PSF sharpening & post focal sensing for the VORTEX coronagraph

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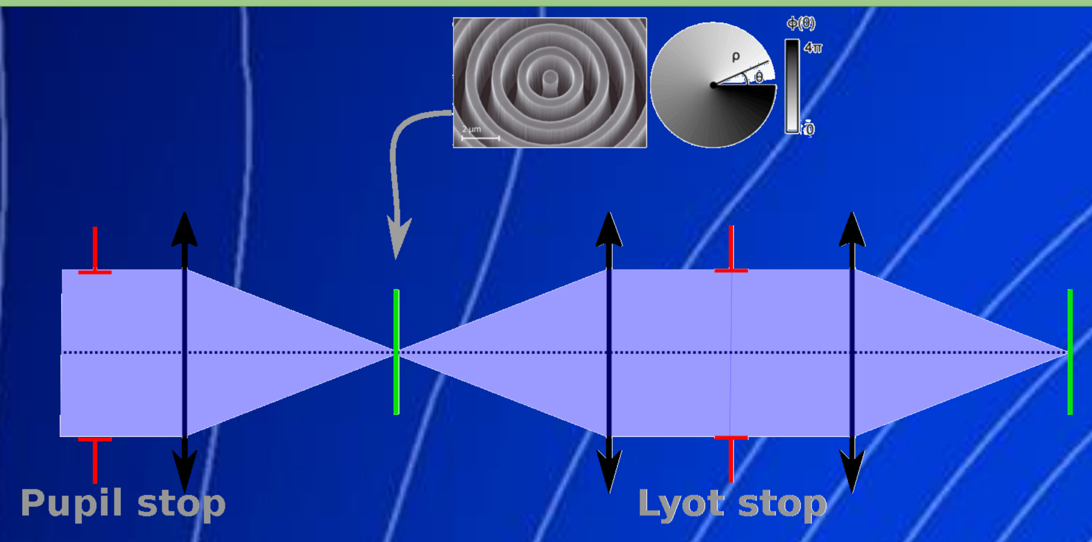
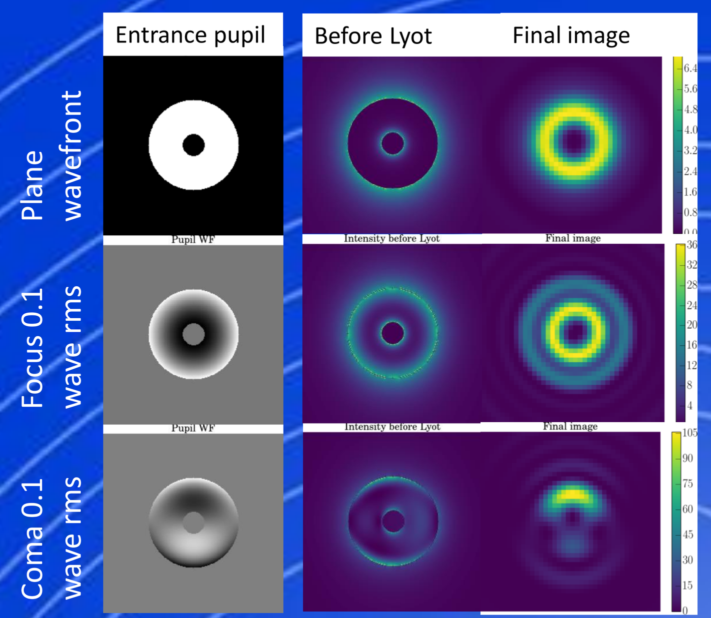
I. The vortex coronagraph



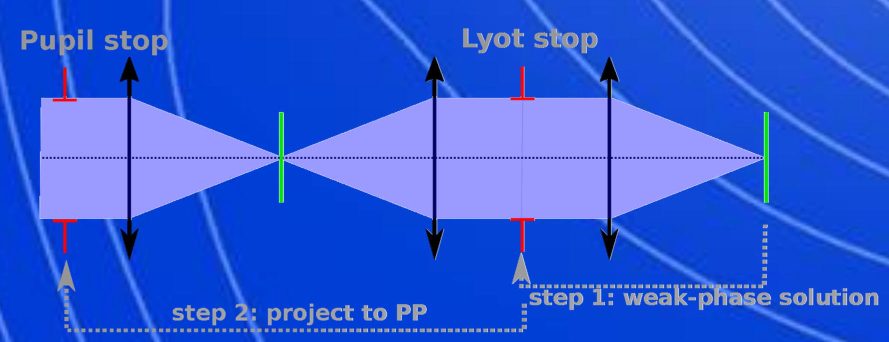


Vortex coronagraphs feature vortex phase masks in their focal plane. The textbook effect is to move the light of an on-axis source outside the geometrical image of the input pupil. Combined with a Lyot stop, it theoretically rejects perfectly the starlight for a clear circular aperture.
One implementation is the annular groove phase mask (AGPM) based on a concentric subwavelength grating etched onto a diamond substrate.
The AGPMs were first installed on VLT/NACO and VLT/VISIR in 2012, followed by LBT/LMIRCam in 2013 and Keck/NIRC2 in 2015.

One key aspect is the control of low-order aberrations to minimize starlight leaks through the Lyot stop. For tip-tilt, a method labelled QACITS has been specifically developed for the vortex and is now available in shared-risk mode at Keck/NIRC2.
The present contribution is intended as a preliminary exploration of LOWFS solutions based on the science images, and tests on the VODCA bench.

III. Weak phase solution with the vortex

The solution proposed here consists in two major steps:
1. Using three images (and known phase diversity), estimate the electric field in the Lyot plane
2. Decompose the real and imaginary part in Zernike modes, and project the results to the pupil stop



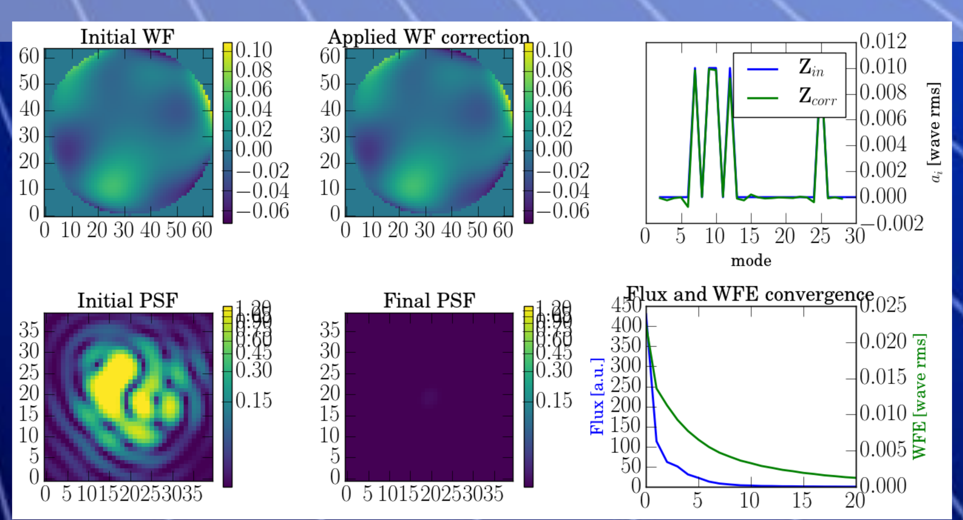
Step 1.: Under the small aberrations hypothesis, the 3 collected images with phase diversity can be written

$$p_1 = |e_1|^2 = |a + ib|^2$$
$$p_2 = |e_2|^2 = |(a + a_{d1}) + i(b + b_{d1})|^2$$
$$p_3 = |e_3|^2 = |(a + a_{d2}) + i(b + b_{ds2})|^2$$

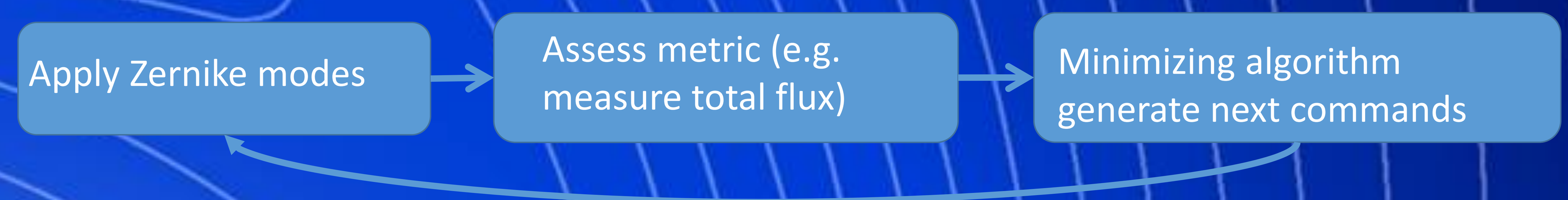
Using the three images *p1, p2, p3*, and knowing a_{d1}, b_{d1}, a_{d2}, b_{d2} (from known phase diversity and model of the coronagraph), one can algebraically get *a, b*, thus the electric field in the Lyot plane $E_{lyot} = \mathcal{F}^{-1}\{a + ib\}$.

Step 2.: Huby et al. have shown that for a circular aperture $E_{lyot} = \mathbf{i}\sum\zeta_j$ with ζ_j a complex function of Zernike polynomials. Thus, after appropriate decomposition of E_{lyot}, one can convert ζ_j to $\boldsymbol{Z_j}$ in the pupil plane.

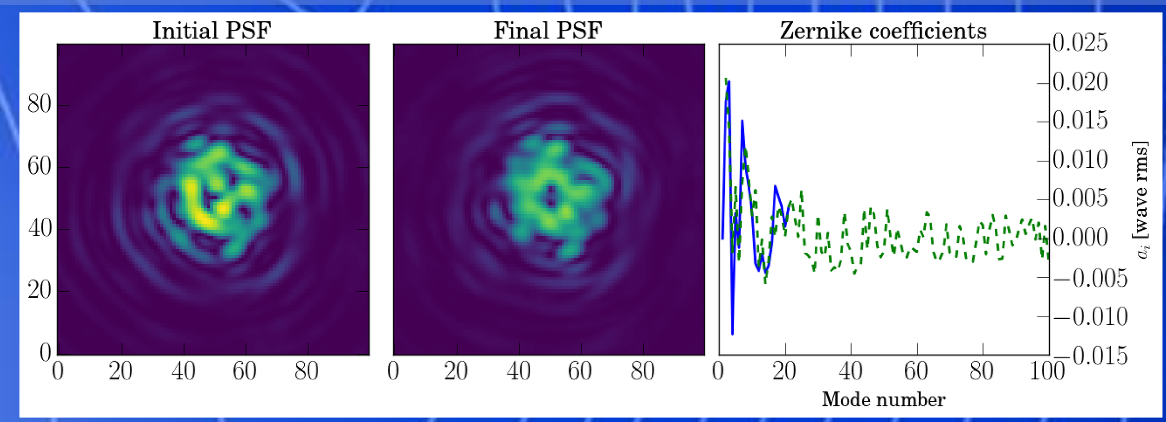
The method is implemented as an iterative procedure, applying a spatial filter when recovering Elyot, and using an integrator and a leaky gain to improve stability.
This is illustrated for a circular aperture and with a few injected modes.



II. PSF sharpening for coronagraphy



As the diagram suggest, the technique aims at minimizing a metric (e.g. max peak intensity for classical imaging or min of the flux in the coronagraphic case) by optimizing a given set of modes.
Using images behind a vortex should allow a more sensitive metric than the Strehl ratio due to the coronagraph sensitivity to aberrations.



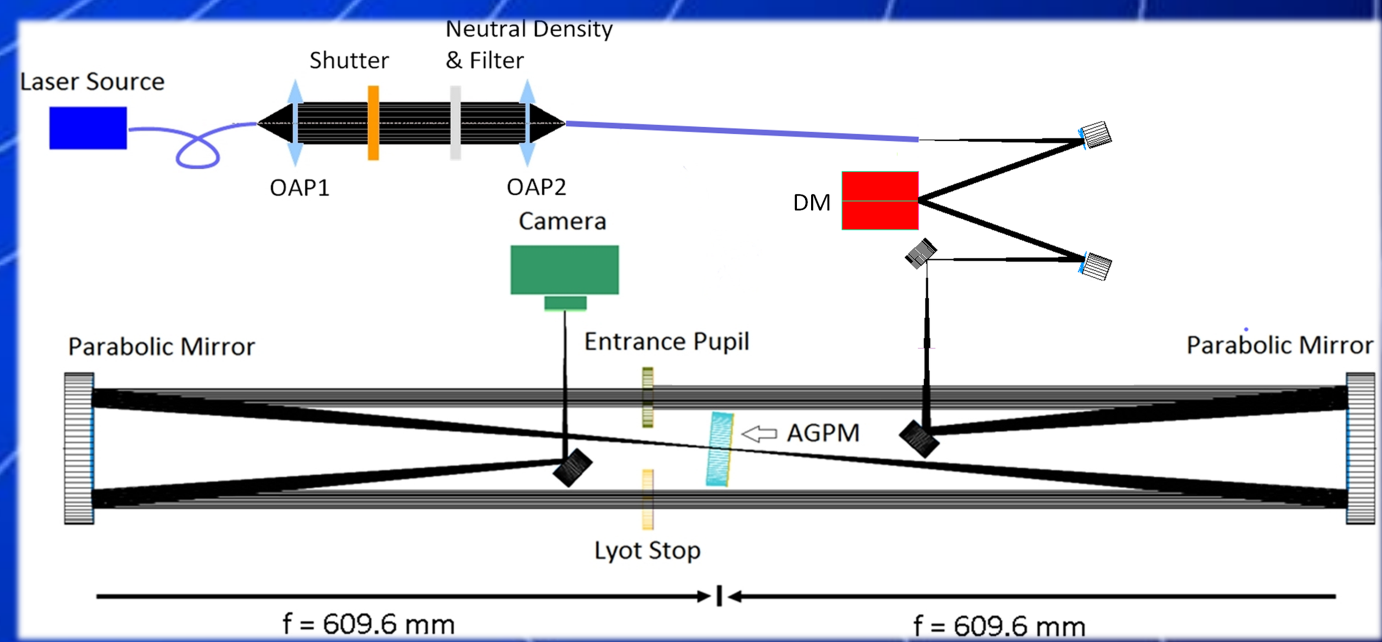
We simulate an aberrated vortex PSF with 100 modes and minimize the flux by optimizing the first 21 modes. The algorithm retrieves accurately the first modes, providing an improved starlight rejection.
This method however requires a large number of frames to perform the minimization.

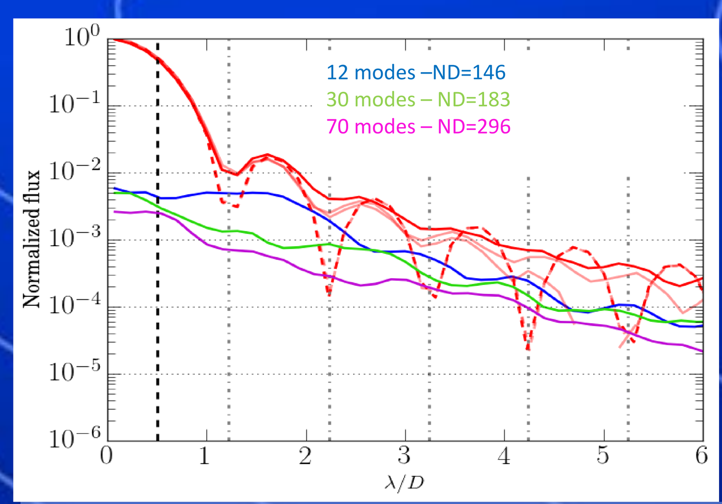
IV. Prospects with VODCA, Vortex Optical Demonstrator for Coronagraphic Applications

VODCA is an achromatic coronagraphic test bench developed at ULg designed to operate in the NIR from ~1 to 5 µm (H to L band), aiming at assessing each AGPM performance precisely.
Its main characteristics are:
- Fully reflective
- Supercontinuum laser source to deliver a broadband beam
- FLIR camera, an infrared InSb camera cooled to 77 K operating at wavelengths ranging from 1.5 to 5 µm
- ALPAO DM-97 currently being integrated

With its DM, it allows to study the influence of aberrations on the delivered performances and test suitable techniques to control NCPA.

A preliminary test with the focal sharpening approach is shown here below





Proof of concept with non-optimum calibration

Prospects are:
- Finalize the integration and calibration of the DM
- Implement the WFS techniques on the bench and optimize them
- Establish the AGPMs intrinsic performances (rejection ratio)

References

Absil et al. 2016: Three years of harvest with the vector vortex coronagraph in the thermal infrared
Huby et al. 2015: Post-coronagraphic tip-tilt sensing for vortex phase masks: the QACITS technique
Mawet et al. 2005: Annular Groove Phase Mask Coronagraph