A rotational shearing interferometer to sense across-the-spider phase discontinuity at ELT

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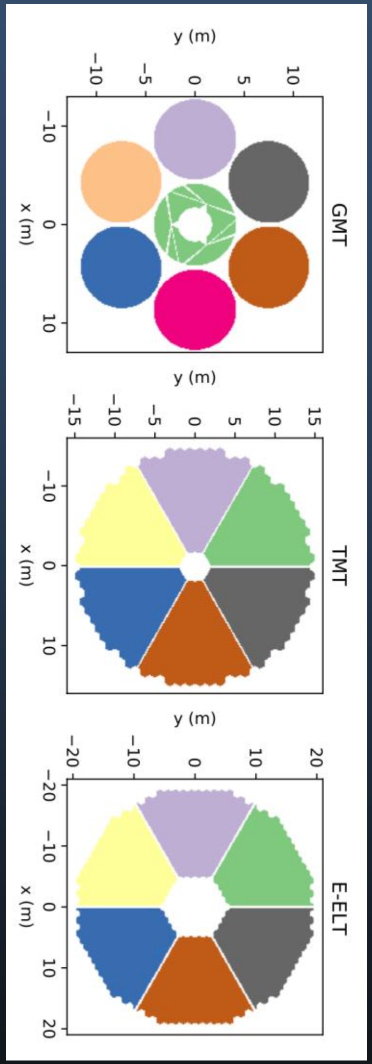
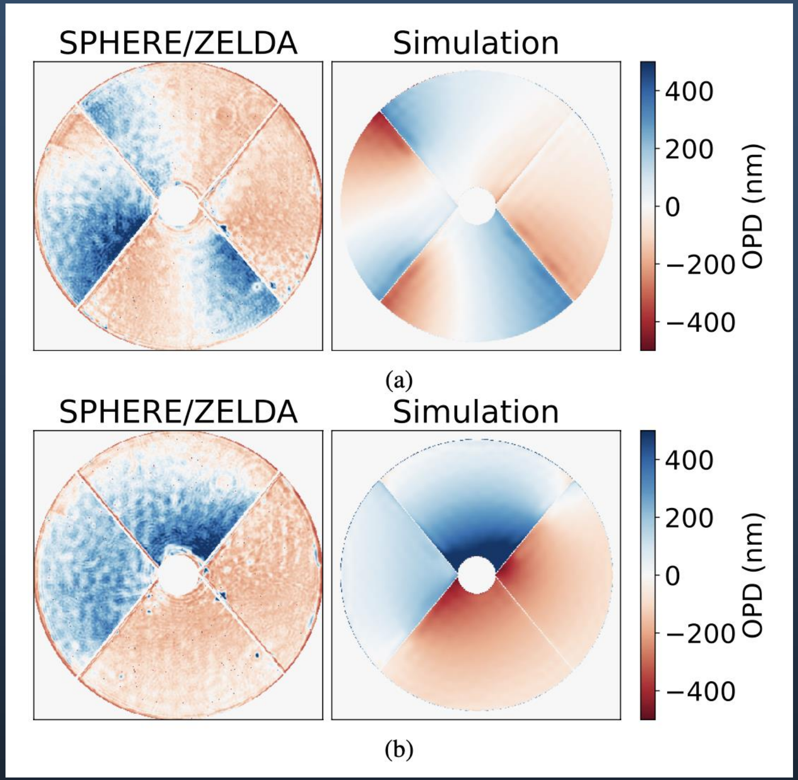
Why Yet Another Petalometer

- ELT/GMT have segmented pupil with thick spider shadows or gaps
- WFSs can't «easily» reconstruct the WF under the gaps
- Acting on DM control (slaving, POLC, …) may reduce unwanted petal pistons
- But is it what we want? Real phase jumps do exist across the spider – pistoning petals is not evil
- What we lack is the capacity to measure the wavefront jumps across the spider.



Wavefront jumps across the spider

Not only atmospheric turbulence, but Low Wind Effect, M1 footprint, …



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Astronomy & Astrophysics

Low-wind-effect impact on Shack–Hartmann-based adaptive optics

Partial control solution in the context of SPHERE and GRAVITY+

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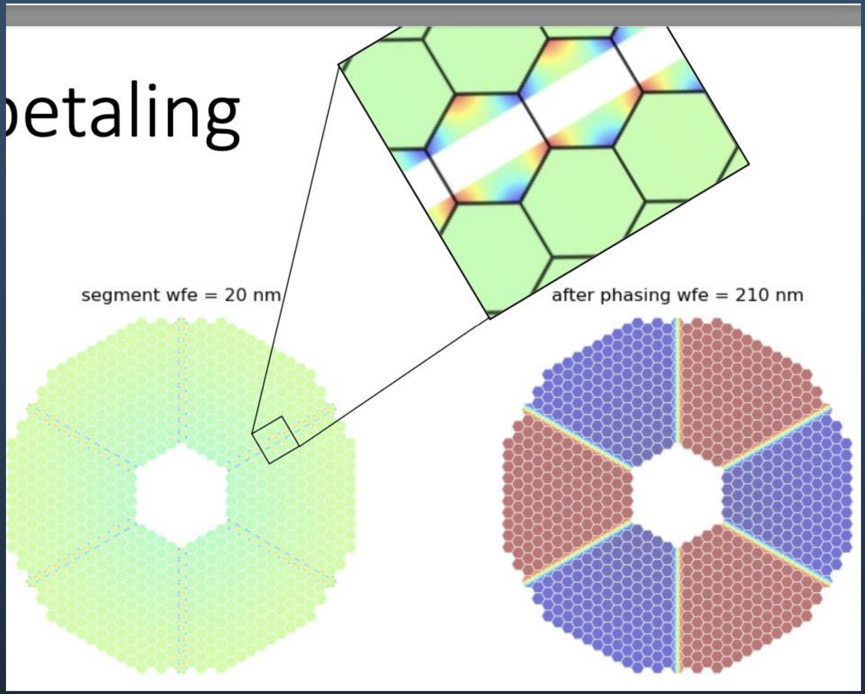
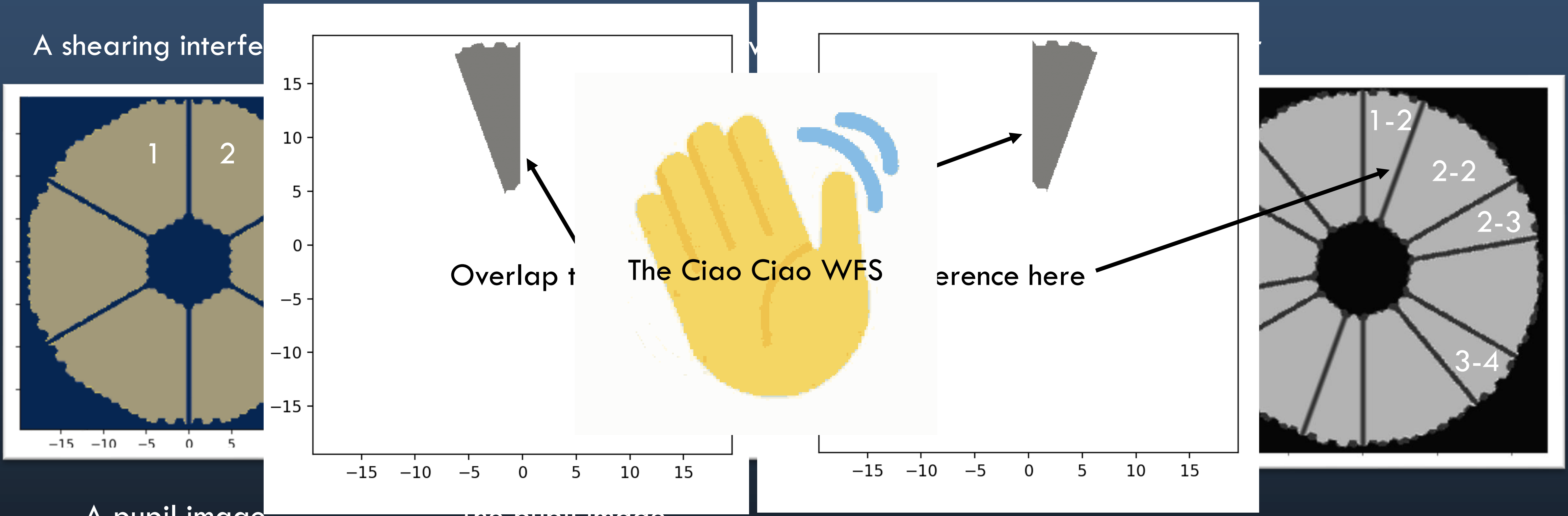


The Nuke wavefront
H. Bonnet, Petal day – Mar 22

WFS concept

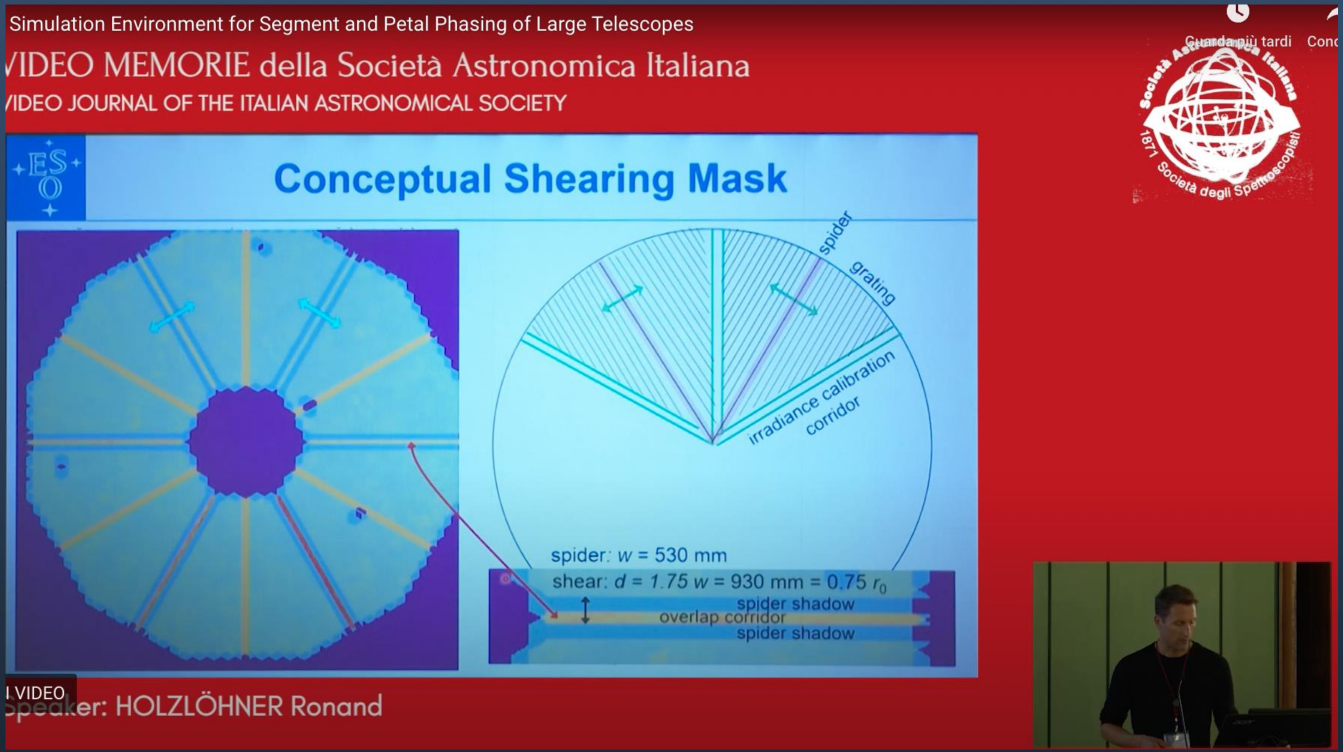
A shearing interfe



A pupil image

The pupil image rotated by $\alpha = 20°$

Other interferometric petalometers



Ron Holzloehner - WFS workshop Firenze
https://www.sait.it/node/470

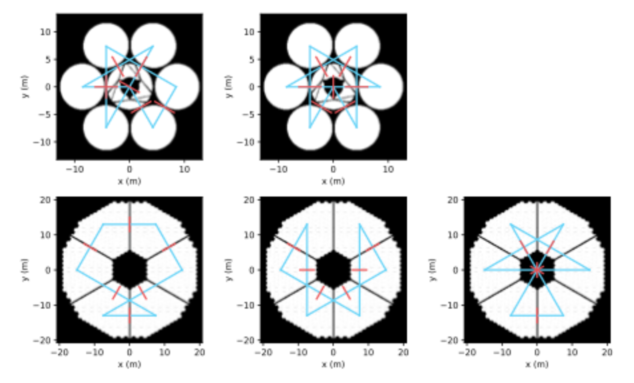


Fig 5 The top row shows the GMT aperture overlaid with the connected baselines. The E-ELT aperture overlaid with the connected baselines is shown on the bottom row. The blue lines show the baselines for each fringe, while the red lines show the direction of the dispersion. Due to redundancy of these pupils there is always 2 red lines that are parallel (the rest are unique). These two dispersion angles must be slightly tilted w.r.t. the perpendicular so as to not overlap. All 5 others are unique.

The Holographic Dispersed Fringe Sensors (HDFS): phasing the Giant Magellan Telescope

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Phase difference reconstruction

$E_1 = A_1 \cos(\omega$

$E_2 = A_2 \cos(\omega$

ssuming $A_1 = A_2 = A$

The phase diffe

Classic 4x $\pi/2$ phase shift to extend capture range to (-π, π)

$I^{\psi} = A + B\cos(\Delta\theta + \psi)$ with $\psi = n\ \pi/2$

$$\begin{cases} I^{0} = A + B\cos\Delta\theta \\ I^{\frac{\pi}{2}} = A - B\sin\Delta\theta \\ I^{\pi} = A - B\cos\Delta\theta \\ I^{\frac{3\pi}{2}} = A + B\sin\Delta\theta \end{cases}$$

$$\Delta\theta = \arctan\frac{I^{3\pi/2} - I^{\pi/2}}{I^{0} - I^{\pi}}$$

- It requires m
- Phase-shifting techniques can be used to extend the capture range to λ. More exposures - slower – needs piston mirror
- Multi-lambda is possible to extend beyond λ - even slower

Impact of residual turbulence

Splitting $\Delta\theta$ in

1. static phase jump j $= \Delta p = p_1 - p_2$ and
2. turbulence $\Delta\varepsilon(t) = \varepsilon_1(t) - \varepsilon_2(t)$ evolving during T

$$\frac{\langle I_{1,2}\rangle_T}{A^2} - 1 = \langle\cos(\theta_1 - \theta_2)\rangle_T = \langle\cos(\Delta p + \Delta\varepsilon(t))\rangle_T = \cos\Delta p\,\langle\cos\Delta\varepsilon(t)\rangle_T - \sin\Delta p\,\langle\sin\Delta\varepsilon(t)\rangle_T$$

$$\boxed{\langle I_{1,2}\rangle_T \propto \cos\Delta p\,\langle\cos\Delta\varepsilon(t)\rangle_T}$$

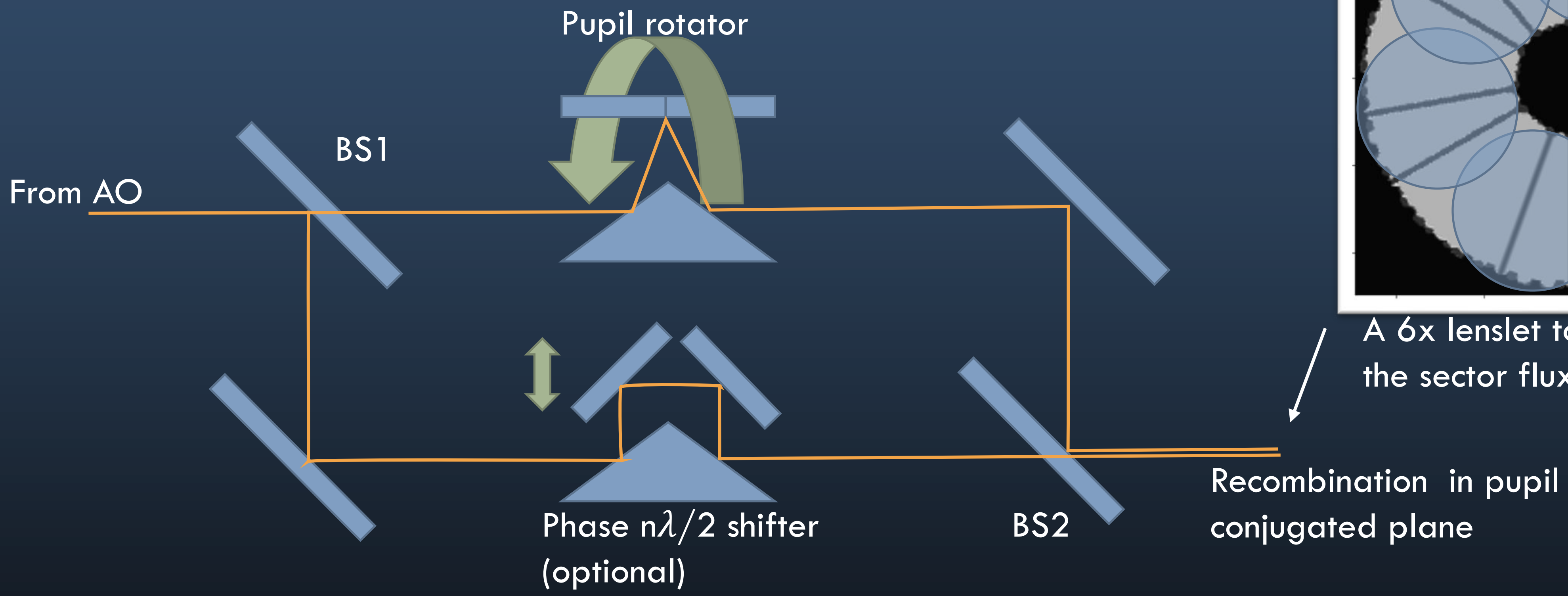
where $\langle\sin\Delta\varepsilon(t)\rangle_T = 0$ assuming $\langle\Delta\varepsilon(t)\rangle_T = 0$ and skewness $\Delta\varepsilon(t) = 0$

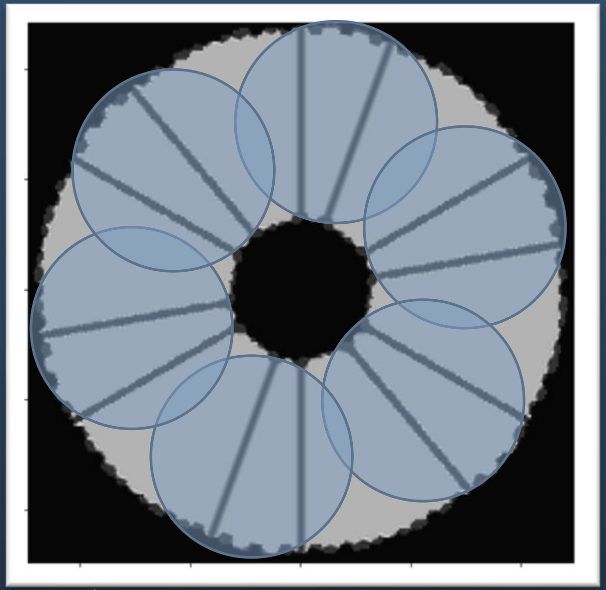
→ the spatial decorrelation of the turbulence biases the measurement of Δp with a factor < 1

Q: Can be estimated from the non-overlapping sectors (for large T)? Or calibrated?

Optical concept

Highly inefficient conceptual idea

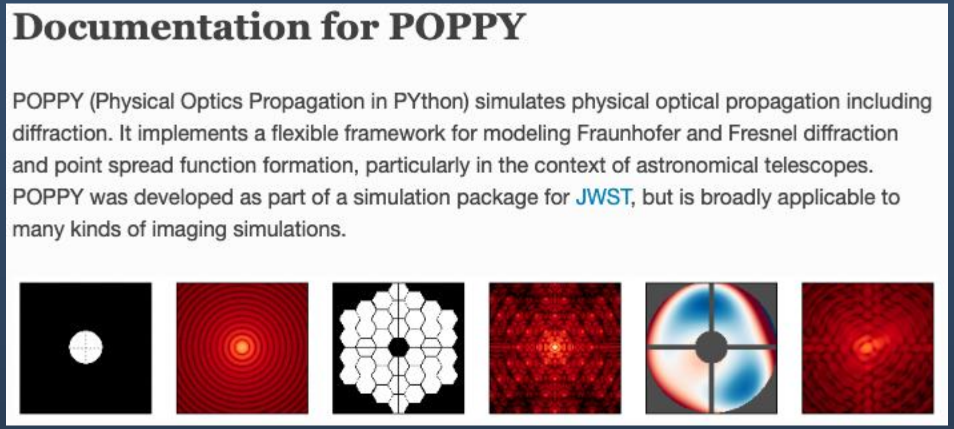




A 6x lenslet to collect all the sector flux onto 6 APD

Optical simulations

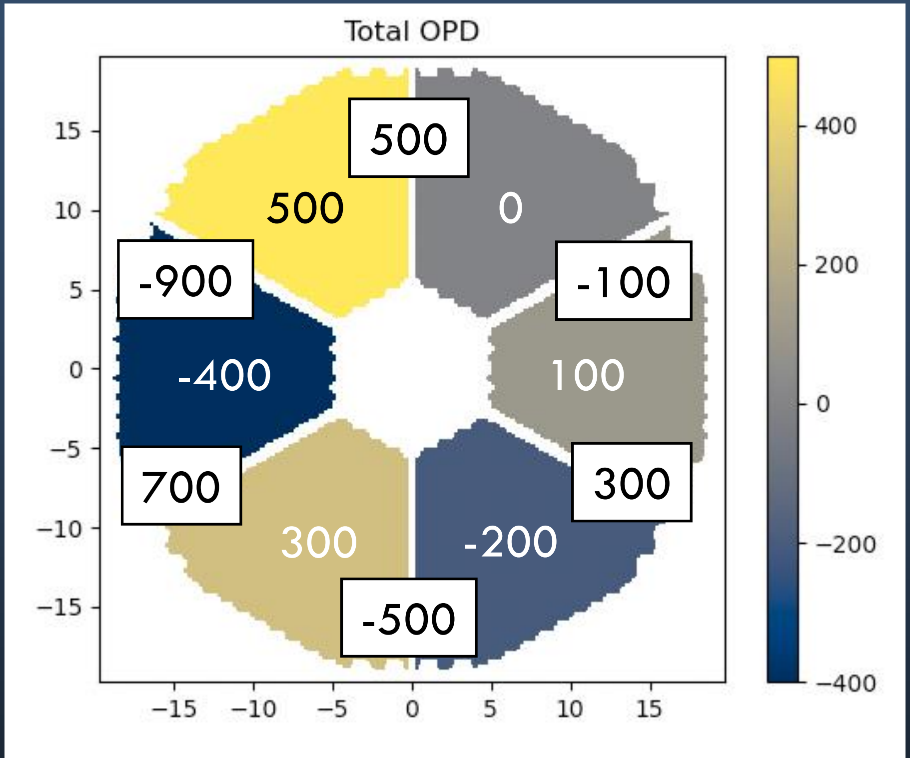
- Based on poppy
- Optical model consists of a stack of pupil layers
  - Residual turbulence from MORFEO simulations
  - Low Order Zernike
  - ELT Pupil Aperture
  - Petaled M4
  - Global Piston for phase shifting
  - Rotator
- 2 identical models are instantiated with different rotation. Output wavefronts are recombined

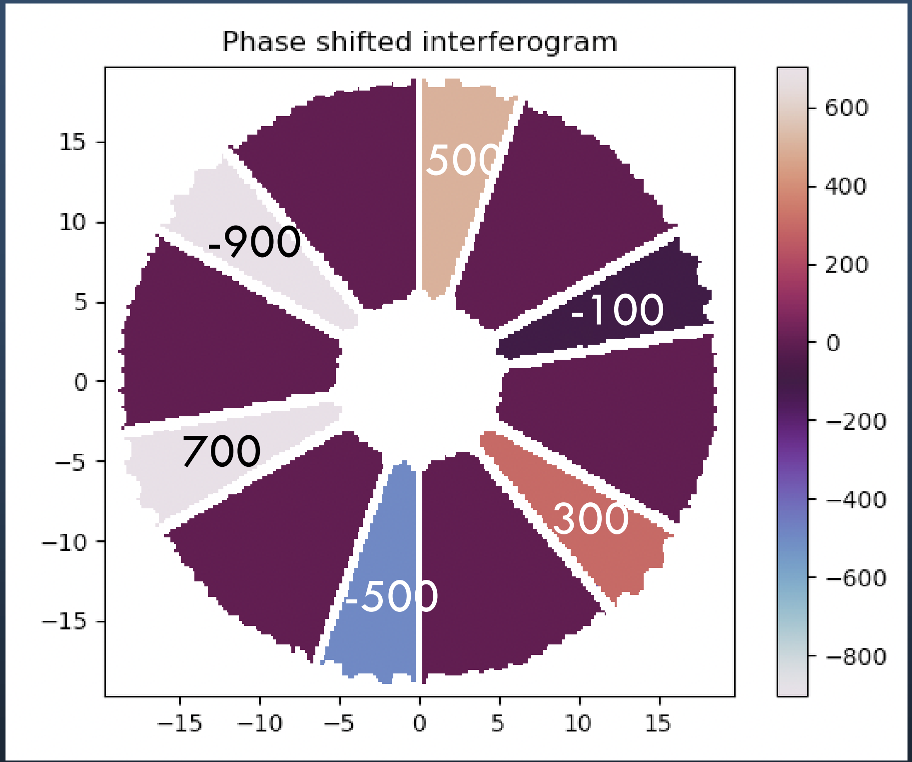


Documentation for POPPY

POPPY (Physical Optics Propagation in PYthon) simulates physical optical propagation including diffraction. It implements a flexible framework for modeling Fraunhofer and Fresnel diffraction and point spread function formation, particularly in the context of astronomical telescopes. POPPY was developed as part of a simulation package for JWST, but is broadly applicable to many kinds of imaging simulations.

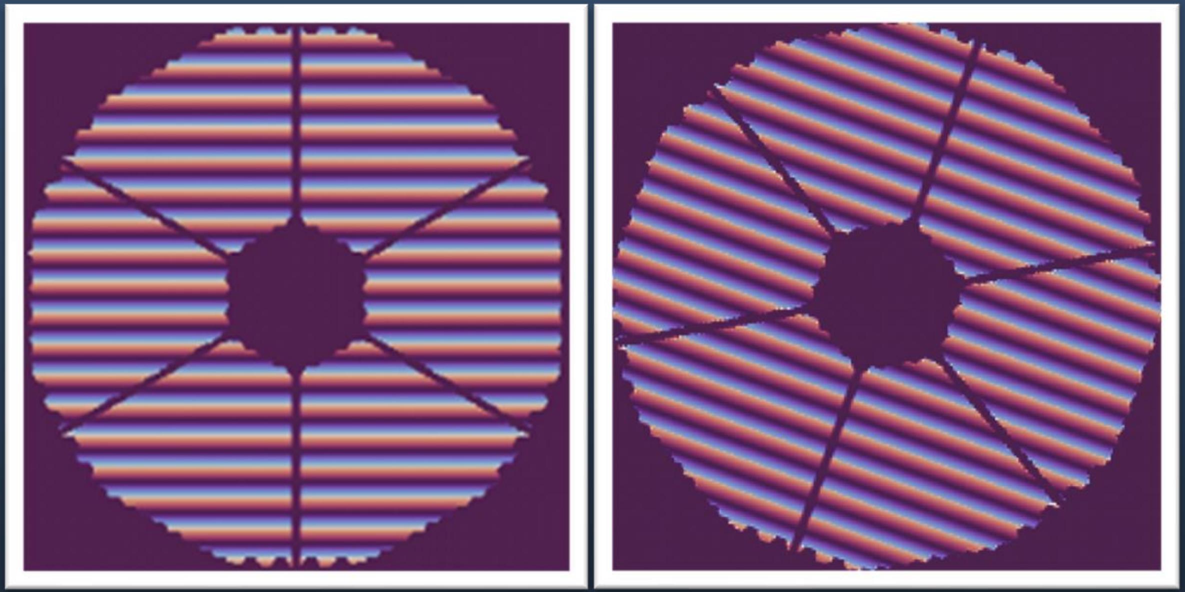
No turbulence case



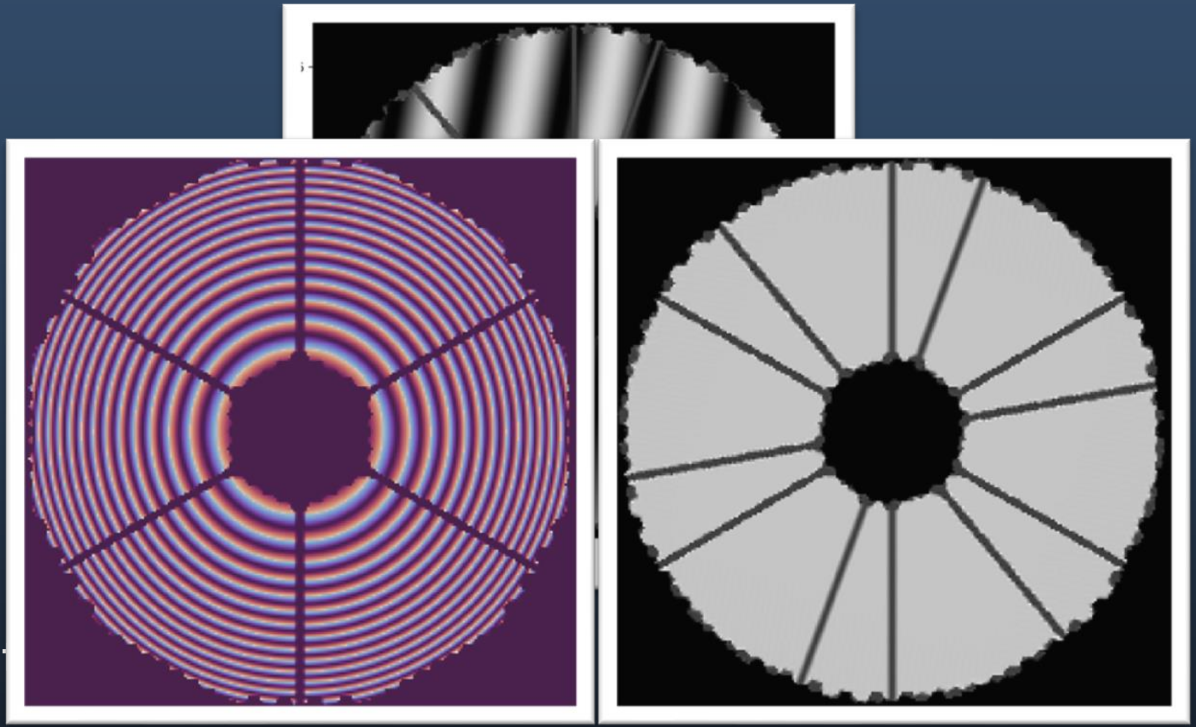


Measured jumps $\vec{j} = [500, -100, 300, -500, 700, -900]\ nm$
Estimated petals $\vec{p} = -cumsum\ \vec{j}\ = [-500, -400, -700, -200, -900, 0]\ nm$
that is correct up to a global piston of -500nm

Rejection of low order aberrations



Residual tilt doesn’t cancel out: it is seen as a rotated til



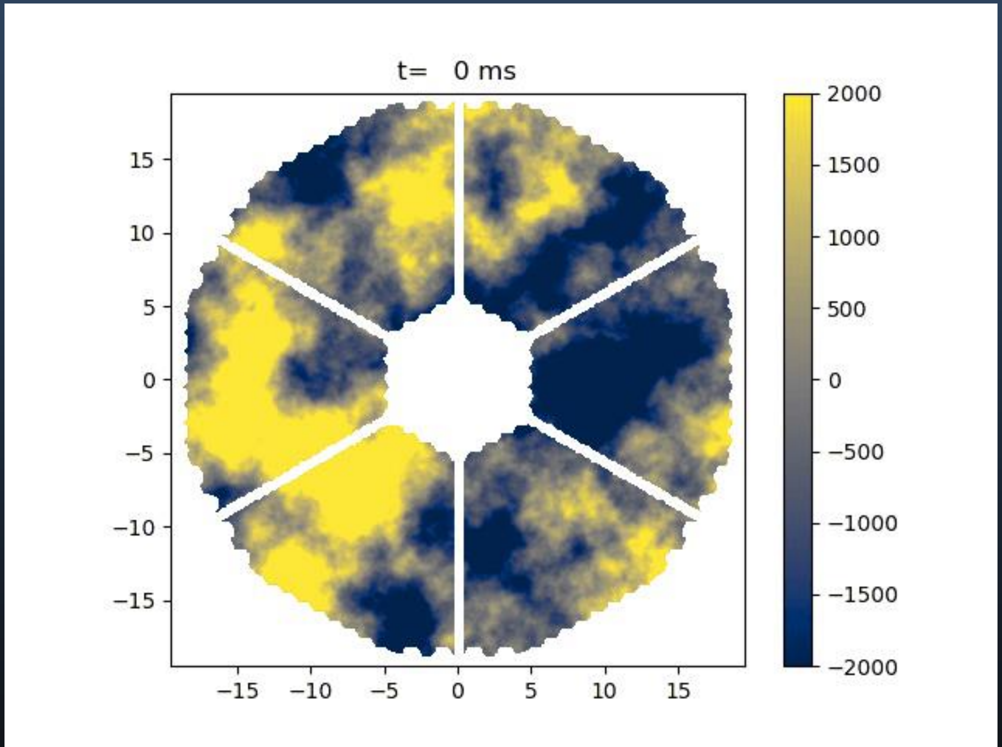
Focus Z4

$$Z_2 - R_\alpha Z_2 = (1 - \cos\alpha) Z_2 - \sin\alpha\, Z_3$$

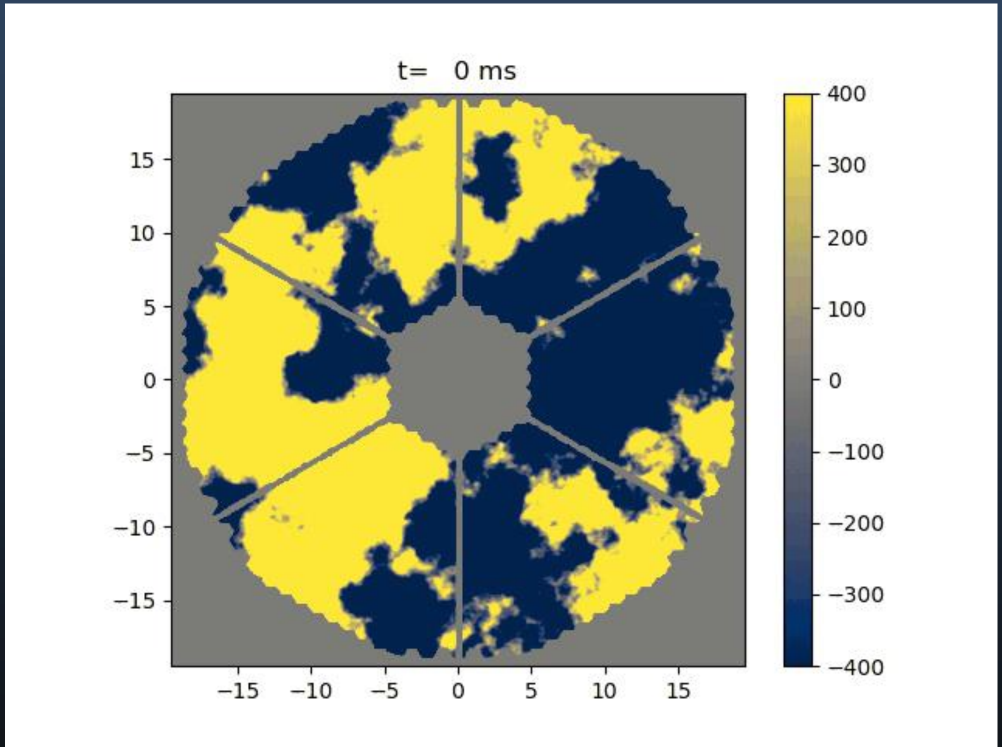
where R_α is the rotation matrix of the pupil image by $\alpha = 20°$

Residual turbulence of MORFEO

MCAO residual turbulence simulated with PASSATA
r0=0.128m, 6 LGS + 3 NGS, M4+1pfDM, POLC-MMSE
Residuals along 45 arcsec off-axis, 2s at 500fps



Cumulative average



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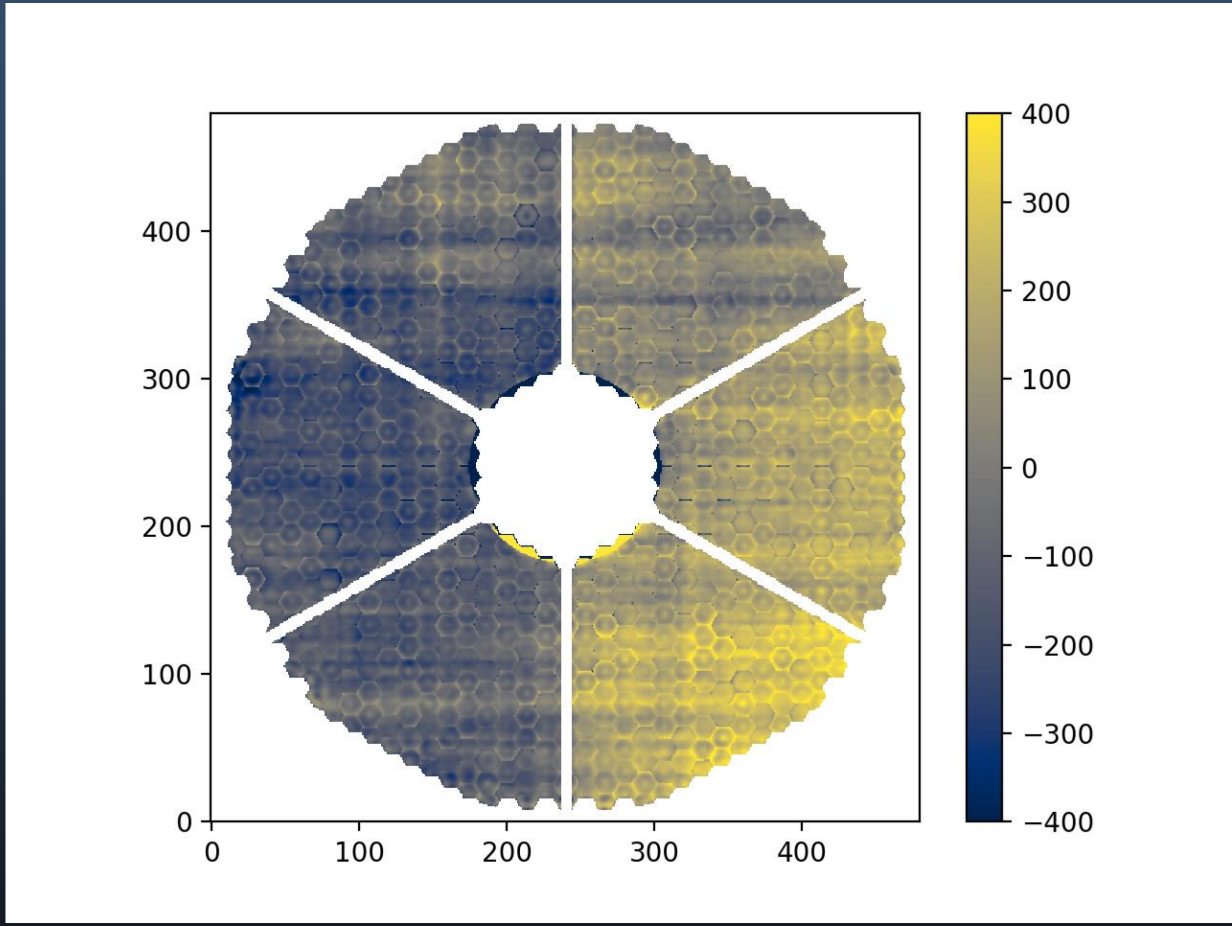
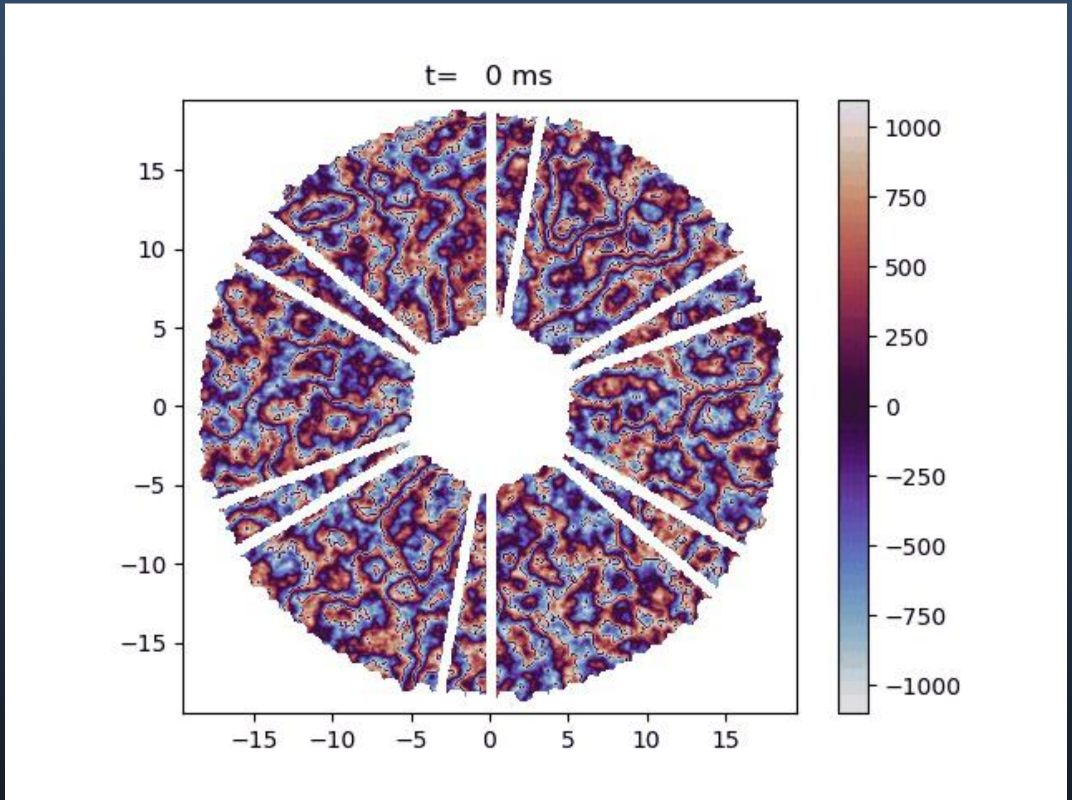


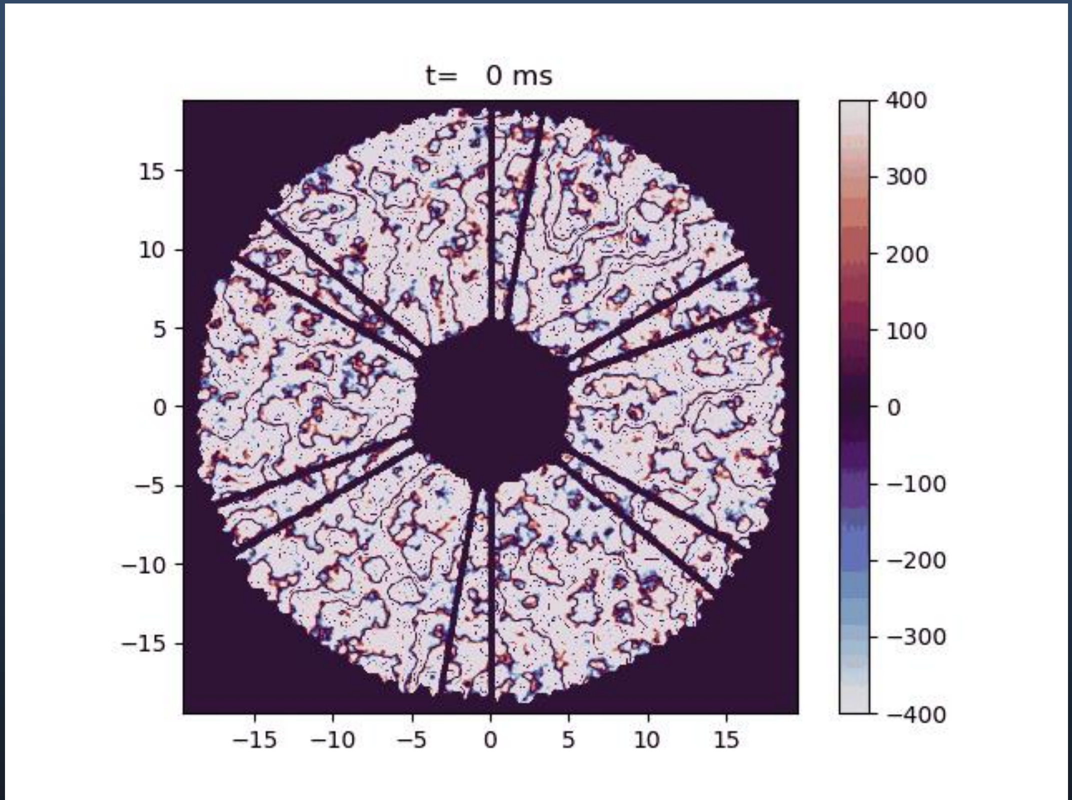
Long exposure (2s) residual phase map.
spatial variance = 220nm rms

We can compute the phase jumps across the spiders
Jumps = [-179, -96, -50, 153, 7, 70] nm

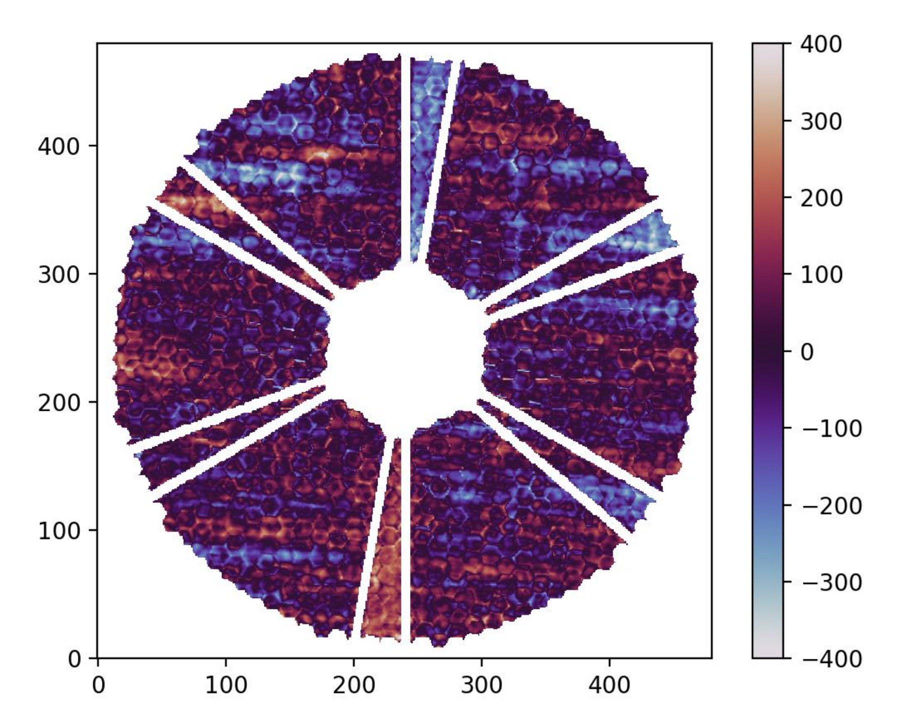
Interferograms of the residual turbulence of MORFEO

Cumulative average





Jumps estimation on residual turbulence



Exposure time=2s
Overlapping α=10°

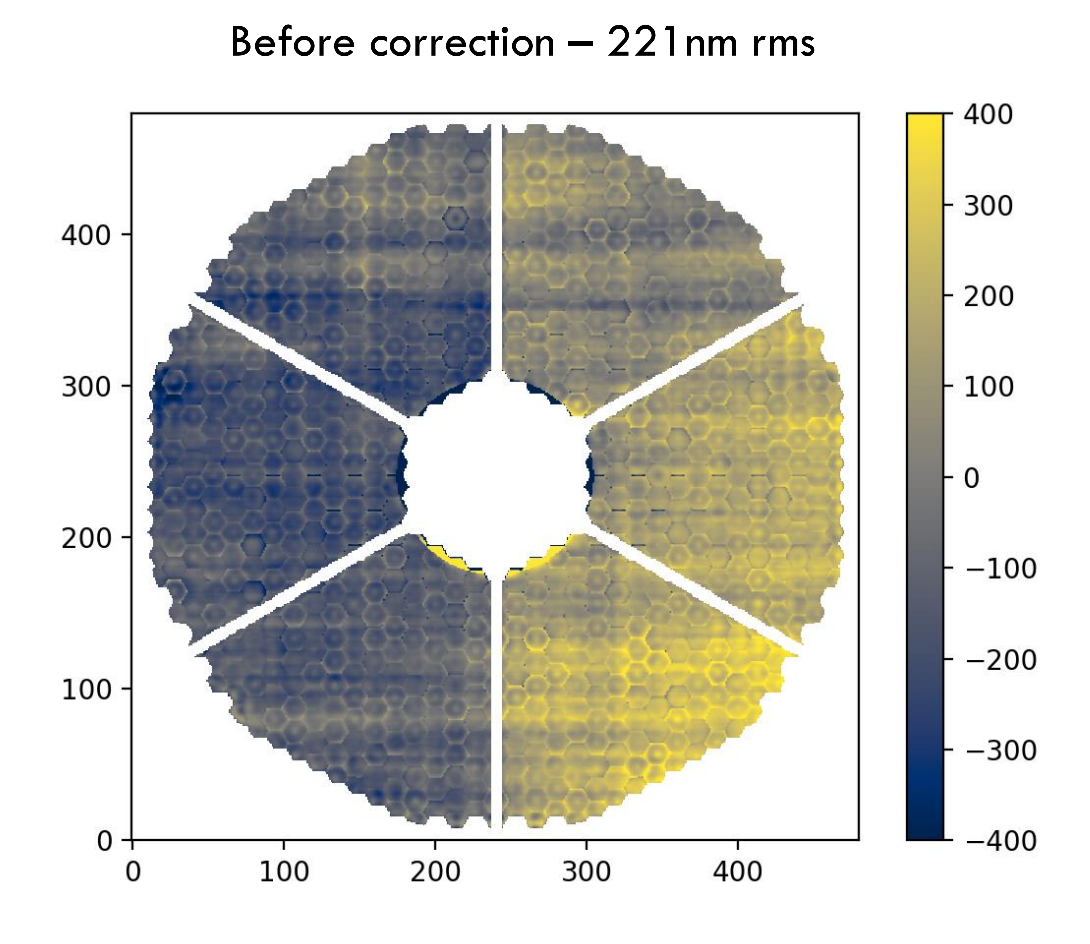
«Real» phase jumps = [-179, -96, -50, 153, 7, 70] nm

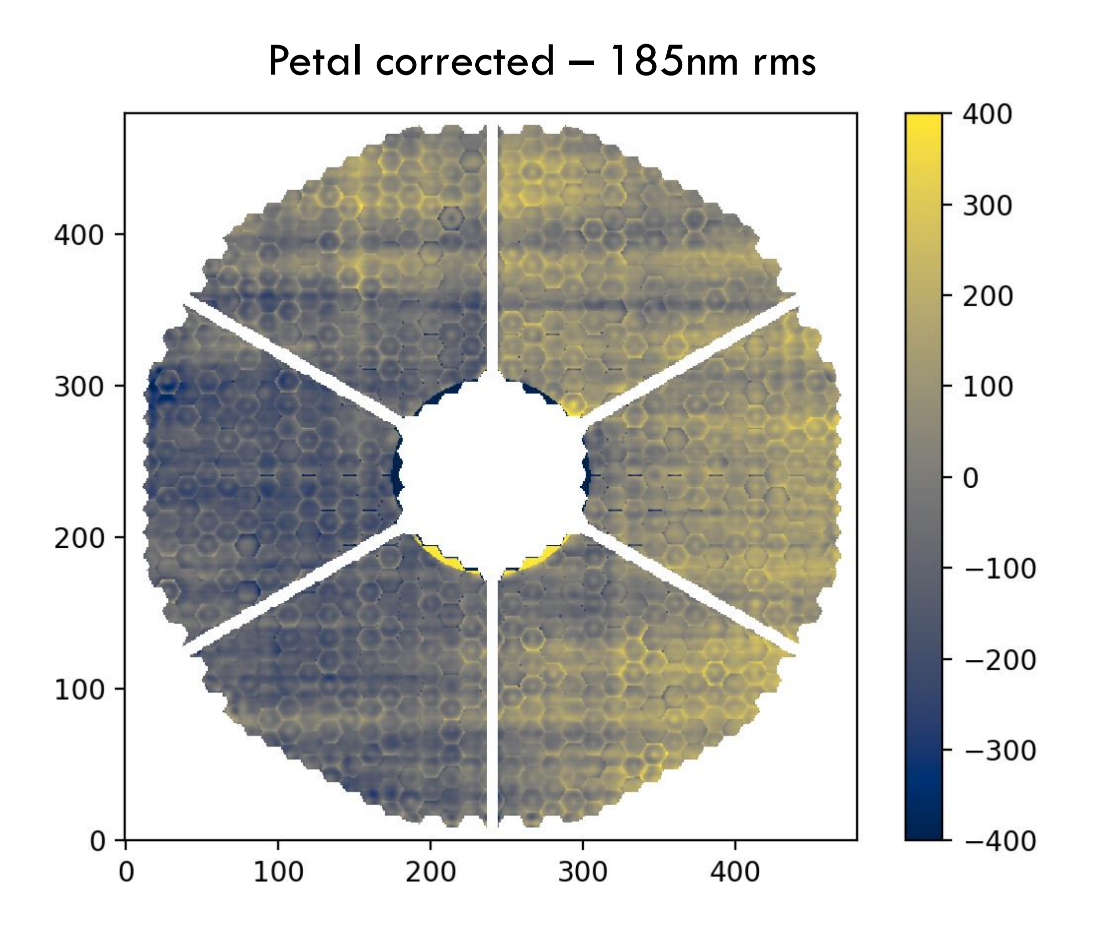
Estimated jumps = [-168, -107, -64, 161, 21, 63] nm

Stdev jumps error = 11nm - Not bad!

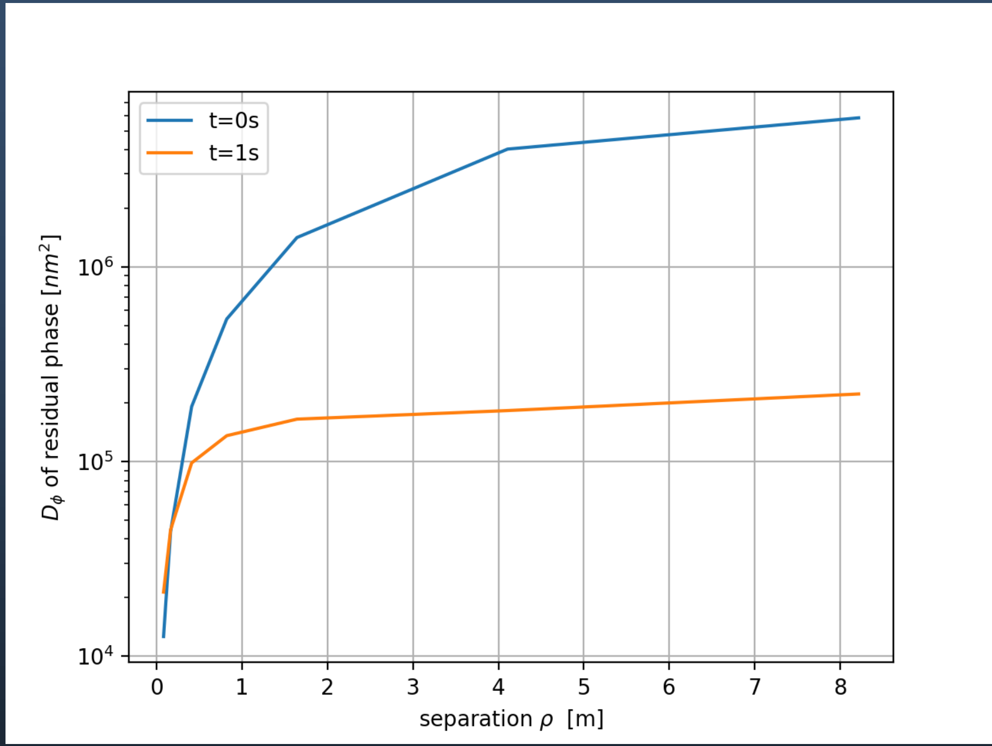
Reconstructed petals = [-33, 74, 138, -24, -45, -108] nm

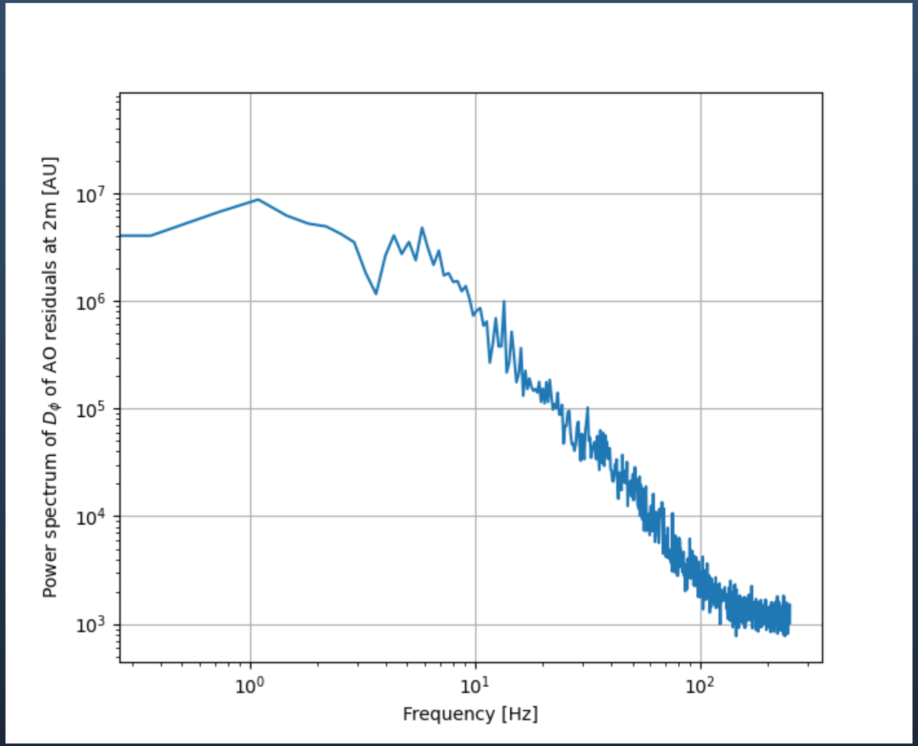
Mimicking petals correction





Spectral properties of the residual turbulence of MORFEO





Structure function

$$D_\varepsilon(\rho) = \langle|\varepsilon(r+\rho) - \varepsilon(r)|^2\rangle_S$$

reaches plateau of about 350nm already at $\rho = 1\, m$

Residual turbulence $\Delta\varepsilon(t) = \varepsilon_1(t) - \varepsilon_2(t)$ with $\rho = 2m$ has a $1/f^2$ power spectrum

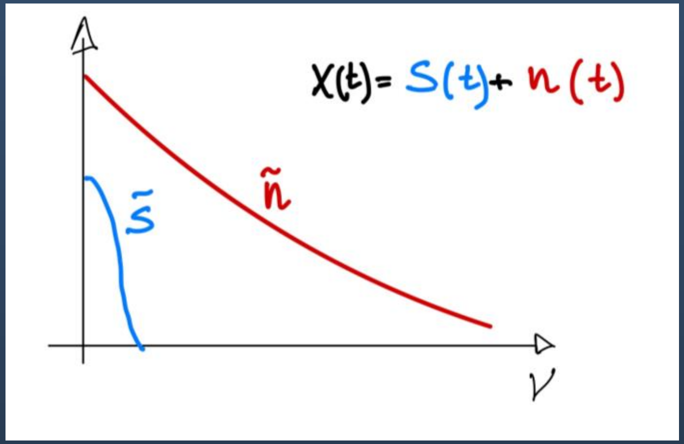
Trying to improve SNR

The residual turbulence is too large to measure the phase difference Δp with good SNR

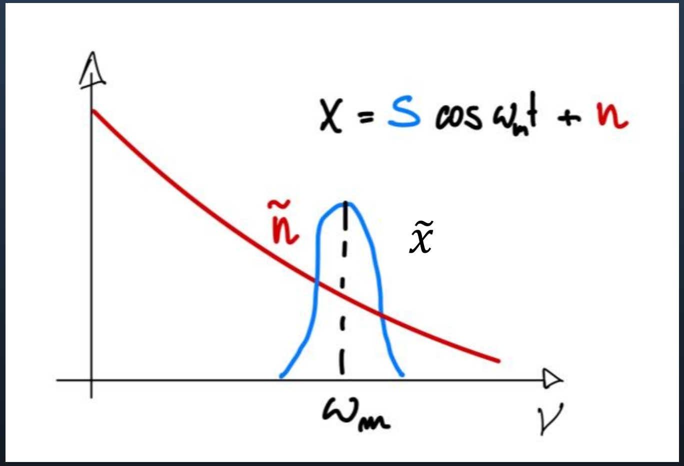
We are interested in a pseudo-static Δp and the temporal power spectrum of the residual is decreasing fast, so…

we can apply homodyne detection (like in push-pull IM, lock-in amplifier, …)

Homodyne detection



Original signal overwhelmend by noise



Modulated signal: spectrum shifted at ω_m

Demodulation: multiply by $\cos \omega_m t$ and average

$$\frac{1}{T}\int_0^T X(t) \cos\omega_m t = \frac{1}{T}\int_0^T S(t) \cos^2\omega_m t + n(t) \cos\omega_m t$$

$$= S(\omega=0) + n(\omega=\omega_m)$$

$$\ll n(\omega=0)$$

using $\frac{1}{T}\int_0^T \cos\omega t \cdot \cos\omega_m t \, dt =$

$= \frac{1}{2}$ iif $\omega = \omega_m$

How to modulate interferograms?

$$S = \cos \Delta\varphi = \cos(\Delta p + \Delta \varepsilon)$$

Non modulated signal

$$S = \cos\left[\Delta p + \Delta \varepsilon + p_m \sin(\omega_m t)\right]$$

Small modulation of Δp

p_m must be small $\lambda/100$ to preserve PSF

... some math later and demodulation ...

$$S_{modem} = -\frac{1}{2} p_m \,\mathrm{sen}\left[(\Delta p + \Delta \varepsilon)_{\omega=0}\right]$$

noise still there

The modulation above is not discriminating among signal and noise: the restored signal is still affected by large noise

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Conclusions

- Yet another petalometer to sense phase jumps across the spider
- Interferometer based on overlapping of 2 rotated pupil images
- Decent jumps retrieval with 2s exposure time also with MORFEO's good seeing residuals
- Attempt to improve SNR with homodyne detection is left as an exercise to the reader

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