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Optical design of the Hobby-Eberly Telescope Four Mirror Spherical Aberration Corrector

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ABSTRACT

The Hobby-Eberly Telescope uses a 11-meter diameter F/1.45 segmented spherical primary mirror. A spherical mirror of this size generates large amounts of spherical aberration. To be used successfully in a tilted optical Arecibo type telescope, the spherical aberration needs to be corrected. This means that tracking of astronomical targets is achieved through moving a tracker optical package which imposes somewhat severe packaging constraints. Given these packaging constraints, novel methods must be employed to correct the aberrations with the Spherical Aberration Corrector contained in the moving tracker optical package. The paper reviews the pertinent requirements, constraints and the resultant design of the Hobby-Eberly Telescope Four Mirror Spherical Aberration Corrector.

Keywords: Telescope Design, Four Mirror, Spherical Aberration

1. INTRODUCTION

1.1 HET Overview

The Hobby-Eberly Telescope is an Astronomical Survey Instrument which uses an 11 meter diameter F/1.45 segmented spherical primary mirror. The aperture of the system limits the use to 9.5 meters of the Primary Mirror. However, since the entrance pupil is not at the Primary Mirror, the beam moves around on the Primary mirror as the Spherical Aberration Corrector/Tracker Optical Package (SAC/TOP) moves through the field angles of interest.[1,2,3]

Previously, a Spherical Aberration Corrector was designed using two mirrors. It was found that the manufacturing costs of the mirror were beyond the cost constraints of the project. Therefore, a new design was sought with the emphasis on manufacturability and cost with a trade-off with performance. Figure 1 shows the PM of the HET with some of the pertinent parameters such as paraxial focus, radius of curvature, clear aperture and PM diameter.

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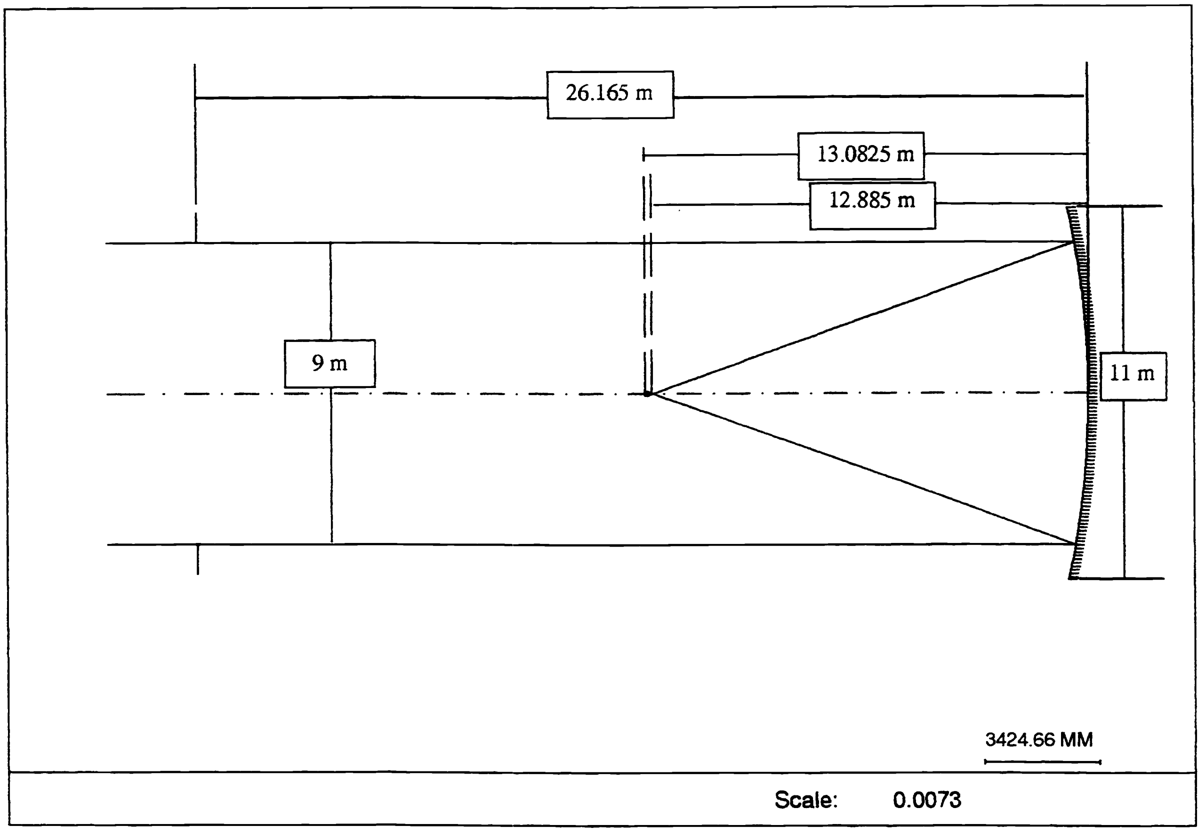
Figure 1: Shows the HET PM plot from Codev with the pertinent parameters such as paraxial focal distance (13.0825meters), Radius of curvature (26.165 meters), Clear Aperture (9 meters), and PrimaryMirror Diameter (11 meters).



1.1 Spherical Aberration

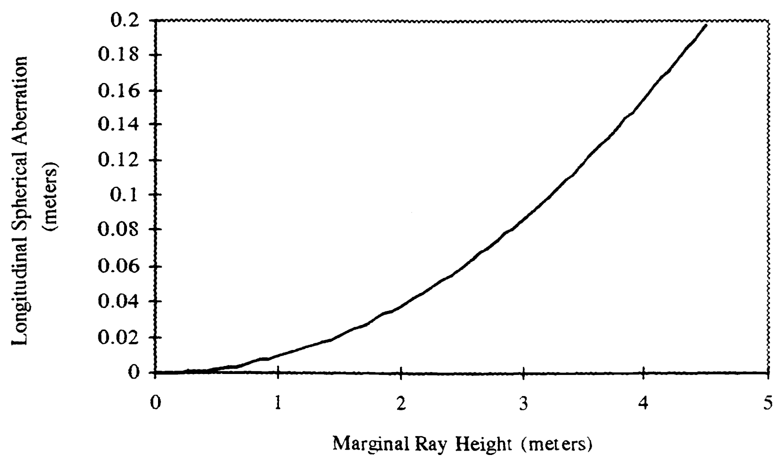
The amount of Spherical Aberration generated by a 9 meter Primary Mirror is enormous. Korsch published the formula for longitudinal spherical aberration as

$$L'-l' = \Delta s'_{sa} = \left(\frac{r}{2}\right)\frac{1-\sqrt{1-\chi^2}}{\sqrt{1-\chi^2}}, \tag{1}$$

where L' is the full aperture focus,
l' is the paraxial focus,
$\Delta s'_{sa}$ is the difference in the foci,
r is the radius of curvature of the spherical mirror,
χ is the ratio of the marginal ray height, h, to the mirror radius, r (i.e., $\chi = h/r$).[4]

Substituting in the radius of 26.165 meters and a marginal ray height of 4.5 meters gives a χ of 0.171985 which translates into an amount of longitudinal spherical aberration of 0.197885 meters (or 7.79 inches). Figure 1 shows the longitudinal spherical aberration as a function of aperture.

Figure 2: Longitudinal spherical aberration versus marginal ray height for a 26.165 meter radius of curvature spherical mirror.

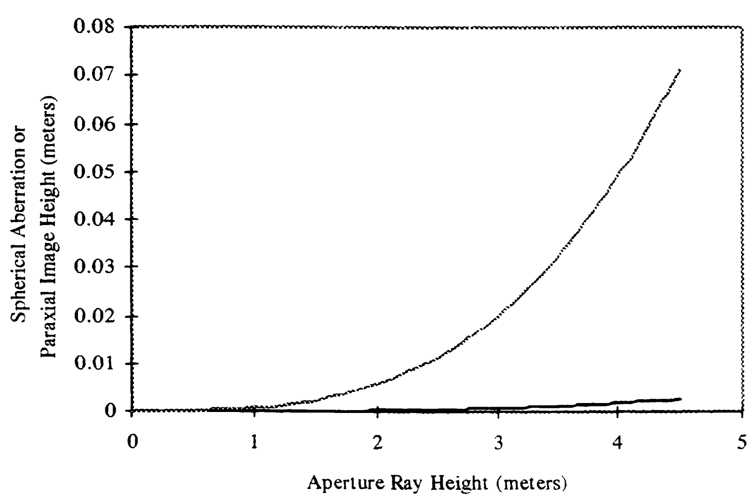


In addition, the amount of lateral spherical aberration is also easily estimated. Korsch also published the formula for lateral spherical aberration as[4]

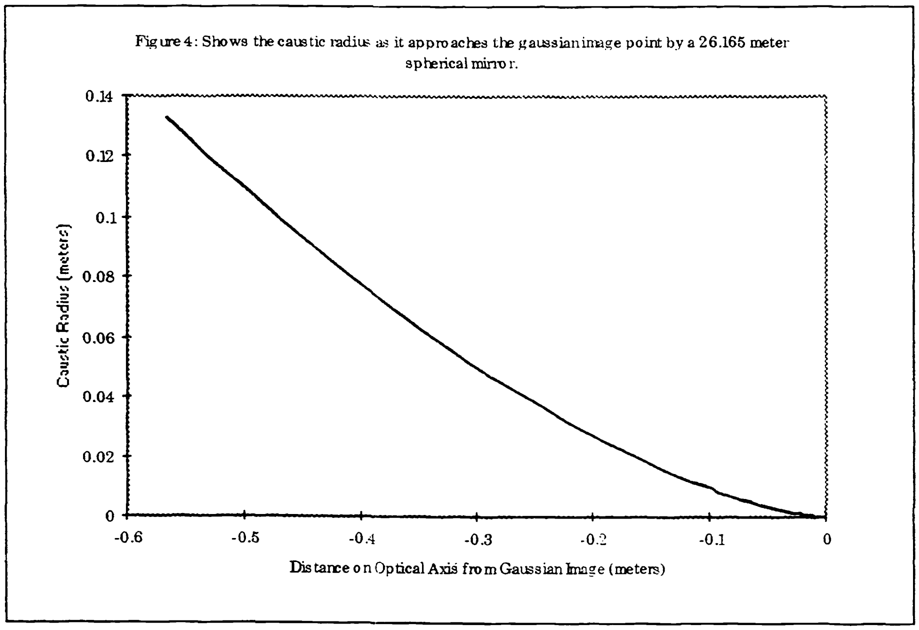
$$\rho'_{sa} = \chi \frac{1-\sqrt{1-\chi^2}}{1-2\chi^2}. \tag{2}$$

Again, by substituting in the appropriate numbers we arrive at the fact that there is 0.414 meters of lateral spherical aberration.

Figure 3: Lateral spherical aberration shown as ray aberration and as paraxial image plane ray height (meters).

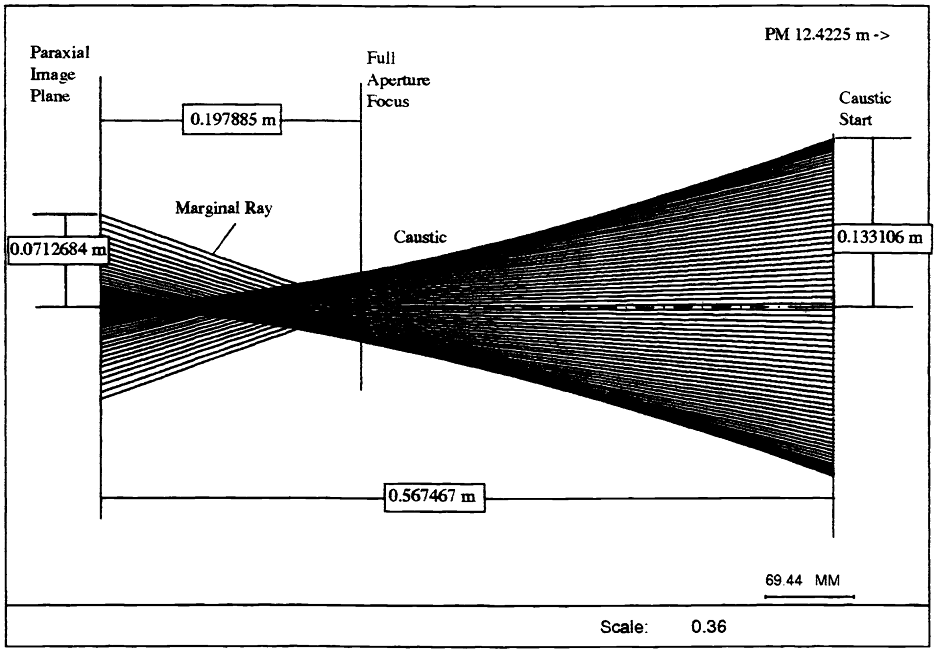


Besides the amount of wavefront error generated by a spherical mirror of such size, the ray caustic will effect the obscuration ratio of the system. The caustic starts 0.567467 meters before the Gaussian image point and has a radius of 0.133 meters. Figure 2 shows the caustic as it approaches the image point for axially parallel incident rays.



This is not the complete view of the ray bundle in the caustic area. As can be seen in the CodeV ray trace of the Primary Mirror focus area, the marginal rays increase the size after they cross the optical axis before the paraxial image plane. The circle of least confusion is located at this point which, for the HET PM, is 0.14511 meters from the paraxial image plane where the radius is 0.016638 meters. These estimates are based on Seidels 3rd order equations and neglect higher order terms. There could be small discrepancies since the start of the caustic based on third order spherical aberration would be located 0.19348 meters from the paraxial image plane. Likewise, third order theory leads us to an image radius of 0.066553 meters at the paraxial image plane as opposed the CodeV result of 0.07112684. In addition to the caustic the field angle requirements must also be keep in mind when sizing the optical components.

Figure 5: Shown is a ray fan which depicts the caustic caused by spherical aberration generated by the HET primary mirror. The radial sizes are important in determining Secondary and Tertiary mirror diameters and obscurations.



This amount of spherical aberration needs to be corrected with the considerations of imaging performance and packaging in mind. Obscuration and vignetting must be considered with the careful consideration of the caustic generated by the spherical aberration of the 9 meter aperture primary mirror. In the next section the pertinent requirements for the HET will be reviewed.

2. REQUIREMENTS

For the redesign exercise, the following requirements were followed. They can be broken into two catagories: Performance and Packaging. The main objective of the redesign was to provide a feasible optical design which was manufacturable within the cost constraints of the HET project. The design shall take into account the existing HET primary mirror (considered a monolith). No more than four optical surfaces after the PM were to be used.

2.1 Performance

Since this goal is to principally provide a more manufacturable and efficient design for building the HET system, several top level requirements had been changed from the previous SAC.

Table 2.1 Performance Requirements		
Requirement	Value	Goal
Final F/#	4.5 to 6.0	5.0
Central Obscuration	31% Linear	
Field of View	0 degrees 0.033 degrees 0.05 degrees	 unvignetted for guiding and acquisition
Image Quality - 0 degrees 0.033 degrees 0.05 degrees	21 microns 0.10 arc- secs 67 microns 0.31 arc- secs 117 microns 0.53 arc- secs	
Entrance Aperture	9 meters	10 meters
Wavelength Band	0.35 μm to 2.5 μm	
Manufacturability	budget limited manufacturing and testing techniques	

2.1 Packaging

The design was also constrained to use the existing SAC mechanical design for the first two mirrors.

Table 2.2 Packaging Requirements

Requirement	Value
Back Focus Clearance	150mm
Baffling	Accessible Exit pupil
Size Diameter Length	0.5 meters 2.5 meters
Re-use of Existing Mechanical Design	Original SAC Design

3. PRELIMINARY DESIGN LAYOUT

3.1 Initial Clamshell

One of the requirements of the redesign was to use the original mechanical design. The original two mirror Gregorian Spherical Aberration Corrector (SAC) design had a spacing between the secondary and tertiary mirrors of 653mm. The diameter of the secondary mirror (SM) and the tertiary mirror (TM) was 490mm and 458mm respectively. A constraint placed on the design was that the mechanical distance from the PM vertex to the vertex of the TM is 12.911 meters. The goal then is to use two mirrors to partially correct the aberrations. Then use a Secondary clamshell to provide the final correction and focal ratio.

The job of the Secondary is to image the Entrance pupil onto the stop which is located at the tertiary mirror. With spherical mirrors, if the entrance pupil is placed at the center of curvature of the mirror then the only spherical aberration is generated. The second job of the secondary is to collimate the light from the PM. Because of the severe amount of spherical aberration, only one aperture zone will be collimated. For packaging purposes it was selected to be full aperture. When this is implemented the radius of curvature of the secondary turns out to be 1.435 meters with a spacing to the TM of 0.670 meters. While this spacing is not the original spacing it was close enough to use the original design with minimal changes. In fact the total track of the SM-TM package (from vertex of TM to Focus) was keep at 0.8 meters. Using this layout has implications in the design of the observatory opening in that it does not minimize the dome opening. A minimized opening would require that the entrance pupil be placed at the dome opening.

The job of the Tertiary Mirror is to form an intermediate focus approximently 130mm behind the SM vertex. To do so requires that the radius of curvature be set at 1.6 meters since the beam on the TM is collimated and the distance to focus is 0.8 meters.

In addition, holes have to be cut in the mirror center to let the light through as it passes from the PM to the SM. The hole has to be large enough to pass the caustic and field angles of interest yet not exceed 31 percent obscuration. Since the stop is at the TM, meeting the 31 percent obscuration with no vignetting is accomplished easily as the beam does not walk on the surface with field angle. The size of Secondary hole is dependent on the final TM radius and the amount of correction (or size of the caustic) provided by the SM-TM pair. In as much the sizing of the SM hole was used as a constraint in the automatic design.

The F/number at this point is F/4.33 which is slightly under our requirement. The secondary clamshell will need to provide final focal length/ratio adjustment as well as aberration correction/balancing.

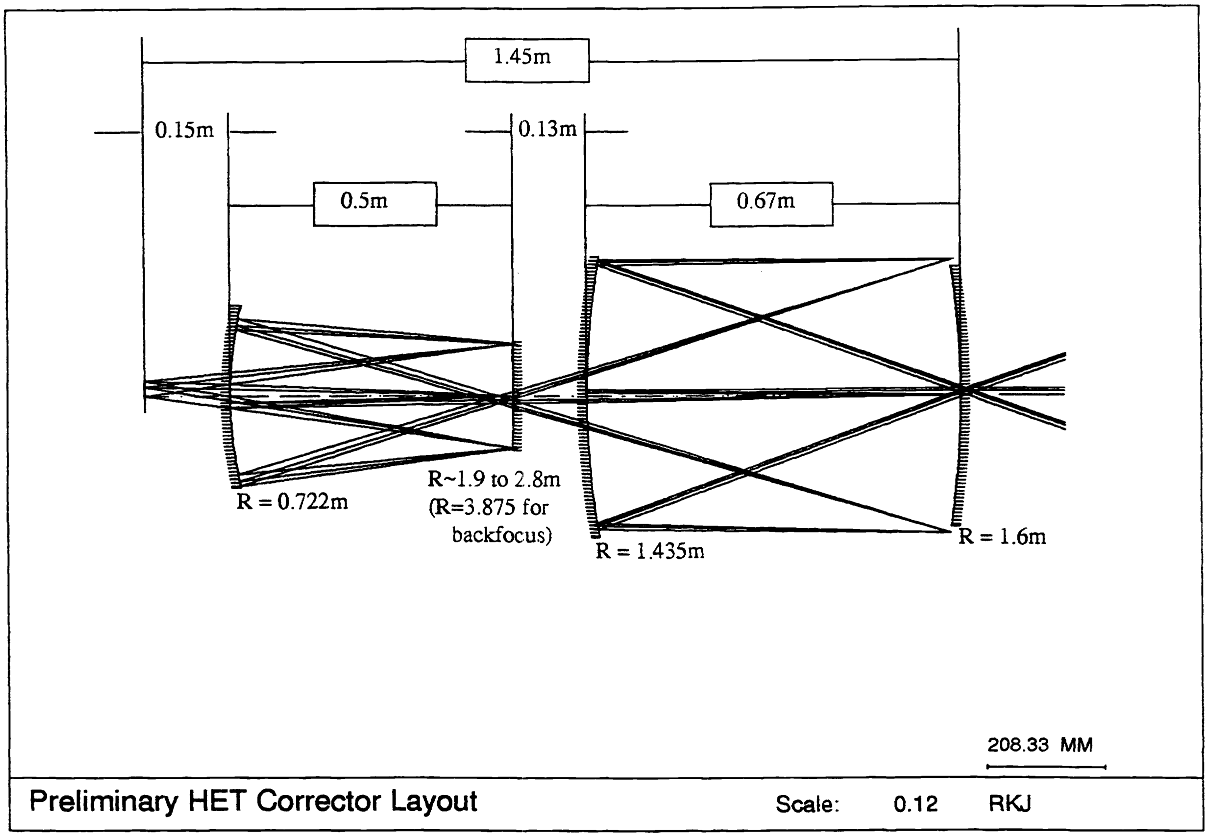
3.1 Secondary Clamshell

The perceived need of the secondary clamshell is to satisfy two purposes: 1) residual wavefront correction, and 2) adjust final focal length. The packaging constraints placed on the secondary clamshell is to have a spacing of less than 0.5 meters and a back focus of 0.150 meters. To correct residual higher order spherical aberration (or at least provide aberration balancing) requires that a surface be available at an image of the stop. This surface would have to be a fifth of sixth mirror as at least the fourth mirror (and possibly a fifth mirror) would be required to image the stop on to a surface.

The purpose of the Quatinary mirror (Q_4M) is to image the stop onto the Quintinary mirror (Q_5M). As the maximum distance from the TM to the Q_4M is 1.3 meters and the distance to the next mirror is 0.5 meters, the radius of curvature of the Q_4M needs to be 0.722 meters.

The purpose of the Q_5M is two-fold. It has to provide final correction/balancing of the spherical aberration to all orders necessary to deliver the image quality requirements and it has to adjust the focal length to provide the proper focal ratio and deliver an image 0.15 meters behind the Q_4M. The concave radii range from 2.80105 to 1.97405 meters to meet the system f-number requirement range of F/4.5 to F/6.0. However, neither provide the back focus to meet the requirement or 0.150 meters. To meet the back focus a radius of 3.875m is needed which reduces the f-number to F/3.86. A sketch of the layout is shown in Figure 6.

Figure 6: Shown are the basic preliminary layout parmeters for the HET spherical aberration corrector.



To provide the necessary back focus and pupil imaging along with the field of view, vignetting and packaging requirements, a delicate balance between the TM, Q_4M, and Q_5M radii, as well as the SM-TM spacing, and Q_4M- Q_5M spacing. These constraints were coded into CodeV and the radii and spacings varied during the optimization process to provide the proper performance.

4. FINAL DESIGN CONFIGURATION

4.1 Layout

The preliminary layout was entered into CodeV along with the constraints. For manufacturability, all but the Q_5M were constrained to be conic. The Q_5M was allowed to have aspheric terms to control higher order spherical aberrations. The final layout is shown in Figure 7. Table 4.1 gives the formula in more detail and precision.

TABLE 4.1: HET Four Mirror Corrector Optical Formula and Data

ELEMENT NUMBER	RADIUS OF CURVATURE	THICKNESS	APERTURE DIAMETER FRONT / BACK	GLASS
OBJECT	INF	INFINITY		
			9000.0215	
		13252.9200		
			9023.1094	
		12911.0000		
1	-26163.9200 CC	-12785.1566	9044.9561	REFL
			95.2048	
		-778.8434		
2	A(1)	678.8434	C-1	REFL
		APERTURE STOP	488.4551	
		0.0000		
3	A(2)	-678.8434	C-2	REFL
			123.4930	
		-219.8459		
			59.3351	
		-555.1189		
4	A(3)	555.1189	C-3	REFL
5	A(4)	-555.1189	C-4	REFL
			114.5784	
	IMAGE DISTANCE =	-318.5200		
IMAGE	INF		73.6373	

NOTES - Positive radius indicates the center of curvature is to the right
Negative radius indicates the center of curvature is to the left
- Dimensions are given in millimeters
- Thickness is axial distance to next surface
- Image diameter shown above is a paraxial value, it is not a ray traced value.

APERTURE DATA

APERTURE	SHAPE		DIAMETER X	DIAMETER Y	DECENTER X	DECENTER Y	ROTATION
C- 1	CIRCLE		496.026				
	CIRCLE	(OBSC)	127.712	127.712			
C- 2	CIRCLE		500.000	500.000			
	CIRCLE	(OBSC)	155.000	155.000			
C- 3	CIRCLE		390.248				
	CIRCLE	(OBSC)	114.578	114.578			
C- 4	CIRCLE		187.545				
	CIRCLE	(OBSC)	59.335	59.335			

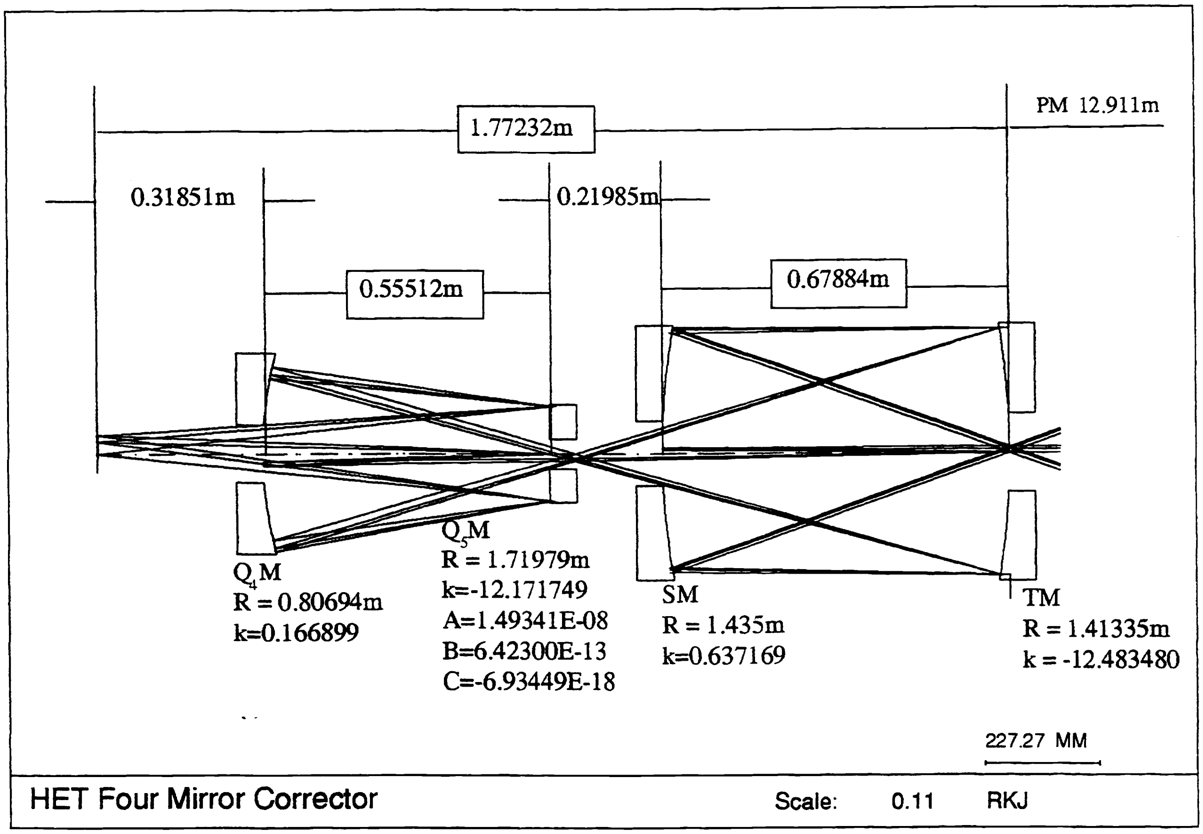
ASPHERIC CONSTANTS

$$Z = \frac{(CURV)Y^2}{1 + (1-(1+K)(CURV)^2 Y^2)^{1/2}} + (A)Y^4 + (B)Y^6 + (C)Y^8 + (D)Y^{10}$$

ASPHERIC	CURV	K	A	B	C	D
A(1)	0.00069686	0.637169				
A(2)	-0.00070754	-12.483480				
A(3)	0.00123924	0.166899				
A(4)	-0.00058147	-12.171749	1.49341E-08	6.42300E-13	-6.93449E-18	0.00000E+00

INFINITE CONJUGATES
- EFL =-42191.0231
- BFL = -318.0154
- FFL =***********
- F/NO = 4.6879
- IMAGE DIST = -318.5200
- OAL = 11824.9553
- PARAXIAL IMAGE HT = 36.8186
- SEMI-FIELD ANGLE = 0.0500
- ENTR PUPIL
  - DIAMETER = 9000.0000
  - DISTANCE = 0.0000
- EXIT PUPIL
  - DIAMETER = 185.5432
  - DISTANCE = 551.7909

Figure 7: Shown are the final layout parmeters for the HET spherical aberration corrector.



The SM is a mild oblate spheroid with an aperture of 0.496m and a center hole of 0.127m. The on axis aperture is ~0.475m which yields a linear obscuration of 0.27. The secondary has a departure of 41.75 waves (@ 0.6328μm) from a best fit sphere. While this is an improvement from the 71.5 waves of the original design, the important fact is that this is a conic section which is tested easier than a general asphere.

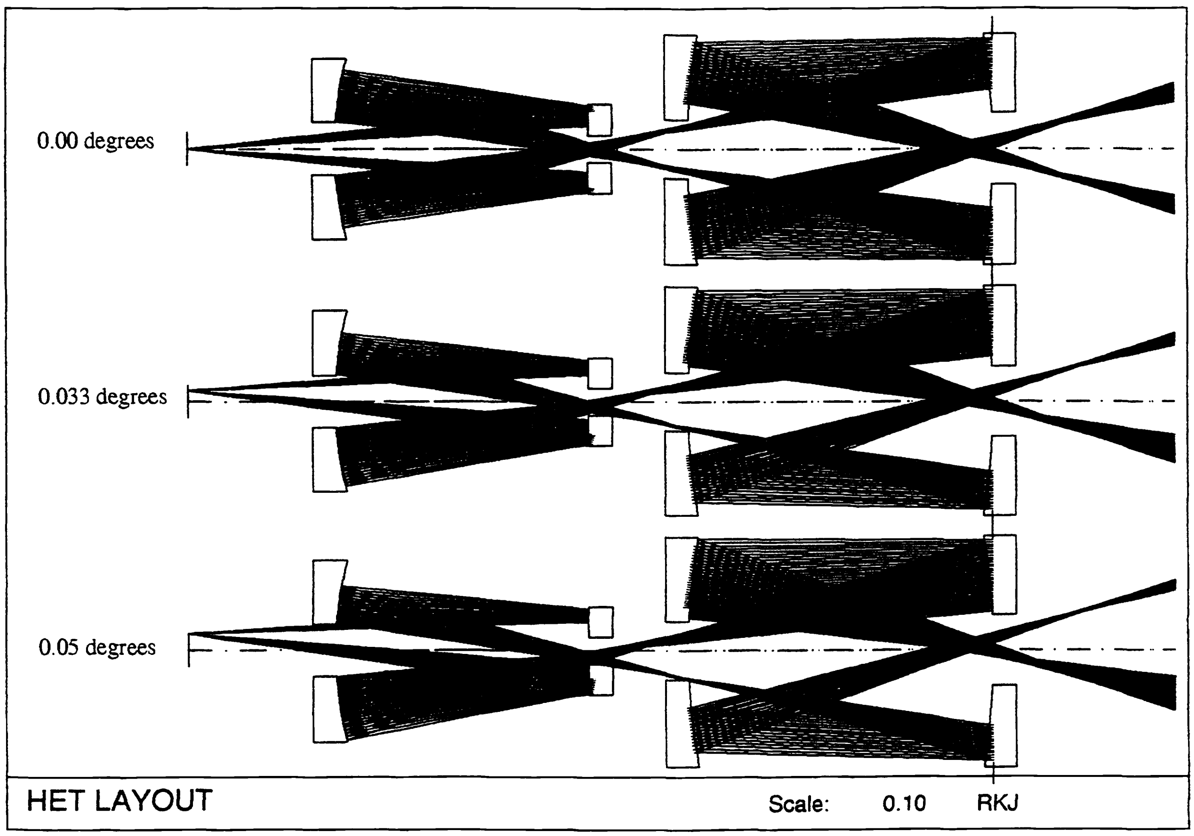
The TM is listed as a pure hyperboloid with an aperture of exactly 0.5 meters and a hole of 0.151 meters diameter. The on axis aperture is ~0.488 meters which yields a linear obscuration of 0.309. The secondary has a departure of 671.37 waves (@ 0.6328μm) from a best fit sphere. Likewise, while this is an improvement from the 1443 waves of departure that the original design had, the important fact is that the TM is a now conic section which can be tested easier than a general asphere.

The Q_4M is another mild oblate spheroid with an aperture diameter of 0.39025m and a hole with a diameter of 0.114578m. The on-axis aperture is 0.3445 meters which yields a linear obscuration of 0.33. The hole is sized to minimize vignetting at the expense of obscuration. To meet the obscuration requirement the hole would have to be 0.1068 meters in diameter. The Q_4M has a conic departure of 23.93 waves from the best fit sphere. As it is a pure conic, testing is simplified.

The Q_5M is the only aspheric (aconic) surface with a base hyperboloid shape and 4^{th}, 6^{th}, and 8^{th} order aspheric terms. It has a diameter of 0.18755 meters and a diameter of 0.059335 m. The on-axis aperture is 0.18712 meters which yields a linear obscuration of 0.317. To meet the obscuration requirement the hole would have to be 0.058 meters in diameter. The Q_5M has a departure of 692.882 waves form the best fit sphere. Since the TM is imaged on the Q_5M, the wavefronts can be added. Doing so shows that the total departure is 1364 waves which approaches the 1443 waves of the original design. This is not strictly true since the reference spheres are different, however, it is an indication that the "correction" of the original TM was split into two surfaces thereby easing the manufacturability and testing requirements.

Figure 8 shows a ray fan for each field angle which makes it through the system without being obscured. One can see that the limiting apertures are the holes in the Q_4M and the SM. Easily seen in the 0.0 field angle case is that the hole in the Q_4M is the limiting obscuration. However, for the larger field angles either the hole in the Q_4M or in the SM limits the bundle of rays passing from the Q_5M to the image or from the TM to the Q_4M.

Figure 8: The amount of vignetting can be seen as the field angle increases. Note that the limiting surface is a draw between the holes in the quantinary and secondary mirrors.



4.1 Performance

The performance of the HET Four mirror spherical aberration corrector is limited by the packaging configuration and desire to produce a design which has affordable, manufacturable and testable optics. The driving aberrations are zonal spherical and astigmatism. The astigmatism was left in on purpose to provide a method of focus control.

Figure 9 shows the amount of residual aberration. The longitudinal spherical aberration curve indicates that a balancing of higher order spherical was used to drive the overall spherical aberration down. Comparison with the original design indicates that there are less crossing indicating the original design was using even higher order terms to suppress the spherical aberration. Also shown in Figure 9 is the astigmatism curve which indicates about 8 times the total astigmatism as the original design but with little field curvature. This provides and accurate method of sensing focus.

Figure 9: Shown is the longitudinal spherical aberration, astigmatism, and distortion curves for the HET four mirror Sphreical Aberration Corrector. Note that the system is limited by spherical aberration and by Astigmatism. The spherical aberration is a combination of third, fifth and seventh order. The obscuration is shown in the longitudinal spherical aberration curve.

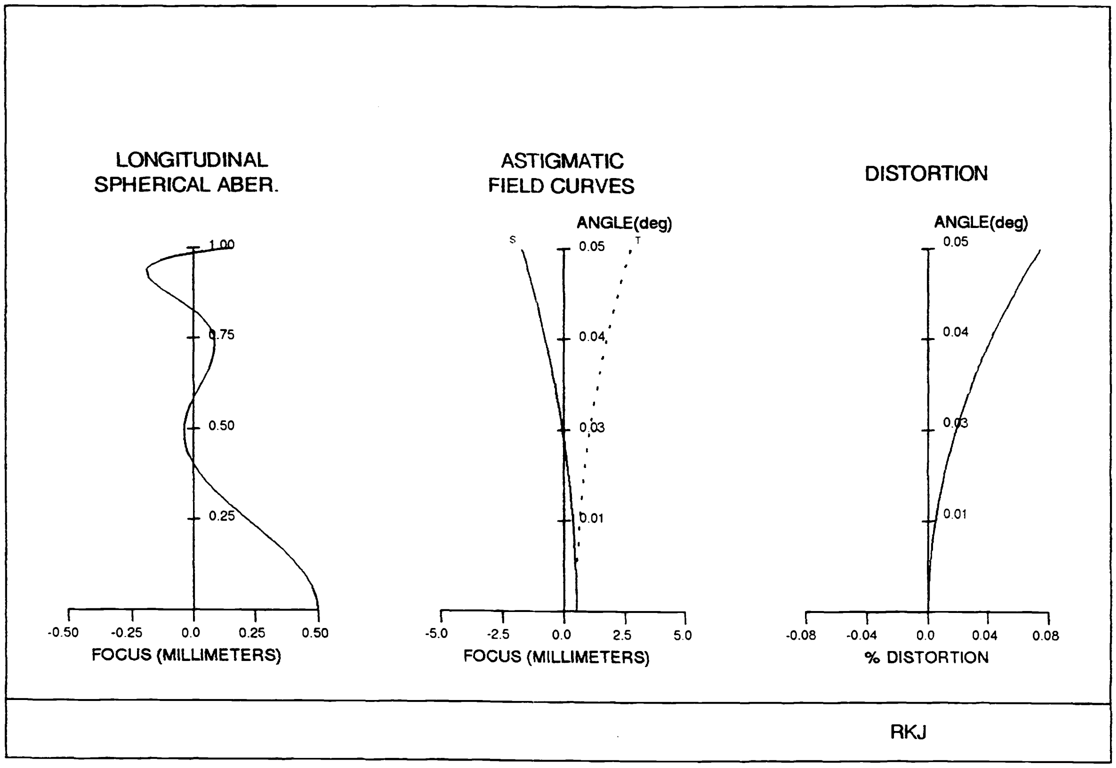
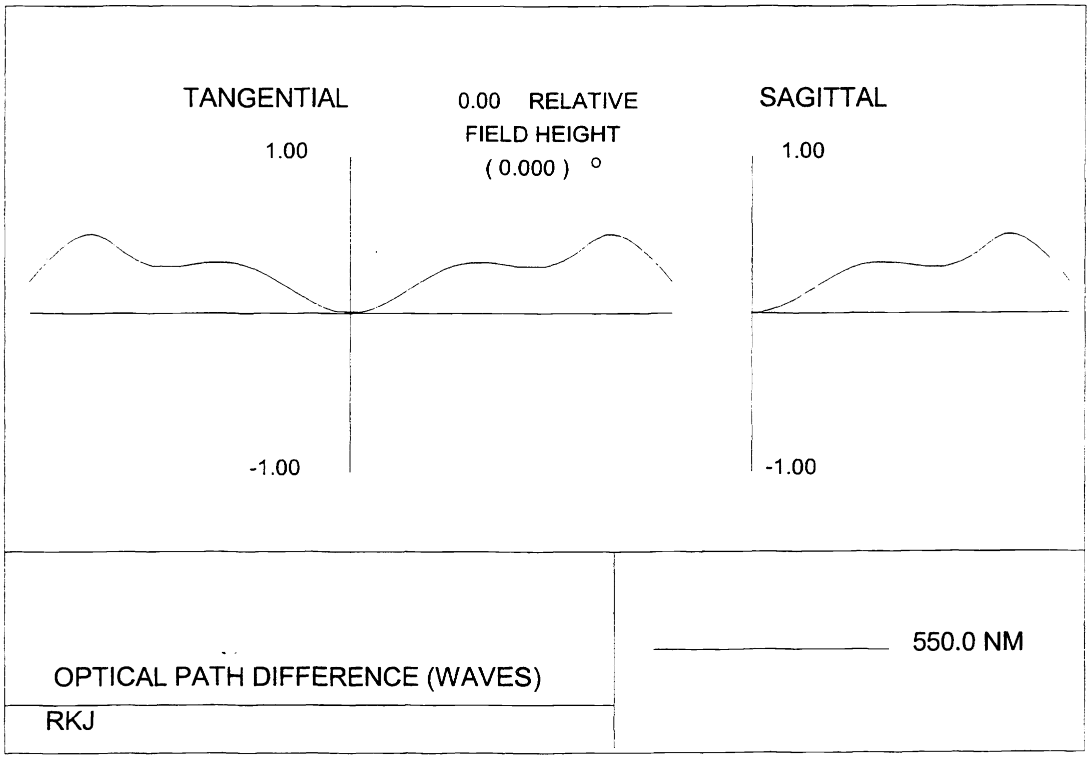


Figure 10 shows an on-axis ray aberration plot in units of OPD (waves). It indicates that over the unobscured aperture the wavefront error on-axis is about 0.25 waves peak to valley. In addition, it shows that 9th order is present and dominate at the edge of the plot which indicates that another aspheric term would be needed to reduce the spherical aberration. The original two mirror corrector design utilized up to 20th order aspheric terms (with a parabolic conic constant) on the TM. While the original two mirror corrector design provided 10 times the correction, the four mirror design delivers sufficient correction to meet the on-axis encircled energy requirement.

Figure 10: Shown is the ray aberration plot for the On-axis aberrations in OPD units. Notice the strong higher order spherical aberration.



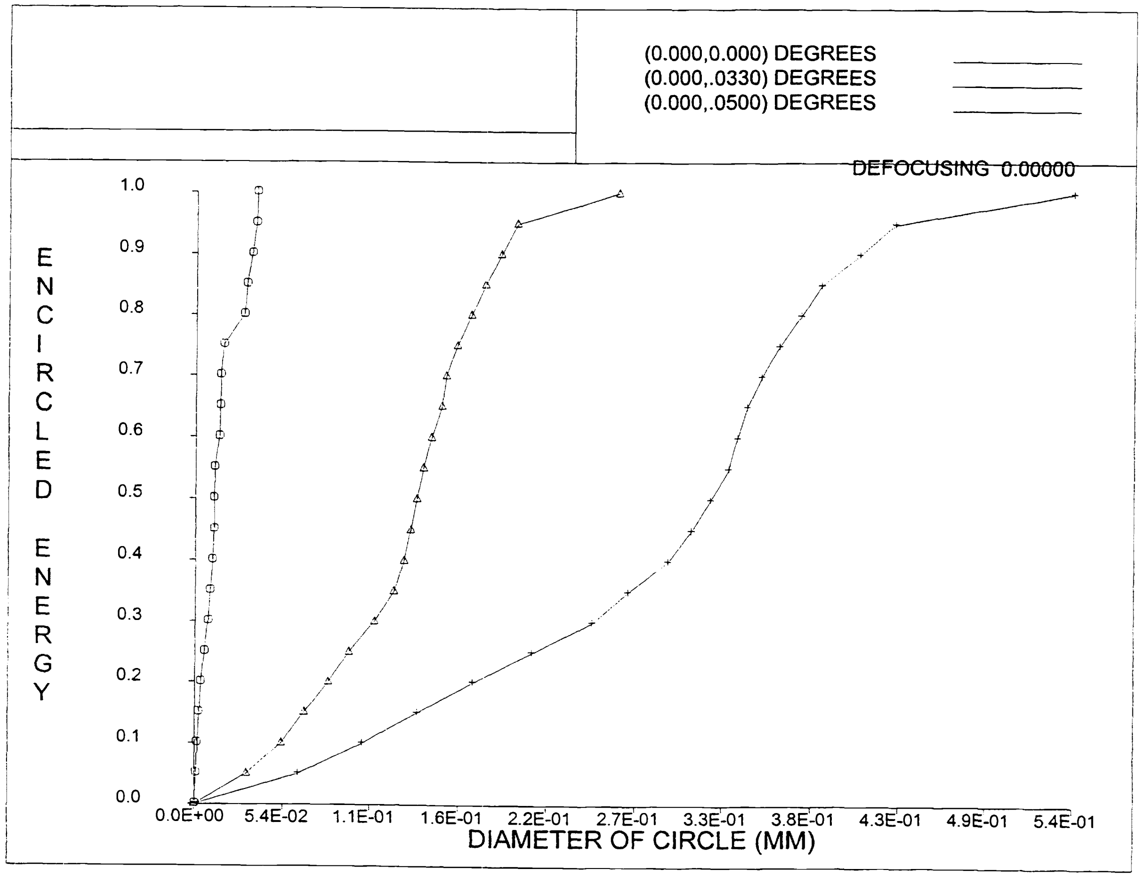
The off-axis ray aberrations also are represented in Figure 9. One can see the undercorrected zonal spherical aberration as well as field curvature (astigmatism). The large amount of astigmatism leads to less than optimal off-axis performance as is indicated in the encircled energy plots in Figure 11. The only way to attack the astigmatism would be to rearrange the system layout and have corrector surfaces near an intermediate image (to provide field correction). Or by using aspheric terms on the SM and Q4M, one could hope to introduce enough higher order aberrations to balance out the third order astigmatism which is more strongly controlled by system geometry and conic constants than by aspherics. This would complicate the system and/or surfaces to the point of approaching the two mirror design and distract from the focus of designing a manufacturable system that meets the budget needs of the HET project. In addition, instruments such as the acquisition camera could be used to optimized the performance for their particular mission.

The encircled energy of the Four Mirror Spherical Aberration Corrector is shown in Figure 11. Numerically the radii for 50% and 80% levels are given in the following Table 4.2.

Table 4.2: Encircled Energy

Field	50%	80%
0.0	11.1 μm	29.26 μm
0.033	136 μm	169 μm
0.05	317 μm	372 μm

Figure 11: Geometical encircled energy is shown in this figure.



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