LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

- LIGO -

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Document Type	**LIGO-T960074-05 -**	**D**	May. 23, 96

Suspension Preliminary Design

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Distribution of this draft:

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1 INTRODUCTION

1.1. Purpose and Scope

This document:

- provides a preliminary design of the suspension mechanical system,
- describes a framework, a sample conceptual design, and critical requirements of the SUS control system, and
- demonstrates by analysis and experience that the preliminary design and the sample conceptual design meet the SUS design requirements.

1.2. Acronyms

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

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

1.3. Applicable Documents

1.3.1. LIGO Documents

[1] LIGO-1401051 Rev. B: LIGO DETECTOR Construction Phase Implementation Plan
[2] LIGO-T950011-08-D: Suspension Design Requirements
[3] LIGO-E950099-01-D: Core Optics Components Requirements (1064 nm)
[4] LIGO-T960040-00-D: Response of Pendulum to Motion of Suspension Point
[5] LIGO-P950006-00-I: Thermal Noise in the Initial LIGO Interferometer
[6] LIGO-T960081-00-D: Pendulum Thermal Noise: Pendulum and Pitch Mode
[7] LIGO-P940011-00-R: Suspension Losses in the Pendula of Laser Interferometer Gravitational-Wave Detector
[8] LIGO-P930001-00-R: Thermal Noise in the Test Mass Suspensions of a Laser Interferometer Gravitational-Wave Detector Prototype
[9] LIGO-T960076-00-D: Estimate of the Effect of Scattered Light on the Suspension Sensor

1.3.2. Non-LIGO Documents

2 GENERAL DESCRIPTION

2.1. Design Requirements

The preliminary design of the suspension system (SUS) must meet the SUS requirements described in[2] LIGO-T950011-08-D: Suspension Design Requirements.

2.2. Design Philosophy

The following design philosophy are considered for the preliminary design:

- Reliability
- Simplicity
- Tractability
- Safety
- As little excess noise as possible

2.3. Design Type

There are three types of the suspension design depending on the size of the suspended optical component: LOS 1, LOS 2, and SOS. However preliminary designs for only LOS1 and SOS are provided in this document because the size of the beam splitter (accommodated in LOS2) is still **TBD** (See [3] LIGO-E950099-01-D: Core Optics Components Requirements (1064 nm)). Besides the final design of LOS2 will be very similar to that of LOS1 except for the size of the suspension assembly.

2.4. Assumptions

The assumed size for the suspended components is listed in Table 1. Although wedge angles for test masses and mode cleaner mirrors are still **TBD**, they are assumed plausibly to make the design possible and consistent.

Table 1: Size and optical clear aperture of suspended components.

Physical Quantity	*LOS1*	*SOS*
Diameter	25 cm	7.62 cm
Thickness	10 cm	2.54cm

Table 1: Size and optical clear aperture of suspended components.

Physical Quantity	*LOS1*	*SOS*
Weight	10.7kg	0.25 kg
Optical Clear Aperture	24 cm (Fore) 19 cm (Back)	2 cm
Wedge Angle	3° vertical thick side up	0° horizontal

3 PRELIMINARY DESIGN OF SUS MECHANICAL SYSTEM

3.1. Design Overview

A preliminary design of the suspension assembly is schematically illustrated in Fig. 1. General features of the design are:

- The suspension assembly is held together by a suspension support structure.
- The optical component is suspended by a single loop of wire from a suspension block (and a wire guide crescent for LOS1) with wire standoffs and guide rods between the suspension wire and the component.
- The optical component is damped and actuated by sensor/actuator heads and magnet/standoff assemblies.
- The optical component is protected during operation or held during transfer by a safety cage and safety stops.
- The suspension support structure is strengthened by stiffening bars to increase its resonance frequencies.

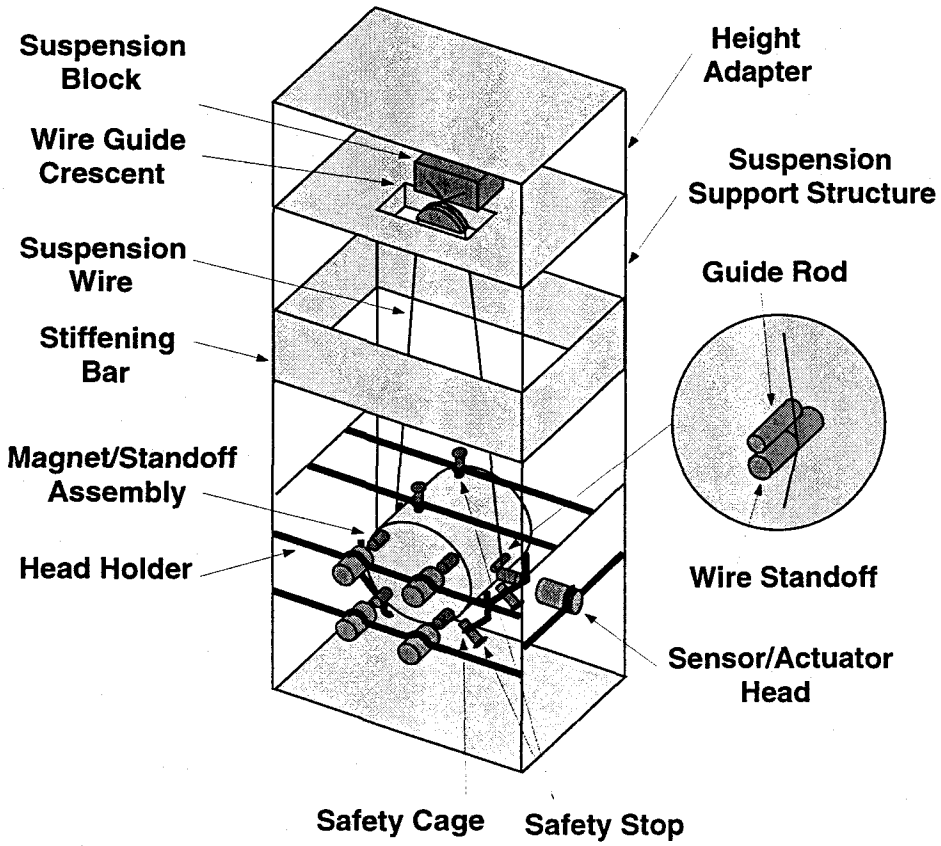

Figure 1: Schematic illustration of the preliminary design of the suspension system.

3.2. Suspension Configuration

A single loop of wire suspends the optical component. A sketch of the configuration of a suspended component is given in Fig. 2. The important design parameters of this single loop suspension are:

- Length of the pendulum ($d_{pendulum}$ in Fig. 2)
- Vertical deviation of the center of mass from the center of cylinder due to wedge of the optical component (d_{CM})
- Distance between the two suspension points at the upper release points (d_{yaw})
- Height from a horizontal level through the center of cylinder to the wire release points (d_{pitch})
- Diameter of the wire standoff ($d_{standoff}$)
- Minimum distance between the wire and the optical component above the wire release points (d_{margin})

These parameters are chosen to satisfy the desired pendulum, pitch, and yaw frequency for non-vanishing d_{margin} as shown in Table 2. (See Appendix A for detail.)

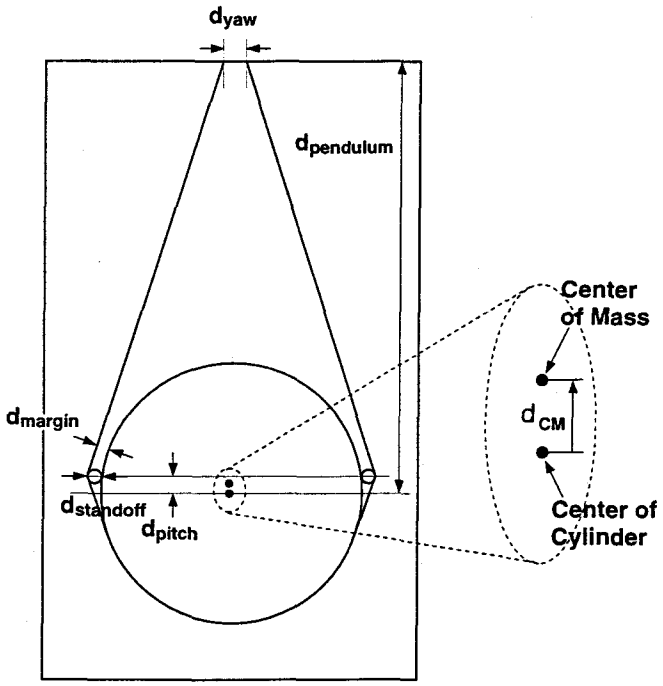

Figure 2: Sketch of the suspension configuration with the definition of parameters.

Table 2: Suspension configuration parameters

Physical Quantity	*Specification*	
	LOS 1 (TM)	*SOS (MC mirror)*
Pendulum Frequency	0.74 Hz	1.0 Hz
Pitch Frequency	0.6 Hz	0.85 Hz
Yaw Frequency	0.5 Hz	0.75 Hz
$d_{pendulum}$	45 cm	24.8 cm
d_{CM}	2.0 mm	0 mm
d_{pitch}	8.9 mm	0.9 mm
d_{yaw}	33.5 mm	15.7 mm
$d_{standoff}$	2.8 mm	1.0 mmD
d_{margin}	1.1 mm	0.8 mm

3.3. Design Detail

The SUS components are listed in Table 3. for SOS and for LOS1.

Table 3: SUS components for SOS.

Name	*Description*	*Drawing Number*
Suspension Block [Top Plate]	Guide and support suspension wire	D960003
Magnet	Neo-35, 2mm dia x 3mm long	D960501, Ref
Sensor/Actuator Head Assembly	Registers position of magnet on optic and damps optic's movement when required.	D960011
Standoff	alum, 1mm dia x 2.2mm long	D960010
Head Holder	Position and hold sensor/actuator head assemblies.	D960002
Suspension Fiber	Holds the optic. 0.012" dia steel music wire.	

Table 3: SUS components for SOS.

Name	*Description*	*Drawing Number*
Wire Standoff	Provides line contacts between optic and suspension wire.	1205184-1
Guide Rod	Positions wire standoff.	1205184-2
Safety Cage	Assorted brackets that position the safety stops.	D960007 D960008-1 D960008-2 D960002
Safety Stop	Assorted teflon screws that act as bumpers or supports for the optic	commercial items 1205311-1

Table 4: SUS components for LOS1.

Name	*Description*	*Drawing Number*
Suspension Support Structure	A welded structure that holds and protects the optic.	D960133
Suspension Block	Guides and supports suspension wire	D960144
Wire Guide Crescent	Welded in wire guide that provides line contacts for the wire to the top plate.	D960135
Sensor/Actuator Head Assembly	Registers position of magnet on optic and damps optic's movement when required.	D960011
Magnet	Neo-35, 2mm dia x 3mm long	D960501
Head Holder	Various brackets that position and hold the sensor/actuator head assemblies.	D960136 D960137 D960141
Suspension Fiber	.012" dia steel music wire	
Wire Standoff	Provides line contacts between optic and suspension wire.	D960755

Table 4: SUS components for LOS1.

Name	*Description*	*Drawing Number*
Guide Rod	Positions wire standoff.	D960146
Safety Cage	Assorted brackets that position the safety stops.	D960138 D960139 D960140 D960142 D960143
Safety Stop	Assorted teflon screws that act as bumpers or supports for the optic	commercial items D960499

3.3.1. Suspension Support Structure

The suspension assembly has a modular support structure. The optical component is suspended from the suspension block (and the wire guide crescent for LOS1), which is fixed to the top plate of the support structure. The sensor/actuator heads and the safety cage are also attached to the support structure. The advantage of this modular support structure is that the system can be assembled and adjusted (including balancing the test mass/mirror in pitch) on a clean bench and then can be transferred into the tank without changing the relative position between the optical component and the sensor/actuator head.

For LOS1 the suspension support structure, the stiffening bars, the safety cage, and the wire guide crescent are all welded together to eliminate excess noise. SOS uses bolts to assemble them.

The legs of the suspension support structure for LOS1 is hollow to satisfy the requirement for the resonance frequency of the structure.

Dimensions:

- LOS1: length 44.5 cm x depth 26.7 cm x height 61.6 cm
- SOS: length 15.6 cm x depth 12.7 cm x height 41.7 cm

3.3.2. Suspension Block and Wire Guide Crescent

A suspension block for SOS is used to position the wire such that it complies with the d_{yaw} (defined in 3.2.3.) requirement. It is mounted to the top of the suspension support structure. Two dowel pins, press fit into the block, guide the wire into its proper position.The wire is then held in place with a clamp.

The LOS1 suspension support structure has a crescent shaped wire guide welded into a hole in the top plate, below the area where the suspension block mounts. As an alternative to the suspension block/clamp means of holding the wire, the crescent may be used, along with a suitable solder, to position and support the wire. The crescent has the same groove, or wire guide, machined into it

as the wire standoff, discussed later. This groove assures line contacts between the wire and the crescent.

3.3.3. Sensor/Actuator Head

The position sensor for a suspended component is a simple edge sensor, which consists of an LED paired with a photodiode, which senses the shadow of a magnet/standoff assembly attached to the component. The force/torque actuator is a fixed coil which drives the magnet attached to the suspended component. The system is illustrated in Fig. 3. The sensor/actuator head is placed so that approximately half the light from the LED is blocked by the magnet. The sensor detects the position of the magnet as the change in the photocurrent. The preamplifier for the sensor is external to the vacuum system.

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

- LED: TLN107A, Toshiba, no outgas was observed after being baked at 70°C.
- PD: TPS703A, Toshiba, no outgas was observed after being baked at 70°C.
  - Distance between PD and LED: 6 mm
- Coil
  - Wire size: **TBD**
  - Coil size: 7.66 mmID, 12.66 mmOD, 5 mmL
- Housing
  - Material: Macor[1]
  - Size: 25.3 mmOD x 25.4 mmL
  - Wire clamp: Wires wrapped around a screw which is threaded into back of the head housing.

1. Machinable glass ceramic: manufactured by Corning.

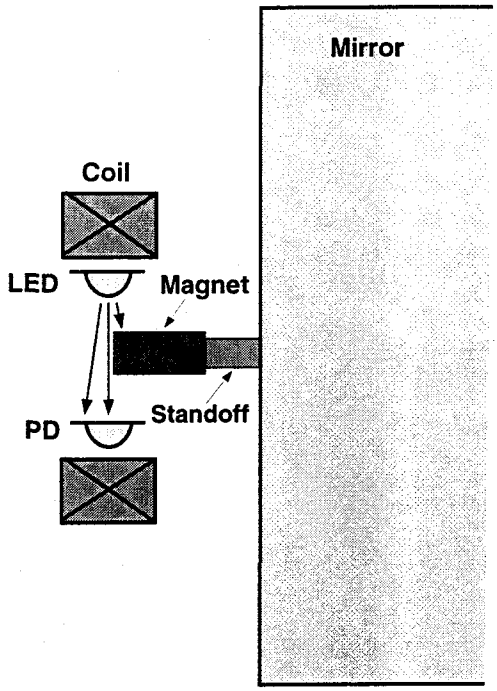

Figure 3: Sensor and actuator

3.3.4. Magnet/Standoff Assembly

The magnet and standoff are bonded into a single assembly which is then epoxied to the suspended component (See Fig. 3).

Six magnet/standoff assemblies are attached on the test mass: four on the back surface and two on the side surface of the test mass. The magnets are placed so that polarity of the magnets is located alternately to prevent the mass from being shaken in position and orientation by time-varying magnetic field.

- Magnet
  - Material: Nd:Fe:B (NEO, Curie temperature 337°C)
  - Dimensions: 1.9 mmD x 3.2 mmL (0.075"D x 0.125"L) for SOS and LOS1
- Standoff
  - Material: aluminum
  - Dimensions: 1.0 mmD x 2.0 mmL (0.04"D x 0.08"L) for SOS and LOS1 except for side standoffs on the LOS1 which are 1.0 mmD x 3.2 mmL (0.04"D x 0.13"L).

3.3.5. Head Holder

The head holders are mounted (for SOS) or welded (for LOS1) on the suspension support structure. The head holder has a hole with machined line contacts and a set screw for the sensor/actuator head so that the sensor/actuator head can be placed and fixed properly without changing its position. The head holder, which is made of stainless, is located far enough from the magnets on the test mass so that the thermal noise caused by the eddy current damping is negligible. The loop of the holder is cut for LOS1 for the same reason.

Minimum distance between the head holder and the magnet[1]:

- 13.9 mm for LOS1
- 15.6 mm for SOS

3.3.6. Suspension Fiber

Steel music wire is used as the suspension fiber material. The diameter of the wire is chosen so that the wire will be loaded to one-half its breakage stress, to obtain the lowest possible wire losses and the smallest number of violin modes in the gravitational-wave signal band, without incurring undue risks due to wire failure or the production of excess non-gaussian noise (through acoustic emission from the loaded wire).[2]

A single loop wire is used.

- Type: Steel music wire
- Density: 7.8 g/cm^3
- Diameter: 0.044 mm for SOS
  0.31 mm for LOS1
- Ultimate Tensile Strength: 0.5 kg for SOS
  21.4 kg for LOS1
- Yield Strength: 75% of Ultimate Tensile Strength
- Violin Mode Frequency: 660 Hz for SOS
  340 Hz for LOS1
- Vertical Frequency: 16 Hz for SOS
  13 Hz for LOS1

1. 13.7 mm for the PNI suspension
2. It should be noted that tests of other fiber materials are intended as part of ongoing R&D and will likely result in a material that has better thermal noise properties and a more stable surface finish. Because of the importance of non-gaussian noise to the overall detector performance, any contemplated replacement for steel music wire should be thoroughly characterized for evidence of acoustic emission prior to its use in LIGO.

3.3.7. Wire Standoff and Guide Rod

Small quartz rods will be used as standoffs where the wire contacts to the suspended component, as shown in Fig. 4. Each rod has a groove in it so that the wire may be repeatedly placed in the same position, which assures the stable balancing of the suspended component. Smaller aluminum guide rods are used for aligning the grooved rod to balance the pitch orientation of the component.

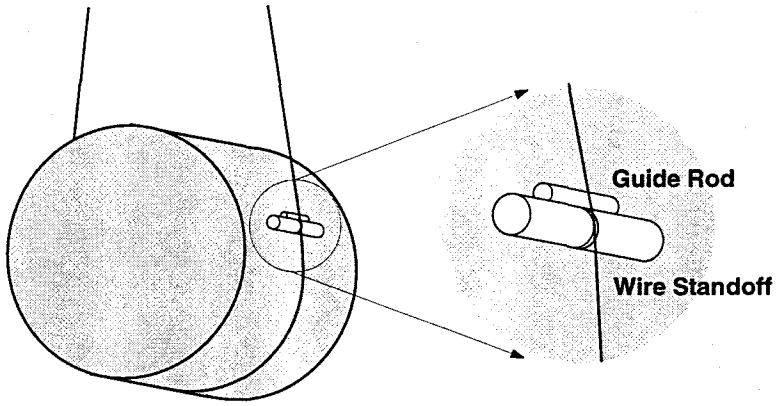

Figure 4: Details of wire standoff attachment

3.3.8. Safety Cage and Safety Stop

The motion of the optical component is restrained within +/- 1 mm by a safety stop mounted on a safety cage to protect the component from large motion. The safety cage is also used to hold the suspended component during installation after it is assembled and balanced on a clean table.

3.3.9. Stray Light Shield

TBD

3.3.10. Glue

Vacseal **TBD** is used for gluing.

3.4. Fixtures

There are a number of fixtures or tools required to mount and align components. The list of them is shown in Table 5.

Table 5: Fixtures and tools required for the SUS system.

Name of Fixture	*Description*	*Drawing Number*
Magnet-to-Standoff Fixture	Bonding standoff to magnet	P/N D960500
Magnet/Standoff Assembly Fixture	Bonding magnet/standoff assemblies to face of optic.	P/N D960050 for LOS1 P/N D960020 for SOS
Kapton Template	Protecting optical coatings when using Magnet/Standoff Assembly Fixture	P/N D960762 for LOS1 P/N D960021 for SOS
Guide Rod Fixture	Positioning and bonding guide rods and side magnet/standoff assemblies	P/N D960147 for LOS1 P/N D960022 for SOS
LED Fixture	Positioning and mounting LED relative to photodiode in the sensor/actuator head	P/N D950126
Dummy Mass	Used for the prototype test.	P/N D960763 for LOS1, 3 deg wedge P/N D960159 for SOS, no wedge
PZT Buzzer	Used for sliding the wire standoff for the pitch balance of the optic.	Existing
Wire & Optics Fixture	Positioning the wire, protecting and moving the optic into position in the LOS1 suspension support structure.	P/N D960753
Lifting Fixture	Transferring and mounting the LOS1 suspension assembly into the tank.	P/N D960761
Electronic Leveler	Leveling optical benches where the optic is balanced.	Commercial Product
Optical Lever Leveler	Balancing the optic on the optical bench.	P/N D960752

3.4.1. Magnet-to-Standoff Fixture

A magnet-to-standoff fixture is used to bond the standoffs to the magnets. This fixture has an epoxy reservoir to control the bond fillet and assure repeatability and alignment.

3.4.2. Magnet/Standoff Assembly Fixture

A magnet/standoff assembly fixture is used to bond the magnet/standoff assemblies to the face of the test mass/mirror. This fixture tightly controls the positioning of the magnet/standoff array. A Kapton template is used to protect the coating of the test mass/mirror.

3.4.3. Guide Rod Fixture

A guide rod fixture allows for positioning and epoxying the guide rods and the side magnet/standoff assemblies to the side of the test mass/mirror. A separate fixture assembly is required for each different wedge. The position of the guide rod is tightly controlled because of it's relationship to the d_{pitch} parameter.

3.4.4. LED Fixture

The relative position of the LED to the photodiode in the sensor/actuator head is controlled by a LED fixture. The LED is mounted into the fixture, the fixture is positioned into the hole in the sensor/actuator head then the LED is bonded to the sensor/actuator head.

3.4.5. Dummy Mass

Each of the different optics has an aluminum dummy mass associated with it that has the same mass and the same center of mass. As they are much less fragile and expensive, these dummy masses are used in the prototype test for assembling the suspensions and using the fixtures.

3.4.6. PZT Buzzer

A PZT buzzer is used to slide the wire standoff by an extremely small amount for the pitch balance of the optic.

3.4.7. Wire & Optics Fixture

Because of its size and weight, the LOS1 requires a fixture assembly to move the optic into position inside of the safety cage. Many of the parts of this assembly are Teflon to protect the optical surfaces. The optic is moved from its container to a Teflon cradle in an upright position. There is a V-groove in the cradle to place the suspension wire in before moving the optic onto the cradle. The V-groove will help maintain the proper position for the wire during the suspending process. Two metal upright brackets are mounted onto the cradle fixture in front and behind the optic, but not touching it. Above the optic, and mounted to the metal brackets, is a Teflon strap that does not come in contact with the optic but will not allow it to tip. The fixture assembly also includes a

metal plate that is the same thickness as the base plate of the suspension structure assembly. The metal plate, cradle fixture, optic, wire, brackets and strap are all assembled next to the suspension structure so that the cradle fixture and all that is mounted to it can be slid along the top of the base plate of the suspension structure and correctly positioned.

3.4.8. Lifting Fixture

Again, because of its weight, the LOS1 has a lifting fixture to move it from one location to another, especially from a clean bench to inside the vacuum tank. The fixture bolts to the underside of the suspension support structure or the underside of the height adapter, whichever is needed. This fixture is aluminum and may be baked for cleanliness. The fixture bolts to an adapter plate on a forklift or hoist.

3.4.9. Electronic Leveler

An electronic leveler is used to level the optical table where the optic is to be balanced.

3.4.10. Optical Lever Leveler

An optical lever leveler consists of a HeNe laser beam and a quadrant photodetector. The optic is balanced in pitch with the help of this system on the leveled optical bench.

3.5. installation

3.5.1. Installation Type

The suspension assembly is mounted to the optics platform with a height adapter (for the BSC chamber) or directly (for the HAM chamber) as shown in Table 6.

Table 6: Suspension assembly installation type.

Suspension Type	LOS 1/LOS 2	LOS 1	SOS
Chamber Type	BSC	HAM	HAM
Installation