2.3 Pyramid Wavefront Sensor

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1. Introduction

MagAO-X will utilize a 2040 actuator deformable mirror (DM) in conjunction with a cutting-edge coronagraph for starlight suppression. A pyramid wavefront sensor (PWFS) will provide high order wavefront sensing. In this paper we present the design of the MagAO-X pyramid wavefront sensor, an alignment guide, and the laboratory performance.

2. System Design

The PWFS of the MagAO-X system consists of an achromatic pyramid, a camera lens, and an OCAM^{2}K EMCCD detector. The MagAO-X pyramid wavefront sensor is designed to operate from 600-1000 *nm* bandwidth and a field of view of two arcseconds. Figure 1 is the bandpass of the MagAO PWFS. We have designed for the same transmission for the MagAO-X PWFS.

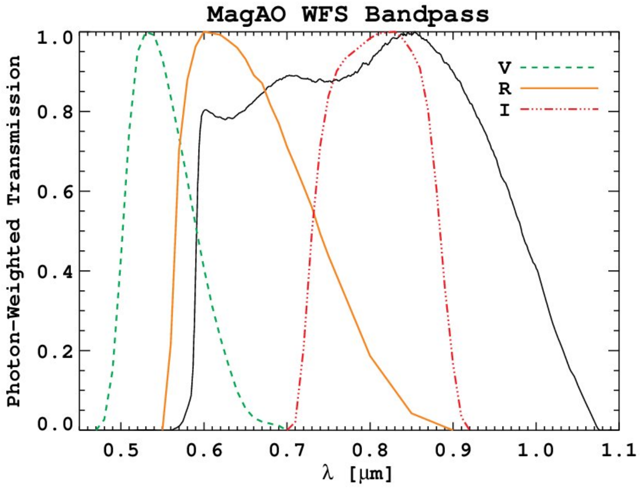
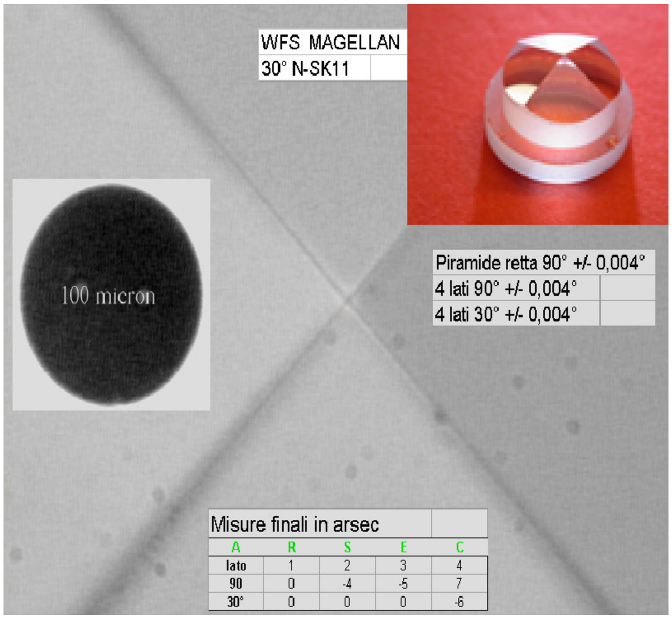


Fig. 1.—: The MagAO pyramid wavefront sensor bandpass, (black curve).(2)

A new camera lens is designed to meet the requirements of the MagAO-X system. These requirements are listed in Table 1. The OCAM^{2}K will be used in 2x2 binning mode, giving us a 48 μm pixel size. This allows the wavefront sensor to be run at 3.6 kHz. We have chosen a pupil size of 56 pixels across each of the pupils, which is slightly over sampled to prevent aliasing of the higher order modes. The pupil separation of 60 pixels was chosen to maximize the OCAM^{2}K detector space.

2.1. Pyramid Design

MagAO-X will uses an excellent achromatic pyramid with a 5 μm tip. The pyramid used in the WFS is a double pyramid, consisting of two four sided prisms aligned back to back. Details of the design done by Tozzi et. al. are summarized here.(7) A picture of the pyramid is shown in Figure 2. The total deviation angle needed for the pyramid wavefront sensor is hard to manufacture. Combining two pyramids makes the polishing process easier and at the same time allows us to control chromatic aberrations by using two different glass types. The glass types were chosen using an I.D.L. optimization routine that selected glass combinations from the Shott and Ohara catalog that would give a suitable deflection angle of the double pyramid. The front prism is made from Shott N-SK11, and the back prism is made from Schott N-PSK53.



Misure finali in arsec

A	R	S	E	C
lato	1	2	3	4
90	0	-4	-5	7
30°	0	0	0	-6

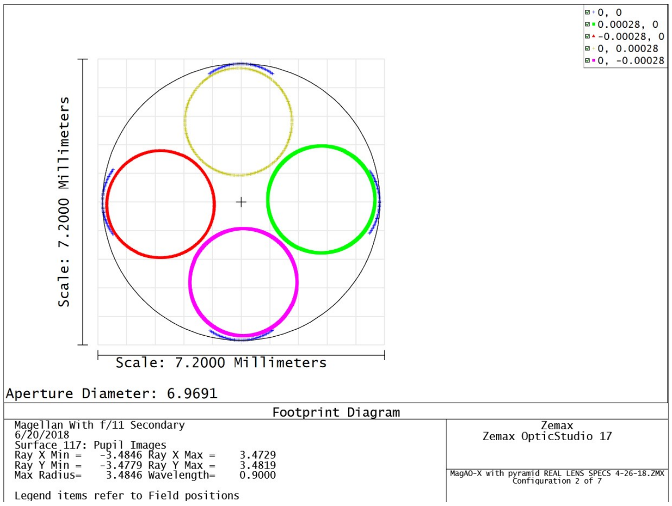
Fig. 2.—: Fabricated pyramid made in Arcetri, Italy by Paolo Stefanini.

Parameter	Requirement
Wavelength Range	600- 1000 nm
Pupil Size	56 pixels; 2.688 mm
Pupil Separation	60 pixels; 2.880 mm
Pupil Tolerances	Δ < 1/10th pixel; 2.4 μm
Lens Diameter	10 mm < D < 20 mm

Table 1:: Parameters for the MagAO-X pyramid wavefront sensor.

2.2. Wavefront Sensor Design

A design of the wavefront sensor was done in Zemax. An F/69 focus created by an off-axis parabolic mirror is imaged onto the pyramid tip. A custom achromatic triplet then images four pupils onto our OCAM^{2}K wavefront sensor camera. A layout of the wavefront sensor optical path done in both Zemax and SolidWorks is shown in Figure 4. We reuse the same off axis parabolic mirror seen by the coronagraph arm of MagAO-X. The double pyramid was modeled by the Arcetri team in Zemax, and that same model is used here. A custom achromatic triplet was designed to give the correct pupil size and separation. The two windows in the OCAM^{2}K detector are included in the design for completeness. The expected pupil footprint on the image plane for 800 *nm* wavelength is given in Figure 3.



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Magellan With f/11 Secondary
6/20/2018
Surface 117: Pupil Images
Ray X Min =   -3.4846 Ray X Max =    3.4729
Ray Y Min =   -3.4779 Ray Y Max =    3.4819
Max Radius=    3.4846 Wavelength=    0.9000

Legend items refer to Field positions
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Fig. 3.—: Beam footprint at the image plane.

2.3. Achromatic Triplet Design

The size and separation of the pupils on the detector directly affects the performance of the PWFS. If the pupils are undersized, there will be aliasing in reconstruction of the higher order modes. If the separation between pupils is not correct, complications will arise when pixels are binned on the detector to change the pupil sampling and the integration time. To ensure the correct size and separations a custom achromatic triplet was designed in Zemax. A schematic of the lens is shown in Figure 5.

3. Initial Results

The camera triplet was manufactured by Rainbow optics and the as-built specifications of the lens was incorporated into the Zemax design. Table 2 shows the system requirements of the MagAO-X system,

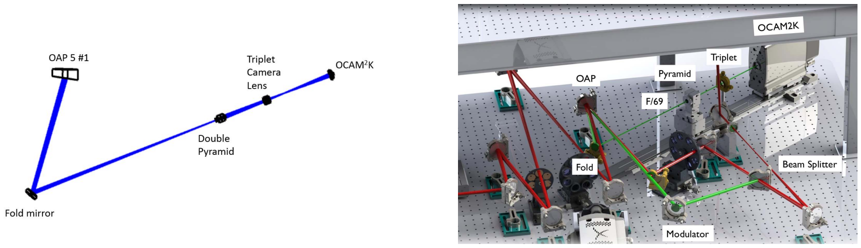
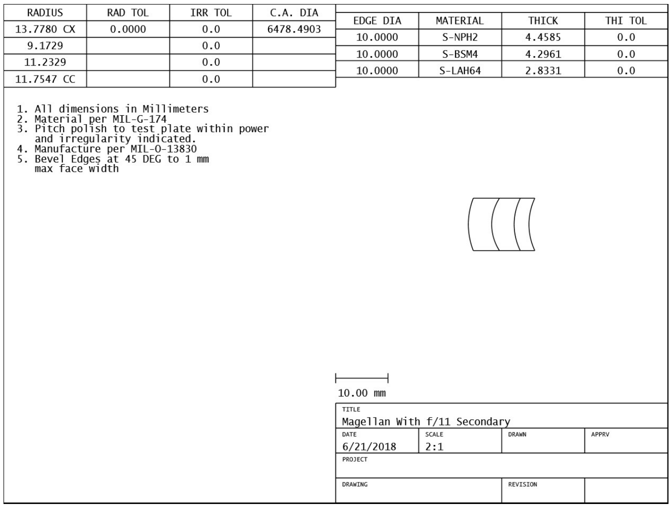


Fig. 4.—: Optical path of the pyramid wavefront sensor. The Zemax ray trace was imported into SolidWorks for the optomechanical design. The red-light path is the science path that goes to the coronagraph. The green light path goes to the pyramid wavefront sensor.



RADIUS	RAD TOL	IRR TOL	C.A. DIA
13.7780 CX	0.0000	0.0	6478.4903
9.1729		0.0	
11.2329		0.0	
11.7547 CC		0.0	

EDGE DIA	MATERIAL	THICK	THI TOL
10.0000	S-NPH2	4.4585	0.0
10.0000	S-BSM4	4.2961	0.0
10.0000	S-LAH64	2.8331	0.0

1. All dimensions in Millimeters
2. Material per MIL-G-174
3. Pitch polish to test plate within power
   and irregularity indicated.
4. Manufacture per MIL-O-13830
5. Bevel Edges at 45 DEG to 1 mm
   max face width

10.00 mm

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Magellan With f/11 Secondary
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Fig. 5.—: Achromatic triplet.

and the expected performance with our fabricated lens.

Parameter	Requirement	As Built
Wavelength Range	600- 1000 nm	600-1000 nm
Pupil Size	56 pixels; 2.688 mm	2.696 mm
Pupil Separation	60 pixels; 2.880 mm	2.857 mm
Pupil Tolerances	Δ < 1/10th pixel; 2.4 μm	Δ_{size}=8 μm, Δ_{sep}=-23 μm
Lens Diameter	10 mm < D < 20 mm	D= 10.1 mm

Table 2:: Parameters for the MagAO-X pyramid wavefront sensor and the as built expected performance from our Zemax model.

4. Alignment

A precise Alignment of the pyramid was performed using a HeNe laser propagating through the full MagAO-X system. The wave front sensor camera defined the optical axis of the system because it was the hardest to tip and tilt. The alignment procedure was as follows:

1. Place the optical rail in about the correct position on the bench. Set up a target at the correct beam height.
2. Using a target on the rail steer the beam from the tip/tilt mirror onto the optical axis of the rail. The goal at this step is to dial out all of the tip/tilt and X position errors. There could be a height error at this stage. If you try and compensate for the height error at this step you will just keep inserting tip/tilt. Move the target to the front and back of the rail. When the target is at the front of the rail, move the rail such that the beam is at the correct X-position (what would be the center of the target if the height is correct). When the target is at the back of the rail move the tip/tilt mirror such that the beam is at the correct X-position. At both positions of the target adjust the tip/tilt of the mirror such that the height of the beam does not change as you slide the target on the rail.
3. Once the tip/tip and X-position is dialed out of the beam path, check the beam height. If there is a height error the cause is from misalignment in optics upstream of the pyramid and must be corrected there.
4. Once the height error is corrected, double check and make sure that the beam is hitting the center of the target when it is at the front and back of the rail.
5. Once the optical axis has been defined place the OCAM camera on the rail. Double check and make sure the adapter of the rail carriage to the OCAM was made correctly, so that the center of the camera is at the height of the beam.
6. Repeat the process of moving the camera back and forth on the rail, centering the beam on the camera. The camera sets the ultimate optical axis because it is very hard to tip/tilt, or adjust in the X/Y position.
7. Next place the pyramid onto the rail. The pyramid mount is a little loose. Adjust the pyramid in its mount by using shim stalk. Slide the pyramid back and forth on the rail, placing shim stock to dial out the tip/tilt in the pyramid. They pyramid will be in the right place when there is no beam deviation when the pyramid is placed onto the focus of the beam.
8. Place the pyramid at the focus of the beam (unmodulated). When the pyramid is at the focus, the pupils should be in the same place on the camera when the pyramid was not in the beam path. Use the OCAM to do a fine focus adjustment of the pyramid. this could mean starting at a large

modulation, and moving to a smaller modulation, realigning the pyramid in Z at each step to dial out the defocus.

9. Place in the camera lens in roughly the correct spot on the optical rail. The goal is to center the beam on the camera lens. If the previous alignment steps were done correctly it should be possible to have the beam centered on the camera lens, and be centered on the camera. If the beam vignettes on either the camera lens or the camera there is some residual tilt that needs to be fixed.

10. Modulate the beam to clean up the pupil. At this step we are doing the fine alignment of the camera lens. A script has been written to fit the pupils with circles, to measure the diameter of the pupils as well as the center-to-center separation. Adjusting the Z position of the camera lens and the camera, align the pupils to be the correct size and separation. If the camera lens is held fixed: moving the camera closer to the camera lens makes the pupils smaller and closer in separation; moving the camera farther away from the camera lens makes the pupils larger and bigger in separation. If the camera is held fixed: if the camera lens is moved farther away: magnification increases resulting in larger pupils; if the camera lens is moved closer magnification decreases and there are smaller pupils.

11. Double check with DM pokes the exact boundaries of the pupil as well as the pupil sizes.

5. Lab Performance

The pyramid wavefront sensor was aligned in the lab using the alignment guide given above. The PWFS was built on an off the shelf optical rail from ThorLabs. Custom adapters from optic to rail carriage were manufactured in house. Figure 6 show the PWFS built on the MagAO-X bench.

The result of this alignment were pupils the size of: and separation:.

The pyramid wavefront sensor has been tested in closed loop with both the woofer and tweeter DMs in the MagAO-X system. The BMC2K DM was used to generate turbulence. we have successfully closed loop in the lab at both 2kHz and our max speed, 3.6kHz. Figure 7 shows the pupils of the MagAO-X system with no modulation. The crescent diffraction pattern on the edge of the pupils can be see. In Figure 8 the pupils under modulation are shown. MagAO-X will be using a modulation 3 lambda/D on sky. Modulations of around 10 lambda/D can be done easily at high speeds with this system. Figure 9 shows the pyramid pupil under modulation and eith turbulence being generated from the DM. Intensity fluctuations that incode phase error can be easily seen within the pupils. Lastly, in Figure 10 the closed loop pupils can be seen. In closed loop the intensity of the pupils is more even, indicative of a flat wavefront. Some uncorrected high spatial frequency phase variations can still be seen in the pupils.

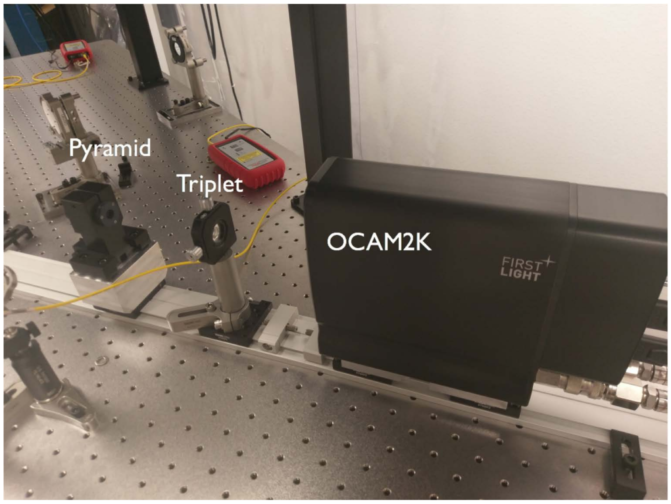

Fig. 6.—: The MagAO-X pyramid wavefront sensor.

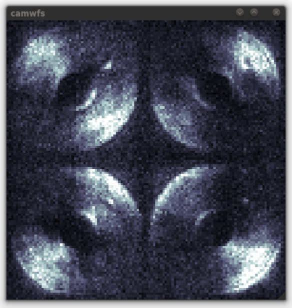

Fig. 7.—: Pyramid pupils with no modulation.

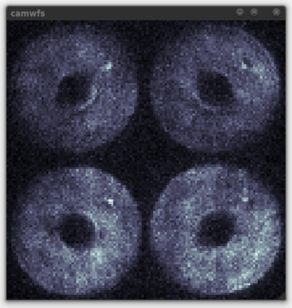

Fig. 8.—: Pyramid pupils with modulation.

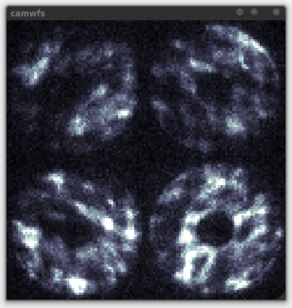

Fig. 9.—: Modulation and loop open.

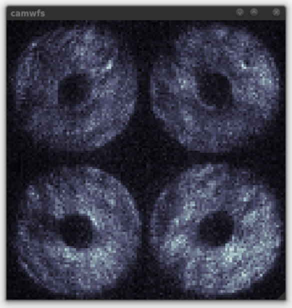

Fig. 10.—: Modulation and loop closed.

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