Here comes trouble

Frantz Martinache

September 25, 2017

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- A coronagraph, is designed to suppress the static diffraction introduced by an optical system: telescope, beam transfer and instrument optics.
- The higher its performance (the contrast at a given separation), the more sensitive it is to changes in the expected system configuration.
- From the ground, coronagraphs are in serious trouble!

An old story

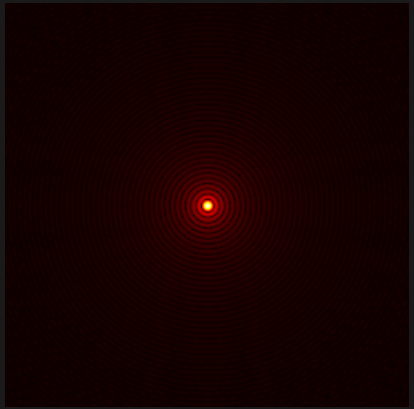
Opticks, Isaac Newton (1704)

“If the Theory of making Telescopes could at length be fully brought into Practice, yet there would be certain Bounds beyond which Telescopes could not perform. **For the Air through which we look upon the Stars, is in a perpetual Tremor** [. . .]

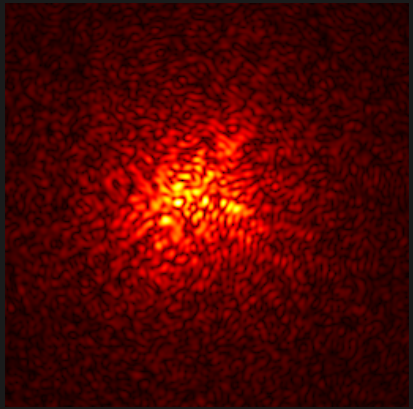
The only Remedy is a most serene and quiet Air, such as may perhaps be found on the tops of the highest Mountains above the grosser Clouds.”

Book I, Prop. VIII, Prob. II

Turbulence and seeing



Theoretical diffraction-limited point spread function.



Experienced instantaneous seeing-limited point spread function

Unless something is done about it, a **telescope larger than a certain size** (typically $\sim$ 0.1 m) **produces images limited by the seeing**.

Atmosphere structure

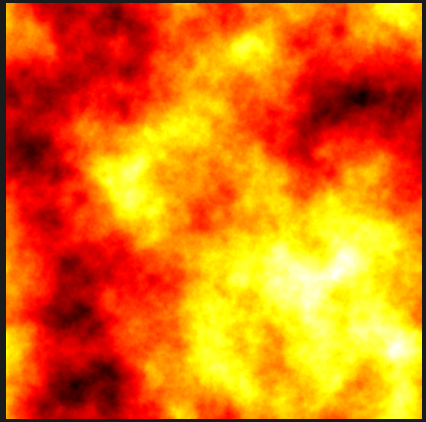
The impact of the atmosphere is quantified by the variance it introduces between two parts of the wavefront, separated by the distance ρ.

$$D_\Phi(\rho) = \left\langle |\Phi_a(r) - \Phi_a(r+\rho)|^2 \right\rangle_r$$

This 2nd order structure function is characterized by one single parameter r_0: Fried's parameter.

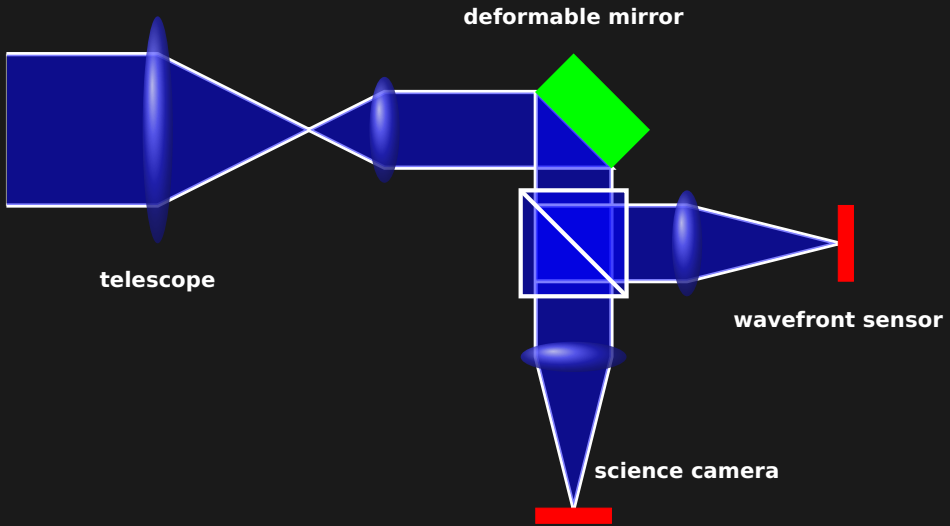
$$D_\Phi(\rho) = 6.88 \left(\frac{|\rho|}{r_0} \right)^{5/3}$$

These perturbations are brought by variations of the refractive index of refraction.



Simulated Kolmogorov phase screen

Adaptive Optics



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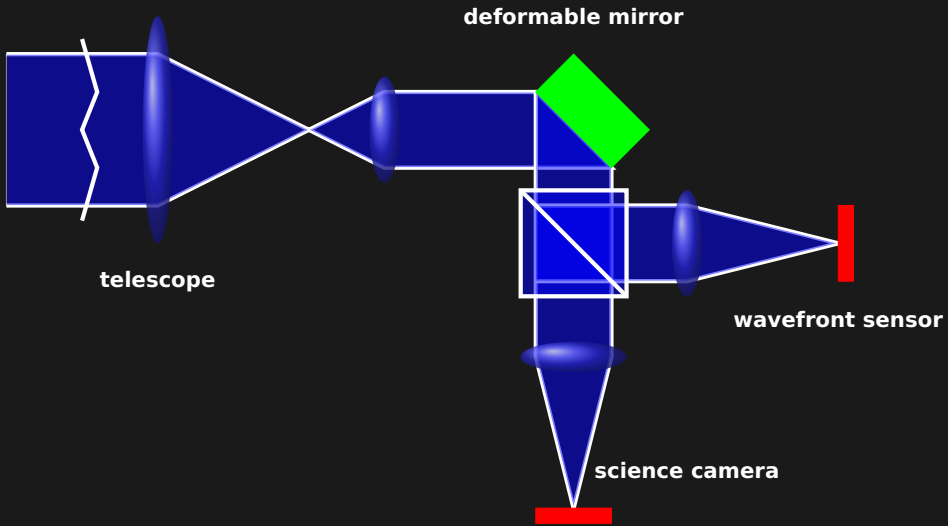

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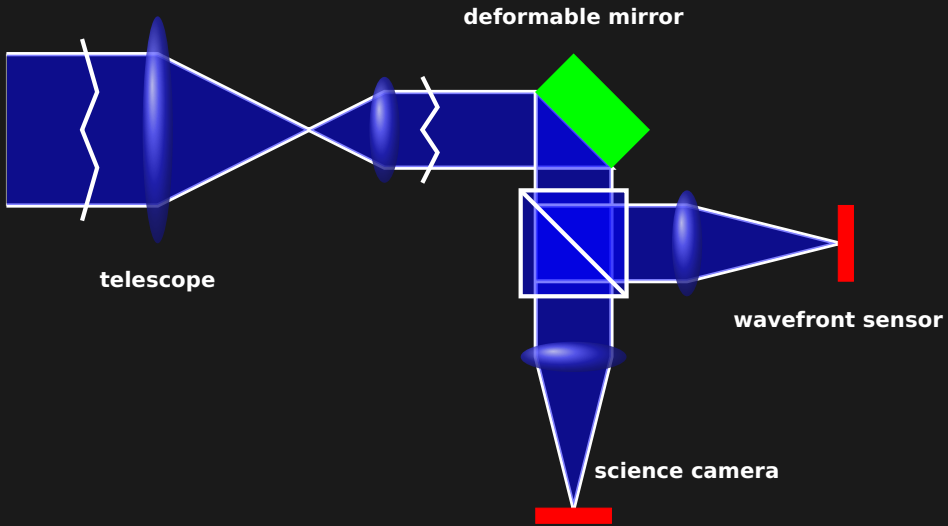

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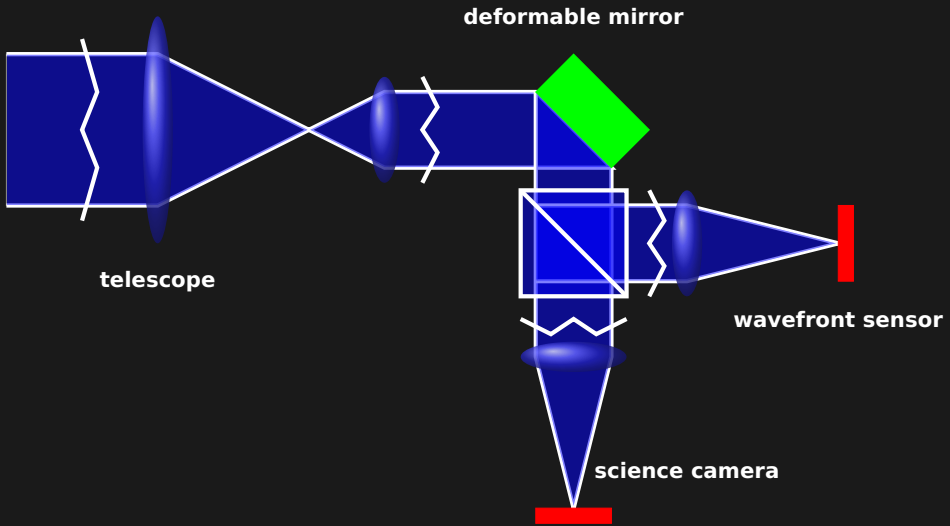

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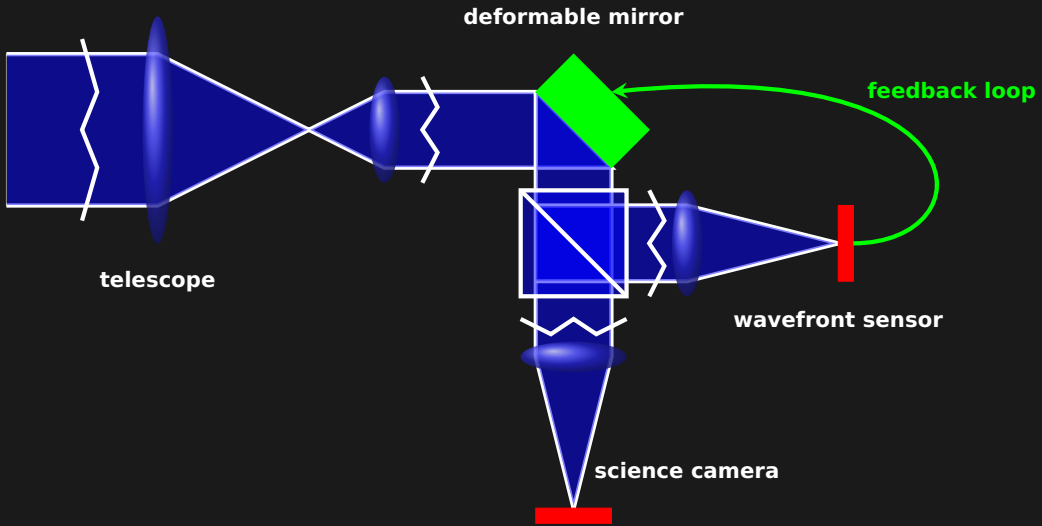

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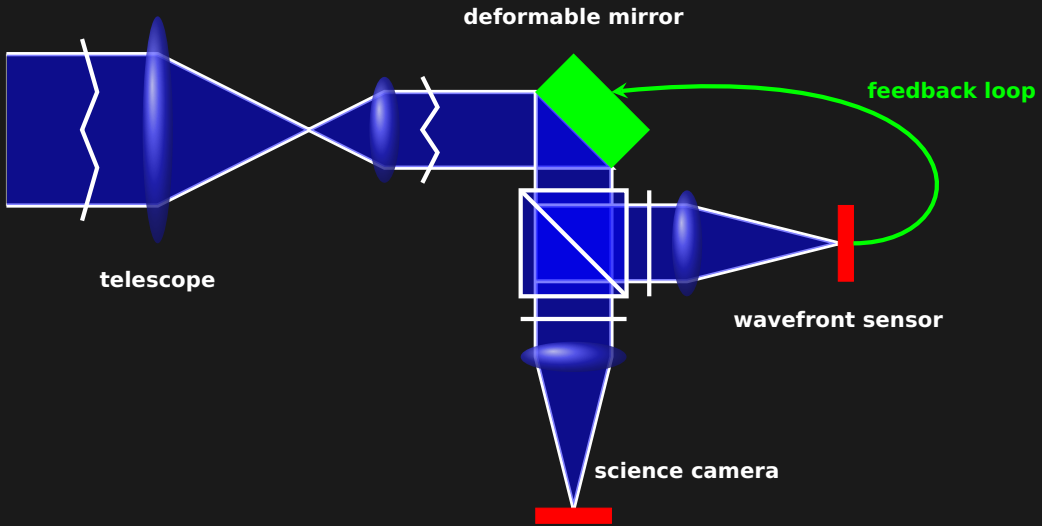
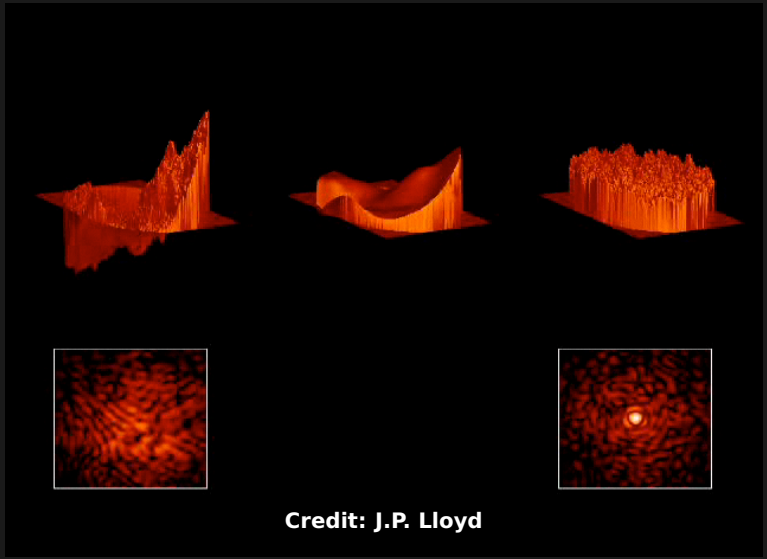
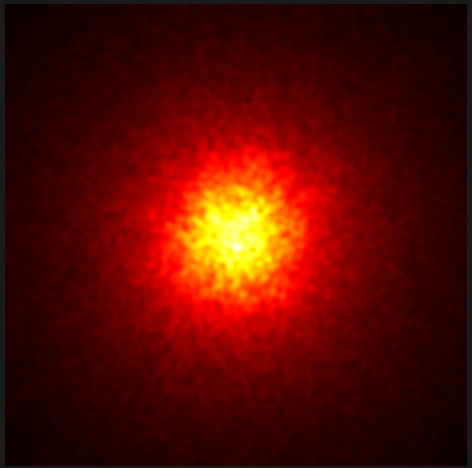


Turbulence filtering



Credit: J.P. Lloyd

Corrected image



Seeing-limited long exposure

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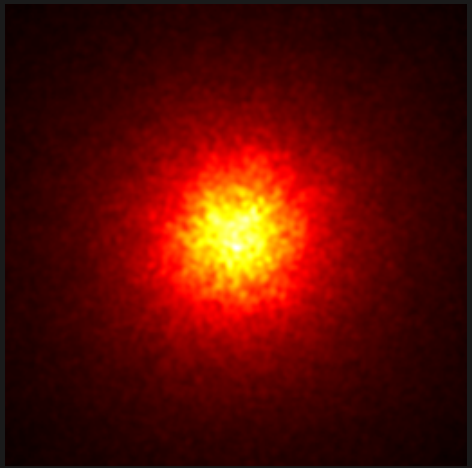

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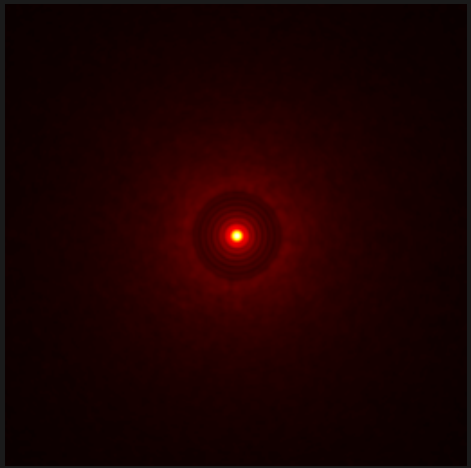

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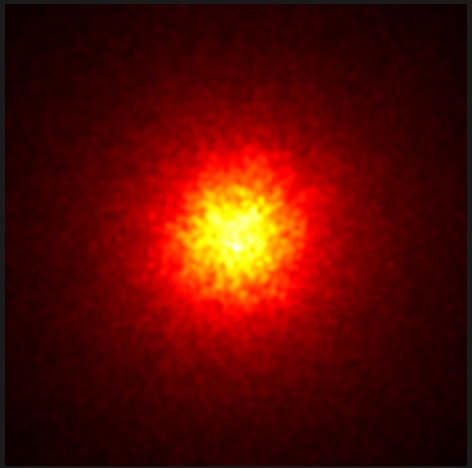

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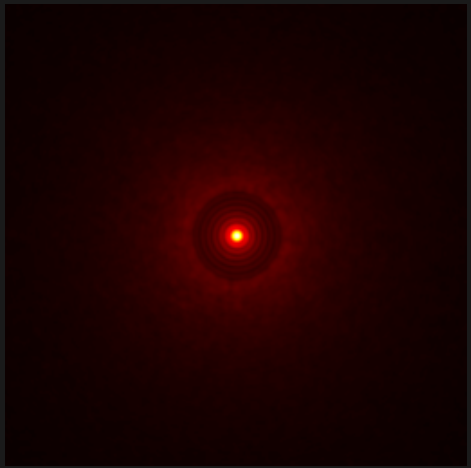
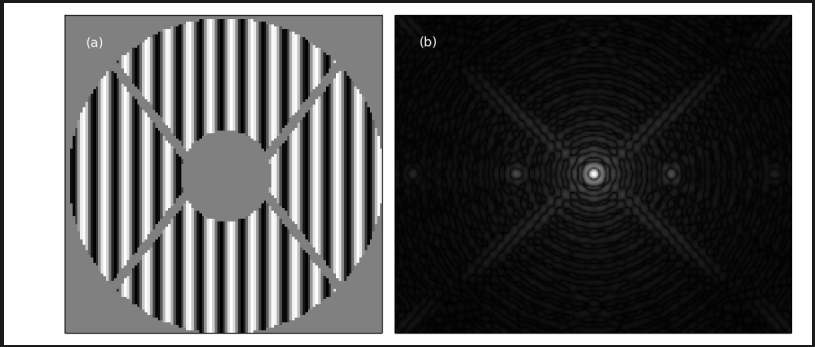


AO-corrected long exposure

AO-corrected **PSF morphology** will depend on the **DM geometry**

Speckles in the focal plane



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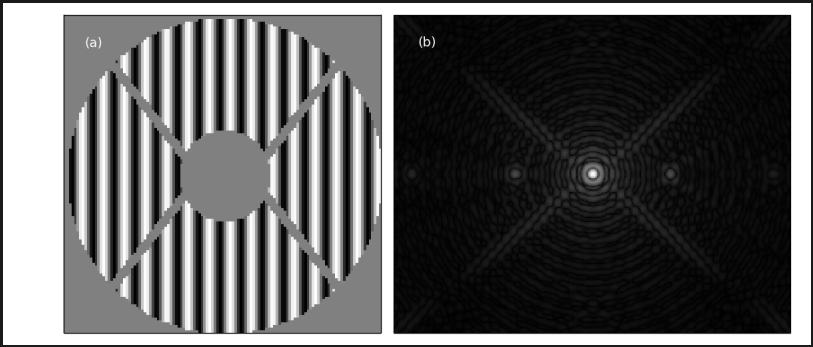

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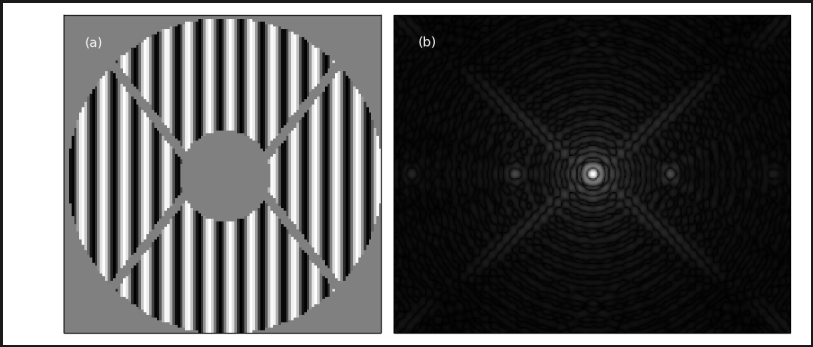

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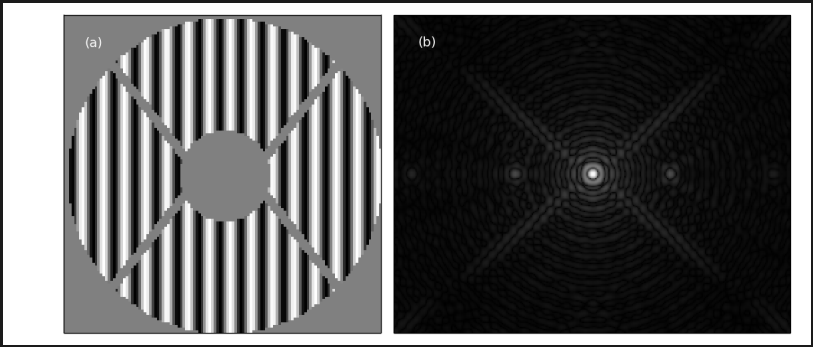

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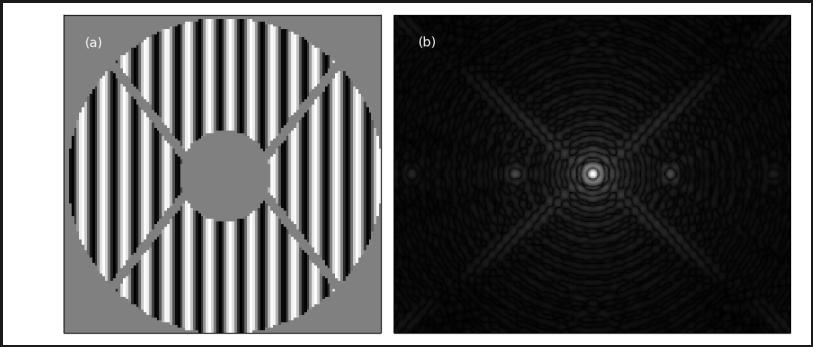

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- $f_c = N_A/2$ (λ/D)

Speckle contrast

The (1D) complex amplitude of a sinusoidal modulation of amplitude α applied by a DM for k cycles at the wavelength λ:

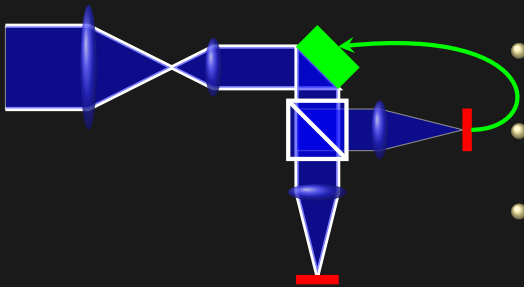
$$\begin{aligned} A(x) &= \exp\left(i(4\pi\alpha/\lambda)\sin 2\pi kx\right) \\ &\approx 1 + i(4\pi\alpha/\lambda)\sin 2\pi kx, \end{aligned}$$

In the focal plane: $I(x) = |\mathcal{F}(A)|^2$. The contrast of the added speckles is:

$$c = (4\pi\alpha/\lambda)^2.$$

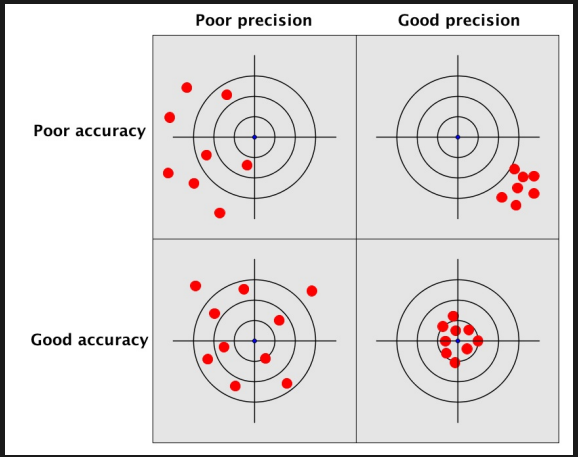
Q: raw contrast requirement within the control region is $c=10^{-6}$.
Required wavefront stability?

Non-common path aberration



- The AO is **blind** to whatever is happening **after the beam splitter**
- This **non-common path error** (NCPA) is at the origin of much grief
- Quasi-static structures are reported to survive over timescales $\sim$ 1 hr
- In the absence of a better solution: post-processing!

Rationale for calibration



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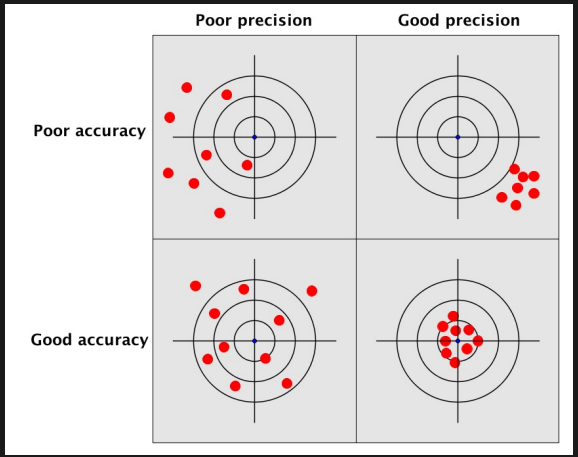

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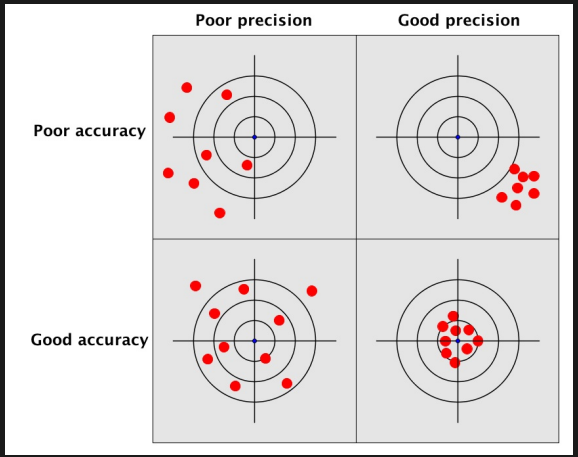

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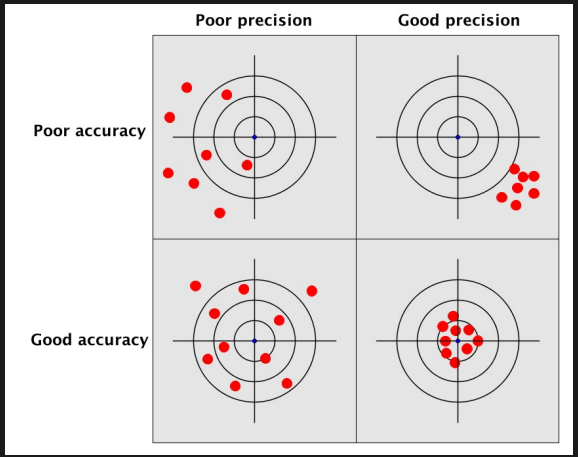

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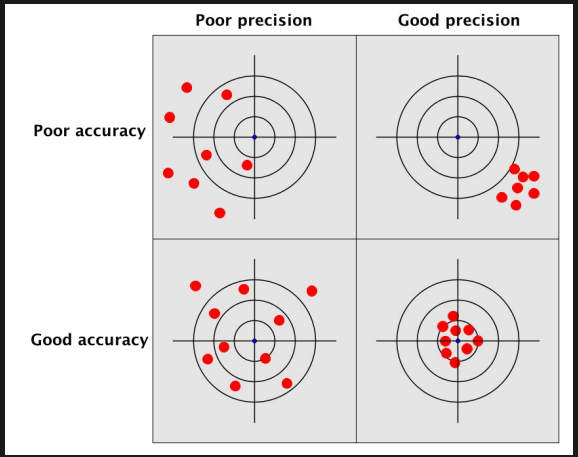

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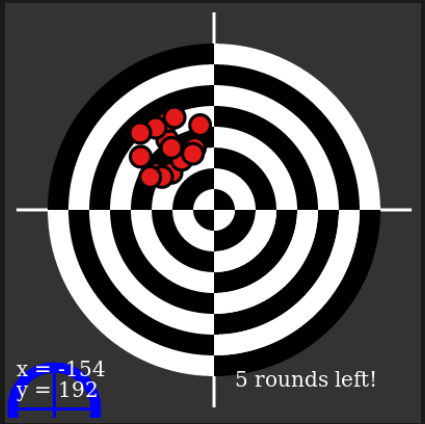
- the solution: data **calibration**
- that’s the rest of the week

Reference subtraction



The grandmother of all calibration techniques!

- **Measure** your bias: acquire a **reference** object
- **Subtract** this bias from the data on your target of interest

This applies to:

- high-contrast imaging: coronagraphic leaks
- interferometry: optical gains and/or offset closure-phases

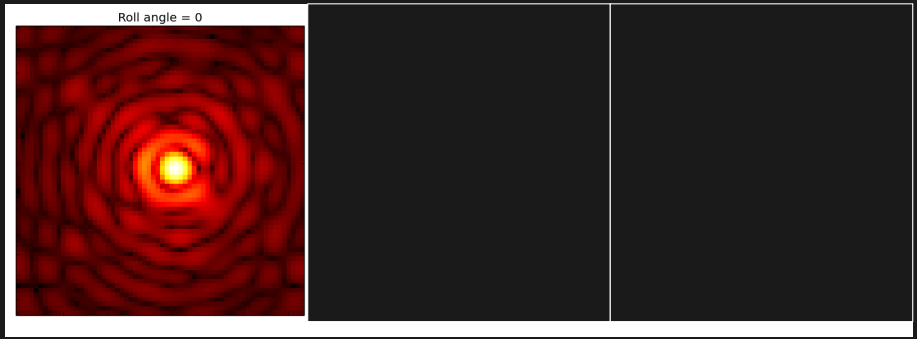
This requires:

- Find good calibrators (an art by itself!)
- Observe plenty of them

Differential measurement

A variant, using the target of interest only:

- (semi-) simultaneous observations affected by the same bias.
- vary one parameter for all observations
- use your knowledge of physics to figure things out!



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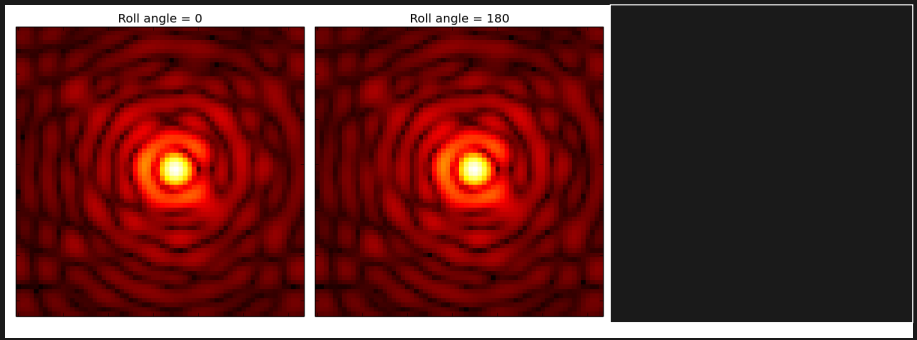

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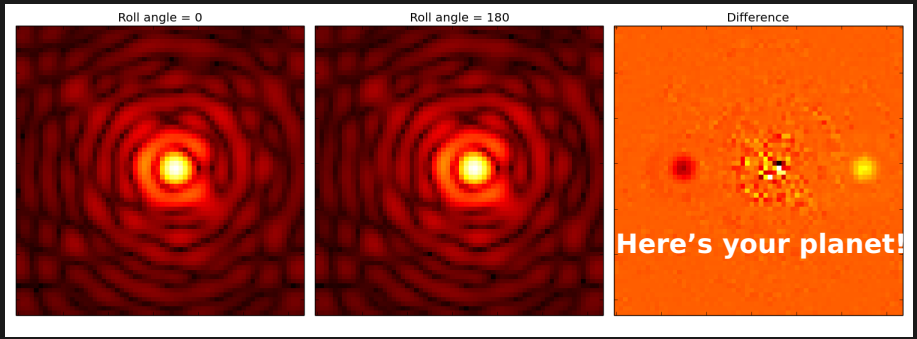

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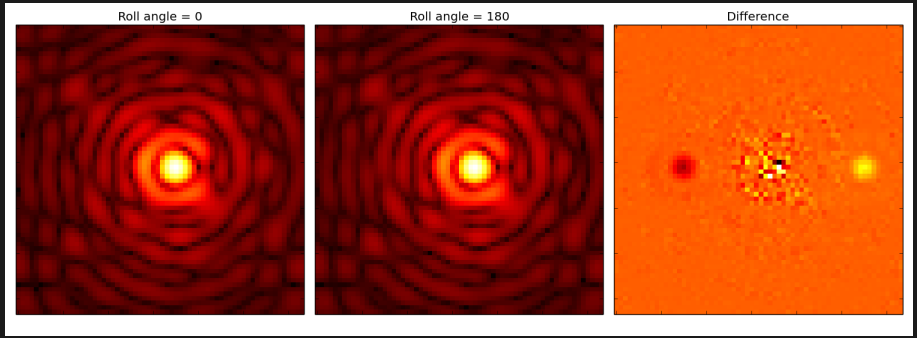
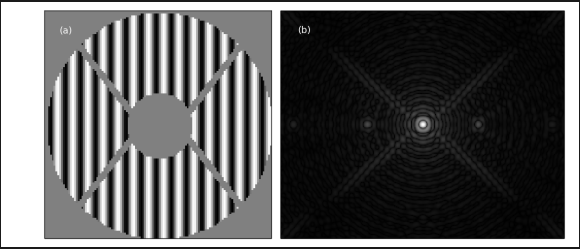


Options include: ADI, PDI, SDI, . . . Interferometry equivalents available!

CDI: Coherent differential imaging



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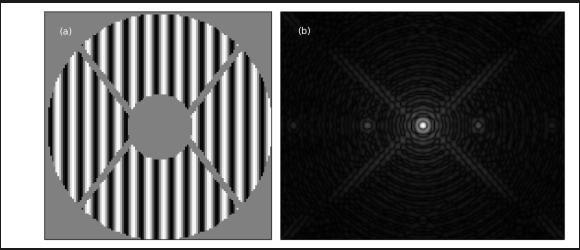

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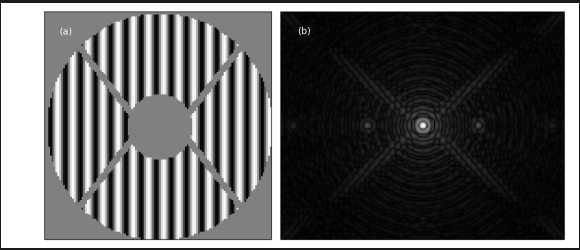

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- The **big** question: is this a **coherent** structure or not?
  - Yes - it can be suppressed!
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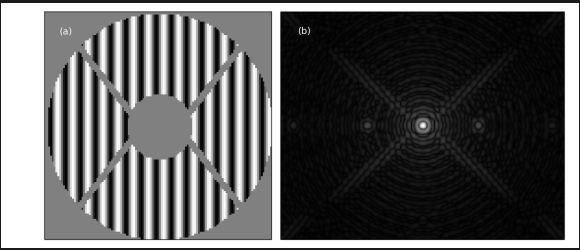

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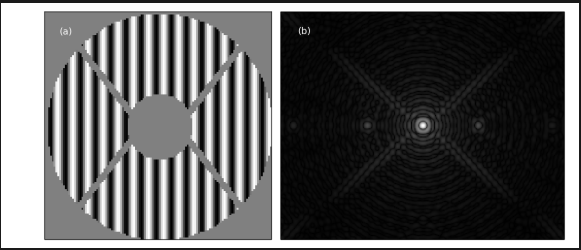

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- It is disturbing for the AO to keep on running while you do this!

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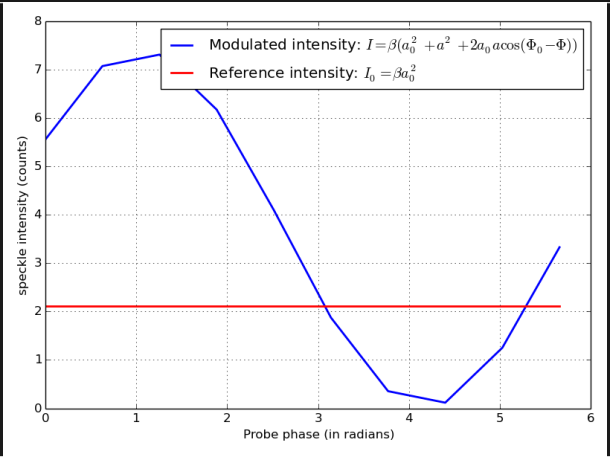

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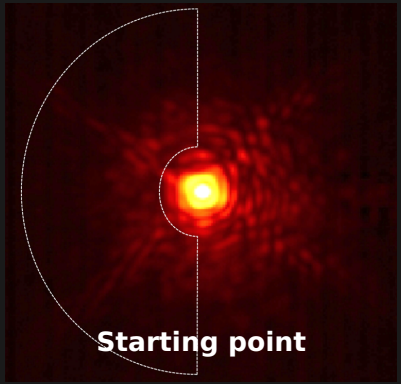

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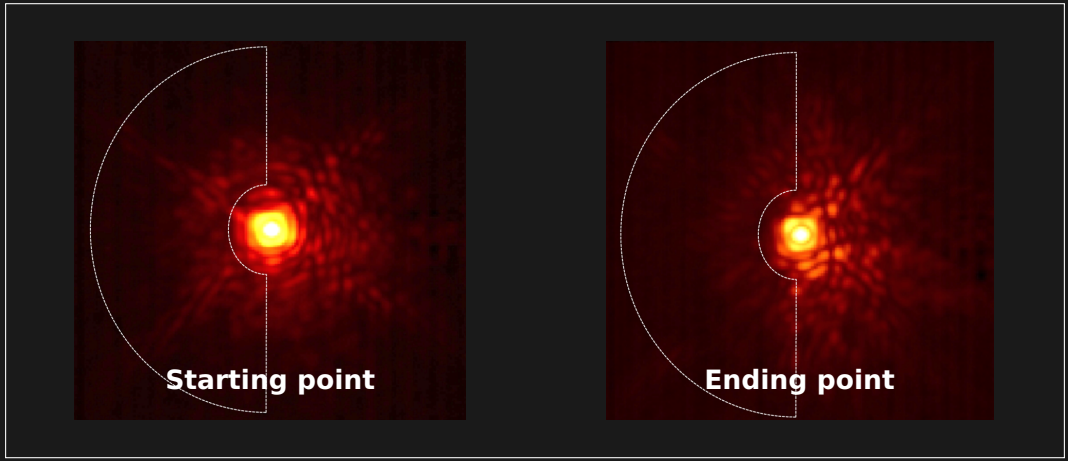

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