2.2 Wavefront Sensor Design

Lauren H. Schatz, Oli Durney, Jared Males

1 Pyramid Wavefront Sensor Overview

The MagAO-X system uses a pyramid wavefront sensor (PWFS) for high order wavefront sensing. The wavefront sensor delivers four pupils sampled by 56 pixels across, giving 2662 illuminated sub-apertures, to control the 2048 actuators on the Boston Micromachines DM tweeter, and 97 actuators on the ALPAO woofer.

2 System Requirements

The pyramid wavefront sensor of the MagAO-X system consists of a prism pyramid, a camera lens, and a OCAM^{2}K EMCCD detector. We use the same four sided double pyramid as the MagAO and LBTAO systems. The MagAO-X pyramid wavefront sensor is designed to operate from 600-1000nm bandwidth. Figure 1 is the bandpass of the MagAO PWFS. We expect a similar transmission for the MagAO-X PWFS.

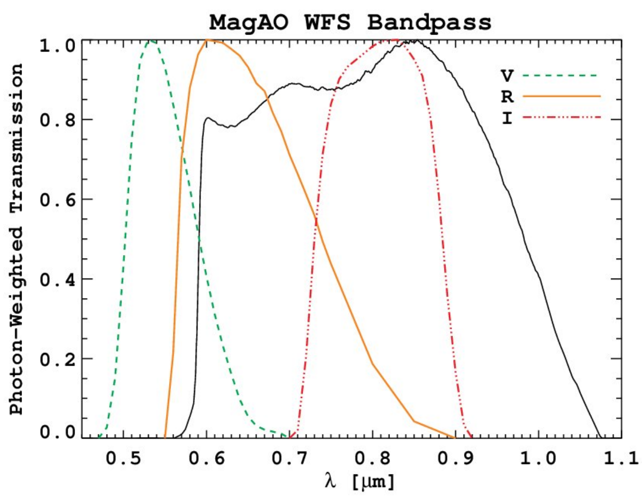


Figure 1: The MagAO pyramid wavefront sensor bandpass.

A new camera lens is designed to meet the requirements of the MagAO-X system. These requirements are listed below. The OCAM^{2}K will be used in 2x2 binning mode, giving us a 48 μm pixel size.

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

2.1 Pyramid Design: MagAO-X will be using a copy of the pyramid prism used in both the LBTAO and MagAO systems. The pyramid is already in hand. A picture of the pyramid is shown in Figure 2. Details of the design done by Tozzi et. al. are summarized here.(1) The pyramid used in the WFS is a double pyramid, consisting of two four sided prisms aligned back to back. The schematic of the double pyramid is given in Figure 3. 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 Hoara 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 Shott N-PSK53.

2.2 Wavefront Sensor Design: A design of the wavefront sensor was done in Zemax. A table of the element thicknesses (or distances), and radii of curvatures pulled from Zemax is shown in table 2. The wavefront sensor consists of the double pyramid. A F/69 focus created by OAP5#1 is imaged onto the pyramid tip. A custom achromatic triplet 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 5. Upstream not shown is the wavefront sensor dichroic pickoff. Except for the high precision flat and dichroic, the light to the wavefront sensor uses the same optical surfaces as the rest of the upstream system to reduce non common path errors. 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 4.

2.3 Achromatic Triplet Design: Pupil sizes and separation are a vital parameter in the operation and performance of pyramid wavefront sensors. A custom achromatic triplet was designed in Zemax, and optimized to give the same pupil size and separation from the 600-1000 nm wavelength range. A schematic of the lens is shown in Figure 6. The OPD error expected from the triplet is expected to be less than 0.5 waves across our wavelength band. The OPD fan is given in Figure 7.

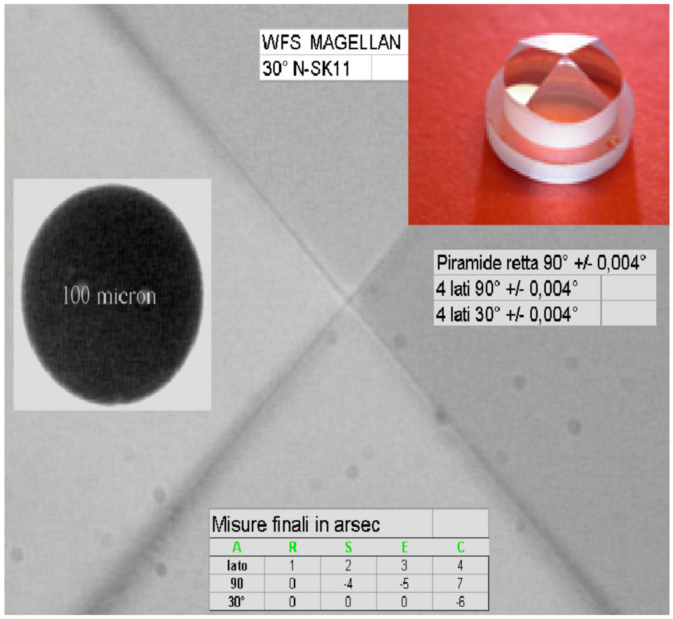


Figure 2: Fabricated pyramid made in Arcetri.

A tolerance analysis was performed to determine lens performance as a function of wavelength and manufacturing constraints. The tolerancing was done using parameters from the Precision grade Optimax manufacturing tolerancing chart. Reasonable values of alignment errors were estimated and included in the tolerancing analysis. The figure of merit used was the RMS angular radii of the lens because the pyramid is an afocal system. A 500 trial Monte Carlo simulation was done for three wavelengths, 600nm, 800nm, and 1000nm. At each wavelength the nominal, mean, and worst RMS angular size (twice the angular radii) was recorded. The difference of the mean and worst angles with respect to the nominal value was calculated. That change in angle was propagated through the system to estimate the change in size we would expect. The propagation is shown in Figure 8, where θ_n is the nominal RMS angular size, and θ_Δ is the change in RMS angular size we use to calculate the estimated change Δy. The distances $x_1 ... x_5$ were taken from the Zemax design, and the indices n_1, n_2, n_3 correspond to air, BK-7, and Sapphire respectively. The index of refraction was adjusted for the different wavelengths when the propagation was calculated. The propagation was calculated using trigonometry and Snell's law. The results are summarized in Figure 9, where the change in size in nanometers is graphed against wavelength. At worst we expect about a 45 nm change in pupil size and separation, and no change on average. Both are well within our tolerance of the change being no greater than 1/10th a pixel, or 2.4μm.

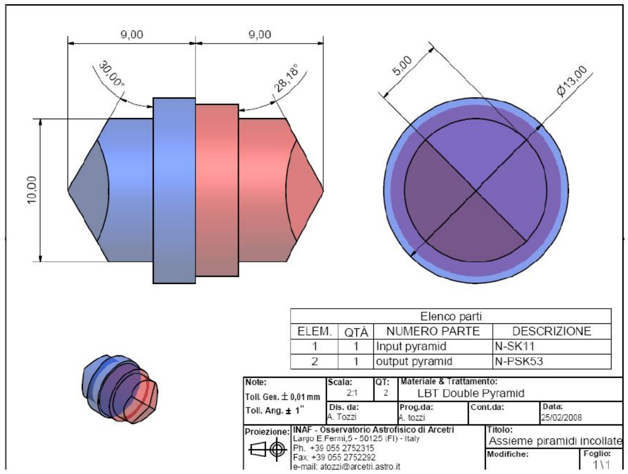


Figure 3: Mechanical design of the DP for LBT. The selected glass are produced by Schott. The diameter of the two pyramid bases are different to distinguish them and to facilitate the mounting.

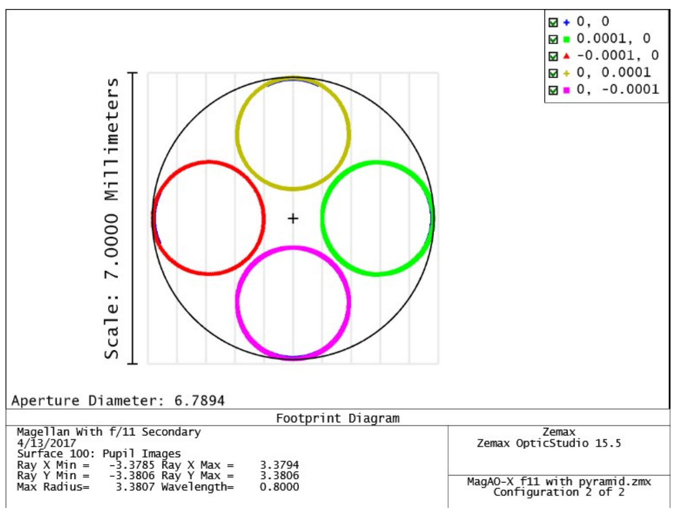
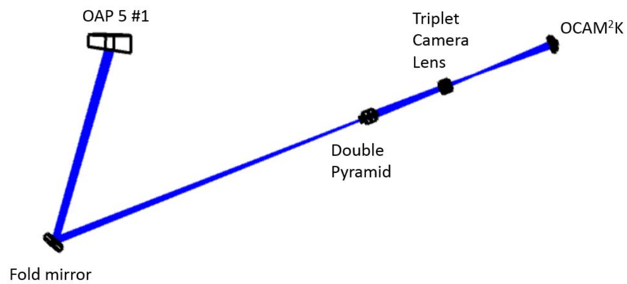


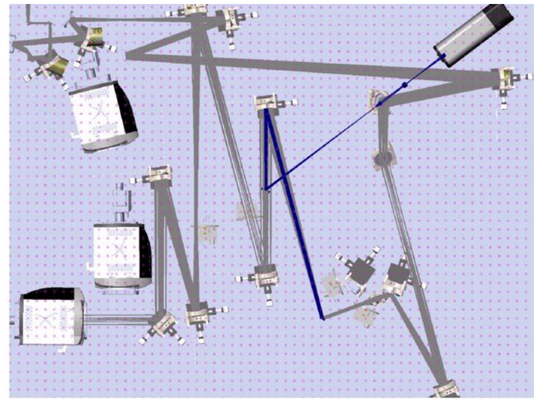
Figure 4: Beam footprint at the image plane done in Zemax.

3 System Performance

A simulation of the expected partial illumination of pupil pixels was done in MATLAB. A binary model of the MagAO-X pupil was generated with 10 times the spatial sampling than our expected PWFS

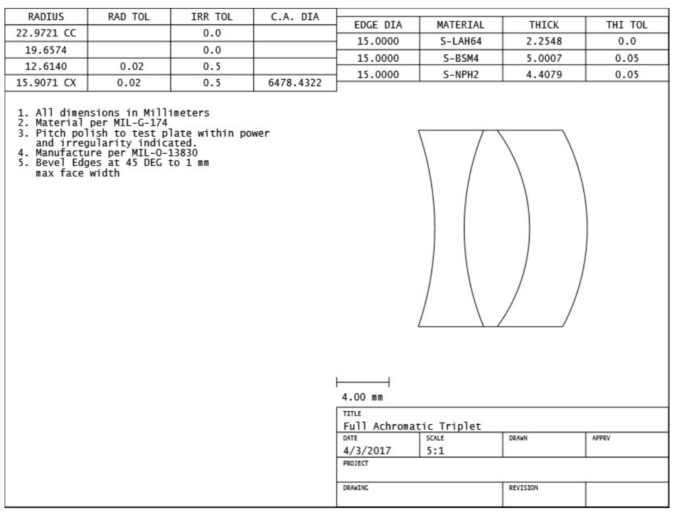


(a) Optical path in Zemax.



(b) Optical path in SolidWorks

Figure 5: Optical path of the pyramid wavefront sensor. The Zemax ray trace was imported into SolidWorks for the optomechanical design.



RADIUS	RAD TOL	IRR TOL	C.A. DIA
22.9721 CC		0.0	
19.6574		0.0	
12.6140	0.02	0.5	
15.9071 CX	0.02	0.5	6478.4322

EDGE DIA	MATERIAL	THICK	THI TOL
15.0000	S-LAH64	2.2548	0.0
15.0000	S-BSM4	5.0007	0.05
15.0000	S-NPH2	4.4079	0.05

Figure 6: Achromatic triplet.

pupil. We then bin down to the expected pupil sampling of our PWFS. That is we start with a pupil of 560 by 560 pixels, and bin down to a 56 by 56 pixel pupil by summing 10 by 10 pixel bins and normalizing. The expected illumination pattern is given by Figure 10.a. A table of the pixel counts are given in Table 1. where the pixel value is given on the X-axis, and the number of pixels with that value are given on the Y-axis. We expect 1958 fully illuminated pixels across our pupil.

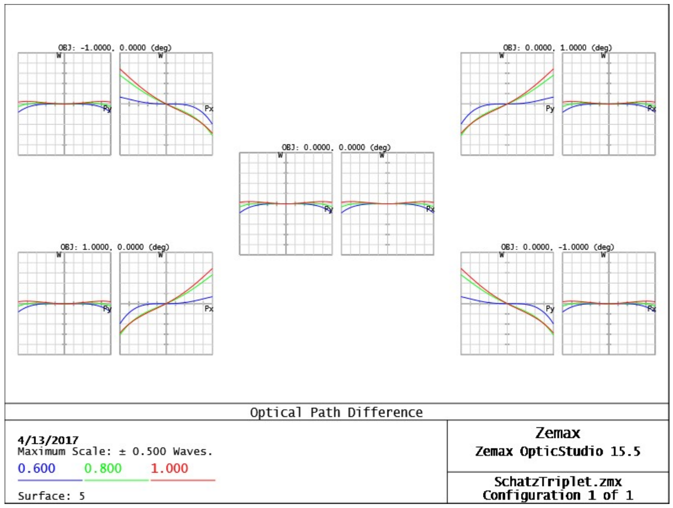


Figure 7: OPD fan of the achromatic triplet.

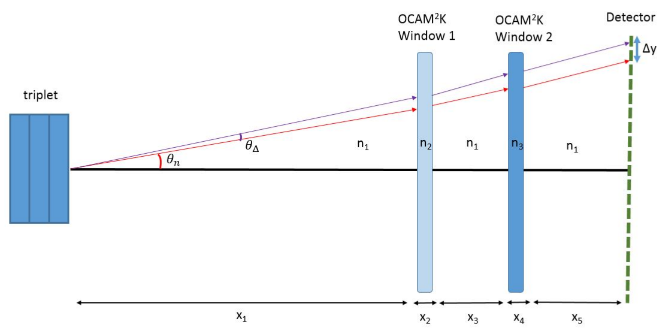


Figure 8: Diagram of the light propagation path used to calculate the change in pupil size.

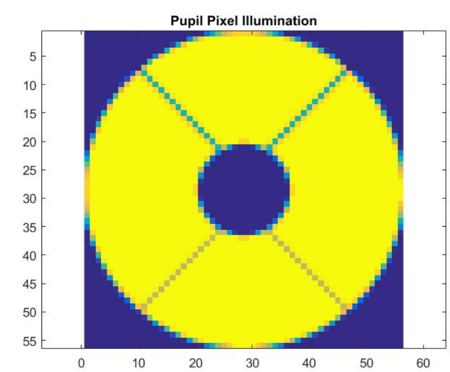


Figure 10: Expected pupil illumination on the PWFS.

% Illumination	# of Actuators
100%	1958
90%	166
80%	24
0%	46
60%	20
50%	18
$<$ 50%	904

Table 1: Pixel illuminations in the 56 by 56 pixel pupil.

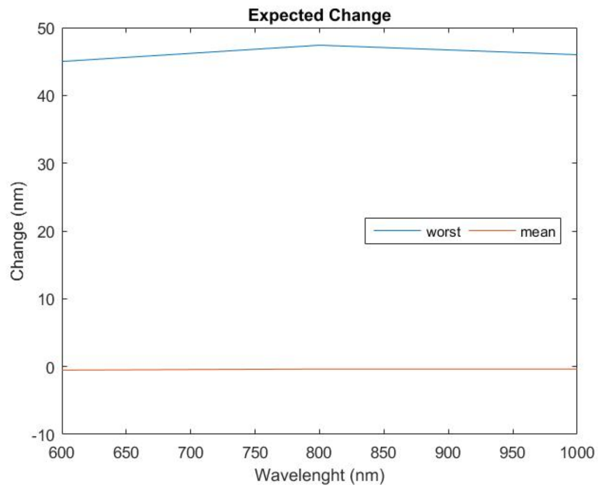


Figure 9: Expected change in pupil size as a function of wavelength.

References

[1] A. Tozzi, P. Stefanini, E. Pinna, S. Esposito, "The Double Pyramid wavefront sensor for LBT", in Adaptive Optics Systems, Proceedings of SPIE, (2008). Vol. 7015, 701558

Element #	Surface	Radius of Curvature	Thickness
76	OAP5#1	1220.83984	0
77	Propagation #1	Infinity	200
78	Coordinate Break	Infinity	0
79	Fold Mirror 2	Infinity	0
80	Coordinate Break	Infinity	-389.625
81	Int. Focal Plane (f/69)	Infinity	0
82	dummy Pyramid Entrance	infinity	-1.5
83	PYR 30°	Non-Sequential	0
84	Dummy Out	Non-Sequential	0
85	PYR 30∘ Base	Non-Sequential	-6.16384
86	PYR 28∘ base	Non-Sequential	-6.23166
87	Dummy In	Non-Sequential	0
88	PYR 28∘	Non-Sequential	0
89	Dummy Out	Non-Sequential	0
90	Propagation	Infinity	-80
91	Triplet Front Surface	-15.88071497	-4.41266
92	Triplet	-12.61981892	-5.00127
93	Triplet	19.13048337	-2.21407
94	Triplet Back Surface	-23.03743881	0
95	propagation	Infinity	-130
96	OCAM window	Infinity	-3
97	propagation	Infinity	-0.82
98	CCD 220 OCAM window	Infinity	-0.9
99	Focal Plane	Infinity	-2.83

Table 2: Table of Zemax surface elements