Flattened Pyramid Wavefront Sensor Demonstration with a Regular Pyramid

Alexander Krawciw[a], Olivier Lardière[b], Jean-Pierre Véran[b], David Andersen[b]
[a]University of Victoria, 3800 Finnerty Rd, Victoria, BC, Canada
[b]National Research Council, Herzberg Astronomy and Astrophysics, Victoria, BC, V9E 2E7, Canada

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 [2, 3], which was already superior to the Shack-Hartmann WFS. This new WFS has never been tested in a lab because the fabrication of a glass pyramid with a very shallow apex angle is technologically challenging. However, there is a simple way to mimic a "Flattened" Pyramid WFS with a regular double-pyramid, originally designed for NFIRAOS [4]. A lens can be arranged in order to overlap the four pupils on the detector. This paper describes the optical setup of the 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.

Keywords: Flattened Pyramid wavefront sensor, Pyramid wavefront sensor, adaptive optics, optical design

1. INTRODUCTION

The Flattened Pyramid Wavefront Sensor (FPWFS) was originally proposed by Fauvarque et al [1]. Conceptually, a pyramid prism with an apex angle of approximately 0.5° would produce a phase to intensity image of optical aberrations by splitting the incoming beam into four intersecting beams across the tip of the pyramid. These four beams would interfere with each other to produce the raw sensor image. The data from the FPWFS is referred to as a *meta-intensity*. The FPWFS has a number of potential benefits. The FPWFS is theoretically more efficient, i.e., it uses less light. In addition, the sensor requires a smaller detector and is more sensitive to high order modes than a Pyramid Wavefront Sensor (PWFS).

1.1 Meta-intensity calculation

The meta-intensity is computed for each pixel within a mask defined region. The mask for the FPWFS is defined as the union of four circles that are translated slightly relative to each other to encompass the FPWFS data. Figure 1 shows a sample mask for the flattened pyramid. Note that the shape is not quite circular due to the shifted circles.

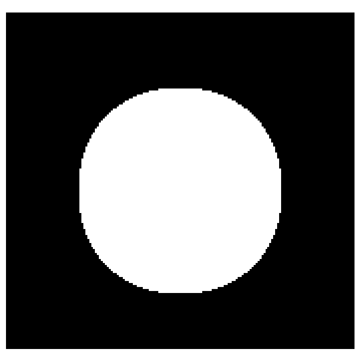

Figure 1: A Flattened Pyramid mask. The union of four shifted circles.

The meta-intensity is computed from the normalised difference from the raw image and a target reference image. The operation was calculated for each pixel using equation (1).

$$mI = \frac{I}{sum(I)} - \frac{I_R}{sum(I_R)} \quad (1)$$

where *mI* is the meta intensity, *I* is the intensity of the pixel, and I_R is the intensity of the same pixel in the reference image. Figure 2 shows a sample meta-intensity calculation.

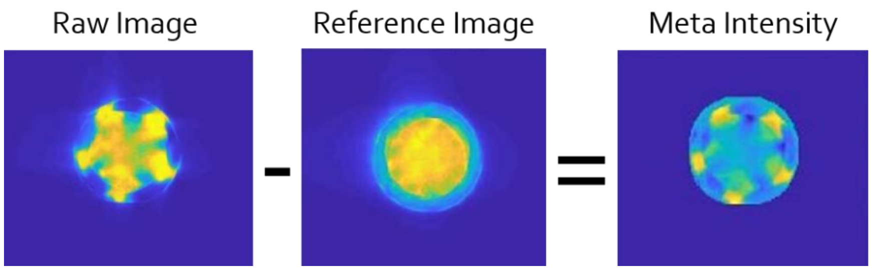

Figure 2: Sample meta-intensity calculation using the Flattened Pyramid sensor.

For traditional wavefront sensors like the Shack-Hartmann WFS and Pyramid WFS, slope offsets can be applied to correct for non-common path aberrations (NCPAs) caused by static aberrations of optical elements. For the Flattened Pyramid Wavefront Sensor, the reference image serves as the target and by extension the slope offset.

2. OPTICAL DESIGN

A pyramid with such small apex angles is technically difficult to manufacture. For this reason, other optical elements were used to emulate the optics of a flattened pyramid. Fauvarque et al. [1] used a Spatial Light Modulator (SLM) for a similar effect.

2.1 "Flattening" the pyramid

An effective method of simulating a flattened pyramid uses a symmetric double pyramid prism made of a single glass. For this design, the entrance pupil is located at infinity. The beam passes through the double pyramid and is split into four parallel collimated beams. These collimated beams are then focussed by a lens onto a detector in a pupil plane where they overlap. This setup is shown in Figure 3. The symmetric double pyramid has the advantage being achromatic.

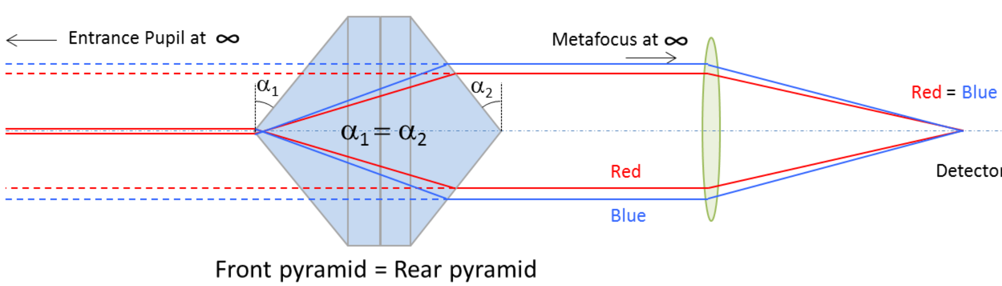

Figure 3: Flattened Pyramid Sensor design using a symmetric double pyramid prism.

2.2 Optical bench setup

In this experiment, the Narrow Field Infrared Adaptive Optics System (NFIRAOS) [2] double pyramid was used instead. This pyramid is not symmetric but has an apex angle difference of 2°. For this reason, an additional lens was placed in front of the pyramid in the testing setup in order to conjugate the entrance pupil with the meta-focus of the pyramid [3] where the four beams intercept.

As an additional feature, the system was designed on an adjustable rail system to achieve any intermediate shear of the pupil images and keep the ability to use the prism as a ‘regular’ PWFS, as shown in Figure 4. This allowed us to investigate the impact of the pupil shear and compare the performance of the FPWFS with the regular PWFS (Sec. 4). The optical components of the rail system are visible in Figure 5.

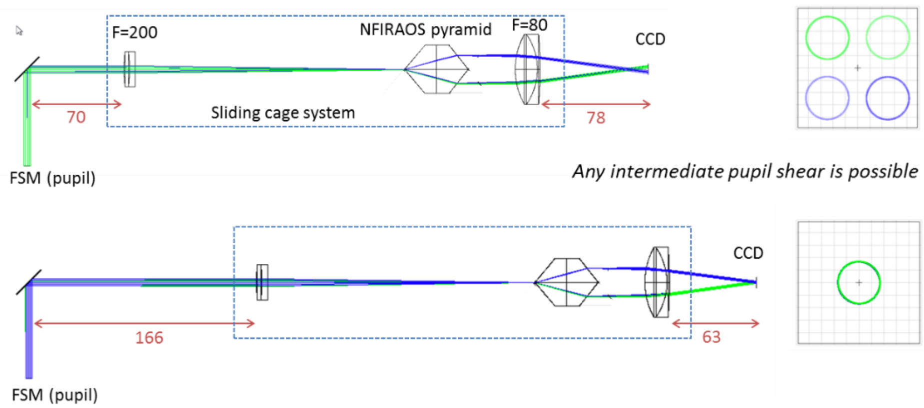

Figure 4: The optical layout for the FPWFS experiment using the NFIRAOS double pyramid (dimensions in mm)

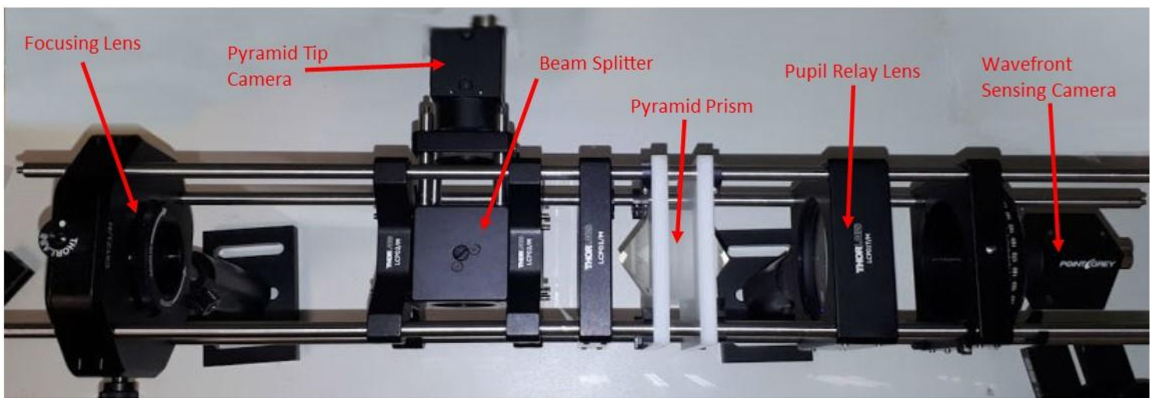

Figure 5: The cage system used for testing the FPWFS

The HAA test bench has a 655nm LED source, an ALPAO DM-97 deformable mirror and an Imagine Optic HASO 3 Shack Hartmann WFS located independently from the pyramid. The science camera used for this experiment was conjugated to the focal plane of the pyramid tip. The detector used was a Point Grey Blackfly S CMOS detector. It was clocked at 45° to match the pupil images orientation and minimize the number of required pixels. Modulation of the beam about the pyramid tip was controlled by a high speed tip-tilt mirror from PI which moved the beam in a circle.

3. FLATTENED PYRAMID WAVEFRONT SENSOR RESULTS

The Flattened Pyramid Wavefront Sensor was successfully implemented on the HAA test bench. The sensor was only able to close an adaptive optics control loop using a modal control. It is not well understood why a zonal control was unsuccessful.

3.1 Effects of Modulation

Modulation of the beam around the pyramid tip increases the linear range of the PWFS. This same approach was applied to the flattened pyramid. In order to study the effects of modulation, a modal interaction matrix was developed. Zernike modes were applied to the DM using the Shack-Hartmann sensor as a reference to create the desired shapes. In order to determine the linear range of the FPWFS, these same shapes were re-applied to the DM and the output of the sensor was evaluated. Figure 6 shows the results of this test without modulation, with modulation of 1.5λ/D and 4λ/D. If the sensor were perfect, the ideal response would be a straight line at a 45° incline.

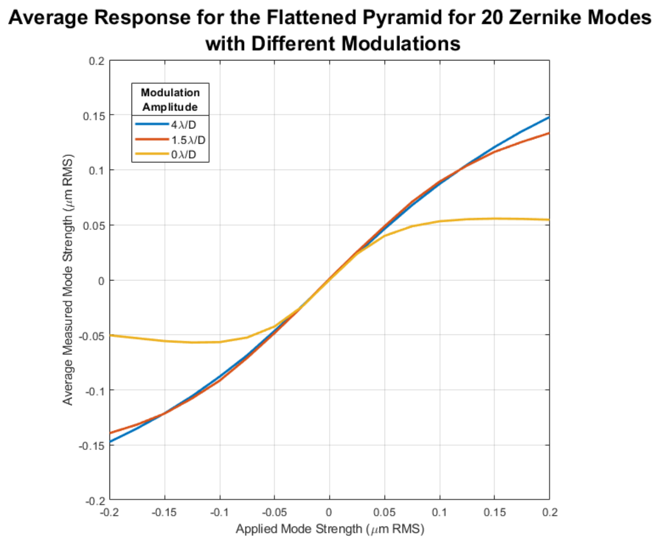

Figure 6: Linear response of the FPWFS

All of the modulations provide a linear response in the range of -0.025μm RMS to 0.025μm RMS. Figure 6 shows that modulation increases the linear range dramatically. This increase in range, however, comes at the expense of sensitivity. This linear range is extremely small, imposing some additional constraints on the sensor. The most problematic occurs because of non-common path aberrations. These are static errors caused by optical elements of the AO system such as beam splitters and lenses. If the science camera and wavefront sensor lie on different paths, which is generally the case in real instruments, the static offset may already be outside of the linear range of the sensor.

3.2 Modal Sensitivity

It was predicted that the FPWFS should provide better correction for high order modes [1]. The autocorrelation ($\vec{a}$) was determined for each mode from the interaction matrix (*IM*) using the formula given in equation (2).

$$\vec{a} = (IM * IM^T)^{-1} \quad (2)$$

Each element of the vector $\vec{a}$ corresponds to the reciprocal of the sensitivity of that mode. Zernike modes 2 to 21 are plotted in Figure 7. As the modulation is decreased, the sensitivity increases. In addition, this corroborates the observation that the FPWFS does not respond well to low order modes, tip and tilt. This result was also observed in the close loop result tests. This lack of sensitivity for tip and tilt is challenging because a mis-aligned beam on the pyramid tip will result in poor correction.

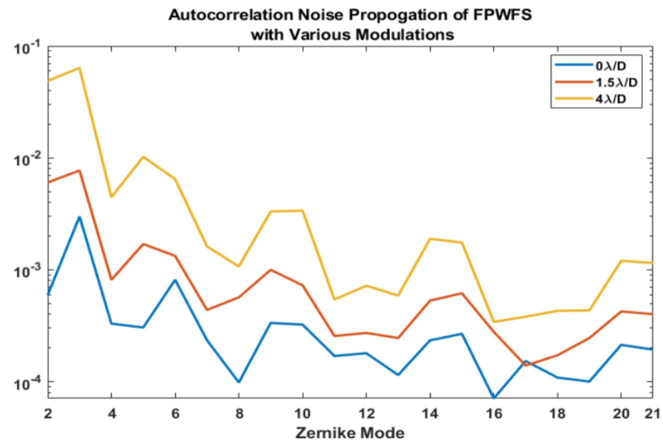

Figure 7: Autocorrelation of the FPWFS interaction matrix for different modulation

4. COMPARISON TO PYRAMID WAVEFRONT SENSOR

In order to compare the FPWFS to a PWFS, a series of standard static aberrations were applied to the DM and both pyramid sensor types closed the loop. The Shack-Hartmann WFS was used to evaluate the closed-loop performance of each pyramid WFS type. In general, the PWFS performed better than the FPWFS. Figures 8 and 9 show the residual wavefront error after each iteration of the loop for different modulations. In these samples, the applied initial mode was 0.12µm RMS astigmatism. 0λ/D modulation is not shown for the PWFS because it did not converge.

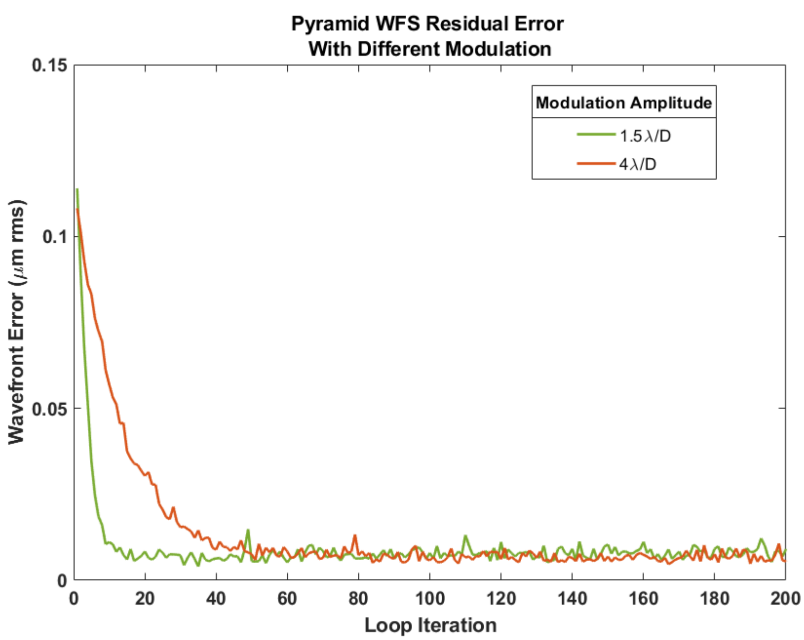

Figure 8: Residual Error for the Regular Pyramid

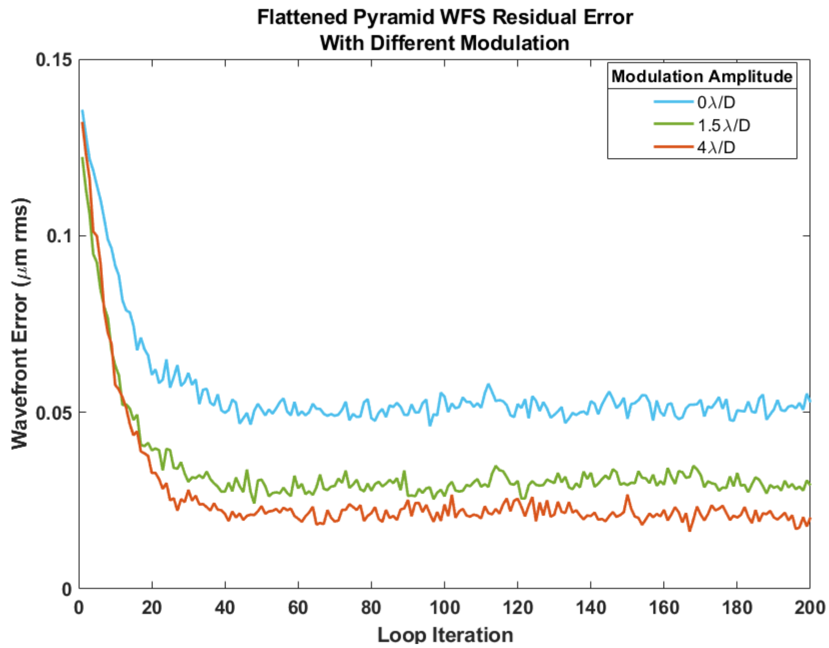

Figure 9: Residual Error for the Flattened Pyramid

Once again, the greater the modulation, the better the quality of the wavefront correction when using the FPWFS. In these tests the PWFS achieved a more accurate and reliable correction to the wavefront. It is valuable that the FPWFS was able to converge without modulation. In comparison with some of the other advantages described earlier, the FPWFS required only 40% of the light required by the PWFS to operate and the detector area required was 50% of the original size.

5. CONCLUSIONS

A Flattened Pyramid Wavefront Sensor was successfully implemented using a double pyramid prism. The FPWFS was able to close a loop for small modes while using approximately half the light required for the PWFS. However, the conventional PWFS remains more reliable and robust for closing an adaptive optics 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 whether the diffracted light that is cropped by the PWFS mask is valuable for the FPWFS.

ACKNOWLEDGMENTS

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