Technical Report #32

F/9 SECONDARY SUPPORT

SYSTEM DESIGN, REV. 1

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August 1997

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August 19, 1997

MEMORANDUM

To: Steve West

FROM: Brian Cuerden
Technical Services

/home/bcuerden/f9sec/text/perf.wpd

SUBJECT: F9 Secondary Support System Design, Rev. 1

Reference 1. Fabricant, D. McLeod, B. and West, S., "Optical Specifications for the MMT Conversion", Version 6a, 7-Jan-97.

SUMMARY

The support performance of the F9 secondary mirror cell is predicted and compared to specifications. Rms WF distortion is 0.0264 waves (at 0.633 microns) at zenith and 0.0536 waves (at 0.633 microns) in going from zenith to 60 degrees from zenith. Rms surface slope is 0.0114 arc-seconds at zenith and 0.1246 arc-seconds in going from zenith to 60 degrees from zenith as compared to a requirement of 0.14 arc-sec rms at zenith and 0.22 arc-sec at 60 degrees from zenith. Structure functions at zenith and 30, 45 and 60 degrees from zenith have been calculated and are below the specification structure function limit allocated to the support system.

INTRODUCTION

The secondary support system consists of 10 lateral supports and 18 axial supports, three fixed axial positioners and three fixed tangential positioners. Loads are sensed at the fixed positioners and are held to a low value (0.25 lbs) by adjusting the pressures in three zones of axial and one zone of lateral supports. At each of the 34 locations on the mirror where a force or position constraint is applied, there is the possibility of inadvertently applying 5 force and moment components in addition to the intended force, and the intended force may vary from its ideal value. For example, at an axial support we wish only to apply a force parallel to the optical axis, Fz, but because of small misalignments, offsets, friction or stiffness in the axial support system, we can expect to obtain in addition Fx, Fy, Mx, My and Mz components. Much of the design of the supports is involved in minimizing the magnitude of these extraneous forces and in making the intended force (Fz in the example) sufficiently accurate to maintain good surface figure.

The magnitude of these error forces can be estimated and the effect of each individual component can be predicted. Since there are 6*34=204 such components, and since most of them can be considered to be statistically independent of the others, the net effect of all these components can be obtained by RSS'ing the effects of each force.

Some of the error forces are not statistically independent. If the axial supports have stiffness, cell bending will result in a support force distribution that induces astigmatic bending of the mirror. With the finite number of axial supports we have, the probability of obtaining a random distribution of error forces having an astigmatic component is too high to ignore (astigmatic bending is the softest mode of deformation of the mirror and we must be particularly careful to keep force error small enough to prevent this deformation mode). The effects of systematic force sets are calculated by FEM analysis and RSS'd into the statistically independent results described above.

Gravity deflections are also included in the "support" term of the secondary error budget. Gravity deflections are calculated by FEM. Since the mirror is figured to meet its polishing budget when supported by axial supports at the same locations as those used in the telescope cell, the zenith pointing gravity sag attributable to the mirror support is zero (already included in the polishing). As the line of sight (LOS) moves away from zenith, the mirror distorts due to the change in gravity and the shift in support forces from the axial supports to the laterals. This is modeled by applying the gravity and support force changes that occur in moving from zenith to some elevation angle to the finite element model. These results are RSS'd in with the other sources of distortion to arrive at a net result for a particular telescope orientation.

Surface figure can be expressed as rms or P-V surface or wavefront distortion, FWHM, encircled energy or as a structure function. All these can be combined using the RSS operation although the details of combining structure functions may not be obvious and are described in Appendix A.

The calculations outlined above were performed on the MMT F9 Secondary Mirror using an initial set of estimated error forces. The initial results exceeded the distortion requirements and the component force effects were searched to find damaging terms. Once a particular component was identified as a major contributor to distortion, the design was changed to reduce the magnitude of that force component. The results of this operation are a performance prediction that meets the requirements for the support system and a large number of design constraints on the secondary support system components. Much of these design constraints are in the form of positional and alignment tolerances. These are identified in Appendix B.

This report describes the results of evaluating and combining a large number of finite element solution sets in accordance with the general procedures outlined above. Due to the large volume of data being processed, the compilations are performed by a computer program using data files generated by other computer programs. Details of this procedure and of the results obtained are described in this report and its Appendices.

DISCUSSION

Secondary Support System Requirements

The F9 secondary support requirements are defined in Reference 1 section 6.2.1. The table lists a support allocation r_o of 89 cm for the F9 secondary. The encircled energy requirement is 0.113 arc-sec FWHM. These requirements apply for zenith pointing. At angles, θ, from zenith, the allowable structure function is $89^*\cos(\theta)^{0.6}$ cm and the required encircled energy requirement is $0.145/\cos(\theta)^{0.6}$ arc-sec rms ($0.113/\cos(\theta)^{0.6}$ FWHM).

Table 1 Summary of f9 Secondary Support Requirements

Requirement	Value	Specification
Rms Surface Slope	$0.145/\cos(\theta_{el})^{3/5}$ arc-sec	Ref 1, Sections 6.2.1, 4.1 and 4.2
Structure Function, r_o, cm	$89^*\cos(\theta_{el})^{3/5}$ cm	Ref 1, Section 6.2.1

The encircled energy requirement for the secondary support is $0.017^*6.69^*1.28\cos(\theta)^{0.6}$

Appendix C

Cell Configuration

The cell configuration is shown in Appendix F. There are 18 axial supports and 10 lateral supports (with an option for 12 lateral supports). The 12 lateral support option has become possible due to a redesign of the lateral support assembly. The new assembly is small enough to permit the addition of the supports at the East and West positions (lateral gravity acts in the North-South direction).

Analysis Procedure

An ANSYS finite element model of the f9 secondary was used as shown in Figure 1. This model is estimated to be accurate to better than 20% so the mass has been adjusted upward 20% to ensure conservatism in the gravity sag results. ANSYS displacement results were processed to remove translation tilt and power after which the rms and P-V deviations, the maximum slope deviation and the structure function was computed. Load cases considered are summarized in Table 2.

Table 2 Summary of Mirror Support Load Cases

Gravity	1 g, Zenith to 60° el, Zenith to 45°, zenith to 30° el and horizon pointing.
Unit Load	Fx, Fy, ...Mz loads were applied to representative support locations. One location on the inner and outer axial support locations and one location on the OD (tangent supports/ lateral force actuator location). These results were used to compute the effects of random mounting force errors. Error forces are estimated in Appendix B. Effects of error forces are obtained by RSS'ing individual effects (see Appendix A, section 2.2.2).
Other	The effects of non-random force distributions (see Appendix A, section 2.2.3 and Appendix B section B.7) were also investigated. Of primary concern is the effect of a sin(2θ) axial force distributions which generate more deflection than randomly distributed forces of the same magnitude.

A detailed description of the methods employed to evaluate and combine these load cases may be found in Appendix A. The magnitude of error forces are calculated in Appendix B.

RESULTS

In Table 3, the total effect of gravity loading and spurious error forces is obtained by RSS'ing all effects. The random error effects are based on the error forces estimated in Appendix B. These error force estimates are in part based on the dimensional tolerances specified in Appendix B. Additional Tables may be found in Appendix C. Structure function plots are provided as Figures 2 to 5. In Appendix D structure function plots are provided that define the contribution to the total error of selected groups of error sources.

Table 3 MMT F/9 Secondary Support Performance, Various Orientations

Orientation	WF Distortion, Waves at 0.632 μ-m	RMS Surface Slope arc-seconds rms	Reference Figure for Structure Function
Zenith Pointing	.0264	.0114	Figure 2
30° From Zenith	.0319	.0718	Figure 3
45° From Zenith	.0405	.1013	Figure 4
60° From Zenith	.0536	.1246	Figure 5

Table 3a F9 Secondary Surface Performance Zenith Pointing

Waves are 0.632 μ-m
See Addendum 1 for error force estimates and backup data

Load Case	Rms Surf Distortion		Slope Error arc-sec rms
	μ-inch	WF, λ	
Gravity, Zenith to Indicated Elev	0	0	0
Fz Friction at 1 lateral	0.0015	0.0001	0.0006
Fz Friction at All Laterals	0.0064	0.0005	0.0022
Fz Friction =0.15sin(2t)	0.0053	0.0004	0.0016
Axials Fz Astig, random	0.0625	0.0050	0.0014
Axials Fz Astig. Cell Bend	0.0656	0.0053	0.0015
Laterals Fz Astig, random	0.0008	0.0001	0.0001
Laterals Fz Astig. Cell Bend	0.0031	0.0002	0.0002
Random Force Errors	0.3154	0.0253	0.0109
RSS Total =	0.3283	0.0264	0.0114

Table 3b F9 Secondary Surface Performance 60 deg From Zenith

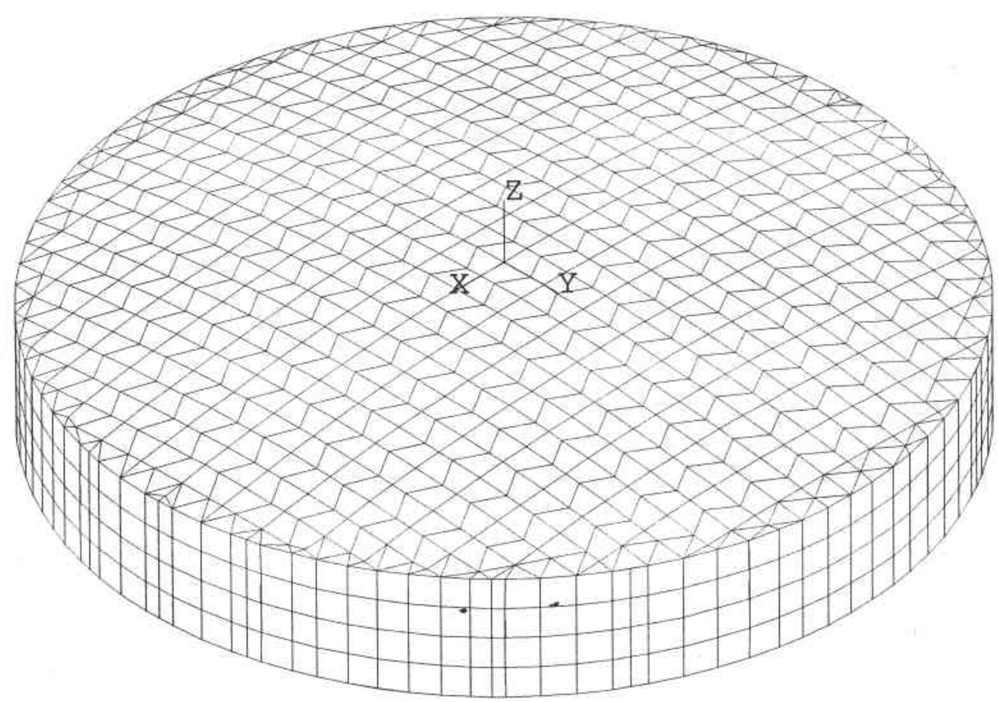
Waves are 0.632 μ-m
See Addendum 1 for error force estimates and backup data

Load Case	Rms Surf Distortion		Slope Error arc-sec rms
	μ-inch	WF, λ	
Gravity, Zenith to Indicated Elev	0.5247	0.0421	0.1238
Fz Friction at 1 lateral	0.0015	0.0001	0.0006
Fz Friction at All Laterals	0.0064	0.0005	0.0021
Fz Friction =0.15sin(2t)	0.0053	0.0004	0.0015
Axials Fz Astig, random	0.0625	0.0050	0.0014
Axials Fz Astig. Cell Bend	0.0656	0.0053	0.0014
Laterals Fz Astig, random	0.0008	0.0001	0.0001
Laterals Fz Astig. Cell Bend	0.0031	0.0002	0.0002
Random Force Errors	0.4029	0.0323	0.0140
RSS Total =	0.6678	0.0536	0.1246

A cell structure model has been developed and used to evaluate the mode frequencies of the rigidly supported telescope cell and the cell bending deflection. Cell bending deflections are used in Appendix B, section B.7.2 in assessing the astigmatic loads applied to the mirror by cell deflections acting through the actuator stiffness.

CONCLUSIONS

The secondary surface figure requirements have been met. Appendix B contains numerous requirements on the cell design that must be satisfied in order to achieve the desired level of support performance.



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ZF =-3.942
VUP =Z
PRECISE HIDDEN

Figure 1a
MMT F9 Secondary, With Lateral Supports

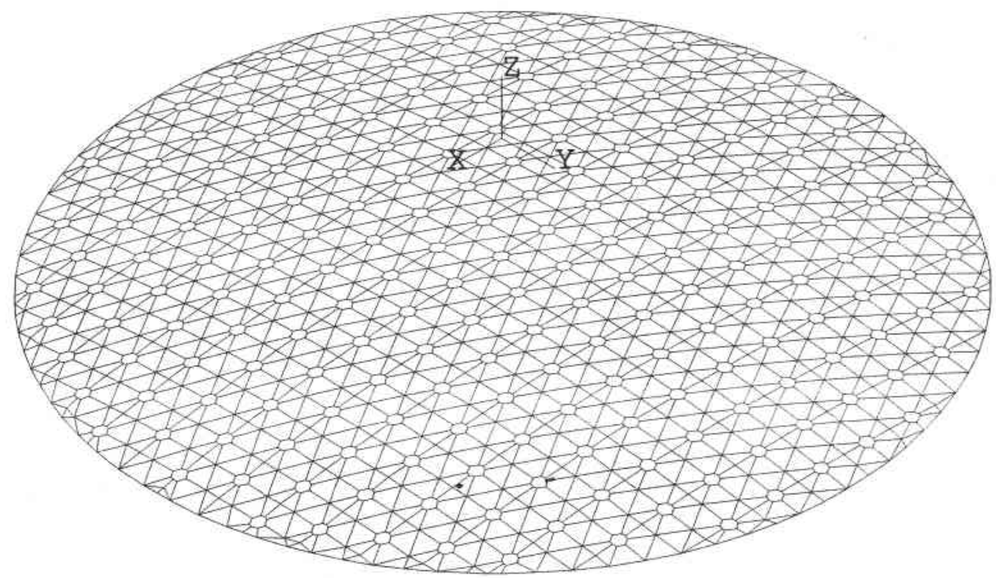

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Figure 16 Backplate
MMT F9 Secondary, With Lateral Supports

1

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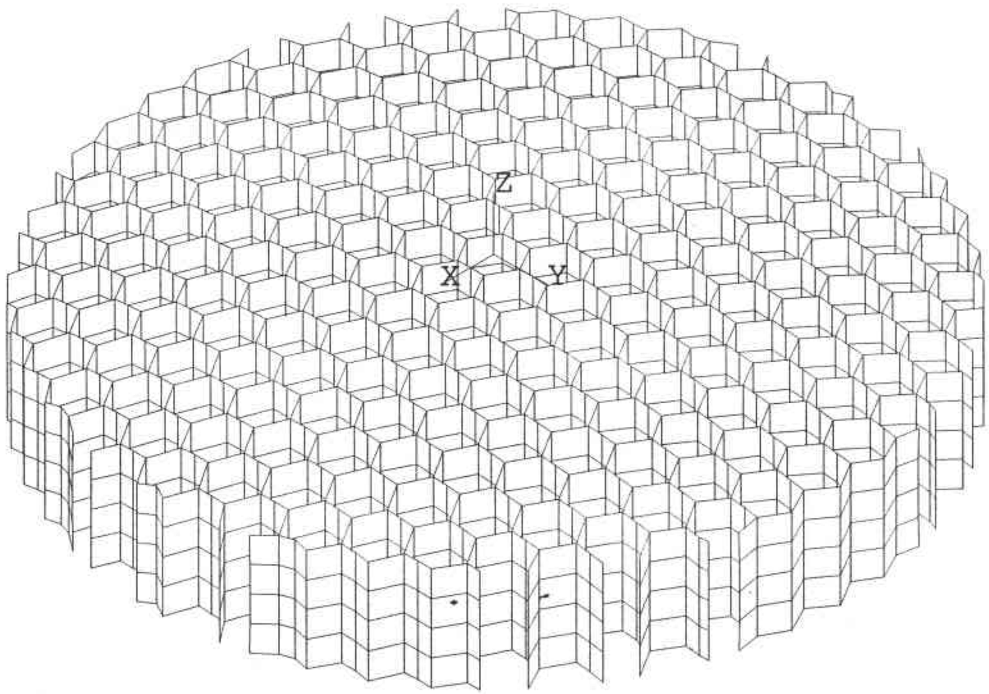
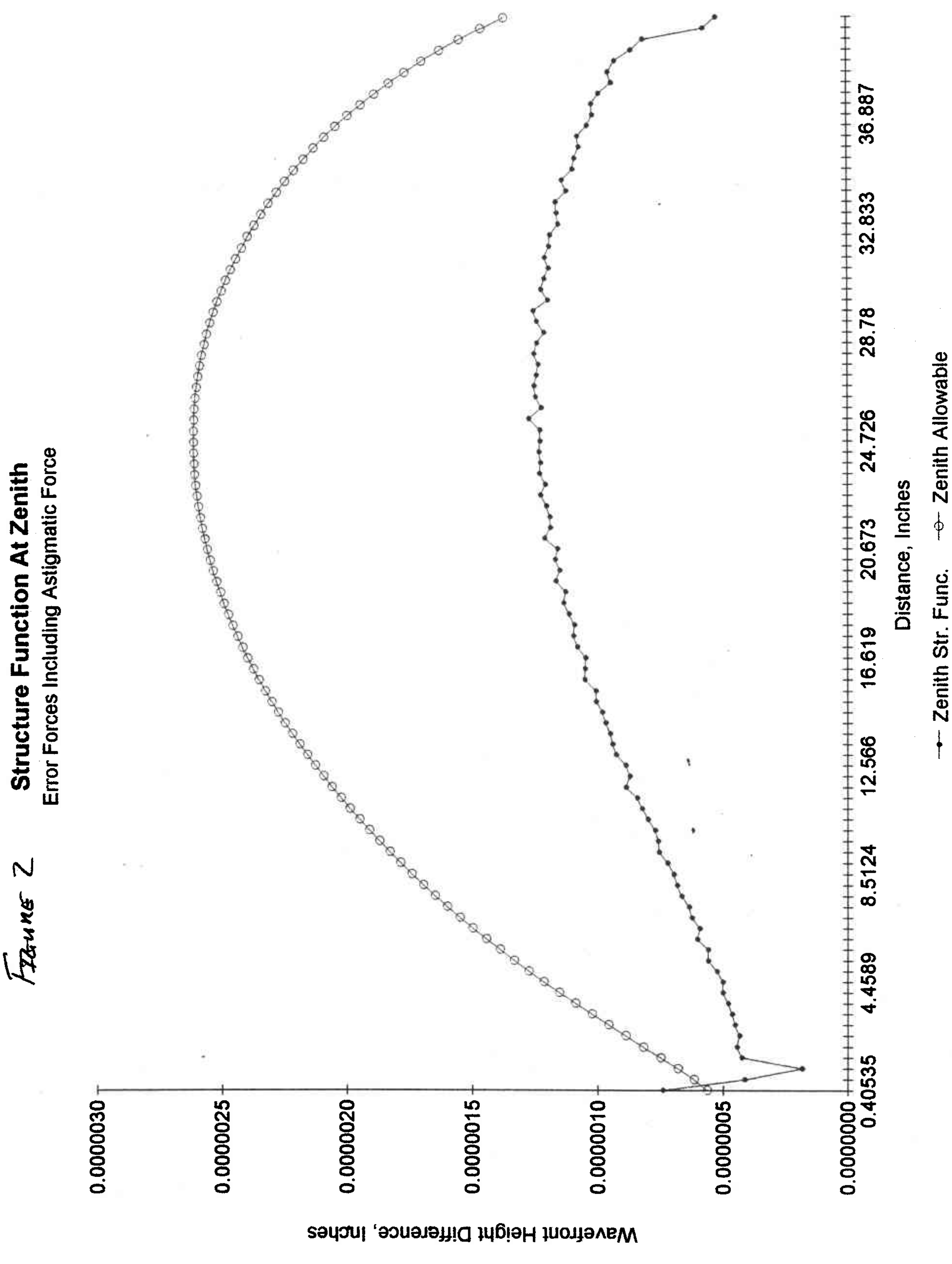


Figure 1c Core Structure

MMT F9 Secondary, With Lateral Supports

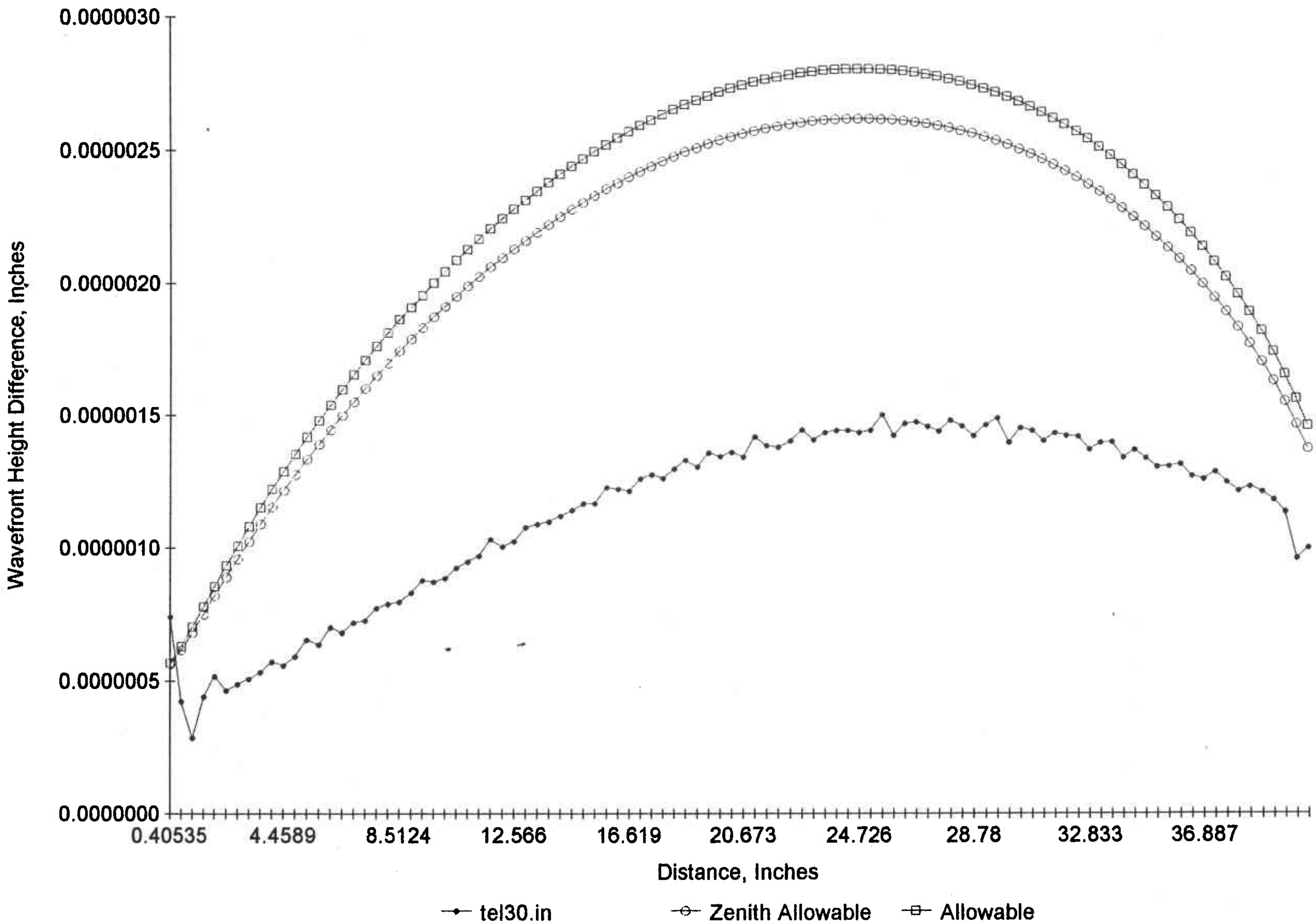
Figure 2



Structure Function At Zenith
Error Forces Including Astigmatic Force
Wavefront Height Difference, Inches
0.0000030
0.0000025
0.0000020
0.0000015
0.0000010
0.0000005
0.0000000
0.40535
4.4589
8.5124
12.566
16.619
20.673
24.726
28.78
32.833
36.887
Distance, Inches
Zenith Str. Func.
Zenith Allowable

Figure 3 **Structure Function 30 Deg From Zenith**

Gravity Change and Error Forces



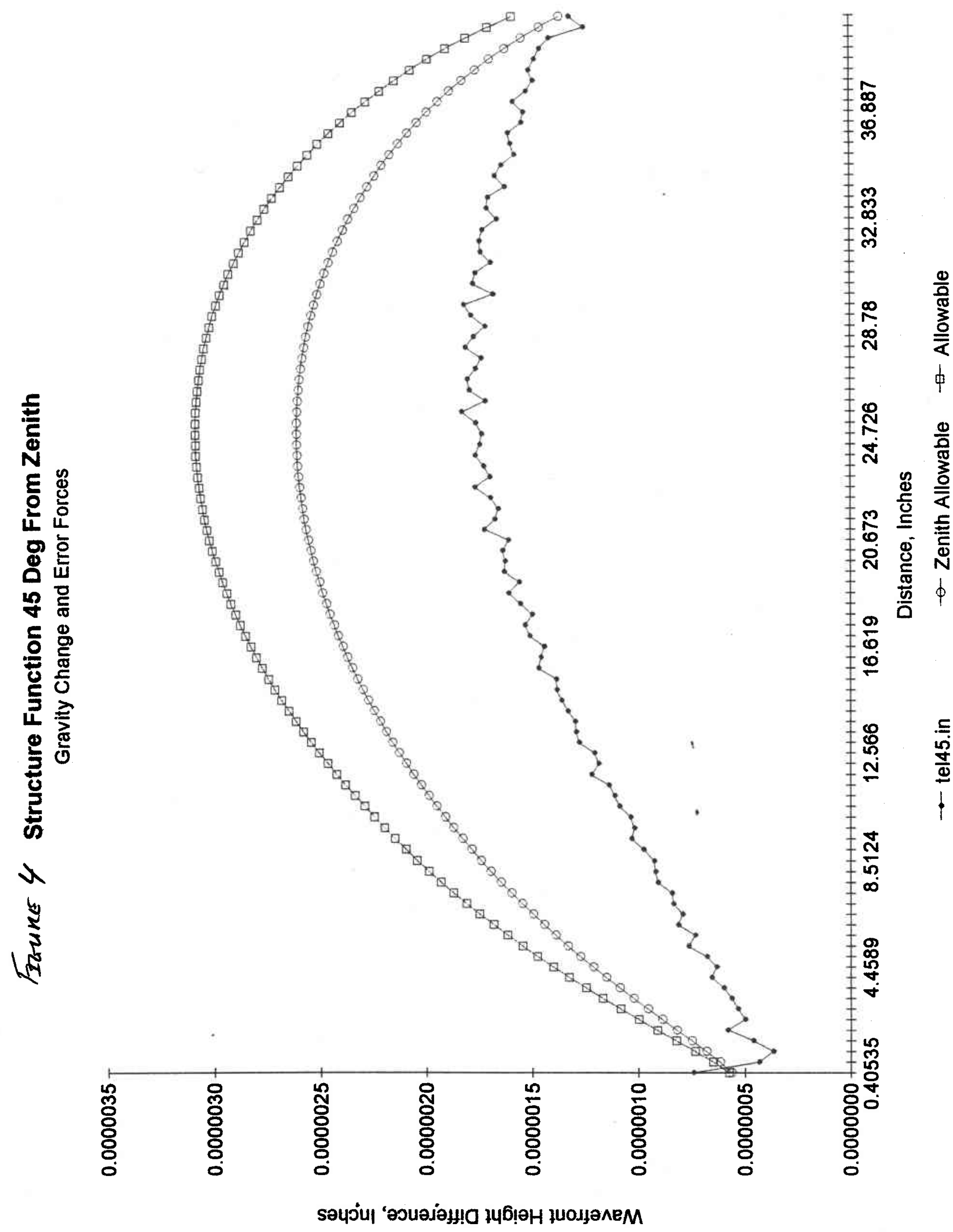
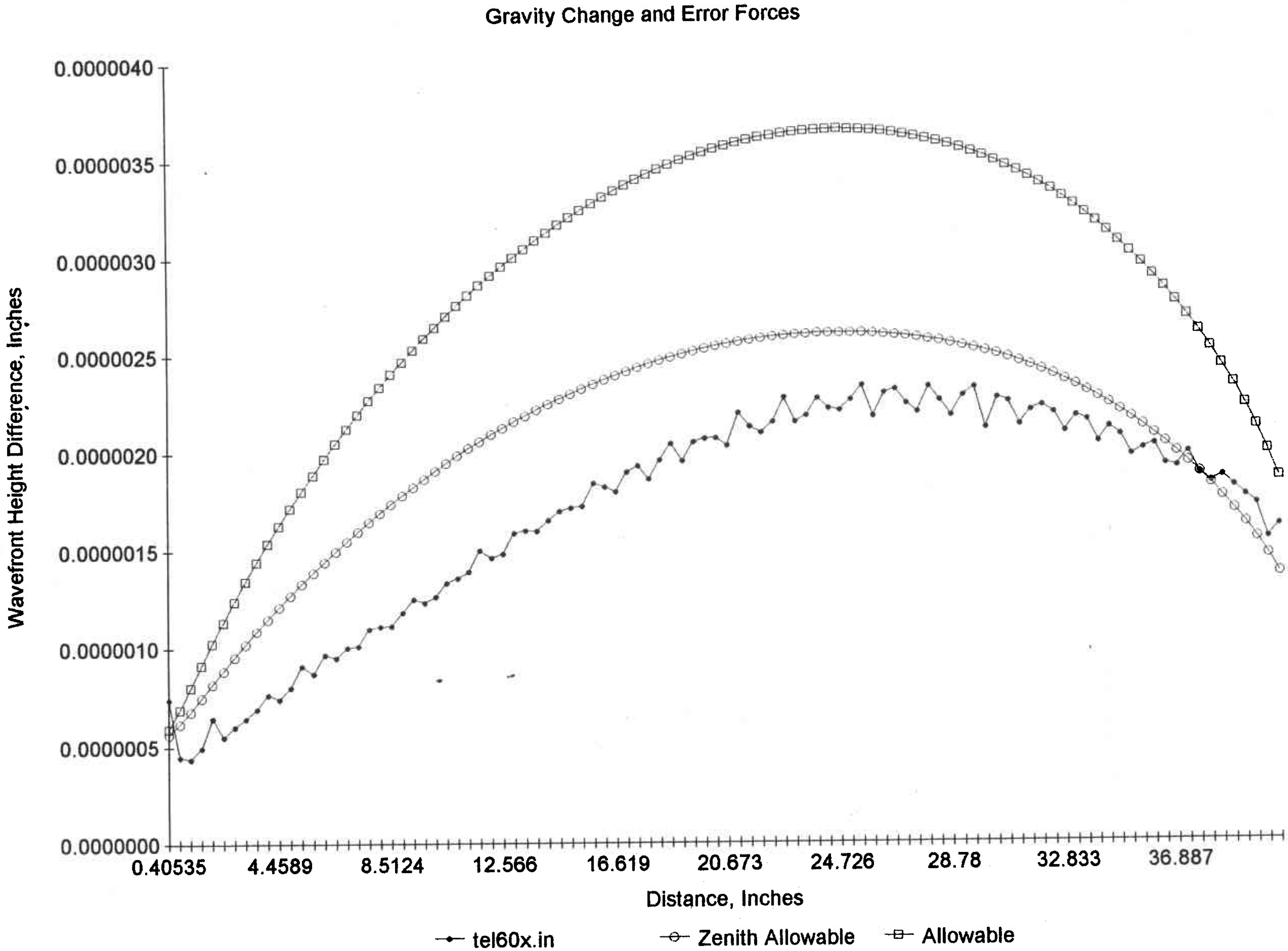


Figure 4 Structure Function 45 Deg From Zenith
Gravity Change and Error Forces
Wavefront Height Difference, Inches
0.0000035
0.0000030
0.0000025
0.0000020
0.0000015
0.0000010
0.0000005
0.0000000
0.40535
4.4589
8.5124
12.566
16.619
20.673
24.726
28.78
32.833
36.887
Distance, Inches
tel45.in
Zenith Allowable
Allowable

Figure 5

Structure Function 60 Deg From Zenith



APPENDIX A SUPPORT PERFORMANCE ANALYSIS METHODOLOGY

This Appendix discusses in a general way the procedures used to demonstrate that the support design can limit the optic's surface deformation to less than that allowed by the specified structure function.

A.1.0 Structure Functions

A.1.1 The Allowable Structure Function

Reference: Hill, J. M., "Error Budget and Wavefront Specifications for Primary and Secondary Mirrors", Technical Memo UA-94-01, Aug 26, 1994

The surface of the optic is required to meet distortion limits specified as a "structure function" (see reference Section 1.0 to 1.4). The structure function allowable (for a secondary mirror) is:

$$\delta^2(x) = 2\sigma^2 + \left(\frac{\lambda}{2\pi}\right)^2 * 6.88\left(\frac{Cx}{r_0}\right)^{\frac{5}{3}} * \left[1 - 0.975\left(\frac{Cx}{D}\right)^{1/3}\right]$$

Where:

$\delta(x)$	is the permissible rms wavefront height difference of two points separated by distance, x (the permissible surface height difference is half this for normal incidence).
σ	is the rms deviation from the mean wavefront due to scattering
λ	is the reference wavelength
C	is the ratio of primary to secondary beam diameter
x	is the distance between points at which the height difference is computed
r_0	is the parameter that defines the allowable magnitude of the structure function. r_0 decreases away from zenith as $r_0(z) = r_0(0)^*\cos(z)^{0.6}$ z is zenith angle, 0 at zenith.
D	is the telescope aperture diameter

The C in the term $(Cx/r_0)^{5/3}$ is the scaling factor for pupil size. This factor may be included in the secondary error budget in which case it must not be included again in this term.

Note that all these variables must have consistent units.

A.1.2 Calculation of the Structure Function of a Distorted Surface

Finite element results for the optical surface distortion consist of a set of displacements at discrete points (nodes) on the optical surface. The structure function is computed as the rms normal displacement difference between nodes that are approximately the same distance apart. Since the nodes may not be uniformly distributed, values are weighted with respect to area. Before calculating the structure function, displacements, tilts and power are removed from the surface normal displacement solution. The calculation of the structure function then proceeds as follows:

For two nodes, i,j, separated by some distance, x, and having associated areas, A_i and A_j:

Compute the area weighted height difference, $\delta_{ij}(x)$ and the average area, A_{ij}:

$$\delta^2_{ij} = 4*(Uz_i - Uz_j)^2 * \frac{(A_i + A_j)}{2}$$

U_{zi} is the surface normal displacement at node i.

Where the factor of 4 converts from surface height difference squared to wavefront height difference squared.

$$A_{ij} = \frac{A_i + A_j}{2}$$

Sum these values into bins depending on the distance between nodes, x_{ij}, so that:

$$Sum_k(\delta^2) = \Sigma\,\delta_{ij}^2 \qquad \text{for } L_k < x_{ij} \leq L_{k+1}$$
$$Sum_k(A) = \sum A_{ij} \qquad \text{for } L_k < x_{ij} \leq L_{k+1}$$

Where L_k are reference lengths for 1% of the secondary diameter to the secondary diameter in 1% increments

$$\delta_k = \sqrt{\frac{Sum_k(\delta^2)}{Sum_k(A)}}$$

δ_k = the calculated value of the structure function for distance L_k.

The δ_{ij} values are computed for all unique node pairs ($\delta_{ii}=0$ and is ignored and $\delta_{ji}=\delta_{ij}$ and so need not be included).

A.1.3 Combining Structure Functions

Calculated structure functions on the same surface are combined by RSS'ing the δ_k values for the various cases being combined to yield a new set of δ_k values.

A.2.0 Calculation of Net Mirror Distortion Attributable to the Support System

The section above describes how the structure function is calculated from a finite element displacement solution, how results from multiple solutions can be combined, and how to calculate the maximum allowable value of the structure function.

In this section, the load cases that must be included in the total solution are discussed as are methods for reducing the number of cases requiring evaluation by taking advantage of symmetry.

A.2.1 Gravitational Deflection

The support system is required to meet its requirements for all operational orientations of the mirror. For secondaries tested nadir pointing on their operational supports gravity sag for this orientation is polished out. As the horizon pointing condition is approached, the mirror surface will exhibit both the lateral gravity distortion and the nadir pointing distortion. The finite element case that models this effect is obtained by applying the following gravitational accelerations:

Surface normal gravity = $(\cos(\theta_{el})-1)*g$
Lateral gravity = $\sin(\theta_{el})*g$

Where: θ_{el} = the elevation angle (zero at the horizon)
g = gravitational acceleration

The structure function for various orientations of the telescope must be evaluated using separate finite element load cases.

A.2.2 Origins of Support Force Errors

Mirrors are generally supported on a kinematic support with auxiliary forces applied to reduce surface distortion. The kinematic support often takes the form of six rods each preventing motion along a particular direction and positioned to constrain each of the six rigid body degrees of freedom. One example of this is three axial supports on the back and three tangent rods on the OD of the mirror. Another example is three bipods on the back of the mirror (Stewart platform). The rod elements are required to constrain motion only along their length but they also introduce small error forces normal to the rod axis and moments about and normal to the rod axis. These error forces may result from frictional or elastic effects depending on the rod construction. Elastic error forces are more likely to be constant or at least predictable than frictional forces which is an advantage in an actively corrected optical system. Friction error forces can be smaller than elastic forces, particularly if rolling element bearings are employed.

The auxiliary forces are usually intended to be a single force component acting in a particular direction at a particular location. The method of interfacing the force actuator to the mirror results in small error forces and moments in addition to the intended force. In addition, the magnitude of the applied force will differ from the intended value by some small amount.

A.2.2.1 Estimating Support Force Errors

No general procedure for estimating error forces can be given since each case is different. Some special purpose programs are available for flex rod analysis and there is some data for Bellafram diaphragms (spring rate and hysteresis). However the error forces are calculated, all six possible force components at each mirror attachment should be evaluated.

A.2.2.2 Random Support Force Errors

Random support force errors are those which are not correlated. Error forces resulting from differential thermal growth of the cell and mirror will not usually be random but errors resulting from installation position errors of individual supports could well be random.

Random support force errors can be evaluated by sampling the effects at one location and using those results at all similar locations. For example, if a mirror is supported at three points on the OD, the structure functions resulting from Fx, Fy,...,Mz can be obtained at one of the locations and the net effect at all three locations obtained by RSS'ing the structure function values at each distance for each force component at each location, i.e.;

$$\delta_i^2 = N[\delta_i^2(F_x) + \delta_i^2(F_y) + ... + \delta_i^2(M_z)]$$

Where:

δ_i	is the i[th] value of the structure function (corresponding to the i[th] distance)
N	is the number of similar locations (including the first location in the count)
$\delta_i(Fx)$	is the i[th] value of the structure function due to Fx being applied at the representative location.

A.2.2.3 Non-Random Errors

These are sets of forces acting on the mirror that are correlated in some way. Examples are forces that result from differential thermal growth or a displacement of the mirror relative to the supports. These effects tend to produce force sets that have net radial, lateral or astigmatic components. Force sets that generate the low order flexural modes of the mirror can yield deflections that are much larger than would be predicted using the random support force analysis procedure above. Non-random force sets must therefore be evaluated by estimating the magnitude and distribution of the non-random sets and applying them as separate load cases to the finite element model. Section B.7 includes a discussion of the probability of getting an astigmatic force distribution of a given magnitude in a finite set of supports.

A.2.2.4 Totalling the Effects of all Error Sources

Gravity, random and non-random height difference errors are combined by RSS'ing the results of sections 2.2.1, 2,2,2 and 2.2.3. Specifically;

$$\delta_{Total} = \sqrt{\delta_g^2 + \delta^2_{Random} + \delta_A^2 + \delta_B^2 + ...}$$

Where:

δ_{Total}	is the net support system rms height difference
δ_g	is the rms height difference for gravity at a particular elevation angle (ref. 2.2.1).
δ_{Random}	is the net random rms height difference error (ref. 2.2.2)
δ_A, δ_B, etc	are the non-random cases (ref 2.2.3)

APPENDIX B Error Force Estimates

B.1 Elastomeric Diaphragm Characteristics

Axial Supports

The axial actators are defined by Figure F3 in Appendix F. These actuators are built around a Bellofram class 4 diaphragm 1.37 x 1.19 x 1.37 height, "C" sidewall thickness, and an .090" convolution.

Effective pressure diameter, D, of the selected diaphragms = 1.28"
Axial Stiffness per unit circumference, k, = 3.1 lb/in/in

Axial Stiffness	$= \pi D k$	= 12.5 lb/inch
Moment Stiffness	$= \pi D^3 k/8$	= 2.6 in-lb/radian
Hysteresis force	$= 0.0018\pi D$	= 0.007 lbs

B.1.1 Axial spring rate per inch of diaphragm circumference = 3.1 lb/in/in

The measured axial stiffness of a four diaphragm hydraulic support having a cumulative diaphragm circumference of 19.63 inches (two 2.0" and two 1.125" diameter diaphragms) was 45.4 lbs/inch. This includes about 15 lb/inch from centering metal leaf springs for a net axial spring rate per inch of diaphragm circumference of 1.55 lb/in/in. Since this data was collected on silicone rubber, light weight, large convolution diaphragms, a factor of safety of 2 is applied to give a design spring rate of 3.1 lb/in/in .

B.1.2 General Expressions for Net Axial and Moment Stiffness of a Diaphragm

Axial Stiffness $= \pi D k$

Moment Stiffness $= \pi D^3 k/8$

Where: D is the diaphragm's effective pressure diameter
k is the diaphragm's axial spring rate per inch of length

The axial stiffness is simply the circumference times the stiffness per unit length. The moment stiffness is obtained as follows:

$I = \pi R^3 t$
$f = MR/(It)$ from which $M = fIt/R = \pi f R^2$
$\delta = f/k$ and $\theta = \delta/R$ so $M/\theta = \pi R^3 k = \pi D^3 k/8$

$R = D/2$
I = the moment of inertia of an annulus of thickness t and radius R

f = the maximum load per unit circumference
M = the net applied moment
δ = the maximum axial deflection at a point at radius R
θ = the rotation of the piston

B.1.3 Hysteresis Forces in Elastomeric Diaphragm Assemblies

The diaphragm hysteresis force is ± 0.0018 lbs/(inch of circumference)
$= \pm 0.0018 \pi D$ lbs per diaphragm

The hydraulic support mentioned in section B.1.1 exhibited hysteresis of ±0.017 lbs for motions of ±0.002" after being stabilized. The diaphragm is stabilized by being kept at a position for an extended time or by being cycled about a position with decreasing amplitude displacements. This hysteresis value is for an average pressure of about 45 psi (15 psi in one chamber and 75 psi in the other). The cited data is for a Dacron reinforced Buna-N diaphragm having an 0.125" convolution. Since the hysteresis is reported to vary with pressure and since only half of the diaphragms in the tested support saw the maximum pressure, the hysteresis force per unit circumference is based on half the total length cited in B.1.1 or 9.8" giving a hysteresis force of 0.0018 lbs/inch of circumference.

B.2 Axial Support Error Forces

The axial support system consists of 18 pneumatic supports in three zones and three hard points equipped with load cells with growth potential to add pzt position adjustment. The load cells limit axial force at each hard point to 0.25 lbs.

The axial support assemblies contain a Belafram diaphragm and a wire connection from a point 1.5 to 1.75 inches below the diaphragm convolution to the mirror back connection which is at least 2.547 above the glass surface. Allowing 1.0 inch for interfaces leaves a minimum of 1.5 inches of wire from a point at least 1.45 inches below the diaphragm convolution to a point 0.86 inches (max) above the glass.

Axial Support design parameters:
convolution to wire 1.5 to 1.75"
free wire length = 1.5" min
glass to free wire = 0.86" max
positioning (relative) = ±0.020"

Special Considerations for Uniform Axial Force:

Adjust wire ends (interface to support) to be reference height

± 0.030"

Obtain height reference (±0.001") on support at 11.4 lbs force (±0.1 lbs) with pressure ±0.5% (0.06 lbs). Net error is ±0.12 lbs.

At assembly, adjust support height to the height reference ±0.005" (0.063 lbs).

Net installation axial error =sort($0.12^2 + 0.063^2$) = 0.14 lbs

Results:	Fr = Ft = 0.0072*Fax = 0.082 lbs max
	Mr = Mt = 0.183 in lbs = 0.016*Fax
	Fax = 11.38 ± 0.14 lbs
	Mz = 0.2 in-lb

B.2.1 Axial Force Error

The axial force error is the hysteresis force (ref B.1) of 0.007 lbs and a force related to the axial spring rate of the support and the uniformity with which the axial positions of the supports are placed. The procedure described above limits the installed axial force error to 0.14 lbs. The hysteresis error is negligible.

B.2.2 Lateral Force Errors (Shears and Moments)

Position error effects (Fr, Ft, Mr, Mt)

The position error is accommodated by rotation of the actuator piston and deflection of the wire. This calculation considers a 2.6 in-lb/radian diaphragm (ref. B.1), a 1.5 inch offset to the top of the wire (L_d) and 1.5 inches of wire (L_w).

$$M_d = L_d{*}V - Fax{*}\delta_1$$
$$\delta_1 = L_d{*}M_d/K_\theta$$
$$V = (\delta-\delta_1){*}Fax/L_W$$

Where: M_d, K_θ = the diaphragm moment and stiffness, K_θ=2.6

L_d = the distance from convolution to wire, 1.5" min.

L_w = the free length of the wire, 1.5" min
V = the shear force
δ, δ_1 = the total deflection and the deflection at the top of the wire, δ = 0.02
Fax = the axial force per support = 11.4 lb max

Combining equations gives:

$$V = \delta^*/(L_w/Fax + L_d^2/(K_\theta + L_d{}^*Fax)) = 0.082 \text{ lbs} \quad (\approx 0.0072^*Fax)$$

The moment referenced to the midplane of the back sheet is:

$$M_{mid\text{-}plane} = V^*(0.86+.22) = 0.089 \text{ in-lb.}$$

There is also a position error moment. Assuming the 0.020 relative error is split (RSS) between mirror and cell (.014" each), the position error moment is:

$$Mpos = .014^*Fax = .16 \text{ in-lb}$$

The RSS net moment is:

$$Mr = Mt = sort(0.089^2+0.16^2) = 0.183 \text{ in-lb}$$
$$= 0.016^*Fax$$

B.2.3 Torsion (Mz)

Assuming 0.060" wire with a strand angle of 20 degrees. The torsion is estimated as:

$Mz = 0.4^*D_{wire}{}^*\sin(20)^*Fax = .093$ in-lb
This is doubled for design, Mz = 0.2 in-lb

B.3 Axial Locator Force Errors

Fr = Ft = 0.19 lbs
Mr = Mt = 0.90 in-lbs
Fax = 0.25 lbs
Mz = 1 in-lb

B.3.1 Flex rod:

Distance between extreme flexures = 5"
Midplane of back to middle of nearest flexure = 1.0"
Flexures: .25 wide by 0.04 thick by 0.5 inches long. 0.03 radii at ends
Rod: 0.25 dia., 0.25" of rod between flexures (steel, E=28e6)
Installation (relative) 0.01" and 0.25 degrees
Maximum axial force = 0.25 lbs

Flexrod input: 7,1,1.75,.25,.04,.43,28e6,.01,.25,.25 (f9flex.in)

Results:

1/5 Fcrit = 398 lbs (max allowable axial load)
Flexure stress at 0.25 lbs = 13,525 psi
Flexure stress at 1g = 24,781 psi
V = 0.19 lbs
M = 0.90 in-lbs

B.3.2 Axial Force Error and Torsion

The axial error force is limited by the load cell to 0.25 lbs.

Torsion must be limited to 1 in-lb by careful assembly.

B.4 Lateral Support System, Pneumatic Supports

The lateral support system consists of 10 pneumatic supports and three tangent rods. The pneumatic supports act in the N/S direction. Compression supports utilize ball decouplers, tension supports use wire connections. Flex rods are used for the three tangential supports. Connections to the glass are invar bonded with RTV. A linear bearing is employed at the mirror face to minimize tensile loads in the coupling rod and react rod torques and axial loads primarily at the rear face.

The supports each contain a pair of 1.0" diameter diaphragms. This results in a more compact cell. The axial stiffness of the pair of diaphragms is 19.5 lb/in. The moment stiffness of an individual diaphragm is 1.22 in-lb/rad. The support moment stiffness is 2.44 in-lb/radian about a line passing through the centers of the two diaphragms and $2.44+0.5*Kax*X^2$ = 21.9 in-lb/rad, where Kax is the axial stiffness of one diaphragm and X is the distance between the centers of the diaphragms.

B.4.1 Ball Decoupler Supports

Fx = 1.2 lbs	accuracy of load applied by the support	
Fy = 0.21 lbs	along elevation axis	$(.05+.0078F_{lat})$
Fz = 0.21 lbs	along optical axis	$(.05+.0078F_{lat})$
Mx = 0.04 in-lbs		
My = 0.44 in-lb	$(0.15+.0142^*F_{lat})$	
Mz = 0.44 in-lb	$(0.15+.0142^*F_{lat})$	

Design Parameters:

Ball decoupler plane alignment = ±0.5 deg
Distance from ball decoupler plane to rod C/L ≤ 0.75"
Ball race contact diameter ≤ 0.75"
Force center position accuracy = ±0.020"
Load/support = 20.5 lbs ±0.19 lbs (±1.2 lbs if height position is 0.06").

Ball decoupler friction:

For μ = 0.005 and a normal force of 20.5 lbs, F_μ = 0.005*20.5 = 0.103
The angular error of 0.5 deg contributes an additional 20.5*sin(.5) = 0.18 lbs

The RSS total error is 0.21 lbs acting along the optical axis and along the elevation axis. An allowance for preload is established as 1/3 the total making:

$$Fy = Fz = 0.05 + 0.0078^*F_{lat}$$

Support Force Accuracy

The lateral support force accuracy is based on the support being installed to within 0.06" of its neutral height (the neutral height is the extension of the support which yields zero force at zero pressure). The force error is 0.06*19.5 = 1.2 lbs.

Moments (My and Mz) result from angular deflection (0.5 deg) of the piston, friction at the ball decoupler plane, and the position error.

Piston Angular deflection of 0.5 deg *2.6 in-lb/radian	= 0.023 in-lb
Ball Decoupler friction, 0.75"*0.21 lbs	= 0.16 in-lb
Position error = 0.02*20.5	= 0.41 in-lb
RSS Total =	0.44 in-lb

An allowance for preload is established as 1/3 the maximum.

$$My = Mz = 0.15 + 0.0142*F_{lat}$$

The torque across the ball decoupler will equal ½*0.75*.005*20.5 = 0.04 in-lbs

B.4.2 Wire Connected Supports

Support design parameters:	convolution to wire 0.625" free wire length = 1.0" min rod center to free wire = 0.25" max positioning (relative) = ±0.020"

Special Considerations for Uniform Axial Force:

Adjust wire ends (interface to support) to be reference height ± 0.030"

Obtain height reference (±0.001") on support at 20.5 lbs force (±0.1 lbs) with pressure ±0.5% (0.10 lbs). Net error is ±0.16 lbs.

At assembly, adjust support height to the height reference ±0.005" (0.098 lbs).

Net installation axial error =sort($0.16^2 + 0.098^2$) = 0.19 lbs

If positioned to 0.06" height, error is 1.2 lbs

Results:	Fx	= 20.5 ± 1.2	
	Fy	= 0.27	($0.013*F_{lat}$)
	Fz	= 0.34	($0.017*F_{lat}$)
	Mx	= 0.34 in lbs	
	My	= 0.3 in lbs	($0.015*F_{lat}$)
	Mz	= 0.3 in-lb	($0.015*F_{lat}$)

B.4.2.1 Axial Force Error

The axial force error is the hysteresis force (ref B.1) of 0.007 lbs and a force related to the axial spring rate of the support and the uniformity with which the axial positions of the supports are placed. The procedure described above limits the installed axial force error to 0.19 lbs. The hysteresis error is negligible. If lateral supports are installed to within ±0.06" of the same height, the error force is 0.06*12.5 =

B.4.2.2 Lateral Force Errors (Shears and Moments)

Position error effects (Fr, Ft, Mr, Mt)

The position error is accommodated by rotation of the actuator piston and deflection of the wire. This calculation considers a 1.22 in-lb/radian diaphragm moment stiffness (D=1.0). The moment stiffness about an axis through the centers of the two diaphragms is 2*1.22 = 2.44 in=-lb/rad. The moment stiffness about an axis passing between the two diaphragms is $2.44+0.5*Kax*X^2 = 21.9$ in-lb/rad where Kax is the axial stiffness of one diaphragm, 9.75 lb/in and X is the distance between the centers of the two diaphragms (2.0 inches). L_d, the distance from the convolution to the wire along the wire axis is 0.625" and L_w, the length of the wire, is 1.0" . Refer to section B.2.2 for equation derivation and definition of the remaining variables.

$V = \delta^*/(L_w/Fax+L_d^2/(K_\theta+L_d^*Fax)) = 0.27$ lbs (≈ 0.013*Fax) along the axis passing between the diaphragms.
$= 0.34$ lbs (≈ 0.017*Fax) along the axis passing through the diaphragm centers and:

The maximum load per support (Fax) is 20.5 lbs

The moment referenced to the center of the rod is:

$M_{mid\text{-}plane} = V*0.25$ so Mz = 0.068 and My = .085 in-lb.

There is also a position error moment, Mpos. Assuming the 0.020 relative error is split (RSS) between mirror and cell (.014" each):

Mpos = .014*Fax = .29 in-lb

The RSS net moment is:

$Mz = sort(0.068^2+0.29^2) = 0.30$ in-lb ($0.015*F_{lat}$)
$My = sort(0.085^2+0.29^2) = 0.30$ in-lb ($0.015*F_{lat}$)

B.4.2.3 Torsion (Mx)

Assuming 0.060" wire with a strand angle of 20 degrees. The torsion is estimated as:

$Mz = 0.4 * D_{wire} * sin(20) * Fax = .17$ in-lb
This is doubled for design, Mz = 0.34 in-lb

B.5 Lateral Locator Force Errors (Tangent Rods)

Fr = Fz = 0.19 lbs
Mr = Mz = 0.90 in-lbs
Ft = 0.25 lbs
Mt = 1 in-lb

B.5.1 Flex rod:

Distance between extreme flexures = 5"
Center of rod to middle of nearest flexure = 1.0"
Flexures: .25 wide by 0.04 thick by 0.5 inches long. 0.03 radii at ends
Rod: 0.25 dia., 0.25" of rod between flexures (steel, E=28e6)
Installation (relative) 0.01" and 0.25 degrees
Maximum axial force = 0.25 lbs

Flexrod input: 7,1,1.75,.25,.04,.43,28e6,.01,.25,.25 (f9flex.in)

Results:
1/5 Fcrit = 398 lbs (max allowable axial load)
Flexure stress at 0.25 lbs = 13,525 psi
Flexure stress at 1g = 24,781 psi
V = 0.19 lbs
M = 0.90 in-lbs

B.5.2 Axial Force Error and Torsion

The axial error force is limited by the load cell to 0.25 lbs.
Torsion must be limited to 1 in-lb by careful assembly.

B.6 Location of Lateral Support Plane Relative to CG

The Lateral Supports are nominally applied in the CG plane. The accuracy with which the support plane must be established is considered in this section.

Most of the finite element results referenced in this report had the lateral support plane located 0.02" forward of the CG. In Table B.6.1, results for different support plane locations are compared.

Table B.6.1 Comparison of Different Support Plane Locations

Tabulated Values are the maximum value of the rms height difference in millionths of an inch (typically occuring at the maximum distance)

	Support Plane Relative to CG, + is Toward Face		
	+.020"	0.00	-0.05"
1g X, 12 Laterals	1.108	0.862	1.050
1g X, 10 Laterals	1.546	1.391	1.414
Zen. to 30, 10 Lat	0.78	0.72	0.75
Zen. to 45, 10 Lat	1.13	1.05	1.14
Zen. to 60, 10 Lat	1.72	1.64	1.58

The results of Table B.6.1 indicate that the support plane must be located from .05" behind the c plane to 0.020" in front of the c plane.
0,-.75

B.7 Astigmatism

Astigmatism is the softest deformation mode of the mirror. Error force distributions that could generate astigmatic deformations must be identified and accounted for. Two sources of astigmatic distortion are considered here, cell bending and random chance.

B.7.1 Randomly Generated Astigmatic Force Distributions

When the 12 axial supports on the outer row are installed, the axial error force of each support is estimated to be 0.14 lbs (see B.2.1). By random chance, the error forces will occasionally include a $\sin(2\theta)$ component. The magnitude of this component was established using a Basic program to generate multiple sets of random numbers from which the $\sin(2\theta)$ component was extracted. By using 1000 or more sets of 12 values, the mean coefficient of the $\sin(2\theta)$ term was driven close to zero, but the standard deviation of the values of the coefficient was 0.24 (for force errors between -1 and +1). For future reference, the standard deviation for the random astigmatic coefficient was compiled for different numbers of supports with the results included in Table B.7.1 .

We want to obtain an estimate for the randomly introduced astigmatism that we won't exceed more than 10% of the time so we need to design to a random astigmatic coefficient that is 1.65 times the standard deviation. Since there are sine and cosine astigmatic terms, the design value for random astigmatism becomes $1.65 * \sqrt{2} * \sigma$ or 2.33σ (σ = the standard deviation). These design values are listed in Table B.7.1 for unit (±) error forces.

Table B.7.1 Normalized Coefficients for Random Astigmatic Force Distributions

# of Forces	# Data Sets	Mean Coef	σ	Design Coef.
6	1000	-0.004	0.345	0.805
8	1000	-0.0003	0.298	0.695
12	2000	0.0005	0.236	0.551
18	2000	-0.0063	0.189	0.441
24	1000	0.0045	0.167	0.390
36	2000	0.0023	0.135	0.315
54	1000	.0006	0.105	0.245

The Design Coefficient is the factor to be applied to the error force in estimating the magnitude of the astigmatic distribution that will occur 10% of the time. It equals 2.33σ.

B.7.2 Astigmatic Forces Generated by Cell Sag

Static analysis of the f9 telescope cell gives astigmatic deflection coefficients of 0.00073 at zenith and 0.00349 at the horizon. Taking the net cell sag to be the sum of twice the axial plus the lateral (assumes face up alignment of the axial supports) gives a deflection of ±0.0050". Acting through the axial actuator stiffness of 12.5 lb/in (ref B.1) this amounts to an astigmatic force coefficient of 0.063 lbs.

The axial force component of the lateral actuators is 25% of the value obtained for an 0.020" position error in section B.4.2.2. Ball decouplers used in half of the lateral supports produce less damaging moment errors. Since astigmatic loads on the lateral supports are relatively benign, the calculation normal force is applied all around. 25% of 0.34 lbs = 0.085 lbs .cd ../

Cell plate deflection summary:

Term	Units	Value 1g X	Value 1g Zenith
Rotx	μ-rad	-13.9	-1.1
Roty	μ-rad	139	4.5
P-V	milli-Inches	7.47	3.86
Zerneke Coefficients			
Sin Astigmatism	milli-Inches	0.087	0.663
Cos Astigmatism	milli-Inches	3.49	-0.286
Power	milli-Inches	0.025	-1.32
Spherical	milli-Inches	0.020	-1.09

Appendix C Net Performance Tables

This Appendix contains summary tables listing rms surface distortion and rms surface slope errors for various elevation angles. Tables C1 and C4 are identical to Tables 3a and 3b.

Table C1 Telescope Pointing Toward Zenith

Waves are at 0.6328 micro-meters

Load Case	Rms Surf Distortion		Slope Error arc-sec rms
	μ-inch	WF, λ	
Gravity, Zenith to Indicated Elev	0	0.0000	0
Fz Friction at 1 lateral	0.0015	0.0001	0.0006
Fz Friction at All Laterals	0.0064	0.0005	0.0021
Fz Friction =0.15sin(2t)	0.0053	0.0004	0.0015
Axials Fz Astig, random	0.0625	0.0050	0.0014
Axials Fz Astig. Cell Bend	0.0656	0.0053	0.0014
Laterals Fz Astig, random	0.0008	0.0001	0.0001
Laterals Fz Astig. Cell Bend	0.0031	0.0002	0.0002
Random Force Errors	0.3154	0.0253	0.0109
RSS Total =	0.3283	0.0264	0.0114

Table C2 Telescope Pointing 30 Degrees from Zenith

Waves are at 0.6328 micro-meters

Load Case	Rms Surf Distortion		Slope Error arc-sec rms
	μ-inch	WF, λ	
Gravity, Zenith to Indicated Elev	0.1660	0.0133	0.0707
Fz Friction at 1 lateral	0.0015	0.0001	0.0006
Fz Friction at All Laterals	0.0064	0.0005	0.0021
Fz Friction =0.15sin(2t)	0.0053	0.0004	0.0015
Axials Fz Astig, random	0.0625	0.0050	0.0014
Axials Fz Astig. Cell Bend	0.0656	0.0053	0.0014
Laterals Fz Astig, random	0.0008	0.0001	0.0001
Laterals Fz Astig. Cell Bend	0.0031	0.0002	0.0002
Random Force Errors	0.3497	0.0281	0.0121
RSS Total =	0.3977	0.0319	0.0718

Table C3 Telescope Pointing 45 Degrees from Zenith

Waves are at 0.6328 micro-meters

Load Case	Rms Surf Distortion		Slope Error arc-sec rms
	μ-inch	WF, λ	
Gravity, Zenith to Indicated Elev	0.3218	0.0258	0.1004
Fz Friction at 1 lateral	0.0015	0.0001	0.0006
Fz Friction at All Laterals	0.0064	0.0005	0.0021
Fz Friction =0.15sin(2t)	0.0053	0.0004	0.0015
Axials Fz Astig, random	0.0625	0.0050	0.0014
Axials Fz Astig. Cell Bend	0.0656	0.0053	0.0014
Laterals Fz Astig, random	0.0008	0.0001	0.0001
Laterals Fz Astig. Cell Bend	0.0031	0.0002	0.0002
Random Force Errors	0.3774	0.0303	0.0131
RSS Total =	0.5043	0.0405	0.1013

Table C4 Telescope Pointing 60 Degrees from Zenith

Waves are at 0.6328 micro-meters

Load Case	Rms Surf Distortion		Slope Error arc-sec rms
	μ-inch	WF, λ	
Gravity, Zenith to Indicated Elev	0.5248	0.0421	0.1238
Fz Friction at 1 lateral	0.0015	0.0001	0.0006
Fz Friction at All Laterals	0.0064	0.0005	0.0021
Fz Friction =0.15sin(2t)	0.0053	0.0004	0.0015
Axials Fz Astig, random	0.0625	0.0050	0.0014
Axials Fz Astig. Cell Bend	0.0656	0.0053	0.0014
Laterals Fz Astig, random	0.0008	0.0001	0.0001
Laterals Fz Astig. Cell Bend	0.0031	0.0002	0.0002
Random Force Errors	0.4029	0.0323	0.0140
RSS Total =	0.6679	0.0536	0.1246

MMT F9 Secondary Error Analysis Load Cases

Loading	File	Zenith	30 deg	45 deg	60 deg
Elevation Angle (from Zenith)		0.000	30.000	45.000	60.000
Gravity, Zenith to Elev		-	f945,4	f945,5	f945,6
Fz friction at 1 lateral	f9secl,4	0.150	0.150	0.150	0.150
" all laterals	f9secl,5	0.150	0.150	0.150	0.150
Fz Friction .15sin(2t)	f9secl,6	0.150	0.150	0.150	0.150
Astig, Random, Axials	f9astx2,2	0.030	0.030	0.030	0.030
Asrtig, Random, Laterals	f9astx2,3	0.011	0.034	0.046	0.055
Astig, Cell Bend, Axials	f9astx2,2	0.032	0.032	0.032	0.032
Astig, Cell Bend, Laterals	f9astx2,3	0.043	0.043	0.043	0.043
Fax = axial support force =		11.400	9.872	8.060	5.700
Flat = lateral support force =		0.000	10.250	14.494	17.753
Axials, Inner Row (6) Fr=.0072*Fax	f9ir,1	0.082	0.071	0.058	0.041
Ft=.0072*Fax	f9ir,2	0.082	0.071	0.058	0.041
Fz=0.14	f9latp,5	0.140	0.140	0.140	0.140
Mr=.016*Fax	f9ir,4	0.182	0.158	0.129	0.091
Mt=.016*Fax	f9ir,5	0.182	0.158	0.129	0.091
Mz=.2	f9ir,6	0.200	0.200	0.200	0.200
Axials, Outer Row (12) Fr=.0072*Fax	f9sec,1	0.082	0.071	0.058	0.041
Ft=.0072*Fax	f9sec,2	0.082	0.071	0.058	0.041
Fz=0.14	f9latp,2	0.140	0.140	0.140	0.140
Mr=.016*Fax	f9sec,4	0.182	0.158	0.129	0.091
Mt=.016*Fax	f9sec,5	0.182	0.158	0.129	0.091
Mz=.2	f9sec,6	0.200	0.200	0.200	0.200
Axial Locators (3) Fr = 0.19	f9sec,1	0.190	0.190	0.190	0.190

Ft = 0.19	f9sec,2	0.190	0.190	0.190	0.190
Fz = 0.25	f9latp,2	0.250	0.250	0.250	0.250
Mr = 0.90	f9sec,4	0.900	0.900	0.900	0.900
Mt = 0.90	f9sec,5	0.900	0.900	0.900	0.900
Mz = 1.0	f9sec,6	1.000	1.000	1.000	1.000
Laterals, Ball Decpled Fx = 1.2	f9secl,7	1.200	1.200	1.200	1.200
$Fy=0.05+.0078*F_{lat}$	f9secl,8	0.050	0.130	0.163	0.188
$Fz=0.05+.0078*F_{lat}$	f9secl,9	0.050	0.130	0.163	0.188
Mx=0.04	f9secl,11	0.040	0.040	0.040	0.040
$My=0.15+.0142*F_{lat}$	f9secl,12	0.150	0.296	0.356	0.402
$Mz=0.15+.0142*F_{lat}$	f9secl,13	0.150	0.296	0.356	0.402
Laterals, Wire Cpling Fx=1.2	f9secl,7	1.200	1.200	1.200	1.200
$Fy=0.013*F_{lat}$	f9secl,8	0.000	0.133	0.188	0.231
$Fz=0.017*F_{lat}$	f9secl,9	0.000	0.174	0.246	0.302
Mx=.34	f9secl,11	0.340	0.340	0.340	0.340
$My=0.015*F_{lat}$	f9secl,12	0.000	0.154	0.217	0.266
$Mz=0.015*F_{lat}$	f9secl,13	0.000	0.154	0.217	0.266
Tangent Rods Fr=0.19	f9secl,7	0.190	0.190	0.190	0.190
Ft=0.25	f9secl,8	0.250	0.250	0.250	0.250
Fz=0.19	f9secl,9	0.190	0.190	0.190	0.190
Mr=0.9	f9secl,11	0.900	0.900	0.900	0.900
Mt=1.0	f9secl,12	1.000	1.000	1.000	1.000
Mz=0.9	f9secl,13	0.900	0.900	0.900	0.900

File Contents (Ref. /home/bcuerden/mmt/f9sec/comb/)

File Name	Load Case	Description
f9ir.stf	1	1K, Fr, inner row
	2	1k, Ft, inner row
	3	1k, Fz, inner row
	4	1 in-K, Mr, inner row
	5	1 in-K, Mt, inner row
	6	1 in-K, Mz, inner row
f9sec.stf	1	1K, Fr, outer row
	2	1k, Ft, outer row
	3	1k, Fz, outer row
	4	1 in-K, Mr, outer row
	5	1 in-K, Mt, outer row
	6	1 in-K, Mz, outer row
	7	1K, Fr, inner row
	8	1k, Ft, inner row
	9	1k, Fz, inner row
	10	1 in-K, Mr, inner row
	11	1 in-K, Mt, inner row
	12	1 in-K, Mz, inner row
	13	1g X on 3 axial and three tang. supports
	14	1g Y on 3 axial and three tang. supports
	15	1g Z on 3 axial and three tang. supports
f9latp.stf	1	1g Z
	2	Fz=1 at 12001 (outer row), Reactions spread among 18 axial supports
	3	Fz=1 at 12002 (outer row), Reactions spread among 18 axial supports
	4	Fz=1 at 12003 (Outer row), Reactions spread among 18 axial supports
	5	Fz=1 at 12013 (inner row), Reactions spread among 18 axial supports
	6	Fz=1 at 12014 (inner row), Reactions spread among 18 axial supports
	7....	not used
f9secl.stf	1	1 g Fz, ϕ = 1.0
	2	1 g Fz, ϕ = 1.05 (inner and outer row forces not equal)
	3	1 g Fz, ϕ = 0.95
	4	Fz = 1 friction at one lateral (Face to back)
	5	Fz = 1 friction at all laterals
	6	Fz = 1*sin(2t) friction
	7	1K Fr at lateral spt
	8	1K, Ft, lateral support
	9	1K, Fz, lateral support
	10	1K, Fz, lateral support, slip joint at

		back
	11	1 in-K, Mr, lateral support
	11	1 in-K, Mt, lateral support
	12	1 in-K, Mz, lateral support
	13	1K, Fr, lateral support
f945.stf	1	1g X, 12 lateral supports
	2	1g Y, 10 lateral supports
	3	1g X, 10 Fx supports, 1% on tangentials
	4	change, zenith to 30 deg from zenith
	5	change, zenith to 45 deg from zenith
	6	change, zenith to 60 deg from zenith

APPENDIX D Breakdown of Contributions to Net Mounting Error

This Appendix contains structure function plots which include selected sets of contributing factors. Similar plots were used to determine which design parameters had to be tightened to obtain acceptable performance. These plots may prove useful during the detail design and checkout phases.

The following lists define the specific content of the plotted curves. Unless otherwise noted, the curve can be regenerated by running combx2 < filename where filename is the curve name followed by the extension .in (ex. tzz.in). These files currently reside in /home/bcuerden/mmt/f9sec/comb . The files which generate the net performance plots at zenith, 30 45 and 60 degrees from zenith are the telz.in, tel30.in, tel45.in and tel60.in files.

Plot D1 Zenith

Z Total	Identical to Figure 2, this is the net mounting error at zenith. Filename is telz.in
tz	This is the contribution of the 18 axial supports and the 3 fixed locators less the fz components which were broken out in tzz below.
tzz	This is the contribution of the fz error force at the 18 axial supports and the three fixed axial locators.
tzlat	This is the contribution of the 10 lateral supports and the three tangent rods (all terms .. fx, fy ... Mz).
tzmisc	These are the three fz friction cases at the lateral support linear bearing.

Plot D2 Zenith

zastig	This consists of the four astigmatic force set results (axial and lateral random and cell bending effects).

Plot D3 Gravity Sag at Zenith

tzabs	This is the zenith gravity sag. This is not included in the zenith mounting performance because it is polished out.

Plot D4 Absolute Performance at Zenith

telzabs	This is the net zenith performance including the zenith gravity sag.

Plot D5 This plot is the zenith performance less the astigmatic force set effects of zastig.

Plot D6 Pointing 60 Degrees from Zenith

Del Gravity	This is the effect of the gravity change from zenith to 60 degrees Ref. input file tla.in
Axial Spts	This is the contribution of the 18 axial supports and the three axial locators. Ref tlb.in
Lateral Spts	This is the contribution of the lateral support system (10 supports plus three tangent rods), Ref tlc.in

Plot D7 Pointing 60 Degrees from Zenith

Str Func	This is the support structure function less the four astigmatic force set cases.
1.2# Faxial	This is the contribution of the 1.2 lb errors along the line of action of the 10 lateral supports. Ref tld.in
Fz Error	This is the contribution of the fz components from the 10 lateral supports. Ref tle.in

Fig D.1 **Structure Function And Allowable**

Total and Selected Contributions At Zen

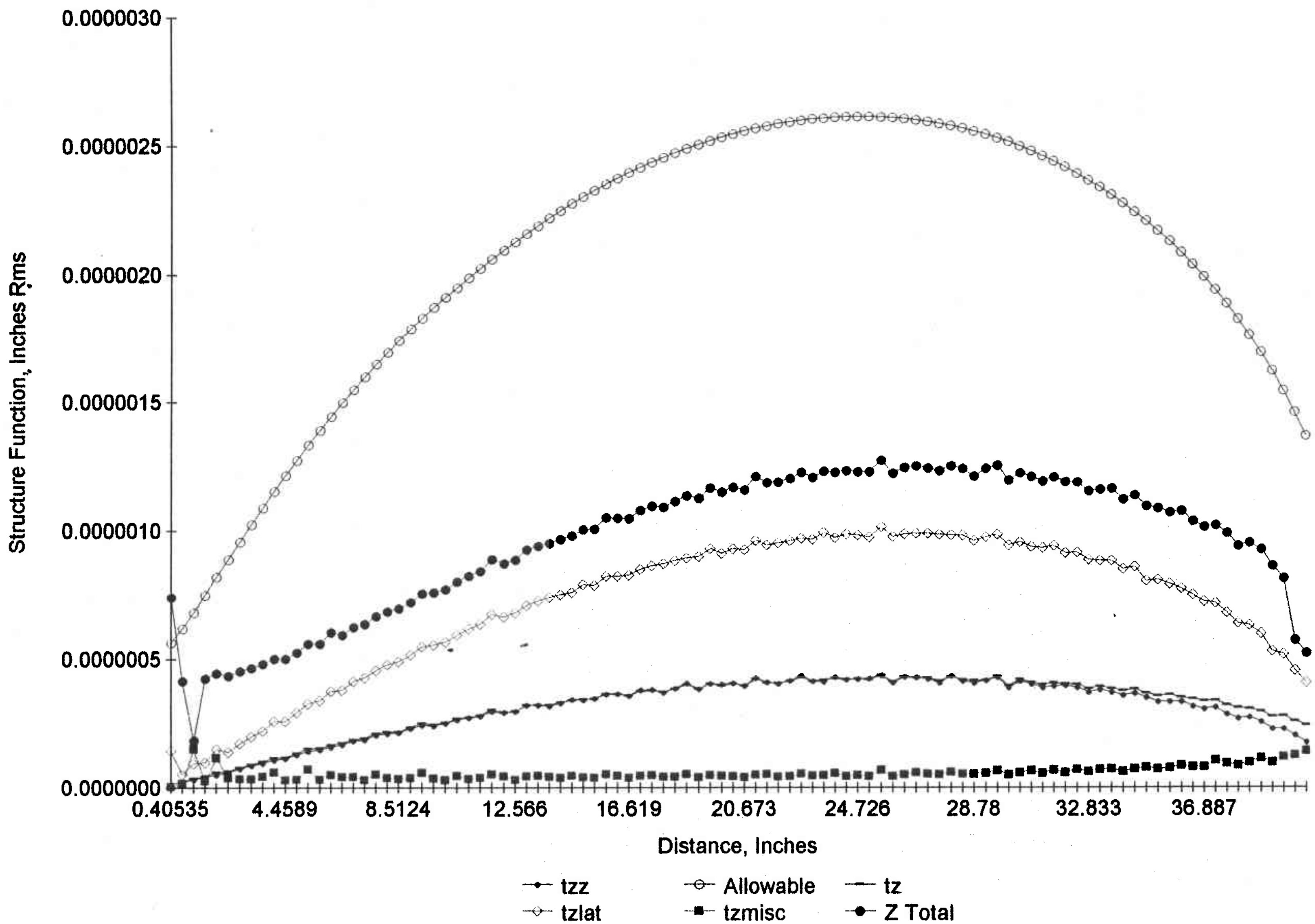


FIG. D2 **Astigmatic Force Sets Contribution**

Zenith Structure Function

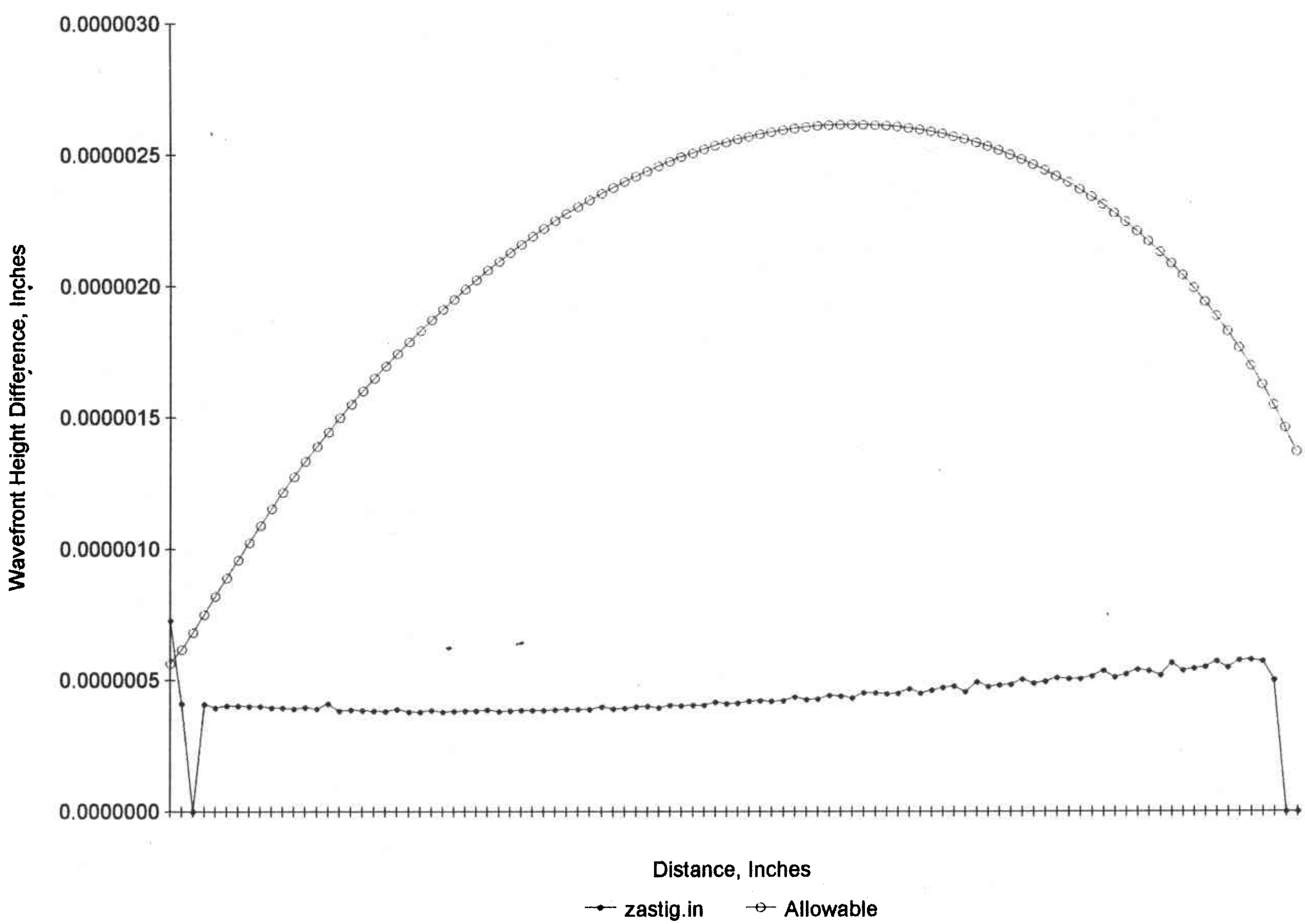


Figure D3 **Structure Function And Allowable**

Gravity Sag At Zenith

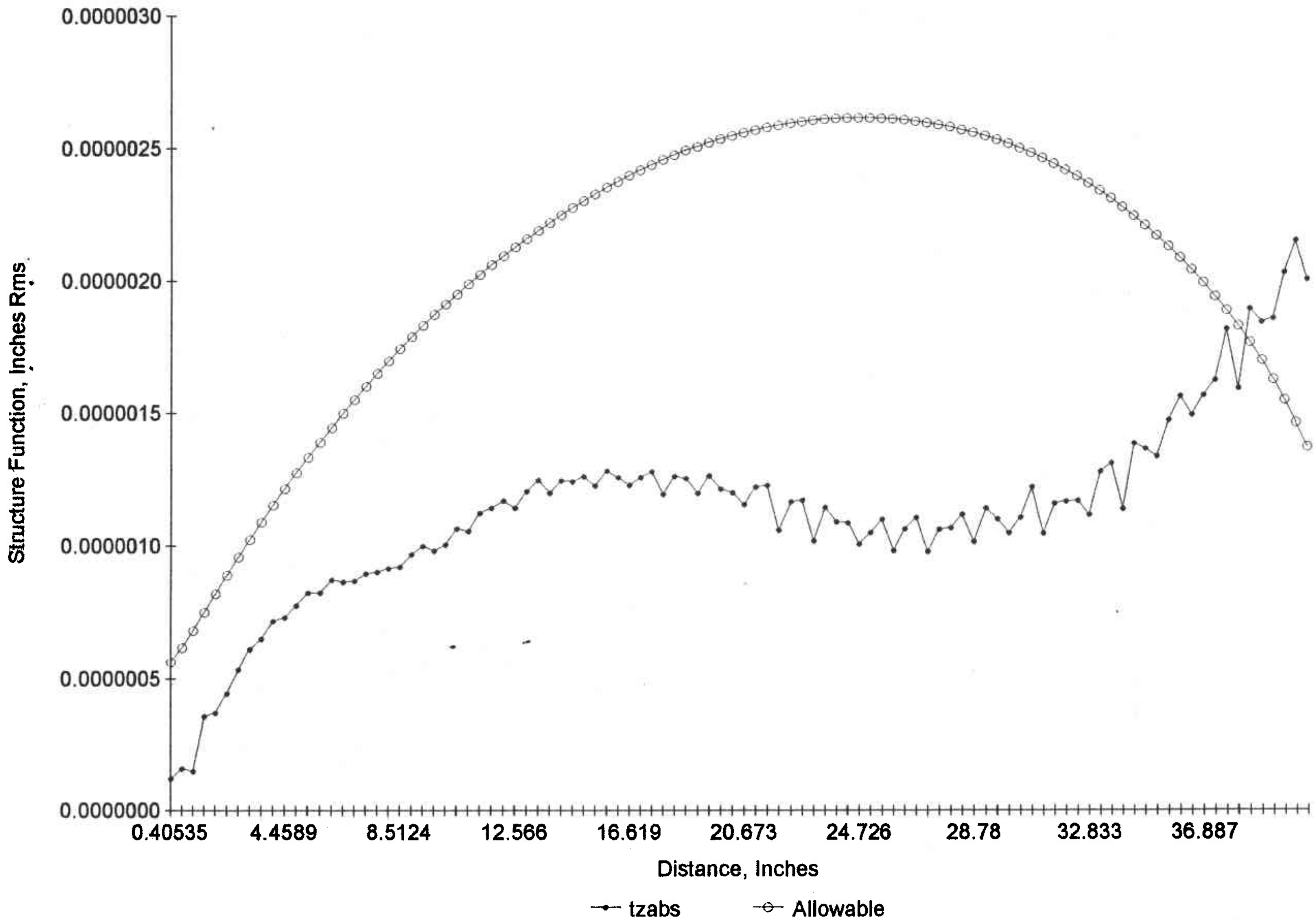


FIGURE 04 **Structure Function And Allowable**

Absolute Performance At Zenith

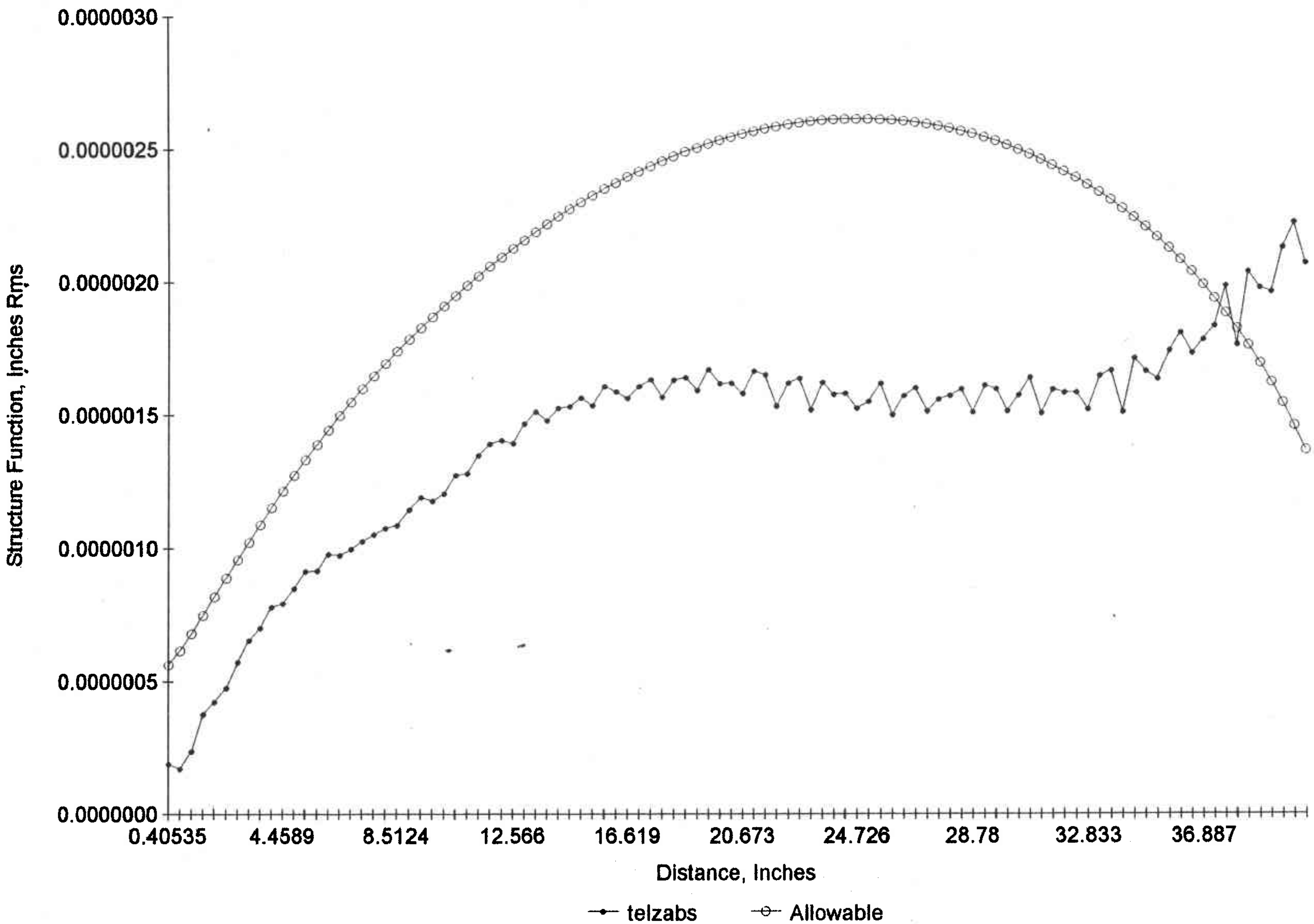


Figure D5 **MMT f9 Secondary Mounting Struct. Func.**

Zenith Pointing less Astigmatic Force Sets

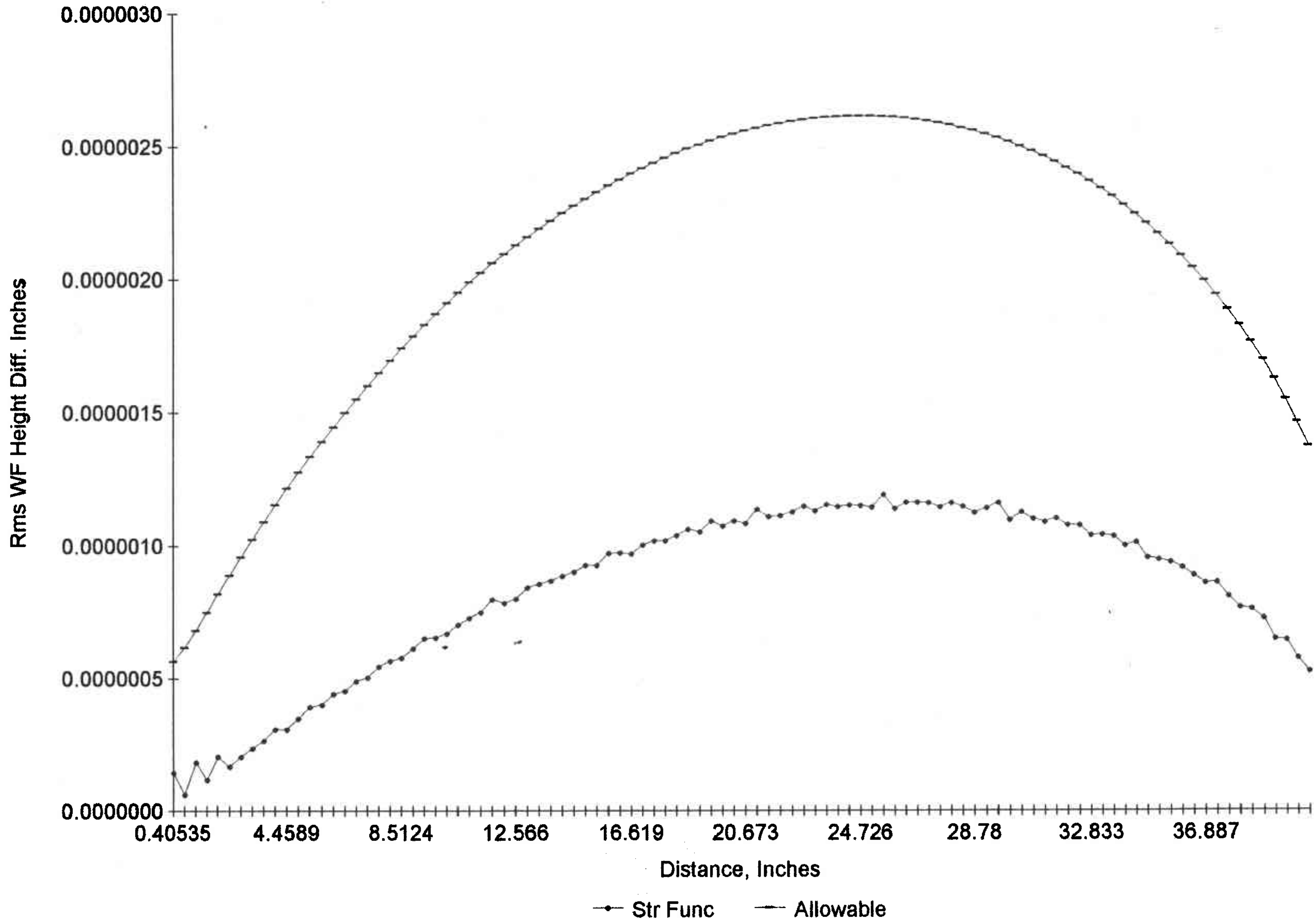


Figure D6 **Structure Function and Allowables**

Total and Contributors at 60 deg

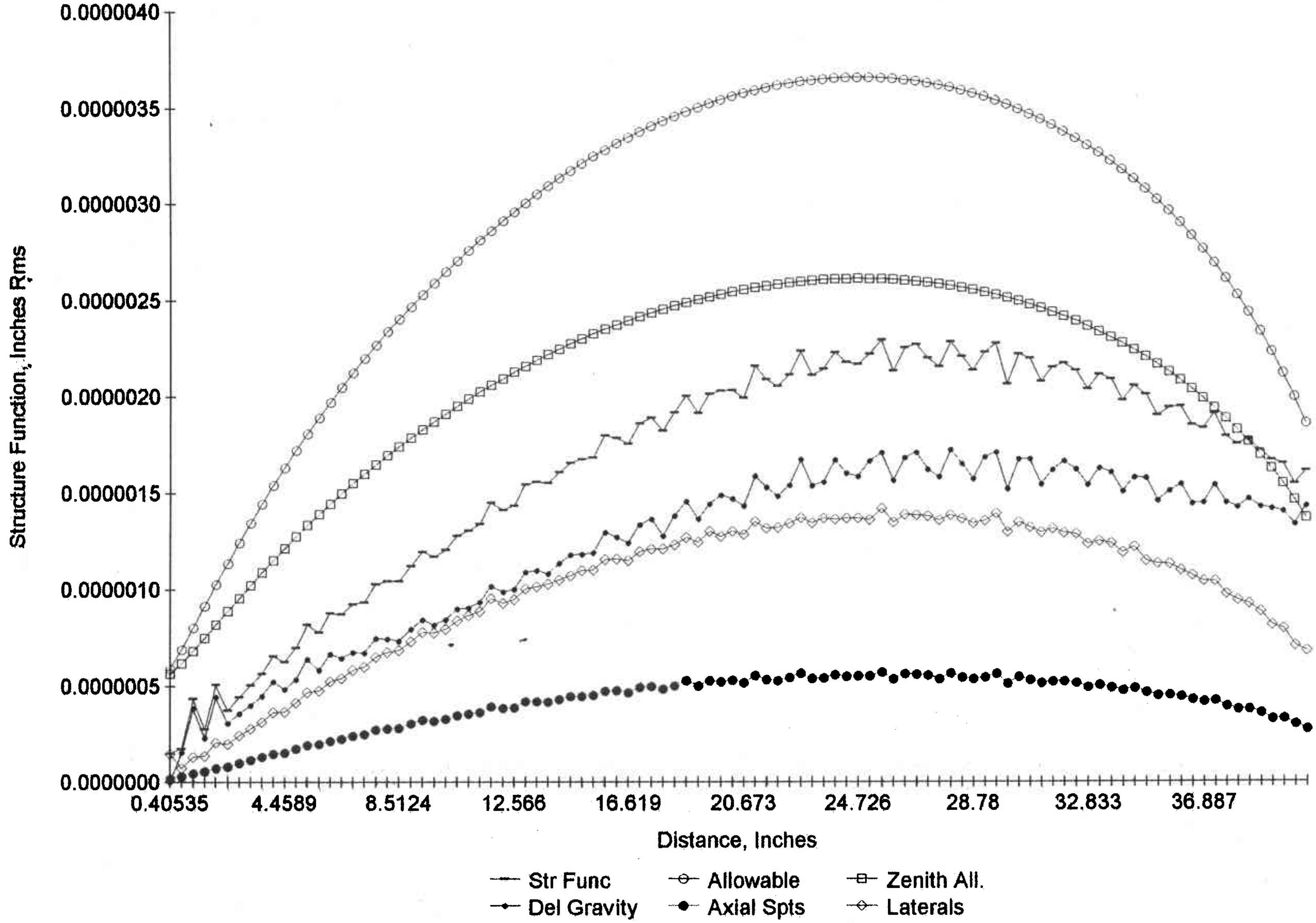
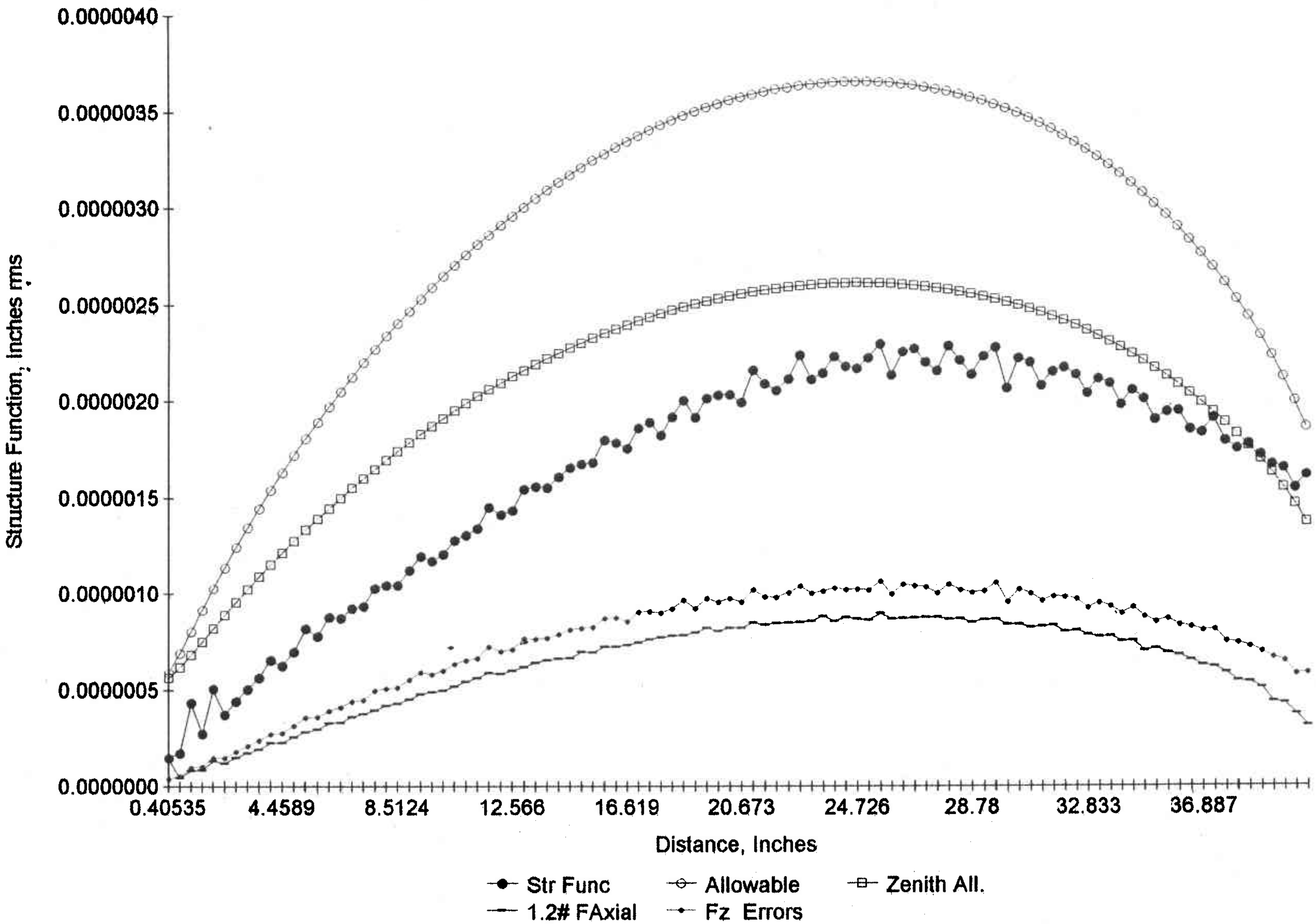


Figure 27 **Structure Function and Allowables**

Total and Contributors at 60 deg



Appendix E   Notes on Generating Net Structure Function Plots

Generating the structure function plots used in this report was a four step process. Intermediate files have been saved to enable revised plots (different error force levels) to be generated with relative ease.

The complete process starts with several ANSYS runs to develop the surface distortion results for various load cases. The program slps is then run to remove translation tilt and power from the ANSYS surface normal displacement results and to generate a file containing the structure function for each load case. Each structure function consists of 100 sets of distance, height difference values. Structure functions are saved to a filename.stf file which have been preserved.

During the process of generating these files it was pointed out to me that the structure function was defined as a wavefront height difference and not a surface height difference. Almost all of the .stf files for the f9 secondary are in terms of surface height difference (the exception is the f9astig.stf file which contains wavefront structure function data). In order to use the existing .stf files, the load case combination program was modified to become the combx2 program which introduces the appropriate factor of 2.

To generate a structure function which is a combination of several available load cases, one simply runs combx2. Input parameters to combx2 contain the definition of the allowable structure function and the names of the files containing the load cases, the load case number of the desired case in a given file, and the scale factor for the load case. Combx2 combines the specified load cases and generates a crude printer plot and a tabular listing of the result. It also writes a filename.spd file which can be loaded into a works spreadsheet for plotting.

All f9 secondary files (combx2 included) are in /home/bcuerden/mmt/f9sec/comb . Numerous sample input files (filename.in) are included.

APPENDIX F Cell Configuration

The cell configuration is shown in Figure F.1 . The lateral and axial support concepts are shown in Figures F.2 and F.3 . The cell structure is aluminum for reduced weight. Thicknesses and all up cell weight are listed below.

Item	Thickness
Cell OD	0.25"
OD at Lateral Supports	0.625
Outer back plate	0.25"
Step down cylinder	0.5"
Center disk	0.5"
Center Webs	0.75"

Weight (including mirror) = 320 lbs

Inertias:

Ixx = Iyy = 100

Izz = 193

CG = 0,0,-5.93 (z=0 is the hexapod interface plane)

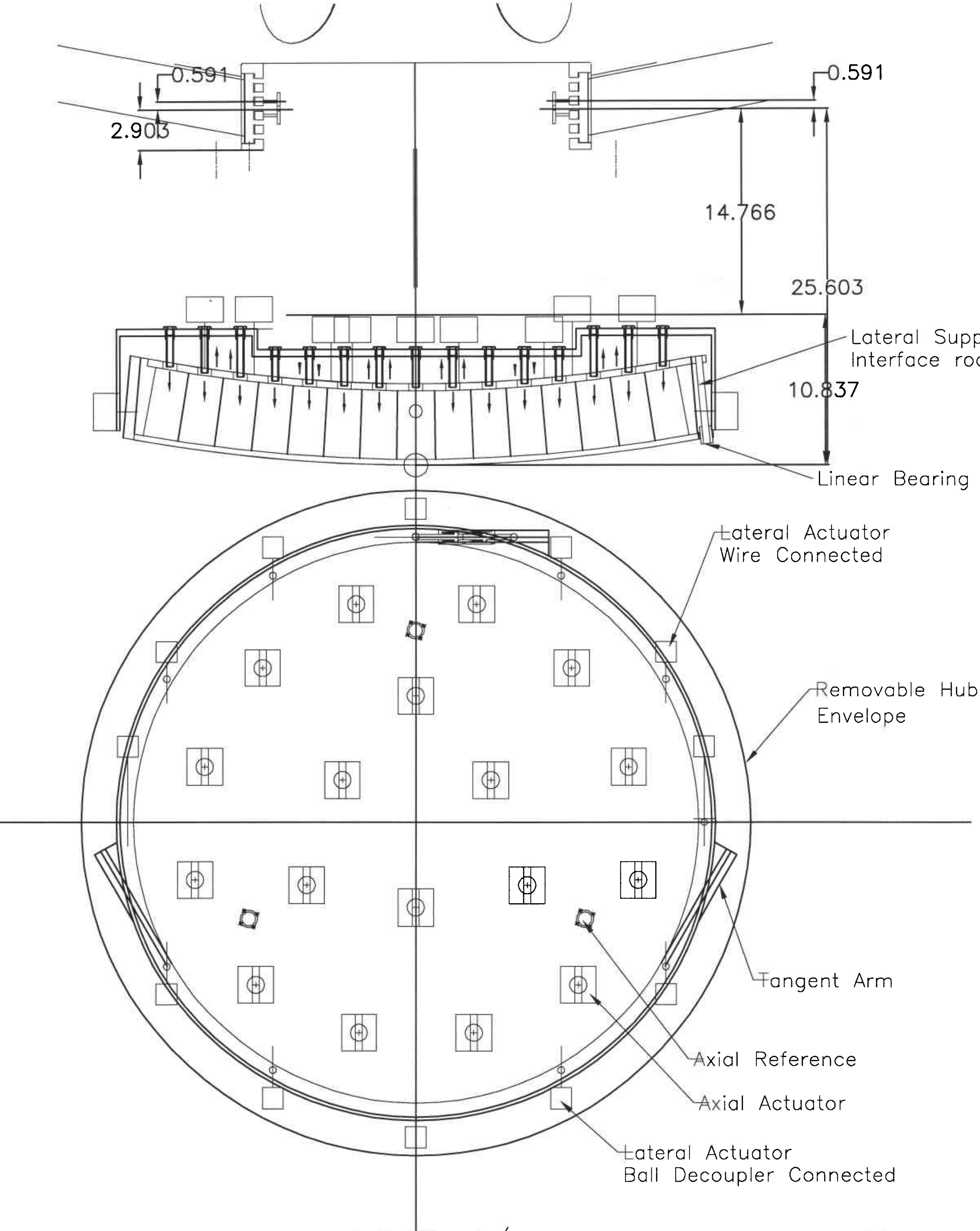


Figure F.1 MMT f/9 Cell Configuration
/home/bcuerden/mmt/f9sec/dwgs/tcell2-drop.dwg

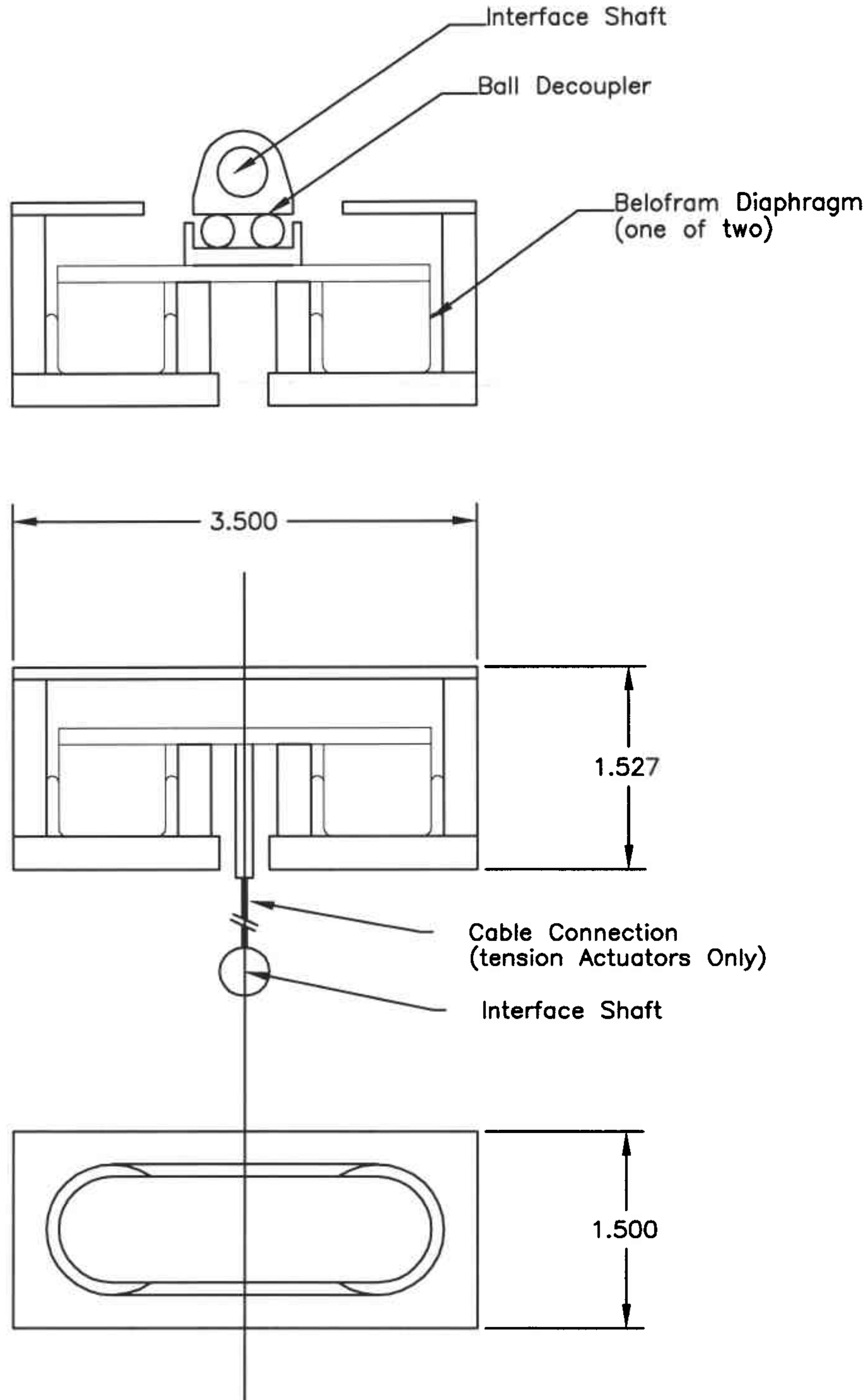


Figure F.2 | Lateral Actuator Concept

/home/bcuerden/mmt/
f9sec/dwgs/axial-spt.dwg

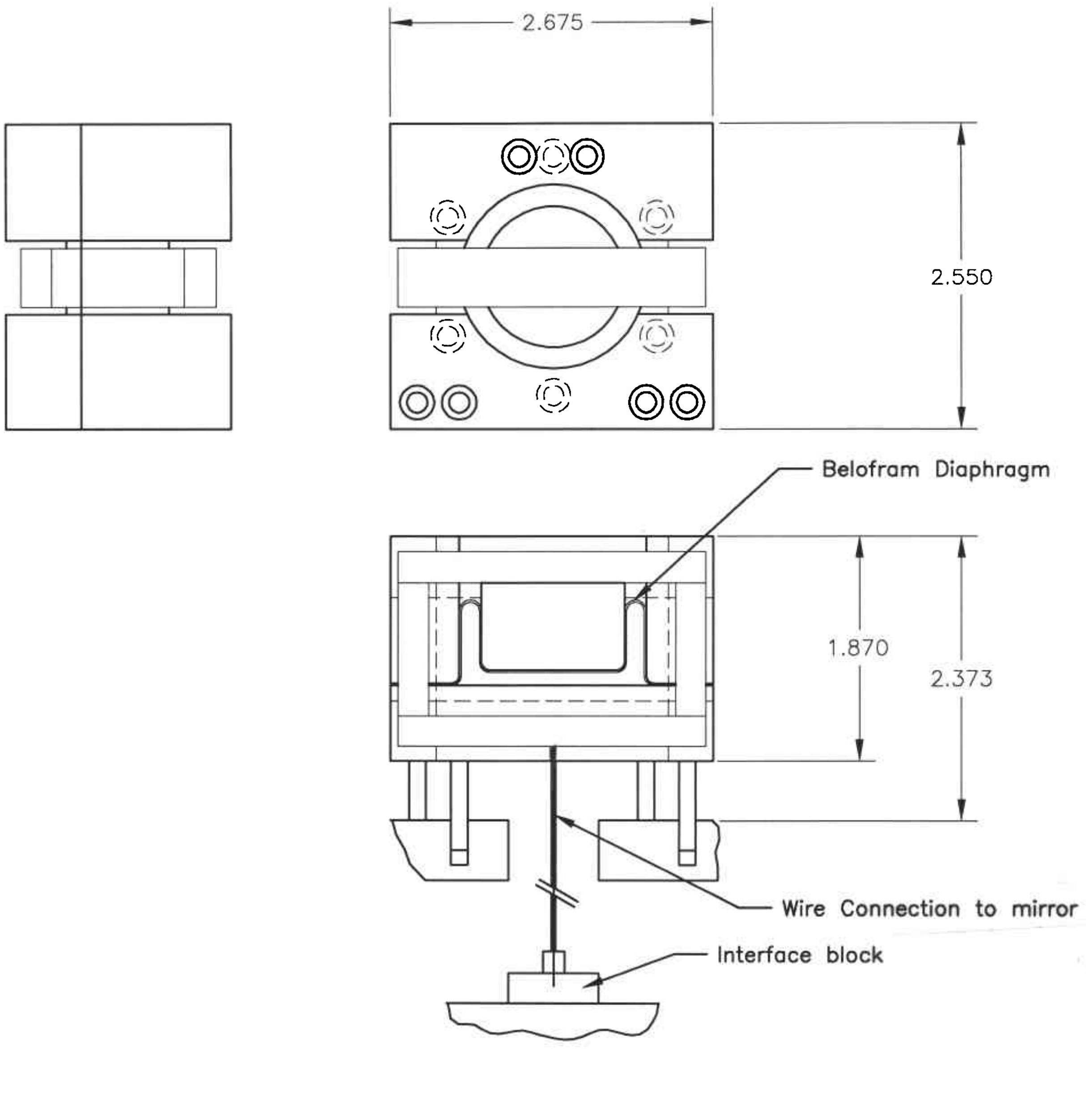


Figure F.3 Axial Actuator Concept
/home/bcuerden/mmt/f9sec/dwgs/
axial−spt.dwg