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AOS: Stray Light Control (SLC)-- Output Faraday Isolator Final Design

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Abstract

This document presents the Final Design for the Output Faraday Isolator (OFI), a component of the AOS Stray Light Control subsystem for aLIGO.

1 Introduction

1.1 Purpose

This document will present the Final Design for the Output Faraday Isolator (OFI), a component of the AOS Stray Light Control subsystem for aLIGO.

1.2 Scope

This document is based on the preliminary design document T0900269-v3_AOS_SLC_PDD. Some of the parameters, such as the wedge angles and orientations of the optical elements in the optical recycling cavities may have changed.

1.3 Supplemental Documents

T1000194-v1_SLC Hazard Analysis.doc

T1000192-v1_OFI test plan.doc

T1000193-v1_OFI production plan.doc

E1000099-v2_SLC-VP installation procedure.doc

1.4 Scattered Light Parameters

The IFO parameters that were used for the design of the OFI are listed in Table 1.

Table 1: IFO parameter values used for scattered light calculation

PARAMETER	VALUE
beam_radius_Faraday;	2.10E-03
IFO_beamwaist;	1.15E-02
lambda;	1.064E-06
IFO_solid_angle;	2.72E-09
dark_port_power;	1.35E-01
BRDF_Faraday	4.9200e-004

1.5 Stray Light Control Block Diagram

A block diagram showing the principal scattering sources of the AOS System, and the baffles and beam dumps is shown in Figure 1.

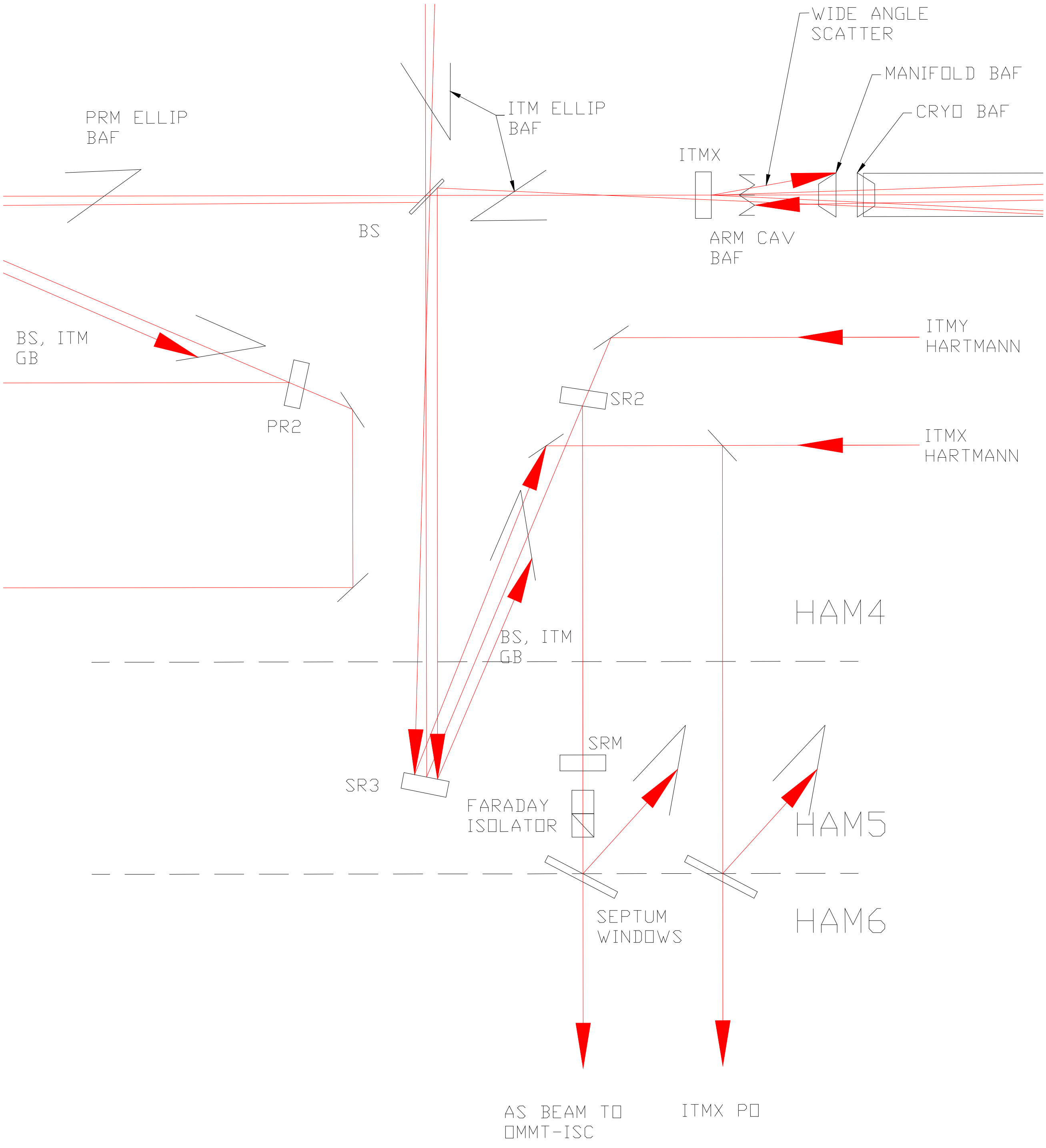

Figure 1: SLC System Block Diagram

The Output Faraday Isolator is located on HAM5 in H1 and L1, and on HAM11 in H2.

1.6 Definitions

1.7 Acronyms

AOS - Auxiliary Optics Support

AR - Antireflection mirror coating

AS - anti-symmetric port signal

HAM - Horizontal Access Module

HR – Hi-reflectance mirror coating

IFO - LIGO interferometer

IO - Input Optics

LIGO - Laser Interferometer Gravity Wave Observatory

mm – millimeter

mrad – milliradian

MTBF – mean time before failure

NA – not applicable

nm – nanometer

ppm - parts per million

PRM – Power Recycling Mirror

Q – quality factor

RH – relative humidity

rms - root-mean-square

rtHz – square root Hertz

SLC – Stray Light Control

SRM – Signal Recycling Mirror

SW – Solid Works

TBD - To Be Determined

W - Watt

1.8 Applicable Documents

1.8.1 LIGO Documents

1. E950111-A LIGO Naming Convention
2. E960022-B LIGO Vacuum Compatibility, Cleaning Methods and Qualification Procedures

3. L970061-00-D Guidance for Seismic Component Cleaning, Baking, and Shipping Preparation
4. M950046-F LIGO Project System Safety Management Plan
5. T040126-A Baffle Furnace Bake Procedure
6. MIL-C-104B
7. M060056-06 Advanced LIGO Reference Design
8. E990303-03 Seismic Isolation Subsystem Design Requirements Document
9. LIGO-T960065-03 Seismic Isolation Design Requirements Document
10. T010076-01 Optical Layout for Advanced LIGO
11. T060073-00 Transfer Functions of Injected Noise
12. T070061-00 AOS: Stray Light Control (SLC) Design Requirements
13. T080064-00 Controlling Light Scatter in Advanced LIGO
14. Robert Schofield (11/17/06 LHO ILOG)
15. T980027-00, Baffling Requirements for the 4K and 2K IFO
16. E980131-A, Component Specification, Faraday Isolator, 20 mm
17. T1000109-v1, aLIGO Output Faraday Isolator Suspension Prototype, Seismic Noise Attenuation Characterization
18. E1000116-v1 Output Faraday Isolator Rotator

1.8.2 Non-LIGO Documents

2 Catalog of SLC Design Requirements

The requirements for the SLC subsystem are derived in T070061-00 AOS: Stray Light Control (SLC) Design Requirements and are referenced below by paragraph number.

These are no changes to the requirements for the Output Faraday Isolator.

1. 4.2 Noise Requirements
2. 4.2.1 Direct Requirements
3. 4.2.2 Implied Requirement for Scattering Surfaces
4. 4.3 Faraday Isolator Requirements
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16. 4.8.11 Transportability
17. 4.8.11 Safety

3 Resolutions of Action Items From PDR

- **Analyze the vibrations and vibration isolation of each SLC component in all six DOF**

Scattered light displacement noise was calculated for all six DOF.

- **Use the seismic motion at LLO as the worst case**

The HAM ISI seismic data for LLO was used in the scattered light displacement noise calculations.

- **Use maraging steel C250 blade springs. Prototype a newly designed blade spring**

An OFI suspension prototype with C250 blade springs was tested.

- **Use sealed Pico Motor**

The sealed model Pico Motor will be used.

4 Risk Registry

The scattered light calculations were based on the pre-2010 LIGO FFT model of the signal recycled IFO. This model ignores the optical spring effect that occurs when the signal mirror is set to the resonant side-band extraction (RSE) configuration. This situation gave rise to the Risk item listed below.

RR-006: If optical spring effect in RSE is ignored in calculating the scattered light noise, then ADLIGO may not meet SRD.

According to Hiro Yamamoto, some of his other models indicate that this is not a serious problem, so the risk is considered to be low.

5 Final Specifications

5.1 Output Faraday Isolator Design Characteristics

The components from the Initial LIGO Faraday Isolators will be re-used and mounted on the suspended table.

A final Solid Works model of the Faraday Isolator suspension is shown in Figure 2. The optical components are isolated by a two-wire pendulum and by vertical blade springs. The suspended table is damped by an eddy current damping plate that mounts to the frame below the Faraday Isolator optical table.

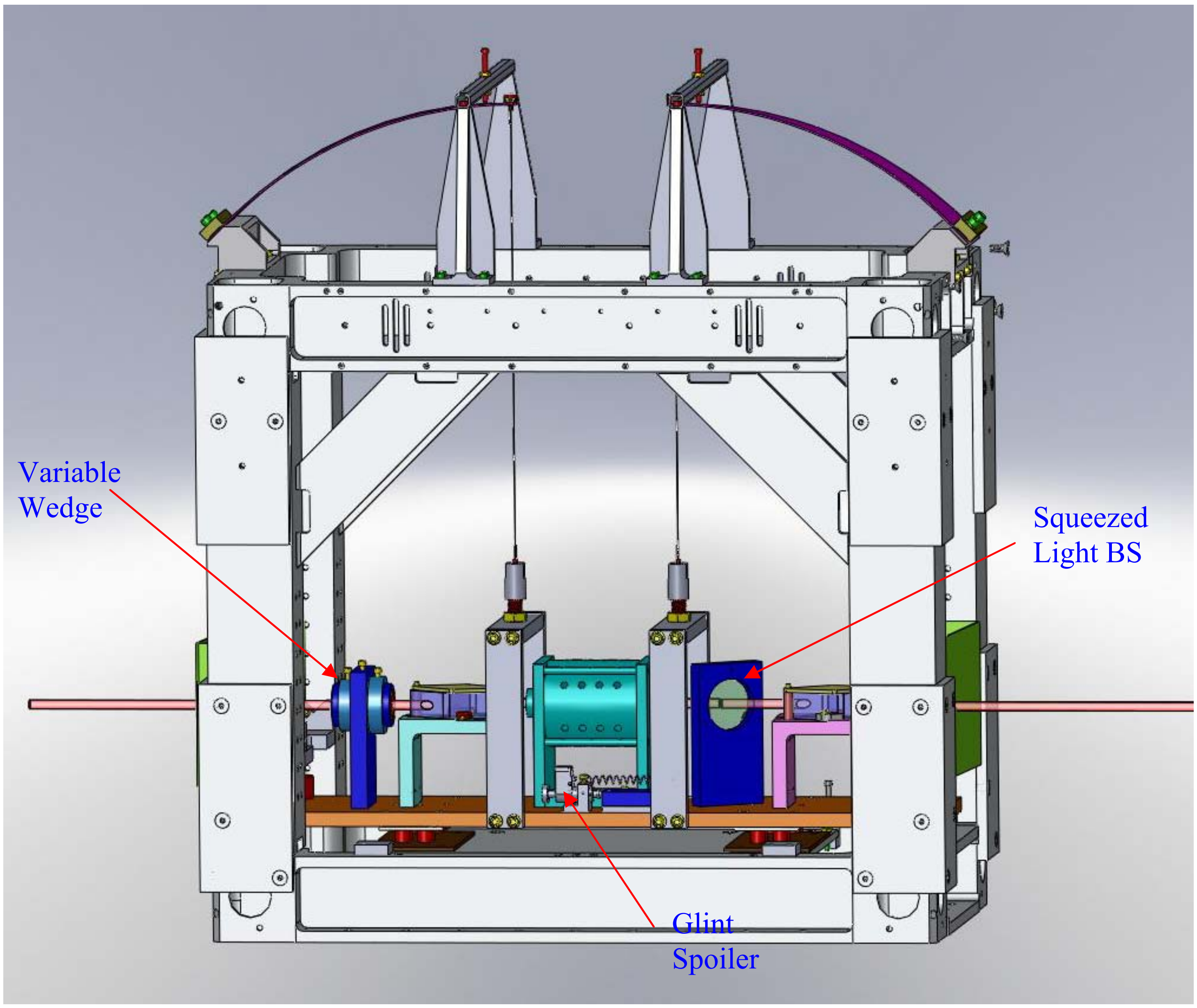

Figure 2: Suspended Faraday Isolator

5.1.1 Input Variable Wedge

Two counter-rotating wedges comprise a variable wedge at the input to the Output Faraday Isolator assembly. The variable wedge will deviate the tilted beam exiting the SRM into a horizontal beam at the first polarizing prism.

5.1.2 Squeezed Light Input Beam Splitter

A Brewster's angle beam splitter will enable injection of an external "squeezed light" beam into the AS port of the IFO.

5.1.3 Glint Spoiler

A remotely controlled Picomotor will provide a small amount of pitch motion to avoid a possible glint from the optical surfaces of the Faraday Isolator wedge surfaces into the AS port of the IFO.

5.1.4 Stay Clear Diameter

The clear aperture of the Faraday Isolator is 20 mm diameter. The AS Gaussian beam diameter at the output of the SRM is approximately 4 mm. The clear aperture of the Faraday Isolator will be pre-aligned within 2 mm of the beam centerline by referencing its position to the center of the ITM.

5.2 Physical Properties

Table 2: Faraday Isolator Characteristics

Parameter	**Value**
Configuration	Single Faraday isolator
Wavelength	1064 nm
Clear Aperture	20 mm
Rotator material	TGG crystal
Rotator crystal wedge angle front and back surface	0.5 deg
Total wavefront distortion	<1 λ @ 633 nm
Rotator transmissivity across clear aperture	>97 %
Input/output polarizer	Calcite, air-spaced Brewster's angle
Polarizer transmissivity per surface	>99.9 %
Half-wave rotation plate	Zero-order quartz

Table 3 : Faraday Isolator Suspension Characteristics

Parameter	Value
Frame	Identical to Output Mode Cleaner
Suspension	Two wire pendulum
Damping	Eddy current
Height adjustment	manual
Yaw adjustment	manual
Pitch adjustment	Remote, Pico Motor

5.3 Output Faraday Isolator Performance Characteristics

The estimated beam power incident on the OFI and the calculated scattered light power from the OFI into the SRM are listed in Table 4.

Table 4: Scattered Light Source, Incident Power and Scattered Power

SCATTERING SOURCE	INCIDENT POWER, W	SCATTERED POWER INTO IFO INJECTION POINT, W
Faraday	1.35E-01	2.71E-11

5.3.1 Faraday Isolator Forward Optical Transmissivity

The measured transmissivity of the Initial LIGO Output Faraday Isolator is 98%. The same optical elements will be re-used, and we expect the same performance.

This meets the requirement 4.3 Faraday Isolator Requirements.

5.3.2 Faraday Isolator Reverse Optical Transmissivity

The measured reverse power transmission of the Initial LIGO Output Faraday Isolator is < 0.0001. The same optical elements will be re-used, and we expect the same performance.

This meets the requirement 4.3 Faraday Isolator Requirements.

5.3.3 Scattered Light Displacement Noise of Output Faraday Isolator

The Seismic motion amplitude of each DOF at the OFI was estimated by attenuating the measured HAM-ISI seismic motion with the measured transmissibilities of the OFI suspension prototype. The component of this residual seismic motion along the OFI optical axis was used to determine the back-scattered light displacement noise. See T1000190-v1.

The displacement along the OFI optical axis caused by the angular DOFs was calculated by considering the relative coordinates of the OFI optics elements with respect to the rotational axis of the OFI suspension and of the HAM-ISI. The HAM-ISI rotational axes are assumed to go through the geometric center of the HAM-ISI optical table. The OFI suspension rotational axes go through the geometric center of the suspension rectangular platform.

Because of the assumption that all the wedge angles are horizontal, there is no coupling with DOFs that generate vertical translation of the OFI´s optics faces. The coupling caused by the wedges is therefore maximized in the horizontal DOFs that produce a translation along the OFI beam axis.

For each DOF, the contribution of each scattering surface is added linearly because of their common motion. The total scattered light displacement noise is estimated as the RMS sum of the contributions from each DOF.

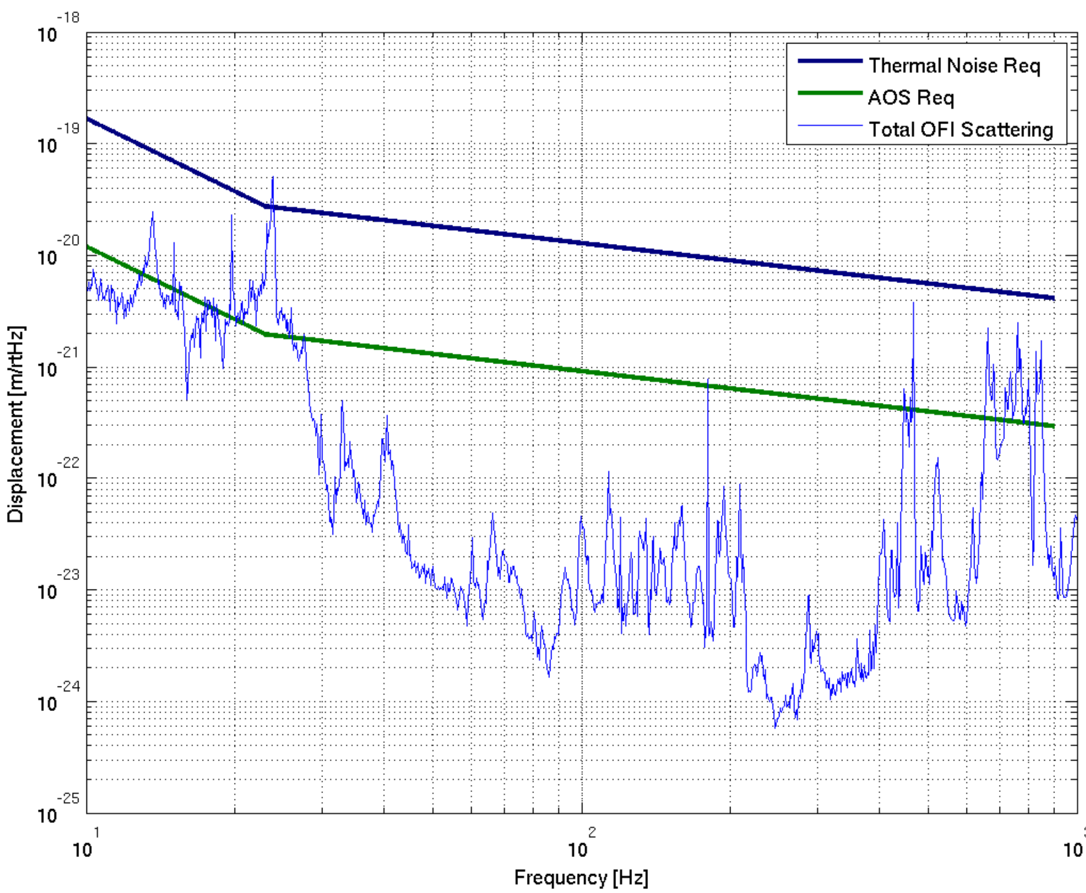

Figure 3: Scattered Light Displacement Noise from OFI

The noise peak around 25 Hz exceeds the thermal noise requirement; however, this noise peak is in the HAM-ISI data. Above 80 Hz, the displacement noise is over estimated due to acoustic coupling of ambient noise into the test structure and the sensors, and is probably an artifact of our measurement process.

6 Design Analysis and Engineering Test Data

6.1 Seismic Attenuation Transfer Functions

See T1000109-v1 for a description of the OFI suspension attenuation measurement.

Transmissibility measurements of the OFI suspension were made in three translational and three angular degrees of freedom (DOF), with various gaps between the magnets and the copper damping plate to determine the desired amount of eddy current damping. A typical result in the horizontal direction, along the beam axis, is shown below.

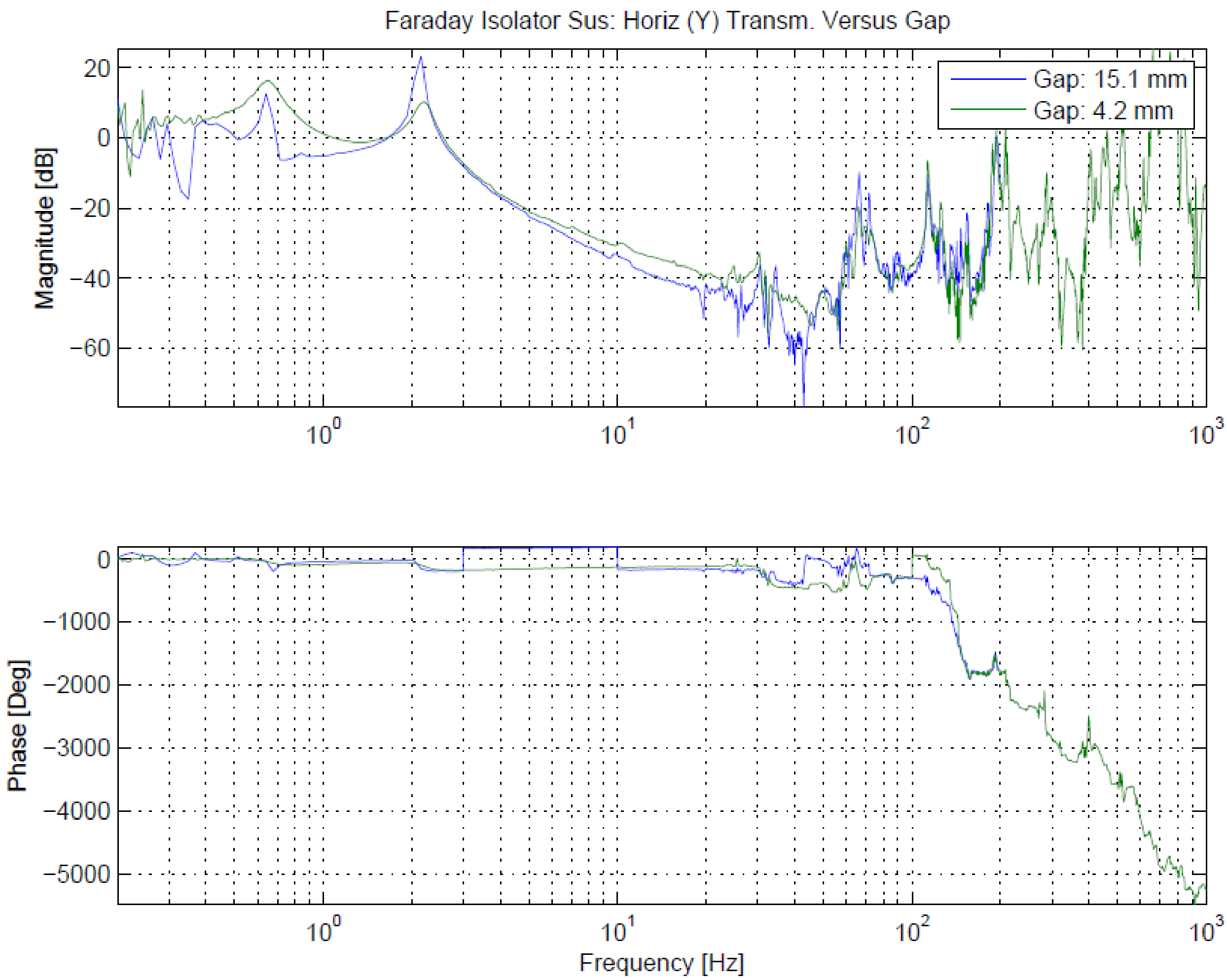

Figure 4: Output Faraday Isolator SUS Transmissibility along Beam Axis.

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6.2 Scattered Light Displacement Noise

6.2.1 BRDF of Faraday Surfaces

The TGG crystal and the wedge surfaces have specified surface roughness < 40 nm, which is considered to be a “super polished surface.” The TGG crystal surface is inclined at 0.5 deg, and the input wedge plate surfaces will be inclined by approximately 0.5 deg to avoid a glint into the IFO. The surface roughness of the Brewster’s angle prisms was not measured.

The backscatter BRDF of the S/N 2 pathfinder optic polished by CSIRO, at an incidence angle of 0.5 deg, is estimated from the measured BRDF data to be 5.6E-4 sr^-1; see T1000147—this would be representative of the TGG crystal and the input wedge plate scatter. The measured BRDF for backscatter from a super polished surface at 56 deg incidence angle is approximately 1E-6 sr^-1; see T080064-00 Controlling Light Scatter in Advanced LIGO—we will assume that the Brewster’s angle prisms have a conservative BRDF 5 E-4 sr^-1.

For purposes of calculating the scattered light displacement noise from the 9 optical surfaces of the Faraday Isolator, we assumed an average value for the BRDF = 5E-4 sr^-1.

6.2.2 HAM ISI Seismic Motion

The seismic motion of the HAM ISI optical table at LLO in the six DOF is described in T0900285-v1 and is shown below.

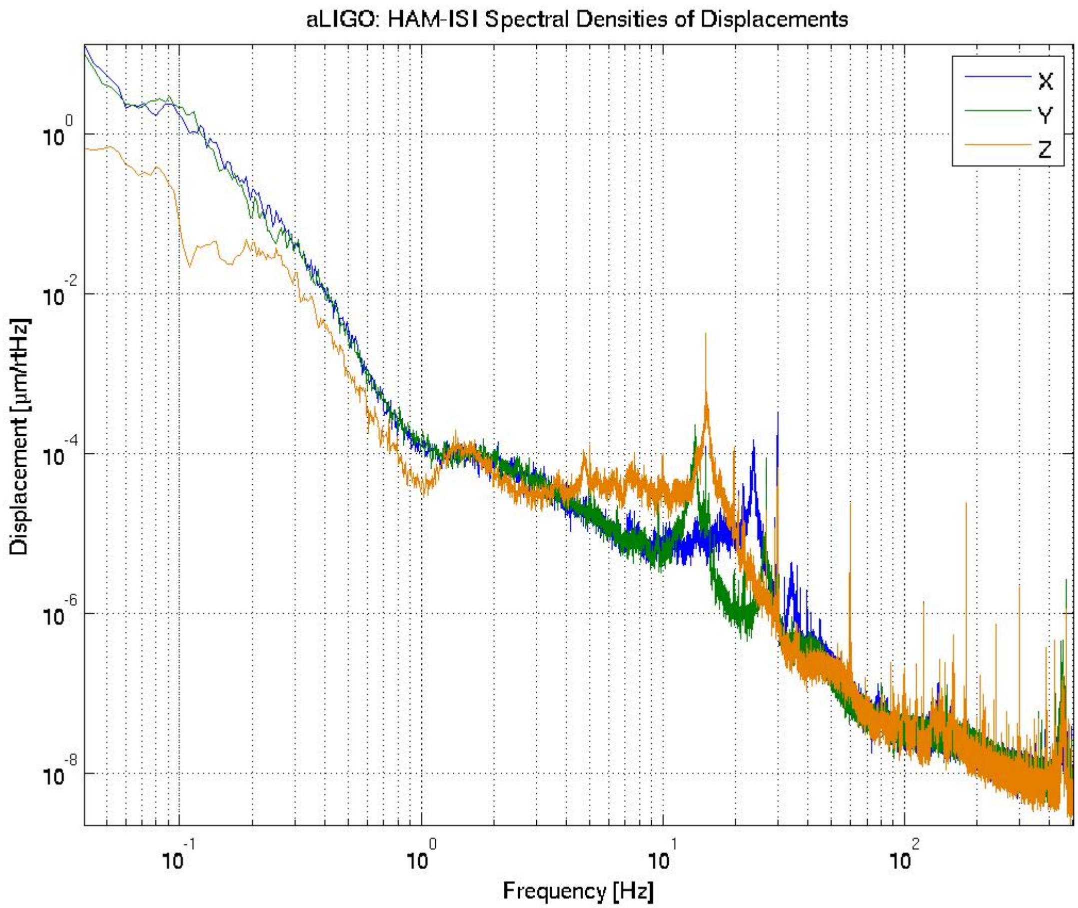

Figure 5: HAM optics table Seismic Motion, Horizontal DOF

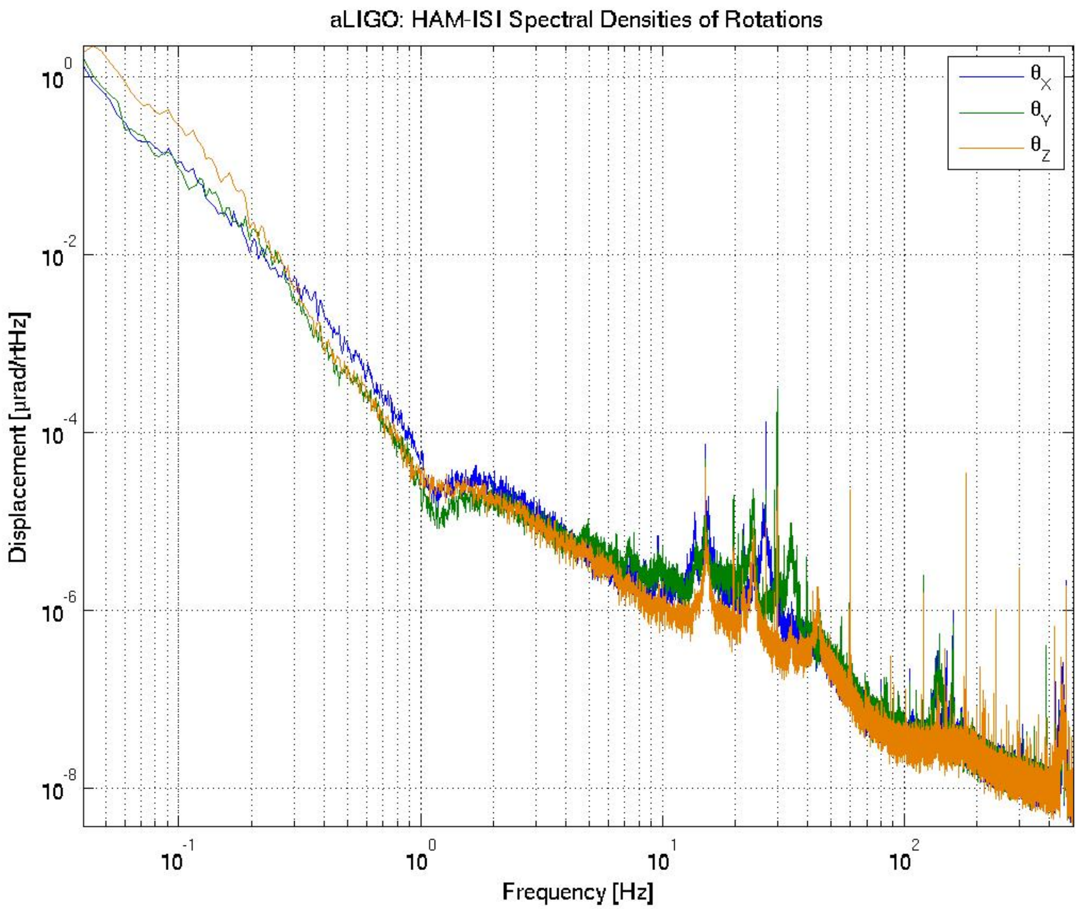

Figure 6: HAM optics table Seismic Motion, Rotational DOF

6.2.3 Motion along the Beam Direction

The optical surfaces of the OFI will scatter light back toward the antisymmetric port of the IFO with varying amounts of displacement noise depending upon the motion of the OFI.

The Output Faraday Isolator has four calcite prism surfaces and one TGG crystal surface on the entrance side. These surfaces are oriented horizontally and will couple X-motion and yaw motion to displacement along the beam direction.

The input wedges have both a horizontal wedge and a vertical and component that will also couple pitch motion and Z-motion into motion along the beam direction. For the purpose of this analysis, the input wedge angles were assumed to be horizontal.

The light scattered by the additional surfaces beyond the Faraday rotator magnet will be attenuated by the reverse transmissivity of the Faraday Isolator (T = 0.001) and will be ignored.

6.2.4 Scattered Light Displacement Noise Calculations

The results of the scattered light Displacement noise are shown below.

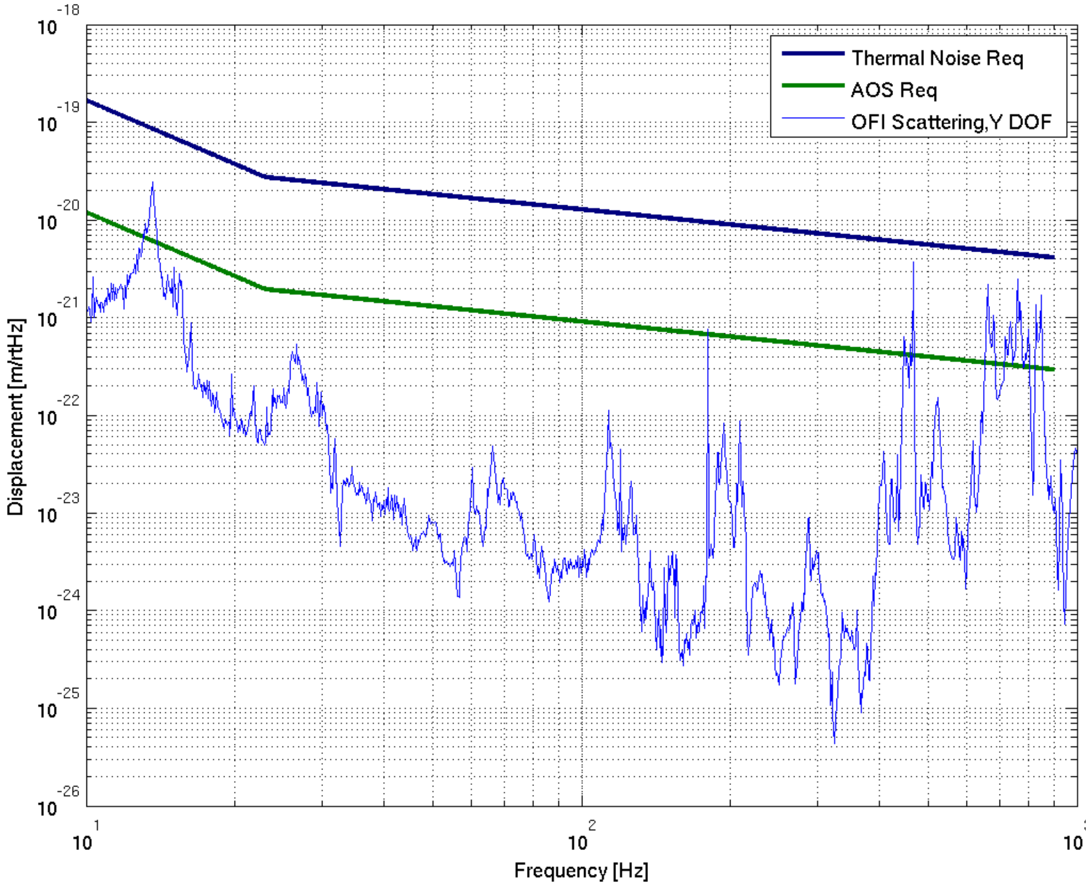

Figure 7: OFI Scattered Light Displacement Noise, Y DOF

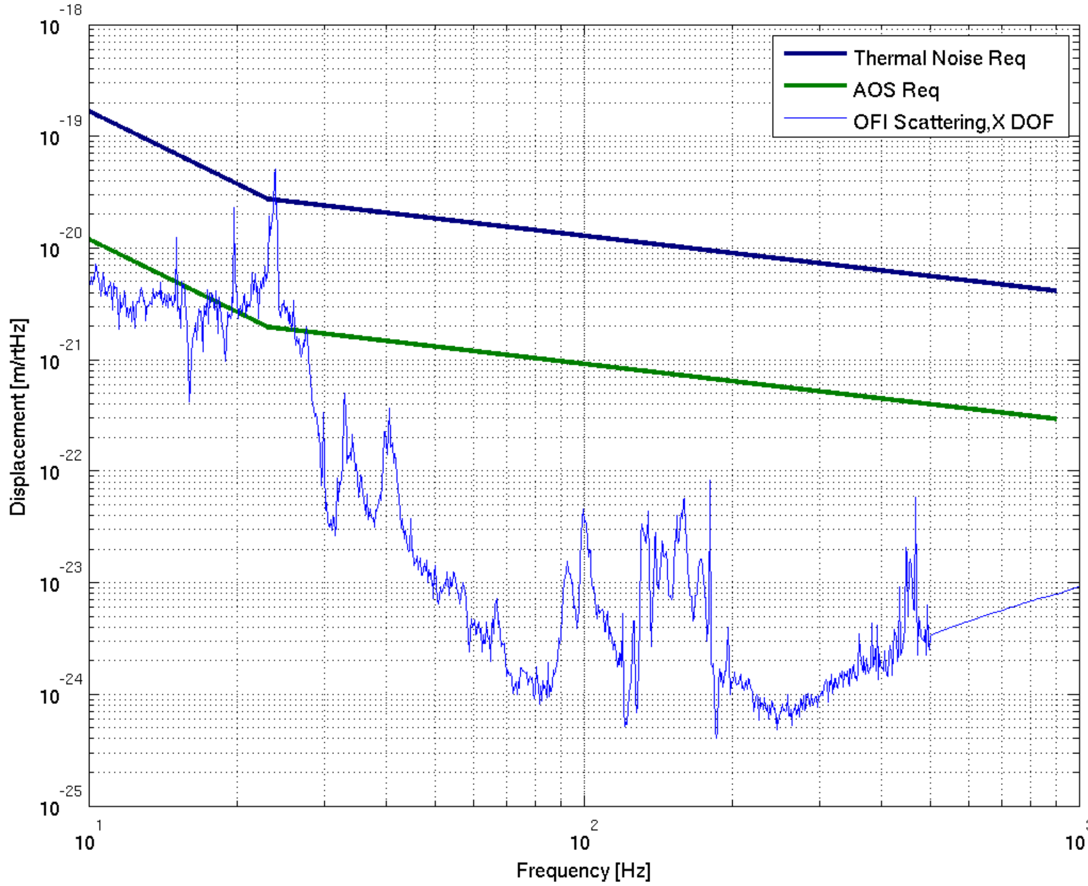

Figure 8: OFI Scattered Light Displacement Noise, X DOF

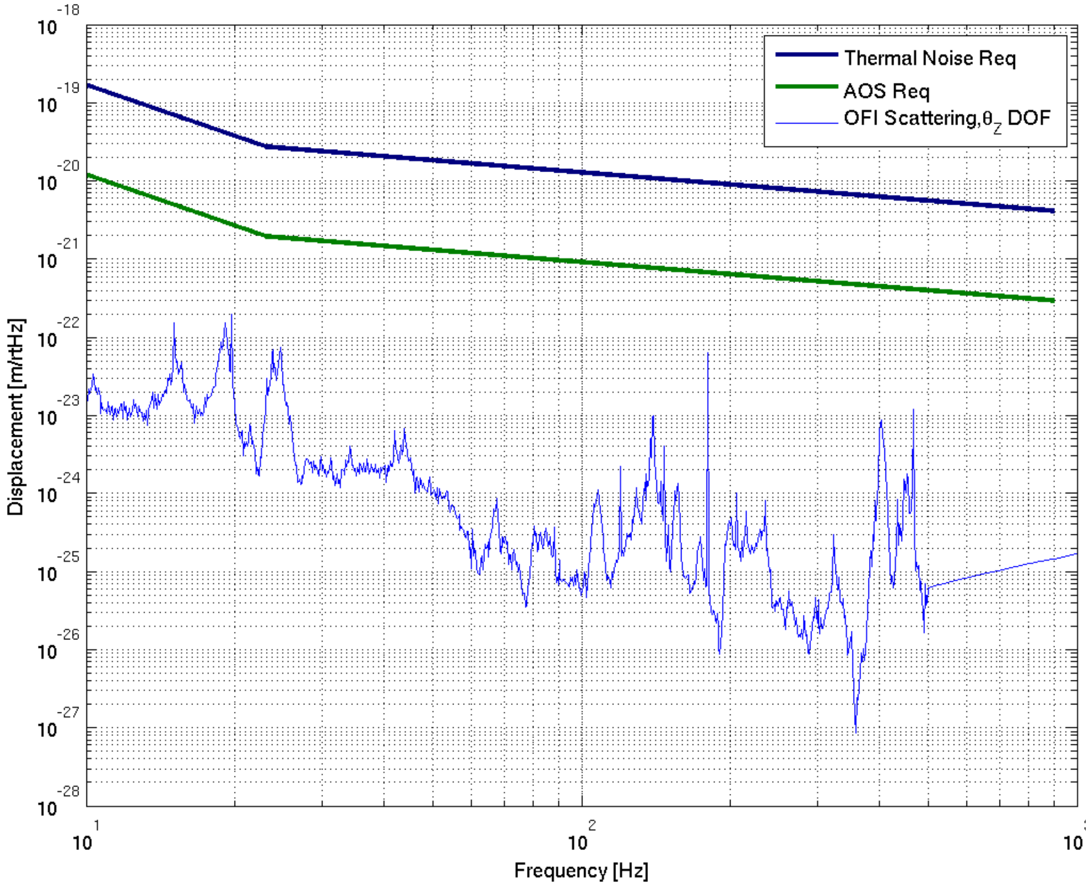

Figure 9: OFI Scattered Light Displacement Noise, Z-Rotation DOF

7 Interface Definitions

7.1.1 Interfaces to other LIGO detector subsystems

7.1.1.1 Mechanical Interfaces

The Faraday Isolator will mount directly to the HAM5, and HAM11 ISI optical tables.

7.1.1.2 Electrical Interfaces

A vacuum feedthrough in the HAM chamber will connect the control wires from the Pico Motor that is used for pitch steering of the Faraday Isolator to the external wiring.

The external wiring will connect to a removable Pico Motor controller circuit during the initial pitch alignment of the Faraday Isolator.

7.1.1.3 Optical Interfaces

The Output Faraday Isolator optical aperture will be centered on the output beam transmitted through the AR face of the SRM.

7.1.1.4 Stay Clear Zone

The clear aperture of the Faraday Isolator is 20 mm diameter. The Gaussian beam diameter at the output of the SRM is approximately 2.5 mm. The clear aperture of the Faraday Isolator will be pre-aligned within 2 mm of the beam centerline.

7.1.2 Interfaces external to LIGO detector subsystems

There are no interfaces external to the LIGO detector.

8 Reliability

The OFI is suspended by a passive two-wire suspension with vertical blade springs. The reliability should be excellent.

The only active device is the Pico Motor, which is used only during the initial alignment of the OFI. Its long-term reliability will not affect the overall reliability of the OFI.

9 OFI Maintainability

The following component is susceptible to failure:

1) Pico Motor.

If this component fails, the failure will be ignored until a major realignment of the beam path requires that the Output Faraday Isolator be realigned. At which time, an incursion into the vacuum chamber will be required, and the Pico Motor will be replaced.

10 Stray Light Control Environmental Conditions

10.1 Natural Environment

10.1.1 Temperature, Pressure, and Humidity

The OFI assemblies are designed to operate in the high vacuum environment of the IFO and in the controlled LVEA environment during installation.

Table 5 Environmental Performance Characteristics

Operating	Non-operating (storage)	Transport
+20C to +25C, 20-70% RH, non- condensing	0C to +60C, 10-90% RH, non-condensing	0C to +60C, 10-90% RH, non- condensing

10.1.2 Seismic Disturbance

The suspended OFI has adequate earthquake protection to withstand extraordinary ground seismic disturbances.

10.1.3 Induced Environment

10.1.3.1 Electromagnetic Radiation

NA

10.1.3.2 Acoustic

NA

10.1.3.3 Mechanical Vibration

NA

11 Stray Light Control Transportability

All components of the OFI are transportable by commercial carrier without degradation in performance.

12 OFI Design and Construction

The design and construction of the OFI allows adequate cleaning, and will fit inside the vacuum baking ovens on site.

12.1 Materials and Processes

The materials and processes used in the fabrication of the OFI are compatible with the LIGO approved materials list.

12.2 Component Naming

All components will be identified using the LIGO Naming Convention (LIGO-E950111-A-E).

12.3 Workmanship

All components will be manufactured according to good commercial practice.

12.4 Interchangeability

Common elements with ordinary dimensional tolerances will be interchangeable.

12.5 Assembly

Fixtures are available for assembly.

Installation fixtures will be developed. TBD

12.6 Logistics

The design includes include one spare OFI.

12.7 Precedence

The relative importance of the positioning of the OFI will be as follows:

Install and align the Core Optics first, then install and align the OFI.

12.8 Qualification

N/A

13 Safety

A hazard/risk analysis will be conducted in accordance with guidelines set forth in the LIGO Project System Safety Management Plan LIGO-M950046-F, section 3.3.2.

TBD

13.1 Stray Light Control Human Engineering

NA

14 Fabrication, Installation, and Test Schedule

TBD

15 Problems and Concerns

The OFI has the same optical properties as the OFIs installed in iLIGO, so the performance is predictable and acceptable.

The suspension structure has been tested and the transfer functions measured. Based on the measured data, the OFI will meet the scattered light displacement noise requirements.

The only long-lead-time fabrication component is the input wedge plate. This item will be ordered in a timely manner to meet the Oct 10, 2010 readiness date.

16 Quality Assurance Provisions

This section includes all of the examinations and tests to be performed in order to ascertain that the fabricated SLC elements conform to the requirements in section 3.

16.1 Vendor Certification

The vendors of optical components for the OFI will certify that the components meet the as-purchased specifications.

16.2 Faraday Rotator Test

EOT is required to make certain tests to verify the specification of the Faraday Rotator component. AOS will conduct final performance tests of the assembled OFI to verify that it meets the LIGO requirements.

16.2.1 Visual Surface Inspection Test

Both faces of the TGG crystal shall be free of visible stains and surface defects when the window is illuminated with a high-intensity light source and viewed in a darkened environment with the unaided eye.

16.2.2 Extinction Ratio Test

Extinction ratio between crossed polarizers for orthogonal polarizations shall be measured, using the test light source.

16.2.3 Optical Transmissivity Test

Optical transmissivity through the clear aperture shall be measured with the test light source.

16.2.4 Test Light Source

A collimated laser beam of 1064 nm wavelength and > 9.0 mm Gaussian beam waist diameter measured at the 1/e^2 power diameter shall fill the clear aperture when making transmissivity and extinction ratio measurements.

16.2.5 Wavefront Distortion Test

The transmitted wavefront distortion over the clear aperture shall be measured at 632.8 nm wavelength with an appropriate interferometer.

16.3 Configuration Management

Configuration control of specifications and designs will be in accordance with the LIGO Detector Implementation Plan.

16.4 Quality conformance inspections

Design and performance requirements identified in this specification and referenced specifications will be verified by inspection, analysis, demonstration, similarity, test or a combination thereof.

Verification of compliance to the requirements of this and subsequent specifications will be accomplished by the following methods or combination of methods:

16.4.1 Inspections

Manufactured parts with LIGO identification numbers or marks will be inspected to determine conformity with the procurement specification.

Witness samples will be acceptable proof of the properties of HR and AR coatings applied to the optical surfaces.

16.4.2 Demonstration

The required attenuation and transmissivity characteristics of the assembled OFI will be demonstrated before installation.

The resonance and damping characteristics of the suspended beam dumps and baffles will be demonstrated before installation.

17 Preparation for Delivery

Packaging and marking of equipment for delivery will be in accordance with the Packaging and Marking procedures specified herein.

17.1 Preparation

- Vacuum preparation procedures as outlined in E960022-B LIGO Vacuum Compatibility, Cleaning Methods and Qualification Procedures will be followed for all components intended for use in vacuum. After wrapping vacuum parts as specified in this document, an additional, protective outer wrapping and provisions for lifting shall be provided.
- Electronic components will be wrapped according to standard procedures for such parts.

17.2 Packaging

Procedures for packaging will ensure cleaning, drying, and preservation methods adequate to prevent deterioration, appropriate protective wrapping, adequate package cushioning, and proper containers. Proper protection will be provided for shipping loads and environmental stress during transportation, hauling and storage. The shipping crates used for large items will use for guidance military specification MIL-C-104B, Crates, Wood; Lumber and Plywood Sheathed, Nailed and Bolted. Passive shock witness gauges will accompany the crates during all transits.

For the viewports, the shipping preparation will include double bagging with Ameristat 1.5TM plastic film (heat sealed seams as practical, with the exception of the inner bag, or tied off, or taped with care taken to insure that the tape does not touch the cleaned part). The bag will be purged with dry nitrogen before sealing.

17.3 Marking

Appropriate identification of the product, both on packages and shipping containers; all markings necessary for delivery and for storage, if applicable; all markings required by regulations, statutes, and common carriers; and all markings necessary for safety and safe delivery will be provided.

Identification of the material will be maintained through all manufacturing processes. Each component will be uniquely identified. The identification will enable the complete history of each component to be maintained (in association with Documentation “travelers”). A record for the optical lever support structures will indicate all weld repairs and fabrication abnormalities.

The specification for marking will state that marking fluids, die stamps and/or electro-etching is not permitted. A vibratory tool with a minimum tip radius of 0.005" is acceptable for marking on surfaces that are not hidden from view. Engraving and stamping are also permitted.