Towards on-sky measurement of non-common path aberrations with coronagraphic phase diversity

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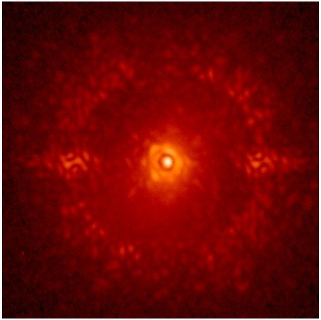
An understatement:
direct imaging of exoplanets is challenging



HIP 73 145 as seen by SPHERE on the VLT
(courtesy SPHERE consortium)

- Very high contrast
- Angular separation
- Quasi-static aberrations

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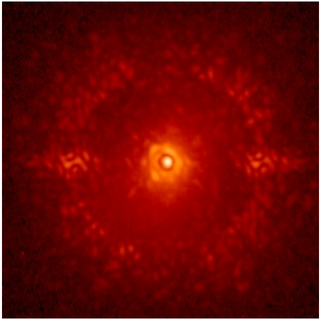

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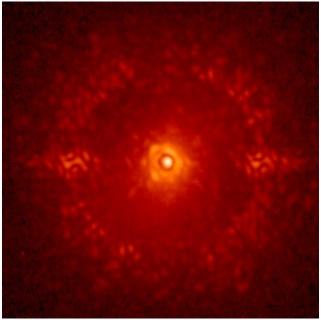

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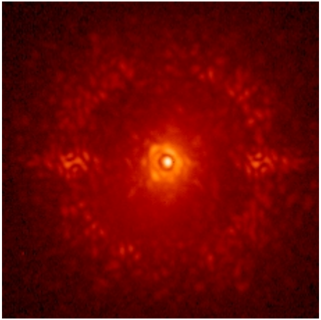

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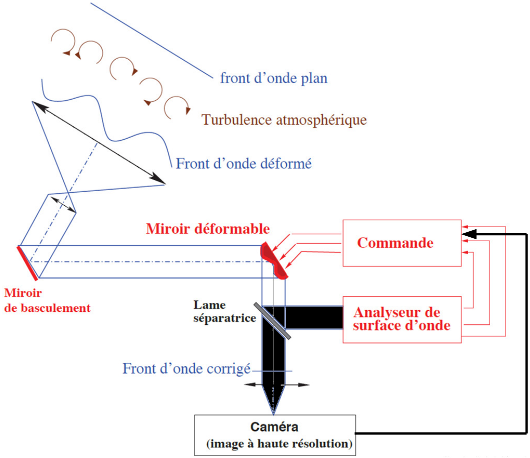
- Very high contrast $\Longrightarrow$ coronagraphy
- Angular separation $\Longrightarrow$ adaptive optics
- Quasi-static aberrations: **Ultimate limitation**

Need for focal-plane wave-front sensing

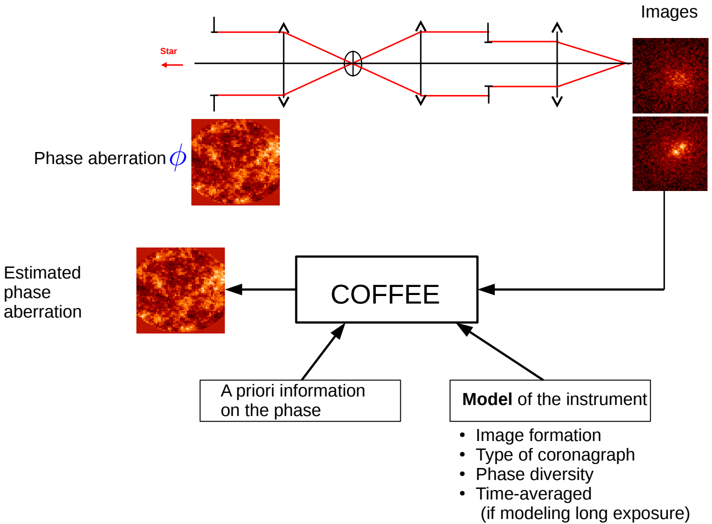


Non-common path aberrations (NCPA)

⇒ need for wave-front sensing using the **scientific camera**

A solution: COFFEE Paul et al. (2013), A&A

Principle of COFFEE: coronagraphic phase diversity



COFFEE: simplified equation

Principle of COFFEE: maximum a posteriori estimation

Minimize

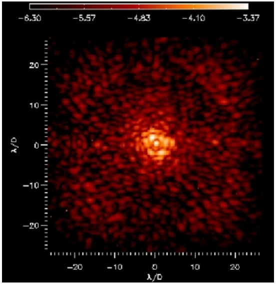
$$J(\phi) = \sum_{(x,y)} \left\| \frac{\text{images}(x,y) - \text{model}[\phi](x,y)}{\sigma(x,y)} \right\|^2 + \mathcal{R}(\phi), \qquad (1)$$

- ϕ: phase aberrations that generates speckles
- "images": set of actual scientific images
- "model": set of outputs of our model of the instrument
- σ: standard deviation of the measurement noise
- $\mathcal{R}$: regularisation term (a priori information on ϕ)

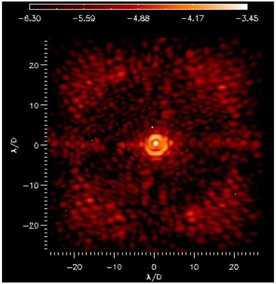
COFFEE in the lab

COFFEE was used for in-lab calibration of SPHERE Paul et al. (2014), A&A **on an internal source**.

Before COFFEE measurement and compensation



After COFFEE measurement and compensation



gain in contrast by factor 2 to 5

Need for an extended COFFEE

Limitations:

- On-sky quasi-static aberrations differ from internal source quasi-static aberrations Milli et al. (2016), Proc. SPIE.
- Quasi-static aberrations evolve during the night (about 1 nm/hour on SPHERE). Martinez et al. (2012), A&A ; Martinez et al. (2013), A&A.

$\Longrightarrow$ Need for aberrations calibration during the night

$\Longrightarrow$ Need for COFFEE on sky

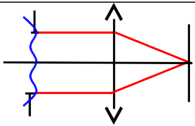
$$J(\phi) = \sum_{(x,y)} \left\| \frac{\text{images}(x,y) - \text{model}[\phi](x,y)}{\sigma(x,y)} \right\|^2 + \mathcal{R}(\phi), \qquad (2)$$

Need for an accurate model of long-exposure coronagraphic image formation accounting for atmospheric turbulence.

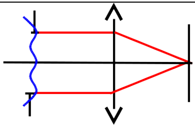
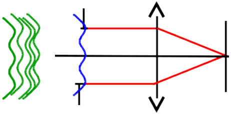
Outline

1. Analytic expression for long-exposure coronagraphic imaging through residual turbulence
2. Integration into COFFEE
3. Experimental validation

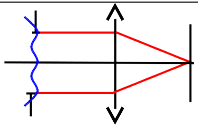
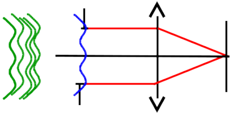
How to model the PSF

	Non-coronagraphic	Coronagraphic
w/o turb	 $h(\phi) = \left\vert \mathcal{F}^{-1}[\exp(\mathrm{i}\phi)] \right\vert^2$	
w turb		

How to model the PSF

	Non-coronagraphic	Coronagraphic
w/o turb	 $h(\phi) = \left\|\mathcal{F}^{-1}[\exp(\mathrm{i}\phi)]\right\|^2$	
w turb	 $h_{le}(\phi, D_\phi) = \langle h(\phi + \phi_t) \rangle_t$	

How to model the PSF

	Non-coronagraphic	Coronagraphic
w/o turb	 $h(\phi) = \left\lvert \mathcal{F}^{-1}[\exp(\mathrm{i}\phi)] \right\rvert^2$	
w turb	 $h_{le}(\phi, D_\phi) = \langle h(\phi + \phi_t) \rangle_t$	
	Roddier (1981): $h_{le}(\phi, D_\phi) = h(\phi) \star h_a(D_\phi)$ Separates turbulence and instrumental aberration	

How to model the PSF

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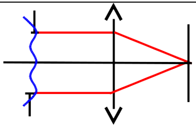
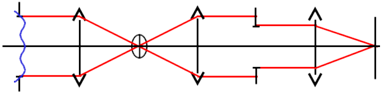
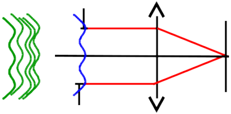
w/o turb	 $h(\phi) = \left\|\mathcal{F}^{-1}[\exp(\mathrm{i}\phi)]\right\|^2$	 $h_c(\phi) = \left\|\mathcal{F}^{-1}\left\{P_d \times \mathcal{F}\left[\mathcal{M} \times \mathcal{F}^{-1}\left(\mathrm{e}^{\mathrm{i}\phi}\right)\right]\right\}\right\|^2$
w turb	 $h_{le}(\phi, D_\phi) = \langle h(\phi + \phi_t)\rangle_t$	
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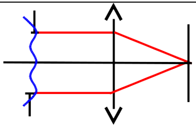
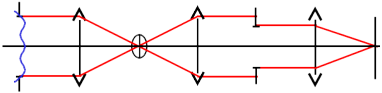
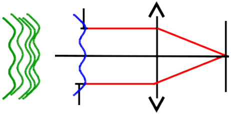
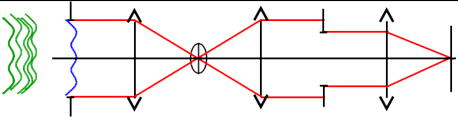
w/o turb	 $h(\phi) = \left\|\mathcal{F}^{-1}[\exp(\mathrm{i}\phi)]\right\|^2$	 $h_c(\phi) = \left\|\mathcal{F}^{-1}\left\{P_d \times \mathcal{F}\left[\mathcal{M} \times \mathcal{F}^{-1}\left(\mathrm{e}^{\mathrm{i}\phi}\right)\right]\right\}\right\|^2$
w turb	 $h_{le}(\phi, D_\phi) = \langle h(\phi + \phi_t)\rangle_t$	 $h_{lec}(\phi, \phi_t) = \langle h_c(\phi + \phi_t)\rangle_t$
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How to model the PSF

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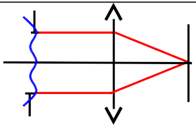
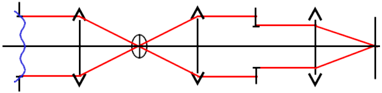
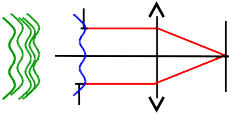
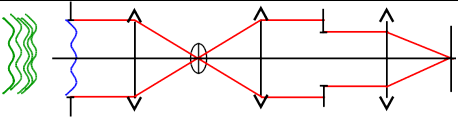
w/o turb	 $h(\phi) = \left\|\mathcal{F}^{-1}[\exp(\mathrm{i}\phi)]\right\|^2$	 $h_c(\phi) = \left\|\mathcal{F}^{-1}\left\{P_d \times \mathcal{F}\left[\mathcal{M} \times \mathcal{F}^{-1}\left(\mathrm{e}^{\mathrm{i}\phi}\right)\right]\right\}\right\|^2$
w turb	 $h_{le}(\phi, D_\phi) = \langle h(\phi + \phi_t)\rangle_t$	 $h_{lec}(\phi, \phi_t) = \langle h_c(\phi + \phi_t)\rangle_t$
	Roddier (1981): $h_{le}(\phi, D_\phi) = h(\phi) \star h_a(D_\phi)$ Separates turbulence and instrumental aberration	Expression that we need $h_{lec}(\phi, D_\phi) = ?$

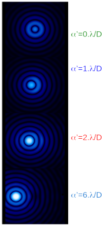
The long-exposure coronagraphic PSF

$$h_{lec}(\alpha; \phi, D_\phi) = \tag{3}$$

Generalisation of Roddier's expression to coronagraphic imaging Herscovici-Schiller et al. (2017), MNRAS

- h_{lec}: mean light intensity at any given point α of the detector
- ϕ: quasi-static aberrations
- D_ϕ: characterizes the statistic of atmospheric turbulence

The long-exposure coronagraphic PSF



$$h_{lec}(\alpha; \phi, D_\phi) = \int_{\alpha'} h_c(\alpha; \phi + \mathrm{tilt}(\alpha'))\, \mathrm{d}\alpha' \qquad (3)$$

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- h_c: coronagraphic model without turbulence

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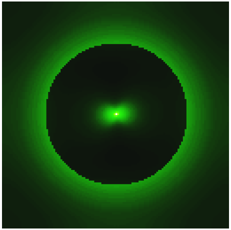

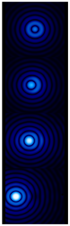

$$h_{lec}(\alpha; \phi, D_\phi) = \int_{\alpha'} h_a(\alpha'; D_\phi) \times h_c(\alpha; \phi + \mathrm{tilt}(\alpha'))\, \mathrm{d}\alpha' \qquad (3)$$

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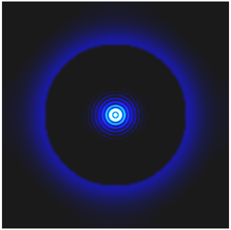
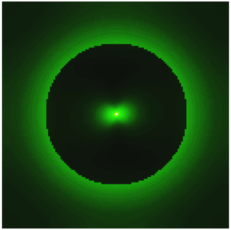
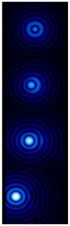
- h_a: atmospheric PSF (energy spectrum density)

The long-exposure coronagraphic PSF







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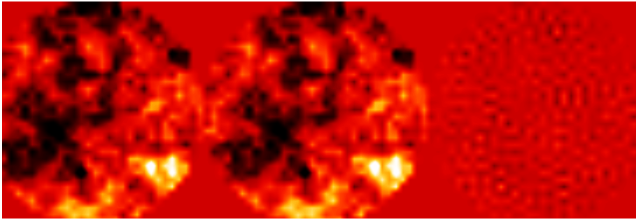
Integration into COFFEE

$$J(\phi) = \sum_{(x,y)} \left\| \frac{\text{images}(x,y) - \text{model}[\phi](x,y)}{\sigma(x,y)} \right\|^2 + \mathcal{R}(\phi), \quad (4)$$

- Inversion of model (calculation of gradients...)
- Acceleration: physical approximations, parallelization

Simulation in a realistic (SPHERE-like) case with noise, turbulence

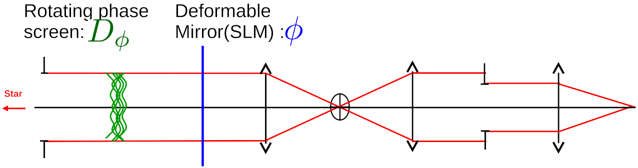


Simulated wave-front, reconstructed wave-front, 100×difference

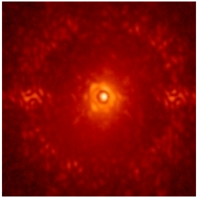
$\phi = 50$nm (RMS); error on estimation < 1nm

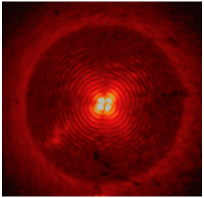
Experimental validation of COFFEE

MITHIC at laboratoire d'astrophysique de Marseille



MITHIC: lab model of SPHERE:

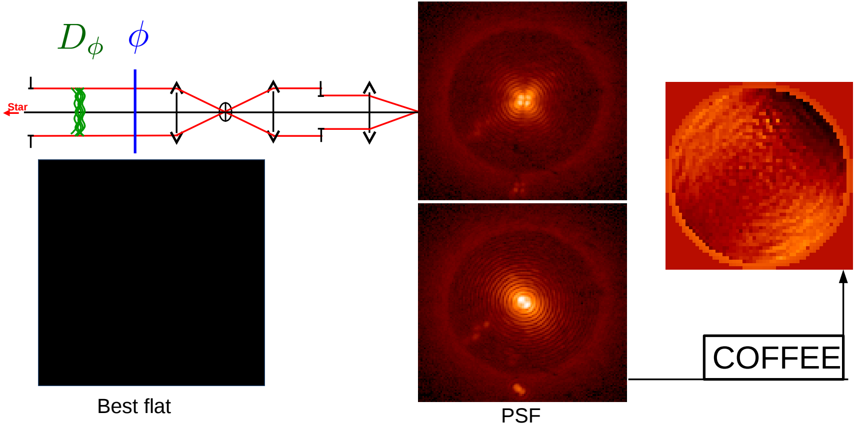




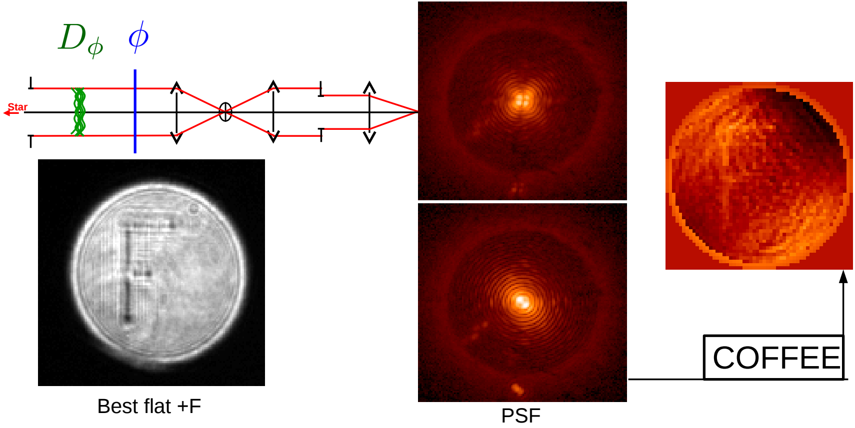
SPHERE PSF
ALC + 50nm NCPA + XAO

PSF on MITHIC
R&R corono + 20nm NCPA + XAO

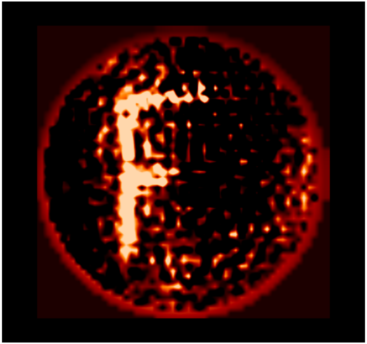
Data on best flat



Data on best flat + F (11 nm)



A preliminary result



(estimated wave-front with best flat) - (estimated wavefront with F):
13 nm RMS (vs 11 nm command)

Conclusion

Summary

- Exoplanet direct imaging: need for coronagraphic wave-front sensing with the scientific camera
- Analytic long exposure PSF derived for any coronagraph & turbulence
- Integrated in the coronagraphic phase diversity
- COFFEE with turbulence validated in lab

Perspectives

- Estimation of turbulence phase structure, D_ϕ
- Estimation of SPHERE NCPA on-sky
- Coupling with dark hole techniques (with Lucie Leboulleux)
- A posteriori data processing of high-contrast images: see **Faustine Cantalloube**'s poster 3062 on MEDUSAE tomorrow.

References

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Martinez, P., Loose, C., Aller Carpentier, E., and Kasper, M. (2012). Speckle temporal stability in XAO coronagraphic images. *Astronomy & Astrophysics*, 541:A136.

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