Image plane phase-shifting WFS for giant telescope active and adaptive optics

François Hénault
UMR 6525 H. Fizeau, Université de Nice-Sophia Antipolis
Centre National de la Recherche Scientifique
Observatoire de la Côte d'Azur
Parc Valrose, 06108 Nice – France

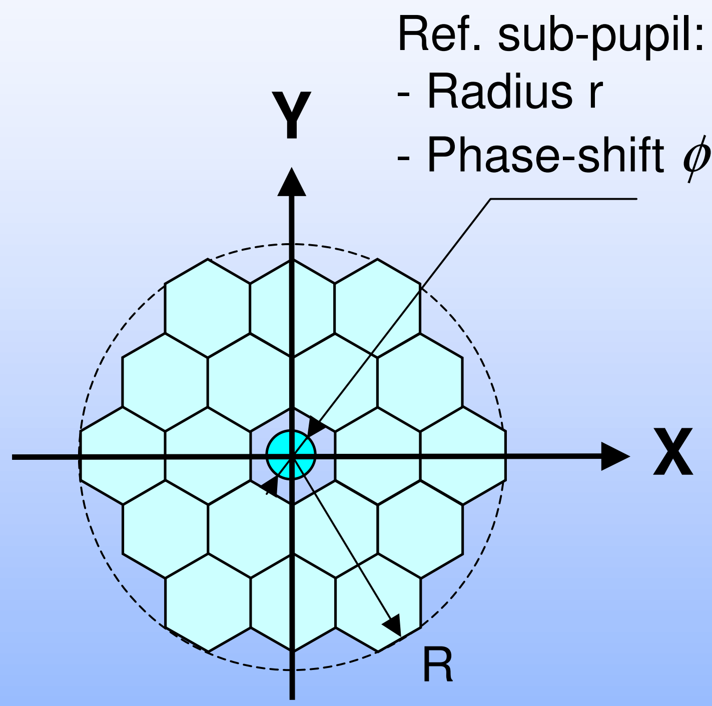
Previous publications

- "Analysis of stellar interferometers as wavefront sensors," Appl. Opt. vol. 44, p. 4733-4744 (2005)
- "Conceptual design of a phase shifting telescope-interferometer," Optics Communications vol. 261, p. 34-42 (2006)
- "Signal-to-noise ratio of phase sensing telescope interferometers," J. Opt. Soc. Am. A vol. 25, p. 631-642 (2008)
- "Telescope interferometers: an alternative to classical wavefront sensors," Proceedings of the SPIE vol. 7015, n° 70155N (2008)
- "Multi-spectral piston sensor for co-phasing giant segmented mirrors and multi-aperture interferometric arrays," Journal of Optics A vol. 11, n° 125503 (2009)

General principle

- There must be a reference sub-pupil (or segment) on the optical surface of the telescope
- Its dimensions are ≤ other segments. It is not necessarily centred
- Three (or four) phase-shifts are successively introduced into the reference sub-pupil:

$$\phi = 0,\ 2\pi/3 \text{ and } -2\pi/3$$



- Three different telescope PSFs are acquired and linearly combined with complex coefficients {1, exp[2$i\pi$/3], exp[-2$i\pi$/3]}
- The result is inverse Fourier transformed → Smoothed replica of the original entrance wavefront <u>including phase</u>

Extending measurement range beyond [-λ/2,λ/2]

- **Goal**: Given a piston error δp, remove the <u>2π ambiguity</u> of this WFS
- Use of a "synthetic wavelength" method based on three neighboring wavelengths λ_1, λ_2 and λ_3
- Linear system to be solved

$$\delta p = (n_1 + \varphi_1)\,\lambda_1$$
$$\delta p = (n_2 + \varphi_2)\,\lambda_2$$
$$\delta p = (n_3 + \varphi_3)\,\lambda_3$$

(φ_1, φ_2, φ_3 measured fractional phases)

- Synthetic wavelength λ_S

$$\frac{1}{\lambda_S} = \frac{1}{\lambda_1} - \frac{2}{\lambda_2} + \frac{1}{\lambda_3}$$

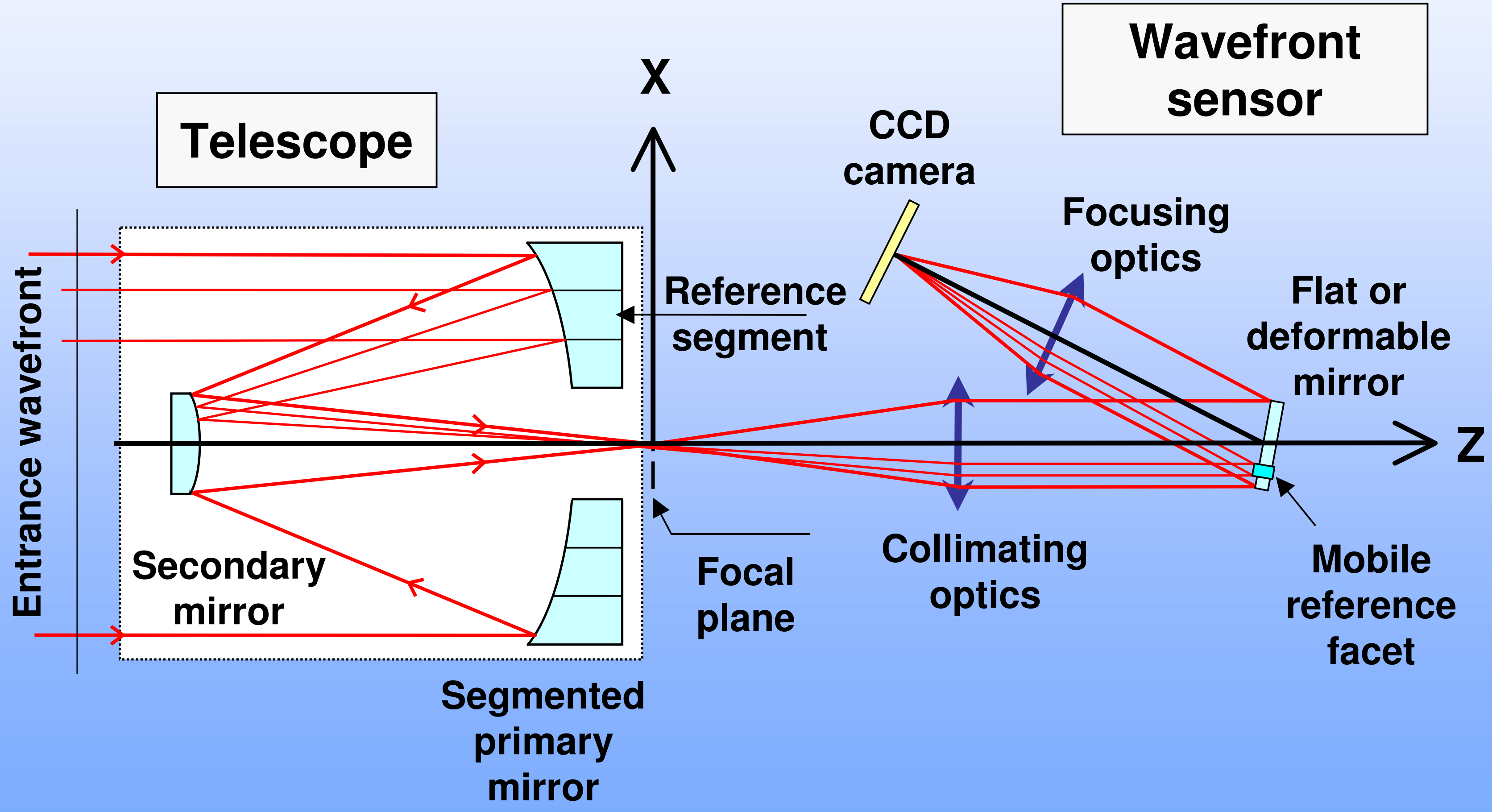
Algorithm

$$\delta p_0 = \lambda_S\,(\varphi_1 - 2\varphi_2 + \varphi_3)$$
$$n_1 = \mathrm{NINT}(\delta p_0/\lambda_1 - \varphi_1)$$
$$n_2 = \mathrm{NINT}(\delta p_0/\lambda_2 - \varphi_2)$$
$$n_3 = \mathrm{NINT}(\delta p_0/\lambda_3 - \varphi_3)$$
$$\delta p_1 = \lambda_1\,(n_1 + \varphi_1)$$
$$\delta p_2 = \lambda_2\,(n_2 + \varphi_2)$$
$$\delta p_3 = \lambda_3\,(n_3 + \varphi_3)$$
$$\delta p = (\delta p_1 + \delta p_2 + \delta p_3)\,/\,3$$

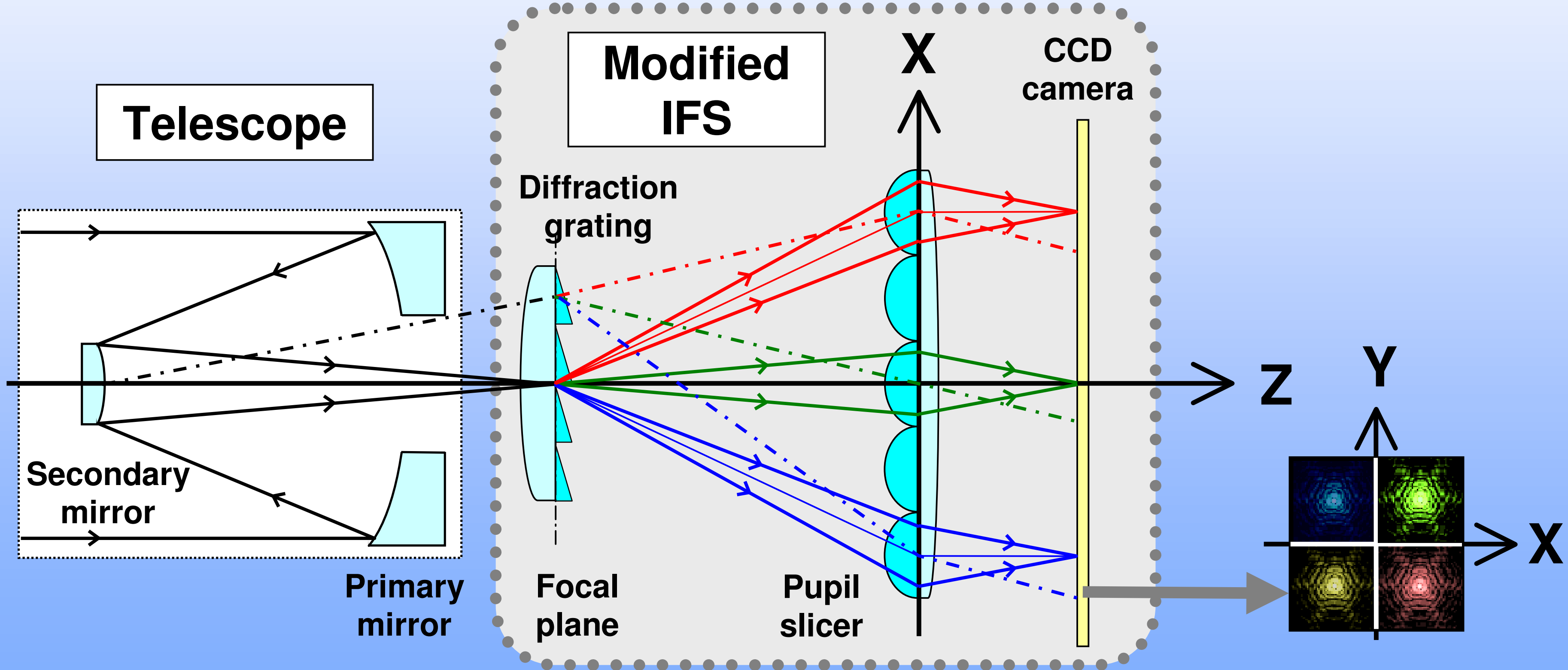
Self-sanity check

$$\Sigma_{\delta p}^2 = \left[(\delta p_1 - \delta p_2)^2 + (\delta p_2 - \delta p_3)^2 + (\delta p_3 - \delta p_1)^2\right]/\,3$$

WFS optical scheme

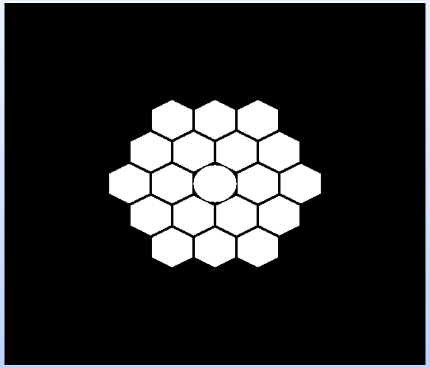


WFS optical scheme (spectral stage)

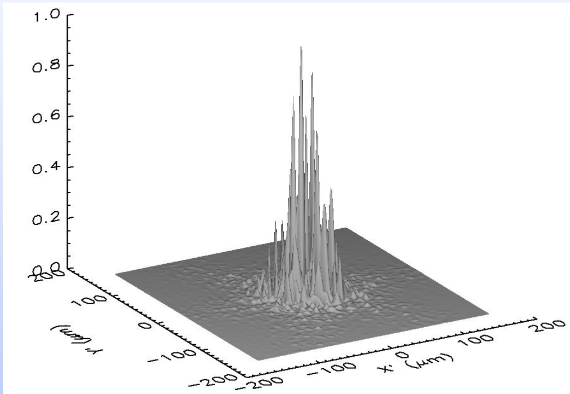


Piston errors reconstruction (1/2)

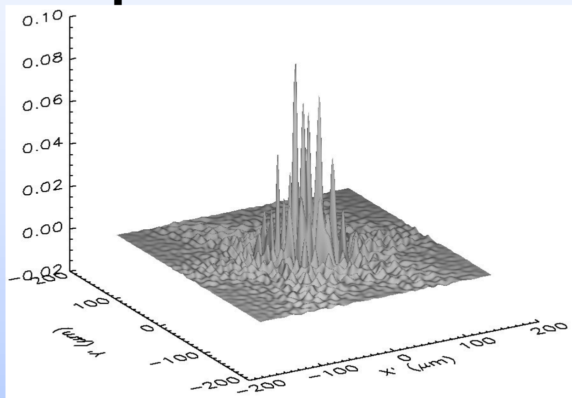
Pupil transmission

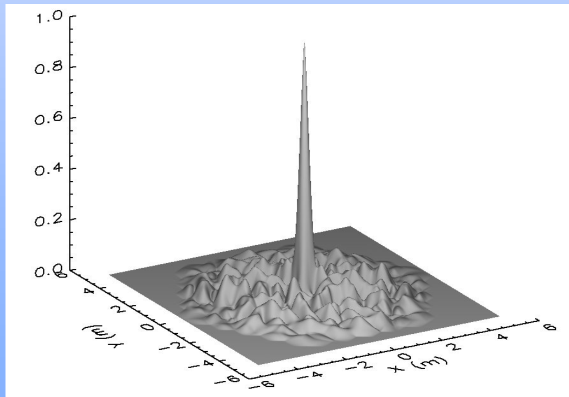


Single PSF acquisition

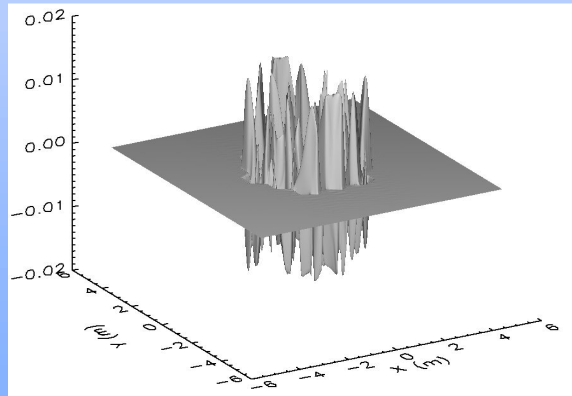


Difference between two phase-shifted PSFs

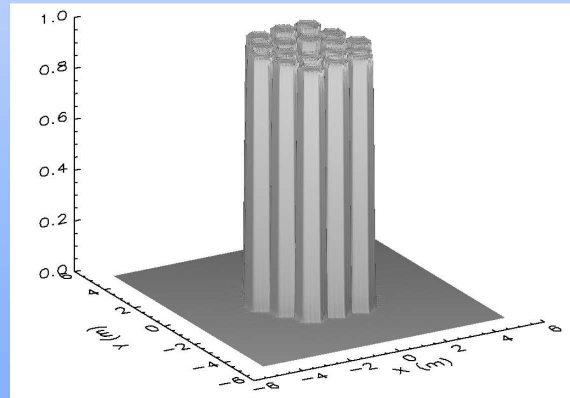




Single MTF acquisition



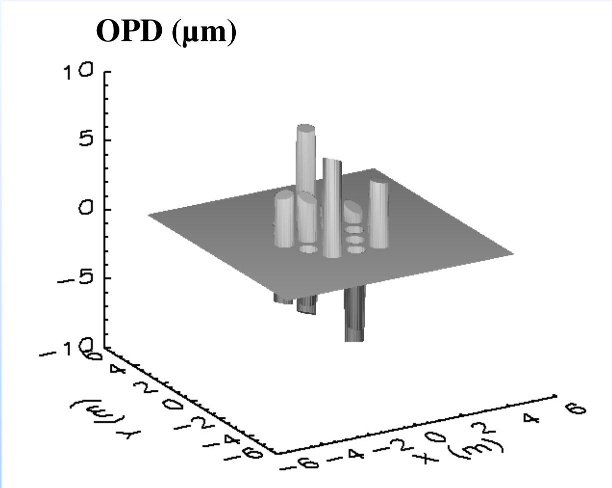
Difference between two phase-shifted MTFs



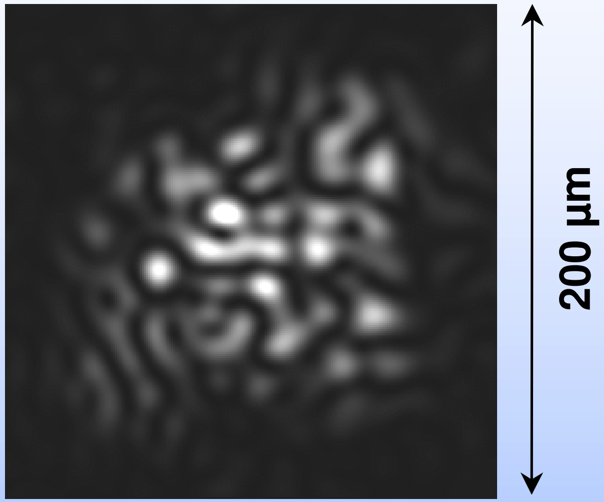
Reconstructed pupil map

Piston errors reconstruction (2/2)

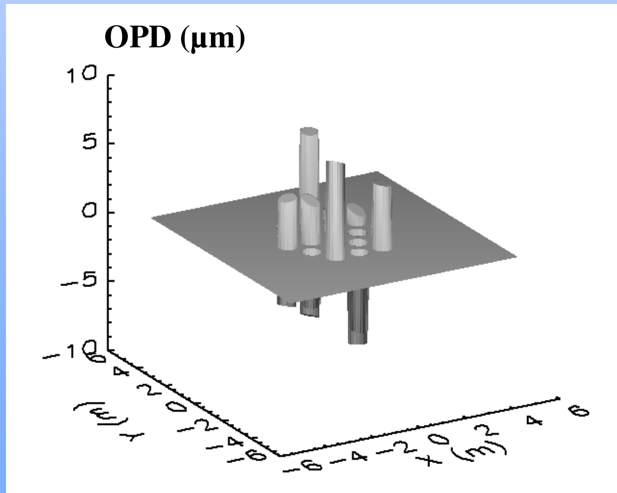
Entrance wavefront



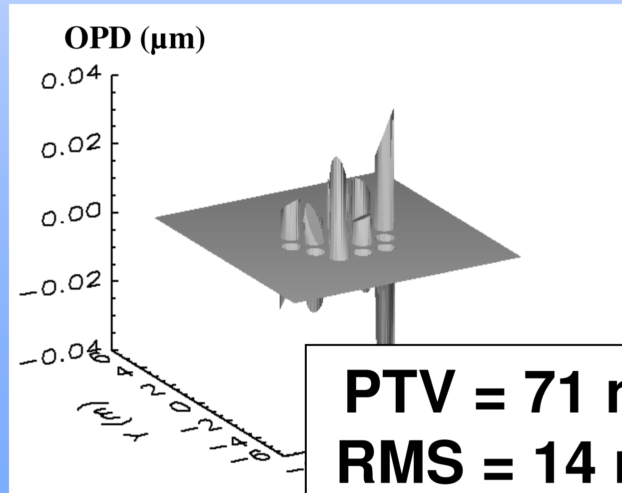
Single PSF acquisition



Reconstructed wavefront

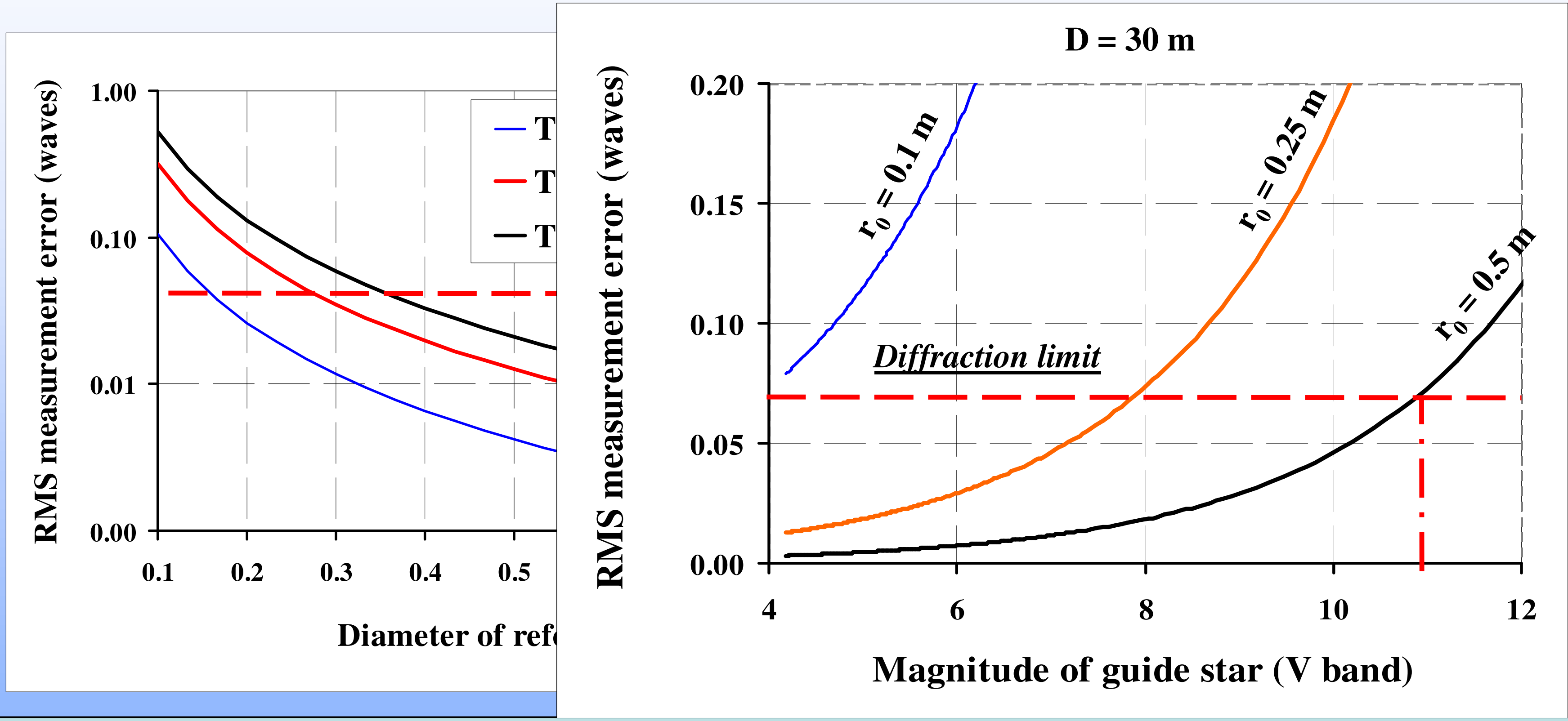


Measurement errors



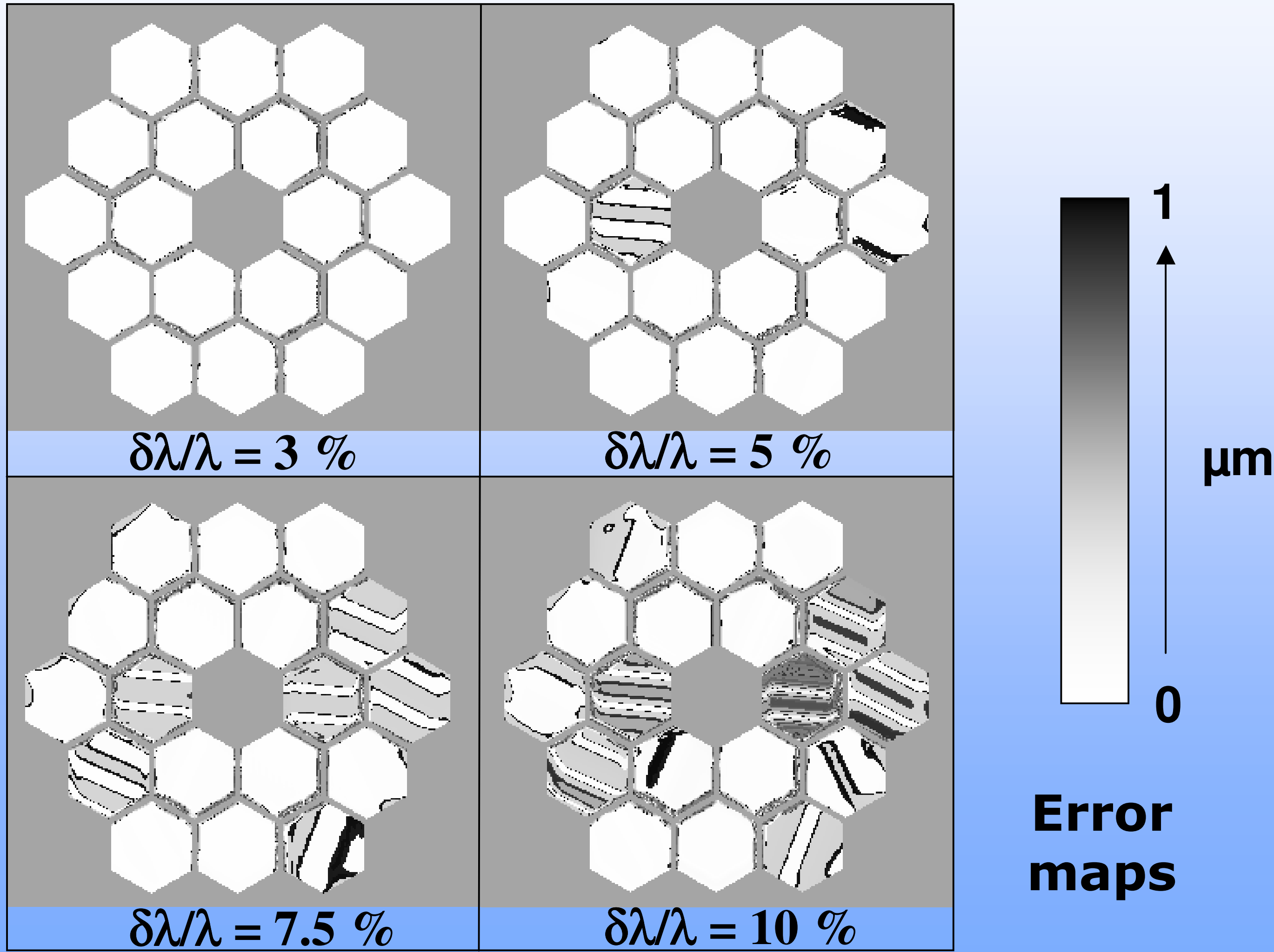
PTV = 71 nm
RMS = 14 nm

Limiting magnitudes in AO mode



- For a 30-m telescope diameter, V = **4**, **8** and **11** respectively in medium, good and excellent seeing conditions

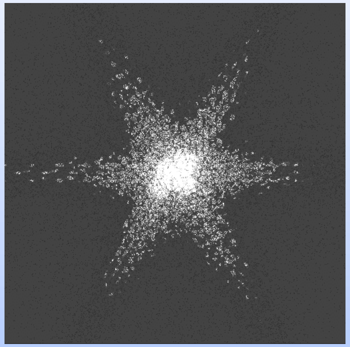
Piston measurement error vs. spectral bandwidth

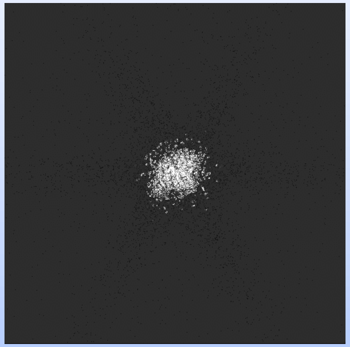


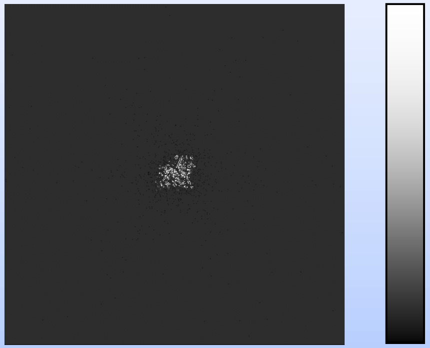
Noise analysis (1/3)

Magnitude 12 | **Magnitude 15** | **Magnitude 18**

Image plane SNR

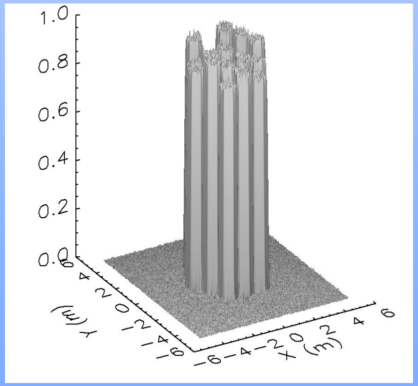


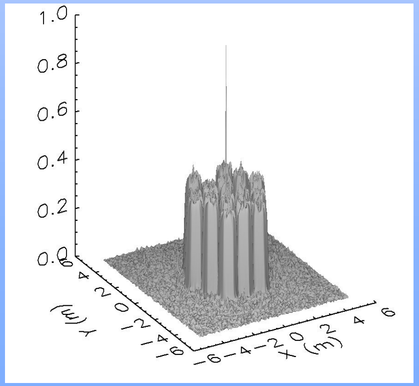


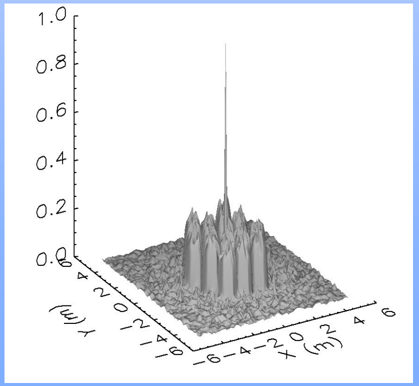


ΔX' = 640 μm

Reconstructed pupil map





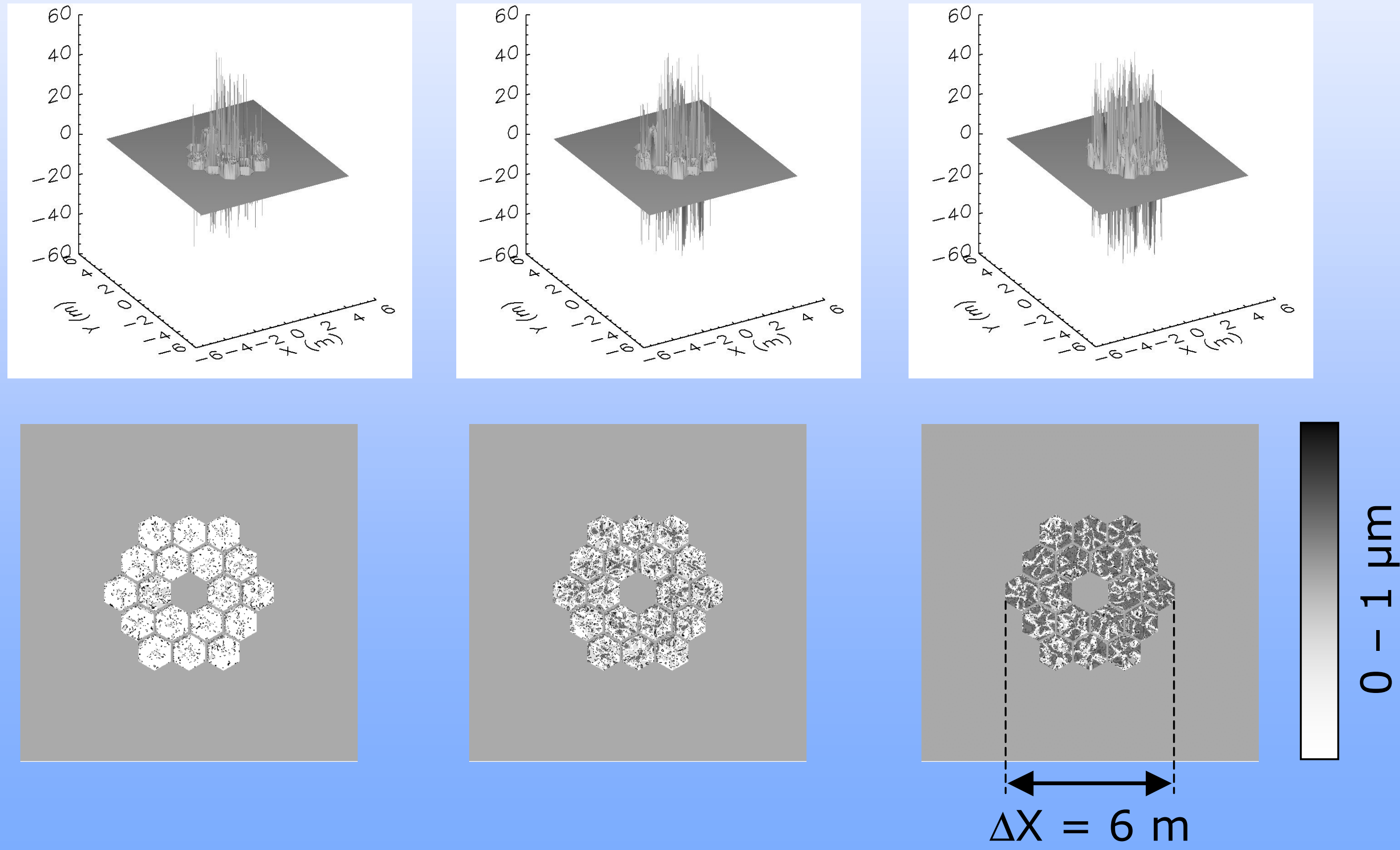


Noise analysis (2/3)

	Magnitude 12	Magnitude 15	Magnitude 18

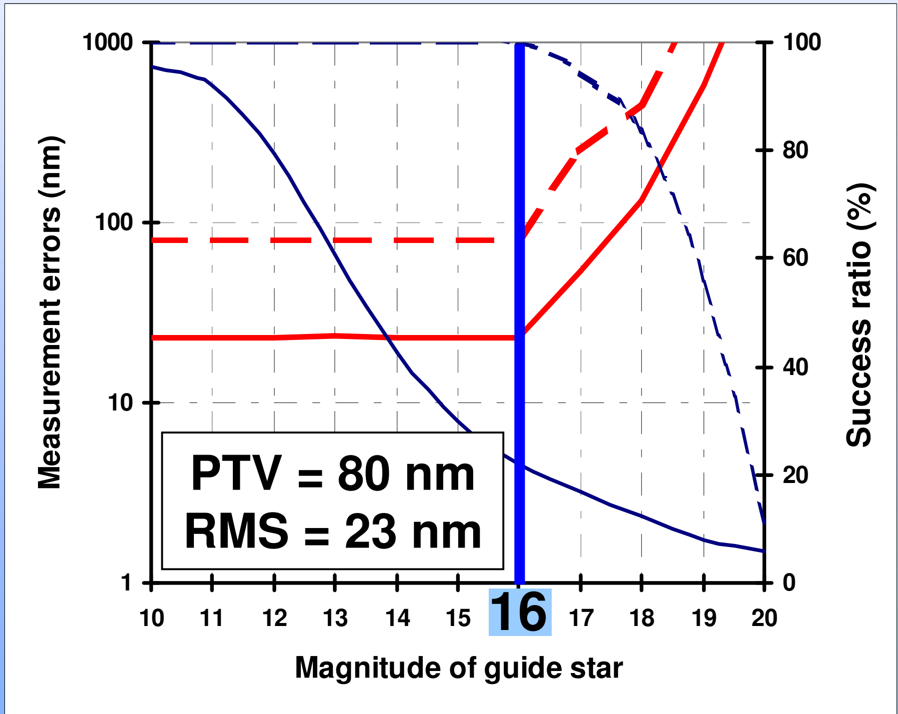
Measured WFE

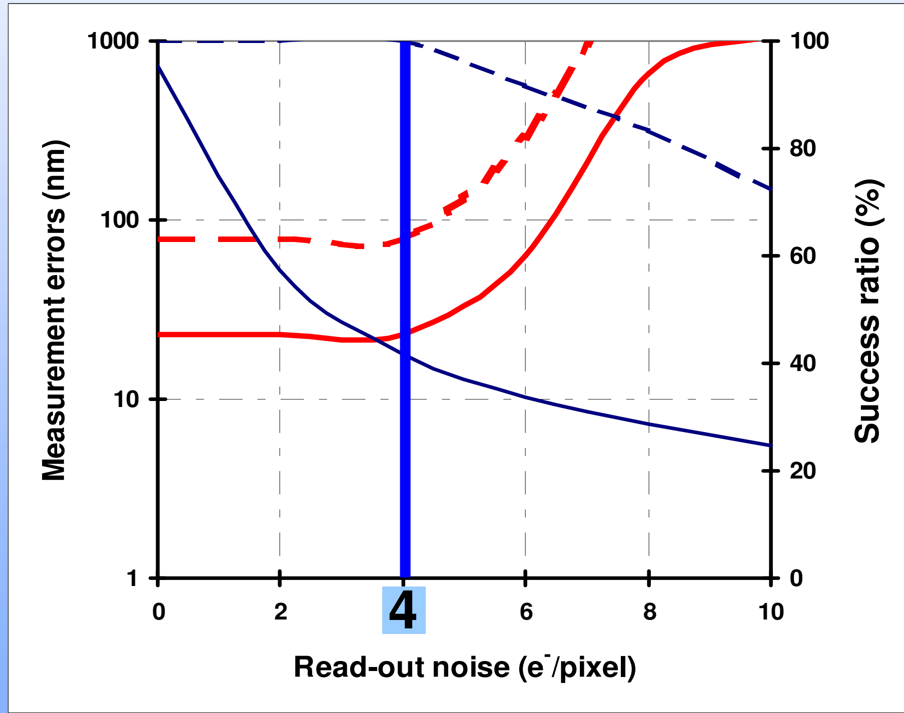
Error map



Noise analysis (3/3)

**Measurement accuracy and Success ratio
vs. Magnitude of guide star and Read-out noise**





Telescope diameter = 6 m; $\delta\lambda/\lambda \approx 5$ %; integration time = 1 sec

Conclusion

- Image plane wavefront sensors can be operated in a phase-shifting mode, introducing different phase-shifts into a reference sub-pupil
- They can perform multi-spectral measurements in order to remove the 2π ambiguity and extend their capture range to [-10,+10 µm] and beyond
- They perform better in space, but may attain magnitude 11 in AO regime, with residual errors around 20 nm RMS
- They are suitable for cophasing large segmented mirrors, but also sparse aperture interferometers
- They can be envisaged as low-order AO wavefront sensors, or as a special form of "phase diversity" methods