LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
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Suspension Design Requirements

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1 INTRODUCTION

1.1. Purpose

This Design Requirements Document (DRD) for Suspension System (SUS) identifies the information necessary to define the SUS subsystem and quantify its relationship to other subsystems.

1.2. Scope

SUS will develop and provide the suspension system for all the suspended components of Core Optics Component (COC) and Input/Output Optics (IOO).

1.3. Definitions

SUS is the system which suspends, protects, damps, and actuates the optics.

1.4. Acronyms

- LOS1: Large Optics Suspension 1
- LOS2: Large Optics Suspension 2
- LOS3: Large Optics Suspension 3
- SOS: Small Optics Suspension

Acronyms for names of subsystems should be referred to [8] "LIGO DETECTOR Workbook", LIGO-M940005-C-D (p. 13).

1.5. Applicable Documents

1.5.1. LIGO Documents

[1] "Alignment Sensing/Control Design Requirements Document", LIGO-T952007-01-I
[2] "Core Optics Components Requirements (1064 nm)", LIGO-E950099-01-D
[3] "Framework of Range Requirement of Suspension Actuator", LIGO-T960070-00-D
[4] "Frequency, Intensity and Oscillator Noise in the LIGO", LIGO-T960019-00-D
[5] "Interferometer Requirements Flowdown to SUS", LIGO-T950061-01-D
[6] "Length Sensing and Control Design Requirements Document", LIGO-T960058-00-D
[7] "LIGO EMI Control Plan and Procedures", LIGO-E960036-A-E
[8] "LIGO DETECTOR Workbook", LIGO-M940005-C-D
[9] "LIGO Naming Conventions", LIGO-E950111-A-E
[10] "LIGO Project System Safety Management Plan", LIGO-M950046-F
[11] "LIGO Science Requirements Document", LIGO-E950018-02-E
[12] "LIGO Vacuum Compatibility, Cleaning Methods and Procedures", LIGO-E960022-00-D
[13] "Mirror-Orientation Noise in a Fabry-Perot Interferometer Gravitational Wave Detector",

LIGO-P940012-00-R
[14] "Mode cleaner Noise Sources", LIGO-T960165-00-D
[15] "Naming Convention and Interface Definition for SUS", LIGO-T950060-00-D
[16] "Response of Pendulum to Motion of Suspension Point", LIGO-T960040-00-D
[17] "Seismic Isolation Design Requirements Document", LIGO-T960065-02-D
[18] "Suspension Design Requirements", LIGO-T950011-14-D
[19] "Suspension Losses in the Pendula of Laser Interferometer Gravitational-Wave Detectors", LIGO-P940011-00-R
[20] "Suspension Preliminary Design", LIGO-T960074-00-D
[21] "Suspension Test Plan", LIGO-T960086-00-D
[22] "Thermally Excited Vibrations of the Mirrors of Laser Interferometer Gravitational-Wave Detectors", LIGO-P940003-00-R
[23] "Thermal Noise in HAM OS", LIGO-T960090-00-D

1.5.2. Non-LIGO Documents

2 GENERAL DESCRIPTION

2.1. Specification Tree

This document is part of an overall LIGO detector requirement specification tree. This particular document is circled in Fig. 1.

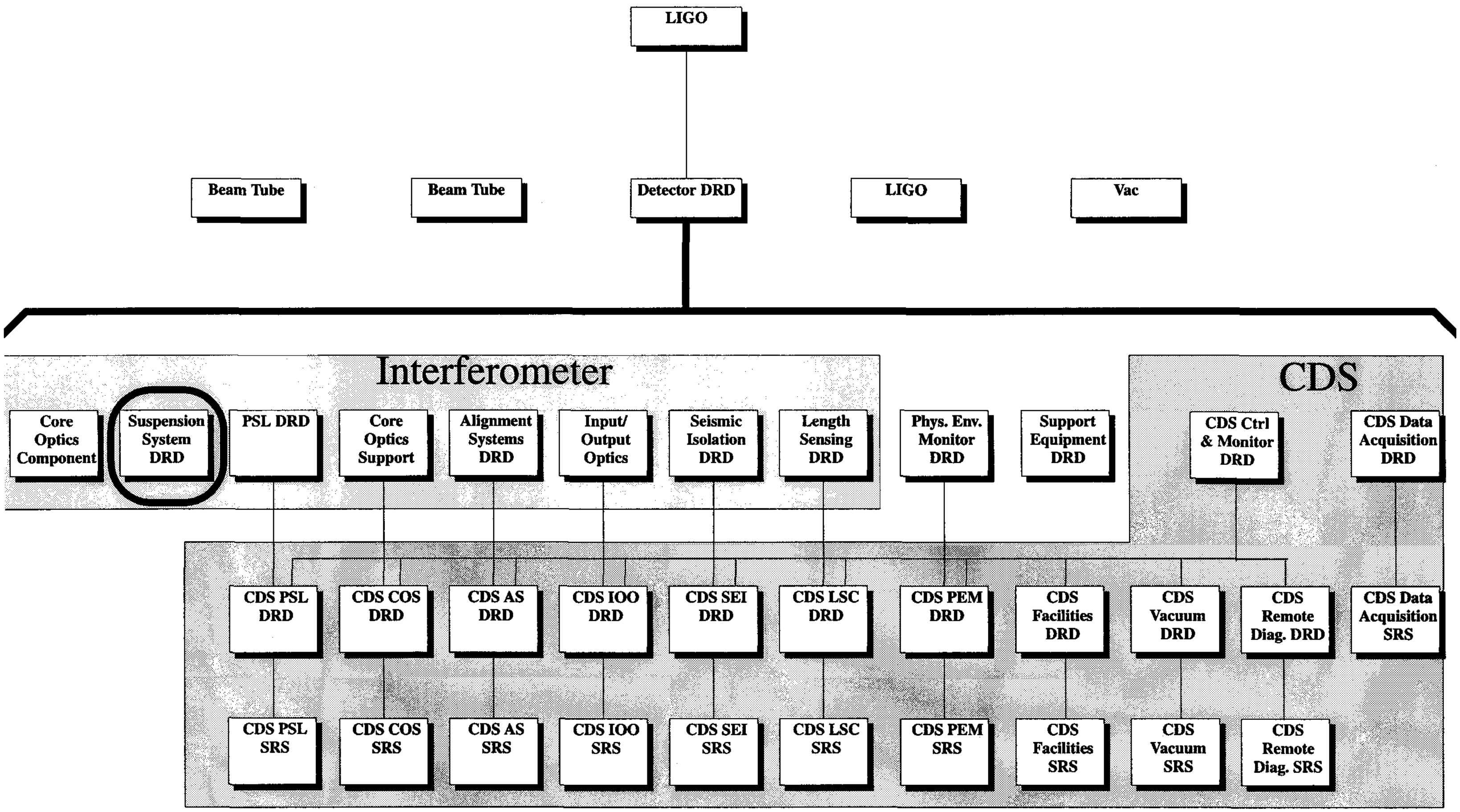


Figure 1: Overall LIGO detector requirement specification tree. SUS DRD is circled.

2.2. Product Perspective

SUS relates to the rest of the system as shown in Fig. 2.

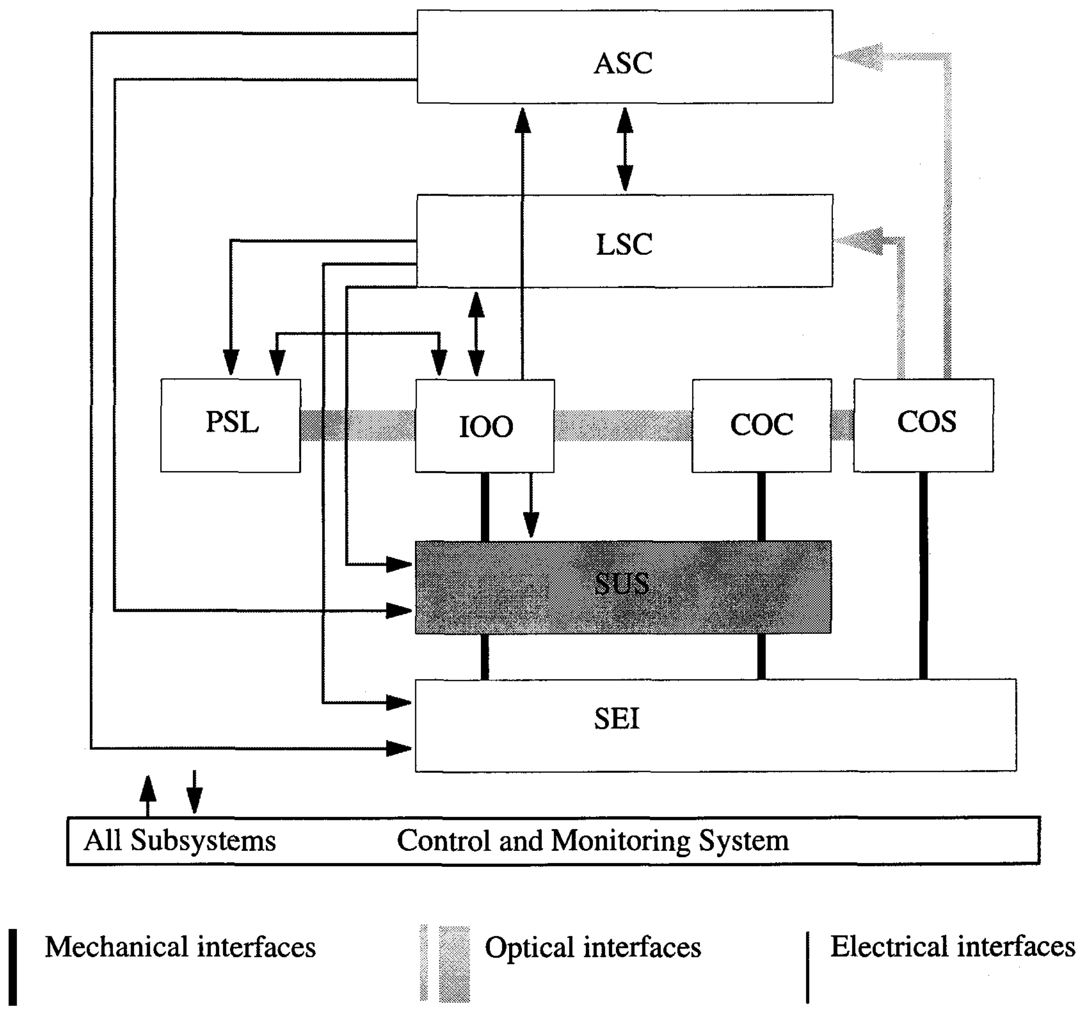


Figure 2: Relationship of SUS to the rest of the detector subsystem. SUS is shaded.

2.3. Product Functions

The main functions of SUS are:

- Suspend a test mass to allow it to move freely horizontally for detection of gravitational waves.
- Isolate an optical component from ground motion by suspending the component.
- Damp the optical component's motion in position and orientation using the local suspension's sensors and actuators.
- Provide control inputs for applying forces and torques to the suspended component in

response to signals from the LSC and ASC systems.
- Suppress the noise related to the SUS system to the desired level.
- Protect the optical components by limiting motion from external disturbance.
- Hold the optical components firmly during installation.
- Reduce the effect of stray/scattered light from the optical component.

2.4. General Constraints

- The initial LIGO must have a sensitivity specified in [11] "LIGO Science Requirements Document", LIGO-E950018-02-E, which SUS must not preclude.
- LIGO must operate continuously, therefore SUS must be designed with high reliability and low mean time to repair.
- LIGO interferometers have strict vacuum-compatibility requirements which constrain the material choices for the SUS components to those materials compatible with [12] "LIGO Vacuum Compatibility, Cleaning Methods and Procedures", LIGO-E960022-00-D.

2.5. Suspension type

There will be four types of suspension systems depending on the size of the suspended optical component: Large Optics Suspension 1 (LOS 1), Large Optics Suspension 2 (LOS 2), Large Optics Suspension 3 (LOS 3), and small optics suspension (SOS). A list of suspended optical components for each suspension system is shown in Table 1.

Chapter 3 describes LOS1/2/3 and Chapter 4 describes SOS.

Table 1: List of suspended optical components

SUS type	*Suspended Optical Components (Subsystem)*
LOS 1	Test Mass (CO), Recycling Mirror (CO), Large Mode Matching Mirror (IOO), Faraday Isolator (IOO)[a]
LOS 2	Beamsplitter (CO)
LOS 3	Large Folding Mirror (CO)
SOS	Mode Cleaner Mirror (IOO), Small Mode Matching Mirror (IOO), Small Folding Mirror (IOO), Small Pick-off (IOO)

a. An adapter ring will be fitted to the Faraday Isolator to fit it into the standard assembly.

3 LARGE OPTICS SUSPENSION 1/2/3

3.1. Assumptions

3.1.1. Assumptions in SUS

3.1.1.1 Single Pendulum

The suspension system employs a single pendulum as opposed to a multi-stage pendulum.

3.1.1.2 Damping by Suspension's Sensor

Test masses are damped using the suspension's sensor signal before and during the lock acquisition. The other suspended components are always (before, during, and after the lock acquisition) damped using the suspension's sensor signal.

3.1.1.3 Suspension's Actuator

The suspension's actuator is used to correct fluctuations on the time scale that is shorter than the microseismic peak (f > 0.15 Hz). The stack support actuator is used to correct fluctuations on the time scale of the microseismic peak and longer.

3.1.2. Assumption in Other Subsystems

3.1.2.1 Size of Optics

The size, wedge, and optical clear aperture of the suspended optics (COC) are listed in [2] "Core Optics Components Requirements (1064 nm)", LIGO-E950099-01-D.

3.1.2.2 Beam Spot Offset

The requirement of the beam spot offset from the center of the optic is 1 mm for the test mass (ASC).

3.1.2.3 Internal Mode Loss of Bare Substrate

The required internal mode loss of the bare substrate of the test mass (COC) is 3×10^{-7}.

3.2. Specific Requirements

3.2.1. Requirements Flowdown

Performance requirements of SOS are derived from system requirements of the interferometer noise and detector availability. Fig. 3 shows the noise and availability requirements flowdown to the SUS subsystem. The requirements for LOS are shaded.

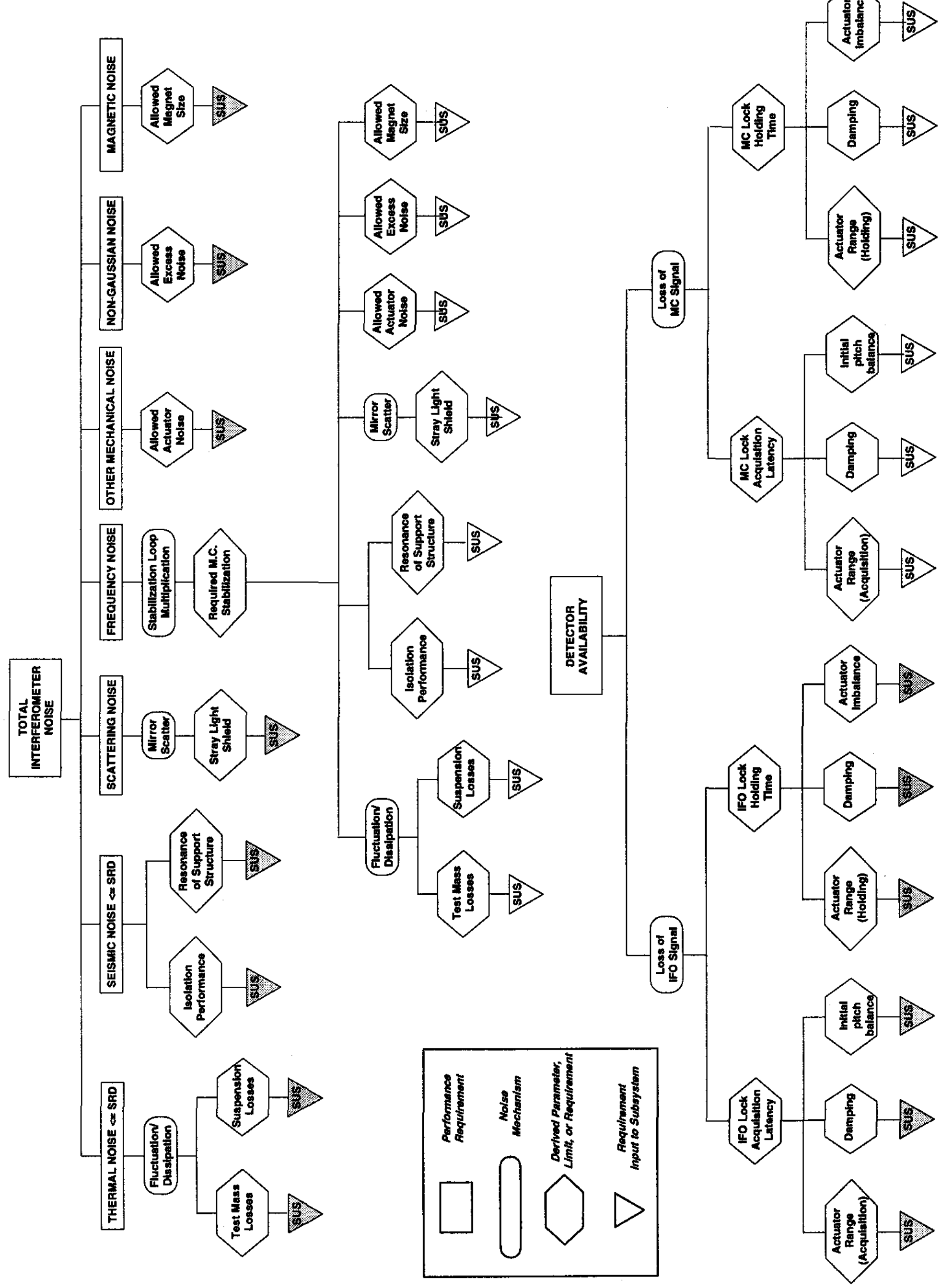


Figure 3: Interferometer noise and detector availability requirements flowdown to LOS.

3.2.2. Detector Availability

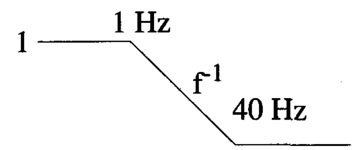
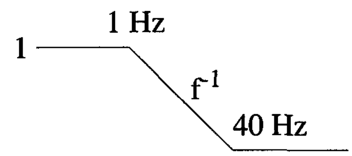
3.2.2.1 Range

The actuator range for LOS is required to provide:

- continuous operation of the LSC system,
- smooth acquisition of the LSC system,
- proper initial alignment, and
- continuous operation of the ASC system.

Table 2 shows the requirement of the suspension range for displacement (operation and acquisition mode) and orientation of the mass. (See [3] "Framework of Range Requirement of Suspension Actuator", LIGO-T960070-00-D).

Table 2: Requirement of the LOS suspension actuator range.

Mode		*DC Peak-to-Peak Motion*	*Weighting Function*
Displacement	Operation	20 μm_{pp}	
	Acquisition	20 μm_{pp}	Frequency Independent Force
Orientation		0.5 $mrad_{pp}$ in pitch 0.5 $mrad_{pp}$ in yaw	

3.2.2.2 Damping

The magnitude and quality of damping of the suspended component for LOS is required to provide:

- stable operation of the LSC system,
- smooth acquisition of the LSC system, and
- negligible up-conversion noise of the spurious interferometer.

In the transfer function from (horizontal, vertical, and pitch/yaw) motion of the suspension point to (horizontal and pitch/yaw) motion of the suspended mass, the maximum allowed amplitude around the resonant frequencies over the amplitude at DC is required to be less than 3.

3.2.2.3 Actuator Imbalance

The four face actuators of LOS are required to be balanced to ensure:

- No significant cross-coupling from the LSC signal to orientation of the optics.
- No significant cross-coupling from the ASC signal to displacement of the optics.

The maximum variation of force exerted by four face actuators is required to be less than 0.01.

3.2.2.4 Initial Pitch Imbalance

The initial pitch imbalance of the optical component is required to be less than 0.1 mrad.

3.2.3. Interferometer Noise

The required interferometer noise specified in [11] "LIGO Science Requirements Document", LIGO-E950018-02-E is $\tilde{x} = 1.0 \times 10^{-18} \mathrm{m}/\sqrt{\mathrm{Hz}}$ at 40 Hz and $\tilde{x} = 1.6 \times 10^{-19} \mathrm{m}/\sqrt{\mathrm{Hz}}$ at 100 Hz. Therefore displacement noise requirement per test mass is $1/\sqrt{4}$ of them, that is $\tilde{x} = 5.0 \times 10^{-19} \mathrm{m}/\sqrt{\mathrm{Hz}}$ at 40 Hz and $\tilde{x} = 8.0 \times 10^{-20} \mathrm{m}/\sqrt{\mathrm{Hz}}$ at 100 Hz. We allocate a portion of this displacement noise to each noise source.

3.2.3.1 Transfer Function of Suspension

The transfer function of the suspension for LOS is required to provide sufficient isolation above 40 Hz to meet the required displacement noise. Table 3 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. See Appendix A.1 for the requirement derivation. Wire violin modes are excluded. Coordination of the requirements between the suspension transfer function and the stack isolation is explained in [17] "Seismic Isolation Design Requirements Document", LIGO-T960065-02-D.

Table 3: Requirements matrix of the transfer function of the LOS suspension system from motion of the suspension point to motion of the suspended mass (f > 40Hz).

Transfer Function (*From* ↓ / *To* →)	*Horizontal (m)*	*Vertical (m)*	*Pitch (rad)*
Horizontal (m)	$< (f_p/f)^2$ m/m $f_p = 0.74$ Hz	N/A	$< \alpha \times (f_p/f)^2$ rad/m $\alpha = 100$
Vertical (m)	$< 3\times10^{-5} \times (f_v/f)^2$ m/m	$< (f_v/f)^2$ m/m $f_v = 13$ Hz	$< \beta \times (f_v/f)^2$ rad/m $\beta = 3 \times 10^{-2}$

3.2.3.2 Resonance of Suspension Support Structure

The resonance of the LOS suspension support structure shall not preclude meeting the required displacement noise. Table 4 shows the requirements for the frequency and Q of the resonance of the suspension support structure. See [23] "Thermal Noise in HAM OS", LIGO-T960090-00-D.

Table 4: Requirements for resonances of the LOS suspension support structure.

Physical Quantity	*Requirement*
Resonant Frequency	> 160 Hz
Q	< 300

3.2.3.3 Thermal Losses

We allocate 100% of the allowed displacement noise between 40 Hz and 100 Hz to thermal noise. There are three kinds of thermal losses with regard to the suspension system (See Appendix A.2 for details):

- internal mode losses due to the suspension attachments,
- suspension (pendulum, pitch/yaw, and vertical mode) losses,
- eddy current damping losses due to interaction between the magnets and the external metal.

Table 5 shows the requirements of the (average effective) thermal loss of the suspension system.

Table 5: Requirements of the (average effective) thermal loss of the LOS suspension system.

Damping Mode/ Mechanism	*Allocation to the Allowed Displacement Noise*		*Loss*
	40 Hz	*100 Hz*	
Internal mode	19%	75%	$< 8.2\times10^{-7}$
Pendulum	90%	58%	$< 6.0\times10^{-6}$
Pitch	10%	6%	$< 5.4\times10^{-4}$
Yaw	10%	6%	$< 7.8\times10^{-4}$
Vertical	10%	6%	$< 2.8\times10^{-3}$
Eddy Current Damping	20	20	$< 7.5\times10^{-7}\times\left(\frac{f}{100\text{Hz}}\right)$
Total	96%	97%	N/A

3.2.3.4 Control Noise

We allocate 10% of the allowed displacement noise ($8.0 \times 10^{-21} \mathrm{m}/\sqrt{\mathrm{Hz}}$ at 100 Hz per test mass) to control noise. Table 6 shows the requirements of the control noise per test mass expressed in displacement or orientation motion. A beam spot offset of 1 mm are assumed for the pitch/yaw requirement.

Table 6: Requirements of the LOS control noise per mass (40 Hz < f < 100 Hz).

Mode	*Allocation to the allowed displacement noise*	*Control Noise*
Displacement	10%	$< 8.0 \times 10^{-21} \times \left(\frac{100\mathrm{Hz}}{\mathrm{f}}\right)^2 \mathrm{m}/\sqrt{\mathrm{Hz}}$
Pitch/Yaw	1% each	$< 8.0 \times 10^{-19} \times \left(\frac{100\mathrm{Hz}}{\mathrm{f}}\right)^2 \mathrm{rad}/\sqrt{\mathrm{Hz}}$
Total	10%	N/A

3.2.3.5 Magnet Strength

The strength of the magnets used for actuation is required to cause no more than 10% of the required displacement noise.

3.2.3.6 Excess Noise

TBD

3.2.4. Size Constraints

The size constraints for LOS are:

- LOS must accommodate a large optical component and must satisfy a condition of optical clear aperture.
- LOS must provide a proper vertical position for its suspended component.

4 SMALL OPTICS SUSPENSION

4.1. Assumptions

4.1.1. Assumptions in SUS

4.1.1.1 Single Pendulum

The suspension system employs a single pendulum as opposed to a multi-stage pendulum.

4.1.1.2 Damping by Suspension's Sensor

A suspended component is always (before and after the lock acquisition) damped using the sensor signals from its respective suspension assembly.

4.1.1.3 Suspension's Actuator

The suspension's actuator is used to correct all the fluctuations during operation.

4.1.2. Assumption in Other Subsystems

4.1.2.1 Size of Optics

The size, wedge, and optical clear aperture of the suspended optics (IOO) are listed in **TBD**.

4.1.2.2 Mode Cleaner Output Frequency Noise

Allowed frequency noise of the light coming out of the mode cleaner (IOO) is

$1.0 \times 10^{-4}\mathrm{Hz}/\sqrt{\mathrm{Hz}}$ at 100 Hz with $f^{-0.5}$ dependence above 100 Hz and f^{-2} dependence below 100 Hz (See [6] "Length Sensing and Control Design Requirements Document", LIGO-T960058-00-D).

4.1.2.3 Beam Spot Offset

The requirement of the beam spot offset from the center of the optic is 3 mm for mode cleaner mirrors (ASC).

4.1.2.4 Level of Mode Cleaner

The requirement of the level of the mode cleaner (IOO) is $3 \times 10^{-4}\mathrm{rad}$.

4.1.2.5 Internal Mode Loss of Bare Substrate

The required internal mode loss of the bare substrate of the mode cleaner mirrors (IOO) is **TBD**.

4.2. Specific Requirements

4.2.1. Requirements Flowdown

Performance requirements of SOS are derived from system requirements of the interferometer noise and detector availability. Fig. 4 shows the noise and availability requirements flowdown to the SUS subsystem. The requirements for SOS are shaded.

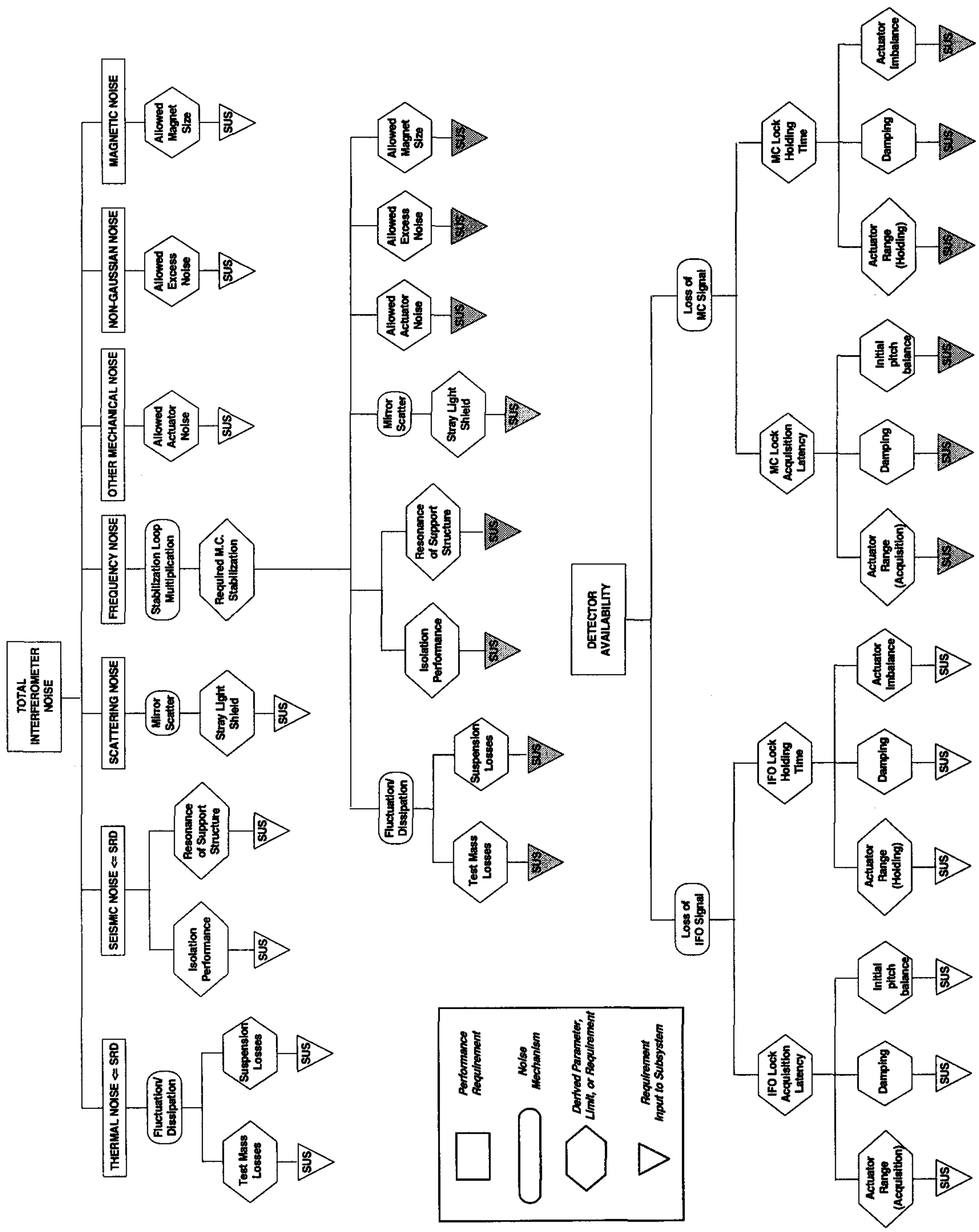


Figure 4: Interferometer noise and detector availability requirements flowdown to SOS.

4.2.2. Detector Availability

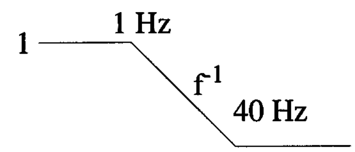
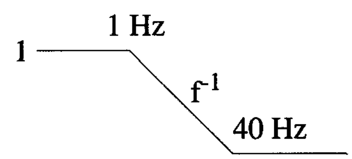
4.2.2.1 Range

The actuator range for SOS is required to provide:

- continuous operation of the LSC and IOO system,
- smooth acquisition of the LSC and IOO system,
- proper initial alignment, and
- continuous operation of the ASC system.

Table 7 shows the requirement of the suspension range for displacement (operation and acquisition mode) and orientation of the mass. (See [3] "Framework of Range Requirement of Suspension Actuator", LIGO-T960070-00-D).

Table 7: Requirement of the SOS suspension actuator range.

Mode		*DC Peak-to-Peak Motion*	*Weighting Function*
Displacement	Operation	40 μm_{pp}	
	Acquisition	40 μm_{pp}	Frequency independent Force
Orientation		3 $mrad_{pp}$ in pitch 3 $mrad_{pp}$ in yaw	

4.2.2.2 Damping

The magnitude and quality of damping of the suspended component for SOS is required to provide:

- stable operation of the LSC and IOO system,
- smooth acquisition of the LSC and IOO system, and
- negligible up-conversion noise of the spurious interferometer.

In the transfer function from (horizontal, vertical, and pitch/yaw) motion of the suspension point to (horizontal and pitch/yaw) motion of the suspended mass, the maximum allowed amplitude around the resonant frequencies over the amplitude at DC is required to be less than 3.

4.2.2.3 Actuator Imbalance

The four face actuators of SOS are required to be balanced to ensure:

- No significant cross-coupling from the LSC and IOO signal to orientation of the optics.
- No significant cross-coupling from the ASC signal to displacement of the optics.

The maximum variation of force exerted by four face actuators is required to be less than 0.01.

4.2.2.4 Initial Pitch Imbalance

The initial pitch imbalance of the optical component is required to be less than 0.5 mrad.

4.2.3. Interferometer Noise

The required frequency noise of the light coming out of the mode cleaner is

$\tilde{\nu} = 1.0 \times 10^{-4} \mathrm{Hz}/\sqrt{\mathrm{Hz}}$ at 100 Hz with $f^{-0.5}$ frequency dependence above 100 Hz and f^{-2} frequency dependence below 100 Hz. Therefore displacement noise requirement per MC mirror is

$\tilde{x}_{MC} = \frac{1}{\sqrt{3}} \cdot \frac{l_{MC} \cdot \tilde{\nu}}{\nu_0} = 2.4 \times 10^{-18} \mathrm{m}/\sqrt{\mathrm{Hz}}$ at 100 Hz, where l_{MC} is the length of the mode cleaner and ν_0 is the frequency of the light. We allocate a portion of this displacement noise to each noise source.

4.2.3.1 Transfer Function of Suspension

The transfer function of the suspension for SOS is required to provide sufficient isolation above 40 Hz to meet the required frequency noise of the light coming out of the mode cleaner. Table 8 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 See Appendix B.1 for the requirement derivation. Wire violin modes are excluded. Coordination of the requirements between the suspension transfer function and the stack isolation is explained in [17] "Seismic Isolation Design Requirements Document", LIGO-T960065-02-D.

4.2.3.2 Resonance of Suspension Support Structure

The resonance of the SOS suspension support structure shall not preclude meeting the required frequency noise of the light coming out of the mode cleaner. Table 8 shows the requirements for the frequency and Q of the resonance of the suspension support structure. See [23] "Thermal Noise in HAM OS", LIGO-T960090-00-D.

Table 8: Requirements for resonances of the SOS suspension support structure.

Physical Quantity	*Requirement*
Resonant Frequency	> 150 Hz
Q	< 300

4.2.3.3 Thermal Losses

We allocate 70% of the allowed MC displacement noise ($1.6 \times 10^{-18} \mathrm{m}/\sqrt{\mathrm{Hz}}$ at 100 Hz per MC mirror) to thermal noise. There are three kinds of thermal losses with regard to the suspension system (See Appendix B.2 for details):

- internal mode losses due to the suspension attachments,
- suspension (pendulum, pitch/yaw, and vertical mode) losses,
- eddy current damping losses due to interaction between the magnets and the external metal.

Table 9 shows the requirements of the (average effective) thermal loss of the suspension system.

Table 9: Requirements of the (average effective) thermal loss of the SOS suspension system.

Damping Mode/ Mechanism	*Allocation to the allowed MC displacement noise*	*Loss*
Internal mode	50%	$< 9.6 \times 10^{-6}$
Pendulum	20%	$< 9.0 \times 10^{-6}$
Pitch	20%	$< 5.3 \times 10^{-4}$
Yaw	20%	$< 6.8 \times 10^{-4}$
Vertical	10%	$< 9.9 \times 10^{-2}$
Eddy Current Damping	30%	$< 2.0 \times 10^{-5} \times \left(\frac{f}{100\mathrm{Hz}}\right)$
Total	70%	N/A

4.2.3.4 Control Noise

We allocate 30% of the allowed MC displacement noise ($7.3 \times 10^{-19} \mathrm{m}/\sqrt{\mathrm{Hz}}$ at 100 Hz per MC mirror) to control noise. Table 10 shows the requirements of the control noise per mass expressed in displacement or orientation motion. A beam spot offset of 3 mm are assumed for the pitch/yaw requirement.

Table 10: Requirements of the SOS control noise per mass (40 Hz < f < 100 Hz).

Mode	*Allocation to the allowed MC displacement noise*	*Control Noise*
Displacement	25%	$< 6.1 \times 10^{-19} \times \left(\frac{100\text{Hz}}{\text{f}}\right)^2 \text{m}/\sqrt{\text{Hz}}$
Pitch/Yaw	10% each	$< 8.2 \times 10^{-17} \times \left(\frac{100\text{Hz}}{\text{f}}\right)^2 \text{rad}/\sqrt{\text{Hz}}$
Total	30%	N/A

4.2.3.5 Magnet Strength

The strength of the magnets used for actuation is required to cause no more than 30% of the required frequency noise of the light coming out of the mode cleaner.

4.2.3.6 Excess Noise

TBD

4.2.4. Size Constraints

The size constraints for SOS are:

- SOS must accommodate a small optical component and must satisfy a condition of optical clear aperture.
- SOS must provide a proper vertical position for its suspended component.

5 GENERAL REQUIREMENTS

This chapter describes general requirements which are common to LOS and SOS.

5.1. General Characteristics

5.1.1. Reliability

Mean Time Between Failures (MTBF) should be **TBD**.

5.1.2. Maintainability

Mean Time To Repair (MTTR) should be less than **TBD**.

5.1.3. Environmental Conditions

5.1.3.1 Natural Environment

5.1.3.1.1 Temperature and Humidity

TBD

5.1.3.1.2 Atmospheric Pressure

TBD

5.1.3.1.3 Seismic Disturbance

TBD

5.1.3.2 Induced Environment

5.1.3.2.1 Electromagnetic Radiation

Per [7] “LIGO EMI Control Plan and Procedures”, LIGO-E960036-A-E

5.1.3.2.2 Acoustic

TBD

5.1.3.2.3 Mechanical Vibration

TBD

5.1.4. 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.

5.2. Design and Construction

5.2.1. Materials and Processes

5.2.1.1 Finishes

- Metal components must have quality finishes on all surfaces, suitable for vacuum finishes.
- All materials must have non-shedding surfaces.

5.2.1.2 Materials

All materials used inside the vacuum must comply with [12] "LIGO Vacuum Compatibility, Cleaning Methods and Procedures", LIGO-E960022-00-D.

5.2.1.3 Processes

5.2.1.3.1 Welding

TBD

5.2.1.3.2 Annealing

TBD

5.2.1.3.3 Cleaning

All materials used inside the vacuum chambers must be cleaned in accordance with [12] "LIGO Vacuum Compatibility, Cleaning Methods and Procedures", LIGO-E960022-00-D.

5.2.2. Component Naming

All components shall be identified using [9] "LIGO Naming Conventions", LIGO-E950111-A-E.

5.2.3. Workmanship

TBD

5.2.4. Interchangeability

All LOS1 components must be interchangeable among LOS1 systems except for those components that depend on wedge value and orientation. All SOS components must be interchangeable among SOS systems except for components that depend on wedge value and orientation.

5.2.5. 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 section 3.3.2. of [10] "LIGO Project System Safety Management Plan", LIGO-M950046-F.

No special considerations for human safety are presented by the suspension design, except for the normal precautions taken with electronics. The suspension actuator electronics will be capable of delivering voltages up to 150 Volts.

The following special precautions must be taken to assure safety of the equipment:

- the suspension hardware and the suspended component are ultrahigh-vacuum components and

must be handled according to approved LIGO procedures to prevent contamination
- the magnet/standoff assemblies are extremely delicate and must be protected during all operations prior to mounting the suspended component into the suspension structure
- tools fabricated from metal or other hard substances should be kept away from the suspended component's polished faces to prevent scratching or marring of these surfaces
- suspended components must always be properly locked into the safety cage before any movement of the suspension structure is attempted

5.2.6. Human Engineering

The suspension design must allow for coarse alignment of the suspended component relative to the suspension support structure to be accomplished on a clean bench outside the vacuum chamber. The alignment procedure is delicate and requires that personnel aligning an optic have comfortable access to the components. Alignment procedures within the vacuum chamber will be restricted to adjustments of the orientation of the suspension support structure. Fine alignment will be accomplished through the suspension actuators.

5.3. Documentation

5.3.1. Specifications

TBD

5.3.2. Design Documents

- Suspension Final Design

5.3.3. Engineering Drawings and Associated Lists

TBD

5.3.4. Technical Manuals and Procedures

5.3.4.1 Procedures

Procedures shall be provided for, at minimum,

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

5.3.4.2 Manuals

TBD

5.3.5. Documentation Numbering

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

5.3.6. Test Plans and Procedures

Test plan is documented in [21] "Suspension Test Plan", LIGO-T960086-00-D.

All procedures shall be developed in accordance with **TBD**.

5.4. Logistics

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

5.5. Precedence

This section should list the relative importance of requirements (or goals) to be achieved by the design.

5.6. Qualification

Test and acceptance criteria.

6 QUALITY ASSURANCE PROVISIONS

This section includes all of the examinations and tests to be performed in order to ascertain the product, material or process to be developed or offered for acceptance conforms to the requirements in section 3.

6.1. General

This should outline the general test and inspection philosophy, including all phases of development.

6.1.1. Responsibility for Tests

Who is responsible for testing.

6.1.2. Special Tests

6.1.2.1 Engineering Tests

List any special engineering tests which are required to be performed. Engineering tests are those which are used primarily for the purpose of acquiring data to support the design and development.

6.1.2.2 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.

6.1.3. Configuration Management

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

6.2. 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:

6.2.1. Inspections

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

6.2.2. Analysis

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

6.2.3. 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.

6.2.4. 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.

6.2.5. 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.

7 PREPARATION FOR DELIVERY

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

7.1. Preparation

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

7.2. 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.

7.3. 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 A REQUIREMENT DERIVATION FOR LOS

A.1. Transfer Function of LOS Suspension

A.1.1. Transfer Function from Horizontal to Horizontal, T_{hh}

The transfer function is required to represent a single pendulum performance.

A.1.2. Transfer Function from Horizontal to Pitch, T_{hp}

The requirement is obtained by demanding the resultant cavity length variation due to pitch motion with a beam spot offset d = 1 mm to be 10% of the transfer function from horizontal to horizontal:

$$d \times T_{hp} < 0.1 \times T_{hh} . \quad (1)$$

A.1.3. Transfer Function from Vertical to Vertical, T_{vv}

The transfer function is required to represent a single spring performance. Incidentally the resultant vertical motion contributes to the cavity length variation due to a misalignment of the optical axis with the local perpendicular to gravity at the test mass chamber (3×10^{-4}).

A.1.4. Transfer Function from Vertical to Horizontal, T_{vh}

The requirement is obtained by demanding the resultant horizontal motion to be 10% of the resultant cavity length variation due to the vertical to vertical transfer function:

$$T_{vh} < 0.1 \times (3 \times 10^{-4}) \times T_{vv} . \quad (2)$$

A.1.5. Transfer Function from Vertical to Pitch, T_{vp}

The requirement is obtained by demanding the resultant cavity length variation due to pitch motion with a beam spot offset d = 1 mm to be 10% of the resultant cavity length variation due to the vertical to vertical transfer function:

$$d \times T_{vp} < 0.1 \times (3 \times 10^{-4}) \times T_{vv}. \tag{3}$$

A.2. Thermal Noise for LOS

A.2.1. Internal Mode

We allocate 19% of the allowed displacement noise at 40 Hz ($\tilde{x} = 9.5 \times 10^{-20} \mathrm{m}/\sqrt{\mathrm{Hz}}$ per test mass) and 75% of the allowed displacement noise at 100 Hz ($\tilde{x} = 6.0 \times 10^{-20} \mathrm{m}/\sqrt{\mathrm{Hz}}$ per test mass) to the internal mode thermal noise.

Thermal noise due to internal vibrations of the test masses was estimated following the method used in [22] "Thermally Excited Vibrations of the Mirrors of Laser Interferometer Gravitational-Wave Detectors", LIGO-P940003-00-R.

$$\tilde{x}_{TM, int}(f) = 2.1 \times 10^{-20} \frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}} \cdot \left(\frac{100\ \mathrm{Hz}}{f}\right)^{1/2} \cdot \left(\frac{\varphi(f)}{10^{-7}}\right)^{1/2} \tag{4}$$

for the average displacement noise per test mass, accounting for the finite spot sizes of the beams on the flat and curved mirrors, and summing over the appropriate internal modes of the mirrors. Therefore the average effective Loss of internal modes with attachments must be less than 8.2×10^{-7}

A.2.2. Pendulum Mode

We allocate 90% of the allowed displacement noise at 40 Hz ($\tilde{x} = 4.5 \times 10^{-19} \mathrm{m}/\sqrt{\mathrm{Hz}}$ per test mass) and 58% of the allowed displacement noise at 100 Hz ($\tilde{x} = 4.6 \times 10^{-20} \mathrm{m}/\sqrt{\mathrm{Hz}}$ per test mass) to the pendulum mode thermal noise.

The spectral density of the displacement due to the pendulum thermal noise is:

$$\tilde{x}^2_{TM, pen}(f) = \frac{4k_B T}{M} \cdot \frac{\omega_0^2 \varphi(f)}{\omega[(\omega_0^2 - \omega^2)^2 - \omega_0^4 \varphi^2(f)]} \tag{5}$$

where $k_B = 1.4 \times 10^{-23}$ J/K, T = 295 K, M = 10.7 kg, and $\omega_0 = 0.74 \times 2\pi$ are Boltzman's constant, the temperature, the mass, and the resonant angular frequency, respectively. $\varphi(f)$ must be less than 6.0×10^{-6}.

A.2.3. Pitch and Yaw Mode

We allocate 10% of the allowed displacement noise at 40 Hz ($\tilde{x} = 5.0 \times 10^{-20} \mathrm{m}/\sqrt{\mathrm{Hz}}$ per test mass) and 6% of the allowed displacement noise at 100 Hz ($\tilde{x} = 5.1 \times 10^{-21} \mathrm{m}/\sqrt{\mathrm{Hz}}$ per test mass) to each of the pitch and yaw mode thermal noise.

Suspension pitch/yaw thermal noise couples with the beam spot offset from the center of mass to be converted into the cavity length variations. Since the requirement for the beam spot offset (ASC) is 1 mm, the required angle fluctuation is $\tilde{\theta} = 5.0 \times 10^{-17} \mathrm{rad}/\sqrt{\mathrm{Hz}}$ 40 Hz and $\tilde{\theta} = 5.1 \times 10^{-18} \mathrm{rad}/\sqrt{\mathrm{Hz}}$ at 100 Hz per test mass both for pitch and yaw.

The spectral density of orientation due to the pitch/yaw thermal noise is:

$$\tilde{\theta}_{\mathrm{TM,\,pit/yaw}}{}^2(f) = \frac{4k_B T}{I} \cdot \frac{\omega_0^2 \varphi(f)}{\omega[(\omega_0^2 - \omega^2)^2 - \omega_0^4 \varphi^2(f)]} \qquad (6)$$

where $k_B = 1.4 \times 10^{-23}$ J/K, T = 295 K, $I = 5.1 \times 10^{-2}$ kgm^2, and $\omega_0 = 0.6 \times 2\pi$ or $0.5 \times 2\pi$ are Boltzman's constant, the temperature, the momentum of inertia, and the resonant angular frequency (for pitch and yaw), respectively. $\varphi(f)$ must be less than 5.4×10^{-4} for pitch and 7.8×10^{-4} for yaw, respectively.

A.2.4. Vertical Mode

We allocate 10% of the allowed displacement noise at 40 Hz ($\tilde{x} = 5.0 \times 10^{-20} \mathrm{m}/\sqrt{\mathrm{Hz}}$ per test mass) and 6% of the allowed displacement noise at 100 Hz ($\tilde{x} = 5.1 \times 10^{-21} \mathrm{m}/\sqrt{\mathrm{Hz}}$ per test mass) to the vertical mode thermal noise. Vertical thermal noise contributes to the interferometer noise due to a misalignment of the optical axis with the local perpendicular to gravity at the test mass chamber, that is 3×10^{-4}. This is the average misalignment for each test mass chamber, both sites, both 4km arms, and can be used for all (although some are strictly at 0 and others at 6e-4). Therefore the vertical motion must be less than $\tilde{z} = 1.7 \times 10^{-16} \mathrm{m}/\sqrt{\mathrm{Hz}}$ at 40 Hz and $\tilde{z} = 1.7 \times 10^{-17} \mathrm{m}/\sqrt{\mathrm{Hz}}$ at 100 Hz per test mass both for pitch and yaw.

The spectral density of displacement due to the vertical thermal noise is:

$$\tilde{z}^2_{\mathrm{TM,\,vert}}(f) = \frac{4k_B T}{M} \cdot \frac{\omega_0^2 \varphi(f)}{\omega[(\omega_0^2 - \omega^2)^2 - \omega_0^4 \varphi^2(f)]} \qquad (7)$$

where $k_B = 1.4 \times 10^{-23}$ J/K, T = 295 K, M = 10.7 kg, and $\omega_0 = 13 \times 2\pi$ are Boltzman's constant, the temperature, the mass, and the resonant angular frequency, respectively. φ(f) must be less than 2.8×10^{-3}.

A.2.5. Eddy Current Damping

We allocate 20% of the allowed displacement noise at 40 Hz ($\tilde{x} = 1.0 \times 10^{-19} \mathrm{m}/\sqrt{\mathrm{Hz}}$ per test mass) and 20% of the allowed displacement noise at 100 Hz ($\tilde{x} = 1.6 \times 10^{-20} \mathrm{m}/\sqrt{\mathrm{Hz}}$ per test mass) to the eddy current damping thermal noise.

The spectral density of displacement due to the eddy current thermal noise in pendulum mode is:

$$\tilde{x}^2_{TM,\,edd}(f) = \frac{4k_BT}{M} \cdot \frac{\omega_0^2\varphi(f)}{\omega[(\omega_0^2 - \omega^2)^2 - \omega_0^4\varphi^2(f)]} \quad (8)$$

where $k_B = 1.4 \times 10^{-23}$ J/K, T = 295 K, M = 10.7 kg, and $\omega_0 = 0.74 \times 2\pi$ are Boltzman's constant, the temperature, the mass, and the resonant angular frequency, respectively. φ(f) must be less than 7.5×10^{-7} at 100 Hz (equivalently 5.6×10^{-9} at 0.74 Hz).

APPENDIX B REQUIREMENT DERIVATION FOR SOS

B.1. Transfer Function of SOS Suspension

B.1.1. Transfer Function from Horizontal to Horizontal, T_{hh}

The transfer function is required to represent a single pendulum performance.

B.1.2. Transfer Function from Horizontal to Pitch, T_{hp}

The requirement is obtained by demanding the resultant cavity length variation due to pitch motion with a beam spot offset d = 3 mm to be 10% of the transfer function from horizontal to horizontal:

$$d \times T_{hp} < 0.1 \times T_{hh}. \quad (9)$$

B.1.3. Transfer Function from Vertical to Vertical, T_{vv}

The transfer function is required to represent a single spring performance. Incidentally the resultant vertical motion contributes to the cavity length variation due to a misalignment of the optical axis with the local perpendicular to gravity (3×10^{-4}).

B.1.4. Transfer Function from Vertical to Horizontal, T_{vh}

The requirement is obtained by demanding the resultant horizontal motion to be 10% of the resultant cavity length variation due to the vertical to vertical transfer function:

$$T_{vh} < 0.1 \times (3 \times 10^{-4}) \times T_{vv}. \tag{10}$$

B.1.5. Transfer Function from Vertical to Pitch, T_{vp}

The requirement is obtained by demanding the resultant cavity length variation due to pitch motion with a beam spot offset d = 3 mm to be 10% of the resultant cavity length variation due to the vertical to vertical transfer function:

$$d \times T_{vp} < 0.1 \times (3 \times 10^{-4}) \times T_{vv}. \tag{11}$$

B.2. Thermal Noise for SOS

B.2.1. Internal Mode

We allocate 50% of the allowed MC displacement noise ($1.2 \times 10^{-18} \mathrm{m}/\sqrt{\mathrm{Hz}}$ at 100 Hz per MC mirror) to the internal mode thermal noise.

Thermal noise due to internal vibrations of the mirrors was estimated following the method used in [22] "Thermally Excited Vibrations of the Mirrors of Laser Interferometer Gravitational-Wave Detectors", LIGO-P940003-00-R.

$$\tilde{x}_{MC,\,int}(f) = 1.3 \times 10^{-18} \frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}} \cdot \left(\frac{100\ \mathrm{Hz}}{f}\right)^{1/2} \cdot \left(\frac{\varphi(f)}{10^{-5}}\right)^{1/2} \tag{12}$$

for the average displacement noise per MC mirror, accounting for the finite spot sizes of the beams on the flat and curved mirrors, and summing over the appropriate internal modes of the mirrors. Therefore the average effective Loss of internal modes with attachments must be less than 9.6×10^{-6}.

B.2.2. Pendulum Mode

We allocate 20% of the allowed MC displacement noise ($4.9 \times 10^{-19} \mathrm{m}/\sqrt{\mathrm{Hz}}$ at 100 Hz per MC mirror) to the pendulum mode thermal noise.

The spectral density of the displacement due to the pendulum thermal noise is:

$$\tilde{x}_{MC,\,pen}^2(f) = \frac{4k_BT}{M} \cdot \frac{\omega_0^2\varphi(f)}{\omega[(\omega_0^2-\omega^2)^2 - \omega_0^4\varphi^2(f)]} \tag{13}$$

where $k_B = 1.4 \times 10^{-23}$ J/K, T = 295 K, M = 0.25 kg, and $\omega_0 = 1 \times 2\pi$ are Boltzman's constant, the temperature, the mass, and the resonant angular frequency, respectively. $\varphi(f)$ must be less than 9.0×10^{-6}.

B.2.3. Pitch and Yaw Mode

We allocate 20% of the allowed MC displacement noise ($4.9 \times 10^{-19} \mathrm{m}/\sqrt{\mathrm{Hz}}$ at 100 Hz per MC mirror) to each of the pitch and yaw mode thermal noise.

Suspension pitch/yaw thermal noise couples with the beam spot offset from the center of mass to be converted into the cavity length variations. Since the requirement for the beam spot offset (IOO) is 3 mm, the required angle fluctuation is $1.6 \times 10^{-16} \mathrm{rad}/\sqrt{\mathrm{Hz}}$ at 100 Hz per MC mirror both for pitch and yaw.

The spectral density of orientation due to the pitch/yaw thermal noise is:

$$\tilde{\theta}_{MC,\,pit/yaw}^{\;2}(f) = \frac{4k_BT}{I} \cdot \frac{\omega_0^2\varphi(f)}{\omega[(\omega_0^2-\omega^2)^2 - \omega_0^4\varphi^2(f)]} \tag{14}$$

where $k_B = 1.4 \times 10^{-23}$ J/K, T = 295 K, $I = 1.0 \times 10^{-4}$ kgm^2, and $\omega_0 = 0.85 \times 2\pi$ or $0.75 \times 2\pi$ are Boltzman's constant, the temperature, the momentum of inertia, and the resonant angular frequency (for pitch and yaw), respectively. $\varphi(f)$ must be less than 5.3×10^{-4} for pitch and 6.8×10^{-4} for yaw, respectively.

B.2.4. Vertical Mode

We allocate 10% of the allowed MC displacement noise ($2.4 \times 10^{-19} \mathrm{m}/\sqrt{\mathrm{Hz}}$ at 100 Hz per MC mirror) to the vertical mode thermal noise.

Vertical thermal noise contributes to the interferometer noise due to a misalignment of the mode cleaner mirrors from the local verticals, that is 3×10^{-4}. Therefore the vertical motion must be less than $8.2\times10^{-16}\mathrm{m}/\sqrt{\mathrm{Hz}}$ at 100 Hz per MC mirror. The spectral density of displacement due to the vertical thermal noise is:

$$\tilde{z}^2_{MC,\,vert}(f) = \frac{4k_BT}{M}\cdot\frac{\omega_0^2\varphi(f)}{\omega[(\omega_0^2-\omega^2)^2-\omega_0^4\varphi^2(f)]} \tag{15}$$

where $k_B = 1.4 \times 10^{-23}$ J/K, T = 295 K, M = 0.25 kg, and $\omega_0 = 16 \times 2\pi$ are Boltzman's constant, the temperature, the mass, and the resonant angular frequency, respectively. $\varphi(f)$ must be less than 9.9×10^{-2}.

B.2.5. Eddy Current Damping

We allocate 30% of the allowed MC displacement noise ($7.3 \times 10^{-19}\mathrm{m}/\sqrt{\mathrm{Hz}}$ at 100 Hz per MC mirror) to the eddy current damping thermal noise.

The spectral density of displacement due to the eddy current thermal noise in pendulum mode is:

$$\tilde{x}^2_{MC,\,edd}(f) = \frac{4k_BT}{M}\cdot\frac{\omega_0^2\varphi(f)}{\omega[(\omega_0^2-\omega^2)^2-\omega_0^4\varphi^2(f)]} \tag{16}$$

where $k_B = 1.4 \times 10^{-23}$ J/K, T = 295 K, M = 0.25 kg, and $\omega_0 = 1 \times 2\pi$ are Boltzman's constant, the temperature, the mass, and the resonant angular frequency, respectively. $\varphi(f)$ must be less than 2.0×10^{-5} at 100 Hz (equivalently 2.0×10^{-7} at 1.0 Hz).

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Suspension Design Requirements

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This is an internal working note
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1 INTRODUCTION

1.1. Purpose

This Design Requirements Document (DRD) for Suspension System (SUS) identifies the information necessary to define the SUS subsystem and quantify its relationship to other subsystems.

1.2. Scope

SUS will develop and provide the suspension system for all the suspended components of Core Optics Component (COC) and Input/Output Optics (IOO).

1.3. Definitions

SUS is the system which suspends, protects, damps, and actuates the optics.

1.4. Acronyms

- LOS1: Large Optics Suspension 1
- LOS2: Large Optics Suspension 2
- SOS: Small Optics Suspension

Acronyms for names of subsystems should be referred to [8] "LIGO DETECTOR Workbook", LIGO-M940005-C-D (p. 13).

1.5. Applicable Documents

1.5.1. LIGO Documents

[1] "Alignment Sensing/Control Design Requirements Document", LIGO-T952007-01-I
[2] "Core Optics Components Requirements (1064 nm)", LIGO-E950099-01-D
[3] "Framework of Range Requirement of Suspension Actuator", LIGO-T960070-00-D
[4] "Frequency, Intensity and Oscillator Noise in the LIGO", LIGO-T960019-00-D
[5] "Interferometer Requirements Flowdown to SUS", LIGO-T950061-01-D
[6] "Length Sensing and Control Design Requirements Document", LIGO-T960058-00-D
[7] "LIGO EMI Control Plan and Procedures", LIGO-E960036-A-E
[8] "LIGO DETECTOR Workbook", LIGO-M940005-C-D
[9] "LIGO Naming Conventions", LIGO-E950111-A-E
[10] "LIGO Project System Safety Management Plan", LIGO-M950046-F
[11] "LIGO Science Requirements Document", LIGO-E950018-02-E
[12] "LIGO Vacuum Compatibility, Cleaning Methods and Procedures", LIGO-E960022-00-D
[13] "Mirror-Orientation Noise in a Fabry-Perot Interferometer Gravitational Wave Detector", LIGO-P940012-00-R

[14] "Mode cleaner Noise Sources", LIGO-T960165-00-D
[15] "Naming Convention and Interface Definition for SUS", LIGO-T950060-00-D
[16] "Response of Pendulum to Motion of Suspension Point", LIGO-T960040-00-D
[17] "Seismic Isolation Design Requirements Document", LIGO-T960065-02-D
[18] "Suspension Design Requirements", LIGO-T950011-14-D
[19] "Suspension Losses in the Pendula of Laser Interferometer Gravitational-Wave Detectors", LIGO-P940011-00-R
[20] "Suspension Preliminary Design", LIGO-T960074-00-D
[21] "Suspension Test Plan", LIGO-T960086-00-D
[22] "Thermally Excited Vibrations of the Mirrors of Laser Interferometer Gravitational-Wave Detectors", LIGO-P940003-00-R
[23] "Thermal Noise in HAM OS", LIGO-T960090-00-D

1.5.2. Non-LIGO Documents

2 GENERAL DESCRIPTION

2.1. Specification Tree

This document is part of an overall LIGO detector requirement specification tree. This particular document is circled in Fig. 1.

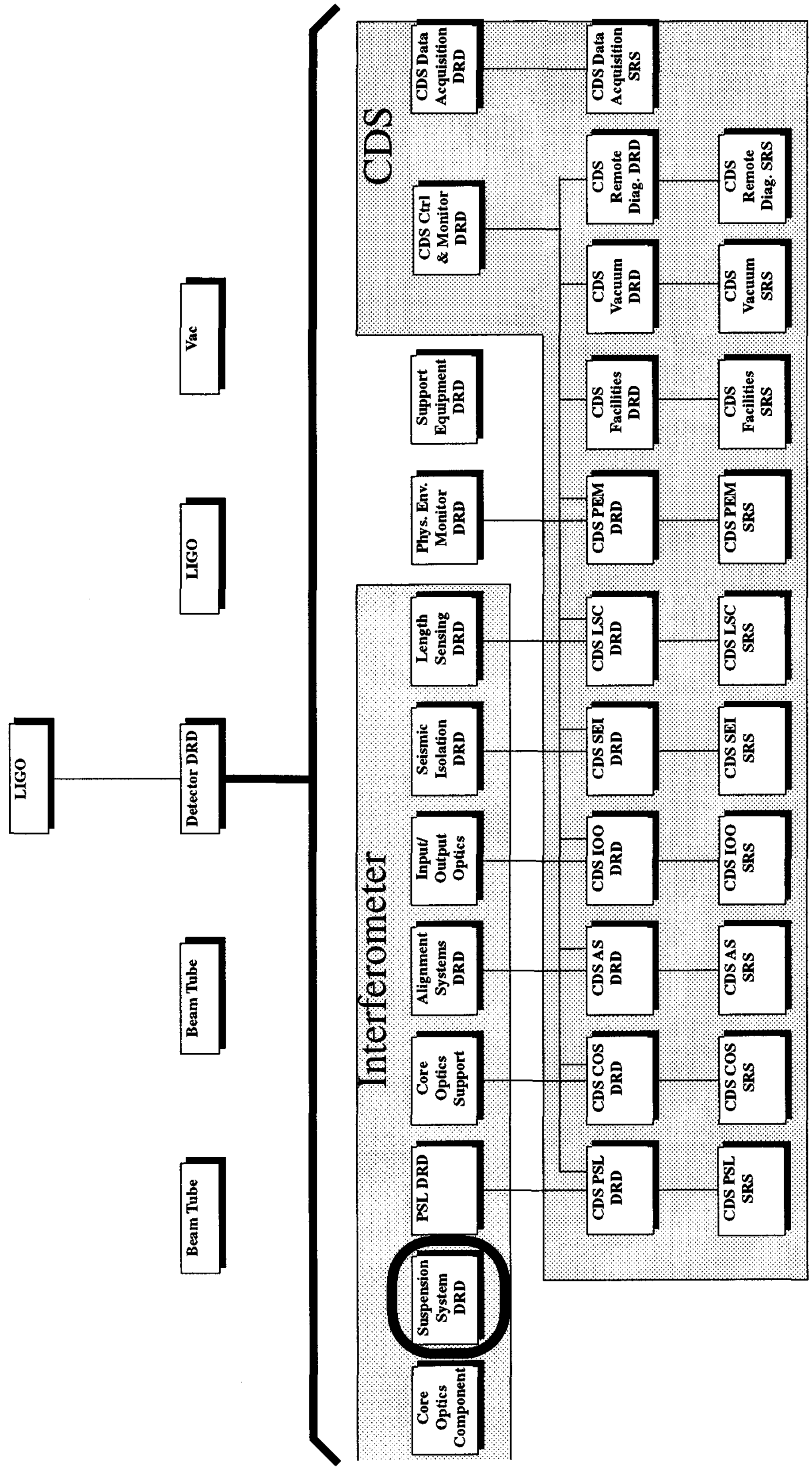

Figure 1: Overall LIGO detector requirement specification tree. SUS DRD is circled.

2.2. Product Perspective

SUS relates to the rest of the system as shown in Fig. 2.

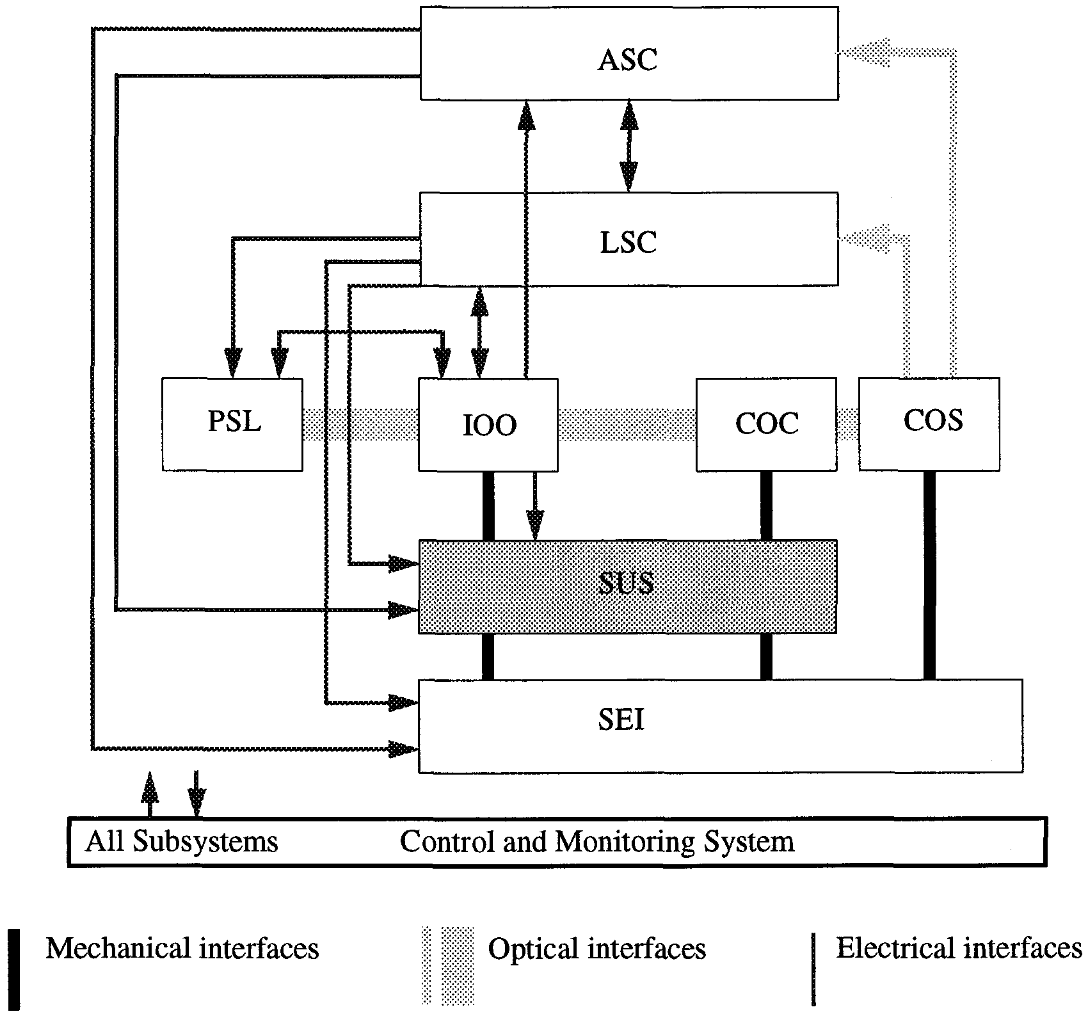

Figure 2: Relationship of SUS to the rest of the detector subsystem. SUS is shaded.

2.3. Product Functions

The main functions of SUS are:

- Suspend a test mass to allow it to move freely horizontally for detection of gravitational waves.
- Isolate an optical component from ground motion by suspending the component.
- Damp the optical component's motion in position and orientation using the local suspension's sensors and actuators.
- Provide control inputs for applying forces and torques to the suspended component in

response to signals from the LSC and ASC systems.
- Suppress the noise related to the SUS system to the desired level.
- Protect the optical components by limiting motion from external disturbance.
- Hold the optical components firmly during installation.
- Reduce the effect of stray/scattered light from the optical component.

2.4. General Constraints

- The initial LIGO must have a sensitivity specified in [11] "LIGO Science Requirements Document", LIGO-E950018-02-E, which SUS must not preclude.
- LIGO must operate continuously, therefore SUS must be designed with high reliability and low mean time to repair.
- LIGO interferometers have strict vacuum-compatibility requirements which constrain the material choices for the SUS components to those materials compatible with [12] "LIGO Vacuum Compatibility, Cleaning Methods and Procedures", LIGO-E960022-00-D.

2.5. Suspension type

There will be three types of suspension systems depending on the size of the suspended optical component: Large Optics Suspension 1 (LOS 1), Large Optics Suspension 2 (LOS 2), and small optics suspension (SOS). A list of suspended optical components for each suspension system is shown in Table 1.

Chapter 3 describes LOS1&2 and Chapter 4 describes SOS.

Table 1: List of suspended optical components

SUS type	*Suspended Optical Components (Subsystem)*
LOS 1	Test Mass (CO), Recycling Mirror (CO), Large Folding Mirror (CO), Large Mode Matching Mirror (IOO), Faraday Isolator (IOO)[a]
LOS 2	Beamsplitter (CO)
SOS	Mode Cleaner Mirror (IOO), Small Mode Matching Mirror (IOO), Small Folding Mirror (IOO), Small Pick-off (IOO)

a. An adapter ring will be fitted to the Faraday Isolator to fit it into the standard assembly.

3 LARGE OPTICS SUSPENSION 1&2

Under construction! See [18] "Suspension Design Requirements", LIGO-T950011-14-D for the latest information.

4 SMALL OPTICS SUSPENSION

4.1. Assumptions

4.1.1. Assumptions in SUS

4.1.1.1 Single Pendulum

The suspension system employs a single pendulum as opposed to a multi-stage pendulum.

4.1.1.2 Damping by Suspension's Sensor

A suspended component is always (before and after the lock acquisition) damped using the sensor signals from its respective suspension assembly.

4.1.1.3 Suspension's Actuator

The suspension's actuator is used to correct all the fluctuations during operation.

4.1.2. Assumption in Other Subsystems

4.1.2.1 Size of Optics

The size, wedge, and optical clear aperture of the suspended optics (IOO) are listed in **TBD**.

4.1.2.2 Mode Cleaner Output Frequency Noise

Allowed frequency noise of the light coming out of the mode cleaner (IOO) is $1 \times 10^{-4}\mathrm{Hz}/\sqrt{\mathrm{Hz}}$ at 100 Hz with $f^{-0.5}$ dependence above 100 Hz and f^{-2} dependence below 100 Hz (See [6] "Length Sensing and Control Design Requirements Document", LIGO-T960058-00-D).

4.1.2.3 Beam Spot Offset

The requirement of the beam spot offset from the center of the optic is 3 mm for mode cleaner mirrors (ASC).

4.1.2.4 Level of Mode Cleaner

The requirement of the level of the mode cleaner (IOO) is $3 \times 10^{-4}\mathrm{rad}$.

4.1.2.5 Internal Mode Loss of Bare Substrate

The required internal mode loss of the bare substrate of the mode cleaner mirrors (IOO) is **TBD**.

4.2. Specific Requirements

4.2.1. Requirements Flowdown

Performance requirements of SOS are derived from system requirements of the interferometer noise and detector availability. Fig. 3 shows the noise and availability requirements flowdown to the SUS subsystem. The requirements for SOS are shaded.

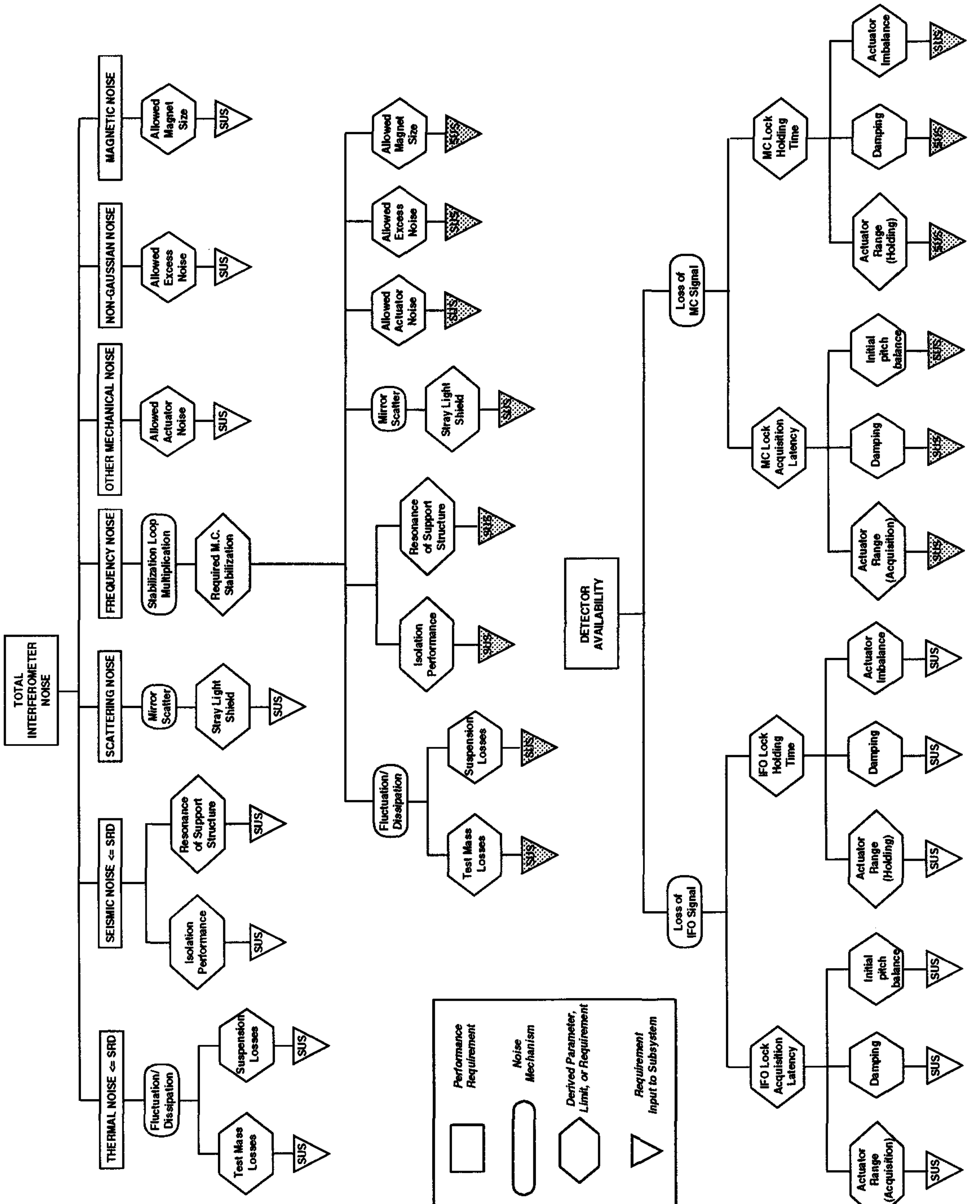

Figure 3: Interferometer noise and detector availability requirements flowdown to SOS.

4.2.2. Detector Availability

4.2.2.1 Range

The actuator range for SOS is required to provide:

- continuous operation of the LSC and IOO system,
- smooth acquisition of the LSC and IOO system,
- proper initial alignment, and
- continuous operation of the ASC system.

Table 2 shows the requirement of the suspension range for displacement (operation and acquisition mode) and orientation of the mass. (See [3] "Framework of Range Requirement of Suspension Actuator", LIGO-T960070-00-D).

Table 2: Requirement of the SOS suspension actuator range.

Mode		*Range ($f < 10$ Hz)*
Displacement	Operation	$5\ \mu m_{pp}$
	Acquisition	$80\ \mu m_{pp}$
Orientation		$3\ mrad_{pp}$ in pitch $1\ mrad_{pp}$ in yaw

4.2.2.2 Damping

The magnitude and quality of damping of the suspended component for SOS is required to provide:

- stable operation of the LSC and IOO system,
- smooth acquisition of the LSC and IOO system, and
- negligible up-conversion noise of the spurious interferometer.

In the transfer function from (horizontal, vertical, and pitch/yaw) motion of the suspension point to (horizontal and pitch/yaw) motion of the suspended mass, the maximum allowed amplitude around the resonant frequencies over the amplitude at DC is required to be less than 3.

4.2.2.3 Actuator Imbalance

The four face actuators of SOS are required to be balanced to ensure:

- No significant cross-coupling from the LSC and IOO signal to orientation of the optics.
- No significant cross-coupling from the ASC signal to displacement of the optics.

The maximum variation of force exerted by four face actuators is required to be less than 0.01.

4.2.2.4 Initial Pitch Imbalance

The initial pitch imbalance of the optical component is required to be less than 0.5 mrad.

4.2.3. Interferometer Noise

The required frequency noise of the light coming out of the mode cleaner is $\tilde{\nu} = 1 \times 10^{-4}\mathrm{Hz}/\sqrt{\mathrm{Hz}}$ at 100 Hz with $f^{-0.5}$ frequency dependence above 100 Hz and f^{-2} frequency dependence below 100 Hz. Therefore displacement noise requirement per MC mirror is $\tilde{x}_{MC} = \frac{1}{\sqrt{3}} \cdot \frac{l_{MC} \cdot \tilde{\nu}}{\nu_0} = 2.4 \times 10^{-18}\mathrm{m}/\sqrt{\mathrm{Hz}}$ at 100 Hz, where l_{MC} is the length of the mode cleaner and ν_0 is the frequency of the light. We allocate a portion of this displacement noise to each noise source.

4.2.3.1 Transfer Function of Suspension

The transfer function of the suspension for SOS is required to provide sufficient isolation above 40 Hz to meet the required frequency noise of the light coming out of the mode cleaner. Table 3 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 Wire violin modes are excluded. Coordination of the requirements between the suspension transfer function and the stack isolation is explained in [17] "Seismic Isolation Design Requirements Document", LIGO-T960065-02-D.

Table 3: Requirements matrix of the transfer function of the SOS suspension system from motion of the suspension point to motion of the suspended mass (f > 40Hz).

Transfer Function — *To* / *From*	*Horizontal (m)*	*Vertical (m)*	*Pitch (rad)*
Horizontal (m)	$< \left(\frac{f_p}{f}\right)^2$ m/m $f_p = 1.0$ Hz	N/A	$< \alpha \times \left(\frac{f_p}{f}\right)^2$ rad/m $\alpha = 30$
Vertical (m)	$< 3\times10^{-5} \times \left(\frac{f_v}{f}\right)^2$ m/m	$< \left(\frac{f_v}{f}\right)^2$ m/m $f_v = 16$ Hz	$< \beta \times \left(\frac{f_v}{f}\right)^2$ rad/m $\beta = 1 \times 10^{-2}$

4.2.3.2 Resonance of Suspension Support Structure

The resonance of the SOS suspension support structure shall not preclude meeting the required frequency noise of the light coming out of the mode cleaner. Table 4 shows the requirements for the frequency and Q of the resonance of the suspension support structure. See [23] "Thermal Noise in HAM OS", LIGO-T960090-00-D.

Table 4: Requirements for resonances of the SOS suspension support structure.

Mode	*SOS*
Resonant Frequency	> 150 Hz
Q	< 300

4.2.3.3 Thermal Losses

We allocate 70% of the allowed MC displacement noise ($1.6 \times 10^{-18}\mathrm{m}/\sqrt{\mathrm{Hz}}$ at 100 Hz per MC mirror) to thermal noise. There are three kinds of thermal losses with regard to the suspension system (See Appendix B for details):

- internal mode losses due to the suspension attachments,
- suspension (pendulum, pitch/yaw, and vertical mode) losses,
- eddy current damping losses due to interaction between the magnets and the external metal.

Table 5 shows the requirements of the (average effective) thermal loss of the suspension system.

Table 5: Requirements of the (average effective) thermal loss of the SOS suspension system.

Damping Mode/ Mechanism	*Allocation to the allowed MC displacement noise*	*Loss*
Internal mode	50%	$< 9.6\times10^{-6}$
Pendulum	20%	$< 9.0\times10^{-6}$
Pitch	20%	$< 5.3\times10^{-4}$
Yaw	20%	$< 6.8\times10^{-4}$
Vertical	10%	$< 9.9\times10^{-2}$
Eddy Current Damping	30%	$< 2.0 \times 10^{-5} \times \left(\frac{f}{100\mathrm{Hz}}\right)$
Total	70%	N/A

4.2.3.4 Control Noise

We allocate 30% of the allowed MC displacement noise ($7.3 \times 10^{-19} \mathrm{m}/\sqrt{\mathrm{Hz}}$ at 100 Hz per MC mirror) to control noise. Table 6 shows the requirements of the control noise per mass expressed in displacement or orientation motion. A beam spot offset of 3 mm are assumed for the pitch/yaw requirement.

Table 6: Requirements of the SOS control noise per mass (40 Hz < f < 100 Hz).

Mode	*Allocation to the allowed MC displacement noise*	*Control Noise*
Displacement	25%	$< 6.1 \times 10^{-19} \times \left(\frac{100\mathrm{Hz}}{\mathrm{f}}\right)^2 \mathrm{m}/\sqrt{\mathrm{Hz}}$
Pitch/Yaw	10% each	$< 8.2 \times 10^{-17} \times \left(\frac{100\mathrm{Hz}}{\mathrm{f}}\right)^2 \mathrm{rad}/\sqrt{\mathrm{Hz}}$
Total	30%	N/A

4.2.3.5 Magnet Strength

The strength of the magnets used for actuation is required to cause no more than 30% of the required frequency noise of the light coming out of the mode cleaner.

4.2.3.6 Excess Noise

TBD

4.2.4. Size Constraints

The size constraints for SOS are:

- SOS must accommodate a small optical component and must satisfy a condition of optical clear aperture.
- SOS must provide a proper vertical position for its suspended component.

The size and the optical clear aperture of small optical components and the height of the beam are summarized in Table 7.

Table 7: Size and optical clear aperture of suspended components.

Physical Quantity	*Value*
Diameter of Suspended Component	7.62 cm
Thickness of Suspended Component[a]	2.54 cm
Weight of Suspended Component	0.25 kg
Required Optical Clear Aperture	ϕ32 mm
Wedge Angle of Suspended Component	0.5° horizontally configured
Beam Height	140 mm

a. The thickness is measured at the thickest part of the substrate.

5 GENERAL REQUIREMENTS

This chapter describes general requirements which are common to LOS1&2 and SOS.

5.1. General Characteristics

5.1.1. Reliability

Mean Time Between Failures (MTBF) should be **TBD**.

5.1.2. Maintainability

Mean Time To Repair (MTTR) should be less than **TBD**.

5.1.3. Environmental Conditions

5.1.3.1 Natural Environment

5.1.3.1.1 Temperature and Humidity

TBD

5.1.3.1.2 Atmospheric Pressure

TBD

5.1.3.1.3 Seismic Disturbance

TBD

5.1.3.2 Induced Environment

5.1.3.2.1 Electromagnetic Radiation

Per [7] "LIGO EMI Control Plan and Procedures", LIGO-E960036-A-E

5.1.3.2.2 Acoustic

TBD

5.1.3.2.3 Mechanical Vibration

TBD

5.1.4. 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.

5.2. Design and Construction

5.2.1. Materials and Processes

5.2.1.1 Finishes

- Metal components must have quality finishes on all surfaces, suitable for vacuum finishes.
- All materials must have non-shedding surfaces.

5.2.1.2 Materials

All materials used inside the vacuum must comply with [12] "LIGO Vacuum Compatibility, Cleaning Methods and Procedures", LIGO-E960022-00-D.

5.2.1.3 Processes

5.2.1.3.1 Welding

TBD

5.2.1.3.2 Annealing

TBD

5.2.1.3.3 Cleaning

All materials used inside the vacuum chambers must be cleaned in accordance with [12] "LIGO Vacuum Compatibility, Cleaning Methods and Procedures", LIGO-E960022-00-D.

5.2.2. Component Naming

All components shall be identified using [9] "LIGO Naming Conventions", LIGO-E950111-A-E.

5.2.3. Workmanship

TBD

5.2.4. Interchangeability

All LOS1 components must be interchangeable among LOS1 systems except for those components that depend on wedge value and orientation. All SOS components must be interchangeable among SOS systems except for components that depend on wedge value and orientation.

5.2.5. 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 section 3.3.2. of [10] "LIGO Project System Safety Management Plan", LIGO-M950046-F.

No special considerations for human safety are presented by the suspension design, except for the normal precautions taken with electronics. The suspension actuator electronics will be capable of delivering voltages up to 150 Volts.

The following special precautions must be taken to assure safety of the equipment:

- the suspension hardware and the suspended component are ultrahigh-vacuum components and must be handled according to approved LIGO procedures to prevent contamination
- the magnet/standoff assemblies are extremely delicate and must be protected during all operations prior to mounting the suspended component into the suspension structure
- tools fabricated from metal or other hard substances should be kept away from the suspended component's polished faces to prevent scratching or marring of these surfaces
- suspended components must always be properly locked into the safety cage before any movement of the suspension structure is attempted

5.2.6. Human Engineering

The suspension design must allow for coarse alignment of the suspended component relative to the suspension support structure to be accomplished on a clean bench outside the vacuum chamber. The alignment procedure is delicate and requires that personnel aligning an optic have comfortable access to the components. Alignment procedures within the vacuum chamber will be restricted to adjustments of the orientation of the suspension support structure. Fine alignment will be accomplished through the suspension actuators.

5.3. Documentation

5.3.1. Specifications

TBD

5.3.2. Design Documents

- Suspension Final Design

5.3.3. Engineering Drawings and Associated Lists

TBD

5.3.4. Technical Manuals and Procedures

5.3.4.1 Procedures

Procedures shall be provided for, at minimum,

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

5.3.4.2 Manuals

TBD

5.3.5. Documentation Numbering

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

5.3.6. Test Plans and Procedures

Test plan is documented in [21] “Suspension Test Plan”, LIGO-T960086-00-D.

All procedures shall be developed in accordance with **TBD**.

5.4. Logistics

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

5.5. Precedence

This section should list the relative importance of requirements (or goals) to be achieved by the design.

5.6. Qualification

Test and acceptance criteria.

6 QUALITY ASSURANCE PROVISIONS

This section includes all of the examinations and tests to be performed in order to ascertain the product, material or process to be developed or offered for acceptance conforms to the requirements in section 3.

6.1. General

This should outline the general test and inspection philosophy, including all phases of development.

6.1.1. Responsibility for Tests

Who is responsible for testing.

6.1.2. Special Tests

6.1.2.1 Engineering Tests

List any special engineering tests which are required to be performed. Engineering tests are those which are used primarily for the purpose of acquiring data to support the design and development.

6.1.2.2 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.

6.1.3. Configuration Management

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

6.2. 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:

6.2.1. Inspections

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

6.2.2. Analysis

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

6.2.3. 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.

6.2.4. 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.

6.2.5. 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.

7 PREPARATION FOR DELIVERY

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

7.1. Preparation

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

7.2. 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.

7.3. 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 A TRANSFER FUNCTION OF SOS SUSPENSION

A.1. Transfer Function from Horizontal to Horizontal, T_{hh}

The transfer function is required to represent a single pendulum performance.

A.2. Transfer Function from Horizontal to Pitch, T_{hp}

The requirement is obtained by demanding the resultant cavity length variation due to pitch motion with a beam spot offset d = 3 mm to be 10% of the transfer function from horizontal to horizontal:

$$d \times T_{hp} < 0.1 \times T_{hh}. \quad (1)$$

A.3. Transfer Function from Vertical to Vertical, T_{vv}

The transfer function is required to represent a single spring performance. Incidentally the resultant vertical motion contributes to the cavity length variation due to a misalignment of the optical axis with the local perpendicular to gravity (3×10^{-4}).

A.4. Transfer Function from Vertical to Horizontal, T_{vh}

The requirement is obtained by demanding the resultant horizontal motion to be 10% of the resultant cavity length variation due to the vertical to vertical transfer function:

$$T_{vh} < 0.1 \times (3 \times 10^{-4}) \times T_{vv}. \quad (2)$$

A.5. Transfer Function from Vertical to Pitch, T_{vp}

The requirement is obtained by demanding the resultant cavity length variation due to pitch motion with a beam spot offset d = 3 mm to be 10% of the resultant cavity length variation due to the vertical to vertical transfer function:

$$d \times T_{vp} < 0.1 \times (3 \times 10^{-4}) \times T_{vv}. \quad (3)$$

APPENDIX B THERMAL NOISE FOR SOS

B.1. Internal Mode

We allocate 50% of the allowed MC displacement noise ($1.2 \times 10^{-18} \mathrm{m}/\sqrt{\mathrm{Hz}}$ at 100 Hz per MC mirror) to the internal mode thermal noise.

Thermal noise due to internal vibrations of the mirrors was estimated following the method used in [22] "Thermally Excited Vibrations of the Mirrors of Laser Interferometer Gravitational-Wave Detectors", LIGO-P940003-00-R.

$$\tilde{x}_{MC,\,int}(f) = 1.3 \times 10^{-18} \frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}} \cdot \left(\frac{100\ \mathrm{Hz}}{f}\right)^{1/2} \cdot \left(\frac{\varphi(f)}{10^{-5}}\right)^{1/2} \quad (4)$$

for the average displacement noise per MC mirror, accounting for the finite spot sizes of the beams on the flat and curved mirrors, and summing over the appropriate internal modes of the mirrors. Therefore the average effective Loss of internal modes due to attachments must be less than 9.6×10^{-6}.

B.2. Pendulum Mode

We allocate 20% of the allowed MC displacement noise ($4.9 \times 10^{-19} \mathrm{m}/\sqrt{\mathrm{Hz}}$ at 100 Hz per MC mirror) to the pendulum mode thermal noise.

The spectral density of the displacement due to the pendulum thermal noise is:

$$\tilde{x}^2_{MC,\,pen}(f) = \frac{4k_B T}{M} \cdot \frac{\omega_0^2 \varphi(f)}{\omega[(\omega_0^2 - \omega^2)^2 - \omega_0^4 \varphi^2(f)]} \tag{5}$$

where $k_B = 1.4 \times 10^{-23}$ J/K, T = 295 K, M = 0.25 kg, and $\omega_0 = 1 \times 2\pi$ are Boltzman's constant, the temperature, the mass, and the resonant angular frequency, respectively. $\varphi(f)$ must be less than 9.0×10^{-6}.

B.3. Pitch and Yaw Mode

We allocate 20% of the allowed MC displacement noise ($4.9 \times 10^{-19} \mathrm{m}/\sqrt{\mathrm{Hz}}$ at 100 Hz per MC mirror) to each of the pitch and yaw mode thermal noise.

Suspension pitch/yaw thermal noise couples with the beam spot offset from the center of mass to be converted into the cavity length variations. Since the requirement for the beam spot offset (IOO) is 3 mm, the required angle fluctuation is $1.6 \times 10^{-16} \mathrm{rad}/\sqrt{\mathrm{Hz}}$ at 100 Hz per MC mirror both for pitch and yaw.

The spectral density of orientation due to the pitch/yaw thermal noise is:

$$\tilde{\theta}_{MC,\,pit/yaw}{}^2(f) = \frac{4k_B T}{I} \cdot \frac{\omega_0^2 \varphi(f)}{\omega[(\omega_0^2 - \omega^2)^2 - \omega_0^4 \varphi^2(f)]} \tag{6}$$

where $k_B = 1.4 \times 10^{-23}$ J/K, T = 295 K, $I = 1.0 \times 10^{-4}$ kgm^2, and $\omega_0 = 0.85 \times 2\pi$ or $0.75 \times 2\pi$ are Boltzman's constant, the temperature, the momentum of inertia, and the resonant angular frequency (for pitch and yaw), respectively. $\varphi(f)$ must be less than 5.3×10^{-4} for pitch and 6.8×10^{-4} for yaw, respectively.

B.4. Vertical Mode

We allocate 10% of the allowed MC displacement noise ($2.4 \times 10^{-19} \mathrm{m}/\sqrt{\mathrm{Hz}}$ at 100 Hz per MC mirror) to the vertical mode thermal noise.

Vertical thermal noise contributes to the interferometer noise due to a misalignment of the mode cleaner mirrors from the local verticals, that is 3×10^{-4}. Therefore the vertical motion must be less than $8.2 \times 10^{-16} \mathrm{m}/\sqrt{\mathrm{Hz}}$ at 100 Hz per MC mirror. The spectral density of displacement due to the vertical thermal noise is:

$$\tilde{z}^2_{MC,\,vert}(f) = \frac{4k_BT}{M} \cdot \frac{\omega_0^2\varphi(f)}{\omega[(\omega_0^2-\omega^2)^2-\omega_0^4\varphi^2(f)]} \tag{7}$$

where $k_B = 1.4 \times 10^{-23}$ J/K, T = 295 K, M = 0.25 kg, and $\omega_0 = 16 \times 2\pi$ are Boltzman's constant, the temperature, the mass, and the resonant angular frequency, respectively. $\varphi(f)$ must be less than 9.9×10^{-2}.

B.5. Eddy Current Damping

We allocate 30% of the allowed MC displacement noise ($7.3 \times 10^{-19} \mathrm{m}/\sqrt{\mathrm{Hz}}$ at 100 Hz per MC mirror) to the eddy current damping thermal noise.

The spectral density of displacement due to the eddy current thermal noise in pendulum mode is:

$$\tilde{x}^2_{MC,\,edd}(f) = \frac{4k_BT}{M} \cdot \frac{\omega_0^2\varphi(f)}{\omega[(\omega_0^2-\omega^2)^2-\omega_0^4\varphi^2(f)]} \tag{8}$$

where $k_B = 1.4 \times 10^{-23}$ J/K, T = 295 K, M = 0.25 kg, and $\omega_0 = 1 \times 2\pi$ are Boltzman's constant, the temperature, the mass, and the resonant angular frequency, respectively. $\varphi(f)$ must be less than 2.0×10^{-5} at 100 Hz.

LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
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Suspension Design Requirements

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DRAFT

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1 INTRODUCTION

1.1. Purpose

This Design Requirements Document (DRD) for Suspension System (SUS) identifies the information necessary to define the SUS subsystem and quantify its relationship to other subsystems.

1.2. Scope

SUS will develop and provide the suspension system for all the suspended components of Core Optics Component (COC) and Input/Output Optics (IOO).

1.3. Definitions

SUS is the system which suspends, protects, damps, and actuates the optics.

1.4. Acronyms

- LOS1: Large Optics Suspension 1
- LOS2: Large Optics Suspension 2
- SOS: Small Optics Suspension

Acronyms for names of subsystems should be referred to [1] LIGO-1401051 Rev. B: LIGO DETECTOR Construction Phase Implementation Plan (p. 13).

1.5. Applicable Documents

1.5.1. LIGO Documents

[1] LIGO-1401051 Rev. B: LIGO DETECTOR Construction Phase Implementation Plan
[2] LIGO-E950018-02-E: LIGO Science Requirements Document
[3] LIGO-E960022-00-D: LIGO Vacuum Compatibility, Cleaning Methods and Procedures
[4] LIGO-E950099-01-D: Core Optics Components Requirements (1064 nm)
[5] LIGO-T960019-00-D: Frequency, Intensity and Oscillator Noise in the LIGO
[6] LIGO-T952007-01-I: Alignment Sensing/Control Design Requirements Document
[7] LIGO-T960070-00-D: Framework of Range Requirement of Suspension Actuator
[8] LIGO-T960065-02-D: Seismic Isolation Design Requirements Document
[9] LIGO-960090-00-D: Thermal Noise in HAM OS
[10] LIGO-T960040-00-D: Response of Pendulum to Motion of Suspension Point
[11] LIGO-T950060-00-D: Naming Convention and Interface Definition for SUS
[12] LIGO-T960058-00-D: Length Sensing and Control Design Requirements Document
[13] LIGO-M950046-F: LIGO Project System Safety Management Plan
[14] LIGO-T950061-01-D: Interferometer Requirements Flowdown to SUS

[15] LIGO-T960074-00-D: Suspension Preliminary Design
[16] LIGO-T960086-00-D: Suspension Test Plan
[17] LIGO-P940003-00-R: Thermally Excited Vibrations of the Mirrors of Laser Interferometer Gravitational-Wave Detectors
[18] LIGO-P940011-00-R: Suspension Losses in the Pendula of Laser Interferometer Gravitational-Wave Detectors
[19] LIGO-P940012-00-R: Mirror-Orientation Noise in a Fabry-Perot Interferometer Gravitational Wave Detector

1.5.2. Non-LIGO Documents

2 GENERAL DESCRIPTION

2.1. Specification Tree

This document is part of an overall LIGO detector requirement specification tree. This particular document is circled in Fig. 1.

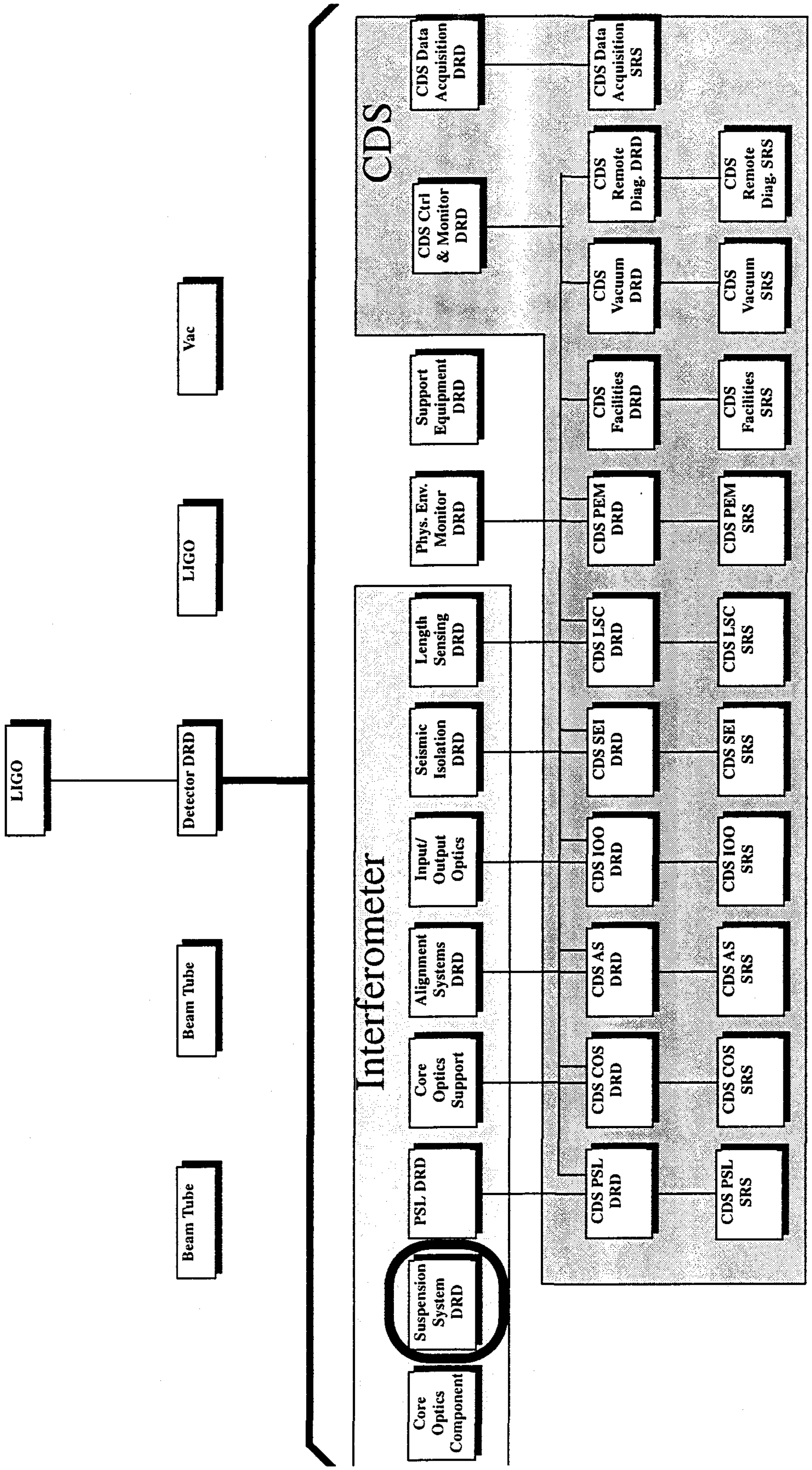


Figure 1: Overall LIGO detector requirement specification tree. SUS DRD is circled.

2.2. Product Perspective

SUS relates to the rest of the system as shown in Fig. 2.

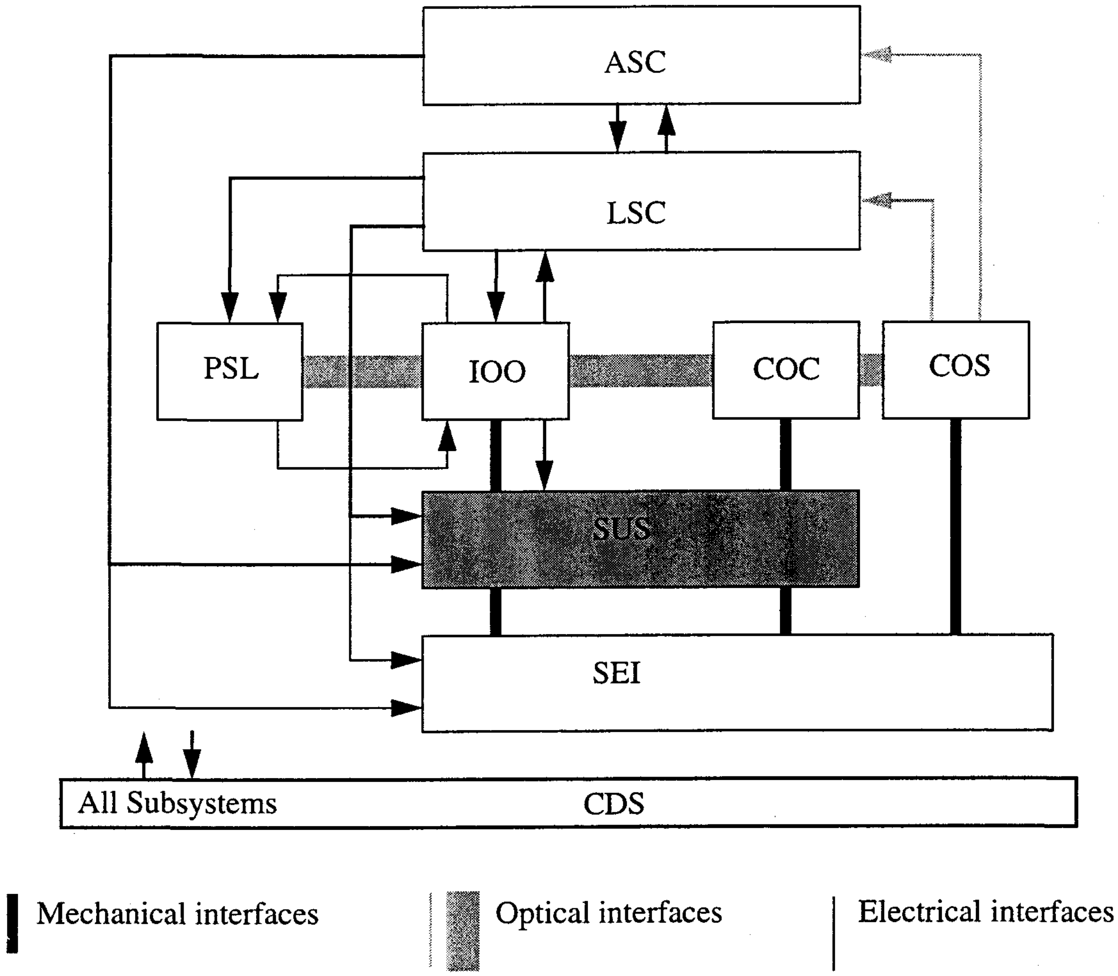


Figure 2: Relationship of SUS to the rest of the detector subsystem. SUS is shaded.

2.3. Product Functions

The main functions of SUS are:

- Suspend a test mass to allow it to move freely horizontally for detection of gravitational waves.
- Isolate an optical component from ground motion by suspending the component.
- Damp the optical component's motion in position and orientation using the local suspension's sensors and actuators.
- Provide control inputs for applying forces and torques to the suspended component in response to signals from the LSC and ASC systems.

- Protect the optical components by limiting motion from external disturbance.
- Hold the optical components firmly during installation.
- Reduce the effect of stray/scattered light from the optical component.

2.4. General Constraints

- The initial LIGO must have a sensitivity specified in [2] LIGO-E950018-02-E: LIGO Science Requirements Document, which SUS must not preclude.
- LIGO must operate continuously, therefore SUS must be designed with high reliability and low mean time to repair.
- LIGO interferometers have strict vacuum-compatibility requirements which constrain the material choices for the SUS components to those materials compatible with [3] LIGO-E960022-00-D: LIGO Vacuum Compatibility, Cleaning Methods and Procedures.

2.5. Assumptions and Dependencies

2.5.1. Assumption in SUS

2.5.1.1 Single Pendulum

The suspension system employs a single pendulum as opposed to a multi-stage pendulum.

2.5.1.2 Suspension Type

There will be three types of the suspension system depending on the size of the suspended optical component: Large Optics Suspension 1 (LOS 1), Large Optics Suspension 2 (LOS 2), and small optics suspension (SOS). A list of suspended optical components for each suspension system is shown in Table 1.

Table 1: List of suspended optical components

SUS type	*Suspended Optical Components (Subsystem)*
LOS 1	Test Masses (CO), Recycling Mirror (CO), Large Folding Mirror (CO), Mode Matching Mirrors (IOO), Faraday Isolator (IOO)[a] **TBD**
LOS 2	Beamsplitter (CO)
SOS	Mode Cleaner Mirrors (IOO), Small Folding Mirrors (IOO), Small Pick-offs (IOO)

a. An adapter ring will be fitted to the Faraday Isolator to fit it into the standard assembly.

2.5.1.3 Damping by Suspension's Sensor

A suspended component is or is not damped using the sensor signals from its respective suspension assembly depending on the type of the optical component and the state of the interferometer.

Table 2 summarizes the state of the interferometer in which optical components are damped by the suspension's sensor.

Table 2: States of interferometer operation in which optical components are damped by the suspension's sensor

Motion	*Test Mass*	*Beamsplitter, Recycling Mirror, MC Mirror, Folding Mirror, Mode Matching Mirror*	*Pick-off, Faraday Isolator*
Longitudinal	Before and during acquisition	Always	Always
Transverse	Always	Always	Always
Orientation	Before acquisition	Before acquisition	Always

2.5.1.4 Suspension's Actuator

The suspension's actuator is used to correct fluctuations on the time scale that is shorter than well below the microseismic peak (f > 0.03 Hz). The stack support actuator is used to correct fluctuations of much longer time scales than the microseismic peak (principally the tidal disturbances).

2.5.2. Assumption in Other Subsystems

2.5.2.1 Size of Optics

The size, wedge, and optical clear aperture of the suspended optics (COC) are listed in [4] LIGO-E950099-01-D: Core Optics Components Requirements (1064 nm).

2.5.2.2 Mode Cleaner Output Frequency Noise

Allowed frequency noise of the light coming out of the mode cleaner (IOO) is $1 \times 10^{-4}\text{Hz}/\sqrt{\text{Hz}}$ at 100 Hz with $f^{-0.5}$ dependence above 100 Hz and f^{-2} **TBD** dependence below 100 Hz (See [12] LIGO-T960058-00-D: Length Sensing and Control Design Requirements Document).

2.5.2.3 Beam Spot Offset

The requirement of the beam spot offset from the center of the optic is 1 mm for test masses (ASC) and 3 mm for mode cleaner mirrors (ASC).

2.5.2.4 Level of Mode Cleaner

The requirement of the level of the mode cleaner (IOO) is $3 \times 10^{-4}\text{rad}$ **TBD**.

2.5.2.5 Vibrational Loss of Bare Substrate

The required vibrational loss of the bare substrate of the test mass (COC) is 3×10^{-7} and that of the mode cleaner mirror (IOO) is **TBD**.

3 REQUIREMENTS

3.1. Requirements Flowdown

Performance requirements of SUS are derived from system requirements of the interferometer noise and detector availability. Fig. 3 shows the noise and availability requirements flowdown to the SUS subsystem.

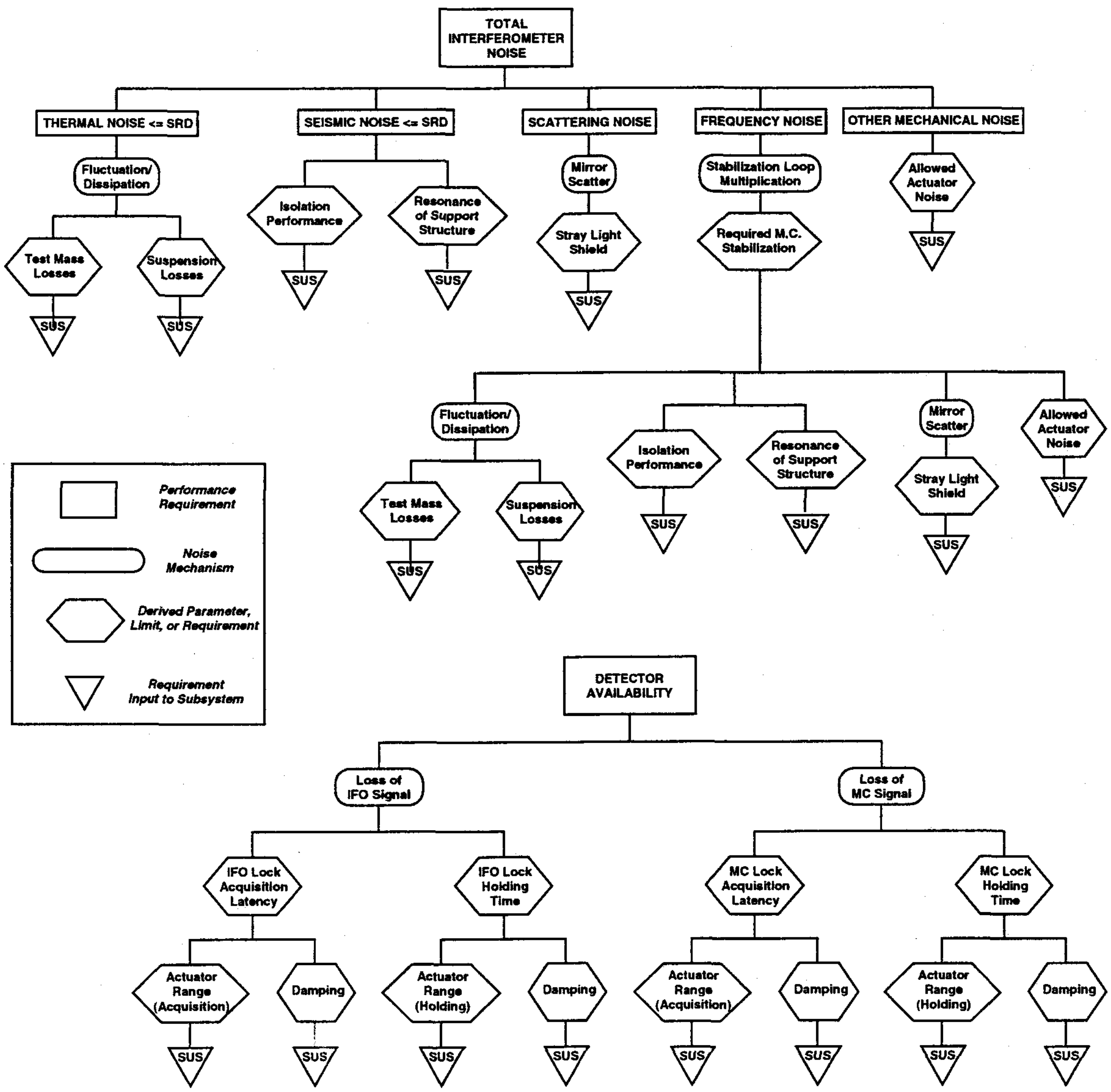


Figure 3: Interferometer noise and detector availability requirements flowdown to SUS.

3.2. Characteristics

3.2.1. Performance Characteristics

3.2.1.1 Detector Availability

3.2.1.1.1 Range

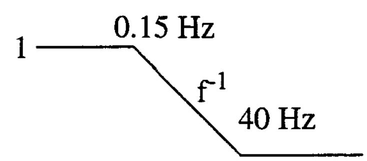
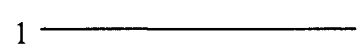
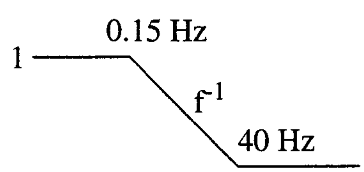
The actuator range is required to provide:

- continuous operation of the LSC system,
- smooth acquisition of the LSC system,
- proper initial alignment, and
- continuous operation of the ASC system.

The requirements of the actuator range are expressed by a DC (DC: defined as f << 0.15 Hz) peak-to-peak motion DC (DC: defined as f << 0.15 Hz) in displacement and orientation and a weighting function (transfer function from the output driver voltage to force normalized in such a way that it is unity at DC.). The weighting function represents the frequency dependence of the range (See [7] LIGO-T960070-00-D: Framework of Range Requirement of Suspension Actuator). Table 3 shows the requirement of the suspension range for displacement (operation and acquisition mode) and orientation of the mass.

These requirements are common to all the three suspensions. Coordination of the requirements between the actuator range and the stack isolation is explained in [8] LIGO-T960065-02-D: Seismic Isolation Design Requirements Document.

Table 3: Requirement of the suspension actuator range.

Mode		*DC Peak-to-Peak Motion*	*Weighting Function*
Displacement	Operation	40 μm_{pp}	
	Acquisition	40 μm_{pp}	
Orientation		1 $mrad_{pp}$	

3.2.1.1.2 Damping

The magnitude and quality of damping the suspended component is required to provide:

- stable operation of the LSC system,
- smooth acquisition of the LSC system, and
- negligible up-conversion noise of the spurious interferometer.

The requirements of damping the suspended component are expressed by the height of the residual bump around the pendulum and pitch/yaw frequencies in the transfer function from (horizontal, vertical, and pitch/yaw) motion of the suspension point to (horizontal and pitch/yaw) motion of the suspended mass. This height of the residual bump is required to be less than 3.

3.2.1.2 Interferometer Noise

3.2.1.2.1 Transfer Function of Suspension

The transfer function of the suspension is required to provide sufficient isolation above 35 Hz to meet the LIGO sensitivity requirement. Table 4 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 except wire violin modes. Coordination of the requirements between the suspension transfer function and the stack isolation is explained in [8] LIGO-T960065-02-D: Seismic Isolation Design Requirements Document. See

Table 4: Requirements matrix of the transfer function of the suspension system from motion of the suspension point to motion of the suspended mass (f > 40Hz).

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), 0.84 Hz (SOS)	Trivial	$< \alpha \times \left(\frac{f_p}{f}\right)^2$ m/m $\alpha = 100$ (LOS1/2), 30 (SOS)
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), 16 Hz (SOS)	$< \beta \times \left(\frac{f_v}{f}\right)^2$ rad/m $\beta = 3 \times 10^{-2}$ (LOS1/2), 1×10^{-2} (SOS)

3.2.1.2.2 Resonance of Suspension Support Structure

The resonance of the suspension support structure is required not to preclude the LIGO sensitivity requirement. Table 5 shows the requirements for the frequency and Q of the resonance of the suspension support structure. See [9] LIGO-960090-00-D: Thermal Noise in HAM OS.

Table 5: Requirements of the (average effective) thermal loss of the suspension system.

Mode	*LOS1/LOS2*	*SOS*
Resonance Frequency	> 160 Hz	> 150 Hz
Q	< 300	< 300

3.2.1.2.3 Thermal Loss

The thermal loss of the suspension system is required to be small enough to meet the LIGO sensitivity requirement. There are three kinds of thermal losses with regard to the suspension system (See Appendix B for detail):

- structural loss of the suspension pendulum, pitch/yaw, and vertical mode,
- structural loss of the mass internal mode due to the suspension attachments,
- viscous loss of the suspension pendulum mode due to interaction between the suspension attachments and the external components.

Requirements for LOS2 will not explicitly established; we simply use the same design for LOS2 as LOS1. Table 6 shows the requirements of the (average effective) thermal loss of the suspension system.

Table 6: Requirements of the (average effective) thermal loss of the suspension system.

Loss Type		*Loss*	
Damping Mechanism	*Mode*	*LOS1*	*SOS*
Structural (Loss: frequency independent)	Vibrational	$< 4\times10^{-7}$	$< 1\times10^{-5}$
	Pendulum	$< 7\times10^{-6}$	$< 5\times10^{-6}$
	Pitch/Yaw	$< 5\times10^{-4}$ / $< 8\times10^{-4}$	$< 3\times10^{-4}$ / $< 9\times10^{-5}$
	Vertical	$< 3\times10^{-3}$	$< 7\times10^{-2}$
Viscous (Loss: linear to frequency)	Pendulum	$< 8\times10^{-7}$ at 100 Hz $< 6\times10^{-9}$ at 0.74 Hz	$< 6\times10^{-5}$ at 100 Hz $< 6\times10^{-7}$ at 1 Hz

3.2.1.2.4 Control Noise

The control noise of the suspension system in total is required to cause no more than 10% of the LIGO displacement noise per degree of freedom for LOS1/LOS2, that is $1.0\times10^{-19}\mathrm{m}/\sqrt{\mathrm{Hz}}$ at 40 Hz with f^{-2} dependence and no more than 10% of the required mode cleaner stability for SOS, that is $3.5\times10^{-19}\mathrm{m}/\sqrt{\mathrm{Hz}}$ at 100 Hz with $f^{-0.5}$ dependence above 100 Hz and f^{-2} **TBD** dependence below 100 Hz. Table 7 shows the requirements of the control noise per mass expressed in displacement or orientation motion. The beam spot offset of 1 mm (LOS1/LOS2) and 3 mm (SOS) are assumed for the pitch/yaw requirement.

Table 7: Requirements of the control noise per mass (f > 40 Hz).

Mode	*Control Noise*	
	LOS1/LOS2	*SOS*
Displacement	$< 5\times10^{-20}\times\left(\frac{40\mathrm{Hz}}{f}\right)^2\mathrm{m}/\sqrt{\mathrm{Hz}}$	$< 2\times10^{-19}\times\left(\frac{100\mathrm{Hz}}{f}\right)^2\mathrm{m}/\sqrt{\mathrm{Hz}}$ (f < 100 Hz) $< 2\times10^{-19}\times\left(\frac{100\mathrm{Hz}}{f}\right)^{0.5}\mathrm{m}/\sqrt{\mathrm{Hz}}$ (f > 100 Hz)
Pitch/Yaw	$< 2\times10^{-17}\times\left(\frac{40\mathrm{Hz}}{f}\right)^2\mathrm{rad}/\sqrt{\mathrm{Hz}}$	$< 6\times10^{-17}\times\left(\frac{100\mathrm{Hz}}{f}\right)^2\mathrm{rad}/\sqrt{\mathrm{Hz}}$ (f < 100 Hz) $< 6\times10^{-17}\times\left(\frac{100\mathrm{Hz}}{f}\right)^{0.5}\mathrm{rad}/\sqrt{\mathrm{Hz}}$ (f > 100 Hz)

3.2.1.2.5 Stray Light Shield

TBD

3.2.2. Physical Characteristics

3.2.2.1 Size Constraints

The size constraints for the SUS subsystem is:

- Three kinds of suspension system must accommodate the corresponding optical component, and must satisfy the corresponding condition of optical clear aperture.
- The suspension system must provide a proper vertical position for the suspended components.

The Size and the optical clear aperture of representative components and the height of the beam for three kinds of chambers are summarized in Table 8 and Table 9.

Table 8: Size and optical clear aperture of suspended components.

Physical Quantity	*LOS1*	*LOS2*	*SOS*
Diameter of Suspended Component	25 cm	25 cm **TBD**	7.62 cm
Thickness of Suspended Component	10 cm	4 cm **TBD**	2.54 cm
Weight of Suspended Component	10.7kg	6.2 kg **TBD**	0.25 kg
Required Optical Clear Aperture	24 cm (Fore) 19 cm (Back)	11 cm **TBD**[a]	2 cm
Wedge Angle of Suspended Component	**TBD**	**TBD**	**TBD**

a. The angle of the incident beam is 45 degrees from perpendicular.

Table 9: Beam height for chambers.

Physical Quantity	*BSC Chamber*		*HAM Chamber*
	Test Mass	*Beamsplitter*	
Beam Height	**TBD**	**TBD**	**TBD**

3.2.3. Interface Definitions

See [11] LIGO-T950060-00-D: Naming Convention and Interface Definition for SUS.

3.2.4. Reliability

Mean Time Between Failures (MTBF) should be **TBD**.

3.2.5. Maintainability

Mean Time To Repair (MTTR) should be less than **TBD**.

3.2.6. Environmental Conditions

3.2.6.1 Natural Environment

3.2.6.1.1 Temperature and Humidity

TBD

3.2.6.1.2 Atmospheric Pressure

TBD

3.2.6.1.3 Seismic Disturbance

TBD

3.2.6.2 Induced Environment

3.2.6.2.1 Electromagnetic Radiation

TBD

3.2.6.2.2 Acoustic

TBD

3.2.6.2.3 Mechanical Vibration

TBD

3.2.7. Transportability

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

3.3. Design and Construction

3.3.1. Materials and Processes

3.3.1.1 Finishes

- Metal components must have quality finishes on all surfaces, suitable for vacuum finishes.
- All materials must have non-shedding surfaces.

3.3.1.2 Materials

All materials used inside the vacuum must comply with [3] LIGO-E960022-00-D: LIGO Vacuum Compatibility, Cleaning Methods and Procedures.

3.3.1.3 Processes

3.3.1.3.1 Welding

TBD

3.3.1.3.2 Annealing

TBD

3.3.1.3.3 Cleaning

All materials used inside the vacuum chambers must be cleaned in accordance with [3] LIGO-E960022-00-D: LIGO Vacuum Compatibility, Cleaning Methods and Procedures.

3.3.2. Component Naming

All components shall be identified using the LIGO Detector Naming Convention (document **TBD**).

3.3.3. Workmanship

TBD

3.3.4. Interchangeability

All LOS1 components must be interchangeable between LOS1 systems except for components that depend on wedges. All SOS components must be interchangeable between SOS systems except for components that depend on wedges.

3.3.5. 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 section 3.3.2. of [13] LIGO-M950046-F: LIGO Project System Safety Management Plan.

No special considerations for human safety are presented by the suspension design, except for the normal precautions taken with electronics. The suspension actuator electronics will be capable of delivering voltages up to 150 Volts.

The following special precautions must be taken to assure safety of the equipment:

- the suspension hardware and the suspended component are ultrahigh-vacuum components and must be handled according to approved LIGO procedures to prevent contamination
- the magnet/standoff assemblies are extremely delicate and must be protected during all operations prior to mounting the suspended component into the suspension structure
- tools fabricated from metal or other hard substances should be kept away from the suspended component's polished faces to prevent scratching or marring of these surfaces
- suspended components must always be properly locked into the safety cage before any movement of the suspension structure is attempted

3.3.6. Human Engineering

The suspension design must allow for coarse alignment of the suspended component relative to the suspension support structure to be accomplished on a clean bench outside the vacuum chamber. This is required because the alignment procedure is quite delicate and requires that personnel aligning an optic have comfortable access to the components. Alignment procedures within the vacuum chamber will be restricted to adjustments of the orientation of the suspension support structure. Fine alignment will be accomplished through the suspension actuators.

3.4. Documentation

3.4.1. Specifications

TBD

3.4.2. Design Documents

- Suspension Final Design

3.4.3. Engineering Drawings and Associated Lists

TBD

3.4.4. Technical Manuals and Procedures

3.4.4.1 Procedures

Procedures shall be provided for, at minimum,

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

3.4.4.2 Manuals

TBD

3.4.5. Documentation Numbering

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

3.4.6. Test Plans and Procedures

Test plan is documented in [16] LIGO-T960086-00-D: Suspension Test Plan.

All procedures shall be developed in accordance with **TBD**.

3.5. Logistics

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

3.6. Precedence

This section should list the relative importance of requirements (or goals) to be achieved by the design.

3.7. Qualification

Test and acceptance criteria.

4 QUALITY ASSURANCE PROVISIONS

This section includes all of the examinations and tests to be performed in order to ascertain the product, material or process to be developed or offered for acceptance conforms to the requirements in section 3.

4.1. General

This should outline the general test and inspection philosophy, including all phases of development.

4.1.1. Responsibility for Tests

Who is responsible for testing.

4.1.2. Special Tests

4.1.2.1 Engineering Tests

List any special engineering tests which are required to be performed. Engineering tests are those which are used primarily for the purpose of acquiring data to support the design and development.

4.1.2.2 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.

4.1.3. 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 A TRANSFER FUNCTION OF SUSPENSION

A.1. Transfer Function from Horizontal to Horizontal, T_{hh}

The requirement is self-evident.

A.2. Transfer Function from Horizontal to Pitch, T_{hp}

The requirement is obtained by demanding the resultant cavity length variation due to pitch motion with a beam spot offset d of 1 mm (LOS1) and 3 mm (SOS) to be 10% of the transfer function from horizontal to horizontal:

$$d \times T_{hp} < 0.1 \times T_{hh} . \quad (1)$$

A.3. Transfer Function from Vertical to Vertical, T_{vv}

The requirement is self evident. The resultant vertical motion contributes to the interferometer noise due to a misalignment of the optical axis with the local perpendicular to gravity at the test mass chamber, that is 3×10^{-4} for both LOS1 and SOS.

A.4. Transfer Function from Vertical to Horizontal, T_{vh}

The requirement is obtained by demanding the resultant horizontal motion to be 10% of the resultant cavity length variation due to the vertical to vertical transfer function:

$$T_{vh} < 0.1 \times (3 \times 10^{-4}) \times T_{vv} . \quad (2)$$

A.5. Transfer Function from Vertical to Pitch, T_{vp}

The requirement is obtained by demanding the resultant cavity length variation due to pitch motion with a beam spot offset d of 1 mm (LOS1) and 3 mm (SOS) to be 10% of the resultant cavity length variation due to the vertical to vertical transfer function:

$$d \times T_{vp} < 0.1 \times (3 \times 10^{-4}) \times T_{vv}. \qquad (3)$$

APPENDIX B THERMAL NOISE

B.1. LOS1

B.1.1. Vibrational Thermal Noise

The vibrational thermal noise requirement for the quadrature sum of all four test masses is $8\times10^{-20}\mathrm{m}/\sqrt{\mathrm{Hz}}$ at 100 Hz with $f^{-0.5}$ frequency dependence.

Thermal noise due to internal vibrations of the test masses was estimated following the method used in [17] LIGO-P940003-00-R: Thermally Excited Vibrations of the Mirrors of Laser Interferometer Gravitational-Wave Detectors:

$$\tilde{x}_{IFO}(f) = 4.2 \times 10^{-20}\frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}} \cdot \left(\frac{100\ \mathrm{Hz}}{f}\right)^{1/2} \cdot \left(\frac{\varphi(f)}{10^{-7}}\right)^{1/2} \qquad (4)$$

for the noise contribution to the interferometer from the four test masses, accounting for the finite spot sizes of the beams on the end and vertex masses, and summing over the appropriate vibrational modes of the test masses. Therefore the average effective loss of vibrational modes due to the sum of loss in the attachments and the intrinsic loss of the substrate must be less than 4×10^{-7}.

B.1.2. Pendulum Thermal Noise

The pendulum thermal noise requirement for the quadrature sum of the four test masses is $1\times10^{-19}\mathrm{m}/\sqrt{\mathrm{Hz}}$ at 100 Hz (thus $5\times10^{-20}\mathrm{m}/\sqrt{\mathrm{Hz}}$ per test mass) with $f^{-2.5}$ frequency dependence.

The spectral density of displacement due to the suspension fiber thermal noise is (See [18] LIGO-P940011-00-R: Suspension Losses in the Pendula of Laser Interferometer Gravitational-Wave Detectors):

$$\tilde{x}^2_{pend}(f) = \frac{4k_BT}{M} \cdot \frac{\omega_0^2\varphi(f)}{\omega[(\omega_0^2-\omega^2)^2-\omega_0^4\varphi^2(f)]} \qquad (5)$$

where $k_B = 1.4 \times 10^{-23}$ J/K, T = 295 K, M = 10.7 kg, and $\omega_0 = 0.74 \times 2\pi$ are Boltzman's constant, the temperature, the mass, and the resonant angular frequency, respectively. $\varphi(f)$ must be less than 7×10^{-6}.

B.1.3. Pitch and Yaw Thermal Noise

Suspension pitch/yaw thermal noise couples with a beam spot offset from the center of mass to produce cavity length variations (See [19] LIGO-P940012-00-R: Mirror-Orientation Noise in a Fabry-Perot Interferometer Gravitational Wave Detector). The displacement noise caused by the pitch/yaw thermal noise must be less than 10% of the LIGO sensitivity, that is, $1\times10^{-20}\mathrm{m}/\sqrt{\mathrm{Hz}}$ per degree of freedom at 100 Hz (thus $5\times10^{-21}\mathrm{m}/\sqrt{\mathrm{Hz}}$ per test mass per degree of freedom) with $f^{-2.5}$ frequency dependence. Since the requirement for the beam spot offset (ASC) is 1 mm, the required angle fluctuation is $5\times10^{-18}\mathrm{rad}/\sqrt{\mathrm{Hz}}$ per test mass per degree of freedom at 100 Hz with $f^{-2.5}$ frequency dependence.

The spectral density of orientation due to the pitch/yaw thermal noise is:

$$\tilde{\theta}^2(f) = \frac{4k_BT}{I}\cdot\frac{\omega_0^2\varphi(f)}{\omega[(\omega_0^2-\omega^2)^2-\omega_0^4\varphi^2(f)]} \tag{6}$$

where $k_B = 1.4\times10^{-23}$ J/K, T = 295 K, $I = 5.1\times10^{-2}$ kgm^2, and $\omega_0 = 0.6\times2\pi$ or $0.5\times2\pi$ are Boltzman's constant, the temperature, the momentum of inertia, and the resonant angular frequency (for pitch and yaw), respectively. $\varphi(f)$ must be less than 5×10^{-4} for pitch and 8×10^{-4} for yaw, respectively.

B.1.4. Vertical Thermal Noise

Vertical thermal noise contributes to the interferometer noise due to a misalignment of the optical axis with the local perpendicular to gravity at the test mass chamber, that is 3×10^{-4}. This is the average misalignment for each test mass chamber, both sites, both 4km arms, and can be used for all (although some are strictly at 0 and others at 6e-4). The displacement noise caused by the vertical thermal noise must be less than 10% of the LIGO sensitivity, that is, $1\times10^{-20}\mathrm{m}/\sqrt{\mathrm{Hz}}$ at 100 Hz (thus $5\times10^{-21}\mathrm{m}/\sqrt{\mathrm{Hz}}$ per test mass) with $f^{-2.5}$ frequency dependence. Therefore the vertical motion must be less than $1.7\times10^{-17}\mathrm{m}/\sqrt{\mathrm{Hz}}$ per test mass) at 100 Hz with $f^{-2.5}$ frequency dependence. The spectral density of displacement noise due to the vertical thermal noise is:

$$\tilde{z}_{vert}^2(f) = \frac{4k_BT}{M}\cdot\frac{\omega_0^2\varphi(f)}{\omega[(\omega_0^2-\omega^2)^2-\omega_0^4\varphi^2(f)]} \tag{7}$$

where $k_B = 1.4\times10^{-23}$ J/K, T = 295 K, M = 10.7 kg, and $\omega_0 = 13\times2\pi$ are Boltzman's constant, the temperature, the mass, and the resonant angular frequency, respectively. $\varphi(f)$ must be less than 3×10^{-3}.

B.1.5. Viscous Damping

Viscous thermal noise is required to be less than 20% of the LIGO sensitivity, that is

$3.2\times10^{--}\mathrm{m}/\sqrt{\mathrm{Hz}}$ (thus $1.6\times10^{--}\mathrm{m}/\sqrt{\mathrm{Hz}}$ per test mass) at 100 Hz with f^{-2} frequency dependence

$$\tilde{x}^2_{visc}(f) = \frac{4k_BT}{M}\cdot\frac{\omega_0^2\varphi(f)}{\omega[(\omega_0^2-\omega^2)^2-\omega_0^4\varphi^2(f)]} \qquad (8)$$

where $k_B = 1.4\times10^{-23}$ J/K, T = 295 K, M = 10.7 kg, and $\omega_0 = 0.74\times2\pi$ are Boltzman's constant, the temperature, the mass, and the resonant angular frequency, respectively. $\varphi(f)$ must be less than 8×10^{-7} at 100 Hz, which corresponds to 6×10^{-9} at 0.74 Hz.

B.2. SOS

Thermal noise requirement for the quadrature sum of the three mode cleaner mirrors is $3.5\times10^{-18}\mathrm{m}/\sqrt{\mathrm{Hz}}$ at 100 Hz with $f^{-0.5}$ frequency dependence above 100 Hz and $f^{-2.5}$ frequency dependence below 100 Hz to ensure the required frequency noise ($1\times10^{-4}\mathrm{Hz}/\sqrt{\mathrm{Hz}}$ at 100 Hz with $f^{-0.5}$ frequency dependence above 100 Hz and $f^{-2.5}$ frequency dependence below 100 Hz) of the light coming out of the mode cleaner.

B.2.1. Vibrational Thermal Noise

The vibrational thermal noise requirement for the quadrature sum of the three mode cleaner mirrors is 70% of the total thermal noise, that is, $2.5\times10^{-18}\mathrm{m}/\sqrt{\mathrm{Hz}}$ with $f^{-0.5}$ frequency dependence.

Thermal noise due to internal vibrations of the mirrors was estimated following the method used in [17] LIGO-P940003-00-R: Thermally Excited Vibrations of the Mirrors of Laser Interferometer Gravitational-Wave Detectors.

$$\tilde{x}_{MCM}(f) = 2.3\times10^{-18}\frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}}\cdot\left(\frac{100\ \mathrm{Hz}}{f}\right)^{1/2}\cdot\left(\frac{\varphi(f)}{10^{-5}}\right)^{1/2} \qquad (9)$$

for the noise contribution to the mode cleaner from the three mode-cleaner mirrors, accounting for the finite spot sizes of the beams on the flat and curved mirrors, and summing over the appropriate vibrational modes of the mirrors. Therefore the average effective Loss of vibrational modes due to attachments must be less than 1×10^{-5}.

B.2.2. Pendulum Thermal Noise

The pendulum thermal noise requirement for the quadrature sum of all three mode cleaner mirrors is less than 20% of the total thermal noise, that is $7.0\times10^{-19}\mathrm{m}/\sqrt{\mathrm{Hz}}$ at 100 Hz (thus $3.5\times10^{-19}\mathrm{m}/\sqrt{\mathrm{Hz}}$ per mirror) with $f^{-2.5}$ frequency dependence.

The spectral density of the displacement due to the pendulum thermal noise is:

$$\tilde{x}^2_{pend}(f) = \frac{4k_BT}{M} \cdot \frac{\omega_0^2\varphi(f)}{\omega[(\omega_0^2 - \omega^2)^2 - \omega_0^4\varphi^2(f)]} \quad (10)$$

where $k_B = 1.4 \times 10^{-23}$ J/K, T = 295 K, M = 0.25 kg, and $\omega_0 = 1 \times 2\pi$ are Boltzman's constant, the temperature, the mass, and the resonant angular frequency, respectively. $\varphi(f)$ must be less than 5×10^{-6}.

B.2.3. Pitch and Yaw Thermal Noise

Suspension pitch/yaw thermal noise couples with the beam spot offset from the center of mass to be converted into the cavity length variations. The pitch/yaw thermal noise requirement is less than 20% (for pitch) and 10% (for yaw) of the total thermal noise, that is $7.0\times10^{-19}\mathrm{m}/\sqrt{\mathrm{Hz}}$ (for pitch) and $3.5\times10^{-19}\mathrm{m}/\sqrt{\mathrm{Hz}}$ (for yaw) at 100 Hz (Thus $3.5\times10^{-19}\mathrm{m}/\sqrt{\mathrm{Hz}}$ (for pitch) and $1.8\times10^{-19}\mathrm{m}/\sqrt{\mathrm{Hz}}$ (for yaw) per mirror) with the $f^{-2.5}$ frequency dependence.

Since the requirement for the beam spot offset (IOO) is 3 mm, the required angle fluctuation is $1.2\times10^{-16}\mathrm{rad}/\sqrt{\mathrm{Hz}}$ (for pitch) and $5.8\times10^{-17}\mathrm{rad}/\sqrt{\mathrm{Hz}}$ (for yaw) per test mass per degree of freedom at 100 Hz with the $f^{-2.5}$ frequency dependence.

The spectral density of orientation due to the pitch/yaw thermal noise is:

$$\tilde{\theta}^2(f) = \frac{4k_BT}{I} \cdot \frac{\omega_0^2\varphi(f)}{\omega[(\omega_0^2 - \omega^2)^2 - \omega_0^4\varphi^2(f)]} \quad (11)$$

where $k_B = 1.4 \times 10^{-23}$ J/K, T = 295 K, $I = 1.0 \times 10^{-4}$ kgm^2, and $\omega_0 = 0.85 \times 2\pi$ or $0.75 \times 2\pi$ are Boltzman's constant, the temperature, the momentum of inertia, and the resonant angular frequency (for pitch and yaw), respectively. $\varphi(f)$ must be less than 3×10^{-4} for pitch and 9×10^{-5} for yaw, respectively.

B.2.4. Vertical Thermal Noise

Vertical thermal noise contributes to the interferometer noise due to a misalignment of the mode cleaner mirrors from the local verticals, that is 3×10^{-4}. The vertical thermal noise requirement is less than 10% of the total thermal noise, that is, $3.5\times10^{-19}\mathrm{m}/\sqrt{\mathrm{Hz}}$ at 100 Hz (thus $1.8\times10^{-19}\mathrm{m}/\sqrt{\mathrm{Hz}}$ per mirror) with the $f^{-2.5}$ frequency dependence. Therefore the vertical motion must be less than $5.8\times10^{-16}\mathrm{m}/\sqrt{\mathrm{Hz}}$ per mirror at 100 Hz. The spectral density of displacement due to the vertical thermal noise is:

$$\tilde{z}^2_{vert}(f) = \frac{4k_BT}{M} \cdot \frac{\omega_0^2\varphi(f)}{\omega[(\omega_0^2 - \omega^2)^2 - \omega_0^4\varphi^2(f)]} \quad (12)$$

where $k_B = 1.4 \times 10^{-23}$ J/K, T = 295 K, M = 0.25 kg, and $\omega_0 = 16 \times 2\pi$ are Boltzman's constant, the temperature, the mass, and the resonant angular frequency, respectively. $\varphi(f)$ must be less than 7×10^{-2}.

B.2.5. Viscous Damping

The viscous thermal noise requirement is less than 70% of the total thermal noise, that is, $2.5\times10^{-18}\mathrm{m}/\sqrt{\mathrm{Hz}}$ at 100 Hz (thus $1.2\times10^{-18}\mathrm{m}/\sqrt{\mathrm{Hz}}$ per mirror) with f^{-2} frequency dependence

The spectral density of displacement due to the viscous thermal noise is:

$$\tilde{x}^2_{visc}(f) = \frac{4k_BT}{M} \cdot \frac{\omega_0^2\varphi(f)}{\omega[(\omega_0^2 - \omega^2)^2 - \omega_0^4\varphi^2(f)]} \qquad (13)$$

where $k_B = 1.4 \times 10^{-23}$ J/K, T = 295 K, M = 0.25 kg, and $\omega_0 = 1 \times 2\pi$ are Boltzman's constant, the temperature, the mass, and the resonant angular frequency, respectively. $\varphi(f)$ must be less than 6×10^{-5} at 100 Hz, which corresponds to 6×10^{-7} at 1 Hz.

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Suspension Design Requirements

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SUSPENSION DESIGN REQUIREMENTS DOCUMENT (DRD)

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1 PURPOSE OF THIS DOCUMENT

This Design Requirements Document (DRD) for the Suspension Design subsystem (SUS[1]) identifies the information necessary to define the SUS subsystem[2] and quantify its relationship to other subsystems. This includes:

- Objective and scope of the SUS activities
- System definition
- Design requirements
- Interfaces
- Conceptual design and specifications
- Testing criteria

2 OBJECTIVES AND SCOPE OF SUS DEVELOPMENT ACTIVITIES

The objective of the SUS task is to develop and provide generic suspension system prototypes so that COS and IOO can design their subsystems using the generic prototype designs. The SUS task is broken into two parallel efforts covering (1) suspensions for large optics (mainly for COS) and (2) suspensions for small optics (mainly for IOO). In each effort, we will establish the requirements, perform the preliminary design, fabricate and test prototypes, and perform the final design.

3 SYSTEM DEFINITION

3.1. Functional Definition

The main functions of the suspension system are:

- Suspend a test mass to allow it to move freely horizontally for detection of gravitational waves.
- Isolate an optical component from ground motion by suspending the component.
- Damp the optical component's motion in position and orientation using the local suspension's sensors and actuators.
- Provide control inputs for applying forces and torques to the suspended component in response to signals from the LSC and ASC systems.
- Protect the optical components by limiting motion from external disturbance.
- Reduce the effect of stray/scattered light from the optical component.

1. In this document, an acronym is used for describing each subsystem. See, for example, the LIGO detector implementation plan document.
2. Although the task of SUS is to provide a design of only a mechanical part of the suspension system, this document refers to the general suspension system including the control system.

3.2. Physical Definition

Physically, the suspension subsystem[1] consists of the following components as shown in Fig. 1:

- Suspension support structure
- Suspension block
- Sensor/actuator head holder
- Sensor/actuator head
- Magnet/vane assembly
- Wire
- Wire standoff
- Safety cage
- Stray light shield
- Suspension platform[2] **TBD**

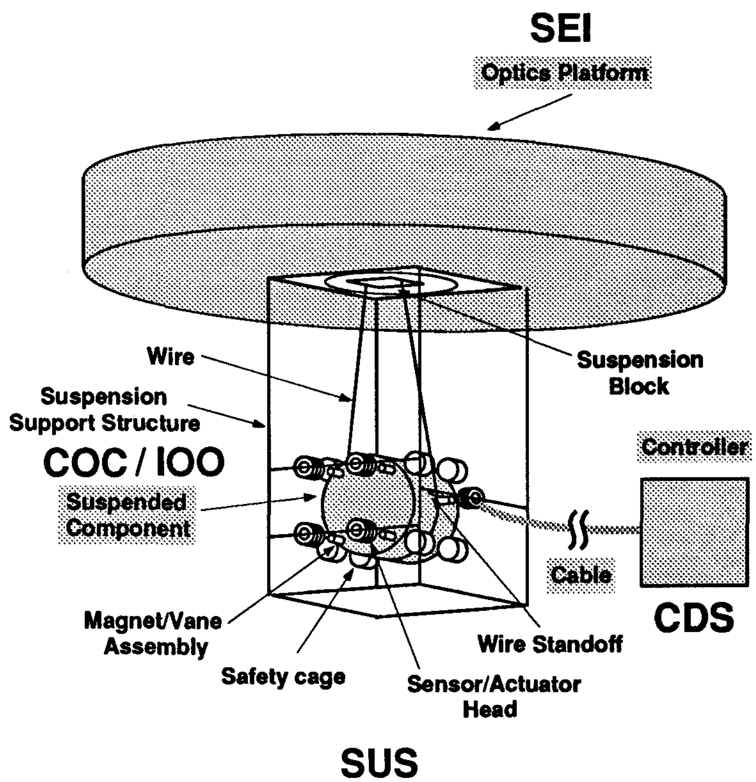

Figure 1: Physical definition of SUS

1. In this section, only a mechanical part of the suspension system is considered; the CDS part of the suspension is excluded.
2. It is a table-type platform to which the suspension assembly (for large optics) is attached in the HAM chamber.

The suspension subsystem interacts with other subsystems to provide a properly suspended and controlled optical component. The following components (shaded components in Fig.1) are parts of other subsystems as indicated in parentheses:

- Suspended optical component (COC/IOO)
- Optics platform (SEI)
- Connector, cabling and the control electronics (CDS)

3.3. Large Optics and Small Optics

Three sizes of optical components are to be suspended:

- Two sizes for large optical components (test mass size and beamsplitter size)
- One size for small optical components (mode cleaner (MC) mirror size).

There will be three types of the suspension system depending on the size of the suspended optical component: Large Optics Suspension 1 (LOS 1), Large Optics Suspension 2 (LOS 2), and small optics suspension (SOS). A list of suspended optical components for each suspension system is shown in Table 1.

Table 1: List of suspended optical components

SUS type	*Suspended Optical Components*
LOS 1	Test Masses (CO), Recycling Mirror (CO), Mode Matching Mirrors (IOO), Faraday Isolator (IOO)[a], Pockels cell (IOO) **TBD**
LOS 2	Beamsplitter (CO), Large Folding Mirrors (CO, IOO), Large Pick-offs (CO)
SOS	Mode Cleaner Mirrors (IOO), Small Folding Mirrors (IOO), Small Pick-offs (IOO)

a. An adapter ring will be fitted to the Faraday Isolator and the Pockels cell **TBD** to fit them into the standard assembly.

3.4. Damping by Suspension's Sensor

A suspended component is or is not damped using the sensor signals from its respective suspension assembly depending on the type of the optical component and the state of the interferometer. Table 2 summarizes the state of the interferometer in which optical components are damped by the suspension's sensor.

Table 2: States of interferometer operation in which optical components are damped by the suspension's sensor

Motion	*Test Mass*	*Beamsplitter, Recycling Mirror, MC Mirror, Folding Mirror, Mode Matching Mirror*	*Pick-off, Faraday Isolator, Pockels cell* ***TBD***
Longitudinal	Before and during acquisition[a]	Always	Always
Transverse	Always	Always	Always
Orientation[b]	Before acquisition	Before acquisition	Always

a. The suspension's sensor signals have poorer signal to noise ratio than the LSC signals; applying the noisier signal from the suspension's sensors to the test masses degrades the interferometer's sensitivity in the gravitational-wave band.

b. The residual orientation fluctuations of the critical optical components controlled by the suspension's sensor is estimated to be only marginally good for lock acquisition.

4 DESIGN REQUIREMENT

One of the primary objectives of the SUS DRD is to establish a complete set of requirements for the SUS subsystem. Requirements for the SUS subsystem is divided into three categories:

- Physical size
- Dynamic range
- Noise

4.1. Size Requirements

The size requirements for the SUS subsystem is:

- Three kinds of suspension system must accommodate the corresponding optical component, and must satisfy the corresponding stay-clear conditions.
- The suspension system must provide a proper vertical position for the suspended components.

The Size and the stay-clear of representative components and the height of the beam for three kinds of chambers are summarized in Table 3 and 4.

Table 3: Size and stay-clear of suspended components.

Physical Quantity	*Test Mass*	*Beamsplitter*	*Mode Cleaner Mirror*
Diameter of Suspended Component	25 cm	30 cm **TBR**	7.5 cm
Thickness of Suspended Component	10 cm	10 cm **TBR**	2.5 cm
Weight of Suspended Component	11 kg	16 kg **TBR**	0.15 kg
Required Stay-clear	20 cm	11 cm **TBR**[a]	2 cm

a. The angle of the incident beam is 45 degrees from perpendicular.

Table 4: Beam height for chambers.

Physical Quantity	*TMC Chamber*	*BSC Chamber*	*HAM Chamber*
Beam Height	-60.0 cm from bottom surface of optics platform	-60.0 cm from bottom surface of optics platform	+20 cm from top surface of stack top plate

4.2. Dynamic Range Requirements

A dynamic range of the SUS actuator[1] is required to satisfy the following primary requirements of subsystems:

- No Saturation on Lock Holding (LSC)
- Capability of Lock Acquisition (LSC)
- No Saturation on Orientation Control (ASC)
- No Saturation on Suspension's Control (SUS)

The dynamic range requirements of SUS are summarized in Table 5. (See Appendix A for detail.

Table 5: Dynamic range requirements

Physical Quantity	*Requirement*			*Unit (Frequency)*
	LOS 1 (TM)	*LOS 2 (BS)*	*SOS (MC mirror)*	
Longitudinal Motion Dynamic Range of Actuator in Operation	$>1\times10^{-5}$	$>1\times10^{-6}$	$>1\times10^{-5}$	m_{pp} (0.1 Hz)
	$>3\times10^{-8}$	$>3\times10^{-8}$	$>3\times10^{-8}$	m_{pp} (1 Hz)
	$>3\times10^{-9}$	$>1\times10^{-9}$	$>3\times10^{-9}$	m_{pp} (10 Hz)
	$>6\times10^{-17}$	Trivial	$>6\times10^{-17}$	m_{pp} (100 Hz)
	$>3\times10^{-16}$	Trivial	$>3\times10^{-16}$	m_{pp} (1 kHz)
Longitudinal Motion Dynamic Range of Actuator in Acquisition **TBR**	$>3\times10^{-5}$	N/A	N/A	m_{pp} (0.1 Hz)
	$>3\times10^{-5}$			m_{pp} (1 Hz)
	$>3\times10^{-7}$			m_{pp} (10 Hz)
	$>3\times10^{-9}$			m_{pp} (100 Hz)
	$>3\times10^{-11}$			m_{pp} (1 kHz)

1. The suspension's actuator is used to correct fluctuations on the time scale of the microseismic peak and shorter. The stack support actuator is used to correct fluctuations of much longer time scales than the microseismic peak (principally the tidal disturbances).

Table 5: Dynamic range requirements

Physical Quantity	*Requirement*			*Unit (Frequency)*
	LOS 1 (TM)	*LOS 2 (BS)*	*SOS (MC mirror)*	
Orientation Dynamic Range of Actuator	$>2\times10^{-3}$	$>2\times10^{-3}$	$>4\times10^{-3}$	rad_{pp} (DC)
	$>6\times10^{-7}$	$>6\times10^{-7}$	$>6\times10^{-7}$	rad_{pp} (0.1 Hz)
	$>2\times10^{-7}$	$>2\times10^{-7}$	$>2\times10^{-7}$	rad_{pp} (1 Hz)
	$>6\times10^{-10}$	$>6\times10^{-10}$	$>6\times10^{-10}$	rad_{pp} (10 Hz)

4.3. Noise Requirements

Noise caused by or related to the suspension subsystem must not preclude the interferometer from achieving the initial LIGO sensitivity. The noise sources which are caused by or related to the suspension system are:

- Thermal noise, which leads to requirements on the losses of suspended components degraded by attachments and suspension fibers
- Seismic noise, which leads to a required transfer function for the suspension
- Control noise, which leads to requirements on both the sensor and the control electronics

Table 6 shows noise requirements for SUS (See Appendix B and C for detail.)

Table 6: Noise requirements

Physical Quantity	*Requirement*			*Unit (Frequency)*
	LOS 1 (TM)	*LOS 2 (BS)*	*SOS (MC mirror)*	
Average Effective Loss of Internal Modes due to attachments	$<4\times10^{-7}$	$<1.6\times10^{-4}$	**TBD**	(100 Hz)
Average Effective Loss of the Pendulum Mode	$<3\times10^{-6}$	$<1.2\times10^{-3}$	**TBD**	(100 Hz)
Transfer Function of Suspended Component (horizontal to horizontal)	$<\left(\frac{0.74\mathrm{Hz}}{f}\right)^2$	$<20\mathrm{x}\left(\frac{0.74\mathrm{Hz}}{f}\right)^2$	$<2000\mathrm{x}\left(\frac{0.74\mathrm{Hz}}{f}\right)^2$	(10 Hz - 100 Hz)
Transfer Function of Suspended Component (vertical to horizontal)	$<6\times10^{-4}$	$<1.2\times10^{-2}$	<1.2	(10 Hz - 0 Hz)
Control Noise	$<5\times10^{-20}$	$<1\times10^{-17}$	$<1.2\times10^{-15}$	$m/\sqrt{Hz}$ (40 Hz)
	$<7\times10^{-21}$	$<1.4\times10^{-18}$	$<6\times10^{-18}$	$m/\sqrt{Hz}$ (100 Hz)
Scattered Light Effect Reduction	**TBD**	**TBD**	**TBD**	N/A

4.4. Performance Requirement Flowdown

Most of the performance requirements (dynamic range and noise requirements) of the SUS subsystem are established so that they satisfy the primary requirements of the detector (or subsystems) together with requirements of other subsystems. Table 7 summarizes such flowdown from primary requirements of the detector (or subsystems) to requirements of SUS and other subsystems.

Table 7: Performance requirement flowdown

Requirement Entry of SUS	*Other Subsystem*	*Requirement Entry of the Subsystem*	*Primary Requirement of Detector/Subsystem to be satisfied*
Longitudinal Motion Dynamic Range of Actuator in Operation (TM, MC Mirror)	Environment + SEI + SUS	Longitudinal Motion of Suspended Component	No Saturation on Lock Holding (LSC)
	LSC	Residual RMS Longitudinal Motion of Suspended Component	
Longitudinal Motion Dynamic Range of Actuator in Acquisition (TM, MC Mirror)	Environment + SEI + SUS	Longitudinal Motion of Suspended Component	Capability of Lock Acquisition (LSC)
	LSC	Acquisition Method	
Orientation Dynamic Range of Actuator (TM, BS, MC Mirror)	Environment + SEI + SUS	Angular Motion of Suspended Component	No Saturation on Orientation Control (ASC)
	ASC	Residual RMS Angular Motion of Suspended Component	
Longitudinal Motion & Orientation Dynamic Range of Actuator (All Components))	Environment + SEI	Longitudinal Motion of Optics Platform/Stack Top Plate	No Saturation on Suspension's Control (SUS)
Loss of Internal Modes due to Attachments (TM, BS)	CO	Loss of Internal Mode for Blank Mass	Internal Mode Thermal Noise (Detector)
Loss of Internal Modes due to Attachments (MC Mirror)	IOO	Loss of Internal Mode for Blank Mass	Internal Mode Thermal Noise of MC Mirror (IOO)
Loss of Pendulum Modes (TM, BS)	N/A	N/A	Pendulum Mode Thermal Noise (Detector)

Table 7: Performance requirement flowdown

Requirement Entry of SUS	*Other Subsystem*	*Requirement Entry of the Subsystem*	*Primary Requirement of Detector/Subsystem to be satisfied*
Loss of Pendulum Modes (MC Mirror)	N/A	N/A	Pendulum Mode Thermal Noise of MC Mirror (IOO)
Transfer function of Pendulum (TM, BS)	Environment + SEI	Motion of Optics Platform	Seismic Noise (Detector)
Transfer function of Pendulum (MC Mirror))	Environment + SEI	Motion of Stack Top Plate	Seismic Noise of MC Mirror (IOO)
Control Noise (TM, BS)	N/A	N/A	Non-Primary Noise (Detector)
Control Noise (MC Mirror)	N/A	N/A	Non-Primary Noise of MC Mirror (IOO)
Scattered Light Effect Reduction	Detector	Raw Scattered Light noise	Scattered Light Noise (Detector/IOO)

5 INTERFACES

Interfaces between SUS and other subsystems are divided into two categories:

- Mechanical interfaces
- Signal interfaces

5.1. Mechanical Interfaces

The suspension subsystem[1] has mechanical interfaces with other subsystems as shown in Table 8 (Ref. Fig.1).

Table 8: Mechanical interfaces between SUS and other subsystems

Other Subsystem	*SUS's Part*	*Other Subsystem's Part*
SEI	Top Plate of Suspension Support Structure	Optics Platform
SEI	Bottom Plate of Suspension Support Structure	Stack Top Plate
COC/IOO	Suspension Wire	Optical Component
COC/IOO	Wire Standoff	Optical Component
COC/IOO	Magnet Standoff	Optical Component
CDS	Sensor/Actuator Head	Connector/cable

1. In this section, only a mechanical part of the suspension system is regarded as the SUS subsystem; the CDS part of the suspension is not included.

5.2. Signal Interfaces

Signal interfaces between SUS and other subsystems are illustrated in Fig. 2 and summarized in Table 9.

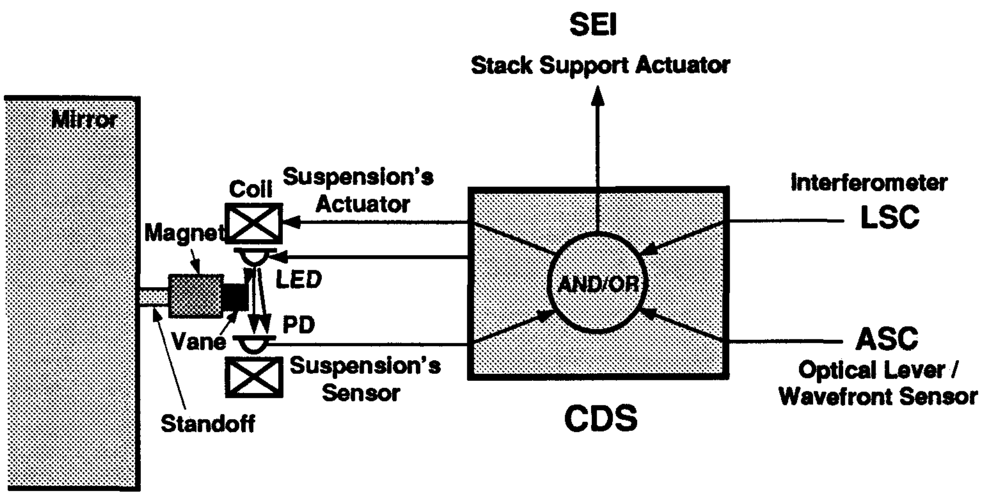

Figure 2: Signal Interfaces

Table 9: Signal interfaces between SUS and other subsystem

Other Subsystem	*Signal*	*Signal Flow* SUS <--> Subsystem
LSC	Interferometer Signal	<--
ASC	Optical Lever Signal and/or Wavefront Sensing Signal	<--
SEI	Stack pushing Signal	Related

6 CONCEPTUAL DESIGN AND SPECIFICATIONS

The suspension system was conceptually designed, considering the requirements to be satisfied as well as the following design philosophy:

- Reliability
- Simplicity
- Tractability
- Safety

A conceptual design of the suspension assembly was schematically shown in Figure 1. General features of the design are:

- The suspension assembly is held together by a suspension support structure.
- The optical component is suspended by a single loop of wire from a suspension block, using wire standoffs between the suspension wire and the component.
- The position and the orientation of the optical component are detected by five edge sensors, consisting of a magnet/vane assembly attached to the optical component and an LED/photodiode pair.
- The optical component is to be damped or to be controlled by five magnet/coil actuators.
- The optical component is protected or held during transfer by a safety cage.

6.1. Suspension Support Structure

The suspension assembly will have a modular support structure. The optical component is suspended from the suspension block, which is fixed to the top plate of the support structure. The sensor/actuator heads and the safety cage are also attached to the support structure.[1] The support structure must have a function of changing coarsely its position and orientation.

The suspension support structure need to be sufficiently rigid so that mechanical resonances do not shake the sensor/actuator head and put excess force on the suspended component.

6.2. Suspension Configuration

A single loop of wire suspends the optical component. A sketch of the configuration of a suspended component is given in Fig. 3. The important design parameters of this single loop suspension are:

- Length of the pendulum ($d_{pendulum}$ in Fig. 3)
- Distance between the two suspension points at the top plate (d_{yaw})
- Height from a horizontal level through the center of mass to the wire release points (d_{pitch})
- Diameter of the wire standoff ($d_{standoff}$)
- Minimum distance between the wire and the test mass/mirror above the wire release points (d_{margin})

1. The advantage of this modular support structure is that the system can be assembled and adjusted (including balancing the test mass/mirror in pitch) on a clean bench or table and then can be transferred into the tank without changing the relative position between the optical component and the sensor/actuator head.

These parameters are chosen to satisfy the desired pendulum, pitch, and yaw frequency for non-vanishing d_{margin} as shown in Table 10. (See Appendix D for detail.)

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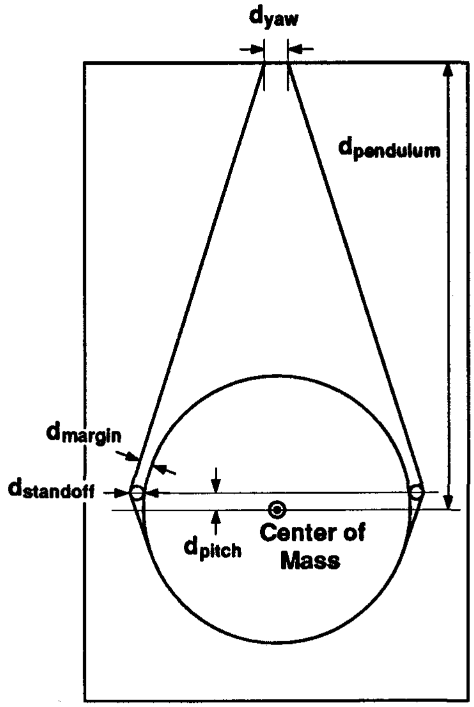


Figure 3: Suspension configuration

Table 10: Suspension configuration

Physical Quantity	*Specification*		
	LOS 1 (TM)	*LOS 2 (BS)*	*SOS (MC mirror)*
Pendulum Frequency	0.74 Hz	0.74 Hz	0.74 Hz
Pitch Frequency	0.5 Hz	0.5 Hz	0.5 Hz
Yaw Frequency	0.5 Hz	0.5 Hz	0.5 Hz
$d_{pendulum}$	45 cm	45 cm	45 cm
d_{pitch}	5 mm	6.5 mm	0.4 mm
d_{yaw}	34 mm	39 mm	9 mm
$d_{standoff}$	3.1 mmD	5.5 mmD	1 mmD
d_{margin}	0.5 mm	0.5 mm	0.9 mm

6.3. Sensor/Actuator Head

The position sensor for a suspended component will be a simple edge sensor, which consists of an LED paired with a photodiode, which senses the shadow of a small vane attached to the component. The force/torque actuator will be a fixed coil which drives a magnet attached to the suspended component. The system is illustrated in Fig. 4. The sensor/actuator head is placed so that approximately half the light from the LED is blocked by the vane. The sensor detects the position of the vane as the change in the photocurrent. The preamplifier for the sensor is external to the vacuum system.[1]

In order to sense the longitudinal position and the orientation (pitch and yaw) of the optical component and to apply forces and torques to it, four sensor/actuator heads are placed in a plane at the back face of the suspended component. An elevation view of the sensor/actuator configuration is shown in Fig. 1. One additional head is placed on the side of the suspended optic to damp its transverse motion.

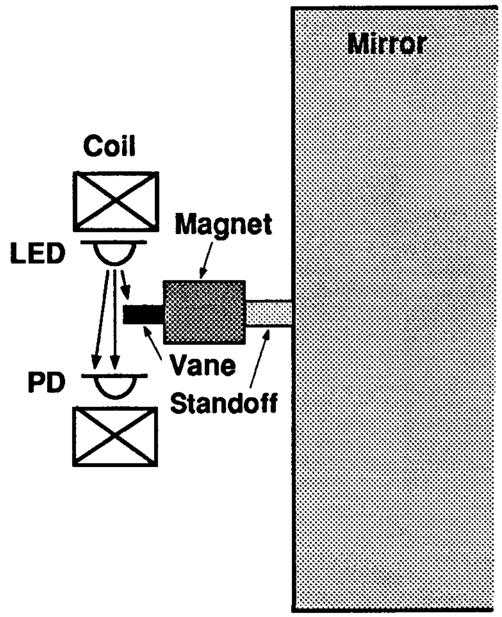


Figure 4: Sensor and actuator

6.4. Magnet/Vane Assembly and Standoff

The magnet and vane are incorporated into a single assembly which is then attached to the suspended component using a standoff to minimize the effects of the magnet/vane assembly on the thermal noise. (See Fig. 4)

6.5. Suspension Fiber

Steel music wire will be used as the suspension fiber material. The diameter of the wire is chosen

1. It was demonstrated by experiment that the sensor noise can satisfy the requirement with this method.

so that the wire will be loaded to one-half its breakage stress, to obtain the lowest possible wire losses and the smallest number of violin modes in the gravitational-wave signal band, without incurring undue risks due to wire failure or the production of excess non-gaussian noise (through acoustic emission from the loaded wire).[1]

6.6. Control Noise

The control noise must satisfy the noise requirements. The following is a reasonable set of specifications necessary to satisfy the noise requirement for the test mass (see Appendix E):

- The equivalent displacement noise of the sensor is $1\times10^{-10}\mathrm{m}/\sqrt{\mathrm{Hz}}$ above 40 Hz.
- The servo loop gain is 5×10^{-9} at 40 Hz, and 7×10^{-10} at 100 Hz.
- The efficiency of the suspension's actuator is 0.02 N/A above 40 Hz.
- The driver current noise including the Johnson noise is $1.5\times10^{-12}\mathrm{A}/\sqrt{\mathrm{Hz}}$ at 40 Hz, and $1.5\times10^{-12}\mathrm{A}/\sqrt{\mathrm{Hz}}$ at 100 Hz.

6.7. Wire Standoffs

Small quartz rods will be used as standoffs where the wire attaches to the suspended component, as shown in Figure 5. Each rod has a groove on it so that the wire may be repeatedly placed in the same position, which assures the stable balancing of the suspended component. Smaller quartz rods are used as guide rods.[2]

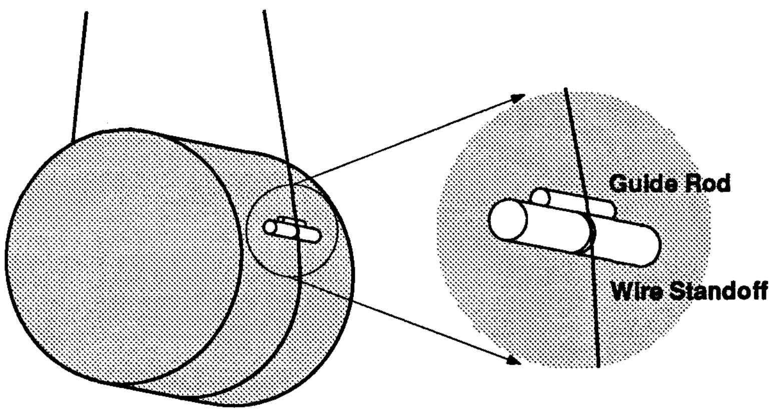


Figure 5: Details of wire standoff attachment

1. It should be noted that tests of other fiber materials are intended as part of ongoing R&D and will likely result in a material that has better thermal noise properties and a more stable surface finish. Because of the importance of non-gaussian noise to the overall detector performance, any contemplated replacement for steel music wire should be thoroughly characterized for evidence of acoustic emission prior to its use in LIGO.
2. These are used for aligning the grooved rod to balance the pitch orientation of the component. The procedure is first to glue the guide rod onto the test mass/mirror, then adjust the wire-standoff rod along the guide rod until the pitch is properly balanced and finally to glue the wire standoff to the test mass/mirror.

6.8. Safety Cage

The motion of the optical component is restrained by a safety cage to protect the component from large motion. The safety cage is also used to hold the suspended component during installation after it is assembled and balanced on a clean table or bench. The safety cage must have adjustments to allow the suspended component to be held firmly by the cage or released. A manually adjustable cage will be used in all locations except for components mounted in TMC chambers, which require motorized cage adjustment in vacuo.

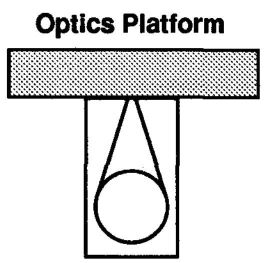
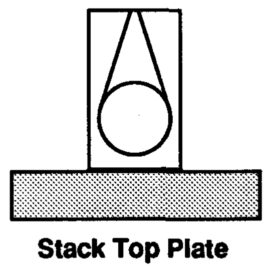
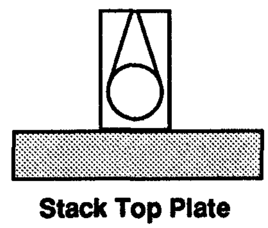
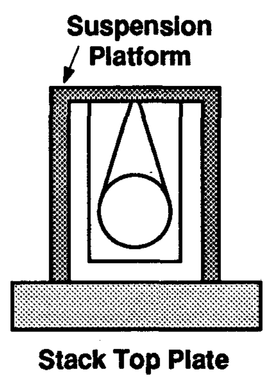
6.9. Stray Light Shield

TBD

6.10. Suspension Assembly Installation

The suspension assembly is directly joined to the optics platform or the stack top plate, depending on a kind of the chambers (See Table 11). An alternative installation method is using a suspension platform **TBD** for LOS 1/LOS 2 in the HAM chamber.[1] The design will be finalized based on finite-element modeling done during the preliminary design.

Table 11: Suspension Assembly Installation

Suspension Type	LOS 1/LOS 2	LOS 1/LOS 2	SOS
Chamber Type	TMC/BSC	HAM	HAM
Installation			
Alternative Method	N/A		N/A

1. The advantage of the suspension platform is as follows: the suspension assembly is always supported by bolting through the top plate. This allows a common suspension assembly design for LOS 1/LOS 2 to be used in all chambers. Furthermore, because the large weight of the suspended, high performance optic is not supported by the suspension-cage side members, this part of the structure can be made of less massive material, while adequately supporting the sensor/adaptor heads and safety cage, which do not need to be as rigidly supported. This allows the common suspension assembly to have a minimum-area silhouette, making best use of the optical free aperture.

6.11. Parts and Specifications

The list of parts used in the above-mentioned conceptual design, and the specifications for physical quantities related to those parts are summarized in Table 12.

Table 12: Parts and specifications

Subdivision	*Part*	*Physical Quantity*	*Specification*		
			LOS 1 (TM)	*LOS 2 (BS, RM)*	*SOS (MC mirror)*
Suspension Support Structure	Side Plate	Size, Material	-[a]	-	-
	Top Plate	Size, Material	-	-	-
	Base Plate	Size, Material	-	-	-
	Position/Orientation Adjuster	Type	-	-	-
Suspension Block	Suspension Block	Clamp Method	Conventional Clamp		
		d_{yaw}	*[b]	*	*
Sensor/Actuator Head Holder	Rear Face Head Holder	Size	-	-	-
		Material	Macor		
		Head Clamping Method	Two guide lines, one screw		
	Side Head Holder	Size	-	-	-
		Material	Macor		
		Head Clamping Method	Two guide lines, one screw		

Table 12: Parts and specifications

Subdivision	*Part*	*Physical Quantity*	*Specification*		
			LOS 1 (TM)	*LOS 2 (BS, RM)*	*SOS (MC mirror)*
Sensor/Actuator Head	Head	Material	Macor		
		Size	-		
		Distance between LED and Photodiode	-		
		Coil Cross Section	-		
		Relative Position of LED-PD to Coil	-		
	LED	Type	Side-view type, non-magnetic		
		Model	-		
		Power	-		
		Collimation	-		
	Photodiode	Type	Side-view type, non-magnetic		
		Model	-		
		Effective Area	-		
		Isolation from Green/Red Beam	-		
	Coil Wire	Material	-		
		Diameter	-		
		Turns	-		

Table 12: Parts and specifications

Subdivision	*Part*	*Physical Quantity*	*Specification*		
			LOS 1 (TM)	*LOS 2 (BS, RM)*	*SOS (MC mirror)*
Magnet/Vane Assembly	Magnet	Material	Nd:Fe:B		
		Size	3 mmD x 5 mmL	-	-
	Vane	Material	-		
		Size	-	-	-
	Magnet Stand-off	Material	Aluminum		
		Size	1 mmD x 3 mmL	-	-
	Glue	Type	-		
Wire	Wire	Material	Steel Music Wire		
		Diameter	0.28 mm	-	-
		$d_{pendulum}$	*	*	*
		d_{margin}	*	*	*
Wire Standoff	Grooved Rod	Material	Quartz		
		Size ($d_{standoff}$)	*	*	*
		Groove Size	-	-	-
		d_{pitch}	*	*	*
	Guide Rod	Material	Quartz		
		Size	1 mmD	1 mmD	1 mmD
	Glue	Type	-		

Table 12: Parts and specifications

Subdivision	*Part*	*Physical Quantity*	*Specification*		
			LOS 1 (TM)	*LOS 2 (BS, RM)*	*SOS (MC mirror)*
Safety Cage	Cage	Material	-		
		Size	-	-	-
	Holding Tip	Material	Teflon		
		Size	-	-	-
	Translator	Mechanism	-	-	-
	Motor	Type	-	N/A	N/A
Stray Light Shield	**TBD**	-	-	-	-
Suspension Platform	**TBD**	-	-	-	-

a. A mark "-" indicates that the specifications will be determined during the preliminary design phase.
b. A mark "*" indicates that the value is shown in another table.

7 TESTING CRITERIA

7.1. Check-out of Assembly/Test Fixtures

Demonstrate gluing of magnet/vane assemblies and guide rods onto aluminum model fixtures (TM, BS, and MCM) using special gluing fixtures (TM, BS, MCM), respectively

7.2. Fit Check and Constructability Verification

There are seven possible reconfigurations of the large and small suspension assemblies (Table 13). Fit checks of all seven configurations must be carried out, using aluminum models in place of the actual optical components. Special note shall be taken of any issues which affect the ability or efficiency with which these assemblies can be constructed or which may affect the ability to service them at the sites.

Table 13: Possible reconfigurations of the large and small suspension assemblies.

Configuration	*Suspension Type*	*Safety Cage Type*	*Height Adapter Type*
1	LOS 1	Manual	Tube
2	LOS 1	Motorized	Tube
3	LOS 1	Manual	Table
4	LOS 2	Manual	Tube
5	LOS 2	Motorized	Tube
6	LOS 2	Manual	Table
7	SOS	Manual	Block

7.3. Alignment Tests

The alignment test will be done only for the LOS 1 suspension and SOS suspension. (Aluminum models will be used in place of optical components.)

- A method to align and balance the optical components using a PZT buzzer to within tolerances prior to gluing down standoffs will be demonstrated.
- It will also be demonstrated that optical components can be dismounted and remounted into proper optical alignment, within design tolerances.
- It will be shown that coarse optical alignment and all clearance adjustments can be performed on a clean table or bench away from the vacuum system.

7.4. Q Measurements

The following Q measurements will be done using the suspension development facility for a suspended test mass and a suspended MC mirror, to ensure that the design provides thermal noise estimates that correspond to or exceed the target thermal noise specification:

- Resonance Q's of suspension wire violin resonances for lowest three harmonics of both wires
- Substrate vibrational mode Q's for lowest five axisymmetric modes

7.5. Sensor/Actuator Head Tests

The sensor/actuator head will be tested:

- Electrical tests of the sensor/actuator head will verify that functionality and sensitivity specifications are met.
- The coupling strength between the actuator coil and magnet will be measured.

7.6. Check-out of Sensor/Actuator Head Testing Procedure

A test fixture will be developed for automated testing of sensor heads and an automated testing procedure will be demonstrated.

7.7. Demonstration of Local Damping

It will be shown that critical damping can be achieved under local control making use of the servo electronics which will be made for the new suspension system for the Mark II interferometer. This will be done for a LOS 1 suspension and SOS suspension. (Aluminum models will be used in place of optical components.)

7.8. Transfer Function Tests

The transfer function will be measured for a LOS 1 suspension and a SOS suspension. (Aluminum models will be used in place of optical components.) The response of the system will be measured for DC and for AC inputs over the relevant range of frequencies to show that the specified forces and torques can be applied to suspended components and that the requirements on mechanical resonances of the system can be met.

7.9. Rigidity Test

Excitation and measurement of higher frequency mechanical resonances will be attempted to identify the resonance frequencies and Q's of these resonances.

7.10. Feedback from R&D

The new suspension system for the Mark II interferometer will be designed to satisfy (wherever possible) the requirements described in this document. One set of the suspension system will be first installed in Mark II to test its performance. The result of the test will be fed back to the SUS design for the detector.

7.11. Fixtures and Instrument for Test

Some of the tests mentioned above require special fixtures or already existing instruments, which are summarized in Table 14.

Table 14: Fixtures to be made and existing instrument for prototype test

Test	*Fixtures to be made*	*Existing Instrument*
Check-out of Assembly/Test Fixtures	Aluminum Model Fixture (TM, BS, MCM), gluing fixtures (TM, BS, MCM)	N/A
Fit Check and Constructability Verification	N/A	Optical Tables in S. Annex Building
Alignment Tests	N/A	PZT Buzzer (in MIT), He-Ne Laser
Q Measurements	N/A	Suspension Development Facility
Sensor/Actuator Head Tests	Sensor/Actuator Test Fixture	N/A
Check-out of Sensor/Actuator Head Testing Procedure	N/A	N/A
Demonstration of Local Damping	Servo Electronics for Mark II (minor modification necessary)	N/A
Transfer Function Tests	N/A	HP 3962
Rigidity Test	N/A	Accelerometer
Feedback from R&D	N/A	Mark II

APPENDIX A: DYNAMIC RANGE REQUIREMENTS

A.1. Longitudinal Motion Dynamic Range of Actuator in Operation

Requirements for the longitudinal motion dynamic range of the actuator in operation is established to satisfy a necessity of no saturation on the lock holding for the test mass and the MC mirror, and to satisfy a necessity of no saturation on the suspension's control for the beamsplitter and other non-critical suspended components.

A.1.1. Interferometer signal feedback (test mass)

Feedback voltages from the interferometer signal to the suspension's actuator must not saturate during the operation mode. The feedback signal is dominated by the seismically excited test mass motion below 40 Hz, by the thermal noise between 40 Hz and 150 Hz, and by the shot noise above 150 Hz. Since the servo unity gain frequency is around 1 kHz, consideration is limited below 1 kHz. The equivalent displacement motion of the feedback signal is:

- At 0.1 Hz $3\times10^{-7}m_{rms}$ with a bandwidth of 0.1 Hz

The seismically excited test mass motion is dominant in the feedback signal, which is, in this case, a pure ground motion.

- At 1 Hz $6\times10^{-10}m_{rms}$ with a bandwidth of 1 Hz

The seismically excited test mass motion is dominant in the feedback signal. The ground motion is $1\times10^{-9}m_{rms}$. The pendulum transfer function is 0.6. The stack transfer function is 1.

- At 10 Hz $1\times10^{-10}m_{rms}$ with a bandwidth of 10 Hz

The seismically excited test mass motion is dominant in the feedback signal. The ground motion is $3\times10^{-9}m_{rms}$. The pendulum transfer function is 1×10^{-2}. The stack transfer function is 3.

- At 100 Hz $2\times10^{-18}m_{rms}$ with a bandwidth of 100 Hz

The thermal noise is dominant in the feedback signal, which is $2\times10^{-18}m_{rms}$.

- At 1kHz $1\times10^{-17}m_{rms}$ with a bandwidth of 1 kHz

The shot noise is dominant in the feedback signal, which is $1\times10^{-17}m_{rms}$.

The peak-to-peak dynamic range for each suspension system is obtained by multiplying relevant numbers by $30 = 3\,(\mathrm{rms} \Rightarrow \mathrm{pp}) \times 3\,(\mathrm{statistic \cdot factor}) \times 3\,(\mathrm{safety \cdot factor})$ and choosing the most stringent one. For example, LOS 1 requires $1\times10^{-5}m_{pp}$ at 0.1 Hz, which comes from (1), and $3\times10^{-8}m_{pp}$, which comes from (2).

A.1.2. Suspension's local control (beamsplitter)

Feedback voltages of the suspension's local control must not saturate. Since the servo loop gain rolls off very steeply above 10 Hz, consideration is only limited below 10 Hz.

- At 0.1 Hz $3\times10^{-8} m_{rms}$ with a bandwidth of 0.1 Hz

The seismically excited component motion is $3\times10^{-7} m_{rms}$. The loop gain is 0.1.

- At 1 Hz $1\times10^{-9} m_{rms}$ with a bandwidth of 1 Hz

The seismically excited suspension's sensor motion and the suspension's sensor noise are comparably dominant in the feedback signal. They are $1\times10^{-9} m_{rms}$.

- At 10 Hz $3\times10^{-11} m_{rms}$ with a bandwidth of 10 Hz

The suspension's sensor noise is dominant in the feedback signal, which is $3\times10^{-10} m_{rms}$. The servo loop gain is 0.1.

A.2. Longitudinal Motion Dynamic Range of Actuator in Acquisition

The 40m interferometer's dynamic range is good enough for the lock acquisition: a voltage of +/- 24 V, a series impedance of 230 ohm, a coil-magnet coupling of 0.02 N/A, and a mass of 1.6 kg. This gives the following dynamic range:

- At 0.1 Hz $3\times10^{-5} m_{pp}$
- At 1 Hz $3\times10^{-5} m_{pp}$
- At 10 Hz $3\times10^{-7} m_{pp}$
- At 100 Hz $3\times10^{-9} m_{pp}$
- At 1 kHz $3\times10^{-11} m_{pp}$

We adopt these numbers as the required dynamic range for the LIGO detector. **TBR**

A.3. Orientation Dynamic Range of Actuator

All the suspended components (except a Faraday isolator) are controlled in orientation by the suspension's sensor before acquisition, and by ASC during acquisition and operation. The more stringent requirement among the two requirement for each frequency is adopted.

- At 0.1 Hz $2\times10^{-8} rad_{rms}$ with a bandwidth of 0.1 Hz

The feedback signal by ASC is larger than that by the suspension's local control at 0.1 Hz. The slab rotation by microseismic peak is the dominant mechanism, and it causes $2\times10^{-8}\mathrm{rad}_{rms}$.

- At 1 Hz $5\times10^{-9}\mathrm{rad}_{rms}$ with a bandwidth of 1 Hz

The feedback signal the suspension's local control is larger than that by ASC at 1 Hz. The suspension's sensor noise is dominant in the feedback signal. They are $1\times10^{-8}\mathrm{rad}_{rms}$ at worst, and the loop gain is 0.5.

- At 10 Hz $2\times10^{-11}\mathrm{rad}_{rms}$ with a bandwidth of 10 Hz

The suspension's sensor noise is dominant at 10 Hz in the feedback signal, which is $3\times10^{-10}\mathrm{rad}_{rms}$ with a bandwidth of 10 Hz. The servo loop gain is 0.05 at most.

The peak-to-peak dynamic range for each frequency is obtained by multiplying relevant numbers by $30 = 3\,(\mathrm{rms} \Rightarrow \mathrm{pp}) \times 10\,(\mathrm{statistic} \cdot \mathrm{factor})$.

At DC the required dynamic range depends on the residual initial misbalance, which is expected to be $5\times10^{-4}\mathrm{rad}$ for large optics and $1\times10^{-3}\mathrm{rad}$ for small optics. The required peak-to-peak dynamic range at DC is obtained by multiplying these numbers by 4(safety factor).

APPENDIX B: SYSTEM-LEVEL NOISE REQUIREMENTS

Before establishing the noise requirements for the suspension subsystem, we summarize the system-level noise requirements for the test mass, the beamsplitter, and the MC mirror as shown in Table 15.

B.1. Test Mass

Displacement noise for test masses was established in Science '92. Quadrature sum of the internal mode and the suspension thermal noise must be lower than $1.4\times10^{-19}\mathrm{m}/\sqrt{\mathrm{Hz}}$ at 100 Hz. Since there are four test masses, a requirement of the thermal noise per mass is $7\times10^{-20}\mathrm{m}/\sqrt{\mathrm{Hz}}$ The seismic noise must be lower than $1\times10^{-18}\mathrm{m}/\sqrt{\mathrm{Hz}}$ at 40 Hz. Since there are four test masses, a requirement of the seismic noise per mass is $5\times10^{-19}\mathrm{m}/\sqrt{\mathrm{Hz}}$. The control noise must be smaller than these numbers by a factor of 10.

B.2. Beamsplitter

The interferometer is 100 times as insensitive to the beamsplitter motion as to the test mass motion, because of a finesse of 100, and the beamsplitter related noise must be a factor of ten better than the above-mentioned test mass noise. Therefore the noise requirement for the beamsplitter is 10 times as loose as that for the (four) test mass.

B.3. Mode Cleaner Mirror

Since the frequency noise of the light coming out of the mode cleaner (without feedback from the arm cavities to PSL/IOO) is further stabilized by the arm cavities and common mode rejected, the noise requirement for the mode cleaner itself is looser than that for the test mass. The noise requirement for the mode cleaner is $1\times10^{-17}\mathrm{m}/\sqrt{\mathrm{Hz}}$ at 100 Hz, and $2\times10^{-15}\mathrm{m}/\sqrt{\mathrm{Hz}}$ at 40 Hz. Since there are three mode cleaner mirrors, the noise requirement per mirror is $6\times10^{-18}\mathrm{m}/\sqrt{\mathrm{Hz}}$ at 100 Hz, and $1.2\times10^{-15}\mathrm{m}/\sqrt{\mathrm{Hz}}$ at 40 Hz.

Table 15: System-level noise requirements

Physical Quantity	*Requirement*			*Unit (Frequency)*
	LOS 1 (TM)	*LOS 2 (BS)*	*SOS (MC mirror)*	
Thermal Noise per mass	$<7\times10^{-20}$	$<1.4\times10^{-18}$	$<6\times10^{-18}$	$\mathrm{m}/\sqrt{\mathrm{Hz}}$ (100 Hz)
Seismic Noise per mass	$<5\times10^{-19}$	$<1\times10^{-17}$	$<1.2\times10^{-15}$	$\mathrm{m}/\sqrt{\mathrm{Hz}}$ (40 Hz)
Control Noise per mass	$<5\times10^{-20}$	$<1\times10^{-17}$	$<1.2\times10^{-15}$	$\mathrm{m}/\sqrt{\mathrm{Hz}}$ (40 Hz)
	$<7\times10^{-21}$	$<1.4\times10^{-18}$	$<6\times10^{-18}$	$\mathrm{m}/\sqrt{\mathrm{Hz}}$ (100 Hz)

APPENDIX C: NOISE REQUIREMENTS

The noise requirements for the SUS subsystem are established based on the above-mentioned system-level noise requirements.

C.1. Vibrational Thermal Noise

Since the vibrational thermal noise and the pendulum thermal noise are comparable, it is reasonable to put the same requirement for both thermal noise. Therefore the vibrational thermal noise requirement per mass is $1\times10^{-18}\mathrm{m}/\sqrt{\mathrm{Hz}}$.

C.1.1. Test Mass

Thermal noise due to internal vibrations of the test masses was estimated following the method of reference [1] (A. Gillespie and F. Raab, "Thermally Excited Vibrations of the Mirrors of Laser Interferometer Gravitational-Wave Detectors," *LIGO Preprint* PP94-3, November, 1994). From that reference we obtain

$$\tilde{x}_{TM}(f) = 5.2\times10^{-20}\frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}}\cdot\left(\frac{100\ \mathrm{Hz}}{f}\right)^{1/2}\cdot\left(\frac{\phi(f)}{10^{-7}}\right)^{1/2}$$

for the noise contribution to the interferometer from the four test masses, accounting for the finite spot sizes of the beams on the end and vertex masses, and summing over the appropriate vibrational modes of the test masses. Therefore the average effective Loss of vibrational modes due to attachments must be less than 4×10^{-7}.

C.1.2. Beamsplitter

TBD

C.1.3. MC mirror

TBD

C.2. Suspension Fiber Thermal Noise

TBD

C.3. Seismic Noise

C.3.1. Test Mass

The seismic noise of the test mass must be lower than the initial LIGO sensitivity below 40 Hz, and must be at least a factor of 10 better than the initial LIGO sensitivity above 40 Hz. It is reasonable to approve the following requirements to satisfy the above-mentioned requirements.

- Transfer function of the suspended component from horizontal to horizontal must be less than $\left(\frac{1\mathrm{Hz}}{f}\right)^2$ between 10 Hz and 40 Hz, and **TBD** above 40 Hz.
- Transfer function of the suspended component from vertical to horizontal must be less than 6×10^{-4} between 10 Hz and 40 Hz (This vertical-to-horizontal coupling is limited by the curvature of the earth.), and **TBD** above 40 Hz.

C.3.2. Beamsplitter

Since the seismic noise requirement for the beamsplitter is looser than that for the test mass by a factor of 20 (see Table 15), the requirement for the beamsplitter pendulum transfer function is accordingly looser, assuming that isolation of the stack is constant.

C.3.3. Mode Cleaner Mirror

The noise requirement for the mode cleaner mirror is more than 2000 times looser than that for the test mass below 40 Hz, so the requirement for the MC mirror pendulum transfer function is accordingly looser.

C.4. Scattered Light Effect Reduction

TBD

APPENDIX D: SUSPENSION CONFIGURATION

The length of the pendulum principally affects the seismic isolation and the contribution of the suspension fiber to the thermal noise. This length can be optimized given the estimated seismic motion at the suspension block, the estimated shot noise, the loss function for the suspension fiber, an estimate of other thermal noise sources and, finally, the waveform for which we want to optimize the sensitivity. This exercise has been done for the case of the LIGO test masses using the coalescence of 1.4 solar-mass, neutron-star binary waveform, yielding a broad optimum for $d_{pendulum}$ between 30-35 cm. (The longer pendulum has the advantage of remaining in the optimal range if the seismic noise performance is improved.) The most critical suspended components in the input/output optics are the mode-cleaner mirrors. A similar optimization has not yet been carried out for the mode cleaner.

It will be necessary to apply torques to balance a test mass or mirror after an initial coarse alignment is done, in order to achieve sufficiently good alignment for lock acquisition. The maximum DC angle change of the test mass/mirror caused by the DC torque must be large enough to overcome any possible residual misalignment of the test mass/mirror angle, following coarse alignment. It is desirable to minimize these alignment torques to minimize noise contributed by any excess electronics noise in the output stages that drive the actuators. Minimizing the resonant frequencies for pitch and yaw motion allow for these torques to be minimized, but increases the importance of micro-seismic noise., which rises to a peak near 0.1 Hz.

The wire standoff diameter $d_{standoff}$ should be chosen to obtain a non-vanishing separation d_{margin} between the suspension fiber and the suspended component, and still it should be small enough not to degrade the vibrational mode Q.

All these consideration has lead to the specifications of the suspension configuration in Table 10.

APPENDIX E: CONTROL NOISE

E.1. Sensor Noise

The noise produced in the suspension's sensor is fed back to the suspension's actuator by the servo control, and it shakes the suspended component. The displacement noise caused by the suspension's sensor noise is simply equal to the equivalent displacement noise of the sensor noise attenuated by the loop gain at a given frequency.

Since only the transverse motion of the test mass is to be controlled by the suspension's sensor during operation, assuming the coupling from the transverse motion to the longitudinal motion is 0.1 for the worst case, the requirement for the test mass sensor noise is a factor of 10 looser than the test mass control noise, that is $5\times10^{-19}\mathrm{m}/\sqrt{\mathrm{Hz}}$ per mass at 40 Hz and $7\times10^{-20}\mathrm{m}/\sqrt{\mathrm{Hz}}$ per mass at 100 Hz. Since it was already verified that an equivalent sensor displacement noise of $1\times10^{-10}\mathrm{m}/\sqrt{\mathrm{Hz}}$ is possible to attain above 40 Hz, the loop gain required at 40 Hz and 100 Hz is 5×10^{-9} at 40 Hz and 7×10^{-10} at 100 Hz, respectively.

These specifications are also satisfactory for the beamsplitter and the mode cleaner mirror.

E.2. Driver Noise

The driver noise is another important control noise. Since somewhat wideband actuators are required to control the test mass to bring the resonance, or to control the MC mirror to further stabilize frequency. Therefore some kind of noise (including Johnson noise) always exists at the output of the driver even though the signal is attenuated enormously before the driver. This noise is characterized by the magnet-coil coupling and current noise. It is assumed that the same type of the magnet & coil as one used for the 40m interferometer will be used for all the suspended components. The required current noise is simply calculated by the equation of momentum.

APPENDIX F: THERMAL NOISE CONSIDERATION

F.1. Test-Mass Vibrational Thermal Noise

The value of $\phi(f)$ was estimated from experimental data obtained during the installation of monolithic test masses into the 40-meter interferometer, which was then scaled to the LIGO application. An average effective loss $\bar{\phi}$ was obtained from measurements on the four lowest frequency axisymmetric mechanical resonances of both of the 1.6-kg monolithic end test masses (with 2 magnet/standoff assemblies glued to each mass) as described in the memo [2] (TBD). The result obtained was $\bar{\phi} = 1.2\times10^{-6}$ with about a 10% variation between masses. This was then assumed to be representative of the losses for other modes which were not measured. It was also assumed that the effective losses were independent of frequency over the relevant band of frequencies. Two scaling factors were then applied as follows. The losses for LIGO masses were assumed to be larger by the ratio of the number of magnet/standoff assemblies to be used in LIGO (5 on each mass) to the number used in the 40-meter interferometer (2 on each mass). (The size of the magnet/standoff assemblies was chosen to be identical in the two cases.) Additionally, the LIGO losses were scaled downward by the ratio of the mass of the test mass used in the 40-meter interferometer to the mass of the LIGO test mass, to account for the smaller fraction of the total vibrational energy that exists near the magnet/standoff assemblies in the LIGO masses. This resulted in a value of $\phi(f) = \overline{\phi_{LIGO}} = 4.4\times10^{-7}$ which then gives the estimated noise contribution

$$\tilde{x}_{TM}(f) = 1.1\times10^{-19}\frac{m}{\sqrt{Hz}}\cdot\left(\frac{100\ Hz}{f}\right)^{1/2}$$

from vibrations of the four test masses in one interferometer. This is compared to the Initial LIGO noise target [3] (Abramovici, et al., *Science,* 256, pp 325-333, (1992)) in Figure A-1.

F.2. Suspension Fiber Thermal Noise

Thermal noise in the suspension fiber caused by motion of the centers of mass of the test mass along the light beam due to the violin and pendulum mode motions of the wire is shown by the curve labelled "Test Mass Suspension Thermal Noise" in Figure A-1. Additionally, thermal noise in the vertical spring mode of the wires will have a component along the light beam due to the deviation of the local verticals between the test mass chambers. This is shown in Figure A-1 by the curve Labelled "Test Mass Vertical Thermal Noise." The thermal noise properties of steel music wire suspensions are detailed in references [4] (A. Gillespie and F. Raab, "Thermal Noise in the Test Mass Suspensions of a Laser Interferometer Gravitational-Wave Detector Prototype," *Phys. Lett. A,* 178, pp 357-363, (1993)) and [5] (A. Gillespie and F. Raab, "Suspension Losses in the Pendula of Laser Interferometer Gravitational-Wave Detectors," *Phys. Lett. A,* 190, pp 357-363, (1994)). Results from these papers were used to generate thermal noise estimates as described below.

F.2.1 Violin Modes

The effective losses were scaled from data obtained with 35-cm-long, 0.003-in-diameter fibers made from steel music wire which supported 0.4 kg per fiber (see Figure 2 of reference [5]) using equation (6) of reference [5]. The result is

$$\phi_1(f) = 3\times10^{-6}\cdot\left(\frac{d}{0.003\text{in}}\right)^2\cdot\left(\frac{0.8\text{kg}}{M}\right)^{1/2}$$

where *d* is the fiber diameter, and *M* is the mass of the suspended test mass, which is supported by a single fiber loop. For the parameters, $d = 0.011$ in and $M = 11$ kg, this gives $\phi_1(f) = 1.1\times10^{-5}$ for the violin modes. The thermal noise for the violin modes was estimated using this loss function and equation (12) of reference [4].

F.2.2 Pendulum Mode

The loss function for the pendulum mode was estimated using

$$\phi_P(f) = \frac{\phi_1(f)}{4} = 5.4\times10^{-6}$$

which is an adaptation of equation (10) of reference [4] to account for the use of a single fiber loop to suspend the test mass. The thermal noise for the pendulum mode was estimated using this loss function and equation (11) of reference [4].

F.2.3 Vertical Spring Mode

The loss function for the vertical spring mode, $\phi_V(f) = 2.5\times10^{-4}$, was obtained from Figure 4 of reference [5]. The thermal noise motion contributed to the interferometer due to a misalignment of the local verticals at the test mass chambers is

$$\tilde{x}_V(f) = \left[\frac{4kT}{\omega M}\right]\cdot\left[\frac{\phi_V\omega_V^2}{\omega^4}\right]\cdot\left[\theta_1^2+\theta_2^2\right]^{1/2}$$

where θ_1 and θ_2 refer to the misalignments in arms 1 and 2, respectively. Taking these misalignments to be $\theta_1 = \theta_2 = 0.6\times10^{-3}$, gives

$$\tilde{x}_V(f) = 4.2\times10^{-21}\frac{m}{\sqrt{Hz}}\cdot\left(\frac{100\ Hz}{f}\right)^{5/2}$$

for the interferometer. This is plotted as the dotted line, labelled "Test Mass Vertical Thermal Noise" in Fig.6.

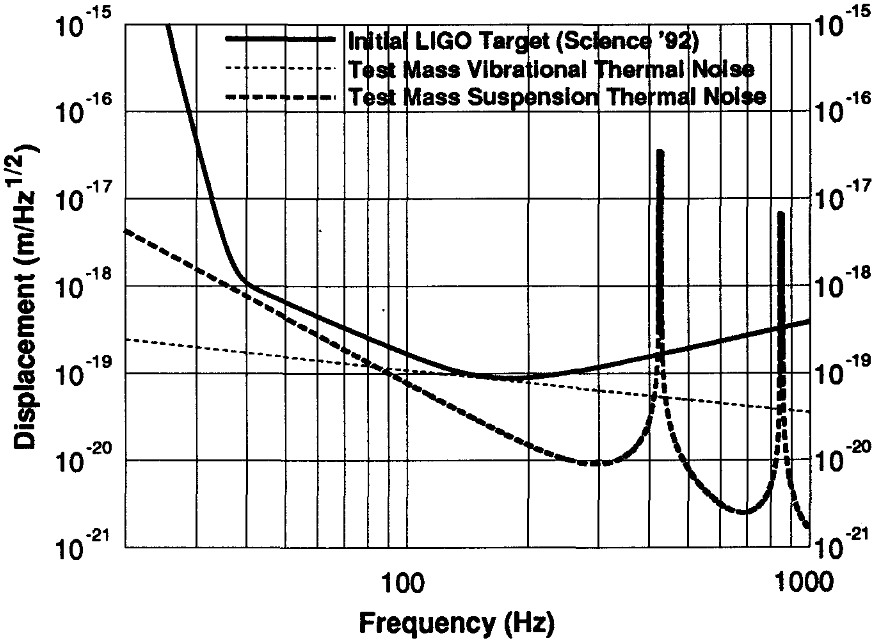


Figure 6: Thermal noise (To be replaced)

F.3 Comparison to the Standard Quantum Limit

A useful benchmark to use for evaluating the "classical" limits imposed by thermal noise is the Standard Quantum Limit which arises from applying the Heisenberg Uncertainty Principle to the position and momentum of a free particle. Using equation (B.49) of the LIGO Construction Proposal (1989), this provides a displacement uncertainty for a single interferometer of

$$\tilde{x}_{SQL}(f) = 1.4\times10^{-20}\frac{m}{\sqrt{Hz}}\cdot\left(\frac{100\ Hz}{f}\right)$$

which is shown in Figure A-1 as the curve labelled "Standard Quantum Limit." This limit depends only on the mass of the test masses and is independent of the test mass material and the type of suspension used.

The estimated total thermal noise is about a factor of ten above the standard quantum limit near 200 Hz where the interferometer is at its peak sensitivity. The dominant thermal noise in this region of the spectrum arises from the internal vibrational modes of the test masses.