The importance of spatial filtering

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Outline

- Spatial and modal filtering
- Single mode waveguides primer
- Application to:
  - V^2 science
  - Nulling interferometry
  - Pupil remapping
- Conclusion

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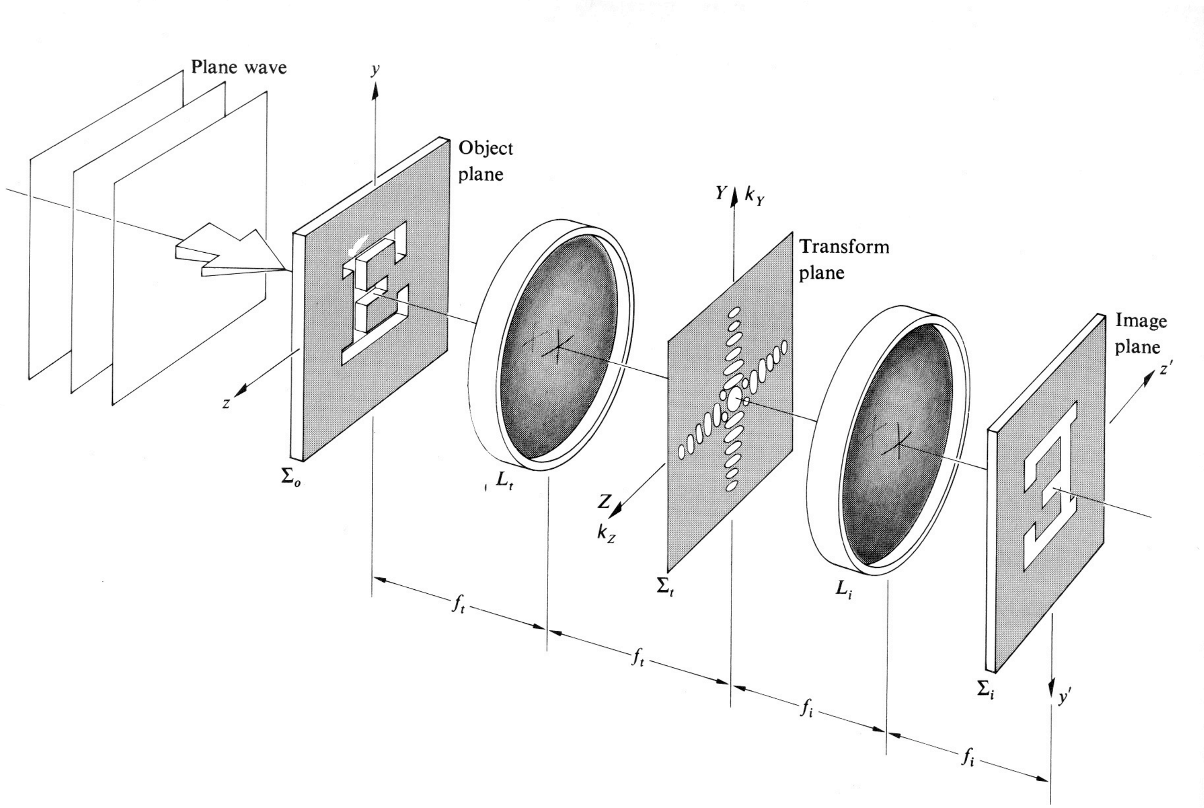
Spatial filtering ?

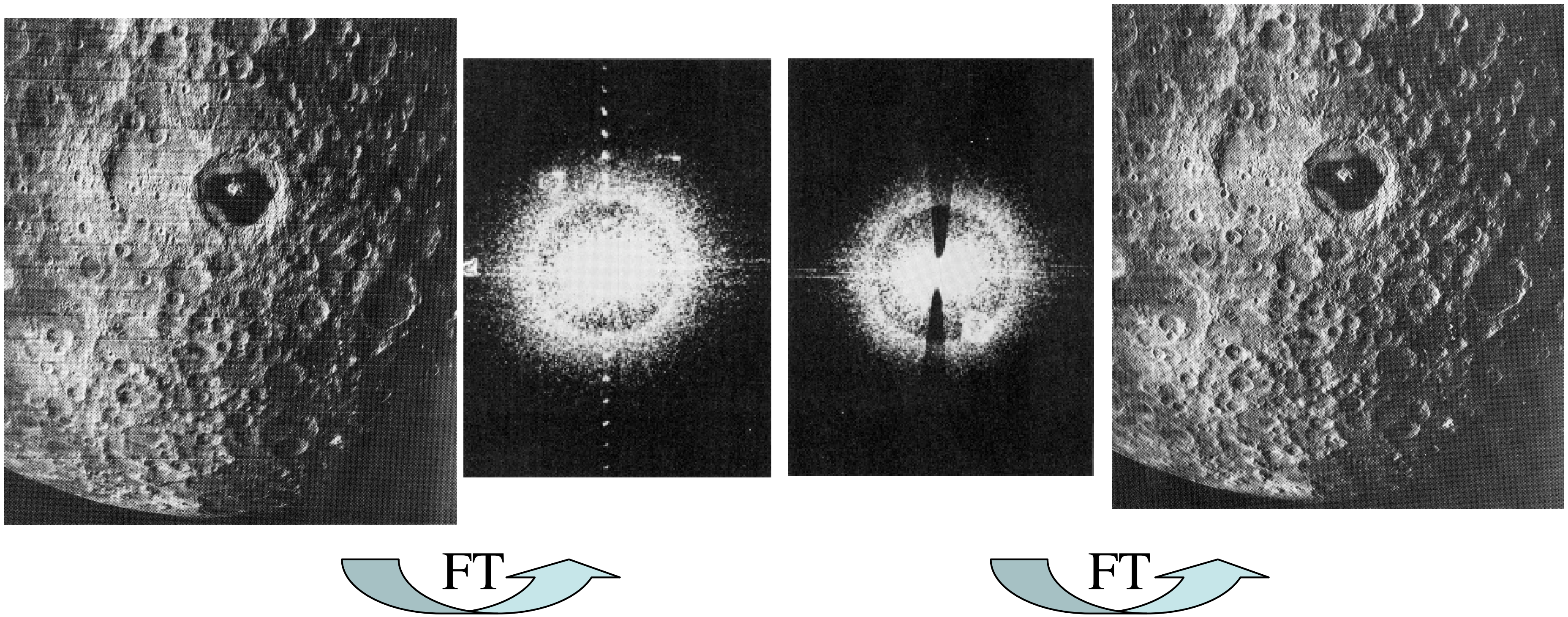


- Exploits the Fourier relationship created by Fraunhofer diffraction between the image and pupil planes

Example (image processing)

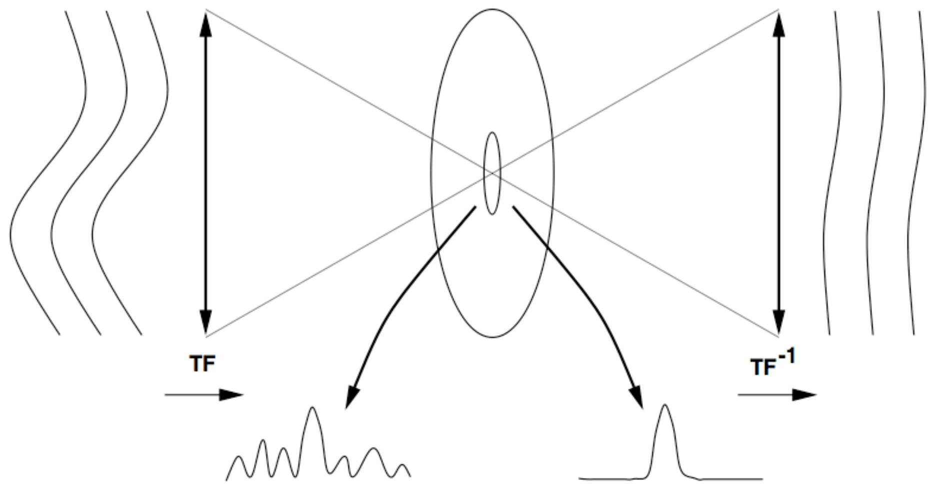
- Spatial frequencies are removed selectively to « clean » the image from artefacts

From Hecht, Handbook of Optics



Spatial filtering with a pinhole

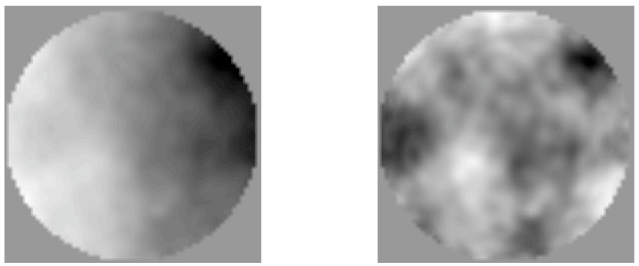
- Low-pass filtering of the wavefront
- Used e.g. for laser beam cleaning
- However:
  - Intensity filter
  - Low-frequency artefacts not removed
  - Residual output phase
  - Strong chromaticity
  - Partial output coherence



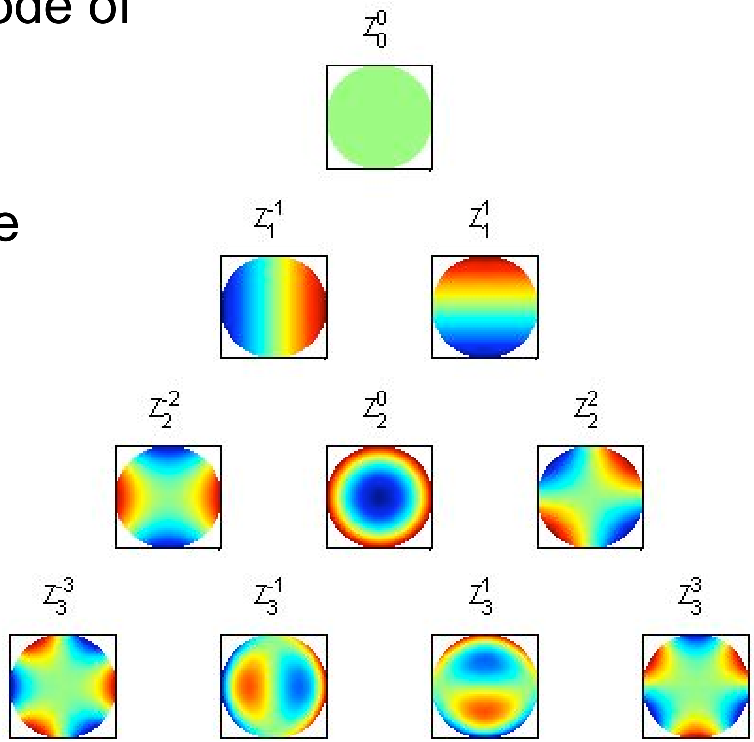
Modal filtering of the wavefront

- A good wavefront is a flat wavefront !
- This corresponds to e.g. the first mode of a Zernike decomposition
- We want to select that mode
- This can be done using single-mode waveguides

With tip-tilt *Tip-tilt removed*



Turbulent wavefront simulation (C. Ruillier)



Zernike wavefront decomposition

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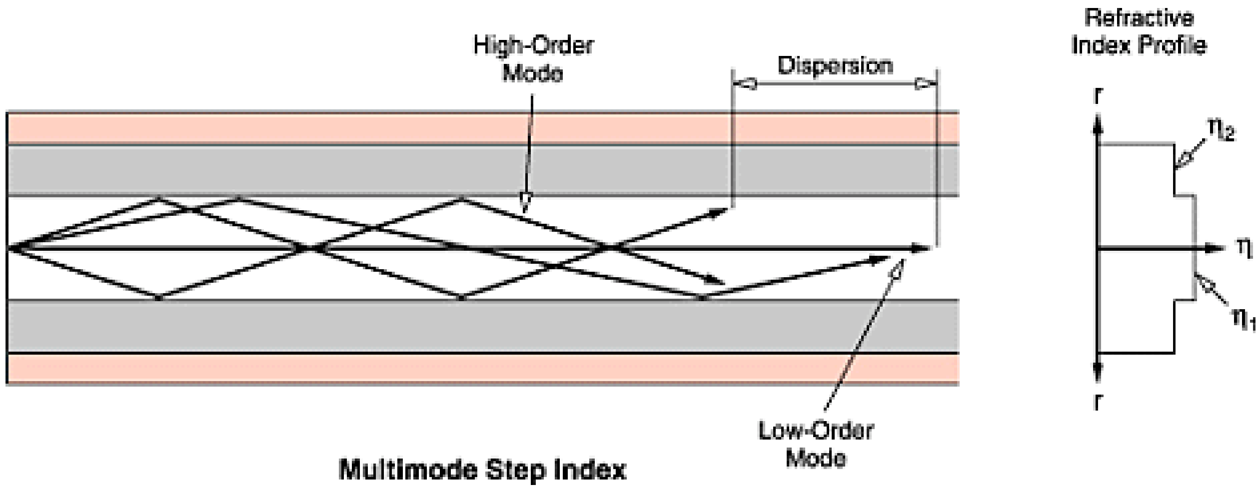
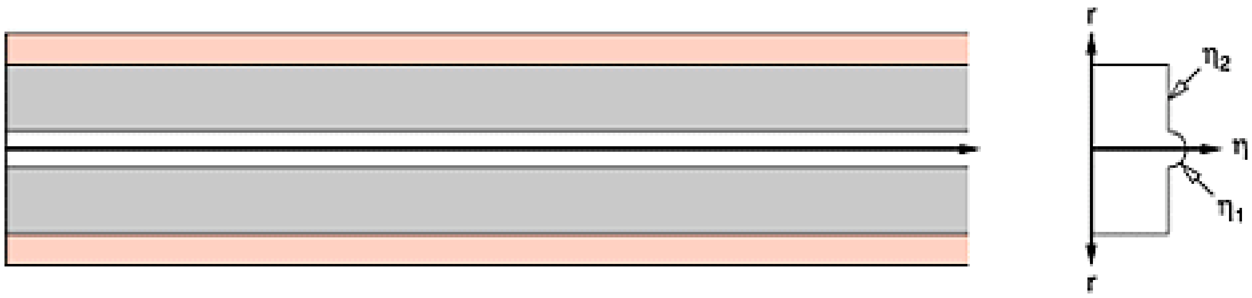
Waveguide ? Multimode



$$\sin\theta_{\lim} = NA = \sqrt{n_{core}^2 - n_{clad}^2}$$

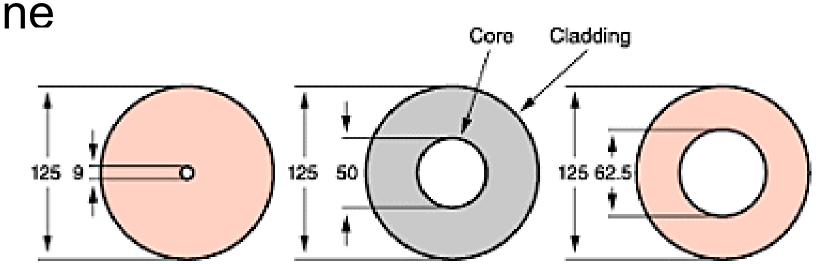
- Large core => ray optics relevant
- Many rays with different pathlengths ("modes")
  - Suitable for spectroscopy, not interferometry
- Uniform light acceptance within cone

« Classical » single-mode fibers



Single-Mode Step Index

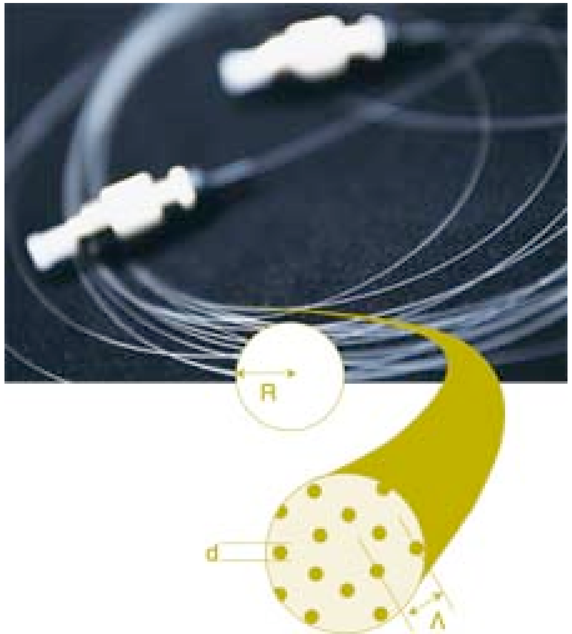
- Optical path well defined (at least for one polarization…)
  - ⇒ Suitable for interferometry
- Core diameter only a few λ
  - ⇒ Ray optics no longer valid
  - ⇒ Use waveguide theory
- During propagation diffraction is balanced by high index core

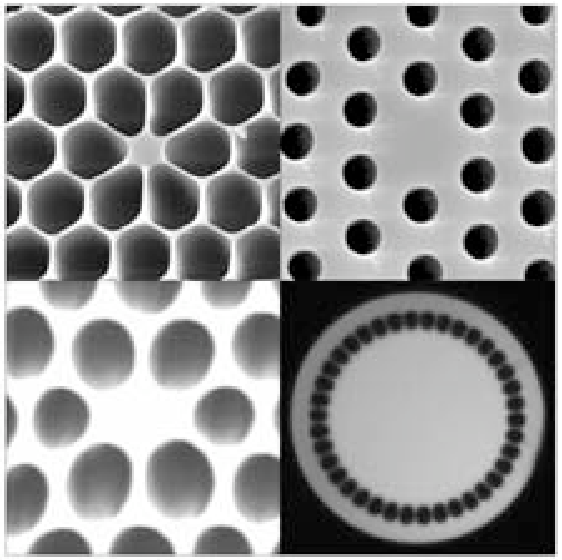


Typical Core and Cladding Diameters (µm)

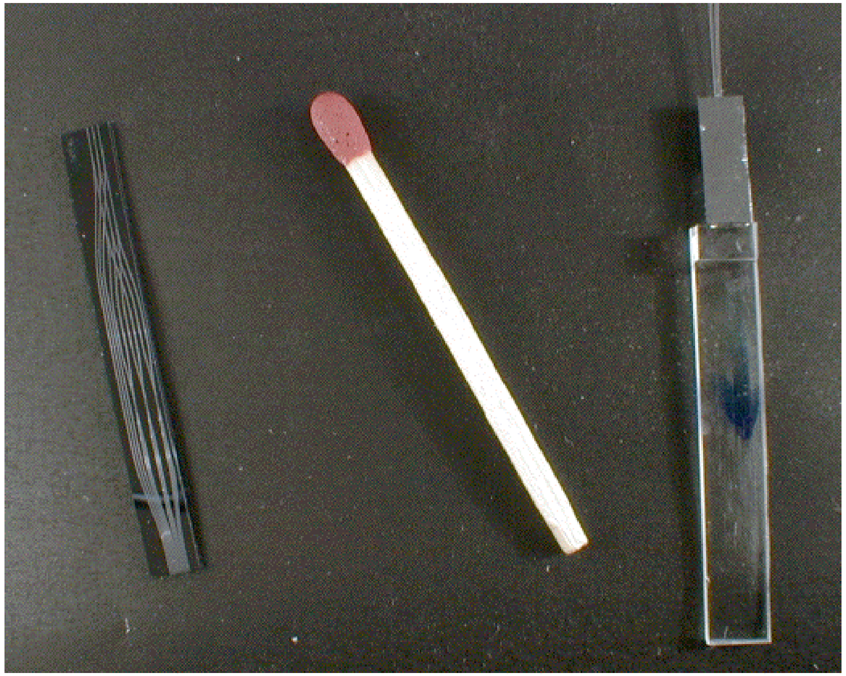
Alternative structures

- Photonic crystal fibers or « holey fibers »
- Integrated optics

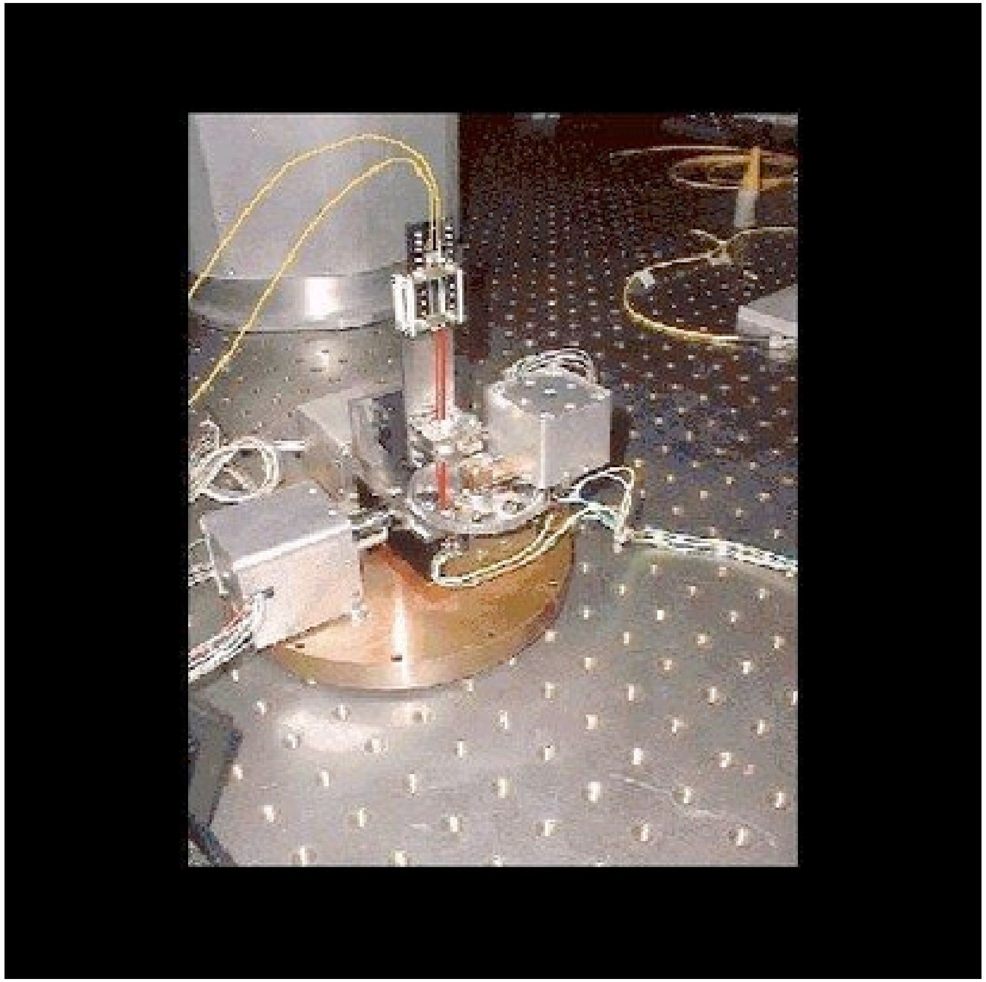




Integrated optics example



The IONIC beam combiner (LAOG/CNRS)



Single-mode waveguides
Fundamental parameters

Numerical aperture

$$\boxed{NA = \sqrt{n_{core}^2 - n_{clad}^2}}$$

Core radius

$$\boxed{a}$$

Wavelength

$$\boxed{\lambda}$$

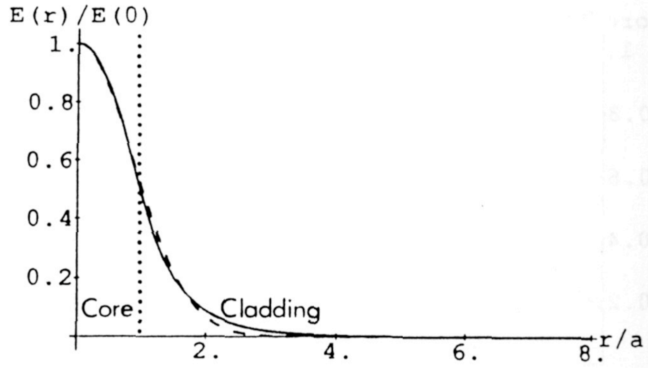
Normalized frequency

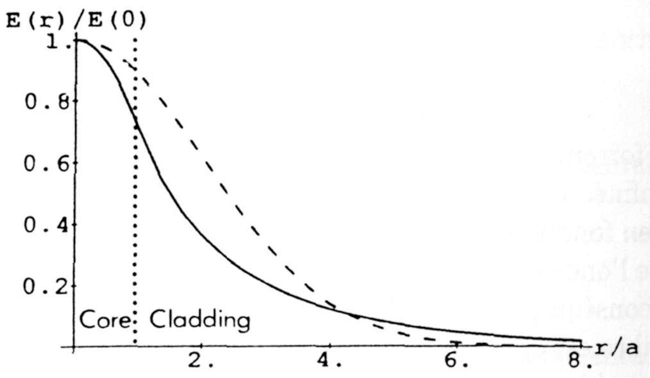
$$\boxed{V = \frac{2\pi\, a\, NA}{\lambda}}$$

- V determines
  - Energy distribution within waveguide
  - Number of modes and modes structure
  - Modes velocity
  - Bending losses, etc…
- V not necessarily isotropic

The fundamental (LP_{01}) mode
($V < 2.405$)

LP_{01} mode structure



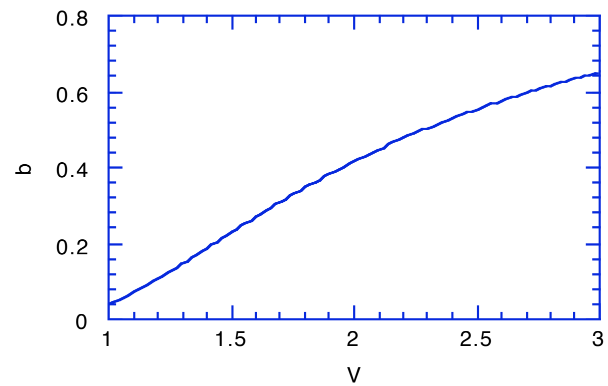


Cutoff wavelength

$$\boxed{\lambda_c = \frac{2\pi\, a\, NA}{2.405}}$$

LP_{01} mode velocity effective index

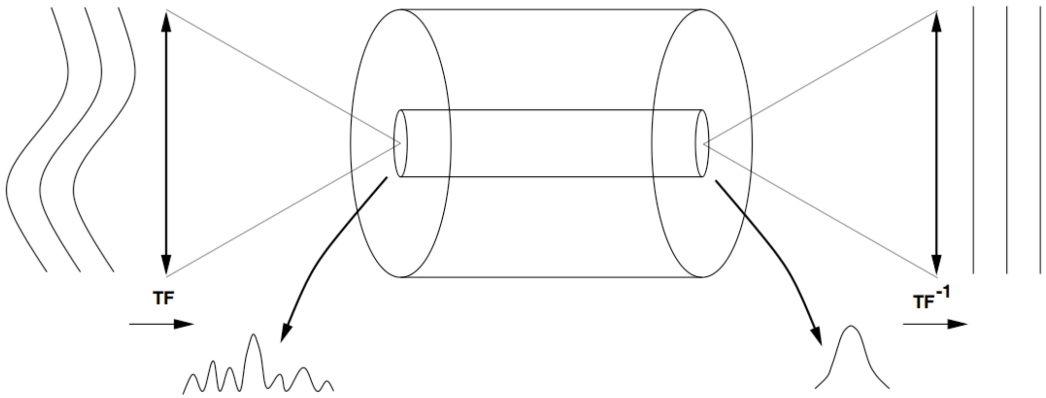
$b = (n - n_{clad}) / (n_{core} - n_{clad})$



- Beam étendue $S\Omega \sim \lambda^2 n$
- A substantial fraction of the energy carried through the cladding
- For $\lambda > \lambda_c$ higher order modes not guided (radiated through the cladding)
- Guiding of LP_{01} mode good up to about $\lambda \sim 2\lambda_c$

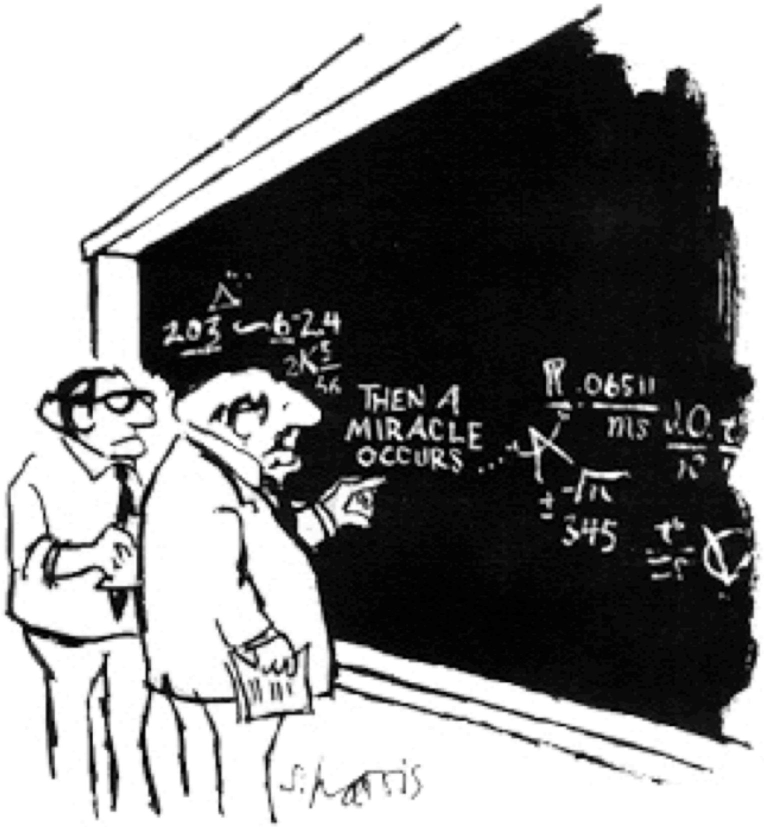
Most important property
(modal filtering or "amnesia effect")

If single-mode,
the beam profile depends on the structure
of the waveguide only,
not on the injection conditions!



The wavefront cleaner…

How is this possible ?



"I think you should be more explicit here in step two."

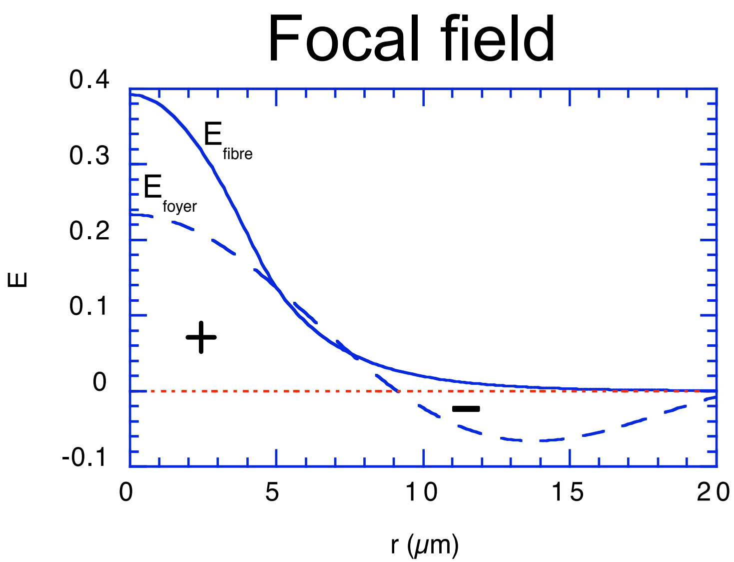
Starlight selection by a SM fiber

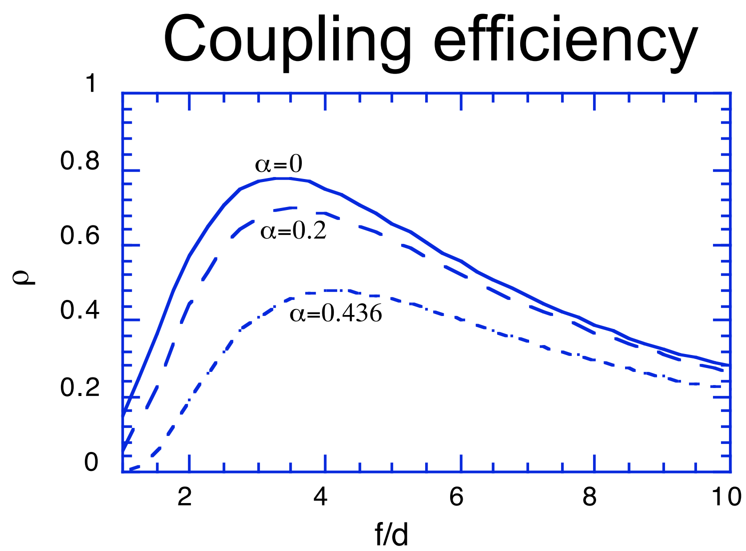
- The incoming electromagnetic field is projected onto the LP_{01} mode
- Coupling efficiency is determined by the value of the overlap integral for the normalized field :

$$\rho = \left| \int \int E_{tel} \; E^{*}_{fibre} \right|^{2}$$

- The overlap integral can be interpreted as the Strehl ratio of the apodized pupil
- The set telescope + fiber behaves like an optical antenna

Diffraction limited case

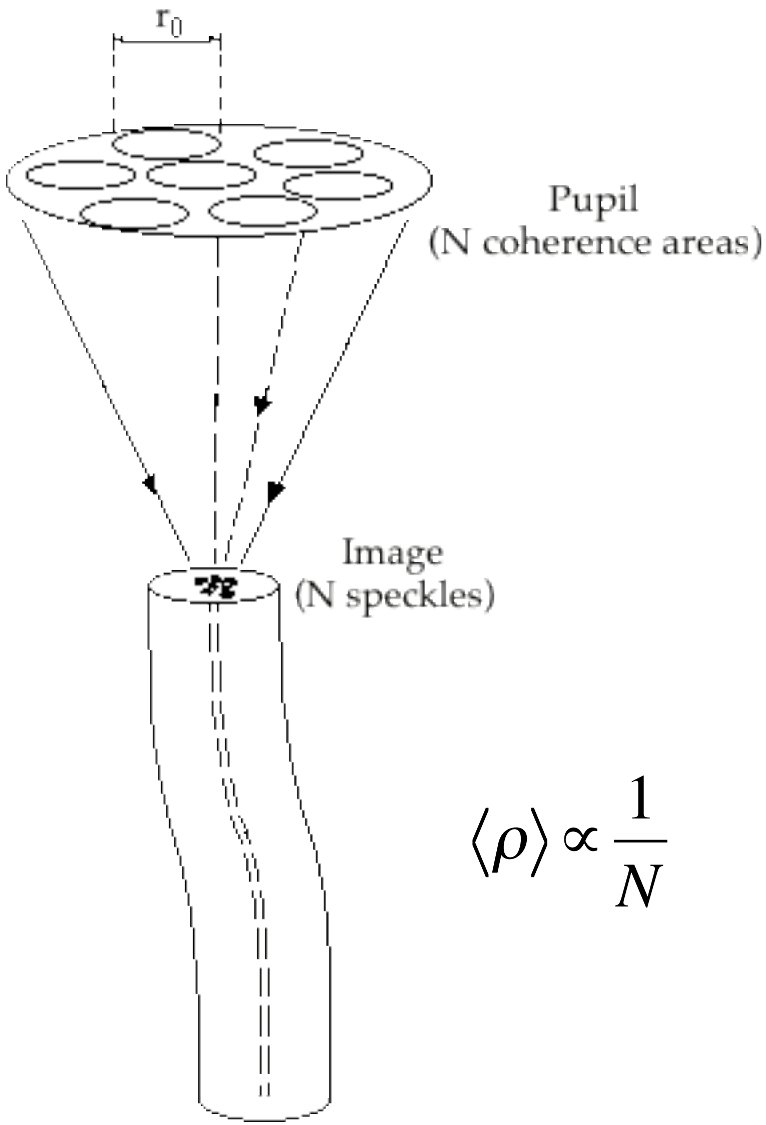




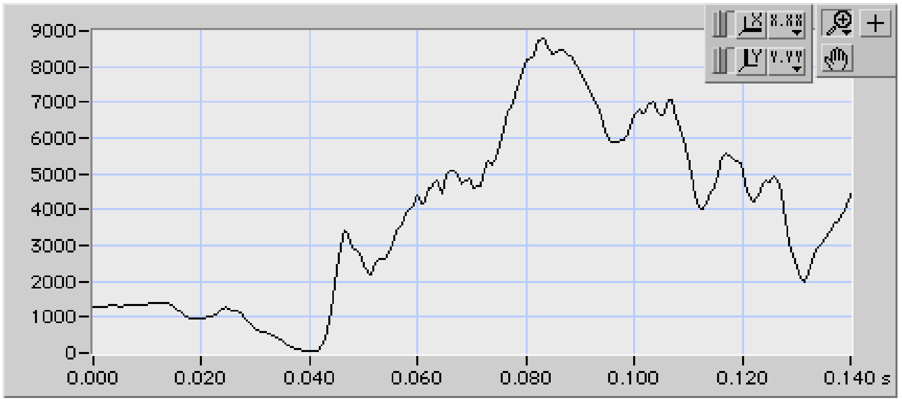
Beware of central obstruction !

Coupling to turbulent starlight

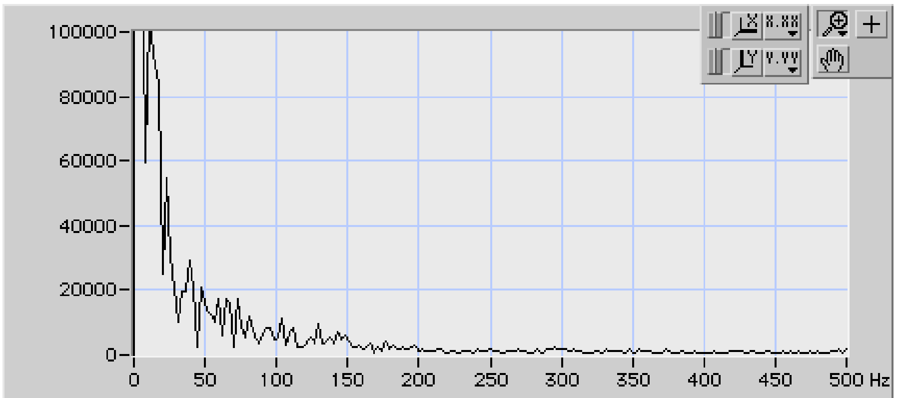
(uncorrected VLT UT example)



$$\langle \rho \rangle \propto \frac{1}{N}$$



Sample time sequence



Amplitude spectrum

With adaptive optics

- SM fibers as fast strehlmeters

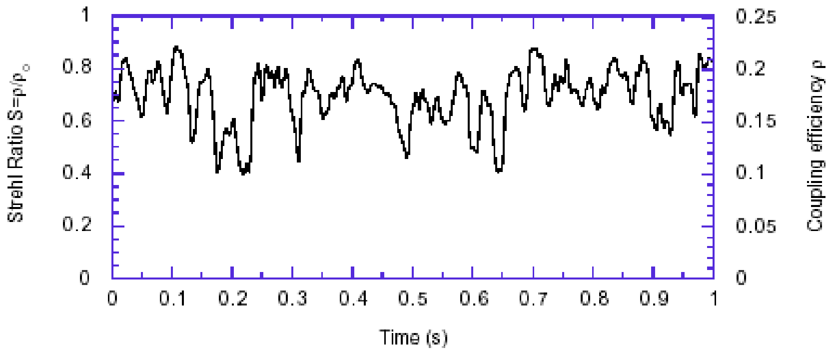


Fig. 5. Strehl ratio and injection efficiency for a stellar source (GM Lup) in a circular core fiber (VF 1078), at the 3.60 m telescope in La Silla corrected by ADONIS. Note the presence of a modulation with a 0.04 s period (25 Hz) induced by a vibration of the telescope tube. The seeing was excellent and very slow ($r_0 = 65$ cm and $\tau_0 = 0.4$ s in K). The reference efficiency for this setup was $\rho_0 = 0.25$ and was calibrated on the internal, artificial point source

*V. Coudé du Foresto et al. 2000, A&AS **145**, 305*

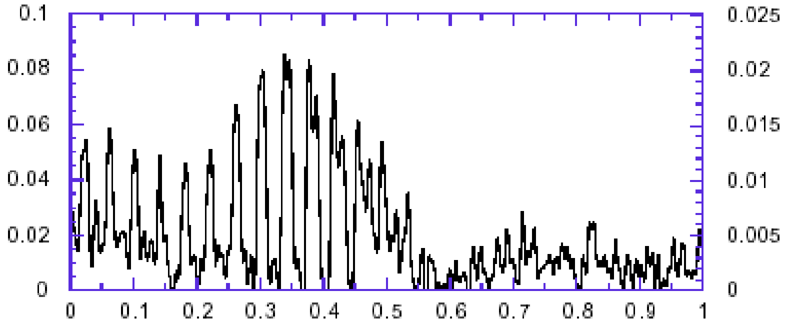


Fig. 7. Strehl ratio and injection efficiency for a stellar source (GM Lup) in a circular core fiber (VF 1078), at the uncorrected 3.60 m telescope in La Silla

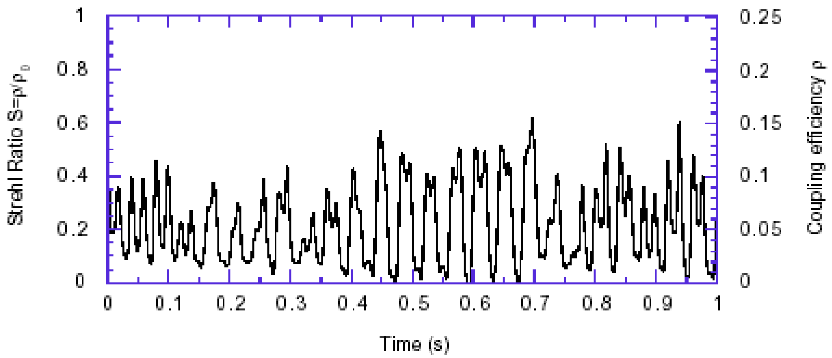
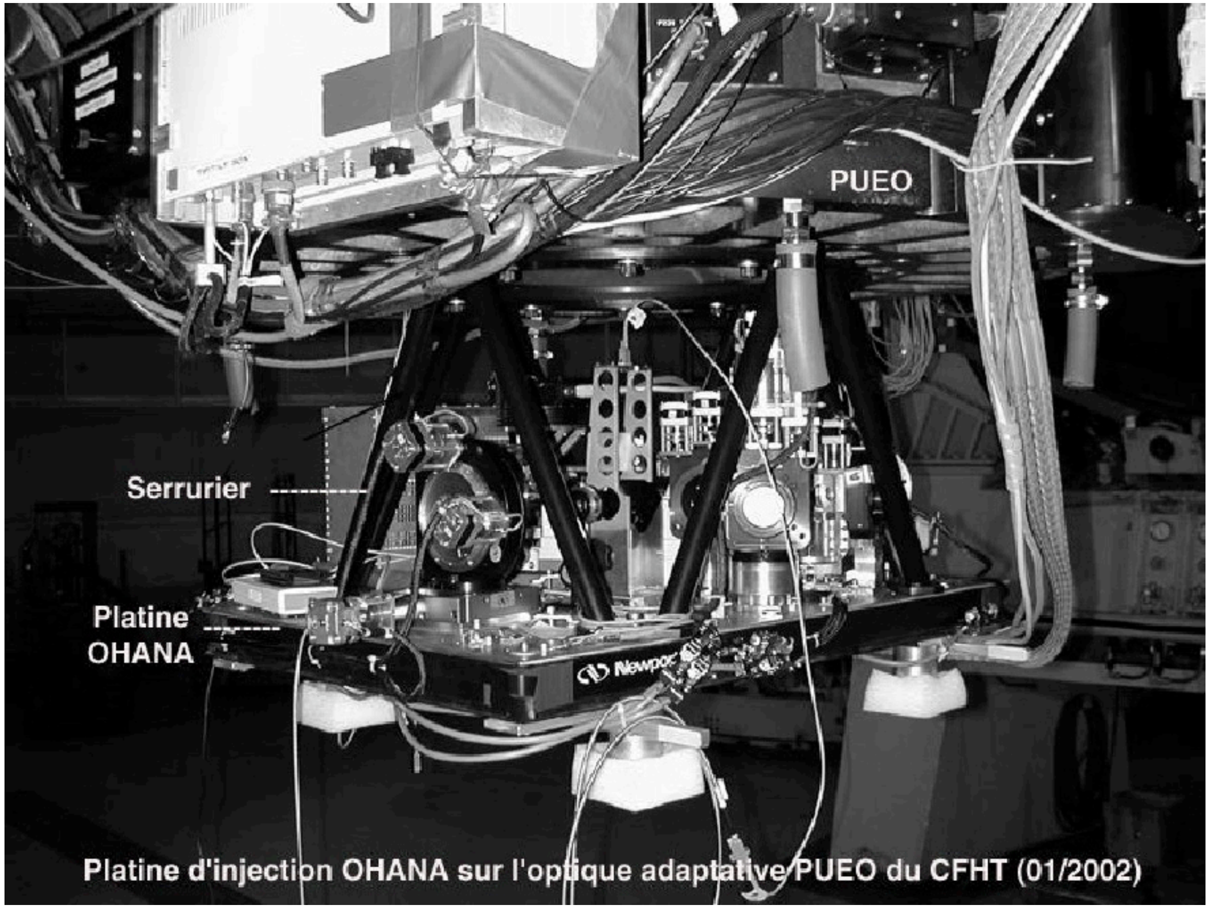


Fig. 6. Another recording of the coupling fluctuations, in identical experimental conditions. The 25 Hz modulation of the injected energy is now total

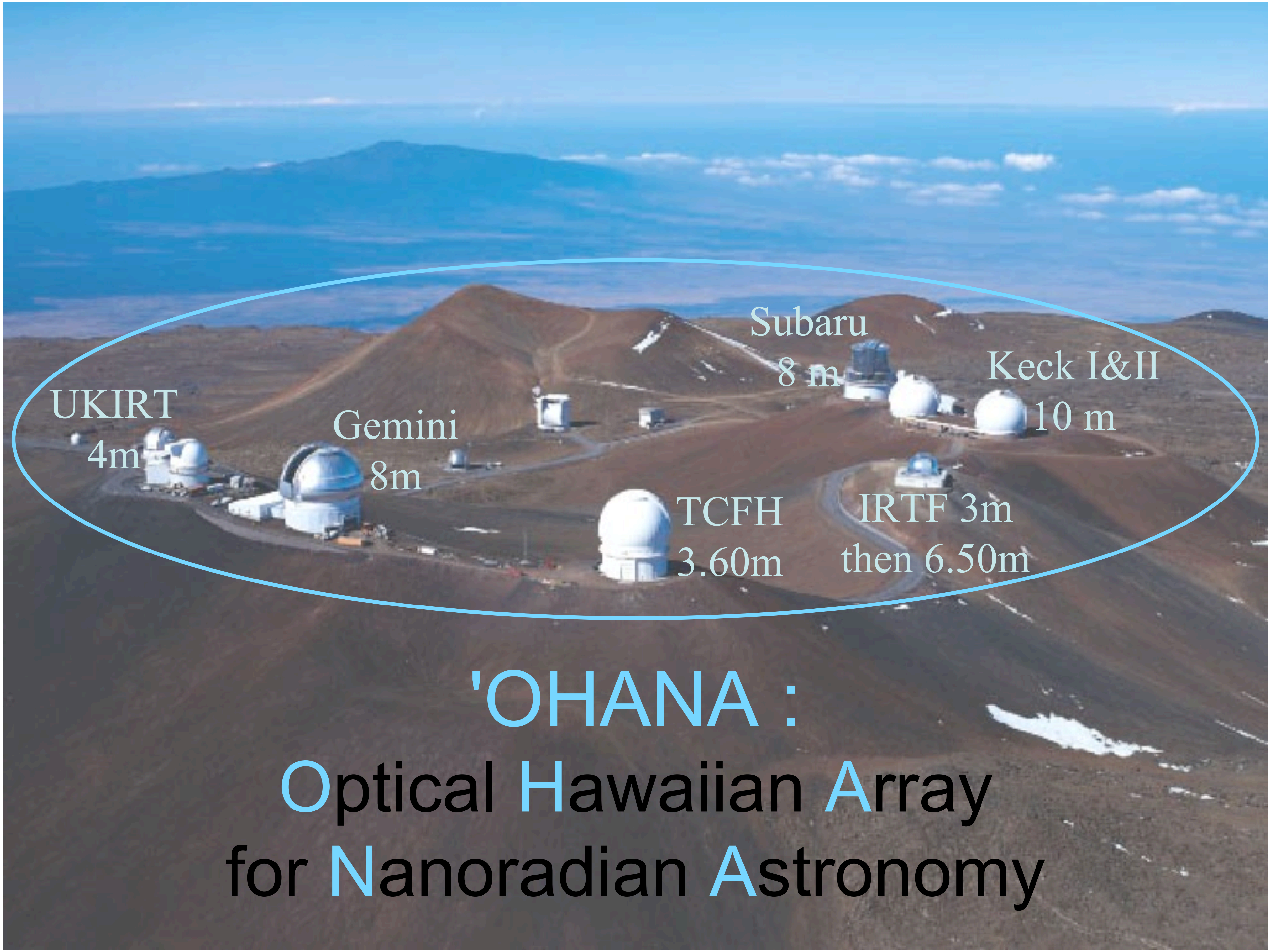
Uncorrected

Corrected

Implementation example:

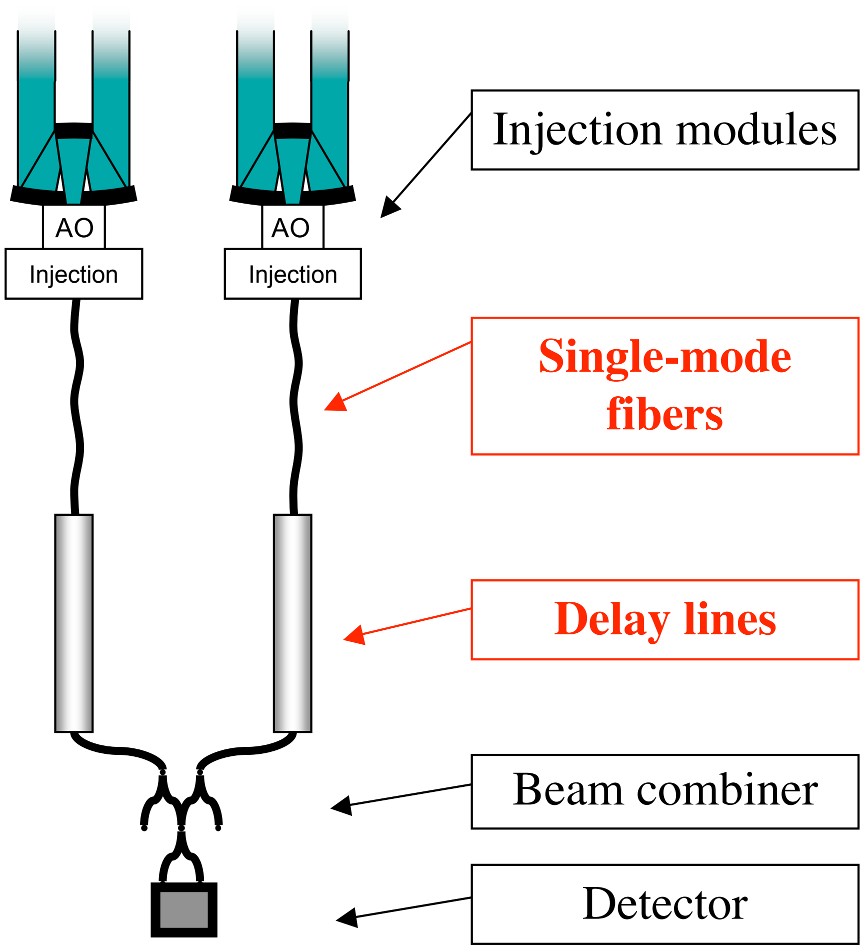


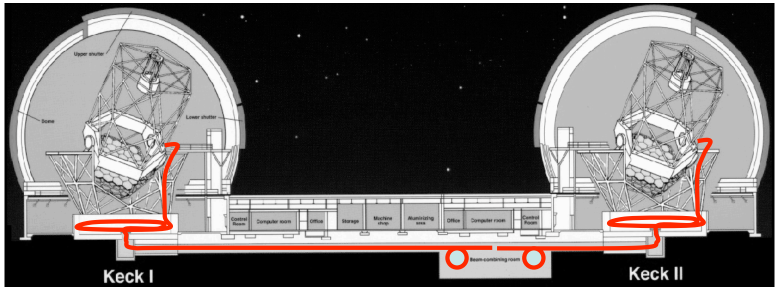
SM fiber injection stage behind the PUEO AO system
at the 3.6m CHFT telescope on Mauna Kea



'OHANA :
Optical Hawaiian Array for Nanoradian Astronomy

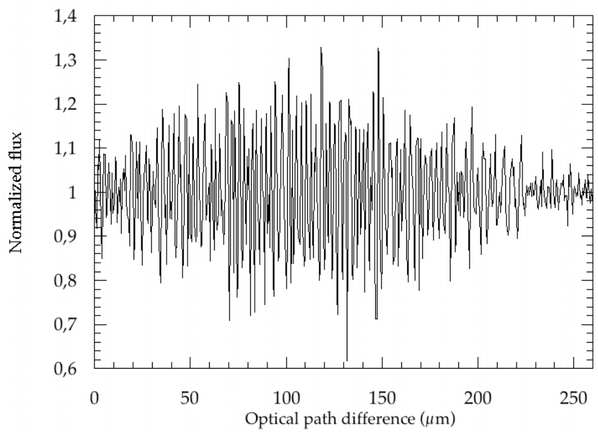
‘Ohana concept





First fringes: Keck I-II with 2x300m fibers

Perrin et al. 2006, Science ***311****, 194*



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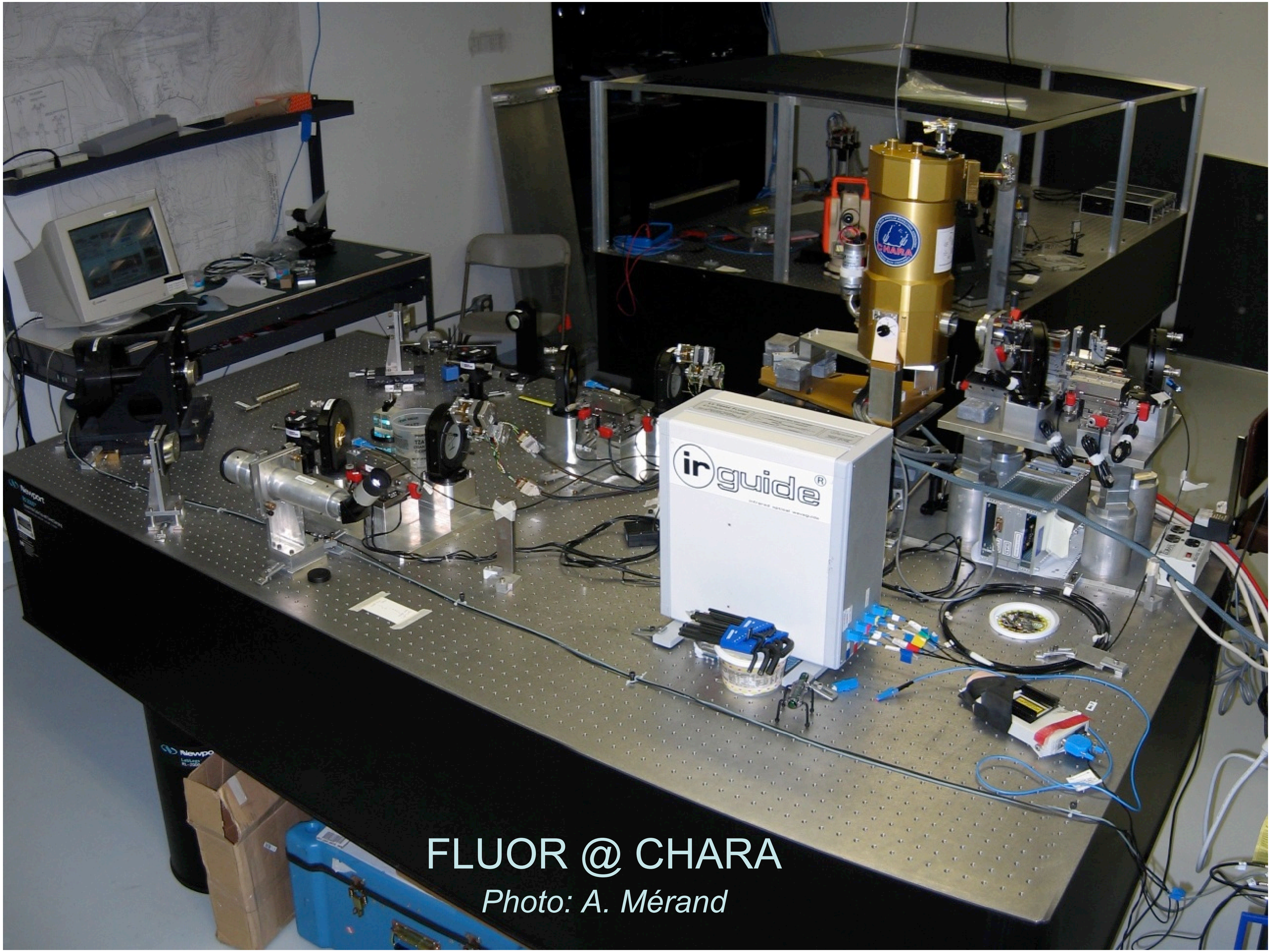
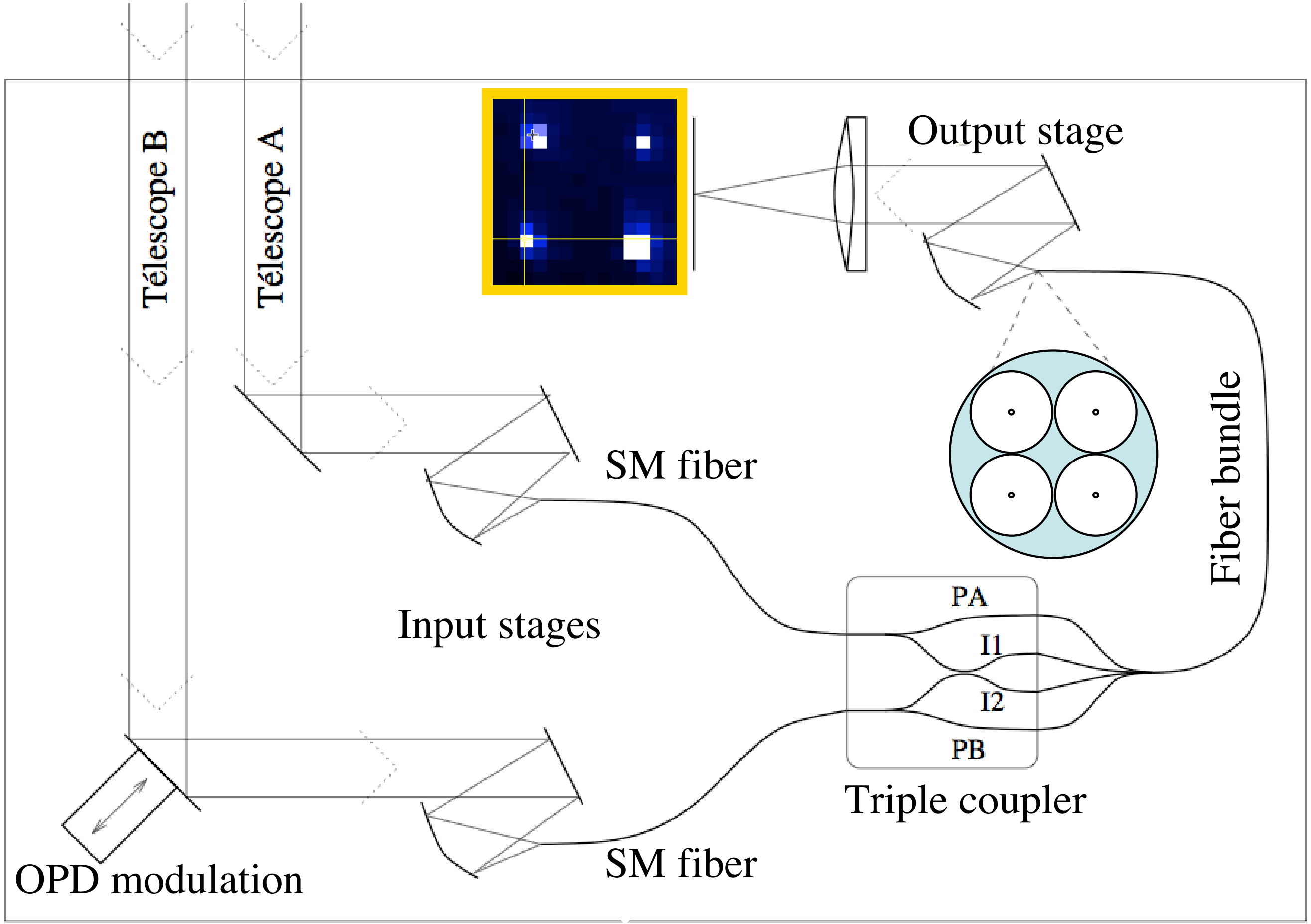


FLUOR @ CHARA

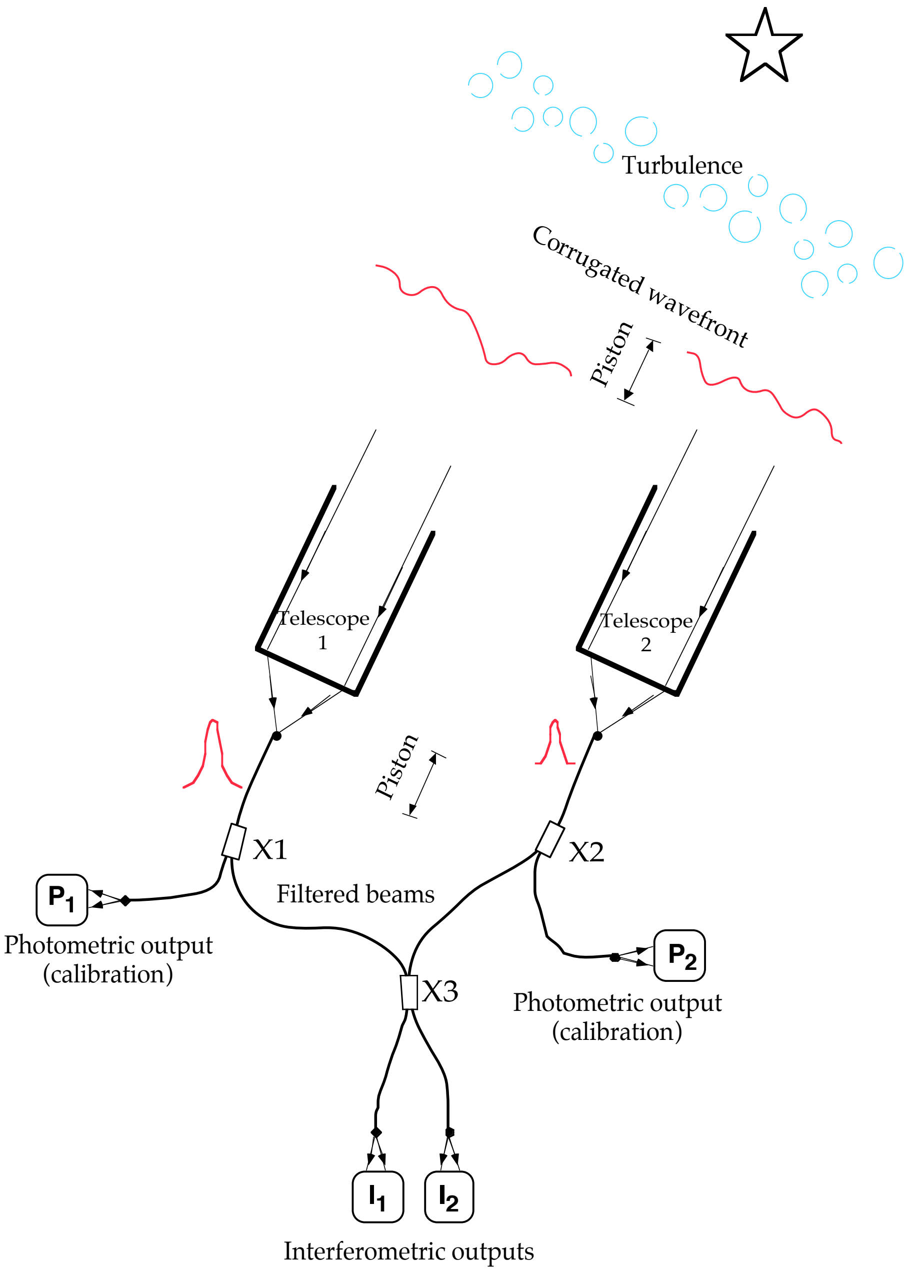
Photo: A. Mérand

Implementation example FLUOR at CHARA



Taking advantage of modal filtering (FLUOR concept)

- No image, no pupil !
- Two inputs:
  - Beam 1 and Beam 2
- Pupil phase corrugations
  - ⇒ intensity fluctuations
  - ⇒ easier calibration
- Piston *not* filtered
- Two-stage, triple X-coupler
  - X_1 and X_2 photometric calibration
  - X_3 beam combination
- Four outputs:
  - I_1, I_2, P_1 and P_2



Raw interferogram

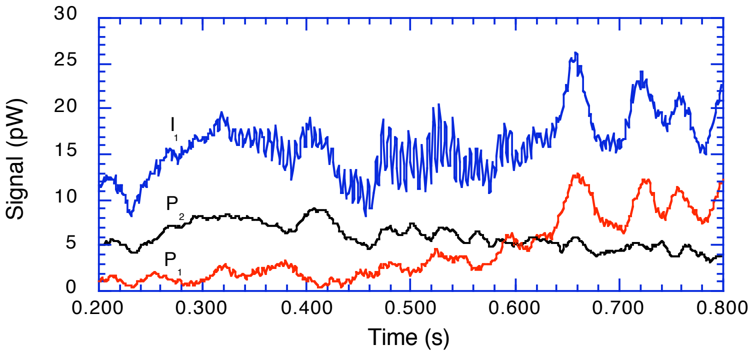
Corrected interferogram

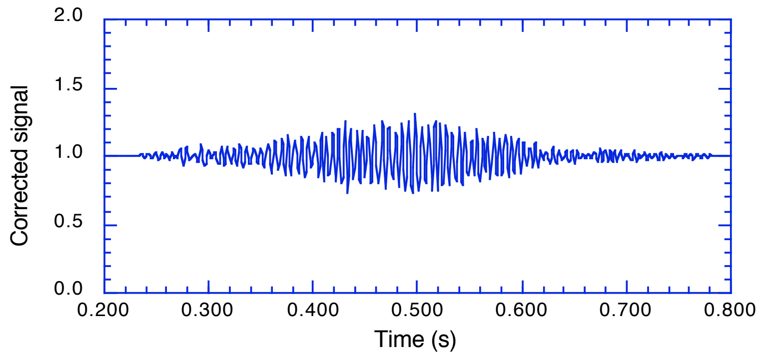
$$I = P_1 + P_2 + 2\sqrt{P_1 P_2}\,\mathrm{Re}\{\gamma_{12}\}$$

γ_{12} `complex degree of coherence between the two beams`

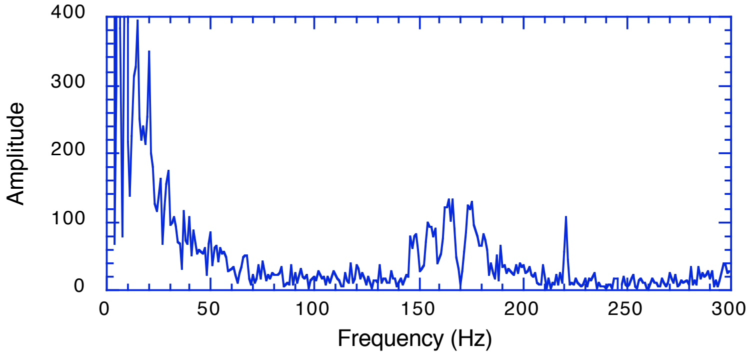
$$\mathrm{Re}\{\gamma_{12}\} = \frac{I - P_1 - P_2}{2\sqrt{P_1 P_2}}$$

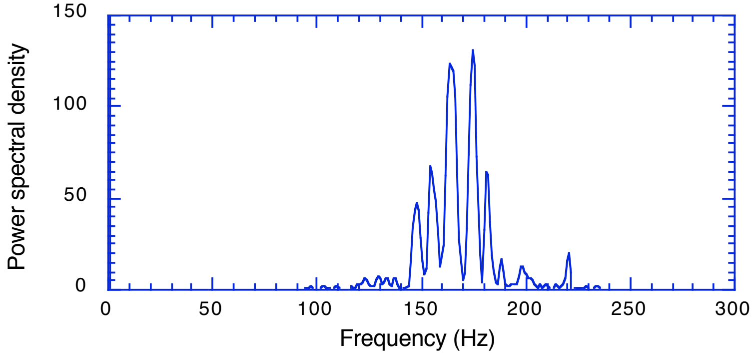
=> coherence measurement free from atmospheric bias





=> higher accuracy V^2 measurement after calibration



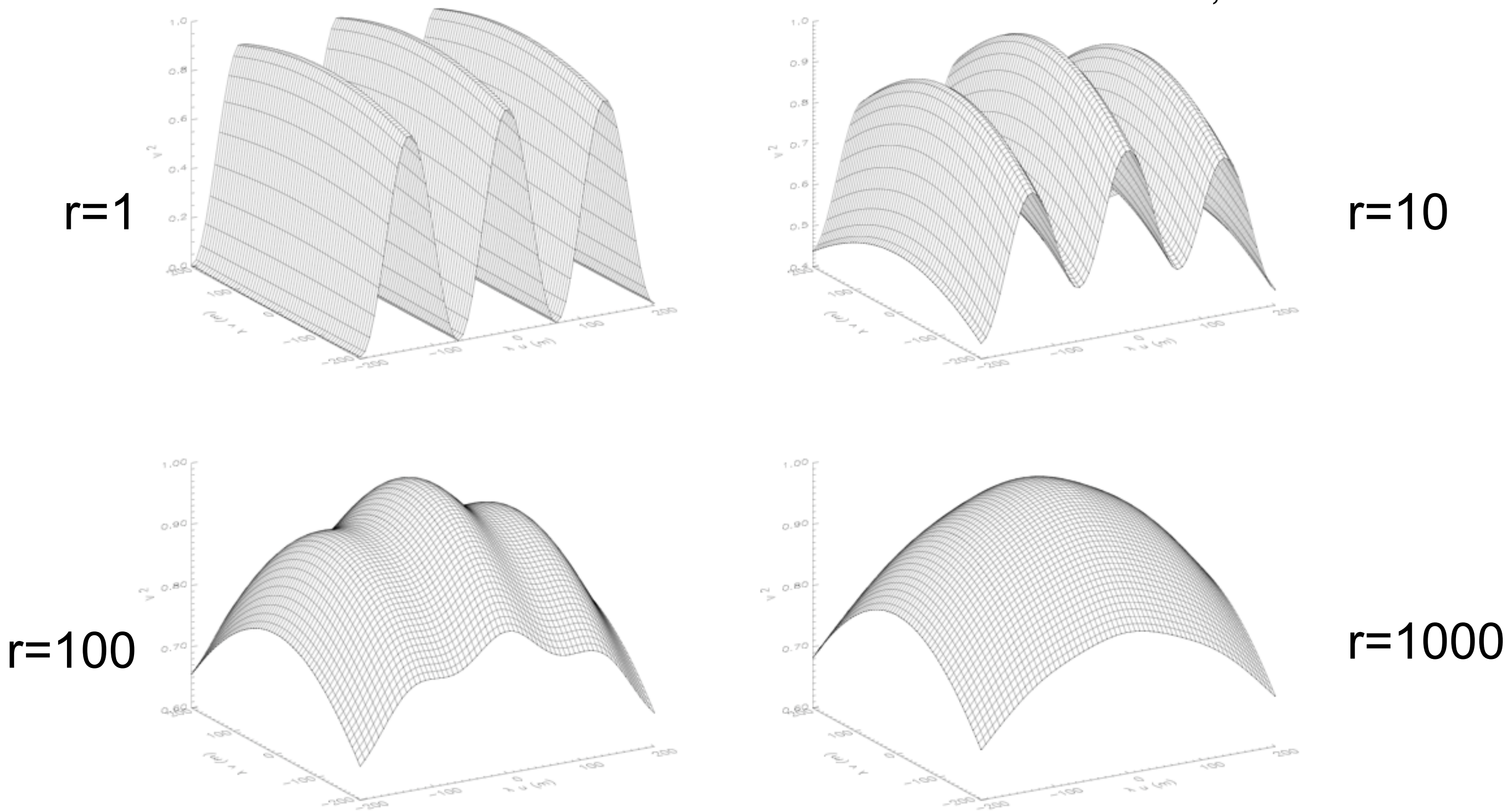


Why is high accuracy V^2 important ?

- For high dynamic range observations
- To discriminate between complex models
- To measure diameters beyond the λ/B limit

Need for high dynamic range

From P. Bordé 2002, PhD thesis

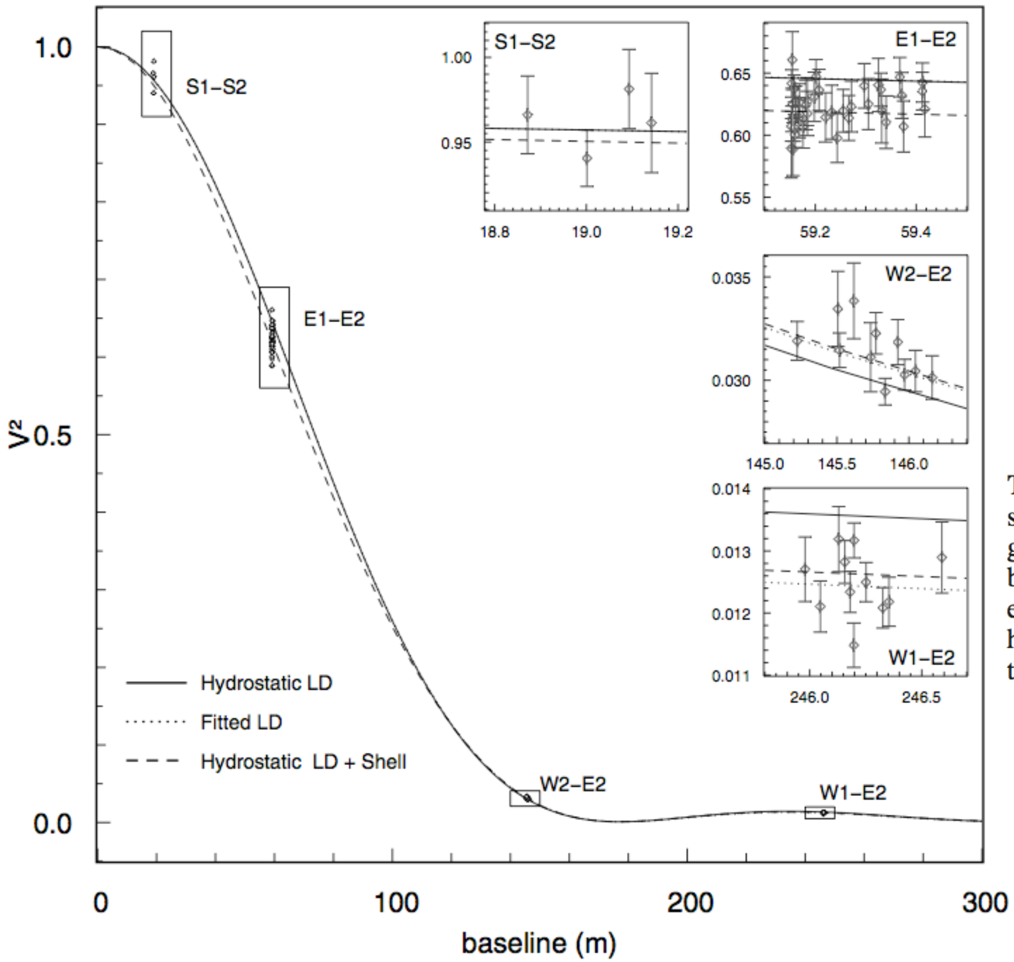


V^2 for a binary system with different luminosity ratios (r)

Discriminate between models

FLUOR/CHARA observations of Polaris

*Mérand et al. 2006, A&A **453**, 155*



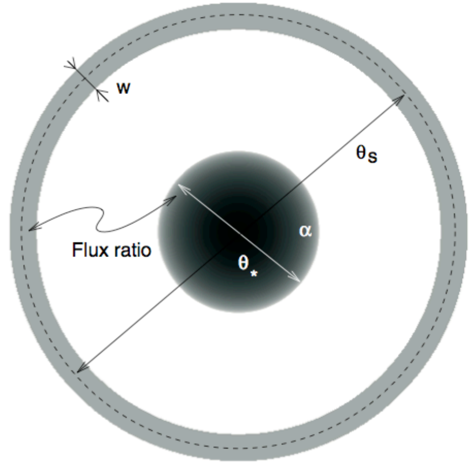


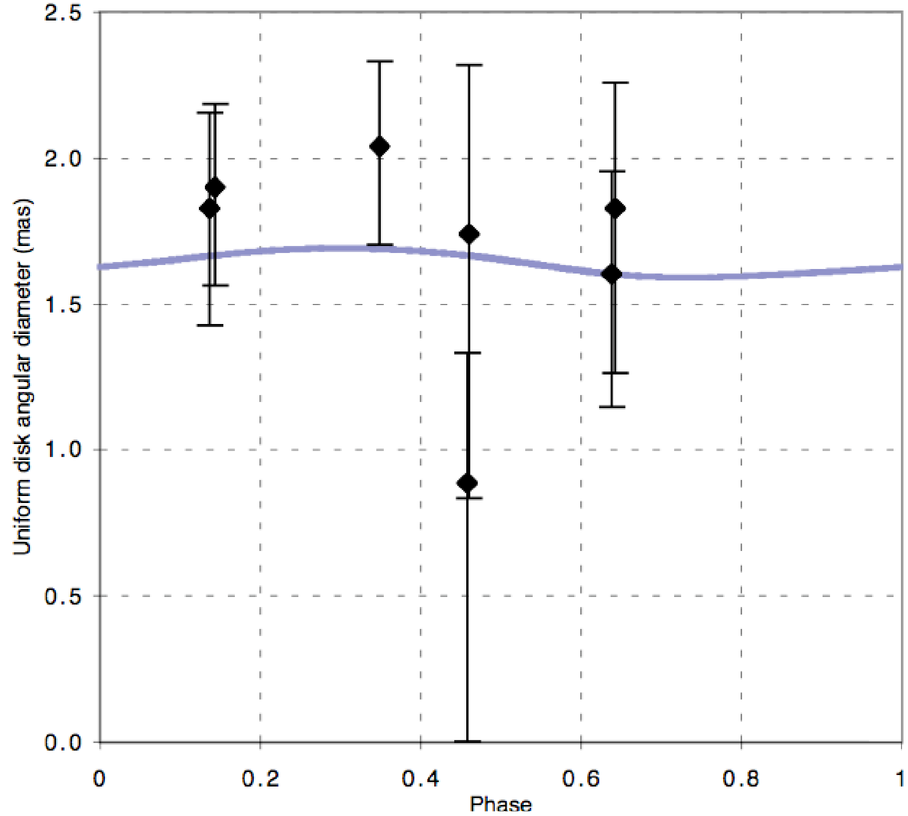
Table 2. Best fit model parameters for Polaris and its CSE. $\theta_\star$ is the stellar angular diameter (mas), α the CLD coefficient, θ_s the shell angular diameter (mas), w the shell width (mas) and $F_s/F_\star$ the relative brightness (Fig. 3). Last column tabulates the reduced χ^2. Only parameters with error bars (lower scripts) have been fitted. The first line is the hydrostatic model; the second line is the adjusted CLD; the model of the last line includes a shell.

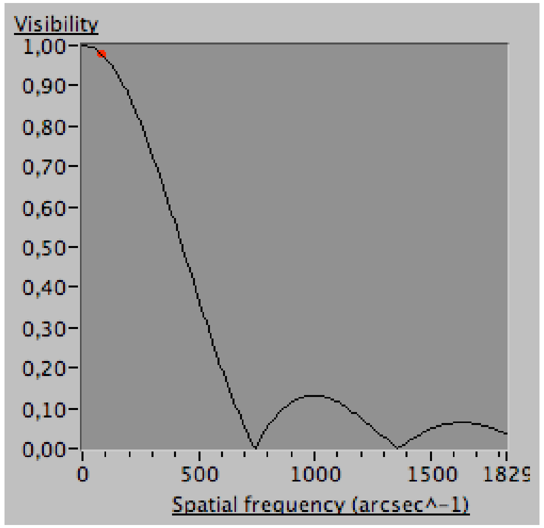
$\theta_\star$	α	θ_s	w	$F_s/F_\star$	χ^2
$3.152_{\pm 0.003}$	0.16	–	–	–	4.5
$3.189_{\pm 0.005}$	$0.26_{\pm 0.01}$	–	–	–	2.5
$3.123_{\pm 0.008}$	0.16	$7.5_{\pm 0.2}$	0.5	$1.5_{\pm 0.4}\%$	1.4

Reach beyond the λ/B limit

FLUOR observations of ζGem on IOTA (38m baseline)

*Kervella et al. 2001, A&A **367**, 876*





$$<\theta_{LD}> = 1.67 \pm 0.15\text{mas}$$

$$\lambda/B = 9\text{mas}$$

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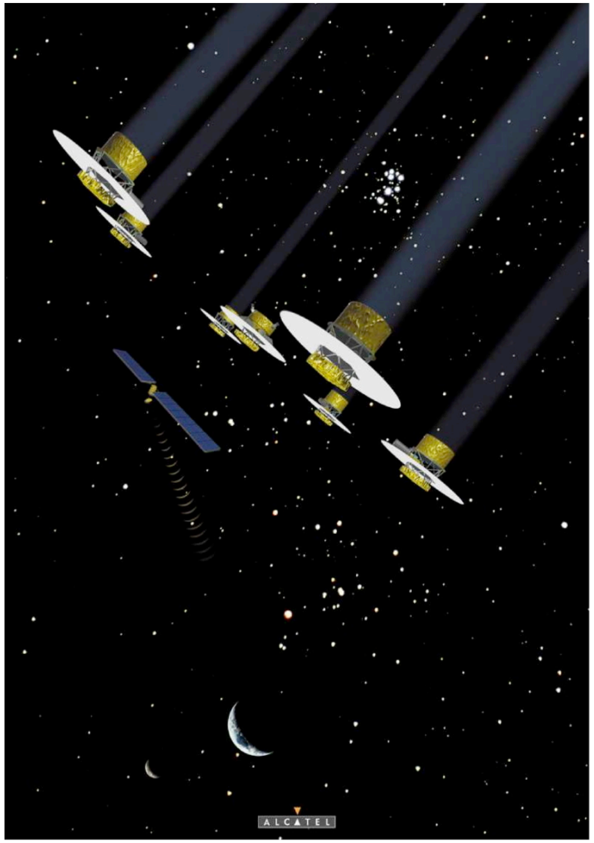
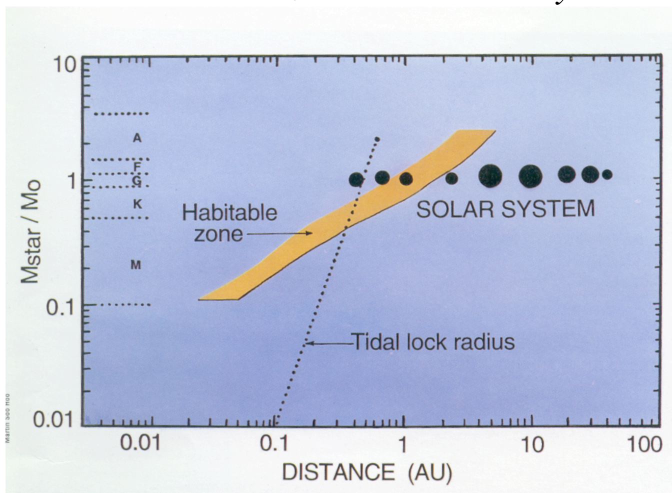
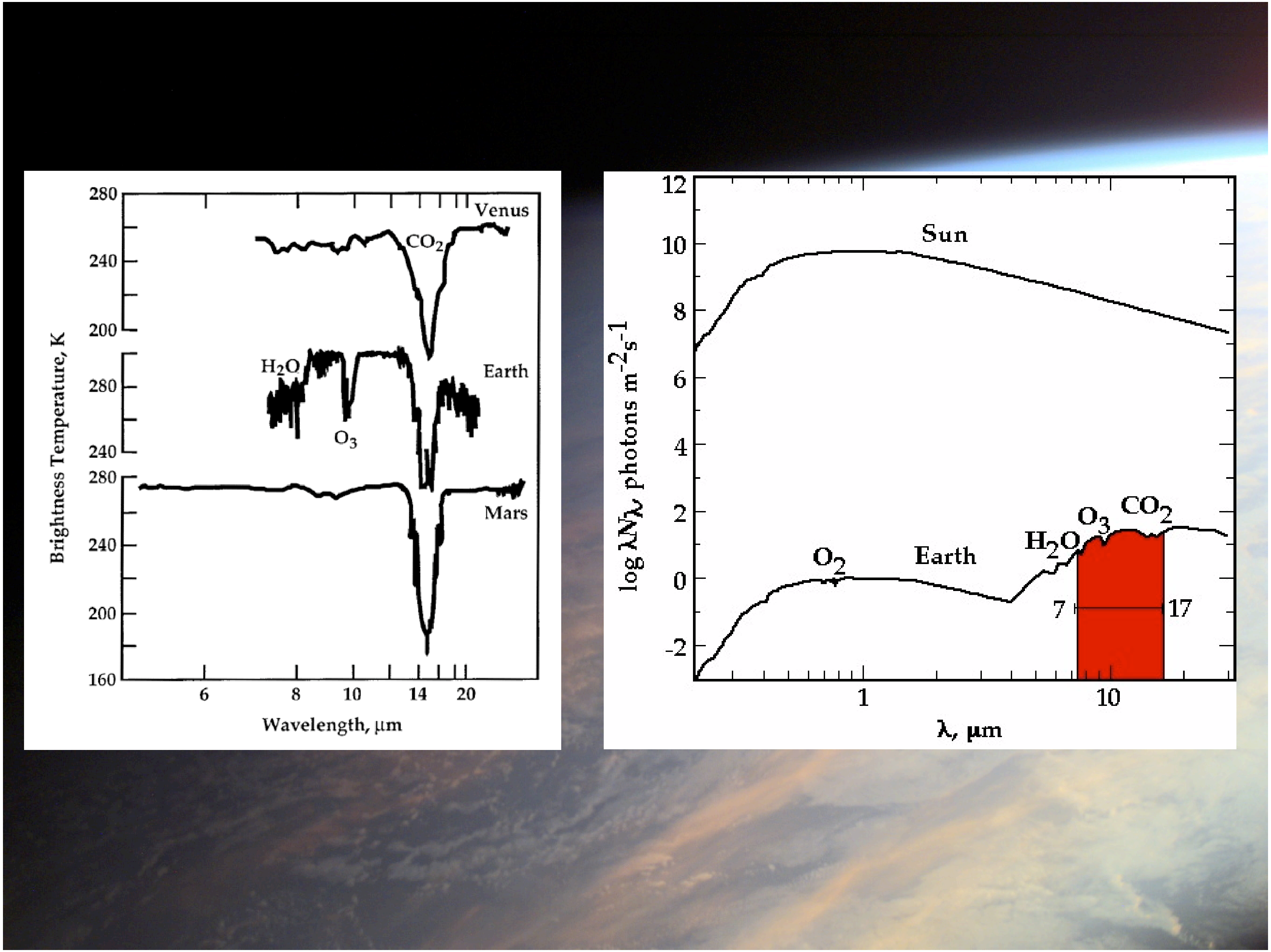
DARWIN and TPF-I



- Goals:
  - Census of telluric planets in the habitable zone of nearby M-F type stars (3–25pc)
  - IR spectroscopy of their atmosphere
- Means:
  - Infrared nulling space interferometer
- Missions:
  - NASA: **TPF-I**
    - Studies 1995-2005
  - ESA: **DARWIN**
    - First proposed 1993
    - Part of Cosmic Vision programme (Theme I)
    - Time frame 2020-2025

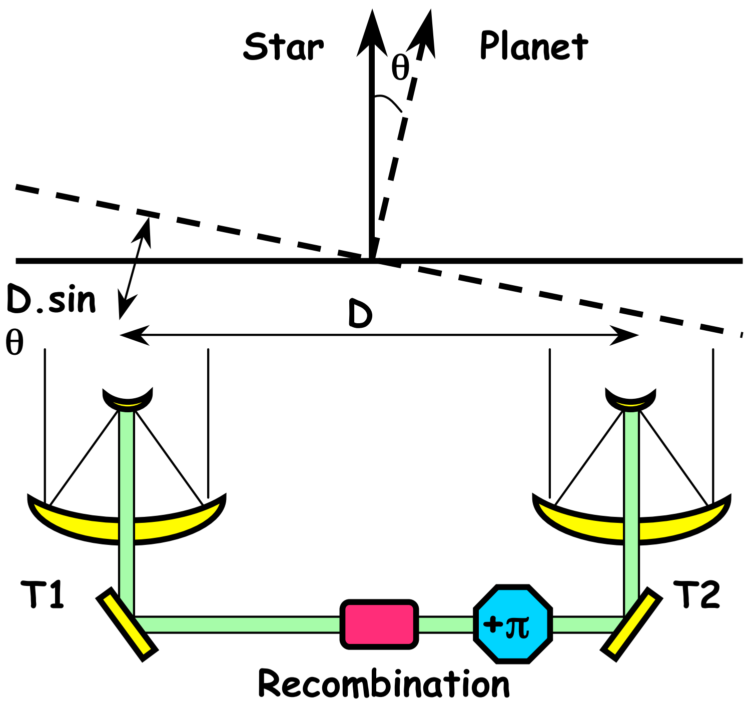
Habitable zone in the solar system



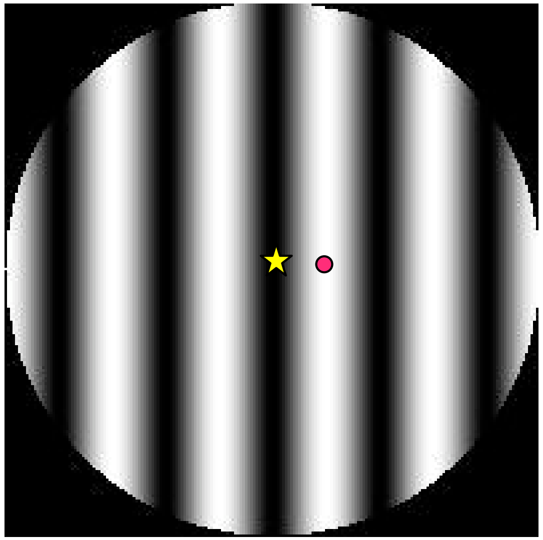


Venus
CO_2
Earth
H_2O
O_3
Mars
280
240
200
280
240
280
240
200
160
6
8
10
14
20
Brightness Temperature, K
Wavelength, μm
Sun
Earth
O_2
H_2O
O_3
CO_2
7
17
12
10
8
6
4
2
0
-2
1
10
$\log \lambda N_\lambda$, photons $m^{-2}s^{-1}$
λ, μm

Interferometric coronography



Principle



Transmission map on the sky

Specifications for a 10^6 rejection ratio

*(Mennesson et al. 2002, JOSA A **19**, 596)*

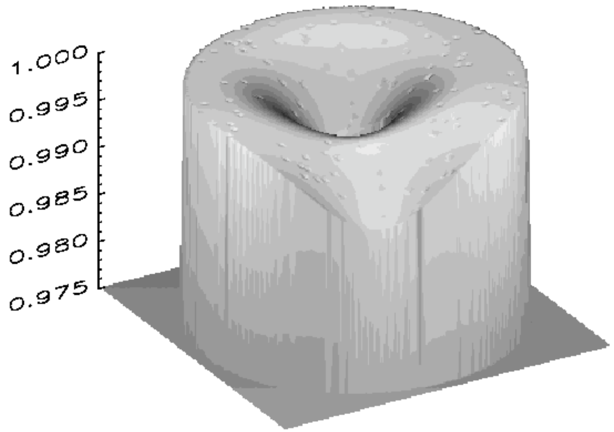
Table 1. Optical Constraints on the Phase,[a] the Amplitude,[a] and the Polarization[b] of the Different Beams in the Case of Spatial Filtering through a Single-Mode Waveguide through a Pinhole and without Any Correction for a Two-Telescope Nulling Interferometer

Type of Defect[c]	No Correction	Pinhole Filtering	Single-Mode Waveguide Filtering
OPD rms (nm) $\lambda = 10\ \mu m$	3.1	3.1	3.1
Tilt rms	$9 \times 10^{-4} \lambda/D$	$9 \times 10^{-4} \lambda/D$	$6.4 \times 10^{-2} \lambda/D$[e]
Wave-front bumpiness (rms)	$\lambda/4400$	$\lambda/400$[d]	$\lambda/63$[e]
Overall amplitude relative shift	4×10^{-3}	4×10^{-3}	4×10^{-3}
Local amplitude relative shift (rms)	2×10^{-3}	2×10^{-2}[d]	0.1
Differential phase shift between polarizations (rad)	2.83×10^{-3}	2.83×10^{-3}	2.83×10^{-3}
Differential rotation of polarization planes (rad)	2×10^{-3}	2×10^{-3}	2×10^{-3}

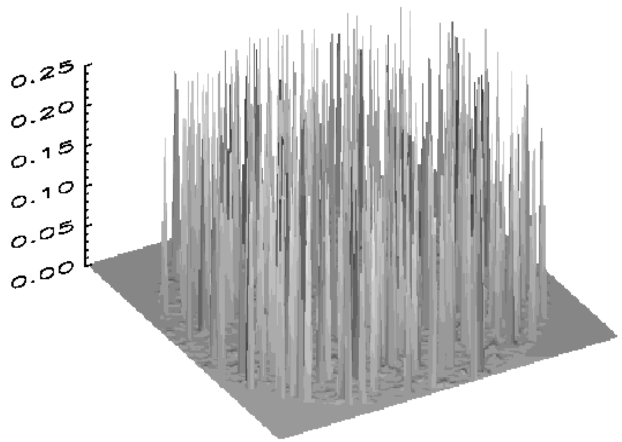
[a] Present work.
[b] Reference 28.
[c] For each considered type of defect, the specification is computed to ensure 10^6 rejection rate. Interactions between various kinds of defects are extensively studied for classical optics (see Ref. 29). λ is the infrared observing wavelength.
[d] Depends on phase defects' spatial spectrum.
[e] Values ensuring injection efficiency at 99% of theoretical maximum.

Sample defective pupil
(λ/200rms and tilt, 1% dust)

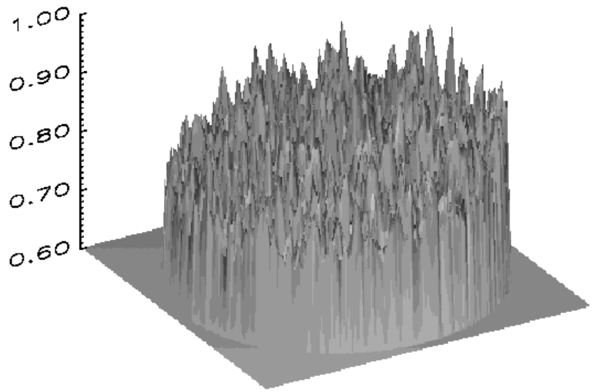
Substractive
recombination



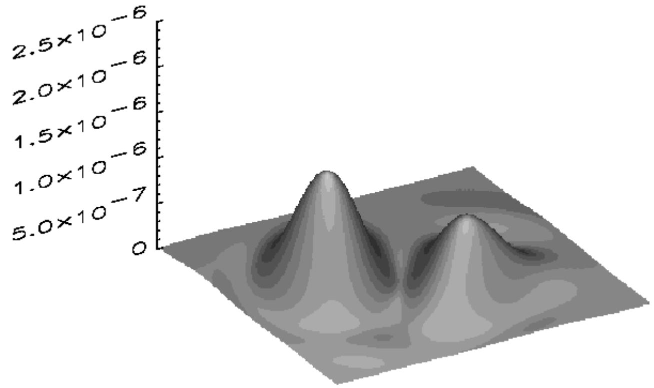
Amplitude



Without modal filtering



Phase



With modal filtering

Modal filtering for nulling Remarks

- Modal filtering is a linear process, like pupil substraction
  => The filter can be placed *before* or *after* the beam combiner
- The filter will block all the more light as the pupil is corrugated :
  ⇒ Need an active control of intensity balance (at 10^{-3} level)
  ⇒ Overall, photons are lost in the process…

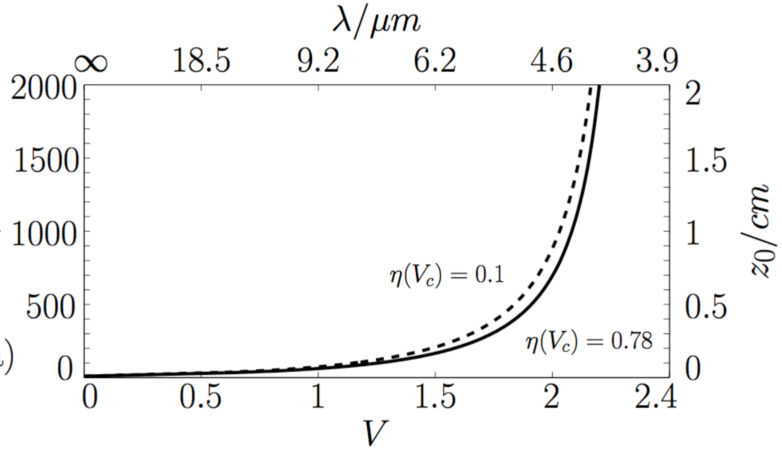
Which fiber length is needed?

Fig. 4. (a) Required minimum filter length z_0, given in multiples of the fiber core radius ρ, as a function of the normalized frequency V for an attenuation coefficient $A = 10^6$ and a relative refractive index difference $\Delta = 0.25\%$. The solid line shows the case of minimum insertion loss, i.e. maximum coupling with $\eta = 0.78$ for $V = V_c = 2.405$, the broken line gives the case of high insertion loss, i.e. poor coupling with $\eta = 0.1$ for $V = V_c$. A second pair of coordinate axes (at the top and at the right) is scaled in wavelengths λ and absolute values for z_0, respectively. Here, parameters of a silver halide mid-infrared fiber are assumed (core diameter: $19\mu m$, core refractive index: $n_{co} = 2.18$, relative refractive index difference: $\Delta = 0.25\%$). (b) Ratio z_0/ρ as a function of the attenuation coefficient A for $V = 1.5$, 2 and 2.2 with $\Delta = 0.25\%$ and $\eta(V_c) = 0.78$.

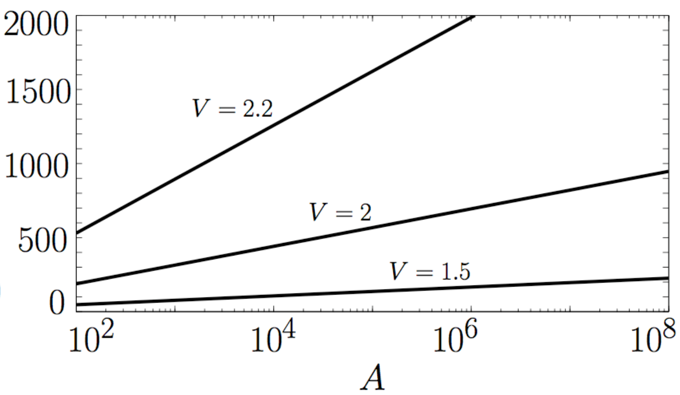
- At least a few thousand λ are needed for proper attenuation of the higher order modes

*Wallner et al. 2002, JOSA-A **19**, 2445*

(a)



(b)

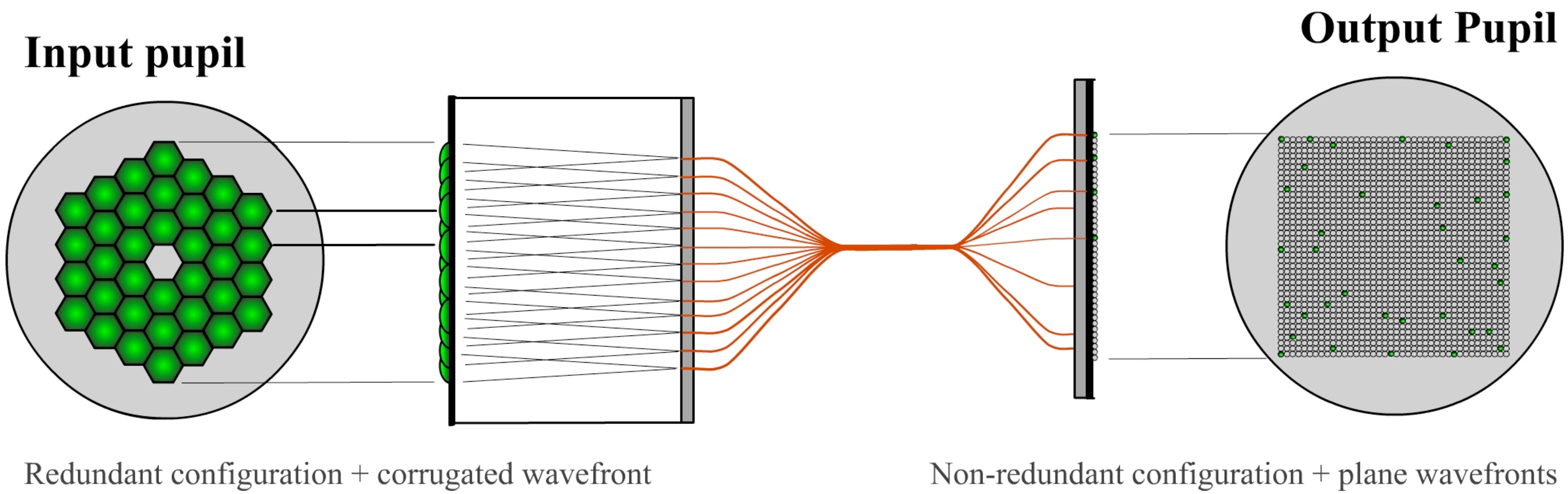


Outline

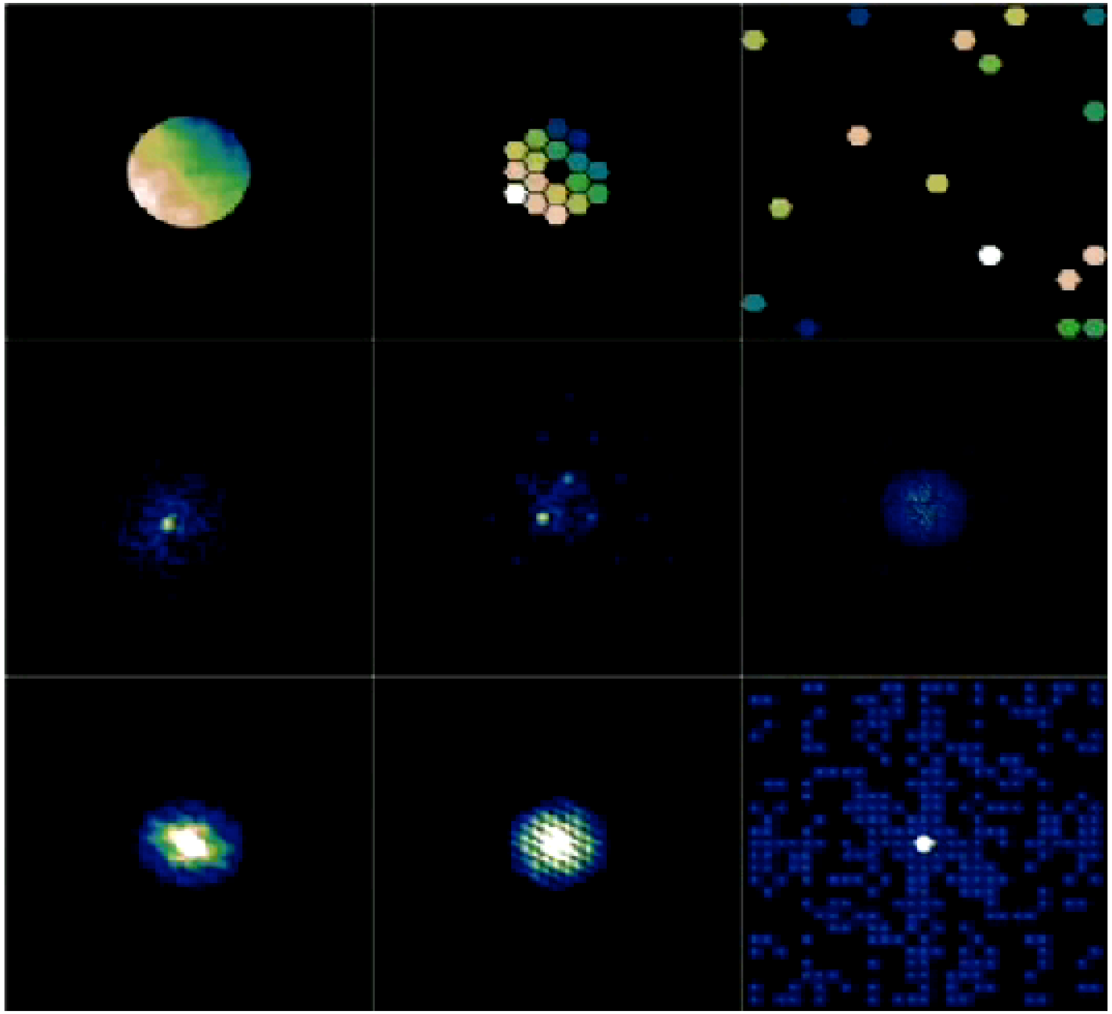
- Spatial and modal filtering
- Single mode waveguides primer
- Application to:
  - V^2 science
  - Nulling interferometry
  - Pupil remapping
- Conclusion

Pupil remapping concept

- High frequency phase perturbations removed by modal filtering
- Non-redundant remapping of the pupil maintains imaging capability while shielding MTF from phase perturbations
- Photon noise limited imaging => high dynamic range
- Currently under development (*Lacour & Perrin 2005, SPIE 5905, 391*)



Pupil remapping example



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Take-home messages

- Modal filtering is « the poor man's AO » as it selects coherent photons (rather than increase their number)
- It trades wavefront phase corrugations for intensity fluctuations
- It is particulary important for high dynamic range applications
- However the piston mode is *not* filtered and should be taken care of (fringe tracking)
- AO still needed for efficient single-mode interferometry with large pupils ($D/r_0 >> 1$)
- SM waveguides also useful for beam transportation and processing