LIGO Laboratory / LIGO Scientific Collaboration

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# TRANSMISSION MONITOR TELESCOPE SUSPENSION (TMS) FINAL DESIGN

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## TABLE OF FIGURES:

# 1 INTRODUCTION

The purpose of this document is to present the Final Design of the TRANSMISSION MONITOR SUSPENSION (TMS) D0900419

## 1.1 SCOPE

This Document will show, System Requirements, Design Approach, Assembly Procedures and the Location of System Interfaces with the BSC chambers. The Transmission Monitor Suspension ( TMS ) Meets applicable aLIGO Design and Material specifications. This document references alignment and installation procedures, also to the First Article (FA) testing and manufacture.

## 1.2 PURPOSE OF THE TMS

- Collects 1064 nm light transmitting through ETM and provides it for Interferometer Sensing and Control
- Mode matches 532 nm light for Arm Length Stabilization
- Provides input for intermittent Hartmann monitoring system
- Transmits any residual 1064 nm radiation to a beam dump

The **TRANSMISSION MONITOR SUSPENSION** (TMS) is an in-vacuum component that is located behind the ETM (End Test Mass) and is mounted to the BSC ISI platform. The TMS Telescope is a reference for beam location and receives the laser beam transmitted through the ETM This beam can be used for interferometer sensing and control. (FIG 1) The TMS is also used in the opposite direction, for injection of the green laser beam used in the Arm Length Stabilization (ALS) scheme. Finally, the TMS also accommodates probe beams for the Hartmann sensor that monitors the curvature of the ETM.

The TMS assembly consists of an optics platform, a suspension for that platform, a beam reducing telescope, and various opto-mechanical and opto-electronic components for beam detection and control. The assembly is split between AOS and ISC, as follows:

### 1.3 GROUP TASK RESPONSIBILITY

| | |
|---|---|
| • Optics platform (Table): | AOS |
| • Suspension: | AOS |
| • Beam reducing telescope: | AOS |
| • Injection and retrieval of primary and reference Hartmann beams: | ISC |
| • Post-telescope optics and electronics for 1064 nm beam detection: | ISC |
| • Pre-telescope optics and electronics for ALS 532 nm beam injection: | ISC |

TRANSMISSION MONITOR SUSPENSION (TMS)

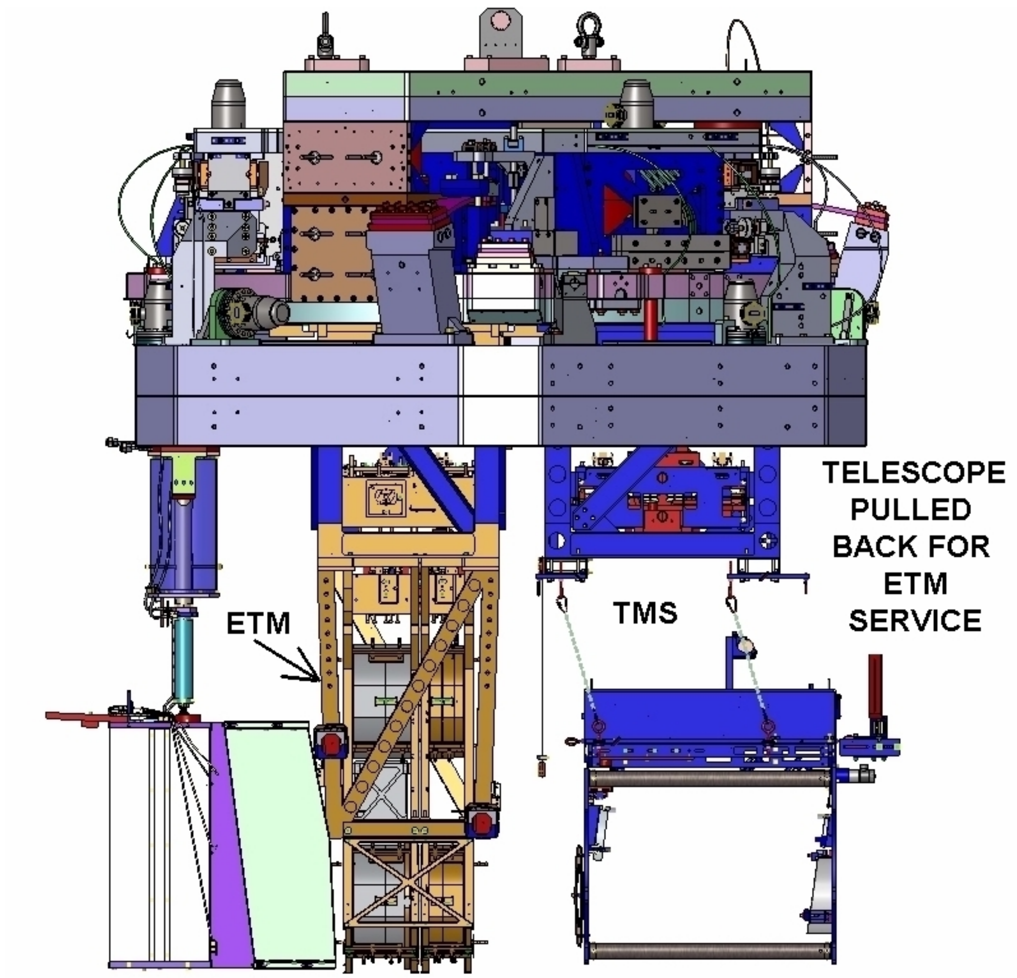


**Figure 1** Transmission Monitor Suspension (TMS) BSC6

(ETM Baffle and Table Shown)

## 1.4 LIGO REFERENCED DOCUMENTS

| | |
|---|---|
| TMS Requirements | D100265 |
| Interface Control Document | E1000222 |
| TMS Interface in BSC9 & 10 (H1), BSC5 & 6 (H2) | E1000501 |

**ASSEMBLIES**

| | | |
|---|---|---|
| TMS Top Assembly | **WBSC6** | D0900419 |
| TMS Top Assembly | WBSC5 | D0900411 |

| | | |
|---|---|---|
| TMS Top Assembly | LBSC4 | D0900435 |
| TMS Top Assembly | LBSC5 | D0900436 |
| TMS Top Assembly | WBSC9 | D0902163 |
| TMS Top Assembly | WBSC10 | D0902168 |
| aLIGO AOS Transmission Monitor System Assembly | | D0901880 |
| aLIGO Upper Intermediate Mass Top Assembly | | D1000549 |
| aLIGO TMS Telescope SUS Wire Assembly | | D1101163 |
| aLIGO TMS Telescope SUS Clamp Assembly | | D1101162 |
| aLIGO TMS Telescope Assembly | | D1002460 |
| aLIGO TMS Telescope Safety Support Beam Assembly | | D1101130 |
| aLIGO Earth Quake restraint Assembly | | D1001781 |
| aLIGO TMS Vertical Safety Wire Assembly | | D1100827 |
| aLIGO TMS Upper SUS Wire Assembly | | D1101166 |
| aLIGO Intermediate Wire Clamp Assy Middle Wire | | D1000441 |
| aLIGO Intermediate Mass Top Assy with Added Mass | | D1000444 |
| aLIGO ISC Transmon Assembly | | D1000484 |
| aLIGO Intermediate Mass Top Assembly | | D1000442 |
| aLIGO TMS Telescope Frame Assembly | | D1003120 |
| aLIGO TMS Tele Secondary Mirror Mount Assembly | | D1001600 |
| aLIGO TMS Telescope F1 Mirror Mount Assembly | | D1000084 |
| aLIGO TMS Telescope F2 Mirror Mount Assembly | | D1000088 |
| aligo_ETM Tele Tube and Inserts Assembly | | D1000243 |
| aLIGO TMS Del-Tron-RS1-1-Horizontal Slide Assy | | D1001892 |
| aLIGO TMS Del-Tron-RS1-1-Vertical Slide Assy | | D1001894 |
| aLIGO TMS Del-Tron-RS1-1-FocusSlide Assy | | D1001951 |
| aLIGO TMS Flexure Secondary Mirror Mt. Assembly | | D1002210 |
| aLIGO Optics Table Top Structural Assembly | | D1001160 |
| Vibration Absorber Assembly | | D1002424 |

## DOCUMENTS AND PROCEDURES

| | |
|---|---|
| ETM Transmon Design | G0900459 |
| Calculations for TMS table sensitivity | G0900293 |
| Zemax Optical Layout | D0900446 |
| Secondary Mirror Specification | E0900349 |
| Primary Mirror Specification | E0900347 |
| Suspension Pitch and Yaw ranges | T1000268 |
| UHV cleaning and qualification procedures | E960022 |
| Materials | E960050 |
| Welding | E0900048 |
| Metals in Vacuum | E0900364 |
| Drawing requirements | E030350 |
| Supplier Quality | Q0900001 |
| Transmon SUS Telescope Alignment Procedure | T1100258 |
| The Advanced LIGO ETM transmission monitor | T0900385 |
| TMS Suspension, Characterization and Tests at CIT | T1000236 |
| ETM TransMon Telescope SUS Installation Plan | E1000097 |
| Bosem Count | E1000042 |
| aLIGO TMS Hazards Analysis | T1000311 |
| Electrical Cable Layout Drawing | C1002284 |
| Electrical Cable Length Requirements | T1100089 |
| Cable Routing Layout | D0900419 |
| Electrical Cables | D1000234<br>D1000568<br>D1000921 |
| Guide for Cable Data Base | T1000040 |
| Cable Data Base | T1000038 |
| TMS Top Mass Assembly Procedure | E1100651 |
| Transmon Procurement Specifications | T1100364 |
| Test to Characterize TMS Suspension | T1000236 |
| aLIGO BSC6 Initial Alignment Tool Layout | D1101260 |

| | |
|---|---|
| TMS Needs Date Document | M1100035 |
| TMS Custom ISC Cable | D1000568 |
| TMS / ICS Seismic to Sus Optics Pico Motor Cable | D1000921 |
| TMS Transportation/Installation and Restraint Procedure | E1100841 |

**MAJOR TOOLING**

| | |
|---|---|
| TMS Optic Table Stabilization Tooling | D1100613 |
| TMS Suspension Setup Table | D1100807 |
| TMS Telescope and Optical Table Transfer Tool | D1100908 |
| TMS Telescope Support Bridge Tool | D1101095 |
| TMS Optical Table Support Bridge Tool | D1101096 |
| TMS Telescope Assembly Balance Bridge Tool | D1101097 |
| TMS Tooling Telescope Alignment Mirror Assembly | D1101361 |
| TMS Tooling BOM | D1101064 |
| TMS Earth Quake Restraint setup gage | D1101486 |
| TMS Upper UIM wire adjustment tooling | D1101759 |

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| | |
|---|---|
| TMS Mass Budget | T1100314 |

## 1.5 ACRONYMS

| | |
|---|---|
| BSC | Beam Splitter Chamber |
| ETM | End Test Mass |
| AOS | Auxiliary Optics System (sub system) |
| ISC | Interferometer sensing and control |
| BRT | Beam Reducing Telescope |
| MTBF | Mean Time Between Failures |
| ALS | Arm Length Stabilization (green beam) |
| RODA | Record of decision agreement |
| TMS | Transmission Monitor Suspension |
| ISI | Interferometer Seismic Isolation |
| ALS | Arm Length Stabilization |

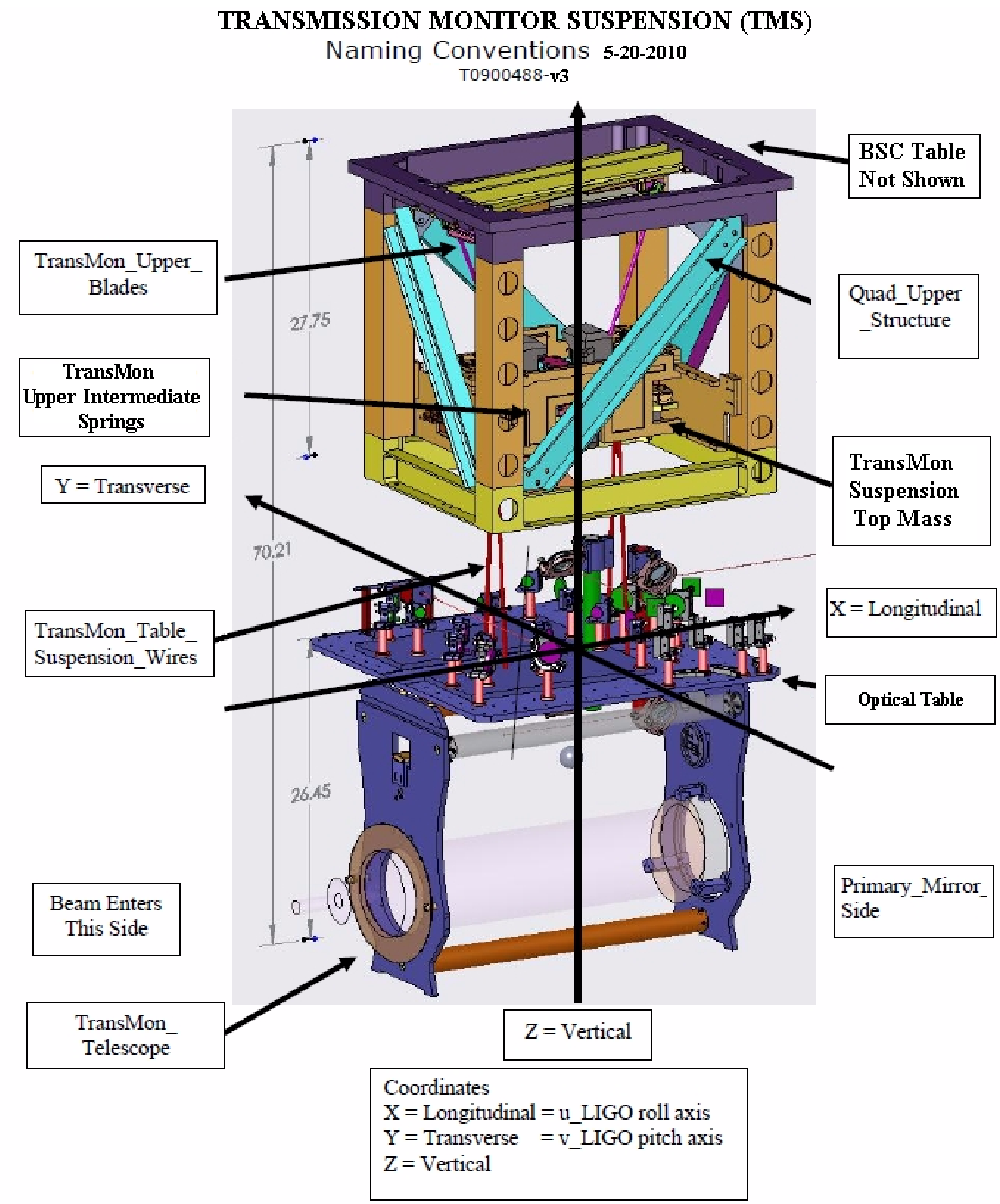


**Figure 2 Naming Conventions**

## 2 TMS DRAWING TREE E1100735

# 3 TMS CHAMBER LOCATIONS (LHO / LLO)

## 3.1 H1 & H2 AT HANFORD, L1 AT LIVINGSTON

TMS_SUS systems are installed in BSC 5/6-H2 and BSC 9/10-H1 at LHO, and in BSC 5/6-H1 at LLO.

**Interface Document** E1000501

BSC-5-H2 (Hanford Only)

BSC-6 H2 (Hanford Only)

BSC-9-H1 & L1 (Hanford and Livingston)

BSC-10-H1 & L1 (Hanford and Livingston )

### 3.1.1 Total number of Assemblies

A Total of 6 Assemblies are installed 4 at LHO, and 2 at LLO, and 1 complete spare unit built, a total of 7 systems. Each site will have a set of assembly and installation tooling, and a temporary structure (Servicing Tooling) to allow stabilization of the TMS, for servicing of the ETM. The structure will permit moving the telescope and optical table back to clear a working space between the ETM, and telescope assembly while providing slack in the suspension wires.

## 3.2 TMS Requirements Document (T0900265)

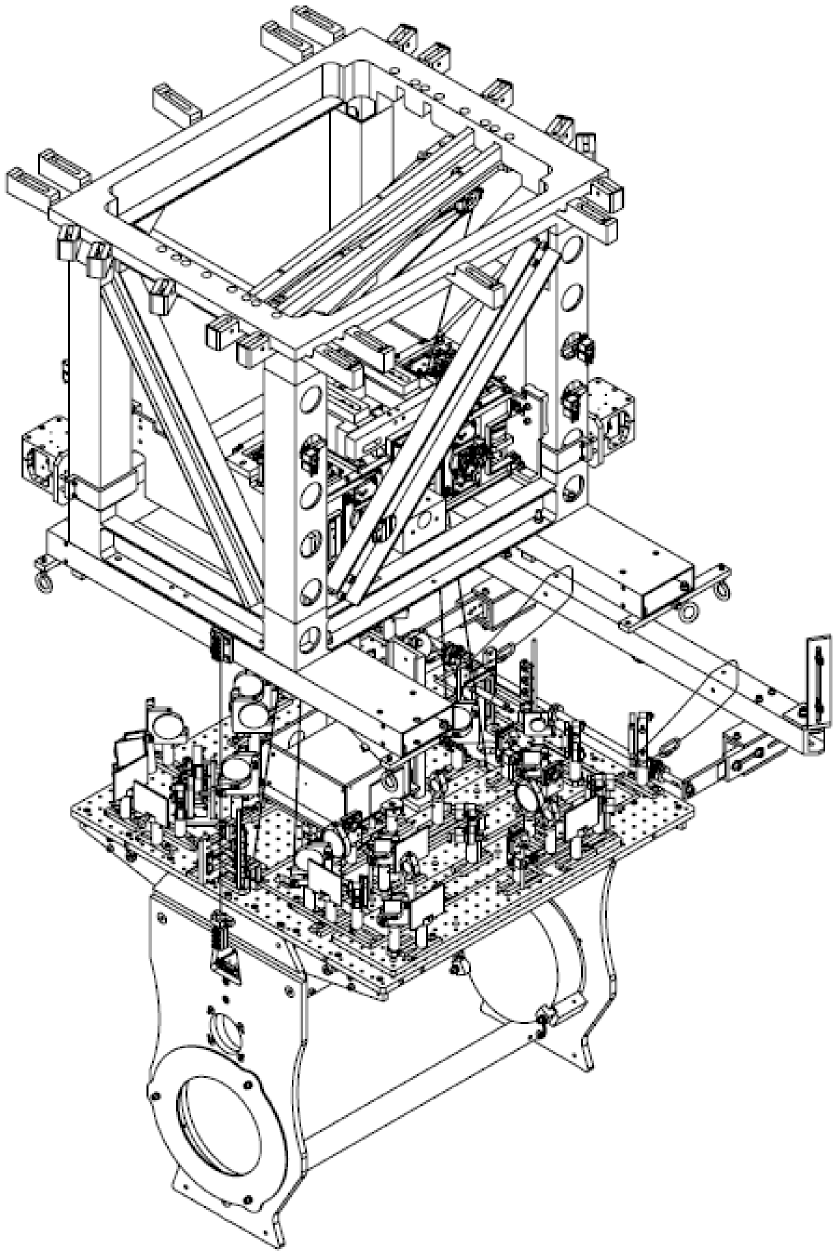

**Figure 3** TMS Top Assembly (WBSC6) D0900419

**The suspension structure top springs in the main frame have an offset that moves the frame to one side. The clearance between the TMS suspension frame and the '0' stage ring is set to .37".** E1000501 **In this arrangement the TMS suspension frame is set for maximum clearance to the ETM.**

# 4. TMS DESIGN DESCRIPTION AND SUMMARY OF REQUIREMENTS

The Major sub assemblies:

| | | |
|---|---|---|
| **a.** | **Suspension** | D1000549 |
| **b.** | **Optical table** | D1000484 |
| **c.** | **Telescope** | D1003120 |
| Interface Control Document | | E1000222 |

## 4.1 SUSPENSION D1000549

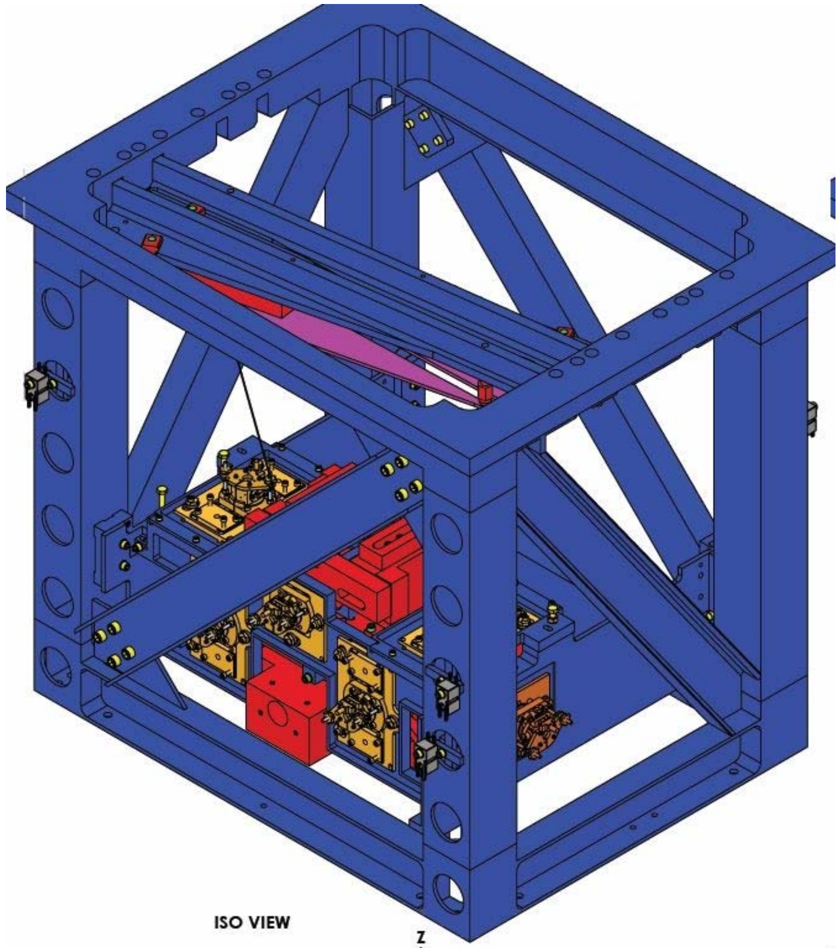


**Figure 4** Suspension Frame and Top Mass

# 5 TMS MASS BUDGET (ACTUAL AND S/W MODEL) T1100314

# 6 TMS PARTS LIST(BOM) PARTS & TOOLING E1100738

# 7 SUSPENSION AND NOISE:

6 DOF of platform are isolated

Suspension eigen-frequencies above 0.5 Hz

All rigid body modes damped to Q<10

Above 10 Hz isolation factor > 1000 all 6 DOF

Displacement noise <~3 pm/ √(Hz)]

Angular noise < ~3f rad/ √(Hz)]

Internal modes of suspension support 150 Hz or higher

At 3 Hz isolation factor >10 all DOF

The following generic requirements apply to the TMS suspension:

• All six degrees-of-freedom of the platform are to be isolated

• Suspension Eigen frequencies should be kept above 0.5 Hz, and preferably above 0.6 Hz (if possible); this is to limit excitation of the modes, since the ISI motion increases steeply below 0.6 Hz

• All rigid-body modes should be damped, to Qs of ~10 or lower

• Internal modes of the suspension support structure should be as high as possible and damped if possible; goal for lowest eigenmode: 150 Hz or higher

• Above 10 Hz: isolation factor of at least 1000, nominally in all six degrees-of-freedom.

• Factor of 10 isolation by 3 Hz (all DOF)

• Below 1 Hz: best effort at minimizing mode amplification and long-term stability; mode amplification would be best confined to the 1-1.5 Hz band, if possible

Note that according to G0900293, isolation from ISI motion is really only needed for the angular DOF, but we are specifying the isolation to apply in all DOF because typically a suspension does not give angular isolation without the displacement isolation as well. However, if a suspension design is found that provides the above isolation for the pitch and yaw DOF of the TMS platform, but not for the other DOF, it may be acceptable.

The acceptable level of TMS platform noise above 10 Hz is a few pico-meters/$Hz^{1/2}$ in displacement, and a few femto-radians/$Hz^{1/2}$ in angle (the actual level shown in the plot on slide 5 is more conservative than it needs to be, by a factor of ~2-3). The isolation requirements above are consistent with this, and these noise targets can be used to evaluate other platform noise sources.

Remote position control - Remote control of the TMS platform is not required in principal for ISC functionality. The ISC beam lines will include remotely adjustable tip-tilt mirrors to center beams on the alignment sensors. However, the trajectory of the beam delivered to the ISC beam lines by the TMS telescope must be close enough to the design value that it is within range of the ISC tip-tilt mirrors and well-within other optical apertures. This may require remote control of some degrees-of-freedom, depending on the initial alignment tolerances and estimated drift of the suspension. A suggested criterion is: let the reduced 1064 nm beam propagate an additional 1 m past the point where it enters the ISC side of the TMS table; at that point, given estimates of alignment errors and uncorrected drifts, the beam should be no more than a couple of mm away from its nominal transverse position, and no more than a mrad off its nominal propagation angle.

The position of the suspended TMS platform within the BSC chamber is a controlled interface between AOS and ISC.

# 8 CABLING AND CONNECTORS:

ELECTRICAL CABLING C1002284

The TMS suspension will have stress-relieved electrical cabling run from the ISC side of the TMS platform up to the ISI platform. This includes providing appropriate non-contact routing and special clamping points for cabling within the suspension (cabling is provided by ISC).

The connectors and cables are constructed of approved materials and be strain relieved. The construction is done with concern to the flexibility of the cable in the interface to the suspended components. OMC uses flexible wires to the table, they are the responsibility of the ISC group.

ELECTRICAL CABLE LENGTHS T1100089

ELECTRICAL CABLE ROUTING LAYOUT

ISC Table and SUS Bosem to BSC Cluster D0900419

# 9 TMS CONSTRUCTION

## 9.1 MATERIALS

We will comply with, LIGO-E960050-v4 no special material considerations using polymers approved for SUS in the same applications (e.g. Osems , wire )

## 9.2 PROCESSES

We will comply with E900048 there are no special welding considerations or other special processes required.

## 9.3 CLEANING

We will comply with E960022; there are no special cleaning considerations.

## 9.4 COMPONENT NAMING

All components shall be identified as required in E030350. 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.

## 9.5 INTERCHANGEABILITY

Interchangeability is not required in this assembly although the majority of parts are interchangeable as a result of the tight manufacturing tolerances.

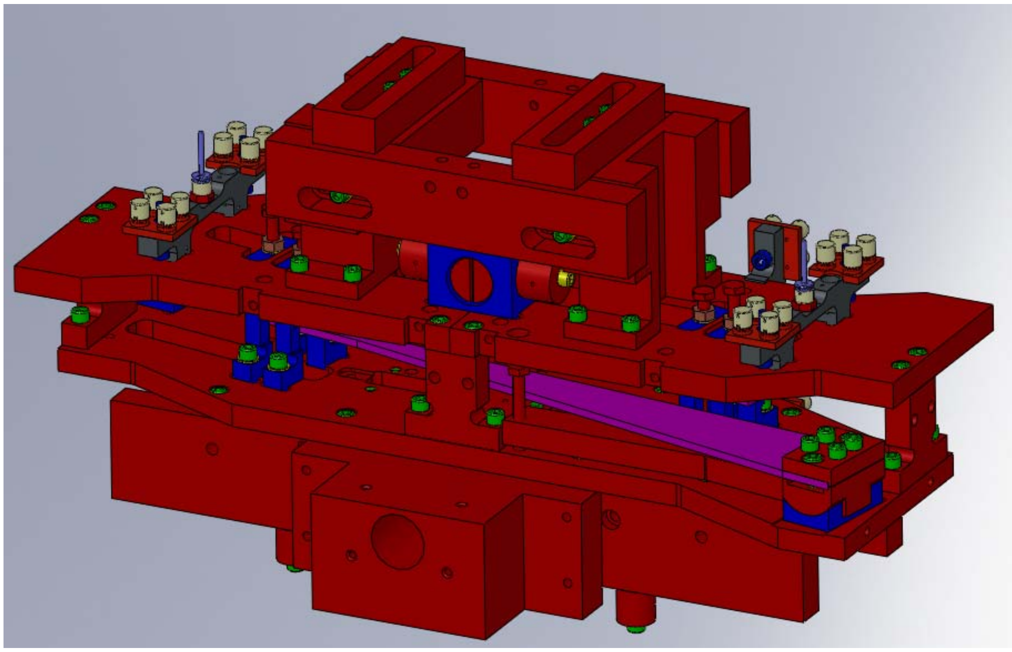

**Figure 5** TMS Top Mass 44 kg D1000444

The TMS platform is suspended from the BSC ISI platform (rather than rigidly attached) for several reasons. First, because of the large distance between the ISI platform and the beam line, a rigid structure would have unacceptable mechanical modes (too low in frequency). Second, some additional vibration isolated is desired in order to mitigate scattered light noise due to any light scattered from the TMS optics back into the arm cavity. Finally, ISC plans on putting two alignment sensors (quadrant photo-detectors) on each TMS, so that all eight alignment degrees-of-freedom (four in each plane ) of the arm cavities can be sensed by the TMS. To keep these alignment sensor signals from being spoiled by motion of the TMS itself, additional isolation beyond the ISI is needed.

The suspension and control system is similar to the Quad suspension control system. Many of the control system components are identical to the Quad system and the supported masses are similar. Utilizing a major portion of the existing Quad upper suspension and components is the preferred approach to simplify the TMS- suspension development and procurement task.

By using already proven sub-assemblies and components of the quad suspension we will save time / cost and risk.

A dynamic model of the above arrangement with the components described below predicts the control and stability of the TMS system.

## 9.6 OPTICS TABLE (OPTICS PLATFORM)

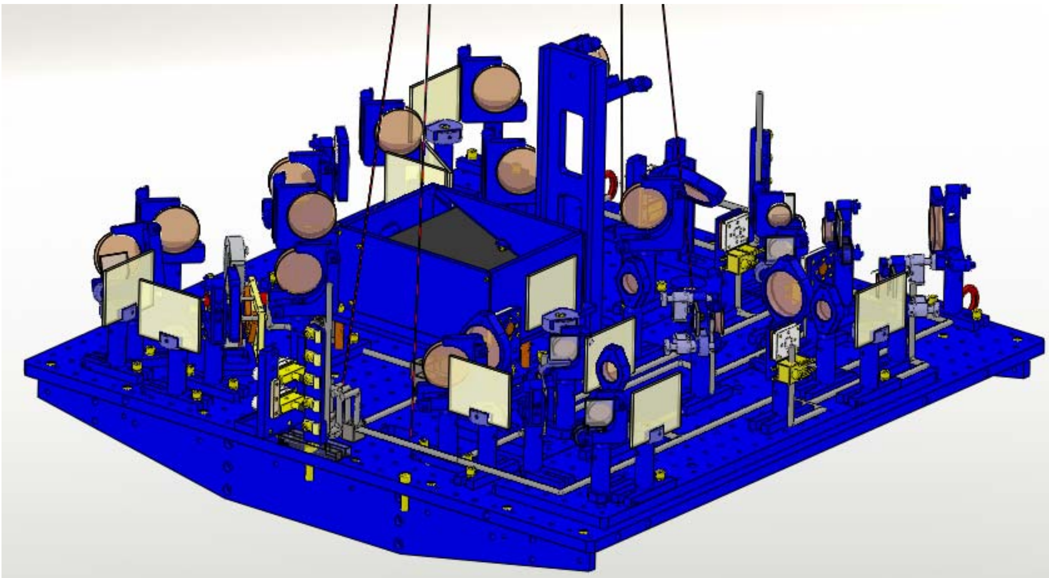

**Figure 6** Optical Table with ISC components Installed **D1000484**

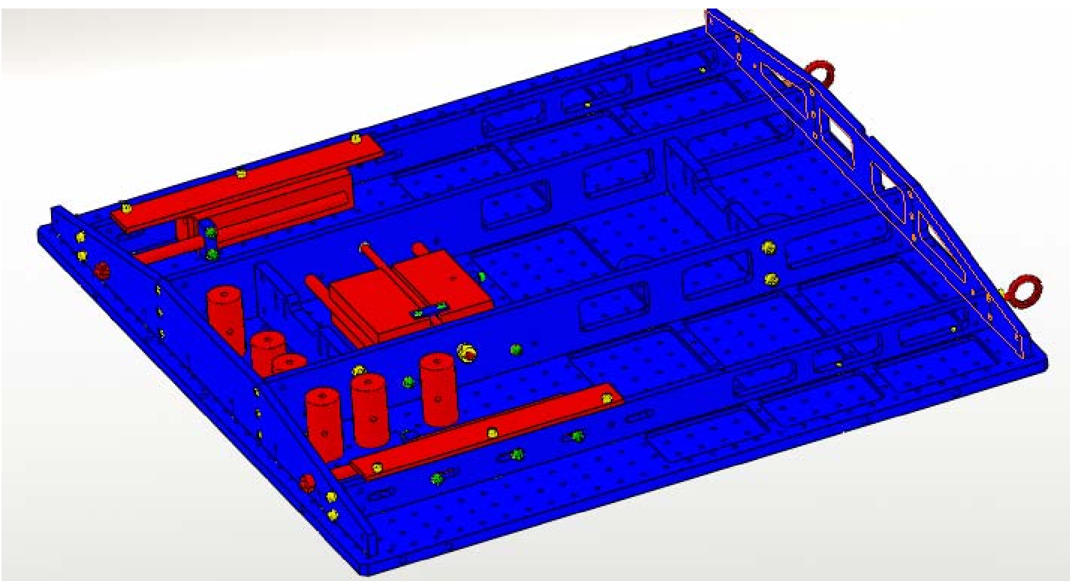

**Figure 7** Optical Table with balance masses (Bottom View) **D1001160**

**THE ISC TABLE OPTICS DESIGN AND INSTALLATION WILL BE REVIEWED SEPARATELY FROM THE TMS**

The **Optics Table** supports both the AOS beam reducing telescope and the ISC components. Discussions between AOS and ISC have led to the following design requirements for the platform:

• One side of the platform is used to mount the beam reducing telescope, and the other side is used for ISC components. Beams are directed from one side to the other through a hole in the platform.

• The nominal size of the platform working surface is 30" x 30". It can be made larger by AOS if possible (but not smaller). The ISC side of the platform should be supplied with a matrix of tapped holes: 1/4-20 on 1 inch centers.

• The platform working surfaces are to be oriented horizontally, with the beam reducing telescope to be mounted on the bottom side of the platform and the ISC components on the
top side.

• Other interfaces with ISC-- although their values are not specified in this document, there are some additional interfaces that must be established between AOS and ISC:

• location of the beam delivered to the ISC side of the of the optics table

is established by the ISC group.

• stay-clear areas on the ISC side of the platform (for suspension) is established by the ISC group

### 9.7 TELESCOPE (BRT) BEAM REDUCING TELESCOPE D1003120

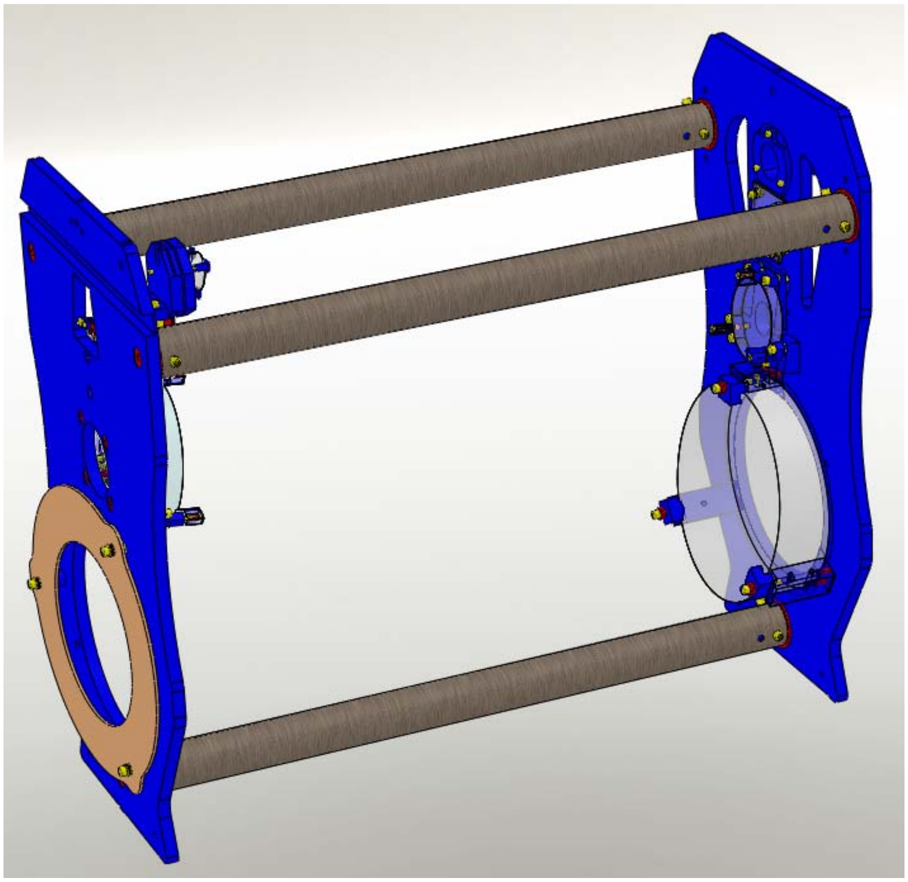

**Figure 8** BEAM REDUCING TELESCOPE Input Beam Baffle Shown

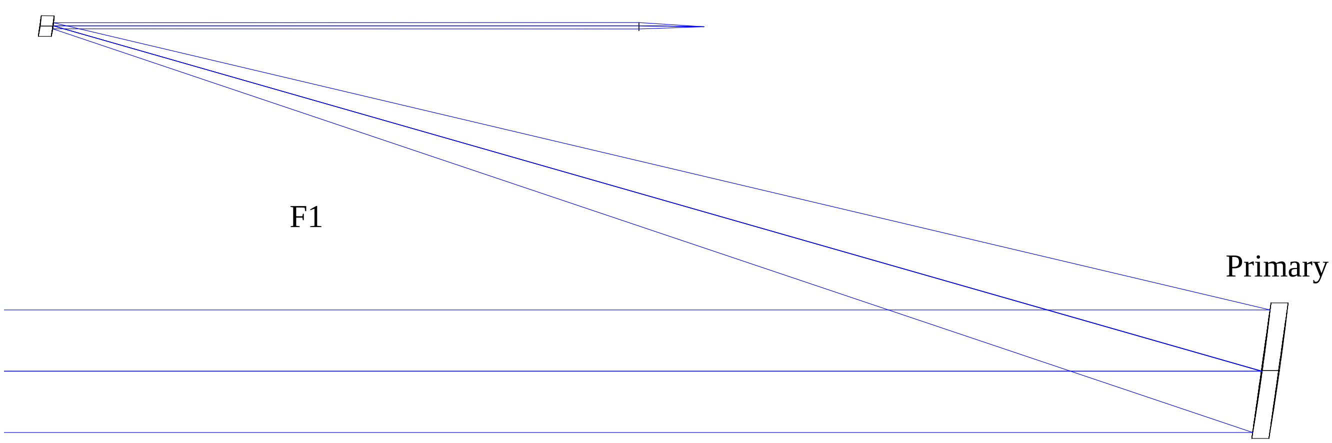


**Figure 9** ZEMAX model of off-axis parabolic telescope

## 9.8 OFF-AXIS PARABOLIC MIRRORS, MANUFACTURING TOLERANCE

| | | |
|---|---|---|
| Ref. | Secondary Mirror Specification | E0900349 |
| | Primary Mirror Specification | E0900347 |

The Telescope Configuration, was optimized with the Zemax Optical Design Program

**Telescope General Specification:**

Off Axis parabolic system 230mm dia primary w/2000 mm fl. 20x reduction.

190 mm ca, the 1064 nm main beam is reduced to fit 2 inch ISC optics

Alignment sensors with 90 degree Gouy phases within ± 10 deg.

Handle 1064nm, 532 nm and 635nm Hartmann sensor wavelength

The telescope delivers a beam with well-known beam parameters and these beam parameters must be stable over time, with 'well-known' and 'stable' clarified in the next paragraph.

As discussed in G0900459, the ISC side of the TMS employs two alignment sensors that by design are separated in Gouy phase by 90 deg. The adjustment and stability of the BRT must be such that this Gouy phase difference does not deviate by more than 10 deg from this design value. The setup and stability of the BRT must also be such that the beam size on the alignment sensors is not more than 10% different than the design value.

Within the above constraints many BRT designs are possible. The current design, as found in D0900446, appears to be adequate: it reduces the beam radius from 62 mm to 3.1 mm over a distance of about 3 m (output beam is at a waist).

For expansion of the ALS green beam, the BRT design should produce an expanded green beam whose beam parameters are stable and within 10% of their design values given the design tolerances. The BRT properties are not required to be the same for the 532 nm beam and the 1064 nm beam (i.e., allowing for refractive lenses, if desired).

Additionally, the BRT must allow for convenient separation of the Hartmann sensor reference beam on the ISC side of the platform.

The secondary mirror (focus element) can be positioned in three orthogonal axes by means of slide mechanisms that can be subsequently locked in place.

### The Advanced LIGO ETM transmission monitor T0900385

Here we describe the TMS optical layout. The TMS assembly is an in-vacuum optics table suspended immediately behind the End Test Mass (ETM) of each interferometer arm

# 10 TMS TELESCOPE ALIGNMENT PROCEDURE

## 10.1 SECONDARY MIRROR TRANSLATION AND TILT CORRECTION

Satisfactory alignment of the telescope can be accomplished by moving only the secondary mirror in five degrees of freedom—tilting in pitch and yaw, de-centering vertically and horizontally, and moving along the optical axis for focus.

The primary mirror is placed in a fixed mirror mount whose mechanical axis is pre-aligned to within 0.1 mrad of the reference optical axis of the telescope. The rms combined error of the mirror mount and the tilt error of the primary is 0.01 deg.

The secondary mirror has the necessary degrees of tilt and translation freedom.

## 10.2 AUTOCOLLIMATOR AND SHACK-HARTMANN INSTRUMENTS

Either an autocollimator beam, or a collimated light source, such as a laser is injected into the secondary end of the telescope along the optical axis, as shown Fig. 12.  The beam will reflect from a mirror when it emerges from the primary mirror and be reflected back through the telescope and emerge after a round trip at the secondary mirror.

The beam splitter shown in the enlarged view will reflect a portion of the return beam to the cross-hairs of the autocollimator or to the Shack-Hartmann wave front sensor Fig. 13.

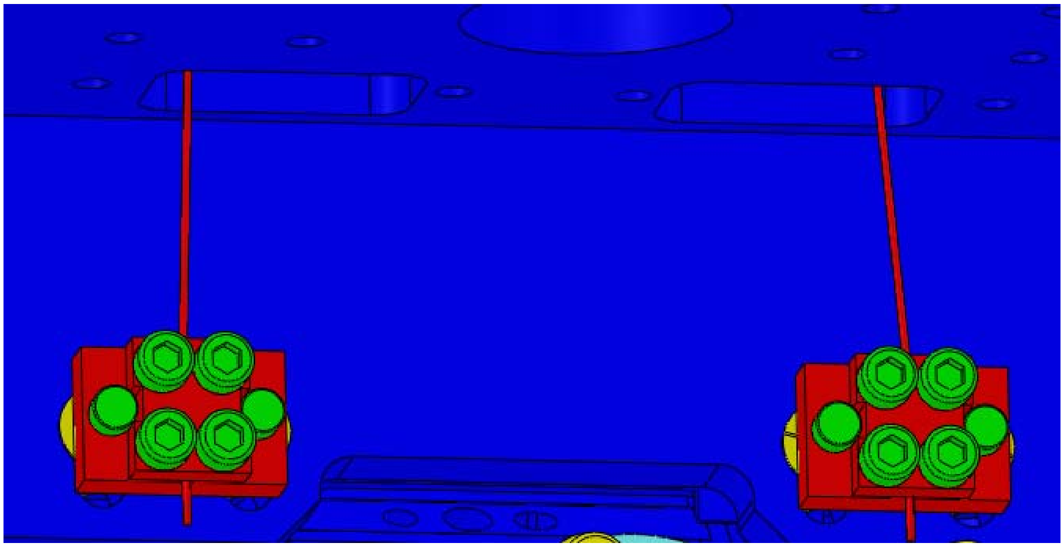

**Figure 10** Suspension Wire Clamp
**(2 of 4 shown) Attachment to Telescope / ISC Optical Table**

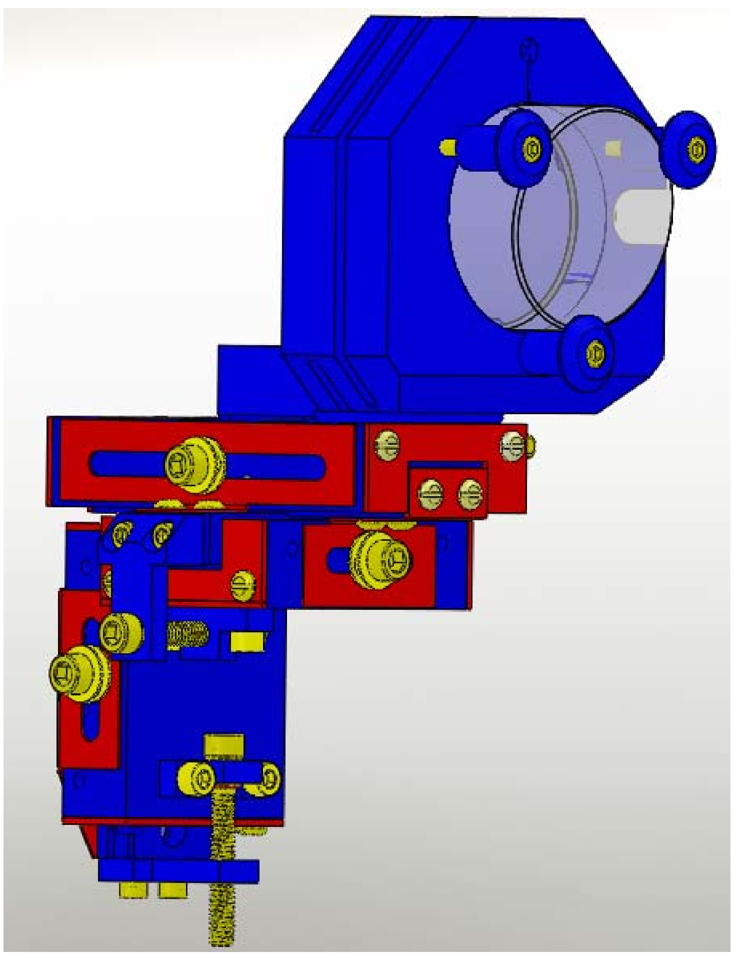

**Figure 11** TMS Telescope Secondary Mirror Mount Assembly

Adjustable in X-Y-Z , azimuth and elevation. D1001600

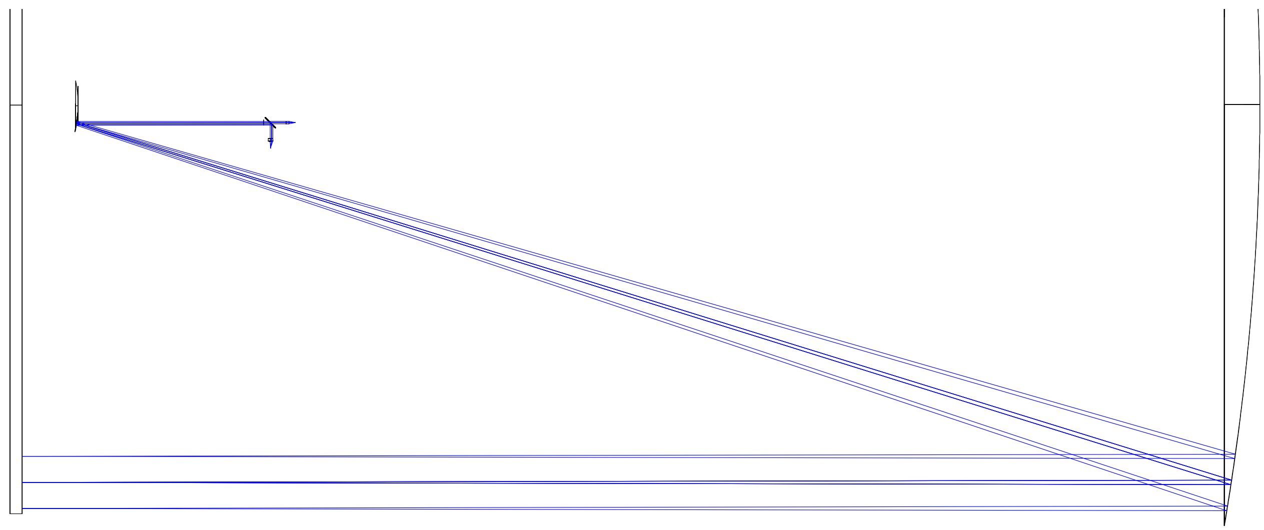

**Figure 12** Double Pass Alignment Beam

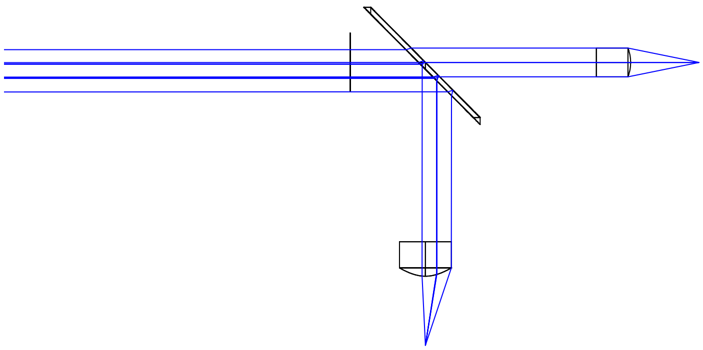

**Figure 13** Alignment Beam Splitter

### 10.3 BEAM SPLITTER

This is for the autocollimator, or for Shack-Hartmann sensor initial mechanical alignment of primary and secondary mirror mounts

#### 10.4.1 Initial Misalignment Conditions

The ZEMAX wave-front map shows the initial aberrations of the wavefront of the telescope beam with the following worst case combination of tilt and de-center errors of the primary and secondary mirrors:

Primary

| | |
|---|---|
| tilt | 0.01 deg |
| decenter | 1 mm |

Secondary

| | |
|---|---|
| tilt | 0.01 deg |
| decenter | -0.3 mm |

Defocus -20 mm

### 10.4.2 Telescope Mounting to Table

Telescope is attached to the Optical Table in three places with cap screws and spacer washers. The invar tubes separating the telescope end plates reduce the expansion and separation of the two end plats to approx 1800 uin over 5 deg F. temperature change with 2400 uin allowed. The difference in expansion of the telescope vs the Optical Table is taken up by a flexure above the invar tubes in the input side of the telescope.

# 11 TMS OPTICAL TABLE LAYOUT

## 11.1 ZEMAX OPTICAL LAYOUT PLAN VIEW

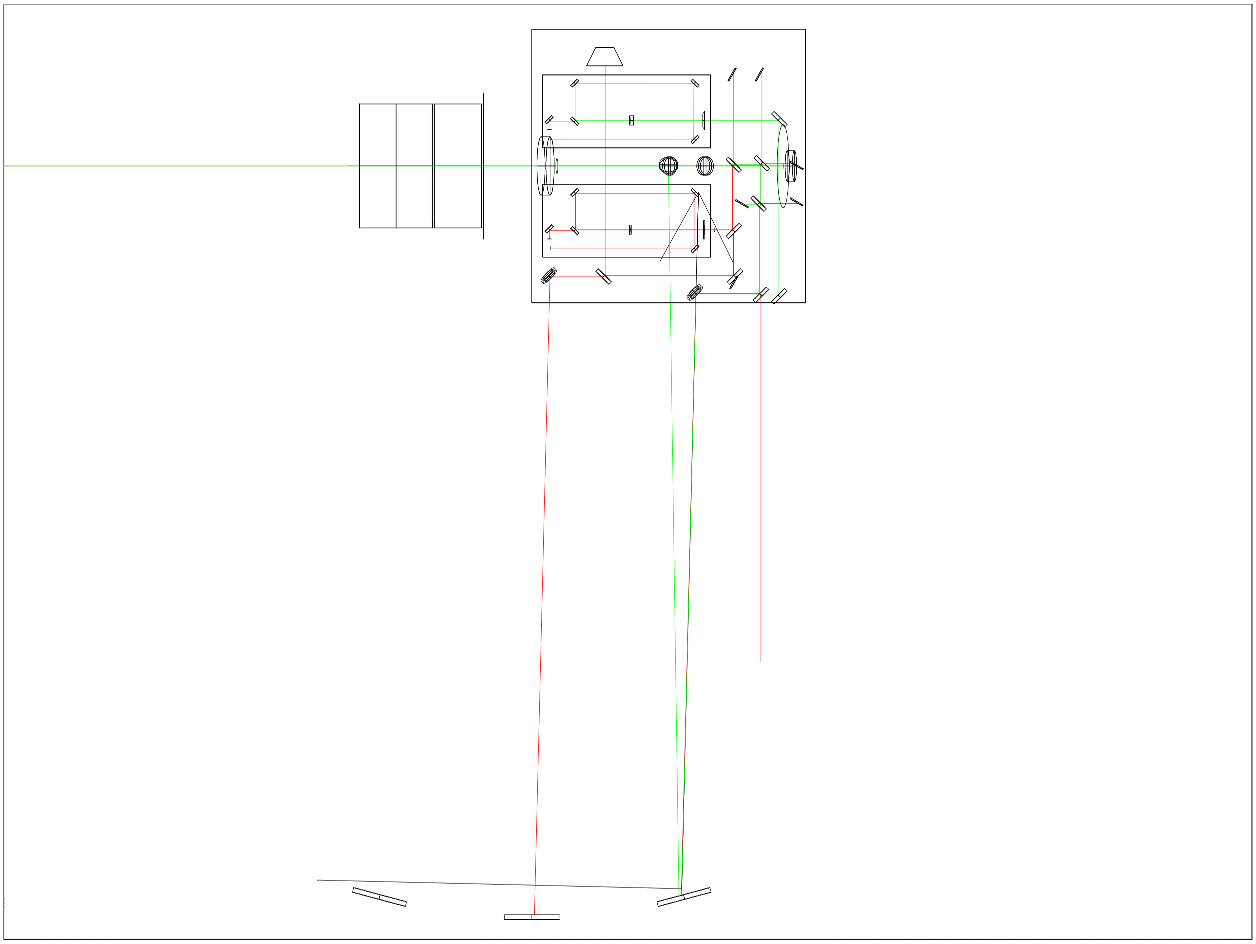

**Figure 14** Layout of TMS Optical Table Input and Output Beam (Plan View)

A plan view of the TMS table with the 1064 nm beam optical path in red and the 532 nm optical path in green is shown in Fig 14.

## 11.2 ZEMAX LAYOUT ELEVATION VIEW

A preliminary ZEMAX design layout of the TMS Suspension with the ETM Telescope placed below the TMS optical table is shown in Fig 15.

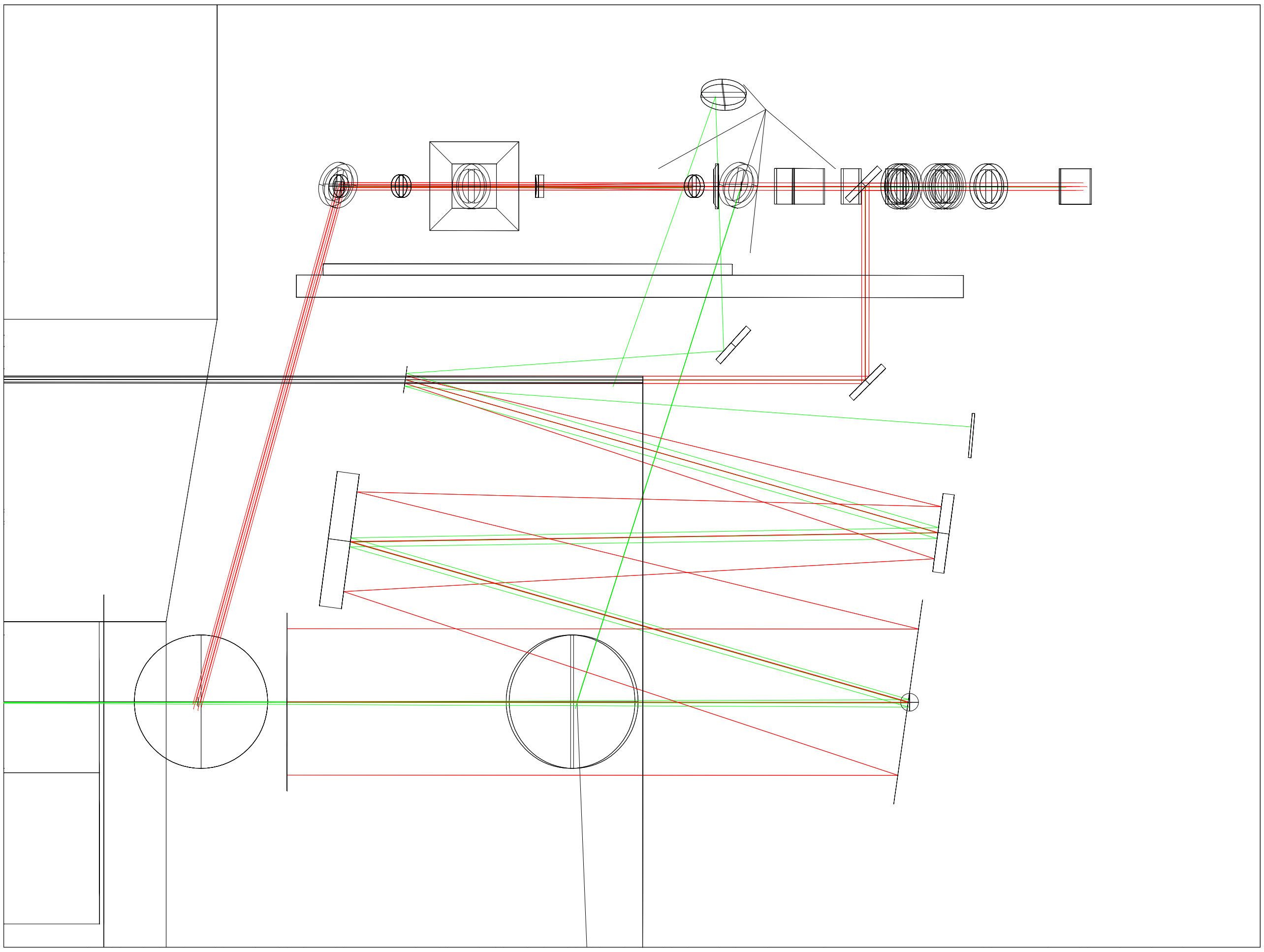

**Figure 15** TMS Telescope Beams (Elevation View)

The Hartmann (green) reference beam exits the telescope above the 1064 (red) ETM transmission beam.

# 12 TELESCOPE ALIGNMENT PROCEDURE

The purpose of this technical note is describe an alignment procedure for the ETM Telescope that uses a combination of an autocollimator for initial coarse alignment, and a Shack-Hartmann wave-front sensor for the final fine alignment.

## 12.1 ZEMAX MODEL

### 12.1.1 SHACK HARTMANN WAVEFRONT SENSOR

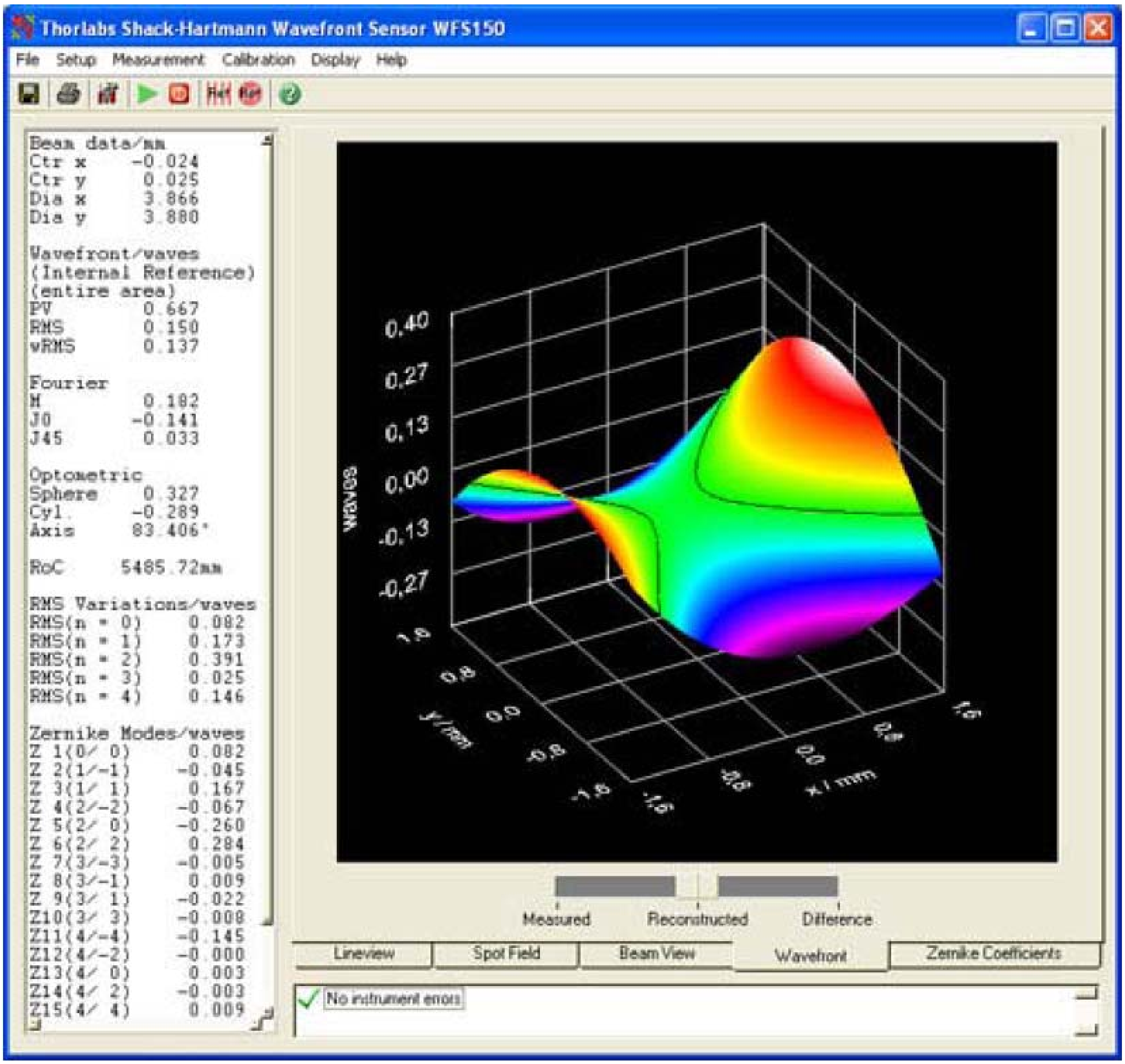


**Figure 16** Wavefront Map from Shack-Hartmann Sensor

### 12.1.2 WAVEFRONT ABERRATION

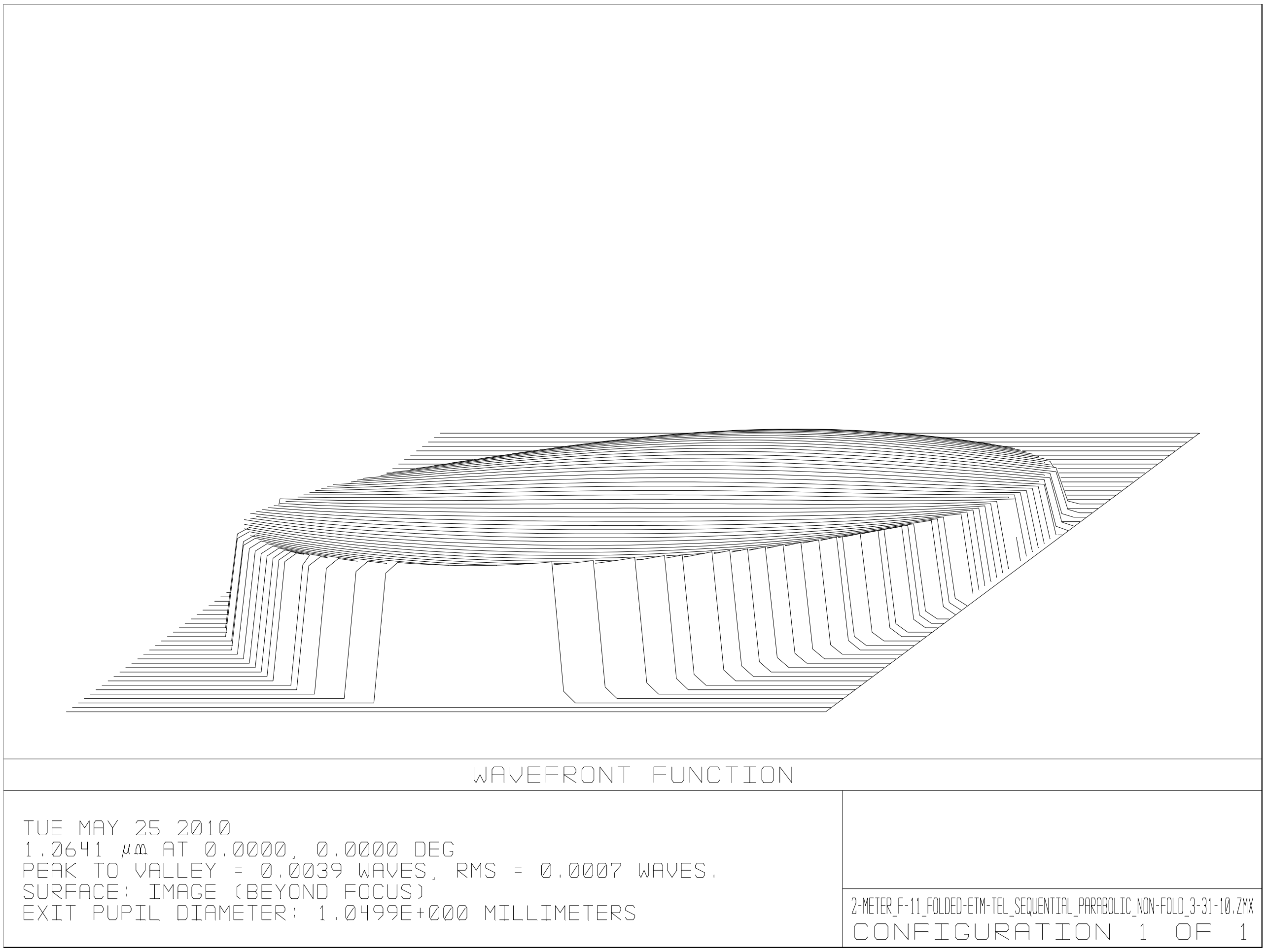


**Figure 17** Wavefront Aberrations after Alignment

Using Five Degrees of Freedom of Secondary Mirror

### 12.1.3 ELLIPTICITY AND WAVEFRONT ABERRATION

The output spot ellipticity and the wavefront aberration of the telescope are summarized in T1100258

# 13 TMS PERFORMANCE CHARACTERISTICS

Using the dynamics model: T1000263 by Mark Barton, and estimated BSC ISI table motion, we have computed the resulting displacement spectra of an un-damped TMS suspension. Modest damping will reduce the resonance peak heights, bringing us close to the performance target at all frequencies Fig 18. More details on the model and the input noise estimates can be found in section **9.1**

Parameters Drawing D0902773 showing suspension wire and TMS telescope and optical table cg locations

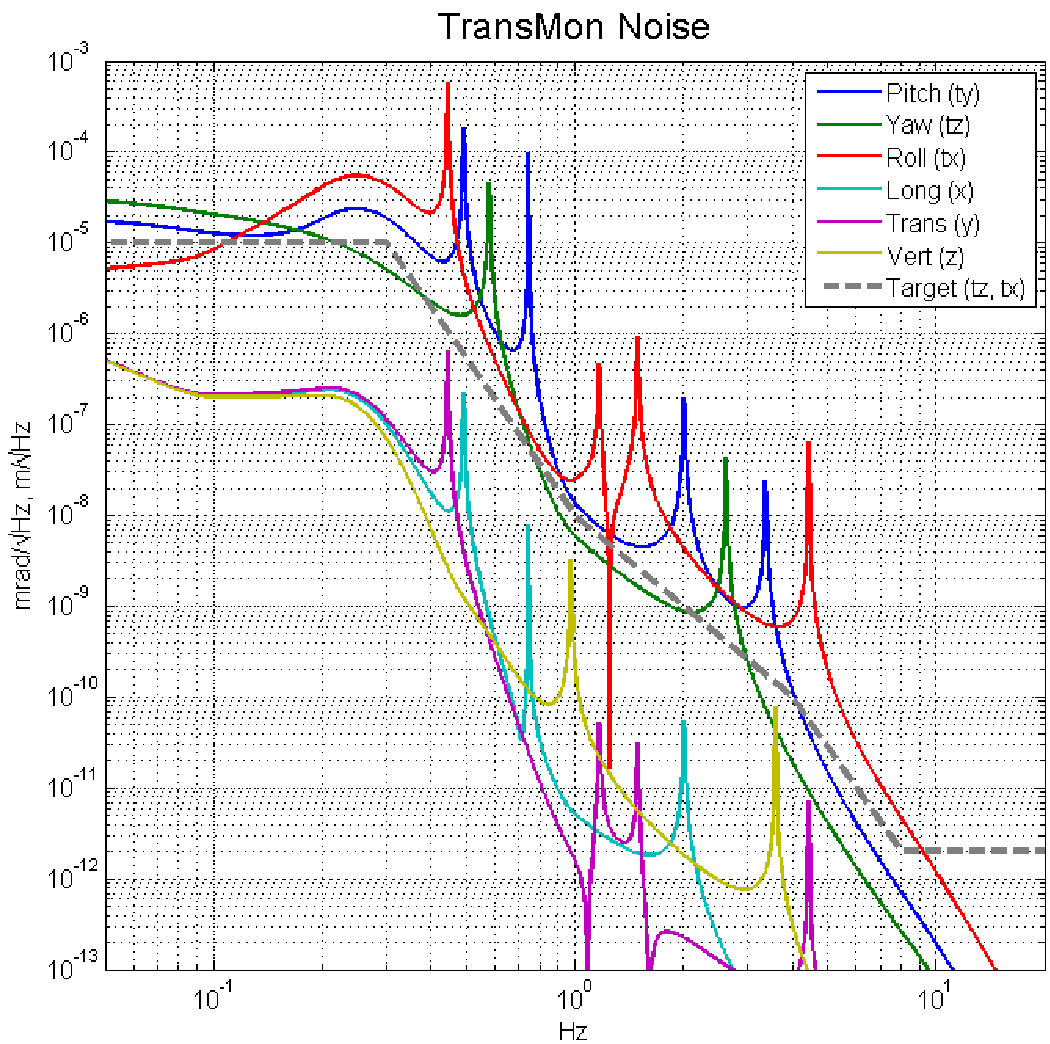


**Figure 18** Estimated displacement and angular noise spectra for the TMS.

The target (dashed grey line) refers only to the pitch and yaw (ty and tz) degrees of freedom. The resonances are left un-damped in this model to facilitate identification of their frequencies, though damping is present in the actual system.

## 13.1 TRANSFER FUNCTIONS AND INPUT NOISE

Displacement transfer functions, shown in Fig. 21, show the transfer of "ground" motion (actually the BSC ISI) to the TransMon table. These transfer functions are computed without damping loops to better show the resonance frequencies of the suspension. The ISI table motion spectra used as the input to produce the noise spectra in the previous section is also shown (Fig 19/20).

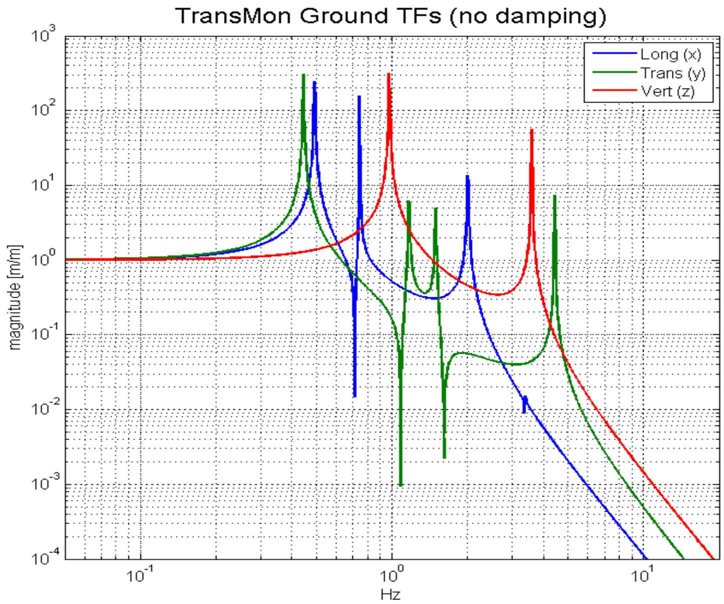


**Figure 19** TMS Ground to Displacement Transfer Functions

(no damping). These transfer functions are of little interest to the noise performance, but should be helpful in characterizing the suspension, and in constructing control and damping loops.

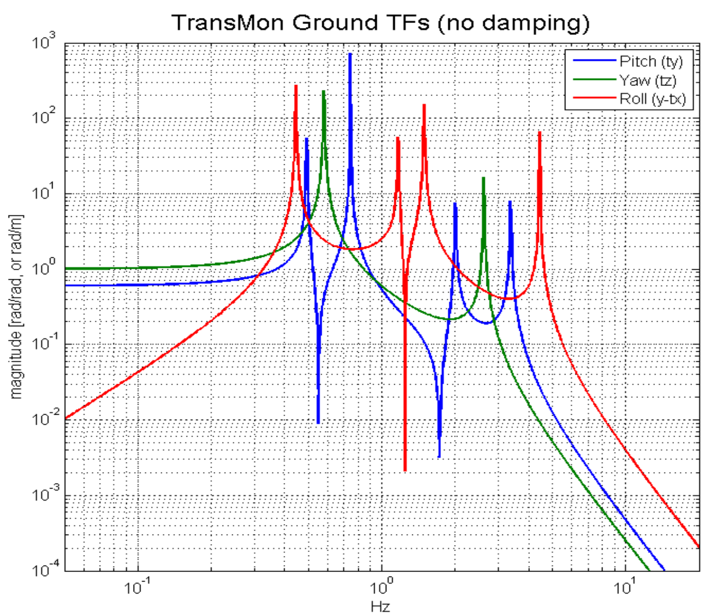


**Figure 20** TMS Ground to Angle Transfer Functions

(no damping). Note that the dominant transfer to ty is from y rather than ty, so this transfer function is shown instead.

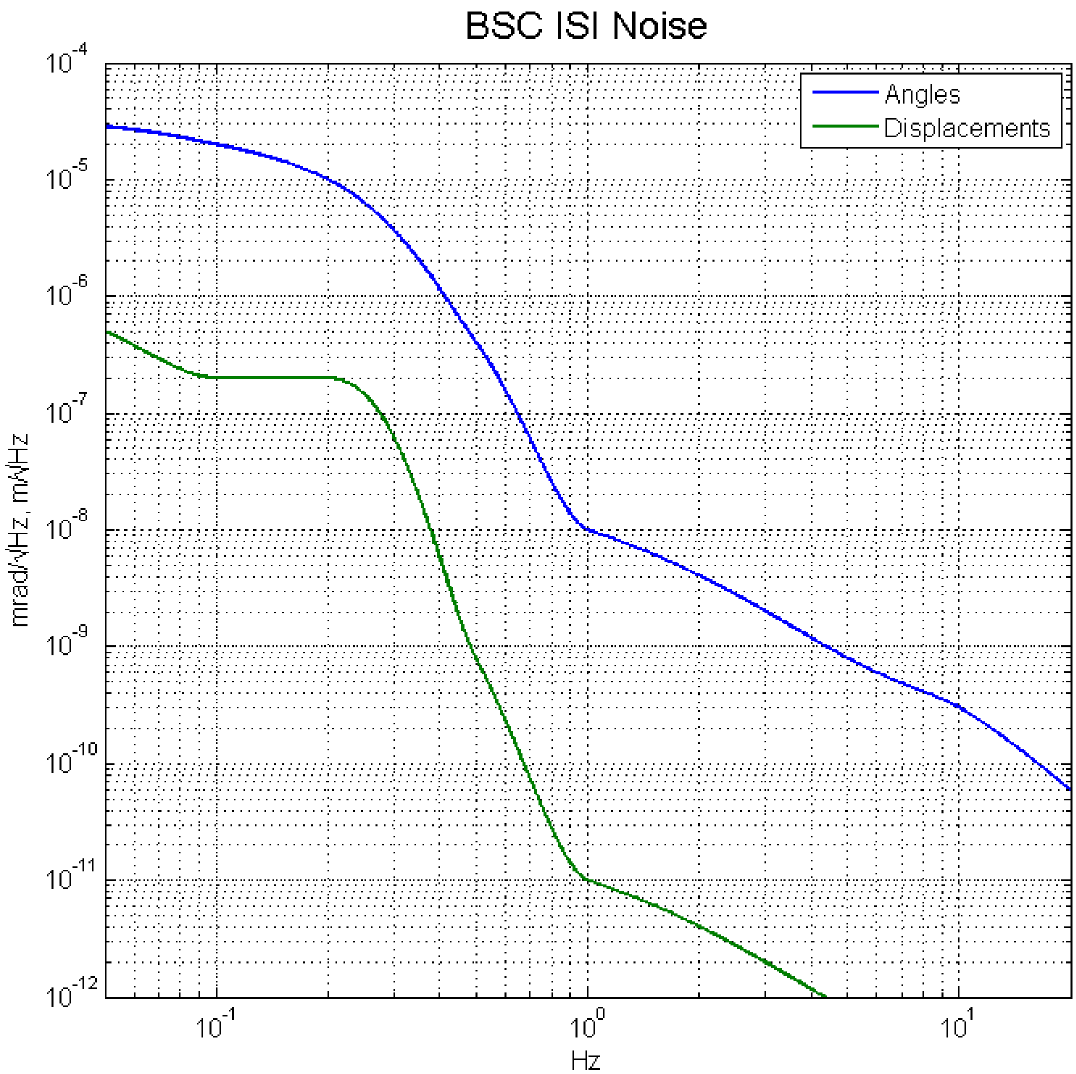


**Figure 21** Displacement noise from BSC ISI used as input to the model

# 14 TMS FAULT DETECTION, ISOLATION AND RECOVERY

## 14.1 EARTH QUAKE RESTRAINT ASSEMBLY (BOTOM VIEW) D1001781

There are passive earthquake stops that minimize motion of the suspended TMS Assembly. The earthquake stops prevent any contact between the TMS and the ETM quad suspension. The earthquake stop rod does not contact the suspended platform, it is centered in the eye ring on the Optical Table.

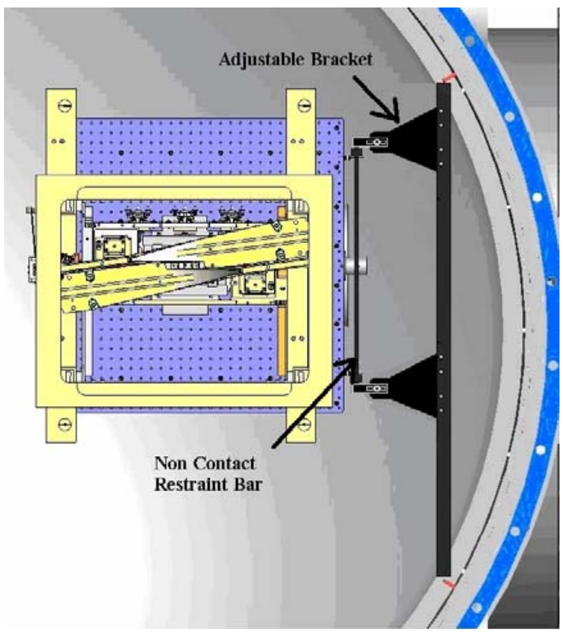


**Figure 22** Earthquake Restraint

### 14.1.1 METHOD OF IMPLEMENTING

Earthquake stop Design is an attachment to the Chamber wall utilizing existing brackets, with mounts that support a rod extending thru eyes located at the end edge of the optical table. In normal operation these will not contact the suspended TMS assembly. This arrangement limits travel motion of the suspended mass and will not interfere with system controls.

### 14.1.2 SOFTWARE WATCH DOGS

These are the same as Suspensions.

# 15 STRESS AND DEFLECTION ANALYSIS OF TMS LARGE MOTION RESTRAINT T1000689

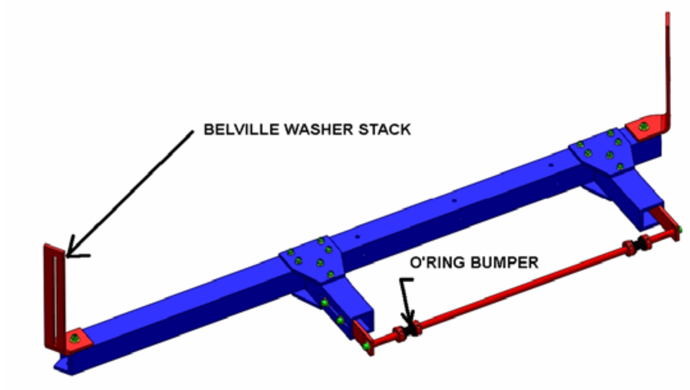


**Figure 23** Earth Quake restraint Assembly (Iso. View) **D1001781**

The Transmission Monitor Suspension (TMS) is restrained from large motion (swinging) by an assembly (fig 36) which attaches to the BSC chamber. The BSC chamber deflects during pump down due to the large atmospheric pressure loads. An analysis was conducted to insure that the TMS large motion restraint system (a) does not deflect so much that it contacts the suspended TMS payload and (b) is not over-stressed. a double belleville washer stack at the bracket interface with the BSC flange, and an o'ring at the rod eye reduce the stresses on the D1001929 angle brackets

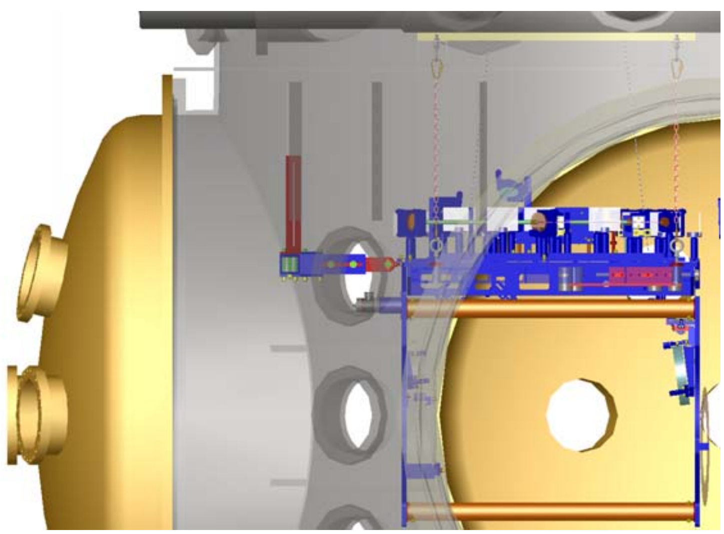

**Figure 24** Earth Quake restraint Assembly in **BSC6** (Side View) **D0900512**

# 16 INTERFACE CONTROL

## 16.1 THE TMS TELESCOPE ASSEMBLY

The TMS Assembly and Optical Table Assembly is offset from the ETM frame assembly by approx 5-6"” in normal operation. This will not be enough access clearance to service the ETM in all instances. will need to be moved back approximately 12” to allow front access to the ETM. There is a fixture that will allow temporary repositioning of the TMS Telescope.

## 16.2 THE TMS TELESCOPE ASSEMBLY SERVICE FIXTURE

The fixture will consist of 4 cable attachments extending from the suspension frame brackets to the TMS telescope assembly. These allow the TMS to back (away) from the ETM. The pull back TMS relocation will not require the suspension wires to be removed or readjusted. **(**Figure 1**)**

# 17 RELEVANT RODA CHANGES AND ACTIONS COMPLETED

There are no relevant RODA's

# 18 INSTALLATION AND INTEGRATION PLAN

See Document E1000097 'ETM' (TMS) Transmon Telescope and Suspension Installation Plan.

# 19 FIRST ARTICLE ASSEMBLY AT CIT

## 19.1 THE TELESCOPE AND SUSPENSION

We have assembled the first article at CIT initially then sent it to LHO for cleaning and re-assembly.

Assembly of the TMS Telescope, Optical Table, and SUS at the site:

These TMS assemblies are accomplished in advance of the needed installation date, and therefore clean storage for the sub assemblies are needed.

At the Hanford Observatory the TransMon Telescope, Optical Table, and SUS are individually assembled and aligned in series using individual clean facilities.

The TransMon Telescope and Optical Table is mated and aligned using tooling made for this task in a clean room next to the Cartridge assembly, while hanging by wires from a temporary fixture to simulate the same stress the assembly will see as when it is installed on the ISI Table on the cartridge.

This operation should take place prior to the attachment to the cartridge, using the finished stored sub-assemblies.

## 19.2 LOADING THE TMS ONTO THE CARTRIDGE AT LHO

TMS is loaded onto the cartridge and pre aligned to the ETM for installation into BSC Chamber.

Procedure:

1. Use a Genie Lift to roughly position the TMS suspension frame assembly to the ISI optical table in the cartridge, using preset location stops D1101260.
2. Lock the suspension top Mass per drawing D1000549
3. Precision-locate the suspension frame assembly on the ISI optical table, using the Quad SUS frame pusher tooling.
4. Secure the suspension frame assembly with clamps.
5. Attach the Telescope / Optic table Assembly to the suspension wires using the D1100908 frame, and table.
6. Connect the suspension wires from the suspension frame to the TMS Telescope assembly.
7. Remove the installation tooling.

Tooling:

Support Tooling is attached to the Telescope Optical Table assembly; to relieve the suspension springs and wire loading during installation.

Weight Specification:

1. The telescope and Optical Table combined weight is 80kg.
2. The suspension frame and top mass weight is approx. 124kg.

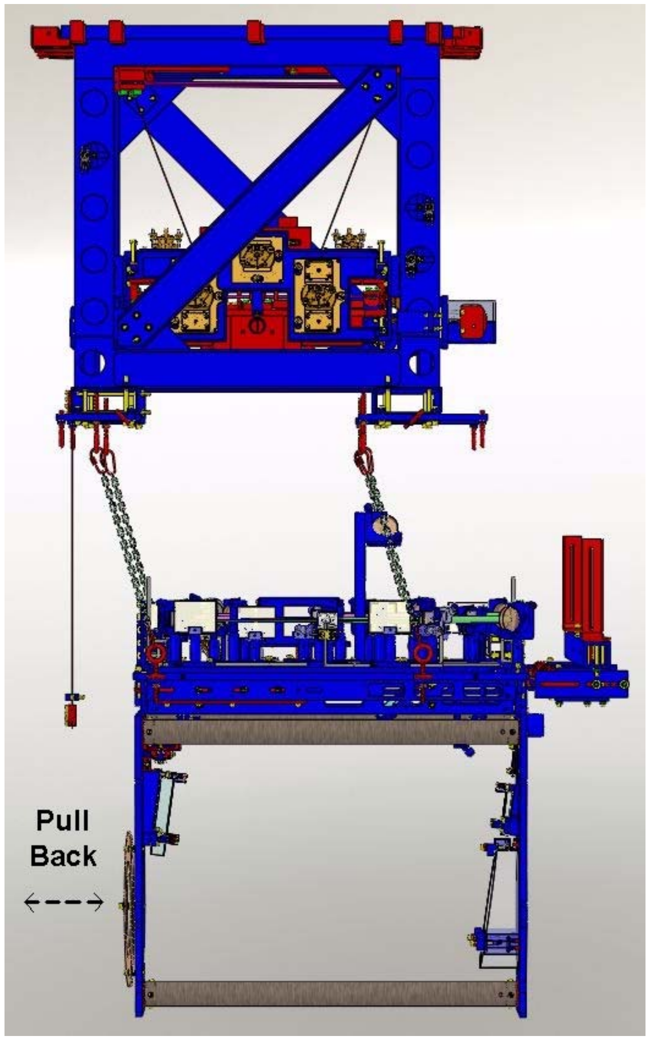


**Figure 25** TMS telescope offset to service the ETM

The ETM quad structure in relation to the TMS structure has approx. clearance of 4.4” minimum, with an additional pull back for ETM service the min is 12.8".

## 19.3 FINAL ALIGNMENT / TOOL SETUPS

**Alignment Procedure After Cartridge Installation in the BSC:**

1. Enable active suspension control, to verify the installation is within the control range.

2. Align the TMS TransMon Telescope SUS to the ETM HR surface, using a test laser beam apparatus, described in **(4.2)**

3. If the TMS assembly is not within the control range, the suspension frame is repositioned on the table.

# 20 LIGO DOCUMENT T1000230

20.1 The purpose of this document is to specify requirements.

For the initial alignment system (IAS) for advanced aLIGO, which is a component of the auxiliary optics system (AOS).

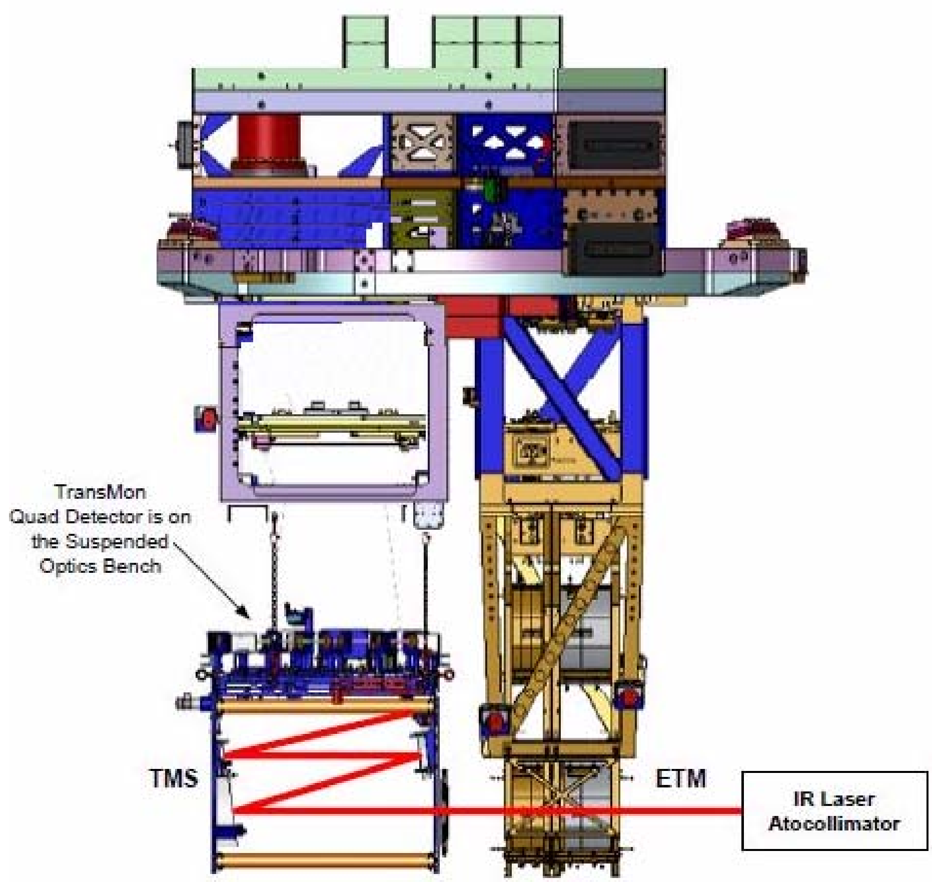


**Figure 26** Alignment of TMS to ETM

In addition to the ETM suspension, each ETM chamber contains a TMS assembly (Figure 30). First the ETM HR face is aligned with the visible laser autocollimator. Then the IR laser autocollimator is set perpendicular to the ETM HR face (by autocollimation). The IR laser autocollimator is then used to project into the TMS. The beam propagates through the pre-aligned TMS assembly to its quad detectors. Centering of the TMS aperture can be checked with a target. Yaw (and if needed pitch) are adjusted to center the beam on the quad detectors.

## 20.2 FLOW CHART AOS/IAS H1,H2 & L1 ETMS ALIGNMENT T1000447

# 21 TMS TELESCOPE ALIGNMENT T1100258

## 21.1 AUTOCOLLIMATORS AND A SHACK-HARTMANN SENSOR

Aligning the TMS Telescope, Two alignment methods are presented: alignment by double pass retro-reflection from a curved ETMHR surrogate mirror, and double pass retro-reflection from a flat mirror. A step-by-step procedure is presented, together with actual data from the Shack-Hartmann sensor during the alignment procedure. Optical aberration theory is used to derive a relationship between the Zernike astigmatic coefficient and the Guoy phase error at the focal plane of the TMS sensing system. The ZEMAX focus parameters for an ideal off-axis parabolic telescope agree with the ABCD Gaussian beam propagation calculations

# 22 TRANSPORTING CARTRIDGE

## 22.1 THE TMS IS TRANSPORTED WHILE ATTACHED TO THE CARTRIDGE.

The TMS telescope is stabilized by two criss cross turnbuckle cables on each side as shown in Fig. 27

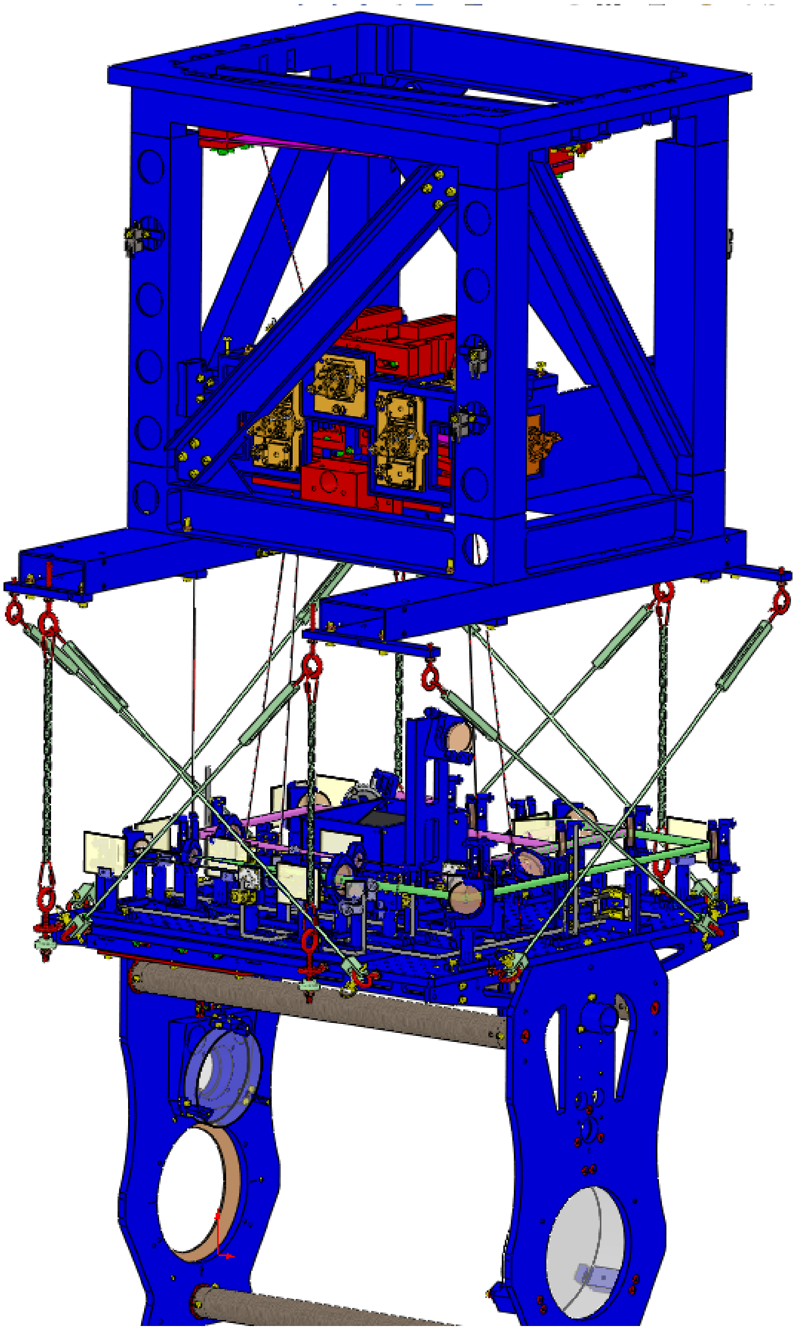

**Figure 27** Stabilization when transporting Cartridge D1101307

# 23 ESTIMATE: TIME AND PERSONNEL TO COMPLETE TMS ASSEMBLY

## 23.1 EQUIPMENT

The TMS assembly task involves moving the large size and weight of the sub-assemblies, some handling will have to be done with the assistance of tooling, fixtures and lifts, specific to the task.

## 23.2 PERSONNEL

There are 2-3 people required to do the installation preparation tasks; a genie lift is necessary for the attachment of the TMS SUS to the cartridge, and the attachment of the TMS Telescope and Optical Table to the TMS Suspension. The TransMon Telescope and Optical Table is supported during the move to the BSC by stabilization tooling. **figure 38**

## 23.3 TIME ESTIMATE

| | |
|---|---|
| 1. SUS assembly | 2 people 4 days each |
| 2. Optical Table | 2 people 4 days each |
| 3. TransMon Telescope | 2 people 4 days each |
| 4. Joining of Optical Table and (TMS) Telescope | 2 people 4 days each |

## 23.4 CARTRIDGE ASSEMBLY OF THE TMS

| | |
|---|---|
| Cartridge Assembly and alignment | 3 people 4 days each |

## 23.5 TMS ALIGNMENT TO ETM IN BSC

| | |
|---|---|
| Chamber alignment | 2 people 4 days each |

# 24 LONG LEAD PROCUREMENTS

## 24.1 TELESCOPE

### 24.1.1 PRIMARY MIRROR

Approx. 7 months for 5 units

### 24.1.2SECONDARY MIRROR

Approx. 6 months for 5 units

## 24.2 SUSPENSION

Note: B-Osems are provided by the UK in sufficient quantity for the TMS

Norna confirmed that SUS are supplying BOSEMs for TMS as per LIGO-E1000042-v2 which shows a count of 36 plus 5 spares. In fact Birmingham have provided a few more BOSEMs than originally anticipated so we can give you a few more spares if needed.

Maraging Steel Springs and processing. The TMS system will use existing drawings and will reproduce parts in the US. Lead time approx. be 6 months

The structural frame Lead time is

Approx. 6 months for 5 units

## 24.3 OPTICAL TABLE (STANDARD MATERIALS AND PROCESSES)

Approx. 3 months for 5 units

### 24.3.1 OPTICAL TABLE COMPONENTS

These have nominal lead times none more than 6 months, and provided by ISC.

# 25 TECHNICAL, COST AND SCHEDULE RISKS AND PLANNED MITIGATION

- Getting the First Article delivered to the Hanford in time for the Long Arm Test.
- Aligning, focusing and maintaining the alignment of the telescope
- Moving beam block in vacuum on an isolated table
- Aligning the telescope to the arm

The optics for first article can be ready in advance of the timeline for hardware assembly for bench test. The mechanical parts are standard machining and predictable for cost and completion. Other risks are mitigated by steps taken in response to the first article setup experience.

## 25.1 PER RISK REGISTRY M080359

No TMS risks are indicated in the risk registry.

## 25.2 PROBLEMS AND CONCERNS

### 25.2.1 SUSPENSION CONCERNS

1. Single source for the B-osems for suspension controls (schedule / cost risk) risk is minimal, we have enough extras from orders for the same part, for the suspensions.

2. TMS Suspension Hybrid meeting the control requirements (schedule risk) minimal risk the control system is nearly identical to the proven Quad system.

### 25.2.2 OPTICAL TABLE CONCERNS

1. The Thermal stability re. the beam dump conducting into the optical table plate moving the telescope causing Horizontal angle change (schedule risk) (Eric and Sam agree this is not an issue of concern based on the power dissipated and the limited interface heat path to the optical table.

# 26 PROCUREMENT PLAN

## 26.1 The Plan

MAJOR COMPONENT GROUP DIVISIONS:

The 7 part groups below will have an RFQ for procurement.

Listed separately are the specialized sets of components that a single shop source is not likely to be proficient at providing.

With the experience of the first article procurements, the break down below seems the most time and cost effective approach.

## 26.2 MAJOR PART GROUPS:

1. Optics
   - Off Axis Parabolas
   - Folding Mirrors
2. Suspension Springs
   - UIM Spring
   - Top Cartridge Spring
3. Secondary Mirror Mount
   - Slide Assemblies
4. Telescope Spreader Tubes
   - Invar Tubes
5. Suspension Structure
6. Machined components and hardware
7. Tooling

The RFQ documents are variations of the existing RFQ's already developed for the first article.

The majority of shop drawings have been updated, and are ready for submission for quote.

# 27 TEST PLAN OVERVIEW

## 27.1SUSPENSION SEISMIC TEST AT CIT

**Ref . T1000236**

**1.** Seismic Attenuation Characterization -Validation of the suspension mathematical models to the measurements using the OSEM position sensors

**2.** Active Control System Characterization –Open loop transfer function measurements for control aws characterization
Validation and fitting of the suspension mathematical models to the measurements using the OSEMs to predict the seismic attenuation below the internal model frequencies

Transfer function measurement using impulsive excitation(hammer) to try to characterize the high frequency transmissibility of some of the DOFs

A**ctive Control System Characterization** For this type of measurements we will require the standard aLIGO digital control system used for the quadruple pendulum control.

Open loop transfer function measurements for control aws characterization
Impulsive response measurements for control laws characterization
step response measurement for telescope pointing characterization
Optimization of the active damping system
Noise budget measurement.

**Seismic Attenuation Characterization** We will not directly measure any transmissibility of the suspension. We will rely on other measurements and simulation to estimate the seismic attenuation of the suspension. Simulation are tuned ad hoc to fit the measurements. This strategy comes after a general decision taken by people involved in the design of the AOS mechanical suspensions.

## 27.1 LAB EQUIPMENT AND TMS TEST SETUP

Test will require TMS dummy mass and setup rig. Setup is made with a standard quad frame, breadboard control system, with new parts per TMS requirements.

The electronics for the sensing and control is already characterized. The following measurements will be done for each single control loop to properly characterize the loop performance:

## 27.2 IDENTIFICATION OF TESTING RESOURCES

Mechanical Modes Content Characterization

For this type of measurements we will require the Bruel & Kjaer modal lab system and some custom made system already available at Caltech. Test suspension assembly at CIT room 318 lab using a dummy mass for Telescope and a BSC overhead Optical Table assembly; with a controls system setup. The test will use the requirements T0900265 to qualify performance. We will follow

## 27.3 TELESCOPE OPTICAL SYSTEM

The off-axis Primary parabolic mirror is tested by the manufacturer to guarantee that the mirror meets the specification E0900347. The Secondary parabolic mirror is tested by the manufacturer to meet specification E0900349. The optics will also be coated tested by the manufacturer and test results included with each optic. T1100258

## 27.4 PLANNED TESTS TO VERIFY PERFORMANCE

**First article Assembly Equipment and Controls Test**

**First Article Assembly and Testing of the TMS Suspension:**

**Ref 17.3**

The suspension was tested at Caltech in Lab room 318, this tested the modified Quad suspension with a dummy load, to determine if it meets the TransMon control system requirements. The suspension was taken apart and shipped to the Hanford Observatory where it was cleaned and reassembled as a first article.

**First Article Assembly and Testing of the TMS Telescope:**

Testing of the first article TransMon Telescope was done at Caltech to verify the alignment procedure. We used dedicated tooling, to be used again later on the full production of six additional units. The telescope was taken apart and and shipped to LHO for cleaning and reassembly

# 28 ENVIRONMENT, SAFETY, AND HEALTH ISSUES

## 28.1 Personnel and Equipment Safety Hazards

Document: aLIGO TMS Hazards Analysis **T1000311**

# 29 QUALITY ASSURANCE PROVISIONS

This section includes the examinations and tests of material or process, and that they conform to the requirements.

## 29.1 GENERAL

This should outline the general test and inspection philosophy, including all phases of development.

## 29.2 RESPONSIBILITY FOR TESTS (TBD)

## 29.3 CONFIGURATION MANAGEMENT

Configuration control of specifications and designs shall be in accordance with the LIGO Detector Implementation Plan.

## 29.4 QUALITY CONFORMANCE

Design and performance requirements identified in this specification and referenced specifications shall be verified by inspection, analysis. 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:

## 29.5 INSPECTIONS

Inspection shall be used to determine conformity with requirements that are neither functional nor qualitative; for example, identification marks.

# 30 GENERAL SYSTEM CONSIDERATIONS

## 30.1 ENVIRONMENTAL CONDITIONS

Environments that the equipment is expected to experience in shipment, storage, service or use. Subparagraphs should include, as necessary, climate, shock, vibration, noise, etc.

## 30.2 ELECTROMAGNETIC RADIATION **E960036**

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 E960036.

## 30.3 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.

## 30.4 FINISHES

Examples: Metal components shall have quality finishes on all surfaces, suitable for vacuum finishes. All sharp edges removed. 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.

## 30.5 SAFETY **M950046**

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 M950046-F section 3.3.2.

# 31 TECHNICAL MANUALS AND PROCEDURES

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

## 31.1 MANUALS

Manuals to be provided in the form of detailed assembly drawings and setup notes.

## 31.2 DOCUMENTATION NUMBERING

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

## 31.3 TEST PLANS AND PROCEDURES

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

## 31.4 LOGISTICS

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

## 31.5 QUALIFICATION : PER ISC TEST AND ACCEPTANCE CRITERIA

# 32 PREPARATION FOR DELIVERY

Packaging and marking of equipment for delivery shall be in accordance with the Packaging and Marking procedures specified herein.

32.1 PREPARATION PER **E960022**

- Vacuum preparation procedures as outlined in LIGO Vacuum Compatibility, Cleaning Methods and Procedures 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.

32.2 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 1.5TM 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.

32.3 MARKING PER **E030350**

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

## 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 which 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 1 Quality Conformance Inspections

TBD

| 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 |
| | | | | | | |
| | | | | | | |

# 33 TMS TEAM

Team Leader/Mechanical Engineer - Ken Mailand - Caltech

Cognizant Scientist - Sam Waldman – MIT

Telescope Optical Design – Mike Smith

Mechanical Engineer – Craig Conley- Caltech

Suspensions Modeling - Matt Evans - MIT

Telescope and Optical Table Development – S. Waldman - MIT

Suspensions Testing – Virginio Sannibale / Bill Kells – Caltech

Suspensions Controls – Jay Heefner – Caltech

Drafting - Jesse Terrazas - Caltech

Drafting - Mike Miller - Caltech

LHO Support - Gerardo Moreno

LHO Support - Bram Slagmolen

SUS Team Support - Betsy Bland

Mechanical Engineer – Jason Fishner- MIT