Optical field/pupil rotator with a novel compact K-mirror for MagAO-X

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ABSTRACT

The Magellan Extreme Adaptive Optics (MagAO-X) is a visible-wavelength adaptive optics (AO) instrument optimized for visible light coronagraphy and exoplanet imaging with the 6.5-m Magellan Clay telescope in Chile. Extremely large telescopes such as the future Giant Magellan Telescope (GMT) will be able to image earth-like exoplanets, given an extreme AO system—such as MagAO-X—exists. MagAO-X is now under development in the lab and undergoing final integration and testing. Technical first light is planned for early 2019, with final commissioning in late 2020. A crucial component to MagAO-X is the "K-mirror," a 3-mirror system designed to rotate the optical field with minimal image wobble or distortion about the optical axis. The K-mirror rotates on a miniature motorized stage to stabilize the pupil in the coronagraph as the telescope tracks the sky. The optical design of MagAO-X required a very compact K-mirror, resulting in a challenging opto-mechanical mount design. We present a novel solution to the compact design of a 50mm max envelope K-mirror for MagAO-X that consists of three < 1-in diameter flat mirrors, all precision glued in place. The K-mirror mount was designed in Autodesk® Fusion 360™ and a prototype was built in the Steward Observatory machine shop. Using inexpensive COTS mirrors, the K-mirror prototype was tested, aligned, and glued with optical feedback in the lab. Once the prototype had proven successful, a final K-mirror mount was fabricated and assembled with invar and precision (0.1nm rms surface roughness, super polished, $\lambda/40$ PV flat) mirrors to develop a compact K-mirror for MagAO-X. The performance of the final hardware is presented here.

Keywords: K-mirror, pupil rotator, extreme, adaptive optics, AO, exoplanets

1. INTRODUCTION

The 6.5-m Magellan Clay telescope is an alt-azimuth design with f/11 Gregorian foci at its Nasmyth locations[1]. There are two forms of image rotating due to the Magellan Clay design. Pupil rotating is the result of the alt-azimuth design, while image rotating is caused by the tertiary mirror folding the light path. Pupil rotating is usually eliminated when the instrument is mounted to the Clay Nasmyth port—which rotates with elevation (as used with MagAO)—however, MagAO-X is assembled on an optical bench that will sit in front of the Nasmyth port (see Figure 1), and will not be able to rotate. This will cause a clocking misalignment between the telescope pupil and the MagAO-X coronagraph mask, wavefront sensor and deformable mirrors (see Males et al. in these proceedings)[2] as the telescope tracks the sky (see Figure 2). Therefore, a K-mirror was introduced to the MagAO-X design to counter this rotating and keep elements aligned with the image of the pupil. Initially, the K-mirror was to be placed within a 120mm inter-OAP cavity in the MagAO-X design, but led to variable field curvature errors between the OAPs, so the K-mirror position was moved to a 60mm cavity over the Gregorian focus (see Figure 3). This resulted in the need for a very compact K-mirror design under 60mm in size (due to the fixed 125mm back focal distance. Although K-mirrors are quite common in astronomical instrumentation (see [3], [4], and [5] for examples), the MagAO-X K-mirror is unique in the fact that it is

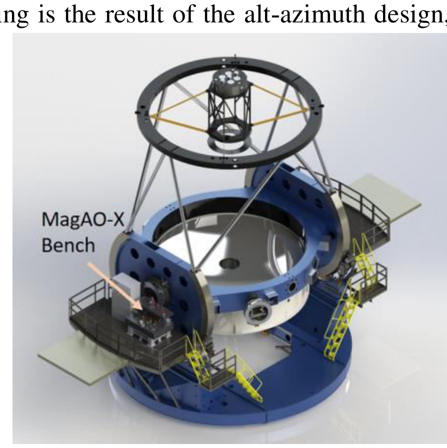

Figure 1 – As the Magellan Clay telescope tracks the sky, the field will rotate, causing image rotating at the Nasmyth port.

the smallest K-mirror ever built. The MagAO-X K-mirror designing process will be discussed here, along with its final performance.

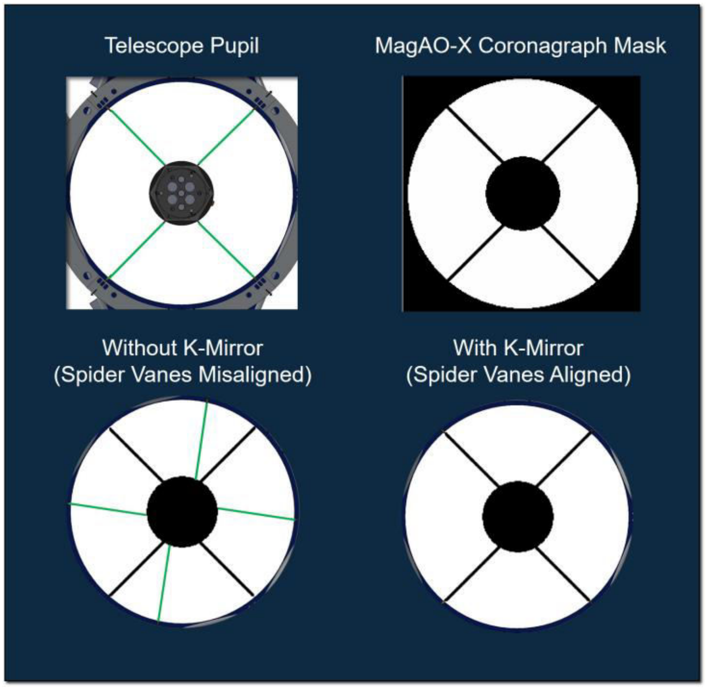

Figure 2 – The Magellan Clay optical design produces a pupil that is asymmetric (top-left) and requires a vector Apodizing Phase Plate (vAPP)[6] coronagraphic mask (top-right). As the telescope rotates, the coronagraphic pupil mask is misaligned in clocking with the pupil (bottom-left). A K-mirror is therefore needed to de-rotate the pupil as the telescope tracks the sky and keep the mask aligned (bottom-right) with the pupil.

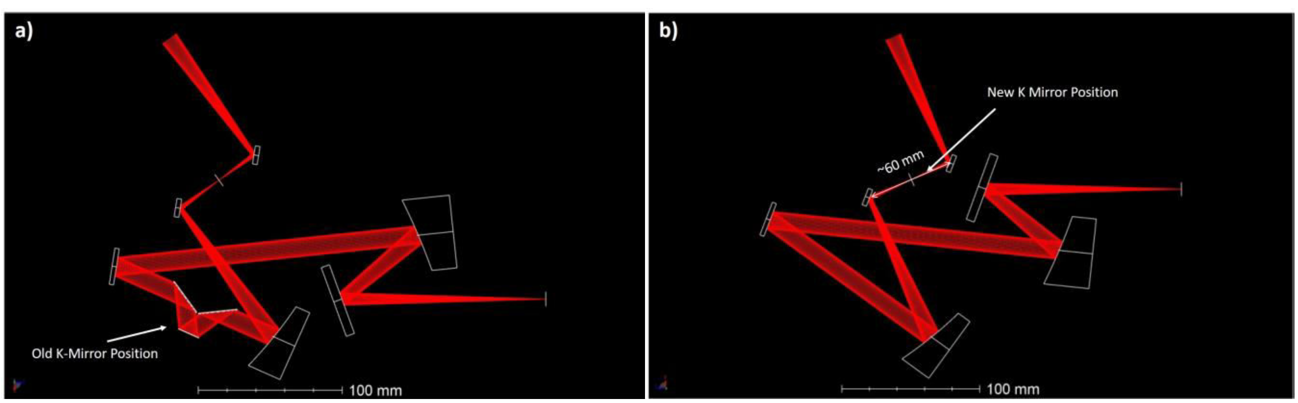

Figure 3 – **a)** The initial K-Mirror position between OAPs, which created variable field curvature errors. **b)** New K-mirror position with correct clocking of OAPs with minimum field curvature errors. The new K-mirror position is a tight 60mm cavity where the Gregorian focus of the Magellan Clay is located. This results in the need for a compact K-Mirror design.

2. DESIGNING THE K-MIRROR

The goal was to create an image rotator with minimal wobble or distortion. This means that the incoming light should be coaxial with the outgoing light (along the optical axis). Three mirrors must be used, with two being 120° apart to create the correct light path (see Figure 4).

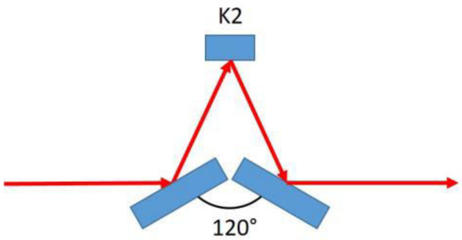

Figure 4 – A K-Mirror consists of 3 mirrors, 2 of which are tilted by 30° with respect to the optical axis. The input light is coaxial with the output light

2.1 Initial Design

MagAO-X was first designed in Zemax and then opto-mechanically designed in SolidWorks (see Close et al. in these proceedings)[7]. The Zemax design was imported into Autodesk® Fusion 360™ to design the K-mirror. Fusion 360™ had errors loading the light path from the MagAO-X design, so FreeCAD and SolidWorks were used in certain cases to visualize the light footprints on the K-mirror. For example, a FreeCAD screenshot of the K-mirror section in the MagAO-X design is shown in Figure 5, where the K-mirror footprints are thin disks. K1 and K3 are 1-in in diameter while K2 is 0.5-in in diameter. These are the default K-mirror diameters set by Zemax in the MagAO-X design. In the Zemax design, a FOV of 14 arcseconds was used, creating the 1-in diameter necessary for K1. However, the maximum FOV that MagAO-X can observe due to its camera is approximately 6x6 arcseconds, indicating that smaller diameter mirrors may be used for the K-mirror. This information became useful when it was apparent that the initial Zemax parameters would cause a collision between K1 and the surrounding optics as the K-mirror rotated. Due to this problem, a diameter of 19mm was chosen for K1 (and K3) in the final design.

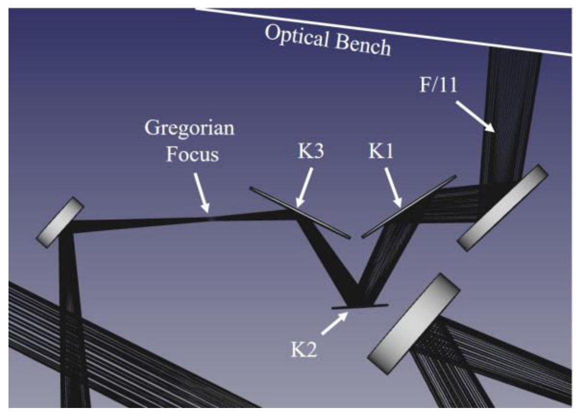

Figure 5 – FreeCAD screenshot of the MagAO-X design. The three thin disks are the default K-mirror footprints.

2.2 The K-mirror Housing

The main component to the K-mirror is the housing that holds the mirrors. The challenge in designing the housing was to avoid contact with the surrounding optics, the light path, and the edge of the optical bench—as seen in Figure 5 and Figure 6. The main idea was to place K1 and K3 inside a tube and mount it to a compact rotating stage. Then, mount K2 onto an arm that extends out from the tube.

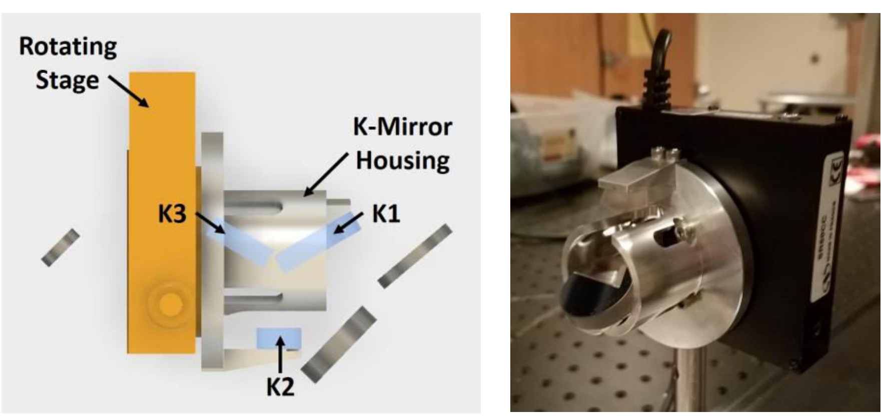

Figure 6 – Fusion 360™ screenshot of the first K-mirror design (left). A 1-in mirror was first used for K1, while K3 is 19mm and K2 is 0.5-in. The K-mirror prototype mounted on the rotating stage (right).

A Newport® SR50CC rotating stage was chosen for the K-mirror, while the housing was designed to mount onto the stage. A cylindrical wedge was designed to hold K1 and K3 at 120° and mount to the housing. The base of the housing is a disk that extends out to the K2 wedge, which bolts onto the edge of the base. Since the surrounding mirrors made it difficult to fit the K-mirror inside this cavity, it was impossible to use the usual kinematic mounts or actuators that one might use for aligning the K-mirror. For this reason, glue was the only solution to mounting these mirrors.

2.3 The Gluing Process

To glue the mirrors, glue channels were machined into the wedges to allow excess glue to run free (see Figure 7). The K-mirror wedges were machined out of invar to reduce CTE mismatch problems between the fused silica and the wedge. Each have three equilateral hard points to which the mirrors adhere to. The glue chosen for this application was Loctite® AA 312, a clear adhesive liquid for bonding metals with glass. A spray primer, Loctite® SF 736, is accompanied with the adhesive. The primer is first applied to the surface, then the adhesive is applied using a dropper. This structural adhesive dries within seconds, so the mirror must be precisely aligned on the surface fairly quickly.

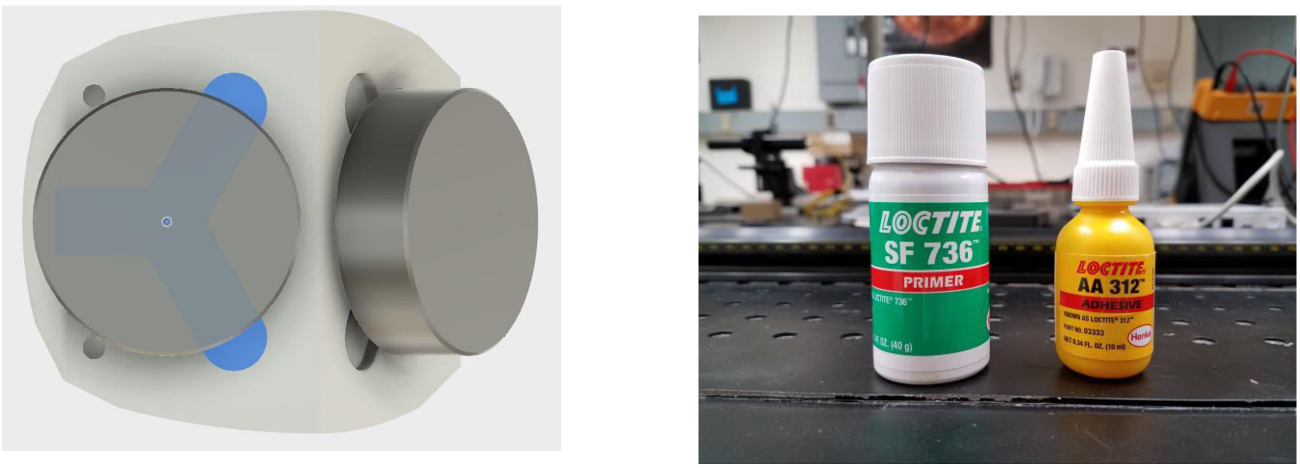

Figure 7 – An outline of the K1 glue channel is shown here behind K3 on the cylindrical wedge (left). The mirrors sit on three hard points and pins help exactly align the mirrors as the glue dries. A primer (right) was applied to the surface of the wedge and three drops of the adhesive (right) were placed on the three hard points. The mirrors were then pressed onto the glue until dry (~30 seconds).

We note that before gluing, the K mirrors were measured on a ZYGO to be λ/80 PV over their inner 80%. After gluing the mirrors, K3 was measured to be λ/100 in the inner 30% (illuminated area) of the K3 mirror, although there was some ~λ/8 trefoil at the edges (see Figure 8).

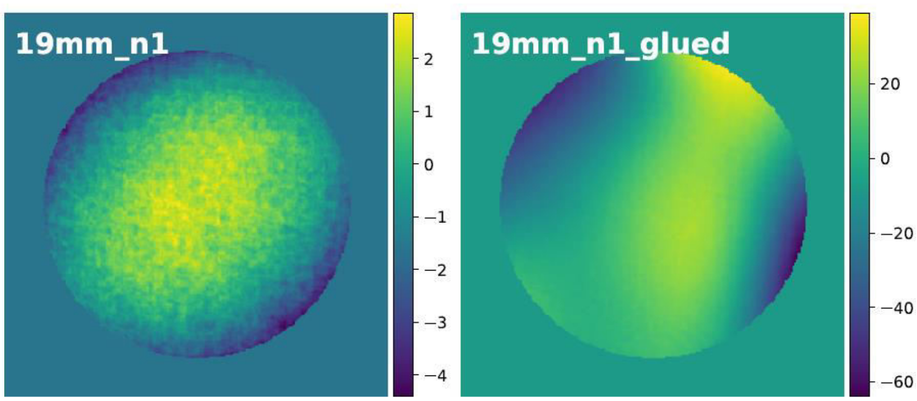

Figure 8 – K3 before (left) and after (right) gluing. The initial measurement from the ZYGO was λ/80 PV over the inner 80% of the surface, while after gluing, the measurement was ~ λ/8 over 80% of the surface. However, the inner 30% (the illuminated area) is ~ λ/100 PV. K1 and K2 have not been measured after gluing yet, but plans are to do so.

2.4 The Prototype and Final Product

A prototype was machined at the Steward Observatory machine shop out of aluminum and cheap Thorlabs mirrors ($\lambda/10$ PV) were glued to the wedges (see Figure 6 for an image of the prototype). The prototype mirror diameters are 1-in diameter for K1, 0.5-in for K2, and 19mm for K3. Since the light footprint on K1 is largest, it would make sense to have a larger diameter for K1, but once it was realized that K1 would collide with the surrounding MagAO-X optics as the K-mirror rotates, its diameter was changed to 19mm for the final product. The wedges that the mirrors glued to were also trimmed to give more room for rotating.

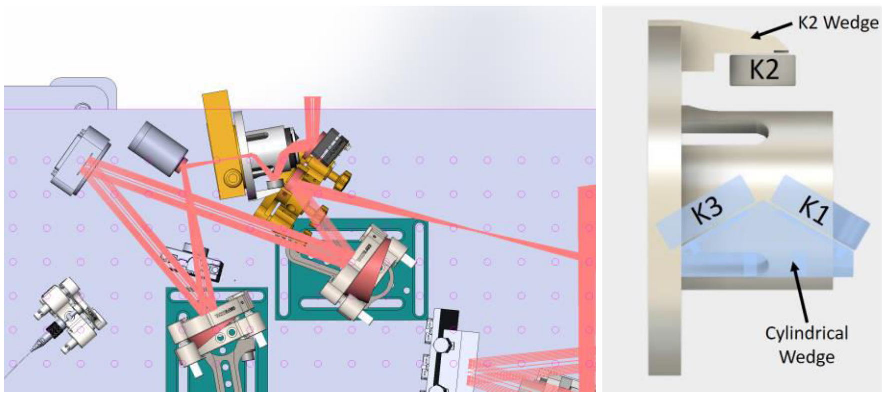

Figure 9 – The K-mirror was input into the MagAO-X SolidWorks model to visualize the surrounding environment (left). There are 2 mirrors on the right side of the K-mirror, while the light path is on the left of—or behind—the K-mirror, showing that this is an extremely tight space for the K-mirror. To give a little more room, the wedges were trimmed and the diameter of K1 was changed to 19mm for the final product. The K-Mirror model after modification (right). This model was used for the final K-mirror product.

3. ALIGNMENT

The alignment of a glued K-mirror is not trivial. A K-mirror system requires the output beam to be aligned precisely with the optical axis while rotating 360°. MagAO-X requires its K-mirror to be aligned within 5 arcminutes[7].

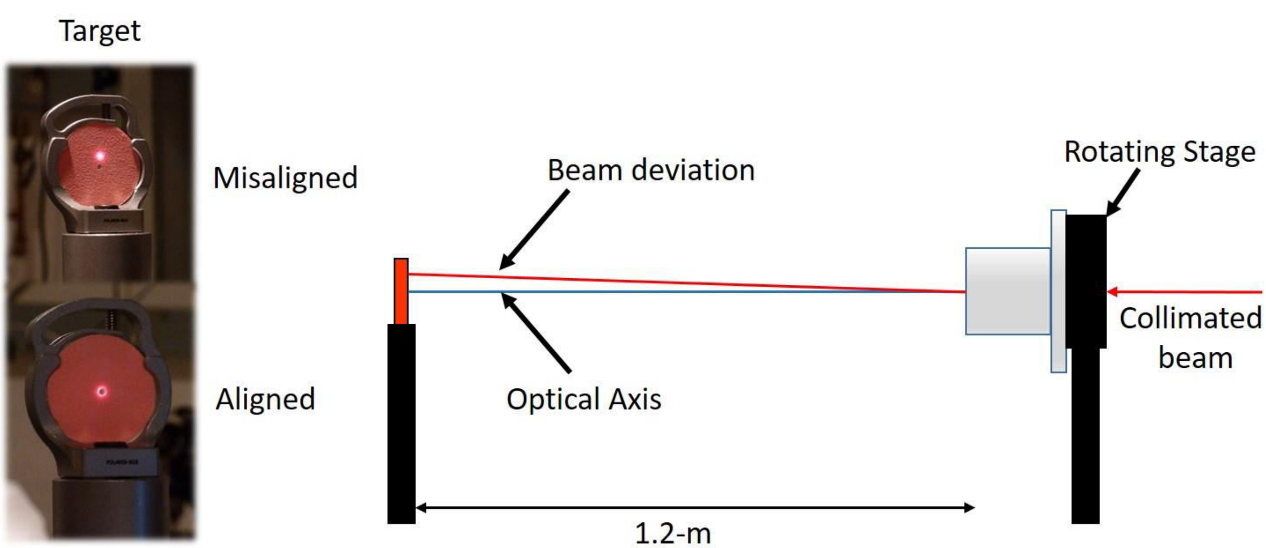

Figure 10 - A collimated 1mm beam was set up in the lab with the K-Mirror prototype and a target mounted on a 2-meter optical rail. Using the SR50CC rotating stage, the K-Mirror was rotated and the beam offset was measured on the target. Then, K2 was adjusted to align the K-Mirror.

3.1 K2 Adjustment

Typically K-mirror systems have actuators and/or kinematic mounts attached to the mirrors to make the alignment process easier, but for MagAO-X, glue was the only option to mounting them. This created a difficult alignment solution. The solution we developed introduces a few degrees of freedom to one of the K mirrors. We gave K2 the ability to shift in piston by use of a “sacrificial washer”—an aluminum spacer between the K-mirror housing and the K2 wedge. By changing the thickness of the spacer, K2’s height could be changed. The default spacer thickness in the model was 0.25-in, but changed to 0.36-in (a number found by trial and error) to align the K-mirror.

The ability to tilt K2 was also made possible by shimming underneath the K2 wedge, as shown in Figure 11. However, it was discovered that no shimming was required for K2 during the alignment process, and that the major misalignment error was due to the rotating stage’s tilt (see section 3.2). Furthermore, since the K2 wedge is bolted to the

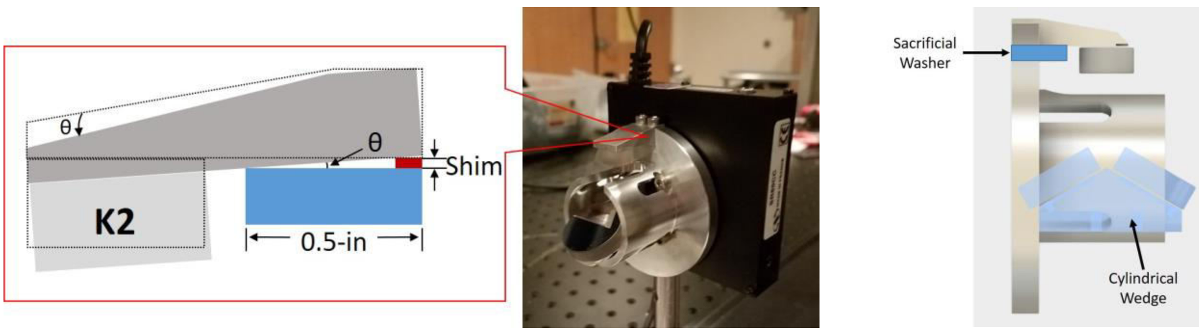

Figure 11 – The K2 mirror may be tilted by use of shim stock (left). Placing shim stock underneath the K2 wedge allows the mirror to be tilted as needed. The K2 mirror may be shifted in piston by changing the thickness of the “sacrificial washer”—an aluminum spacer (right).

K-mirror housing with M3 screws, we know that the tightness of the bolts may introduce a tilt on K2 somewhere between ± 4 arcminutes—a number that corresponds to applying a 0.0005-in shim underneath the K2 wedge. So although shim stock was not applied, there may be some K2 tilt introduced due to the tightening of the M3 screws, even though it is very minor. In summary, the ability to piston and tilt K2 are degrees of freedom that help counter any errors in the K-mirror caused by the machining and gluing process.

3.2 Stage Alignment

An additional parameter for aligning the K-mirror was introduced by adjusting the pitch of the rotating stage itself. Since the MagAO-X optical elements are mounted 5-in above the optical bench, the K-mirror rotating stage was mounted on a Thorlabs adjustable optical post to adjust the K-mirror height to 5-in. This post caused a misalignment in the pitch of the stage, so it needed to be corrected. This was achieved by placing a long lens tube inside the K-mirror housing with 2 glass diffusers (see Figure 12). Using the same 1mm collimated beam in the initial setup, the height and tilt of the stage was measured with the glass diffusers, and shim stock was used to correct the offset.

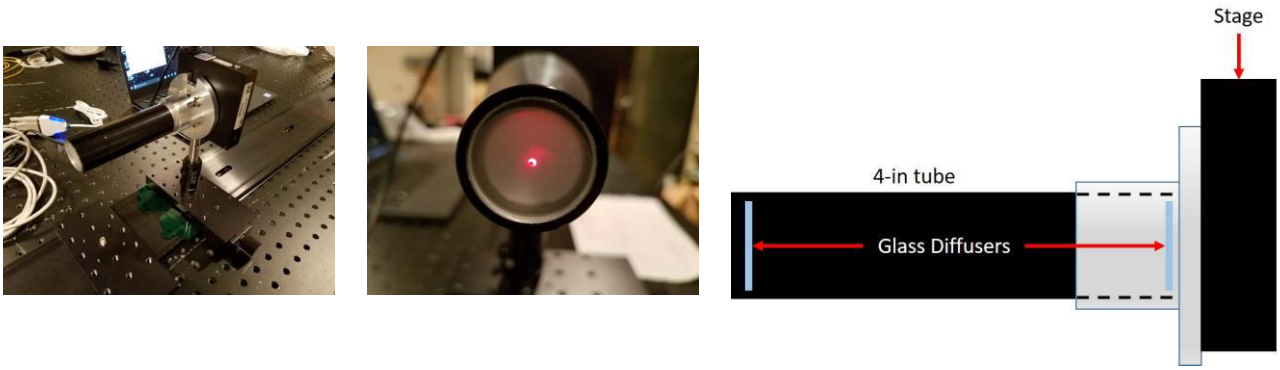

Figure 12 – To eliminate pitch or yaw misalignment in the stage, the mirrors were removed and a 4-in tube with 2 glass diffusers was inserted into the K-mirror housing (right). One glass diffuser (closest to the stage) was used to adjust the height of the K-mirror, while the other was used to measure the pitch of the stage. By seeing where the collimated beam hits the glass diffusers, the stage height and tilt was aligned (middle). Shim stock was used (left) to correct for the pitch misalignment and improve the K-mirror alignment.

To avoid the unsteady Thorlabs adjustable posts, MagAO-X uses 1-in diameter custom stainless steel Polaris® posts for all of its optical elements (see Close et al. in these proceedings)[7]. This method was also planned for the K-mirror, but a custom adapter was needed to mount the 1-in post to the rotating stage. This custom mount was designed in Autodesk® Fusion 360™ and machined in the Steward Observatory Machine Shop out of stainless steel. Images of the custom mount are shown in Figure 13. The custom mount helps stabilize the rotating stage's height, pitch, and yaw alignment due to its rigid structure.

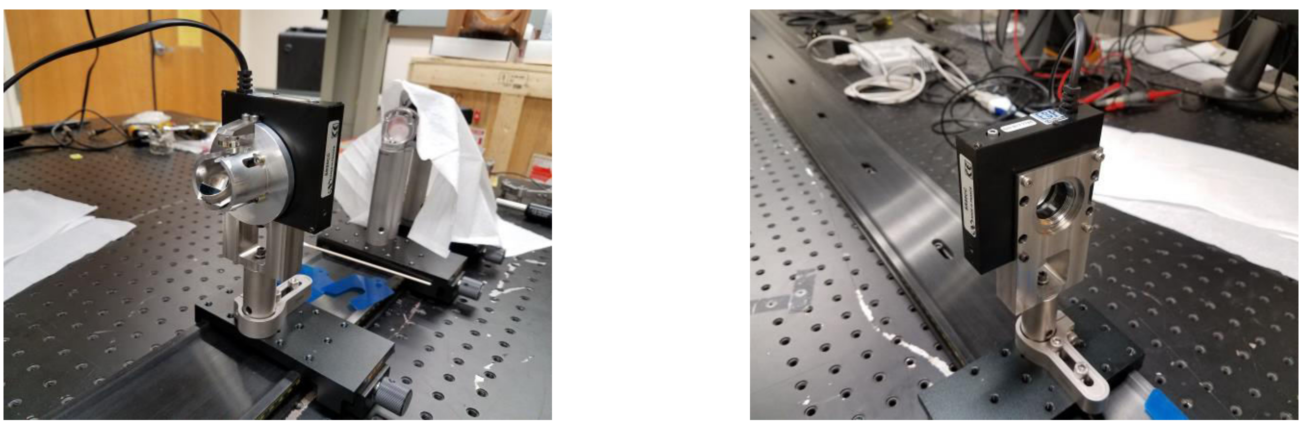

Figure 13 – A custom stainless steel adapter was designed to mount a Polaris® 1-in diameter post to the Newport® SR50CC rotating stage. The custom mount is needed to properly bolt the rotating stage to the post and provide a more rigid structure for holding the stage.

3.3 Results

The K-mirror is now aligned within ± 1 arcminute of wobble over 360° of rotating. The progression of the K-mirror alignment is shown below in Figure 14. Each video shows the beam deviation from the K-mirror on a target 1.2 meters away as the K-mirror rotates 360° (see Figure 10 for a 2D diagram of the setup).

Figure 14 – Video 1 shows the first observation of the K-mirror alignment over one 360° rotation. The beam deviation was ± 29 arcminutes. Video 2 shows an improved alignment of the K-mirror where the beam deviation was ± 7 arcminutes. The beam also starts to rotate twice around the target, an expected result when rotating a mirror. Video 3 shows the final K-mirror alignment with ± 1 arcminute of wobble.

3.4 Steering Mirror

It is worth mentioning that the K-mirror's alignment will be aided by a pupil steering mirror—the next element in the optical path after the K-mirror (see Figure 9 and Close et al. in these proceedings)[7]. Initially, a PI 331 fast tip/tilt platform was to be used for the pupil steering mirror—as seen in Figure 9—but instead it was decided to use a Polaris® kinematic mirror mount with piezoelectric adjusters (see Figure 15). The closed loop piezoelectric angular range of the pupil steering mirror is 3.4 arcminutes (optical). This is more than we need for MagAO-X since the entire 360° range of the K-mirror only has ± 1 arcminute of wobble (we only need ~30° of K-mirror rotating for MagAO-X, which is much less than ± 1 arcminute of wobble), well within the 3.4 arcminute range of the pupil steering mirror.

Figure 15 – 0.5-in Polaris® kinematic mirror mount with piezoelectric adjusters. This will be used to stabilize the MagAO-X pupil at the micro level from effects due to wind jitter, vibrations, and K-mirror wobble.

4. CONCLUSION

The MagAO-X K-mirror has been successfully designed and is now aligned in the lab with < 1 arcminute of wobble over 360°of rotating (well within the internal 6 arcminute pupil alignment system of MagAO-X; see Close et al. in these proceedings)[7]. Due to the complexity of the MagAO-X design, the K-mirror needed to be as small as possible, which resulted in the creation of the smallest K-mirror ever built—with a total size of 2.2-in including the Newport® SR50CC rotating stage. The K-mirror also has no actuators, meaning the structure is more rigid. A solution to align the K-mirror was developed and tested in the lab to prove that the MagAO-X K-mirror works. Future work for this project will include simulating the Magellan Clay telescope on the MagAO-X bench and integrating the K-mirror into the full optical system. Final K-mirror alignment procedures will take place on the MagAO-X bench in the next few months.

ACKNOWLEDGMENTS

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