Post-coronagraphic PSF sharpening with the vortex coronagraph

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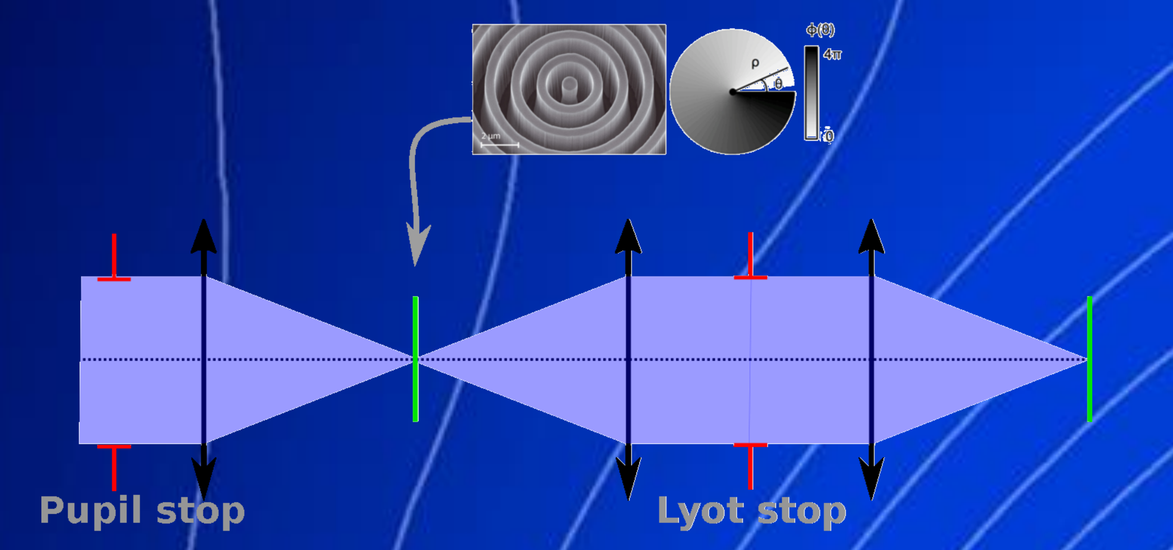
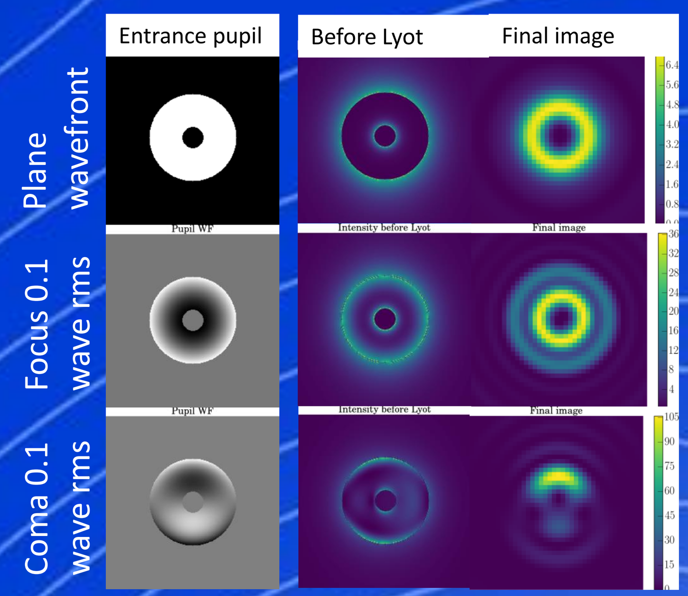
I. The vortex coronagraph





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.

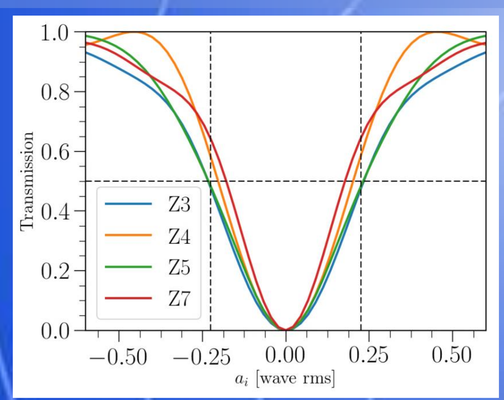
One implementation is the annular groove phase mask (AGPM) based on a concentric subwavelength grating etched onto a diamond substrate.

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 in small angle coronagraphy is the control of low-order aberrations to minimize starlight leaks through the Lyot stop. The leak quickly increases with the level of aberrations, as illustrated on the right for Zernike modes.

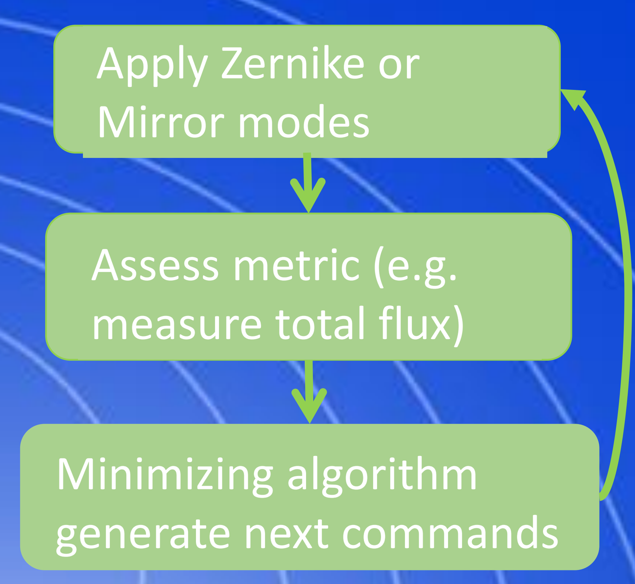
A proper control of LOWFS / NCPA allows to correctly assess the intrinsic performances of the coronagraph, and potentially improves the on-sky operations.

Here, we present two methods and one laboratory demonstration.



II. PSF sharpening for coronagraphy

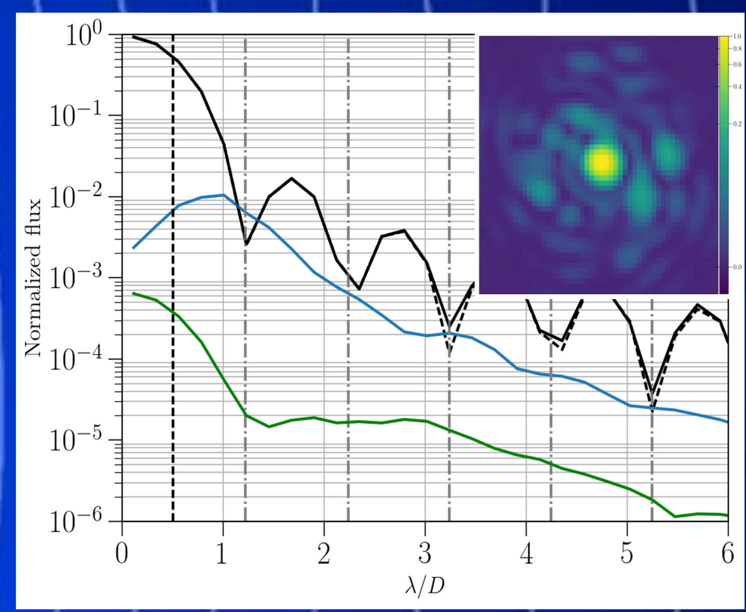
The empirical method is based on the optimization of a given metric. In our case we minimize the flux in the image plane by optimizing a given set of modes, see the sketch below. Using images behind a vortex is much more sensitive than classical PSF sharpening typically maximizing the Strehl ratio.



Simulation & Result

We simulate an aberrated vortex PSF with 100 modes (blue) and minimize the flux by optimizing the first 91 modes. A residual aberration of 20nm wf rms is added to provide a more realistic curve (green). The final post-vortex PSF is represented top right and can be compared to lab measurements below.

The method works well in simulation: it is robust and accurate. It is however time expensive as it requires a large number of frames to perform the minimization.



III. Application on 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 optics
- Supercontinuum laser source to deliver a broadband beam from 1 to 4µm
- FLIR camera, an infrared InSb camera cooled to 77 K operating from 1.5 to 5 µm
- ALPAO DM-97, with the 13.5mm clear aperture acting as entrance pupil.

To control the DM we choose to use a mirror modal basis built by SVD decomposition of the influence function matrix, and additionally including pure tip and tilt.

Data are acquired at 60Hz with 40 images averaged at each iterations. With 1000-10000 function evaluations, the minimization can take up to about 1 hour (depending on the number of modes optimized).

Laboratory results

We apply the focal plane sharpening method on one AGPM with a wide L-band filter (3.5-4µm), see right.

One can see that the peak rejection ratio is quickly achieved (>1:1000 here) as the number of corrected modes is increased. The control radius is also seen to recede to larger radii.

The estimated level of speckle noise on the bench is ~1 – 2 × 10^{-5} in the 0-4 λ/D – consistent with the DM best flat WFE. The contrast at > 1.5λ/D is ~2 ×10^{-5} or about 11.7mag.

Limitations are:

- Jitter and turbulence on the bench,
- Flux variation (from source)
- Ultimately the DM best flat and stability
- Time consumption

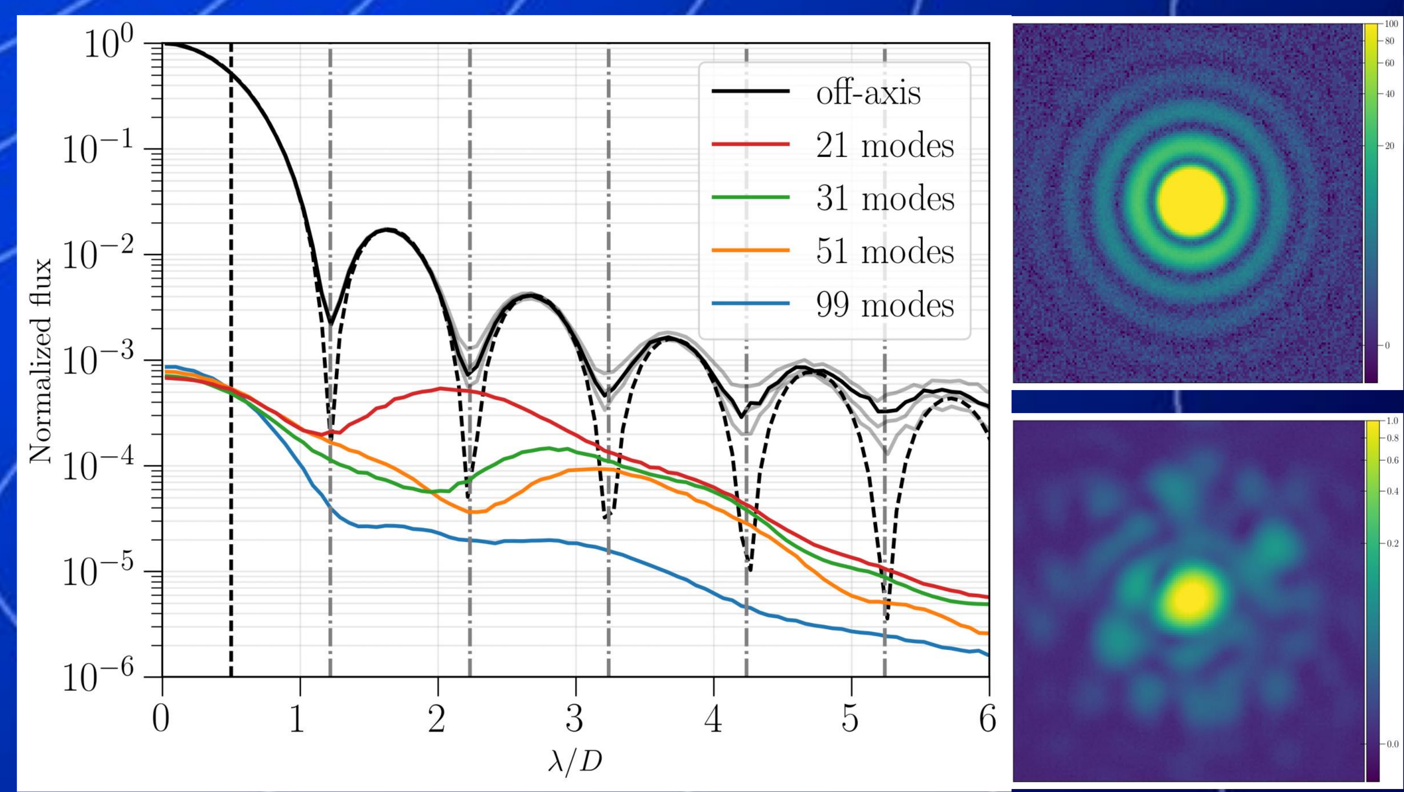
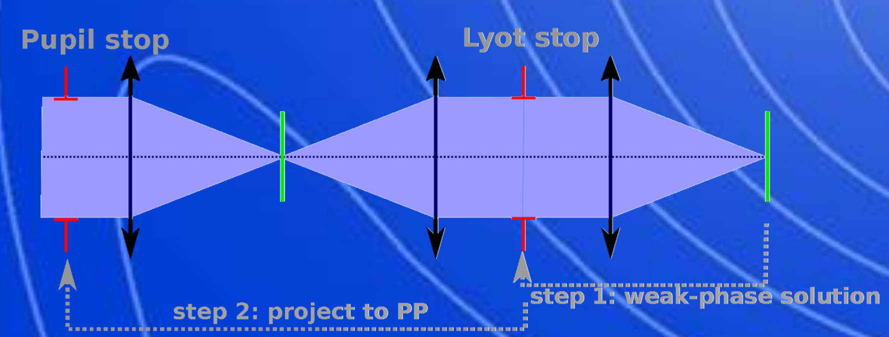


Figure right. Off-axis (top) and coronagraphic (bottom) PSF with all modes corrected. Images are represented in arcsinh scale. The coronagraphic image is scaled by a factor 100 and the off-axis images is saturated in the core. The first Airy ring can be partially seen in the coronagraphic image.

IV. Weak phase solution with the vortex

The solution proposed here consists in two major steps:

1. Using 3 images (2 with known *phase or amplitude* 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



In some more details…

Step 1.: Under the small aberrations hypothesis, the 3 collected images with 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 or amplitude diversity and model of the coronagraph), one can algebraically get *a* and *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 $E_{lyot} = \mathbf{i}\sum \boldsymbol{a}_j \zeta_j$ with $\boldsymbol{a}_j$ the Zernike coefficients in the pupil plane, and ζ_j a complex function of Zernike polynomials: $\zeta_j = \sum \boldsymbol{C}_{jk} Z_k$. Thus, after appropriate decomposition of E_{lyot} in Zernike coefficients $\boldsymbol{b}_j$, one can recover the Zernike coefficients $\boldsymbol{a}_j$ in the pupil plane:

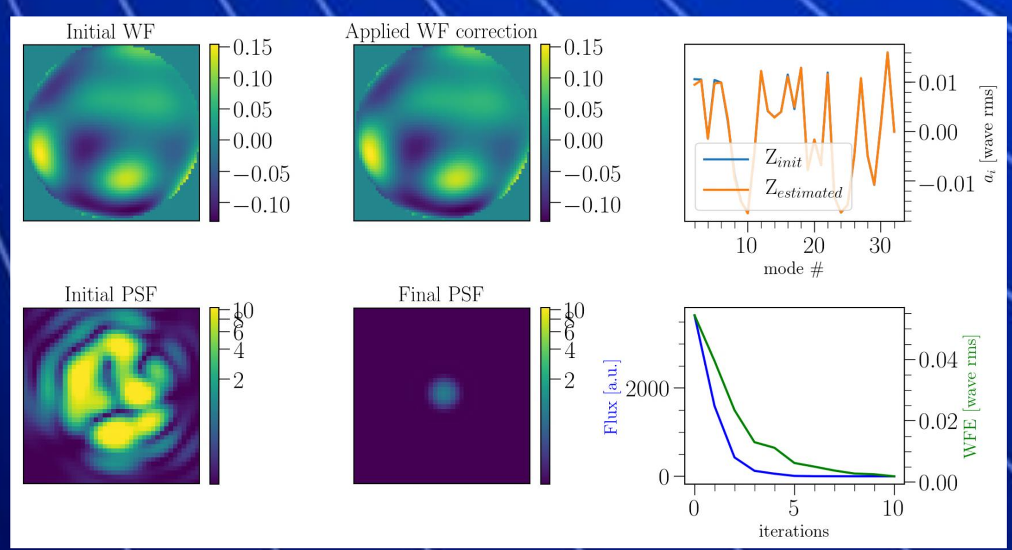
$$a = (b_{real} + i\, b_{imag})[-C_{imag} + i\, C_{real}]^{-1}$$

Simulation & result

The method is implemented as an iterative procedure using an integrator to improve stability.

We illustrate the method injecting 0.05 wave rms (~200nm at 3.75 µm) on 30 modes. We use amplitude diversities (0.25% and 1% of the pupil area). In just a few iterations, the simulation is able to recover the aberrations and drastically improve the on-axis rejection.

Operational range and stability, in particular in the case of annular pupils, requires further investigation.



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