CHARA TECHNICAL REPORT

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Optical Layout and Error Budget for the Telescope, Catseye, and Beam Compressor

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1. INTRODUCTION

The optical layout of the telescope, catseye and compressor in the CHARA array are schematically shown in Figure 1. The 1 m telescope provides a 125 mm diameter collimated beam which passes folding mirrors (including tilt correction and adaptive elements), catseye and beam compressor to form a 25 mm diameter beam to prepare for selection and combination.

The error budget distribution is based on the tolerance of peak-to-valley $(p - v)$ wavefront error at 0.6328 microns wavelength. The $p - v$ error contribution of the telescope, catseye, and beam compressor are listed in the following table:

telescope	0.2
catseye	0.13
beam compressor	0.2

2. TELESCOPE

The telescope is an aplanatic afocal system with an $f/2.5$ primary mirror. The primary and secondary mirrors are confocal paraboloids with a beam demagnification of 8. If the telescope has a field of view of $\pm 2''$, the deviations of the output beams will be $\pm 16''$. Table 1 lists the optical parameters.

The errors, which come from imperfect mirrors, alignment, tracking, and temperature, are itemized in the following terms.

1. Radius errors: Radius errors mainly introduce spherical aberration and defocus. Since the two mirrors are confocal paraboloid surfaces, aberrations produced by the radius errors can be totally compensated by reposition of the secondary mirror. The only thing to be changed is the width of the output beam. For example, if the radius error

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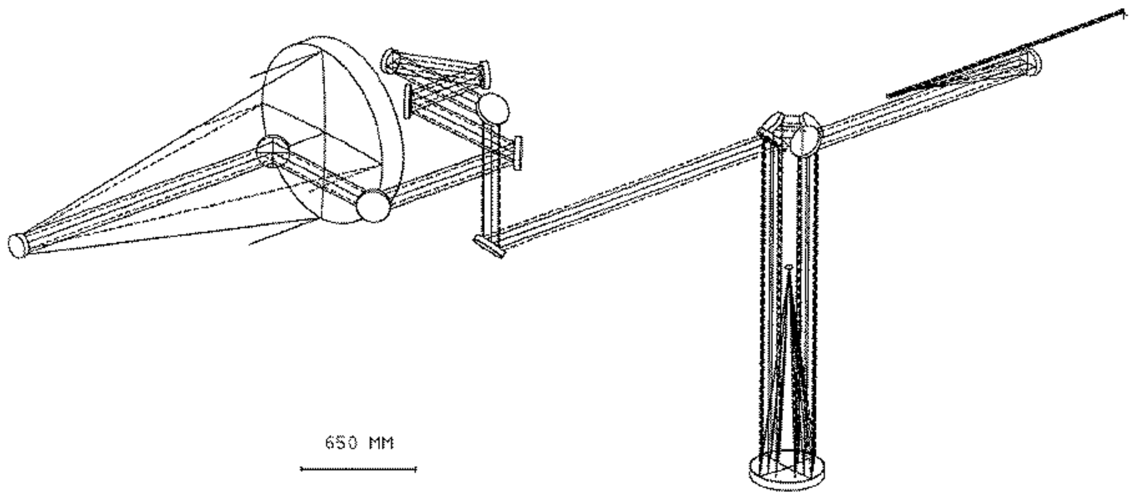


FIGURE 1. Optical layout of the telescope, catseye, and beam compressor. Separations between them are quite reduced for clarity.

TABLE 1. Telescope with an $f/2.5$ primary mirror

	radius (mm)	separation (mm)	conic constant	diameter of clear aperture (mm)
primary	-5000		-1	1000
secondary	-625	2187.5	-1	125

of the secondary and primary mirror are δr and δR, the diameter of the output beam will be changed by δr/5 and -δR/40 respectively after the secondary mirror position adjustment.

2. Conic constant errors: Conic constant (CC) errors also introduce spherical aberration and defocus, some of which can be compensated by adjusting the secondary mirror position. Figure 2 shows the wavefront before and after the adjustment when the conic constant of the primary has an error of δCC = -0.0005. The $p - v$ is reduced from 0.094λ to 0.025λ by moving the secondary mirror 0.003 mm away from the primary mirror. The error tolerance of the conic constant of the secondary mirror is much looser. If δCC = -0.001, the wavefront error will be 0.025λ of $p - v$ and is reduced to 0.007λ of $p - v$ by moving the secondary $0.7\,\mu$m towards the primary.

3. Irregular errors: Irregular errors, including cylindrical errors, zone error, and fluctuation on the primary and secondary mirrors, should be less than $\lambda/10$.

4. Decenter and tilt: Decenter of the secondary mirror produces coma and wavefront tilt. The leftmost drawing in Figure 3 shows the wavefront produced by 0.04 mm decenter of the secondary mirror. The $p - v$ is 0.24λ. The tilt term can be compensated by the tilt correction mirror in the system. The rightmost drawing in Figure 3 shows that

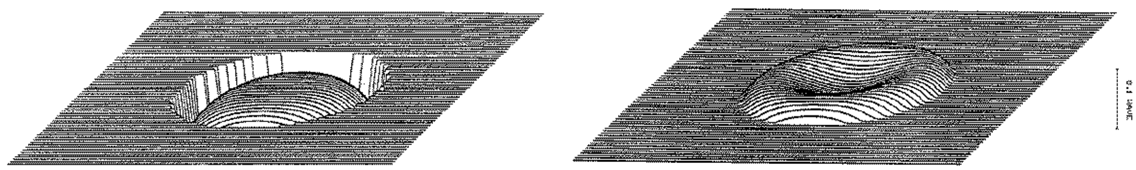


FIGURE 2. The contour plot at left is the wavefront when there is -0.0005 conic constant error on the primary mirror. The $p - v$ is 0.094λ. The plot at right shows that the wavefront $p - v$ is reduced to 0.025λ by moving 0.003 mm away from the primary mirror.

FIGURE 3. The contour plot at left is the wavefront when there is 0.04 mm decenter error on the secondary mirror. The $p - v$ is 0.24λ. The plot at right shows wavefront on best tilt surface. The $p - v$ reduces to 0.08λ.

the above wavefront is reduced to 0.08λ $p - v$ on the best tilt surface. It is not very difficult for a careful mechanical design to keep the decenter error within 0.04 mm.

The decenter also changes the direction of the output beam. For example, the output beam will drift 0.45 mm after traveling 200 meters if the secondary mirror has 0.04 mm decenter error and no tilt correction.

The tilt of the secondary mirror produces nearly the same kind of aberrations as that of decenter. Figure 4 shows the wavefront produced by a 10 arcsec tilt of the secondary mirror.

If they have opposite sign, the tilt and decenter can compensate each other. In fact, the telescope can be designed to be a coma-free structure, in which the decenter and tilt can passively compensate each other for different zenith distance. Although there will be no coma in such a structure, the output beam deviation still exists.

5. Axial motion: Axial motion of the secondary mirror produces defocus and spherical aberration. One micron secondary axial motion will introduce about 0.03λ $p - v$ wavefront error.

   This error cannot be compensated by the telescope itself, but can be compensated by stroking of the catseye. To compensate the above aberration, the catseye needs $7.4\,\mu$m stroking distance. Figure 5 shows that the wavefront of $5\,\mu$m secondary motion is compensated by $37\,\mu$m catseye stroking.

Table 2 lists the error budget of the telescope. Here we suppose that the secondary mirror position can be adjusted to compensate the radius and conic constant errors and that the best tilt wavefront surface can be chosen for the tilt and decenter errors.

Decreasing the primary f number will reduce the length of the telescope, lower the housing and mounting costs, and improve the stiffness. The length of an $f/2$ primary mirror tele-

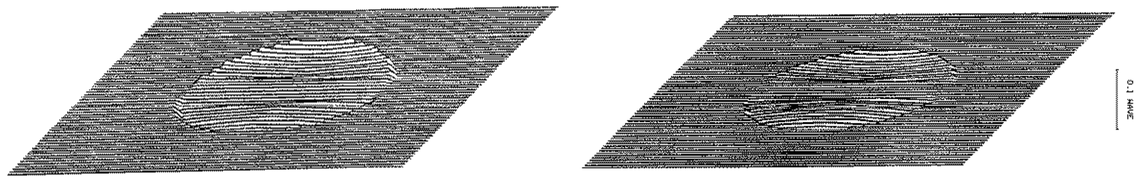


FIGURE 4. The contour plot at left is the wavefront when there is $10''$ tilt error on the secondary mirror. The $p-v$ is 0.08λ. The plot at right shows wavefront on best tilt surface. The $p-v$ reduces to 0.02λ.

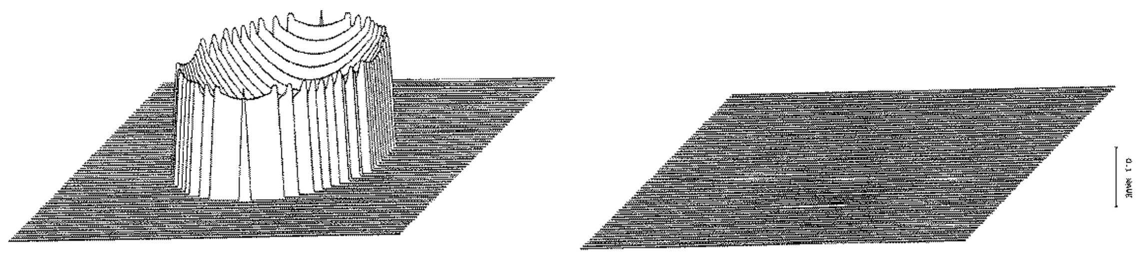


FIGURE 5. The contour plot at left is the wavefront when the secondary has 0.004 mm axial motion. The $p-v$ is 0.16λ. The plot at right shows the error is compensated by 0.037 mm flat mirror stroking of the catseye.

scope can be reduced 437 mm as shown in Figure 6. The disadvantage is that the aspherical departure will increase to twice as large as that of the $f/2.5$ mirror, and the error budget is more stringent. For comparison, Tables 3 and 4 list the optical parameters and error budget for a $f/2$ primary mirror telescope.

3. CATSEYE

The collimated light from the telescope is reflected four times between the paraboloid, the focal length of which is 1200 mm, and the secondary flat mirror of the catseye, as shown in Figure 1. The diameter of the beam from the telescope is 125 mm, while the central area reserved for the flat mirror is 150 mm with a field of view of $\pm 2''$ needing ± 15.5 mm more. All these make the clear aperture of the paraboloid mirror 431 mm. Figure 7 shows how the aperture of the catseye is enlarged by the field beams. The f number of the paraboloid is $f/2.78$ which gives a $f/9.6$ convergent beam cone.

The -0.0005 conic constant error on the primary mirror will produce 0.031λ $p-v$ wavefront error as shown in Figure 8 (after four reflections on the mirror).

Every micron stroking distance will produce 0.0084λ $p-v$ wavefront error. Figure 9 shows the wavefront of 5 μm stroking.

Unless the tilt angle of the flat mirror is much larger than 10 arcminutes, the wavefront error produced by the tilt secondary flat mirror will be so small that it can be neglected. However 10 arcminutes of whole catseye tilt will introduce 0.015λ $p-v$ errors. The error budget for the catseye is listed in Table 5.

The tilt will not change the direction of the output beam, but will change the lateral position

TABLE 2. Telescope error budget ($f/2.5$ primary)

	Parameters error	$p-v$ wavefront error (in wavelength)
primary radius	$\pm 10\,\mathrm{mm}$	0
conic constant	± 0.0005	0.025
irregular		0.1
secondary radius	$\pm 2\,\mathrm{mm}$	0
conic constant	± 0.001	0.007
irregular		0.08
decenter	$\pm 0.04\,\mathrm{mm}$	0.08
tilt	$\pm 10''$	0.02
axial motion	$\pm 0.004\,\mathrm{mm}$	0.124
sum		0.2

TABLE 3. Telescope with an $f/2$ primary mirror

	radius (mm)	separation (mm)	conic constant	diameter of clear aperture (mm)
primary	-4000		-1	1000
secondary	-500	1750	-1	125

TABLE 4. Telescope error budget ($f/2$ primary mirror)

	Parameters error	$p-v$ wavefront error (in wavelength)
primary radius	$\pm 8\,\mathrm{mm}$	0
conic constant	± 0.00025	0.025
irregular		0.1
secondary radius	$\pm 1.6\,\mathrm{mm}$	0
conic constant	± 0.00066	0.007
irregular		0.08
decenter	$\pm 0.022\,\mathrm{mm}$	0.08
tilt	$\pm 5''$	0.02
axial motion	$\pm 0.002\,\mathrm{mm}$	0.124
sum		0.191

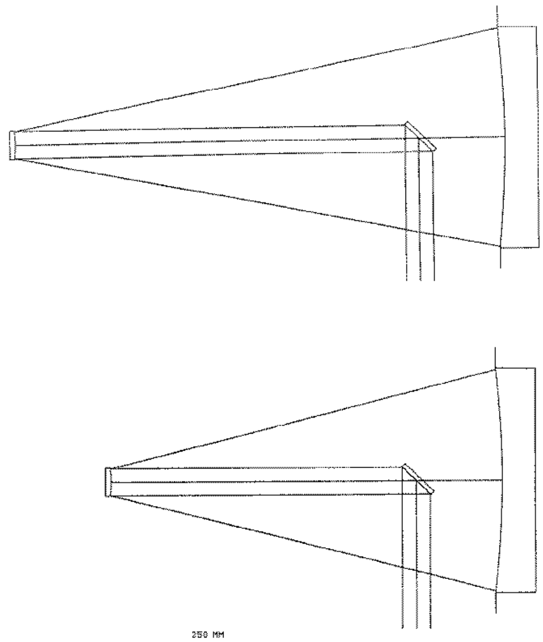


FIGURE 6. The upper telescope has an $f/2.5$ primary mirror which is 437 mm longer than the lower one, which has an $f/2$ primary mirror.

in both tangential and sagittal direction. The change is about $2\times f\times\theta$, where f is the catseye focal length and θ is the tilt of catseye or flat mirror in radians. For example the $10'$ tilt of whole catseye or flat mirror will produce about 7 mm movement in both direction.

TABLE 5. Error budget for double pass catseye

	Parameters error	$p-v$ wavefront error (in wavelength)
primary mirror radius	± 6 mm	0
conic constant	± 0.0005	0.031
irregular		0.1
stroke	± 0.005 mm	0.041
whole catseye tilt	$\pm 10'$	0.015
flat folding mirrors (4)	0.02λ	0.04
sum		0.12

4. BEAM COMPRESSOR

The beam compressor is an off-axis Gregorian system, as shown in Figure 10. Both the primary and secondary are concave paraboloids. The off-axis of the chief ray is 87.5 mm on the primary mirror. The input and output beam diameters are 125 mm and 25 mm

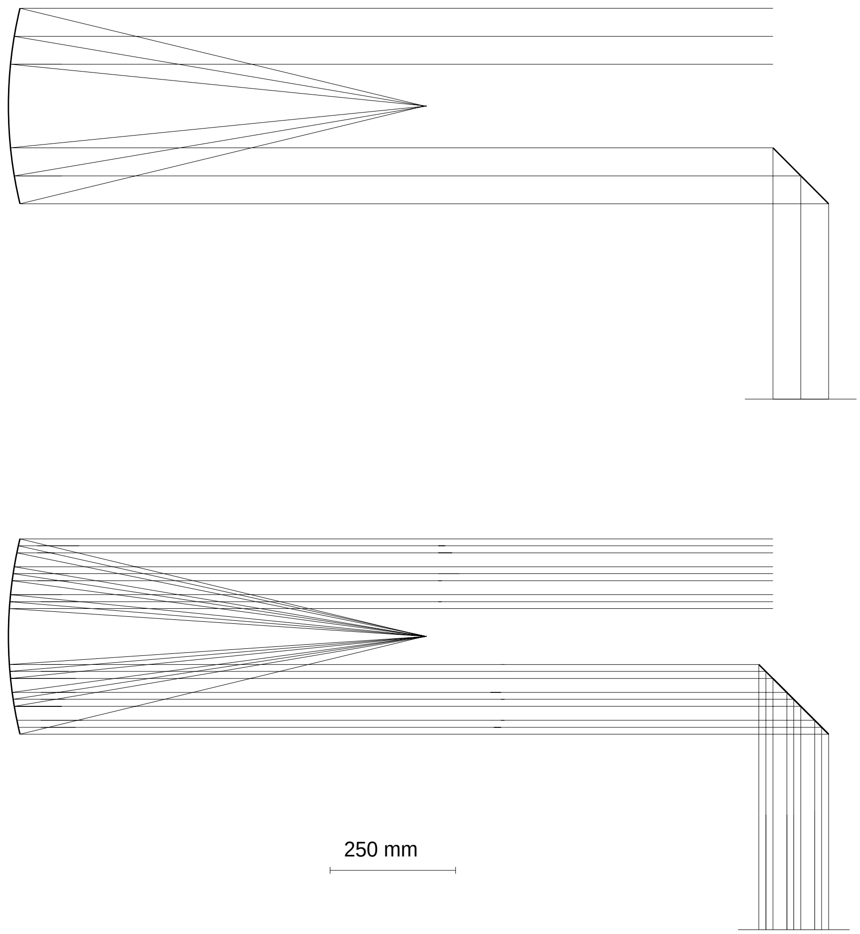
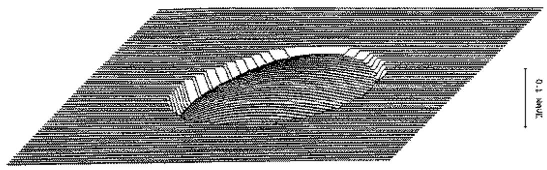


FIGURE 7. The upper diagram is the cross section of the catseye for centered field of view. The lower one shows the aperture when the field of view of the telescope is $\pm 2''$. The catseye is positioned 200 m away from the telescope.

respectively. The deviation of the beam of $\pm 2''$ field from the telescope becomes $1'.33$. Table 6 lists the optical parameters for the beam compressor.

The tolerance analysis is very similar to that of the telescope, except that the best tilt surfaces are not used here for the tilt and decenter errors. In this system, more tolerance is distributed to the decenter, tilt, and axial motions which are mainly related to alignment. Table 7 lists the error budget. Figures 11 through 14 show the wavefront produced from the errors.

The compressor is not a symmetric system, which means some polarization will be introduced, although it is very weak. For an aluminum coating, the polarization is only 0.025%.



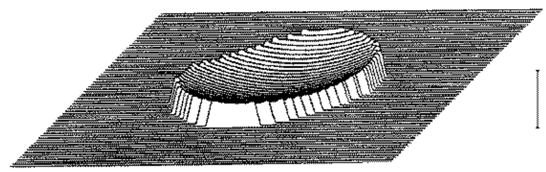


FIGURE 8. (left) Wavefront when the paraboloid mirror of the catseye has -0.0005 conic constant error. The $p - v$ is 0.031λ.

FIGURE 9. (right) Wavefront when the flat mirror of the catseye has 5 mm stroking distance. The $p - v$ is 0.041λ.

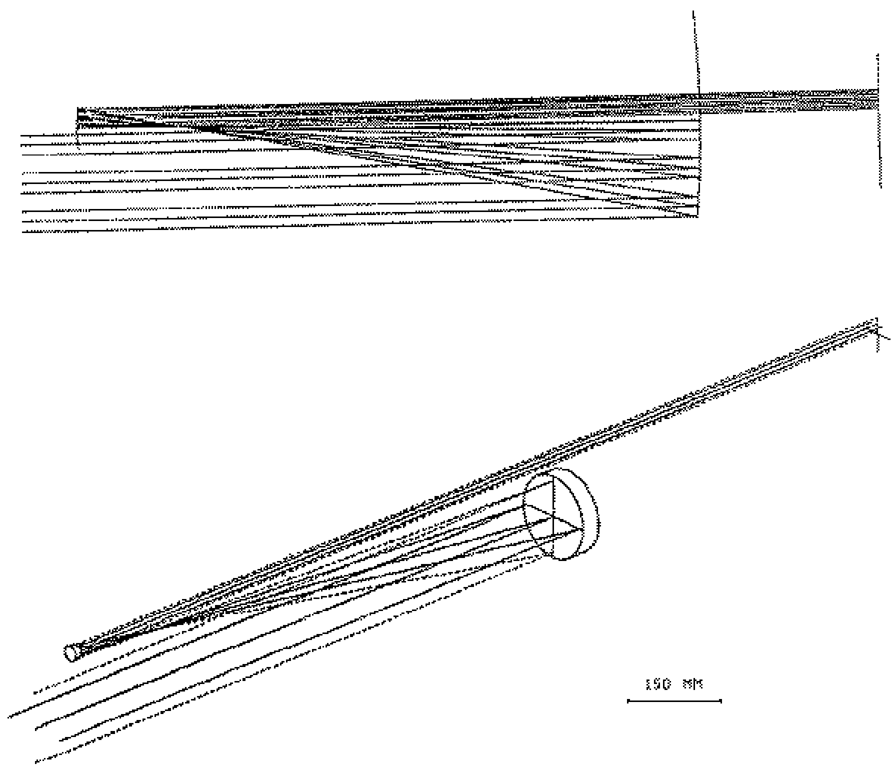


FIGURE 10. The upper drawing is the tangential section of the beam compressor, which is part of a Gregorian afocal system. The lower one shows only the used part of the compressor.

TABLE 6. Parameters of the compressor

	radius (mm)	separation (mm)	conic constant	diameter of clear aperture aperture (mm)
primary	-1680		-1	156
secondary	-336	1008	-1	3.12

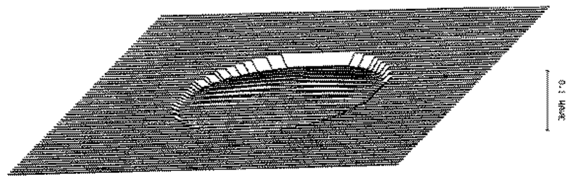
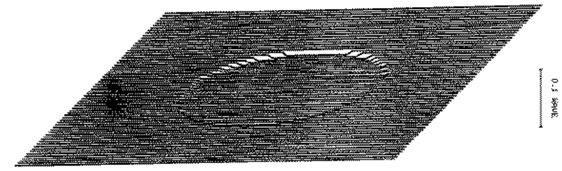
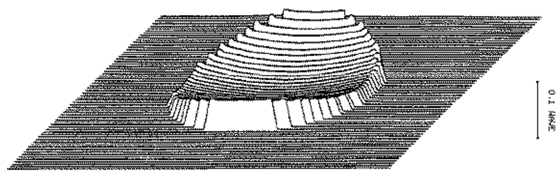
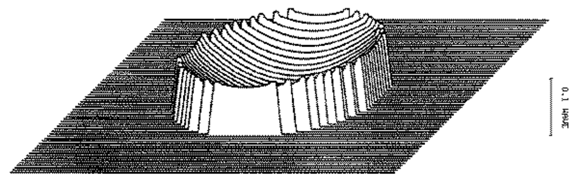





FIGURE 11. (upper left) Wavefront when the primary mirror of the compressor has -0.001 conic constant error. The $p - v$ is 0.021λ.

FIGURE 12. (upper right) Wavefront when the secondary mirror of the compressor has -0.002 conic constant error. The $p - v$ is 0.008λ.

FIGURE 13. (lower left) Wavefront when the secondary mirror of the compressor has 0.1 mm decenter error. The $p - v$ is 0.08λ.

FIGURE 14. (lower right) Wavefront produced when the secondary mirror of the compressor has 0.02 mm axial movement. The $p - v$ is 0.086λ.

TABLE 7. Error budget for the beam compressor

	Parameters error	$p - v$ wavefront error (in wavelength)
Primary radius	± 2 mm	0
conic constant	± 0.001	0.021
irregular		0.1
secondary radius	± 0.5 mm	0
conic constant	± 0.002	0.008
irregular		0.1
decenter	± 0.1 mm	0.08
tilt	$\pm 30''$	0.02
axial motion	± 0.02 mm	0.086
sum		0.186