APPENDIX 4.4.A

STRAWMAN STRUCTURAL DESIGN OF A 30-M GSMT
Strawman Structural Design

of a 30-m

Giant Segmented Mirror Telescope

(GSMT)

prepared for

National Optical Astronomy Observatories
950 N. Cherry Avenue
Tucson, Arizona 85726

prepared by

Simpson Gumpertz & Heger Inc.
297 Broadway
Arlington, Massachusetts 02474
Tel.: 781 643-2000
Fax: 781 643-2009

Comm. 20000 8 January 2001
1. INTRODUCTION

1.1 Purpose

The purpose is to develop a strawman concept of the structure for a strawman optical design of a 30-m optical telescope, and to use this structural concept to evaluate the expected structural behavior needed in developing other aspects of the telescope design, in particular with respect to the adaptive optics system.

1.2 Scope

The scope of the work was to develop and analyze a strawman structural design of a telescope with a 30-m segmented primary. This included the design of the following:

Rafts to support groups of mirror segments
- The space truss system, the backstructure, to support the rafts
- The braced tripod to support the prime focus instrument or secondary mirror
- The transition structure which connects the backstructure to elevation bearings, drive arcs and counterweight supports
- The azimuth structure which rotates in azimuth and supports the elevation bearings

The design concept was used to illustrate the space available for instruments.

The analyses provided the following:
- Natural frequencies and mode shapes of the structure
- Deflections due to gravity
- Order of magnitude response to dynamic wind loads.

In addition, the required envelope for an enclosure was examined and a strawman enclosure concept outlined.

1.3 Design parameters

The following are the input parameters used in developing the design:

**M1**
- 30-m diameter f/D =1.0
- Mirror segments are hexagonal about 1.2 m across flats
- Mirror segments about 50 mm thick, 100 kg/sq m
- Weight of each segment is 200 kg. This includes glass 125 kg, whiffle tree 40 kg, position actuators 3 at 10 kg each, edge sensors and misc. 5 kg.
- Height from bottom of each actuator to mirror surface 0.5 m
- Actuator stiffness ~ 100 N per micron

**M2**
- 2-m diameter and 200 kg
- Mechanism for fast tip/tilt/focus and slower positioning weighs 2 tonnes and fits in envelope 2-m diameter by 2-m long
Prime Focus
• Instrument package weighs 3 tonnes and fits in envelope 1.8-m dia by 3-m long

Cassegrain and Nasmyth Foci

Option 1
• 30 tonnes at Cass

Option 2
• 10 tonnes at Cass and 30 tonnes at Nasmyth
2. STRAWMAN DESIGN OF STRUCTURE

This section of the report describes the strawman structural design of a telescope with a 30-m segmented primary.

We selected a layout of 619 hexagonal mirror segments and 91 rafts as shown in Fig. 2-1. A typical raft supports seven mirror segments. Each mirror segment is supported by actuators mounted on the raft structure and each raft is supported by another level of actuators mounted on the elevation structure.

The elevation and azimuth structures of the telescope are shown in Figs. 2-2 through 2-5. The function of the elevation structure is to support the segmented primary, the prime focus instrument and the M2 mirror; the elevation structure itself is supported on azimuth structure.

The elevation structure can be divided into three components: the tripod to support the prime focus instrument and the M2 mirror, the backstructure to support the rafts, and the hexagonal ring beam and elevation wheel structure which provides a transition structure from the backstructure to the azimuth structure.

The legs of the tripod are planar trusses braced by cables. The legs and bracing cables extend to outriggers outside the primary; this minimizes blockage and eliminates the need for penetrations through the M1 surface.

The elevation bearings are located within the elevation structure and are supported by stub shafts projecting from the azimuth structure. Consequently, there is no change in the moments applied to the elevation structure as the telescope rotates in elevation; also the forces and moments on the stub shafts remain constant.

This design of the elevation structure also provides a large Nasmyth platform located at the intersection of the elevation and azimuth axes, this platform is supported on the azimuth structure and does not rotate in elevation.

2.1 Mirror Segment and Raft Layout

We selected the mirror segment and raft layout shown in Fig. 2-1 as the strawman design. It consists of 619 hexagonal mirror segments and 91 (85 typical and 6 special) rafts. Each mirror segment is 1.152 m across flats and is to be supported in a statically determinate manner on actuators mounted on the front face of the raft structure. Each typical raft supports seven mirror segments; six special raft at the perimeter support four mirror segments. Each raft is supported by a hexapod mounted from the front face of the elevation backstructure.

In this study, we assumed that the mirror segments would project as regular hexagons on the aperture plane

2.2 Raft Structure

The design of the raft structure is shown in Figs. 2-6 and 2-7. The raft structure consists of a space truss with triangular grillage supported through a non-adjustable hexapod structure mounted on a triangular base. An adjustable hexapod connects the triangular base to the front face of the backstructure. The position of the raft can be controlled by the actuators in the adjustable hexapod.
2.3 Backstructure

The backstructure is a space truss in which each joint on the front face is a support point for the hexapod which in turn supports the raft. The layout of the mirror segments and the rafts is shown in Fig 2-1. The layout of the front face, back face and the posts and diagonals between the front and back face of the truss are shown in Figs. 2-8 through 2-10. The configuration is a triangular grillage of trusses, with approximately half as many nodes on the back face as on the front face.

The backstructure is divided into three zones. The members are grouped as front face chords, back face chords, posts and diagonals. The members in each of the groups are considered to have similar properties in a given zone.

2.4 Tripod Structure

The tripod structure, as shown in Fig. 2-11, supports the prime focus instrument, the M2 mirror and the positioner. Each of the tripod legs is a planar truss assembly and is braced out of plane at two locations along its length by prestressed cables attached to mid-depth of the truss.

2.5 Transition Structure and Counterweight Support

This portion of the elevation structure, as shown in Fig. 2-12, connects the backstructure to its support points on the azimuth structure. It consists of a hexagonal ring beam and transverse members, a cone structure, drive arc, counterweight and bracing members. The elevation bearings are located aft of the side members of the hexagonal ring beam. The cone structure provides out of plane stiffness to the hexagonal ring and also serves to transfer the counterweight load to the hexagonal ring beam. The counterweight consists of a steel box filled with concrete. The counterweight is shaped in such a way that it will clear the members of the azimuth structure. Braces are required to provide torsional restraint of the counterweight mass and drive arc supports.

2.6 Azimuth Structure

The azimuth structure supports the elevation structure through the elevation stub shafts. The azimuth structure also houses the elevation drives and the azimuth drives. The four corners of the base of the azimuth structure are supported by hydrostatic bearings. At the center of the base of the azimuth structure, there is a pintle bearing to keep the structure centered.

2.7 Instrument Space

The purpose of this section is to identify the space available for instruments within the current telescope structure conceptual design.

The coordinate system is based on the origin at the vertex of the primary, the x axis is parallel to the elevation axis, the z axis is along the optic axis, and the y axis is up when the telescope points to horizon. The elevation axis is at z = -7.925 m (-312 in.). The optic, elevation, and azimuth axes intersect at a point.

There are three main spaces, which are described in general terms as follows. The locations and shapes are illustrated in Figs. 2-13 through 2-23, and dimensions are shown in Figs. 2-24 through 2-26.
1. The Upper Cassegrain Space. This space moves in elevation; it is in the reflector backstructure centered at \( z = -3.7 \) m and has truss members going through it. Its overall dimensions are approximately \( 18 \) m \( \times \) \( 15.5 \) m \( \times \) \( 1.2 \) m. Note that although the clear height is only \( 1.2 \) m, access is practical in that there is good headroom between truss members.

2. The Lower Cassegrain Space. This space moves in elevation. It is in the space within the hexagonal beam and cone structure behind the reflector backstructure centered at \( z = -7.2 \) m; its overall dimensions are approximately \( 10 \) m \( \times \) \( 5.5 \) m \( \times \) \( 4.5 \) m.

3. The Nasmyth Platform. This space is supported on the azimuth structure and therefore does not move in elevation. It is located between the elevation bearings, and is centered at \( z = -6.9 \) m; its overall dimensions are approximately \( 16 \) m \( \times \) \( 6 \) m \( \times \) \( 4 \) m.

The clear space centered on the optic axis from the vertex of the primary to the Upper Cassegrain Space is a 1.5-m-diameter cylinder. The clear space from the Upper Cassegrain Space along the optic axis to the intersection with the elevation axis is a 3-m-diameter cylinder.

Light can be directed to instruments in the Upper Cassegrain Space or pass through that space to the elevation axis where a flat mirror that rotates with the elevation structure can direct the light either along the elevation axis to instruments on the Nasmyth platform or to the Lower Cassegrain Space.

2.8 Weight and Inertias

The total weight of the elevation structure, that is the weight supported on the elevation bearings, is \( 0.7E6 \) kg and the inertia about the elevation axis is \( 88E6 \) kg m\(^2\).

The total combined weight of the elevation and azimuth structures, that is the total weight on the hydrostatic bearings, is \( 1.4E6 \) kg and the inertia about the azimuth axis is \( 170E6 \) kg m\(^2\) when the telescope is horizon pointing.
3. **FINITE ELEMENT ANALYSES**

3.1 **Finite Element Models**

3.1.1 **Finite Element Model of Raft Structure**

The finite element model (FEM) of the raft structure is shown in Figs. 2-6 and 2-7. The structural members were modeled as beam elements. The mirror segments and whiffle-tree supports were modeled as lumped masses.

The FEM of the raft structure was analyzed to obtain natural frequencies and associated mode shapes, and deflections due to gravity loads.

3.1.2 **Finite Element Model of Elevation and Azimuth Structure**

The finite element model of the elevation and azimuth structure is shown in Figs. 2-2 through 2-5. The structural members were modeled as truss and beam elements. The stiffness of bearings and drives were modeled with spring elements. The mirror segments and raft structures were modeled as lumped masses.

The FEM of the elevation and azimuth structure was analyzed to obtain natural frequencies and associated mode shapes, and deflections due to gravity loads with the telescope at zenith and horizon pointing. This FEM was also used to perform random response analyses to obtain order of magnitude response of the telescope to dynamic wind loads (see Section 4 for details).

3.2 **Results of Finite Element Analyses**

3.2.1 **Natural Frequencies and Mode Shapes**

The natural frequencies and modes of the raft structure are listed in Table 3-1. The mode shapes of the raft structure are shown in Figs. 3-1 through 3-4.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency (Hz)</th>
<th>Mode Shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 &amp; 2</td>
<td>5.8</td>
<td>Side sway</td>
</tr>
<tr>
<td>3</td>
<td>12.0</td>
<td>Torsional</td>
</tr>
<tr>
<td>4 &amp; 5</td>
<td>21.5</td>
<td>Clamshell</td>
</tr>
<tr>
<td>6</td>
<td>21.8</td>
<td>Vertical</td>
</tr>
</tbody>
</table>

The natural frequencies and modes of the elevation and azimuth structures for zenith and horizon pointing for the locked-rotor condition are listed in Table 3-2. The mode shapes of the elevation and azimuth structures for zenith and horizon pointing are shown in Figs. 3-5 through 3-12.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency (Hz)</th>
<th>Mode Shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 &amp; 2</td>
<td>5.8</td>
<td>Side sway</td>
</tr>
<tr>
<td>3</td>
<td>12.0</td>
<td>Torsional</td>
</tr>
<tr>
<td>4 &amp; 5</td>
<td>21.5</td>
<td>Clamshell</td>
</tr>
<tr>
<td>6</td>
<td>21.8</td>
<td>Vertical</td>
</tr>
</tbody>
</table>
Zenith Pointing

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency (Hz)</th>
<th>Mode Shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.17</td>
<td>Nodding (Elevation)</td>
</tr>
<tr>
<td>2</td>
<td>2.24</td>
<td>Side sway</td>
</tr>
<tr>
<td>3</td>
<td>2.70</td>
<td>Torsional (Azimuth)</td>
</tr>
<tr>
<td>4</td>
<td>3.09</td>
<td>Tripod</td>
</tr>
</tbody>
</table>

Horizon Pointing

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency (Hz)</th>
<th>Mode Shape</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.16</td>
<td>Nodding (Elevation)</td>
</tr>
<tr>
<td>2</td>
<td>2.16</td>
<td>Torsional (Azimuth)</td>
</tr>
<tr>
<td>3</td>
<td>2.27</td>
<td>Side sway</td>
</tr>
<tr>
<td>4</td>
<td>3.09</td>
<td>Tripod</td>
</tr>
</tbody>
</table>

3.2.2 Gravity Deflections

The deformed shapes of the raft structure for 1g gravity load in +X, +Y, and +Z directions are illustrated in Figs 3-13 through 3-15. The displacements and rotations of the mirror segments for 1g gravity load in +X, +Y, and +Z directions are listed in Table 3-3.

Table 3-3 – Displacements and Rotations of Mirror Segments for Gravity Loads

<table>
<thead>
<tr>
<th>1 g Gravity Load in +X Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mirror Segment</td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>S1</td>
</tr>
<tr>
<td>S2</td>
</tr>
<tr>
<td>S3</td>
</tr>
<tr>
<td>S4</td>
</tr>
<tr>
<td>S5</td>
</tr>
<tr>
<td>S6</td>
</tr>
<tr>
<td>S7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>1 g Gravity Load in +Y Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mirror Segment</td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>S1</td>
</tr>
<tr>
<td>S2</td>
</tr>
<tr>
<td>S3</td>
</tr>
<tr>
<td>S4</td>
</tr>
<tr>
<td>S5</td>
</tr>
<tr>
<td>S6</td>
</tr>
<tr>
<td>S7</td>
</tr>
<tr>
<td>Mirror Segment</td>
</tr>
<tr>
<td>----------------</td>
</tr>
<tr>
<td>S1</td>
</tr>
<tr>
<td>S2</td>
</tr>
<tr>
<td>S3</td>
</tr>
<tr>
<td>S4</td>
</tr>
<tr>
<td>S5</td>
</tr>
<tr>
<td>S6</td>
</tr>
<tr>
<td>S7</td>
</tr>
</tbody>
</table>

See Fig. 3-2 for locations of mirror segments.

The deformed shapes of the elevation and azimuth structures for zenith and horizon pointing gravity load are illustrated in Figs 3-16 and 3-17. The displacements of the rafts with respect to the central raft for zenith and horizon pointing gravity load are show in Figs. 3-18 through 3-27.
4. **DYNAMIC WIND RESPONSE**

We performed random response analyses to obtain order of magnitude response of the structure to dynamic wind loads. In the following sections, we will discuss the input wind spectra used in this study, the method of analysis, and the results.

4.1 **Input Wind Spectra**

The input wind spectra used in this study are based on actual pressure and velocity measurements taken by Dr. David Smith at Gemini South Telescope atop Chile's Cerro Pachón. The following two cases were chosen since they are real configurations which might occur during an observation and cover calm to windy conditions:

Case 1: Vent gate closed, wind screen closed, telescope pointing into wind, and zenith angle = 30 deg.
Case 2: Vent gate open, wind screen open, telescope pointing into wind, and zenith angle = 30 deg.

In both cases, the average outside wind speed is between 11.5 and 13 m/s which matches typical operational wind speeds.

Figs. 4-1 and 4-2 show the average power spectral density (PSD) of all the M1 pressure sensors for the two cases. The two design spectra are used to generate the forces to be applied to the M1 mirrors. Figs. 4-3 and 4-4 show the power spectral density for the velocity sensor located just below the M2 unit for the two cases. The two design spectra are used to generate forces to be applied to the M2 mirror and its supporting structure.

4.2 **Method of Analysis**

To estimate the order of magnitude response of the structure to dynamic wind loads, we performed random response analyses using the finite element model described in the previous section.

To represent the dynamic wind load on the M1 mirrors, we applied a random excitation force normal to the mirror surface at the center of each of the 91 rafts. The magnitude of the force on each raft was computed based on the average M1 pressure power spectral density shown on Figs. 4-1 and 4-2. In this study, these forces were assumed to be uncorrelated random excitations. This is consistent with the actual pressure measurements taken at Gemini South which indicate that the wind pressures would be correlated within a raft but uncorrelated from raft to raft.

The wind load on the M2 mirror and its supporting structure was applied as random excitation forces on the M2 mirror, along the tripod legs, and on the apex of the tripod. The magnitude of the forces was computed based on the wind velocity power spectral density shown on Figs. 4-3 and 4-4. The forces along each tripod leg were grouped into three separate zones. The forces within each zone were assumed to be completely correlated and the forces from different zones were assumed to be uncorrelated. The telescope was assumed to be at zenith pointing in this study.

4.3 **Results**

Power spectral density curves and RMS values of the displacements and rotations were computed for all 91 rafts and the M2 mirror. Figs. 4-5 through 4-12 show the power spectral
density curves for the displacements and rotations of the central raft and the M2 mirror for the two cases analyzed. Table 4-1 summarizes the minimum, average and maximum RMS response of the 91 rafts and the M2 mirror for the two cases analyzed.

Table 4-1 – RMS Response of Telescope Structure at Rafts and M2

<table>
<thead>
<tr>
<th></th>
<th>TX, RMS (μm)</th>
<th>TY, RMS (μm)</th>
<th>TZ, RMS (μm)</th>
<th>RX, RMS (μrad)</th>
<th>RY, RMS (μrad)</th>
<th>RZ, RMS (μrad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vent Gates Closed, Wind Screen Closed</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Telescope Pointing into Wind, and Zenith Angle = 30 deg.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum among Rafts</td>
<td>0.32</td>
<td>5.35</td>
<td>0.40</td>
<td>0.368</td>
<td>0.018</td>
<td>0.114</td>
</tr>
<tr>
<td>Average among Rafts</td>
<td>0.88</td>
<td>6.00</td>
<td>2.70</td>
<td>0.447</td>
<td>0.101</td>
<td>0.153</td>
</tr>
<tr>
<td>Maximum among Rafts</td>
<td>1.75</td>
<td>6.86</td>
<td>6.42</td>
<td>0.630</td>
<td>0.261</td>
<td>0.264</td>
</tr>
<tr>
<td>M2</td>
<td>16.80</td>
<td>39.35</td>
<td>0.66</td>
<td>0.633</td>
<td>1.543</td>
<td>21.850</td>
</tr>
<tr>
<td>Vent Gates Open, Wind Screen Open</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Telescope Pointing into Wind, and Zenith Angle = 30 deg.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum among Rafts</td>
<td>1.66</td>
<td>13.75</td>
<td>1.27</td>
<td>0.945</td>
<td>0.074</td>
<td>0.297</td>
</tr>
<tr>
<td>Average among Rafts</td>
<td>2.79</td>
<td>15.41</td>
<td>7.03</td>
<td>1.158</td>
<td>0.308</td>
<td>0.387</td>
</tr>
<tr>
<td>Maximum among Rafts</td>
<td>4.71</td>
<td>17.54</td>
<td>16.55</td>
<td>1.615</td>
<td>0.777</td>
<td>0.664</td>
</tr>
<tr>
<td>M2</td>
<td>42.60</td>
<td>99.91</td>
<td>2.08</td>
<td>1.664</td>
<td>3.899</td>
<td>54.638</td>
</tr>
</tbody>
</table>
5. ENCLOSURE CONCEPTS

The size and configuration of the enclosure depends on, amongst other factors, the clear space needed inside. For the strawman telescope concept we have developed the required envelope is as follows:

- For full motion in elevation inside the enclosure the required envelope is 30m wide by 60m long by 60m high.
- To allow full motion in azimuth as well as in elevation requires an envelope 90m in diameter by 60m high.
- The envelope size can be reduced by using a co-rotating enclosure and limiting the range of motion in elevation when the enclosure is closed.

One approach is to use a tall co-rotating enclosure in which the telescope can move between, say, 45° and 90° in elevation. In such a design, the envelope is 30m wide by 47m long by 60m high, and rotates about an azimuth axis 15m from one end.

Alternately, one could use a low and long co-rotating enclosure in which the telescope is stowed near 0° elevation, i.e. horizon pointing. The required envelope would be 30m wide by 60m long by 30m high and would rotate about an azimuth axis 15m from one end.

In considering the fixed versus co-rotating enclosures, the relevant tradeoffs are size of the enclosure versus increased cost of the rotation system.

With respect to the limited elevation range within the enclosure, the critical issues are:

- Maintenance of the telescope is limited to the near zenith or near horizon attitudes.
- The risk that a malfunction would prevent the movement of the telescope to the stow elevation and thus prevent closing the enclosure.

A strawman tall co-rotating enclosure concept to house the 30-m strawman telescope concept was developed based on a scaled up taller variation of the enclosure of the 15-m JCMT. The concept is shown in Figs 5-1 through 5-3.

Another approach could be to use a scaled down variation of the concept for an enclosure for a 50-m telescope proposed by Andersen and Christensen SPIE Conf. Munich 2000 Vol. 4004 p. 373.
Fig 2-1 – Mirror Segment and Raft Layout

Fig. 2-2 – Elevation and Azimuth Structures – Isometric View
Fig. 2-3 – Elevation and Azimuth Structures – Front Elevation

Fig 2-4 – Elevation and Azimuth Structures – Side Elevation
Fig 2-5 – Elevation and Azimuth Structures – Plan View

Fig. 2-6 – Raft Structure with Seven Mirror Segments – Isometric View
Fig. 2-7 - Raft Structure with Seven Mirror Segments – Plan View

Fig. 2-8 – Front Face of Backstructure – Plan View
Fig. 2-9 – Back Face of Backstructure – Plan View

Fig. 2-10 – Backstructure – Isometric View
Fig. 2-11 – Tripod Structure – Isometric View

Fig. 2-12 – Transition Structure and Counterweight Support – Isometric View
Fig. 2-13 – Upper & Lower Cassegrain Spaces and Nasmyth Platform shown with Backstructure, Hex Beam and Cone Structure – Isometric View

Fig. 2-14 – Upper & Lower Cassegrain Spaces and Nasmyth Platform shown with Hex Beam and Cone Structure – Isometric View
Fig. 2-15 – Upper & Lower Cassegrain Spaces and Nasmyth Platform shown with Hex Beam and Cone Structure – Top View

Fig. 2-16 – Upper & Lower Cassegrain Spaces and Nasmyth Platform shown with Hex Beam and Cone Structure – Front View
Fig. 2-17 – Lower Cassegrain Space and Nasmyth Platform shown with Hex Beam (One Side Beam Removed) and Cone Structure – Isometric View

Fig. 2-18 – Lower Cassegrain Space and Nasmyth Platform shown with Hex Beam (One Side Beam Removed) and Cone Structure – Side View
Fig. 2-19 – Upper Cassegrain Space shown with Central Space Above (1.5 m Cylinder) and Below (3.0 m Cylinder) – Isometric View

Fig. 2-20 – Upper Cassegrain Space shown with Central Space Above (1.5 m Cylinder) and Below (3.0 m Cylinder) – Side View
Fig. 2-21 – Lower Cassegrain Space shown with Hex Cross Beam – Isometric View

Fig. 2-22 – Nasmyth Platform shown with Alidade Cross Beam – Isometric View
Fig. 2-23 – Nasmyth Platform shown with Alidade Cross Beam – Side View
PLAN

Floor  Z=-4.369m. [-172in.]
Ceiling  Z= -3.124m. [-123in.]
Floor to ceiling height 1.245m. [49in.]

SECTION A-A

Showing posts and diagonals

Fig. 2-24 – Upper Cassegrain Space
Fig. 2-25a – Lower Cassegrain Space - Isometric View

Fig. 2-25b – Lower Cassegrain Space - Plan View
Fig. 2-26b – Nasmyth Platform - Plan View

Fig. 2-26c – Nasmyth Platform - Side View
Fig. 3-1 – Mode Shape Of Raft Structure - Mode 1 = 5.8 Hz

Fig. 3-2 – Mode Shape Of Raft Structure - Mode 2 = 12.0 Hz
Fig. 3-3 – Mode Shape Of Raft Structure - Mode 3 = 21.5 Hz

Fig. 3-4 – Mode Shape Of Raft Structure - Mode 4 = 21.8 Hz
Fig. 3-5 – Mode Shape For Zenith Pointing - Mode 1 = 2.17 Hz

Fig. 3-6 – Mode Shape For Zenith Pointing - Mode 2 = 2.24 Hz
Fig. 3-7 – Mode Shape For Zenith Pointing - Mode 3 = 2.70 Hz

Fig. 3-8 – Mode Shape For Zenith Pointing - Mode 4 = 3.09 Hz
Fig. 3-9 – Mode Shape For Horizon Pointing - Mode 1 = 2.16 Hz

Fig. 3-10 – Mode Shape For Horizon Pointing - Mode 2 = 2.16 Hz
Fig. 3-11 – Mode Shape For Horizon Pointing - Mode 3 = 2.27 Hz

Fig. 3-12 – Mode Shape For Horizon Pointing - Mode 4 = 3.09 Hz
Fig. 3-13 – Deformed Shape (50x) Of Raft Structure For 1g Gravity Load In +X Direction

Fig. 3-14 – Deformed Shape (50x) Of Raft Structure For 1g Gravity Load In +Y Direction
Fig. 3-15 – Deformed Shape (500x) Of Raft Structure For 1g Gravity Load In +Z Direction

Fig. 3-16 – Deformed Shape For Gravity Load - Zenith Pointing
Fig. 3-17 – Deformed Shape For Gravity Load - Horizon Pointing
Fig. 3-18 – Normal Displacement (µm) Of Rafts With Respect To Central Raft
Gravity Load - Zenith Pointing

Fig. 3-19 – Tangential Displacement (µm) Of Rafts In Radial Plane With Respect To Central Raft - Gravity Load - Zenith Pointing
Fig. 3-20 – Circumferential Displacement (µm) Of Rafts With Respect To Central Raft Gravity Load - Zenith Pointing

Fig. 3-21 – Rotation (µRad) Of Rafts About Tangential Direction In Radial Plane With Respect To Central Raft - Gravity Load - Zenith Pointing
Fig. 3-22 – Rotation (µRad) Of Rafts About Circumferential Direction With Respect To Central Raft - Gravity Load - Zenith Pointing

Fig. 3-23 – Normal Displacement (µm) Of Rafts With Respect To Central Raft Gravity Load - Horizon Pointing
Fig. 3-24 – Tangential Displacement (µm) Of Rafts In Radial Plane With Respect To Central Raft - Gravity Load - Horizon Pointing

Fig. 3-25 – Circumferential Displacement (µm) Of Rafts With Respect To Central Raft Gravity Load - Horizon Pointing
Fig. 3-26 – Rotation (μRad) Of Rafts About Tangential Direction In Radial Plane With Respect To Central Raft - Gravity Load - Horizon Pointing

Fig. 3-27 – Rotation (μRad) Of Rafts About Circumferential Direction With Respect To Central Raft - Gravity Load - Horizon Pointing
Fig. 4-1 – Average M1 Pressure Power Spectral Density
Vent Gates Closed, Wind Screen Closed, Pointing into Wind, Zenith Angle = 30 deg.

M1 Average Pressure Prms = 0.14 Pa
Design Spectrum
Fig. 4-2 – Average M1 Pressure Power Spectral Density
Vent Gates Open, Wind Screen Open, Pointing into Wind, Zenith Angle = 30 deg.

M1 Average Pressure Prms = 5.22 Pa
Design Spectrum
Fig. 4-3 – Wind Velocity Power Spectral Density
Vent Gates Closed, Wind Screen Closed, Pointing into Wind, Zenith Angle = 30 deg.

Measured at M2, \( V_{rms} = 1.67 \) m/s

Design at \( 1.0^*f^{(-5/3)} \)
Fig. 4-4 – Wind Velocity Power Spectral Density
Vent Gates Open, Wind Screen Open, Pointing into Wind, Zenith Angle = 30 deg.

Measured at M2, \( V_{rms} = 2.07 \, m/s \)
Design at \( 2.5^*f^{(-5/3)} \)
Fig. 4-5 – Central Raft Displacement Power Spectral Density
Vent Gates Closed, Wind Screen Closed, Pointing into Wind, Zenith Angle = 30 deg.
Fig. 4-6 – Central Raft Rotation Power Spectral Density
Vent Gates Closed, Wind Screen Closed, Pointing into Wind, Zenith Angle = 30 deg.
Fig. 4-7 – Central Raft Displacement Power Spectral Density
Vent Gates Open, Wind Screen Open, Pointing into Wind, Zenith Angle = 30 deg.
Fig. 4-8 – Central Raft Rotation Power Spectral Density
Vent Gates Open, Wind Screen Open, Pointing into Wind, Zenith Angle = 30 deg.
Fig. 4-9 – M2 Displacement Power Spectral Density
Vent Gates Closed, Wind Screen Closed, Pointing into Wind, Zenith Angle = 30 deg.
Fig. 4-10 – M2 Rotation Power Spectral Density
Vent Gates Closed, Wind Screen Closed, Pointing into Wind, Zenith Angle = 30 deg.
Fig. 4-11 – M2 Displacement Power Spectral Density
Vent Gates Open, Wind Screen Open, Pointing into Wind, Zenith Angle = 30 deg.
Fig. 4-12 – M2 Rotation Power Spectral Density
Vent Gates Open, Wind Screen Open, Pointing into Wind, Zenith Angle = 30 deg.
Fig. 5-1 – Scaled Up and Taller Variation of JCMT Enclosure - Floor Plan

Fig. 5-2 – Scaled Up and Taller Variation of JCMT Enclosure - Roof Plan
Fig. 5-3 – Scaled Up and Taller Variation of JCMT Enclosure - Section A