LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

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Test-Mass Suspension Subsystem Design Requirements Document

DRAFT

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1 Introduction

1.1 Purpose

The Requirements and Interface Specification for the Advanced LIGO Test Mass Suspension system are given. In this version of the document, requirements have not flowed down from a systems design; rather, this document serves to inform Systems of a point design performance for a first iteration.

1.2 Scope

The scope of this document is limited to the specific requirements for the suspension subsystem (SUS) for the test masses in the BSC chambers. It includes information necessary to quantify the relationship and define the interfacing to other subsystems, in particular the seismic isolation subsystem (SEI), core optics (COC), and the auxiliary optics subsystem (AOS). Together these subsystems describe the critical mechanical design from local ground to the sensitive optics. The general requirements for all types of suspensions are given in a companion document (LIGO-T000053).

The requirements for all sensors and actuators, including electronics and actuator coatings on the test masses, for the ITM and ETM suspensions are treated in this document. In-vacuum wiring between the feedthrough and the connection block on the suspension system is not included in the assumed scope.

NOT included in this document or subsystem are the photon drive actuator and any thermal lensing compensation scheme (attached to the suspension cage or otherwise); these addressed in the AOS documentation.

There are several types of suspensions for Advanced LIGO. Suspension designs for optics other than the test masses (ITM and ETM) will be detailed in other documents. Provisionally, there are the following types of suspensions, where we assume that each numbered type below uses a unique optic dimension:

1. Test mass suspensions, which can be for End Test Masses (ETM) or Input Test Masses (ITM)
2. Beamsplitter suspension (BS)
3. Folding mirror suspensions (FM), used in second interferometer at a given site. The BS and FM have the same diameter; the FM and TM have the same thickness.
4. Recycling mirror suspensions, Power and Signal (PRM, SRM), and final Mode-matching suspension (nominally MMT3)
5. Mode cleaner suspensions
6. Beam-steering suspensions and initial mode-matching mirror suspensions

The conceptual design is presented in a separate companion document (T000012).

1.3 Applicable Documents

- LSC White Paper baseline design description (T990080-01-D)
- LIGO II Suspension Reference Design, The GEO Suspension Team, Jan 31 2000, T000012-00-D)
- LIGO II Suspension Conceptual Design Document (T000012, in progress).
- Universal Suspension Subsystem Design Requirements Document (LIGO-T000053, in progress).

2 General description

2.1 Product Perspective

The suspension forms the interface between the seismic isolation and the suspended optics. It provides seismic isolation and the means to control the orientation and position of the optic. These functions are served while minimizing the compromise of the thermal noise performance of the optics and while contributing thermal noise from the suspension within requirements.

The core optic is attached to the suspension fiber during the suspension assembly process and becomes part of the suspension assembly. Features on the test mass will be required for attachment and potentially for actuation.

The test mass suspension system is mounted (via bolts and/or clamps) to the BSC seismic isolation system by attachment under the BSC SEI optics table.

Local signals are generated and fed to actuators to damp solid body motions of the suspension components; in addition, control signals generated by the interferometer sensing/control (ISC) are received and turned into forces on the test mass to obtain and maintain the operational lengths and angular orientation.

There are two variants of the test mass suspension: one for the ETM which carries potentially non-transmissive actuators behind the optic, and one for the ITM which must leave the input beam free to couple into the Fabry-Perot arm cavity.

2.2 Product Functions

The suspension system must fulfill the following general functions:

- Optimize the thermal noise performance of the suspension and test mass given the material properties of those components
- Provide vibration isolation in conjunction with the isolation subsystem
- Provide a mechanical and functional interface with the isolation system
- Provide a mechanical and functional interface with the core optics system
- Provide sensors and actuation for local damping, suitable to maintain the total motion of the test mass or optics component within a level required for lock acquisition and normal operation. This must be considered in conjunction with the isolation and global control actuators. Control noise levels must lie below the target prescribed noise levels.
- Provide suitable actuation for global control, in conjunction with the isolation subsystem.
- Provide support for the test mass in a way which does not impair the functioning of the optical interferometer, either by occulting the light, causing stray reflections, or by responding to stray light.

2.3 Assumptions and Dependencies

The internal thermal noise calculation depends upon the spot size on the mirror. The working value is 6 cm w_0 for both ITM and ETM.

All thermal noise calculations depend on the test mass size and material. We assume a sapphire test mass with dimensions: $m = 40$ kg, diameter = 31.4 cm, thickness = 13 cm. If fused silica is instead chosen for the test mass some requirements will need revision.

3 Requirements

3.1 Introduction

The practical procedure for determining the requirements for the suspension is as follows; some iteration is of course performed.

1. Parameterized models for the thermal noise performance of the suspension fibers and of the target test mass materials are made
2. Coarse mechanical (e.g., height) and electronic (e.g., damping system noise) limitations are determined
3. Best-guess parameters are inserted and a first cut at the range of performance and trades involved are generated
4. System trades are performed: The resulting performance curves are compared with other noise sources and with potential sources of signals, and the technical risk and cost are weighed
5. Requirements for the thermal noise performance and test mass material and size are established by the systems group and given to the suspensions group
6. The suspension subsystem group determines the mechanical and electrical design, and delivers the suspension isolation and actuator specification to systems where it is passed on to seismic isolation (i.e., the suspension design takes precedence in determining the isolation available).

The process is presently roughly at step 3 above. There are several top-level system trades to be performed which have great impact on the suspension design, and the choice of fibers or ribbons, and detailed requirements or anticipated specifications will have to await their resolution:

- Choice of test mass material and dimensions
- Choice of lower-frequency limit of observation band
- Optical noise in the range 10-50 Hz.

3.2 Characteristics

3.2.1 Performance Characteristics

The following values appear to be possible using known materials performing consistent with measured parameter values and present best models for this application.

3.2.1.1 Noise performance

Table 1: Noise performance requirements

Parameter	Value	Discussion
Longitudinal thermal noise due to test mass internal modes	5×10^{-20} m/√Hz at 10 Hz, falling roughly as 1/f	Figure 1; see section 3.2.1.1.1.

Longitudinal thermal noise due to pendulum motion	10^{-19} m/√Hz at 10 Hz, falling roughly as $(1/f)^2$	
Pitch thermal noise	4×10^{-17} rad/√Hz at 10 Hz, falling roughly as $(1/f)^2$	Requirement driven by offset of beam from center of mirror
Yaw thermal noise	4×10^{-17} rad/√Hz at 10 Hz, falling roughly as $(1/f)^2$	Requirement driven by offset of beam from center of mirror
Vertical transverse thermal noise	10^{-16} m/√Hz at 10 Hz, falling roughly as $(1/f)^2$	Assumes vertical to longitudinal motion coupling of 10^{-3}
Horizontal transverse thermal noise	TBD	Will not be a stringent requirement; based on unknown coupling to longitudinal motion
Longitudinal technical noise	1/10 of thermal noise above lower-frequency cutoff	
Pitch technical noise	1/10 of thermal noise above lower-frequency cutoff	
Yaw technical noise	1/10 of thermal noise above lower-frequency cutoff	
Vertical transverse technical noise	1/10 of thermal noise above lower-frequency cutoff	
Horizontal transverse thermal noise	1/10 of thermal noise above lower-frequency cutoff	

3.2.1.1.1 Longitudinal displacement, internal thermal modes

The internal thermal noise performance can divided into ‘intrinsic’ and ‘extrinsic’ categories. The intrinsic sources of thermal noise derive from mechanisms which are not limited by the suspension design, such as the internal losses and thermoelastic effects in the test mass material, although the size and shape of the mass and reflected beam will influence the observed thermal noise. Intrinsic noise is an input parameter to the suspension design. The extrinsic sources of noise derive from things that are done to the test masses: polishing, coating, attachments. We require that the extrinsic sources of noise not significantly increase the thermal noise set by the intrinsic sources. The thermal noise depends on

Mechanical properties:

- material and size of the test mass (Ref: systems group)
- the best isolated measurements of the chosen test mass material (Ref: Braginsky, Saulson et al., Rowan, Willems)
- the compromise anticipated from the attachment system (Ref: Rowan, GEO)

- the compromise anticipated from the optical polishing and coating (Ref: Harry, GEO, Willems)
- any additional compromise from the actuation (Ref: Braginsky)

Optical properties:

- the optical beam size (Ref: systems group)
- the contributions from reflection from the surfaces of the optics and from transmission through the optics (Ref: Zucker, Braginsky)

Assumes sapphire mass; corresponds to 5×10^{-9} loss factor. Uses Bench version 1.7, Cagnoli's Maple thermal noise model version XXX.

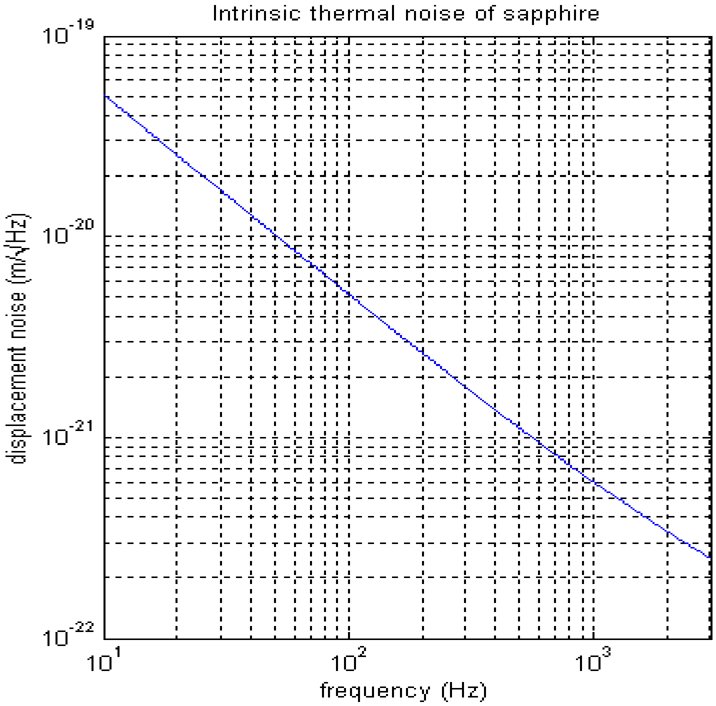

Figure 1: Intrinsic thermal noise of sapphire test mass

3.2.1.1.2 Longitudinal displacement, pendulum suspension thermal noise

The principal trade is in the choice of ribbon or cylindrical fibers. If ribbons are chosen, the aspect ratio must be determined. The performance depends upon

- Losses in fused silica (Ref: Saulson, GEO)
- Scaling with surface to volume ratio
- Scaling of unloaded vs. loaded fibers and ribbons
- Consequences of twists or transitions to cylinders in ribbons (needed to allow motion in 2 DOF) (Ref: TBD)

3.2.1.1.3 Pitch thermal noise

The energy in this mode is stored in tension in the suspension fibers (or in the twists of a ribbon) and the losses may be large. The coupling to pitch depends on the position of the optical beam; for a specific suspension design, there is a point which will give minimum coupling (Ref: Levin). The technical noise will also have a position-dependent coupling and the two optima may not be in the same place; to be considered in the technical requirements. The value of allowed angular noise is traded against the positioning accuracy; the specification quoted in the table assumes centering within 3cm. The estimates for possible performance are based on

- Material losses in fused silica (Ref: Saulson)
- Measurements on as-built systems (Ref: GEO)

3.2.1.1.4 Yaw thermal noise

The energy in this mode is largely stored in the gravitational field and thus the losses can be small. In the case of a cylindrical fiber, the optic axis model can probably be reused. In the case of the ribbon, calculations and tests will be needed. Again, the positioning of the beam is important and this requirement needs to be set along with a centering precision. However, as opposed to the case for pitch the point of minimum coupling will be at middle of the mirror. The specification quoted in the table assumes centering within 3cm.

3.2.1.1.5 Vertical transverse thermal noise

The LIGO beams are a maximum of 6×10^{-4} rad away from local vertical, making this the minimum coupling from vertical to longitudinal thermal noise. Practical experience leads to an anticipation of 10^{-3} coupling from vertical to horizontal. We require that the vertical contribution be equal or less than the longitudinal contribution, allowing 10^{3} more noise in the vertical or ~10^{6} greater loss. For the ITM, which is a transmissive optic with a vertical wedge, vertical transverse thermal noise will also couple to longitudinal noise in the short degrees of freedom (power recycling cavity, signal cavity, Michelson fringe). The requirement based on this coupling is TBD.

Additionally, the frequency of the vertical bounce mode shall be below 10Hz.

In the horizontal transverse direction, the losses of the pendulum should be comparable to those of the longitudinal direction and there is no fixed misalignment giving a minimum coupling; this requirement is based on couplings which are TBD.

3.2.1.1.6 Longitudinal displacement technical noise

We require that this be a negligible contribution in the GW band, thus 1/10 in amplitude of the thermal noise. Sources of technical noise include but are not restricted to: sensor and actuator noise, stray electric charges on the test mass or suspension, ambient magnetic field fluctuations at the magnetic actuators, and excess noise due to creep events in the suspension materials.

3.2.1.1.7 Pitch technical noise

We require that this be a negligible contribution in the GW band, thus 1/10 in amplitude of the thermal noise at the chosen beam position. The sources of technical noise listed in 3.2.1.1.6 are also relevant here.

3.2.1.1.8 Yaw technical noise

We require that this be a negligible contribution in the GW band, thus 1/10 in amplitude of the thermal noise at the chosen beam position. The sources of technical noise listed in 3.2.1.1.6 are also relevant here.

3.2.1.1.9 Transverse technical noise

We require that this be a negligible contribution in the GW band, thus 1/10 in amplitude of the thermal noise for the given transverse to longitudinal coupling. The sources of technical noise listed in 3.2.1.1.6 are also relevant here.

3.2.1.2 Seismic isolation performance

The seismic isolation will be determined by the pendulum lengths; these will be chosen to give the best thermal noise performance and to make the system mode coupling best for the damping system within the mechanical constraints. Thus, the suspension design dictates the isolation which is 'flowed up' to the Systems group. The system document will freeze the partitioning of isolation between SEI and SUS, and then SUS designs to that requirement. The test mass motion due to seismic noise will depend on numerous couplings of the six degrees of freedom of the platform motion to the six degrees of freedom of the test mass. Rather than enumerate them all we instead specify the seismic motion requirements at the test mass, given the platform noise spectrum given in the Seismic Isolation Subsystem Design Requirements Document LIGO-E990303-03-D. The seismic isolation requirements arrived at by this process are given in the following table:

Table 2: Isolation performance requirements

Longitudinal	10^{-19} m/√Hz at 10 Hz, falling faster than $(1/f)^4$	
Pitch axis	4×10^{-17} rad/√Hz at 10 Hz, falling faster than $(1/f)^4$	
Yaw axis	4×10^{-17} rad/√Hz at 10 Hz, falling faster than $(1/f)^4$	
Horizontal transverse	TBD	
Vertical transverse	10^{-16} m/√Hz at 10 Hz, falling faster than $(1/f)^4$	Assumes vertical to longitudinal motion coupling of 10^{-3}

The specified frequency rolloff of the seismic noise at the suspension is conservative and should easily be achieved by the combined SEI-SUS system. It is chosen to guarantee that seismic noise falls off much more rapidly with frequency than thermal noise.

3.2.1.3 Control performance

The control performance requirements, broadly stated, are that the suspension be capable of acquiring lock as part of a globally controlled advanced LIGO configuration, with the arm cavity powers and dynamic characteristics appropriate for the laser powers and arm cavity finesses set by the systems group, and that with the SEI it should provide sufficient dynamic range and bandwidth to control the locked interferometer during operation. The SEI will provide large actuation range at low frequency (≤100mHz).

The local damping shall reduce the Q of all body modes to less than 10.

All DOF sensors and all DOF actuators are to be accessible to the suspension control system, with the potential of frequency-dependent cross-coupling terms.

The control (and entire) system will perform correctly for angles the mounting table of up to 100 microrad (TBR).

3.2.2 Interface Requirements

3.2.2.1 Interfaces to other LIGO detector subsystems

3.2.2.1.1 Mechanical Interfaces

3.2.2.1.1.1 Auxiliary Optics

SUS will receive requirements from AOS for points of attachment on the suspension ‘cage’ for light baffles.

3.2.2.1.1.2 Core Optics

The dimensions of the optics are the primary interface between COC and SUS. This includes any wedges in the optics and all flat surfaces polished into the optics for attachments to the suspension. These dimensions are partially specified by SUS with respect to thermal noise and attachment needs, and partially by COC. Flatness and polish requirements for the attachment surfaces will be given to COC by SUS and are not specified here.

SUS will also give requirements to COC for thermal noise introduced by the test mass surface polish and mirror coatings; these requirements are not specified here. Coatings required for actuation (e.g. an electrostatic drive) are part of the SUS design.

3.2.2.1.1.3 Seismic Isolation

The suspension should be capable of attachment to the SEI platform via the bolt holes provided therein. The weight of the suspension combined with any other suspensions, auxiliary optics, and counterweights that share the same SEI platform must not exceed the 800kg limit set by the SEI design. This requirement will be pushed hardest by the combination of ITM and FM suspensions in the 2K IFO.

The moments of inertia of the suspension will be given to SEI as a design parameter.

The suspension cabling should have provision for attachment to the SEI platform.

3.2.2.1.2 Electrical Interfaces

3.2.2.1.2.1 AOS

SUS will give requirements to AOS for the bandwidth and dynamic range of the photon drive actuator. These requirements are not yet specified here.

3.2.2.1.2.2 Core Optics

Any grounding of core optics will be through cabling attached to the suspension chain.

3.2.2.1.2.3 Seismic Isolation

All electrical cabling from the suspension to outside the vacuum envelope will anchor to the SEI platform.

See also section 3.2.2.3.1.

3.2.2.1.3 Optical Interfaces

3.2.2.1.3.1 AOS

The suspension will provide a clear aperture for any IFO laser paths, including any wedge and ghost beams reflecting from the optics. It will also provide clear apertures for the photon actuator and optical lever beams. The local sensors will not be susceptible to light from the photon actuator or optical lever at a level that would disrupt control or introduce technical noise above the levels specified.

Scatter from the suspension frame surfaces is not expected to be a significant source of noise in the detector and so no requirements are made on their reflectivity or perpendicularity.

3.2.2.1.3.2 Core Optics

The suspension will not obstruct the main IFO beam. The ETM reaction mass may partially obstruct any transmitted monitor field at a level that is TBD; the ITM reaction mass, if any, must not introduce reflective or diffractive loss above the levels of losses elsewhere in the short cavities of the IFO.

The local sensors will not be susceptible to light from the IFO at a level that would disrupt control or introduce technical noise above the levels specified.

3.2.2.2 Interfaces external to LIGO detector subsystems

The suspensions for the 2K IFO shall not obstruct the 4K IFO beams.

3.2.2.3 Induced Electromagnetic Radiation

3.2.2.3.1 Magnetic fields emitted

The magnetic motors shall not generate fields that will compromise the seismic isolation system sensors (which are coil-and-magnet technology).

3.2.2.3.2 Magnetic field susceptibility

The magnetic environment must be such that the induced motion in the highest suspension stage carrying permanent magnets is significantly smaller than the residual seismic motion without the fields. The seismic isolation system actuators generate fields.

3.3 Precedence

Those requirements relating to thermal noise have the highest priority. Compromises in the seismic isolation or the actuation can be more probably compensated in other subsystems.