LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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Technical Report	**LIGO-T960058-00 - Dxx**	3/26/96

Length Sensing and Control Design Requirements Document

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Distribution of this draft:

LSC Design Requirements Review Board

This is an internal working note
of the LIGO Project.

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1 INTRODUCTION

1.1. Purpose

The purpose of this document is to describe the design requirements for the Length Sensing and Control (LSC) subsystem. Primary requirements are derived (“flowed down”) from LIGO principal science requirements. Secondary requirements, which govern Detector performance through interactions between LSC and other Detector subsystems, have been allocated by Detector Systems Engineering.

1.2. Scope

The LSC subsystem scope provides for all aspects of interferometer length control involved in maintaining the signal sensitivity required for LIGO. These aspects include lock acquisition, linear feedback control, and length variation readout and calibration. Not included in the LSC scope is any aspect of the performance of LIGO optics, interferometer alignment, production of light or actuation of input light stabilization. The scope of this subsystem includes the following LSC hardware: photodetectors and related protective shutter, RF source, phase shifters, mixers, cabling, and LSC control electronics. It does not include: suspension or seismic isolation actuators, beam shaping optics, vacuum system viewports or hardware, or phase modulators.

The LSC subsystem is shown in relation to the Detector subsystems in figures 1 and 2 below. All LSC hardware and software is being implemented through the CDS group.

1.3. Definitions and Acronyms

- PSL - Prestabilized laser
- IOO - Input / Output Optics
- COC - Core Optics Components
- ASC - Alignment Sensing and Control
- SUS - Suspension Control
- SEI - Seismic Isolation
- CDS - Control and Data Systems
- SYS - Detector Systems Engineering
- IFO - LIGO interferometer
- SRD - LIGO Science Requirements Document
- L_+ - Arm cavity common mode length
- L_- -Arm cavity differential mode length
- l_+ - Michelson cavity common mode length
- l_- - Michelson cavity differential mode length

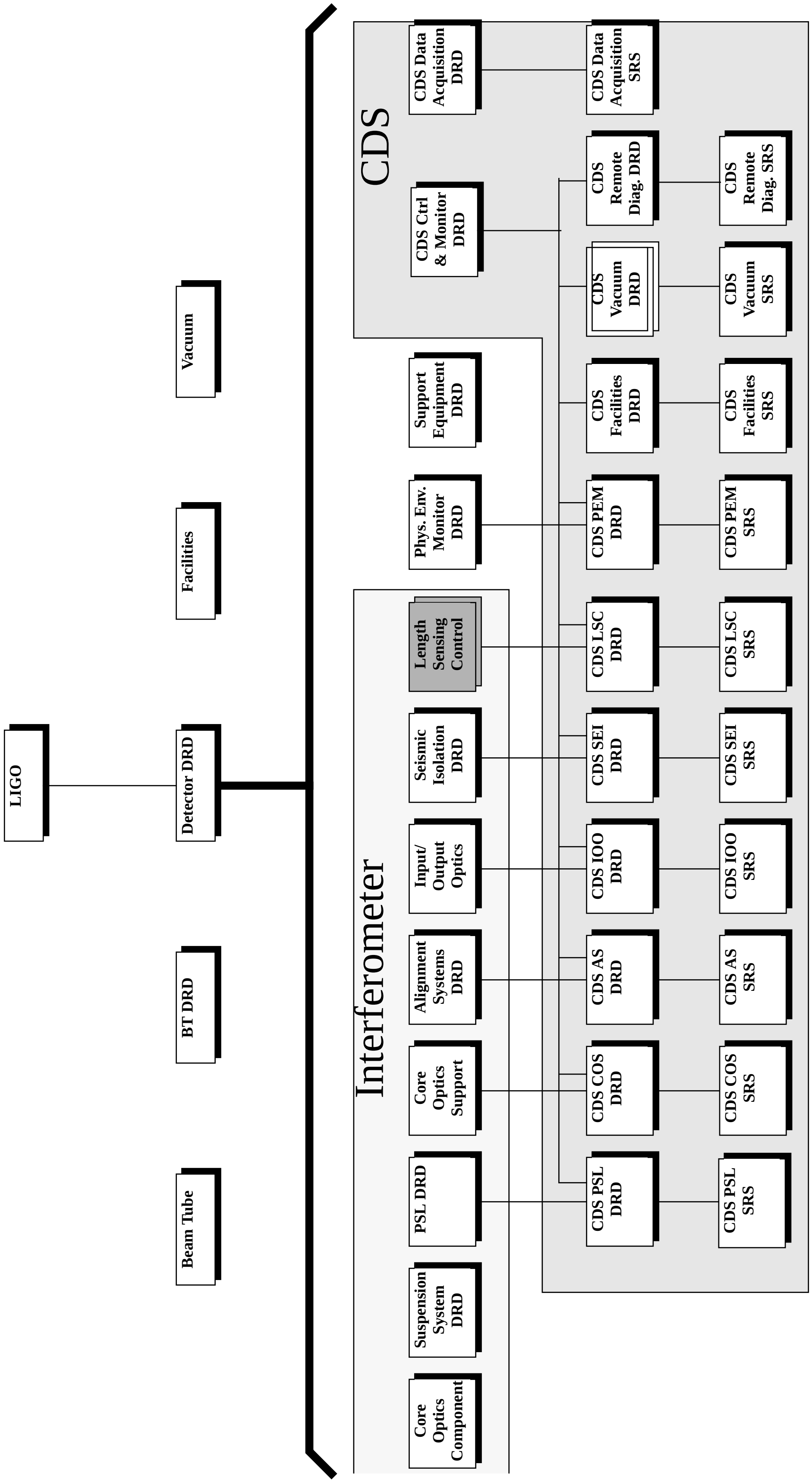

Figure 1: LIGO Specification Tree

1.4. Applicable Documents

1.4.1. LIGO Documents

1.4.1.1 LIGO Science Requirements Document : LIGO-E950018-02-E

1.4.1.2 SYS DRD : LIGO-T950065-00D

1.4.1.3 LSC Conceptual Design Description: LIGO-T960027-00-I

1.4.1.4 Prestabilized Laser DRD (B DCC)

1.4.1.5 Core Optics Components DRD : LIGO-E950099-01-D

1.4.1.6 Suspension DRD: LIGO-T950011-06-D

1.4.1.7 Frequency, Intensity and Oscillator Noise in the LIGO : LIGO T960019-00D

1.4.1.8 Shot noise in the Length Error Signals : LIGO-T960042-00-D

1.4.1.9 Length Control RMS Deviations from Resonance : LIGO-T960067-00-D

1.4.2. Non-LIGO Documents

1.4.2.1 "A Passive Vibration Isolation Stack for LIGO: Design, Modeling, and Testing", J. Giaime, P. Saha, D. Shoemaker, L. Sievers, Rev. Sci. Instrum. 67, 208

2 GENERAL DESCRIPTION

2.1. Product Perspective

LSC provides the control system to bring the interferometer lengths to resonance with the light source, sense interferometer deviations from resonance and apply the feedback necessary to cancel them. It also provides for readout of these deviations, including the Gravitational Wave signal. In executing these functions it must interact with SUS and SEI to actuate the lengths, and PSL/IOO to control the light parameters. Finally, it must interact with ASC to ensure that the interferometer is sufficiently well aligned to provide proper LSC functioning.

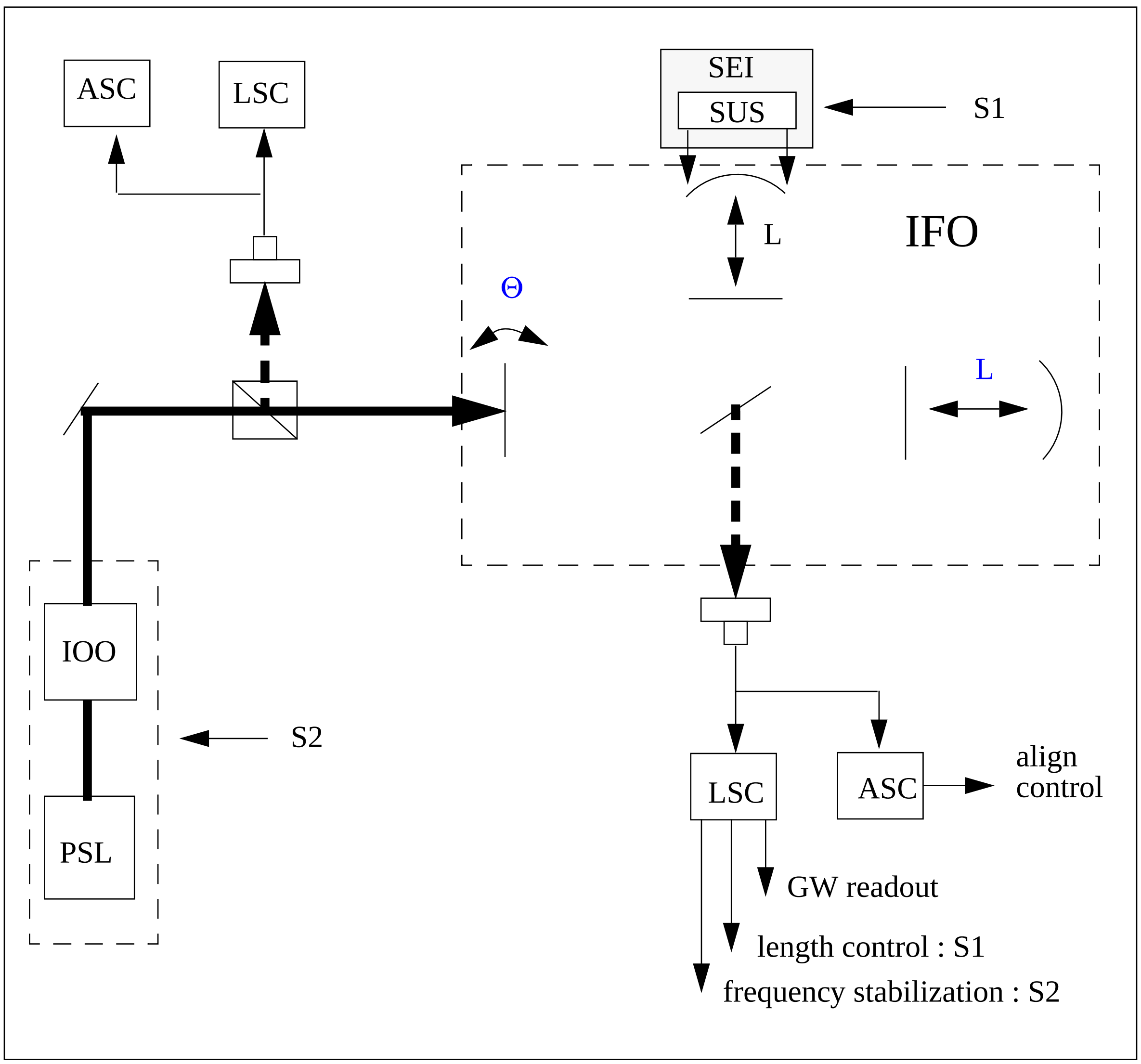

Figure 2: Relation of LSC to other Detector subsystems

2.2. Product Functions

The LSC main function is to provide length control and readout compatible with primary scientific requirements for the LIGO. It provides frequency stabilization feedback to the IOO and PSL. It also provides modulation sidebands and the reference signal for ASC, as well as diagnostic readouts for other Detector subsystems, including ASC, PSL, IOO and SUS.

2.2.1. Modes of Operation

The LSC subsystem performs different functions in each of its modes of operation. The following modalities apply to the LSC:

2.2.1.1 Acquisition mode function

- Lock acquisition - the mode in which the IFO lengths controlled by LSC are concurrently brought to their linear operating regime
- Self test - a diagnostic procedure is invoked to test the working of this mode

2.2.1.2 Transition mode functions

In this mode the controlled lengths are in their linear operating regime. The following functions apply:

- Length control - the lengths are held within the linear operating point
- Strain readout - deviations from resonance are read out
- Self test - a diagnostic procedure is invoked to test the working of this mode

2.2.1.3 Detection mode functions

In this mode the controlled lengths are in their linear operating regime and deviations from resonance are sufficiently small to allow detection of strain signals within 90% of the LIGO sensitivity specifications. The following functions apply:

- Length control - the lengths are held within a specified RMS deviation from resonance
- Strain readout - deviations from resonance are read out
- Strain calibration - the strain sensitivity of the length extraction system is calibrated (as necessary)
- Self test - a diagnostic procedure is invoked to test the working of this mode

2.2.1.4 Diagnostic mode and frequency response calibration

This mode provides additional diagnostics of LSC functions, and also diagnostics for external subsystems. It also provides for a swept sine calibration of the gravity wave signal readout.

2.3. Constraints, Assumptions and Dependencies

The following factors have been assumed in this document, and are consistent with or have been **flowed down from the SYS DRD (1.4.1.2);** (configuration control established TBD SYS).

2.3.1. LIGO Scientific Requirements Document parameters (see 1.4.1.1)

- Displacement Sensitivity
  - x (100 Hz) = 10^{-19} m / $Hz^{1/2}$
  - x (10 kHz) = 4 x 10^{-18} m / $Hz^{1/2}$
- Gravitational Wave Signal band - 40 Hz to 10 kHz
- Shot noise limited performance
  - $h_{shot} = h_0 (1+(f/f_0)^2)^{1/2}$
  - $h_0 = 1.1 \times 10^{-23} / Hz^{1/2}$
  - f_0 = 90 Hz
- Availability - 90%
- IFO input power - 6 W

2.3.2. IOO Output Light Noise (see 1.4.1.4 and 1.4.1.7)

- $\delta\nu/\nu < 4 \times 10^{-4}$ Hz / $Hz^{1/2}$ at f = 100 Hz and < 4 x 10^{-6} Hz / $Hz^{1/2}$ at f = 10 kHz
- $\delta I/I < 10^{-8}$ Hz / $Hz^{1/2}$ for f > 40 Hz

2.3.3. Seismic excitation of Test Mass (see 1.4.1.3, 1.4.1.6, 1.4.2.1)

- 4 layer Viton seismic stack; Q = 5
- Livingston Parish Seismic Spectrum
- Single pendulum; f = 0.7 Hz
  - Test mass open loop $\Delta x_{rms} = 10^{-6}$ m over ~10 sec period

2.3.4. Core Optics parameters (see 1.4.1.5)

- Loss per optic (‘bare losses’ and microroughness) - 50 ppm
- Arm storage time mismatch < 1%
- Contrast defect < 0.1%
- Recycling gain of 30
- ~86 % sideband transmission to GW port, ~1 % carrier reflection from recycling mirror
  - ~600 mW sideband power at GW port
  - ~400 mW IFO reflected power
- ETM transmission of 1 - 10 ppm

2.3.5. Detector subsystem functionality

- ASC alignment performance consistent with LSC requirements is assumed.
- IOO performance consistent with LSC requirements assumed, including
  - frequency and intensity stabilization as per 2.3.2

- phase modulation of light (given LSC drive signals)

2.3.6. Expected IFO parameter variations

- Accretion of optical losses : <100 ppm / optic
- Core Optics alignment variations of TBD radians (as during ASC acquisition)

3 REQUIREMENTS

3.1. Introduction

The LSC subsystem derives its requirements from the top-level LIGO requirements for sensitivity and availability. The requirements are grouped into sections corresponding to the following modes of the LSC: lock acquisition, transition, detection, and diagnostics. The accompanying conceptual design document will address these groups correspondingly.

We derive all noise requirements below assuming that the related noise amplitude spectral density is held to 10% of the LIGO sensitivity *h(f)* at all in-band frequencies.

3.2. Characteristics

3.2.1. Performance Characteristics

3.2.1.1 Lock Acquisition

The interval of lock acquisition must be compatible with the LIGO availability requirement and the expected time over which the initial alignment system can maintain alignment necessary for lock acquisition. This gives requirements on the acquisition time and the settling time for the control system (including servo transients and excitation of the violin resonances of the suspension wires.)

3.2.1.1.1 Transition times requirements

- The time to move from acquisition to linear control mode is to be < 40 sec. (TBD SYS)
- The allowed settling time from linear control to detection mode is < 2 min. (TBD SYS)

3.2.1.2 Detection

The control and signal extraction of the interferometer in detection mode must be compatible with the LIGO sensitivity requirements as outlined in the SYS DRD (1.4.1.2). From this we derive the following requirements on the LSC subsystem for the 4 km IFO (requirements for the 2 km are the same, except for TBD):

3.2.1.2.1 RMS deviations from resonance

Length sensitivity is degraded by deviations from resonance which couple secondary noise sources to the gw output or lower the interferometer stored power. We require (see 1.4.1.9):

Table 1: Requirements on RMS Deviations from Resonance

Length	*Allowed RMS deviation*	*Noise Mechanism*	*GW S/N degradation*
1. L_-	1×10^{-12} m	intensity noise -> strain noise	0.5 %
2. L_+	4×10^{-12} m	loss of 1% arm stored power	0.5 %
3. l_-	1.3×10^{-10} m	intensity noise -> strain noise	0.5 %
4. l_+	5×10^{-10} m	loss of 1% arm stored power	0.5 %

1,3. $x_{noise} = L_{-(rms)}$ $(\Delta I / I)$; see 1.4.1.7. $(\Delta I / I)$ is given in 2.3.2.
2,4. Deviation from fringe center causes lower arm/recycling cavity field amplitude. See 1.4.1.9

3.2.1.2.2 Control system loop gains

Loop gains shall be sufficient to ensure (see 1.4.1.3):

- Required RMS deviations from resonance in 3.2.1.2.1

3.2.1.2.3 Auxiliary (L_+,l_+,l_-) sensor shot noise

We require (see 1.4.1.3):

- Limitation of noise produced at the gw output from auxiliary sensor shot noise to the 10% sensitivity level.

3.2.1.2.4 Laser frequency noise

Laser frequency noise, coupling to a mismatch in arm cavity storage time to produce strain noise, is suppressed through LSC feedback. We require adequate control gain and sensor noise so that (see 1.4.1.7, 1.4.1.3):

- Laser frequency noise < 10^{-7} Hz / Hz$^{1/2}$ at f =100 Hz, 4×10^{-7} Hz / Hz$^{1/2}$ at f =1 kHz, and 4×10^{-6} Hz / Hz$^{1/2}$ at f = 10 kHz

3.2.1.2.5 Motion of globally uncontrolled degrees of freedom

Implementation of the above requirements will leave IFO degrees of freedom which are locally damped but not under interferometric control. To prevent upconversion of scattered light which could produce in-band phase noise, we require:

- Maximum velocity of globally uncontrolled length degrees of freedom < 5 λ / sec.

3.2.1.2.6 Control system robustness

All control modes shall be robust and easily adaptable to expected interferometer parameter variations by electronic parameter change.

3.2.1.2.7 Control system electronic noise

We require servo electronic noise, defined as input referred noise from the photodetector output to the SUS controller, to be at the level of:

- < 10% photodiode shot noise for all signal control loops

3.2.1.2.8 RF modulation requirements

We require (see 1.4.1.7):

- AM noise <-160 dBc / Hz$^{1/2}$ at f >100Hz
- Phase noise < -70 dBc / Hz$^{1/2}$ at 100 Hz and <-120 dBc / Hz$^{1/2}$ at 10 kHz
- modulation depth (TBD)

3.2.1.2.9 RF photodiode performance

We require (see 1.4.1.2, 1.4.1.3):

- Quantum efficiency > 0.8
- Acceptable DC power level in detection mode of 0.6 W : ~500mW sidebands, ~100 mW carrier
- Adequate protection shall be provided against power surges during acquisition and loss of lock
- Spatial uniformity < 10^{-3} (TBD)

3.2.1.3 Calibration

Knowledge of the correspondence between the GW signal in voltage and the strain *h* is required at all times in detection mode. We require:

- Strain output shall be calibrated within (TBD SYS).

3.2.2. Diagnostics

The diagnostic mode will provide the means to determine the proper functioning of the LSC, and provide measurement of the performance of other subsystems. The following diagnostic capabilities are required of the LSC:

- LSC Diagnostics
  - complete servo loop transfer function measurements
  - servo electronic noise and null offsets
  - photodiode sensitivity and noise
  - LSC response to laser light pointing, frequency and intensity modulation
  - other (TBD)
- Diagnostic Services
  - IFO cavity storage time measurements (ringdowns)

- recycling gain
- contrast defect
- operation of various configurations: single cavity, recycled Michelson, coupled cavity
- open loop test mass seismic excitation
- other (TBD SYS)

3.2.3. Physical Characteristics

3.2.4. Interface Definitions

3.2.4.1 Interfaces to other LIGO detector subsystems

LSC provides interferometer control through feedback actuation to SUS and SEI. Frequency stabilization is provided through an interfaces with PSL and IOO. Signal extraction is obtained through optical phase information transmitted via the IOO interface. LSC also accepts and provides monitor and control inputs, used in acquisition, linear control, detection and diagnostic modes, to the PSL and ASC.

3.2.4.1.1 Mechanical Interfaces

- Shared external optics platform (supplied by ASC) to which photodiode heads are mounted.
- CDS cables attached to photodiodes.

3.2.4.1.2 Electrical Interfaces

The LSC provides for the following signal interfaces, illustrated in fig 3. They are listed as control loop and monitor / diagnostic interfaces in tables 2 and 3 below.

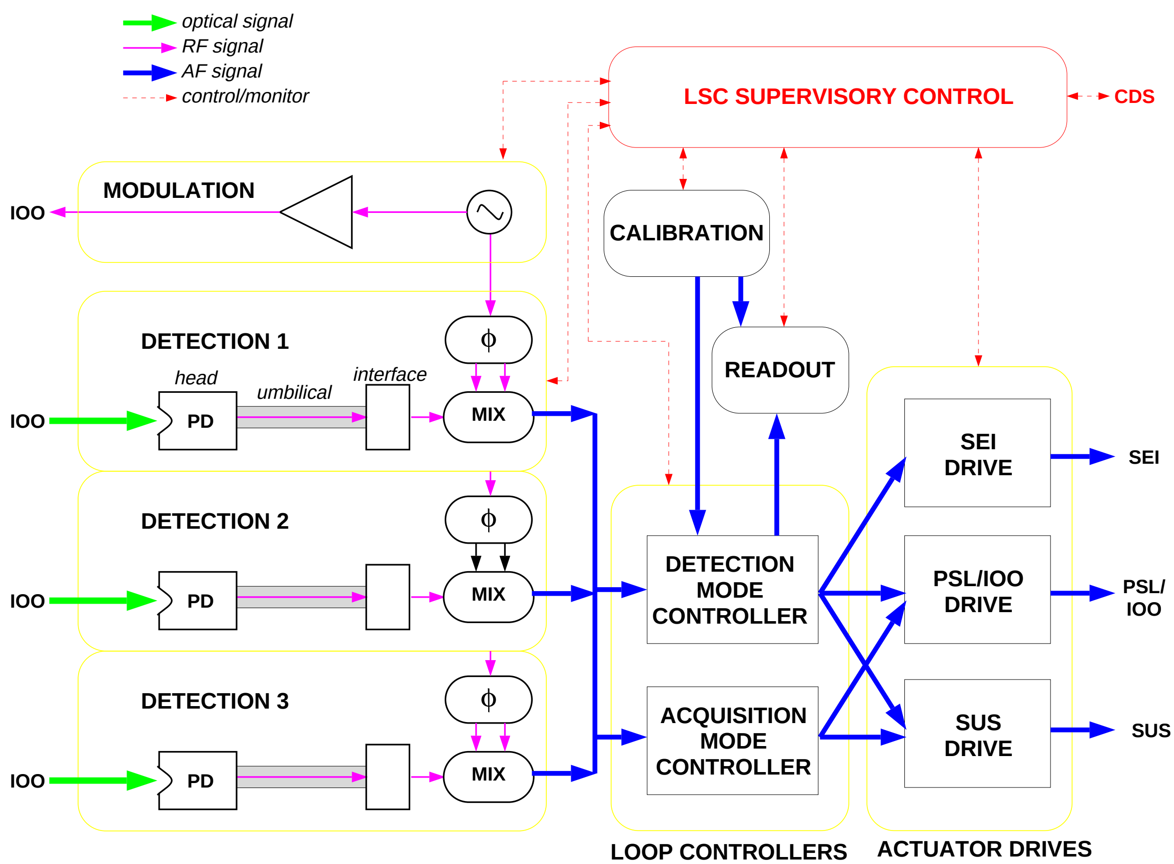

Figure 3: Signal Interfaces

Table 2: Control Loop Signal Interfaces

Subsystem	*Function of Interface*	*Signal Direction*
PSL	Frequency correction feedback	To PSL
IOO	Modulation drive	To IOO
SUS	lock acquisition actuation length control actuation	To SUS To SUS
SEI	length control actuation	To SEI
ASC	RF reference signal	From LSC

Table 3: Monitor Interfaces

Subsystem	*Function of Interface*
PSL	Monitor of lock status
PSL	Light Modulation •Frequency •Intensity •Pointing
IOO	Monitor of lock status
ASC	Monitor of lock status
SEI	Monitor of actuator level

3.2.4.1.3 Optical Interfaces

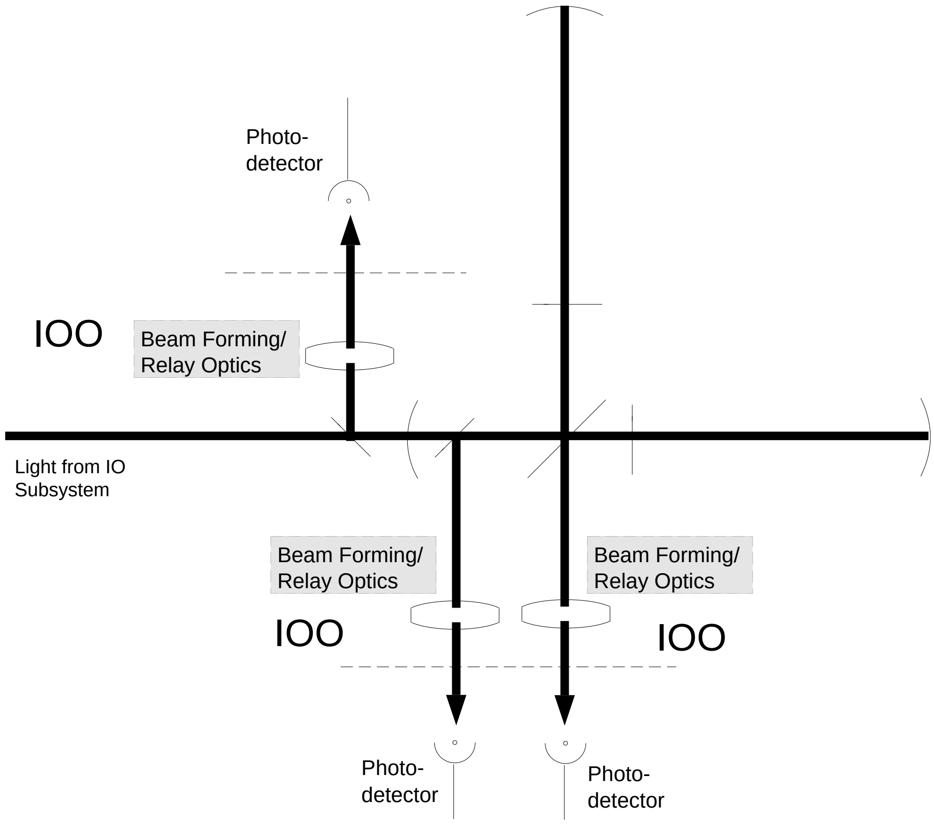

Figure 4: LSC Optical Interfaces

LSC receives its optical inputs from the Input/Output Optics subsystem, shown in figure 4.

The following table lists the optical interface properties.

Table 4: LSC Optical Interfaces

LSC Interface	*Other Subsys Interface*	*Interface and Its Characteristics*	*Drawing/ Doc #*
Photodetector	IOO output beam forming & relay optics	• beam size • beam ellipticity • mode quality	TBD

3.2.4.2 Stay Clear Zones

The stay clear zones required for the LSC are shown in figure 5. The dimensions and locations are TBD. Other stay clear dimensions TBD.

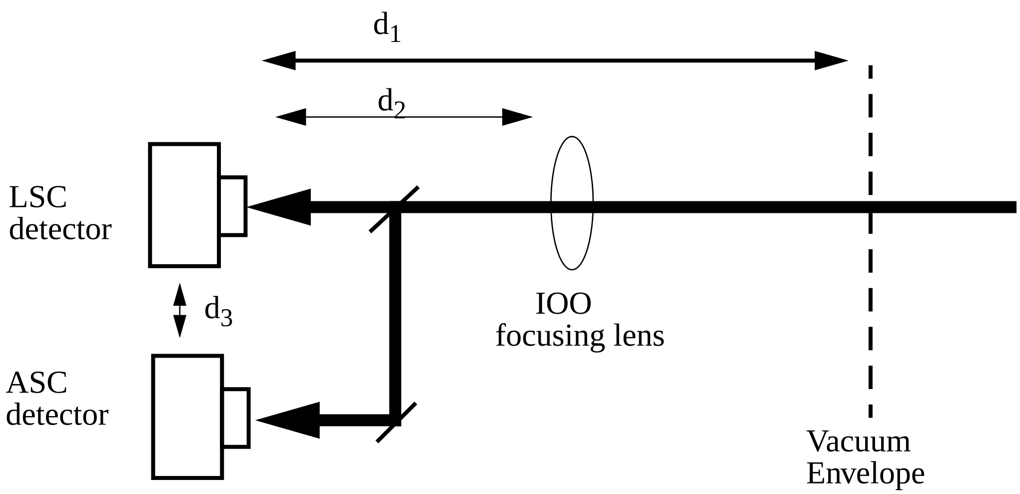

Figure 5: Stay clear dimensions

3.2.4.3 Interfaces external to LIGO detector subsystems

None.

3.2.5. Reliability

Mean Time Between Failures (MTBF) (TBD SYS)

4 QUALITY ASSURANCE PROVISIONS

4.1. General

The LSC hardware and software is to be provided by CDS. Refer to CDS LSC DRD for details of quality assurance provisions.

4.1.1. Responsibility for Tests

CDS will provide tests to demonstrate hardware functionality.

4.1.2. Special Tests

- Photodiode optical transfer function.
- Photodiode overload protection.