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Flattened Pyramid Wavefront Sensor Demonstration with a Regular Pyramid

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Abstract

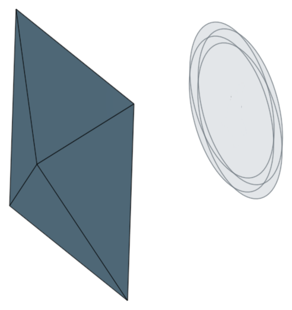
Wavefront sensors (WFS) are key-components for Adaptive Optics (AO) systems to deliver diffraction-limited images with current ground-based telescopes and future Extremely Large Telescopes. A new WFS concept, the Flattened Pyramid WFS (FPWFS), seems very promising in theory [1], with performances exceeding the "conventional" Pyramid WFS, which was already superior to the Shack-Hartmann WFS.

This new WFS has never been tested in a lab so far because the fabrication of a glass pyramid with a very shallow apex angle is extremely difficult, if not impossible. However, we found a very simple way to mimic a "Flattened" Pyramid WFS with a regular double-pyramid, originally designed for NFIRAOS, and a lens arranged in an appropriate fashion in order to overlap the four pupils on the detector. This poster describes the optical setup of Flattened Pyramid WFS test-bed built in the NRC-HAA AO lab, as well as the algorithms used to reconstruct the wavefront, and compares its performance with a conventional Pyramid WFS.

1—Flattened Pyramid Concept

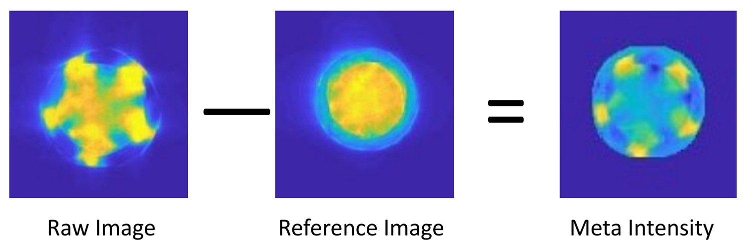
The flattened pyramid splits the incoming beam at the image plane into four pupils that are separated by a small shear. These beams interfere with each other to produce a phase to intensity mapping (Fauvarque et al., 2015) [1].

Each circular pupil overlaps as shown in the image to the right. The shear refers to the a distance between the centre of the circles. The pyramid angle is exaggerated.



Meta Intensity

$$mI = \frac{I}{sum(I)} - \frac{refI}{sum(refI)}$$



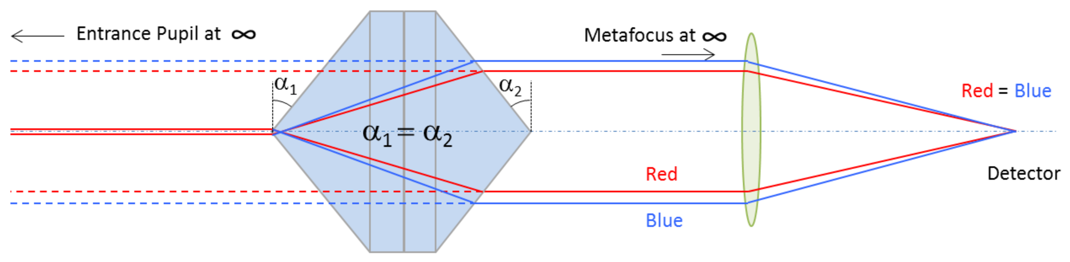
Expected Benefits

- Efficient light use and less light use
- Smaller detector
- High sensitivity to high order modes
- Lower noise propagation

2—Optical Design and Tricks

Optimal Design:

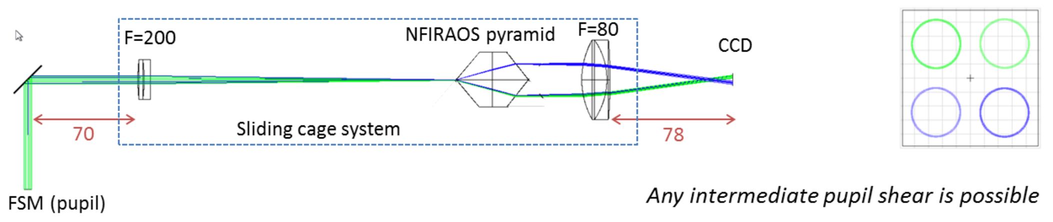
- A symmetric single-glass double pyramid works like a FPWFS and is fully achromatic. Any glass and any apex angle are suitable.
- Requires a telecentric input focal plane (or a field lens if needed).
- Probably the best and most economical design solution for a FPWFS.



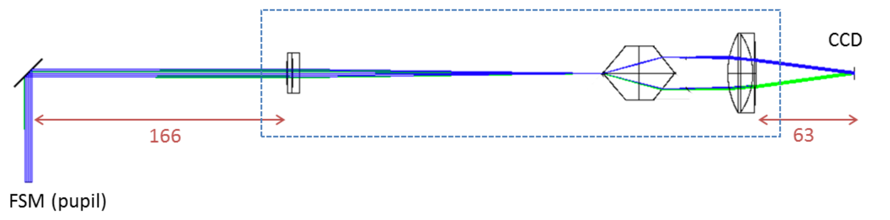
Front pyramid = Rear pyramid

Alternative Design Solution:

- Actually, any double-pyramid can be used for a FPWFS, but it may not be achromatic anymore, which is acceptable for a lab experiment.
- To convert a conventional PWFS to a FPWFS, we just need to conjugate the pupil with the metafocus of the pyramid [4]. This can be done in a few seconds with sliding optics.



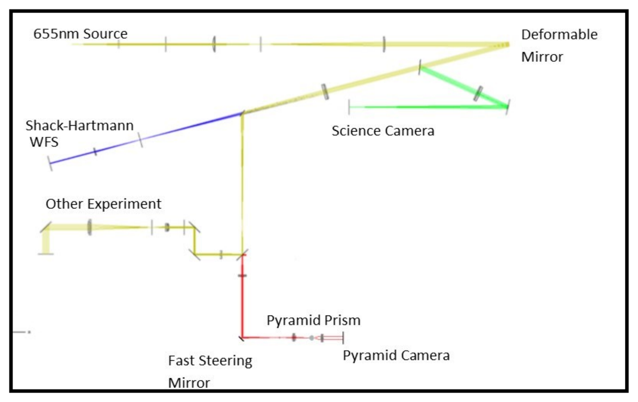
Regular PWFS



Flattened PWFS

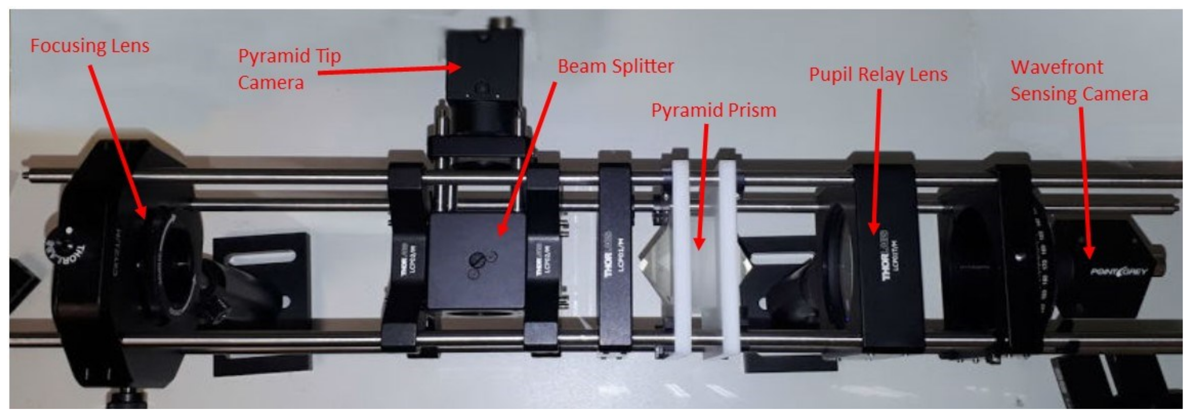
3—Optical Bench Setup

The HAA bench has a source, an ALPAO 97 actuator DM and a Shack Hartmann located independently from the pyramid. The science camera used for this experiment was the one at the tip of the pyramid.



NRC AO lab WFS Bench Design

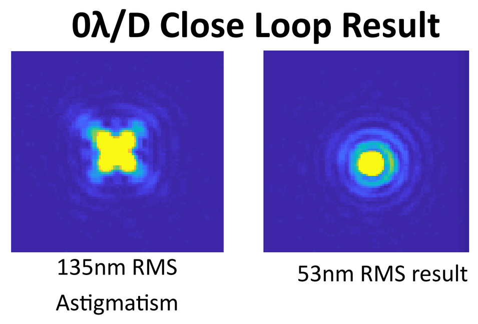
The cage system was slid towards and away from the FSM (pupil plane) to change between flattened and conventional PWFS. The position of the WFS camera on the rails controlled the pupil shear.



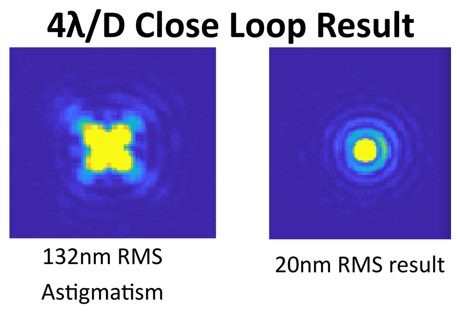
4—Flattened Pyramid Results

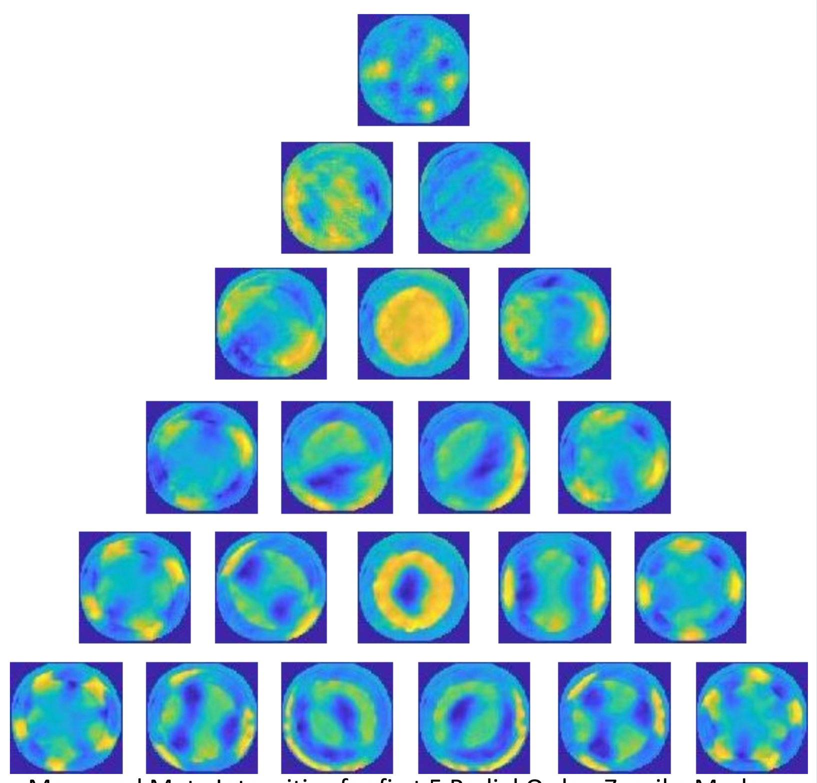
The flattened pyramid was able to close an AO loop for small aberrations. Only a modal interaction matrix converged with small modulation (0-4λ/D).

0λ/D Close Loop Result



4λ/D Close Loop Result



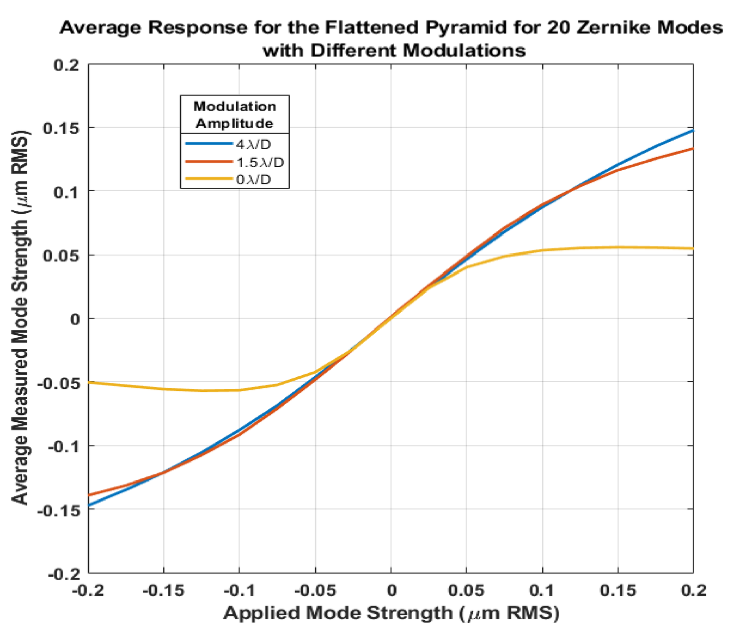


Measured Meta Intensities for first 5 Radial Order Zernike Modes

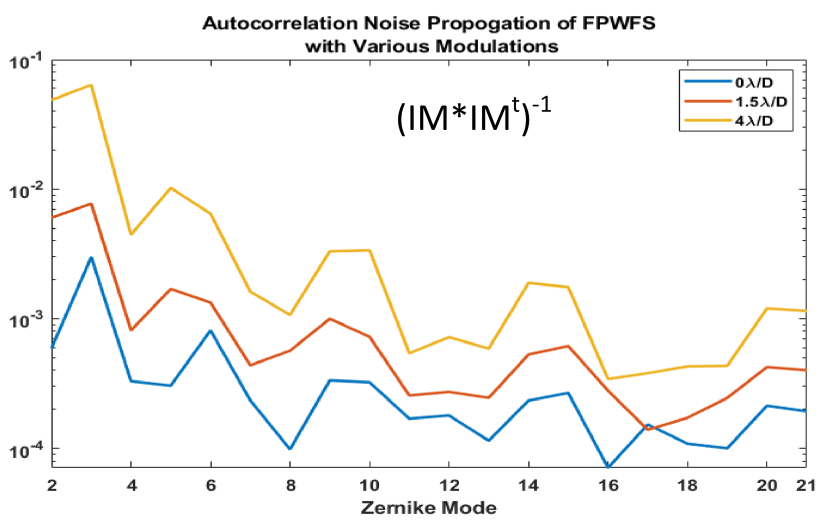
5—Effects of Image Modulation

Modulation was applied to the tip of the pyramid and the effects were studied.

Modulation greatly increased the dynamic range of the FPWFS. The test was conducted by applying a mode to the DM and comparing that with the strength of that mode measured by the FPWFS.



The FPWFS was more sensitive with less modulation. It is clear for all modulations that the FPWFS is very poor at identifying tip and tilt. This is consistent with close loop results.



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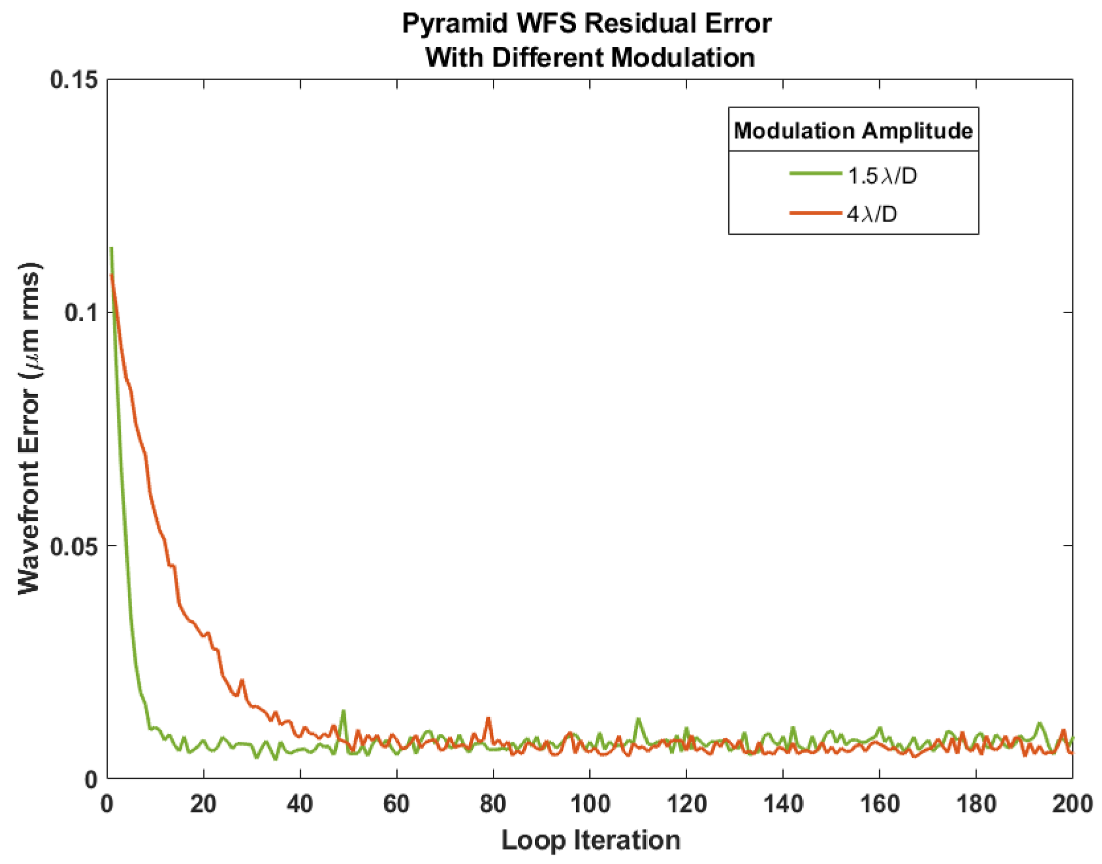
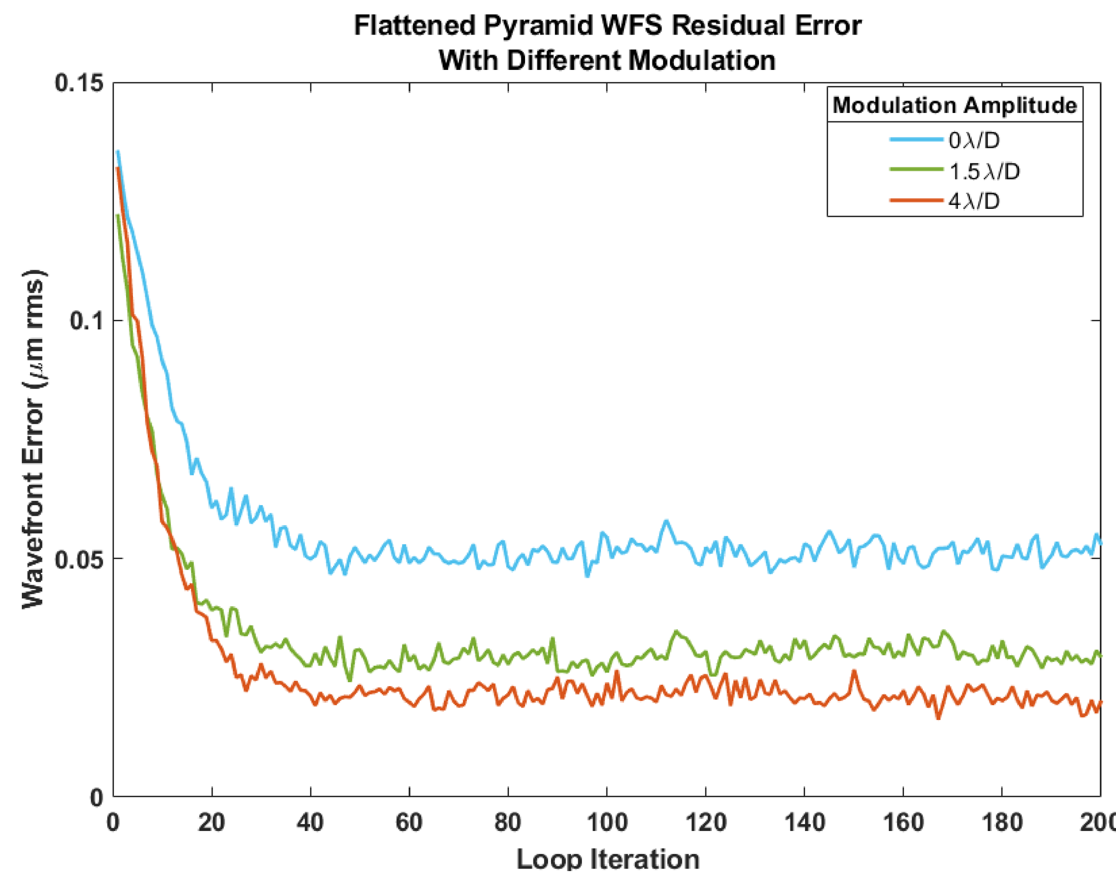
6—Comparison to Conventional Pyramid WFS

The same initial shape was applied to the DM and the two sensors closed the loop. The Shack Hartmann measured the wavefront error independently to assess the quality of the correction.





The conventional pyramid provided a better correction than the FPWFS in these tests. Additionally, the flattened pyramid improved with increased modulation.

The flat pyramid required only 40% of the light required for the PWFS. This is advantageous because less light must be diverted to the wavefront sensor. In addition, the camera sensor size required was 50% less in each direction.

Conclusions

The flattened pyramid wavefront sensor was successfully implemented for the first time using a pyramid prism. The FPWFS was able to close a loop for small modes while using approximately half the light required for the PWFS. Currently though, the conventional PWFS remains more reliable and robust for closing the loop. Given that the dynamic range is so small (50nm RMS without modulation) the FPWFS has issues with non-common path aberrations. If the science camera and FPWFS lie on different paths, it is hard to apply a slope offset so that the image is corrected at the science camera. This may limit the usability of this sensor.

It would be interesting to study the effects of a broadband source on the FPWFS in order to reduce the reliance on modulation. In addition, it would be beneficial to understand in greater detail if the diffracted light that is cropped from the PWFS is valuable or noise in for the FPWFS.

References

1. O Fauvarque et al., "Variation around a pyramid theme: optical recombination and optimal use of photons". OSA Optics Letters, vol. 40, pp.3528-3531 (2015).
2. M. van Kooten et al. "Alternative pyramid wavefront sensors", JATIS vol. 3 (2017).
3. R. Ragazzoni, "Pupil plane wavefront sensing with an oscillating prism", J. of Modern Optics vol. 43 (1996).
4. Lardiere et al. "Specifications, procurement and testing of the TMT-NFIRAOS double-pyramid prisms", this conference, POSTER-SEN-200.