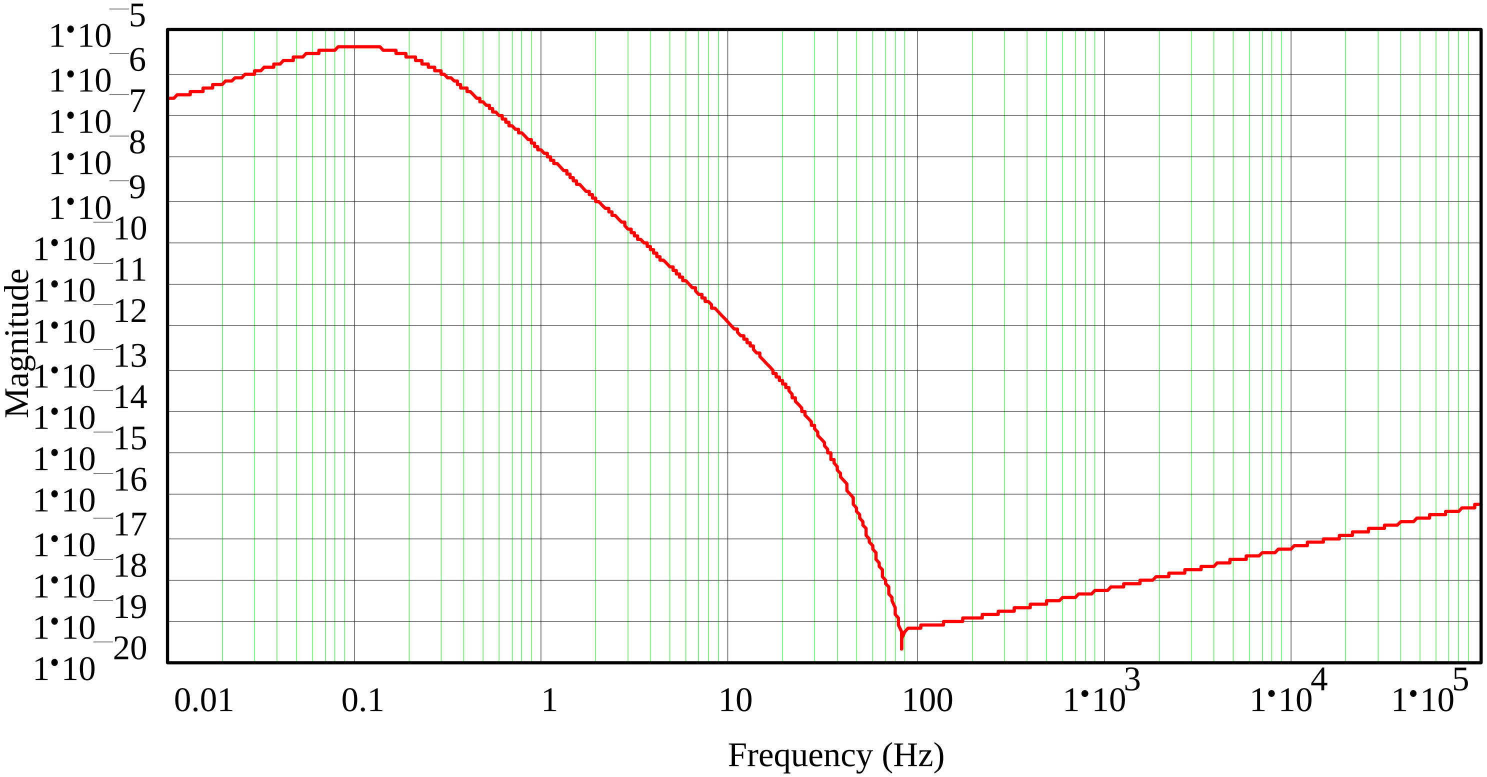


Figure 13: Approximate model of the seismic noise plus shot noise used as input to the closed loop servo model. Magnitude is in m/rtHz.

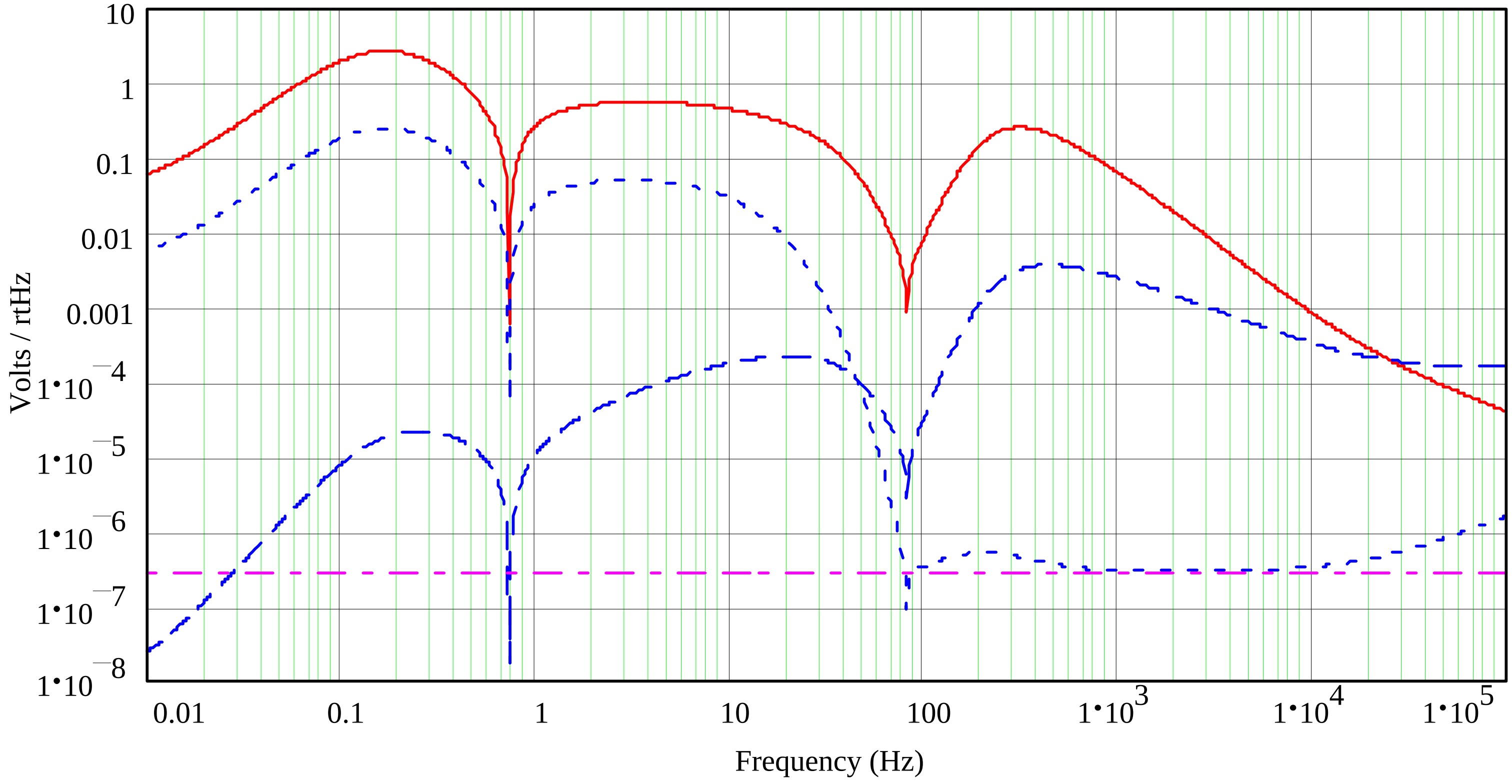


Figure 14: Seismic and shot noise at the input to the ADC after whitening filter (solid line), with no whitening filter (dotted line), digitization noise due to 1µsec clock jitter (dashed line), and quantization noise from figure 14 (dash-dot line).

Prototype & First Article Test Plans

- ❑ LSC subsystem is very difficult to test as an isolated system
- ❑ Several areas of completely new techniques & technologies:
  - ›› lock acquisition
  - ›› digital control system
  - ›› high power detection/InGaAs photodiodes
- ❑ How do we make meaningful tests of these components?

Lock Acquisition

- 40 meter recycling program - differences between 40m and LIGO prevent success with 40m being directly applied to LIGO, but:
  - 40m testing can point out unforeseen problems with planned acquisition sequence
  - 40m experience may lead to new (better) ideas on how to do the acquistion
  - validation of the acquisition modeling output (SMAC)

Photodetectors

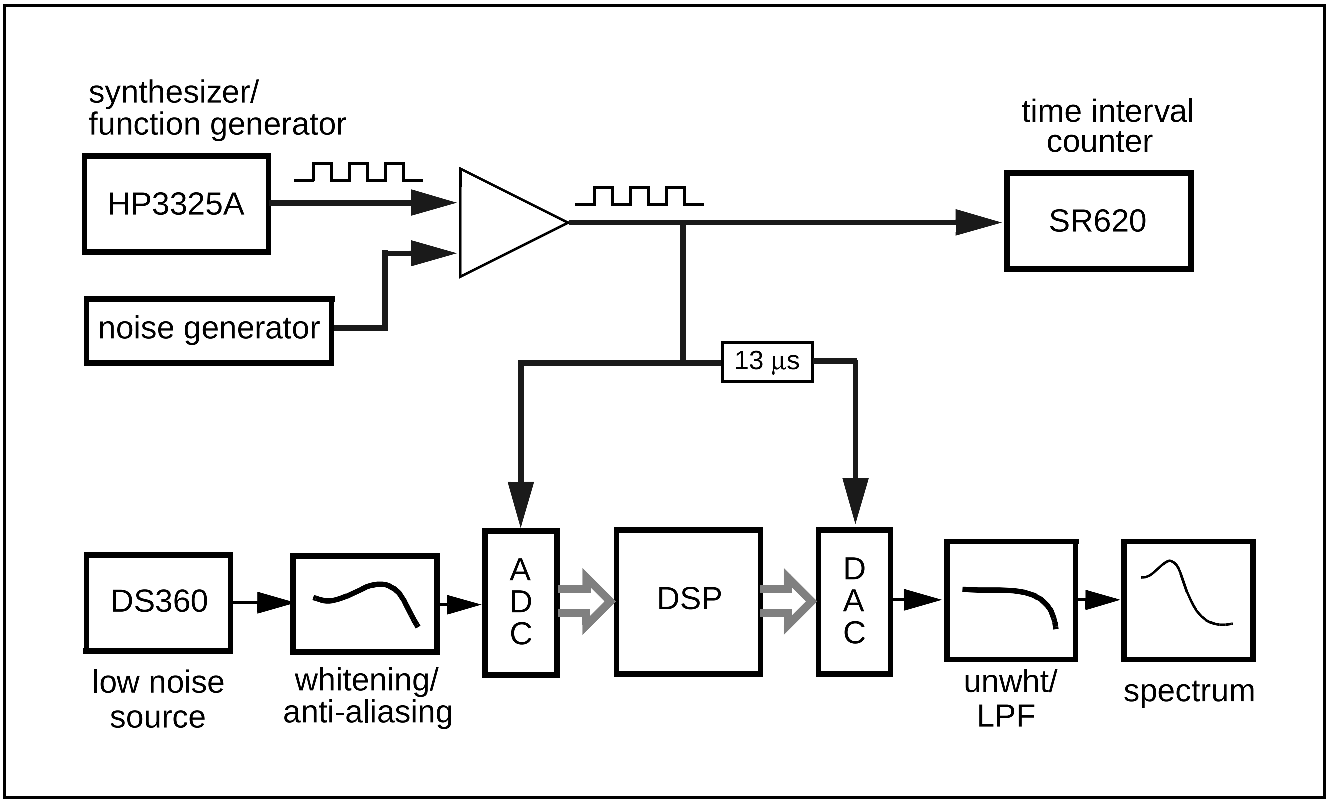
- Additional Device tests:
  - photodiode backscattering
  - high power transient behavior (w/ high power laser)
  - non-linearity and harmonic distortion - synthesize a realistic AM waveform on the light (based on output of Detection mode simulations)
- Photodetector Assembly tests
  - Initial PD for the PNI - using a 2mm Hamamatsu diode with a modified version of the new (40m) CDS preamp package
  - First article LIGO detector assembly will be built in the final design phase, & tested for:
    - Backscattering
    - Adequacy of heatsinking
    - Transient protection
    - RFI (adequacy of shielding)
    - Alignment issues
    - tested on PNI

Signal Processing Tests

- Tests broken up into three parts, to isolate specific aspects of the technology:
  - single channel, open loop tests
  - single channel, closed loop tests
  - multiple channel tests

Signal Processing tests

❑ Single channel, Open loop:



- ❍ ADC noise as a function of sampling frequency & clock jitter
- ❍ dynamic range limits
- ❍ DAC output noise
- ❍ time delays/latencies in the chain
- ❍ coding of the DSP for transfer function implementation
- ❍ whitening/unwhitening filters

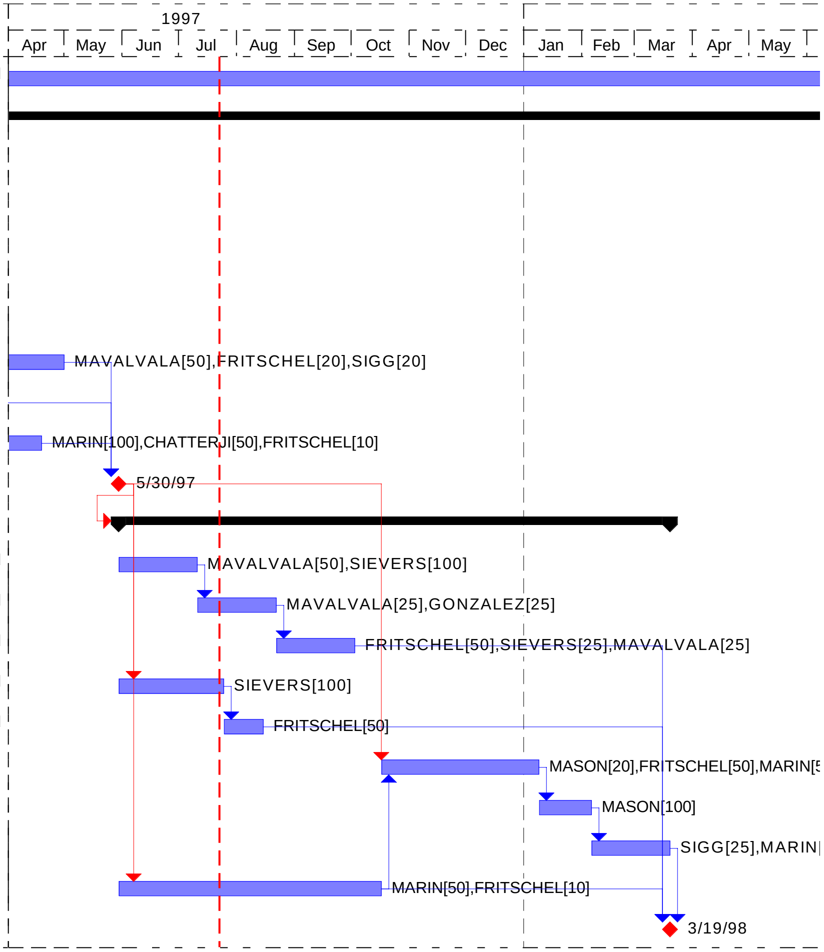
Signal Processing Tests

- ❑ Single channel, closed loop
  - ›› verify stable operation of the loop
  - ›› perform diagnostic functions on loop, such as a closed loop transfer function, step response
  - ›› components to be included in the loop are TBD
- ❑ Multiple channel tests
  - ›› implementation of all four length channels
  - ›› testing the interfacing of the various sensors via the network/reflective memory
  - ›› testing software & processing performance for the full system

LSC Final Design: Baseline

ISC REPLAN - Wed 7/23/97 15:39

ID	Task Name	Start	Finish	Late Start	Late Finish	Free Slack	Total Slack
1	ISC MANAGEMENT	Mon 1/1/96	Thu 12/31/98	Fri 6/14/96	Wed 6/16/99	119d	119d
2	LSC- SUMMARY	Tue 1/3/95	Wed 6/16/99	Tue 1/3/95	Wed 6/16/99	0d	0d
3	LSC INTERFACE DET	Tue 1/3/95	Tue 4/30/96	Tue 1/3/95	Tue 4/30/96	0d	0d
4	LSC TEST PLAN	Fri 12/1/95	Tue 4/30/96	Fri 12/1/95	Tue 4/30/96	0d	0d
5	LSC CONCEPTUAL D	Fri 12/1/95	Tue 4/30/96	Fri 12/1/95	Tue 4/30/96	0d	0d
6	LSC OPERATIONS	Tue 1/3/95	Thu 2/29/96	Tue 1/3/95	Thu 2/29/96	0d	0d
7	LSC DRR	Tue 4/30/96	Tue 4/30/96	Tue 4/30/96	Tue 4/30/96	0d	0d
8	LSC PRELIMINARY D	Fri 5/17/96	Wed 4/30/97	Fri 5/17/96	Thu 5/29/97	21d	21d
9	LSC ACQ SERVO MO	Tue 1/3/95	Wed 1/1/97	Tue 1/3/95	Wed 1/1/97	0d	0d
10	LSC PD PROTO TEST	Sat 11/30/96	Fri 4/18/97	Sat 11/30/96	Thu 5/29/97	29d	29d
11	LSC PDR	Fri 5/30/97	Fri 5/30/97	Fri 5/30/97	Fri 5/30/97	0d	0d
12	LSC FINAL DESIGN-S	Fri 5/30/97	Thu 3/19/98	Fri 5/30/97	Thu 3/19/98	0d	0d
13	LSC - CONTROL	Fri 5/30/97	Thu 7/10/97	Fri 11/14/97	Thu 12/25/97	0d	120d
14	LSC - CONTROL	Fri 7/11/97	Thu 8/21/97	Fri 12/26/97	Thu 2/5/98	0d	120d
15	LSC SEQUENC	Fri 8/22/97	Thu 10/2/97	Fri 2/6/98	Thu 3/19/98	120d	120d
16	LSC - ACQUISIT	Fri 5/30/97	Thu 7/24/97	Fri 1/2/98	Thu 2/26/98	0d	155d
17	LSC - SEQUEN	Fri 7/25/97	Thu 8/14/97	Fri 2/27/98	Thu 3/19/98	155d	155d
18	LSC - PD OPTICA	Fri 10/17/97	Thu 1/8/98	Fri 10/17/97	Thu 1/8/98	0d	0d
19	LSC - PD THER	Fri 1/9/98	Thu 2/5/98	Fri 1/9/98	Thu 2/5/98	0d	0d
20	LSC - PD ELECT	Fri 2/6/98	Thu 3/19/98	Fri 2/6/98	Thu 3/19/98	0d	0d
21	LSC -PD FIRST A	Fri 5/30/97	Thu 10/16/97	Fri 5/30/97	Thu 10/16/97	0d	0d
22	LSC FDR	Thu 3/19/98	Thu 3/19/98	Thu 3/19/98	Thu 3/19/98	0d	0d



LSC Final Design: Update Actual PDR

ISC REPLAN - Wed 7/23/97 15:50

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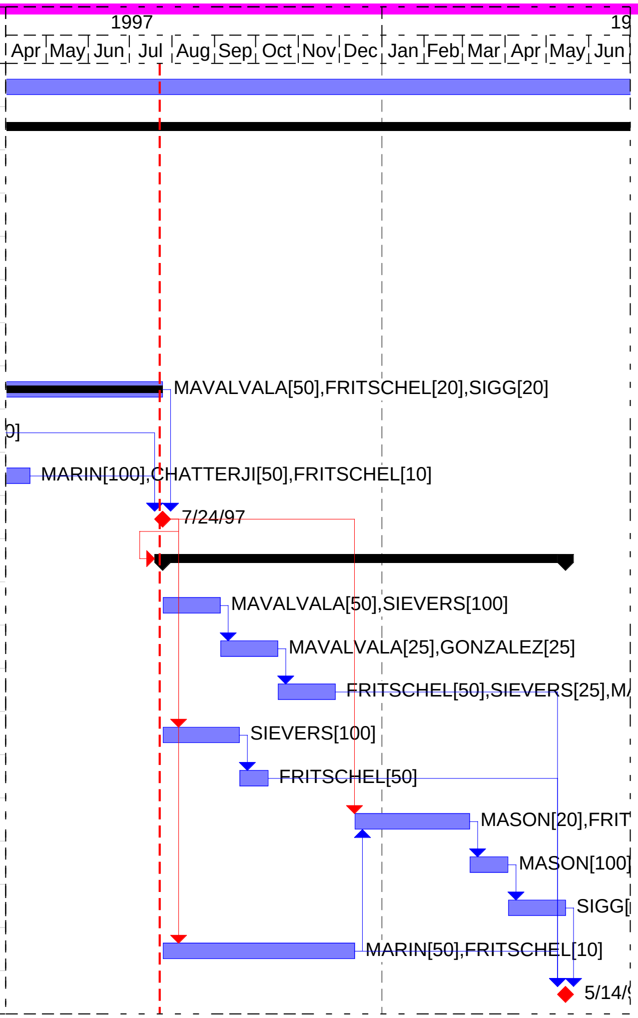
1	ISC MANAGEMENT	Mon 1/1/96	Thu 12/31/98	784d
2	LSC- SUMMARY	Tue 1/3/95	Wed 8/11/99	1202d
3	LSC INTERFACE DET/FAC	Tue 1/3/95	Tue 4/30/96	346d
4	LSC TEST PLAN	Fri 12/1/95	Tue 4/30/96	108d
5	LSC CONCEPTUAL DESIGN	Fri 12/1/95	Tue 4/30/96	108d
6	LSC OPERATIONS SERVO MODEL	Tue 1/3/95	Thu 2/29/96	303d
7	LSC DRR	Tue 4/30/96	Tue 4/30/96	0d
8	LSC PRELIMINARY DESIGN	Fri 5/17/96	Thu 7/24/97	310d
9	LSC ACQ SERVO MODEL	Tue 1/3/95	Wed 1/1/97	522d
10	LSC PD PROTO TEST	Sat 11/30/96	Fri 4/18/97	100d
11	LSC PDR	Thu 7/24/97	Thu 7/24/97	0d
12	LSC FINAL DESIGN-SUMMARY	Fri 7/25/97	Thu 5/14/98	210d
13	LSC - CONTROL LOOP DESIGN & VALIDA	Fri 7/25/97	Thu 9/4/97	30d
14	LSC - CONTROL LOOP ROBUSTNESS	Fri 9/5/97	Thu 10/16/97	30d
15	LSC SEQUENCING & DIAG FINAL DESIGN	Fri 10/17/97	Thu 11/27/97	30d
16	LSC - ACQUISITION SEQUENCE DESIGN	Fri 7/25/97	Thu 9/18/97	40d
17	LSC - SEQUENCE TRANSITION ANALYSIS	Fri 9/19/97	Thu 10/9/97	15d
18	LSC - PD OPTICAL DESIGN	Fri 12/12/97	Thu 3/5/98	60d
19	LSC - PD THERM/MECH DESIGN	Fri 3/6/98	Thu 4/2/98	20d
20	LSC - PD ELECT DESIGN	Fri 4/3/98	Thu 5/14/98	30d
21	LSC -PD FIRST ARTICLE TEST	Fri 7/25/97	Thu 12/11/97	100d
22	LSC FDR	Thu 5/14/98	Thu 5/14/98	0d



LSC Final Design: Raid ASC Workforce

ISC REPLAN - Wed 7/23/97 15:46

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2	LSC- SUMMARY	Tue 1/3/95	Wed 3/10/99	1092d
3	LSC INTERFACE DET/FAC	Tue 1/3/95	Tue 4/30/96	346d
4	LSC TEST PLAN	Fri 12/1/95	Tue 4/30/96	108d
5	LSC CONCEPTUAL DESIGN	Fri 12/1/95	Tue 4/30/96	108d
6	LSC OPERATIONS SERVO MODEL	Tue 1/3/95	Thu 2/29/96	303d
7	LSC DRR	Tue 4/30/96	Tue 4/30/96	0d
8	LSC PRELIMINARY DESIGN	Fri 5/17/96	Thu 7/24/97	310d
9	LSC ACQ SERVO MODEL	Tue 1/3/95	Wed 1/1/97	522d
10	LSC PD PROTO TEST	Sat 11/30/96	Fri 4/18/97	100d
11	LSC PDR	Thu 7/24/97	Thu 7/24/97	0d
12	LSC FINAL DESIGN-SUMMARY	Fri 7/25/97	Thu 12/11/97	100d
13	LSC - CONTROL LOOP DESIGN & VALIDATION	Fri 7/25/97	Thu 9/4/97	30d
14	LSC - CONTROL LOOP ROBUSTNESS	Fri 9/5/97	Thu 10/16/97	30d
15	LSC SEQUENCING & DIAG FINAL DESIGN	Fri 10/17/97	Thu 11/27/97	30d
16	LSC - ACQUISITION SEQUENCE DESIGN	Fri 9/5/97	Thu 10/30/97	40d
17	LSC - SEQUENCE TRANSITION ANALYSI	Fri 10/31/97	Thu 11/20/97	15d
18	LSC - PD OPTICAL DESIGN	Fri 7/25/97	Thu 10/16/97	60d
19	LSC - PD THERM/MECH DESIGN	Fri 10/17/97	Thu 11/13/97	20d
20	LSC - PD ELECT DESIGN	Fri 10/17/97	Thu 11/27/97	30d
21	LSC -PD FIRST ARTICLE TEST	Fri 7/25/97	Thu 12/11/97	100d
22	LSC FDR	Thu 12/11/97	Thu 12/11/97	0d