



LIGO Laboratory / LIGO Scientific Collaboration

LIGO-T000092-02-D

ADVANCED LIGO

10/4/00

Auxiliary Optics Support System
Design Requirements Document, Vol. 1
Thermal Compensation System

Michael Smith, Phil Willems

Distribution of this document:
LIGO Science Collaboration

This is an internal working note
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California Institute of Technology
LIGO Project – MS 18-34
1200 E. California Blvd.
Pasadena, CA 91125
Phone (626) 395-2129
Fax (626) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Project – NW17-161
175 Albany St
Cambridge, MA 02139
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

LIGO Hanford Observatory
P.O. Box 1970
Mail Stop S9-02
Richland, WA 99352
Phone 509-372-8106
Fax 509-372-8137

LIGO Livingston Observatory
P.O. Box 940
Livingston, LA 70754
Phone 225-686-3100
Fax 225-686-7189

<http://www.ligo.caltech.edu/>

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1 Introduction

1.1 Purpose

The purpose of this document is to describe the design requirements for the Thermal Compensation System (TCS) of the Auxiliary Optics Support (AOS). Primary requirements are derived (“flowed-down”) from the LIGO principal science requirements. Secondary requirements, which govern Detector performance through interactions between AOS and other Detector subsystems, have been allocated by Detector Systems Engineering (see Figure 1.)

1.2 Scope

The AOS system is comprised of the following distinct subsystems: Stray Light Control (SLC), Thermal Compensation System (TCS), PO Mirror Assembly and Telescope, Initial Alignment System (IAS), Optical Lever System (OptLev), Photon Calibrator, Output Mode-Matching Telescope (OMMT), and Viewports.

1.2.1 Thermal Compensation System (TCS)

The Thermal Compensation System subsystem will sense and correct thermally generated wavefront distortions in the core optics to a level that does not interfere with the IFO sensitivity and operation. It will provide controllable compensation optics (compensator plates), as well as heating elements for these optics (resistive ring heaters and/or carbon dioxide lasers). Any special viewports and mirrors required by the heating elements are within the scope of this subsystem. All radiative shields required for the operation of the subsystem or to isolate it from nearby subsystems are within the scope of this subsystem. If suspensions are required for the compensation optics, these are outside the scope of the TCS subsystem. Sensors for monitoring the thermally distorted wavefronts in the IFO are within the scope of this subsystem.

Thermal compensation and thermal aberration sensing of optics that are not core optics (for example, the mode cleaner mirrors or mode matching telescope mirrors) are not within the scope of this subsystem.

1.3 Definitions

The term ‘cold’ or ‘cold state’ refers to the thermal and phase profile of an optic in the steady state with no light or thermal compensation heat incident upon it.

The term ‘thermal compensation’ is herein interpreted to mean the control of an optic’s transmissive or reflective phase profile by means of adding heat to that optic, or one nearby, with a suitable spatial profile. This does not necessarily require making the temperature distribution of the optic uniform, and is not intended to mean so. Nor does it necessarily mean maintaining the transmissive or reflective phase profile of the optic to match its cold state.

1.4 Acronyms

LIGO - Laser Interferometer Gravity Wave Observatory

IOO - Input Optics
DRD - Design Requirements Document
SRD - Science Requirements Document
PRM - Power Recycling Mirror
SRM – Signal Recycling Mirror
BS - Beam Splitter
ITM – Input Test Mass
ETM - End Test Mass
AR - Antireflection Coating
HR - Reflective mirror coating
PO - Pick-off Beam
CP – Compensation Plate
SEI - Seismic Isolation subsystem
SUS - Suspension subsystem
ppm - parts per million
ISC- Interferometer Sensing and Control
LSC - Length Sensing and Control
COC - Core Optics Components
ASC - Alignment Sensing and Control
IFO - LIGO interferometer
HAM - Horizontal Access Module
BSC - Beam Splitter Chamber
BRDF - Bi-directional Reflectance Distribution Function
TBD - To Be Determined
APS - anti-symmetric port signal
SPS - symmetric port signal
WFS – Wavefront Sensing System
rms - root-mean-square
p-v, peak to valley

1.5 Applicable Documents

1.5.1 LIGO Documents

Core Optics Components Design Requirements Document: LIGO-T000127-01-D

Ryan Lawrence's PhD. Thesis : LIGO-P030001-00-R

Investigation of Suspension of Compensator Plate in ITM Reaction Chain: LIGO-T040038-00-R

Cavity Optics Suspension Subsystem Design Requirements Document: LIGO-T010007-03-D

LIGO Interferometer Operating at Design Sensitivity with Application to Gravitational Radiometry: Stefan Ballmer, PhD. Thesis, in preparation

DC Readout for Advanced LIGO, Peter Fritschel, LIGO-G030460-00-D

Advanced LIGO Detector Design Requirements Document: LIGO-Exxx

LIGO Vacuum Compatibility, Cleaning Methods and Procedures, LIGO-E960022-00-D

LIGO Naming Convention (LIGO-E950111-A-E)

LIGO Project System Safety Management Plan LIGO-M950046-F

LIGO EMI Control Plan and Procedures (LIGO-E960036)

Derivation of CDS Rack Acoustic Noise Specifications, LIGO-T960083

Specification Guidance for Seismic Component Cleaning, Baking, and Shipping Preparation (LIGO-L970061-00-D)

1.5.2 Non-LIGO Documents

Compensation of Strong Thermal Lensing in Advanced Interferometric Gravitational Waves Detectors, Jerome Degallaix, PhD. Thesis, in preparation

2 General description

2.1 Specification Tree

This document is part of an overall LIGO detector requirement specification tree. This particular document is highlighted in the following figure.

2.2 Product Perspective

Figure 1: Overall LIGO detector requirement specification tree

2.2.1 Thermal Compensation System Perspective

The Thermal Compensation System (TCS) contains compensator plates (CP) that are positioned in the BSCs, between the BS and ITMs in each interferometer arm. Ring heater elements will be co-located with the compensator plates, and the whole will be shielded to prevent heating of nearby optics and hardware. A carbon dioxide laser heater beam will enter the vacuum through a zinc selenide viewport and may be directed to the compensator plate by one or more mirrors. The carbon dioxide lasers themselves, and the components required for their stabilization and control, will be outside the vacuum housing on an optical table. All of the above equipment will serve the purpose of correcting optical aberrations in the recycling cavities. Additional ring heaters will heat the periphery of the ITMs for HR radius of curvature compensation. The ring heaters will be powered by stable power supplies outside the vacuum.

TCS will contain sensors which sample the thermal wavefront distortions within the interferometer, either from samples of the IFO beam picked off at appropriate points, or directly from the optics themselves using dedicated probe beams. These sensors may be partially in common with the Wavefront Sensing System (WFS). TCS will also contain servo electronics that will derive control signals from the sensors and feed them back to the heater elements.

2.3 Thermal Compensation System Functions

Absorption of the high laser power will produce thermal distortion of the core optics. These distortions will be detected by optical sensors and compensated by applying corrective thermal distortions to compensator plates between the ITMs and the BS, as well as to the test masses directly. This system will also correct for static curvature errors in the test masses, and tune the arm cavity mode spectra as a means of controlling acoustic parametric instabilities. TCS also samples the phase profiles of the ITM and ETM HR radii of curvature and the ITM/CP and BS transmissions using dedicated sensors, and it samples the IFO beam directly using phase cameras.

2.4 General Constraints

2.4.1 Thermal Compensation System Constraints

The heater elements in the Thermal Compensation System will operate in the presence of equipment that is sensitive to changes of temperature, primarily SUS and SEI. The need to insulate TCS from these other systems will constrain the design.

LIGO must operate continuously, therefore this subsystem must be designed with high reliability and low mean time to repair. This is particularly true of all in-vacuum components.

Because it controls the wavefronts of interferometer beams, the TCS will influence the Wavefront Sensing system (WFS). This influence is unavoidable, so the TCS operation must be made compatible with WFS operation.

2.5 Assumptions and Dependencies

2.5.1 Core Optics Parameters

The following optics parameters were taken from the Core Optics Components Design Requirements Document: LIGO-T000127-01-D.

Physical Quantity	RM	SM	BS	ITMx	ITMy	ETM
AR coating @ 1060 nm	~0.001	<0.0001	<0.0002	<0.0002	<0.0002	<0.0003
mirror reflectivity @ 1060 nm	0.94	0.95	0.5	0.995	0.995	0.99994
refractive index @ 1064 nm	1.44963		1.44963	1.44963	1.44963	1.44963
1ppm power contour radius, mm	168		168	168	168	168
beam radius parameter w, mm	60		60	60	60	60
Mirror diameter, mm	265	265	350	340	340	340
Mirror thickness, mm	100	100	60	200	200	200

Note FM is missing.

2.5.2 Material Parameters

The amount of thermal aberration expected depends upon the material parameters of fused silica and the absorption of the coatings. It is assumed that the absorption of the ITM HR coatings will be .5 ppm. The absorption of fused silica (Heraeus Suprasil 312) is assumed to be 2 ppm/cm. The following table lists the other relevant parameters for fused silica.

Young's modulus	72.8 GPa
Poisson's ratio	.170

Thermal expansion coefficient	$5.5 \times 10^{-7}/\text{K}$
Thermal conductivity	1.38 W/m/K
Density	2196 kg/m ³
Heat capacity	740 J/kg/K
Temperature dependence of refractive index (dn/dT)	$8.7 \times 10^{-6}/\text{K}$
Emissivity	.9
Elasto-optic coefficient p_{11}	.121
Elasto-optic coefficient p_{12}	.270

Table 1: material parameters of fused silica (from Lawrence 2003)

2.5.3 Interferometer Design Parameters

The Thermal Compensator System can potentially inject stray light into the interferometer, most likely through the sensor probe beams. The stray light calculations were based on the following assumed parameters:

Laser input power	125 watts
SPS power	2.5 watts
APS power	1.0 Watt
IFO Gaussian beam radius, w	60 mm
Recycling cavity gain	16.8
Arm cavity gain	789

2.5.4 Suspension Parameters

The following displacement noise parameters are taken from the Cavity Optics Suspension Subsystem Design Requirements Document LIGO-T010007-03-D.

Mirror	Displacement noise requirement
Folding mirror	$2 \times 10^{-17} \text{ m}/\sqrt{\text{Hz}}$ at 10 Hz, falling to $6 \times 10^{-19} \text{ m}/\sqrt{\text{Hz}}$ at 100 Hz
Test mass mirror	$1 \times 10^{-19} \text{ m}/\sqrt{\text{Hz}}$ at 10 Hz, falling faster than $(1/f)^4$, except for a possible bounce peak mode at up to

	12 Hz
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2.5.5 Seismic Environment

The scattered light noise calculations in this document are based on the assumption that the rms velocity of scattering surfaces is sufficiently low so that up-conversion of large amplitude low frequency motion does not produce in-band phase noise. This is true for the vacuum housing and is also true of the SEI platforms for stack Q's less than 1000. See Seismic Isolation DRD, LIGO-T960065-02-D, and Locally Damped Test Mass Motion, LIGO-T970092-00-D.

The ground noise spectrum for the scattered light noise calculations is assumed to be the LIGO Composite Ground Noise Spectrum for frequencies between 10 and 1000 Hz, as described in figure 10, LIGO-T960065.

3 Requirements

This section contains the specific requirements of the product to be developed. This is the most important part of the document. It must be:

Unambiguous: every requirement listed has only one interpretation

Complete: Inclusion of all significant requirements

Verifiable: A requirement is verifiable if and only if there exists some finite cost-effective process whereby the final product can be checked/tested to meet the requirement. If no method can be devised to determine if the product meets a particular requirement, either (1) the requirement should be removed, or (2) a point in the development cycle should be identified at which the requirement can be put into a verifiable form.

Consistent: No two requirements should conflict with each other.

Modifiable: The structure and style should be such that any necessary changes can be made easily, completely, and consistently.

Traceable: Backward (references to source of requirements, such as a higher level specification, design, or standards) and Forward (unique numbering of requirements such that they can be identified/referenced in design and test documentation).

Usable during operations and maintenance: often items are modified during commissioning and maintenance periods. The requirements should specifically call out critical areas (such as failure of this component to meet this requirement can cause severe injury), and other such items, such that this fact is not lost to maintenance personnel.

3.1 Thermal Compensation System Requirements

3.1.1 Introduction

Requirements flow down tree from Detector DRD should be included in this section.

Nonuniform heating of the input test masses and beamsplitters of the interferometer by absorption of the main interferometer beam causes thermal lensing through three distinct physical effects: thermorefraction, thermal expansion, and the elasto-optic effect, which is induced by thermal expansion. Thermal aberration will occur in the other core optics as well, but to such a lesser degree that there is no anticipated need to compensate those optics. Below we enumerate the aspects of interferometer performance affected by power absorption and the corresponding requirements on TCS to control them.

3.1.2 Thermal Effects and the Requirements on the Thermal Compensation System and TCS Controls

3.1.2.1 Arm cavity mode structure

Thermoelastic expansion of the test masses will distort their HR surfaces, changing the structure and spectrum of the resonant modes of the arm cavity. Using the baseline assumptions for

Advanced LIGO, the fundamental mode spot size is expected to shrink from 6 cm in the cold state to approximately 5.3 cm at full power without compensation of the test masses. This reduction in spot size will increase thermal noise and reduce arm cavity coupling to the input beam.

Acoustic parametric instabilities may be present at high optical power. These instabilities are governed in part by phase matching between the arm cavity's transverse optical mode splitting and an acoustic mode of a test mass mirror. Thermal compensation of the test masses' radii of curvature provides a method to adjust the transverse optical mode spacing and control the instability.

With these effects in mind, one requirement on TCS can be stated,

TCS shall be able to adjust the arm cavity spot size by adding up to 35 km thermal radius of curvature to all test masses' HR faces.

3.1.2.2 RF sideband power buildup

The interferometer length and angular sensing and control rely upon RF sideband light resonating in the interferometer with the carrier light as a source of heterodyne error signals. These RF sidebands must resonate in the recycling cavities with high optical power and good mode overlap with the carrier light to provide useful error signals. For an interferometer that is optimally coupled while cold, thermal aberrations at higher power will distort the recycling cavities, reducing their power gain for the RF sidebands. Left uncompensated, at some input laser power the RF sideband power in the recycling cavities will reach a maximum- the thermal aberration losses will more than offset the increased injected sideband power if the input laser power is increased further.

Therefore,

TCS shall compensate the thermal aberrations in the recycling cavities sufficiently that the RF sideband power in the recycling cavities does not decrease as the input laser power is increased, up to an input laser power of 120W.

3.1.2.3 Arm cavity coupling

As a result of thermal aberrations in the recycling cavity, and to a lesser extent changes in the arm cavity modes themselves, the coupling of optical power into the arm cavities is diminished by thermal aberrations. The arm cavity gain may drop by 17% at full uncompensated input power¹. This gain reduction reduces the sensitivity of the interferometer in the optical noise limited frequency range by increasing shot noise.

Therefore,

TCS shall maintain the arm cavity gain to at least 95% of its nominal value.

¹ Ryan Lawrence, Ph.D. thesis.

3.1.2.4 Dark port power coupling

If any differential thermal effects are present (for example, thermal aberration in the beamsplitter), the resulting differential phase errors between the arms will increase the contrast defect and thereby the light power at the interferometer dark port. Much of this light will be in higher order transverse modes and will be greatly attenuated by the output mode cleaner. Some of this excess light, which is equivalent to a mismatch of arm reflectivities, will be in the fundamental mode, and will be passed by the output mode cleaner. This excess light will increase the shot noise at the detector without a corresponding increase in interferometer sensitivity.

This issue is complicated by the DC readout scheme adopted for gravitational wave detection. A small amount (of order 100 mW) of carrier light will be intentionally passed to the dark port, because of static arm mismatch (approximately 1.6 mW) and partly from deliberate fringe offset. The ratio of static arm mismatch carrier light to fringe offset carrier light is chosen to set the homodyne phase angle.

TCS shall maintain the arm mismatch component of the homodyne dark port signal to within 1 mW of its nominal value.

3.1.2.5 Gravitational wave sideband output coupling

The gravitational wave sidebands must resonate in the signal recycling cavity in order to achieve signal recycling. Any aberration in the signal recycling cavity will convert gravitational wave sideband power into higher order optical modes that are rejected by the output mode cleaner and/or reduce the extraction efficiency of the sidebands from the arms.

Therefore,

TCS shall maintain the extraction efficiency of the gravitational wave sidebands through the signal recycling cavity to the dark port to at least 95% of its nominal value.

3.1.2.6 Quantitative estimates of the thermal compensation requirements

It is the extraction efficiency of the gravitational wave sidebands through the signal recycling cavity that sets the most stringent requirements on TCS, so we consider that in detail. This can be estimated by considering two extreme cases of absorption in the mirrors: perfectly homogeneous absorption and point absorption. Based upon the thermal modeling reported in document LIGO-T-060068-00-R, the level of optical path variation that causes 5% loss of the gravitational wave sideband extraction efficiency in a marginally stable signal recycling cavity is approximately .08 radians for either homogeneous absorption or a single point absorber. Thus, requiring the precision of the thermal compensation to be better than the maximum tolerable level of residual phase error after thermal compensation, we achieve .08 radians of phase error, or $\lambda/47$, as the lower limit to the needed precision.

A 0.1% round trip loss from the signal recycling cavity causes 5% loss of gravitational wave sideband signal at the dark port. It is therefore desirable to compensate aberrations in the core optics in a region that contains at least 99.9% of the main IFO beam power- a circle of radius 112 mm centered on the optic. The size of the compensation profile provided by TCS in the recycling cavity shall be at least this large.

Any TCS sensor must be able to detect the ITM/CP and beamsplitter optical path distortions with at least the $\lambda/47$ precision stated above. Conservatively setting the precision to one-tenth this level, we get $\lambda/470$ sensitivity. The necessary spatial resolution of the sensor is determined by the requirement that the thermal feature of a point absorber not lie unseen between two pixels of the sensor pattern. Again referring to document LIGO-T-060068-00-R, this pixel spacing must be less than 1cm. As above, the minimum radius of the TCS wavefront probe area is 112 mm.

It bears repeating here that these quantitative estimates of the TCS and TCS sensor requirements are meant to express TCS performance in a manner amenable to measurement independent of the Advanced LIGO interferometer (for example, on a test bed). They are derived from the requirements on interferometer performance, and as such, they are *secondary* to the requirements on the interferometer performance listed in the subsections above. In particular, should the interferometer performance requirements change (for example, due to adoption of stable recycling cavities), these quantitative requirements must be re-evaluated.

3.1.3 Thermal Compensation System Noise Requirements

There are several paths through which TCS can inject noise into the IFO. These include motion of the CP, fluctuations of injected compensation heat, radiation and heat noise from TCS probe beams, scattered TCS probe light, and acoustic and electromagnetic noise from TCS components. We deal with each separately.

3.1.3.1 Compensation Plate Noise Motion

The noise injected by an individual CP is injected only into a single arm of the recycling cavities. Therefore, its injected noise has a similar effect as Folding Mirror noise, and must meet the same requirements. For reference, the longitudinal displacement noise requirement for the Folding Mirrors is 2×10^{-17} m/ $\sqrt{\text{Hz}}$ at 10 Hz, falling to 6×10^{-19} m/ $\sqrt{\text{Hz}}$ at 100 Hz.²

Because the CP has no HR surfaces, the noise motion requirements for the CP are relatively modest. In particular, the IFO should exhibit no sensitivity to motion of the CP along the beam axis. Because the CP will function as a lens and will be wedged, there will be sensitivity to transverse motion. The wedge angle on the CP is 5 arc-minutes. The focal length of the CP at the maximum expected IFO power is expected to be approximately 5 km. This introduces an equivalent sagitta of 180 nm over the area of the IFO beam, compared with 0.17 mm from the wedge, so the coupling of transverse to longitudinal motion by the wedge dominates. This coupling is 8.8×10^{-5} , so the transverse noise requirement becomes 2.2×10^{-13} m/ $\sqrt{\text{Hz}}$ at 10 Hz, falling to 7.1×10^{-15} m/ $\sqrt{\text{Hz}}$ at 100 Hz. Since the CP is suspended from a quadruple pendulum in nearly the same manner as the ITM, this requirement is expected to be easily met.

The internal thermal noise of the CP must satisfy the same requirement. The internal thermal noise of the CP is estimated to be more than an order of magnitude below the noise exiting the arm cavity.³

² Cavity Optics Suspension Subsystem Design Requirements Document: LIGO-T010007-03-D.

³ Compensation of Strong Thermal Lensing in Advanced Interferometric Gravitational Waves Detectors, Jerome Degallaix, PhD. Thesis, in preparation.

3.1.3.2 Fluctuations of Injected Compensation Heat

Because TCS operates by thermally injecting optical phase variations into the TMs and CP, rapid fluctuations of the TCS power can inject phase noise into the IFO. Mechanisms for TCS noise coupling have been analyzed.⁴ These include local thermal expansion and refractive index change, thermal flexure, and radiation pressure. The effect of this noise is more severe for TM compensation than for CP compensation, due to the more stringent TM noise requirements. For reference, the TM longitudinal displacement noise requirement is 1×10^{-19} m/ $\sqrt{\text{Hz}}$ at 10 Hz, falling faster than $(1/f)^4$, except for a possible vertical bounce peak at up to 12 Hz. The technical longitudinal displacement noise (which TCS noise is) is required to be no more than 1/10 of these. The CP noise requirement is described in Section 3.1.3.1.

It is noted that direct sensing of the TCS heat power with sufficient dynamic range to demonstrate sufficiently quiet actuation directly on the TM is not possible with current technology. Therefore, for TM compensation intrinsically quiet actuators (i.e. incandescent heaters) are preferred over heaters that require active power stabilization (i.e. CO₂ lasers).

While they are not anticipated to be a significant noise source, radiation pressure and heat fluctuations from the TCS sensor beams on the CP and TM must also satisfy the above requirements.

3.1.3.3 Scattered TCS Sensor Light

At present, there are two candidate sensors for monitoring the thermal aberrations of the ITMs and BS individually: Hartmann sensors and white-light phase-modulated interferometers. Both of these use injected probe beams to sense the phase profile of the optic, and can therefore potentially scatter harmful light into the IFO, in particular to the dark port. At the dark port detector, the probe light can interfere with the homodyne detection scheme by varying the DC optical power (nominally 1.6 mW⁵), and it can also inject noise within the Advanced LIGO bandwidth.

The TCS sensors shall not inject more than 0.3 mW of DC optical power to the dark port detector. Within the Advanced LIGO band, the TCS sensors are required to not scatter more than 1/10 the SRD light power.

Scattered TCS sensor light can also interfere with other systems in the detector, e.g. optical levers, OSEMs, etc. This requirement, as well as that for acoustic and electromagnetic noise, is dealt with in the interface requirements below.

3.1.4 Thermal Compensation Centering Requirements

3.1.4.1 Compensator Centering

In initial LIGO, finite element modeling indicated that the annular TCS pattern must be centered on the ITM to within 1 cm for adequate thermal compensation. In Advanced LIGO, with its TCS sensors to monitor the actual phase profile in the ITM/CP pair, the strategy will be to measure the

⁴ LIGO Interferometer Operating at Design Sensitivity with Application to Gravitational Radiometry: Stefan Ballmer PhD. Thesis, in preparation.

⁵ DC Readout for Advanced LIGO, Peter Fritschel, LIGO-G030460-00-D.

phase profile and use a suitably masked CO₂ laser projector to correct for any inhomogeneities in the ITM/CP absorption profile. The compensated phase profile can then be sensed and used to improve the CO₂ laser projector profile and alignment. For this reason, no requirement on the CO₂ laser projector centering is specified.

The compensation plate will be suspended from the ITM reaction chain, and the ring heater will be mounted on or near the ITM SUS structure. The tolerance for the ETM reaction mass transverse displacement is 1 mm; this is adequate for the centering of the CP to the ITM.

An ellipticity of 0.1 in a prototype shielded ring heater can cause deviations at the 10 nm level in the phase profile of a compensated optic at large radii. Nevertheless, the resulting phase profile made a factor of 68 compensation of an experimental thermal lens⁶. Assuming a linear scaling between ellipticity and residual phase error, reducing the ellipticity to 0.01 will reduce the deviations in phase profile to 1nm. The radius of the shielded ring will be of order 200 mm in Advanced LIGO, so an ellipticity of 0.01 corresponds to a radius error of 2mm. *Therefore, the centering of the shielded ring heater to the CP shall be within 2 mm.*

3.1.4.2 Sensor Centering

The use of the TCS sensors to measure the phase profile of the optics requires that these be accurately registered to the axis of the optic. It is not necessary that the sensor probe be centered to the optic itself, only that the location of the optic axis be accurately identified in the sensor output. *Therefore, the centering of the sensor probe to the optic face shall be within 10 mm. The position of the center of the optic shall be identifiable in the sensor output to within 1 mm.*

3.1.5 Thermal Compensation System Optical Characteristics

The recycling cavities in Advanced LIGO require minimal losses to maintain their finesse. *The total surface reflection loss from the compensation plates shall not exceed 100 ppm. Ghost beams from these surfaces shall be captured on baffles.*

To reduce unwanted scatter in the recycling cavities, *the clear aperture of the CP and shielded ring heater shall contain entirely the combined clear aperture of the recycling mirrors and beamsplitter.*

The compensation plate shall not introduce optical path inhomogeneities that in combination with the recycling cavity core optics exceeds requirements.

3.1.6 Thermal Compensation System Interface Definitions

3.1.6.1 Interfaces to other LIGO detector subsystems

3.1.6.1.1 Mechanical Interfaces

Due to severe space limitations, the compensator plates will be suspended from the recoil pendulums of the ITM suspensions by metal wire loops. This has been investigated by SUS and found to be feasible.⁷ The ring heater, compensator plate shield, and any additional shielding for

⁶ Ryan Lawrence, op. cit.

⁷ Investigation of Suspension of Compensator Plate in ITM Reaction Chain: LIGO-T040038-00-R.

nearby components will either be bolted to the ITM suspension cage (and folding mirror cage in the folded IFO) or suspended in front of the suspension cage from the SEI platform. The cables carrying power to the ring heater will be clamped to the SEI platform before exiting the vacuum. The mass of any ring heater assembly that is attached to the suspension structure must not exceed XXX kg.

3.1.6.1.2 Electrical Interfaces

The cables carrying power to the ring heater will be clamped to the SEI platform before exiting the vacuum.

3.1.6.1.3 Optical Interfaces

The compensator plates will be traversed by the beam in the power recycling cavity. Ghost beams introduced by the compensator plates must be sufficiently weak not to significantly reduce the recycling gains, and they must be suitably dumped onto baffles.

Stray light from the TCS sensors must not interfere with the normal operation of other optically sensitive hardware in Advanced LIGO, such as optical levers and OSEMs.

3.1.6.1.4 Stay Clear Zones

The ring heater and shielding for the compensator plates will stay outside the scatter zone for the power recycling cavity beam. At the Hanford site, the shielding for one interferometer will not block the light paths for the other.

3.1.6.1.5 Interfaces external to LIGO detector subsystems

There are no interfaces external to LIGO detector subsystems.

3.1.7 Thermal Compensation System and TCS Controls Reliability

All in-vacuum components should have a MTBF identical to other similar in-vacuum components- the CP similar to a suspended optic, TCS steering mirrors and telescopes similar to other steering mirrors and telescopes, TCS viewports similar to other viewports. The relatively unique in-vacuum components are the shielded ring heaters, which must operate for long periods while radiating up to hundreds of watts of incandescent power. These will be integrated into the SUS structure and must have an MTBF similar to other such parts of the SUS assembly, such as the fused silica ribbons.

The remaining components are out of vacuum, but are needed for continuous operation of the IFO. Therefore, their MTBF should be 5 years.

3.1.8 Thermal Compensation System and TCS Controls Maintainability

For all extra-vacuum TCS equipment, sufficient spares shall be retained to allow for repair or replacement of equipment within one day.

All shielded ring heater electronics shall maintain test points as close as practical to the ring heater for the purpose of accurate input power monitoring. The CO₂ laser projector shall include a power meter to measure fluctuations in the power to the CP. Both these measurements must be sensitive enough to detect fluctuations that could be observable in the gravitational wave port.

The CO₂ laser projector shall include provisions for measurement of the compensation heat profile outside the vacuum during commissioning exercises.

The amount of time required to procure masks with new profiles for the CO₂ laser projector shall not exceed 2 weeks.

All TCS optics will be cleanable by standard optics cleaning procedures.

3.1.9 Thermal Compensation System and TCS Controls Environmental Conditions

3.1.9.1 Natural Environment

3.1.9.1.1 Temperature and Humidity

The following table lays out the environment TCS must be able to withstand.

Table 2 Environmental Performance Characteristics

Operating	Non-operating (storage)	Transport
+0 C to +50 C, 0–90 % RH	40 C to +70 C, 0–90 % RH	40 C to +70 C, 0–90 % RH

3.1.9.1.2 Atmospheric Pressure

All TCS viewports must withstand 1 atmosphere pressure differential.

3.1.9.1.3 Seismic Disturbance

Restraint against seismically induced large motion is required. This requirement is assumed to be automatically met for all TCS hardware outside the vacuum or bolted rigidly to the SEI or SUS structures. Suspended components in vacuum shall include stops to prevent swinging into nearby delicate components and provisions to damp large amplitude motion.

3.1.9.1.4 Induced Environment

3.1.9.1.4.1 Electromagnetic Radiation

Electrical equipment associated with the subsystem shall meet the EMI and EMC requirements of VDE 0871 Class A or equivalent. The subsystem shall also comply with the LIGO EMI Control Plan and Procedures (LIGO-E960036).

3.1.9.1.4.2 Acoustic

Equipment shall be designed to produce the lowest levels of acoustic noise as possible and practical. As a minimum, equipment shall not produce acoustic noise levels greater than specified in Derivation of CDS Rack Acoustic Noise Specifications, LIGO-T960083.

3.1.9.1.4.3 Mechanical Vibration

Mechanical vibration from the subsystem shall not increase the vibration amplitude of the facility floor within 1 m of any other vacuum chambers and equipment tables by more than 1 dB at any frequency between 0.1 Hz and 10 kHz. Limited narrowband exemptions may be permitted subject to LIGO review and approval.

3.1.10 Thermal Compensation System and TCS Controls 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.

3.1.11 Thermal Compensation System and TCS Controls Design and Construction

3.1.11.1 Materials and Processes

3.1.11.1.1 Finishes

Ambient Environment: Surface-to-surface contact between dissimilar metals shall be controlled in accordance with the best available practices for corrosion prevention and control.

External surfaces: External surfaces requiring protection shall be painted purple or otherwise protected in a manner to be approved.

- Metal components shall have quality finishes on all surfaces, suitable for vacuum finishes. All corners shall be rounded to TBD radius.
- All materials shall have non-shedding surfaces.
- Aluminum components used in the vacuum shall not have anodized surfaces.
- Optical table surface roughness shall be within 32 micro-inch.

3.1.11.1.2 Materials

A list of currently approved materials for use inside the LIGO vacuum envelope can be found in LIGO Vacuum Compatible Materials List (LIGO-E960022). All fabricated metal components exposed to vacuum shall be made from stainless steel, copper, or aluminum. Other metals are subject to LIGO approval. Pre-baked viton (or fluorel) may be used subject to LIGO approval. All materials used inside the vacuum chamber must comply with LIGO Vacuum Compatibility, Cleaning Methods and Procedures (LIGO-E960022-00-D). This in particular applies to the shielded ring heater, which may contain materials such as nichrome heated to incandescence.

The only lubricating films permitted within the vacuum are dry plating of vacuum compatible materials such as silver and gold.

3.1.11.1.3 Processes

3.1.11.1.3.1 Welding

Before welding, the surfaces should be cleaned (but baking is not necessary at this stage) according to the UHV cleaning procedure(s). All welding exposed to vacuum shall be done by the tungsten-arc-inert-gas (TIG) process. Welding techniques for components operated in vacuum shall deviate from the ASME Code in accordance with the best ultra high vacuum practice to eliminate any

“virtual leaks” in welds; i. e. all vacuum welds shall be continuous wherever possible to eliminate trapped volumes. All weld procedures for components operated in vacuum shall include steps to avoid contamination of the heat affected zone with air, hydrogen or water, by use of an inert purge gas that floods all sides of heated portions.

The welds should not be subsequently ground (in order to avoid embedding particles from the grinding wheel).

3.1.11.1.3.2 Cleaning

All materials used inside the vacuum chambers must be cleaned in accordance with Specification Guidance for Seismic Component Cleaning, Baking, and Shipping Preparation (LIGO-L970061-00-D). To facilitate final cleaning procedures, parts should be cleaned after any processes that result in visible contamination from dust, sand or hydrocarbon films.

Materials shall be joined in such a way as to facilitate cleaning and vacuum preparation procedures; i. e. internal volumes shall be provided with adequate openings to allow for wetting, agitation and draining of cleaning fluids and for subsequent drying.

3.1.11.1.4 Component Naming

All components shall be identified using the LIGO Naming Convention (LIGO-E950111-A-E). This shall include identification (part or drawing number, revision number, serial number) physically stamped on all components, in all drawings and in all related documentation.

3.1.11.2 Thermal Compensation System and TCS Controls Workmanship

Any fluid handling equipment used in TCS shall be free from leaks in normal operation.

3.1.11.3 Thermal Compensation System and TCS Controls Interchangeability

Spares shall be procured for all sensitive TCS components. Additionally, all TCS actuators shall be interchangeable at the component level between IFOs and between arms of a single IFO, where practical. Exceptions to this requirement include: CPs, which may have IFO-specific wedge angles, masks for CO₂ laser projectors, which may be tailored to specific ITMs, and in-vacuum steering mirrors and telescopes for CO₂ laser projector beams, which may also be tailored to specific ITMs. All TCS sensors will be interchangeable where practical. Exceptions to this requirement may include in-vacuum steering mirrors and telescopes, which may be tailored to specific core optics.

3.1.11.4 Thermal Compensation System and TCS Controls 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.

3.1.11.5 Thermal Compensation System and TCS Controls Human Engineering

TCS will include invisible Class IV lasers. Appropriate safety procedures, such as warning signs and interlocks, will be used in conjunction with this system.

The incandescent heaters in TCS will carry large exposed currents, and dissipate large amounts of heat. Interlocks will be used to prevent them from being operated at pressures above 10^{-3} Torr.

3.1.12 Thermal Compensation System and TCS Controls Assembly and Maintenance

Assembly fixtures and installation/replacement procedures shall be developed in conjunction with the AOS hardware design. These shall include (but not be limited to) fixtures and procedures for:

- AOS component insertion and assembly into the vacuum chambers without load support from the chambers
- assembly of the in vacuum components in a clean room (class 100) environment
- initial alignment of the AOS components

3.1.13 Thermal Compensation System and TCS Controls Documentation

3.1.13.1 Thermal Compensation System and TCS Controls Specifications

TBD.

3.1.13.2 Thermal Compensation System and TCS Controls Design Documents

The following Design Documents shall be produced:

- Advanced LIGO TCS Preliminary Design Document (including supporting technical design and analysis documentation)
- Advanced LIGO TCS Final Design Document (including supporting technical design and analysis documentation)
- Advanced LIGO TCS Prototype/Test Plans
- Advanced LIGO TCS Installation and Commissioning Plans and Procedures

3.1.13.3 Thermal Compensation System and TCS Controls Engineering Drawings and Associated Lists

A complete set of drawings suitable for fabrication must be provided along with Bill of Material (BOM) and drawing tree lists. The drawings must comply with LIGO standard formats and must be provided in electronic format. All documents shall use the LIGO drawing numbering system, be drawn using LIGO Drawing Preparation Standards, etc.

3.1.13.4 Thermal Compensation System and TCS Controls Technical Manuals and 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

Manuals shall be provided detailing the procedures listed above.

3.1.13.5 Thermal Compensation System and TCS Controls Documentation Numbering

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

3.1.13.6 Thermal Compensation System and TCS Controls Test Plans and Procedures

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

3.1.14 Thermal Compensation System and TCS Controls Logistics

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

3.1.15 Thermal Compensation System and TCS Controls Precedence

Precedence in the TCS design shall be given to compensating thermal effects in the IFO core optics during high power operation. Acoustic parametric instabilities, though potentially controllable with the TCS system, can also potentially be controlled in other ways, and are not currently well understood enough to motivate specific requirements and so take lower precedence. Thermal control of static imperfections in the IFO core optics also takes lower precedence.

3.1.16 Thermal Compensation System and TCS Controls Qualification

The shielded ring heater must pass a vacuum compatibility test under full operating current before passing design review or before installation in Advanced LIGO. Any shielded ring heater power supplies must demonstrate suitably low power noise, based upon thermal models or measurements of the ring heater thermal low-pass noise smoothing and the required power noise of the ring heater.

All carbon dioxide laser projectors must demonstrate sufficiently low intensity noise before installation, based upon the noise coupling for the likely compensation patterns to be used in the projectors. This likely compensation pattern will be developed based upon measurements of the ITMs' absorption profiles.

All TCS sensors will be demonstrated to have adequate sensitivity by measurement of a test optic. This test optic need not be full scale, as the TCS actuator and sensor telescopes will be independently verified to provide suitable magnification.

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

4.1.1 Responsibility for Tests

The responsibility for testing TCS components lies with AOS.

4.1.2 Special Tests

4.1.2.1 Engineering Tests

The range of actuation available to a CO₂ laser projector is limited by the noise performance of the laser. Tests shall be performed to determine what intensity stability level can be reasonably expected of the CO₂ laser in Advanced LIGO.

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

- Vacuum preparation procedures as outlined in LIGO Vacuum Compatibility, Cleaning Methods and Procedures (LIGO-E960022-00-D) shall be followed for all components intended for use in vacuum. After wrapping vacuum parts as specified in this document, an additional, protective outer wrapping and provisions for lifting shall be provided.
- Electronic components shall be wrapped according to standard procedures for such parts.

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. The shipping crates used for large items should use for guidance military specification MIL-C-104B, Crates, Wood; Lumber and Plywood Sheathed, Nailed and Bolted. Passive shock witness gauges should accompany the crates during all transits.

For all components which are intended for exposure in the vacuum system, the shipping preparation shall include double bagging with Ameristat 1.5™ plastic film (heat sealed seams as practical, with the exception of the inner bag, or tied off, or taped with care taken to insure that the tape does not touch the cleaned part). Purge the bag with dry nitrogen before sealing.

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.

Identification of the material shall be maintained through all manufacturing processes. Each component shall be uniquely identified. The identification shall enable the complete history of each component to be maintained (in association with Documentation “travelers”). A record for each component shall indicate all weld repairs and fabrication abnormalities.

For components and parts that are exposed to the vacuum environment, marking the finished materials with marking fluids, die stamps and/or electro-etching is not permitted. A vibratory tool with a minimum tip radius of 0.005" is acceptable for marking on surfaces that are not hidden from view. Engraving and stamping are also permitted.

6 Notes

Appendix A Quality Conformance Inspections

Appendixes are used to append large data tables or any other items which would normally show up within the body of the specification, but, due to their bulk or content, tend to degrade the usefulness of the specification. Whenever an Appendix is used, it shall be referenced in the body of the specification.

Appendix 1 shall always contain a table that lists the requirements and the method of testing requirements. An example table follows. Additional appendixes can contain other information, as appropriate to the subsystem being specified.

Table 3 Quality Conformance Inspections

Paragraph	Title	I	A	D	S	T
3.2.1	Performance Characteristics					X
3.2.1.1	Controls Performance		X			
3.2.1.2	Timing Performance'		X			X