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Alignment Sensing/Control Design Requirements Document

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1 INTRODUCTION

1.1. Purpose

The purpose of this document is to define the content of the Alignment Sensing and Control (ASC) subsystem, describe the design requirements for the ASC, and to identify the interfaces of the ASC with the other Detector subsystems and the Facilities.

This document supersedes the initial ASC DRD, LIGO-T952007-00-I. In this revision the focus is on the design requirements for the ASC; as far as possible, all description and references to the conceptual design are separated into the ASC Conceptual Design. In addition the Action Items generated in the first ASC DRR are addressed (Appendix 4).

1.2. Scope

The ASC (including the CDS component) comprises the sensors and fiducial references and control systems for initial setup and for intermediate and final alignment of the IOO (design only; see below) and COC optics. The subsystem includes:

- any hardware and/or algorithms for determining the initial interferometer optical axes
- any hardware and/or algorithms for determining the initial alignment of the IOO and COC suspended optics
- any hardware and/or algorithms for determining and controlling the beam position on the COC suspended optics, including any sensors, vacuum viewports (those not included in the COS scope), mounting equipment, optics, and any control electronics and software for this function
- sensors and controls for maintaining the interferometer alignment during operations, including any special optics required for the alignment sensors, mounting provisions, and any control electronics and software for this function
- a complete design of the alignment system for the mode cleaner and other in-vacuum IOO optics; the production and implementation of the ASC design is the responsibility of the IOO (University of Florida)
- external (to the vacuum) mounting platforms at the interferometer outputs, to serve the mounting space needs of Detector photodetector systems

The ASC specifically does not include:

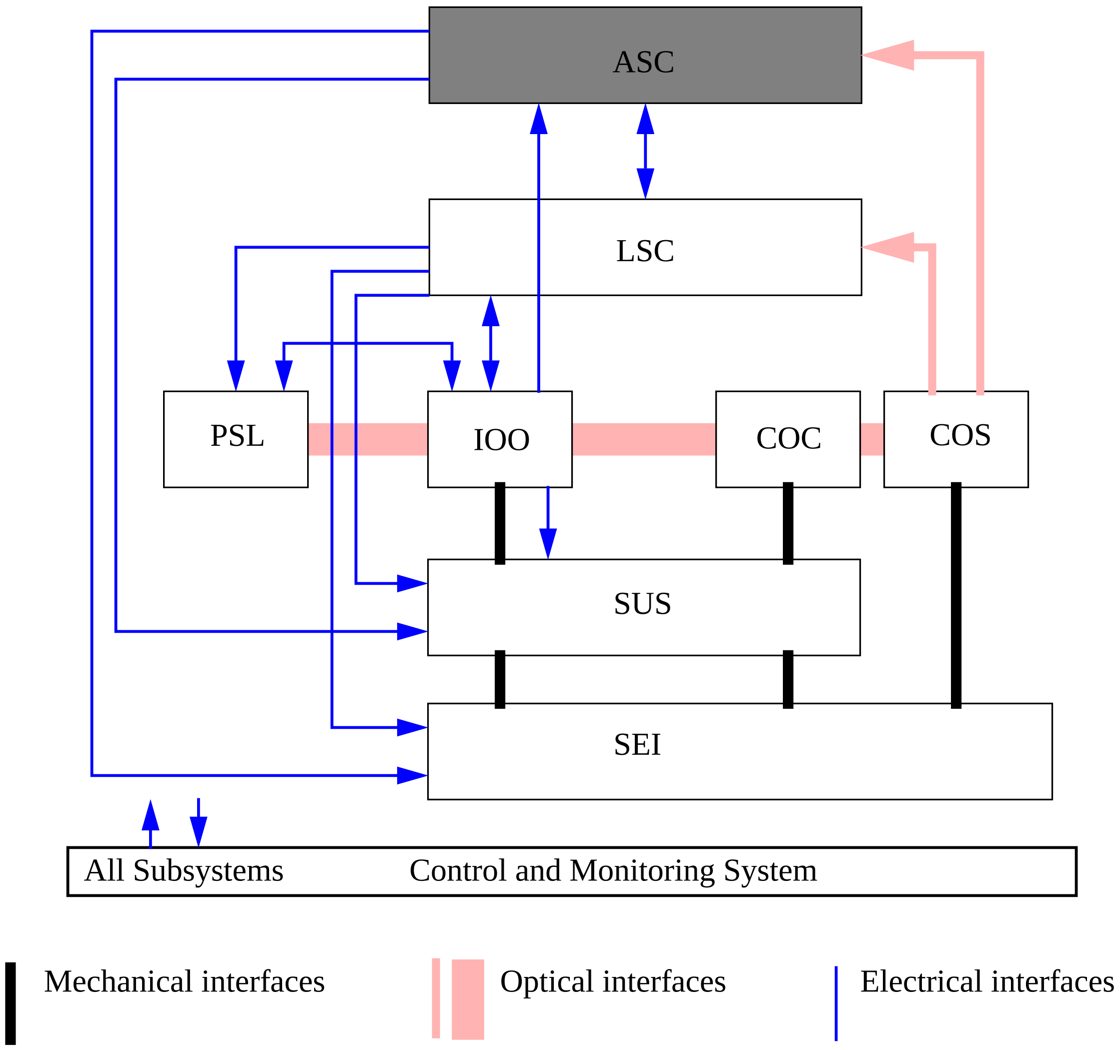
- in-vacuum relay optics or vacuum viewports for extracting the 1.064 μm interferometer beams from the vacuum system
- any alignment functions for the Prestabilized Laser (PSL) subsystem
- any hardware and/or algorithms for determining the axial positions of the IOO or COC optics; i.e., the cavity lengths are not determined by ASC

2 GENERAL DESCRIPTION

2.1. Specification Tree

This document is part of an overall LIGO detector requirement specification tree; refer to the SYS DRD for a diagram of the tree.

2.2. Product Perspective



2.3. Product Functions

The function of the ASC is to bring the interferometer into alignment and maintain a degree of alignment that allows the interferometer to operate with a performance consistent with LIGO's primary science requirements. The various operating and installation conditions of the interferometer make it useful to define several modes of operation for the ASC. These modes and the functions that the ASC provides in each are described below.

2.3.1. Initial Alignment Mode

Initial Alignment (IA) includes the initial positioning of all suspended optics and the establishment of the input beam direction. It also includes achievement of the Acquisition Alignment tolerance for the COC optics. The functions in this mode are:

- provide a means for determining the initial orientation (in pitch[1] and yaw) of each suspended optic (includes all IOO suspended optics and the COC optics)
- determine and control the pointing of the input beam such that it is aligned down the beam tubes and is centered on the COC optics
- adjust the alignment of the COC optics such that they are within the Acquisition Alignment tolerance (see **3.2.1.2**)

2.3.2. Acquisition Alignment Mode

Acquisition Alignment is the mode in which the mode cleaner is in its operational mode (i.e., it is resonant and aligned), and the alignment of the COC optics is within the Acquisition Alignment tolerance. This status is maintained throughout the duration of the LSC Acquisition Mode. The functions in this mode are:

- sense and control the alignment of the (resonant) mode cleaner
- maintain the alignment of the COC optics within the Acquisition Alignment tolerance continuously over the Acquisition Alignment time (see **3.2.2.**)

2.3.3. Detection Mode

This mode of the ASC occurs when the LSC is in either its Transition Mode or Detection Mode (see LSC DRD for definitions). In this mode the COC optics are maintained at an alignment which allows detection of strain signals within the LIGO sensitivity specifications. The functions in this mode are:

- sense and control the alignment of the mode cleaner
- sense and control the alignment of the COC optics, including providing a measure of the misalignment of the relevant ten degrees-of-freedom
- sense and control the centering of the beam on the COC optics, including providing a measure of the de-centering on each COC optic

2.3.4. Diagnostic/Calibration Mode

This is a mode (in fact a set of modes) that may be accessed from the preceding modes. The functions of this mode are:

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[1] Note that with the current suspension design (single loop) the pitch angle is predetermined.

- provide diagnostic capability to determine the performance of the ASC
- enable implementation of calibration procedures within the ASC (e.g., determination of the sensor sensitivities)
- provide a measure of the mode matching of the IOO beam to the interferometer
- support diagnosis of other subsystems

2.4. Definition of Orientation Degrees-of-freedom

In describing the alignment of the interferometer, the beamsplitter orientation is taken as a reference. The orientation of an optic about a horizontal axis is referred to as ‘pitch’, and the orientation about a vertical axis is referred to as ‘yaw.’ The physical pitch angle of an optic is labelled θ, and the physical yaw angle is ϕ; the origin (θ, $\phi = 0$) is the orientation at which the optic normal (coated surface) is parallel with the beam axis. Normalized optic angles are also used; these are the physical angles divided by the beam divergence angle in the arm cavities ($\lambda/\pi\omega_0$). The normalized pitch (yaw) angle is labelled Θ (Φ).

Coordinate system: The following coordinate system is used for the alignment modeling. The *z*-axis of the coordinate system is always pointing in the direction of the beam propagation. The *y*-axis is defined to be vertical and upward. This then makes the *x*-axis horizontal and perpendicular to beam propagation direction. Since the beamsplitter mirrors the image in the horizontal direction, but not in the vertical direction, the coordinate system for the off-line arm is left-handed

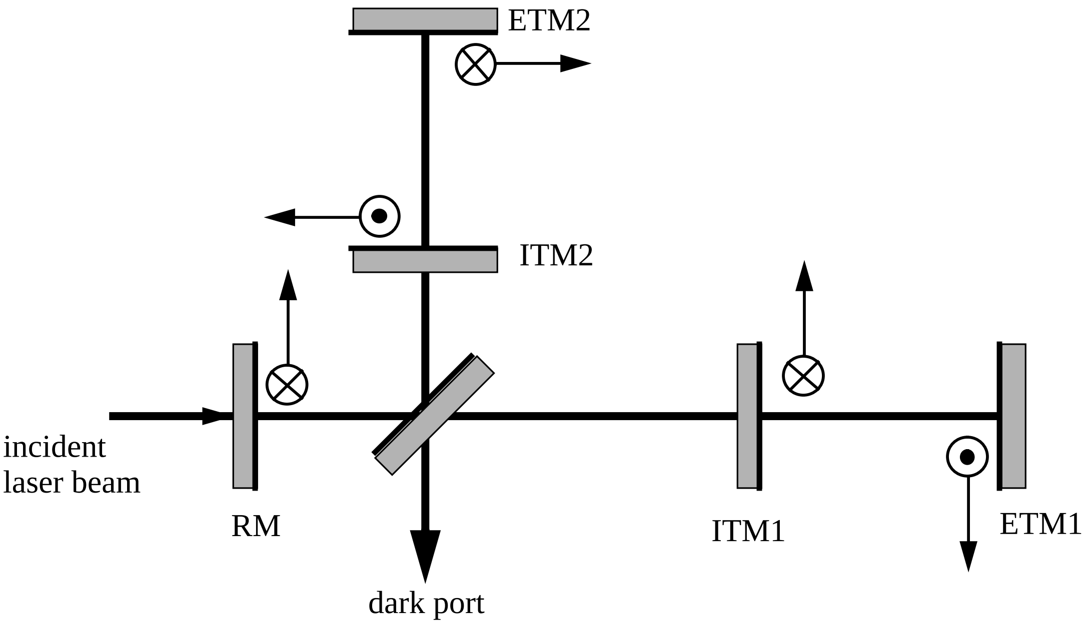

Figure 1 Sign convention of the misalignment angles.
Shown are the rotation axes (vectors) for both horizontal and vertical misalignments.

for the incident beam. After reflection at the ETM mirror, the coordinate system becomes again right-handed.

	incident	reflected
input laser beam	right-handed	left-handed
on-line arm	right-handed	left-handed
off-line arm	left-handed	right-handed
antisymmetric port	right-handed	

Table 1 Coordinate system orientations.

The sign convention for the angles is shown in Figure 1, in terms of the rotation vectors for the mirror tilts; the convention is defined such that the normals of the coated mirror surfaces rotate in the same sense (upward or downward, into or out of the page) for a given direction (when taking the mirroring by the beamsplitter into account for the off-line arm). A positive tilt angle corresponds to a right-handed rotation around the axis defined by the rotation vector.

One basis for expressing the angles uses the individual optic angles; for pitch:

$$\left[\theta_{ITM1}\ \theta_{ETM1}\ \theta_{ITM2}\ \theta_{ETM2}\ \theta_{RM}\right]$$

Another useful basis uses common and differential angles of the test masses; this is obtained by a rotation of the above basis: (for pitch)

$$\begin{bmatrix} \Delta\theta_{ETM} \\ \Delta\theta_{ITM} \\ \overline{\theta_{ETM}} \\ \overline{\theta_{ITM}} \\ RM \end{bmatrix} \equiv \frac{1}{\sqrt{2}} \begin{bmatrix} 0 & -1 & 0 & 1 & 0 \\ -1 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & \sqrt{2} \end{bmatrix} \begin{bmatrix} \theta_{ITM1} \\ \theta_{ETM1} \\ \theta_{ITM2} \\ \theta_{ETM2} \\ \theta_{RM} \end{bmatrix}$$

2.5. Assumptions and Dependencies

2.5.1. LIGO SRD requirements

The following requirements on the LIGO detector sensitivity and availability, as given in the Science Requirements Document, directly influence some of the requirements for the ASC described in section **3**.

1. Sensitivity: The initial LIGO displacement sensitivity requirement is given in the SRD. The displacement requirement, $\mathbf{x}$, is defined such that the strain sensitivity is $h(f) = \mathbf{x}(f)/L$, where $L = 4$ km; i.e., $\mathbf{x}(f)$ is the differential arm length sensitivity.

2. Availability goals: 90% for single interferometer operations; 85% for double coincidence; 75% for triple coincidence.

2.5.2. Detector Noise Budget Allocation

Each noise mechanism originating within the ASC or through an interaction between the ASC and another Detector subsystem(s) is to be controlled so that the equivalent displacement sensitivity as given by the SRD displacement curve is degraded by no more than 0.5% in the gravity wave band of 40 Hz - 10 kHz. The specific noise mechanisms which fall in this category, preceded by the subsystem(s) which contribute, are:

1. ASC. Misalignment of the mode cleaner, leading to less than optimal output power from the mode cleaner.
2. ASC. Misalignment of the interferometer COC optics, leading to degraded shot noise limited sensitivity (due both to lower power in the cavities and increased noise at the output).
3. ASC. Reduction of effective optical power due to apportionment of anti-symmetric port light to the Alignment System.
4. ASC & IO. Misalignment of the interferometer COC optics, coupling with fluctuations of the input beam direction, leading to (phase) noise at the output.
5. ASC & SUS. Misalignment of the beam centroid with respect to the center-of-rotation of the optics, leading to displacement noise in the presence of optic orientation noise.
6. ASC & SUS. Displacement noise produced by alignment control signals and cross coupling in the suspension controllers.

2.5.3. Detector Subsystem Parameters

In determining the design requirements in section **3**, the following assumptions concerning the performance of the other Detector subsystems have been made. A change in any of these assumptions may necessitate a change in the ASC requirements.

2.5.3.1 LSC performance

- Transition time from LSC acquisition to linear control mode: < 40 seconds
- Alignment tolerance at which length acquisition is achievable: < 0.5 μradian per degree-of-freedom per optic

2.5.3.2 IOO performance

- Interferometer Input Beam pointing fluctuations (each direction):
  beam angle fluctuations: $< 3 \times 10^{-14}$ rad/√Hz at 150 Hz
  beam translation fluctuations: $< 1 \times 10^{-10}$ m/√Hz at 150 Hz

2.5.3.3 SUS performance

- Angular actuator range: as given in Table 2 below, and in *LIGO-L960390-00-D* (corrections to

SUS DRD)

- Controller angular noise as given in SUS DRR, *LIGO-T950011-14*, Table 7
- Thermal noise of pitch/yaw modes (from SUS DRR, *LIGO-T950011-14*, Appendix B):

Optic type	*Pitch/yaw thermal noise*
LOS1	$\leq 5\times10^{-18}\times(100\ \mathrm{Hz}/\mathrm{f})^{5/2}(\mathrm{rad}/\sqrt{\mathrm{Hz}})\quad(40 < f < 150\ \mathrm{Hz})$
SOS	pitch: $\leq 1.2\times10^{-16}\times(100\ \mathrm{Hz}/\mathrm{f})^{5/2}(\mathrm{rad}/\sqrt{\mathrm{Hz}})\quad(40 < f < 150\ \mathrm{Hz})$ yaw: $\leq 5.8\times10^{-17}\times(100\ \mathrm{Hz}/\mathrm{f})^{5/2}(\mathrm{rad}/\sqrt{\mathrm{Hz}})\quad(40 < f < 150\ \mathrm{Hz})$

2.5.3.4 COC parameters

- Mirror radii of curvature as given in COC Conceptual Design, *LIGO-T960016-00-D.*
- Apertures of COC optics as given in COC Conceptual Design, *LIGO-T960016-00-D.*

3 REQUIREMENTS

3.1. Introduction

The ASC subsystem derives its requirements from the top-level LIGO requirements for sensitivity and availability, and from secondary requirements imposed by interactions with other IFO subsystems and the LIGO facilities. These secondary requirements are defined and allocated in conjunction with Detector Systems Engineering. The performance requirements for the ASC are conveniently grouped into requirements for each mode of the ASC, as described in section **2.3.**

3.2. Performance requirements

3.2.1. Initial Alignment Mode

3.2.1.1 Installation of In-Vacuum Optical Components

In order to facilitate the installation of optical components in the vacuum chambers, the ASC subsystem is required to provide transverse (to the beam axis) position information in the chambers, such that a fiducial point on an optical component can be located to within a distance TBD[1] of the optic axis. This information is to be available during the initial installation phase, and anytime that a chamber is open.

For installation of suspended components, the ASC is also required to provide information that allows the orientation of each optic (i.e., the normal of the coated surface) to be aligned with the beam axis to within 10% of the SUS actuator angular dynamic range. The angular dynamic range

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[1] The necessary accuracy will depend upon the range and resolution of the mechanical adjustment provided for the in-vacuum optical components. We expect that an accuracy of ~1 mm will be sufficient.

for the LOS1, LOS2, and SOS optics is 2 mrad p-p in pitch and yaw (LIGO-T960390-00-D). The ASC orientation information must thus be accurate to within ± 0.1 mrad of the final beam axis.

3.2.1.2 Acquisition Alignment

The ASC is required to adjust the mode cleaner alignment to enable the length locking of the mode cleaner, and to adjust the alignment of the COC optics and IO injection optics such that the LSC Acquisition Alignment tolerance is achieved.

Mode Cleaner Acquisition Alignment: Large angle misalignment modeling of a single cavity has shown that a useful length error signal exists up to a mirror misalignment (single d.o.f.) of about (1/2 × divergence angle of the cavity mode)[1]. We take the mode cleaner acquisition alignment to be: 1/5 × cavity mode divergence angle (specification of the actual angle will follow the design of the mode cleaner geometry).

After initial alignment setup procedures, the mode cleaner acquisition alignment must be achieved in a time period which does not significantly impair interferometer availability.

LSC Acquisition Alignment tolerance: The COC alignment tolerance which enables the LSC length locking of the interferometer is taken to be 0.5 μ–radian per angular degree-of-freedom of the interferometer (TBR).[2]

3.2.2. Acquisition Alignment Mode

In the Acquisition Alignment Mode the mode cleaner is locked and aligned at its final alignment, and the alignment of the COC optics is maintained at the LSC Acquisition Alignment tolerance. It is assumed that the mode cleaner can be locked in length and angle in a negligibly short time, such that a separate mode for mode cleaner acquisition is unnecessary.

Mode Cleaner Final Alignment: During normal operation of the mode cleaner, the alignment must be such that the TEM_{00} power transmission is no less than 99% of the maximum (i.e., the perfectly aligned case). The final alignment state must be achieved within 5 seconds of length lock of the mode cleaner.

LSC Acquisition Alignment time: The COC alignment is required to be held within the LSC Acquisition Alignment tolerance for a time adequate to permit LSC acquisition, without significantly impairing availability.

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[1] Private communication from Daniel Sigg. Results are contained in a mathematica notebook file in ~sigg/ModalModel/wide.ma

[2] At this time, this number (which is 1/20 of a beam divergence angle) is a crude estimate, based on the large angle single cavity modeling. This number is one of the central issues for the optical response and control modeling efforts currently underway.

3.2.3. Detection Mode

3.2.3.1 Mode Cleaner Alignment Tolerance

We adopt the same requirement as in section **3.2.2.** for the Mode Cleaner final alignment: the alignment must be such that the TEM_{00} power transmission is no less than 99% of the maximum.

3.2.3.2 Misalignment Tolerance, COC

Misalignments of the ten angular degrees-of-freedom of the COC optics cause a degradation of the interferometer sensitivity in two ways[1]:

1. *Shot noise limited sensitivity.* Misalignments reduce the power in the recycling and arm cavities (and possibly increase the power at the anti-symmetric port), and thus lead to a poorer shot noise limited sensitivity (relevant for frequencies above 150 Hz).
2. *Beam pointing sensitivity.* Misalignments create a first order sensitivity of the differential phase shift to fluctuations of the input beam pointing (shifts and tilts).[2]

We require that the misalignment tolerance be such that neither of these mechanisms degrades the strain sensitivity of the perfectly aligned LIGO by more than 0.5% (in the detection band, 40 Hz - 10 kHz).

The misalignment tolerances for the degrees-of-freedom defined in section **2.4.** are given in Table 2; also given are the degradation in the shot noise sensitivity and the beam jitter-misalignment noise at 150 Hz (assuming the IOO beam jitter level given in section 2.5.3.2) caused by the maximum allowed misalignment.

Degree of freedom	*Allowed misalignment, rms*	*Degradation of shot noise sensitivity*	*Beam jitter - Misalignment noise at 150 Hz*
$\Delta\theta_{ETM}$, $\Delta\phi_{ETM}$	1.0×10^{-8} rad (each d.o.f.)	0.5% (sum over all d.o.f.)	$\delta L_{-} = 1 \times 10^{-20}$ m/$\sqrt{Hz}$
$\bar{\theta}_{ETM}$, $\bar{\phi}_{ETM}$			*negligible*
$\Delta\theta_{ITM}$, $\Delta\phi_{ITM}$			$\delta L_{-} = 1.6 \times 10^{-21}$ m/$\sqrt{Hz}$
$\bar{\theta}_{ITM}$, $\bar{\phi}_{ITM}$			*negligible*
θ_{RM} , ϕ_{RM}			*negligible*

Table 2 COC Alignment requirements in Detection Mode, expressed in the common-differential basis. δL_{-} is the equivalent differential arm cavity length.

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[1] Other effects, such as a loss of common mode rejection for amplitude or frequency noise, are expected to be much less important.

[2] A somewhat related effect is the coupling of rms mirror misalignments with gw-frequency mirror angular noise (due to thermal noise, e.g.). This effect has been shown to be small enough to be negligible. See *"Modal Model Update 3: Small Angle Regime,"* LIGO-T960115-00-D.

An alternative means of expressing the requirements is also presented, using a different basis set. This basis, labelled u_i, represents the axes of the misalignment variance-ellipsoid; it is defined and described in Appendix 5. Table 3 gives the alignment requirements in this basis. The beam jitter sensitivity in this basis is the same as in Table 2, since this mechanism is primarily sensitive to misalignments in the u_2 direction.

Degree of freedom	*Allowed misalignment, ψ_i rms*	*Degradation of shot noise sensitivity (each dimension)*
u_1	1.0×10^{-8} rad	0.14%
u_2	1.0×10^{-8} rad	0.1%
u_3	3.0×10^{-8} rad	0.007%
u_4	5.0×10^{-8} rad	0.003%
u_5	1.0×10^{-7} rad	0.002%

Table 3 COC Alignment requirements in Detection Mode, expressed in the u_i basis

The ASC is also required to provide a measure of the misalignment of each of these degrees-of-freedom, to an accuracy of 1 nanoradian and at a rate of at least 10 Hz.

The calculations leading to requirements in Table 2 and Table 3 are described in Appendix 5.

3.2.3.3 Centering Tolerance

De-centering of the beam on the interferometer mirrors affects the interferometer in two ways:

1. *Lever arm effect.* Angular fluctuations of the test masses produce optical length changes in the arm cavities; the optical length noise is the product of the angular noise and the beam offset from the test mass center of rotation, which itself may arise from a combination of static and slowly varying misalignments. Sources of angular fluctuations are, in roughly decreasing order of importance:
    i. Thermal noise of pitch and yaw modes
    ii. Coil driver noise
    iii. Seismic noise
2. *Diffraction (aperture) loss.* The diffraction loss for the TEM_{00} mode increases when the beam is not centered on the interferometer mirrors, due to their finite aperture.

3.2.3.3.1 COC optics

For the test masses, the mechanism in 1.i. above is the most important, leading to the requirement:

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

For the beamsplitter and recycling mirror (and folding mirrors for the 1/2 length), diffraction loss is the primary concern. The requirement is tightest for the beamsplitter, but we take a uniform tolerance for these optics, determined by the strictest requirement:

The beam centroid must be maintained within a radius of 5 mm of the nominal beam position on the beamsplitter[1], and of the center of rotation for the recycling mirror and the folding mirrors in the 1/2 length interferometer.

We also require that the ASC provide a measure of the beam centroid position with respect to the center of each optic during Detection Mode, to an accuracy of 0.5 mm for the test masses and 2.5 mm for the other COC optics, and at a rate of at least once per 10 minutes.

Details of the considerations leading to this requirement are given in Appendix 6.

3.2.3.3.2 Mode Cleaner mirrors

For the mode cleaner mirrors, only the lever arm mechanism is significant. The required frequency stability of the mode cleaner is 10^{-4} Hz/√Hz at 100 Hz, and is limited by thermal noise at this frequency. The lever arm effect is allotted 20% (for pitch) and 10% (for yaw) of the total thermal noise budget. This is further divided between pitch/yaw noise and decentering. The SUS requirements for pitch/yaw noise at 100 Hz are: pitch $< 1.2 \times 10^{-16}$ rad/√Hz; yaw $< 5.8 \times 10^{-17}$ rad/√Hz. The ASC centering requirement is:

The beam centroid must be maintained within a radius of 3 mm of the center of rotation of the mode cleaner mirrors.

3.2.3.4 Control System Noise Allowance

In the gravity wave band (typically above the alignment control band), the noise from the alignment control signals must not overly-degrade the interferometer's noise performance. Alignment control signals couple with non-orthogonality in the SUS controllers to produce displacements of the suspended optics. In addition, the pure angular component of the control signals produces angular noise above the control band; this angular noise should be small enough that the centering tolerance is not significantly affected. These considerations lead to a combined ASC/SUS requirement, and to a ASC requirement for each type of optic, as follows:

For alignment control signals applied to the test masses and the beamsplitter (and the folding mirrors in the 1/2 length interferometer), we require that:

- the displacement noise produced by the ASC/SUS subsystems in the GW band be no greater than 10% of the SRD curve
- the angular noise produced in the gw band must be: a) 40-150 Hz: < 50% of the angular noise due to the noise sources listed in section 3.2.3.3 for these optics; b) above 150 Hz: no higher

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[1] The nominal position of the beam on the 50/50 surface of the beamsplitter has not been determined at this date; it may be shifted from the geometrical center in the horizontal direction by up to a centimeter.

than the 150 Hz level. (Note: the angular noise will be dominated by the pitch/yaw thermal noise - cf. section 2.5.3.3)

For alignment control signals applied to the recycling mirror and the IO steering mirrors, we require that:

- the displacement noise produced by the ASC/SUS subsystems in the gw band be no greater than the maximum allowed displacement thermal noise (as in Appendix B.1 of the SUS DRD) for these optics
- the angular noise produced in the gw band must be: a) 40-150 Hz: < 50% of the angular noise due to the noise sources listed in section 3.2.3.3 for these optics; b) above 150 Hz: no higher than the 150 Hz level.

For alignment control signals applied to the mode cleaner mirrors, we require that

- the displacement noise produced by the ASC/SUS subsystems in the gw band be no greater than 10% of the length stability requirement of the mode cleaner
- the angular noise produced in the gw band must be: a) 40-150 Hz: < 50% of the angular noise due to the noise sources listed in section 3.2.3.3 for these optics; b) above 150 Hz: no higher than the 150 Hz level.

Controlled Optic	*Displacement Noise* (m/√Hz)	*Angular Noise* (rad/√Hz)
Test masses (CO)	$< \mathbf{x}(f)/20$	$< 2.5\times10^{-18}(100\text{ Hz}/f)^{2.5}$ $40 < f < 150$ Hz $< 1\times10^{-18}$ $f > 150$ Hz
Beamsplitter (CO), Large Folding Mirror (CO)	$< 5\,\mathbf{x}(f)$	
Recycling Mirror (CO), Steering Mirrors (IOO)	$< 5\times10^{-20}(100\text{ Hz}/f)^{2.5}$ $f < 100$ Hz $< 5\times10^{-20}(100\text{ Hz}/f)^{1/2}$ $f > 100$ Hz	
Mode Cleaner Mirrors (IOO)	$< 2\times10^{-19}(100\text{ Hz}/f)^{2.5}$ $f < 100$ Hz $< 2\times10^{-19}(100\text{ Hz}/f)^{1/2}$ $f > 100$ Hz	$< 3\times10^{-17}(100\text{ Hz}/f)^{2.5}$ $40 < f < 150$ Hz $< 1\times10^{-17}$ $f > 150$ Hz

Table 4 Control System Noise Allowance. Values are for each optic of the specified type.

3.2.3.5 Power Allocation

It is required that any reduction of the interferometer's effective optical power due to apportionment of anti-symmetric port light to the Alignment System degrade the shot-noise limited sensitivity by no more than 0.5%. Thus the ASC can be apportioned no more than 1% of the anti-symmetric port power.

3.2.4. Commissioning & Diagnostic Requirements

The ASC must be able to perform diagnostics to determine the proper functioning of the ASC in the Detection Mode, and to support the operation of the interferometer in a subset of alternate optical configurations (single cavity, etc.). The following functions must be provided for:

1. Determination of offsets in the lock-points from the optimal alignment.
2. Determination of gw-detection band noise produced by alignment control system.
3. Determination of closed loop transfer functions of the control loops.
4. Monitoring of feedback torques applied to the controlled optics.
5. Providing a measure of the degree of mode matching in the interferometer

The ASC must also be able to support more global diagnostics involving other Detector subsystems; adding the following capability to the above functions should ensure that any such global diagnostic can be supported:

- Capability of producing controlled misalignments in all angular degrees-of-freedom, both in the control band (below 40 Hz; as controlled servo offsets, or slowly varying offsets) and in the gw band.

3.3. Interface Definitions

See:

LIGO-T950069-00-D, *Naming and Interface Definition for ASC Wavefront/Centering*
LIGO-T950074-00-D, *Naming and Interface Definition for ASC Initial Alignment*
LIGO-T950070-00-D, *Naming and Interface Definition for Optical Lever*

3.4. Environmental Conditions

3.4.1. Natural Environment

3.4.1.1 Temperature and Humidity

Table 5 Environmental Performance Characteristics

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

3.4.1.2 Atmospheric Pressure

The ASC components shall function under normal Atmospheric pressure conditions (0.7-1.1 ATM).

3.4.1.3 Seismic Disturbance

The Seismic background and Facility Drift are primary sources against which this system operates. No special requirements are put on these disturbances, however, due to cost realities.

3.4.2. Induced Environment

3.4.2.1 Electromagnetic Radiation

The ASC subsystem shall comply with the guidelines and procedures laid out in LIGO-E960036-02-E, **LIGO EMI CONTROL PLAN AND PROCEDURES**.

3.4.2.2 Acoustic

3.4.2.3 Mechanical Vibration.

3.5. 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.

3.6. Design and Construction

3.6.1. Materials and Processes

3.6.1.1 Finishes

Mounting surfaces will be designed to make a well-defined plane of contact. Kinematic mounts will be used where possible.

3.6.1.2 Materials

Any in-vacuum components must be prepared with only approved vacuum-compatible materials and manufactured, cleaned, and handled according to procedures approved for in-vacuum equipment.

3.6.1.3 Processes

3.6.2. Component Naming

All components shall be identified using the LIGO Detector Naming Convention (LIGO-T950111-01-E). This shall include identification physically on components, in all drawings and in all related documentation.

3.6.3. Workmanship

3.6.4. Interchangeability

3.6.5. 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 the LIGO Project System Safety Management Plan LIGO-M950046-F, section 3.3.2.

3.6.6. Human Engineering

3.7. Documentation

3.7.1. Specifications

3.7.2. Design Documents

3.7.3. Engineering Drawings and Associated Lists.

3.7.4. Technical Manuals and Procedures

3.7.4.1 Procedures

Procedures shall be provided for both electrical and optical alignment:

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

3.7.4.2 Manuals

3.7.5. Documentation Numbering

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

3.7.6. Test Plans and Procedures

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

3.8. Logistics

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

3.9. Precedence

3.10. Qualification

4 QUALITY ASSURANCE PROVISIONS

4.1. General

4.1.1. Responsibility for Tests

4.1.2. Special Tests

4.1.2.1 Engineering Tests

A prototype unit shall be tested to meet specifications, and to determine the extent to which it exceeds specifications, before the Final Design Review.

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

5 PREPARATION FOR DELIVERY

5.1. Preparation

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

5.2. Packaging

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

5.3. Marking

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

Appendix 1 Definitions

Pitch	Angle of motion around a horizontal axis; also called ‘θ’
Yaw	Angle of motion around the vertical axis; also called ‘ϕ’
$\mathbf{x}(f)$	Curve of initial LIGO differential displacement sensitivity, as given in the Science Requirements Document

Appendix 2 Acronyms and Abbreviations

ASC	Alignment Sensing and Control
CDS	Control and Data System
COC	Core Optics Components
COS	Core Optics Support
ETM	End Test Mass
IA	Initial Alignment
IOO	Input/Output Optics
ITM	Input Test Mass
LOS1, LOS2	Large Optic Suspension, Type 1 & 2
LSC	Length Sensing and Control
PSL	Prestabilized Laser
RM	Recycling mirror
SOS	Small Optic Suspension
SRD	Science Requirements Document
SUS	Suspension System
SYS	Detector Systems Engineering

TBR To Be Reviewed

Appendix 3 Applicable Documents

LIGO Documents

LIGO-E950018-02-E LIGO Science Requirements Document

LIGO-T960095-00-I ASC DRD, or Alignment Sensing and Control Overall Design Requirements Document (First version)

LIGO-T950070-00-D Naming Convention and Interface Definition for Optical Lever

LIGO-T950112-00-D ASC Optical Lever Specifications and Conceptual Design (rough draft)

LIGO-T950069-00-D Naming and Interface Definition for ASC Wavefront/Centering

LIGO-T950049-00-D ASC Centering Subsystem Description

LIGO-T950074-00-D Naming and Interface Definition for ASC Initial Alignment

LIGO-T960081-00-D Pendulum thermal noise: pendulum and pitch modes

LIGO-T960120-00-D Misalignment-Beam Jitter Coupling in LIGO

LIGO-T960113-00-D Modal Model Update 1: Interferometer Operators

LIGO-T960114-00-D Modal Model Update 2: GW-Sensitivity to Angular Misalignments

LIGO-T960115-00-D Modal Model Update 3: Small Angle Regime

LIGO-T950011-14-D Suspension Design Requirements

LIGO-T960390-00-D Correction of SUS DRD and PDD

LIGO-E960036-02-E LIGO EMI Control Plan and Procedures

LIGO-T950111-01-E LIGO Naming Conventions

Non-LIGO Documents

None.

APPENDIX 4 ASC DRR I ACTION ITEMS

ASC Design Requirements and Flowdown:

1. *Derive required centering accuracy and allowed angular motion of suspended components, based on following considerations:*
    1.1 *Interaction between beam miscentering and noise in test mass orientation (including effect of noise in optical lever or wavefront sensing).*

This has been done - see section **3.2.3.3** and Appendix 6 (the noise of the optical lever and/or wavefront sensor is required to be less than the suspension thermal noise).

1.2 Vertical seismic noise coupling to tilt forces on test masses.

This is being included in the analysis of environmentally induced orientation fluctuations; this appears in the ASC Conceptual Design, as it relates to the servo gain requirements.

1.3 Effect of angular noise in input beam coming from mode cleaner, including effect of recycling cavity on carrier and sidebands, and accounting for the motion of multiple mirrors.

This has been done using a dynamic modal model - see section **3.2.3.2** and Appendix 5.

1.4 Static and fluctuating diffraction loss.

1.5 Surface figure imperfections coupled to lateral motion of test masses.

These (1.4 & 1.5) has been examined with the FFT program - see Appendix 6.

2. *Calculate (using the "FFT Program", modal model, or other modeling effort now under development) the interaction between length sensing and alignment wavefront sensing. Estimate the range of the wavefront sensing, and the allowed misalignment range before loss of length sensing signal.*

These are critical issues for the optical modeling efforts currently underway. Results will be incorporated into the ASC design at the PDR stage.

3. *Consider the use of wavefront sensing on the mode cleaner mirrors.*

This is the current conceptual design for the mode cleaner alignment (this AI should appear in the Conceptual Design section).

4. *Calculate alignment sensitivity of recycling cavity, including a comparison of the nearly degenerate case (as may be achieved with very large radius of curvature of recycling mirror) and the degenerate case (recycling and input cavity mirrors perfectly flat).*
5. *Evaluate whether the centering accuracy requirement necessitates transverse (sideways or vertical) actuators for the seismic isolation stacks.*

It has been concluded that the centering requirement does necessitate transverse actuators. It is expected that re-centering by these actuators will be performed roughly once per month.

6. *Reconsider specification of 0.9/1.0 allowed signal-to-noise degradation due to imperfect alignment; a value closer to 1.0/1.0 may be feasible.*

The current requirement is for an allowed degradation of 0.99/1.0.

7. *Consider whether a modification to the interferometer configuration, such as a Mach-Zehnder readout, would significantly relax the alignment requirements.*

No modeling has been done.

8. *Estimate the effect of simultaneous misalignments in several mirrors, as driven by seismic noise, perhaps by Monte Carlo calculation.*

9. *Document the assumed insensitivity of wavefront sensing to decentering and photodiode non-uniformity.*

Errors due to these effects have been calculated; see the document *"Wavefront Sensor"*, D. Sigg.

10. *Specify the angular dynamic range required of SUS actuators, in the 0.1 to 10 Hz band.*

This has been done; the range is ± 2 $\mathrm{mrad}_{\mathrm{pk}}$.

11. *Clarify the distinction between requirements on seismic noise level and noise in suspension actuators.*

First version of ASC DRD specified suspension actuator noise in relation to seismic noise. This is no longer done; suspension actuator (angular) noise is given in $\mathrm{rad}/\sqrt{\mathrm{Hz}}$.

12. *Decide on partition of "dog leg" pick-off beam for initial pointing monitor between IOO and Initial Alignment.*

This is an issue for the conceptual design (see the ASC Conceptual Design Document).

13. *Include requirements for CDS Remote Diagnostics.*
14. *Eliminate the "Alignment requirement for stability of LSC" entry in Table 2; it is redundant with the acquisition requirement.*

The revised ASC requirements are consistent with this suggestion.

Design Requirements Document

15. *Define the scope of the ASC in terms of functionality, software, and hardware.*

This is done in section **1.2.**

16. *Define ASC interfaces to other subsystems, including "signal" interfaces (the latter may be included by reference to a controlled version of an Interface Control Document).*

Interfaces are included in the interface documents listed in section 3.3.

17. *Define a standard format for state transition diagrams, and implement in Figure 2. Include explanatory text for Figure 2.*

The state transition diagram being referred to was in the original version of the DRD, but has been eliminated in this version.

18. *Standardize and unify naming conventions for mirrors and similar components, and for states of the interferometer.*

These conventions are described under section 2 of this document.

19. *Clarify the numerical value of the centering requirement (numbers between 3.5 mm and 3.8 cm are stated).*

This has been done - see section **3.2.3.3** and Appendix 6.

APPENDIX 5 BASIS OF DETECTION MODE ALIGNMENT REQUIREMENT

Shot noise degradation:

The effect of misalignment on the shot noise limited sensitivity has been studied with the modal model. This study and the results are detailed in LIGO-T960114-00-D - a summary is given here.

The misalignment of an angular degree-of-freedom causes a quadratic reduction in the shot noise limited sensitivity. The degradations of signal-noise due to misalignments of multiple degrees-of-freedom do not necessarily add linearly. The effect of multiple misalignments can be described by a degradation- (or variance-) ellipsoid in the 5 dimensional angular space. If the axes u_i of this ellipsoid are used as a basis to express the misalignment angles ψ_i , the effects of multiple misalignments do add to give the resulting sensitivity:

$$\frac{SNR_{\text{misaligned}}}{SNR_{\text{aligned}}} = 1 - 2\sum_{i=1}^{5}\left(\frac{\psi_i}{\sigma_i}\right)^2$$

where σ_i are the lengths (variances) of the ellipsoid axes, and the factor of two accounts for both pitch and yaw misalignments. We require that ($SNR_{\text{misaligned}} / SNR_{\text{aligned}} \geq 0.995$).

The directions of the ellipsoid axes and the variances are given in Table 1. The most sensitive misalignment is a common rotation of the ITM against an opposite rotation of the recycling mirror; nearly as sensitive is a mode involving a differential misalignment of the ETMs against an ITM differential misalignment in the opposite direction (the signs are the same in Table 1 because of the sign convention given in Figure 1). The alignment of the ETM mirrors is as critical as the alignment of the ITM and RM mirrors.

The basis u_i is an alternative basis in which to express the alignment requirements. In this basis there are only two very critical degrees-of-freedom, u_1 and u_2 ; allowing a larger tolerance for the other degrees-of-freedom - as shown in Table 3 - may be useful when implementation issues are taken into account. The amplitude of misalignment in this bases is labelled ψ_i (Ψ_i in normalized units).

	variance	ellipsoid axis					u_i
	σ_i^2	$\Delta\theta_{ETM}$	$\Delta\theta_{ITM}$	$\overline{\theta_{ETM}}$	$\overline{\theta_{ITM}}$	RM	
signal-to-noise	6.34	0.001	–0.002	**0.395**	**–0.745**	**–0.537**	u_5
	0.790	0.014	–0.030	**0.918**	**0.319**	**0.232**	u_4
	0.160	**0.418**	**–0.908**	–0.031	–0.007	–0.011	u_3
	0.00107	**0.909**	**0.4138**	0.000	–0.004	0.005	u_2
	0.000737	–0.004	–0.007	–0.002	**–0.586**	**0.811**	u_1

Table 1 Variances and axes directions of the misalignment variance ellipsoid. The variances are in normalized units - i.e., units of the arm cavity beam divergence angle (squared).

Beam jitter coupling:

The beam jitter-misalignment coupling has also been studied with the modal model. This study and the results are detailed in LIGO-T960120-00-D - a summary is given here.

A misalignment allows a first order coupling of fluctuations in the input beam direction to gw output signal; it is a source of phase noise. Not surprisingly, the effect is most sensitive to the differential modes of misalignment. The coupling can be described in terms of the equivalent arm differential displacement signal produced by the product of mirror misalignment and beam direction fluctuations:

$$\delta L_{-} \;=\; 1.95\times10^{-20}\left[\left(\frac{\Delta\theta_{\mathrm{ETM}}+0.45\Delta\theta_{\mathrm{ITM}}}{10^{-8}\ \mathrm{rad}}\right)\left(\frac{\alpha}{10^{-8}/\sqrt{\mathrm{Hz}}}\right)\right.$$
$$\left.+\,0.16\left(\frac{\Delta\theta_{\mathrm{ETM}}+0.5\Delta\theta_{\mathrm{ITM}}}{10^{-8}\ \mathrm{rad}}\right)\left(\frac{x}{10^{-8}/\sqrt{\mathrm{Hz}}}\right)\right]\ \frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}}$$

where α is the beam tilt and x the beam translation at the interferometer input in units of the beam divergence angle and waist size (in the arm cavity), respectively. Since the beam jitter couples essentially to misalignments along the u_2 direction, this can be written as:

$$\delta L_{-} \;\approx 7.1\times10^{-21}\left(\frac{\psi_2}{10^{-8}\ \mathrm{rad}}\right)\left(\frac{\alpha+0.16x}{4\times10^{-9}/\sqrt{\mathrm{Hz}}}\right)\ \frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}}$$

This is in each direction (horizontal and vertical), so if the misalignment is held to 10^{-8} rad, the beam jitter must be $< 4\times10^{-9}/\sqrt{\mathrm{Hz}}$ at 150 Hz to meet the displacement noise requirement.

Misalignment-beam jitter noise also affects the arm common mode or laser frequency error signal. In this case, beam jitter couples essentially to misalignments along the u_1 direction. The above level of beam jitter, coupling with a misalignment of $\psi_1 = 10^{-8}$ rad, produces an error signal equivalent to a frequency noise of ~ 10^{-9} Hz/√Hz. Since the required level of frequency stabilization is < 10^{-7} Hz/√Hz, this imposes no new requirements on the beam jitter or the alignment.

APPENDIX 6 BASIS OF CENTERING REQUIREMENT

Lever Arm Effect. The sources of test mass angular noise leading to the centering requirement in **3.2.3.3.** are quantified below:

1. *Thermal Noise.* Thermal noise of the pitch mode of the test masses has been modeled by G Gonzalez (LIGO-T960081-00-D, *"Pendulum thermal noise: pendulum and pitch modes"*), assuming that the loss in that mode is determined completely by the suspension wire loss. Taking the suspension parameters in the SUS DRD, and a frequency independent wire loss of

10^{-3} , the pitch thermal noise is calculated to be: $\tilde{\theta}(f) = 2.25\times10^{-17}\times(40\ \mathrm{Hz}/f)^{5/2}(\mathrm{rad}/\sqrt{\mathrm{Hz}})$. Another useful way to express the result is with the ratio of the pendulum displacement noise to the pitch angular noise. In the relevant band of 40-150 Hz, this ratio is constant and equal to (1/80)(meters/radian). The displacement noise due to the pitch mode is thus equal to the pendulum displacement noise at a vertical beam offset of 1/80 m = 12.5 mm.

The pitch/yaw thermal noise requirement for the SUS subsystem is given in the SUS DRD (LIGO-T950011-14), Appendix B.1.3.: $< 5\times10^{-18}\times(100\ \mathrm{Hz}/f)^{\overline{5/2}}(\mathrm{rad}/\sqrt{\mathrm{Hz}})$ for pitch and yaw (for the LOS optics). This leaves some margin for higher mechanical loss than that modeled above.

2. *Coil Driver Noise.* The SUS requirement on the allowed control noise in pitch/yaw per mass is given in the SUS DRD (LIGO-T950011-14), section **3.2.1.2.4.**: $< 2\times10^{-17}\times(40\ \mathrm{Hz}/f)^2(\mathrm{rad}/\sqrt{\mathrm{Hz}})$.
3. *Seismic Noise.* Seismically induced angular noise will be much smaller than the above. Pitch noise is produced by displacement noise of the support point, with a transfer function of $(\theta/x)(f \gg f_p, f_\theta) = ((2\pi)^2 f_p^2 f_\theta^2)/(g f^2)$, where f_p and f_θ are the pendulum and pitch eigenfrequencies, respectively. For a conservative ground motion upper limit of 10^{-16} m/√Hz at 40 Hz, this leads to a pitch noise of 5×10^{-20} rad/√Hz. For yaw motion, a worst case estimate of the yaw noise of the suspension support point is to take the support point displacement noise and a lever arm of order the optics platform radius, ~ 1 m. With the further isolation provided by the pendulum, this leads again to negligible yaw noise of the optic.

The dominant source is pitch/yaw thermal noise, with the coil driver noise being slightly smaller. At 40 Hz, the noise due to both sources is 3.6×10^{-17} rad/√Hz. For the beam centering, there is one relevant degree-of-freedom - the radial offset of the beam centroid from the center of rotation (call it d). The SRD sensitivity is $\mathbf{x} = 10^{-18}$ m/√Hz at 40 Hz, and the displacement noise due to the lever arm effect should be a factor of 20 below this, per optic. This gives a centering tolerance of $d < 1.4$ mm. We round this off to a slightly tighter requirement of $d < 1$ mm.

Beamsplitter displacement noise can be up to a factor of 100 higher than that of the test masses. Given that the pitch/yaw thermal noise requirements for the beamsplitter are the same as for the test masses, it is clear that the lever arm effect is unimportant for any reasonable beamsplitter beam offset.

Recycling mirror displacement noise will serve as a noise term to the laser frequency stabilization. However the required frequency stability of $10^{-7}\ \mathrm{Hz}/\sqrt{\mathrm{Hz}}$ at 100 Hz requires a recycling cavity length stability of only $\leq 5\times10^{-16}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$. Again since the pitch/yaw thermal noise requirement for the recycling mirror is the same as for the test masses, displacement noise due to the lever arm effect will be negligible.

Diffraction. The effects of de-centered beams on the optical performance have been investigated by simple overlap integrals of the TEM_{00} mode with the aperture, and by the FFT model.

The overlap integral results for a normal-incidence optic (test masses and recycling mirror) can be summarized simply: a 1 cm shift of the beam center with respect to the aperture center results in an aperture loss that is roughly double that for the centered case (the aperture loss for the centered case depends on the ratio of the beam size to aperture size). The COC requirement for aperture loss is (Table 6 of the COC DRD) < 1 ppm for the ETM, and < 0.3 ppm for the ITM. At this level, a doubling of the aperture loss due to de-centering is tolerable.

Overlap integrals for the beamsplitter (45° incidence) were examined in the COC DRR, Appendix A. The COC requirement for aperture loss is < 100 ppm for the beamsplitter. Since this is already a trade-off with the BS diameter, we would like to not increase this loss due to de-centering. Figure A.1 of the COC DRD shows that the aperture loss is below 100 ppm for offsets of up to 1 cm from the beam position corresponding to minimum aperture loss (in the horizontal direction). These conclusions were recently supported with an FFT analysis of the effect of the beam position on the beamsplitter.[1]

The FFT model has been used to further investigate the effects of aperture shifts on the test masses and recycling mirror, using the flat-curved geometry and mirrors having 50 ppm/bounce loss, but otherwise perfect (no distortions). The aperture sizes were such that the aperture loss for a centered beam was ~1 ppm; an offset of 1 cm was given to one of the core optics, corresponding to ~2 ppm aperture loss for that optic. Power levels, contrast defect, and effective length change were examined to gauge the effect of the offset.

The changes in power levels and contrast defect were comparable in magnitude to those caused by the initial 1 ppm aperture loss; that is, they were negligible. The effective length changes were also small (10^{-14} - 10^{-15} m). The conclusion is that a 1 cm offset of the beam from the aperture center of the test masses and the recycling mirror has a negligible effect on the interferometer optical performance.

In conclusion, the tolerable de-centering on a test mass is 1 mm, as given by angular noise-lever arm coupling. The tolerable shift from the nominal beam position on the beamsplitter is as much as 1 cm (depending on the nominal position), as given by aperture loss (in the horizontal direction; in principle the could be greater in the vertical direction). We take a requirement of 5 mm of tolerable shift (in any direction) on the beamsplitter, the recycling mirror, and for the folding mirrors in the 1/2-length interferometer.

Note that because of the wedge angles of the optics, the center of mass (rotation) is offset from the aperture center. For a 3° wedge on a 10 cm thick optic (the maximum wedge being considered for the test masses and recycling mirror), the offset is 2 mm.

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[1] Bill Kells, private communication, June 1996.