LIGO LOS and SOS Electronics PDR

- Scope

  ›› This review covers the design and performance requirements for all electronics hardware and software to be used for the suspension controls of the LIGO Large and Small Optics

- Organization of Presentation

  ›› Introduction

  – Product functions

  – General Constraints

  – Differences from existing 40 meter systems

- Satellite Amplifier

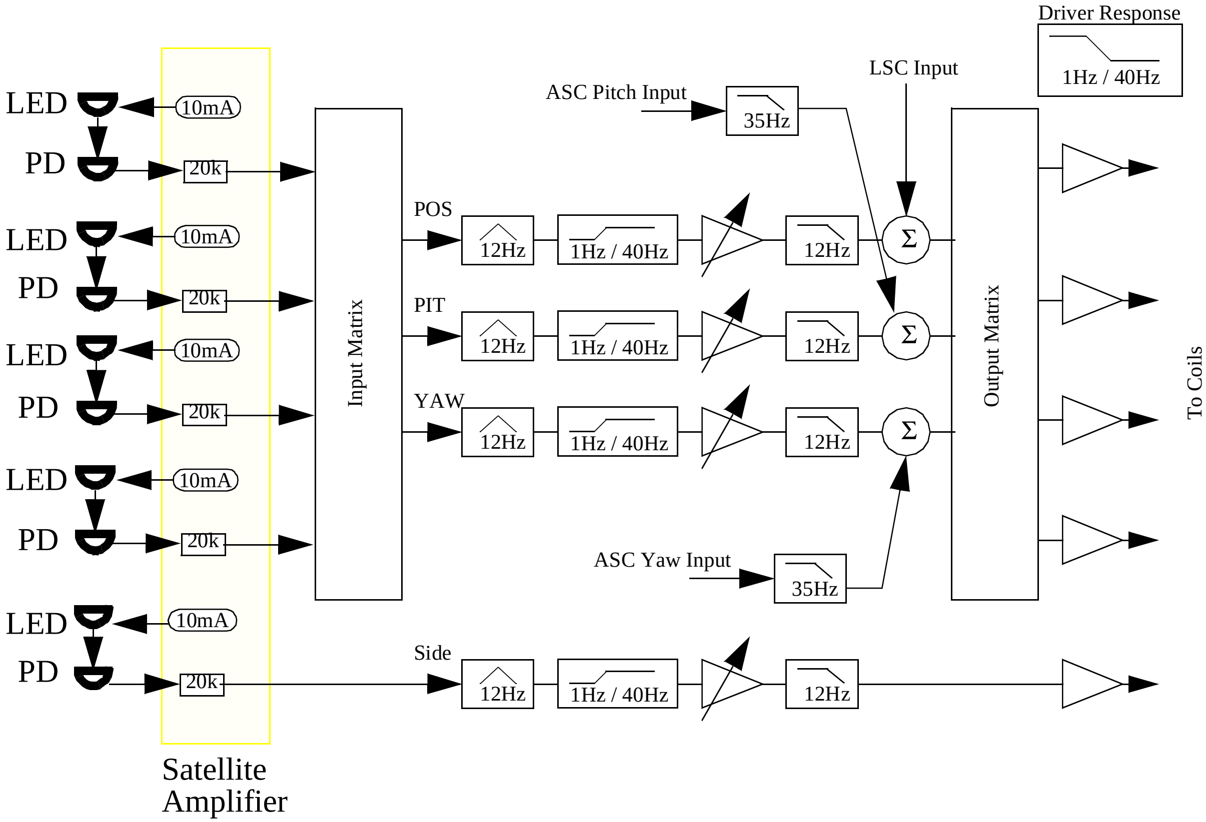
  ›› Requirements

  ›› Design and Implementation

LIGO LOS and SOS Electronics PDR Organization of Presentation (cont'd)

- Large Optic Suspension (LOS) Electronics
  - ››Requirements
  - ››Design and Implementation
- Small Optic Suspension (SOS) Electronics
  - ››Requirements
  - ››Design and Implementation
- System Layout and Design
  - ››Location and number of devices
  - ››Operator screens, alarms, back-up and restore, monitor and test points
  - ››Data acquisition signals
- Cost, Schedule, Technical Risk

LIGO LOS and SOS Electronics Block Diagram



LIGO LOS and SOS Product Functions

- Photodiode/LED Electronics
  - ››Local read back of optic orientation and position used for local damping of optic
  - ››Constant current source for LED
  - ››Conversion of photodiode current to voltage
- Suspension Controller
  - ››provide a locally damped optic for use by the interferometer
  - ››provide for input of ASC and LSC signals to optic for “global” control of pitch, yaw and longitudinal position

LIGO LOS and SOS Electronics General Constraints

- Equipment Locations
  - ››All equipment located in standard CDS racks.
  - ››Pre-amps, etc. located closer to optics being controlled
- Vacuum Cabling and Devices Internal to the Vacuum Chamber
  - ››Must adhere to established LIGO standards for vacuum processes and materials

LIGO LOS and SOS Electronics General Constraints

- LEDs, Photodiodes and Coil Cross Section
  - LED: Toshiba TLN107A
  - Photodiode: Toshiba TPS703A
  - Coil:
    - Wire Size- #32 AWG teflon coated, ~310 turns
    - Coil Size- 7.66 mm ID, 12.66 mm OD, 5 mm L
  - Housing:
    - Macor, gold plated
    - Size:25.3 mm OD x 25.4 mm L (SOS), 25.3 mm OD x 48.3 mm L (LOS)

Differences from 40 Meter Beam Splitter and Recycling Mirror Systems

- Output Coil Driver

  ››Redesigned to meet LIGO requirements

  ››Design incorporates a 1 Hz pole and 40 Hz zero in driver with compensating 1 Hz zero and 40 Hz pole in controller.

- LSC Injection Point

  ››New coil driver allowed LSC injection prior to output matrix which eliminates the separate LSC output matrix

- Filtering

  ››New coil driver allowed the last 8 poles of the chebychev filter to be placed prior to the output matrix. This reduced the number of filters from 5 to 4.

Differences from 40 Meter Beam Splitter and Recycling Mirror Systems

- ASC Input

  ››The 35 Hz, 4th order elliptic filter required by ASC has been incorporated into the design.

  ››This replaces the separate AC and DC "global" gain paths required for the 40 meter and simplifies the design.

- Input Matrix

  ››Testing on the 40 meter has shown that the input matrix does not need to be adjustable by the operator

  ››This simplifies the design and operation of the system

LOS and SOS Satellite Amplifier

- Satellite amplifier design and requirements for LOS and SOS are identical
- Requirements
  - LED Drive Current
    - provide a constant 10 mA to each LED (5 total per system)
    - accuracy: +/- 1%
    - stability and drift: 1% over entire operating temperature range
    - Output referred noise: less then $(100pA)/(\sqrt{Hz})$ for freq > 10 Hz
  - PD Current to Voltage Conversion
    - Output referred noise: less then $(17nV)/(\sqrt{Hz})$ for freq > 10 Hz
    - Transimpedance: 20 Kohms, +/- 1%

LOS and SOS Satellite Amplifier

- Design
  - ››Identical to the design used for the 40 meter EV, BS and RCM suspension system
  - ››Meets all requirements for LIGO LOS and SOS
  - ››Fully tested and operational on 40 meter systems for more than 1 year

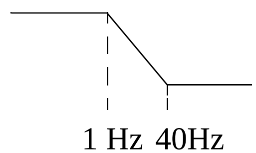
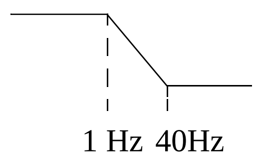
LOS Design Requirements

- Provide “pseudo-critical” damping in the local damping and control mode of operation
- Provide ASC input for pitch and yaw control
  - ››Gain: 25µrad/Volt, adjustable by operator in +/- 25% in 0.5% increments
  - ››35 Hz, 4th order elliptic, 4 dB passband ripple, 60 dB stopband attenuation
  - ››Input referred noise: less than $(1\mu V)/(\sqrt{Hz})$ for freq < 40 Hz

LOS Design Requirements (cont’d)

- Dynamic Range and Output Noise

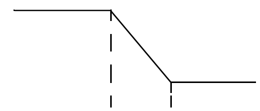
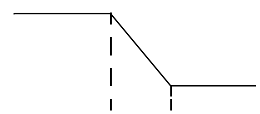
Table 1: LOS Controller Dynamic Range and Output Noise

	Mode of Operation	*Dynamic Range*	*Output Noise*
Local Damping and Control	Local damping and control mode	20 $\mu m_{p\text{-}p}$ 	$5x10^{-20}\left(\frac{f}{40}\right)^{-2}(m/(\sqrt{Hz}))$ f > 40 Hz **
ASC Pitch Input to Optic	All modes	500 $\mu rad_{p\text{-}p}$, 	$1x10^{-17}((rad)/(\sqrt{Hz}))$ f > 40 Hz

LOS Design Requirements (cont'd)

- Dynamic Range and Output Noise (cont'd)

Table 1: LOS Controller Dynamic Range and Output Noise

	Mode of Operation	*Dynamic Range*	*Output Noise*
ASC Yaw Input to Optic	All modes	500 $\mu rad_{p\text{-}p}$,  1 Hz 40Hz	$1x10^{-17}((rad)/(\sqrt{Hz}))$ f > 40 Hz
LSC Input to Optic	LSC Acquire	20 $\mu m_{p\text{-}p}$ Flat response	N/A
LCS Input to Optic	LSC Locked	20 $um_{p\text{-}p}$  1 Hz 40Hz	$5x10^{-20}\left(\frac{f}{40}\right)^{-2}(m/(\sqrt{Hz}))$ f > 40 Hz

LOS Local Damping Servo Design for Pitch and Position

- The position and pitch d.o.f are coupled. The equations of motion are:

$$F - \frac{Mg}{l}x + \frac{Mgd}{l}\Theta_2 - K_1 x = Ms^2 x$$

$$T + \frac{Mgd}{l}x - \frac{Mgd(d+l)}{l}\Theta - K_2\Theta_2 = Is^2\Theta_2$$

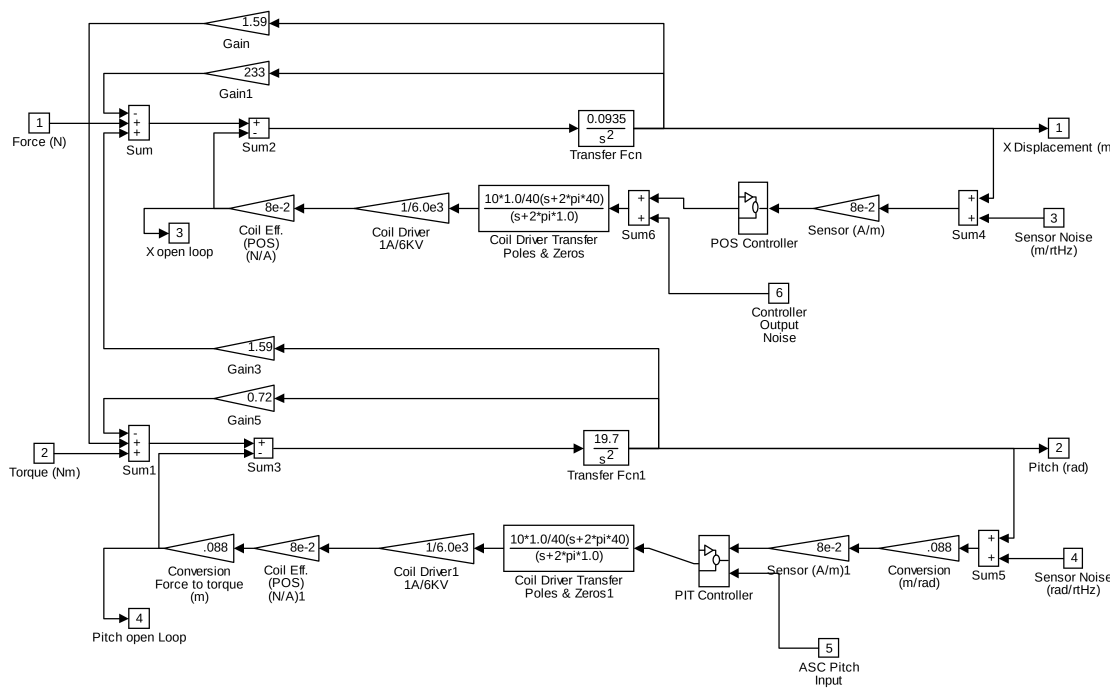
where,

M=10.7 Kg, g=9.8 m/s^2

l=0.45 m, d=0.0068 m, $I=5.07\times10^{-2}$ m^{2}Kg.

LOS Local Damping Servo Design (cont'd)

- Simulink Model for position and pitch d.o.f.:



LOS Position Controller

- Transfer function is 10 pole, 1 db passband ripple,12 Hz Chebychev with a zero at DC

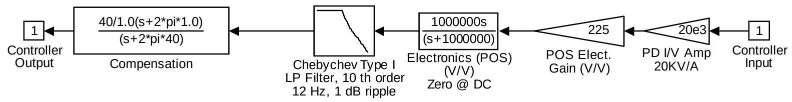


Figure 1: LOS Position Controller

LOS Position Controller (cont'd)

- LOS position nichols plot

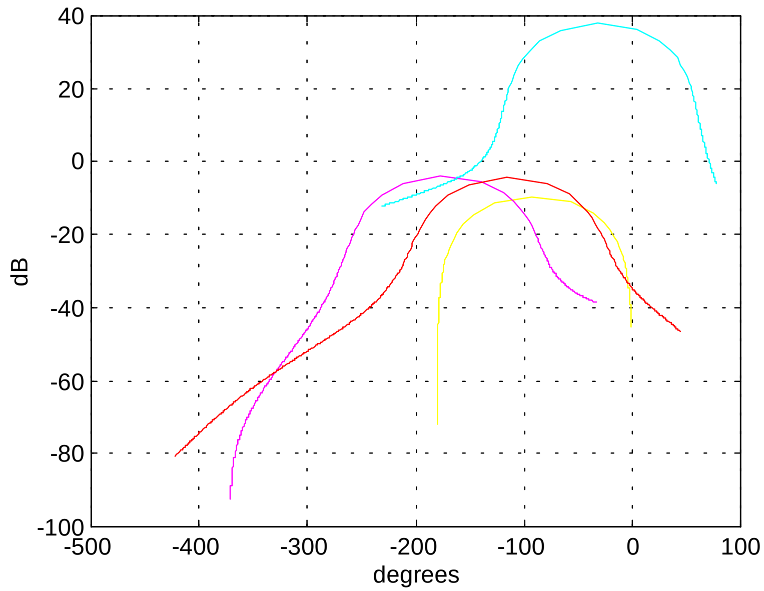


Figure 1: Nichols Plot for LOS Position Degree of Freedom

- Approx. 45 degrees of phase margin (cyan)

LOS Pitch Controller

- Transfer function is 10 pole, 1 db passband ripple,12 Hz Chebychev with a zero at DC

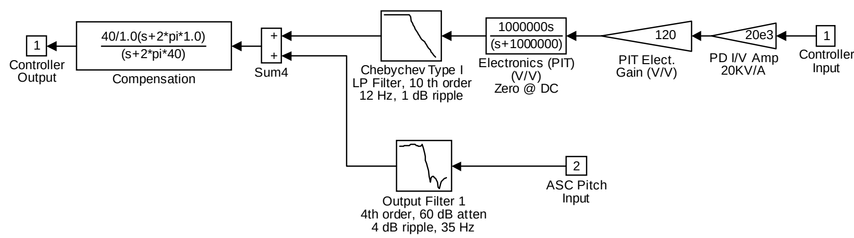


Figure 1: LOS Pitch Controller

LOS Pitch Controller (cont'd)

- LOS pitch nichols plot

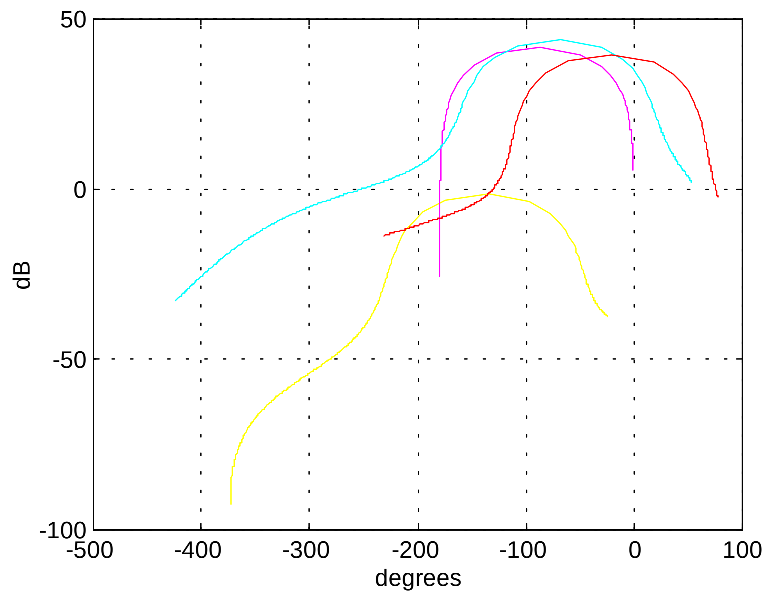


Figure 1: Nichols Plot for LOS Pitch Degree of Freedom

- Approx. 45 degrees of phase margin (red)

LOS Local Damping Servo for Yaw

- Simulink Model for Yaw d.o.f

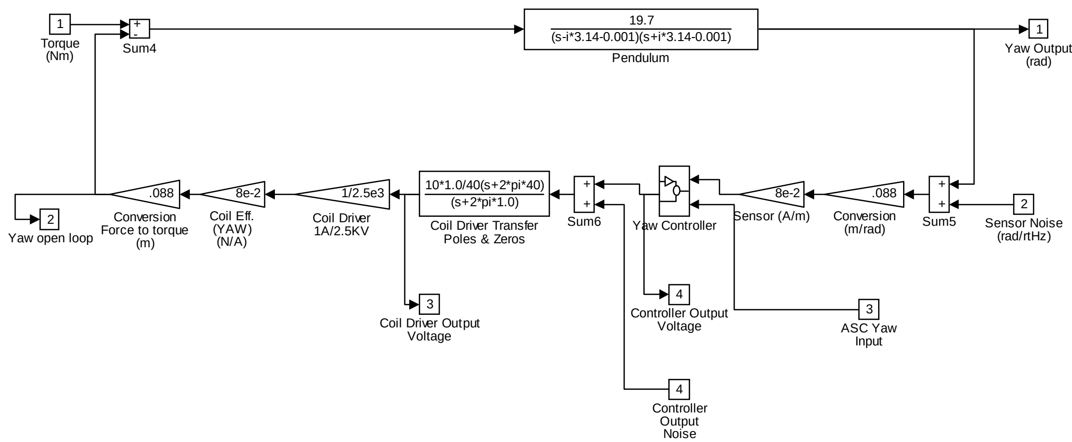


Figure 1: LOS Simulink Model for Yaw Degree of Freedom

LOS Yaw Controller

- Transfer function is 10 pole, 1 db passband ripple,12 Hz Chebychev with a zero at DC

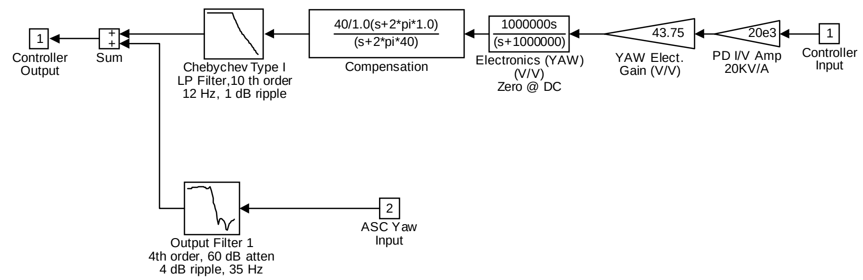


Figure 1: LOS Yaw Controller

LOS Yaw Controller (cont'd)

- LOS Yaw nichols plot

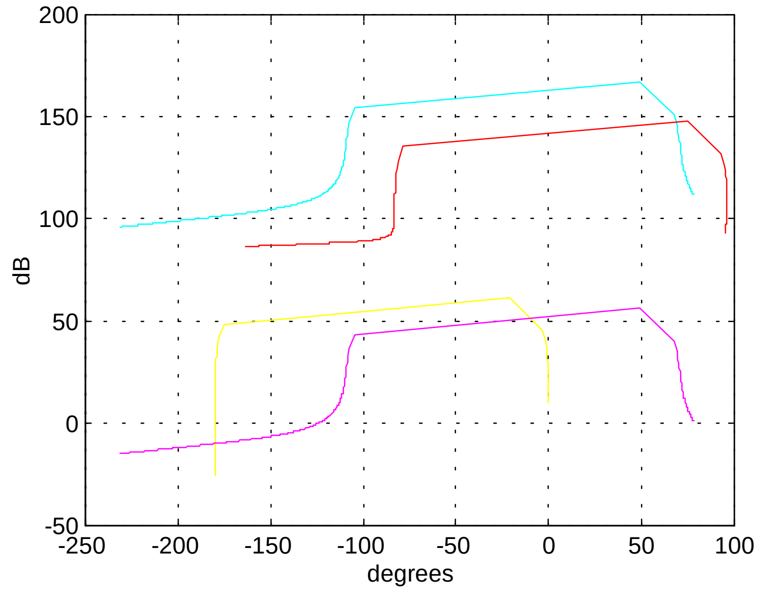


Figure 1: Nichols Plot for LOS Yaw Degree of Freedom

- Approx. 55 degrees of phase margin (magenta)

LOS Suspension Controller Electronics Implementation

- Input and Output Matrices

  ›› Input matrix will not be operator adjustable. It will be adjusted during module calibration to give the appropriate response

  ›› Output matrix will be operator adjustable via DACs used in a programmable configuration.

  – Adjustment: 0 to 100% in min 0.5% steps per leg

  – Design is the same as used for the BS and RCM suspension systems (ref. D961292)

LOS Suspension Controller Electronics Implementation (cont'd)

- Servo Filter Function

  ››Filter function is the same as BS and RCM suspension system with the exception that the cut off freq. has been changed to 12 Hz.

  ››Filter function will be implemented in analog circuitry

  ››The BS and RCM suspension designs have been tested and operational for more than 1 year.

LOS Suspension Controller Electronics Implementation (cont'd)

- Coil Driver

  ››A new design has been developed to meet the LIGO LOS dynamic range and noise requirements

  ››Modeling and testing shows that the circuit will allow the LOS to meet the requirements

LOS Suspension Controller Electronics Implementation (cont'd)

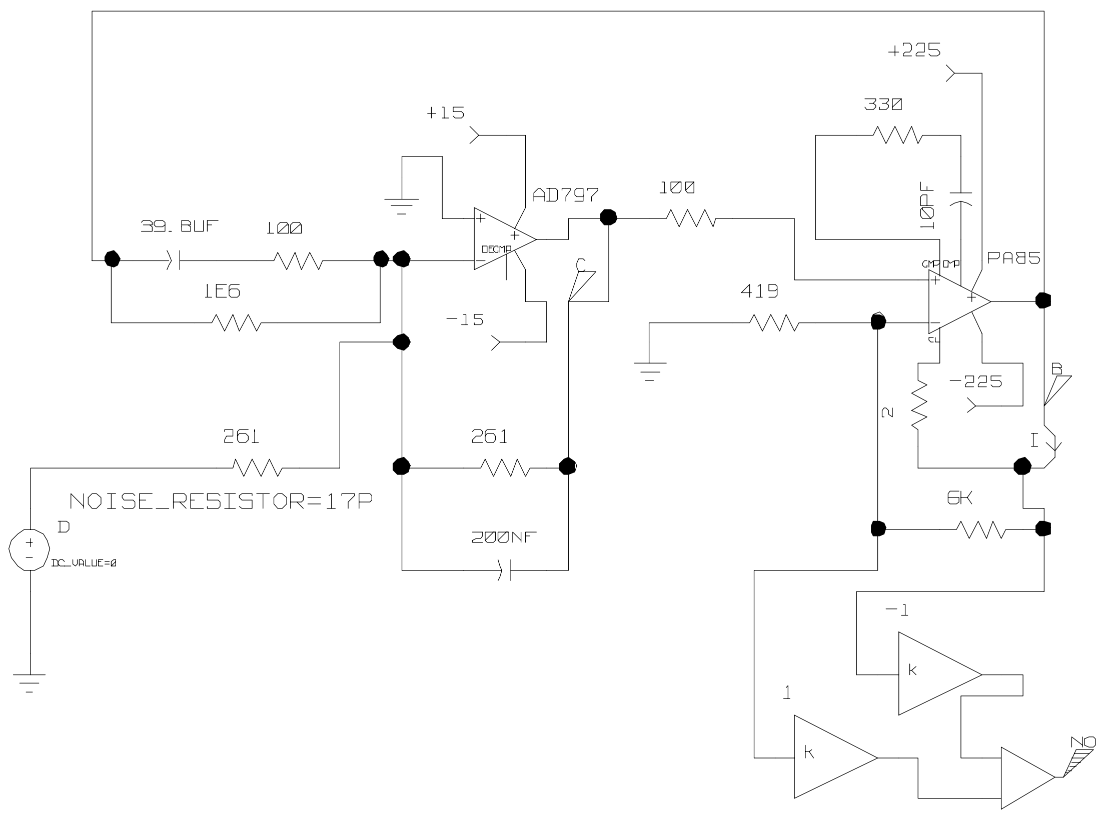


Figure 1: Analog Workbench Model of LOS Coil Driver

LOS Suspension Controller Electronics Implementation (cont'd)

- Coil Driver Theory of Operation

  ››The 40 Hz zero required by LSC is set by the 39.8 uF and 100 ohm resistor tied to the inverting input of the AD797. These components also set the corner frequency for the noise suppression in the feedback loop.

  ››The 1 Hz pole is set using the following equation:

$$F_{pole} = \frac{40Hz}{GK}$$

where, G is the gain of the PA-85 stage, in this case 15.3 and K is the gain of the AD797 stage in the loop above 40 Hz, in this case 2.61.

  ››The gain of the circuit for frequencies below 1 Hz is G. The gain at frequencies above 40 Hz is 1/K.

LOS Suspension Controller Electronics Implementation (cont'd)

››The output noise voltage of the PA-85 stage is suppressed by a factor GK at frequencies greater than 40 Hz. This suppresses the current noise in the coil since the current noise is the root sum of the squares of the PA-85 output current noise (~Vnoise/6000) and the current noise at the inverting input of the PA-85

››The Run/Acquire mode option required for the controller will be implemented by providing a switch to open the feedback loop within the coil driver when acquire mode is selected. The response of the coil driver circuit will then be flat from DC to frequencies greater than 10 KHz and have a gain of 23.7 dB (the nominal gain of the circuit from DC to 1 Hz when the feedback is engaged).

LOS Suspension Controller Electronics Implementation (cont'd)

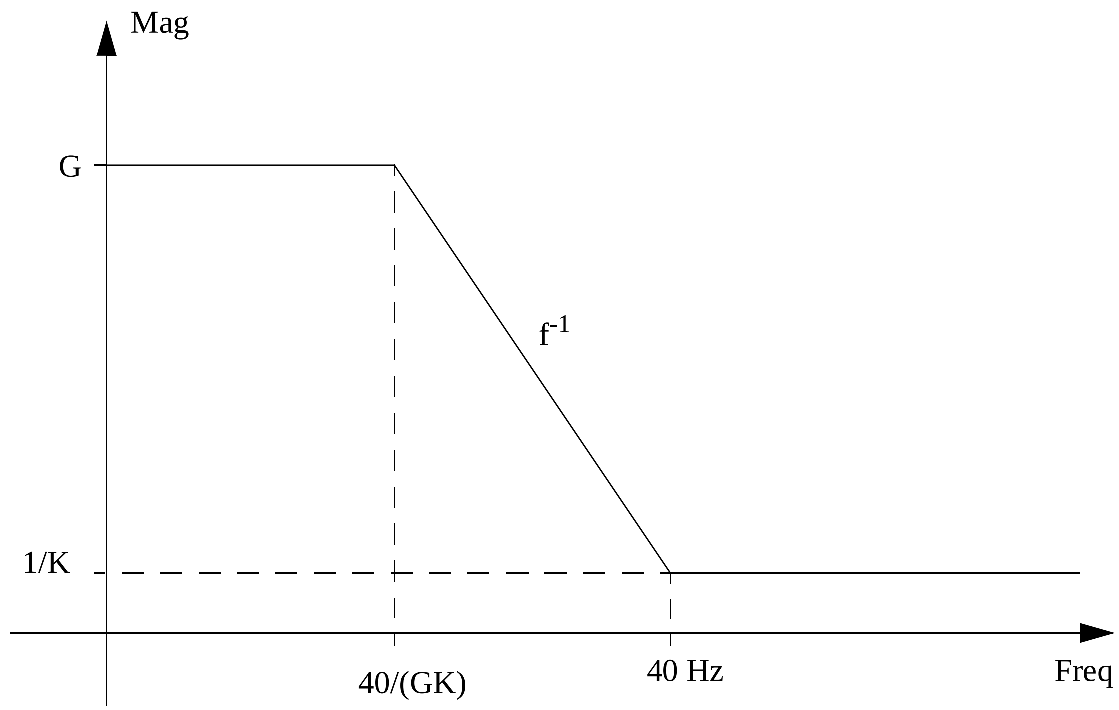


Figure 1: Coil Driver Response versus Frequency

LOS Suspension Controller Electronics Implementation (cont'd)

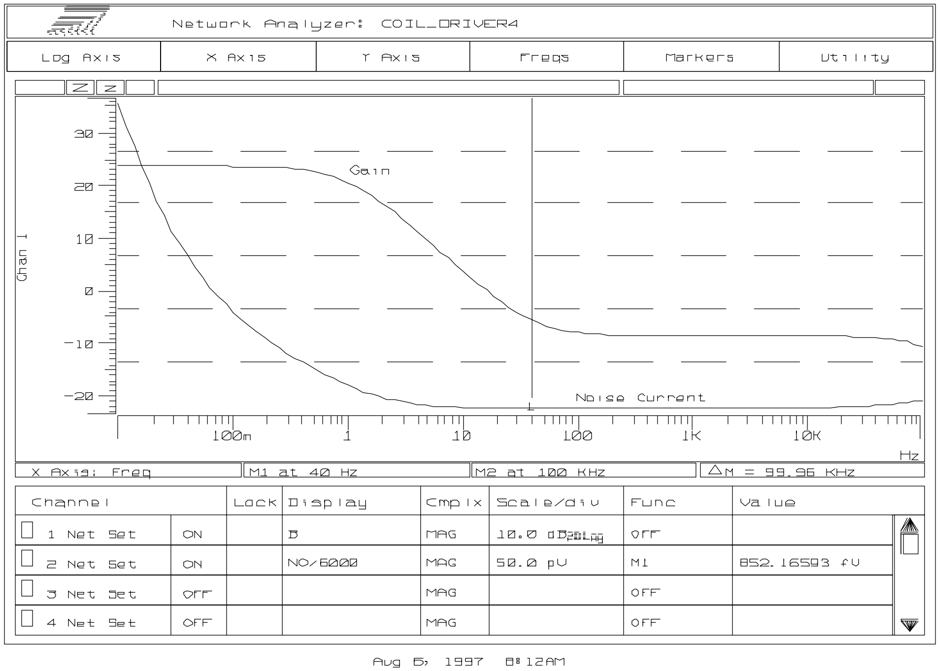


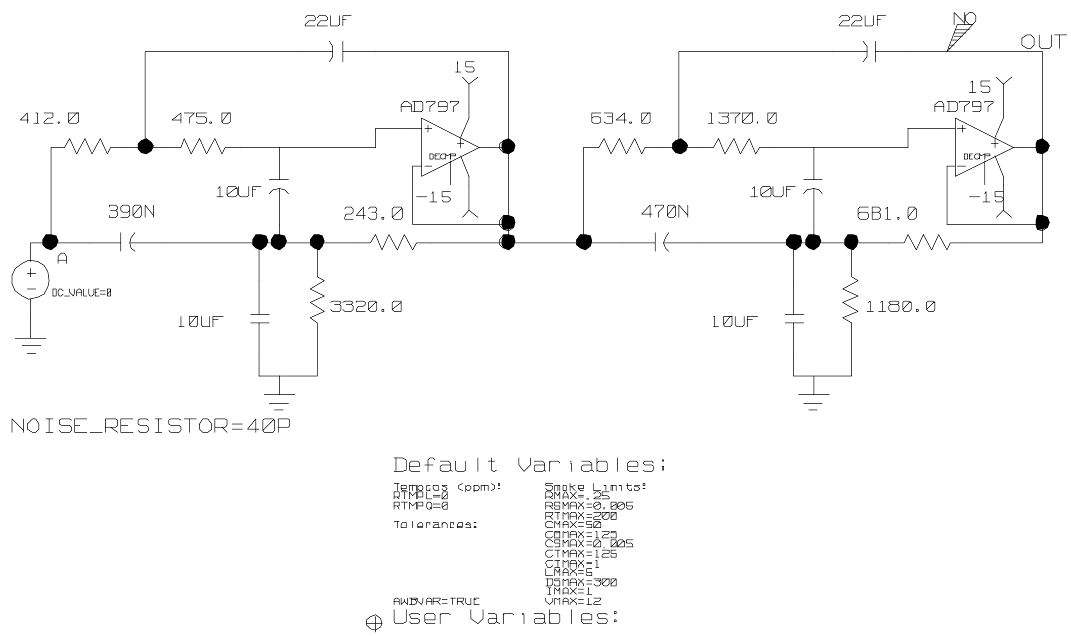
Figure 1: Analog Workbench Predictions for LOS Coil Driver

LOS Suspension Controller Electronics Implementation (cont'd)

- LOS Coil Driver Test Results

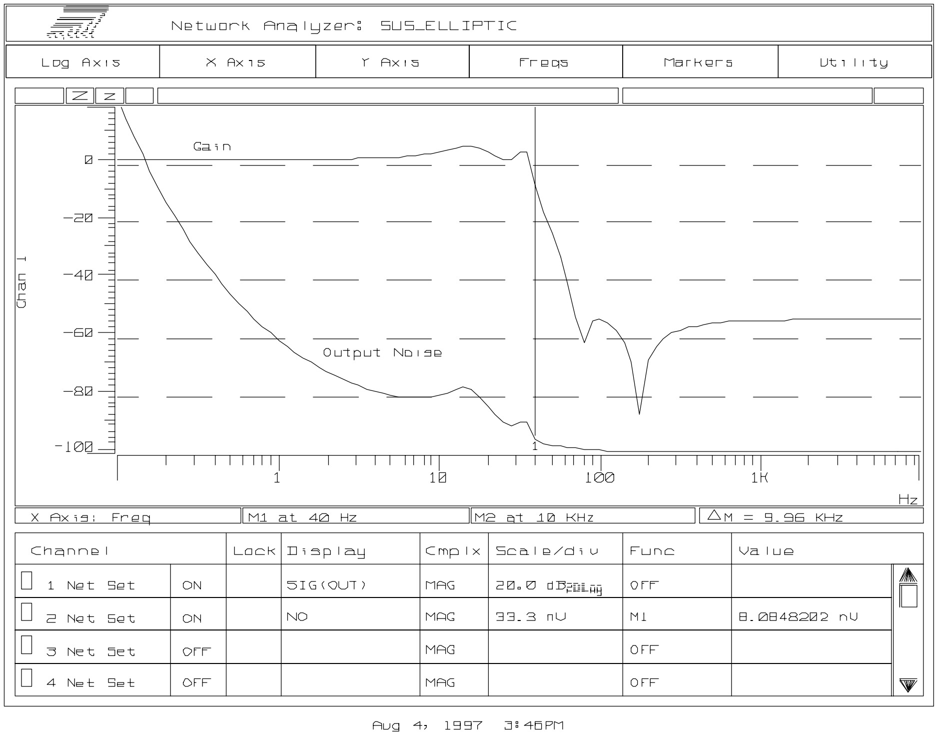
LOS Suspension Controller Electronics Implementation (cont’d)

- LOS ASC Input Elliptic Filter



LOS Suspension Controller Electronics Implementation (cont'd)

- LOS ASC Input Elliptic Filter



LOS Suspension Controller Electronics Implementation (cont'd)

- LOS ASC Input Elliptic Filter
  - ››Function will be implemented in analog circuitry
  - ››Circuit was tested and performance verified to match model predictions
  - ››Circuit meets LIGO LOS and ASC requirements
- LOS LSC Input
  - ››Input will be provided to LSC
  - ››Injection will be into a summing node prior to output matrix
  - ››Transfer function: 1 μm/volt (TBR) at DC, pole at 1 Hz and zero at 40 Hz

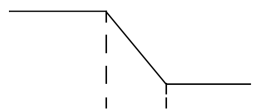
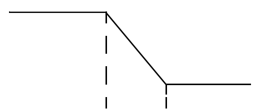
SOS Design Requirements

- Provide “pseudo-critical” damping in the local damping and control mode of operation
- Provide ASC input for pitch and yaw control
  - ››Gain: 150μrad/Volt, adjustable by operator in +/- 25% in 0.5% increments
  - ››35 Hz, 4th order elliptic, 4 dB passband ripple, 60 dB stopband attenuation
  - ››Input referred noise: less than $(1\mu V)/(\sqrt{Hz})$ for freq < 40 Hz

SOS Design Requirements (cont'd)

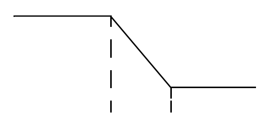
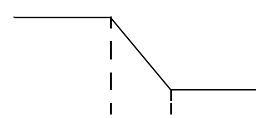
- Dynamic Range and Output Noise

Table 1: SOS Controller Dynamic Range and Output Noise

	Mode of Operation	*Dynamic Range*	*Output Noise*
Local Damping and Control	Local damping and control mode	$80\mu m_{p-p}$ 	$3.8x10^{-18}\left(\frac{f}{40}\right)^{-2}(m/(\sqrt{Hz}))$ f > 40 Hz **
ASC Pitch Input to Optic	All modes	3 $mrad_{p\text{-}p}$, 	$1x10^{-17}((rad)/(\sqrt{Hz}))$ f > 40 Hz

SOS Design Requirements (cont'd)

Table 1: SOS Controller Dynamic Range and Output Noise

	Mode of Operation	*Dynamic Range*	*Output Noise*
ASC Yaw Input to Optic	All modes	3 $mrad_{p\text{-}p}$,  1 Hz 40Hz	$1x10^{-17}((rad)/(\sqrt{Hz}))$ f > 40 Hz
LSC Input to Optic	LSC Acquire	80 μmeter Flat response	N/A
LCS Input to Optic	LSC Locked	$80\mu m_{p-p}$  1 Hz 40Hz	$3.8x10^{-18}\left(\frac{f}{40}\right)^{-2}(m/(\sqrt{Hz}))$ f > 40 Hz

SOS Local Damping Servo Design for Pitch and Position

- The position and pitch d.o.f are coupled. The equations of motion are:

$$F - \frac{Mg}{l}x + \frac{Mgd}{l}\Theta_2 - K_1 x = Ms^2 x$$

$$T + \frac{Mgd}{l}x - \frac{Mgd(d+l)}{l}\Theta - K_2\Theta_2 = Is^2\Theta_2$$

where,

M=0.25 Kg, g=9.8 m/s^2

l=0.248 m, d=0.0009 m, I=1.04x10^{-4} m^{2}Kg.

SOS Local Damping Servo Design (cont'd)

- Simulink Model for position and pitch d.o.f.:

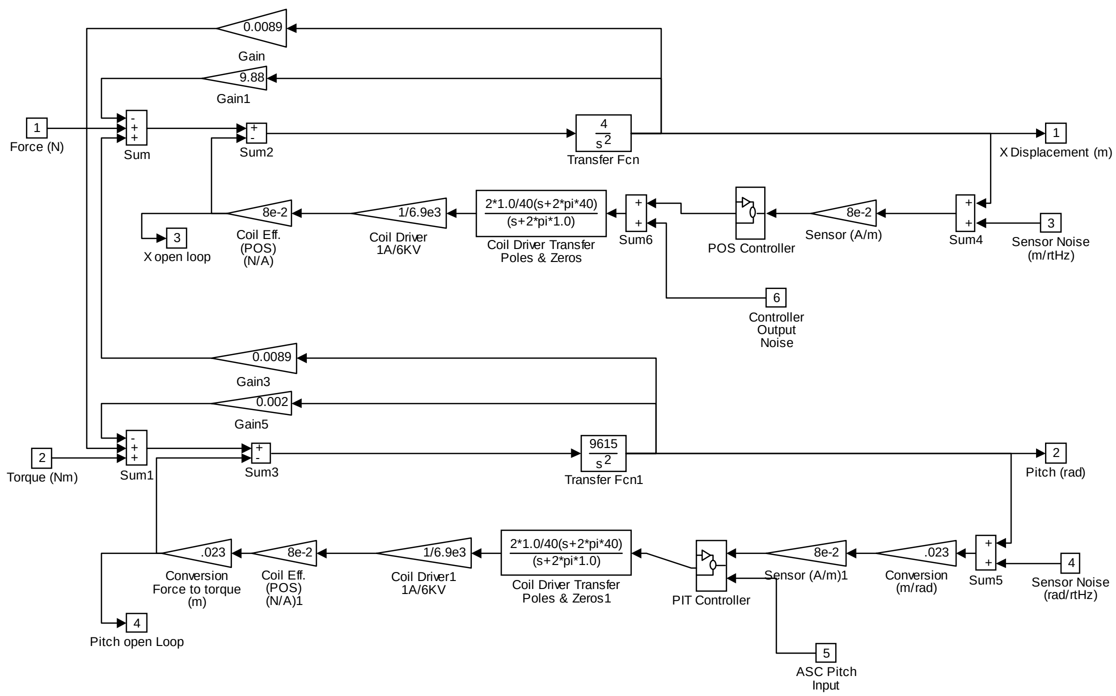


Figure 1: SOS Simulink Model for Position and Pitch Degrees of Freedom

SOS Position and Pitch Controllers

Transfer function is 10 pole, 1 db passband ripple,12 Hz Chebychev with a zero at DC

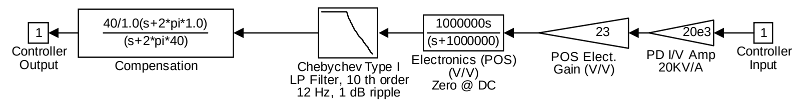


Figure 1: SOS Position Controller

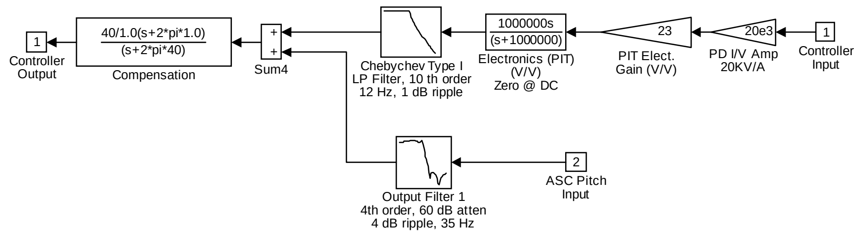


Figure 2: SOS Pitch Controller

SOS Position and Pitch Controllers (cont'd)

- Nichols plots for both position and pitch show greater than 45 degrees of phase margin.

SOS Local Damping Servo for Yaw

- Simulink Model for Yaw d.o.f

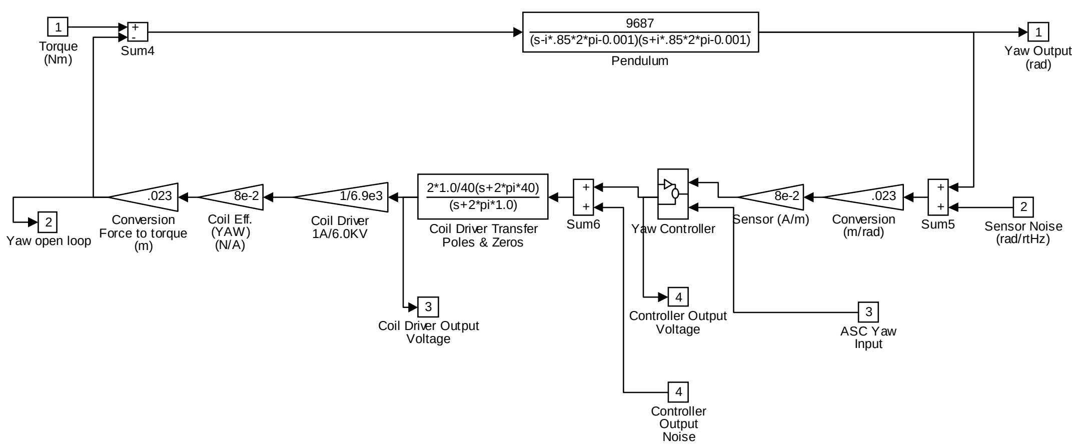


Figure 1: SOS Simulink Model for Yaw Degree of

SOS Yaw Controller

- Transfer function is 10 pole, 1 db passband ripple,12 Hz Chebychev with a zero at DC

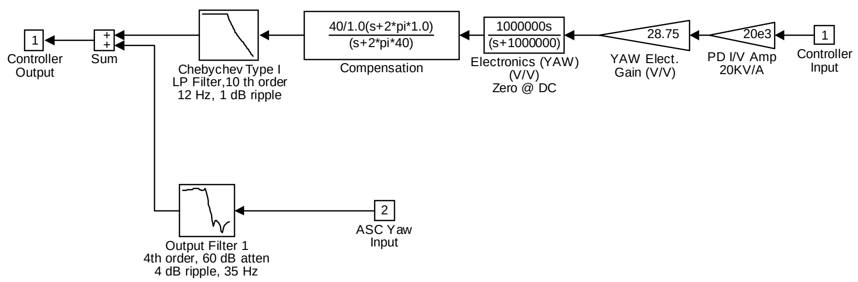


Figure 1: SOS Yaw Controller

- Nichols plots show approx. 55 degrees of phase margin

SOS Suspension Controller Electronics Implementation

- Input and output matrices will be identical to LOS.
- Servo filter function will be identical to LOS with the exception of gains.
- Coil driver similar to LOS:
  - Feedback resistor in series with coil and input resistor changed to 6.94K
  - Driver input resistor and feedback resistor on AD797 changed to 2K
  - Supply voltage on PA-85 reduced to +/- 15 volts
  - Run/Acquire mode implemented in the same manner as LOS
- ASC input filter the same as LOS with the exception of gain
- LSC input the same as LOS

LIGO LOS and SOS System Layout and Design

Table 1: 4 Km Interferometer Suspension Systems

Type	*Quantity*	*Optic Being Controlled*
LOS	7	beam splitter recycling mirror 2 ea. ITM 2 ea. ETM IOO Mode Matching Mirror
SOS	5	3 ea. IOO Mode Cleaner Mirrors 2 ea. IOO Mode Matching Mirrors

Table 2: 2 Km Interferometer Suspension Systems

Type	*Quantity*	*Optic Being Controlled*
LOS	9	beam splitter recycling mirror 2 ea. ITM 2 ea. ETM IOO Mode Matching Mirror 2 ea. Folding Mirrors
SOS	5	3 ea. IOO Mode Cleaner Mirrors 2 ea. IOO Mode Matching Mirrors

LIGO LOS and SOS System Layout and Design (cont'd)

.

Table 1: Suspension Electronics Rack Locations

Suspension System	*Equipment Rack*
4 Km IOO systems	1X5
4 Km BS/RCM/ITM	1X9
4 Km ETM	1X21
2 Km IOO systems	2X5
2 Km BS/RCM/ITM	2X1
2 Km ETM	1X18

LIGO LOS and SOS System Layout and Design (cont'd)

- Vacuum cabling and connections to sensor actuator heads
  - ››Similar to BS and RCM suspension systems which used kapton cables and connectors manufactured by Ceramaseal and ISI.
  - ››Final vacuum compatibility testing is not complete.
  - ››The final design of the vacuum cabling is not complete at this time, but when it is the techniques will be incorporated into the LOS and SOS.

LIGO LOS and SOS System Layout and Design (cont'd)

- Operator screens similar to the BS and RCM will be developed
- Control and Monitor points:
  - »Photodiode amplifier voltage monitors
  - »POS, PIT, YAW, SIDE input voltage monitors
  - »Coil driver output current monitors
  - »PIT and YAW bias voltage adjust
  - »Run/Acquire Mode select
  - »POS, PIT, YAW, SIDE polarity invert select
  - »Output matrix gain adjust
  - »POS, PIT, YAW, SIDE gain adjust

LIGO LOS and SOS System Layout and Design (cont'd)

- Test Inputs:
  - ››POS, PIT, YAW, SIDE test inputs
  - ››Coil driver test inputs
  - ››LSC test input
- Back-up and Restore Signals
  - ››POS, PIT, YAW and SIDE gain settings
  - ››Output matrix gain settings
  - ››PIT and YAW bias settings

LIGO LOS and SOS System Layout and Design (cont'd)

- Operator Alarms:
  - ››POS, PIT, YAW, SIDE input signals approaching high or low limits (MINOR)
  - ››POS, PIT, YAW, SIDE input signals beyond high or low limits (MAJOR)

LIGO LOS and SOS System Layout and Design (cont'd)

- Data Acquisition Signals.

Table 1: Suspension Data Acquisition Channels and Rates

Signal	*Quantity (per controller)*	*Sample Rate (samples/sec)*
Coil Driver Output Voltage	5	16 K
Photodiode Input Voltage	5	128
POS, PIT, YAW, SIDE Gain	4	1
Output Matrix Gain Settings	12	1
POS, PIT, YAW, SIDE Invert/Non-invert Status	4	1
Run/Acquire Mode Status	1	1

LOS and SOS Electronics Cost, Schedule and Technical Risk

- Cost

Table 1: LOS and SOS Hardware Costs

System	Baseline Estimate	New Estimate to Complete
WA 4K IFO LOS and SOS	$204K	$147K
WA 2K IFO LOS and SOS	$235K	$169K
LA 4K IFO LOS and SOS	$204K	$147K
TOTAL	$643K***	$463K

*** Cost numbers estimated from baseline IOO and COS cost book entries

LOS and SOS Electronics Cost, Schedule and Technical Risk (cont'd)

- Schedule
  - Baseline PDR Nov. 1997
  - Delivery of IOO SOS electronics to Hanford in Apr. 1998
  - Delivery of LOS systems starting in Nov. 1998
- Schedule risk: Low to Medium
  - CDS manpower shortages could impact delivery of IOO systems if other tasks consume resources

LOS and SOS Electronics Cost, Schedule and Technical Risk (cont'd)

- Technical Risk: Low

  ››All parts of the system have been tested and meet design requirements.

  ››Many parts of the system have been used on 40 meter systems that have been operational for more than 1 year.