LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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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
- 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.

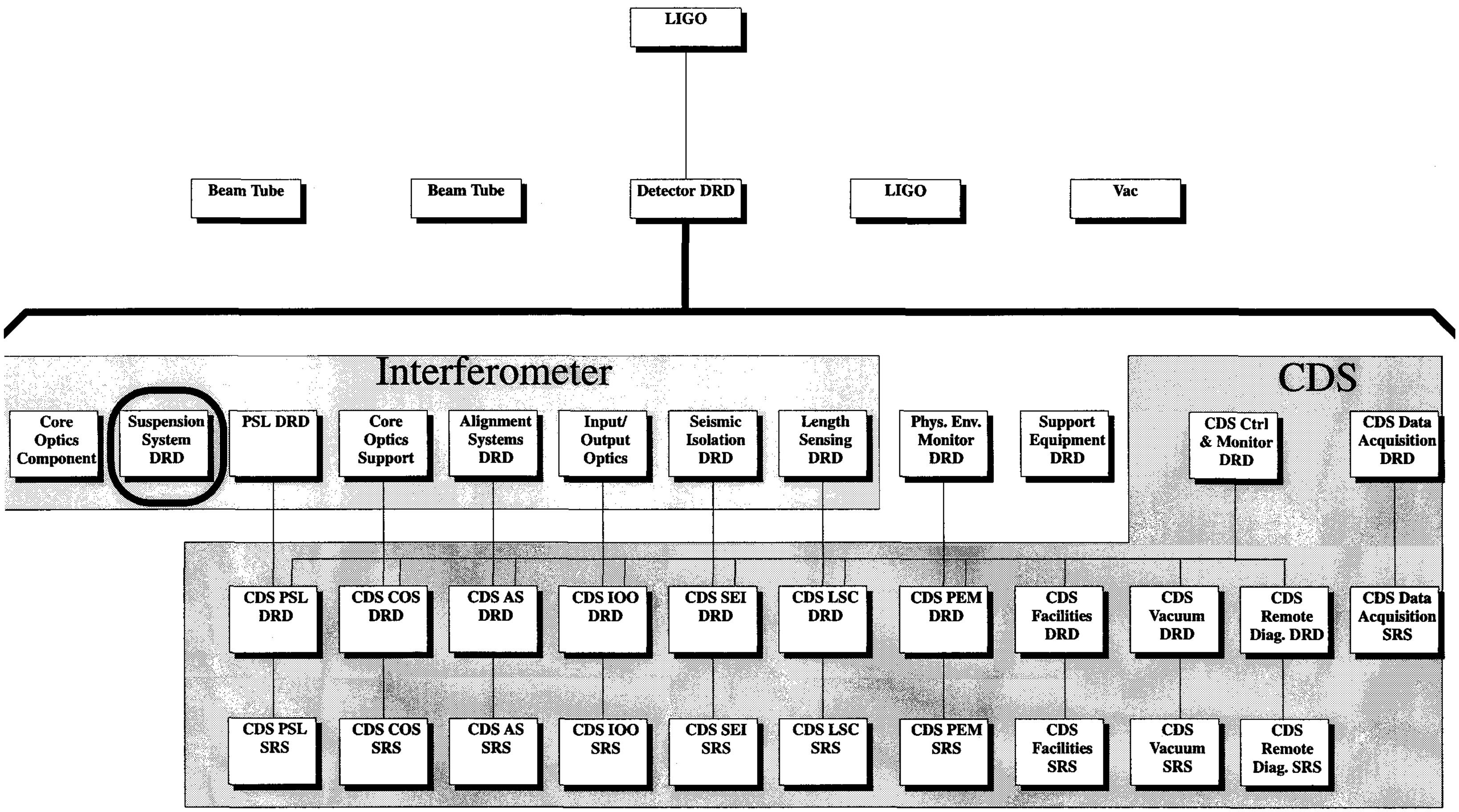


Figure 1: Overall LIGO detector requirement specification tree. SUS DRD is circled.

2.2. Product Perspective

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

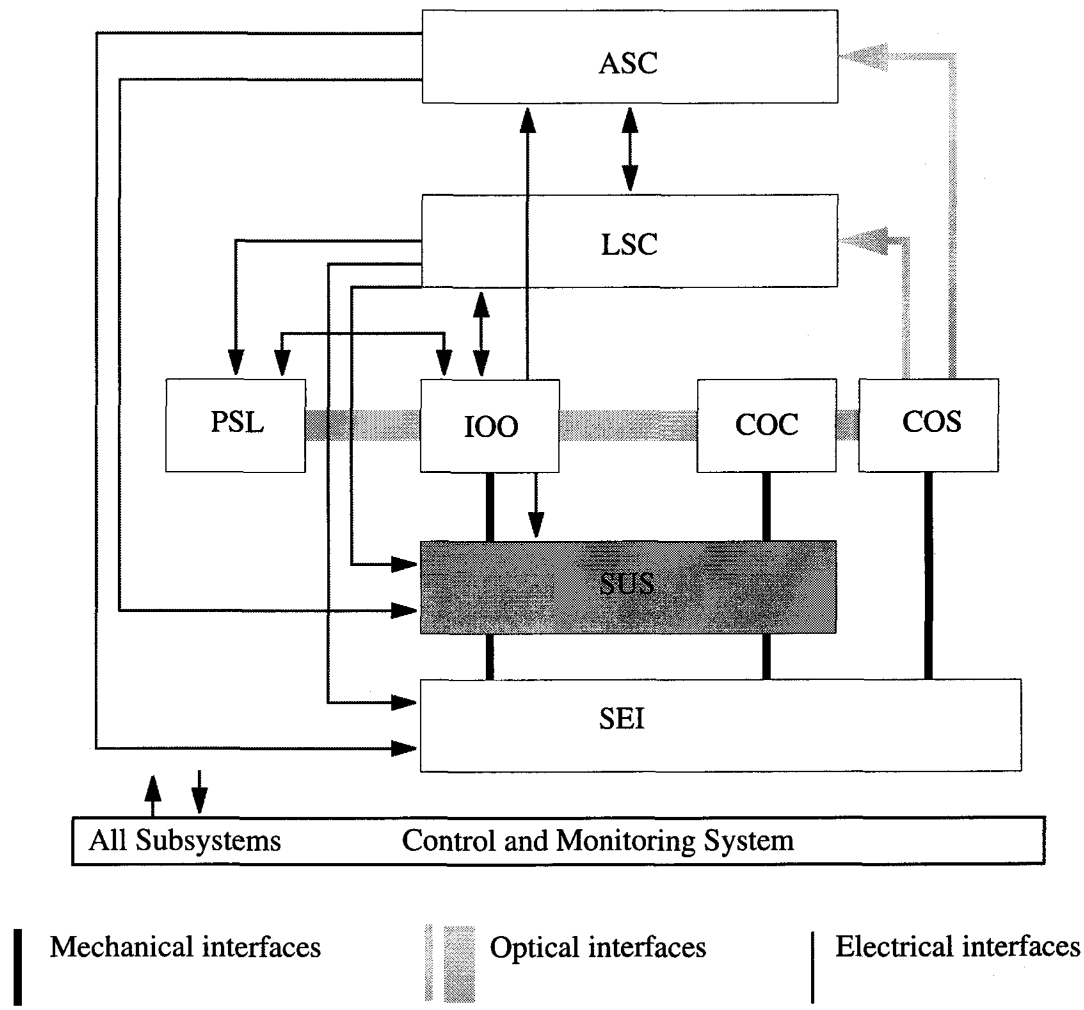


Figure 2: Relationship of SUS to the rest of the detector subsystem. SUS is shaded.

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.

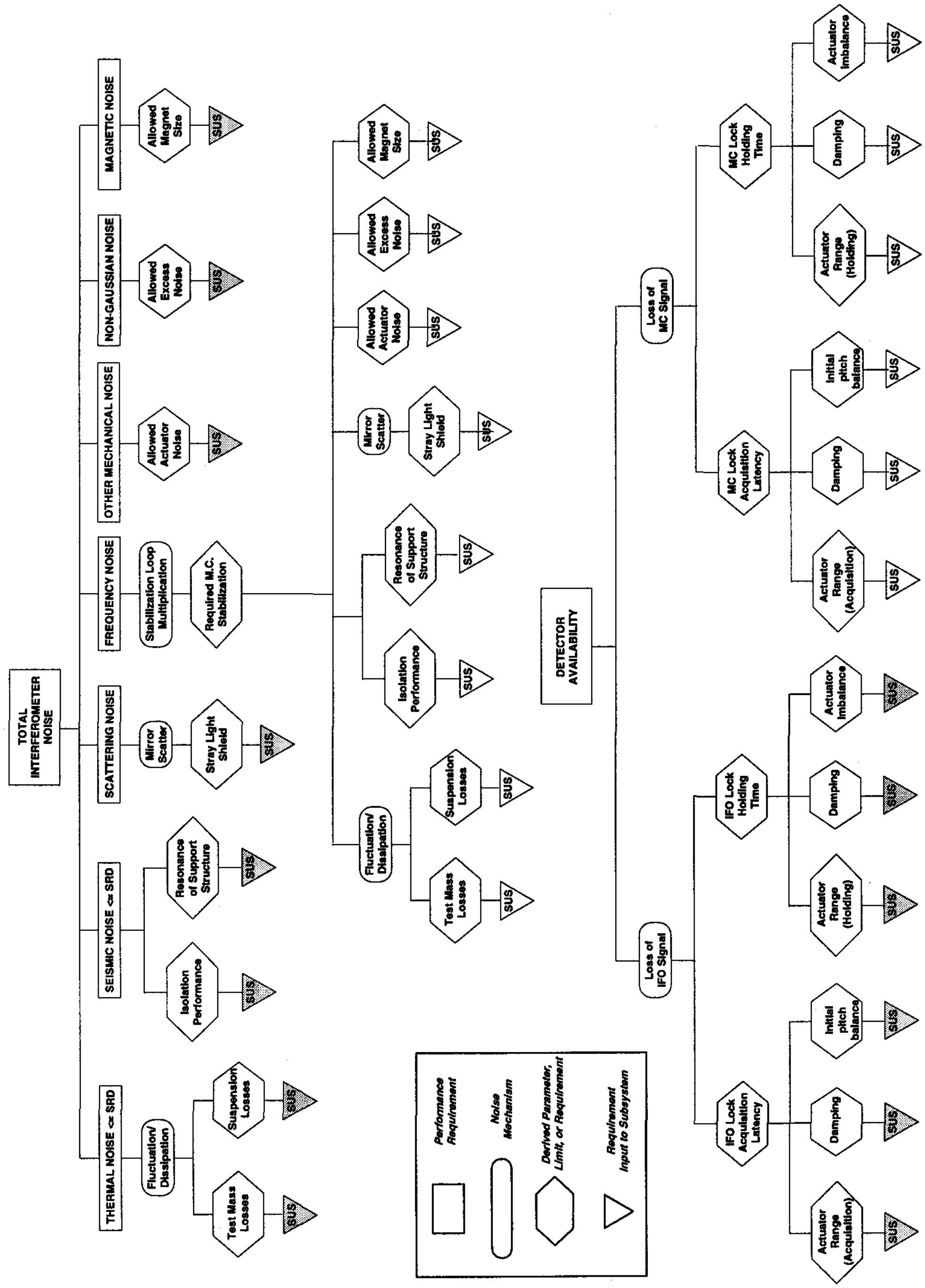


Figure 3: Interferometer noise and detector availability requirements flowdown to LOS.

3.2.2. Detector Availability

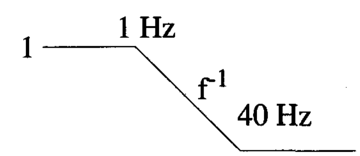
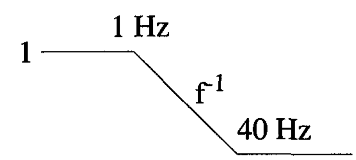
3.2.2.1 Range

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 — *To* / *From*	*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)	$< 3{\times}10^{-5} \times (f_v/f)^2$ 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	$< 7.5 \times 10^{-7} \times \left(\frac{f}{100Hz}\right)$
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 3×10^{-4} 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.

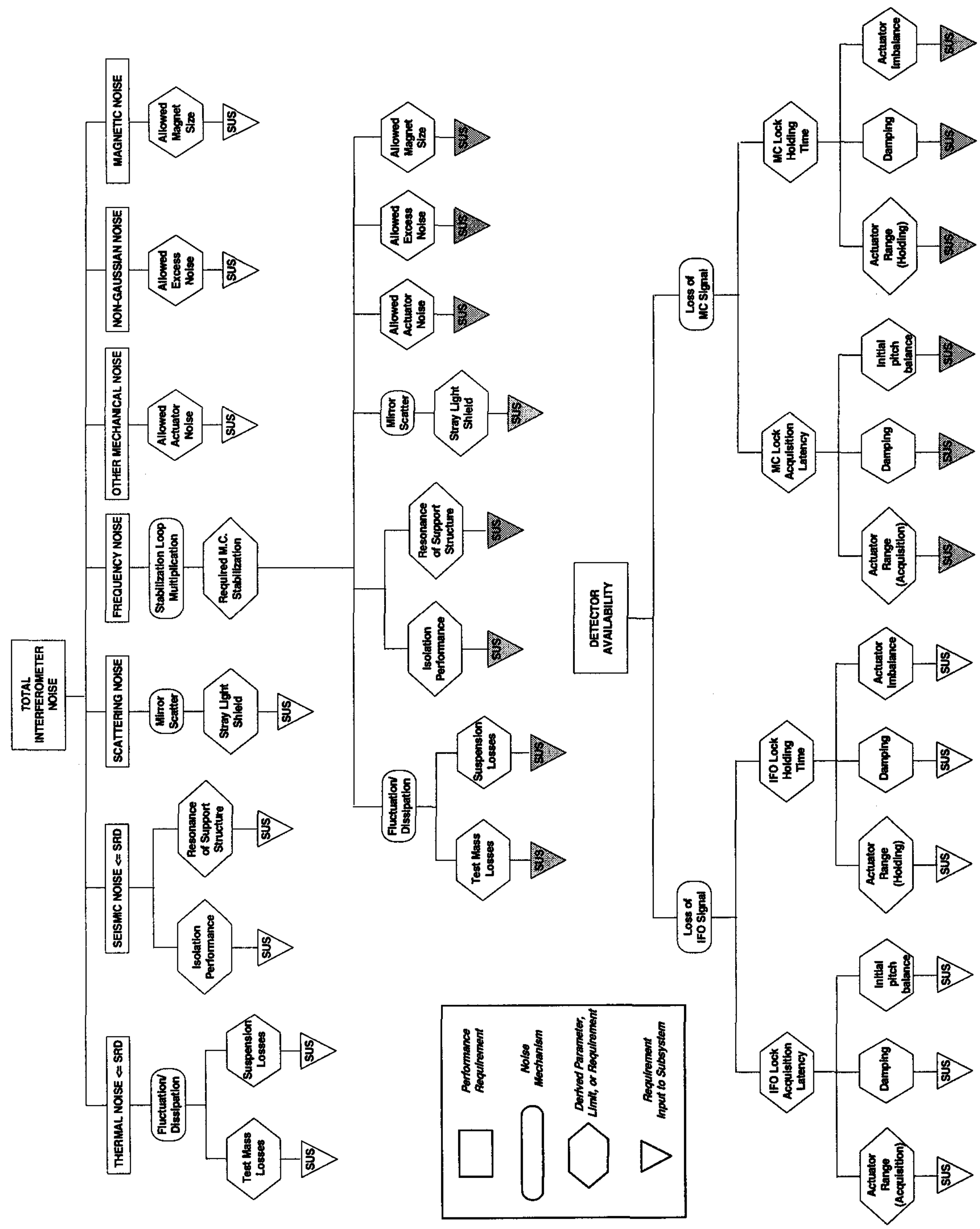


Figure 4: Interferometer noise and detector availability requirements flowdown to SOS.

4.2.2. Detector Availability

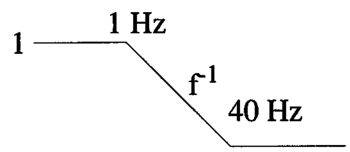
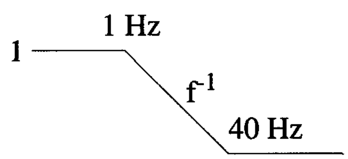
4.2.2.1 Range

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.