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Contract/Phase II
Exhibit III
Design Requirements for the In-Vacuum Mechanical Elements of the Advanced LIGO Seismic Isolation System for the BSC Chamber

A. References (on enclosed CD, Exhibit II); note that in case of apparent conflict between a referenced document and this text, this text shall take precedence.

1. Actuator drawings: Planning Systems Incorporated: #0487-LIGO-D110-042804-SCS, #0487-LIGO-d210-042804-SCS
2. Chamber SolidWorks files: HAM-Chamber, HAM Support Rod, HAM Expansion Bellows Assembly, BSC Chamber Lower, BSC Chamber Upper, BSC Support Rod, BSC Expansion Bellows Assy.
3. D020525-00, Advanced Seismic Isolation Technology Demonstrator (309 files)
4. Displacement Sensor drawings: ADE #020536-A01 (10 mm sensor), ADE #033968-01 (20 mm sensor)
5. External Support Parts: for BSC (9 files), for HAM (14 files)
6. Seismometer Lock files: STS2Locker5
7. D000241-C, LIGO II Stiff Active Seismic Isolation System
8. D010120-D, Cable Clamps, 40M
9. D030100-A, ADVLIGO SEI BSC Optical Table & Structure Limits
10. D030169-02, ADVLIGO SEI Corner Configuration
11. D047780-B, ICD, GS-13 Seismometer
12. D047781-B, ICD, L-4C Seismometer
13. D047782-B, ICD, STS-2 Seismometer
14. D961094-04, HAM Assembly
15. D970412-01, BSC Overall Assembly
16. D972001-B, BSC Top Assembly
17. D972121-F, BSC Support Tube Weldment
18. D972501-B, HAM Top Assembly
19. D972610-G, HAM Support Tube Weldment
20. E960022-B, LIGO Vacuum Compatibility, Cleaning Methods and Qualification Procedures
21. E960050-B, LIGO Vacuum Compatible Materials List
22. E990452-L, SPP-080 Rev. O, Cleaning & Preserving LIGO BSC & HAM Aluminum Weldments and Machined Shims
23. E990453-N, SPP-081 Rev. O, Final Cleaning and Packaging of LIGO S.S. Support Tubes, Leg Elements and Balance Weights
24. E990456-B, SPP-093 Rev. C, FT-IR Test Procedure, BSC Downtube & Support Table Assembly, D972210
25. E040022-A, Structure and Suspension Compliance
26. E040136-01, Seismic Isolation System (SEI) Payload Mass Properties

B. General:

1. The structure's purpose is to provide a mounting surface for optical components that is isolated from the local floor vibration. The BSC structure will be mounted in a LIGO BSC chamber. The elements of a structure are shown schematically in plan view in D000241, LIGO II Stiff Active Seismic Isolation System; this contract is limited to the in-vacuum portion of this schematic. The structure consists of three stages that are interconnected with springs. Stage 0 mounts on existing chamber support elements. It supports Stage 1 with three blade springs and flexures, and has actuators mounted that adjust the position of Stage 1. Stage 1 will have seismometers mounted to track its motion and displacement sensors to monitor its position with respect to Stage 0. Stage 1 supports Stage 2 with three blade springs and flexures, and has actuators mounted that adjust the position of Stage 2. Stage 2 has seismometers mounted to track its motion and displacement sensors to monitor its position with respect to Stage 1.
2. The Technology Demonstrator files D020525 depict a prior design that has much the same features as the subject of this task; it is included as reference only.
3. The structure shall be designed to be shipped as an assembled module (except for the pods, which are shipped separately). Custom crating shall be designed and provided, with adequate bracing and packaging to hold the units securely under severe shipping loads.

C. Stage Structures:

1. Major structure elements shall be made of aluminum to keep weight to a minimum, while minimizing material costs.
2. The BSC structure Stage 0 shall mount on a sufficient quantity of the bosses of each of the two Support Tubes (D972121) in the BSC Chamber (D972001), such that resonant frequency requirements of Section C.9 are met.
3. The optical table of the BSC structure, shown in D030100, shall be of inverted configuration, as compared with the Technology Demonstrator structure. That is to say, optical components shall be clamped to the bottom of the Optical Table, rather than to the top.
4. As shown in D030100, mounted hardware on the BSC support tubes shall not protrude more than 1.90" (4.8 cm) beyond the inboard interface bosses of the Support Tubes. Tool access shall be within 2.88" (7.3 cm) beyond that point.
5. The BSC structure assembly shall include a means for lifting with a crane hook, above its center of gravity, such that the dimension from the position of the axis of the support tube to the center of the hook pin shall not be greater than 56.93" (144.6 cm). No part of the BSC structure assembly shall extend more than 1.5" (3.8 cm) above the center of the hook pin (see D030100). The hook pin shall be no larger than 2.0" (5.1 cm) dia., and the lift clevis ears shall be spaced to clear a hook of 1.5" width.
6. All portions of the structure shall fit within the BSC chamber with a minimum clearance of 0.5" (1.3 cm). Note that Chamber SolidWorks files are provided for convenience in solids modeling; however, information from drawing D970412 is

to be used for confirming clearance with the BSC chamber. The three, separate stages of each structure shall fit together with inter-stage clearances of at least 0.2” (0.5 cm), except at displacement sensor, actuator, spring and flexure elements.

7. The structure shall be designed to survive shipping loads and earthquake shock loads of 1.0 g vertical and 0.5 g horizontal for an assembled module.

8. The structure (other than the springs and flexures) shall be evaluated for stress by traditional aerospace stress analysis methods, using a yield factor of safety of 1.25, and an ultimate factor of safety of 1.4, taking into account the reheat effects of materials used.
The structure must be suitably stiff to allow proper functioning of the servo control systems. The criteria stated below for the various structural elements or stages apply to the structure complete with mounted displacement sensors, dummy seismometers, actuators, and a payload configuration, per Section H.4.iii. Finite Element models of the complete design must be constructed to quantitatively predict and document compliance with these requirements. In addition to the structure being designed, the finite element model shall also include (on Stage 0) (see External Support Parts for the BSC): the support tubes, mounting caps and bases, crossbeams, crossbeam attachment plates and crossbeam feet (pointed at 45^o, toward the chamber center). Assume that Stage 0 is a free body for analysis purposes.

Assume a sinusoidal excitation, that applies a force, p(t) = $p_0$cos(2*pi*f*t), where f = frequency and t = time, along the actuator's nominal force axis, exerted between two stages (i.e., action on stage 1 and reaction on stage 0, or action on stage 2 and reaction on stage 1). On the higher-numbered “action” stage, this excitation will cause a sinusoidal displacement x_a(t) at the actuator mount in the force direction. It will also cause sinusoidal displacements of the seismometers, and relative displacements across the displacement sensors. Let x_s(t) be the displacement of the L-4C or GS-13 seismometer base along its axis, or the relative displacement of a displacement sensor in the direction perpendicular to the target. The frequency-domain Fourier coefficient X(f) is defined by x(t) = Re{X(f)*cos(2*pi*f*t)}. X(f) is complex, i.e., X(f) = |X(f)| exp{i phase(X(f))}. Let X’(f) be the Fourier coefficient computed using only rigid body motion and the first twelve system modes.

For the following actuator/seismometer pairs, the phase of the transfer function Xs/Xa shall be greater than -90 degrees for all frequencies below 500 Hz:

- Actuation of a single tangential or vertical stage 0/1 actuator, response of the corresponding (coaligned) L-4C seismometer;
- Actuation of a single tangential or vertical stage 1/2 actuator, response of the corresponding (coaligned) GS-13 seismometer.

For the following actuator/seismometer pairs, the phase of the function (Xs/Xa)/(X’s/X’a) shall be greater than -90 degrees for all frequencies below 150 Hz:

- Actuation of a single tangential stage 0/1 actuator, response of either opposite (not coaligned) tangential L-4C seismometer;
- Actuation of a single tangential stage 0/1 actuator, response of any vertical L-4C seismometer;
- Actuation of a single vertical stage 0/1 actuator, response of either opposite (not coaligned) vertical L-4C seismometer;
- Actuation of a single vertical stage 0/1 actuator, response of any tangential L-4C seismometer;
- Actuation of a single tangential stage 1/2 actuator, response of either opposite (not coaligned) tangential GS-13 seismometer;
- Actuation of a single tangential stage 1/2 actuator, response of any vertical GS-13 seismometer;
- Actuation of a single vertical stage 1/2 actuator, response of either opposite (not coaligned) vertical GS-13 seismometer;
- Actuation of a single vertical stage 1/2 actuator, response of any tangential GS-13 seismometer.

For the following actuator/seismometer pairs, the phase of the function (Xs/Xa)/(X’s/X’a) shall be greater than -90 degrees for all frequencies below 100 Hz (TBR: 50 Hz?):

- Actuation of a single tangential or vertical stage 0/1 actuator, response of any of the six stage 0/1 displacement sensors;
- Actuation of a single tangential or vertical stage 1/2 actuator, response of any of the six stage 1/2 displacement sensors.

LIGO may waive any of these requirements if models of structure configuration properties pass an evaluation of control performance.

9. Other than the 12 rigid body modes (reference: D.1.a.,c.iii) the minimum design resonant frequency for all parts of Stages 1 and 2 shall be 150 Hz. The payload configurations for which this requirement should be met are defined in H.4.ii.
10. Kinematic Locator devices are required between Stage 0 and Stage 1, and between Stage 1 and Stage 2 (see D030169) to serve the following functions and characteristics.
    - **Kinematic Design**: the devices shall place the stages at their proper relative (operational, neutral) orientations in all 6 degrees of freedom (DOFs) in a repeatable manner, without adding strain to the components for a multitude of purposes: assembly, alignment, installation of displacement sensors, installation of actuators, adjustment of operational limit stops, etc.
    - **Repeatable**: the tolerance on this placement shall be +/- 0.001” (+/- 0.025 mm).
    - **Zero Motion:** a means (such as springs) shall be provided to aid in clamping stages together adequately in their kinematic locators such that zero motion is assured.

- **Accessible:** the devices shall be accessible to technicians, even when the structure is installed in the BSC chamber.
- **Convenient:** the engagement and disengagement of the devices shall be designed with operator convenience in mind.
- **Durable:** the devices shall be sufficiently hardened and procedures shall be such as to prevent their damage during engagement or disengagement.
- **Disengagement:** when the seismic isolation is operational, the kinematic locator devices shall be backed off or removed to prevent interfering with actuator motion.

11 Lockdown systems are required between Stage 0 and Stage 1, and between Stage 1 and Stage 2 (see D030169) to serve the following functions and characteristics.

- **Clamping (non-operational):** when set for the clamping mode, the lockdown system shall lock the stages in all 6 DOFs in their respective operating positions and prevent relative motion between stages when exposed to earthquakes (as described above) or shipping loads (withstanding 50% larger than the maximum expected loadings).
- **Protection (operational):** when set for the operational mode, the lockdown system shall provide "stops" to limit travel during an earthquake so as to prevent contact at the actuators and at the displacement sensor/target pairs.
- **Repeatable**: the placement tolerance on the clamping position and the protection stops positions shall be +/- 0.003" (0.08 mm).
- **Survival:** these devices shall be designed such that they will not yield due an earthquake or shipping/handling event.
- **Accessible:** the devices shall be accessible to technicians, even when the structure is installed in the BSC chamber.
- **Convenient:** the engagement, adjustment and disengagement of the devices shall be designed with operator convenience in mind.
- **Durable:** the devices shall be designed such and procedures shall be written such as to prevent their damage during use and exposure.

12 Heavy structure elements shall have lifting provisions to aid in assembly.

13 The radii of gyration of Stage 1 and Stage 2 (without payload installed) shall be at least 45% of the stage's maximum physical radius (measured from the vertical centerline of the structure), with the preferred value being at approximately 80% of that radius.

D. Actuators, Seismometers, Displacement Sensors, Springs & Flexures:

1. Components shall be provided for as follows (refer to the in-vacuum portion of D000241 and also see D030169):
   a. between Stage 0 and Stage 1:
      i. magnetic actuators, PSI 0487-LIGO-d210 (50 lb_f continuous stall) (see drawing), 6 each, 2 at each of 3 "corners", one vertical and one tangential. Note: for this document, the term "tangential" refers to a component having its axis perpendicular to the line connecting the center of the structure with the displacement

sensor's axis at the sensing plane of the sensor element (or, in the case of actuators and seismometers, "…with the actuator's/ seismometer's axis at the center of the actuator/seismometer"), in plan view. The plane defined by the actuation centers of the 3 tangential actuators shall be within 0.040" (1 mm) of the plane defined by the lower zero moment points (LZMPs; see definition in iii. below) of the 3 flexures at that interface. These 2 planes shall be parallel to within 1 mrad. Each tangential actuator shall have its axis parallel to the plane defined by the LZMPs to within 1 mrad. The "bobbin" (wired) side of the actuators shall be attached to the ground side of each stage interface, for directed heat transfer; for instance, the bobbin side of the Stage 0-Stage 1 actuators shall be attached to Stage 0, which is closer to ground state. The actuator mounting design shall be by means of an oversize adapter plate to facilitate replacement of the actuator with a one of a different, but similar design. The adapter plate shall allow for actuator dimensions of at least 0.79" (2.0 cm) larger in each direction.

ii. capacitive displacement sensors, ADE Technologies, 20 mm ceramic passive probes (see drawing), 6 each, 2 at each of 3 "corners", one vertical and one tangential. Each pair shall be at least 39" (1 m) from the other two pair at this stage interface. Each position shall be made with added mounting holes and spacers to alternatively mount the 10 mm ADE sensors. The displacement sensor targets shall be made of 1100 aluminum, at least twice as wide as the 20 mm dia. sensors, with a surface flatness of 0.0004" (10 micrometer) and a surface finish of 0.000004" (0.1 micrometer). The tangential sensor axes shall coincide with the plane defined by the actuation centers of the three tangential actuators to within 1 mm. The axes of the sensors for vertical displacement shall be perpendicular to the plane defined by the actuation centers of the three tangential actuators to better than 1 mrad. The axis of the each vertical displacement sensor shall be placed (as closely as practical) near the axis of the vertical actuator that spans the same stages at that corner. The target standoff for the 20 mm dia. and the 10 mm dia. displacement sensors shall be 0.080" (2 mm) .

iii. spring and flexure sets, 3 each, 1 at each of 3 "corners", of Maraging 300 steel; springs of trapezoidal pattern; springs and flexures to be designed for a maximum stress of 35% of yield strength, with a goal of 30%, when operating at the working load at 1 g and with the flexure laterally offset as much as 1 mm from its nominal location. Exceptions for stress risers shall be proposed to the Contract Technical Manager for approval.

Springs:
Max stiffness: 4225 lb_f/in (7.4e5 N/m)
Max length: 19.7” (50 cm)
Max base width: ½ of length
The radial position of the flexure rod centers shall fall at between 60% and 90% of the maximum structure physical radius, measured from the structure’s vertical centerline.

Stages 1 and 2 each have 6 rigid body degrees of freedom. The frequencies of these 12 coupled rigid body modes (which involve elastic deflection of the springs and flexures) shall lie between 1.2 and 10 Hz.
Within this range, lower stiffness is preferred.
The payload configurations for which this requirement should be met are defined in H.4.i.

The flexures shall be designed such that the upper zero moment point of each flexure shall lie on the neutral axis of its spring. The zero moment points are defined by the following length from the fillet tangent at each end:

$$z = (1/k) * \tanh(k*L/2)$$

where $k = \mathrm{sqrt}\{P/(E*I)\}$ and L = flexure length, P = flexure load, E = Young’s modulus, and I = flexure area moment of inertia. The springs and flexures shall be located within the structure such that the flexures lie at the corners of an equilateral triangle, which is centered in the structure in the X-Y plane.

b. on Stage 1 (mounted in pods):
   i. seismometer, Mark Products L-4C (D047781), 6 each, 2 within each of 3 instrument pods or in separate pods, one vertical, +/- 1 mrad, and one tangential, +/- 1 mrad. For pod clearance purposes, the wiring connector will be in the form of a circuit board, coaxial with the L-4C, and fitting within a 2.00” (5.1 cm) diameter cylinder by 0.38” (1.0 cm) thick.
   ii. broadband seismometer, 3-axis, Streckeisen STS-2 (D047782), 3 each, 1 within each of 3 instrument pods; each seismometer’s axes directed as follows: +z axis vertical (upward), +/- 1 mrad, +y axis tangential, +/- 1 mrad, and +x axis radial (toward the center of the structure), +/- 1 mrad. Each STS-2 will have 3 devices for remotely locking and unlocking each axis (see Seismometer Lock file STS2Locker5.SLDASM).

c. between Stage 1 and Stage 2:
   i. magnetic actuators, PSI 0487-LIGO-d110 (7 lb_f continuous stall) (see drawing), 6 each, 2 at each of 3 “corners”, one vertical and one tangential. Configuration, position, mounting and location tolerances are as in D.1.a.i above. The horizontal actuator plane at the Stage 1-2 interface shall lie within +/- 1.57” (+/- 4 cm)

vertically with regard to the horizontal actuator plane at the Stage 0-1 interface.

ii. capacitive displacement sensors, ADE Technologies #020536-A01, 10 mm ceramic passive probes (see drawing), 6 each, 2 at each of 3 “corners”, one vertical and one tangential. Each pair shall be at least 39” (1 m) from the other two pair at this stage interface. Each position shall be made with added mounting holes to alternatively mount the 20 mm ADE sensors. The displacement sensor targets shall be made of 1100 aluminum, at least twice as wide as the 20 mm dia. sensors, with a surface flatness of 0.0004” (10 micrometer) and a surface finish of 0.000004” (0.1 micrometer). The tangential sensor axes shall coincide with the plane defined by the LZMPs of the flexures. The axes of the sensors for vertical displacement shall be perpendicular to the plane defined by the actuation centers of the three tangential actuators to better than 1 mrad. The axis of each vertical displacement sensor shall be placed (as closely as practical) near the axis of the vertical actuator that spans the same stages at that corner. The target standoff for both the 10 mm dia. and the 20 mm dia. displacement sensors shall be 0.020” (0.5 mm).

iii. spring and flexure sets: , 3 each, 1 at each of 3 “corners”, of Maraging 300 steel; springs of trapezoidal pattern; springs and flexures to be designed for a maximum stress (including stress concentrations) of 35% of yield strength, with a goal of 30%, when operating at the working load at 1 g and with the flexure laterally offset as much as 1 mm from its nominal location. Exceptions for stress risers shall be proposed to the Contract Technical Manager for approval.

Springs:
Max stiffness: 2512 lb_f/in (4.4e5 N/m)
Max length: 19.7” (50 cm)
Max base width: ½ of length
. The radial position of the flexure rod centers shall fall at between 70% and 90% of the maximum structure physical radius, measured from the structure’s vertical centerline.

Stages 1 and 2 each have 6 rigid body degrees of freedom. The frequencies of these 12 coupled rigid body modes (which involve elastic deflection of the springs and flexures) shall lie between 1.2 and 10 Hz.
Within this range, lower stiffness is preferred.
The payload configurations for which this requirement should be met are defined in H.4.i.

The flexures shall be designed such that the upper zero moment point of each flexure shall lie on the neutral axis of its spring. The springs and flexures shall be located within the structure such that the flexures lie at the corners of an equilateral triangle, which is centered in the structure in the X-Y plane.

d. on Stage 2 (mounted in pods):
   i. Seismometer, Geotech GS-13 (D047780), 6 each, 2 at each of three “corners”, 1 vertical, +/- 1 mrad, and 1 tangential, +/- 1 mrad. It is permissible to mount the unit by means of the three end studs, for both the tangential and the vertical axis configurations. For pod clearance purposes, the wiring connector will be in the form of a circuit board, coaxial with the GS-13, and fitting within a 2.00” (5.1 cm) diameter cylinder by 0.38” (1.0 cm) thick. Each GS-13 will have a device for remotely locking and unlocking the instrument .

2. Access shall be provided for installation, adjusting and removal of all pods, actuators, sensors, springs and flexures (including when the structures are in their respective chambers).

E. Instrument Pods:

1. This task provides for the design of the instrument pods, which will include provisions for installing seismometers and lock/unlock devices. The actual seismometers and lock/unlock devices, however, are to be provided by others.
2. The instrument pods will be removable (including when the modules are in their respective chambers) for maintenance. They should be repositionable upon replacement with an angular tolerance of 0.1 mrad in roll and pitch for the pod containing the STS-2 and 1.0 mrad for all other pod angle degrees of freedom and with a positional accuracy of 0.004” (0.1 mm).
3. The seismometers with their lock/unlock devices will be contained within the pods.
4. All instruments will be mounted in the pods quasi-kinematically.
5. Each Stage 1 pod shall contain an STS-2 seismometer and two L-4C seismometers. Alternatively, each Stage 1 seismometer may be mounted in a separate pod, for packaging efficiency. The Stage 1 pod shall accommodate mounting of the three lock/unlock devices (one for each axis) for the STS-2 seismometer, as defined by drawings in the file, STS2Locker5. Dynamic requirements stated elsewhere will drive the L-4C pods quite close to the actuators of their corner. It is preferred that the Stage 1 pods be located (as closely as practical) on-axis with the vertical actuators between Stages 0 and 1, given the geometric constraints. Provide height in the structure bay where the STS-2 pods are mounted for 1” (2.54 cm) additional growth in the pod height in the future.
6. Each Stage 2 pod shall contain a GS-13 seismometer. The Stage 2 pod shall accommodate mounting of the lock/unlock device for the GS-13 seismometer, as defined by TBD. It is preferred that the vertical Stage 2 pods be located (as

closely as practical) on-axis with the vertical actuators between Stages 1 and 2, and that the tangential Stage 2 pods be located (as closely as practical) on-axis in the plane of the tangential actuators between Stages 1 and 2.

7. The pods shall be sealed with reliable, ultrahigh vacuum seals; one acceptable type would be Conflat[*](CF)-type knife-edge flanges with flat copper gaskets.
8. The pods shall be filled with a trace gas mixture of 10 +/-1% neon in air for identification of leakage. This requirement can be met by performing pod assembly inside a glove box filled with 100% trace gas mixture at atmospheric pressure.
9. Each pod shall have a CF-type flange welded to provide electrical access as follows:
   i. The Stage 1 pods containing the STS-2 units shall have a 4.50" OD CF-type flange
   ii. The Stage 1 pods containing the L-4C units, if separate from those containing the STS-2 units, shall have a 2.75" OD CF-type flange
   iii. The Stage 2 pods shall have a 2.75" OD CF-type flange.

   This flange shall be compatible with repeated matings to a stainless steel CF-type flange of the same diameter, using copper gaskets, and still pass the pod leak test. Access shall be provided for the following planned connectors: STS-2 pods, one each D25; L-4C pods, one each D9; GS-13 pods, one each D9. If the STS-2 and L-4C units are housed in a single pod, one each D25 and one each D9 or, alternatively, two each D25s.
10. The interface between the stage and the instrument pod will be three 1.0" (2.5 cm) diameter, mounting pads.
11. Each pod shall pass a 1 x 10^{-10} tl/sec leak test, using helium in a hood type test.

F. Alignment:

1. The axes of the displacement sensors shall be aligned to better than 1% (i.e., a tangential sensor shall be tangential to <0.01" (0.25 mm) over 1" (2.5 cm)).
2. Each displacement target shall be adjusted to be parallel to its displacement sensor to within 1 mrad.
3. An alignment jig shall be provided to align each actuator coil with respect to its magnet such that its close tolerance side gap is balanced, side-to-side, to within 0.004" (0.1 mm) and it is mid-range in the directions of stroke and large tolerance side gap, to within 0.040" (1.0 mm). Actuator mounting feature details shall accommodate this alignment, and the jig design and procedures shall be such that the spacing is maintained upon jig removal.
4. Misalignment of the flexures and spring attachments could cause the system to suffer horizontal misalignments when released from the 6 DOF kinematic locators. The misalignment of the flexures and spring attachments shall not cause the suspended location of the system to be misaligned by more than 0.004" (0.1 mm) at any location between stage 0 and stage 1, and 0.002" (0.05 mm) between stage 1 and stage 2.

[*] Conflat is a registered trademark of Varian Vacuum Products

5. A procedure and fixturing shall be provided for installing the springs and flexures without damage to the spring, the flexure or any other part of the system. Note that the flexure is easily damaged.

G. Optical Table:

1. The BSC structure optical table portion of Stage 2 shall be a circular plate of 6061-T6 aluminum, with a minimum OD of 76.77" (195 cm).
2. The optical table shall be centered in the BSC chamber's plan view.
3. The optical table shall contain a matrix of ¼-20 holes containing wire inserts of Nitronic 60 material with minimum length of 0.375" (0.95 cm) at a spacing of 2.00" (5.08 cm) x 2.00" (5.08 cm), spread over the entire surfaceThe holes shall have an 82^{o} countersink of 0.390" (0.99 cm) diameter. One axis of the matrix shall be parallel to the axes of the chamber support tubes.
4. The optical table shall be flat within 0.01" (0.25 mm), with a surface finish of 64 rms or better.
5. The bottom surface of the optical table shall be 14.55" (37.0 cm) above the structure upper interface with the BSC Chamber Support Tubes. No part of the BSC structure shall protrude into an imaginary vertical axis box of cross sectional dimensions the size of the clipped rectangle in Drawing D030100 at the plane of the optical table and extending downward, and reducing to dimensions of 66.0" (168 cm) x 49.45" (125.6 cm) with the 66.0" (168 cm) dimension parallel to the chamber's support tubes) from 6.0" (15.24 cm) below the optical table and below. See Drawing D030100 for the shape and size of the "stay clear" zone and fastening tool access limits.

H. Masses:

1. The following masses are defined as part of the BSC Structure; the total of these shall be limited to a maximum of 8236 lb_m (3736 kg); less mass is much preferred.
   i. all Structure elements defined elsewhere in these requirements, except for the Payload described in H.2 below, including structural members, pods, seismometers, actuators, displacement sensors.
   ii. trim masses, which shall be bolted to Stages 1 and 2 in locations and in increments of mass to simultaneously make each stage level (correcting the levelness of each stage for variations in spring stiffness) to within 0.2 mrad. A means for measuring the levelness of each stage in the assembled condition shall be provided. The trim mass shall be able to accommodate a +/- 10% change in the mass of the Caltech provided items (actuators, seismometers, position sensors and associated cabling).
   iii. balance masses, which shall be bolted to Stages 1 and 2 in locations and in increments of mass to properly locate the center of gravity (CG) of Stages 1 and 2 in accordance with H.4, when a Payload (see H.2) is installed.
2. The following masses are defined as the Payload:

i. the aggregate of masses of individual nonsuspended components mounted on the optical table in a chamber; use 992 lb_m (450 kg) for modeling purposes

ii. the aggregate of masses of individual suspended components mounted on the optical table in a chamber; use 772 lb_m (350 kg) for modeling purposes

These payload components are the responsibility of the LIGO project. The contractor is only responsible to emulate the mass properties of the payload for the purpose of testing the assembly in accordance with the Statement of Work requirement c.7. The total payload mass (both non-suspended and suspended masses) shall be 1764 lb_m (800 kg) for a BSC system.

3 The design shall be capable of accommodating the payload mass properties of the layout scenarios defined in E040136-01.

4. The following payload configurations shall be used for verifying frequency requirements by analysis.
   i. Rigid Body Modes:
      a. Analysis: The requirements on the rigid body frequencies (sections D.1.a.iii and D.1.c.iii) shall be met with a 992 lbm (450 kg) mass, centered with respect to the optics table and set at (1) the surface of the optics table and (2) at a distance of 35.9 in (0.911 m) below the optics table. These two representations of the payload shall be constrained to follow the optics table. Any required (or nominal) trim, balance or ballast mass should also be attached to the system.
      b. Test: For the purpose of modal testing (SOW section c.7), the payload can be represented as 1764 lb_m (800 kg) mass distributed uniformly on the optics table (with no requirement to emulate the vertical position of the payload c.g.) Any required (or nominal) trim, balance or ballast mass should also be attached to the system.
   ii. Minimum structural frequency of Stage 2.
      a. Analysis: The minimum frequency requirements of section C.11 shall demonstrated to be met via finite element analysis (with the margin defined in SOW, section b) shall be met with a 992 lbm (450 kg) mass, centered with respect to the optics table and set at (1) the surface of the optics table and (2) at a distance of 35.9 in (0.911 m) below the optics table. These two representations of the payload shall be constrained to follow the optics table. Any required (or nominal) trim, balance or ballast mass should also be attached to the system.
      b. Test: For the purpose of modal testing (SOW section c.7), the payload may be represented in (a) above, or as a 1764 lbm (800 kg) mass distributed uniformly on the optics table (with no requirement to emulate the vertical position of the payload c.g. or footprint). Any required (or nominal) trim, balance or ballast mass should also be attached to the system.

iii. Transfer Functions of Stage 2.
   a. Analysis: The transfer function requirements of section C.10 shall be demonstrated to be met via finite element analysis (with the margin defined in SOW, section b) for the scenarios given in E040136-01, with the following exceptions or caveats: (a) of the listed payload items, only the quadruple pendulum structure needs to have its center of mass, position and footprint represented, (b) all other payload mass is to be represented by an effective center of mass position constrained to follow the entire optics table.
   b. Test: Modal testing (referred to in H.4.ii.b above) shall be used to validate the model (referred to in H.4.iii.c above).

5. The CG of the combined Stage 2 of the BSC structure and the nonsuspended portion of the payload for each of the layout scenarios defined in E040136-01 shall lie at +/- 4.72" (+/ 12 cm) vertically with regard to the horizontal actuator plane at the Stage 1-2 interface. As an alternative, LIGO may waive this requirement if models of structure configuration properties for specific payload cases that are provided pass an evaluation of control performance.
6. The Stage 1 CG shall lie at +/- 1.57" (+/- 4 cm) vertically with regard to the horizontal actuator plane at the Stage 0-1 interface.

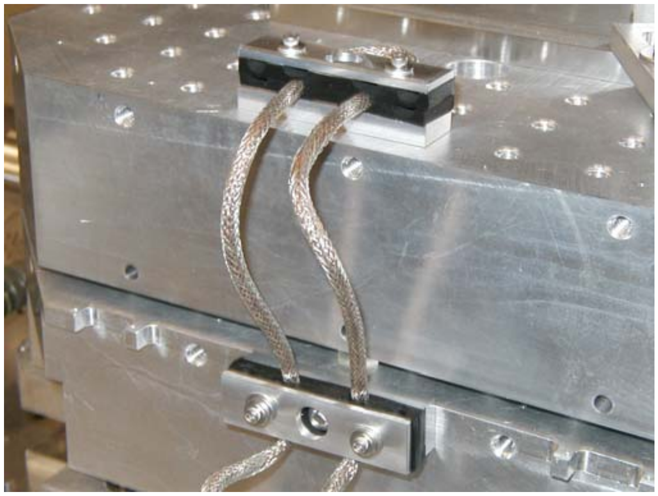
I. Cabling:

1. Clamping and routing provisions shall be made for the following control system cables, at each of three equally spaced areas around each structure. These cables shall be clamped at each stage that they traverse in sequence of suspension hierarchy, with cables spaced and routed such that they do not touch each other, do not touch any other items between clamps and will not sag over time to a position that causes them to touch. Clamps to be used will be as shown on D010120-D, Cable Clamps, 40M; the assembly is as shown in this photo (following) of a smaller unit. This task provides the mounting provisions for the clamps and cables; clamps and cables are provided by others. The following list is for each of three positions around each structure.

   Stage 1 (cables clamped at Stage 0 and Stage 1):
   - STS-2 broadband seismometer, 1 ea, 9 twisted pair of 28 ga conductors per, with shield
   - L4-C seismometer, 2 ea, 3 twisted pair of 28 ga conductors per, with shield
   - capacitive displacement sensor, 2 ea, 1 coax of 28 ga (minimum) conductors per
   - PSI d210 voice coil actuator, 2 ea, 1 twisted pair of 12 ga conductors per, with shield

   Stage 2 (cables clamped at Stage 0, Stage 1 and Stage 2):
   - GS-13 seismometer, 2 ea, 4 twisted pair of 28 ga conductors per, with shield

- capacitive displacement sensor, 2 ea, 1 coax of 28 ga (minimum) conductors per
- PSI d110 voice coil actuator, 2 ea, 1 twisted pair of 16 ga conductors per, with shield
- Optical Suspension controls, 5 ea, 12 twisted pair of 28 ga conductors per, with shield



Cable clamp assemblies, 4 cable capacity

J. Vacuum Compatibility:

1. The structures shall be designed for an ultrahigh vacuum environment.
2. All materials exposed to the vacuum environment shall be in accordance with the approved materials list (E960050). That document shows two lists: Table 1 for approved materials, and Table 2 for materials that could possibly be provisionally approved, if required and conditions permit.
3. All welds shall be made as full penetration welds to eliminate trapped volumes caused by welding.
4. Other trapped volumes (except for pod interiors) shall be provided with holes for venting during pumpdown. Holes shall be through holes wherever practical, to facilitate cleaning.
5. All tapped holes (except for the taps for wire inserts in the Optical Table) shall be made with 0.005” (0.13 mm) oversize taps for minimizing the potential for galling.
6. All nuts used external to the pods shall be retapped with 0.005” (0.13 cm) oversize taps for minimizing the potential for galling.
7. Stainless steel screws shall be used in aluminum tapped holes, and silver-plated stainless steel screws shall be used in stainless steel tapped holes, for minimizing the potential for galling. Silver plated screws shall be made undersized (or electropolished) to account for plating thickness, and the plating thickness shall be controlled accordingly.

8. Lubricants (other than silver plating) are not acceptable in the assembled structures.
9. Processing (small parts): parts that are small enough to be ultrasonically cleaned and vacuum baked shall be processed by the LIGO Project as detailed in E960022 (Appendix A, with screening test per 6.1.2). This processing shall be performed in 2 lots: BSC stainless steel, and BSC aluminum.
10. Processing (large parts): parts too large to be vacuum baked shall be processed in a manner similar to that detailed in procedures listed in E990452, E990453 and E990456, with the following additional details:
    - assembly: once sampling results have been approved and the parts have been baked, the structure is assembled in a clean room, with cleanliness maintained. Pods are not part of the assembled module.
    - packaging: ultrahigh vacuum clean aluminum foil, 0.0015” (0.038 mm) thickness,with fold lap seams and Class 100 polyolefin plastic sheeting (double bagged) with annealed copper tie wire (inner bag) and heat sealed seams (outer bag) used to package the structure, following an explicit wrapping plan.

K. Thermal:

1. Thermal Straps across stages:

   Three braided (or otherwise flexible) copper (OFHC) straps should be added between Stage 2 and Stage 1 and between Stage 0 and Stage 1. The straps from Stage 1 to Stage 0 should be located to conduct heat from the vicinity of the STS-2 pods on the Stage 1 structure to an adjacent point on the Stage 0 structure. The straps from Stage 2 to Stage 1 should also be in the vicinity of the STS-2 pods if practical; Otherwise locate these straps clocked equidistantly from the STS-2 stages. The straps should be bolted to each stage with a thin, annealed, foil (~0.002") of aluminum (or similar vacuum compatible, malleable, low resistance material) to form a low thermal resistance contact. The straps should have a ratio of effective cross sectional area to length of 0.11 inch each, while not restricting the relative motion of the stages nor contributing significantly to the stiffness between the stages. The surface finish of the aluminum structure at each bolted attachment should be <= 60 microinches rms. The attachment should be made with 2 (or more) 1/4-20 UNC high strength bolts with threaded inserts and torqued to the maximum allowed by standard practice.

2. Actuator interfaces:

   Bobbin connections shall be made at four faces for the purpose of reduced thermal resistance: the two opposite ends of the bobbin bottom, and the two opposite ends of the bobbin top. The small actuator bobbin top should be joined to the bobbin bottom with members comprised of copper (preferrably OFHC) braid, rod or bar. The two ends of the bobbin in the large actuator can be connected with copper or, alternatively, with an integral aluminum structure. The ratio of effective cross-sectional area to length, of the sections which join the two opposite ends of the bobbin top and the bobbin bottom, shall be no less than 0.053 inch for the small actuator and 0.15 inch for the large actuator.

The mechanical joints at the interface between the structure and the actuators, and between the actuator mount ("oversize interface plate" of section D.1.a.i) and the structure should include a thin, annealed, foil (aluminum or similar vacuum compatible, malleable, low resistance material) to lower the contact resistance. The screw size at the bobbin attachment is specified in the actuator ICD. High strength screws should be used at these attachments and torqued to the maximum allowed by standard practice. If the connection from opposite faces of the bobbin is not made with an integral structure, then the copper (preferably OFHC) braid or rod should be attached at the non-bobbin interface with 1/4-20 UNC high strength bolts with threaded inserts and torqued to the maximum allowed by standard practice. The surface finish on the faces of the connections should be <= 60 microinches rms.

L. Drawing Notes:

The following notes shall be added to all shop drawings, as appropriate:

1. All dimensions in inches
2. Dimensions and tolerancing per ASME Y14.5M-1994
3. Surface texture per ANSI/ASME B46.1-1985
4. Grinding aluminum is prohibited to mitigate the embedment of abrasive particles
5. Remove all burrs and break sharp edges to a maximum of 0.015”
6. All inside corners to be 0.015” radius max.
7. Countersink 82 degrees all tapped holes to major diameter
8. Countersink 82 degrees approximately 0.015 deep all drilled holes
9. Parts shall be thoroughly cleaned to remove all oil, grease, dirt and chips
10. All aluminum welding done by a GTAW process using 2% thoriated tungsten welding electrodes and ER4043 filler material
11. All stainless steel welding done by a GTAW process using 2% thoriated tungsten welding electrodes and ER308L filler material
12. All machining fluids shall be water soluble and free of sulfur, chlorine and silicone, such as Cincinnati Milacron’s Cimtech 410 (stainless steel)
13. Etch or stamp the drawing part number on noted surface of the part and then a three digit serial number. Serial numbers start at 001 for the first part and proceed consecutively. Use 0.07” high characters. Example: D010165-A 001