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- LIGO -
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# Input Output Optics
# Design Requirements Document

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This is an internal working note
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# 1 INTRODUCTION

## 1.1. Purpose

The purpose of this document is to describe the design requirements for the Input Output Optics (IOO) subsystem. Primary requirements are derived ("flowed down") from LIGO principal science requirements. Secondary requirements, which govern Detector performance through interactions between IOO and other Detector subsystems, have been allocated by Detector Systems Engineering.

## 1.2. Scope

The IOO subsystem scope provides for all aspects of conditioning of the laser light after the PSL and before the IFO input, and direction of the IFO reflected light to the LSC and ASC. It includes RF modulation of the light, acquisition and operation of the mode cleaner, and mode matching of the light to the IFO. It does not include beam steering to the IFO. The scope of the IOO includes the following hardware: phase modulation Pockels cells, photodetectors and related protective shutter, cabling and IOO control electronics, Faraday isolator, mode cleaner optics and mode matching telescopes. It does not include: suspensions, RF oscillator, or IFO beam steering optics.

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

## 1.3. Definitions and Acronyms

- PSL - Prestabilized laser
- LSC - Length Sensing and Control
- 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
- MC - Mode Cleaner
- RF - Radio Frequency
- GW - Gravitational Wave
- DRD - Design Requirements Document
- SRS - Software Requirement Specification
- TBD - To Be Determined

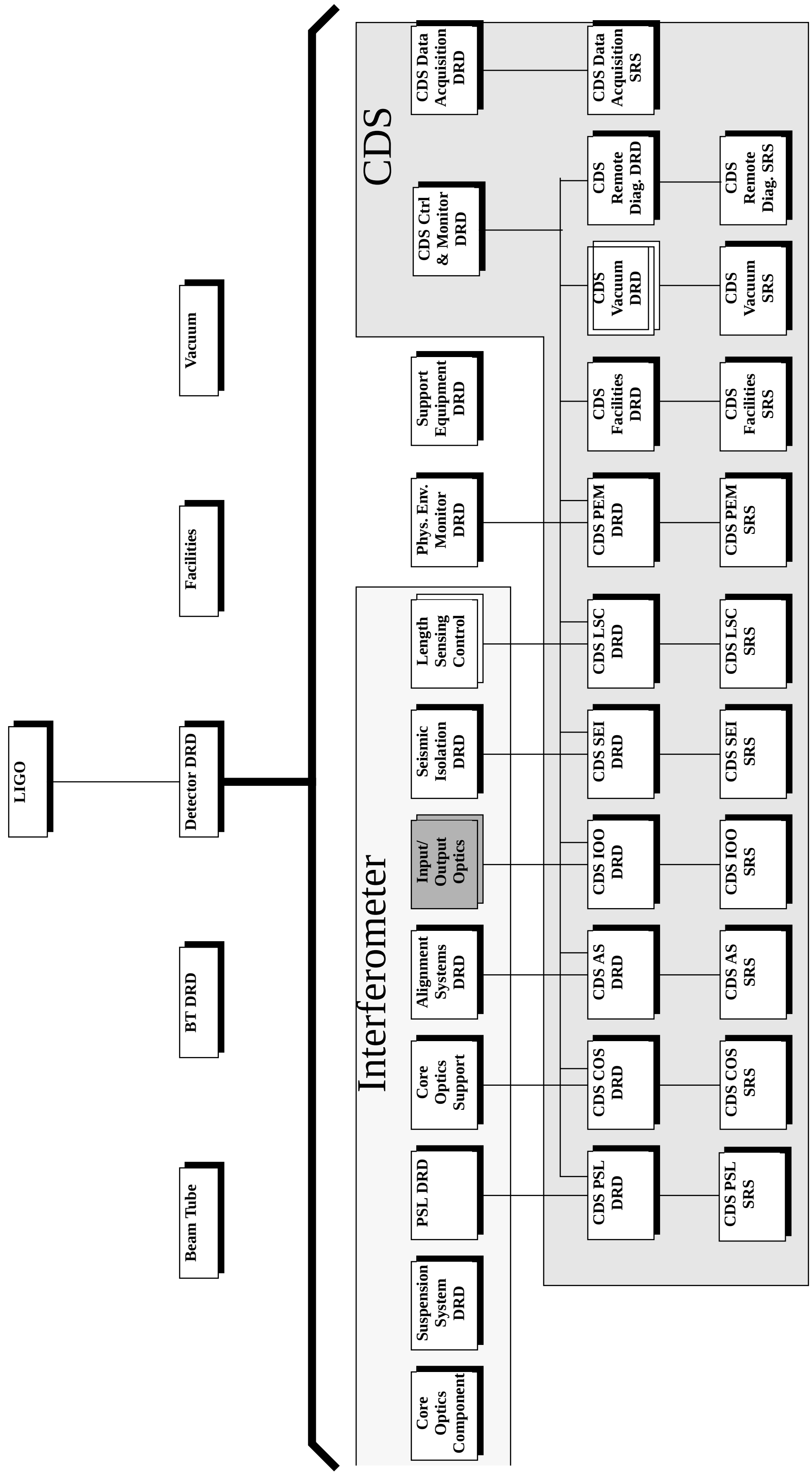


**Figure 1: LIGO Specification Tree**

## 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 DRD: LIGO-T960058-00-D

#### 1.4.1.4 Prestabilized Laser DRD: LIGO-T950030-02-D

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

### 1.4.2. Non-LIGO Documents

# 2 GENERAL DESCRIPTION

## 2.1. Product Perspective

The Input Output Optics STILL CARRIES THE 'OUTPUT' IN THE NAME? primary function is to provide a filter of the PSL light so that it is of sufficient stability to be used as a measure of the LIGO arm cavity lengths. The IOO also is responsible to deliver the light with proper shape to resonate in the IFO, and to direct the IFO reflected light to the LSC and ASC subsystems. Finally, it appends and monitors the modulation sidebands used to derive signals in the length and alignment sensing and control subsystems. INTENSITY STABILIZATION OUTPUT SHOULD BE SHOWN; ASK PF IF THE ALIGNMENT REFLECTED LIGHT IS DETECTED ALSO WHERE YOU HAVE THE LENGTH DETECTED; SHOULD REMOVE PSL OR INDICATE THAT IT IS NOT PART OF THE TASK (GREYED OUT OR WHATEVER)

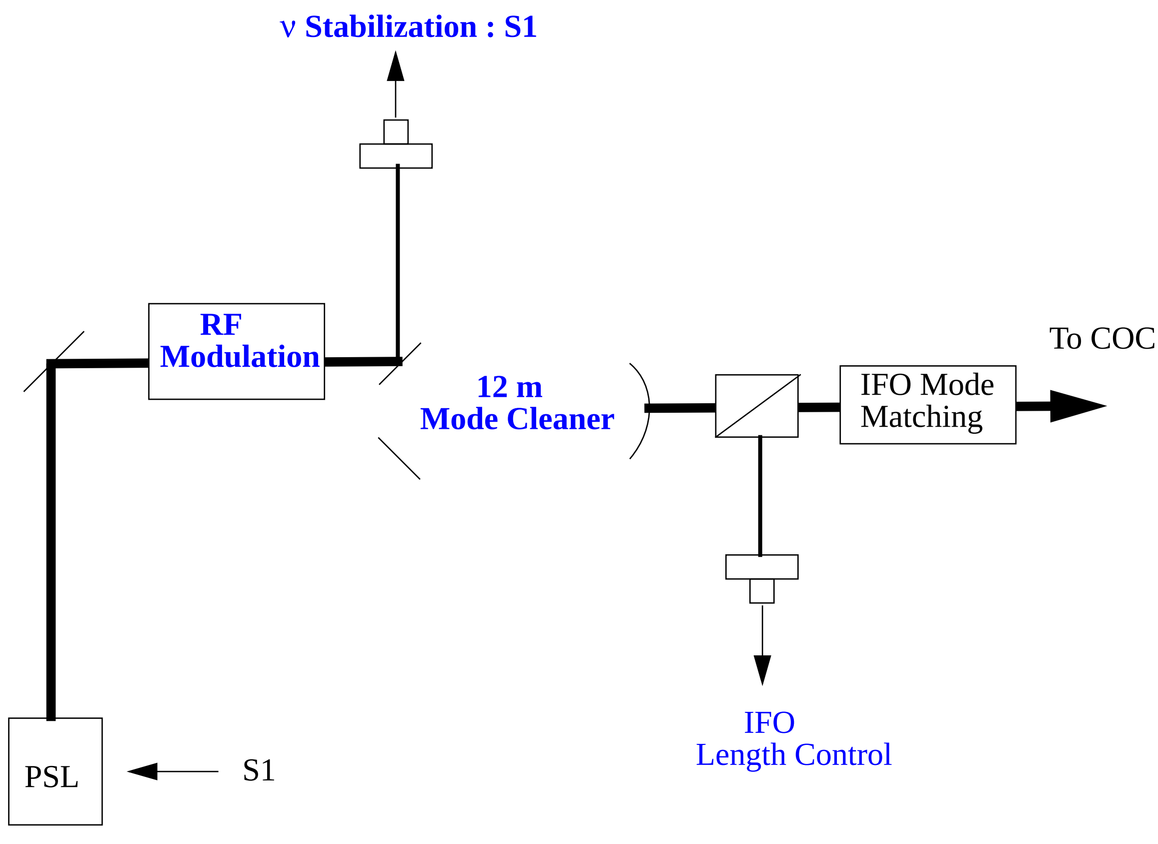


**Figure 2: Relation of IOO to other Detector subsystems**

## 2.2. Product Functions

The IOO main function is to condition the laser light so that its use as a measurement tool is compatible with primary scientific requirements for the LIGO. This involves the following 4 categories of functions.

### 2.2.1. RF modulation

The LSC and ASC subsystems require frequency components of the laser light (sidebands) which are either resonant only in the recycling cavity or do not resonate at all in the IFO. The IOO must provide for the production and monitor of these sidebands. IOO DOES NOT PRODUCE THE RF FREQS; INSTEAD, A SIGNAL AT THE REQUIRED RF POWER TO DRIVE THE MODULATORS IS DELIVERED BY LSC. CHECK WITH MIKE, BUT THIS KEEPS THE NOISE CONSIDERATIONS IN ONE SUBSYSTEM (LSC)

### 2.2.2. Mode Cleaner

The laser light must be frequency and spatially stabilized before it can be used to provide length and alignment sensing for the IFO. The 12 m mode cleaner provides active frequency noise supression below 8 kHz, passive frequency noise supression above 8 kHz, and passive spatial stabilization at all frequencies. WHY 8 KHZ? THROUGHPUT? MAYBE THIS IS DISCUSSED LATER. I WAS TENDING TOWARD REQUIRING 1 KHZ.

### 2.2.3. Mode Matching

The light must be delivered to the IFO with a proper shape so that it will resonate and not be rejected. Thus the IOO provides for the mode matching of the light between the mode cleaner and IFO WITH SOME ADJUSTABILITY TO ACCOMMODATE IMPERFECT CORE OPTICS. It also provides mode matching between the PSL and mode cleaner.

### 2.2.4. Output Optics

The IOO directs the IFO reflected light to the LSC and ASC subsystems. AHH.

## 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 (see fig. 3)
    - x (100 Hz) = $10^{-19}$ m / $Hz^{1/2}$
    - x (10 kHz) = 4 x $10^{-18}$ m / $Hz^{1/2}$

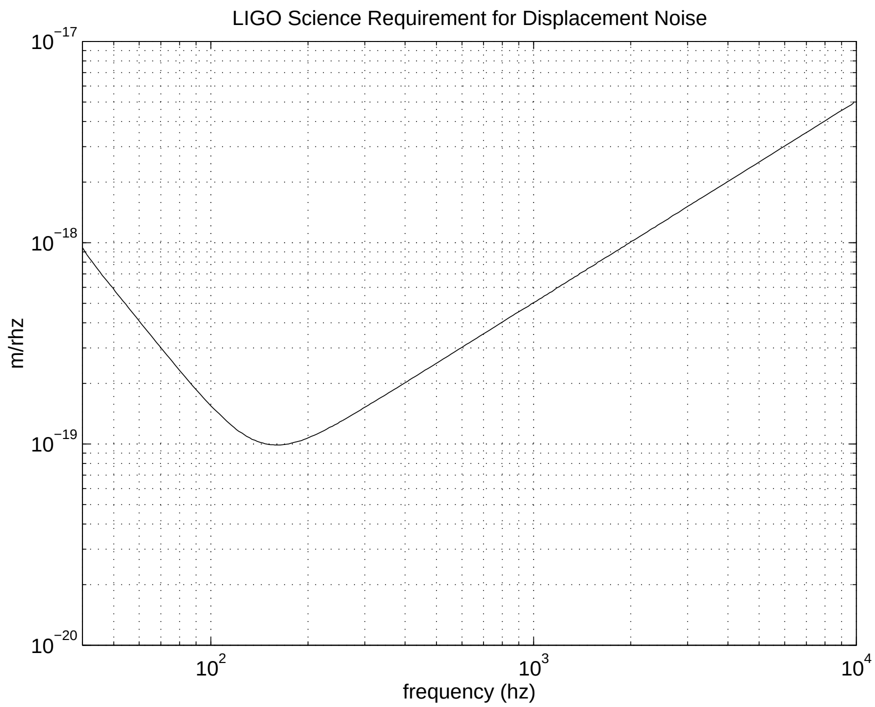


**Figure 3: SRD Displacement Sensitivity**

- 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%
- POWER COUPLED INTO IFO TEM00 MODE  IFO input power - 6 W

### 2.3.2. PSL parameters

- Frequency noise * 10^-4 HZ/RHZ F>40 hZ
- Beam jitter
  - Low frequency (<40 Hz)
  - In band ASK PF IS HE NOW HAS A NUMBER, GIVEN ALIGNMENT OF 10% SN
- Intensity noise GET FROM LSC DRD

### 2.3.3. Seismic excitation of mode cleaner mirror

- 4 layer Viton seismic stack; Q = 5 SEI DOES NOT HAVE A REQUIREMENT FOR THIS. IT CAN BE USED AS A REASONABLE ASSUMPTION, BUT ALL FIGURES DEPENDING ON IT SHOULD BE FLAGGED.
- Livingston Parish Seismic Spectrum
- Single pendulum; f = 1 Hz
  - Test mass open loop $\Delta x_{rms} \sim 10^{-8}$ m

### 2.3.4. Core Optics parameters I DON'T THINK THAT MANY OF THESE NUMBERS ARE RELEVANT, AND SHOULD NOT BE COPIED AROUND IF NOT (I MAY CHANGE THEM!)

- GET INPUT GAUSSIAN PARAMETERS AND RANGE GIVEN TOLERANCE REQUIREMENTS GIVEN TO POLISHERS FROM COC/KELLS
- Loss per optic ('bare losses' and microroughness) - 50 ppm
- Recycling gain of 30
- ~86 % sideband transmission to GW port, ~1 % carrier reflection from recycling mirror
  - ~400 mW sideband power at GW port
  - ~100 mW IFO reflected power
- arm cavity waist
  - position
  - size

### 2.3.5. Detector subsystem functionality

### 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 IOO subsystem derives its requirements from the top-level LIGO requirements for sensitivity and availability. The requirements are grouped into sections corresponding to the following functions of the IOO: RF modulation, mode cleaner, IFO mode matching, and output optics. 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 Overall IOO requirements

#### *3.2.1.1.1 Power throughput*

The throughput of the IOO shall be ~ 0.7 (TBD SYS) I HAVE WRITTEN DOWN 0.65; ANYTHING HIGHER WOULD BE MARVELOUS, BUT IS IT REALISTIC?

#### *3.2.1.1.2 Alignment stability*

The (in-band) alignment stability DEFINE: RMS MOTION OVER 0.01 < F < 10KHZ of the entire IOO subsystem shall not compromise that achieved directly after the mode cleaner. WE NEED A NUMBER HERE. START WITH QUOTING THE RMS ANGLE FLUCTUATIONS*2 THAT ARE DUE TO THE NOMINAL SEISMIC ENVIRONMENT, AND WE WILL SEE IF ASC CAN HANDLE THAT, OR IF A BEAM POINTING CONTROL SYSTEM IS NEEDED.

### 3.2.1.2 RF Modulation

The IOO provides the OPTICAL MODULATION FOR THE RF sidebands used in the length and alignment sensing. The requirements include modulation frequencies, modulation depths, and relative stability of the mode cleaner resonance and modulation frequency. THE MODULATION FREQUENCY IS PERFECTLY STABLE ON THIS SCALE. SO JUST PUTS REQS ON MC LOCKING.

#### *3.2.1.2.1 MC LENGTH*

AS NEEDED TO BE RESONAT FOR THE TWO MOD FREQS REQUIRED BELOW

#### *3.2.1.2.2 Modulation frequency*

We require a frequency which resonates in the recycling cavity and an additional frequency which is not resonant in the IFO. Both frequencies SHALL be integral multiples of the mode cleaner free spectral range.

#### *3.2.1.2.3 Modulation depths*

- Resonant sideband (set by GW shot noise - TBD SYS)
- Non-resonant sideband (set by reflected light shot noise and ASC sensitivity - TBD SYS)
- RANGE OF MODS AROUND NOMINAL DEPTH TO ACCOMMODATE DIAGNOSTICS AND DEGRADATION

#### *3.2.1.2.4 Modulation cross products*

Possible modulation cross products, far from IFO resonance and anti-resonance, can mix to give in-band signals. To avoid assoicated noise, the RF modulation is applied in such a way that no SIGNIFICANT modulation cross products will occur.

#### *3.2.1.2.5 Modulation frequency stability*

Detuning of the modulation frequency from the mode cleaner resonance couples with oscillator phase noise to produce amplitude modulation of the transmitted sidebands. Limiting this induced RFAM to 10% of shot noise requires the RF frequency to be held within ~1 (TBD) Hz of the mode cleaner exact resonance. OTHER WAY AROUND: THAT THE MC RESONANCE BE HELD WITHING XX% OF THE RF FREQ DELIVERED TO THE IO.

### 3.2.1.3 Mode Cleaner

The mode cleaner provides frequency and spatial stabilization. Requirements are derived from SYS ALLOCATIONS (SOUNDS GRAND) of PSL noise and LSC and ASC light stability demands.

#### *3.2.1.3.1 Frequency Stabilization*

The SYS frequency noise requirement of < $1 \times 10^{-7}$ Hz / $Hz^{1/2}$ on the light at the IFO input assumes noise suppression feedback to the PSL from the mode cleaner. We require:

- Frequency noise < $3 \times 10^{-4}$ Hz / $Hz^{1/2}$ at f = 100 Hz, $1 \times 10^{-5}$ Hz / $Hz^{1/2}$ at f = 10 kHz CAN'T GET 1E-4 AT 100 HZ?
- Low pass filter corner frequency of 8 kHz

#### *3.2.1.3.2 Spatial Stabilization*

- Attenuation of 01, 10 modes by a factor of ~1000 (TBD SYS)
- Attenuation of all other modes by a similar factor (TBD SYS)
- No frequency degeneracy of spatial modes with the fundamental up to mode 15?

#### *3.2.1.3.3 Alignment*

- Low frequency - mode cleaner power throughput must be consistent with IOO throughput requirement
- In - band - the MC jitter rejection must not be compromised by MC mirror angular noise

#### *3.2.1.3.4 Availability*

The IOO availability will be limited by the lock acquisition time of the mode cleaner, and any degradation in performance due to thermal stress or optical contamination. We require:

- Lock acquisition time < 20 sec (TBD SYS)

- Stored light intensity of < 100 kW / cm$^2$ (TBD SYS)

#### 3.2.1.4 Mode Matching

The IOO mode matching requirements are derived from the demands of IFO stored power, shot noise on the LSC reflected light signals, and ASC recycling cavity alignment signals.

The modal composition of the light as it leaves the IOO shall be SUCH THAT THE COUPLING INTO THE IFO IS 0.95 - DON'T NEED TO SPECIFY FURTHER, DO WE? FROM THE SYS DRD:

##### *3.2.1.4.1 Optical efficiency of Input Optics (IOO)*

The net efficiency of IO $TEM_{00}$ optical power transmission from PSL output to COC input shall be 0.65 or greater. The output power is the sum for the carrier used for GW detection and side-bands on that carrier. If a subcarrier or additional modulation is used, the efficiency for the carrier may not be reduced.

##### *3.2.1.4.2 Coupling efficiency from IO to COC (IO)*

The coupling efficiency from the Input Optics to the Main Interferometer GW carrier and side-bands $TEM_{00}$, mode parameters as described in interfaces, (COC) shall be $0.6 / 0.65 = 0.923$ or higher. This is for the optimal alignment, and includes both low-order mismatching and more general high-order distortions.

- < (TBD) TEM01
- < (TBD) all higher order modes

## 3.2.2. Diagnostics

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

- IOO Diagnostics
  - complete servo loop transfer function measurements
  - servo electronic noise and null offsets
  - ALL SENSORS photodiode sensitivity and noise
  - mode cleaner storage time
  - IOO response to laser light pointing, frequency and intensity modulation
  - other (TBD)
- Diagnostic Services
  - open loop mode cleaner mirror 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

IOO maintains mode cleaner lock through feedback actuation to SUS and provides frequency stabilization feedback to the PSL. It has an optical interface with COC at the steering input to the IFO. It provides the reflected IFO light to LSC and ASC. Finally, IOO also accepts and provides monitor and control inputs to LSC and PSL.

#### *3.2.4.1.1 Mechanical Interfaces*

- SUS suspension wire and wire standoff used in suspending mode cleaner mirrors; ATTACHMENTS (MAGNETS)
- SEI optics platform used in bolting components

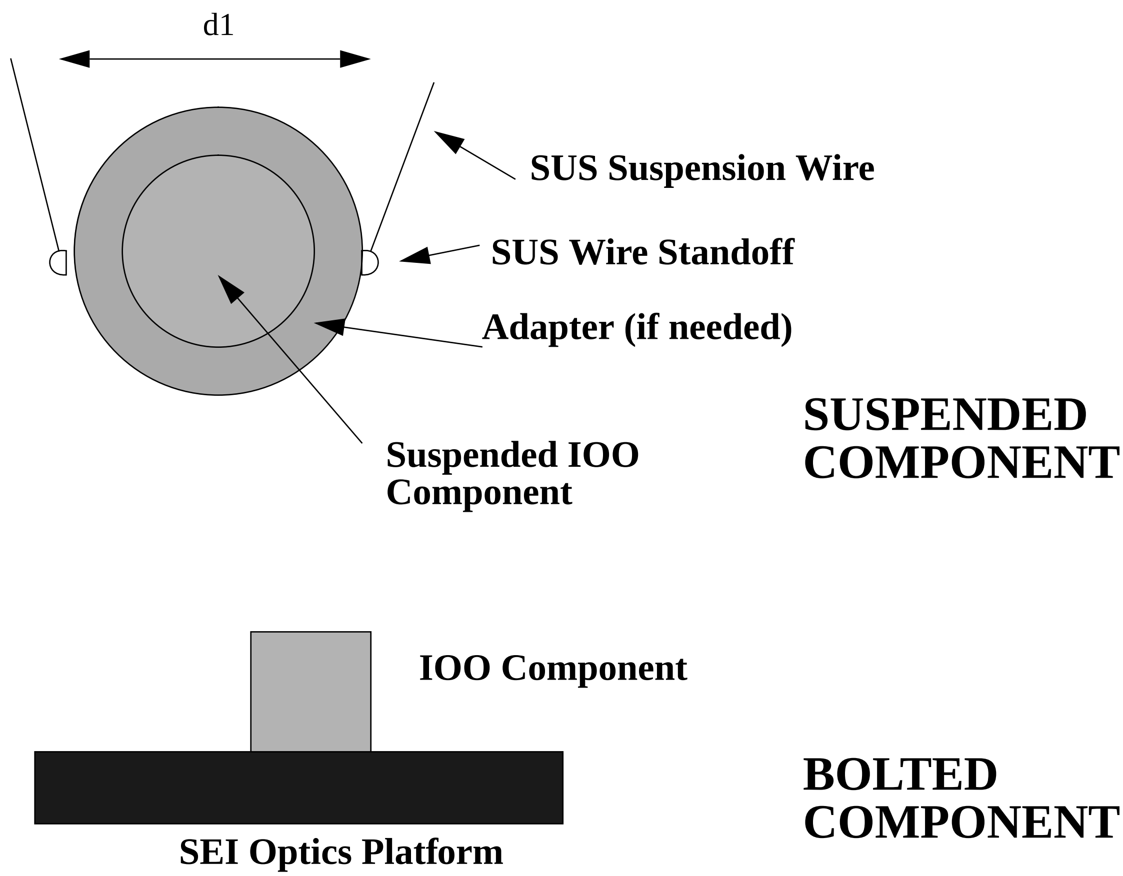


**Figure 4: Mechanical Interfaces between the IOO and other Subsytems**

| *Mechanical Mounting Interfaces* | | | *Drawing/ Doc #* |
|---|---|---|---|
| ***IOO Mounting Surface*** | ***Other Subsytem Mounting Surface*** | ***Interface and its Characteristics*** | |
| Suspended component (or adapter) | Suspension wire (SUS) | | |
| Suspended component (or adapter) | Wire standoff (SUS) | | |
| Bolted component | Optics platform (SEI) | | |

### 3.2.5. Electrical Interfaces

The IOO provides for the following signal interfaces, illustrated in fig 5. They are listed as control loop and monitor / diagnostic interfaces in tables 2 and 3 below.

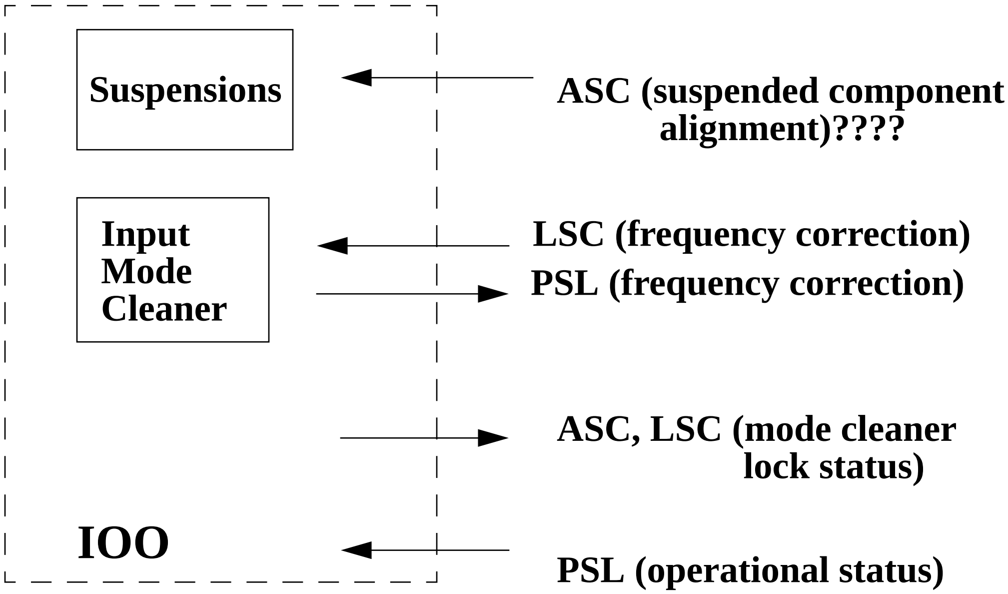


**Figure 5: Signal Interfaces between IOO and other Detector subsystems**

**Table 1: Control Loop Signal Interfaces**

| *Subsystem* | *Function of Interface* | *Signal Direction* |
|---|---|---|
| PSL | Frequency correction feedback | To PSL |
| LSC | Modulation drive | To IOO |
| SUS | lock acquisition actuation<br>length control actuation | To SUS<br>To SUS |

**Table 2: Monitor Interfaces**

| *Subsystem* | *Function of Interface* |
|---|---|
| PSL | Monitor of lock status |
| PSL | Light Modulation (freq., intensity, pointing) |
| LSC | Monitor of lock status |
| ASC | Monitor of lock status |

### *3.2.5.0.1 Optical Interfaces*

LSC receives its optical inputs from the Input/Output Optics subsystem, shown in figure 6.

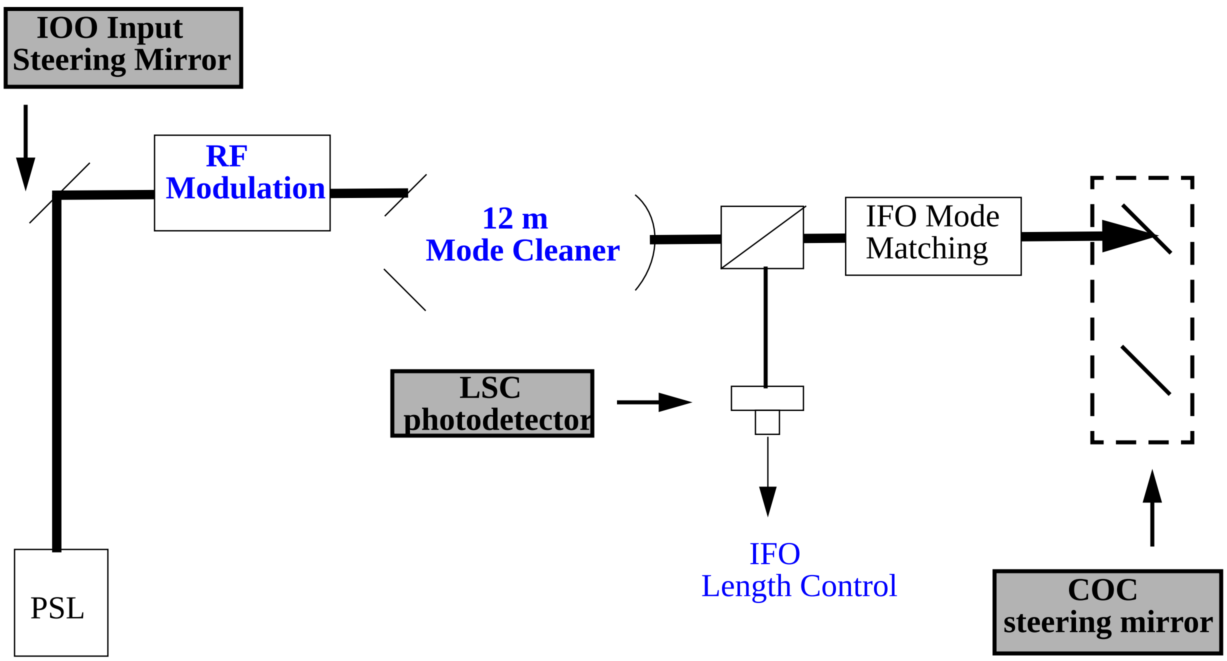


**Figure 6: IOO Optical Interfaces**

The following table lists the optical interface properties.

**Table 3: IOO Optical Interfaces**

| *IOO Interface* | *Other Subsys Interface* | *Interface and Its Characteristics* | *Drawing/ Doc #* |
|---|---|---|---|
| Input steering mirror | PSL output beam | | TBD |
| Faraday Isolator | LSC photodetector, ASC PHOTODETECTORS (FOR COC ALIGNMENT) | | |
| Output beam | COC steering mirror | | |

#### 3.2.5.1 Stay Clear Zones

The stay clear zones required for the LSC are shown in figure 7. The dimensions and locations are TBD. Other stay clear dimensions TBD.

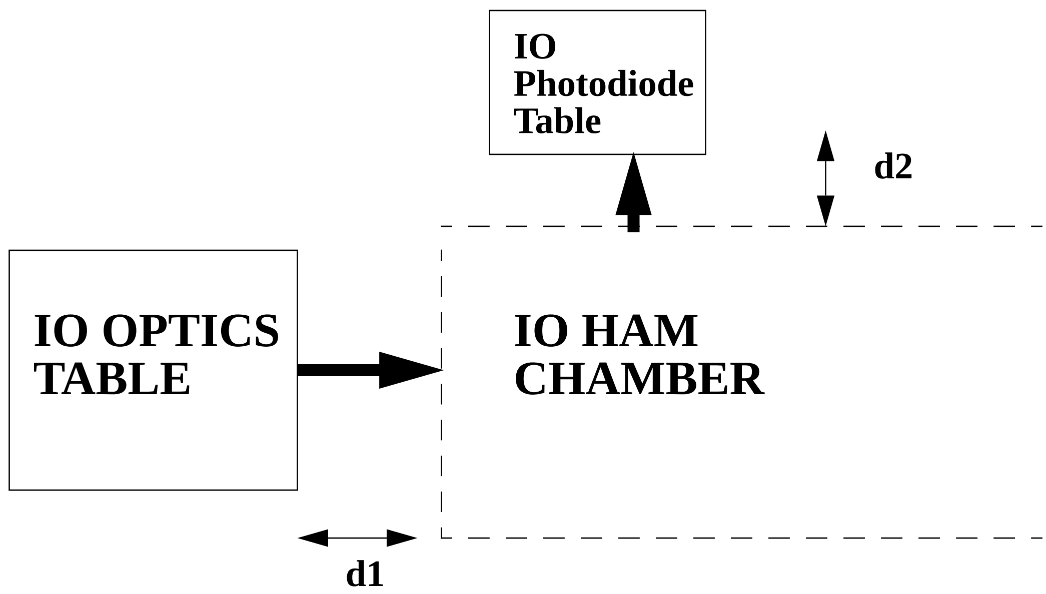


**Figure 7: Stay clear dimensions**

### 3.2.6. Interfaces external to LIGO detector subsystems

### 3.2.7. Reliability

Mean Time Between Failures (MTBF) (TBD SYS)

# 4 QUALITY ASSURANCE PROVISIONS

## 4.1. General

### 4.1.1. Responsibility for Tests

CDS will provide tests to demonstrate hardware functionality.

NEED TO PUT BACK IN THE 'BOILERPLATE' SECTIONS TO BE SURE NOT TO MISS ANYTHING (LIKE IN-VACUUM MATERIALS AND CLEANLINESS REQUIREMENTS). SORRY.