The use of an axicon beam-shaping element in non-modulated pyramid wavefront sensors

COPL Centre d'optique, photonique et laser

UNIVERSITÉ LAVAL

Guillaume Allain[1], Denis Brousseau[1], Simon Thibault[1], Jean-Pierre Véran[2]

[1] Université Laval, Centre d'optique, photonique et laser

[2] CNRC Herzberg, Institute of Astrophysics

Objectives

- Develop a wavefront sensor used to measure low order aberration in high contrast imaging instruments. (LOWFS)
- The low photon count due to high refresh rate leads us towards using a pyramid-based wavefront sensing (PWFS) method for a more efficient reconstruction.
- The level of precision needed and the intended use in space-like conditions imposes non-time-modulated options.
- The manufacturing defects of the apex in available pyramids can be problematic as most of the energy is concentrated there and could be scattered, thus unusable for wavefront sensing

Use of an axicon

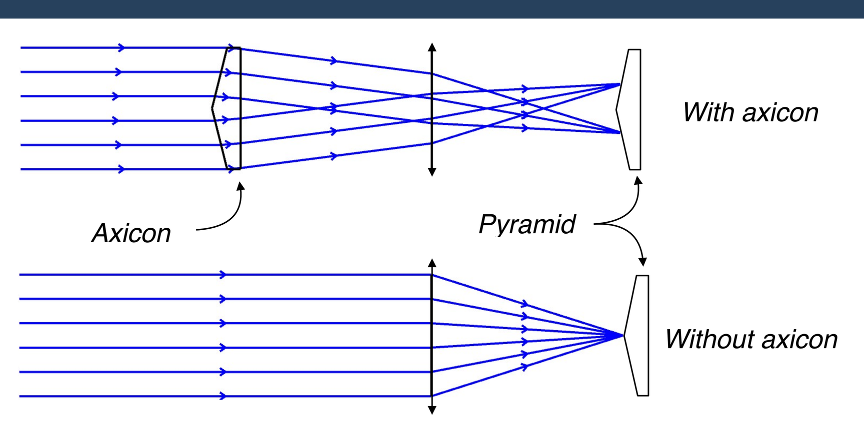
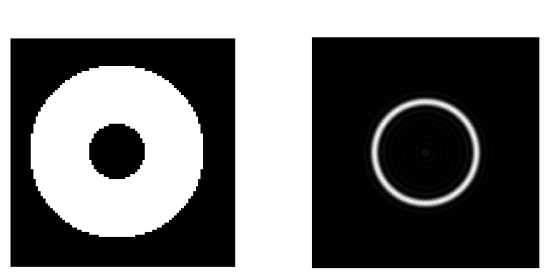


Fig 1. Effect of an axicon on the PSF

An axicon is a radially symmetrical optical element shaped into a cone (or a pyramid having an infinite number of sides). Its effect on a collimated beam is to split the point spread function into a symmetrical annulus around the optical axis. This guarantees that next to no light is incident to the apex of the pyramid.

When placed at the pupil plane of a telescope having a central obscuration, the axicon apex defects can be ignored while maintaining the annulus in the image plane (where a pyramid would be located). The effect can be viewed as a type of « spatial modulation », where a conventional PWFS would use dynamic modulation (using a tip-tilt mirror).



a. Pupil plane *b. Image plane*

Fig 2. Irradiance footprint in different planes

Python simulations

An object-oriented python program has been written to simulate an axicon-pyramid wavefront sensor. This modular program can also be used to simulate other kinds of phase shifting optical elements for wavefront sensing studies.

The code is based on Fourier optics to approximate the behavior of an adaptive optics system. Effects such as limited photon count and dispersion can be taken into account.

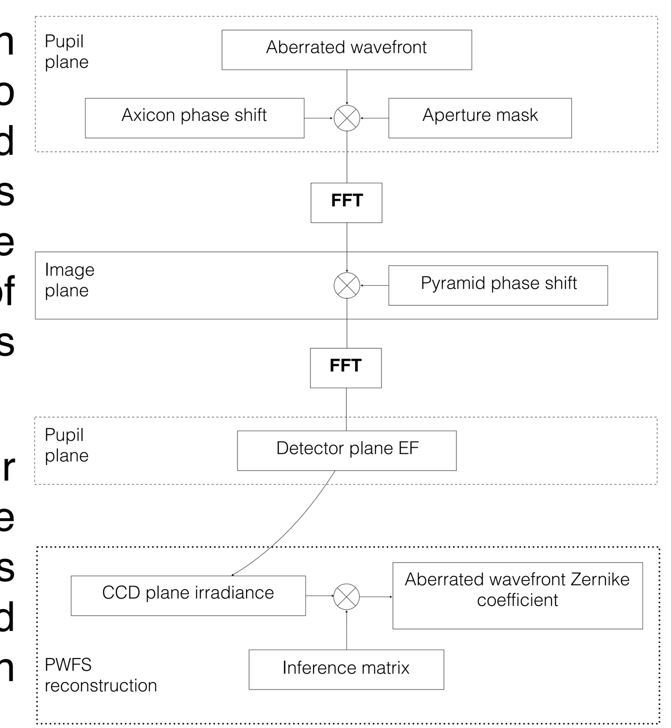
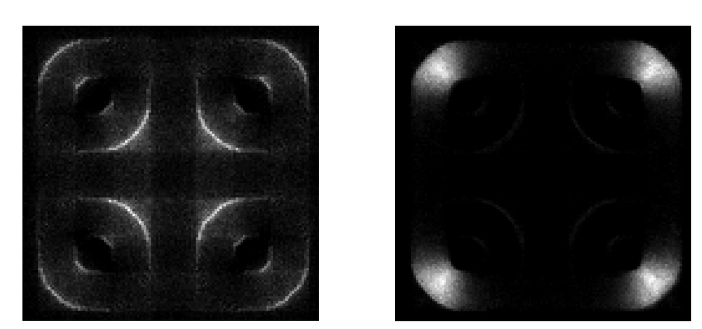


Fig 3. Python code flow chart

Figure 4 shows a typical exemple of CCD image plane that is returned when running the program. It is possible to see how the axicon shifts the light on the outside of the imaged sub-pupils



a. Conventional pyramid *b. Added axicon in pupil plane*

Fig 4. Imaged sub-pupils (no aberrations)

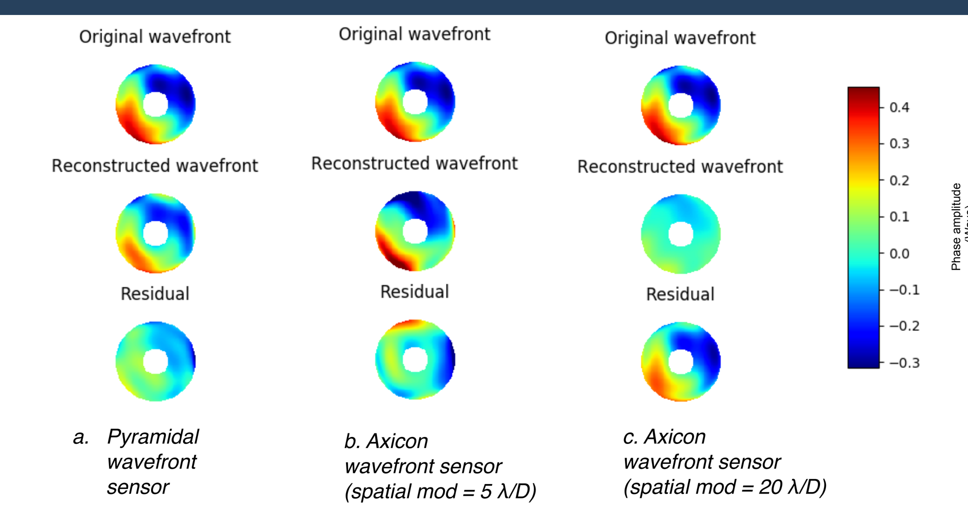


Fig 5. Wavefront reconstruction examples for conventional PWFS and axicon-PWFS approach

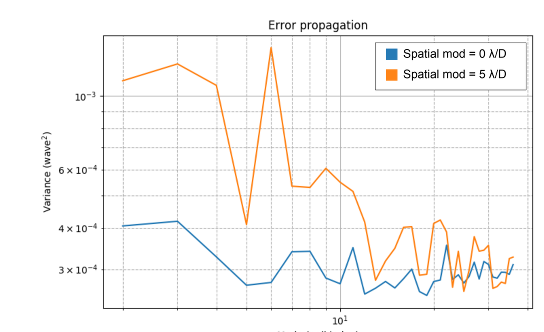
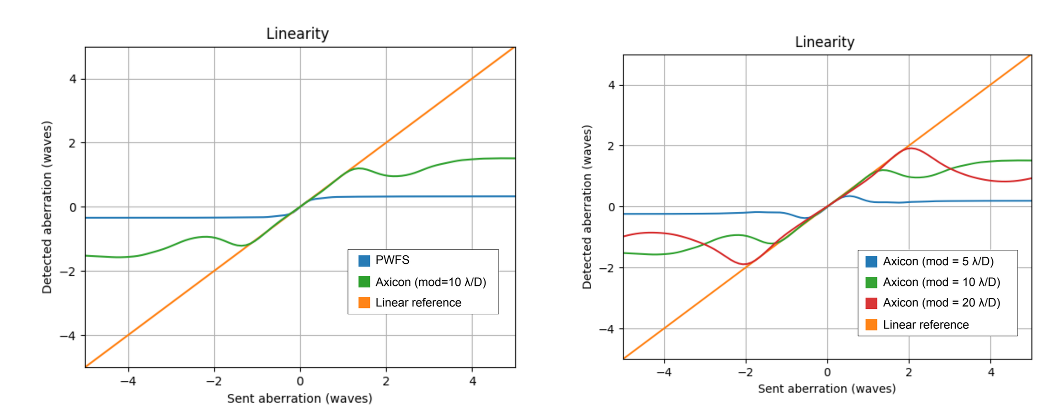


Fig 6. Noise propagation computed as variance of noisy (shot noise) reconstruction



a. Comparison between un-modulated PWFS and axicon-pwfs approach. *b. Comparison between different spacial modulation amplitudes*

Fig 7. System reconstruction linearity for tilt aberration

Preliminary lab results

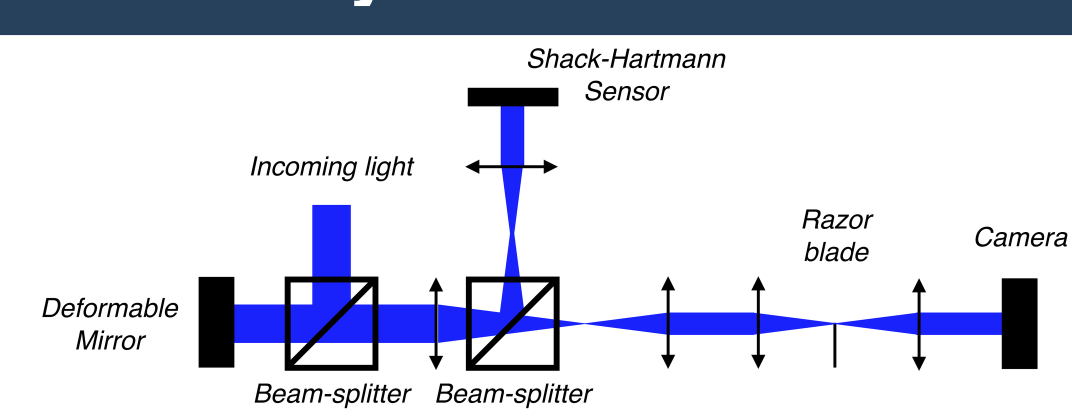
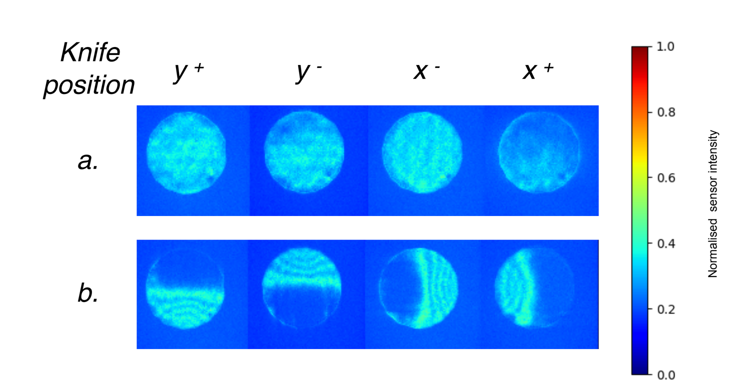


Fig 7. Optical schematic of the test bench

A prototype of the LOWFS was designed by modifying an existing AO test bench. Because no pyramid was available at the time, a moving razor blade was used as a way to split the image plane beam. Different aberrations can be generated by closing the loop using an ALPAO DM and a Shack-Hartmann sensor. The axicon phase shift is added numerically to the aberration induced by the deformable mirror.

In the case of a 1D pyramid system (where the pyramid only has 2 faces), the intensity distribution in the imaged pupil is very similar to the simulations. This setup makes it possible to reconstruct simple wavefront aberrations using both system and confirm the differences outlined by the python simulations.



a. Conventional pyramid *b. Added axicon in pupil*

Fig 8. Pupil image at different knife positions

Next steps

HiCIBaS

The *High Contrast Imaging Balloon System* (*HiCIBaS*) is a balloon-borne telescope developed by the LRIO at Université Laval. The mission is focused on testing new optical components for future high contrast missions in space-like conditions. It will also be possible to record the behavior of atmospheric turbulence at a 35km altitude.

The combination of an axicon and a pyramid wavefront sensor makes it interesting for this type of mission because it is free of moving components, retains the attributes of a pyramid wavefront sensor and increase linearity response.

On-sky data

An early version of the wavefront sensor is currently being designed and will be tested at the 1.6m telescope of the *Observatoire du Mont-Mégantic* using Université Laval's AO test bench. Université Laval's on-sky AO test-bench[1] is designed to directly compare two types of wavefront sensor on-sky at the same time. A Shack-Hartmann sensor will be used for closing the loop on the sky while leaving controlled residual levels of low-order aberrations to be measured by the axicon-pyramid sensor.

1: On-sky AO test bench ", Proc. SPIE 9909, Adaptive Optics Systems V, 99092V (August 11, 2016); doi:10.1117/12.2233029;

Partners

The *HiCIBaS* project is supported by the FAST grant from CSA that fund s university research project on space-like missions.

Nüvü camera's EMCCD are used as the main camera for the LOWFS that will be used on the *HiCIBaS* project.