CHARA TECHNICAL REPORT

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Telescope Alignment Errors

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1. ABSTRACT

In this technical report we show how the insufficient precision of the previous telescope alignment procedure could be the cause of the observed astigmatism. A better alignment procedure is needed in order to achieve the specified wavefront quality. We propose a new procedure using more precise equipment.

2. INTRODUCTION

The CHARA Array has six Alt-Az coudé telescopes (Fig. 1). They are Mersenne type telescopes consisting of a matched pair of confocal parabolic mirrors. The pair of mirrors was specified to achieve less than 0.15 waves at $\lambda = 632.8$ nm, or 100 nm, P-V wavefront error. However, astigmatism in the W1 beam after the M4 mirror was noticed early on (Proc. SPIE Vol. 4838, pp 1201-1207).

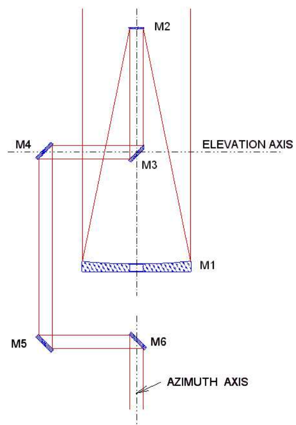

FIGURE 1. The layout of the CHARA Array telescopes.

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The "Classic" pupil plane beam-combiner especially in K'-band is fairly tolerant to wave-front aberrations, but the visual and fiber based IR beam-combiners are not. Since the commissioning of these types of beam-combiners at CHARA, astigmatism was noticed in beams coming from other telescopes. Test results showed that the astigmatism was present in beams right at the telescopes. Improving the alignment of the main telescopes became increasingly important.

The CHARA array telescopes are afocal telescopes, so an auxiliary telescope was used to form images as close to M1-M2 as possible. The auxiliary telescope was custom designed to fit between M4 and M5 on the telescope fork for testing purposes. The image quality of the auxiliary telescope was tested and verified as a stand alone system before use.

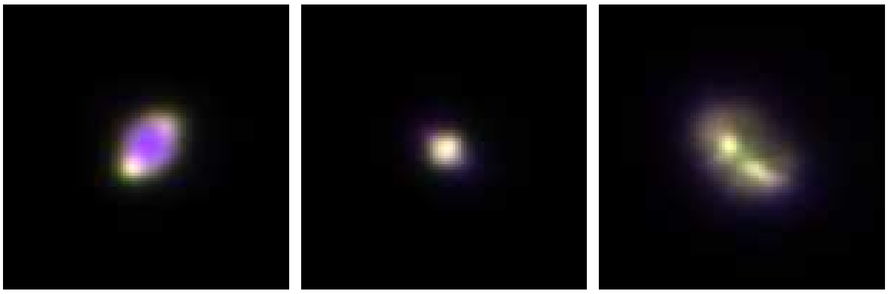

FIGURE 2. The first and third images are defocused images of Deneb through S1. These images are characteristic of astigmatism. The middle image was taken at the best focus.

Figure 2 shows three images of Deneb taken through S1. The defocused annular pupil images (left and right), both displayed in a 9 arcsec square field, are distorted by astigmatism. Several observers have reported the double-core images, which can be seen in Fig. 2. The images shown here are the result of shift-add and frame selection processes to reduce the low order seeing effects. To illustrate the scale of aberration, we include two contour plots (Fig. 3), both represent the red components of the images. The first is ε_2 Lyrae, the second one corresponds to the middle image of Deneb shown in Fig. 2. One tick mark represents one pixel on both axes in both plots. The separation of the two components in ε_2 Lyrae is 2.2 arcsec that corresponds to approximately 15 pixels in the picture, so the pixel scale is 0.15 arcsec/px. The 50% contour in the Deneb image fits into a rectangle of 11 px by 9 px, that is 1.6 arcsec by 1.3 arcsec.

The test images illustrate that the image quality of S1 telescope is worse than it could be. The two defocused images in Fig. 2 clearly show astigmatism. The contour lines of the best-focus Deneb image in Fig. 3 are not circularly symmetric either. All test images are averaged over about a minute. The larger image size of approximately 1.5 arcsec at the best focus could be due to bad seeing, but one would expect a circularly symmetric averaged image, if the seeing was the limiting factor.

3. ASTIGMATISM AS A RESULT OF ALIGNMENT ERROR

In a Mersenne telescope the focal points of the two parabolic surfaces have to coincide. A system is free of aberrations when this criterion is met, and the primary mirror receives the starlight on axis. The outgoing beam direction could be adjusted by rotating the secondary mirror around the common focal point. This adjustment is only limited by the size of the

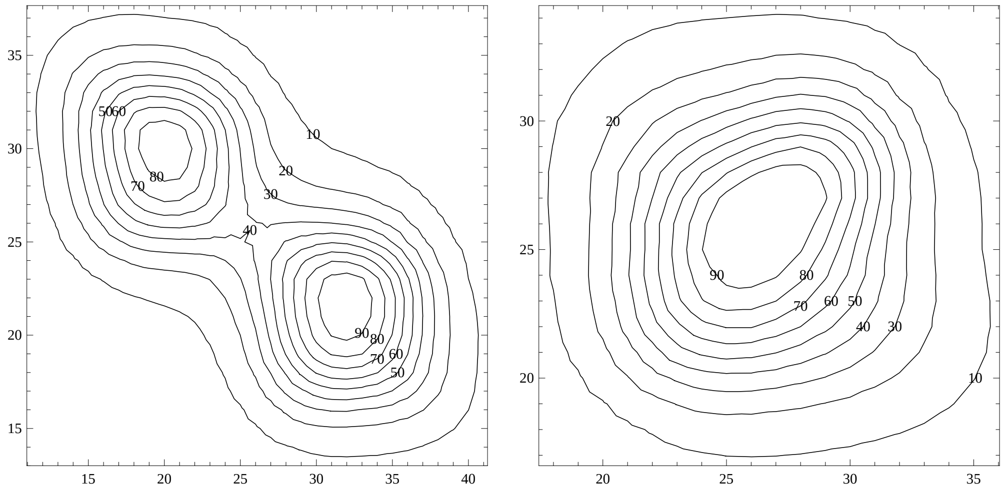

FIGURE 3. Contours of red image components of ε_2 Lyrae, a binary star, and of the middle image in Fig. 2 of Deneb. One tick mark equals to one pixel on the axes shown. The 50% contour in the Deneb image is about 1.5 arcsec in diameter.

secondary mirror. In reality, the mount of a secondary usually is not designed to provide tilts around its focal point. In our case, the secondary can be tilted in fine steps around a point about 1-inch behind the mirror surface; it can be coarsely positioned in the plain of the upper telescope frame; and it can be finely translated in the nominal beam direction for focusing the telescope. The alignment procedure has to position the secondary close enough to the optical axis of the primary, so that available fine adjustments have enough range to reach a position where wavefront errors are within tolerance. Such a position can be found with a final systematic search until the best possible alignment is achieved.

Astigmatism is a sign of the system not being rotationally symmetric. All CHARA M1 and M2 matched pairs are within specification according to interferometric measurements, provided by the manufacturer. Therefore the mirrors themselves are not likely the reason behind the astigmatism, but mirror support problems could be suspected. The most plausible explanation is misalignment. It is not trivial though why astigmatism is the dominant aberration as opposed to coma.

We built a ZEMAX model of the telescope and made calculations to follow our alignment procedure. This ZEMAX model revealed a way to have severe astigmatism, zero coma and unvignetted beam simultaneously. The comparison of tolerances given by ZEMAX calculations with the estimated errors in the original alignment procedure indicates that a more precise alignment procedure is all that is needed to achieve the specified beam quality.

3.1. Centering Error ZEMAX Calculation

Finding a point on the optical axis of the primary mirror was not part of the alignment procedure. The telescope axis was chosen where the primary axis was assumed to be. Given that, one could suspect that the secondary mirror was off the primary axis.

ZEMAX calculations illustrate the effect of a possible centering error at M2. Let's assume that the telescope is pointing at a star, that is the star is on the true axis of M1. Also assume the axis of M1 and M2 are parallel, but M2 is decentered by 3 mm. This misalignment causes mostly coma and a small amount of astigmatism. Using the parameters of our mirrors, the calculated P-V wavefront error with respect to the centroid is over 6.2 waves (Fig. 4).

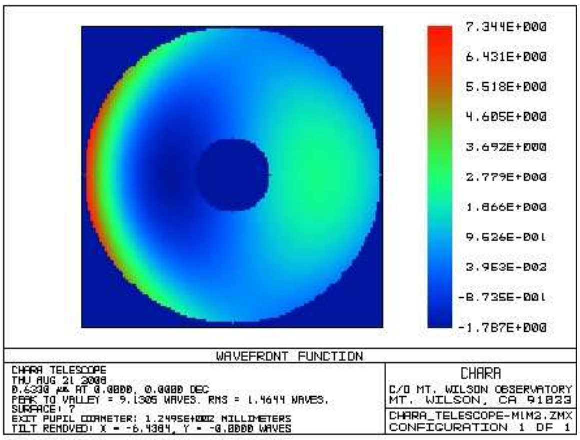

FIGURE 4. Centering error at M2 causes coma

The effect of decentering can be mitigated by tilting M2 by 0.55 degrees around an axis that intersects its axis perpendicularly at its vertex. This tilt decreases the P-V aberration to 0.42 waves, that is almost entirely defocus (Fig. 5).

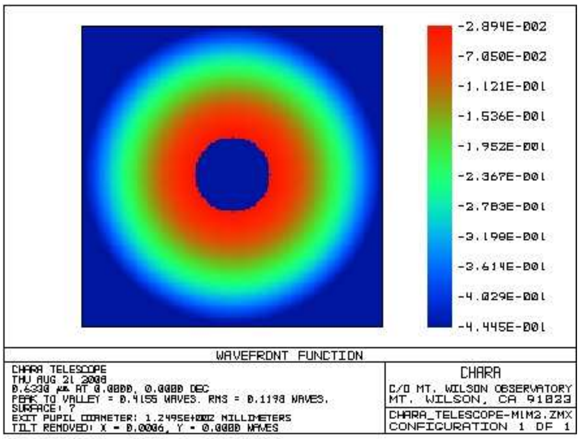

FIGURE 5. Coma can be eliminated almost entirely by tilting M2. The residual aberration is defocus.

If the telescope is refocused at this point by moving M2 away from M1 only by 10μm, the wavefront quality would be excellent and the Strehl-ratio$\simeq$1. However, the tilt of M2 alters the outgoing beam direction by 1.1 degrees, which causes severe vignetting in the coudé path. To restore the proper beam direction, the telescope needs to be offset by 0.55 deg / 8 = 0.069 deg, which moves the star off axis. This last step has virtually no effect on coma, which stays close to zero, but introduces astigmatism. The P-V wavefront aberration increases to 0.89 waves and the Strehl-ratio drops to 0.24. The result is almost pure 3-d order astigmatism (Fig. 6).

The resulting astigmatism depends on the initial centering error, as it is shown in Fig. 7. In

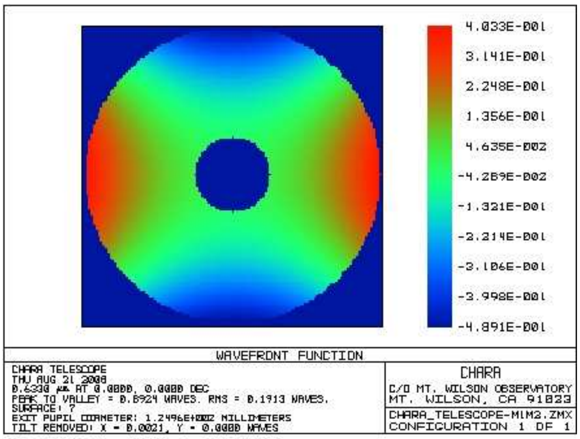

FIGURE 6. After restoring the beam direction by repointing the telescope, i.e. putting the star off axis, astigmatism becomes the dominant aberration.

order to meet the original beam quality requirement of better than 0.15 waves P-V wavefront error at $\lambda = 632.8$ nm (P-V = 100 nm), the center of the secondary has to be closer than 1.2 mm to the axis of the primary mirror according to these ZEMAX calculations for the CHARA telescopes.

3.2. Error Estimation in the Old Alignment Procedure

The procedure consisted of 6 main steps.

1. Defining the optical axis
2. Positioning M2
3. Tilting M2
4. Tilting M1
5. Focusing
6. Small adjustments to improve image quality

3.2.1. Defining the Optical Axis of the Telescope

There were two requirements:

- The optical axis of the telescope has to go through the vertex of the primary mirror.
- The optical axis has to intersect the elevation axis in order to minimize beam shear while the telescope is moving in elevation.

The primary mirror is mounted in the telescope frame in such a way that the mirror cannot be translated, but it can be tilted with respect to the frame.

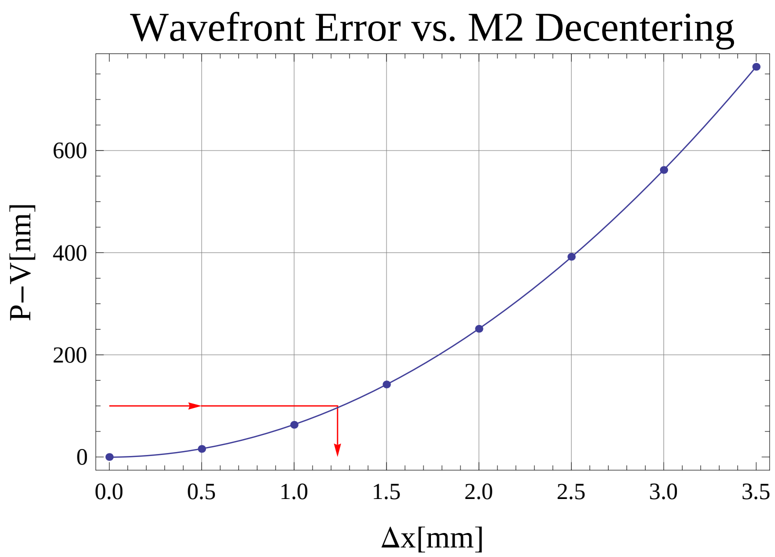

FIGURE 7. Results of ZEMAX calculations made for CHARA telescopes are shown. On the Y axis, the best achievable peak to valley wavefront error is plotted against the distance of the vertex of M2 from the axis of M1. The telescope was specified to have less than 100 nm P-V wavefront error, this means that the vertex of M2 cannot be further that 1.2 mm from the axis of M1 mirror.

We chose the optical axis with respect to the telescope frame. A telephoto lens with a camera attached was looking toward M2 along the telescope axis, and it was mounted under the support cage of the primary mirror. The axis was defined by one point on the elevation axis and the position of the camera lens. This axis intersected the surface of M1 at a point near the vertex. Using the telescope frame as a reference, this chosen telescope axis could miss the vertex of the primary mirror by several millimeters.

For the alignment, the elevation axis was quite accurately represented by a kevlar string, pulled between the elevation bearings.

The axis of the alignment camera was transferred also to the finder telescope by acquiring the same star in both.

3.2.2. Positioning the Secondary Mirror

We used the video camera to position M2 on the chosen telescope axis. We pulled two additional kevlar strings across the telescope axis. The strings were adjusted until they appeared on the video to intersect one-another on the kevlar string representing the elevation axis. The optical axis had to be represented by a dot on the protective window of the monitor, because the depth of focus was not enough to see all significant elements at the same time. Due to parallax on the monitor screen, and the unknown stability of the axis of the camera lens during refocusing, this setup could allow 2-3 mm centering error at M2.

The combined errors of defining the optical axis outside the vertex of M1, and positioning M2 on the optical axis could easily lead to 3 mm centering error, which was assumed in the ZEMAX calculation.

3.2.3. Tilting the Secondary Mirror

The optical axis of the alignment video camera was by definition our telescope axis. We adjusted the tilt of M2 to this axis. M2 was tilted until the reference kevlar strings and their images in M2 overlapped on the video. This was done precisely, ($\pm 10\ \mu$m) with the tilt actuators on M2. However, with this step we effectively propagated the centering error to a tilt error. If there was a centering error of 3 mm, in order to make the string images overlap on the screen, M2 would be tilted by 0.55 degrees.

3.2.4. Tilting the Primary Mirror

In the original procedure M1 mirror tilt was adjusted after positioning and tilting of M2 still using the alignment video camera as a reference. The telescope axis, or alignment camera axis, was transferred earlier to the finder telescope by acquiring and centering a star in both the finder and the alignment camera.

A star was centered in the finder telescope, and M1 was tilted with respect to the frame until the image of the star was centered in the alignment camera. At this point, M2 might already be 0.55 degrees off from the alignment camera axis, so we had to tilt M1 to receive the star off axis in order to meet the predefined beam direction. As a result, the true axis of M1 might end up even further away from M2 center than the original centering error of M2. The beam became astigmatic depending on the initial centering error as shown in Fig. 7.

3.2.5. Focusing the main telescope

After M3, M4 and M5 were installed and aligned to the coudé path, it was possible to focus the main telescope. The above mentioned auxiliary telescope, inserted between M4 and M5, was used as a focus reference. In this step M2 was moved along its axis, by finely translating all tilt actuators by the same amount. If mirror axes were not perfectly aligned, focusing and tilting of M2 had to be done iteratively.

3.2.6. Visual Image Quality Check and Adjustments

After focusing, the main telescope image quality was checked visually through the auxiliary scope. Small amounts of residual coma, if present, were eliminated by iteratively tilting M2 and re-centering the star in the auxiliary scope by repointing the main telescope, in other words moving M1-M2 as a unit. Coma could be effectively eliminated this way, but correcting for astigmatism would require translating M2 in order to place it closer to the axis of M1. The M2 mount was not designed to allow fine translation adjustment in that direction.

4. NEW ALIGNMENT PROCEDURE

To be able to align a Mersenne telescope well, the true axis of the primary mirror has to be precisely known and the secondary mirror has to be placed on that axis. We also have to meet the requirement of a fixed out coming beam from an Alt-Az coudé telescope. In the newly proposed procedure the optical axis of the aligned system will match the optical axis of the primary mirror with a better accuracy. The center of curvature of the primary mirror will be found optically, this will provide at least one point that is on the ideal axis. Another significant difference is that the tilt of primary mirror will be fixed first with respect to the frame. The secondary mirror will then be positioned on the optical axis. The major steps will be as follows:

1. Finding the center of curvature of M1
2. Adjusting M1 tilt with respect to the frame in order to have M1 axis intercept the elevation axis.
3. Positioning and tilting M2
4. Focusing
5. Performing a search based on quantitative image evaluation to optimize M2 tilt and focus.

Another technical report will describe the procedure in detail. In order to implement the new procedure, new tools have to be purchased or made.

- An 8" fold mirror, and a structure to hold the large mirror above the telescope upper frame. This will fold the optical axis of the main telescope, so that one can access the center of curvature of M1.
- A point source at the center of curvature of M1, plus mounting with two translations.
- Two auto-collimating alignment telescopes: one coaxial with the elevation axis, and one defining the telescope axis Both alignment telescopes need custom mounting.
- A mounted pentaprism, 20 arcsec or better accuracy, to use it at the intersection of the elevation axis and the telescope axis.
- M3 mounting on the telescope needs to be remade to have a kinematic base, so that M3 mirror can be removed and repositioned precisely.

5. CONCLUSION

We think that the root of astigmatism in the telescope beams is the less than adequate precision of the previous alignment procedure. In some cases M2 ended up too far from the optical axis of M1. Astigmatism will not be significant according to our calculations, if we can assure that the secondary mirror is centered within 1.2 mm of the primary mirror axis. In that case a systematic search over a reasonable parameter space should be able to find an optimum alignment, which keeps the wavefront error under 100 nm P-V. We have designed a new telescope alignment procedure to meet this goal. The new procedure will be described and evaluated in a future technical report. Development of an effective search algorithm along with quick image evaluation method is under way.