Double-Pyramid Wavefront Sensors: Tolerance Relaxation and Cheaper Alternatives using Achromatic Double-Roof Prisms

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ABSTRACT

We present the current design of the double-pyramid planned for the TMT-NFIRAOS Visible Natural Guide Star WFS and its manufacture challenges to meet all the requirements in terms of tip size, pupil image quality and mapping on the detector pixels. We show that the angular tolerance of the pyramid can be relaxed from ±6 arcsec. to ±2 arcmin. without significant impact on the AO performance, which is within the capabilities of most optical suppliers and reduces the fabrication cost by a factor 10 or more. Then we compare the pyramid design to a new concept using two double-roof prisms, optically equivalent to an achromatic double-pyramid and offering very similar performance. Roof prisms are easier to manufacture to tolerance than pyramids since there is no tip. We also present an adjustable version of the achromatic double-roof prism allowing very fine adjustments of the positions of the four pupils onto the detector pixels, which can relax the manufacture tolerance of the prisms even more.

Keywords: Pyramid wavefront sensor, double-roof prism, optical design

1. PYRAMID WAVEFRONT SENSOR CONCEPT

A square pyramid made of glass is located at the focal plane to split up the light and form four images of the pupil through a relay lens (Figure 1). Then the wavefront slopes can be derived from the pixel intensity as follow:

$$S(x) = \frac{(I_1 + I_4) - (I_2 + I_3)}{I_1 + I_2 + I_3 + I_4}$$

$$S(y) = \frac{(I_1 + I_2) - (I_3 + I_4)}{I_1 + I_2 + I_3 + I_4}$$

This processing involves a pixel-wise difference and normalization that requires an accurate pupil mapping on the detector with no differential distortion or rotation among the four pupil images. Common distortions due to the upstream adaptive optics (AO) system are cancelled out by the difference and have no impact on the slope measurements.

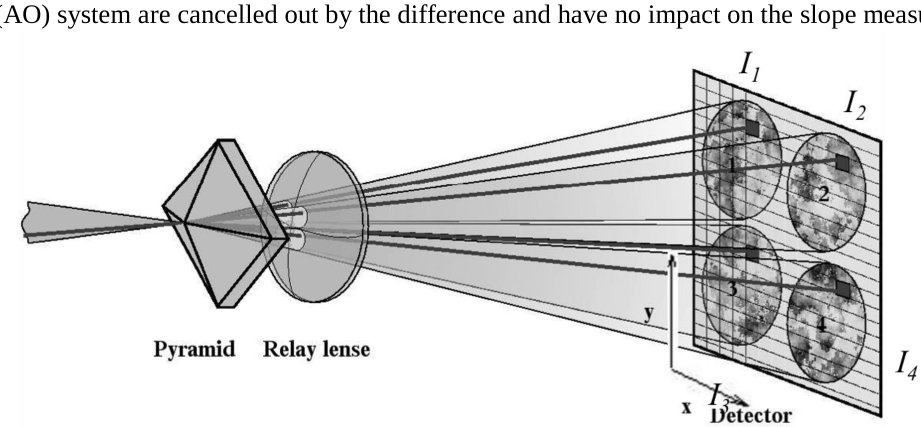

Figure 1: Concept of the pyramid wavefront sensor (Ragazzoni, 1996) (Ref. [1]).

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2. EXAMPLE: TMT NFIRAOS PYRAMID WFS

NFIRAOS, the multi-conjugate AO system for the Thirty Meter Telescope (TMT) will be using 6 sodium laser guide stars (LGS) in addition to a natural guide star (NGS) acting as a truth wavefront sensor to compensate the spurious aberrations due to the LGS elongated spots. The optical layout of the truth wavefront sensor, named VNW for Visible Natural Wavefront sensor (Ref. [2], [3]), is depicted in Figure 2. VNW involves a double-pyramid (Ref. [4]) made of two different glasses, which works exactly as a single pyramid but has no or little chromatic aberrations, similarly to a doublet lens versus a singlet lens.

The key-requirements of NFIRAOS VNW are summarized in Table 1, along with their impact on the pyramid prescription. It is worth noting that the pyramid must be optimized at the same time than the pupil relay lens in order to mitigate differential pupil distortion. The distortion of the relay lens can actually compensate a fraction of the distortion due to the pyramid itself.

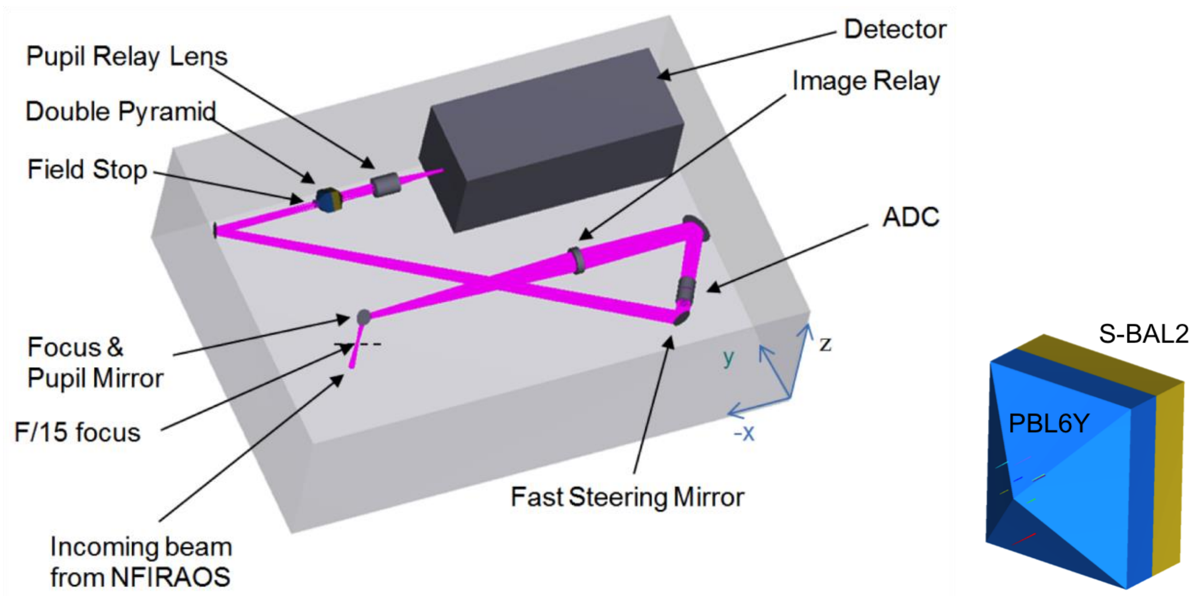

Figure 2: Left: Optical layout of VNW, the TMT NFIRAOS pyramid wavefront sensor. Right: Double pyramid and glasses.

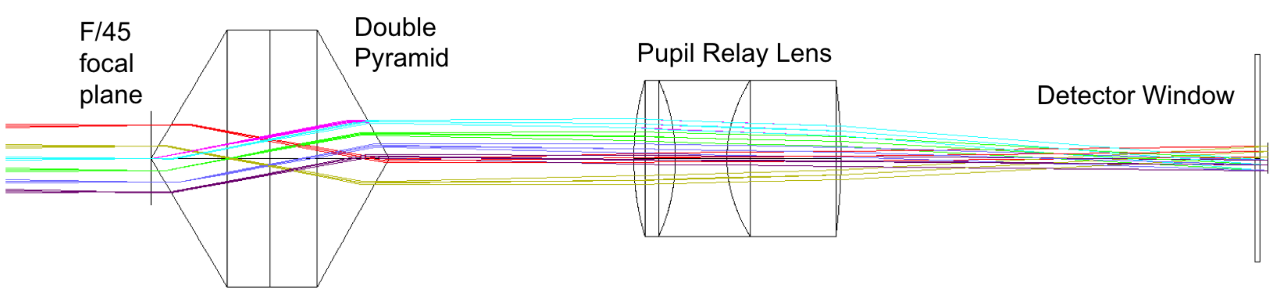

Figure 3: Ray tracing through the double pyramid, the pupil relay lens and the detector. The tip of the front pyramid is located in a focal plane while the detector is located in a pupil plane.

Table 1: Key-requirements of the TMT NFIRAOS pyramid WFS.

#	Requirement	Specification	Impact on Pyramid
600	Patrol field	2 arcmin (262mm), F/15, curved field	
400	F/ratio on pyramid tip	F/45	Roof size < 20mm
310	Wavelength range	610-785 nm	Achromatic design
650	ADC residual correction (focal plane)	<16um PTV (2.5mas on sky)	
610	Entrance field of view	2"on sky (13.2mm@F/45)	Dimensions, central thickness
630	Pupil image diameter	96 ± 1 pixels (± 0.2 pix. initially)	
640	Interpupil distance	128 ± 12 pixels (± 0.2 pix. initially)	Angular tolerance <±2arcmin. (<±6arcsec. initially)
670	Pupil image quality (incl. lateral color)	Spot radius: avg.<5.4um (0.26pix) max<8um (0.38pix)	Flatness <λ/30 RMS
680	Differential pupil distortion	<0.4 pixel PTV	Global optimization with pupil relay lens
700	NCPA aberrations	<50 nm rms	
710	Throughput losses	<20%	
720	Image modulation	0--30 λ/D (nominal is 5l/d)	

3. PUPIL MAPPING TOLERANCE RELAXATION

Imperfect pyramids and pupil relay lenses may generate four types of pupil mapping errors that will impact the slope measurements:

- Position error of the pupil centres
- Lateral color
- Differential distortion
- Differential rotation

Figure 4 gives an illustration of each of these common pupil mapping errors. The pyramids made for the Large Binocular Telescope (LBT) (Ref. [4]) or the Giant Magellan Telescope (GMT) have extremely tight angular tolerances (<5 arcsec) to get an almost-perfect pupil mapping matching the detector pixel grid within ±0.2pixel. Only one supplier was able to meet such requirements for a cost of about 135k$ per item (Table 2).

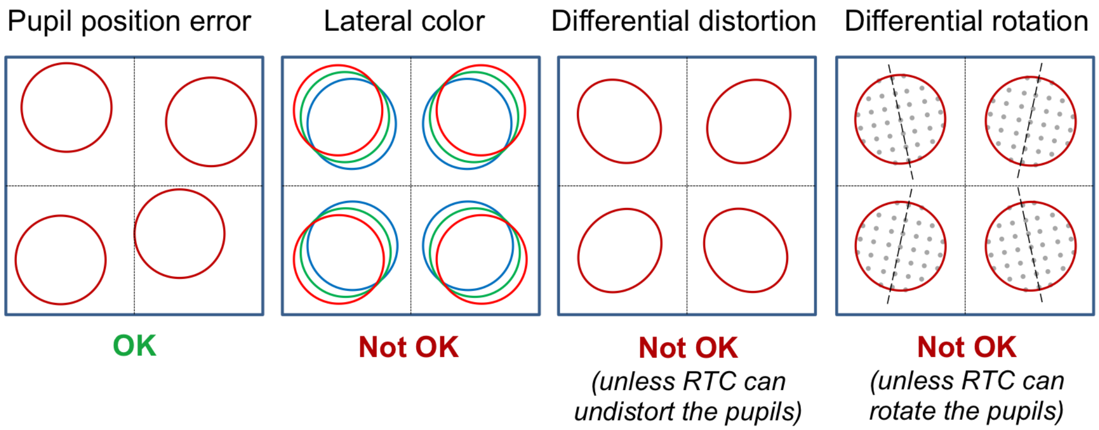

Figure 4: Most common pupil mapping errors impacting slope measurements.

However, recent simulations show that a shift up to 0.5 pixel on one of the four pupils induces no or little incremental error compared to 0.2 pixel (Figure 5) as long as the interaction matrix is measured in the same condition (Ref. [5]). This means that the pupil images can land on any pixels of the detector since the coordinates of the active pixels to be read by the real-time computer (RTC) can usually be adjusted by software. This also relaxes long-term stability requirements of the whole instrument. Any pupil drift can be compensated by software.

Consequently, the fabrication and assembly tolerances of the double pyramid of NFIRAOS have recently been relaxed to 2 arcmin., which is the tolerance of most commercial prisms and within the capabilities of a large number of suppliers (Table 2).

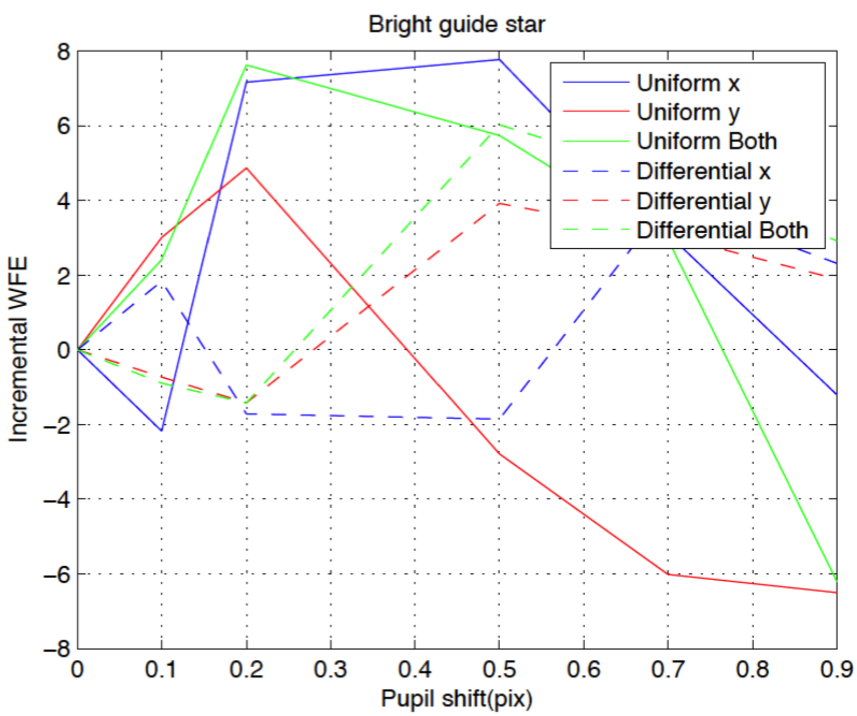

Figure 5: Incremental wavefront error (WFE), in nm rms, induced by a pupil shift (Credits: Lanqi Wang, Ref.[5]).

Table 2: Initial and relaxed tolerances for the NFIRAOS double-pyramid. Currency is Canadian dollar (CAD).

	Pupil position tolerance	**Pyramid angular tolerance**	**Availability**	**Cost for one double pyramid**
Initial tolerance	±0.2 pixel	±6 arcsec.	Only one supplier	135k CAD
Relaxed tolerance	±5 pixels	±2 arcmin.*	Several suppliers	<10k CAD

* limited by lateral color.

4. DOUBLE-ROOF PRISM CONCEPT

After relaxation of the angular tolerance, the size of the pyramid tip (<20mm) is the remaining fabrication challenge. The intersection of four surfaces always forms a roof if one of the surfaces is slightly thicker or not exactly orthogonal to the others (**Figure 6**).

The solution is to use two identical roof prisms facing each other, front-to-front, with a 90^o angle (Figure 7). Both roofs are located at the focal plane and are almost in contact with a air gap of about 0.1mm.

The double-roof prism is optically equivalent to a single pyramid and has significant advantages over a pyramid:

- A roof prism is very cheap to make (~3k CAD for 2 items)
- There is no tip to fabricate
- Edges between two surfaces can be as sharp as 5μm without special effort.

One downside of double-roof prisms is the greater number of surfaces compared to a pyramid, which may impact the throughput of the WFS. The assembly and alignment of the prisms with respect to each other is not seen as a challenge since we can rely on the mechanical tolerance of the mount. A spacer can prevent the prisms from colliding and keep the air gap as small as 0.1mm. Collisions must be avoided, as this would damage the edges of both roofs.

Subaru Telescope (NAOJ) provided us with two roof prisms we have assembled and tested at NRC and compared to a double pyramid (Ref. [6]) (Figure 8).

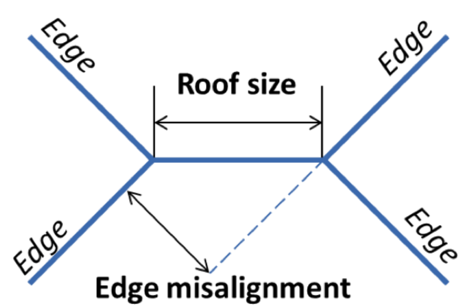

Figure 6: Close-up of a pyramid tip.

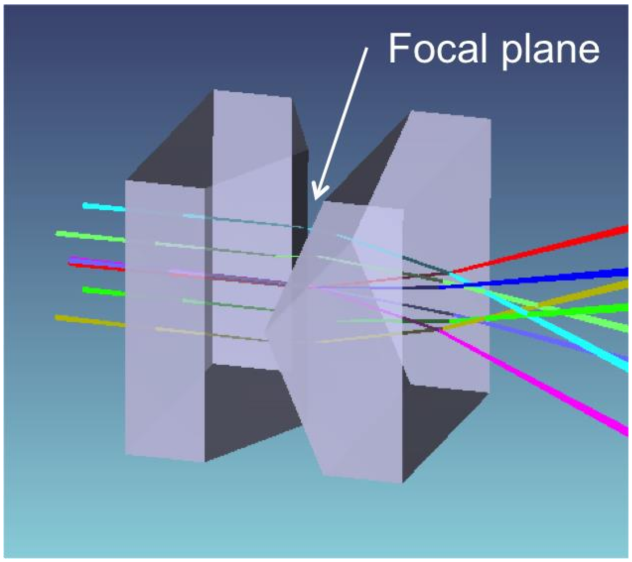

Figure 7: Double-roof prism concept.

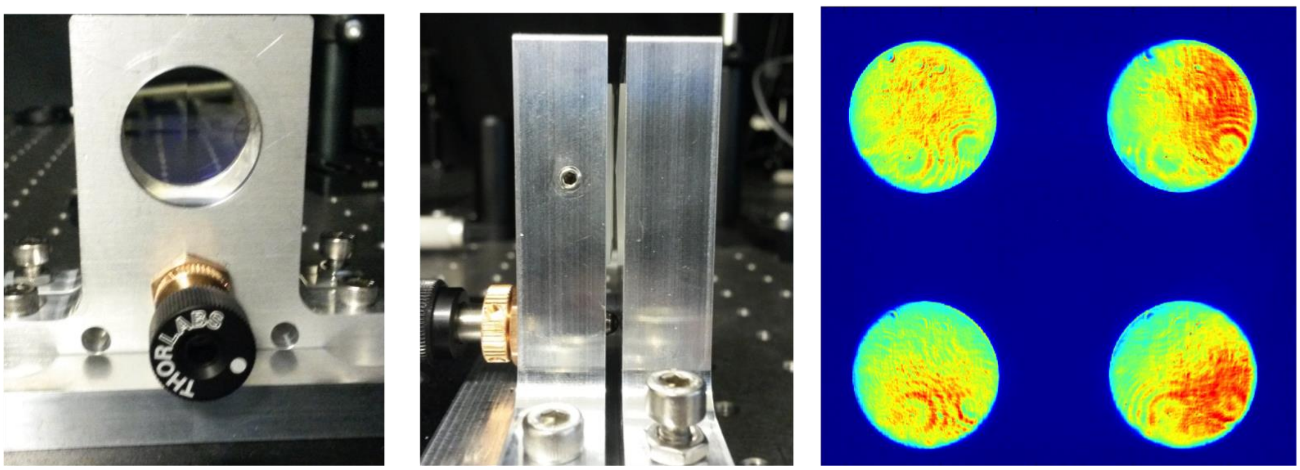

Figure 8: Double roof-prism assembled and test at NRC-HAA (left and center) and image of the four pupils from which the slopes of the wavefront can be extracted (right).

5. ACHROMATIC DOUBLE-ROOF PRISM DESIGNS

If a double-roof prim is equivalent to a single pyramid, then a double-double-roof prism should be equivalent to a double-pyramid. For simplicity we refer to this concept as "Achromatic double-roof prism". We found two possible designs for achromatic double-roof prisms:

- Quadruple roof-prism (Figure 9)
- Double-roof prism followed by corrector wedges, which has two variants:

Rigid version (Figure 10a)
Adjustable version (Figure 10b and Figure 11)

If a perfect pupil mapping is required, the adjustable version allows very fine adjustments of the positions of the four pupil centres onto the detector pixels, even with relaxed angular tolerances on the prisms.
Table 3 compares the performance in terms of lateral color and pupil distortion of a single pyramid, a double pyramid, a double roof-prism and an achromatic double roof-prism (rigid version).

It is worth noting that a double-roof prism produces the same mount of lateral color than a single pyramid made of same glass. Calcium fluorite (CaF_2) is the least dispersive glass giving the minimum lateral color for single-glass optics. Using an appropriate combination of two glasses can reduce the lateral color to almost zero, regardless of the chosen design, pyramid or roof prism. However the residual pupil distortion remains 10 times higher for the roof prisms compared to the NFIRAOS double-pyramid. It might be possible to reduce this distortion with further design optimizations, using thinner roof prisms or other glass combinations, but the performance presented in Table 3 are the best we obtained so far.

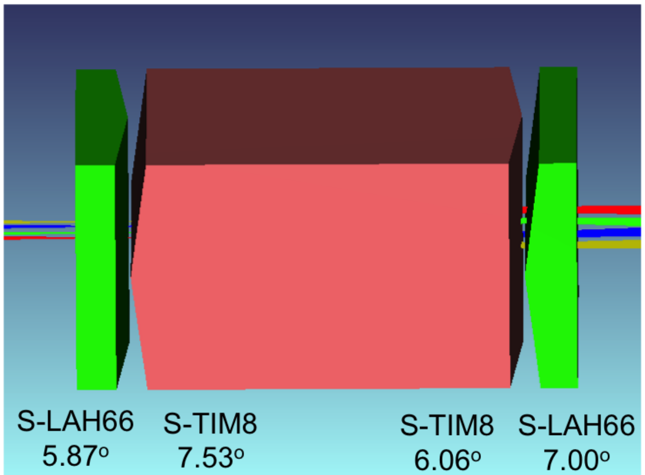

Figure 9: Quadruple-roof prism. The focal plane is located on the left side of the central block. Glasses and roof angles are mentioned for each block.

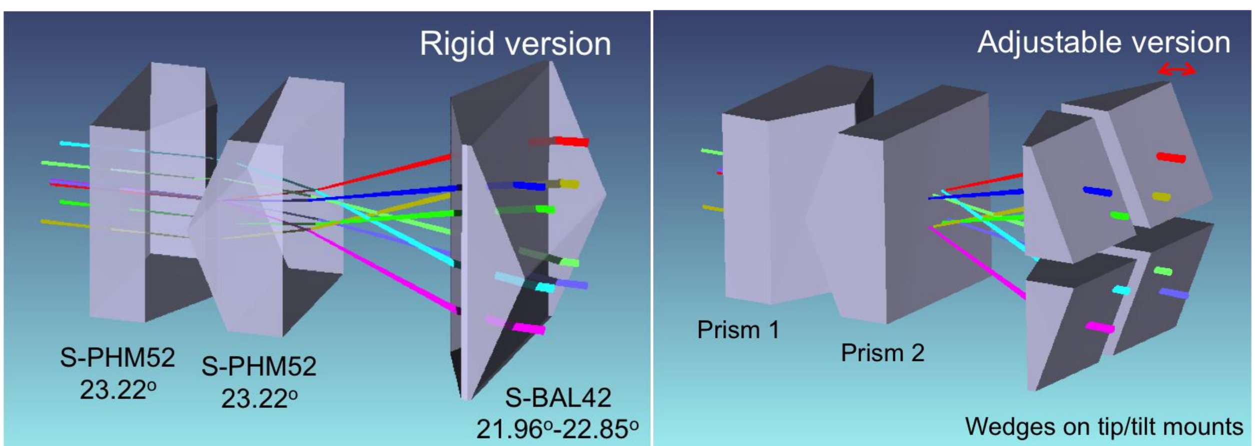

Figure 10: Double-roof prisms followed by corrector wedges: (a) rigid version, (b) adjustable version where the corrector is cut into four pieces to allow individual tip/tilt adjustments of each wedge and relax the angular tolerances on prisms 1 and 2.

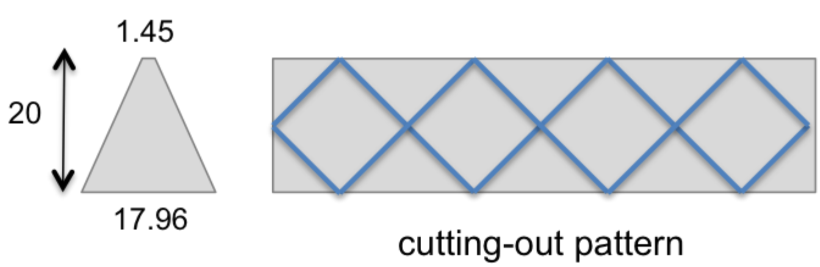

Figure 11: The adjustable version is made of four 30.24° wedges clocked at 45°. The four wedges can be fabricated and cut-out from a single 30.24° wedge.

Table 3: Performance comparison. Lateral color and pupil distortion are expressed in percent of the pupil diameter.

Design	Apex/roof angle	Lateral Color	Pupil Distortion
Single Pyramid (CaF_2)	2.77deg	0.6%	0.029%
Double Pyramid (NFIRAOS)	40/38deg	0.03%	0.017%
Double-Roof Prism (CaF_2)	1.95deg	0.6%	0.084%
Achromatic Double-Roof Prism (rigid version)	~22deg	0.03%	0.18%

6. CONCLUSION

A pupil mapping matching exactly the pixels of the detector does not seem necessary to achieve optimal AO performance. Relaxing the pupil position errors from ±0.2 to ±5 pixels also relaxes the fabrication tolerance of the pyramids (or double-roof prisms) from ±6 arcsec. to ±2 arcmin., which is within the capabilities of most optical suppliers. This reduces the fabrication cost by a factor 10 or more.

The double-roof design is interesting for applications where the size of the pyramid tip is an issue. This concept can be achromatized too with an extra double-roof prism or with wedges that, if needed, can be tilted to finely tune the position of the pupils on the detector. However the double-pyramid still gives better performance in terms of differential pupil distortion and throughput.

REFERENCES

[1] R. Ragazzoni, "Pupil plane wavefront sensing with an oscillating prism", J. of Modern Optics Vol. 43 (1996).

[2] G. Herriot et al., "NFIRAOS", these proceedings (2017).

[3] E. Mieda et al., "Current status and implementation of pyramid truth wavefront sensor on NFIRAOS simulation bench at NRC-Herzberg", these proceedings (2017).

[4] A. Tozzi et al., "The double pyramid wavefront sensor for LBT," Proc. SPIE 7015, 701558–701558–9 (2008).

[5] L. Wang et al., "Pyramid WFS Tolerance Study for NFIRAOS NGS AO", these proceedings (2017).

[6] M. van Kooten et al., "Fast modulation and dithering on a pyramid wavefront sensor bench", SPIE Vol. 9909 (2016).