LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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Input Optics Test Plan

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Detector

This is an internal working note
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1 INTRODUCTION

1.1. Purpose

The purposes of this document are to define the contents and scope of the Input Optics subsystem (IOO) test plan, based on the design requirements for the IOO.

The principal intended audience for this document is the LIGO Detector team.

1.2. Scope

The principal function of the IOO test plan is to define top-level test requirements insofar as practical using the IOO as a stand-alone system. This document is intended to cover a test plan for all of the IOO subsystems, including the RF modulation, mode cleaner, interferometer mode matching, optical isolation, and all of the functional components of each subsystem. Although the IOO has multiple interfaces with other subsystems, this document does not address tests which relate to global system testing.

1.3. Applicable Documents

1.3.1. LIGO Documents

1.3.1.1 IOO

- *Input Optics Design Requirements*, J. Camp, D. Reitze, and D. Tanner, LIGO-T960093-02-D
- *Input Optics Conceptual Design,* J. Camp, D. Reitze, and D. Tanner, *LIGO-T960170-00-D*
- *Input Optics Final Design,* Rana Adhikari, Aaron Bengston, Yasha Buchler, Tom Delker, David Reitze, Qi-Ze Shu, David Tanner, Sanichiro Yoshida, *LIGO-T980009-01-D*
- Design Considerations for LIGO Mode-Matching Telescopes, T. Delker, R. Adhikari, S. Yoshida, and D. Reitze, *LIGO-T970143-00-D*
- *Mode Matching Wavefront Sensor,* Qi-Ze Shu, Rana Adhikari, David Reitze, David Tanner, *LIGO-T980021-00-D*
- *Mode Cleaner Noise Sources,* J. Camp, *LIGO-T960164-00-D*

1.3.1.2 Other Relevant Documents

- *Mode Cleaner Length/Frequency Control Design,* P. Fritschel, N. Mavalvala, D. Ouimette, LIGO-T970218-01-D
- *IO Mode Cleaner Wavefront Sensing and Control*, N. Mavalvala, LIGOT970098-01-D
- *(Infrared) Pre-Stabilized Laser (PSL) Conceptual Design,* R. Abbott, P. King, R.Savage, S Seel, *LIGO-T970087-00-D*
- *(Infrared) Pre-Stabilized Laser (PSL) Design Requirements,* R. Abbott, P. King, R.Savage, S Seel,*LIGO-T970080-09-D*
- *Small Optics Suspensions Final Design,* S. Kawamura, *LIGO-T970135-02-D*
- *Frequency Stabilization in LIGO,* J. Camp, LIGO-T0165-00-D

- *Optical Vernier Method for in-situ Measurement of of the Length of Long Fabry-Perot Cavities*, M. Rakhmanov, M. Evans, and H. Yamamoto, LIGOT98xxxx.
- *Misalignment - Beam Jitter Coupling in LIGO*, P. Fritschel, LIGO-T960120-00-D

1.3.2. Non-LIGO Documents

2 GENERAL DESCRIPTION

See Input Optics Design Requirements Document and Input Optics Final Design Document

3 REQUIREMENTS

3.1. Introduction

3.2. Performance Characteristics

3.2.1. Overall IOO requirements

3.2.1.1 Optical efficiency of Input Optics

The net efficiency of IOO 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.

TESTS:

- Calibrated power measurements and laser beam profiler measurements at the input of the IOO and at the input to the mode matching telescope (directed out of vacuum via steering mirror to IOT7).
- Separate measurements of reflectivity subsequent to vacuum installation to account for loss.
- Final verification of TEM_{00} coupling will be measured using the bullseye diode on the locked IFO.

DOCUMENTATION:

- Normalized power measurements
- Table of in-vacuum mirror optical properties
- Beam profile measurements
- Bullseye measurement results

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

TEST:
- Quadrant photodiode and spectrum analyzer, mounted on IOT7 table, at two distances from output of mode cleaner; to meet requirements OR to be shot-noise limited at 10 mA of photocurrent per segment whichever is more lax.

DOCUMENTATION:
- Jitter noise spectrum plots

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.

TEST:
- Excite a mirror using a PZT buzzer and measure error signal at dark port

DOCUMENTATION:
- Error signal

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 depending on PSL/IOO testing of allowed back propagating power levels at which PSL reacts).

TEST:
- Measurement of the back-reflected power in the orthogonal polarization channel from the in vacuum FI and at input to the IOO (or before the Faraday isolator in the PSL)

DOCUMENTATION:
- Certification

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.

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

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) must be passed by the mode cleaner and therefore be integral multiples of the mode cleaner free spectral range.

TEST:
- Modulation frequencies set by CDS RF oscillators
- Measurement of the mode cleaner FSR
- OSA measurements of the transmitted mode cleaner light to verify transmission.

DOCUMENTATION
- Mode cleaner FSR
- OSA power spectra

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.

TEST:
- RF drive voltage set properly by CDS
- Optical spectrum analyzer measurements of the light on the PSL table.

DOCUMENTATION
- OSA power spectrum plots

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.

TEST: Cross products will be present on the light due to serial modulation at up to an amplitude level of $\sim 6 \times 10^{-3}$ for some cross products. Only a few of them are admitted to the recycing cavity (at an amplitude $< 10^{-7}$).
- Optical spectrum analyzer measurements of the light on the PSL table, after MC.

DOCUMENTATION
- OSA power spectrum plots

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 < 100 Hz.[1]

1. Mode Cleaner Noise Sources, LIGO-T0164-00-D

TEST:

- Demodulated RF photodiode signal of the amount of excess intensity noise on transmitted MC light induced by a laser frequency dither on the input light to the MC. To be shot noise limited at maximum photocurrent.

DOCUMENTATION:

- Certification

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

TEST:

- Use the mode cleaner error signal to measure the noise as limited by that sensing system.

DOCUMENTATION:

- MC LSC closed loop gain measurements

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.

TEST:

- See P. Fritschel, "Mode Cleaner Installation and Test Plan", LIGO T99xxxx, Section 1.6.1

DOCUMENTATION

- MC LSC closed loop gain measurements.
- Power spectra of MC LSC electronics 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

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1. Frequency Stabilization in LIGO, LIGO-T0165-00-D
2. Mode Cleaner Noise Sources, LIGO-T0164-00-D

TEST:

- Measure intensity noise using a photodiode at max. allowed photocurrent and audio spectrum analyzer.

DOCUMENTATION:

- Intensity noise spectrum

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[1]: $\varepsilon_1 < 3.5 \times 10^{-9} / \mathrm{Hz}^{1/2}$
- Attenuation of all other modes by a similar factor (TBD SYS)
- No frequency degeneracy of spatial modes with the fundamental up to mode 15

TEST: Similar to Section 3.2.1.2

- Quadrant photodiode and spectrum analyzer, mounted on IOT7 table, at two distances from output of mode cleaner; to meet requirements OR to be shot-noise limited at 10 mA of photocurrent per segment whichever is more lax.

DOCUMENTATION:

- Jitter noise spectrum analyzer plot

3.2.3.5 Mode Cleaner Alignment

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

TEST:

- Quadrant photodiode on IOT7 to measure output from MC after calibrated dither of PZT in tip/tilt of the MC alignment mirror

DOCUMENTATION:

- Transfer function θ_{in}/θ_{out}

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.[3]

TEST:

- Dither MC1,2,3 and measure MC LSC output error signal

DOCUMENTATION:

- Certification

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1. Misalignment - Beam Jitter Coupling in LIGO, LIGO-T960120-00-D
2. see (2) above
3. ASC DRD, LIGO-T952007-03-I

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

TESTS:

- Lock Acquisition: statistics (~10 cycles) for the time to lock the system from cold start and from warm start.
- Stored Light Intensity: DC PD input power monitor; periodic cavity ringdown measurements.

DOCUMENTATION:

- Lock acquisition statistics
- MC finesse

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:

- $\sim 10^{-3}$ $TEM_{01,\,10}$
- $\sim 10^{-3}$ all higher order modes

TEST: For fully locked IFO

- $TEM_{01,\,10}$: ASC alignment signals for locked IFO
- $n + m = 2$: Bullseye mode matching measurement
- all other modes: ASC camera monitoring of RM, ITM, ETM

DOCUMENTATION:

- Bullseye data after final repositioning of the MMTs

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).[1] 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

TEST:

- Low Frequency: ASC IFO control signals from WFS on ISC7.
- In-band: Quadrant photodiode and spectrum analyzer, mounted on ISC7 table for monitoring light back reflected from the RM (unlocked IFO), at two distances from RM to be shot noise limited at10 mA photocurrent

DOCUMENTATION:

- Jitter spectrum

1. 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
- 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

TESTS AND DOCUMENTATION: Measurements of

- complete servo loop transfer function measurements
- servo electronic noise and null offsets: See P. Fritschel, "Mode Cleaner Installation and Test Plan", LIGO T990125, Section 1.6.1
- photodiode sensitivity and noise for all IOO sensors
- mode cleaner storage time
- IOO response to laser light pointing, frequency and intensity modulation - see above tests
- open loop mode cleaner mirror seismic excitation: Monitor control input voltage to (summed) coil actuators using spectrum analyzer
- variation in RF sideband modulation depth: optical spectrum analyzer on IOT7
- variation in IFO mode matching efficiency: periodic bullseye measurements
- sideband detuning from mode cleaner