LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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Detector Subsystems Requirements			
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LIGO Detector and LIGO Systems Engineering

This is an internal working note
of the LIGO Project.

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1 INTRODUCTION

1.1. Purpose

This Detector Subsystems Requirements Document (DRD) is intended to establish the requirements flowdown and noise budget for the initial LIGO Detector.

1.2. Scope

This Subsystems Requirements Document (DRD) details the requirements imposed on LIGO Systems Integration by the science goals and engineering constraints of the LIGO project, and contains specifics of how these requirements relate to the design and construction of the first Detector to be installed in LIGO. It also establishes uniform requirements for materials handling, reliability, and testing. A top-level conceptual design of the interferometer is given to give substance to the requirements.

1.3. Definitions

1.3.1. DETECTOR SUBSYSTEM DIVISIONS, TOP-LEVEL CONCEPTUAL DESIGN

The subsystems are as follows:

- Pre-Stabilized Laser (PSL), consisting of
  - a cw Nd:YAG solid-state laser with a wavelength of 1.06 μ m, single frequency and spatial mode
  - self-contained frequency and intensity pre-stabilization; inputs are provided for external higher-sensitivity sensors later in the interferometer, and for commissioning and initial alignment states (modulation, intensity reduction)
  - any light conditioning to meet spatial mode quality and RF intensity noise requirements
- Input Optics Optics (IOO): The optics, suspensions, and control systems between the PSL and the Core Optics Components and Support with these principal components:
  - a suspended-mirror resonant-cavity mode cleaner used in transmission to filter the light spatially and temporally, and to provide a frequency reference for further stabilization of the laser frequency
  - the application of phase modulation to the light which is used for the Length and Alignment readout
  - the gaussian mode-matching of the light to the mode supported by the Core Optics
- Core Optics Components (COC): The principal interferometer optical components and suspensions. The basic configuration is a Michelson interferometer with Fabry-Perot cavities in the arms. It employs power recycling The components are:
  - beamsplitter (BS)
  - input test masses (ITM)
  - end test masses (ETM)

  - power recycling mirror (RM)
- Core Optics Support (COS): Handling of the light beams from the COC:
  - baffling of stray light within the vacuum envelope
  - control/extinction of ghost beams from COC wedged surfaces
  - the optics to relay the light out of the interferometer to the detectors, including the principal output optics
  - internal relay optics and viewports for monitoring the light in the interferometer
- Seismic Isolation (SEI): All seismic isolation and support systems between the civil construction facility interface and the Suspensions.
  - in-vacuum passive multi-stage seismic isolator
  - actuators external to the vacuum to complement the suspension actuators.
- Suspensions (SUS): The suspensions for optics. The suspensions deliver pendulum isolation, are designed to limit thermal noise from the pendulum and from the internal modes of the test masses, and provide translational and angular freedom for the test masses. Actuators based on permanent magnets attached to the test masses and coils fixed to the suspension structure control these degrees of freedom to maintain the interferometer operating point (resonance of cavities, Michelson path length difference). There are three types of suspensions:
  - LOS1: carries test masses, recycling mirror, folding mirrors, some components in IOO
  - LOS2: carries the beamsplitter
  - SOS: most components in IOO
- Length Sensing/Control (LSC): The control system for acquiring and maintaining the operating lengths (resonance, ‘lock’) for the interferometer. The operational mode uses RF phase-modulated light and synchronous demodulation to obtain information on the lengths; feedback signals are applied to the test masses (via the Suspension actuators), and to the Pre-Stabilized Laser and IOO Mode Cleaner. An asymmetry in the Michelson interferometer and a common-mode modulation (‘Schnupp’ modulation) are used to read out the GW signal.
- Alignment Sensing/Control (ASC): The control system for acquiring and maintaining the operating alignment for the Core Optics and the IOO Mode Cleaner. The operational mode uses RF phase-modulated light and synchronous demodulation to obtain information on the angles; feedback signals are applied to the suspension actuators. All monitoring of light powers and spatial mode matching in the interferometer is carried by ASC.
- Physics Environmental Monitor (PEM): All monitoring of the environment, with the objective of providing veto and regression information. Also provides means of excitation of the interferometer to measure coupling from the environment to the interferometer output. This system is independent of the optical interferometer.
- Control and Data System (CDS): The software and electronic hardware for the interferometer:
  - the communications and data processing backbone
  - the control and monitoring system
  - the data acquisition and interferometer diagnostics
  - the vacuum controls
  - the interferometer subsystem electronics and control systems

1.3.2. Detector Performance Requirements Flowdown

The performance of LIGO detectors is characterized in three ways:

- by the strain sensitivity specified as a power spectral density, or PSD, which is most directly related to the detection of periodic or semi-periodic sources of gravitational radiation. This is used to characterize stationary, and quasi-stationary, noise sources.
- by the strain sensitivity specified as a pulse height distribution, which is relevant for the detection of burst sources (and is composed of a gaussian and a non-gaussian distribution)
- by the *availability*, or fraction of the time that the detector is operating at the specified level of sensitivity. Both the ratio of operating to non-operating time, and the duration of continuous operation, are specified.

The Science Requirements Document E950018-00 (SRD) sets these performance criteria. The requirements flowdown converts these performance requirements to design constraints on the subsystems, via models of noise propagation, experimental results, and engineering estimates of performance.

1.3.3. Frequency Ranges

These are definitions of frequency ranges to give consistency to discussions.

- Drift: $f < 0.1$ Hz
- Control: $0.1 < \; < 40$ Hz
- GW signal band: $40 < \; < 10^4$ Hz
- Above GW signal band: $10^4 < \; < 10^6$ Hz
- RF band: $10^6 < \; < 10^8$ Hz

1.4. Acronyms

ASC: Alignment Sensing/Control

BS: BeamSplitter

CC: Civil Construction

CDS: Control and Data System

COC: Core Optics Components

COS: Core Optics Support

Det: Detector (as system)

DRD: Design Requirements Document

DSR: Detector Subsystems Requirements (document)

ETM: End Test Mass

FM: Folding Mirror

FMCS: Facilities Monitoring and Control System

IOO: Input/Output Optics

ITM: Input Test mass

LSC: Length Sensing/Control

LIGO: Laser Interferometer Gravitational-wave Observatory

PEM: Physics Environmental Monitor

PSL: Pre-Stabilized Laser

RM: Recycling Mirror

SEI: Seismic Isolation

SRD: Science Requirements Document

SUS: Suspension

SYS: Detector Systems Engineering

VE: Vacuum Equipment

1.5. Applicable Documents

The most recent revision of these documents should be used. For LIGO Detector documents, it is the individual author's responsibility to bring any conflicts or changes to the attention of the person maintaining this document (the Detector Subsystems Requirements Document, or DSR). The DSR takes precedence over the detector subsystems documents, including the Design Requirement Documents.

1.5.1. Internal LIGO documents

- Science Requirements Document E950018-00 (SRD)

Interferometer Design Requirements Documents (DRD):

- ASC DRD T952007
- CDS Control and Monitoring DRD T950054
- CDS Data Acquisition T960009
- CDS Interferometer Diagnostics T960107
- COC DRD E950099
- COS DRD TBD
- IOO DRD T960093
- LSC DRD T960058

- PEM DRD T960127
- Argon PSL DRD T950030; to be updated with YAG PSL DRD
- SEI DRD T960065
- SUS DRD T950011

Interface documents:

- Interface consistency between subsystems, Sievers T950110 and attached Interface documents
- Interface control document, LIGO System and Detector—Civil Construction, Coyne E950090

Documents relating to the environment:

- Measurement of Optical Path Fluctuations due to Residual Gas in the LIGO 40 Meter Interferometer, Zucker et al. P940008
- Issues and considerations on the beam tube bake, Weiss T960124
- Beam Tube Qualification Test, Weiss T960125
- Document on narrow-band disturbances
- Derivation of CDS Rack Acoustic Noise Specifications, Lazzarini T960083
- Vibrational and Acoustic Requirements for the LIGO Facilities, Lazzarini L950238; Estimates for Motions due to Sound Fields, Weiss 16.02.95
- Vacuum Equipment Specification (LIGO-E940002), amended in the final contract, PC145730, section 4.6
- A. Rohay, *Ambient Ground Vibration Measurements at the Hanford, Washington LIGO Site* (C950572). Livingston-site report in preparation.
- EMI Control plan and procedures, Systems Engineering E960036

Documents relating to mirror displacement:

- A Passive Isolation Stack for LIGO, Giaime T962005
- Note on Electrostatics in the LIGO suspensions, Weiss 6 June 95
- Magnet size considerations; interference and coil power dissipation, Zucker T960126
- ASC: Environmental Input to Alignment Noise, Gonzalez T960103
- Response of pendulum to motion of suspension point, Kawamura T960040
- Cross-coupling in the suspension controllers, Fritschel L960596
- Comparison of forces and torques from feedback servos for LSC and ASC, Gonzalez servo.fm (needs DCC#)
- Radiation Pressure Noise in LIGO, Camp/Yamamoto T960128

Documents relating to phase noise:

- Nd+3 Laser Specifications, Abramovici/Shoemaker E950081
- Frequency, Intensity and Oscillator Noise in the LIGO, Camp T960019
- Shot noise sensitivity of the length control error signals, Fritschel T960042
- Proposed initial detector MC and RC baseline lengths, Zucker T960122
- Length Control RMS Deviations from Resonance, Camp T960067
- Misalignment-Beam Jitter Coupling in LIGO Fritschel T960120
- Spatial Uniformity of Silicon Photodiodes, Lantz T952007
- COC Surface Radii Tolerances DRAFT, Kells T960144
- Numerical thermal analysis of complicating factors of optics... (SURF Report) Coyne/Djambazov DCC#

Documents relating to materials preparation:

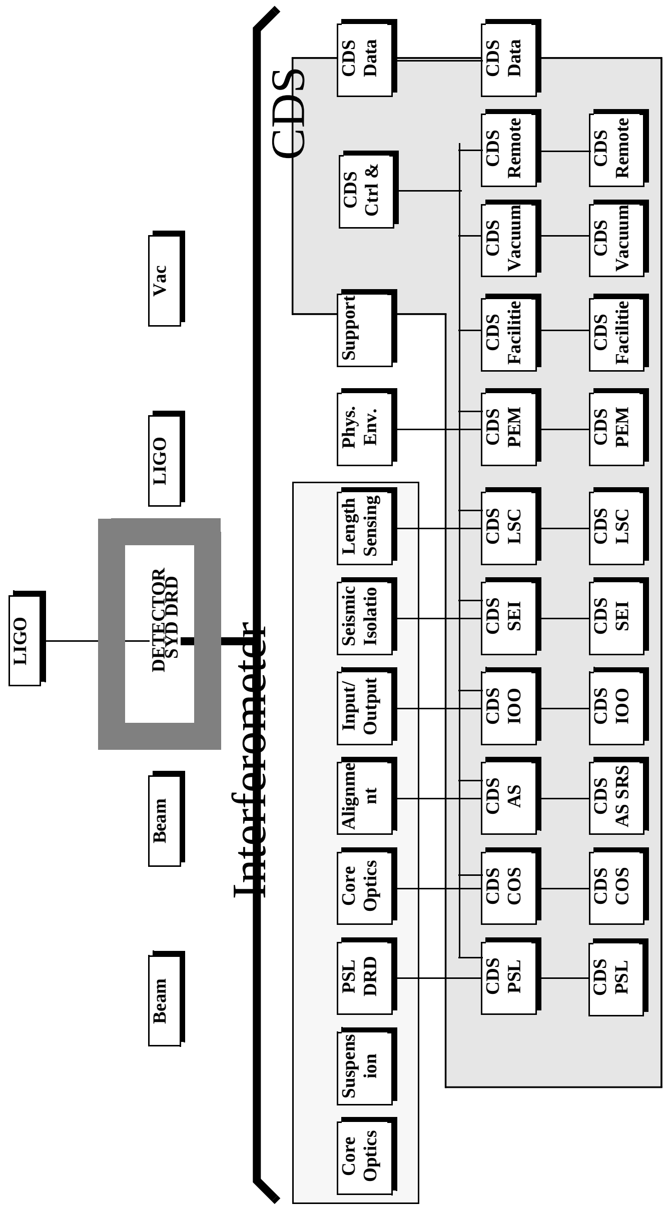
- LIGO Vacuum Compatibility, Cleaning Methods and Qualifications Procedures, Young E960022
- LIGO Vacuum Compatible Materials List, Young E960050

1.5.2. NON-LIGO DOCUMENTS

- J.-Y. Vinet, P.Hello, C.N. Man and A.Brillet, J. Phys. France, Vol.2, pp.1287-1303 (1992). “A high accuracy method for the simulation of non-ideal optical cavities”
- ‘Non-stationary shot noise and its effect on the sensitivity of interferometers’, Niebauer et al., Phys Rev A 43 (1991) 5002
- mirror heating and impact on interferometers, Winkler et al., Phys Rev.

2 GENERAL DESCRIPTION

2.1. Specification Tree



2.2. Product Perspective

The SYS activity supplies all of the subsystems with their performance requirements, and that flowdown is the topic of this document. PEM has little (or no) connection to the other interferometer subsystems to ensure that it give an independent measure of the environment; it can make a limited set of measurements independent of CDS (local recording) but relies on the Data Acquisition System for normal operation. LSC and ASC carry the principal sensing and control systems in the interferometer, and thus have rich interfaces with the other subsystems. CDS plays a special role as an interconnector between subsystems. The arrows indicate the flow of requirements. Figure 2 shows a crude block diagram of the interferometer with the principal signal flows, interfaces, and physical relationships indicated.

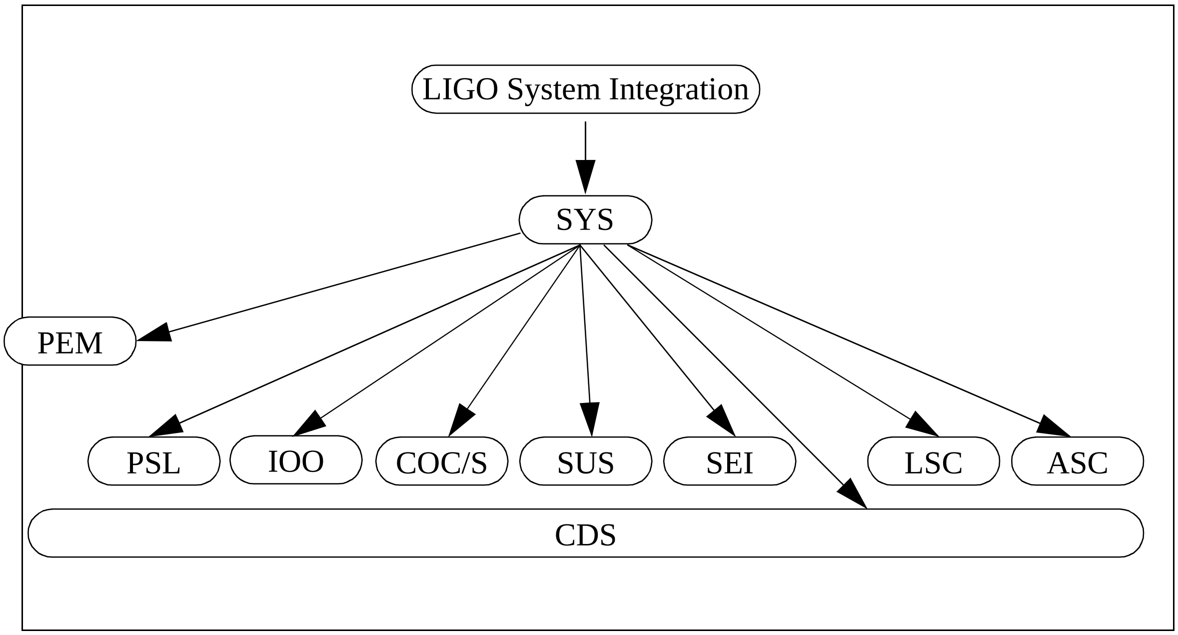


Figure 1: Product Perspective

2.3. Product Functions

This document fulfills the following functions:

- requirements flowdown, consistent with the SRD
- interface specification and maintenance
- specification and maintenance of interferometer optical layout, including properties and positions of all interferometer optical elements and the heights of beams; interferometer configuration
- specifying vacuum qualification, bakeout/certification hardware

2.4. General Constraints

The initial detector configuration consists of two interferometers at the WA site, of length 2 km and 4 km, and one interferometer at the LA site, of length 2 km. The entire clear aperture of the Beam Tube modules (1 m diameter clear aperture) is assumed to be available for these interferometers. The Vacuum Equipment provides an envelope which constrains the optics placement

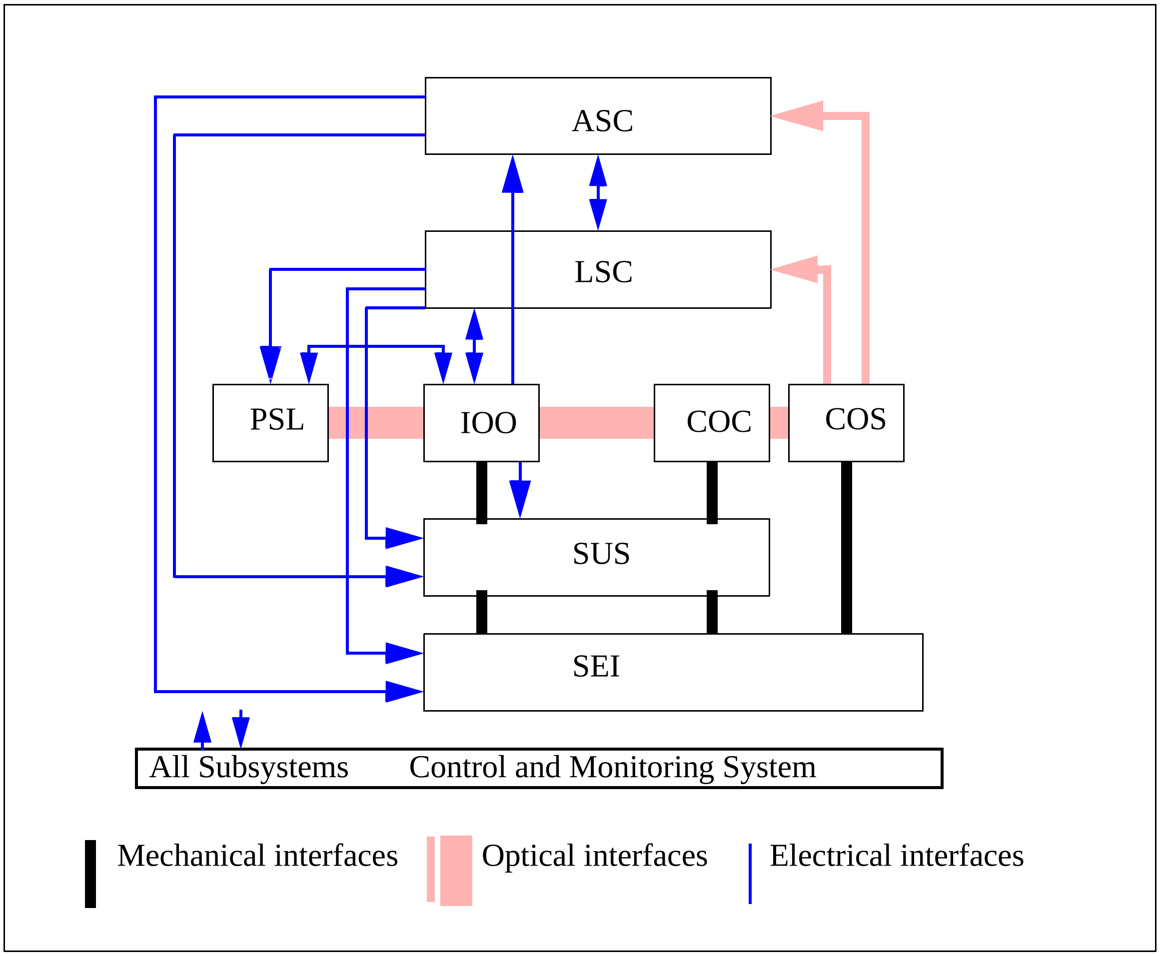


Figure 2: Interferometer principal interfaces and relationships

and the interfaces for e.g., the seismic isolation. Interfaces to the Vacuum Equipment and Civil Construction are specified in the Det-VE and Det-CC ICDs. Detector equipment external to the vacuum system is placed in stay-clear zones in the LVEA; interfaces are described in the Det-CC ICD.

2.5. Assumptions and Dependencies

The design of subsystems, and their interfaces, is intended to meet or exceed the requirements for initial interferometers specified in the SRD. The initial interferometer design must also include provision for upgrading to more sensitive 'enhanced' interferometers without a significant disruption to operations. Possible early enhancements for which the impact shall be considered in subsystem design include

- increased input laser power, by about a factor of 10
- alternative interferometer readout configurations
- replacement of core optics components with higher-quality optical components
- changes in substrate material for lower thermal noise
- improvement of passive and/or active seismic isolation

- improvement of the suspension system (e.g., a double pendulum; electrostatic actuation)

2.6. Environment

Significant design drivers due to aspects of the environment external to Detector are given here for reference.

2.6.1. Seismic environment

The seismic noise is the principal environmental input to the gaussian noise limited performance. While not strictly stationary, it shows trends which change on time scales long compared with most GW sources, and so can be treated as a locally stationary noise. It is to be monitored by the PEM to allow an accurate estimate of the ground noise contribution to the interferometer performance.

The natural ambient seismic noise has been measured at the sites, for vertical and horizontal motion. The buildings will themselves modify the seismic environment, by acting as a low-pass filter with resonances, and by coupling wind to the ground motion. The building may increase the noise by internally generated noises with the requirement not to exceed the Ligo Standard Spectrum of the LIGO ‘89 NSF Proposal. The Vacuum Equipment makes further contributions, of a best effort level (See Vacuum Equipment Specification (LIGO-E940002), amended in the final contract, PC145730, section 4.6). The tilt motion is also of interest (see ASC: Environmental Input to Alignment Noise, Gonzalez T960103).

2.6.1.1 Drift frequencies

Tides, meteorological effects. See the SEI DRD T960065.

2.6.1.2 Control frequencies

Microseismic peak; see A. Rohay, Ambient Ground Vibration Measurements at the Hanford, Washington LIGO Site (C950572). Livingston-site report in preparation.

2.6.1.3 GW-signal band frequencies

The noise input is different for the Hanford and Livingston sites, and for different times of day; see Figure 3, from L. Sievers, based on measurements; see A. Rohay, Ambient Ground Vibration Measurements at the Hanford, Washington LIGO Site (C950572). Livingston-site report in preparation.. The building has TBD effect on the natural site noise, leading to a parent spectrum TBD. The seismic noise in translations and tilts and over the km baseline is documented in ASC: Environmental Input to Alignment Noise, Gonzalez T960103 and SEI DRD T960065.

2.6.2. Non-stationary seismic environment

Requires documentation.

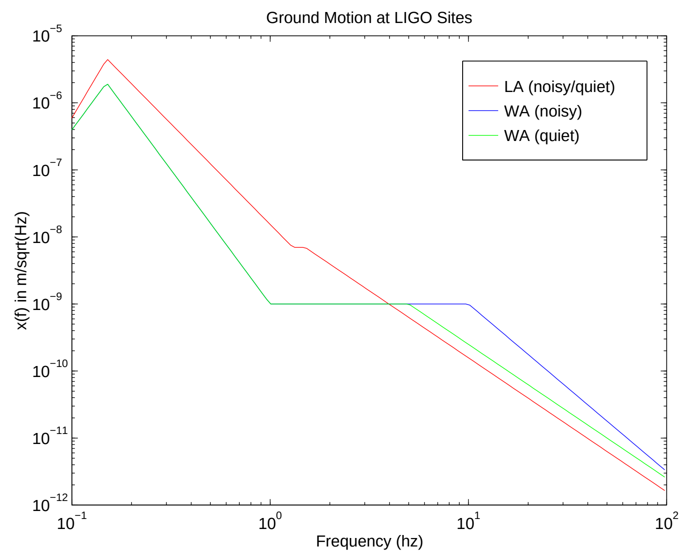


Figure 3: Ground Noise at LIGO sites

2.6.3. NARROW-BAND SEISMIC ENVIRONMENT

The civil construction generates narrow-band disturbances; refer to the SRD, and Document on narrow-band disturbances.

2.6.4. ACOUSTIC ENVIRONMENT

The acoustic environment is dominated by noise generated in the building; wind and rain may also be contributors. Refer to Derivation of CDS Rack Acoustic Noise Specifications, Lazzarini T960083, and Vibrational and Acoustic Requirements for the LIGO Facilities, Lazzarini L950238; Estimates for Motions due to Sound Fields, Weiss 16.02.95. PEM monitors the acoustic environment to verify compliance and allow veto/regression.

2.6.4.1 Quasi-stationary

2.6.4.2 Non-stationary

2.6.5. ELECTROMAGNETIC ENVIRONMENT

See EMI Control plan and procedures, Systems Engineering E960036 for guidelines for circuit design. No specifications have yet been developed, however.

2.6.6. VACUUM

2.6.6.1 Optical pathlength fluctuations

The composition and pressure level of the residual gas in the BT and VacEq are determined by requirements in the SRD. This leads to a stochastic variation in the optical pathlength; see 3.3.2.1. See also Measurement of Optical Path Fluctuations due to Residual Gas in the LIGO 40 Meter Interferometer, Zucker et al. P940008; Beam Tube Qualification Test, Weiss T960125. PEM monitors the partial pressure to verify compliance.

2.6.6.2 Cleanliness

The contamination level and composition due to the BT and VacEq are determined by requirements in the SRD. This forms an environmental background for contamination. To this is added contamination from the installed in-vacuum detector components, leading to requirements for allowed materials and cleaning procedures (See 3.4.6.). PEM monitors the cleanliness to verify compliance.

3 REQUIREMENTS

3.1. Introduction

Figure 4 is the flowdown tree for the principal Gaussian noise terms to requirements imposed on detector subsystems. The top-level requirements are specified in the SRD, and enter the trees as “Total Detector Noise” and “Detector Availability.” They determine subsystem requirements via noise coupling mechanisms or via states that affect availability, respectively. The internal designs of the subsystems are constrained to meet these lowest-level requirements, but otherwise remain free for optimization of performance and reduction of cost. In general, SYS specifies down to a level where there are no more inter-subsystem trades to be made.

The Performance Requirements are organized by noise source, not by subsystem, which means that requirements for a given subsystem may be spread throughout the discussion below. The impacted subsystem will be indicated by the three-letter acronym for each requirement; a database with cross-references will be created to ease lookup. In those cases where a subsystem requirement is constrained by more than one noise source (e.g., substrate dimensions, due to the impact on both shot noise and thermal noise), the subsystem requirement will be given in one place but with a cross-reference at all impacted noise sources.

3.2. Flowdown of Gaussian Noise for the Primary Noise Sources

The design implications of total allowed interferometer noise depend on the origin of the noise, and on the noise coupling mechanisms. The noise falls into two categories: ‘primary’ noise sources which determine the initial interferometer sensitivity, namely shot noise, test mass and

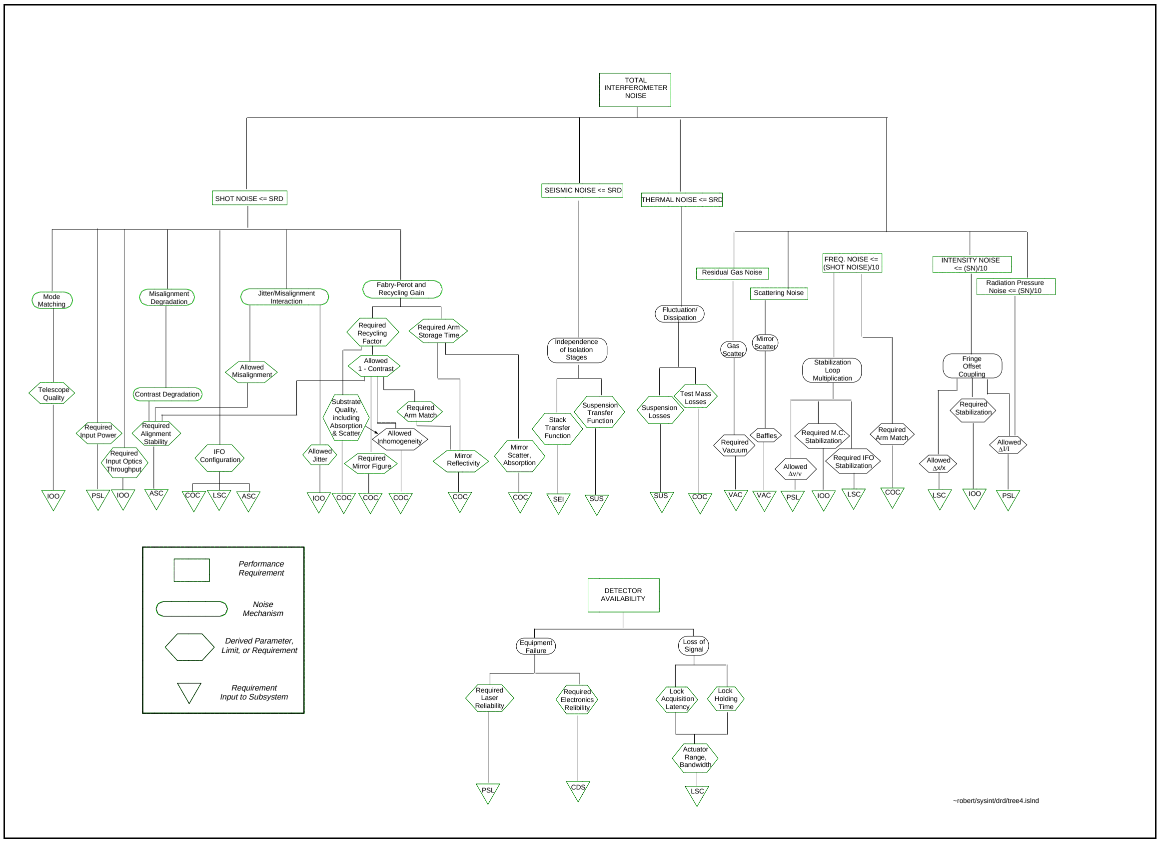


Figure 4: Gaussian noise flowdown

test-mass suspension thermal noise, and seismic noise; and 'technical' noise which can be engineered to lie below the initial interferometer sensitivity, consisting of sources such as electronic noise in sensors and actuators or thermal noise entering through indirect routes. Unless otherwise noted, noise sources are assumed to add in quadrature (square root of sum of squares) when 'flowing up' the noise budget. The subsystem designs are constrained to limit the effect of each technical noise source to a level lower than the allowed overall noise by a linear factor of at least 10. Noise sources are specified in the units most natural to the system, but with the relationship to strain to be made explicit.

The SRD gives (SRD Figure 3.3.1-1, reproduced in Figure 5) an envelope of GAUSSIAN noise, in strain, for the combined performance of the three initial LIGO interferometers (4km and 2km in Hanford, 4km in Livingston). This Detector Subsystems Requirements Document gives the interferometer parameters expected to deliver this performance.

Not yet correctly addressed: Narrow-band exceptions to the SRD curve, of electronic (e.g., mains peaks) or mechanical (e.g., violin string resonances) origin.

Figure 5 also shows the present prediction of the interferometer gaussian noise performance. Appendix 1 give the parameter set used to generate this noise prediction. As of this time, there is no guaranteed consistency between the values in the body of the Requirements Flowdown and the form of the curve; this is, however, the goal. The seismic isolation model used for this plot is a

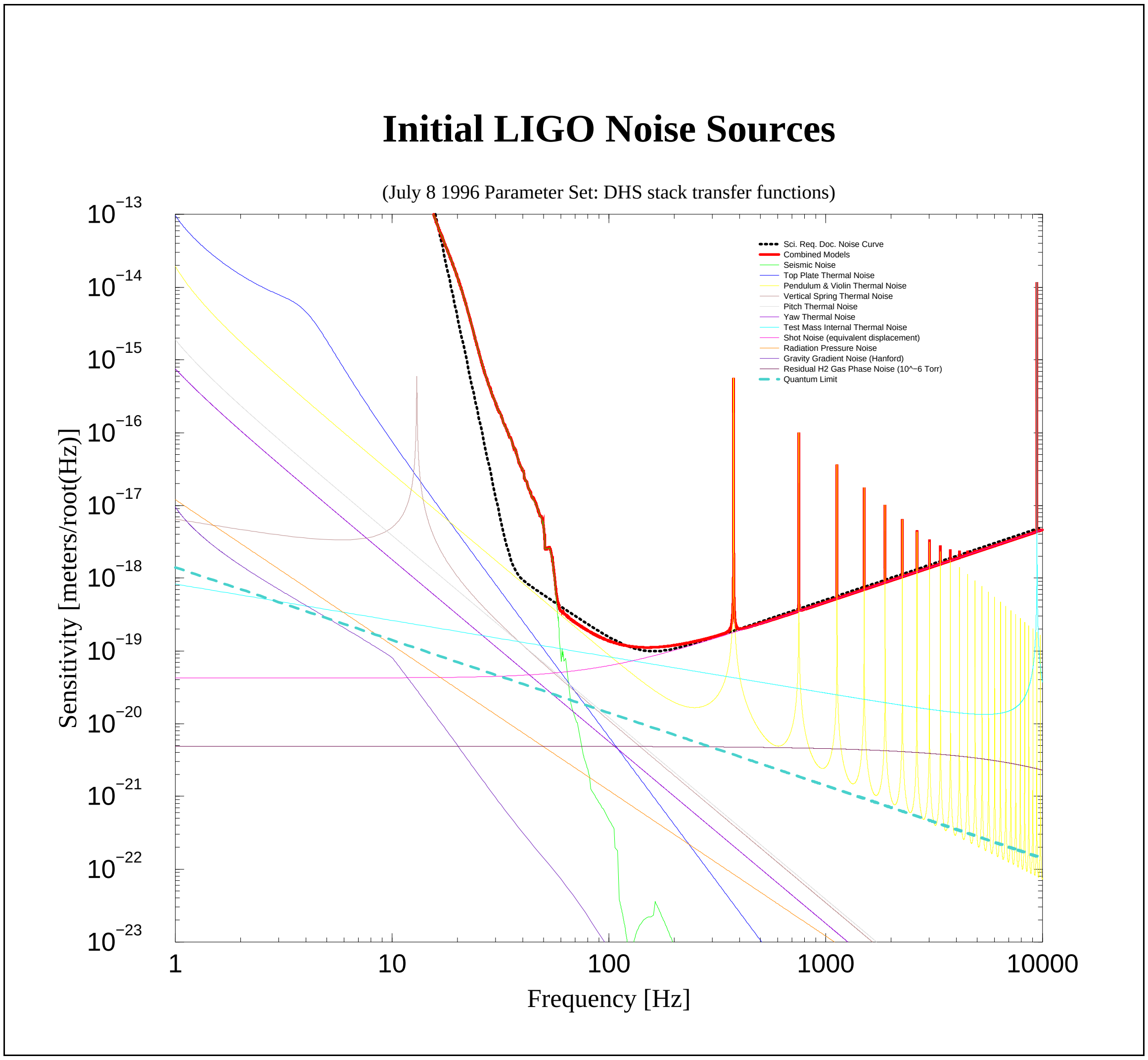


Figure 5: SRD Requirement (upper dotted line) and model 8 July 96

projection of the performance of the SS-Viton stack with doubled springs to show noise sums in the thermal noise region, but this is not a planned design path.

3.2.1. Seismic Noise Requirement and Flowdown

3.2.1.1 SRD Top-level requirement

Seismic noise shall not exceed the following level (in strain) as given in the SRD:

$$h_{\text{seismic}} = h_{0\text{s}}\left(\frac{30\ \text{Hz}}{f}\right)^{14},\ h_{0\text{s}} \ = \ 3.0\times10^{-21}\frac{1}{\sqrt{\text{Hz}}} \quad \text{in the region from } 20 < f < 60\ \text{Hz.}$$

The seismic noise requirement places requirements on the active substage, passive isolation system (‘stack’), and pendulum isolation.

3.2.1.2 Overview

Several models are used to obtain the requirements for the interferometer subsystems consistent with the requirement. The seismic excitation based on measurements at the sites (see 2.6., Environmental Input) as modified by the buildings and distances from station-to-station forms the input to the combined system. The pendulum transfer function is constrained by the requirements for thermal noise, and so forces design constraints on the isolation system.

3.2.1.3 Active substage, Drift Actuators, and Passive Stack (SEI)

This is presently in a trade study with SUS, and thus may show changes.

3.2.1.3.1 Drift frequencies

The allowed drift for the isolation components in the vacuum system are given in Table 1. These values are based on the performance observed in the SS-Viton stacks designed for the R&D prototypes (Ref: A Passive Isolation Stack for LIGO, Giaime T962005).

Table 1: Maximum allowed drift for the in-vacuum seismic isolation

category	yearly drift	thermal drift	drift rate at day 20
x translation	3 mm	$<1\text{x}10^{-5}$ m/day	$6\text{x}10^{-10}$ m/sec
y translation	3 mm	$<1\text{x}10^{-5}$ m/day	$6\text{x}10^{-10}$ m/sec
z translation	3 mm	$<1\text{x}10^{-5}$ m/day	$6\text{x}10^{-10}$ m/sec
x rotation	0.4 mrad	$2\text{x}10^{-6}$ rad/day	$8\text{x}10^{-11}$ rad/s
y rotation	0.4 mrad	$2\text{x}10^{-6}$ rad/day	$8\text{x}10^{-11}$ rad/s
z rotation	4 mrad	$2\text{x}10^{-5}$ rad/day	$8\text{x}10^{-10}$ rad/s

3.2.1.3.2 Control frequencies

The SEI system must compensate all lengths against all sources of low frequency motion. A trade is underway to determine if the SEI must compensate only up to 0.1 Hz or to up to frequencies higher than the microseismic peak (0.16 Hz).

3.2.1.3.3 Resonances

The Q of the SEI system resonances, in particular in the range from 1-30 Hz, must be limited to avoid increasing the demand on the LSC and ASC control systems. The resonances shall not exceed TBD $Q < 70$ (critical parameter, to be discussed) for such resonances. See ASC: Environmental Input to Alignment Noise, Gonzalez T960103.

The internal resonances of the suspension system must not violate the TBD requirement for GW-signal band narrow-band resonances or control systems.

3.2.1.3.4 GW signal band frequencies

In the GW band, the requirement is the determined by the Seismic input, the pre-determined Suspension transfer function, and the SRD performance requirement. It is shown graphically in Figure 6 for the horizontal isolation. See the SEI DRD for further details.

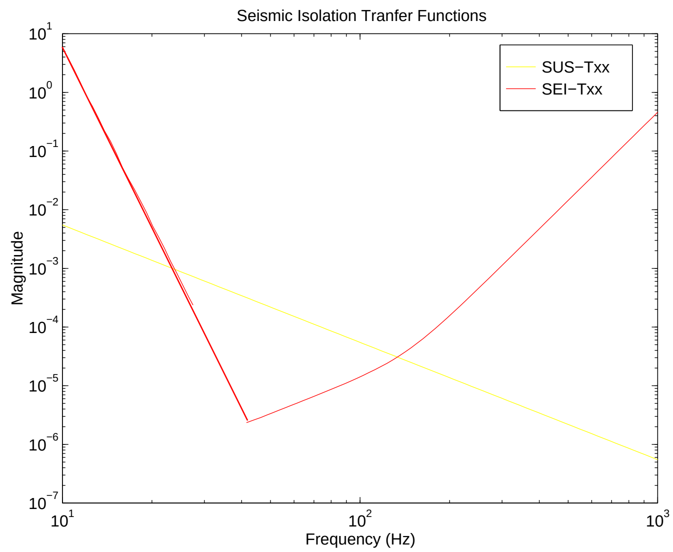


Figure 6: Horizontal-to-horizontal transfer function (SEI-T_{xx}) requirement for BSC-SEI. The transfer function for the single-stage pendulum (SUS-T_{xx}) is also shown.

3.2.1.4 Pendulum Suspension (SUS)

The SUS system delivers isolation, and limits the mechanical losses of the system to meet thermal noise requirements. Here we address the isolation requirements for the COC.

Table 2 shows the requirements of the transfer function of the suspension system from (horizontal, vertical, and pitch/yaw) motion of the suspension point to (horizontal, vertical, and pitch/yaw) motion of the suspended mass. Reference: SUS DRD T950011

3.2.2. Thermal Noise Requirement and Flowdown

3.2.2.1 Overview

The thermal noise requirement is developed from models developed by Saulson, Gillespie and Raab (see COC DRD E950099), and the losses used in those models are based on experiments with full-scale and scaled test masses. The losses allowed are partitioned between the COC (losses for the bare substrate materials chosen) and the SUS (degradation allowed due to attachments and suspension).

Table 2: Requirements matrix of the transfer function of the suspension system from motion of the suspension point to motion of the suspended mass (f > 35Hz).

Transfer Function / *To* — *From*	*Horizontal (m)*	*Vertical (m)*	*Pitch (rad)*
Horizontal (m)	$< \left(\frac{f_p}{f}\right)^2$ m/m f_p = 0.74 Hz (LOS1/2)	Trivial	$< \alpha \times \left(\frac{f_p}{f}\right)^2$ rad/m α = 100 (LOS1/2)
Vertical (m)	$< 3\times10^{-5} \times \left(\frac{f_v}{f}\right)^2$ m/m	$< \left(\frac{f_v}{f}\right)^2$ m/m f_v = 13 Hz (LOS1/2)	$< \beta \times \left(\frac{f_v}{f}\right)^2$ rad/m $\beta = 3 \times 10^{-2}$ (LOS1/2)

3.2.2.2 SRD Top-level requirement

Thermal noise shall not exceed the following level (in strain) as given in the SRD:

$h_{thermal} = h_0(100/f)^2$, $h_0 = 3.8\times10^{-23}(1/(\sqrt{\mathrm{Hz}}))$ in the region from $30 < f < 160$ Hz. The contribution at all other frequencies shall be negligible.

Note that the slope of this requirement is not the expected slope of the thermal noise from an internally-damped pendulum suspension nor that expected from the internal modes of the test masses, and thus the predicted thermal noise will not follow this form.

To meet this top level requirement from the SRD, requirements are established for the pendulum thermal noise and the internal mode thermal noise, assuming internal damping in both cases.

3.2.2.3 Losses allocated to COC

Substrate materials shall be chosen which have been characterized such that we believe that they show less than 2×10^{-7} TBD mechanical loss for internal resonance modes at GW-signal band frequencies.

3.2.2.4 Losses allocated to SUS

The thermal loss of the suspension system is required to be small enough to meet the LIGO sensitivity requirement, with the COC intrinsic losses as a design input.

The vibrational thermal noise requirement for the quadrature sum of all four test masses shall be less than or equal to $8\times10^{-20}\mathrm{m}/\sqrt{\mathrm{Hz}}$ at 100 Hz with an $f^{-1/2}$ frequency dependence. This calculation requires the COC geometry and beam sizes, which are a design input.

The pendulum thermal noise requirement for the quadrature sum of the four test masses shall be less than or equal to $1\times10^{-19}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$ at 100 Hz (thus $5\times10^{-20}\mathrm{m}/\sqrt{\mathrm{Hz}}$ per test mass) with an $f^{-5/2}$ frequency dependence. In addition, thermal noise from the pendulum suspension shall not contribute more than 1/10 the total noise budget at any frequency $10 < f < 25$ Hz and $300 < f < 10^4$ Hz with the exception of thermally-driven suspension wire resonances, which shall have a fractional width of less than $\Delta f/f_0 < 10^{-5}$ and which shall have frequencies which differ by 2% or less between suspensions, and between wires on a given suspension.

3.2.3. Shot Noise Requirement and Flowdown

3.2.3.1 SRD Top-level requirement

Shot noise shall not exceed the following level (in strain) given in the SRD:

$$h_{\mathrm{shot}} = 1.26\times10^{-23}\left(\frac{f}{100\ \mathrm{Hz}}\right)\frac{1}{\sqrt{\mathrm{Hz}}}\ ,130 < f < 10^4\ \mathrm{Hz}\,.$$

This places requirements on the laser power, power efficiency of the input optics and interferometer, and the allowed misalignment. The SRD does not break down the noise sources, but simply gives an upper limit to the quadratic sum of the three primary noise sources (seismic, thermal, shot); thus, no ‘knee frequency’ due to the storage time of the arm cavities is given above.

SYS chooses an initial arm knee frequency of 90 Hz, so writes the requirement as:

$$h_{\mathrm{shot}} = h_0\sqrt{1+\left(\frac{f}{f_0}\right)^2},\ h_0 = 1.09\times10^{-23}\frac{1}{\sqrt{\mathrm{Hz}}},\ 130 < f < 10^4\ \mathrm{Hz}\,.$$

3.2.3.2 Overview

Several models are used to obtain the requirements for the interferometer subsystems consistent with the requirement: the FFT Optics model (see J.-Y. Vinet, P.Hello, C.N. Man and A.Brillet, J. Phys. France, Vol.2, pp.1287-1303 (1992). “A high accuracy method for the simulation of non-ideal optical cavities”) to determine COC requirements and some configuration parameters, semi-analytic models of the modulation-demodulation system (LSC DRD T960058, Shot noise sensitivity of the length control error signals, Fritschel T960042) for modulation frequencies and depths, and the Alignment Modal Model (see ASC DRD T952007) for the alignment requirements.

3.2.3.3 Definition of ‘(0.005)’

The tolerance for most of the factors affecting the shot noise are determined by allowing each one to degrade the ideal shot nose by 0.005. An individual contributor at this level is identified by the label (0.005) in the subheading title line; the net contribution (one or several degrees-of-freedom) within that subheading may degrade the shot noise at most by 0.005.

3.2.3.4 Calibration

System Integration to develop the top level requirements for stability, absolute and frequency-dependent precision. LSC will advise on technical capability.

3.2.3.5 Net effective input light power to Interferometer

The power coupled into the TEM_{00} mode of the interferometer (the Recycling Cavity) shall be 6 W or greater. This is distributed among subsystems as summarized in Table 3, and described in the following paragraphs.

Property	*Requirement*	*Reference*
PSL output power	8.5 W	
IOO optical efficiency	0.75	
IOO coupling efficiency to COC	0.95	
Net power input to interferometer, carrier and GW sensing sidebands	≥ 6.0 W	
Coupling from COC to ASC/LSC (COS)	0.99	
ASC/LSC Antisymmetric port splitter	0.01/0.99	
GW antisymmetric port photodiode quantum efficiency	0.8	

Table 3: Power allocation

3.2.3.5.1 Laser power and wavelength (PSL)

The laser power delivered by the PSL subsystem in the TEM_{00} mode, parameters as described in interfaces, shall be 8.0 W or greater. The laser wavelength shall be 1064 nm.

3.2.3.5.2 Optical efficiency of Input Optics (IOO)

The net efficiency of IO TEM_{00} optical power transmission from PSL output to COC input shall be 0.75 or greater. 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 and GW-detection SB may not be reduced. This includes any degradation due to imperfect alignment (or matching) of the mode cleaner, and any light pickoffs required.

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. This is for the optimal alignment, and includes both low-order mismatching and more general high-order distortions. The IOO shall have a range of output mode matching parameters TBD which allows this coupling to be maintained for the range of initial parameters calculated given the COC radius precision requirements, and the range of parameters calculated for heating-induced mirror distortion. This coupling requirement will be refined to give explicit allowed mode content, based on requirements coming from ASC and LSC.

3.2.3.5.3 Coupling efficiency and quality from COC to LSC/ASC via COS (COS)

The net efficiency for the coupling of the output ports of the interferometer (symmetric, antisymmetric ports; first ‘wedge beam’ from the Beamsplitter and two ITM) shall be 0.99 or greater, as measured from the wedge beam as it leaves the optic to the point of interface outside the vacuum to the ASC/LSC sensors.

There shall be no added wavefront distortion greater than $\lambda \diagup 10$ between the originating COC surface(s) and the interface.

3.2.3.6 Phase sensing system

3.2.3.6.1 Configuration (SYS)

The interferometer shall be a recombined-beam Michelson with Fabry-Perot cavities in the arms. Power recycling is implemented. All control signals are obtained from the primary and secondary surface reflections/transmissions of these optics (i.e., there are no separate pickoff optics); all such reflections are to be made available to viewports. The GW readout shall be performed via an asymmetry in the difference in path from the BS to the two ITMs and a common-mode phase modulation applied to the input light before the mode cleaner. The polarization shall be s or p TBD. The critical parameters for the modulation system are indicated in Table 4, and for optical components are in Table 5. The configuration is more fully described in the LSC DRD.

Property	*Requirement*	*Reference*
Recycling cavity optical length (physical length shorter due to substrate index)	9.38 m (4km) 11.67 m (2km)	3.2.3.6.2
Mode cleaner optical length	12.55 m (4km) 14.75 m (2km)	3.2.3.6.2
Schnupp optical length asymmetry (4 km)	± 15.5 cm nominal; -1 to +25 cm range	3.2.3.6.3
GW readout modulation frequency (4 km)	24.0 MHz	3.2.3.6.4.2
GW readout modulation depth (4 km)	$\Gamma = 0.45$ nominal; range TBD $0 < \Gamma < 1.0$	3.2.3.6.4.4
ASC non-resonant sideband frequency	TBD	
ASC non-resonant sideband modulation depth	TBD	

Table 4: Modulation System properties

3.2.3.6.2 Lengths of cavities

The lengths of the optical systems are given in Table 4, “Modulation System properties,” on page 21 and Table 5, “Optics properties, 4 km Interferometer,” on page 25. All of these lengths are for the optical length, with the physical length corrected for the path in the higher-index substrate.

3.2.3.6.3 Interferometer Schnupp (detection) asymmetry (LSC) (0.005)

The difference in optical path length from the BS 50-50 coating to the ITMs shall be optimized according to our best understanding of the optics properties with a precision which degrades the ideal sensitivity by no more than 0.005 (with the modulation depth adjustable to optimize for a given asymmetry). The present best estimate for the 4 km system is shown in Table 4, "Modulation System properties," on page 21. It shall be adjustable (with vent/pumpdown but no machining). The description of the optimization of the asymmetry and modulation depth, given the frequency of modulation, losses in the interferometer, and contrast defect, is found in LIGO-T960042-00-D Shot noise sensitivity of the length control error signals.

3.2.3.6.4 Phase Modulation system

3.2.3.6.4.1 Modulation-Demodulation efficiency (LSC)

The modulation-demodulation system shall have an signal-to-noise efficiency no worse than that for sinusoidal modulation and demodulation. See 'Non-stationary shot noise and its effect on the sensitivity of interferometers', Niebauer et al., Phys Rev A 43 (1991) 5002

3.2.3.6.4.2 Carrier and GW sideband readout frequencies (IOO)

The GW detection phase modulation sidebands applied to the main carrier shall be at ±24.0 MHz. The constraints on the frequencies are documented in Proposed initial detector MC and RC baseline lengths, Zucker T960122.

3.2.3.6.4.3 Non-resonant sidebands for Alignment readout (ASC)

A second set of sidebands will be applied to the carrier, frequency and mod depth TBD, to aid the ASC system. These sidebands are chosen to be non-resonant in the main interferometer to distinguish motions of the recycling mirror from other components.

3.2.3.6.4.4 Relative intensities and modulation depths (nominal and available) (IOO) (0.005)

The modulation depth of the GW readout sidebands on the carrier shall be optimized for our best knowledge of the optics properties, and shall be adjustable during operation with a precision which gives a shot-noise limited sensitivity within 0.005 of the optimal. The present best estimate is shown in Table 4, "Modulation System properties," on page 21.

3.2.3.6.5 ASC-LSC symmetric port splitter

The beamsplitter which divides light from the symmetric port between the LSC and the ASC shall direct 0.95 of the light to the LSC photodiode system and 0.05 of the light to the ASC alignment wavefront sensors with net losses of $< 10^{-3}$.

3.2.3.6.6 ASC-LSC antisymmetric port splitter

The beamsplitter which divides light from the antisymmetric port between the LSC and the ASC shall direct 0.99 of the light to the LSC photodiode system and 0.01 of the light to the ASC alignment wavefront sensors with net losses of $< 10^{-3}$.

3.2.3.6.7 Antisymmetric photodetector quantum efficiency (LSC)

The quantum efficiency for conversion of light from the point after the beamsplitter between LSC and ASC splitter to LSC photocurrent shall be 0.8 or greater, including any losses due to light division optics.

3.2.3.7 Deviations from optimal lengths (LSC)

These length control requirements are established to maintain the circulating power and thus the shot-noise limited sensitivity; other length control requirements are determined by technical noise sources, and are given in section 3.3.2.. This is documented in Length Control RMS Deviations from Resonance, Camp T960067.

3.2.3.7.1 Arm cavities (0.005)

The deviation of the sum of the lengths (two times the average length, to meet the definition of L_+) of the arm cavities from the optimal shall be held to $L_+ < 4\times10^{-12}$ m RMS.

3.2.3.7.2 Recycling cavity (0.005)

The deviation of sum of the lengths of the two recycling cavity arms (two times the average length; note the significant intentional asymmetry) from the optimal shall be held to $l_+ < 5\times10^{-10}$ m RMS. Arm cavities (0.005)

3.2.3.8 Angular alignment of core optics components (ASC) (0.005)

The interferometer COC shall be held within 1×10^{-8} rad (static+rms) of the optimal alignment for each optic. ASC may apportion this in detail among the optics, so long as the sensitivity to beam jitter does not exceed that for the simple requirement.

This requirement is driven by two noise/degradation mechanisms. One is the degradation of the shot-noise limited performance due to misalignment which is limited to 0.005, and is documented in the ASC DRD T952007 section 3.2.3.2. The second is the coupling of beam jitter (see section 3.3.2.4) and static or RMS misalignment, making these two requirements directly (and to lowest order linearly) coupled; once the first criterion is fulfilled, it drives the requirement for the beam jitter. This is documented in Misalignment-Beam Jitter Coupling in LIGO Fritschel T960120.

3.2.3.9 Centering of beams on the COC (ASC)

We mention here requirements driven by the shot-noise limited performance. Other requirements for technical noise sources are noted and then given in the appropriate section on technical noise sources.

3.2.3.9.1 Test masses

The beams shall be centered with a precision sufficient to limit light scattered out of the TEM_{00} due to mis-centering to be less than a 0.1 ppm change from the centered case (negligible compared to other TM losses). This is a less stringent requirement than that in section 3.3.1.1.2, which gives the requirement imposed by the coupling of angular thermal noise into longitudinal noise or in section 3.3.1.4.3, coupling of suspension angular control system noise into longitudinal noise.

3.2.3.9.2 Beamsplitter and Recycling mirror

The beams shall be centered with a precision sufficient to limit light scattered out of the TEM_{00} mode due to mis-centering to be less than 100 ppm (negligible compared to other losses in the recycling cavity).

3.2.3.10 Core Optics characteristics impacting shot noise (COC)

The interferometer optical system impacts the shot-noise limited sensitivity through

- optical efficiency of the interferometer: losses (absorbed scattered light, absorption)
- contrast degradation
- frequency response to GWs

See the COC DRD for details of the trade-offs between these parameters.

3.2.3.10.1 Optics requirements

The optic and beam sizes are determined in a trade involving the diffraction losses (set at 1 ppm per bounce for the test masses), thermal noise (maximum spot size to mirror size, and overall minimum mirror diameter; thickness to maintain high internal mode frequencies), and manufacturability. Other optics properties are summarized here for convenience. The 2km system is to be

Property	*Requirement*	*Reference*
Optic Sizes	TM, RM: 25 cm dia., 10 cm thick	
	BS: 25 cm dia., 4 cm thick	
Coated surface	24 cm dia.	
Beam Sizes	ITM: 3.6343 cm w_0	
	ETM: 4.5655	
	BS: 3.6359	
	RM: 3.6377	
Radii of Curvature (tolerances to maintain strain sensitivity to 0.95 nominal)	ITM: 14571 m; $-0.07< \Delta R_{ITM}/R_0 <0.01$	
	ETM: 7400.0 m; $\Delta R/R_0$ of 0.03	
	BS: flat/flat, tolerance TBD	
	RM: 9998.33m; $-0.01<\Delta R_{RM}/R_0< 0.05$	
Surface figure	equivalent to '$\lambda/600$ Calflat' (HeNe)	

Property	*Requirement*	*Reference*
Mirror transmissions	ITM: 0.030 ± 0.00015	
	ETM: 10<T<20 ppm	
	BS: 0.50 ± 0.01 TBD	
	RM: Overcoupled, 0.1 E field reflected	
AR Coatings:	ITM, RM: 600 ± 300 ppm	
	BS, ETM: 200 ± 100 ppm	
Mirror losses:	50 ppm scatter+absorption	
Substrate index	1.44963 (Heraeus), 1.44968 (Corning)	
Substrate OPD for BS, ITM, RM	5×10^{-7} p-v, $\lambda = 632.8$ nm, cntr 150 mm 2.5×10^{-6} p-v, $\lambda = 632.8$ nm, cntr 225 mm	
Substrate absorption	<2 ppm/cm	
Substrate scatter	<5 ppm/cm	

documented, but the present model has all optics parameters identical, leading to a shorter arm storage time.

Table 5: Optics properties, 4 km Interferometer

3.2.3.10.2 Reflected carrier at recycling mirror

The reflected TEM_{00} power from the recycling mirror shall be TBD (critical parameter to be determined) $>0.01\ P_{inc}$, and the recycling cavity shall be overcoupled to achieve this reflectivity (i.e., the RM shall have a larger transmission than the sum of the recycling cavity losses), and shall be maintained for the allowed range of mirror degradation**.**

3.2.3.10.3 GW frequency response

The arm cavities for the 4 km system shall have an average corner frequency of 90 ± 9 Hz TBD). The requirement on the tolerable difference between the two arms is determined by technical noise sources (see 3.3.2.3.1).

3.3. Flowdown of Gaussian Noise for the Technical Noise Sources

Unless otherwise noted, each of the following noise sources are required to lie at least a factor of 10 below the primary noise sources as required by this document at all frequencies in the GW-signal band (measured in noise equivalent strain). The noise sources are assumed to add in quadrature (square root of sums of squares); thus, each noise source can increase the noise by $(1^2 + 0.1^2)^{1/2} = 1.005$. They are broken into noise sources leading to physical motions of the interferometer components and noise sources which imitate or cause phase noise in excess of shot noise. Each net contributor at this level is flagged as ‘(10%)’

In general, those sources causing mechanical motion make a contribution which falls with frequency, and those causing excess phase noise are relatively flat in the GW-signal band. This, a rough estimate of the excess noise from all sources should sum these two contributions separately. At present, there are of order 10 mechanical sources and 10 excess phase noise sources.

3.3.1. MECHANICAL MOTION OF SUSPENDED COMPONENTS

3.3.1.1 Thermal noise for non-primary contributors

3.3.1.1.1 Thermal noise from the SEI isolation system (10%)

Thermal noise from the final stages of the SEI isolation system shall not contribute more than $(\quad) / 10$ in the frequency range from $10 < \quad < 150$ Hz and will be negligible at all other frequencies.

3.3.1.1.2 Thermal noise from pitch and yaw (10%)

Mis-centering of the beam in conjunction with thermally-excited pitch and yaw leads to changes in path length. This makes a 10% noise contribution which passes through $x = (\quad) / 10$ $f = 40 Hz$ with a $f^{5/2}$ characteristic. Because we are at the limit of technology for the thermal noise, the achievable performance there dictates the centering requirement. See the SUS DRD T950011 and ASC DRD T952007.

3.3.1.1.2.1 SUS requirements for pitch and yaw thermal noise

The pitch/yaw thermal noise requirement for the SUS subsystem is $< 5\times10 \times (\quad)^{5/2} (\quad \sqrt{\quad})$ for pitch and yaw (for the LOS optics); see the SUS DRD (LIGO-T950011-14), Appendix B.1.3.

3.3.1.1.2.2 ASC requirements for test mass centering

The beam centroid must be maintained within a radius of 1.0 mm of the center of rotation of each test mass.

3.3.1.2 SEI on-line stack actuator motion (10%)

The operational-mode stack actuator shall make a contribution of 10% of the SRD in the frequency range from $10 < f < 30$ Hz and shall make a negligible contribution for higher frequencies.

3.3.1.3 SEI stack internal noise generation (10%)

Any generation of excitation of the in-vacuum seismic isolation system optical table due to the components themselves (masses, springs, cabling, etc.)

3.3.1.4 SUS actuator

3.3.1.4.1 Coil Driver noise, longitudinal motion (10%)

The quadratic sum of the control noise of the suspension systems in total shall cause no more than 10% of the SRD required LIGO displacement noise, that is 1.0×10 [illegible] $\mathrm{m}/\sqrt{\mathrm{Hz}}$ at 40 Hz with f^{-2} dependence.

Driven by the specification for the COC masses and the environmental seismic input.

3.3.1.4.2 ASC-SUS displacement to angle coupling of SUS controllers/actuators (10%)

The suspension controller-actuator system will produce some accidental translation when a pure angular motion is commanded. The ASC GW-band noise is due to contributions of the sensors above the ASC servocontrol band.

3.3.1.4.2.1 ASC Angular noise in the GW band

The angular motion of the COC due to the ASC contribution shall be no more than $2.5\times10^{-18}(100/f)^{2.5}\ \mathrm{rad}/\sqrt{\mathrm{Hz}}$, $40 < f < 150$ Hz; $1\times10^{-18}\mathrm{rad}/\sqrt{\mathrm{Hz}}$, $f > 150$ Hz. See section 3.2.3.4 Control System Noise Allowance in ASC DRD.

3.3.1.4.2.2 SUS TM Controller orthogonality

For the TM's, the orthogonality shall be less than or equal to 10^{-2} TBR from $40 < f < 150$ Hz. For the BS, the orthogonality shall be less than or equal to 10^{-2} TBR from $40 < f < 150$ Hz.

3.3.1.4.3 ASC-SUS angle to displacement coupling of SUS controllers/actuators

The suspension controller-actuator system will produce some accidental rotation when a pure translations is commanded. This leads to a cross-coupling of ~0.1, and determines the requirement in 3.3.1.4.2.2 above. See Cross-coupling in the suspension controllers, Fritschel L960596, and Comparison of forces and torques from feedback servos for LSC and ASC, Gonzalez servo.fm (needs DCC#)

3.3.1.5 COC Light intensity fluctuations exciting test masses (radiometer effect) (10%)

The beamsplitter must split the power evenly to avoid the excess intensity fluctuations from exciting the test masses differentially. The intensity fluctuations are set in section 3.3.2.2.2 below. See Radiation Pressure Noise in LIGO, Camp/Yamamoto T960128. This is a weak requirement, and the balance of mirror heating determines the BS balance requirement.

3.3.1.6 SUS response to magnetic fields (10%)

Rough draft. SUS shall choose the smallest magnets consistent with the SUS mission; CDS shall then limit proximity and current noise in conductors to prevent motion of test masses at a level greater than the $(SRD)/20$ per test mass.

A rough guide (See Magnet size considerations; interference and coil power dissipation, Zucker T960126) is that magnetic fields must be less than $B < 10^{-12}\mathrm{T}/(\sqrt{\ \ })$, or equivalently noise currents in unbalanced conductors 1 m distant of less than $A < 50\mu\mathrm{A}/\sqrt{\mathrm{Hz}}$ if magnets comparable to those used on the 40m/5m interferometers are used.

3.3.1.7 SUS Electrostatic forces (10%)

Not resolved. The principle concern is due to migration of patches of charge on the dielectric surface of the mirror leading to time-varying forces on the mirror. See Note on Electrostatics in the LIGO suspensions, Weiss 6 June 95.

3.3.2. Excess phase noise

In general, requirements are first set for the optics performance and LSC/ASC control system based on primary noise requirements and technology limits; then the requirements below are derived such that the technical noise contributions are at 10% of the primary noise performance of the interferometer. Reference Frequency, Intensity and Oscillator Noise in the LIGO, Camp T960019, LSC DRD T960058, ASC DRD T952007. In most cases, the LSC design determines parameters for the ASC, IOO, and PSL subsystems.

3.3.2.1 Optical pathlength fluctuations due to residual gas

The requirements for the fluctuations in the optical path due to imperfect vacuum in the VacEq and BT are not determined by Detector, but instead by the SRD. The expected level for the initial detector and pumping system is ~ $5\times10^{-21}\mathrm{m}/\sqrt{\mathrm{Hz}}$ in the GW band, which makes a negligible contribution compared to the SRD curve. See Issues and considerations on the beam tube bake, Weiss T960124 and Beam Tube Qualification Test, Weiss T960125.

3.3.2.2 Light intensity fluctuations (LSC, PSL, IOO) at antisymmetric port (10%)

Deviations of the interferometer from the ‘dark fringe’ lead to input intensity fluctuations in the ligh.t appearing as signals. See Camp LIGO-T960067-00-D Length Control RMS Deviations from Resonance.

3.3.2.2.1 LSC

The main differential path length shall be held to $L_1 - L_2 < 1\times10^{-12}$ m RMS. The Michelson differential path length shall be held to $l_1 - l_2 < 1.3\times10^{-10}$ m RMS. This limits the feedthrough of intensity noise to the interferometer sensing outputs.

3.3.2.2.2 PSL

The fractional light intensity fluctuations at the input to the IOO shall be $\delta I(f)/I < 10^{-6}$ $1/\sqrt{\mathrm{Hz}}$ for $40 < f < 10000$ Hz. The fractional light intensity fluctuations at the input to the COC (recycling mirror) shall be $\delta I(f)/I < 10^{-8}$ $1/\sqrt{\mathrm{Hz}}$ for f > 40 Hz for the carrier and for the sidebands used for GW detection. PSL is required to meet both of these requirements

3.3.2.2.3 IOO

IOO shall provide a suitable sample of light to allow PSL to meet the requirement 3.3.2.2.2.

3.3.2.3 Light frequency fluctuations (COC, PSL, IOO) (10%)

Asymmetries in the interferometer allow common-mode frequency fluctuations in the input light to appear as signals. See Camp LIGO-T960067-00-D Length Control RMS Deviations from Resonance.

3.3.2.3.1 COC

The arm cavity storage times shall be matched to $(\tau_1 - \tau_2)/\tau_{ave} < 0.01$.

3.3.2.3.2 PSL

The light frequency fluctuations at the input to the IOO shall be $\delta\nu(f) < 10^{-1}\ \mathrm{Hz}/\sqrt{\mathrm{Hz}}$ at 100 Hz, falling as f^{-1} to 1 kHz and maintaining $\delta\nu(f) < 1\times10^{-2}\ \mathrm{Hz}/\sqrt{\mathrm{Hz}}$ up to at least $f = 10$ kHz, and with a $f^{-2.5}$ frequency dependence below 100 Hz. TBD; critical requirement to be discussed.

3.3.2.3.3 IOO

The light frequency fluctuations at the input to the COC (recycling mirror) shall be $1\times10^{-4}\ \mathrm{Hz}/\sqrt{\mathrm{Hz}}$ at 100 Hz with $f^{-0.5}$ frequency dependence above 100 Hz and $f^{-2.5}$ frequency dependence below 100 Hz. This is limited by the thermal noise in the mode cleaner mirrors, so is a fixed point in the design (see SUS DRD T950011). This requirement applies independently to the carrier and the sideband light.

3.3.2.4 Light beam geometry fluctuations (ASC, IOO, PSL) (10%)

This noise source contributes at a level of 10% of the SRD. See **LIGO-T960120-00-D** Misalignment-Beam Jitter Coupling in LIGO.

3.3.2.4.1 ASC (coupling to beam geometry fluctuations)

The alignment requirement for the COC is determined by the shot-noise performance requirement (see 3.2.3.8). That requirement then drives the beam jitter requirements.

3.3.2.4.2 IOO (beam geometry fluctuations)

The beam motion in angle and position is required such that with the ASC alignment given in 3.2.3.8 that the quadrature sum of the additional noise from angle and position noise will be less than 0.5% of the SRD.

Thus, the angular fluctuations of the beam at the input to the COC shall be $\alpha(f > 150\ \mathrm{Hz}) = 3\times10^{-14}(\mathrm{rad}/\mathrm{Hz}^{1/2})$ and may rise as $1/f^2, (X < f < 150)$ for lower frequencies. The displacement fluctuations of the beam at the input to the COC shall be $x(f > 150\ \mathrm{Hz}) = 1\times10^{-10}(\mathrm{m}/\mathrm{Hz}^{1/2})$ and may rise as $1/f^2, (X < f < 150)$ for lower frequencies.

3.3.2.4.3 PSL (beam geometry fluctuations)

The angular fluctuations of the beam at the input to the IO shall be $\alpha(\quad) = 3\times10^{11}(\quad)$ and may rise as $1/f^2$, $(\quad)$ for lower frequencies. The displacement fluctuations of the beam at the input to the IO shall be $x(\quad) = 1\times10^{7}(\quad)$ and may rise as $1/f^2$, $(\quad)$ for lower frequencies.

3.3.2.5 Modulation system phase and amplitude fluctuations (LSC) (10%)

The phase fluctuations and the amplitude fluctuations of the RF modulation clock shall not make a net contribution to the strain sensitivity greater than 10% of the primary noise sources. See Frequency, Intensity and Oscillator Noise in the LIGO, Camp T960019.

- 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

3.3.2.6 Length sensing/control (LSC)

The technical noise due to the length sensing/control system contributes to the noise budget as follows.

3.3.2.6.1 Main L_- photodetection system (10%)

The technically-limited main differential length sensing/control system (L_-); e.g., photodetector amplifier noise, photodetector linearity.

3.3.2.6.2 Auxiliary L_+, , l_- sensing systems (10%)

The shot- and technically-limited sensing and control system for the auxiliary lengths (l_-, l_+ and L_+)

3.3.2.7 Angular DOF sensing/control (ASC) (10%)

The sensing and control system for the angular degrees of freedom shall not make a net contribution to the strain sensitivity greater than 10% of the primary noise sources. This places requirements on the angular motion due to the alignment sensing and control, and on the centering; the trade is performed within the ASC subsystem.

This is distinct from the degradation of sensitivity due to imperfect alignment (see 3.2.3.8).

3.3.2.8 Parasitic interferometers (SUS, COC, IOO, PSL) (10%)

Rough draft. Parasitic interferometers are defined as accidental interferometers due to reflections or scattering within the Rayleigh angle of the beam. They can contribute by direct effects (modulation of the path length at GW frequencies, or allowing recombination of the light from different times and thus time-varying phase), or by up-conversion (motions of scatters with an amplitude greater than a wavelength and at velocities such that 2π of phase change takes place in a GW-band period ($1/40$ sec or less).

Parasitic interferometers from all sources shall not make a net contribution to the strain sensitivity greater than 10% of the primary noise sources; this is to be allocated among the nominally independent sources below; requires some calculation to do this correctly.

3.3.2.8.1 SUS

The motion of the operational interferometer suspended components (COC, IOO) with respect to the VacEq and BT surfaces shall be less than $v_{\mathrm{RMS}}/\lambda < 5$ TBD for the RMS motion integrated over all frequencies; see LSC DRD T960058. This places requirements on the active damping of the Beamsplitter and Recycling Mirror.

3.3.2.8.2 COC

The COC shall have a wedge such that less than TBD integrated power lies within the Rayleigh angle.

3.3.2.8.3 IOO

The reflectivity of the complete IOO subsystem within the Rayleigh angle shall be less than TBD 10^{-8} in power as viewed from the COC.

3.3.2.8.4 PSL

The product of the motion of the PSL subsystem with respect to the IOO suspended optics times the reflectivity of the complete PSL subsystem within the Rayleigh angle shall be less than TBD $\mathrm{reflectivity} \times \mathrm{motion} < 10^{-6} \times 10^{-9}/f^2 \ \mathrm{m/Hz}^{1/2}$ in power. This may require active isolation or compensation of the motion in the GW band.

The relative motion between the largest reflector in the PSL and the IOO suspended components shall be less than TBD 0.5λ ($\lambda = 1.06\mu\mathrm{m}$) for the RMS motion integrated over frequencies TBD $f > 1$ Hz. This places requirements on the control-frequency seismic isolation of the PSL.

3.3.2.9 Scattered light (COC, COS, IOO, PSL, LSC) (10%)

Rough partial draft. There are several paths for scattered light: beam-tube reflections, VacEq reflections, laser. Scattered light from all sources shall not make a net contribution to the strain sensitivity greater than 10% of the primary noise sources; this is allocated among the various paths below.

3.3.2.9.1 COC

The COC are the primary source of scattered light. The available technology (substrate materials, polishing and coating) and phase-sensing requirements largely determine the possible performance and thus the scatter requirements.

3.3.2.9.1.1 Substrate scatter

The substrate material shall scatter less than 5ppm/cm TBD. The available substrate material shows ~2ppm/cm Rayleigh scatter, and some additional scatter due to inclusions is anticipated.

3.3.2.9.1.2 Wide-angle scatter

The integrated wide-angle scatter from the polished, coated surfaces of each of the elements of the COC shall be less than TBD ppm

3.3.2.9.1.3 Narrow-angle scatter

The narrow-angle scatter (angles comparable to the Rayleigh angle) is determined by the shot-noise limited sensitivity.

3.3.2.9.2 COS

The COS are the primary sink of scattered light; this subsystem is responsible for the control of the beams generated by the COC.

3.3.2.9.3 SUS

Stray light shields.

3.3.2.9.4 IOO

Stray light shields.

3.3.2.9.5 PSL

Stray light shields.

3.3.2.9.6 LSC

Spatial uniformity of the photodetector shall be 10^{-3} RMS TBD (figure achieved with Si; see Spatial Uniformity of Silicon Photodiodes, Lantz T952007. Reflectivity in the Rayleigh angle shall be less than TBD.

3.3.2.10 Mirror Heating

This is a concern for both the phase-noise performance and for the availability of the interferometer. Here we consider the requirement to balance the power in the arms of the interferometer to ensure that any common-mode absorption in the ITM substrate or coatings does not excessively degrade the contrast.

Differential ITM ($\Delta R_{ITM}/R_0$) out of tolerance of at least $\pm$ 0.12 can be allowed to stay within 5% strain degradation (see COC Surface Radii Tolerances DRAFT, Kells T960144). Calculations of the distortion of the ITMs due to substrate and nominal 1 ppm coating absorption show significant fractional change in radius (see Numerical thermal analysis of complicating factors of optics...

(SURF Report) Coyne/Djambazov DCC#; mirror heating and impact on interferometers, Winkler et al., Phys Rev. Thus, we require balance of much better than 0.12 for the beamsplitter, or:

The beamsplitter shall split the input beam evenly to a precision of 1% TBR or better (better than 49.5/50.5).

3.4. Flowdown of Availability Requirement

This section is only a sketch of the needed requirements.

The SRD states that 'The goal for the initial detector is the ability to maintain at least one interferometer in operation at an annually integrated availability of 90% with minimum continuous operating periods of 40 hours, allowing for short term loss of lock. Such loss of lock may occur in order to accommodate long-term, low frequency drift (i.e., out of the GW measurement band) by shifting resonant operation from one longitudinal mode to another.'

3.4.1. ALL SUBSYSTEMS

We require that all interferometer subsystems be designed to operate continuously WITHOUT loss of 'lock' (even for short times) for 40 hours, during normal seismic conditions (90% percentile TBD for either site). This requires that actuators (in particular SEI and SUS) be capable of compensating for up to daily variations in length and angle, and that the PSL not jump modes during normal operation over this time period.

3.4.1.1 SEI Actuator range and dynamic response

The SEI actuators will fulfill the top level requirement 3.4.1. for the longitudinal servo control given the SUS requirement for range 3.3.1.3.

3.4.1.2 SUS Actuator range and dynamic response

The SUS actuators shall have a displacement range for the TMs of $\geq \pm 20 \mu m$ for frequencies below the pendulum resonant frequency, with a simple pole at 0.15 Hz.

3.4.2. LSC, ASC RE-ACQUISITION TIME

We require that the re-acquisition of the LSC-ASC Detection Mode after a loss of lock be less than 180 sec TBD (after a period of no more than 300 sec TBD of downtime and no adverse operating conditions as the point of departure).

3.4.3. COMMISSIONING

The detector subsystems must allow a staged approach to bringing the interferometer on-line. Specifically, LSC and ASC must have control/modulation systems which are consistent with control of subsets of the interferometer optics. This will receive further definition through a joint Detector-SystemsEngineering effort.

3.4.4. INITIAL ALIGNMENT

3.4.4.1 PSL

The PSL laser shall allow a continuous modulation of intensity 1.0 to 0.5 by remote command at ‘chopping’ rates up to 2 Hz and a slew time for 1.0 to 0.5 or 0.5 to 1.0 of 0.05 sec.

The PSL laser shall allow a calibrated reduction in intensity of the output beam from full power to 10 mW in steps no coarser than factors of 3 in power, by remote command, with an attenuator change time no longer than 1 sec. The beam may be interrupted during attenuator change. The intensity and frequency control systems must remain closed-loop but with reduced performance requirements, specifics TBD.

3.4.5. TIMING ACCURACY

The strain data acquired from the detector shall have an absolute time-stamp accuracy of less than 10 μ sec TBD as implemented through the CDS Data Acquisition system. The time-stamp accuracy for the PEM data shall be sufficient to allow the optimal use of the data collected; in general, the data shall have a time-stamp accuracy of the pulse rise time, inverse bandwidth, or 10 μ sec (whichever is greater).

3.4.6. CLEANLINESS

The optics will become contaminated through exposure to the imperfect vacuum, causing increased loss as a function of time. The allowable degradation is not prescribed by the SRD, and so we adopt a reasonable criterion: The shot-noise limited sensitivity shall not be degraded to more than 1.10 TBD the initial (SRD-prescribed) sensitivity in one year of operation; $h_{\text{one year}} < 1.10 \times h_0$. The rate of contamination is an environmental parameter determined by the VacEq and BT initial cleanliness and by the required procedures for cleaning and allowed materials determined by SYS. Thus, this requirement places constraints on the cleanliness and materials selection.

3.4.6.1 Allowed in-vacuum materials

Only materials listed in LIGO-E960022-02-E LIGO Vacuum Compatibility shall be used in the detector construction.

3.4.6.2 Cleaning procedures

Cleaning procedures detailed in LIGO-E960022-02-E LIGO Vacuum Compatibility shall be followed for all detector materials used in vacuum.

3.5. Non-Gaussian Pulse Rate

Needs considerable development.

The non-Gaussian pulse rate determines the sensitivity threshold for burst detection that is consistent with the required “false alarm” rate in triple coincidence of R(fa)<1/10 yr.

3.6. 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.

3.7. Design and Construction

3.7.1. 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 <u>*LIGO Project System Safety Management Plan*</u> *LIGO-M950046-F, section 3.3.2.*

3.8. Documentation

3.8.1. Interface Control Document

Presently separately documented for each subsystem (see Interface consistency between subsystems, Sievers T950110 and attached Interface documents). An Interface Control Document will be prepared.

3.8.2. Interferometer Optical Layout

The optical layout is in preparation as an aid to interface issues and their document. It will show the positions relative to the vacuum system of all interferometer optical components, including mirrors, pickoffs, modulators, and isolators, both inside and outside of the vacuum system. Also, parameters of the components, such as mirror transmissions and dimensions, are specified as part of the layout.

General principles:

- The axial (i.e., along the optical axis) position of the optical components, and the tolerance for this positioning, shall be defined by the optical layout
- All first reflection ‘wedge beams’ shall be brought out of the interferometer with high optical efficiency (.99) and with low wavefront distortion ($\lambda/10$) (COS); beams shall not be clipped such that more than 10^{-4} TBD of the power is lost
- Light transmitted from the two ETM shall be brought out of the interferometer with high optical efficiency (.99) and with low wavefront distortion ($\lambda/10$) (COS)

3.8.3. Technical Manuals and Procedures

3.8.3.1 Procedures

Procedures shall be provided for, at minimum,

- Shipping and receiving
- Vacuum bakeout, preparation and certification of components to be installed in vacuum
- Optics cleaning procedures and cleanliness certification
- Fabrication and pre-integration
- *Initial installation and setup of equipment*
- *Normal operation of equipment*
- *Normal and/or preventative maintenance*
- *Troubleshooting guide for any anticipated potential malfunctions*

3.8.3.2 Manuals

- Vacuum materials manual, including list of materials approved for use in vacuum and outgassing budget for components used in vacuum.
- Electrical interference manual, including sensitivity to electrical interference and allowed generation of electrical interference.

3.8.4. Documentation Numbering

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

3.8.5. Test Plans and Procedures

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

3.9. Logistics

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

4 QUALITY ASSURANCE PROVISIONS

4.1. General

The required performance of the LIGO Detector will be validated as far as practicable by a combination of analytical models, numerical simulations, and experiments. As an example, the model for the effect of residual gas was successfully tested in the 40 m interferometer, providing assurance that if the pressure specifications are met, residual gas in the beam tubes will not degrade the noise performance. The modeling and simulation efforts are particularly critical for parts of the design for which there are no simple scaling rules, such as the optical configuration.

4.1.1. Responsibility for Tests

Each subsystem task leader is responsible for delivering a subsystem that has been tested to meet the requirements imposed by SYS.

4.1.1.1 Reliability Testing

Reliability evaluation/development tests shall be conducted on items with limited reliability history that will have a significant impact upon the operational availability of the system.

4.1.2. Configuration Management

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

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

4.2.1. Inspections

Inspection shall be used to determine conformity with requirements that are neither functional nor qualitative; for example, identification marks.

4.2.2. ANALYSIS

Analysis may be used for determination of qualitative and quantitative properties and performance of an item by study, calculation and modeling.

4.2.3. DEMONSTRATION

Demonstration may be used for determination of qualitative properties and performance of an item and is accomplished by observation. Verification of an item by this method would be accomplished by using the item for the designated design purpose and would require no special test for final proof of performance.

4.2.4. SIMILARITY

Similarity analysis may be used in lieu of tests when a determination can be made that an item is similar or identical in design to another item that has been previously certified to equivalent or more stringent criteria. Qualification by similarity is subject to Detector management approval.

4.2.5. TEST

Test may be used for the determination of quantitative properties and performance of an item by technical means, such as, the use of external resources, such as voltmeters, recorders, and any test equipment necessary for measuring performance. Test equipment used shall be calibrated to the manufacture's specifications and shall have a calibration sticker showing the current calibration status.

5 PREPARATION FOR DELIVERY

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

5.1. Preparation

Equipment shall be appropriately prepared. For example, vacuum components shall be prepared to prevent contamination.

5.2. Packaging

Procedures for packaging shall ensure cleaning, drying, and preservation methods adequate to prevent deterioration, appropriate protective wrapping, adequate package cushioning, and proper containers. Proper protection shall be provided for shipping loads and environmental stress during transportation, hauling and storage.

5.3. 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 shall be provided.

APPENDIX 1 NOISE MODEL PARAMETERS

#	*parameter*	*value*	*units*
1	pi	3.1415926535897932	none
2	speed of light	299792458.0	m/s
3	permeability	12.566370614e-7	N/A^2
4	permittivity	8.854187817e-12	N/m
5	Newton const	6.6725985e-11	m^3/kg/s^2
6	Planck const	6.6260755e-34	Js
7	hbar	1.05457266-34	Js
8	electron charge	1.60217733e-19	C
9	Bohr magneton	9.2740154e-24	J/T
10	nucl magneton	5.0507866e-27	J/T
11	fine-struct const	7.29735308e-3	none
12	Rydberg const	10973731.534	m^-1
13	Bohr radius	0.529177249e-10	m
14	electron mass	9.1093897e-31	kg
15	elec magn moment	928.47701e-26	J/T
16	electon g-factor	2.002319304386	none
17	muon mass	1.8835327e-28	kg
18	muon magn moment	4.4904514e-26	J/T
19	muon g-factor	2.002331846	none
20	proton mass	1.6726231e-27	kg
21	neuton mass	1.6749286e-27	kg
22	Avogadro const	6.0221367e23	mol^-1
23	Faraday const	96485.309	C/mol
24	molar gas const	8.314510	J/mol/K
25	Boltzmann const	1.380658e-23	J/K

#	*parameter*	*value*	*units*
26	Stefan-Boltzmann	5.67051e-8	W/m^2/K^4
27	atomic mass unit	1.6605402e-27	kg
28	room temperature	295.37	K
29	mirror IE mass	10.8	kg
30	mirror IV mass	10.8	kg
31	mirror PE mass	10.8	kg
32	mirror PV mass	10.8	kg
33	mirror IE loss	4.0e-7	none
34	mirror IV loss	4.0e-7	none
35	mirror PE loss	4.0e-7	none
36	mirror PV loss	4.0e-7	none
37	mirror radius	12.5	cm
38	mirror length	10.00	cm
39	mirror Young Modulus	0.717e12	cgs units
40	mirror Poisson Ratio	0.16	cgs units
41	mirror density	2.20	g/cm^3
42	obsolete #1	0	none
43	num mirror modes	1000	none
44	mirror range freq min	5000.0	Hz
45	mirror range freq max	200000.0	Hz
46	mirror range freq step	50.0	Hz
47	radial terms in mirror	20	none
48	axial terms in mirror	20	none
49	radial vol elements	40	none
50	axial vol elements	40	none
51	wire diameter	0.003	INCHES
52	num violin modes	32	none
53	wire IE freq 1	376.0	Hz
54	wire IE Q 1	9.0e4	none
55	wire IE freq 2	376.0	Hz
56	wire IE Q 2	9.0e4	none
57	wire IE freq 3	376.0	Hz
58	wire IE Q 3	9.0e4	none
59	wire IE freq 4	376.0	Hz
60	wire IE Q 4	9.0e4	none
61	wire IV freq 1	376.0	Hz
62	wire IV Q 1	9.0e4	none
63	wire IV freq 2	376.0	Hz
64	wire IV Q 2	9.0e4	none

#	*parameter*	*value*	*units*
65	wire IV freq 3	376.0	Hz
66	wire IV Q 3	9.0e4	none
67	wire IV freq 4	376.0	Hz
68	wire IV Q 4	9.0e4	none
69	wire PE freq 1	376.0	Hz
70	wire PE Q 1	9.0e4	none
71	wire PE freq 2	376.0	Hz
72	wire PE Q 2	9.0e4	none
73	wire PE freq 3	376.0	Hz
74	wire PE Q 3	9.0e4	none
75	wire PE freq 4	376.0	Hz
76	wire PE Q 4	9.0e4	none
77	wire PV freq 1	376.0	Hz
78	wire PV Q 1	9.0e4	none
79	wire PV freq 2	376.0	Hz
80	wire PV Q 2	9.0e4	none
81	wire PV freq 3	376.0	Hz
82	wire PV Q 3	9.0e4	none
83	wire PV freq 4	376.0	Hz
84	wire PV Q 4	9.0e4	none
85	pendulum freq IE	0.744	Hz
86	pendulum freq IV	0.744	Hz
87	pendulum freq PE	0.744	Hz
88	pendulum freq PV	0.744	Hz
89	arm 1 length	4000.0	m
90	arm 2 length	4000.0	m
91	laser wavelength	1.064e-6	m
92	laser incident power	6.0	W
93	photodiode efficiency	0.80	e/photon
94	RF modulation depth	0.45	radians
95	recycling power gain	30.00	none
96	IE mirror reflectivity	0.999995	amplitude
97	IE mirror loss	50.0e-6	ppm
98	IV mirror reflectivity	0.9849	amplitude
99	IV mirror loss	50.0e-6	ppm
100	PE mirror reflectivity	0.999995	amplitude
101	PE mirror loss	50.0e-6	ppm
102	PV mirror reflectivity	0.9849	amplitude
103	PV mirror loss	50.0e-6	ppm

#	*parameter*	*value*	*units*
104	stray power on p-diode	0.024	% Pinc
105	test mass inertia IE	5.12e-2	kg*m^2
106	test mass inertia IV	5.12e-2	kg*m^2
107	test mass inertia PE	5.12e-2	kg*m^2
108	test mass inertia PV	5.12e-2	kg*m^2
109	cntrl block inertia IE	4.1e-5	kg*m^2
110	cntrl block inertia IV	8.8e-6	kg*m^2
111	cntrl block inertia PE	4.1e-5	kg*m^2
112	cntrl block inertia PV	8.8e-6	kg*m^2
113	dev from center IE	1.0e-3	m
114	dev from center IV	1.0e-3	m
115	dev from center PE	1.0e-3	m
116	dev from center PV	1.0e-3	m
117	dif pitch mode freq IE	0	Hz
118	dif pitch mode freq IV	0	Hz
119	dif pitch mode freq PE	0	Hz
120	dif pitch mode freq PV	0	Hz
121	dif pitch mode Q IE	2000	none
122	dif pitch mode Q IV	2000	none
123	dif pitch mode Q PE	2000	none
124	dif pitch mode Q PV	2000	none
125	com pitch mode freq IE	0.6	Hz
126	com pitch mode freq IV	0.6	Hz
127	com pitch mode freq PE	0.6	Hz
128	com pitch mode freq PV	0.6	Hz
129	com pitch mode Q IE	1250	none
130	com pitch mode Q IV	1250	none
131	com pitch mode Q PE	1250	none
132	com pitch mode Q PV	1250	none
133	dif yaw mode freq IE	0	Hz
134	dif yaw mode freq IV	0	Hz
135	dif yaw mode freq PE	0	Hz
136	dif yaw mode freq PV	0	Hz
137	dif yaw mode Q IE	4000	none
138	dif yaw mode Q IV	4000	none
139	dif yaw mode Q PE	4000	none
140	dif yaw mode Q PV	4000	none
141	com yaw mode freq IE	0.5	Hz
142	com yaw mode freq IV	0.5	Hz

#	*parameter*	*value*	*units*
143	com yaw mode freq PE	0.5	Hz
144	com yaw mode freq PV	0.5	hz
145	com yaw mode Q IE	4000	none
146	com yaw mode Q IV	4000	none
147	com yaw mode Q PE	4000	none
148	com yaw mode Q PV	4000	none
149	vert spring freq IE	13.00	Hz
150	vert spring freq IV	13.00	Hz
151	vert spring freq PE	13.00	Hz
152	vert spring freq PV	13.00	Hz
153	vert spring Q IE	333.33	none
154	vert spring Q IV	333.33	none
155	vert spring Q PE	333.33	none
156	vert spring Q PV	333.33	none
157	beam angle to horiz IE	3.10e-4	radians
158	beam angle to horiz IV	3.10e-4	radians
159	beam angle to horiz PE	3.10e-4	radians
160	beam angle to horiz PV	3.10e-4	radians
161	stack down tube length	0.90	meters
162	stack lever arm length	0.63	meters
163	horz pendulum Q IE	3.333e5	none
164	horz pendulum Q IV	3.333e5	none
165	horz pendulum Q PE	3.333e5	none
166	horz pendulum Q PV	3.333e5	none
167	topplate mass IE	250	kg
168	topplate mass IV	250	kg
169	topplate mass PE	250	kg
170	topplate mass PV	250	kg
171	TP vel damp freq IE	4	Hz
172	TP vel damp freq IV	4	Hz
173	TP vel damp freq PE	4	Hz
174	TP vel damp freq PV	4	Hz
175	TP vel damp Q IE	3	none
176	TP vel damp Q IV	3	none
177	TP vel damp Q PE	3	none
178	TP vel damp Q PV	3	none
179	TP int damp freq IE	6	Hz
180	TP int damp freq IV	6	Hz
181	TP int damp freq PE	6	Hz

#	*parameter*	*value*	*units*
182	TP int damp freq PV	6	Hz
183	TP int damp loss IE	0.33333	none
184	TP int damp loss IV	0.33333	none
185	TP int damp loss PE	0.33333	none
186	TP int damp loss PV	0.33333	none
187	end beamspot radius	4.565	cm
188	vertex beamspot radius	3.634	cm
189	LA ground density	2000.0	kg/m^3
190	LA Raleigh sound speed	188.0	m/s
191	LA P-wave sound speed	500.0	m/s
192	LA S-wave sound speed	200.0	m/s
193	WA upper ground density	2000.0	kg/m^3
194	WA lower ground density	2000.0	kg/m^3
195	WA Raleigh sound speed	253.8	m/s
196	WA upper P-wave snd spd	600.0	m/s
197	WA lower P-wave snd spd	1550.0	m/s
198	WA upper S-wave snd spd	270.0	m/s
199	WA lower S-wave snd spd	420.0	m/s
200	WA depth to lower layer	5.0	meters
201	vertex Mtest separation	4.1	meters
202	hydrogen mass	2.0	amu
203	water mass	18.0	amu
204	nitrogen mass	28.0	amu
205	oxygen mass	32.0	amu
206	carbon monoxide mass	28.0	amu
207	carbon dioxide mass	44.0	amu
208	methane mass	16.0	amu
209	hydrocarbon mass	41.0	amu
210	H2 polarizibility	7.4e-19	m^3
211	H2O polarizibility	1.4e-18	m^3
212	N2 polarizibility	1.6e-18	m^3
213	O2 polarizibility	1.6e-18	m^3
214	CO polarizibility	1.8e-18	m^3
215	CO2 polarizibility	2.38e-18	m^3

#	*parameter*	*value*	*units*
216	CH4 polarizibility	2.36e-18	m^3
217	H2 partial pressure	5.0e-9	torr
218	H2O partial pressure	1.0e-7	torr
219	N2 partial pressure	1.0e-7	torr
220	O2 partial pressure	1.0e-10	torr
221	CO partial pressure	1.0e-8	torr
222	CO2 partial pressure	1.0e-8	torr
223	CH4 partial pressure	1.0e-10	torr
224	hydrocarbon part press	1.0e-11	torr
225	radius vertex mirror	14558.0	meters
226	radius end mirror	7402.0	meters