Length Sensing & Control (LSC)

Final Design Review

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LIGO-G980111--00-D

FDR Outline

- Introduction & committee charge (DHS, 5')
- Scope & system overview (MZ, 10')
- Photodetectors (MZ, 15')
- Modulation, demodulation, & shutters (PF, 10')
- Acquisition mode controls (BW, 20')
- Detection mode controls (PF/NM, 30')
- Whitening & signal conditioning (PF, 10')
- LSC mixed-signal control test on the PNI (ED, 15')
- Implementation staff, schedule & budget (MEZ, 10')
- Discussion and action items (DHS, ?)

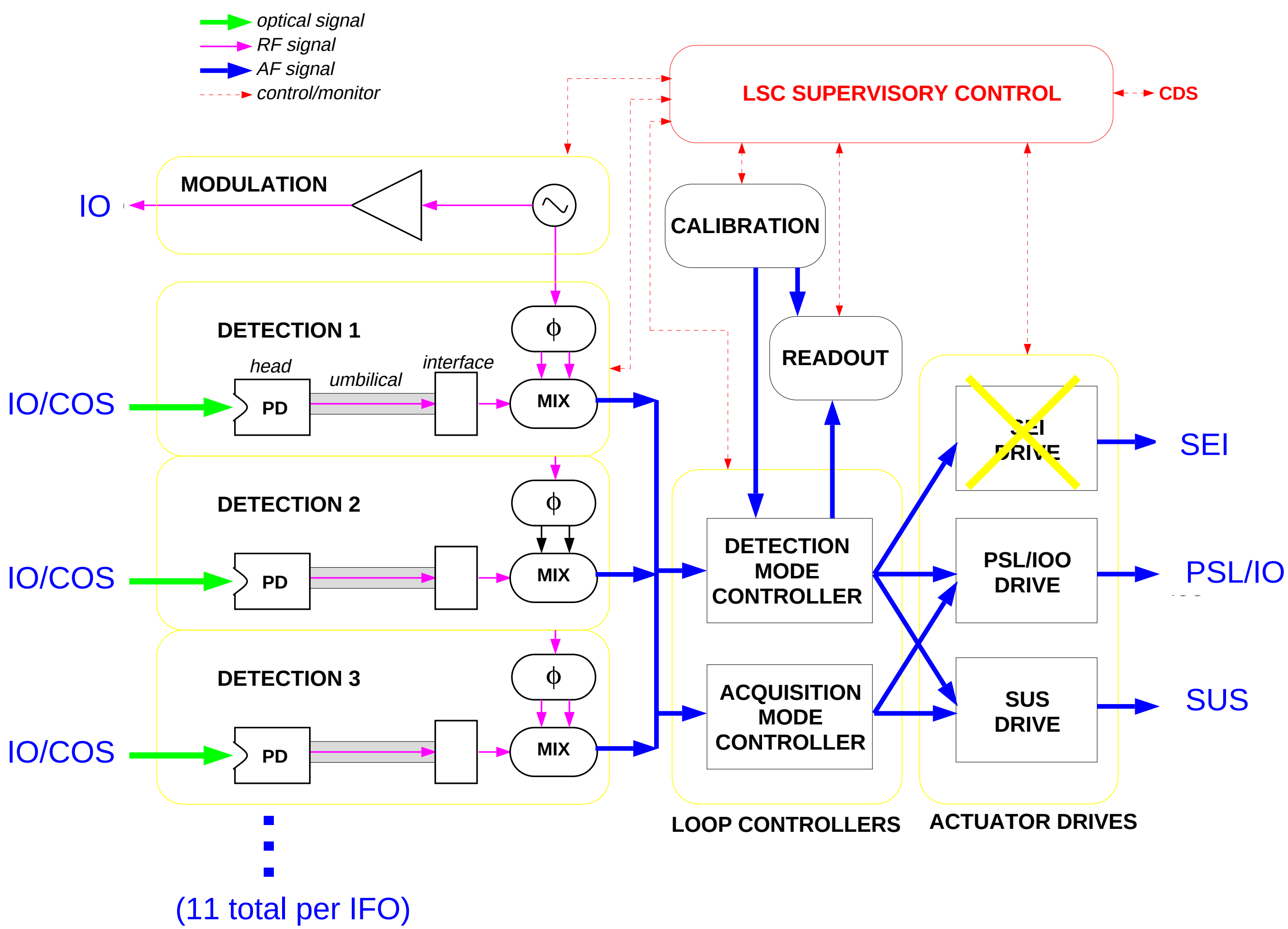
LSC Overview

- 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 Deliverables

- LSC hardware:
  - ❑ photodetectors
  - ❑ electrooptic shutters
  - ❑ mechanical shutters
- Other design deliverables
  - ❑ Control dynamics & signal conditioning specifications
  - ❑ Gain, noise & dynamic reserve allocation
  - ❑ Diagnostic ‘hooks’
  - ❑ System-level supervisory control, states & transitions
- Electronics hw/sw under LSC/CDS (FDR~ 2/99), but...
  - ❑ A fairly definite hw/sw implementation has been developed; required to enable certain basic design decisions

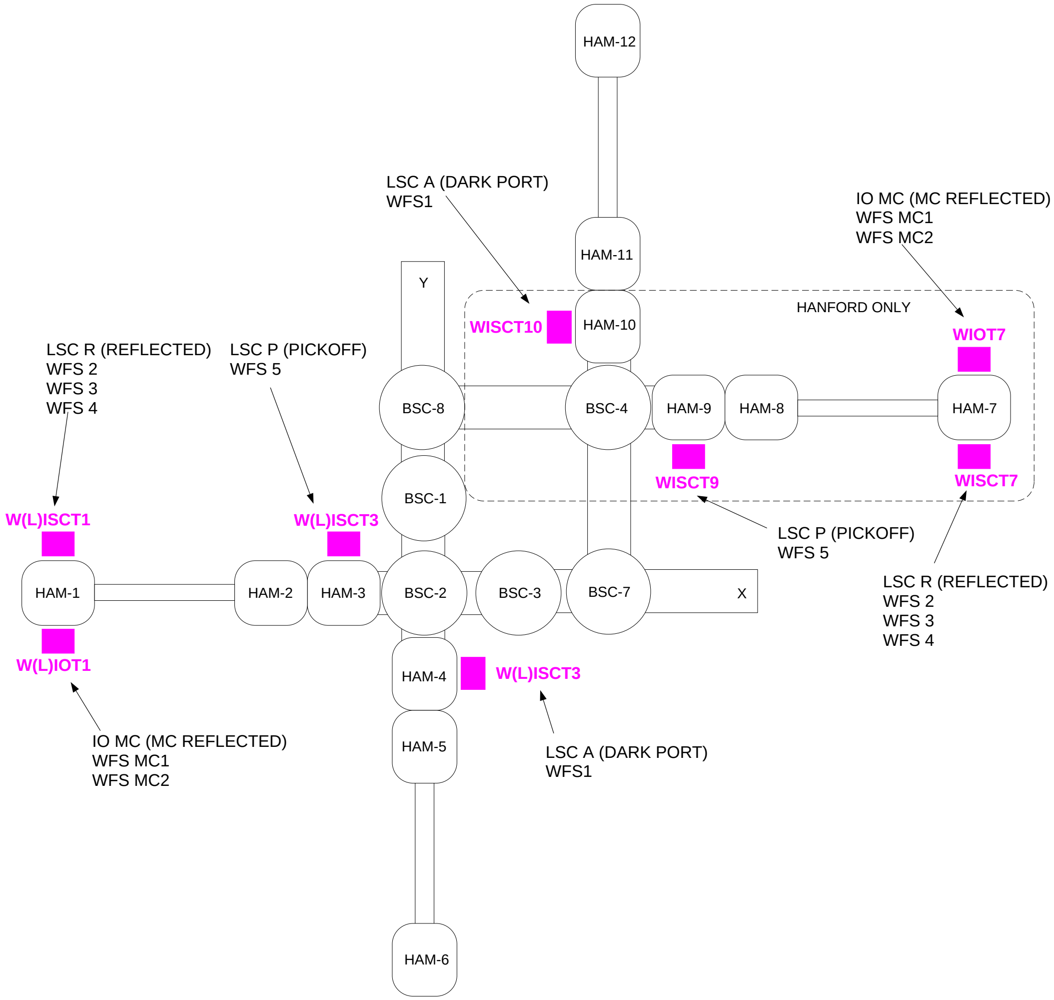
Functional/interface schematic



Principal LSC Interfaces

- ASC
  - ❑ LSC diodes, shutters squat on ISC tables (mostly ASC)
  - ❑ Operations of ASC and LSC coupled (for all modes + transitions)
- IO/PSL
  - ❑ IO supplies EO modulator
  - ❑ IO & PSL are "meta-actuators" for common-mode (laser frequency)
  - ❑ IO provides recycling cavity reflection beam
- COS
  - ❑ COS relays signal beams out to ISC tables
- SUS
  - ❑ TM longitudinal control actuation is via SUS controllers

LSC Detector Locations



Photodetectors: Primary requirements

Requirement	*Value*	*Driven by*
quantum efficiency[a]	> 80%	shot noise
steady-state power capacity	> 1.2 W	thermal lensing, coating figure
transient energy capacity	> 3 J	loss of lock transients, dark port
electronic noise	SRD/10	sensitivity
backscattering[b]	$x_{sc} \cdot m \cdot \sqrt{\mathrm{BRDF}} \leq 2.4 \times 10^{-11} \mathrm{m\text{-}str}^{-1/2} / \sqrt{\mathrm{Hz}}$	scattered-field phase noise

a. Transmission efficiency of extra-vacuo COS telescopes, which are physically integrated with ISC components the external ISC tables, is regulated separately; see T970071-01-D, *COS Design Requirements*.

b. x_{sc} is the motion (spectral density) of the photodetector (w.r.t. the IFO optics); m is the ratio of the beam size at the beamsplitter to the beam size at the photodiode; and BRDF is the bidirectional-distribution function for the diode surface. Value holds for $f > 200$ Hz; see LSC DRD for details.

PD: working conditions by location

location (4k, 2k)	*port*	*CW locked (W)*	*CW unlocked (W)*	*transient energy (J)*	*transient pk. power (W)*	*atten. factor*	*no. PD modules req'd*
IOT1, 7	MC	.1	10	0.3	40	.3	1
ISCT1, 7	R	.1	6	0.3	24	.5	1
ISCT3, 9	P	.1	.01	~	~	1	1
ISCT4, 10	A	1.2	<.01	3	300	1	8

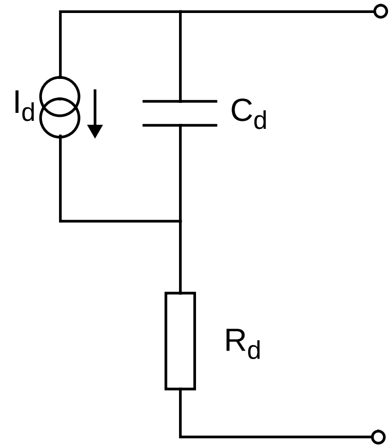
1 more requested for IO diagnostics 7/24

EG&G C306426 Photodiode Properties

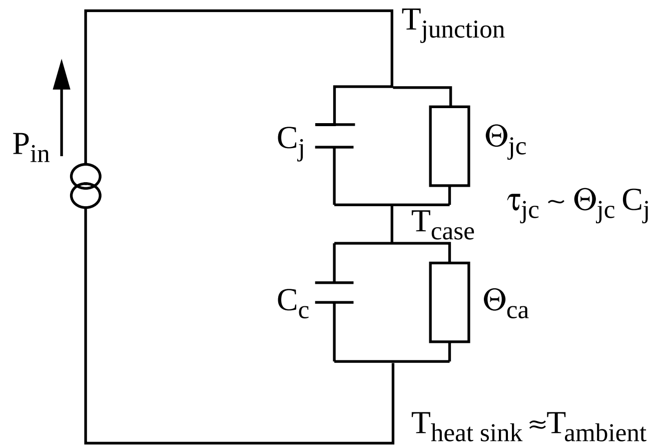
parameter	*symbol*	*value*	*units*	*notes*
detector type	-	-	-	InGaAs PIN diode
active area diameter	$\boldsymbol{d}$	2.0	mm	
1064 nm responsivity	$\boldsymbol{R}$	$0.71 \pm .03$	A/W	window removed
external quantum efficiency	η	83 ± 3	%	derived from $\boldsymbol{R}$
1064 nm surface reflectance	R	2	%	10° inc., P pol.
1064 nm backscatter	BRDF	$3.7 * 10^{-5}$	sr^{-1}	2.5° inc., 6.5° scat.
surface microroughness	σ_z	2.8	nm_{rms}	over 10 X 10 µm area
jct.-case thermal impedance	Θ_{jc}	17	°C/W	
jct. thermal time constant	τ_{jc}	0.16	s	
junction capacitance	C_d	70	pF	@ 10 VDC bias, 25°C
		85	pF	@ 5 VDC bias, 25°C
		140	pF	@ 1 VDC bias, 25°C
series resistance	R_d	9	Ω	(~bias-independent)
capacitance temp. coeff.	α_C	+0.04	pF/°C	avg., 20°C - 100°C

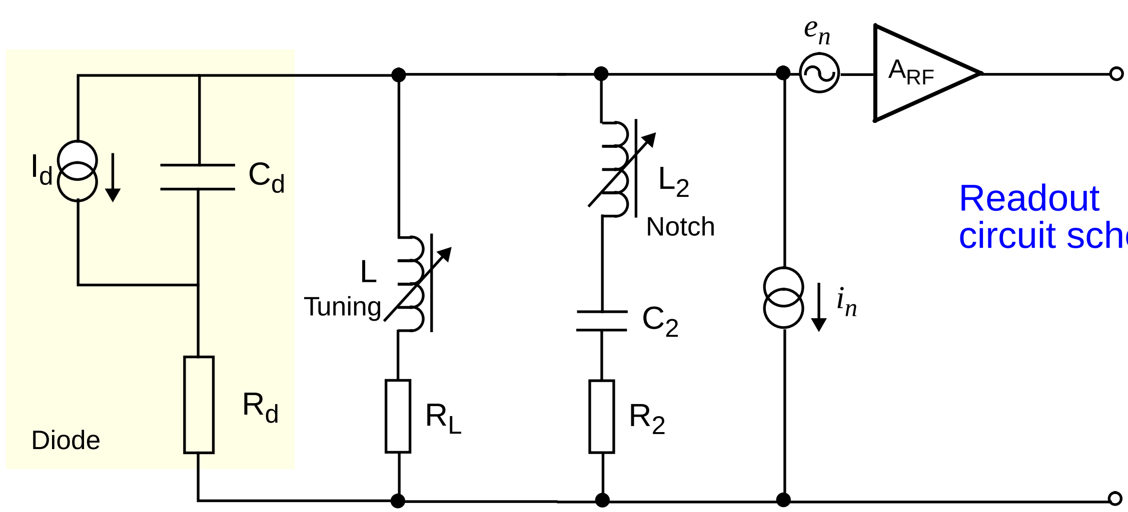
Schematic equivalent circuits

Electrical



Thermal



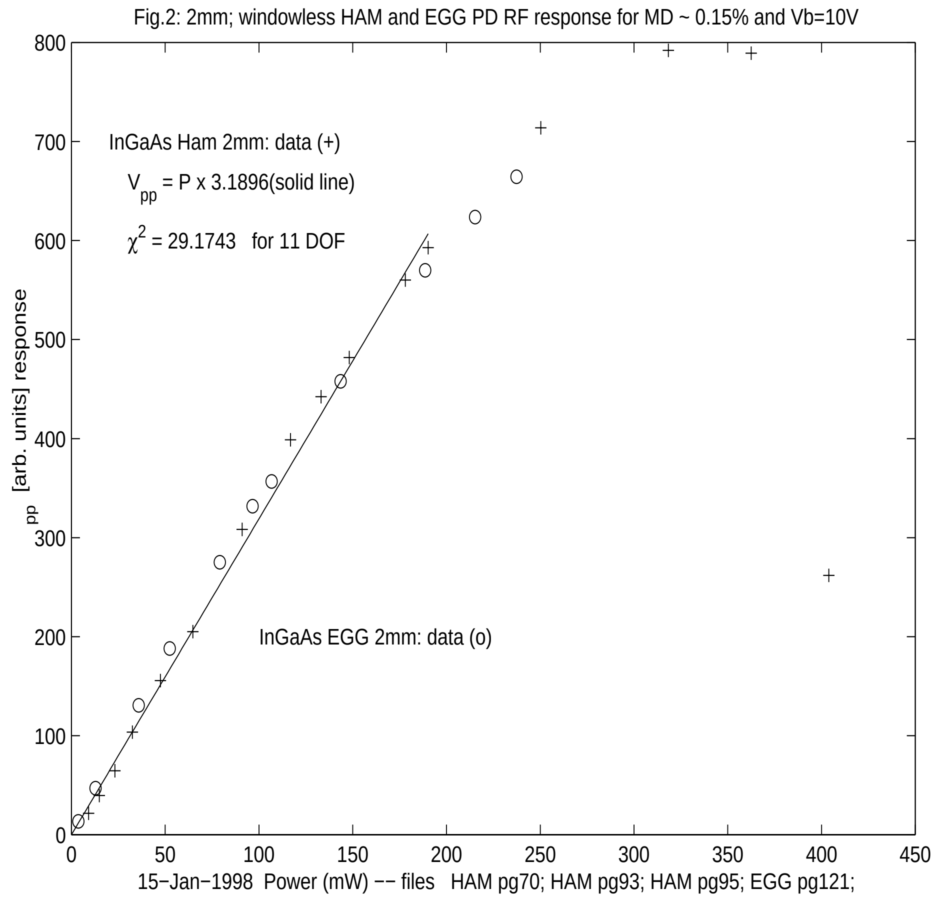


Readout circuit schematic

Front-end noise, linearity & no. of diodes

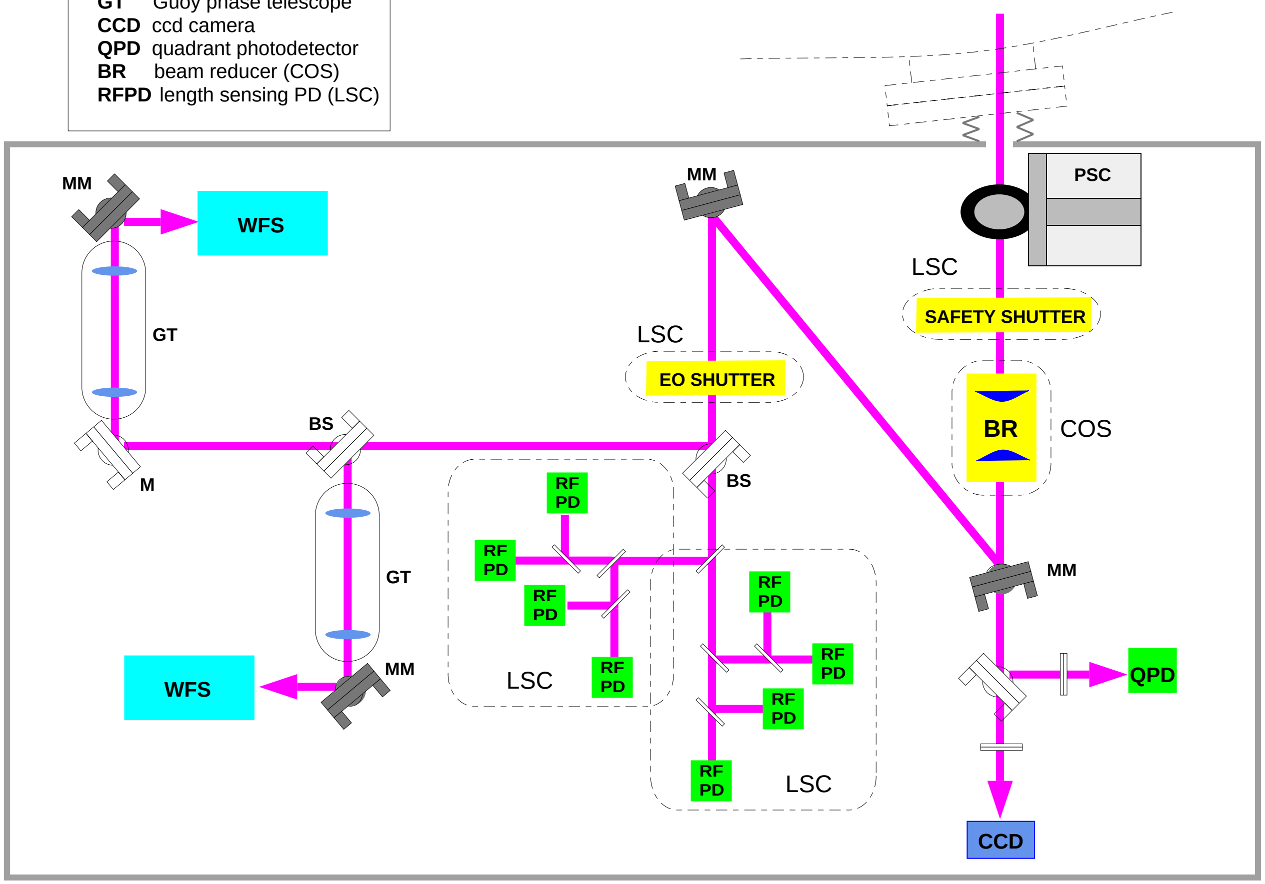
- Need quad. sum of thermal, amp. current, amp. voltage noise < 1/10 SRD (~ shot noise)
  $\Rightarrow$ I > 26 mA (choose I > 50 mA for margin)
- Power flux not as critical as total power dissipation (for our conditions)
- RF & DC linearity OK (within 5%) up to ~ 180 mA
- PNI test validated no significant spurious effects at 45 mA
- 1.2 W expected at dark port divided 8 ways gives 107 mA per diode
  - ❑ Junction temp. will equilibrate about 20C above ambient
  - ❑ Resulting LC detuning, plus IR bias drop in substrate, compensated by "preloading" plus negative-impedance bias circuit

RF linearity measurement



PD: schematic layout (dark port, partial)

PSC periscope
WFS wavefront sensor
M mirror
BS beamsplitter
MM motorized mirror
GT Guoy phase telescope
CCD ccd camera
QPD quadrant photodetector
BR beam reducer (COS)
RFPD length sensing PD (LSC)



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Transient power handling

- Three varieties of power overload:

  ❑ Loss of L-, l- ; dumps ~ 3 J (stored energy in machine) out dark port; timescale ~ 10 ms or longer ($\Longrightarrow$ need shutter)

  ❑ Loss of L+ and MC lock; sharp transient (rise < 10 μs?) to 4x incident power, decay ~ cavity storage time w/ beat wiggles ($\Longrightarrow$ need fast shutter)

  ❑ Unlocked steady state at reflected, MC ports is 1X incident power (6W, 10W respectively); but all available is needed for SNR when locked ($\Longrightarrow$ need variable attenuator)

- Clamping supply current helps reduce dissipation to ~1x incident power (I^2R + incident ~ 8X incident in operation)
- Time constant of PD too long for conduction to help for transients; $\Delta T_j(\tau_{pulse} \rightarrow 0) = E_{pulse} \cdot \Theta_j / \tau_j \approx E_{pulse} \cdot 106°\mathrm{C/J}$
- Peak temp. for each diode at dark port $\Rightarrow$ 86°C

PD thermal transient model

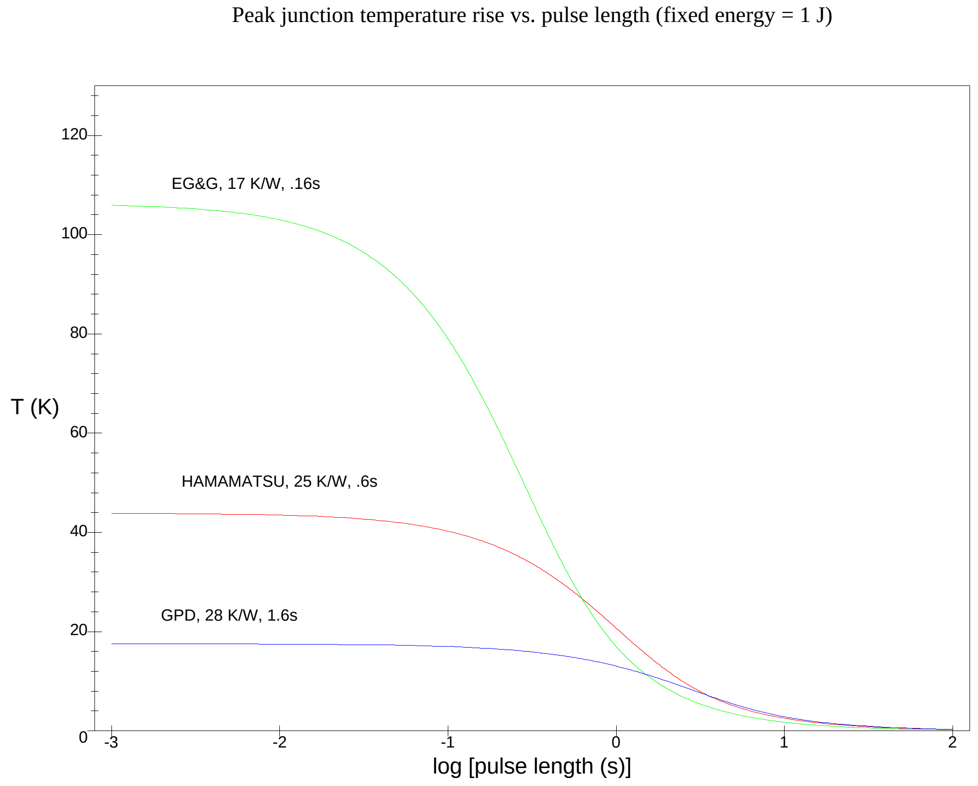
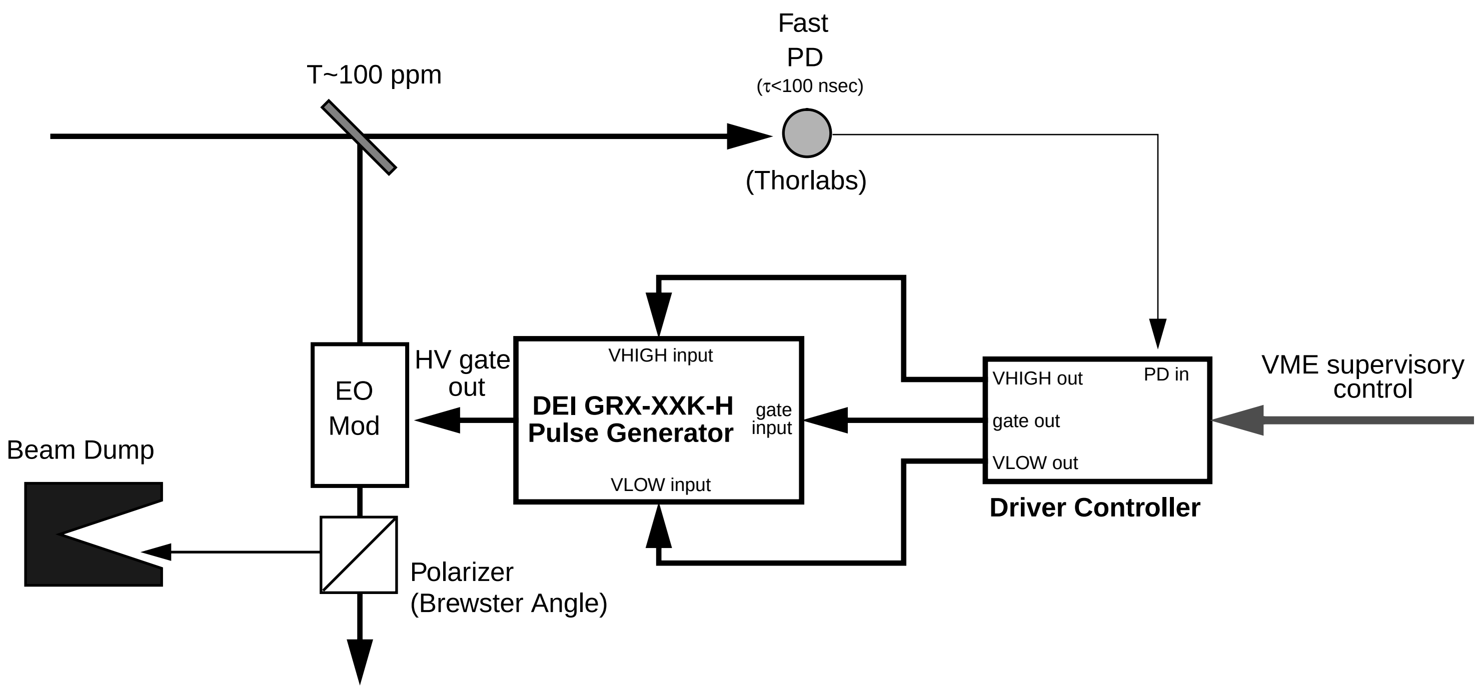


Figure 1: Calculated peak junction temperature rise above ambient vs. pulse length in EG&G C30642G, Hamamatsu G5832-2 and GPD GAP-2000 2 mm- diameter InGaAs photodiodes for 1 Joule (total dissipated) rectangular pulse. Based on measured Θ_{jc} and τ_{jc} .

PHOTODETECTOR PROTECTION: E-O SHUTTER

- E-O shutter chosed for:
  - speed of response (want 100's of microseconds)
  - transmission level is controllable – useful for acquisition
- Implemented on:
  - Mode Cleaner reflected port
  - Interferometer reflected port
  - Anti-symmetric port (may not be needed for diode protection)

E-O SHUTTER DESIGN



- Control features:
  - ‘closed’ transmission level
  - ‘open’ transmission level
  - trigger level
  - automatic open
- E-O modulator (Q-switch)
  - 8 mm aperture, $LiNbO_3$
  - 3.4 kV half-wave voltage
  - Transmission: 98% w/ windows, >99% w/out (spec)
  - 1000:1 extinction

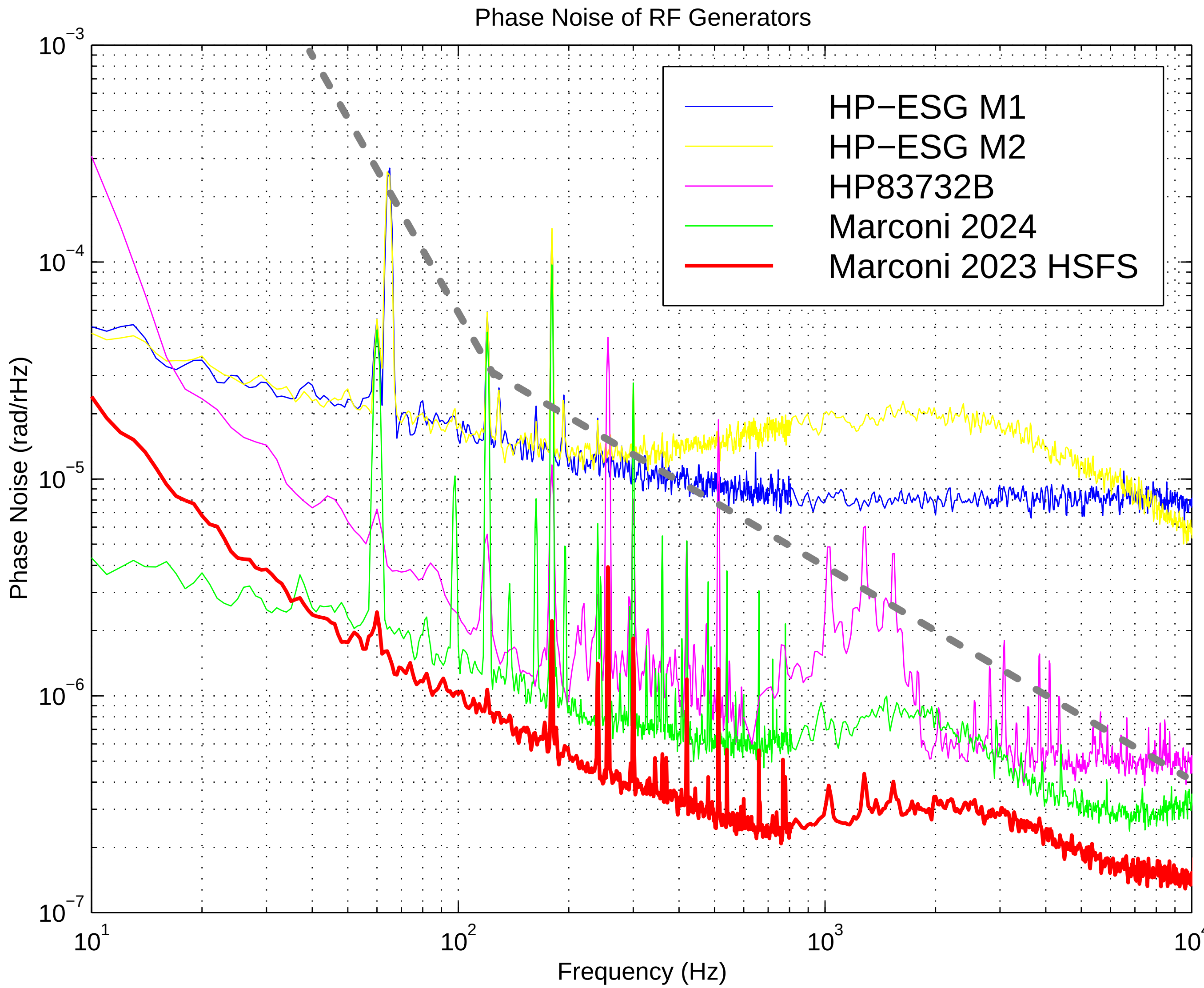
Optical Efficiency Budget

item	*est. loss (dB)*	*comments*
periscope	–.01	REO hi-R
relay mirrors	–.01	REO hi-R
lenses	–.02	REO AR V-coat
EO shutter Xtal	–.044	LaserMetrics, no windows
polarizer	–.022	Lambrecht Brewster-cut
ASC WFS pickoff	–.044	1% total for WFS, QPD & video
beamsplitter chain	–.05	REO 50% T / AR V-coat
photodiode	–.81	83% ± 3% measured
TOTAL	–1.01	= 79.3%

Modulation Source

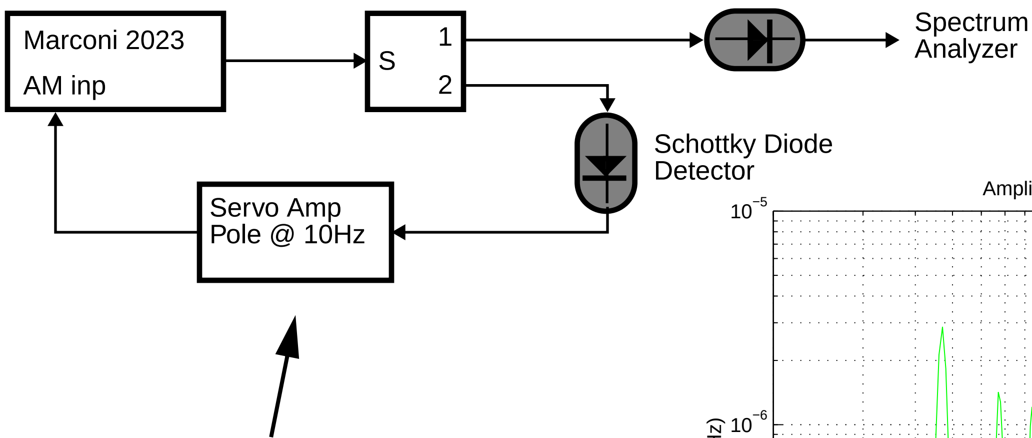
- Main requirements:
  - Phase noise: 2×10^{-5} rad/√Hz at 200 Hz, falling as 1/f
  - Amplitude noise: 5×10^{-8} /√Hz, relative, above 200 Hz
  - RF power: ≥ 0.5 W (maximum mod. depth of ~1.4)
  - Frequency tunability of ~several hundred Hertz desirable for setup
  - Phase & amplitude modulation capabilities for diagnostics
- Commercial signal generator selected: Marconi 2023
  - 9 kHz – 1.2 GHz
  - 1 Hz frequency resolution
  - oven controlled crystal oscillator option
  - AM & PM; internal & external

Signal Generator Phase Noise

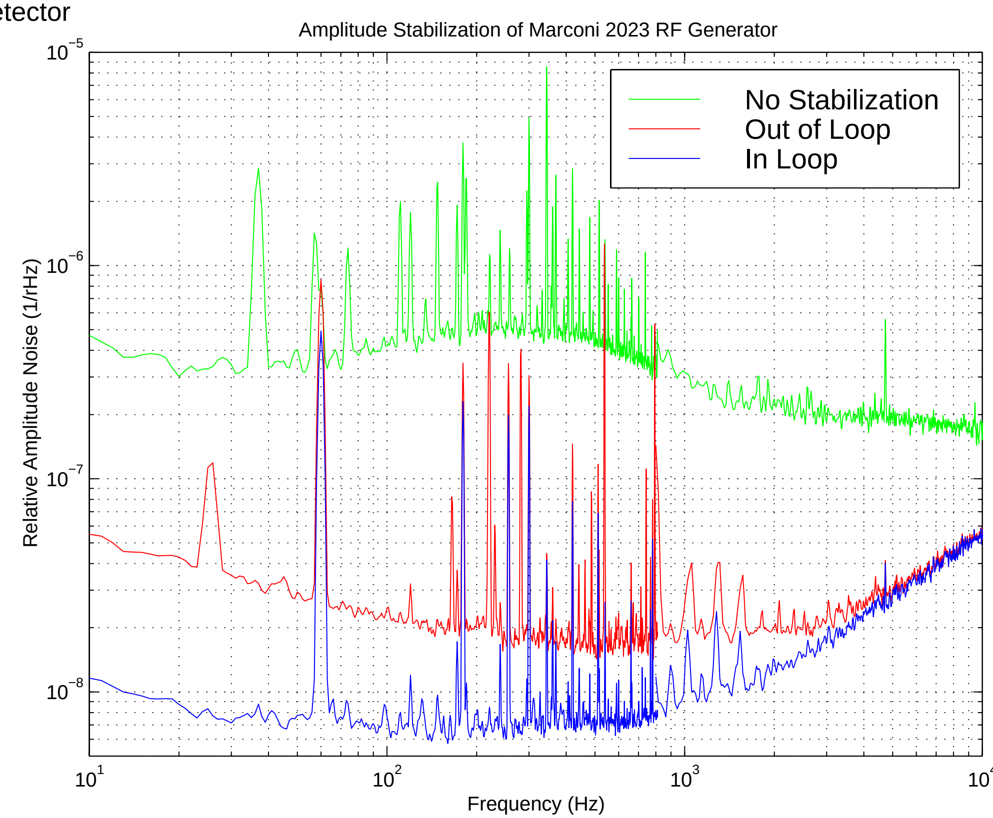


AMPLITUDE NOISE

- AM of generator is above requirement – use feedback to suppress it:



Modulation amplitude control (DC & AC mod.) is implemented with a summing junction(s) in the servo amplifier



DEMODULATION

- Signal at each port is demodulated in both RF phases; each phase is sampled by LSC ADCs
- Multiple channels at AS port to be summed in analog prior to sampling (to cut down on I/O transfer overhead), but individual photodetector I & Q channels still sampled by DAQS for diagnostics
- Mixer linear range should allow >13 dBm RF
- Phase shifting: I&Q orthogonal to ~1° ; global phase shift in steps of ~1° (not necessarily remotely controlled)

Lock Acquisition

- Design constraints/considerations
- Controllers
- Triggers and Switching
- Things to do

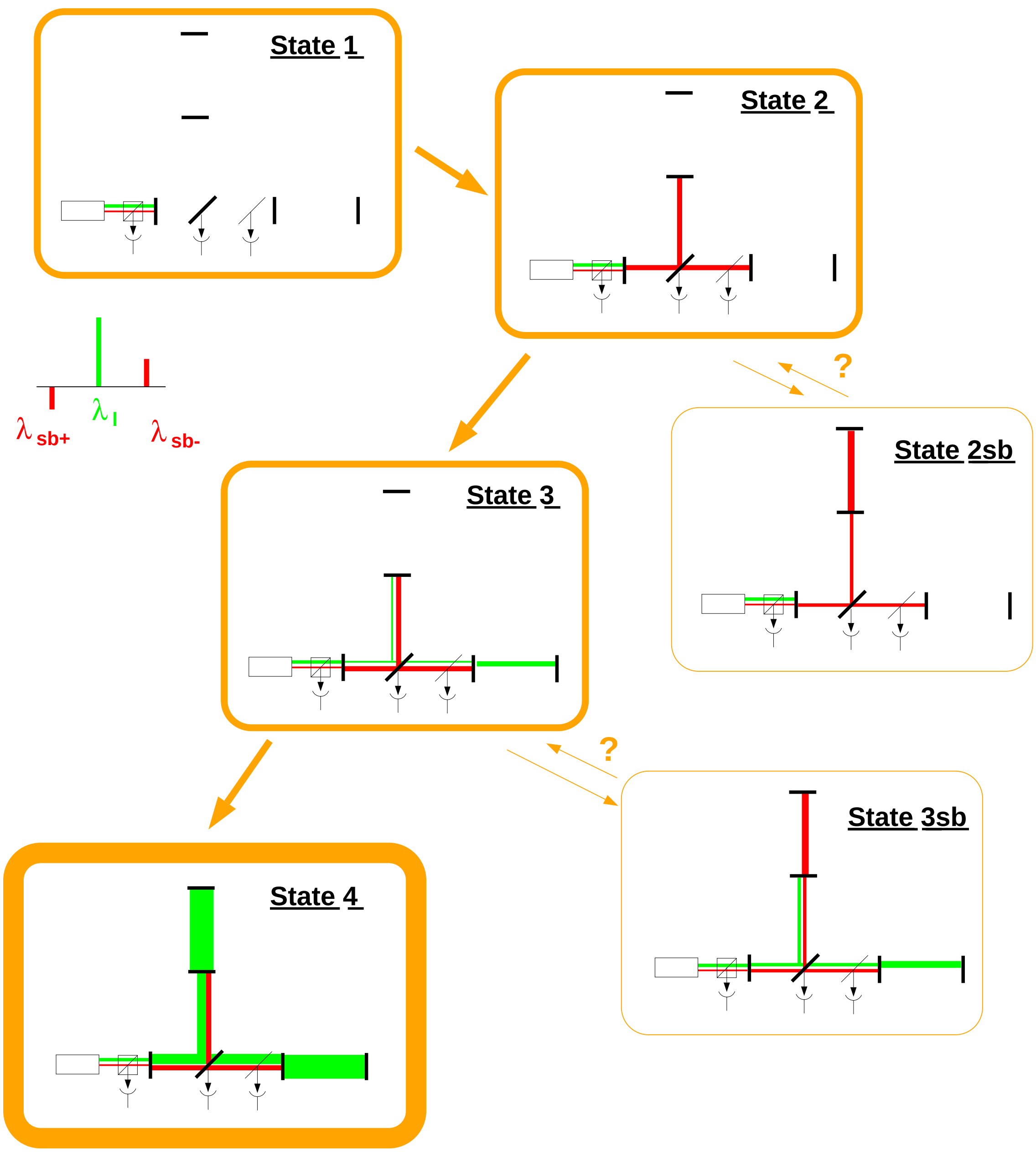
Design Considerations/ Constraints

- Acquisition time
- State transition
- Stability
- Ground motion
- Actuator limits
- Internal TM resonances

Acquisition Time

- L- threshold velocity of 3 lambda/s achieved
- l- threshold velocity of 0.5 lambda/s achieved
- MTTL of seconds implied and simulated

State Transitions



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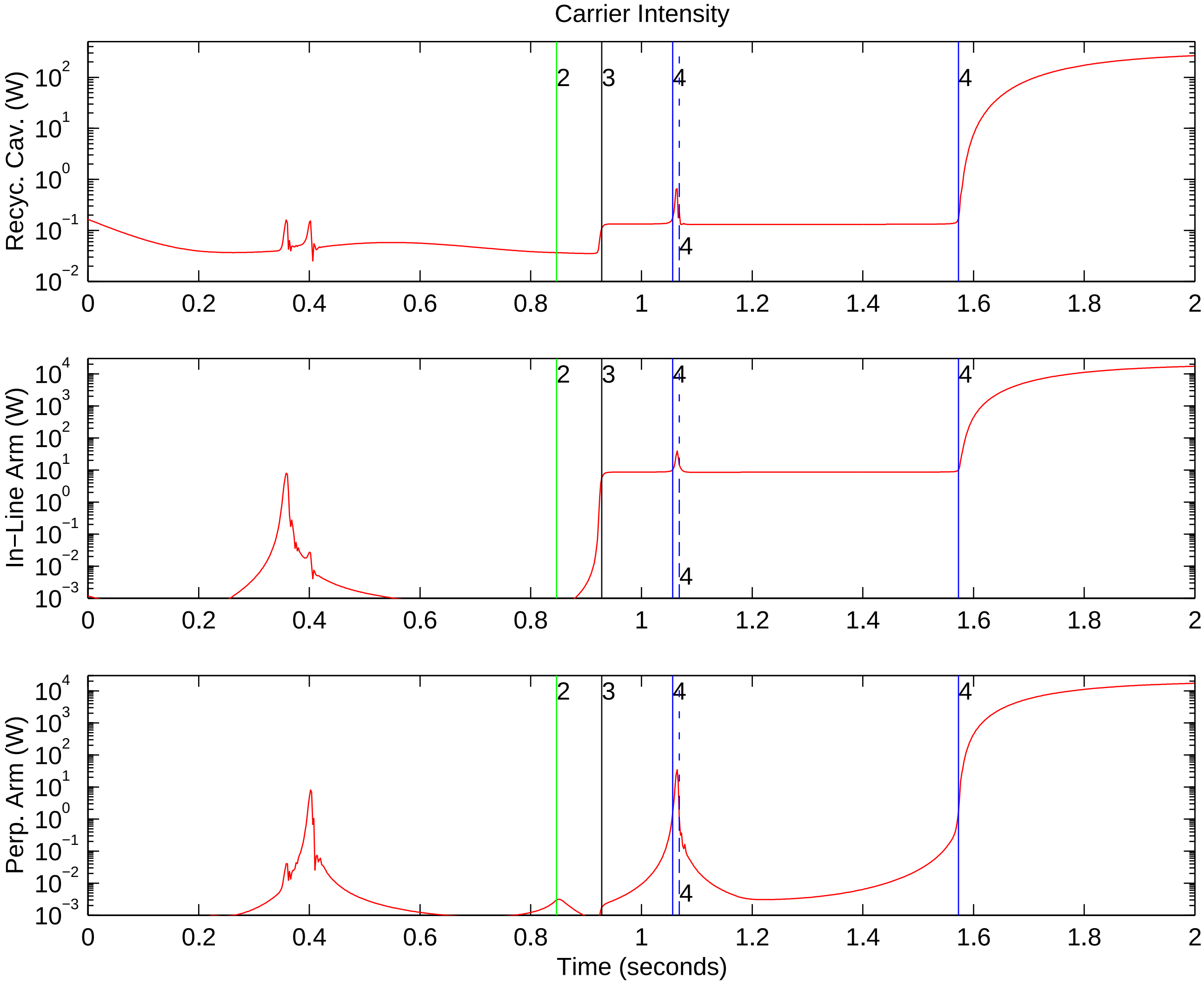

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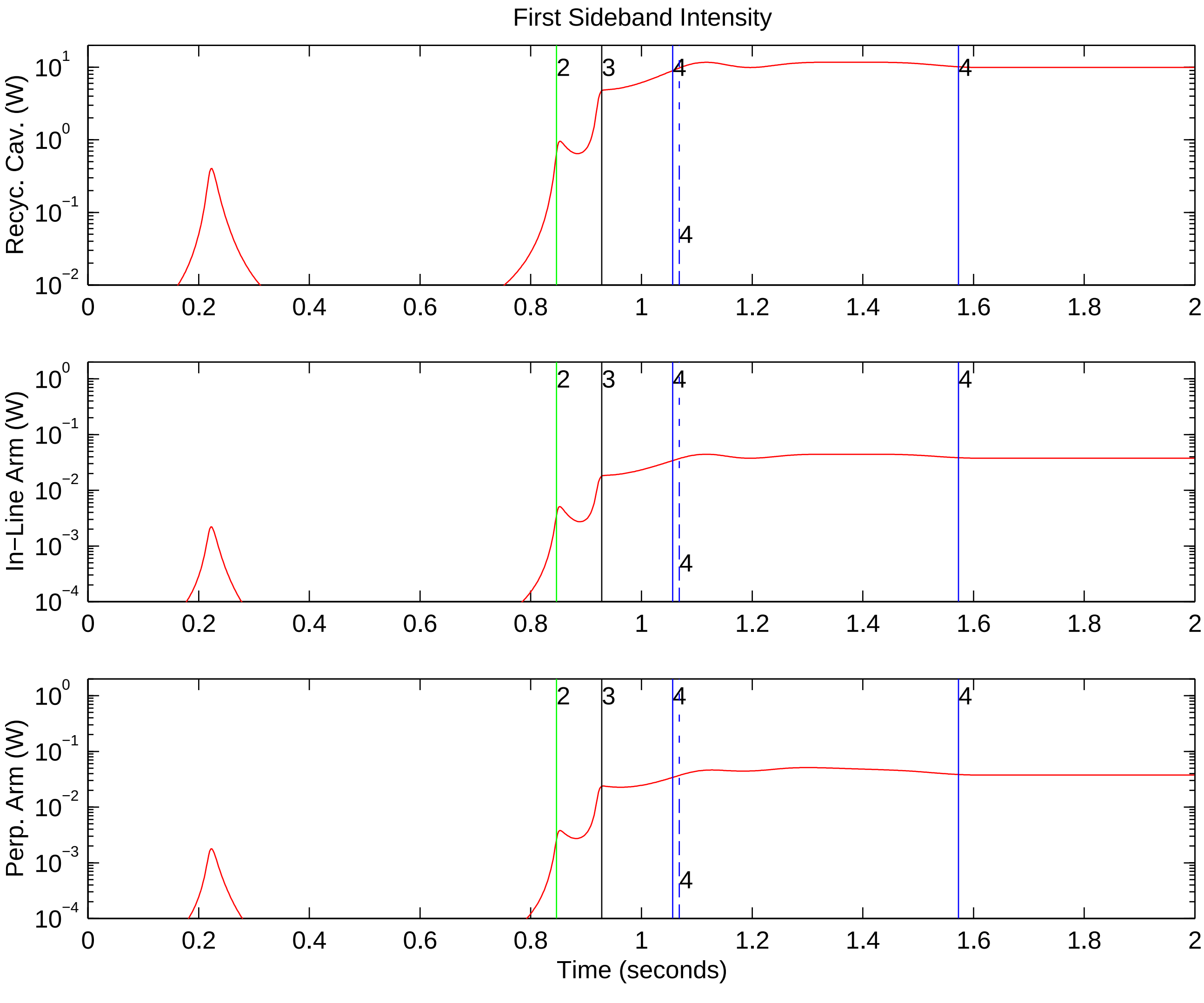
State Transitions

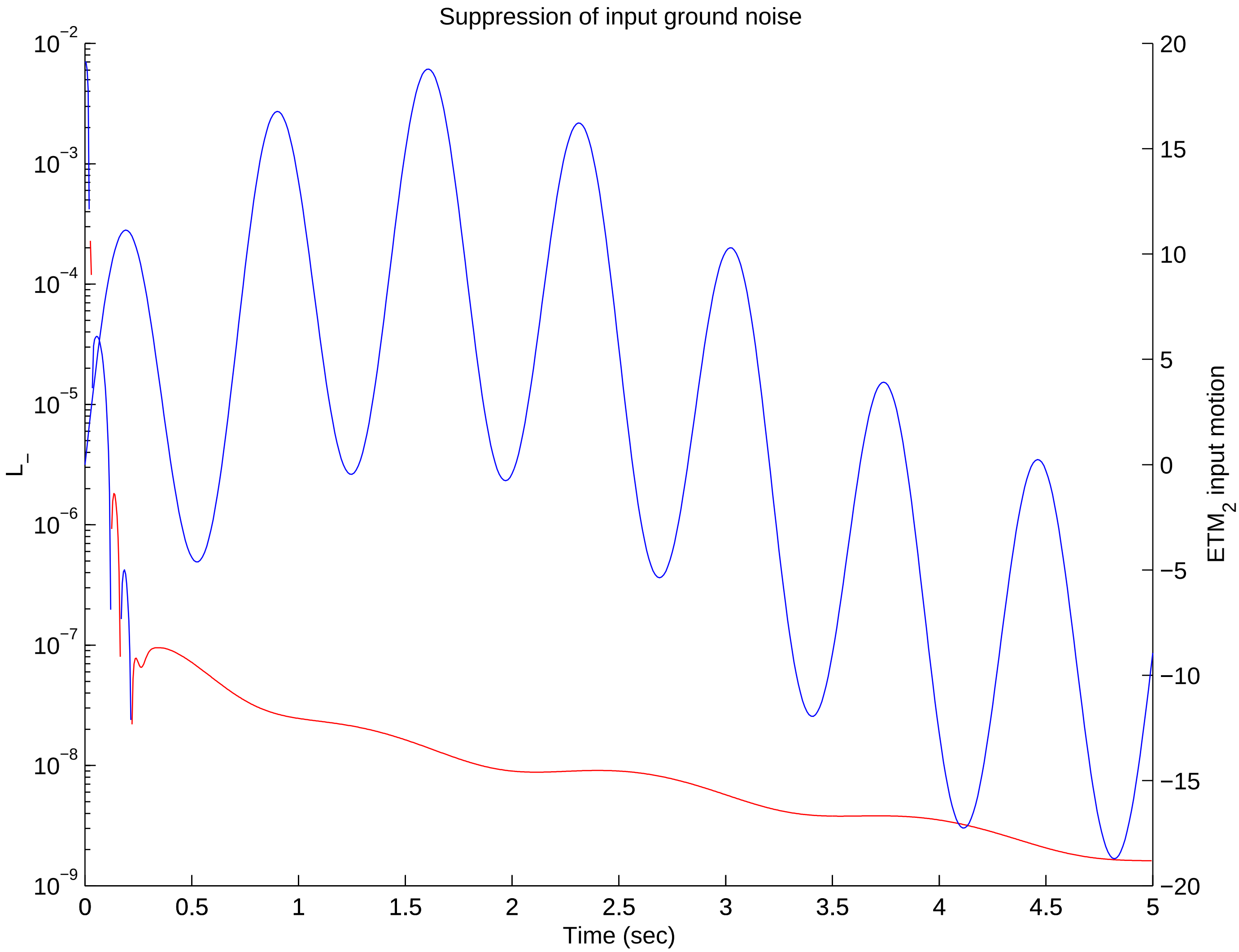


Stability

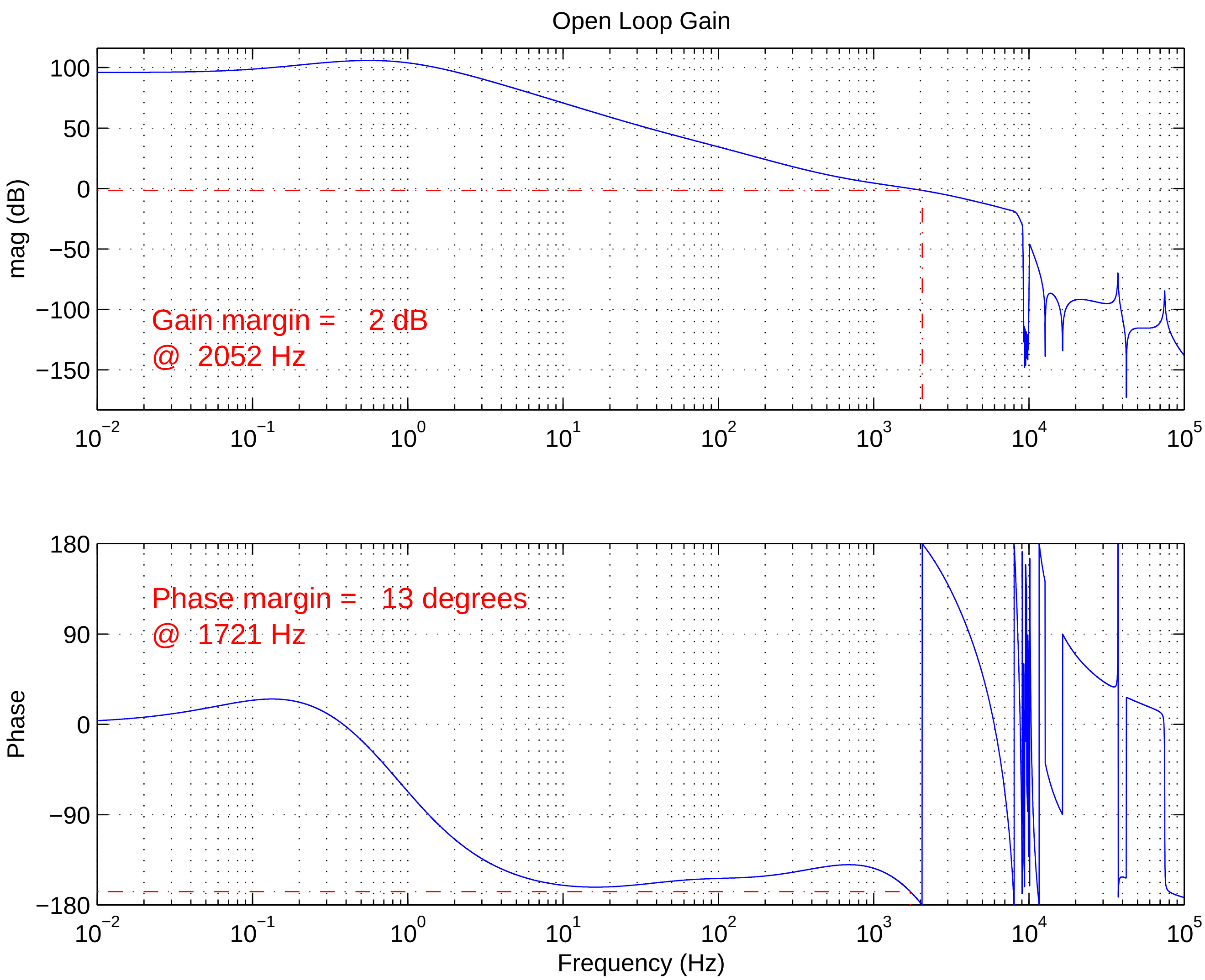
Controller		State 3 Gain (dB)			State 3 Phase (deg.)			State 4 Gain (dB)			State 4 Phase (deg.)		
c_{11}	$S_{PI} \to \phi$	∞	@	–	43	@	372 Hz	∞	@	–	50	@	13.7 kHz
c_{22}	$S_{RI} \to l_+$	16	@	1.11 kHz	36	@	413 Hz	30	@	1.12 kHz	87	@	110 Hz
c_{33} (acq)	$S_{AQ} \to L$		@			@		2	@	2.05 kHz	13	@	1.72 kHz
c_{33} (det)	$S_{AQ} \to L$		@			@		18	@	1.28 kHz	45	@	272 Hz
c_{44}	$S_{PQ} \to l$	9	@	378 Hz	34	@	188 Hz	4	@	379 Hz	17	@	278 Hz

Table 1: Gain and phase margins of controllers

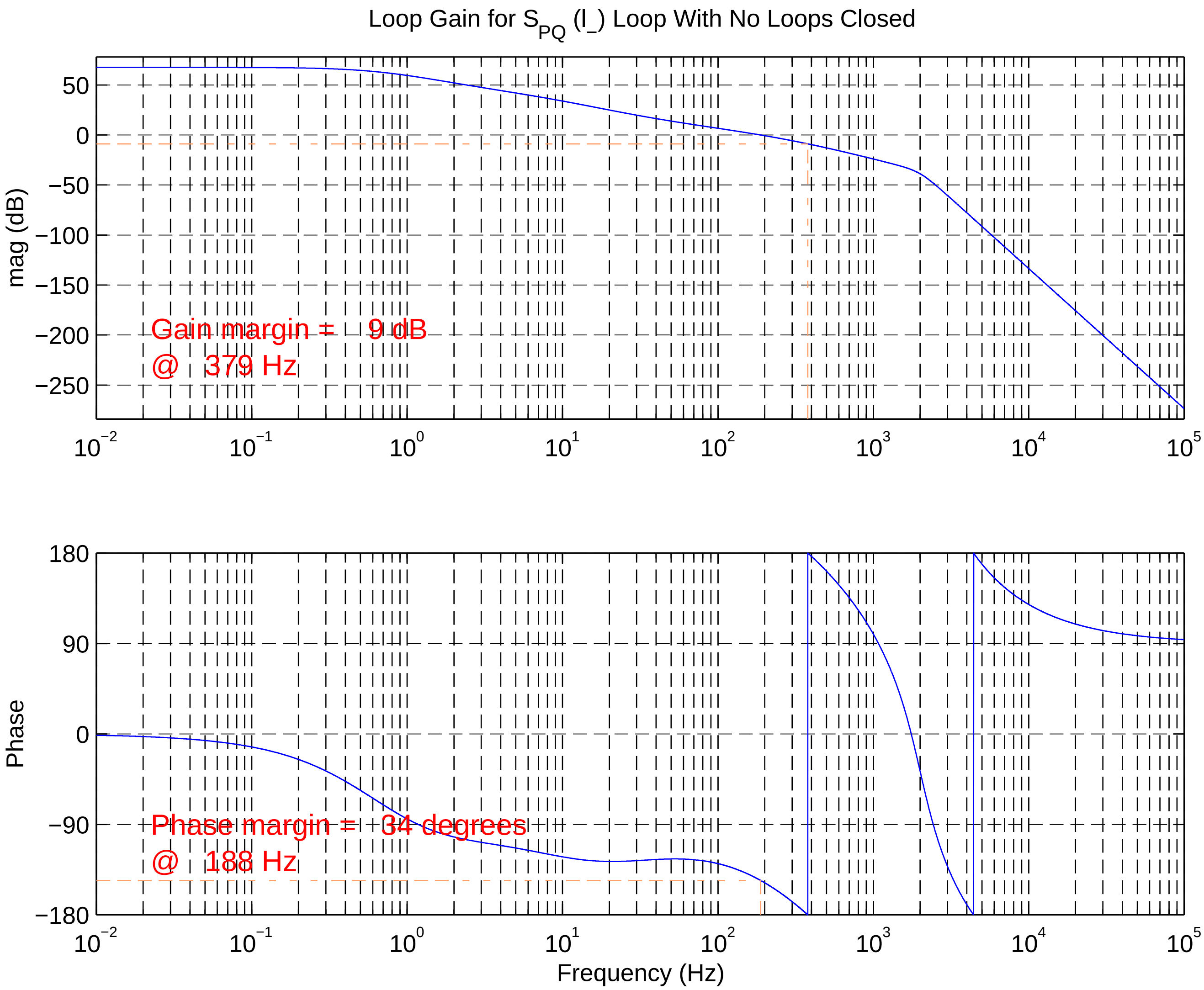
Ground Motion



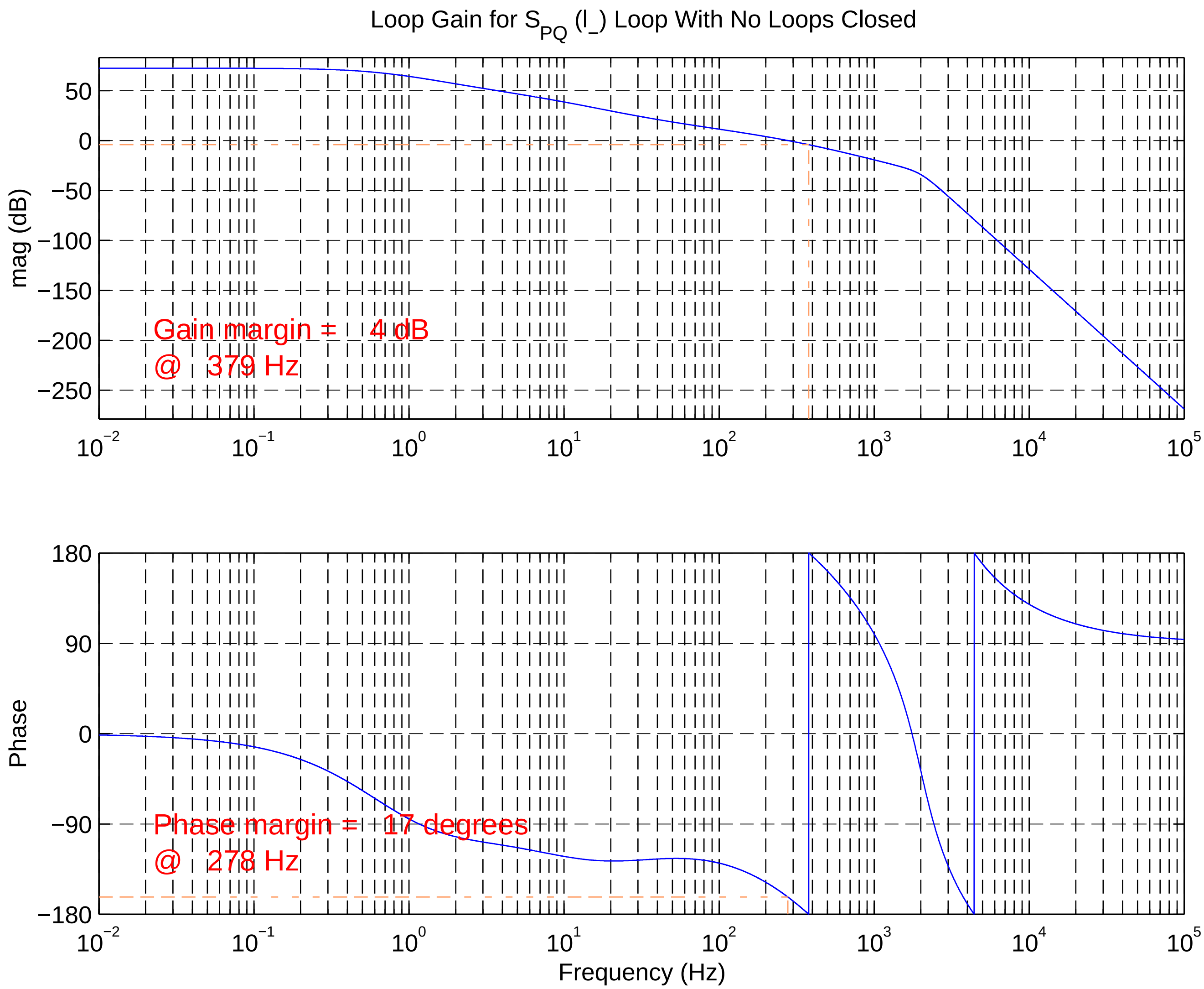
L- Open Loop Gain, State 4



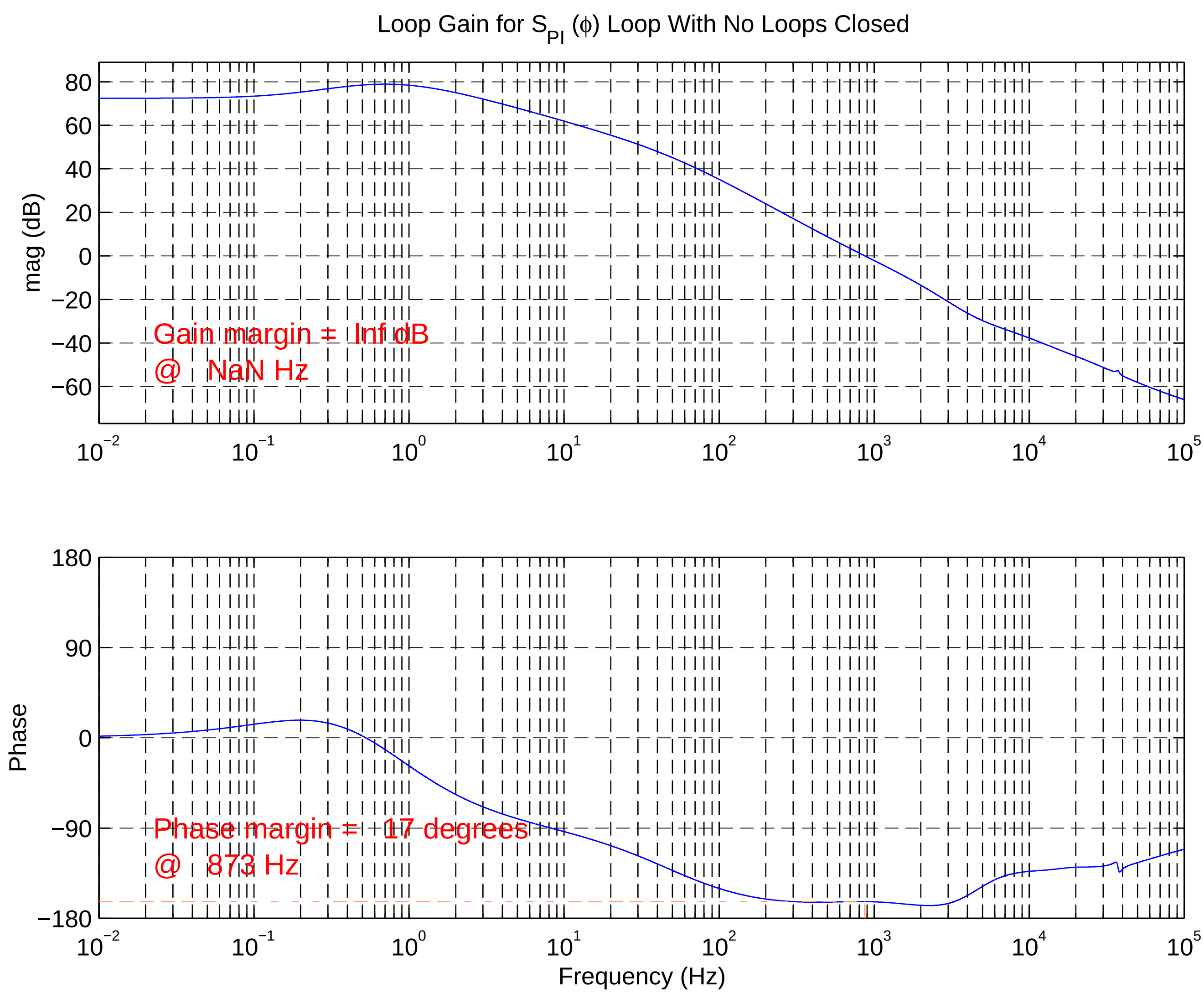
l- Open Loop Gain, State 3



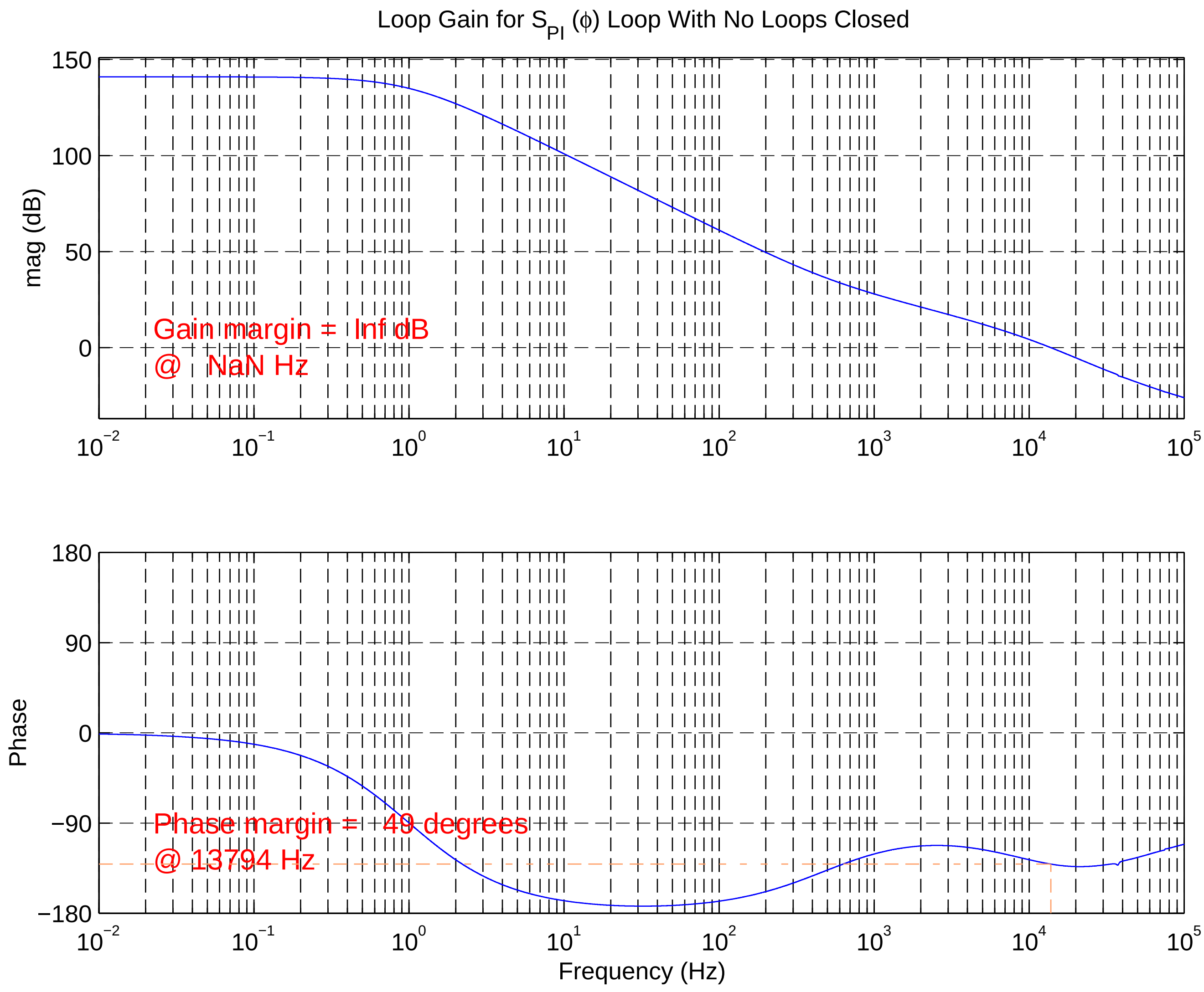
l- Open Loop Gain, State 4



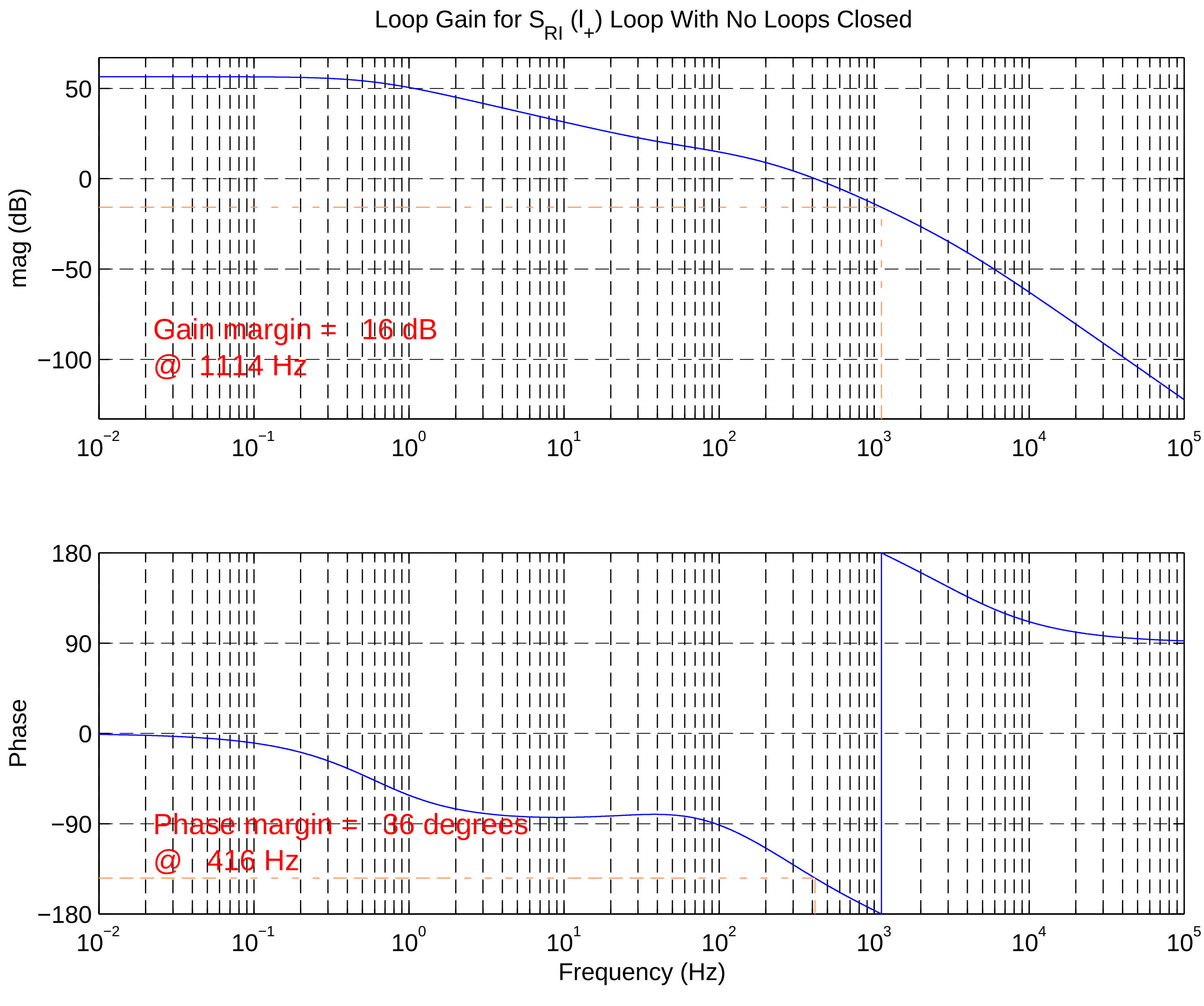
Laser Frequency Open Loop Gain, State 3



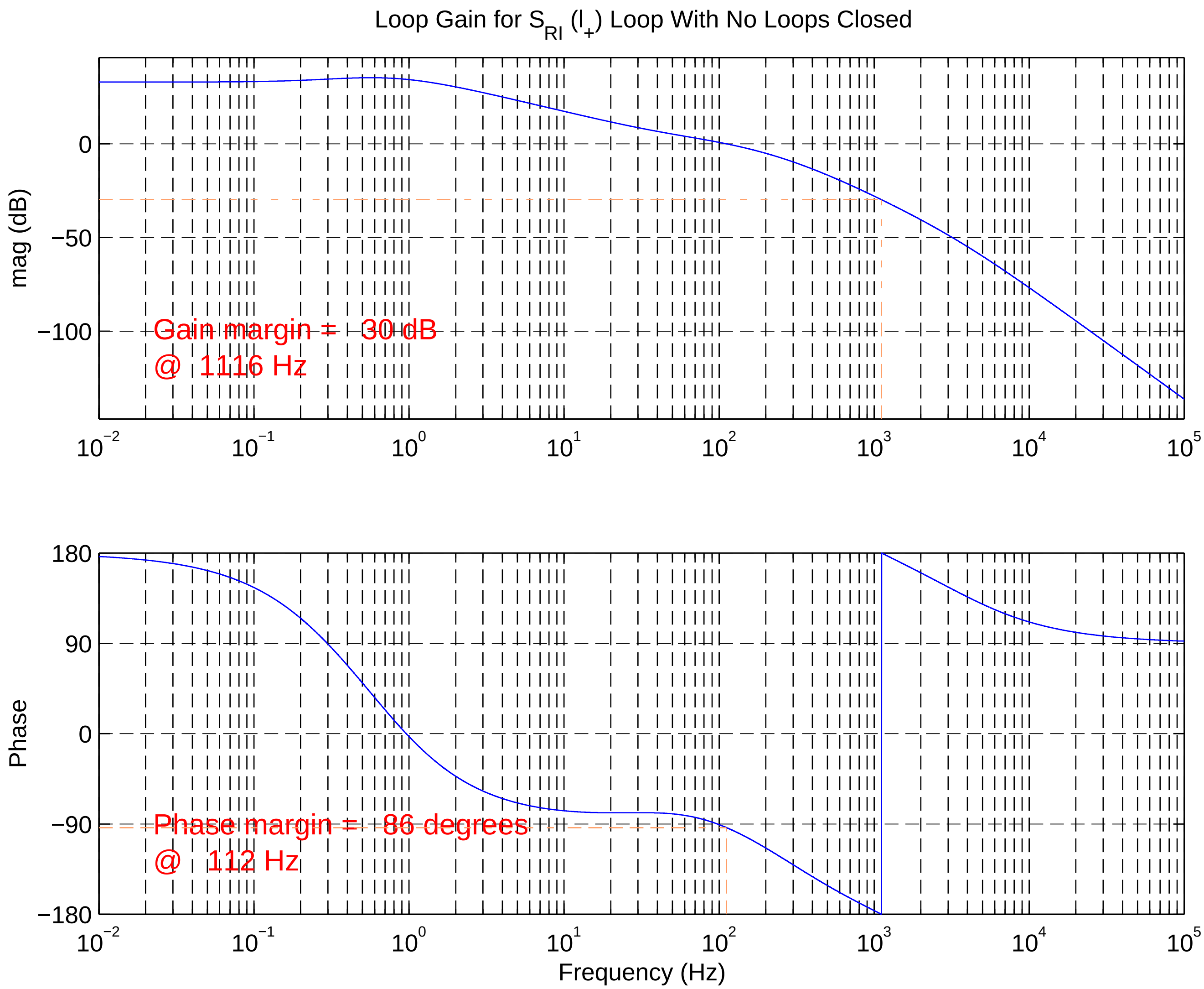
Laser Frequency Open Loop Gain, State 4



l+ Open Loop Gain, State 3



l+ Open Loop Gain, State 4



Triggers and controller switching

State Transition	Loop	Trigger	Effect
$1 \rightarrow 2$	l	$P^{tr}_{s\|\|}$ & $P^{tr}_{s\perp} \geq 0.4\ \mu$W	State 2 acquired, enable l_+ loop
$2 \rightarrow 3$	$l_\pm$	$P^{tr}_{c\|\|} \mid P^{tr}_{c\perp} > 0.1$ mW	30 dB gain, $\pm\, l_\pm$ actuator sign
$3 \rightarrow 4$ (acq)	L	$P^r_c < 0.02$ & $P^a_c > 0.1$ W	enable L loop
4 (acq) $\rightarrow$ 4 (det)	all	$P^{tr}_{c\|\|}$ & $P^{tr}_{c\perp} > 0.1$ W	switch to detection mode

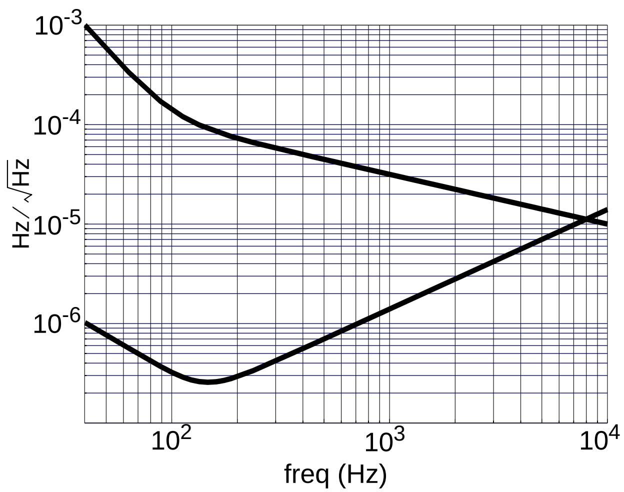
Table 1: Transition through the acquisition states, showing triggers and controller enabling. c – carrier, s – sideband, tr – transmitted, a – asymmetric port, r – reflected port.

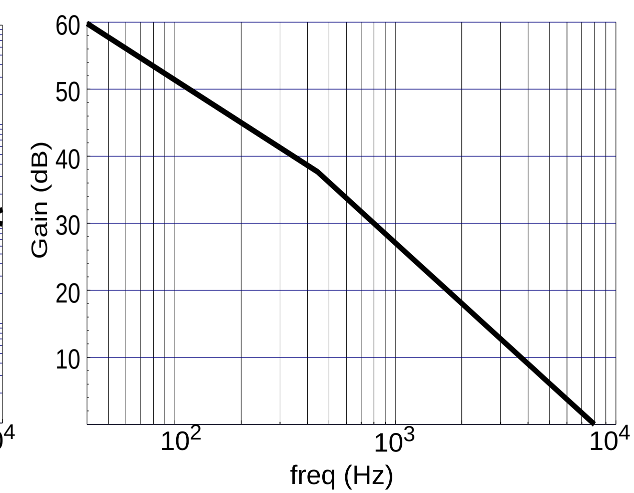
Things To Do

- Switch to detection mode stably
- Frequency crossovers to MC, PSL, IFO
- Physical triggers
- Continue simulations - explore gain/bandwidth/ initial condition phase space
- Evolve SMAC as diagnostic tool for LIGO turn-on
- Alignment effects on lock acquisition

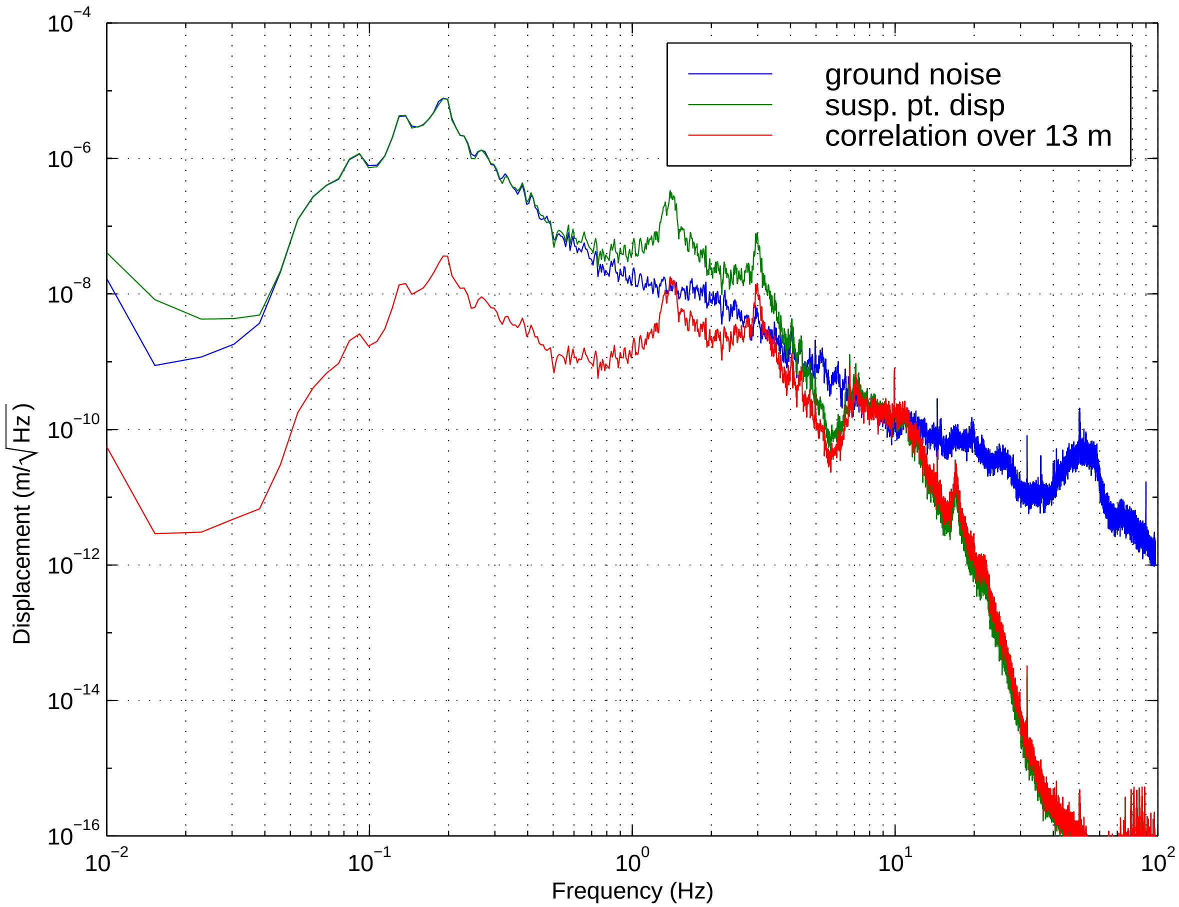
Detection Mode Reqs: Residual Fluctuations

Degree of freedom	*Residual deviation*	*Units*	*Coupling mechanism*
$\delta Lm + (\pi/(2F))\delta lm$	1×10^{-13}	m_{rms}	Amplitude noise coupling
$\delta lm + (\pi/(2F))\delta Lm$	1×10^{-9}	m_{rms}	Amplitude noise coupling
$\delta(k_l \cdot Lp)$	9×10^{-6}	rad_{rms}	Arm cavity power reduction
$\delta(k_l \cdot lp)$	7×10^{-4}	rad_{rms}	Arm cavity power reduction





SEISMIC INPUTS – CORRELATION MODEL



D.o.f.	*rms*	*p-p*	*ratio*
Ground	1.9 µm	12.4 µm	6.5
RM s.p.	2.0 µm	12.8 µm	6.4
Lm s.p.	3.0 µm	19.0 µm	6.3
Lp s.p.	3.3 µm	20.0 µm	6.0
lm s.p.	9 nm	63.0 nm	7.0
lp s.p.	20 nm	163 nm	8.1

SEISMIC INPUTS – VERTICAL MODE

- f_V = 13 Hz (19 Hz for beamsplitter)
- Q = 2000 (may be closer to 1000 sitting on stack)
- Coupling: $s_V = \xi \cdot \tilde{z}_g(f_V) \cdot T_{zz} \cdot \sqrt{Q_V \cdot f_V}$; $z_g = 10^{-9}$ m-rms; $T_{zz} = 0.5$
- ξ: bulk propagation (α(n–1)) + surface (β) effects

Degree of freedom	*Displacement (m_{rms})*	*Coupling coefficient (ξ)*	*Coupling due to*
Lm	6×10^{-11}	7×10^{-4}	Earth's curvature
lm	1×10^{-9}	1×10^{-2}	20 mrad wedge angle (ITM)
Lp	6×10^{-11}	7×10^{-4}	Earth's curvature
lp	2×10^{-9}	1×10^{-2} 2×10^{-2}	20 mrad wedge angle (ITM), & 20 mrad surface angle (RM)

GAIN CONSTRAINT: TM INTERNAL MODES

- Require open loop gain <1 at TM modes to ensure stability
- Transmissibility from force applied at magnets to TM surface calculated via FEA model (D Coyne), with Q=1.3M

	Mode description	*Resonant frequency (Hz)*	*Transmissibility (m/N)*	*Maximum servo gain*
Test Masses & RM	Non-axisymmetric, astigmatic mode	6595	2×10^{-10}	-6 dB
	First symmetric (drum head) mode	9206 (calc.) 9476 (meas.)	2×10^{-4}	-131 dB
	Second symmetric mode	14475	3×10^{-6}	-103 dB
Beamsplitter	Non-axisymmetric, astigmatic mode	3785	3×10^{-8}	-30 dB
	Symmetric (drum head) mode	5578	1.6×10^{-3}	-133 dB
	Second symmetric mode	14630	9×10^{-7}	-85 dB

- Solution: 80dB stopband filter centered at 9.4kHz (probable digital implementation) + 20 dB from anti-alias filter

SHOT NOISE

- Port power levels predicted by 'baseline' FFT model
- Also used to compute DC plant matrix elements

Port/Sensor	*Power (Carrier + SB = Total)*	*Shot noise current A/√Hz*	*Equivalent Length Noise (DC)*
Antisymmetric/S_{AQ}	0.30 + 0.86 = 1.16 W	4.19×10^{-10}	$\delta\tilde{L}_m = 4.3\times10^{-20}$ m/$\sqrt{\text{Hz}}$
RC pickoff/S_{PI}	65 + 6 = 71 mW	9.05×10^{-11}	$\delta\tilde{l}_p = 5.6\times10^{-17}$ m/$\sqrt{\text{Hz}}$
RC pickoff/S_{PQ}		8.67×10^{-11}	$\delta\tilde{l}_m = 1.7\times10^{-16}$ m/$\sqrt{\text{Hz}}$
Reflected/S_{RI}	0.13 + 0.16 = 0.29 W	2.04×10^{-10}	$\delta\tilde{L}_p = 9.1\times10^{-21}$ m/$\sqrt{\text{Hz}}$
Reflected/S_{RQ}		1.53×10^{-10}	$\delta\tilde{l}_m = 2.1\times10^{-17}$ m/$\sqrt{\text{Hz}}$

OTHER CONSIDERATIONS

- Phase Margins: designed to be at least 50 degrees for stability of response around unity gain frequency

  ›› effect of delays included in predicted phase margin (though not explicitly in Matlab models)

- Electronics noise

  ›› Three significant noise sources, sum must be ‘10x below’ SRD sensitivity:

  - photodetector electronics noise
  - ADC input voltage noise
  - DAC output voltage noise

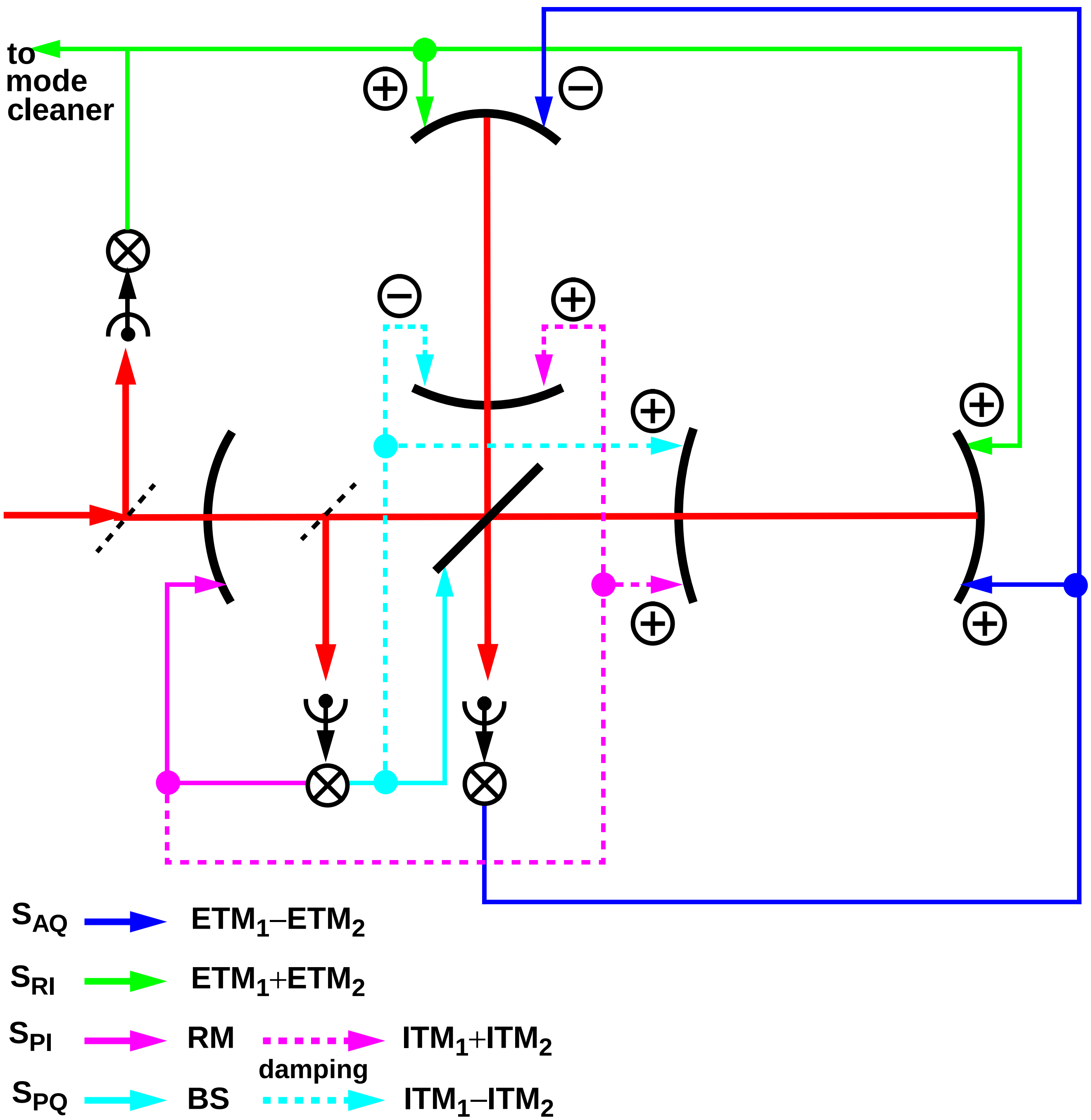
- Actuator dynamic ranges

  ›› ranges of frequency actuators important for designing crossovers

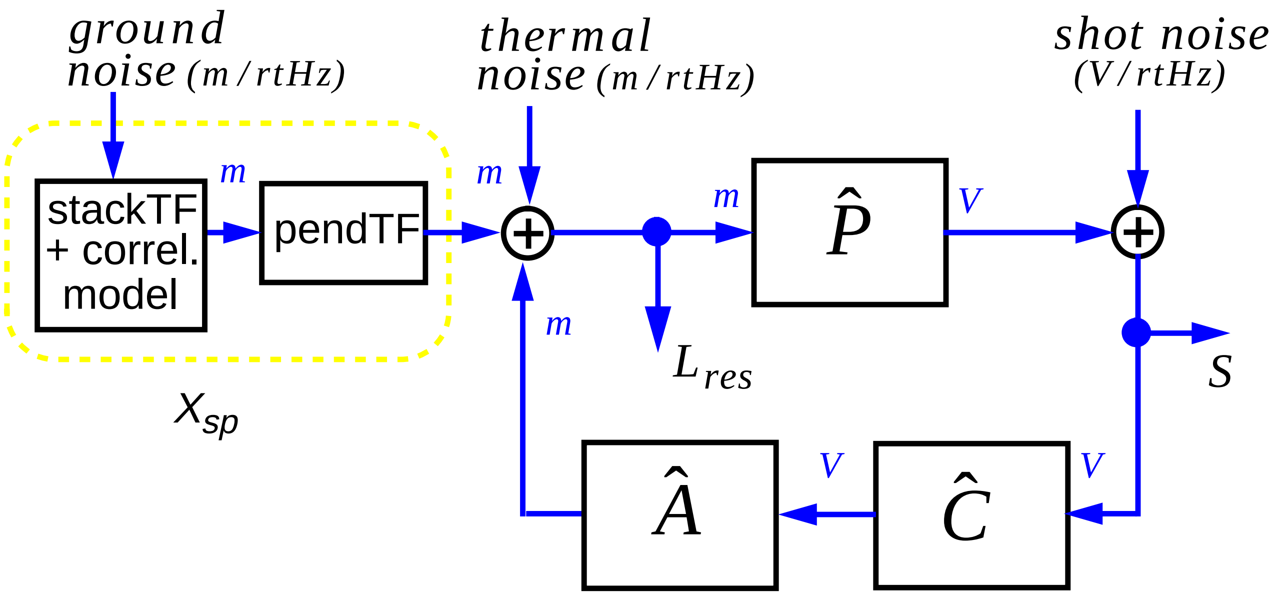
  ›› suspensions: supposed to have sufficient range by design (BS & RM ranges have recently been increased so that this is so)

SUMMARY OF GAIN REQUIREMENTS

Degree(s) of freedom	Frequency range	Gain	Reason
All	DC	50 — 200 dB	achieve required residual deviation
Lm, Lp, lp (lm)	9.5 kHz (5.6 kHz)	< –135 dB	internal resonance of RM, TMs (BS)
Lm, lm, lp	13 Hz	> 20 dB resonant gain	vertical mode of suspensions
lm	> 20 Hz	< 0 dB	sensing noise at pick-off couples to GW signal via off-diagonal plant element
Lp	> 40 Hz	> –60 dB relative to overall loop gain	achieve required frequency noise suppression above 40 Hz
Lp	> 40 Hz	> –80 dB relative to overall loop gain	Lp couples to GW signal via TM suspensions imbalance
lp	DC	> 100 dB	residual lp couples to GW signal via demodulator phase error


to
mode
cleaner
S_{AQ} → $ETM_1 – ETM_2$
S_{RI} → $ETM_1 + ETM_2$
S_{PI} → RM
damping
$ITM_1 + ITM_2$
S_{PQ} → BS
$ITM_1 – ITM_2$

Multi-Input Multi-Output Control System Model

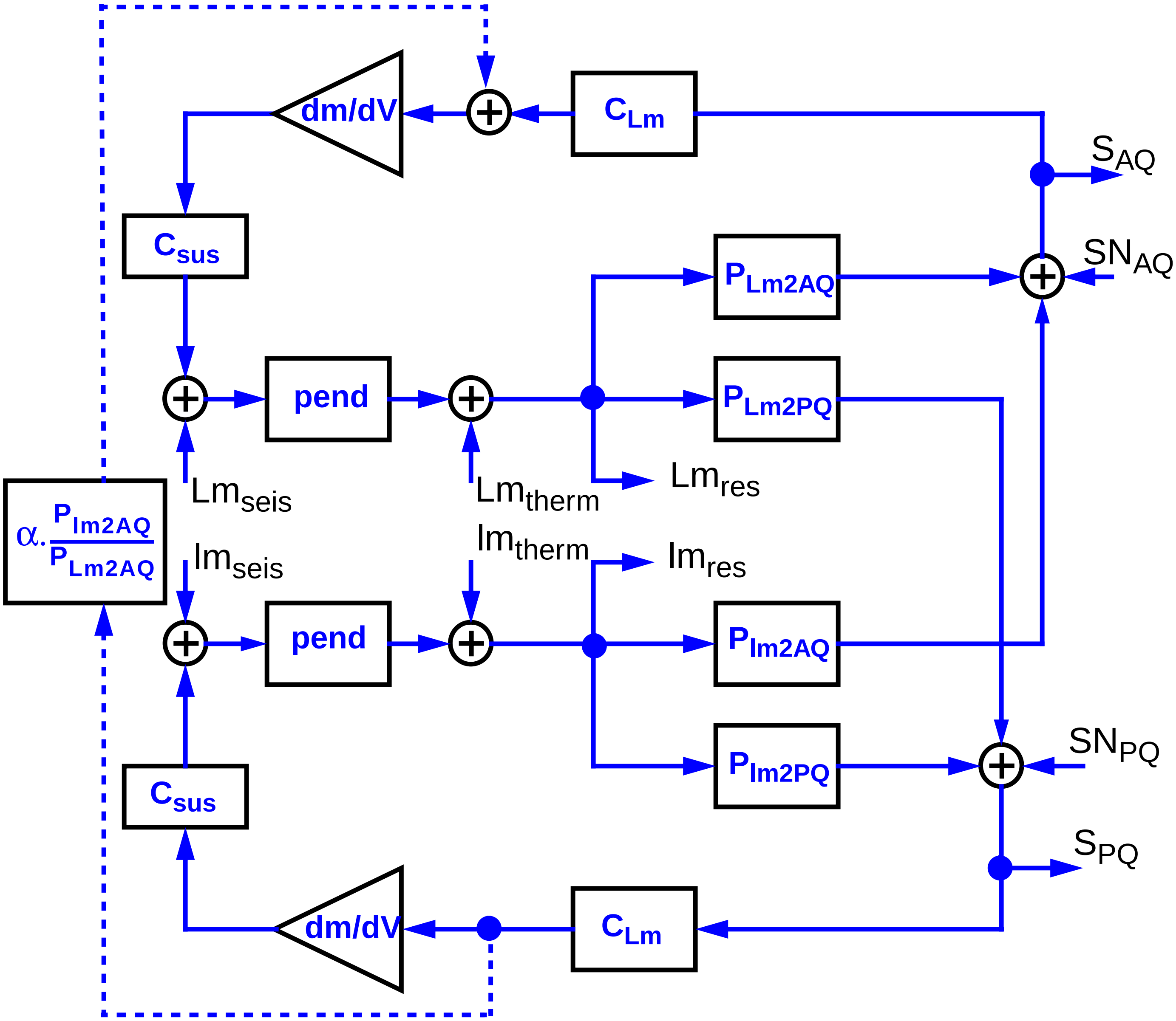


$$\vec{L}_{res} = \hat{M}^{-1}(X_{sp}\vec{L}_{gnd} + \vec{L}_{therm} + \hat{A}\hat{C}\vec{S}_{shot})$$

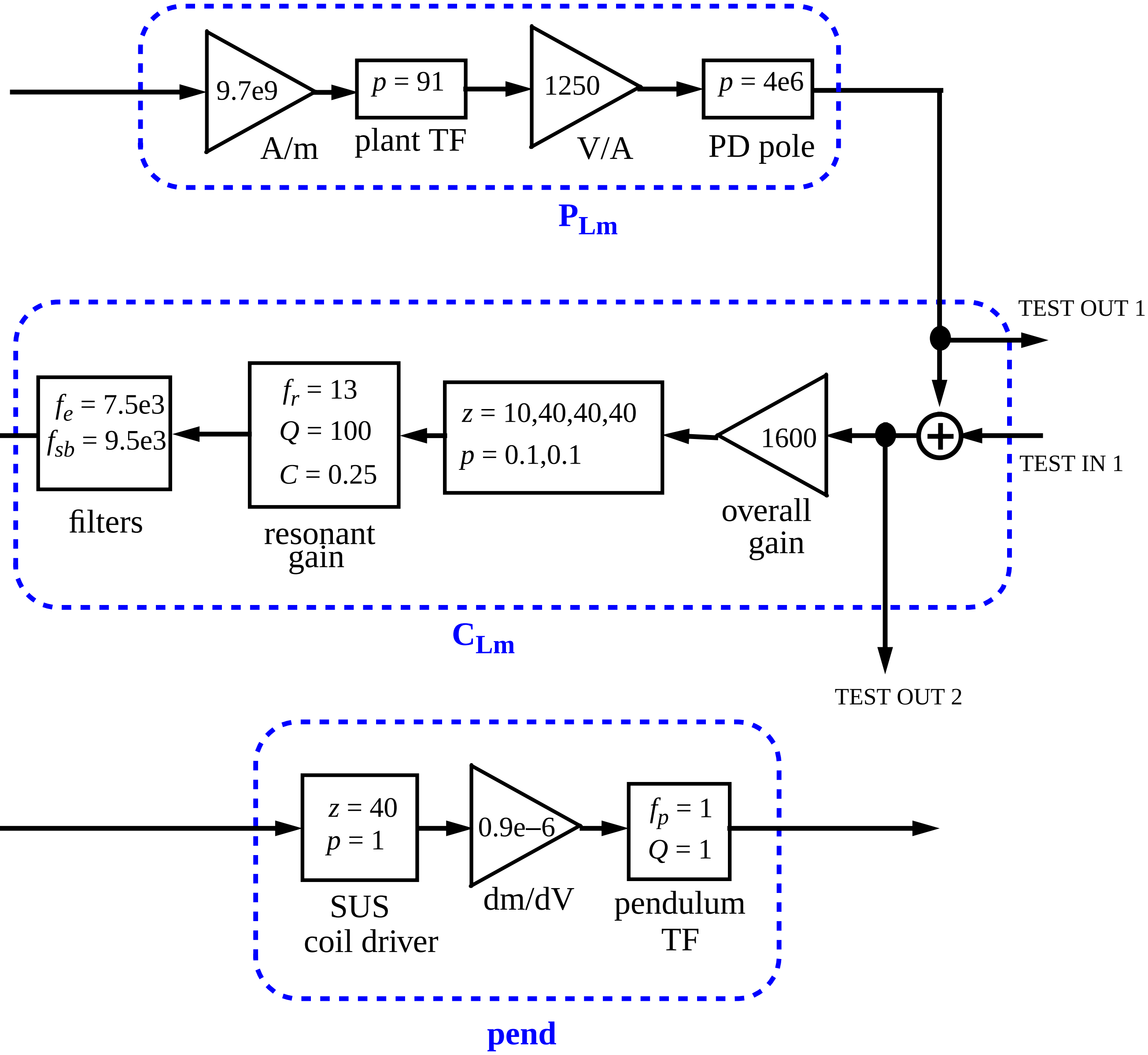
$$\hat{M} = \hat{1} - \hat{A}\hat{C}\hat{P}$$

- **plant matrix block-diagonal ⇒ treat common-mode and differential-mode d.o.f. independently**

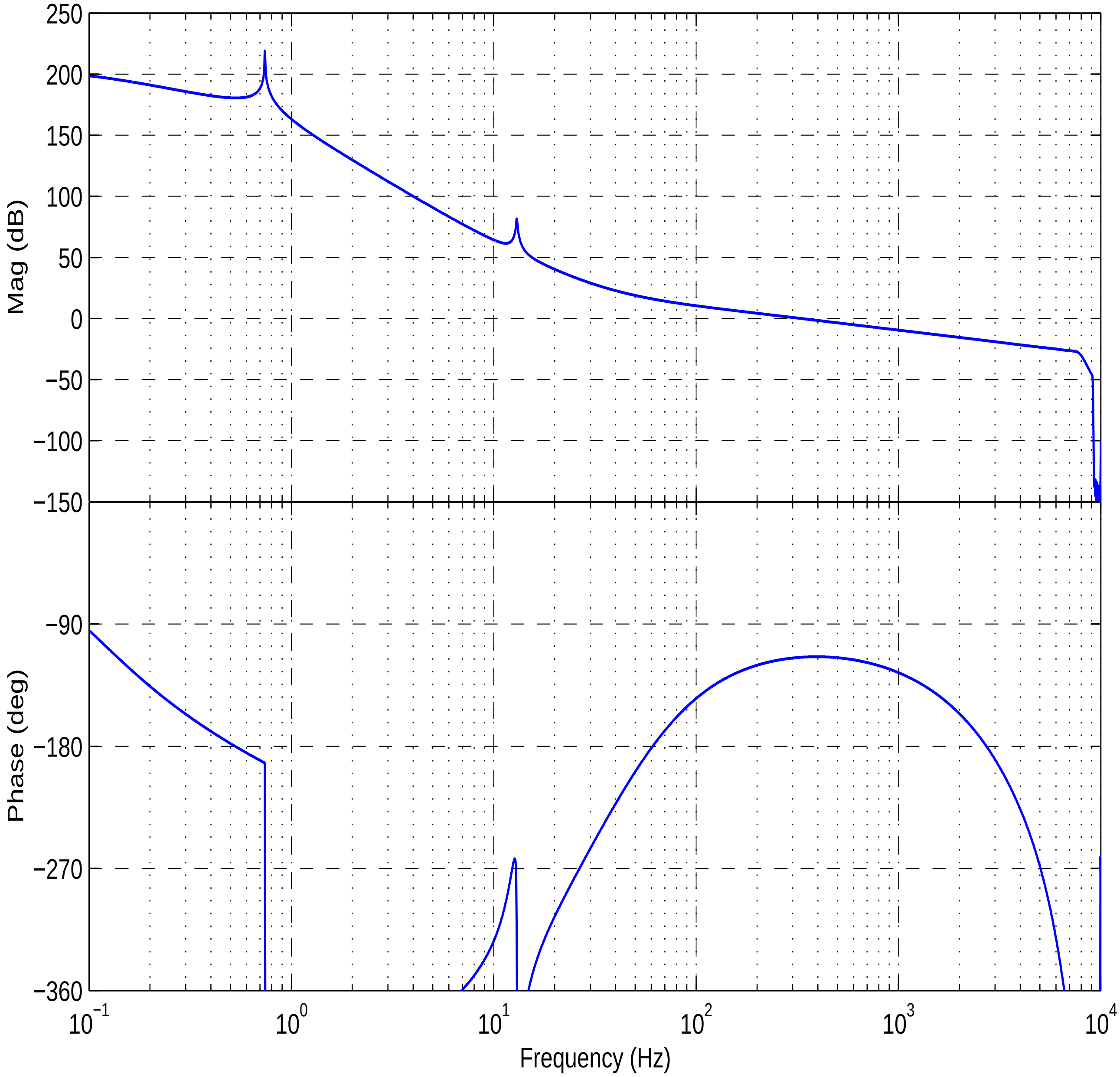
Differential-Mode System Block Diagram



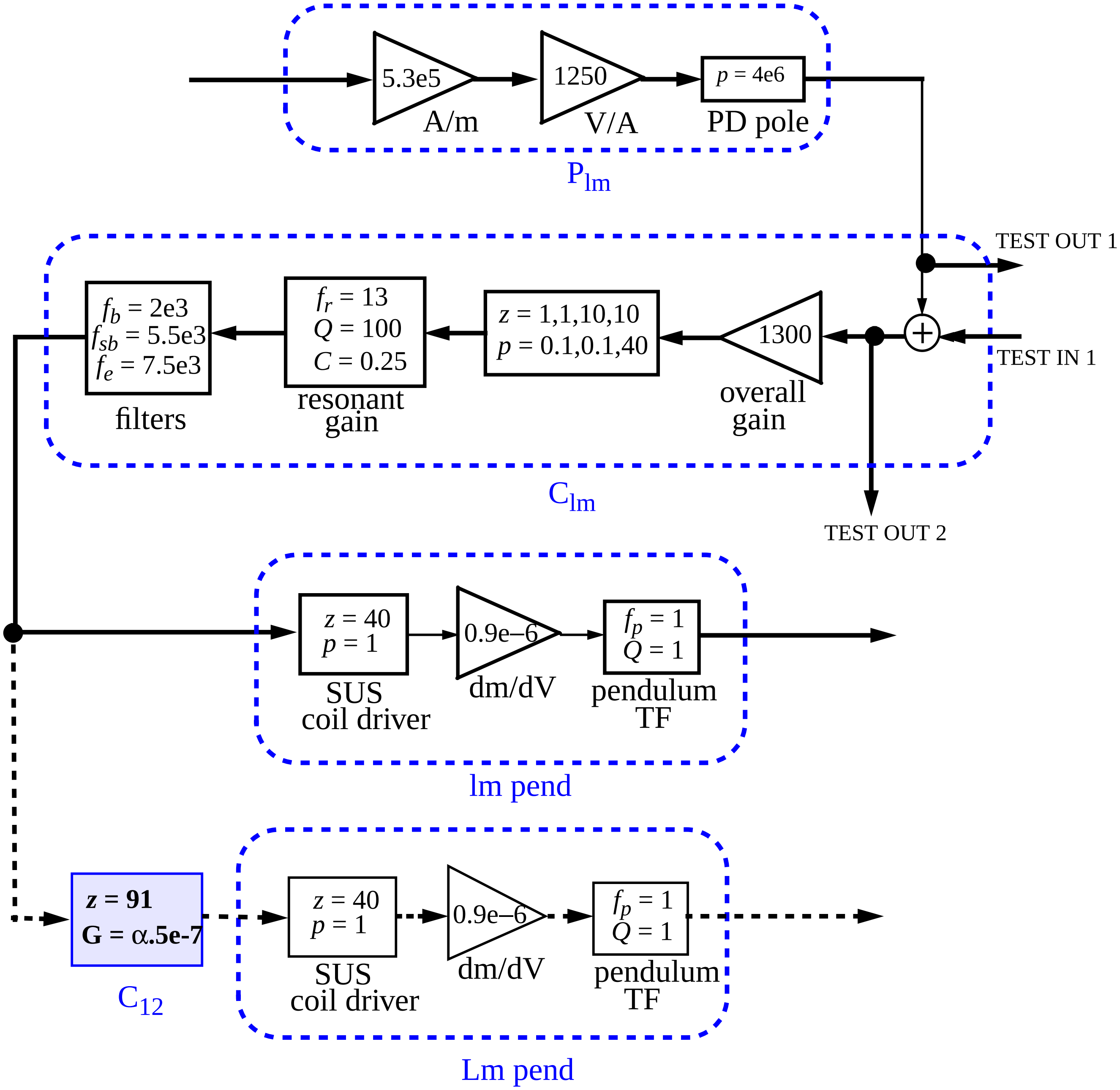
Lm System Blocks



Lm Open-loop Gain

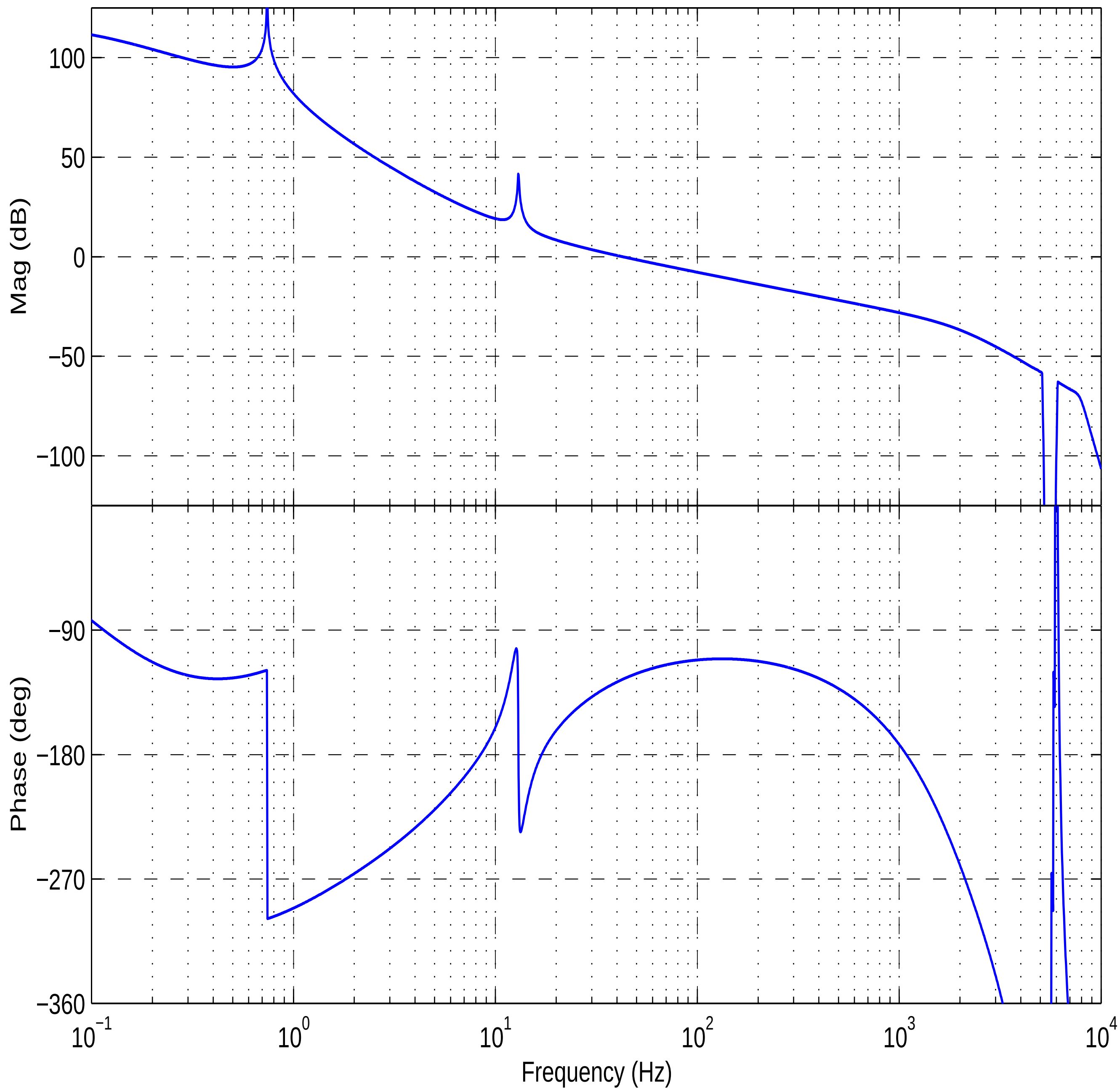


lm System Blocks



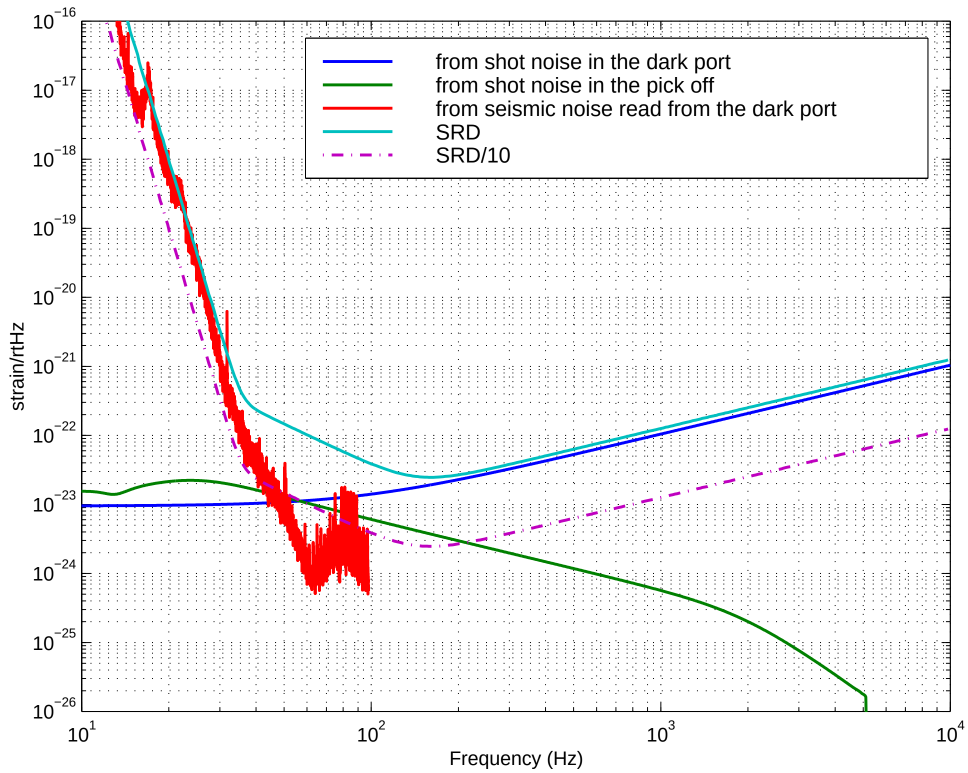
LIGO-G980111-00-D

lm OPEN-LOOP GAIN



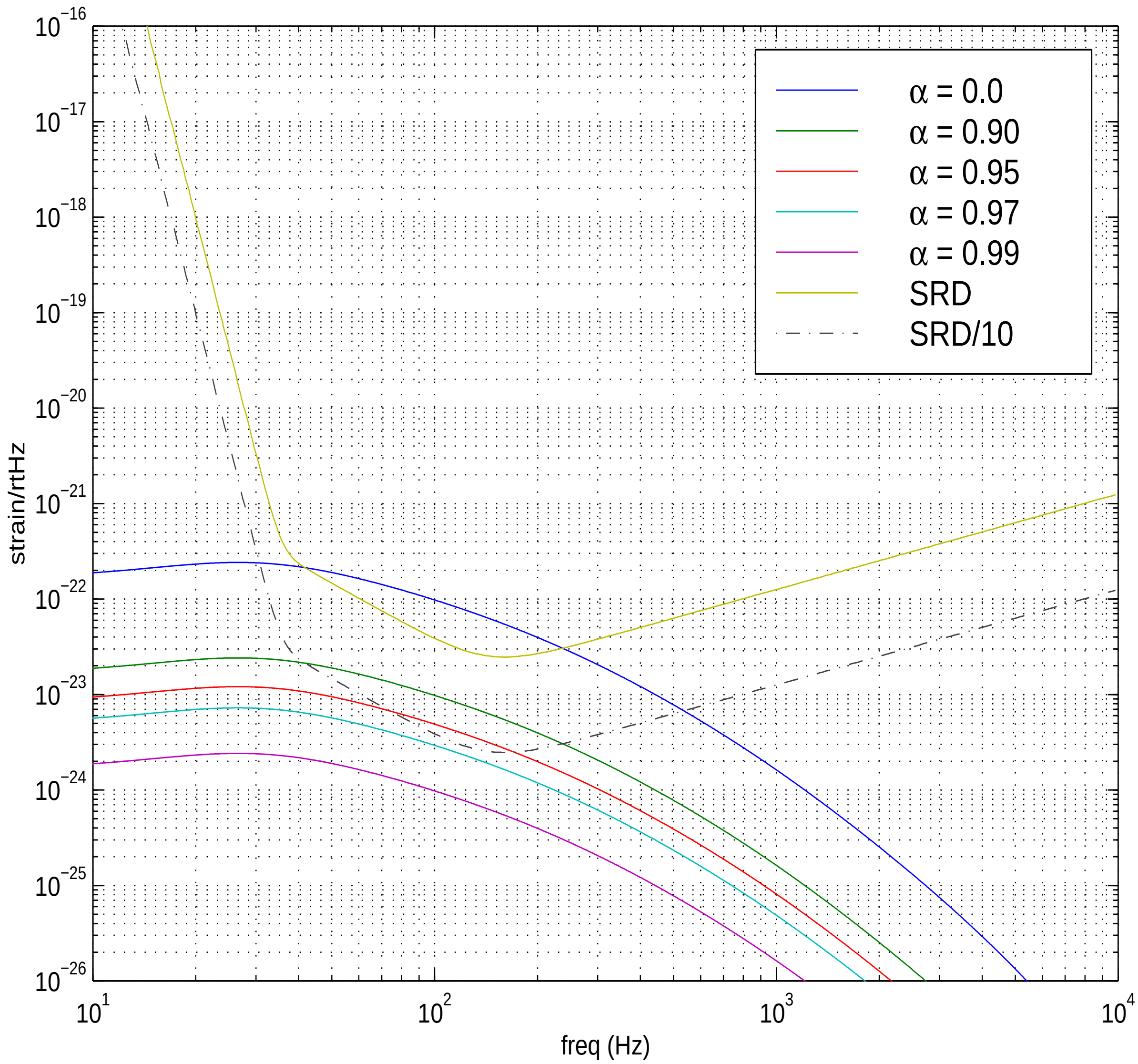
Performance Summary for Differential-mode Loops

Performance Data	Lm	lm	Units
Gain at DC	205	110	dB
Unity gain bandwidth	330	43	Hz
Phase margin	66	55	degrees
Gain at 9.48 kHz (5.58 kHz)	–140	(–141)	dB
Residual length deviation	10^{-14}	5×10^{-12}	m_{rms}
Control signal at coil driver	3.1	0.13	μm_{rms}



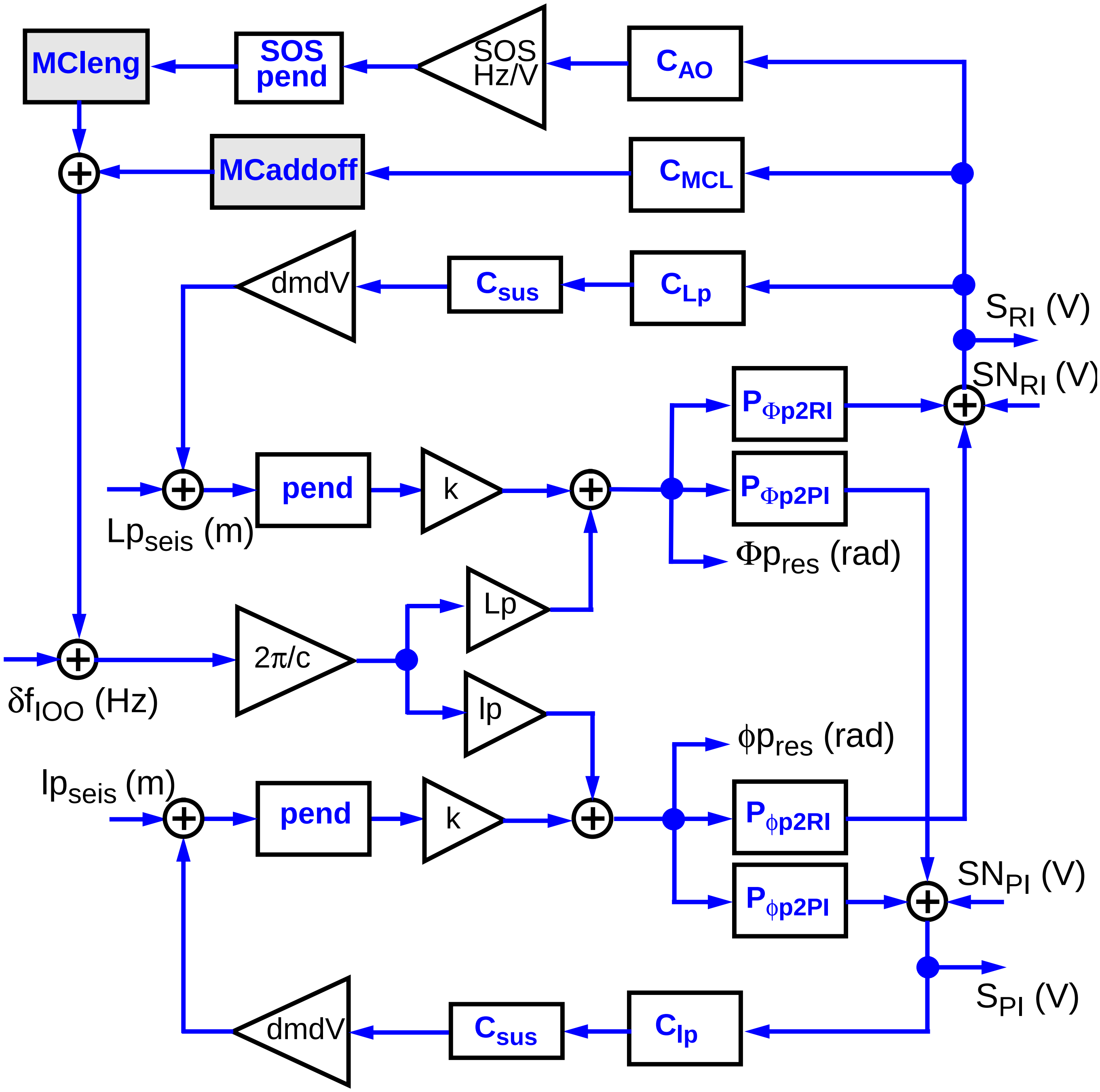
Non-diagonal Control Matrix At Work

- add *Im* control signal to *Lm* to cancel feedthrough of shot noise at S_{Pl} to GW signal

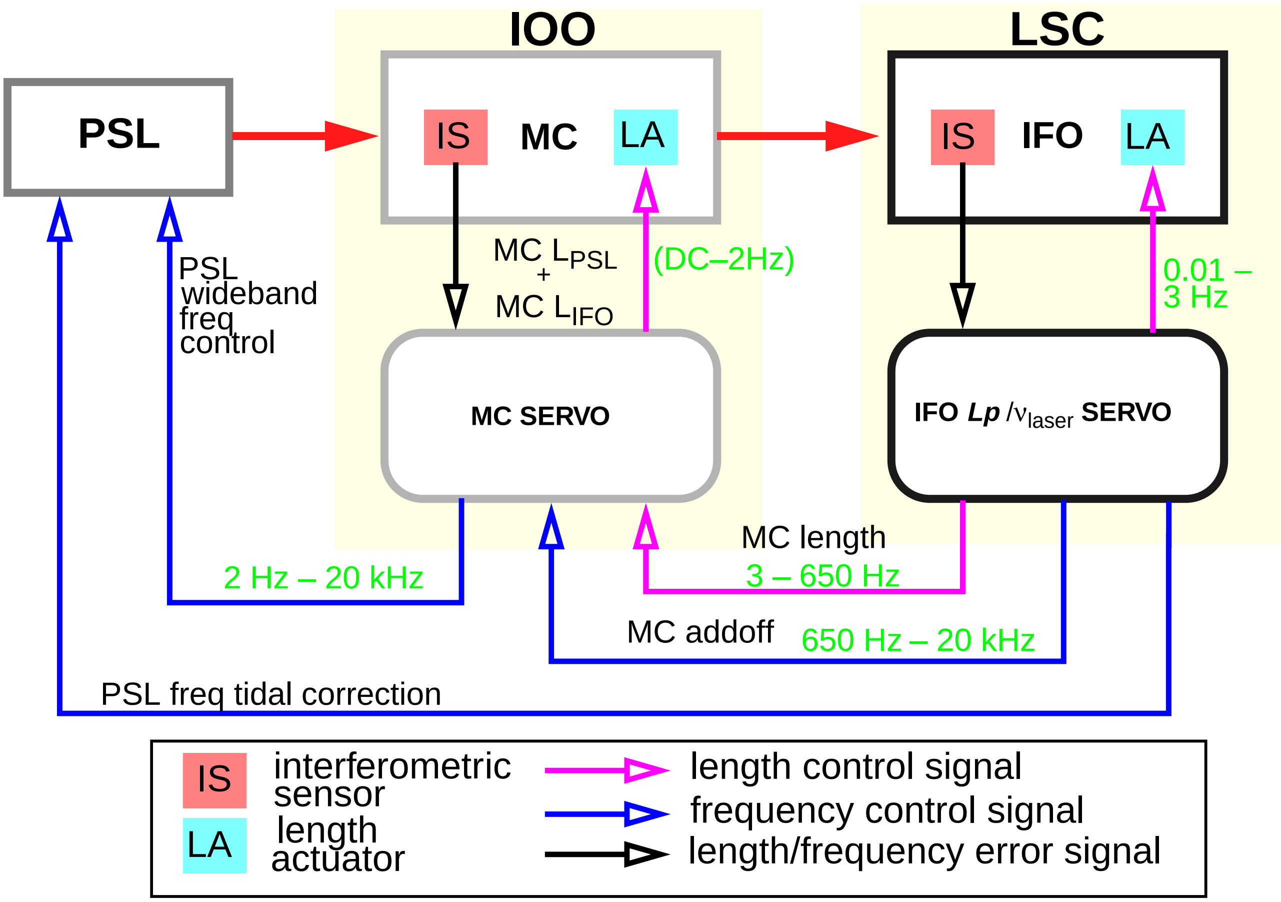


LIGO-G980111-00-D

Common-mode System Block Diagram

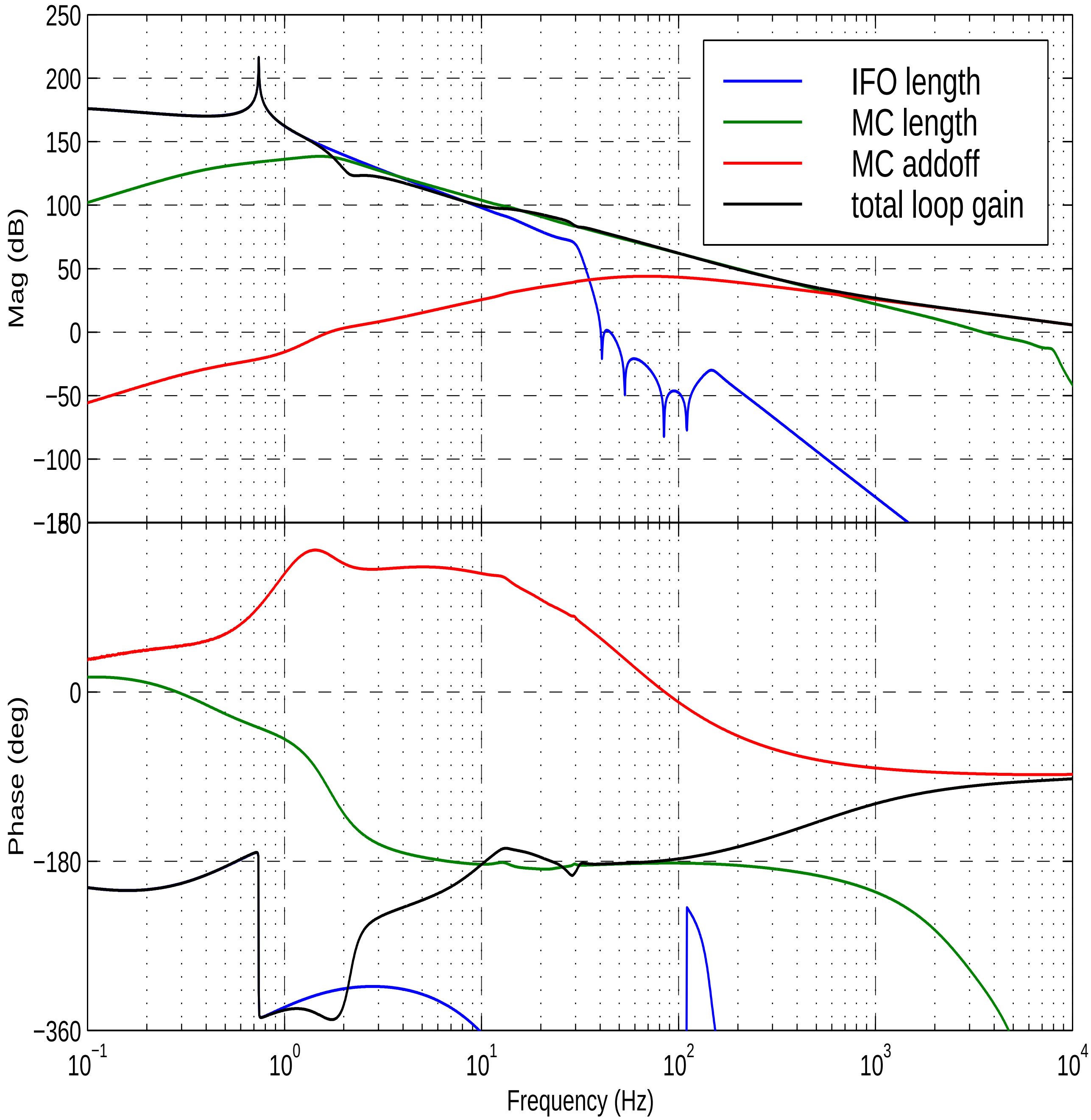


FREQUENCY CONTROL TOPOLOGY



- **Lp/frequency servo has three actuation paths**
  - *Lp* ➡ ETMs
  - δν ➡ mode cleaner length ➡ PSL wideband actuator
  - δν ➡ additive offset of mode cleaner servo error point
- **Need 60 dB of gain frequency noise suppression at 40 Hz ⇒ aggressive filtering**

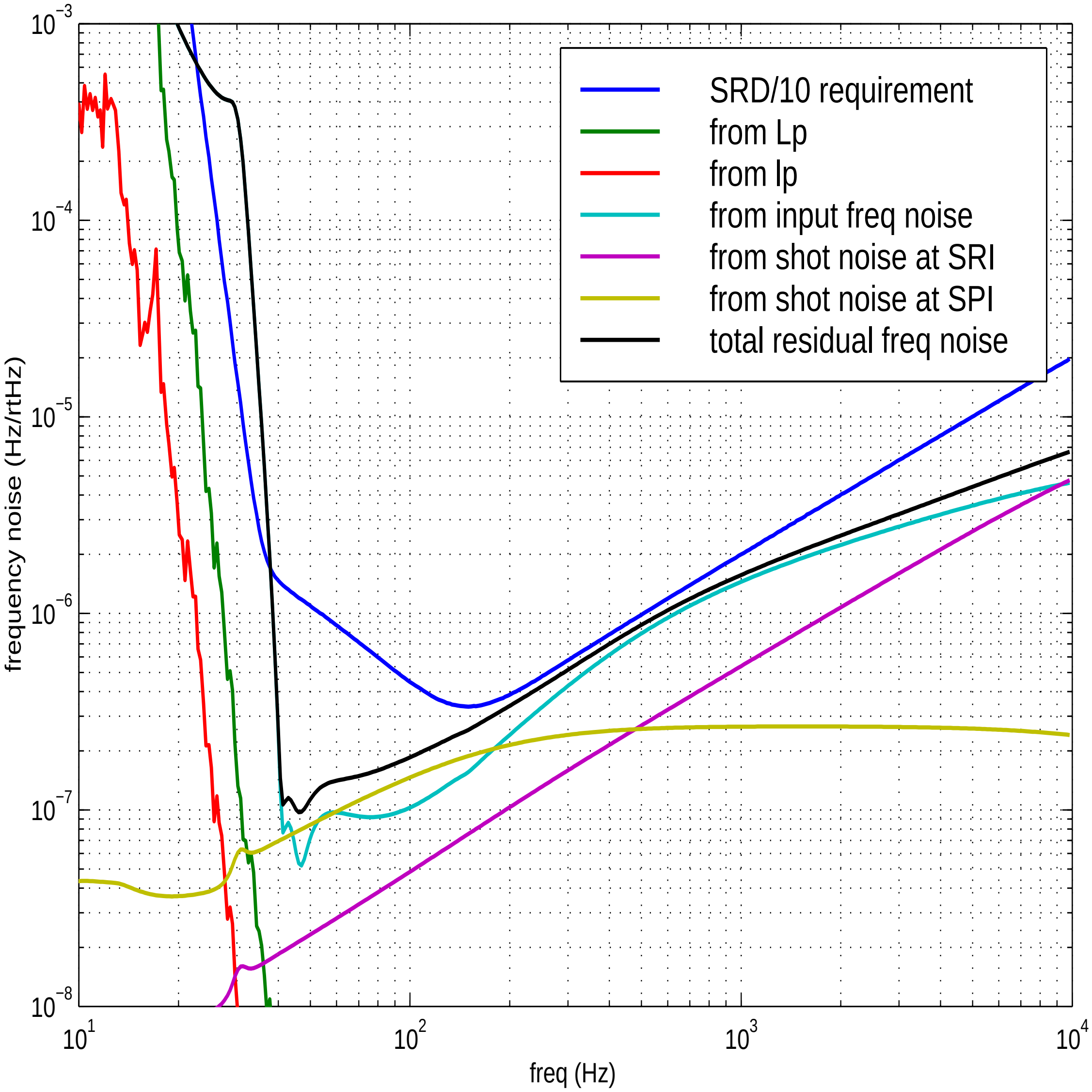
Lp/MCleng/MCaddoff
OPEN-LOOP GAINS



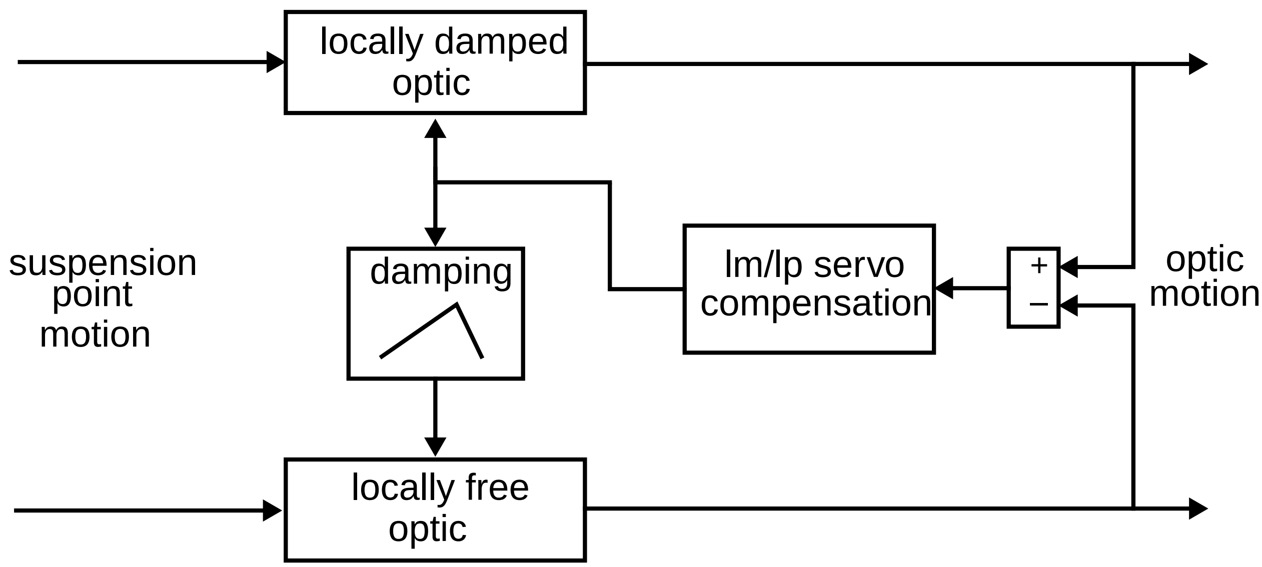
PERFORMANCE SUMMARY FOR COMMON-MODE LOOPS

Performance Data	***Lp*/df**	***lp***	**Units**
Gain at DC	180	120	dB
Unity gain bandwidth	21000	130	Hz
Phase margin	94	70	degrees
Lp/MC length crossover frequency	3.7		Hz
MC length/additive offset crossover freq.	650		Hz
Gain at 9.48 kHz	–200	–160	dB
Residual phase deviations	6×10^{-7}	4×10^{-5}	radian_{rms}
Error signals	0.2	0.03	V_{rms}
Drive signals	Lp: 3.1 MC leng: 1200 MC addoff: 2.3	lp: 1.1	μm_{rms} Hz_{rms} mHz_{rms}

Residual Frequency Noise



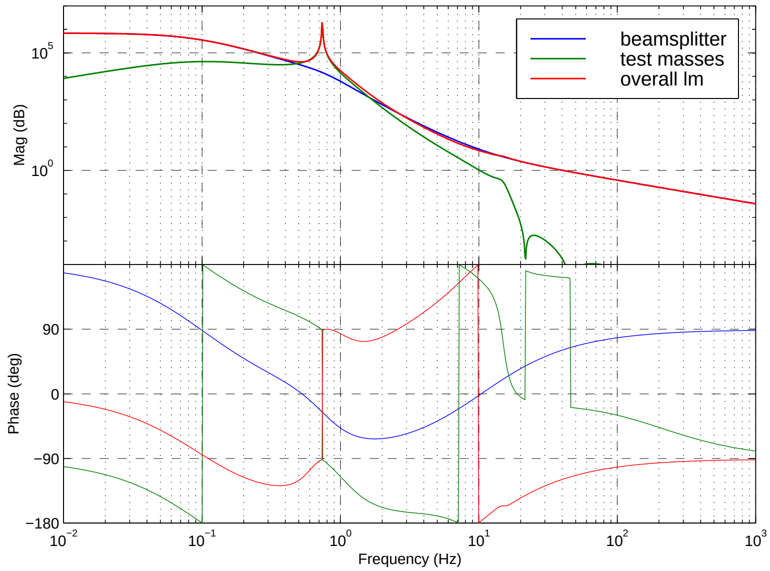
TEST MASS DAMPING PATHS



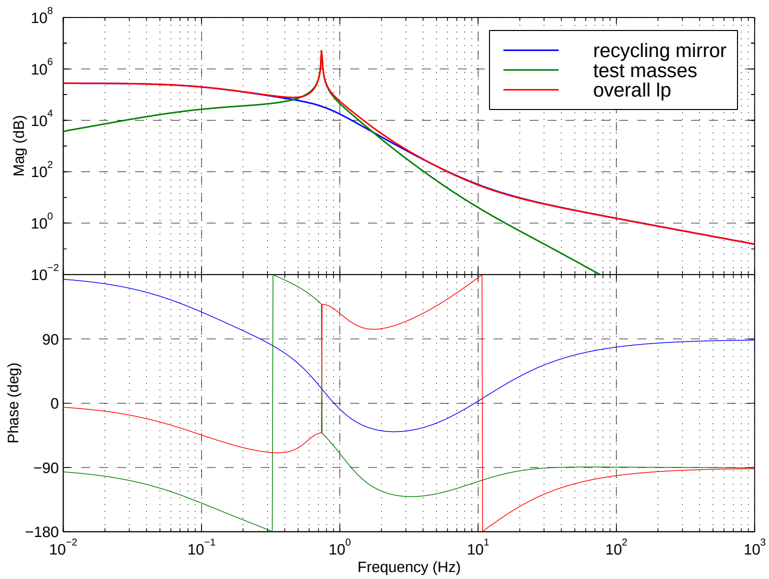
Loop	**Sensitivity @ 40 Hz (m/√Hz)**	**GW channel coupling**	**Damping path gain req. @ 40 Hz**	**Damping servo**
Recycling cavity	6×10^{-17}	5%	–35 dB	Zero @ DC 2nd order Chebyshev @1 Hz (+ pole@20 Hz for stability)
Michelson	1.5×10^{-16}	100%	–65 dB	Zero @DC 2nd order Chebyshev @1 Hz 4th order elliptic @ 20 Hz, 30 dB stop

Open-loop Response of *lm* and *lp* Loops with TM Damping

❑ *lm* loop



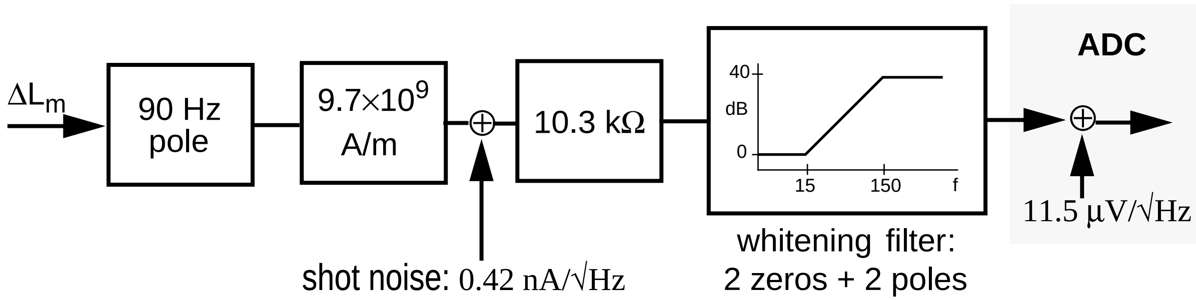
❑ *lp* loop



SIGNAL CONDITIONING REQUIREMENTS

- Suppress ADC & DAC noise (at least 10x below signal)
  - ›› ADC: 11.5 μV/√Hz at f_s = 16384; +/– 10 V range
    - ~10^6 √Hz pk-noise ratio
    - AS error signal: few x 10^6 √Hz pk-noise ratio
  - ›› DAC: 7.0 μV/√Hz at f_s = 8x16384; +/– 5 V range
    - ~10^6 √Hz pk-noise ratio
    - Lm control signal: ~10^8 √Hz pk-noise ratio
- Anti-aliasing for ADCs
  - ›› Nyquist frequency: 8192 Hz; signal (shot noise) is white above this
  - ›› Upper GW frequency: 7 kHz
  - ›› Want to minimize phase shift in the control band
  - ›› AA filter: 6th order elliptic; 60 dB stopband, 0.1 dB ripple, f_c = 7500 Hz

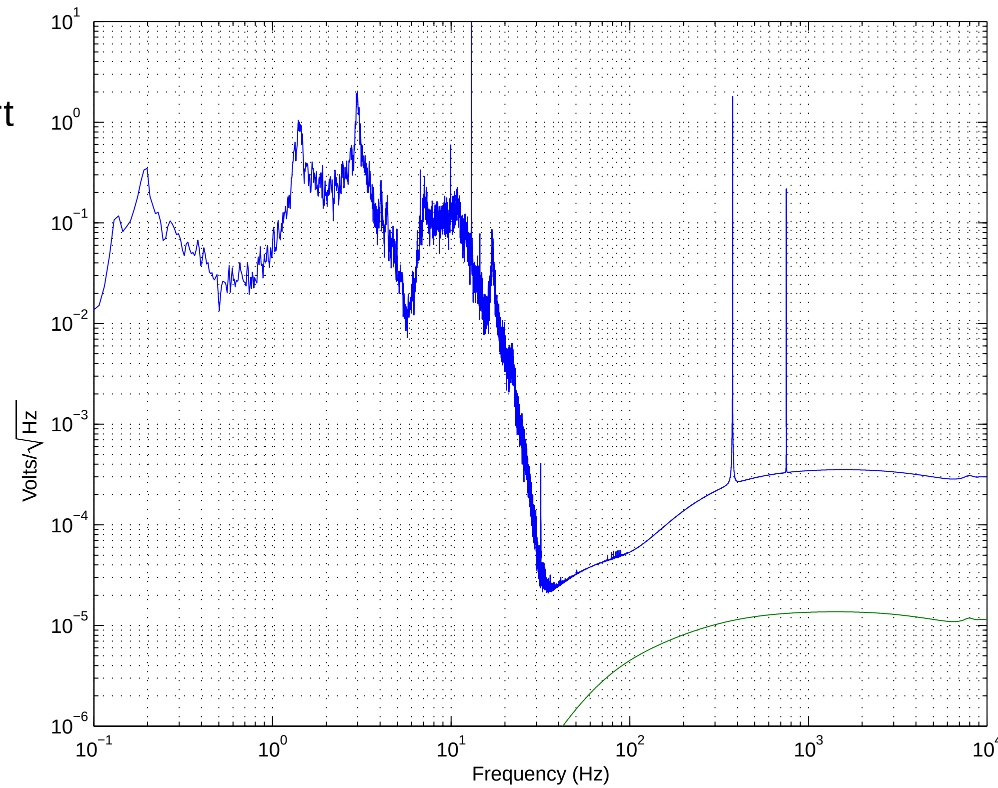
WHITENING FILTER – AS ERROR SIGNAL



Headroom: pre-ADC gain is adjusted so that signal is 1V-rms at ADC input (10 Vpk)

Whitened AS port error signal & ADC noise :

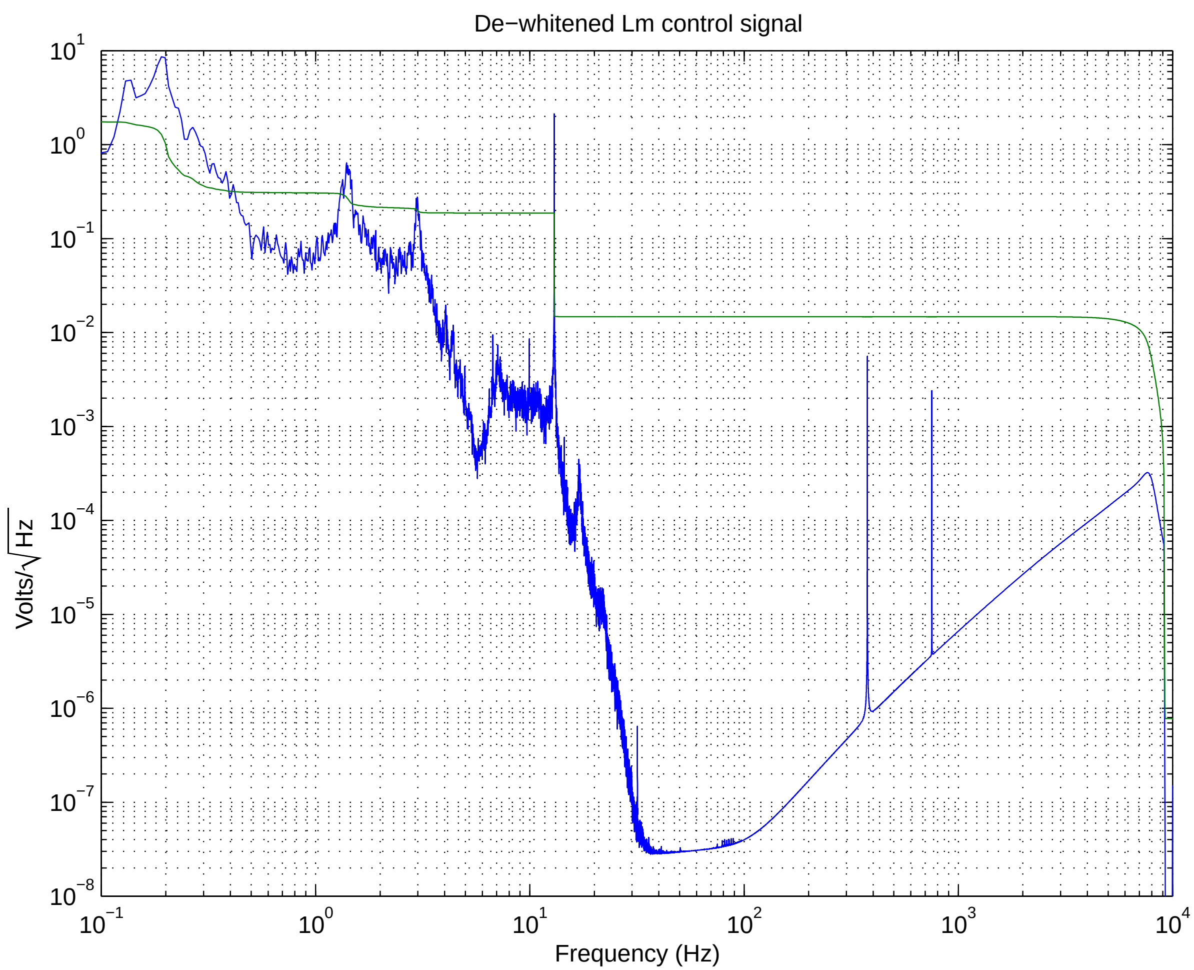
All channels summed prior to sampling.



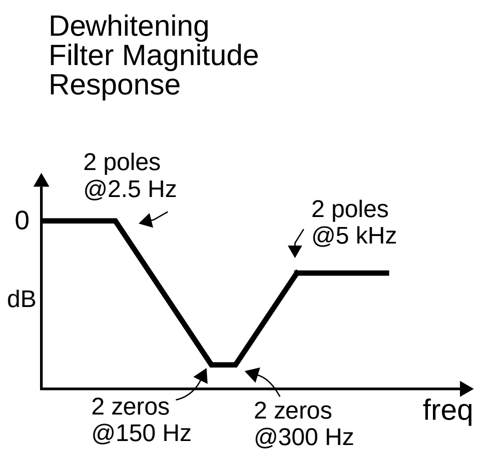
Other 3 error signals require 1 zero/pole section.

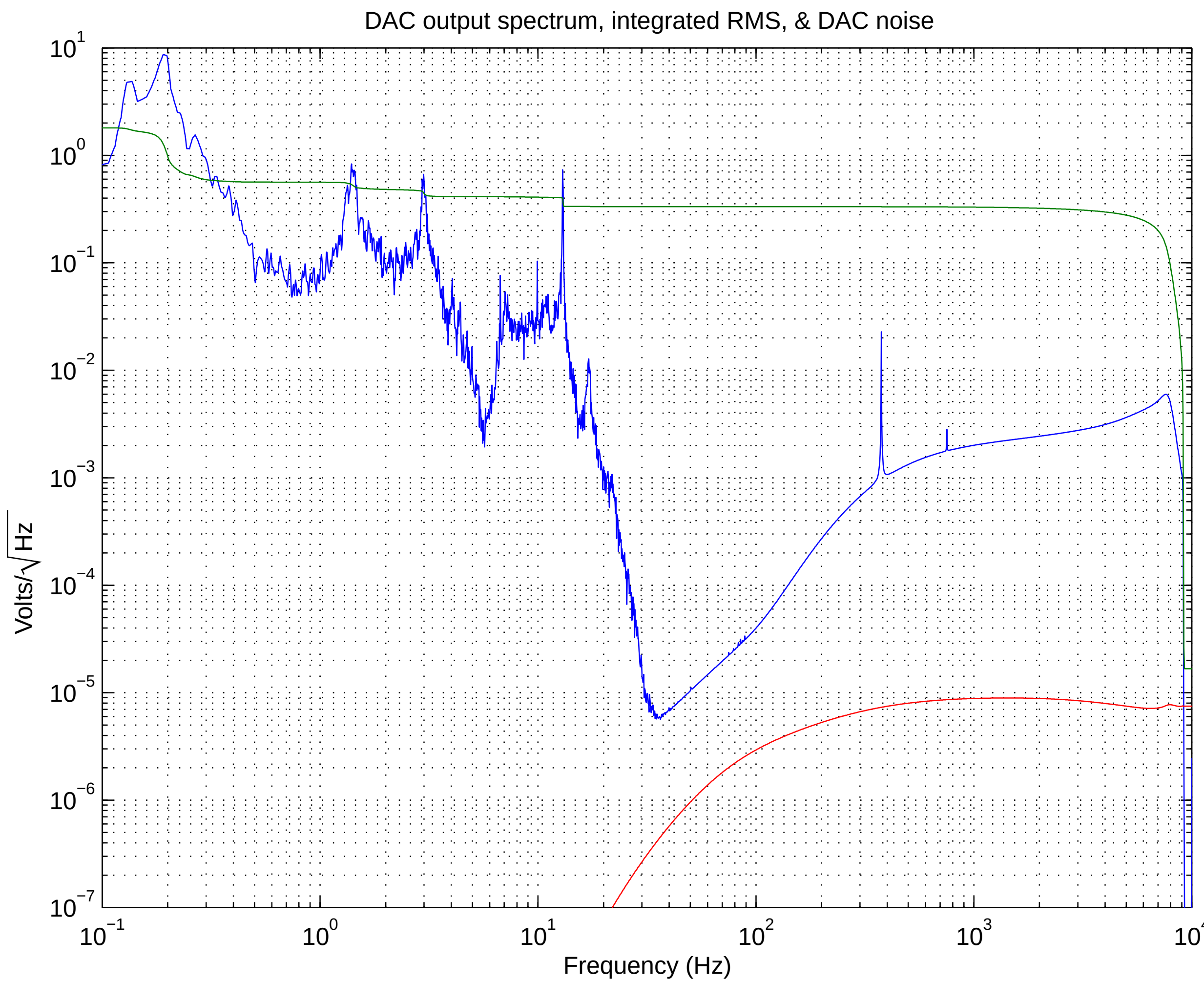
POST DAC – DEWHITENING

- Input to suspension controller: Lm control signal

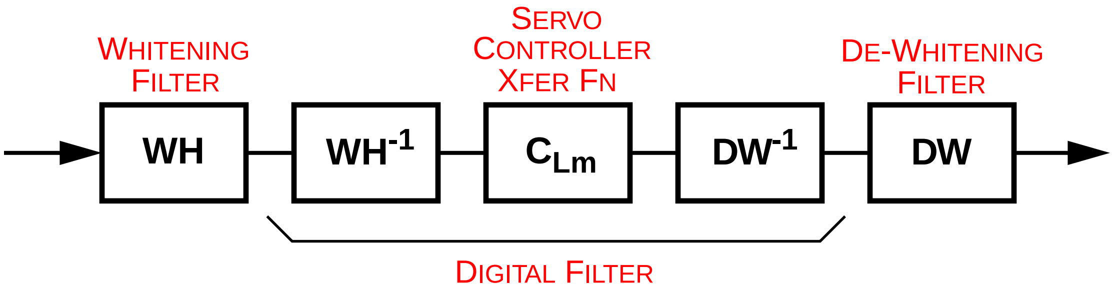


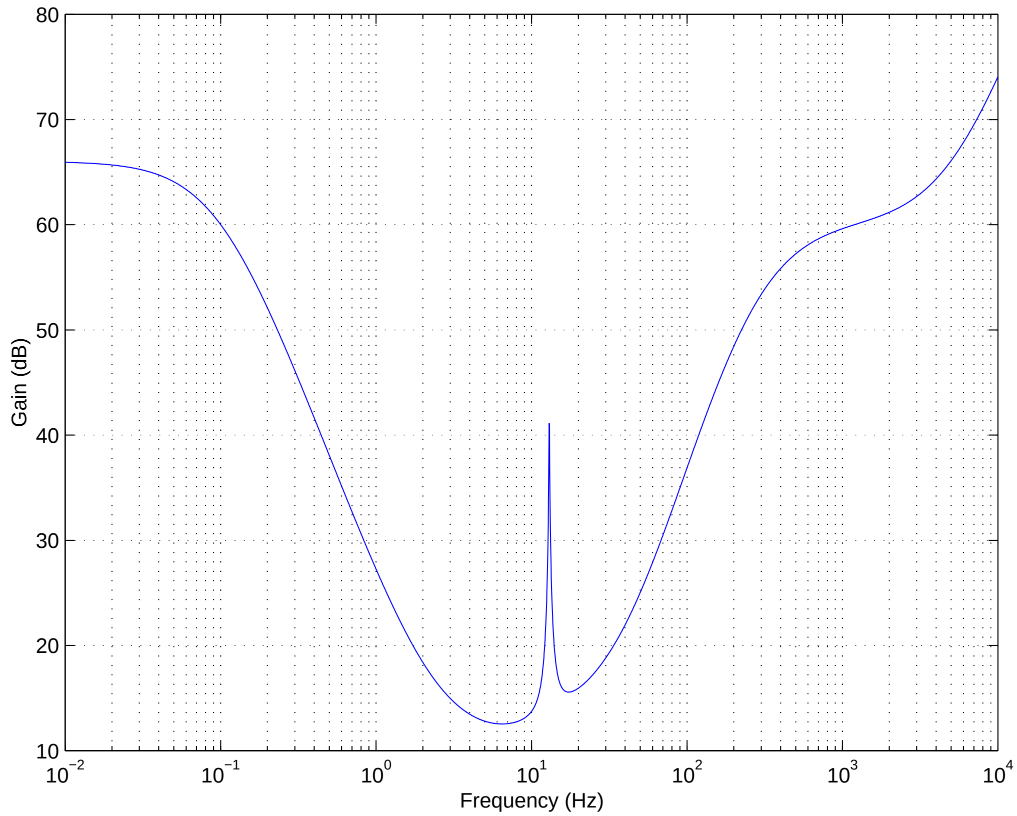
DEWHITENING FILTER





DIGITAL FILTER



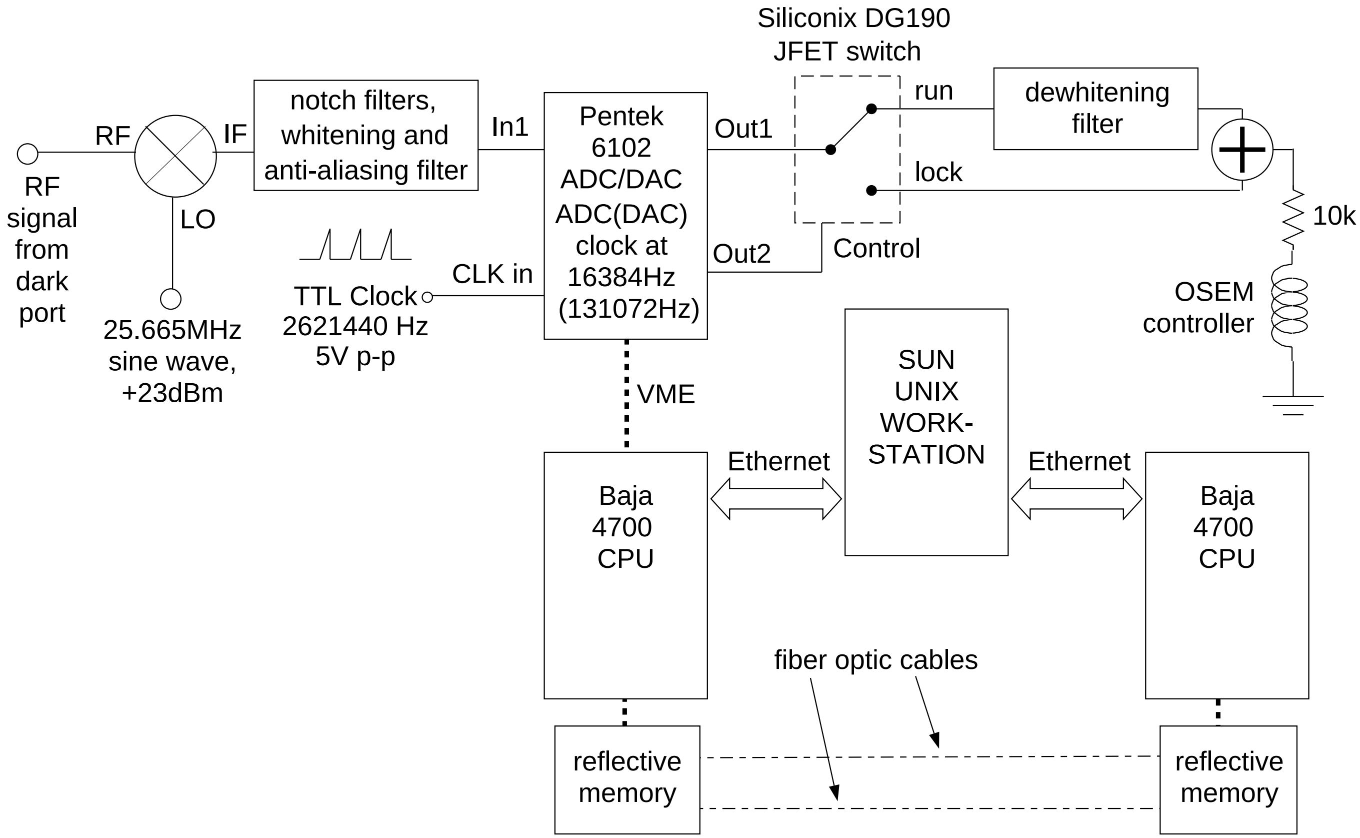


PNI DIGITAL L_M LOOP TEST

Questions Addessed by the Test:

- What are the noise contributions from the digital servo and associated analog circuits ?
- How can a digital servo be used to lock a suspended inteferometer ?
- What is the phase noise of the MIT phase noise inteferometer (PNI) ?
- Can inteferometer diagnostics be implemented in the digital domain ?

THE DIGITAL SERVO PROTOTYPE

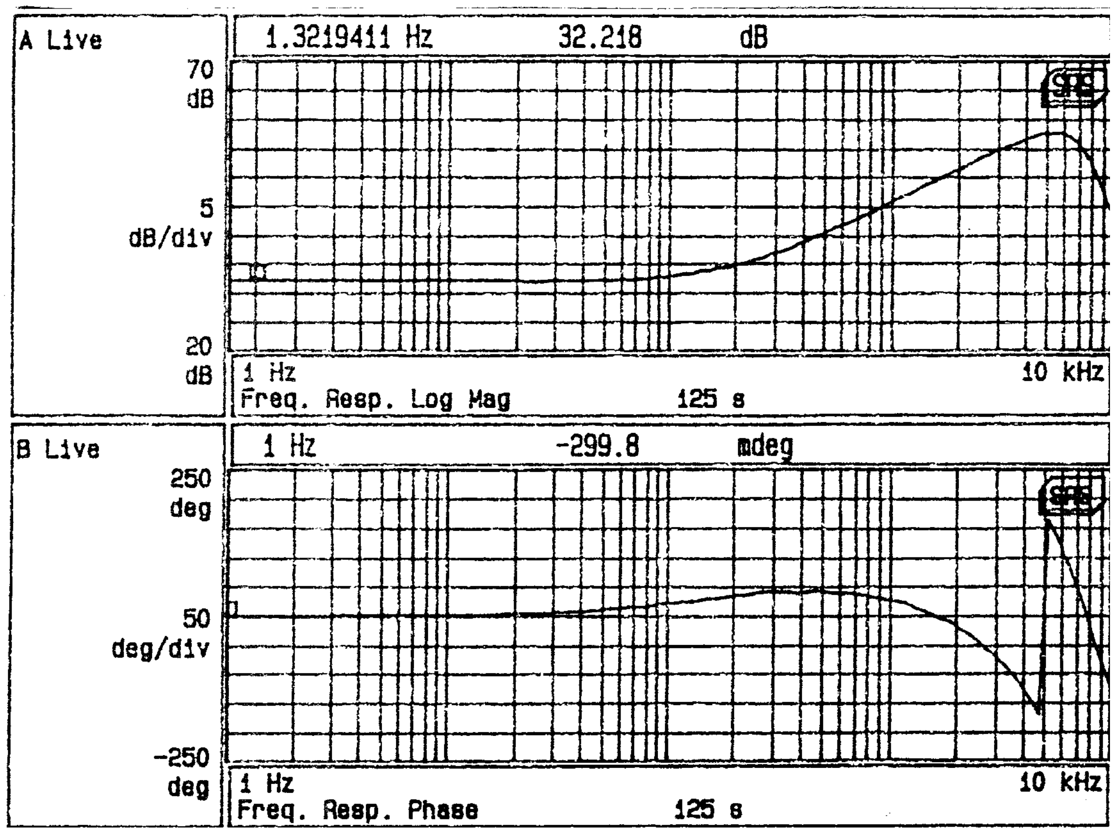


Schematic diagram of the elements of the digital L_m servo prototype.

DYNAMIC RANGE OF THE PENTEK 6102 ADC/DAC

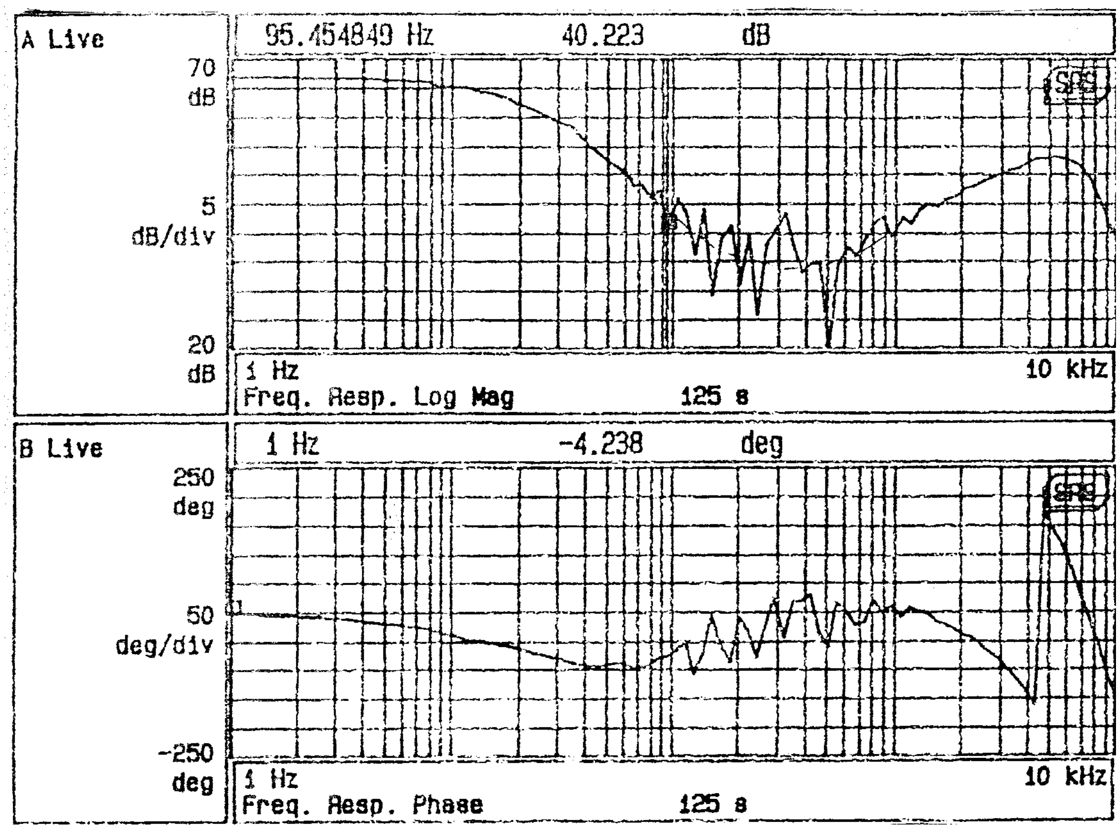
- Measured noise level at DAC output was ~10μV/rtHz with no digital IIR filter.
- Noise level is ~2 orders of magnitude greater than that anticipated due to quantization of the analog signal at the ADC.
- Excess partly due to analog circuit components on the ADC chip itself.
- Over the full bandwidth of the ADC, the noise level is 0.9mV_{rms}. Since the full scale voltage at the DAC output is 5V, the VOLTAGE DYNAMIC RANGE of the ADC/DAC is ~4.5 orders of magnitude.

DIGITAL SERVO IN LOCK MODE



Open loop gain of the servo electronics in lock mode. The electronics consists of the notch, whitening, and anti-aliasing filters followed by a digital filter. The de-whitening filter is bypassed.

DIGITAL SERVO IN RUN MODE

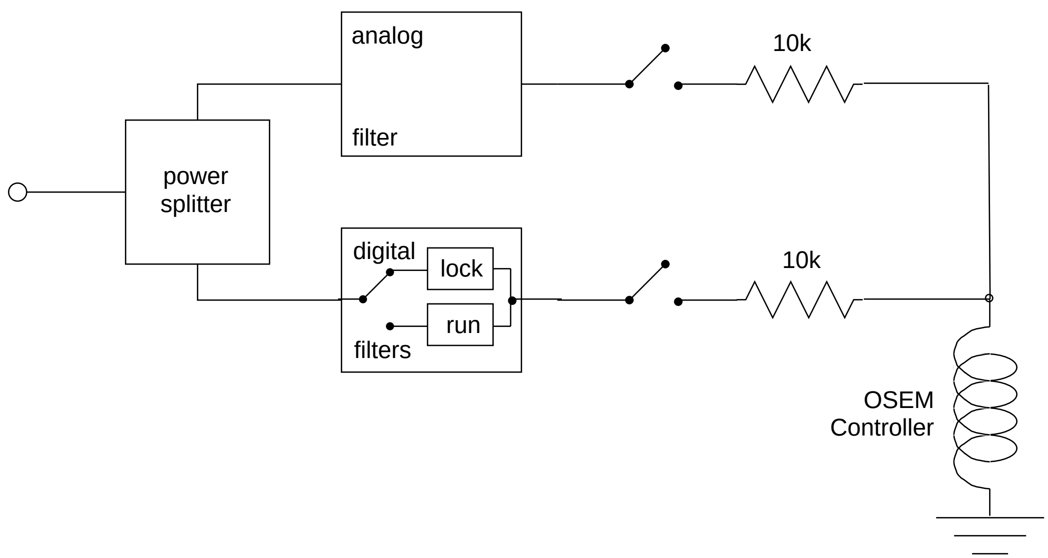


Open loop gain of the servo electronics in run mode. The electronics consists of the notch, whitening, and anti-aliasing filters followed by a digital filter and the de-whitening filter.

LOCKING THE INTEFEROMETER

- Initially, PNI locked using the digital servo alone in run mode. Locking took a long time (~1/2 hour), probably due to restricted bandwidth and dynamic range of digital filter.

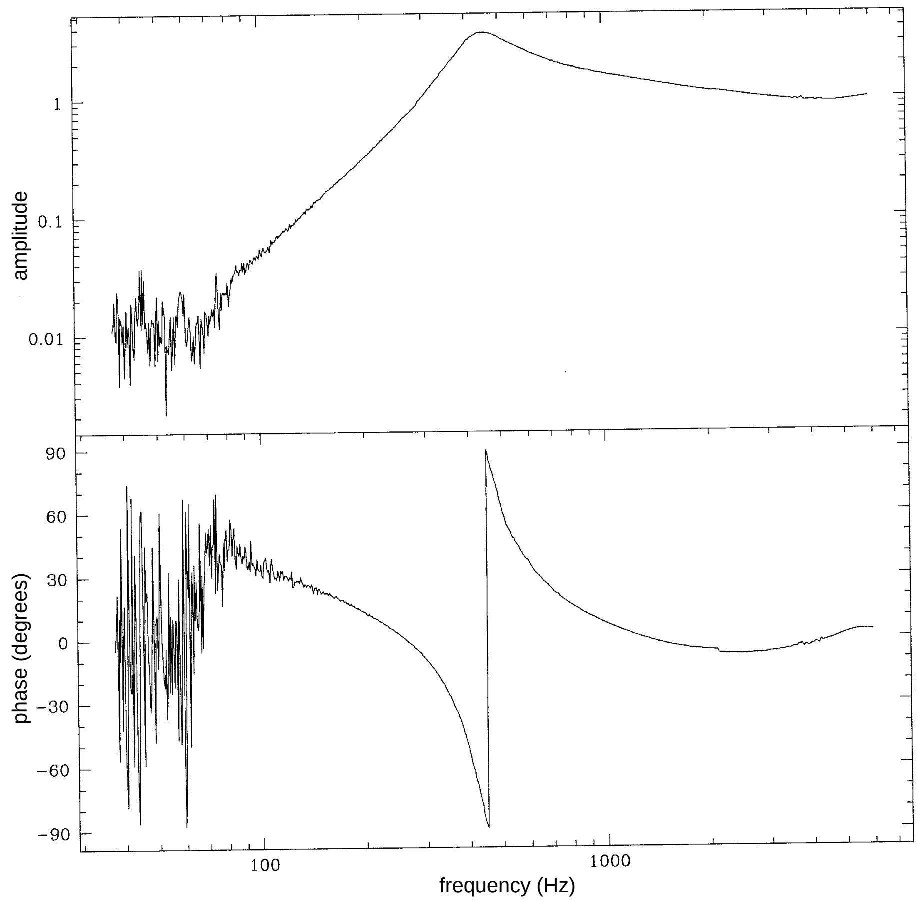
- Subsequently, a different locking technique was adopted. The PNI was locked with the analog servo connected and the digital servo disconnected. On locking (after ~1 min.) the digital servo was connected in lock mode, and the analog servo disconnected. Finally,the digital servo was switched in to run mode.



Schematic diagram of the arrangement of analog and digital servo elements for locking the PNI.

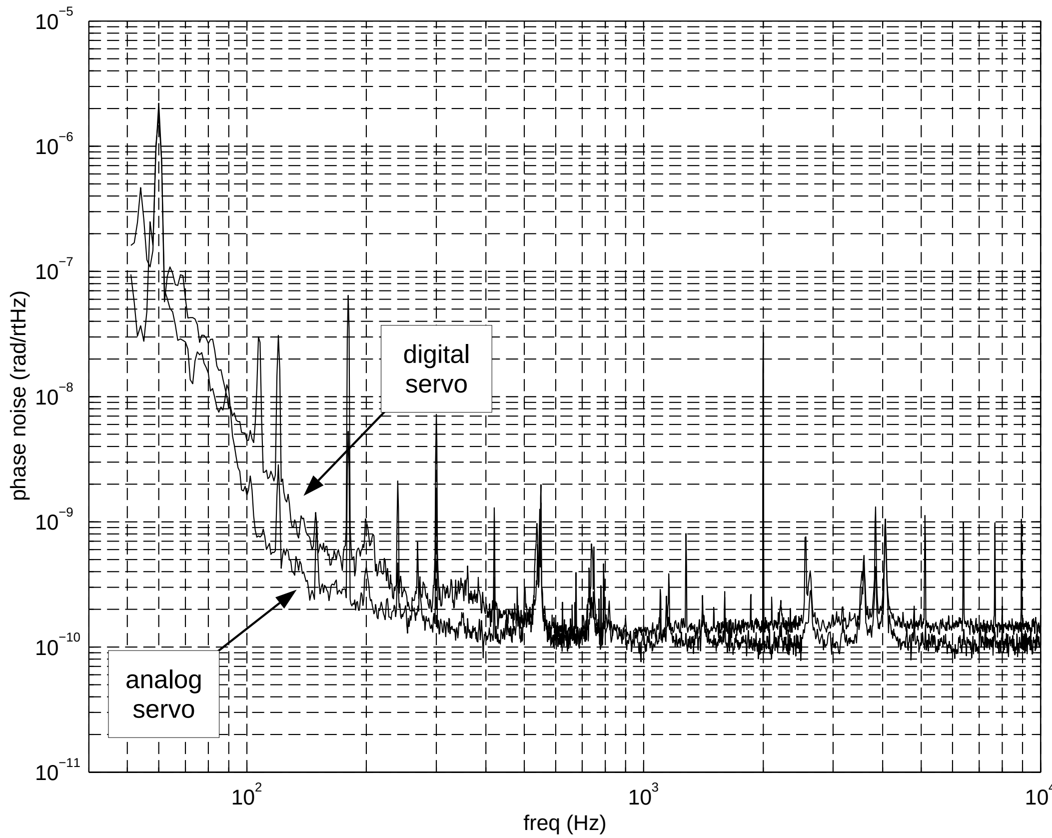
CLOSED LOOP GAIN

- Measured using digital signal injection into servo loop via reflective memory.



Closed Loop Gain of the PNI measured using diagnoistics implemented digitally via a reflective memory loop.

PHASE NOISE OF DIGITAL PNI



Phase noise of the PNI with the digital and analog servos in use.

CONCLUSIONS

– The PNI digital servo experiment has shown that a digital servo can be to run a LIGO prototype inteferometer, yielding phase noise results comparable with those for the analog servo.

– The PNI digital servo experiment has successfully demonstrated application of software diagnostics similar to those being written for LIGO.

– The dynamic range of the digital servo using the Pentek 6102 ADC/DAC is ~4.5 orders of magnitude.

– The digital servo was used successfully to lock the PNI, however a more efficient locking method was locking the machine using an analog servo with a high dynamic range and bandwidth, and subsequently switching to a digital servo for data-taking.

Staff

- Optical layout, engineering, procurement
  - K. Mason
- Sensor integration/test
  - M. McInnes, P. Fritschel, M. Zucker
- Site installation/commissioning support (starting 10-11/98; 1-1.5 FTE average, + site liaison)
  - P. Fritschel, E. Daw, N. Mavalvala, B. Ware, M. Zucker
  - D. Sigg (Hanford site liaison)
- CDS electronics design/fab/test/SW support (now -> 12/99)
  - P. Fritschel, E. Daw, N. Mavalvala, B. Ware

Construction EAC vs. budget[1]

Item	Budget ($k)	EAC ($k)	Δ ($k)
LSC personnel	1,076	1,778	(702)
LSC hardware	609	257	352
ASC personnel	1,385	2,757	(1,372)
ASC hardware	3,419	1,694	1,725
total	**6,489**	**6,486**	**3**

1. LIGO Construction (WBS 1.x) only; does not include installation (LIGO Ops, WBS 2.x)

Hardware budget detail

LSC;HW

							2/98 EAC				Current EAC		
TOTAL LENGTH SENSING/CONTROL ETC (5E517-5H517):							$1,236,321						
LSC (5E517-5H517): Hardware							$247,420				$256,645		
Group	Equipment	Wa2k	Wa4k	La4k	total	Cost (ea)	Total		rev. total	rev. Cost	Current EAC	Committed	Reference
shutter	EO shutter	3	3	3	9	$3,700	$33,300		9	$3,700	$33,300		
shutter	EO driver	3	3	3	9	$2,500	$22,500		9	$2,500	$22,500		
shutter	polarizer & mount	6	6	6	18	$1,400	$25,200		18	$1,400	$25,200		
shutter	spares	1		1	2	$7,600	$15,200		2	$7,600	$15,200		
calibrator	LD control & detector	2	2	2	6	$8,060	$48,360		6	$8,060	$48,360		
calibrator	detector amplifier	2	2	2	6	$905	$5,430		6	$905	$5,430		
calibrator	optics mtg. hardware	2	2	2	6	$600	$3,600		6	$600	$3,600		
calibrator	FC laser diode w/connector	2	2	2	6	$2,455	$14,730		6	$2,455	$14,730		
calibrator	port mounts	4	4	4	12	$400	$4,800		12	$400	$4,800		
calibrator	port mount hardware	4	4	4	12	$150	$1,800		12	$150	$1,800		
calibrator	spares	1			1	$12,000	$12,000		1	$12,000	$12,000		
calibrator	shipping	1	1	1	3	$1,800	$5,400		3	$1,800	$5,400		
PD	LD/bias T/mount/optics	1		1	2	$3,400	$6,800		2	$3,400	$6,800		
PD	InGaAs PIN (bare)	10	10	10	30	$160	$4,800	1	40	$111	$4,440	5/26/98	PP270004-75PF EGG Canada
PD	spares	5	5	5	15	$160	$2,400		15	$160	$2,400		
DSP proto/FA	VME crate w/PS	1	0	0	1	$4,500	$4,500		1	$4,500	$4,500		
DSP proto/FA	BAJA CPU w/memory	1	0	0	1	$8,500	$8,500		1	$8,500	$8,500		
DSP proto/FA	Pentek 6102 I/O	1	0	0	1	$7,500	$7,500		1	$7,500	$7,500		
DSP proto/FA	Reflective memory module	2	0	0	2	$6,000	$12,000		2	$6,000	$12,000		
DSP proto/FA	demod/preamp board	1	0	0	1	$1,600	$1,600		1	$1,600	$1,600		
DSP proto/FA	whiten/AA module	1	0	0	1	$2,500	$2,500		1	$2,500	$2,500		
DSP proto/FA	unwhiten/SUS drive	1	0	0	1	$2,500	$2,500		1	$2,500	$2,500		
DSP proto/FA	PD module	1	0	0	1	$2,000	$2,000		1	$2,000	$2,000		
DSP proto/FA	VME bus analyzer	0	0	0	0	$0	$0	1	1	$9,585	$9,585	4/9/98	PP266692-75JH (VMetro)

Personnel budget detail

LSC;PER

LSC (5E517-5H517): Personnel & Travel								$988,901
Category	ID	FTE	months	MM or #	rate		Total	
sr. eng/sci	TBD	1	12	12				
	Fritschel	0.5	15	7.5				
	Zucker	0.5	15	7.5				
postdoc	Mavalvala	0.25	15	3.75				
postdoc	Ware	0.5	15	7.5				
postdoc	Daw	1	15	15				
jr. eng	N/A	0	12	0				
contract eng.	TBD	1	12	12				
contract eng. >3/99	TBD	1	11	11				
tech specialist	N/A	0	12	0				
tech specialist >3/99	N/A	0		0				
contract tech	TBD	1	9	9				
contract tech >3/99	TBD	1	11	11				
travel	trips to Caltech, Hanford, LA			16	$2,250		$36,000	

Delivery schedule

LSC_mile

5F517 LSC fab status update as of 6/25/98 mez							
SEQ	ID	MILESTONE	PLAN DATE	RAW WT	SUM(RW)	% WT	CUM %
1	5	LSC Init Fab	7/15/98	15	124	12.10%	12.10%
2	7	LSC_1	7/31/98	8	124	6.45%	18.55%
3	8	LSC_2	8/31/98	8	124	6.45%	25.00%
4	9	LSC_3	9/30/98	8	124	6.45%	31.45%
5	153	LSC IOT7 ready	10/23/98	15	124	12.10%	43.55%
6	10	LSC_4	10/30/98	8	124	6.45%	50.00%
7	11	LSC_5	11/27/98	5	124	4.03%	54.03%
8	12	LSC_6	12/25/98	3	124	2.42%	56.45%
9	13	LSC_7	1/29/99	5	124	4.03%	60.48%
10	179	LSC ISCT7 ready	2/11/99	10	124	8.06%	68.55%
11	14	LSC_8	2/26/99	1	124	0.81%	69.35%
12	196	LSC ISCT9 ready	3/12/99	10	124	8.06%	77.42%
13	15	LSC_9	3/31/99	1	124	0.81%	78.23%
14	213	LSC ISCT10 ready	4/16/99	8	124	6.45%	84.68%
15	16	LSC_10	4/30/99	1	124	0.81%	85.48%
16	275	LSC LIOT1 ready	5/7/99	2	124	1.61%	87.10%
17	17	LSC_11	5/31/99	1	124	0.81%	87.90%
18	302	LSC LISCT1 ready	6/4/99	2	124	1.61%	89.52%
19	320	LSC LISCT3 ready	6/25/99	2	124	1.61%	91.13%
20	18	LSC_12	6/30/99	1	124	0.81%	91.94%
21	338	LSC LISCT4 ready	7/23/99	2	124	1.61%	93.55%
22	398	LSC WIOT1 ready	9/24/99	2	124	1.61%	95.16%
23	425	LSC WISCT1 ready	11/19/99	2	124	1.61%	96.77%
24	443	LSC WISCT3 ready	12/24/99	2	124	1.61%	98.39%
25	461	LSC WISCT4 ready	1/21/00	2	124	1.61%	100.00%
				124		100.00%	