Concept Design Report
Mirror segment support system
California Extremely Large Telescope
CELT Report #16

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1. INTRODUCTION

A concept design has been developed for the mirror segment support system for the California Extremely Large Telescope. The work has entailed considerable finite element analysis and numerous CAD layouts. A total of 62 finite element models, many with multiple load cases, were created and solved. The most important of these results are summarized below with the aid of pertinent FEA graphics plots. The CAD drawings which best show the current design are included in this report as figures “CAD-1" through “CAD-8". During the period of performance of this work, informal weekly reports were submitted. They are also included in the addendum of this report along with vendor quotations and other miscellaneous background information.

2. AXIAL SUPPORT SYSTEM

As shown in drawing CAD-1, the segment was specified as hexagonal, 1 m across points, 45 mm thick and made of Schott Zerodur glass ceramic. In addition, it was required that the support system be designed and optimized with 18 axial support points and a lateral support that worked from the back surface (no holes or pockets in the mirror).

For 18 supports of a hexagonal segment the smallest fundamental geometry consists of a 1/12th segment wedge indicated by the phantom lines in Figure 1, “Axial Support Geometries”. Such a system includes 4 possible topologies, analyzed initially with finite element models CELT3, CELT4, CELT7, and CELT8 also indicated in Figure 1. (Note that the small round symbols are support locations, the larger square symbols actuator centers).

2.1 Surface distortion and support topologies

During the finite element optimizations it was recognized that a support which defines the minimum peak-to-valley (p/v) surface distortion would not necessarily also define the minimum rms. This is particularly true for the two topologies without supports near the corners. In other words, by allowing the corners (with a relatively small area) to droop somewhat, the supports can do a better job of minimizing deflections of the rest of the segment, which has a much larger area. Therefore two additional optimizations are included in Figure 1 - CELT5 based on the CELT4 topology and CELT30 based on the CELT3 topology. Note that in both cases the rms lowered even though the peak-to-valley increased.

Topologies CELT(3 & 30) and CELT(4 & 5) define actuator centers which are rotationally symmetric with respect to the hexagon while topologies CELT7 and CELT8 do not. It was initially assumed that this lack of symmetry would be undesirable due to complicating system design and increasing hardware cost. However, the minimum-rms topology is currently the unsymmetric CELT7. (Its final optimization yielded a p/v surface distortion of 19.6 nm. Although not yet calculated, the rms will certainly be a little less than 5.06 nm, an earlier result with a slightly higher p/v.) CELT7 has been more highly optimized than the other geometries. However, it is expected that with further optimization of the symmetric topologies they will define an rms surface distortion which is still about 1 nm greater than CELT7. This results from the fact that the CELT7 topology has two supports on a radial line to the corners of the hexagon and it therefore does a better job of controlling the corners. In summary, there is a trade to be evaluated of the (approximate 1 nm) performance gain against potential complications which might result from the unsymmetric geometry.

2.2 Finite element analysis

Three-dimensional solid elasticity (brick) elements were used to calculate the surface distortion due to axial gravity. One of the models (CELT7) is shown as Figure 3. Nodal restraints were used to define symmetry boundary conditions in the YZ plane and beam elements end-released to define only axial stiffness were used on the skewed plane as shown. Nodal loads, although not shown, were used to support the model from below, while axial gravity element loading was applied directly to the brick elements. The single vertical (axial-only) beam element at the origin was used to verify the vertical balance of the model (equilibrium defines that it should have zero force).

The optimizations were done by a combination of moving nodal loads and varying their relative magnitudes in order to minimize the peak-to-valley surface distortion. A highly exaggerated deflected plot of the surface shape was generated by mirror/rotating the 1/12th segment surface around the Z axis. Shown as Figure 5, the print-through from each of the 18 supports is apparent. The dithered color contour plot directly from CELT7 is shown as Figure 6. A summary of the results for all 6 geometries follows:

Surface distortion due to 1 g axial gravity

Geometry (model)	**Peak-to-valley, nm**	**RMS, nm**	**Comments**
CELT3	29.3	6.9	Symmetric. Not highly optimized.
CELT30	27.3;24.6	6.3	CELT3 topology better optimized.
CELT4	29.0	6.8	Symmetric. Not highly optimized.
CELT5	38.3;20.3	6.14	CELT4 topology better optimized.
CELT7	19.6	(< 5.06)	Not symmetric. RMS not calculated. Most highly optimized.

Surface distortion due to 1 g axial gravity			
CELT8	28.5	7.11	Not symmetric.

2.3 Axial support hardware

The axial support hardware was designed to be inexpensive to manufacture in large quantities. Assembly views are included in drawings CAD-1and CAD-2, with detailed views in drawings CAD-4 and CAD-6. As shown, each system includes:

2.3.1 18 rod flexures (ref CAD-2 and CAD-6), an epoxied assembly comprised of 2 aluminum sleeves, 1 aluminum axial support pad, 2 piano wire flexures, and a silicone pad. The silicone pad is glued with silicone adhesive to the axial support pad and later to the back of the segment with the same silicone (ref weekly report, "Assembly Plan"). The rod flexure serves to stiffly transfer axial load to the segment while accommodating tilt motions and manufacturing tolerances without inducing significant deflections of the segment. Each rod flexure assembly weighs only about 0.5 oz. so that deleterious effects due to self-weight under lateral gravity are also negligible.

2.3.2 6 tri-plates (ref CAD-2 and CAD-4), a ½" thick triangular aluminum plate which acts as a load spreader from the whiffletree ends to the rod flexures. The tri-plates are laser cut, Blanchard ground, and production drilled and tapped as shown.

2.3.3 6 tri-plate pivots (ref CAD-2 and CAD-6), an epoxied assembly that connects the tri-plates to the ends of the whiffletree beams. This is done in a way that assures no bending transfers to the segment due either to axial force or moment errors on the tri-plates that might result from horizon gravity. This is discussed in some detail in appendix report "Surface distortion due to Tri-plate Pivots under horizon gravity".

2.3.4 3 whiffletrees (ref CAD-2), a mechanical assembly with (2) 1/4" side plates and 2 whiffletree blocks. The assemblies are aluminum.

2.3.5 2 whiffletree pivots (ref CAD-2). Baselined as TRW Lucas Aerospace "Free-Flex Pivots", they serve to (somewhat) stiffly apply the actuator force to the whiffletrees with only small moment error. Due to their significant cost and less than ideal performance, these will likely be custom-designed during the Preliminary Design phase.

With approximately 1,300 support systems (1,080 active units plus 1/6th rotated spares plus 40 actual spares), there are a total of 23,400 rod flexures, 7,800 tri-plates and tri-plate pivot flexures, and 3,900 whiffletrees and whiffletree pivots. Additional construction and assembly details are described in the weekly report "Assembly Plan" in the appendix.

3. LATERAL SUPPORT SYSTEM

With the lateral support at the back surface of the segment, a moment exists under lateral gravity due to the axial eccentricity of the lateral force with respect to the c.g. plane of the segment. A number of methods and geometries were evaluated for the lateral support system. These included:

Three supports at the back surface (at the actuator locations) using the axial supports to react the moment.

A single central support at the back surface using the axial supports to react the moment.

A “unified support” in which a single system of struts is used for both the axial and lateral support functions.

The above methods were shown to exhibit very large surface distortion due to significant moment existing in the segment over relatively large distance scales. Peak-to-valley distortion ranged from many hundred nanometers to as high as about 6 microns. The next method tried employed a single central support at the back surface using levered counterweights in close proximity to the load application to react the moment. It was discovered that the surface distortion was highly dependent on the local geometry for the lateral load application as compared to that for the moment compensation. Refining these geometries progressively (using 7 iterations) reduced the peak-to-valley surface distortion from 143 nm to 10.5 nm.

While the lateral support system provides a soft definition of the mirror segment rotationally about the local optic axis, this will likely not be adequate in operation. The segment needs to be positioned rotationally with modest accuracy to achieve optical tolerances. It is anticipated that a reasonably stiff tangent arm, perhaps including a small electromechanical actuator, will be included during the preliminary design phase. The current rotational definition via the silicone pads at the lateral support is sufficiently soft to accommodate significant rotational adjustment.

3.1 Axisymmetric design

At this point it was recognized that there is one additional important constraint on the lateral support system. All segments except those on the central vertical plane of the mirror array experience compound lateral force components. That is, for these segments as the telescope rotates from zenith toward horizon, the lateral gravity vector rotates in a plane that is skewed with respect to those segments. And the magnitude and alignment of the skew depends on the location for the segment within the mirror array. Therefore, the lateral support must be "axisymmetric", or work for any rotational orientation of lateral gravity with respect to the local optic axis for the segment.

The method chosen to achieve this was simply that of attaching a counterweight (not levered) directly to the back of the segment. Two kinematic attachment geometries were initially considered, shown as "geometries 1 and 2" in Figure 2. They were found to cause relatively large surface distortion (the reasons are described in the weekly report "Axisymmetric Lateral Support System" in the appendix). However, if the counterweight attaches with 6 silicone pads, it would apply the moment compensation forces with a very similar geometry to that of the earlier levered counterweights. Although slightly locally over constrained, the pad design was shown to be sufficiently compliant to keep surface distortion due to thermal and manufacturing effects to a negligible level (also described in the weekly report).

3.2 Finite element analysis

Brick elements were also used to calculate the surface distortion due to the lateral support. Shown as Figure 4, the final lateral support model CELT33 used nodal loads (not shown) to apply the lateral support force and moment compensation forces. Lateral gravity element loading was used to apply the lateral load directly to the brick elements. A half-segment model was used due to load and structure symmetry.

The surface distortion of the final optimized design is shown highly exaggerated in Figures 7 through 9, which have been mirrored to a full segment. As shown there, the surface distortion due to 1 g lateral gravity was calculated as 10.54 nm p/v, 1.5 nm rms. Figure 10 is a dithered color contour plot of the surface near the support. This local view was provided because a larger-scale view would be misleading due to relatively large tilt of the model which was an artifact of the model restraint.

In addition to calculations of surface distortion due to the lateral support, models CELT35 thru CELT40 were used to predict and optimize the structural performance of the disk flexure. The resulting favored design exhibited the following properties:

Disk Flexure Structural Properties				
Model (thickness)	**Material**	**Axial Force Error at 0.6 mm**	**Radial Defln @ 1g, in.**	**Von Mises Stress, ksi**
CELT40 (.025)	17-7ph s.s.	.54 lb	.0041	21.6

Model CELT35 (.020 in. thickness) was also tested for non-linearity. After the full .6 mm axial motion the axial stiffness increased by only 10.4%. It is therefore believed that all of the considered designs will exhibit acceptably low non-linearity.

One important structural feature of the disk flexures is their strength, since they are thin and must radially support the approximate 180 pound weight of the segment and moment counterweight. A crude manual calculation was performed using American Institute of Steel Construction (AISC) criteria. By this criteria, and with .025 in. thickness, these designs might not be adequately stable. However, the geometry is not at all similar to the kinds of beams and structures for which the AISC formulae were developed. A physical stability test was therefore conducted of the CELT40 design. The results were promising, although not conclusive because the tested material was a little thicker (.031 in. as opposed to .025 in.) but considerably lower strength than the design flexure. Therefore, a more definitive test should be conducted during the preliminary design phase.

3.3 Lateral support hardware

The hardware for the axisymmetric lateral support described above and modeled in CELT33 is shown in drawings CAD-1 and CAD-3 through CAD-5. It consists of:

3.3.1 Moment counterweight, a precision weldment of the 14# annular counterweight and counterweight extension tube. The annular counterweight (CAD-4) is a production lathe part. Using a standard hot rolled steel tubing size, the i.d. and o.d. are sized, the shallow recess machined, then it is parted off with a plunge cut. The counterweight extension tube (CAD-5) is made from 5" o.d. x .065 wall CREW (cold rolled electric welded) mild steel tubing. The part is precision cut to length, the slot is milled, then two access holes made by hole saw and the 6 small holes drilled using a drill jig. The milled slot is sufficiently long to allow sliding the moment counterweight back to disconnect the disk adapter fitting to the end of the 3 ½" square lateral support tube. The 5" diameter counterweight extension tube, with its thin wall and minimal clearance to the tabs on the moment force ring helps minimize distortion of the ring during torquing of the six small screws.

3.3.2 Moment force ring (CAD-3 and CAD-5), glued to the segment with .16 in. thick Dow 3145 silicone RTV. It serves to connect the moment counterweight to the glass and distribute the moment forces in a controlled way. Made from invar, it is premachined on a lathe then the integral tabs are N.C. milled.

3.3.3 Lateral force puck (CAD-3 and CAD-5), glued to the segment with .12 in. thick Dow 3145 silicone RTV. It transfers the lateral shear force from the disk flexure to the segment to support the horizon gravity component of the segment weight. It is made from invar.

3.3.4 Disk flexure (CAD-3), the center of which screws to the end of the lateral support tube while the three ends screw to the lateral force puck. It transfers the lateral shear force from the lateral support tube to the lateral force puck while isolating this system from axial forces. Under the full +/- .6 mm travel of the axial actuators the axial force error from the disk flexure defines surface distortion in the segment which is acceptably small. The disk flexure is made from .025 thick 17-7PH stainless steel using wire edm. Actually, approximately 50 disk flexures can be wire electrical-discharge machined simultaneously and in one setup so that these parts, although complicated, will be inexpensive.

3.3.5 Disk adapter fitting (CAD-5), which connects the disk flexure to the end of the lateral support tube. The final shear-type friction connection minimizes assembly axial force error in the disk flexure.

3.3.6 Zenith counterweight (CAD-3 and CAD-4), mounted to the lateral support tube with small flexures (not yet designed) and connected to the annular counterweight via a tie rod and transverse pin. It supports the zenith gravity component of weight of the moment counterweight and moment force ring and thereby eliminates surface distortion of the segment from this source.

4. Miscellaneous analyses and results

In addition to the axial and lateral support optimizations summarized above, numerous related calculations were made which relate in various ways to the support system. A brief summary follows:

4.1 Warping harness influence functions

Model CELT34 was created to determine the segment distortion due to applying 1 N-m moments around: a.) the whiffletree pivot, b.) the tri-plate pivot parallel to the X axis and c.) the tri-plate pivot parallel to the Y axis. Based upon the CELT5 topology, the results were reported and are to be used by UCSC for estimating what effects can be corrected by the warping harness.

4.2 Rotation of segment due to disk flexure

Model CELT41 was used to determine whether the disk flexure defines a rotation of the segment due to its geometry under a pure lateral load. It was shown that it does not.

4.3 Surface distortion due to thermal effects of lateral support

Models CELT42, 43, 44 and 48 were created to determine distortion due to the large bonded lateral support fittings under thermal loading (the -60 deg F differential from the fabrication environment to the minimum operating temperature) . The distortion was estimated to be 7.1 nm p/v, and approximately 1.6 nm rms. It was also demonstrated that it is both important to use invar for the fittings and silicone adhesive to soften the distortion effect. Surprisingly, CELT48 indicates that it is slightly better to glue the invar lateral force puck continuously to the segment (without an annular interruption in the silicone).

4.4 Surface distortion due to rod flexures under maximum tilt of segment

Model CELT45 showed that the surface distortion under maximum segment tilt (due to one actuator fully retracting .6 mm, a second fully extending .6 mm) was 5.65 nm p/v, 1.34 nm rms. Since this is a highly unlikely operating condition, it can be concluded that the rod flexures are adequately compliant in bending. The results are described in more detail in the weekly report dated December 28, 2000. In addition, models CELT46 and CELT47 demonstrated that the rod flexures, with small diameter piano wire flexures at each end, are considerably more efficient than using a solid-diameter rod for the full length of the assembly.

4.5 Surface distortion caused by eliminating zenith counterweight

Models 49 and 50 were used to determine the increase in surface distortion if the zenith counterweight is eliminated and the moment counterweight zenith gravity self-weight is supported directly as a somewhat concentrated load at the center of the segment. The result was that the distortion increased from 21.5 nm to 28 nm p/v, or 5.06 nm to 6.7 nm rms. The results are described in more detail in the weekly report dated January 22, 2001.

4.6 Surface distortion due to tri-plate pivots under horizon gravity

Models CELT51 through CELT53 were used to optimize the piano wire tri-plate pivots and to show that, properly designed, they contribute virtually zero surface error. The analysis and results are described in detail in the weekly report dated January 27, 2001. The tri-plate pivot flexures and rod flexures should be stability tested as a system in the Preliminary Design phase, since this is difficult to calculate accurately by theoretical means.

4.7 Error sensitivity analysis

Models CELT54 through CELT58 were created and solved to determine surface figure error sensitivity to manufacturing and assembly errors. Model CELT54 is shown as Figure 11 below. The analysis is described in detail in the weekly report dated February 1, 2001. Dithered color contour plots are included for load cases 2 through 5 as Figures 12 through 15 below. Graphics plots for other load cases are not included due to large tilts which are artifacts of the model restraint and which mask the actual deflected shape of the segment.

4.8 Surface distortion due to wind pressure gradients

Models CELT59 through CELT62 were used to calculate surface distortion due to linear pressure distribution (two orthogonal directions) and one higher order effect [P =(2.405 x R^2) - 1]. Based upon a very high peak pressure of 1 psi, the results are linear and scaleable to realistic pressures the system is likely to experience. The results are described in more detail in the weekly report dated February 5, 2001. The dithered color contour plot for the higher order case is provided as Figure 16, since it is meaningful without tilt caused by model restraint and support compliance. Although dynamic components of wind pressure cannot likely be compensated by the mirror active support, steady and very low frequency components likely can, and these results may be helpful in quantifying those corrections.

4.9 Stiffness of the axial support system

The axial support system has been designed to achieve a local first resonant frequency of 60 Hz. This resonance would result if the axial deflection of the segment under a purely axial 1 g load were .0027 in. The calculated deflection under this load is:

(Lucas pivot)*	.00180 in.
Whiffletree beam	.00006 in.
Triplate pivot	.00012 in.
Triplate	.00023 in.
Rod piano wire	.00013 in.
Rod	.00003 in.
Rod piano wire	.00013 in.
Silicone	.00009 in.
Total	.00259 in.

*1/2" Lucas pivot. A larger pivot, at considerably higher stiffness, could likely be used. However, the ½" pivot would define lower surface distortion due to extremes of actuator motion. A custom designed pivot would also likely be stiffer. Since this entry is the dominant (most compliant) one, significant gain might be made here during the preliminary design.

The local first resonant frequency of the segment on its lateral support system has been estimated to be 30 Hz.

4.10 Natural frequency and modeshapes

Although not comprehensive, some initial modal analysis has been performed. Model CELT63 was used to calculate the axisymmetric bending frequency and modeshape for the mirror on three supports at the actuator locations. CELT64 was used to calculate free vibration modes. The mirror on three supports had an axisymmetric bending mode frequency of 439 Hz. The first four free-vibration modes were:

1. 337 Hz - First astigmatism (linear bending).
2. 337 Hz - (Orthogonal mode).
3. 536 Hz - Axisymmetric bending.
4. 719 Hz - Second astigmatism (linear bending).

4.11 Support system weight

A weight summary of the support system as it is currently designed follows:

I. Axial Support System		
A. Rod flexure pads - .013 lb	x 18	.271
B. Rod flexure rods - .03 lb	x 18	.539
C. Sleeve 2 - .0056 lb	x 18	.100
D. Piano wires		.009
E. Tri-plates (aluminum, ½") - 2.39 lb	x 6	14.340
F. Whiffletree blocks (aluminum) - .063 lb	x 6	.375
G. Whiffletree beams (aluminum, 2 - 1/4") - 1.65 lb	x 3	4.941
Total weight, axial support system		20.60

I. Lateral Support System		
A. Lateral force puck (invar)		.834
B. Moment force ring		2.506
C. Counterweight extension tube (mild steel)		3.500
D. Moment Counterweight		14.169
E. Zenith counterweight		5.478
F. Disk flexure		.259
G. Disk adapter fitting		.140
Total weight, lateral support system		26.90

Total weight of Segment Support System	**47.50 lbs (21.6 kg)**

The above weight exceeds the specification by about 50%, but for good reason. Normally one would expect a lateral support, acting at a single concentrated location, to be considerably lighter than the axial support which supports the same weight but distributed over a large area. Here the lateral support weighs considerably more than the axial support as a result of the requirements of acting at the back surface and being axisymmetric (i.e. due to the moment and zenith counterweights). The budgeted weight requirement should be re-evaluated during the preliminary design phase.

5. Surface distortion error summary

The following is a summary of many of the calculated surface errors:

Surface Distortion Error Summary		
Comments, error source	**Peak-to-valley, nm**	**RMS, nm**
Axial support, 1 g axial gravity, CELT7 topology	19.6	< 5.06
Lateral support, 1 g lateral gravity.	10.54	1.5
Disk flexure axial force error at full .6 mm axial travel	18.2	4.8
Thermal effect acting on lateral support, -60 deg F	7.1	1.6
Rod and tri-plate flexures under maximum segment tilt	5.65	1.34
Eliminating zenith counterweight (axial sprt, increase of)	19.6 to 28	5.06 to 6.7

Surface errors due to wind pressure gradients, manufacturing and assembly errors, and other calculations resulted in scaleable information which is too intricate to present in a simple table. In these cases the individual sections of this and the weekly reports must be used.

6. Assembly plan and cost estimate

A concept design level Assembly Plan and Cost Estimate have been developed. They are presented in detail in the appendix weekly report dated February 24, 2001. A brief summary follows:

1. Axial Support System Hardware	*****553.31**
2. Axial Support System Assembly	**141.92**
3. Lateral Support System Hardware	**247.20**
4. Lateral Support System Assembly	**159.80**
Total cost per segment	**$1102.23**

******* Includes $314.70 for Lucas flex pivots, which can likely be reduced in next design phase.

Many of the above hardware costs came directly or indirectly from bids. The assembly labor times were gotten using the typical “industrial engineering time/motion” technique, using a stopwatch and going through the motions required for each task. The stopwatch times were increased by 50% to allow for unforseen inefficiencies. In fact, the lateral support assembly times were again doubled, since the part quantities are low and being that conservative has only a small effect on cost.

On the other hand, the estimate is based upon a concept design which is sure to change. And it is very likely that some components (especially assembly labor) have been overlooked. But it is the author's opinion that if this very simple hardware design is preserved through subsequent design phases and a good job is done in the manufacturing phase, the support system cost per segment should be well under the budgeted $2,000 per segment.

7. Conclusions

A concept design has been developed for the mirror segment support of the California Extremely Large Telescope. The axial and lateral support assemblies have a somewhat unusual appearance due to the requirements of being manufactured and assembled at very low cost and working entirely from the back surface. The current design has a good chance of meeting the system requirements once a formal error budget is finalized. If the simple design is maintained through future design phases and a good job is done during construction the support system cost per segment will be under the budgeted $2,000 cost per segment.