CHARA TECHNICAL REPORT

No. 109 May 28, 2021

Telescope and Coude Path Alignment

Procedures after mirror recoating

by

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ABSTRACT:

This report describes the optical alignment procedures and considerations when re-installing freshly coated mirrors. Techniques for the alignment of the secondary and tertiary spider arms are described in the Appendix. The procedures described here are the latest ones we followed.

1. INTRODUCTION

Mirrors in the telescopes and along the coude paths need regular recoating. The procedures we developed for setting up the correct beam path constantly evolved. A set of new tools have been built or acquired over the years to make the alignment more precise and convenient.

The CHARA telescopes are Mersenne beam compressors in an Alt-Az coude arrangement. A 125 mm output beam from each telescope is transported through evacuated pipes to the beam combination facility.

To minimize angular error and beam shear while the telescope is tracking a star, the axis of the output beam from the telescope has to be on both the azimuth and elevation axes. For the best possible beam quality, the alignment of the two power elements, M1 and M2, has to be optimized. We believe the procedures described here are necessary and sufficient to put the optics where they need to be for transporting a beam with good optical quality toward the laboratory.

2. THE COUDE BOX AND THE AZIMUTH AXIS

Most fold mirrors along the coude path have a small hole drilled in the center. These holes serve as references for the alignment process. The green alignment laser is used to position and tilt the mirrors in the coude box. The M7 mirror is the most critical since it is on the azimuth axis.

2.1. Positioning of M7

All M7 mounts have already been placed to their correct positions with respect to the azimuth axes; that is, the azimuth axis at each telescope intersects M7 within the hole at its center. The mirror substrate can be removed and reinstalled without removing the mount from the coude box. The position of the freshly coated mirror is expected to be close to its optimal position.

If the position of M7 is in doubt and needs to be checked, it has to be done before M6 is in place (Figure 1).

There is an alignment jig (Figure 2) for checking the position of M7. It can be placed over the ring where M6 will be mounted. For this check, the post holding up the screen can be easily removed. The bottom plate of this jig has three hard points to rest on the ring and two dowel pins that need to be pressed against the inner edge of the ring to guide the jig. A small down-looking alignment telescope is installed on a tilt mount. One can watch the hole in M7 through the telescope (or with a camera) from above while the telescope is turning in azimuth (Figure 1).

If the azimuth axis intersects M7 in its center hole, the hole stays stationary in the telescope regardless of the azimuth angle.

If not, translate the M7 mount by rotating the whole coude box. The feet of the coude box allows for small rotation around one of its legs. The M7 mount is clamped at some telescope, so its possible to nudge the mount in the box.

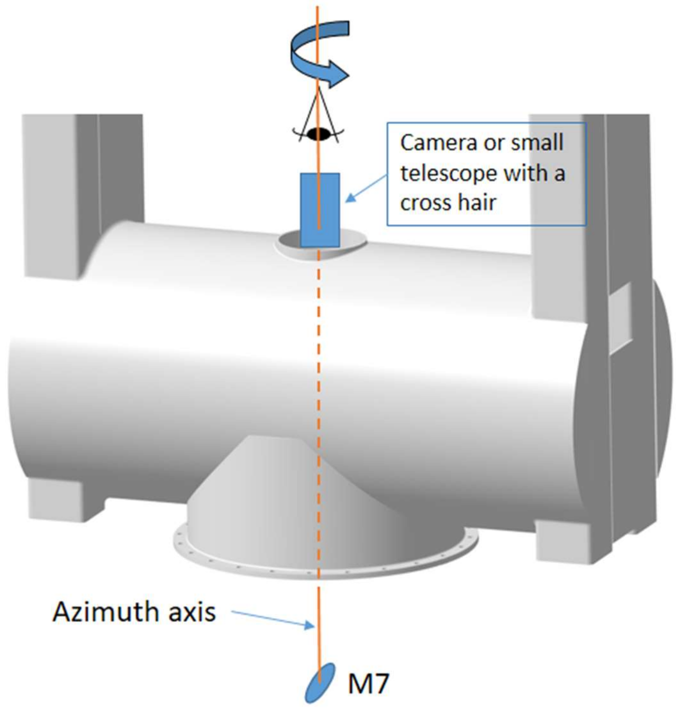


Figure 1. M7 position check

2.2. Alignment of the mirrors in the coude box

Depending on the arm of the array, there are a different number of mirrors in the coude boxes. The S coude boxes have three mirrors: M7, M8, and M9. The W coude boxes contain M7 and M8. There is only one mirror, M7, in the E coude boxes.

In each case, the beam has to be centered on the vacuum window at the end of the light pipe and has to be centered on M7. The vacuum windows and positions of the coude box mirror mounts have already been set. The mirrors can be removed and reinstalled without removing the mounts from the Coude box with the exception of M9 in the S coude boxes. The whole M9 mount has to be taken out from the S coude box to mount the mirror. Once the mirror has been installed, the mount goes back very close to its original position.

Before proceeding with the alignment, all mirrors have to be installed in the coude box, and the light pipe has to be evacuated. The alignment laser beam should be carefully aligned in the lab up to the point of the

back of the front rail target. This will ensure that the beam is going correctly into the light pipe.
The current alignment laser is bright however, if more laser flux is needed to see the beam on a paper target in the coude box, the engineering beam path could be used.

If the same pop mirror is still in the beam since the telescope was last used, and the laser is aligned to the back of the front rail target, the laser should be visible on a paper target placed over the first mirror in the coude box after the vacuum window.

Center the laser beam on the first mirror in the coude box by tilting M10.

Inspect the centered beam on a paper target, check for any vignetting by the vacuum window or the bellow between the vacuum window and the coude box.

Tilt M9 or M8, if needed, to center the unvignetted beam on M7. The easiest place for a final check of the laser beam after M7 is at M6. Place a clean piece of paper over the hole in the fork. Any vignetting will clearly show up on the paper screen with the alignment laser at full power. Keep in mind that the beam diameter is only 125 mm, so the beam has to be unvignetted within a circle of 125 mm.

If the beam is centered on M7 but vignetted, a unique solution may have to be figured out especially in case of the E telescopes, where there is no optical surface to adjust between the vacuum window and M7. If adjustments are necessary in the coude area, always make sure that the laser beam is well aligned in the lab.

2.3. Setting M7 tilt

After the steps in 2.2, the alignment laser is centered on M7. The next step is tilting M7 until the laser beam is parallel with the azimuth axis.

The easiest way to achieve this is by projecting the alignment laser to the screen above the down-looking alignment telescope used for centering M7. (Fig. 2) If the angle of M7 is incorrect, the spot on the screen moves along an arc as the telescope is moving in azimuth.

First, make sure that the M7 remote adjustment is in the middle of its range. Mark the spot on the screen, then rotate the telescope 180 degrees in azimuth and mark the spot there too. Loosen the lock screws and manually tilt M7 until the projected spot is halfway between the two marks.

Figure 2. The alignment jig to be placed over the M6 hole. This jig is useful for checking M7 position with respect to the azimuth axis and for setting M7 tilt initially.

Later, when the alignment is complete, another routine coude alignment should be done to verify that the M7 remote alignment actuators stay comfortably in their range.

3. REINSTALLING AND ALIGNING M5 AND M6

Important! Take notes, pictures when the mirrors are removed. It will help during reinstallation, especially pay attention when you remove M6. There are spacers under it that can fall on M7, so close the M7 cover before working on M6.

3.1. Mounting M5 mirror

It is better to mount M5 mirror before M6, because the center hole of M5 will be the target for aligning the M6 mirror. Some steps of mounting M5 mirror require two persons.

3.1.1. Removing the M5 mount

Even though it is possible to take M5 substrate out of the mount without removing the mount from the Adaptive Optics (AO) board, the mount has to be removed for re-installation. First, unplug and remove the motorized M5 cover as a whole assembly by taking out the two mounting screws. See Figure 3.

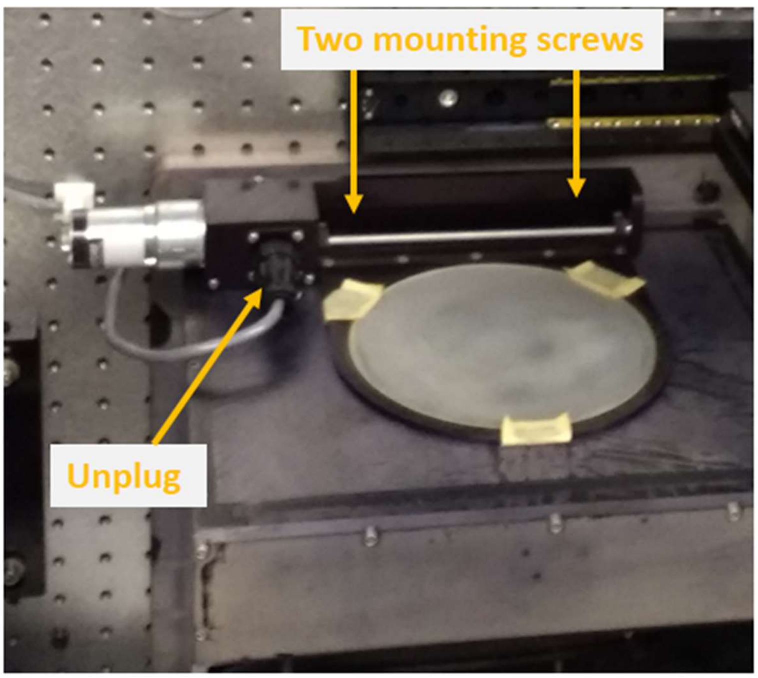


Figure 3. The motorized M5 cover. When taking off the cover, unplug the cable and unscrew the two mounting screws (not visible in the picture). Slowly lift away the assembly; there could be shims under it.

It is also necessary to take out the bottom of the AO board cover and remove the bottom front edge of the cover frame. See Figure 4.

When removing the mount from the AO board ensure that you are not going to lose any of the mirror pads; put them with the mounting screws and inserts in a secure place. Attempting to remove the mount from the board alone is very risky!

Once the mount is off, wipe the accumulated dust from the inside surfaces of the mount, then prop it up on the floor such that the hard points holding the mirror are facing upward and are roughly in a horizontal plane. Remove the small side plate (Figure 4.) at the top to retract the spring plunger holding the top side pad.

Figure 4. The M5 mount on the AO board.

3.1.2. Mounting M5 mirror

Place the small pads onto the round hard points, then gently place the mirror surface down to the small pads. Ensure that all three pads are flat against the mirror surface.

Ease the mirror away from one of the lower side points and slide the side pad between the hard pint and the mirror. Slightly lifting the mirror helps, but don't lose the small pads. The side pads are cylindrical toward the mirror; ensure that the cylindrical shape of the side pad follows the curvature of the mirror substrate.

Repeat for the second side pad. Keep checking that the small pads are still properly in place. Now the mirror can rest against the two lower pads.

Slide the final side pad in place, and drive in the spring plunger to hold the side pad firmly against the side of the mirror. Do not over tighten, leave room for the spring action! Again, ensure that the curvature of the

side pad matches the side of the mirror and all the small pads at the mirror surface are in place.
Install the safety ring. Retract the small spring plungers from the safety ring. Fasten the safety ring to its place with the six screws, and then drive the small spring plungers to touch and hold the back of the mirror. Do not over tighten; leave room for a little spring action!

Fasten the side plate to the mount.

3.1.3. Fastening M5 mount to the board

Two persons are necessary for this step. One person is holding the mount with the mirror in it to the AO board at the right place, and the other drives the bolts.

3.1.4. Restoring the covers

Reinstall the M5 mirror cover, check it, and leave it closed. Restore the AO board cover box.

3.2. Mounting and aligning M6 mirror

Mounting M6 starts in the machine shop. Most steps require two persons. You will need the proper metric Allen key for driving the screws between the mount and the crown.

3.2.1. Pressing in the crown

Before mounting M6, the mounting crown has to be pushed into the recess at the back of the substrate. This has to be done on the granite block in the shop to make sure that the crown is inserted properly and to avoid damaging the mirror in the process.

Make sure that the granite block is free of any debris. Place a tissue over the block and cover it with a lens tissue for the best protection of the mirror surface.

Place the mirror face down onto the lens tissue. Place the crown over the recess and make sure that the crown is oriented properly. There’s a mark

on the crown as well as on the substrate. The crown tends to rotate slightly when pressed in. A degree or so error doesn't matter.
Push down the crown vertically with one decisive move.

When done, make sure the crown sits properly: the crown should touch the substrate at three places 120 degrees apart. If the crown is tilted, gradually pry it out by going around with something wide to prevent chipping the substrate.

3.2.2. Fastening the crown to the mount

This is a two-person job. Let the mount rest on its back, such that the mirror will be facing upward when the crown will be fastened. One person holds the mirror near the final position, and the other person holds the mount and drives the metric mounting screws through the holes in the mount into the crown. It is easiest to start with the top screw.

3.2.3. Securing the M6 mount in its place

Before doing this, ensure that the M7 cover is closed to protect the mirrors already in the coude box. The way M6 is fastened is somewhat different at each telescope because the forks are different. Be careful when lowering M6 in the fork. Pointy sheet metal screws are sticking inward.

Grab the black nut on the mount and lower it slowly and vertically. When the mount sits on the spacers, you can move the mirror laterally.

The M6 mirror has to be centered on the azimuth axis, and the beam has to be centered on M5 unvignetted. The M6 mounts were shimmed a bit differently to meet these requirements, and the clamps also had to accommodate the tapped hole pattern at the given fork. The good position of the M6 mount is roughly outlined on each fork. We recommend refreshing the marks before the mount is taken out. Taking pictures may also help.

Once the mount is sitting on the spacers near the correct position, tighten down the mount as much as to prevent the shims from falling.

3.2.4. Aligning M6 mirror

For this step, the lab alignment laser is used, and two persons can accomplish the task faster. The alignment laser has to be checked in the lab as usual up to the back of the front rail target.

Open the M7 cover, and watch the beam on a paper screen in the coude box right above M7, and if needed, adjust M10 tilt to center the beam on the M7 hole.

Up in the dome, watch the beam on the M5 cover. The shadows of the M7, M6, and M5 center holes will not be on top of each other at first; there will be three black dots. The goal is to move M6 until they overlap.

This can be accomplished by rotating the M6 mount and maybe translating it a little. Note that when you try to tighten the clamps, the dots will move again relative to one another. Find out what the dots are doing while tightening and account for it. Make the dots as close-packed as possible.

Clamp down the mount to secure it. After the mount is clamped down, it is possible to tilt the mirror using the three cogwheels on the top of the mount. By tilting M6, the dots could be further moved to form a tight spot.

In the end, make sure that the clamps are tight enough and the mirror centers are in a tight cluster on the M5 screen.

Mount the protective lid over the M6 mount.

3.3. Tilting M5 mirror

The beam path between M5 and M4 is nominally parallel to the AO board, and the center of the beam is 6 inches from the board. The AO board was initially set up in such a way that when the beam is centered on M4 and M5 it is also vertical. After we finished the first alignment with the AO board in place, we fastened a fiducial clamp (see Figure 5.) to the board just under M4 to quickly find a point on the desired beam axis. The clamp accepts a 1-inch post holder. The center of a 6-inch high target will mark a point on the desired beam axis. The optical axis ideally intersects the elevation axis at the center hole of M4.

Turn the BARE splitter into the beam with the carousel, and center the laser beam on the target in the fiducial clamp shown in Figure 5 by turning the micrometer screws in the M5 mount.

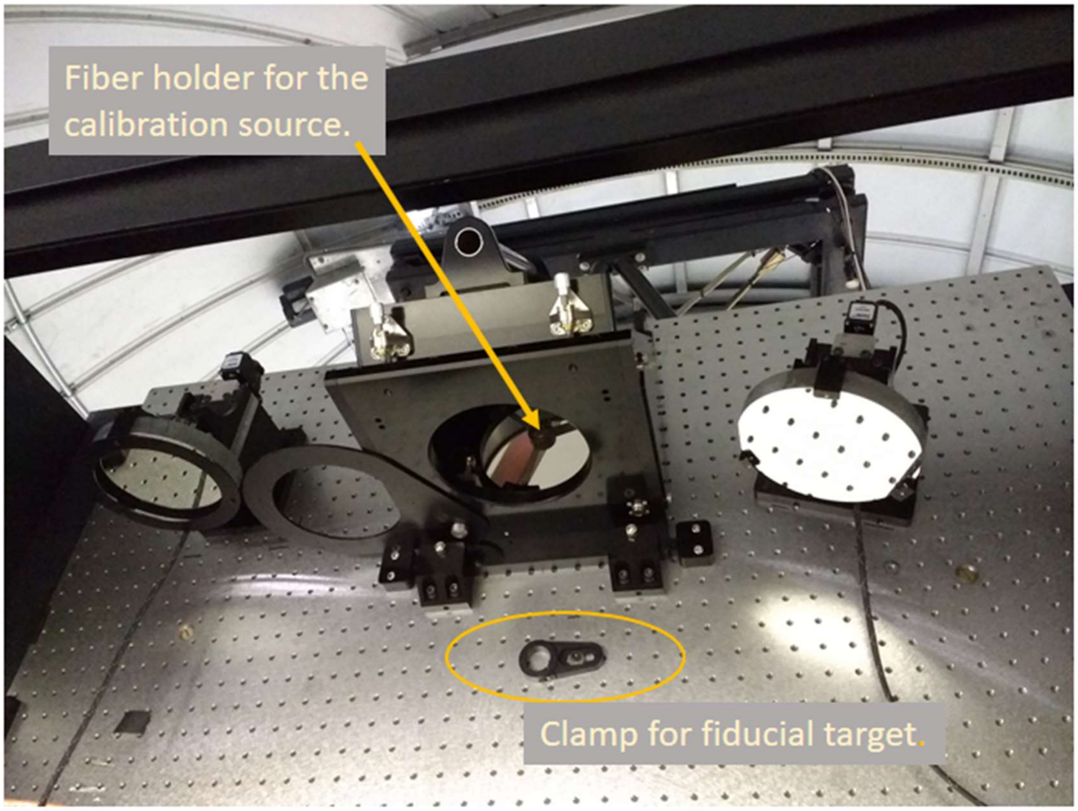


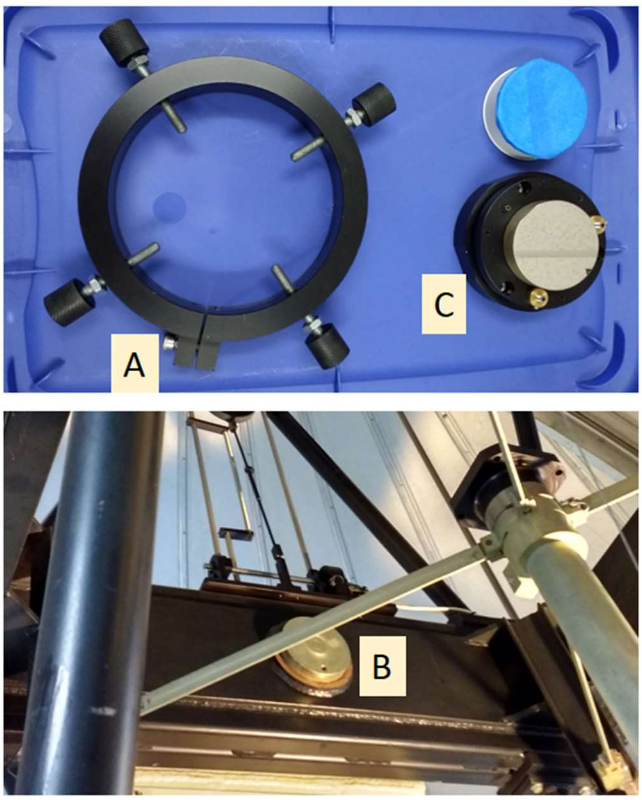
Figure 5. The top portion of the AO board. The new M4 mount is in the middle. The center hole of the M4 mirror should be on the elevation axis. A target centered at 6-inch off the AO board can be secured in the fiducial clamp for setting M5 tilt and also for setting the alignment scope tilt.

4. THE ELEVATION AXIS AND M4

The optical axis between M3 and M4 mirrors must be the elevation axis of the telescope. We continue to use the center holes of the mirrors to position them. First, we have to find the elevation axis and then place the center holes of M3 and M4 to it.

A new mount was designed to make the solid M4 mirror interchangeable with the deformable mirror (DM). The mirror surfaces will be nominally at the same position after swapping them. Use the solid M4 mirror during alignment, the DM cannot be used at this stage, and its center is not marked.

We will use one of the Brunson alignment telescopes (AT1) with a right angle eyepiece and the elevation axis mirror (EAM). See Figure 6.



1. Secure the collar with the socket head screw (A) to the elevation shaft flange (B).

2. Place the mounted elevation axis mirror (C) between the thumb screws.

The elevation axis mirror mount is magnetic, it will stick to the flange. It can be translated with the thumb screws and tilted with the little micrometer screws using an Allen key.

Figure 6. Setting up the elevation axis mirror

4.1. Finding the elevation axis

M1, M4, and EAM with its collar (Figure 6) are installed, but M3 is not. Two persons needed: one is looking into AT1, the other is making the adjustments.

4.1.1. Mounting the Brunson alignment scope (AT1)

Put AT1 on the AO board just above the M5 mount to look up into M4. When fastening the mounting block, ensure that its horizontal position across the table is correct for placing AT1 centered on the desired beam path.

The mounting block places the pivot point of AT1 at 6 inches. Centering the fiducial target (Fig. 5) in AT1 makes the line of sight parallel to the board.

4.1.2. Finding EAM cross-hair in AT1

The center of EAM is marked by a cross-hair on its surface. Focus ATI on the cross-hair. Illuminate the mirror surface from the side, if needed. It is best to search for the image while the AT1 light is turned off. The image's contrast is low due to the fiber holder in the M4 mount, but the cross-hair can be clearly seen once found.

The tilt of M4 and its position is not critical at this point as long as you can see the cross-hair. It is best to center the EAM on AT1's cross-hair at first by tilting M4. Leave M4 tilt as is until you are ready to start step 4.2.

4.1.3 Centering EAM on the elevation axis

Drive the telescope up/down (max 90/min 16) in elevation and watch the center of EAM moving in the field. Translate EAM using the thumbscrews in the collar until the mirror center remains stationary in AT1 regardless of elevation. This is not a trivial thing to do when one needs to find the center of a small circle from an arc spanning only 74 degrees.

The following routine can be used when EAM is close to the rotation center: Before each elevation move, place AT1's cross-hair to EAM cross-hair. At the end of the elevation move translate EAM to half the distance between the two cross-hairs as they appear in AT1.

4.1.4 Setting EAM tilt

The next step is to make EAM perpendicular to the elevation axis. Turn on the illumination in AT1 and focus it on the image of the auto-reflection target on the front lens of the alignment telescope.

Drive the telescope up/down and tilt the EAM by the micrometer screws until the image of the auto-reflection target remains stationary* in AT1.

The tilt adjustment on AT1 can be used again to mark the starting positon of the auto-reflection target with the cross hair in AT1 before each elevation move.

In the end, you may have to iterate between translating and tilting EAM until the movement of both the mirror center and the image of the auto-reflection target is minimal.

> * Due to flexure, it is impossible to eliminate all image motion, but it can be reduced to the extent of less than the separation of the double line in the cross-hair of AT1.

4.2. Aligning M4

After the procedure described in 4.1, EAM is centered on the elevation axis and its surface perpendicular to it. Two persons are needed: one is looking into AT1, the other is making the adjustments.

4.2.1 Set AT1 on the desired beam axis

The mounting block already holds the pivot point at the right place. When AT1 cross hair is centered on the fiducial target (Fig. 5), the optical axis of AT1 is on the desired beam axis. Remove the fiducial target.

4.2.2. Check/adjust the position of M4 center hole

Focus on M4 center hole and check if the hole is centered.

If there is an up/down error, move the base of M4 mount perpendicularly to the board; in other words, shim the whole M4 mount. This step has already been done at each scope. Since removing M4 does not require removing the whole mount, it is not likely that the existing shims have to be altered.

If there is a large left/right error nudge the mount left/right on the board. “Nudgers” were made for that. The nudgers can be seen on either side of M4 mount in Figure 5. This step also has already been done at each scope.

Note that if you move the base of M4 mount, the calibration source is also affected.

4.2.3. Tilting M4

The image of the auto-reflection or the auto-collimation target may be slightly off in the AT1. Tilt M4 to center them. Auto-collimation is more sensitive.

4.2.4. A more sensitve test

Ideally, the reflected image of the M4 hole by EAM should also be centered in AT1. This is a more sensitive test of the position of the M4 center hole. You might want to iterate between translating and tilting M4 until you are satisfied with this more sensitive test result.

Now, M4 is aligned, and the optical axis of AT1 coincides with the telescope's elevation axis.

5. THE OPTICAL AXIS OF THE TELESCOPE

The optical axis of the telescope has to intersect the elevation axis at the center of M3.

In our case, both M1 and M2 mirrors have mounting holes bored at their center. We assume that the vertices of the paraboloids are centered in the mounting holes. We can assume that this is correct to a few mm for M1 (manufacturer's claim), and not worse than that for M2.

5.1. M1 vertex and the axis of the telescope

We have installed a cross-hair in the central post of M1 as close as possible to the mirror surface. It represents the vertex of M1. We used a pentaprism to reflect the elevation axis and the second Brunson alignment telescope to define the desired axis of the telescope. This axis goes through the vertex of M1 and intersects the elevation axis at 90 degrees. The M3 and M2 supports have been centered on this axis. The procedure is described in the Appendix.

5.2. The M2 support

If we assume that the support of M2 is at the right place, we could use the M2 nut as a reference for the telescope axis, and to align M3. A target (Figure 7.) with a perpendicular screw at the back could be screwed into the M2 nut.

We also assume that the M2 mounting rod is already closely aligned with the telescope optical axis when using this target. The alignment of the rod to the telescope axis could be verified later, as outlined in 5.3.4.

Figure 7. Target at M2

5.3. M3

We use the center hole in M3 to position the mirror on the elevation axis. The mirror has to be tilted to reflect the elevation axis to the telescope axis. We assume that AT1 has already been aligned along the elevation axis. M2 mirror is not installed at this point, only its mounting rod.

5.3.1 Mounting of M3

The M3 mirror is mounted similarly to M6. Use the same procedure outlined in 3.2.1 to press in the crown.

Assemble the mount in the dome and secure it to the M3 post. The mount has 6 degrees of freedom, and it is a gimbal mount.

5.3.2 Placing M3 center hole on the elevation axis

Identify the center hole of M3 in AT1, and translate M3 until the M3 hole is centered. Adjust left-right direction with opposing screws. Height adjustment can be made using the captive nut after releasing the clamp.

5.3.3. Tilting M3

Focus AT1 to the M2 target (Fig. 7.) on the M2 nut, and tilt M3 until the target is centered.

5.3.4. Positioning M3 center along the elevation axis

One could verify if the depth of M3 along the elevation axis is correct by checking whether the long M2 post lines up with the line of sight. Remove the post and focus to the end of the M2 tube. If the tube looks off-center in M3, adjust the position of M3 along the elevation axis and tilt it until both the front and the back of the M2 post are centered.

The M3 mount allows for some translation along the elevation axis. The M3 assembly has to fit within the shadow of the secondary. As long as this condition is met, the M3 and M2 supports do not need adjustment.

5.4. Setting the Finder Scope

Assuming that AT1 is still looking along the elevation axis and then through M3 along the telescope axis, the next step is to set the finder scope origin to the direction of the telescope axis. For this step, we use AT1 and a star.

To minimize the error due to telescope flexure, we always used stars at high elevation.

Remove the M2 post and center a bright star in AT1 by moving the telescope.

Adjust the finder telescope to center the star in the window on the computer screen, and set the Finder origin to the star while the star in AT1 is on the cross-hair.

From now on, the finder telescope is the reference for pointing direction.

6. TILTING M1

We will tilt M1 to make its axis close to the telescope's optical axis, currently coincident with the axis of AT1. We use a 5.5-inch flat mirror (M2F) in place of M2 to reflect the focal point of M1 to a relatively easily accessible place.

6.1. Setting up M2F perpendicularly to the telescope axis

Assemble the secondary mount and install the secondary post.

Remove the corner cube mount.

Install the M1 alignment cage without the XY stage. See Figure 8. Ensure that all setscrews are tight so that sagging is minimal.

Install the M2F mirror on the M2 mount.

Use the secondary motors (MERCURY) to tilt the flat until the auto-reflection and auto-collimation targets are centered in AT1.

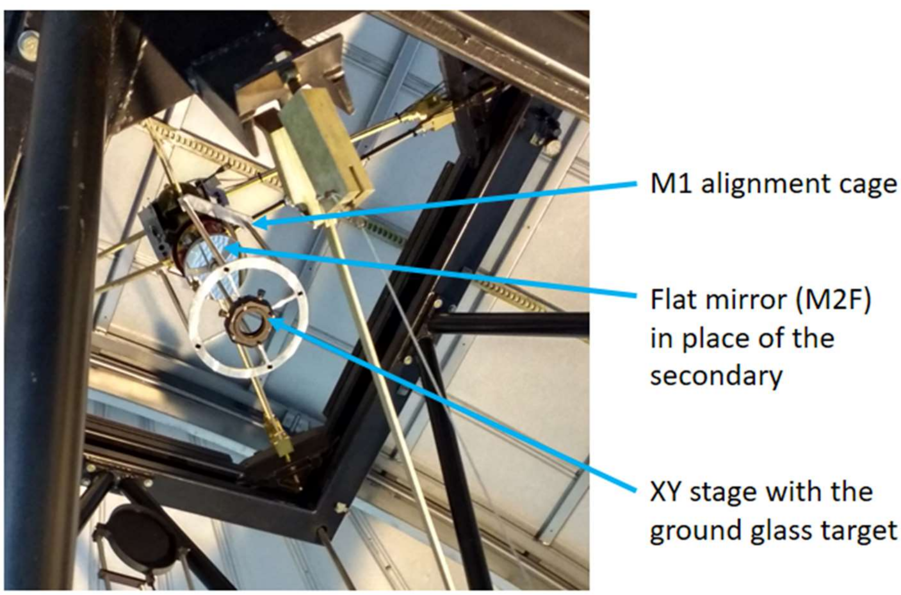


Figure 8. The setup for tilting M1 mirror

6.2. Setting a target on the telescope axis

Install the XY stage with the ground-glass target on the M1 alignment cage. Once the XY stage is installed, move the telescope to a higher elevation where you will still be able to center the target. Translate the target by the thumbscrews until the target is centered in AT1.

6.3. Tilting M1 to place its optical axis to the telescope axis

Acquire a bright star and center it on the Finder origin (the finder and AT1 axes are parallel).

Focus AT1 onto the ground glass and find the image of the star made by M1 on the ground glass. If the spot is too big to see it clearly, translate M2F by the focus motors.

Make sure that the central hub is loose before any M1 tilt adjustment. If the central hub of M1 is not released or sticky, one can distort the mirror by tilting it!

Make sure the star is still centered in the Finder, and tilt M1 until the image of the star seen in AT1 is centered on the ground-glass target. Lock down M1 adjustments.

Remove M2F and the M1 alignment cage.

Re-install the corner cube.

7. ALIGNMENT OF M2

Install M2.

Focus AT1 to infinity. While a star is still centered on the Finder origin, tilt M2 until the star is centered in AT1. (Here, we again assume that the hole in M2 is centered on its vertex.)

Once the star is centered in AT1, M1 and M2 are at a good starting point for optimizing the image quality.

8. TUNING THE TELESCOPE ALIGNMENT

Although the telescope is geometrically aligned, it does not usually provide the best possible wavefront due to the uncertainties of the centering of M1 and M2 and uncertainties in the geometrical alignment itself. Telescope flexure and tracking error during the procedure, and subjective judgments are all affecting the outcome.

The fine-tuning process aims to improve the beam quality. The beam quality is evaluated by inspecting the image of a star first by eye through the telescope alignment scope (TAS) or TAS2, followed by wavefront measurements.

There are two approaches for tuning: tilting both M1 and M2 or translating and tilting M2 and not touching M1. Neither of these is easy with the CHARA telescopes.

The first approach could be dangerous, as the M1 mounting was not designed for tilting the mirror. It could be tilted a little, but if the central hub of M1 is not released or sticky, one can distort the mirror by adjusting the whiffle tree to tilt it.

The second approach is not workable with the current M2 mounting. If CHARA can acquire hexapods, the second approach would be the better one.

8.1. Calibrating and focusing TAS or TAS2

Neither TAS nor TAS2 is perfect. The measured Strehl of TAS was over 90%, while it was about 75% for TAS2. This has to be taken into account when evaluating the main telescope.

Before using TAS2 on the main telescope, it needs to be calibrated by taking wavefront measurements while not looking through the main telescope. Put one of the TAS2 bases on the side of the telescope next to the finder (S1 may still have it installed) and look at a bright star.

Using the "loop" feature of Frontsurfer, take several hundred WFS measurements over a few minutes, then calculate the Zernike coefficients. Also, focus the WFS, if needed, until the coefficient of Z4 is ~0.

When the WFS is already in the pupil plane, focus the eyepiece as well to the star.

The measured Zernike coefficients of TAS2 need to be subtracted from those measured on the main telescope.

8.2. Correcting coma

The most apparent aberration after the geometrical alignment is coma and defocus. The presence of these aberrations indicates that the foci of M1 and M2 are not coincident. Pure axial displacement would manifest as focus error, and pure lateral displacement would show up as coma. These are the easiest aberrations to correct.

8.2.1. Install TAS2. The BARE AO splitter should be in the beam.

8.2.2. Acquire a bright star, and center it on the Finder origin.

8.2.3. Tilt TAS2 to center the star in the field. (TAS has a projected cross-hair for reference, TAS2 has not at this point.)

Depending on the amount of coma present in the star's image, the telescope may or may not need focusing just yet. Sometimes it is easier to see what to do when the image is out of focus. When coma is present, the image is not symmetric, the shadow of the secondary is off-center in an out-of-focus image.

8.2.4. Move the image in the direction where the annulus of the defocused image is the widest. If the secondary shadow is on the right in the image, move the image to the left by tilting M2.

8.2.5. Bring the star back to the center of the field in TAS2 by moving the main telescope. (The Finder origin you set before is no longer the pointing reference.)

Repeat steps 8.2.4 and 5 until the image looks symmetric. Watch the speckles also, and take your time when you are close.

Good seeing helps a lot. Focus or defocus the telescope as needed and use high magnification (5 mm eyepiece) when you are close.

8.2.6. Finally, use the wavefront sensor to evaluate how coma changes when making the small adjustments. This way coma can be completely (<0.1 waves) eliminated

8.2.7. Adjust the Finder origin to the star and save the new coordinates.

8.3. Correcting astigmatism

There can be more than one reason for astigmatism. It can be due to misalignment even with perfect optics or stressed/distorted optics even when the alignment is perfect.

It follows from simple geometry that if the foci of M1 and M2 in a Mersenne telescope are coincident, and the axis of M1 points to the star, the output beam is along the axis of M2, and the wavefront is flat. Astigmatism in Mersenne telescope with perfect optics arises because the second condition is not met, i.e., the axis of M1 is not pointing to the star.

If the mirrors themselves are not rotationally symmetric due to mechanical issues, the result is again astigmatism. Fixing the mirror support will mitigate this problem, but it is difficult to completely eliminate it.

The solution is the intentional misalignment of the telescope to eliminate astigmatism inherent in the optics or due to mechanical problems.

The following simple-looking algorithm eliminates astigmatism regardless of its origin.

After coma has already been eliminated, tilt M1 by a small amount and tilt M2 to bring the image back to the center in TAS. Since the telescope's magnification is 8x, M2 needs a tilt of 8x larger than that of M1 to achieve that. It is important to track the star by the Finder during these adjustments.

I recommend using the Fsurfer/loop command to collect several hundred wavefront measurements after each tilt and calculate $TA = \sqrt{a_5^2 + a_6^2}$ for total astigmatism and $TC = \sqrt{a_7^2 + a_8^2}$ for coma, where a_i is the coefficient of the Zernike polynomial Z_i.

The goal is to point the axis of M1 in the direction which minimizes astigmatism while keeping the foci of M1 and M2 coincident to minimize coma. If you do this precisely and the tracking is good astigmatism will change, but coma remains negligible. It will take some trial and error.

There are a couple of issues that make this procedure not nearly as easy as it sounds. First, it is a slow and tedious process, especially during the winter shutdown when it is cold, and the seeing is often bad. Bad seeing slows things down because one needs to collect more wavefront measurements to evaluate *TA* and *TC*.

The beam rotates in an ALT-AZ telescope as the telescope is tracking, so the tilt direction that was good 15 min ago may not be good now.

The telescope is flexing as the elevation changes, and therefore, the alignment is changing as well. This is perhaps the most serious problem. Misalignment due to flexing may result in more astigmatism than tilting M1, and one can get lost.

Tilting M1 is not necessarily repeatable. Going forward with one adjustment and then coming back may result in somewhat different astigmatism. This is especially troublesome when making minor adjustments.

The errors accumulate with every step, so sooner or later, the coma will not be negligible. The above algorithm requires negligible coma, so you have to go back and get rid of it. Did we say it is a slow and tedious process?

8.3. Focusing the Telescope

When tweaking the M1 and M2 makes no further improvements, the final step to focus the telescope. If the WFS was put in the pupil plane during calibration, translate M2 until the focus term averages to zero.

One can double-check image quality and focus by eye if the star was focused with a high powered eyepiece during calibration. The star also has to be in focus through the main telescope. Defocus M2 by 10-20 μm on either side of the focus and watch how the image changes.

8.4. Thoughts on Automation

In our experience, under the given circumstances, it was virtually impossible to eliminate astigmatism completely.

The tweaking could be done automatically, and that was our goal, but we couldn't achieve it. M2 already has motors for tilting, and some M1 also have them. The actuators for the others are in hand but not installed.

Tilting and translating M2 by a hexapod would be a better approach, and perhaps it will happen one day.

9. FINISHING STEPS

Remove TAS2.

Make a routine alignment with the alignment laser, and a coude alignment.

Ideally, the alignment laser should be centered on the M2 target. 1-2 mm error is acceptable. Telescope flexure causes at least that much error while tracking a star.

APPENDIX

THE TELESCOPE AXIS

Overview

The optical axis of the telescope has to coincide with the axis of M1. Additionally, the optical axis has to intersect the elevation axis. The angle subtended by these two axes is not critical, but it is convenient to set it to 90^{o}.

Since M1 is laterally constrained in the mirror-cell, the position of its vertex is fixed in the telescope frame. We assume that the vertices of M1 and M2 are centered in their central hole. According to the manufacturer, this is correct to a few millimeters for M1 and a few tenths of a millimeter for M2. We have installed a crosshair in the central post of M1 as close as possible to the mirror surface to represent the vertex of M1.

Thus, to correctly position M2, we need a line of sight that goes through the vertex of M1 and intersects the elevation axis perpendicularly.

Lateral positioning of the M2 mount can be done by adjusting the length of the spider arms. Finer adjustments are possible by adjusting the setscrews at each roller supporting the M2 post. However, neither of these adjustments are practical when we are in the phase of optimizing the image quality of the telescope. At that stage, the position of M2 in relation to the optical axis may be changed by slightly tilting M1.

Procedure

1. Ensure that AT1 is looking along the elevation axis; in other words, AT1 and M4 are aligned as described in Section 4.

2. Install the pentaprism (PP) at the top of the central post using its custom mount, Fig. 9. This step requires removing the M3 mount completely. (As of May 2021, the PP mount is stored in the East storage area.)

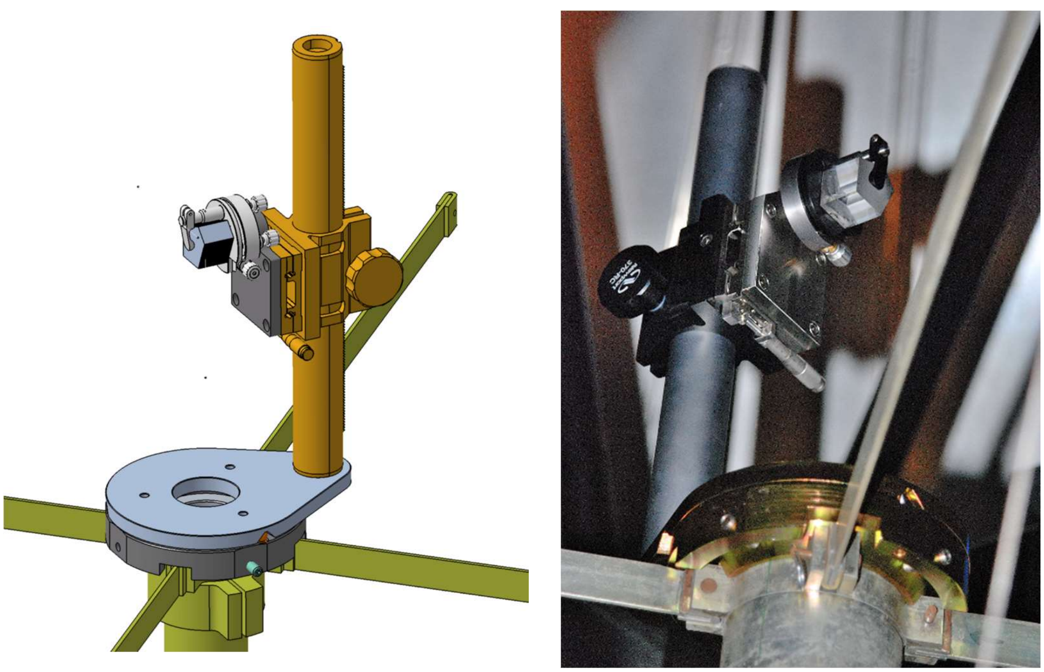


Figure 9. The pentaprism mount

3. Center the front face of the PP on the elevation axis. (Centering of PP is not critical as long as one can look through the prism and see the M1 crosshair.)

4. Center the M1 crosshair in AT1 by either translating the prism along and turning it around the elevation axis or turning it around the elevation axis and another axis perpendicular to the plane defined by the

elevation axis and the optical axis of the telescope. The line of sight in AT1 is turned 90° by the pentaprism. So, when the M1 crosshair is centered in AT1, the line of sight through the pentaprism follows an axis that intersects the elevation axis perpendicularly and goes through the vertex of M1. Therefore, AT1's line of sight through the pentaprism defines the optical axis of the telescope. M2 will be centered on this axis.

5. To center M2 on the telescope's optical axis, one could turn the PP by 180° to see M2, but that would not be easy to do accurately. Instead, mount the second Brunson alignment telescope (AT2) with the inline eyepiece and the relay mirror under M1 to look toward the PP through the central hole in the M1 mirror cell, as shown in Figure 10.

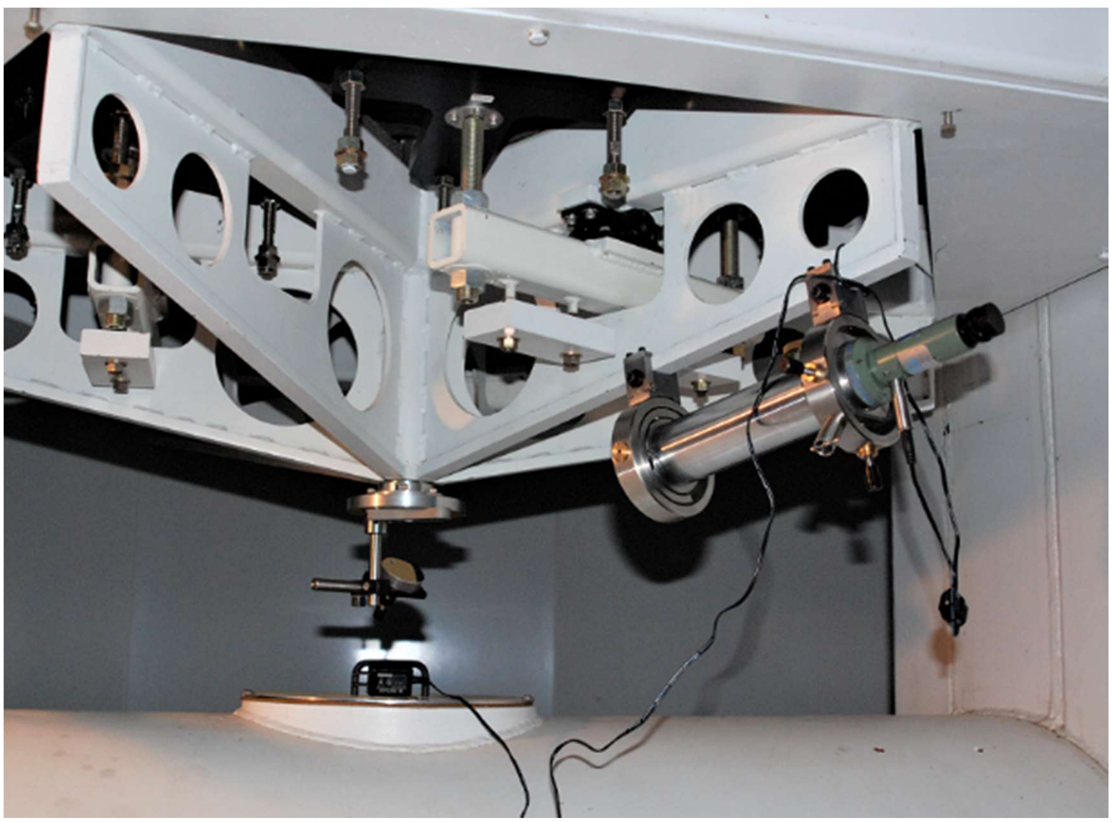


Figure 10. The setup for centering M2 mount on the telescope axis. The relay mirror is hanging from a base that extends to grab the inside of the middle tube. The custom clamps on the Brunson alignment scope were designed to grab the M1 mount.

6. Iterate between tilting the relay mirror and AT2 until both the auto-reflection target (or auto-collimation target) of AT1 and the crosshairs of M1 are centered in AT2. When this is done, the optical axis

of AT2 coincides with the reflected optical axis of AT1; that is, the optical axis of the telescope is now defined by the line of sight of AT2.

7. Remove the PP mount and center M2 mount on the AT2 line of sight. Lateral positioning of M2 can be done by adjusting the length of the spider arms, best done by three persons: one looking through AT2 and two working on the opposite sides of the telescope frame. Finer but very limited adjustments are possible by adjusting the setscrews at each rollers supporting the M2 post.