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- LIGO -
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Input Optics
Design Requirements Document

Jordan Camp, David Reitze, David Tanner

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IOO Design Requirements Review Board

This is an internal working note
of the LIGO Project.

California Institute of Technology
LIGO Project - MS 51-33
Pasadena CA 91125
Phone (818) 395-2129
Fax (818) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Project - MS 20B-145
Cambridge, MA 01239
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

WWW: http://www.ligo.caltech.edu/

1 INTRODUCTION

1.1. Purpose

The purpose of this document is to describe the design requirements for the Input Optics 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 (see Figure 1).

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, mode matching of the light to the IFO, and beam steering into the IFO. The scope of the IOO includes the following hardware: phase modulation Pockels cells, photodetectors and related protective shutter (if needed), cabling and IOO length control electronics, Faraday isolator, mode cleaner optics, suspension (fabrication), mode matching telescopes, and large beam steering optics. The IOO specifically does not include the RF oscillator or suspension designs, baffling of scattered light in the HAMs, the Output Optics, RF photodiodes for PSL or LSC/ASC diagnostic signals.

The IOO subsystem is shown in relation to the Detector subsystems in Figures 1 and 2 below. All IOO hardware and control 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

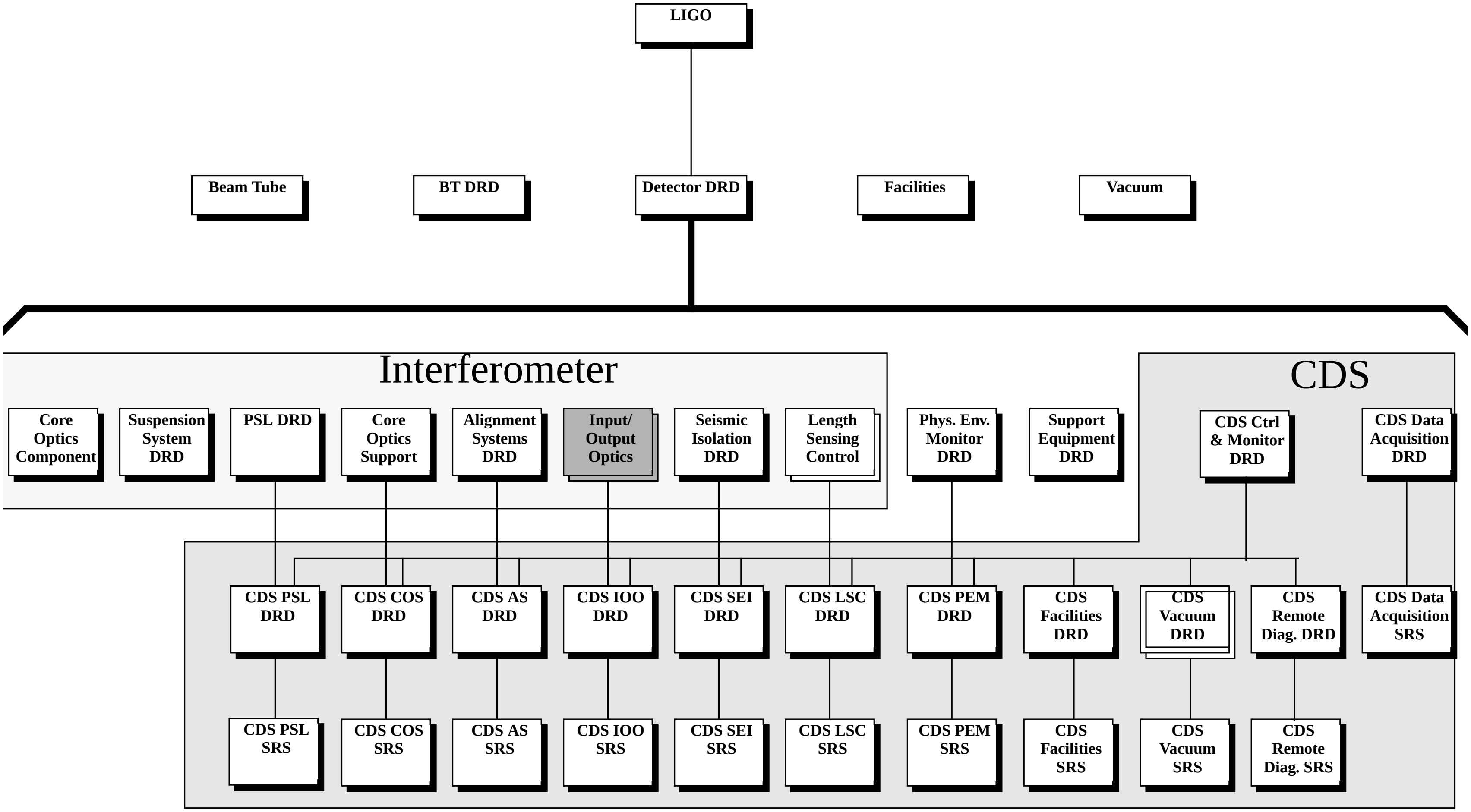

Figure 1: LIGO Specification Tree

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 Detector Subsystems Requirements: LIGO-E960112-04-D

1.4.1.3 LSC DRD: LIGO-T960058-00-D

1.4.1.4 ASC DRD: LIGO-T952007-03-I

1.4.1.5 SUS DRD: LIGO-T950011-14-D

1.4.1.6 Prestabilized Laser DRD: LIGO-T950030-02-D

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

1.4.1.8 Mode Cleaner Noise Sources: LIGO-T960165-00-D

1.4.1.9 Frequency Stabilization in LIGO: LIGO-T960164-00-D

1.4.1.10 Modal Analysis of Mode-Matching Telescope Configurations in LIGO (to be written)

2 GENERAL DESCRIPTION

2.1. Product Perspective

The primary function of the Input Output Optics (IOO) is to provide a temporal and spatial 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 for delivering the light with the proper gaussian shape parameters to resonate in the IFO, and to direct the IFO reflected light to the LSC and ASC subsystems. Finally, it imposes and monitors the modulation sidebands used to derive signals in the length and alignment sensing and control subsystems. The relationship of the IOO to other detector subsystems is shown in Figure 2. The conceptual layout of the IOO is displayed in Figure 3.

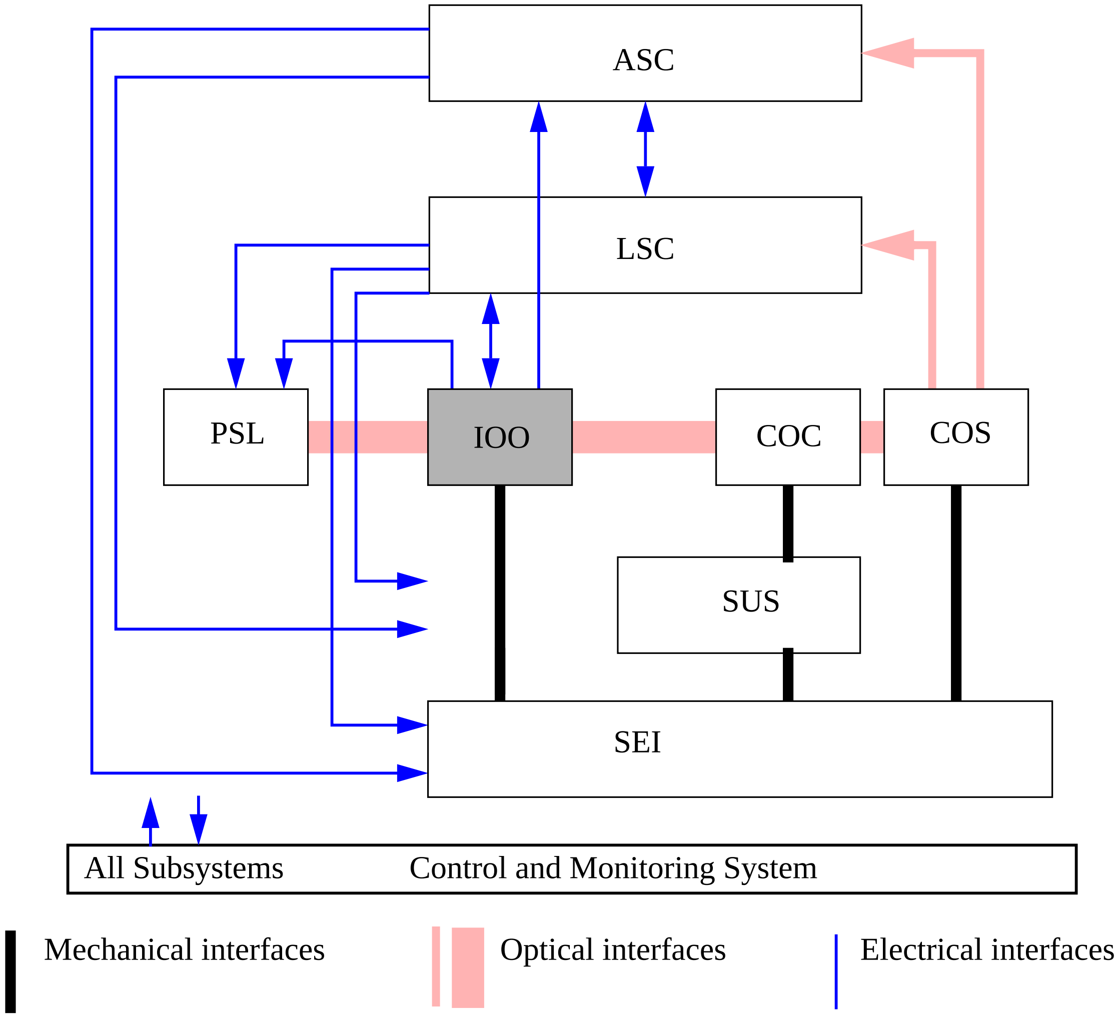

Figure 2: **Relationship of IOO to the rest of the detector subsystem. IOO is shaded.**

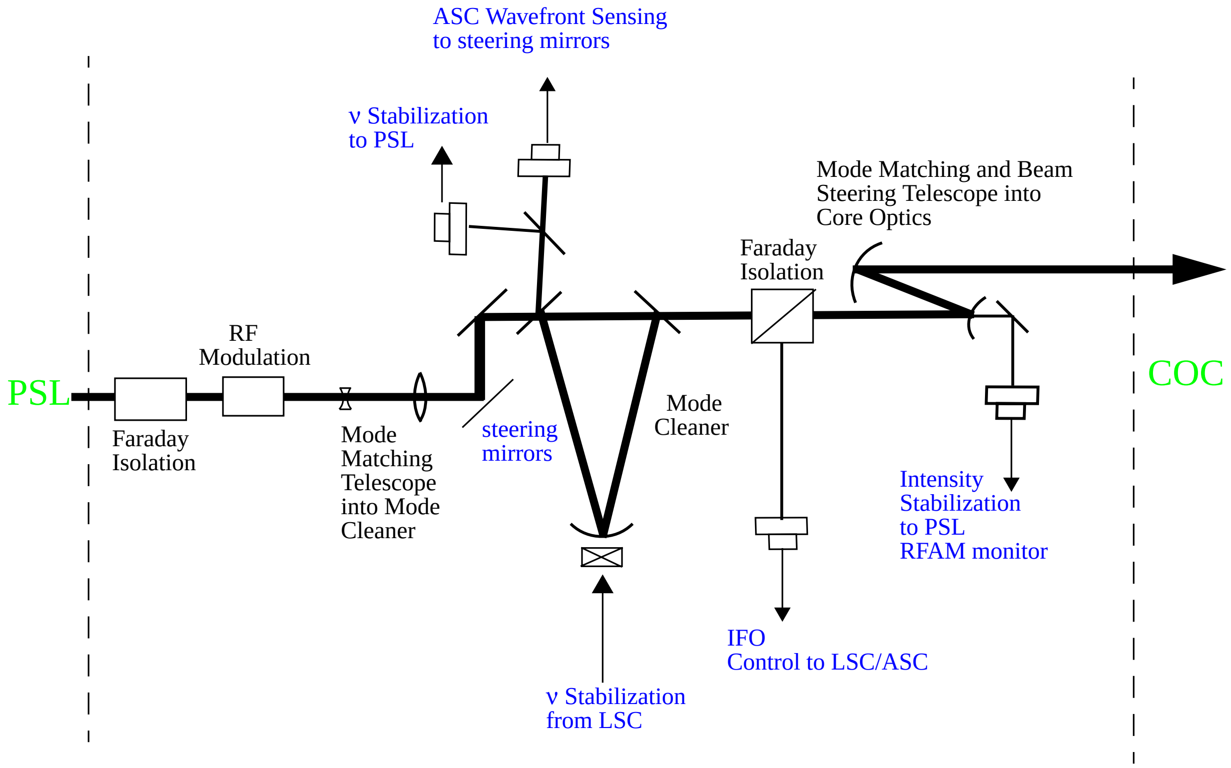

Figure 3: Conceptual layout of IOO optical components

2.2. Product Functions

The IOO conditions the laser light so that its properties are compatible with the primary scientific requirements for the LIGO. This function separates into the following four categories.

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 are not resonantat all in the IFO. The IOO must provide for the production and monitor of these sidebands using RF signals from the 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 mode cleaner provides active frequency suppression through feedback to the PSL, passive frequency noise suppression above its cavity pole frequency, and passive spatial stabilization at all frequencies.

2.2.3. Mode Matching

The light must be delivered to the IFO with a proper gaussian mode so that it will resonate in the IFO and not be rejected. Thus the IOO provides for the mode matching of the light between the mode cleaner and the core optics components of the interferometer. The mode matching telescope must be adjustable to accommodate small deviations from design specification in the core optics. The IOO also provides mode matching between the PSL and mode cleaner.

2.2.4. Optical Isolation

Back-reflected light returning to the PSL from optical components in the IFO and IOO can couple into the PSL and introduce excess phase noise. Thus the IOO must provide optical isolation between the COC and the PSL.

2.2.5. Diagnostics

The IOO must provide diagnostic capabilities for its own functions and for that of other subsystems.

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

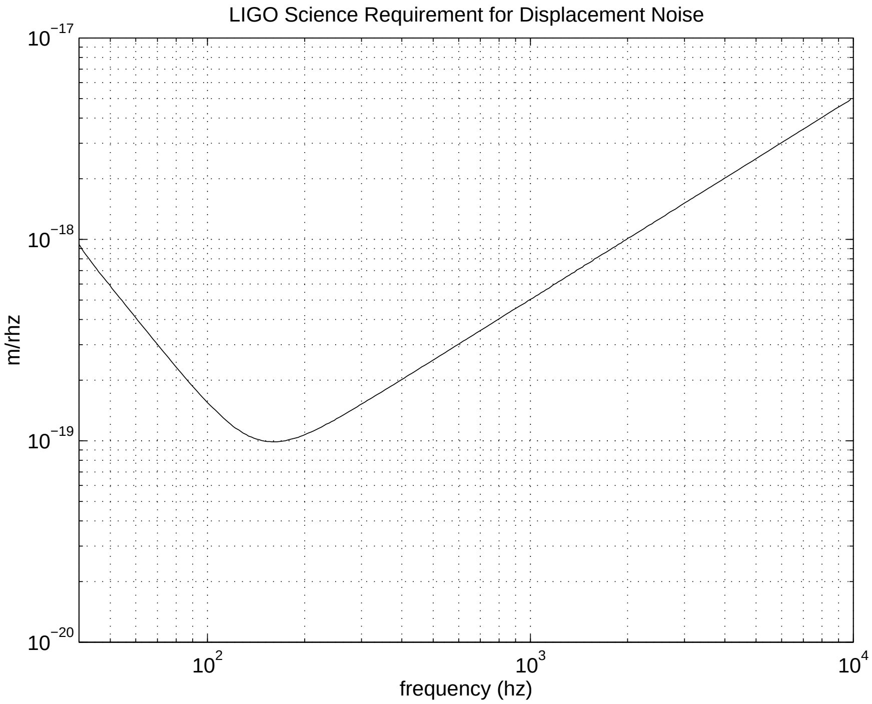

Figure 4: SRD Displacement Sensitivity

- 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
- Operational availability - 90%
- Input power (TEM_{00} mode) into the interferometer - 6 W

2.3.2. PSL parameters

- Output power in TEM_{00} mode: 8.0 W
- Frequency noise: $\delta\nu(f) < 10^{-2}$ Hz/Hz$^{1/2}$, 40 Hz < f < 10 kHz
- Beam jitter: $\varepsilon_1(f) \sim 2 \times 10^{-6}$ / Hz$^{1/2}$ f = 100 Hz
- Intensity noise: $\delta I(f) / I < 10^{-6}$ / Hz$^{1/2}$, 40 Hz < f < 10 kHz

2.3.3. Seismic excitation of suspended optics

- 4 layer Viton seismic stack; Q < 5 (TBD)
- Livingston Parish Seismic Spectrum
  - Angular fluctuations:

    Low frequency $\alpha_{rms} \sim 5 \times 10^{-7}$ rad (4 km baseline)

    In-band $\alpha \sim 10^{-18}$ rad/Hz$^{1/2}$ (100 Hz) (pendulum thermal noise)
  - Displacement fluctuations:

    Low frequency $x_{rms} \sim 1 \times 10^{-6}$ m (4 km baseline)

    In-band $x \sim 10^{-22}$ m/Hz$^{1/2}$ (100 Hz)

2.3.4. Suspensions

- Suspension design supplied by SUS
  - LOS1 for 25 cm diameter, 10 cm thick optics
  - SOS for 7.6 cm diameter, 2.54 cm thick optics
- Small optics suspension f = 1 Hz
- Large optics suspension f = 0.74 Hz

2.3.5. Core Optics parameters

- Recycled Michelson interferometer with Fabry Perot cavities in the arms.
- See table:

Table 1: Core Optics Parameters

	Units	4k	2k	+/-
Telescope primary--recycling mirror optical path	m	16.4	16.4	1.5
Recycling mirror radius of curvature	m	9998	9998	–0.01, + 0.05
Recycling mirror thickness	cm	10	10	Nominal
Recycling mirror rear surface tilt	mrad	39.095	39.095	
Recycling mirror--input test mass optical path	m	9.38	11.67	1.25
Resonant modulation frequency, f_m	MHz	24.493	29.486	TBD (1)
Non-resonant modulation frequency, f_n	MHz	61.232 (TBD/ ISC)	68.800 (TBD/ ISC)	From f_m
Input test mass radius of curvature	m	14558	14558	–0.015, + 0.015
Input test mass thickness	m	0.1	0.1	Nominal
Input test mass rear surface tilt	mrad	34.9	34.9	
Arm cavity optical path	m	4000	2000	Nominal
End test mass radius of curvature	m	7400	7400	TBD
End test mass thickness	m	0.1	0.1	Nominal
Arm cavity stability factor $g_i g_e$		0.333	0.629	Derived
Arm/recycling cavity waist (from ITM)	m	975	601	TBD
Arm/recycling cavity waist size	cm	3.51	3.13	TBD

- Optical materials
  - Fused quartz, n = 1.44963

2.3.6. Expected IFO parameter variations

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

3.2. Performance Characteristics

3.2.1. Overall IOO requirements

3.2.1.1 Optical efficiency of Input Optics

The net efficiency of IO TEM_{00} optical power transmission from PSL output to COC input shall be 0.75 or greater, determined by the requirement that at least 6.0 W of TEM_{00} light be coupled into the COC. The output power is the sum for the carrier used for GW detection and sidebands on that carrier. If a subcarrier or additional modulation is used, the efficiency for the carrier may not be reduced.

3.2.1.2 Output Beam In-band Alignment Stability (Jitter)

Alignment fluctuations at the input of the COC couple to angular motion of the test masses to give in-band displacement signals. The (in-band) alignment stability of the entire IOO subsystem shall not compromise that achieved directly after the mode cleaner, including the mode-matching telescope. The output beam alignment stability requirement is[1]

- Angular Fluctuations:
  $\alpha(f) = 3 \times 10^{-14}$ rad/$Hz^{1/2}$ and may rise as $1/ f^{2}$ below 150 Hz
- Displacement Fluctuations:
  $x(f) = 1 \times 10^{-10}$ m/$Hz^{1/2}$ and may rise as $1/ f^{2}$ below 150 Hz

3.2.1.3 Parasitic interferometers

Light which reflects or scatters into the Rayleigh angle of the beam contributes to the in-band signal directly (through phase modulation at GW frequencies) and indirectly (through frequency shifting of scattered and reflected light into GW band due to mirror motions). An upper limit of 10^{-8} of reflected power (TBD SYS) is allowed to scatter into the Rayleigh cone.

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[1] Misalignment - Beam Jitter Coupling in LIGO, LIGO-T960120-00-D

3.2.1.4 Optical Isolation

Optical isolation is required to separate the PSL from IFO and IOO back reflected light. The required isolation level is taken to be ~ 70 dB (TBR).

3.2.2. 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.

3.2.2.1 Modulation frequencies

We require a frequency which resonates in the recycling cavity and an additional frequency which is not resonant in the IFO. Both frequencies (chosen by LSC, TBD) must be passed by the mode cleaner and therefore be integral multiples of the mode cleaner free spectral range.

3.2.2.2 Modulation depths

- Resonant sideband (set by GW shot noise considerations) - $\Gamma \sim 0.5$
- Non-resonant sideband (set by reflected light shot noise and ASC sensitivity) - $\Gamma \sim 0.05$
- The IOO must provide for a range of modulations about the specified depths to accommodate diagnostic functions and potential degradation. (TBD SYS)

3.2.2.3 Modulation cross products

The modulation sidebands provide the frequency reference against which IFO lengths changes are measured. Possible modulation cross products, far from IFO resonance and anti-resonance, can mix to give in-band signals. To ensure the cleanest possible frequency reference, we require a modulation spectrum with no cross-products.

3.2.2.4 Mode Cleaner free spectral range stability

Detuning of the modulation frequency from the mode cleaner FSR couples with oscillator phase noise to produce amplitude modulation of the transmitted sidebands. Limiting this induced RFAM to 10% of shot noise on 6 W laser light requires the RF modulation frequency and the mode cleaner free spectral range to be held equal within < 2 Hz.[1]

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[1] Mode Cleaner Noise Sources, LIGO-T0164-00-D

3.2.3. Mode Cleaner

The mode cleaner provides frequency and spatial stabilization of the laser light. Requirements are derived from SYS allocations of PSL noise and LSC and ASC light stability demands.

3.2.3.1 Mode Cleaner Frequency Stabilization

The SYS frequency noise requirement of $< 1 \times 10^{-7}$ Hz / Hz$^{1/2}$ on the light at the IFO input requires a mode cleaner frequency stability consistent with LSC L_+ loop gains and expected PSL frequency noise.[1] We require:

- Mode Cleaner frequency noise (limited by mirror vibrational thermal noise)[2]: $\delta\nu(f) < 10^{-4}$ Hz / Hz$^{1/2}$ at f = 100 Hz; 1×10^{-5} Hz / Hz$^{1/2}$ at f = 10 kHz
- Shot noise of frequency sensing below frequency noise at all in-band frequencies

3.2.3.2 Mode Cleaner Length Control System Noise

The length control system will contribute no more than 10% of the limiting displacement noise.

3.2.3.3 Mode Cleaner Intensity Stabilization

The light intensity fluctuations at the IFO input consistent with SYS specifications assumes intensity stabilization feedback to the PSL from the IOO. This stabilization is done after the mode cleaner to suppress beam jitter-induced intensity noise. We require:

- Intensity noise after mode cleaner - $\delta I(f) / I < 10^{-8}$ / Hz$^{1/2}$, 40 Hz < f < 10 kHz for both carrier and sideband

3.2.3.4 Mode Cleaner Spatial Stabilization

- Attenuation of 01, 10 modes at the PSL output to a level consistent with ASC beam jitter requirements[3]: $\varepsilon_1 < 3.5 \times 10^{-9}$ / Hz$^{1/2}$
- Attenuation of all other modes by a similar factor (TBD SYS)
- No frequency degeneracy of spatial modes with the fundamental up to mode 15

3.2.3.5 Mode Cleaner Alignment

- Low frequency: beam jitter -> frequency noise must be kept below mode cleaner thermal noise, requiring $\theta_{rms} < 3 \times 10^{-7}$ rad[4] (100 Hz)
- In - band: the MC jitter rejection must not be compromised by MC mirror angular noise, requiring $\theta < 10^{-12}$ rad / Hz$^{1/2}$ (100 Hz)

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[1] Frequency Stabilization in LIGO, LIGO-T0165-00-D

[2] Mode Cleaner Noise Sources, LIGO-T0164-00-D

[3] Misalignment - Beam Jitter Coupling in LIGO, LIGO-T960120-00-D

[4] see (2) above

3.2.3.6 Mode Cleaner Beam Centering

The beam spot must be centered in the mode cleaner mirrors to a precision of 3 mm to avoid length-misalignment couplings.[1]

3.2.4. 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 to fully operational state < 20 sec
- Stored light intensity of < 150 kW / cm^2

3.2.5. Mode Matching

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

3.2.5.1 Coupling efficiency from IO to COC

The coupling efficiency from the Input Optics to the Main Interferometer GW carrier and sidebands TEM$_{00}$, mode parameters as described in interfaces, (COC) shall be 0.95 or higher. The telescope will provide this level of coupling with adjustability to accommodate deviations in COC specifications. This is for the optimal alignment, and includes both low-order mismatching and more general high-order distortions.

The remaining modal composition shall be:

- $< 10^{-3}$ TEM$_{01, 10}$
- $< 10^{-3}$ all higher order modes

3.2.5.2 Mode matching telescope alignment stability

Perturbations of the mode matching telescope may enhance the coupling of noise sources to gravitational wave noise (in band) and reduce coupling efficiency into COC (low frequency).[2] We require that any telescopic magnification of pointing drift or jitter does not compromise the alignment stability of the IOO output beam into the COC:

- Low frequency drift: telescope pointing must be consistent with COC coupling efficiency requirements
- In-band noise: telescope angular and displacement fluctuations must be consistent with ASC requirements for beam jitter at the input of the COC

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[1] ASC DRD, LIGO-T952007-03-I

[2] Modal Analysis of Mode-Matching Telescope Configurations in LIGO, to be written

3.2.6. 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
  - photodiode sensitivity and noise for all IOO sensors
  - mode cleaner storage time
  - IOO response to laser light pointing, frequency and intensity modulation
  - other (TBD SYS)
- Diagnostic Services
  - open loop mode cleaner mirror seismic excitation
  - variation in RF sideband modulation depth
  - variation in IFO mode matching efficiency
  - sideband detuning from mode cleaner resonance
  - other (TBD SYS)

3.3. Physical Characteristics

3.3.1. Interfaces to other LIGO detector subsystems

IOO provides frequency stabilization feedback to the PSL. It has an optical interface with COC at the recycling mirror 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.

3.3.1.1 Mechanical Interfaces

- SEI optics platform used in bolting components

The mechanical interfaces are listed in the following table.

Table 2: Mechanical Interfaces

Mechanical Mounting Interfaces			***Drawing/ Doc #***
IOO Mounting Surface	***Other Subsytem Mounting Surface***	***Interface and its Characteristics***	
Bolted component	Optics platform (SEI)		

3.3.2. 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 1 and 2 below.

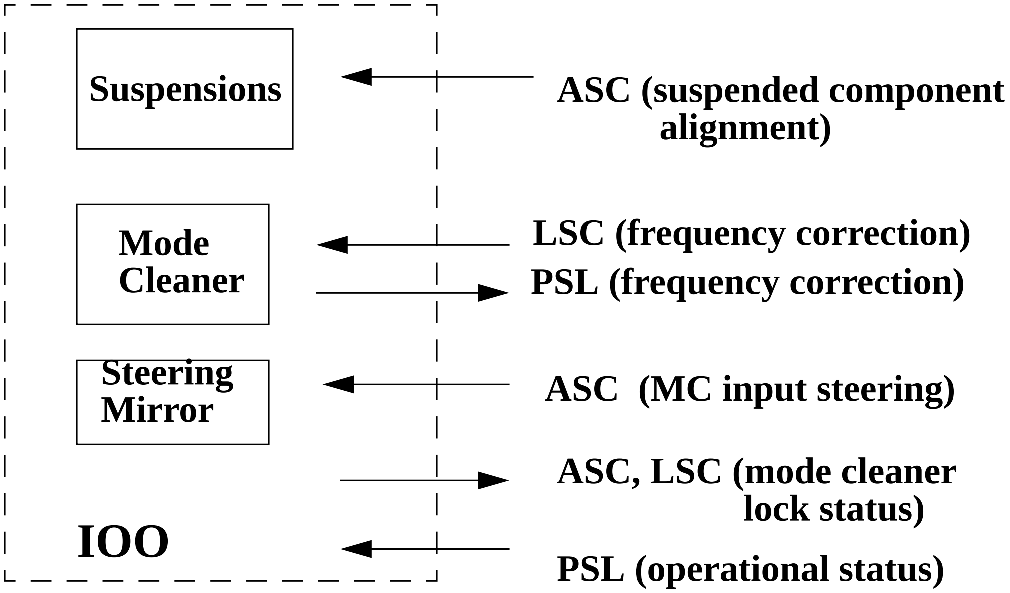

Figure 5: Signal Interfaces between IOO and other Detector subsystems

Table 3: Control Loop signal Interfaces

Subsystem	*Function of Interface*	*Signal Direction*
PSL	Frequency correction feedback	To PSL
LSC	Modulation drive	To IOO
LSC	Frequency correction feedback	To IOO
SUS	Lock acquisition actuation Length control actuation	To SUS To SUS
ASC	Mode cleaner input beam steering	To IOO
ASC	Suspended component alignment	To IOO

Table 4: 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

3.3.3. IOO Optical Interfaces

The IOO optical interfaces are shown in figure 7.

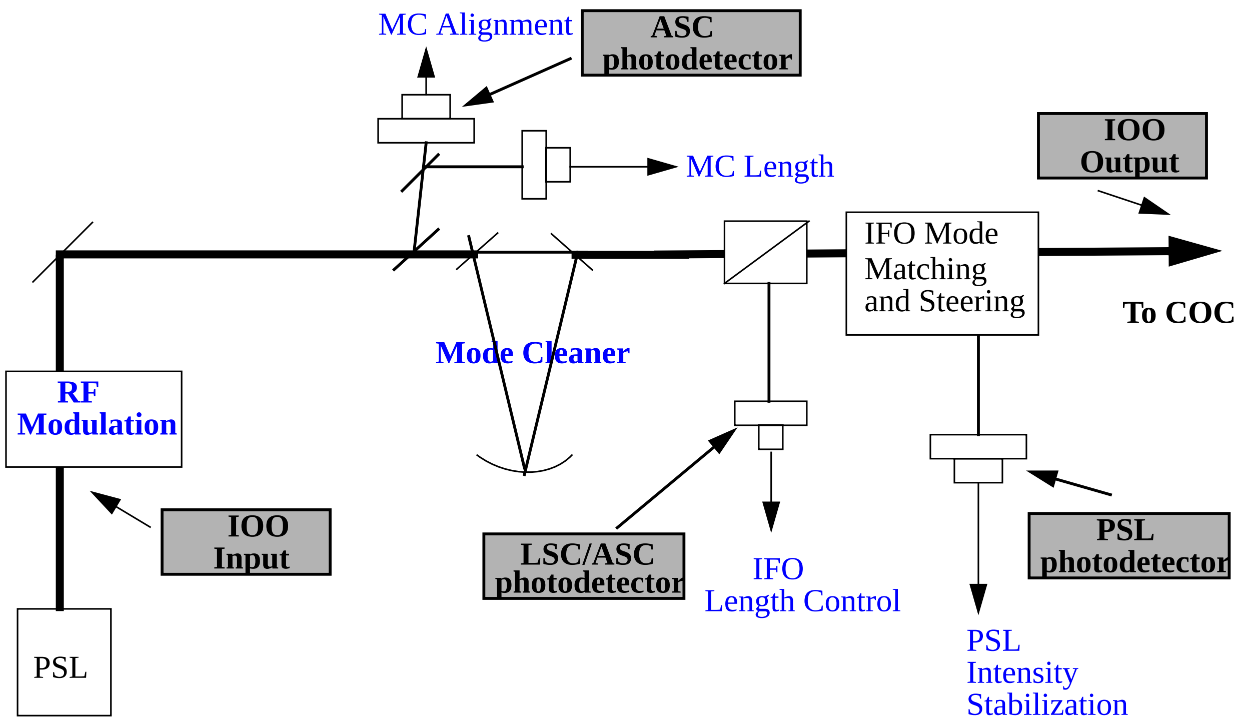

Figure 6: IOO Optical Interfaces

The following table lists the optical interface properties.

Table 5: IOO Optical Interfaces

IOO Interface	*Other Subsys Interface*	*Interface and Its Characteristics*	*Drawing/ Doc #*
IOO Input	PSL output beam		TBD
Input MC mirror	ASC Wavefront Sensor		

Table 5: IOO Optical Interfaces

IOO Interface	*Other Subsys Interface*	*Interface and Its Characteristics*	*Drawing/ Doc #*
Telescope	PSL photodetector		
Faraday Isolator	LSC, ASC photodetector		
Output beam	COC		

3.3.3.1 Stay Clear Zones

The stay clear zones required for the IOO are shown in figure 8. The dimensions and locations are d1=3 ft, d1=Other stay clear dimensions are TBD.

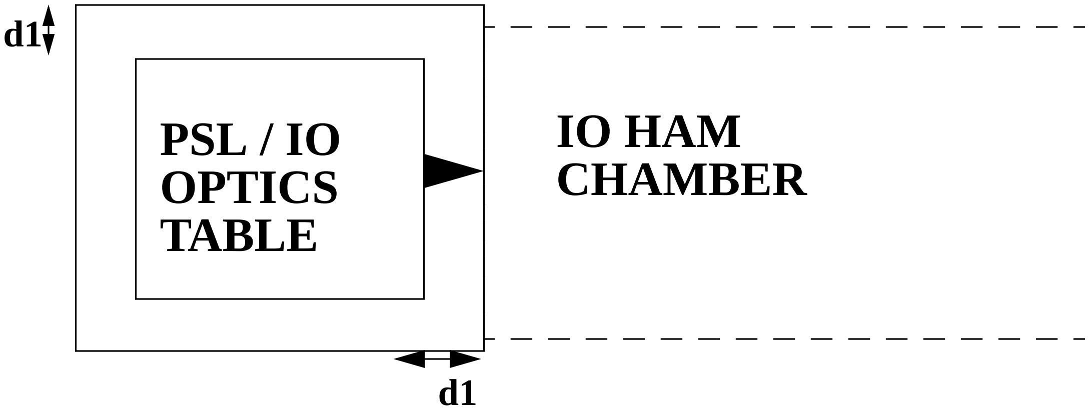

Figure 7: Stay clear dimensions

3.3.4. Interfaces external to LIGO detector subsystems

None.

3.3.5. Reliability

Mean Time Between Failures (MTBF) (TBD SYS).

3.3.6. Environmental Conditions

The facility requirements are adequate for the proper functioning of the IOO subsystem

3.3.6.0.1 Temperature and Humidity

Table 6: Environmental Performance Characteristics

Operating	*Non-operating (storage)*	*Transport*
+0 C to +50 C, 0-90%RH	-40 C to +70 C, 0-90% RH	-40 C to +70 C, 0-90% RH

3.3.7. Transportability

All items shall be transportable by commercial carrier without degradation in performance. As necessary, provisions shall be made for measuring and controlling environmental conditions (temperature and accelerations) during transport and handling. Special shipping containers, shipping and handling mechanical restraints, and shock isolation shall be utilized to prevent damage. All containers shall be movable for forklift. All items over 100 lbs. which must be moved into place within LIGO buildings shall have appropriate lifting eyes and mechanical strength to be lifted by cranes.

3.3.7.1 Materials

All materials of the IOO must meet the LIGO vacuum certification standard (TBD). Special attention will be paid to the materials of the Faraday Isolator.

3.3.8. Component Naming

All components shall identified using the LIGO Detector Naming Convention (document TBD). This shall include identification physically on components, in all drawings and in all related documentation.

3.3.9. Safety

This item shall meet all applicable NSF and other Federal safety regulations, plus those applicable State, Local and LIGO safety requirements. A hazard/risk analysis shall be conducted in accordance with guidelines set forth in the LIGO Project System Safety Management Plan LIGO-M950046-F, section 3.3.2.

3.4. Documentation

3.4.1. Design Documents

Design documents of the IOO will be provided throughout the requirements and preliminary and final phases.

3.4.2. Engineering Drawings and Associated Lists

Any drawings to be provided and any standard formats that they must comply with, such as shall use LIGO drawing numbering system, be drawn using LIGO Drawing Preparation Standards, etc

3.4.2.1 Procedures

Procedures shall be provided for, at minimum,

- *Initial installation and setup of equipment*
- *Normal operation of equipment*
- *Normal and/or preventative maintenance*
- *Troubleshooting guide for any anticipated potential malfunctions*

3.4.3. Documentation Numbering

All documents shall be numbered and identified in accordance with the LIGO documentation control numbering system LIGO document TBD

3.4.4. Test Plans and Procedures

All test plans and procedures shall be developed in accordance with the LIGO Test Plan Guidelines, LIGO document TBD.

3.5. Logistics

The design shall include a list of all recommended spare parts and special test equipment required.

4 QUALITY ASSURANCE PROVISIONS

4.1. Responsibility for Tests

TBD.

4.2. Quality conformance inspections

Design and performance requirements identified in this specification and referenced specifications shall be verified by inspection, analysis, demonstration, similarity, test or a combination thereof per the Verification Matrix, Appendix 1 (See example in Appendix). Verification method selection shall be specified by individual specifications, and documented by appropriate test and evaluation plans and procedures.