Fibered interferometry

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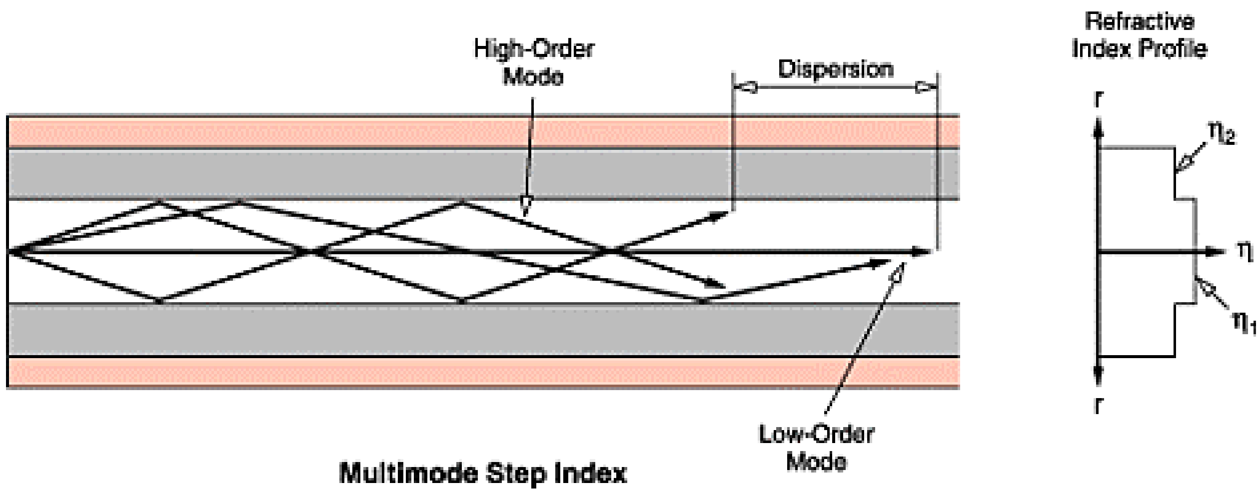
Outline

- A fiber primer: structures and materials
- Single-mode fibers properties
- Modal filtering in V^2 interferometry
- Modal filtering in nulling interferometry
- Other fiber functions
- Future projects

Fibers ? Multimode

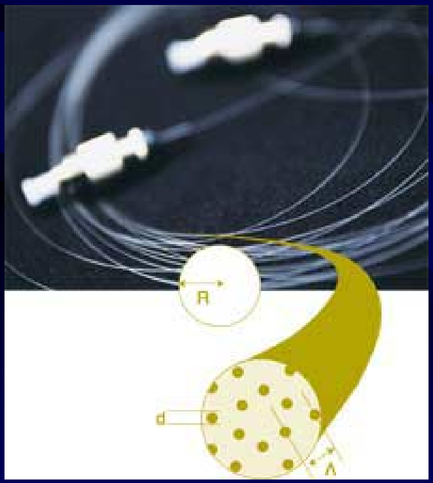


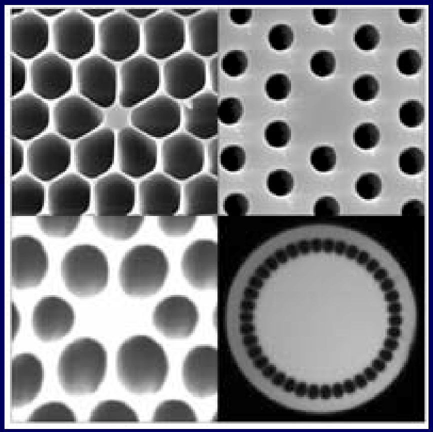
$$\sin\theta_{\text{lim}} = NA = \sqrt{n_{core}^2 - n_{clad}^2}$$

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

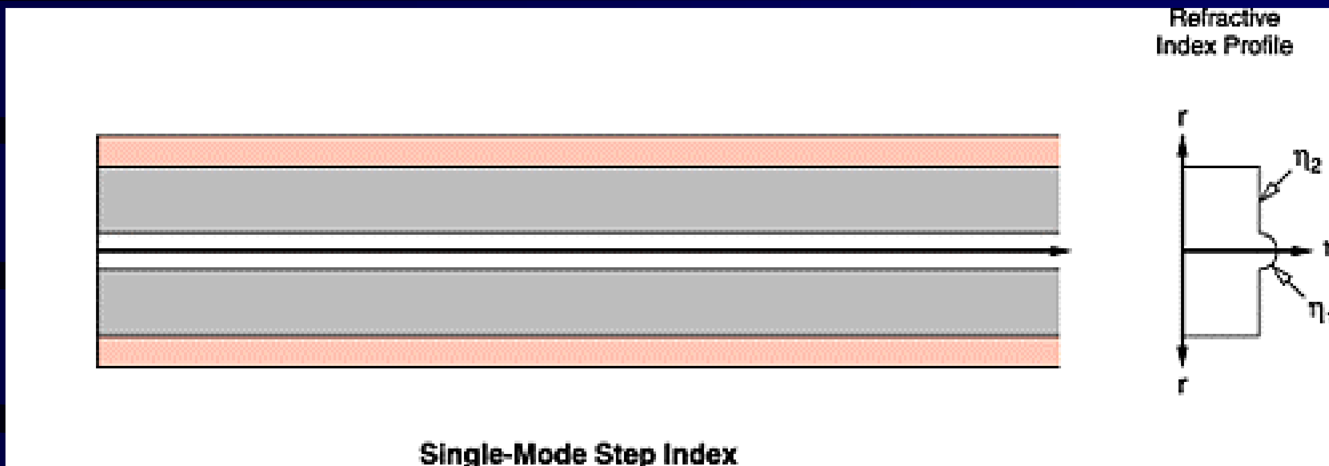
Alternative structures

- Hollow waveguides (microwaves)
- Photonic crystal fibers



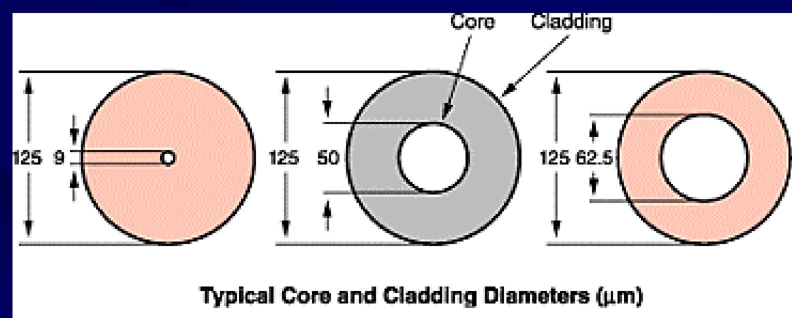


Single-mode fibers



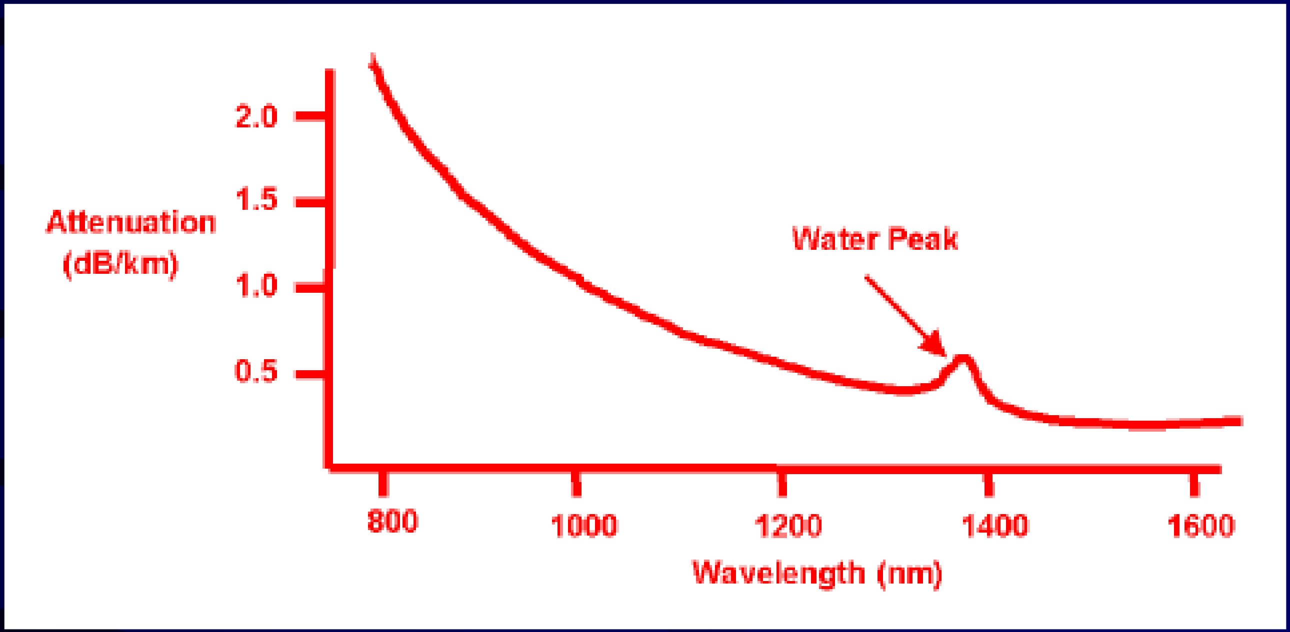
Single-Mode Step Index

- Optical path well defined (at least for one polarization…)
  - ⇒ Suitable for interferometry
- Core diameter only a few λ
  - ⇒ Ray optics no longer valid,
  - Þ use waveguide theory



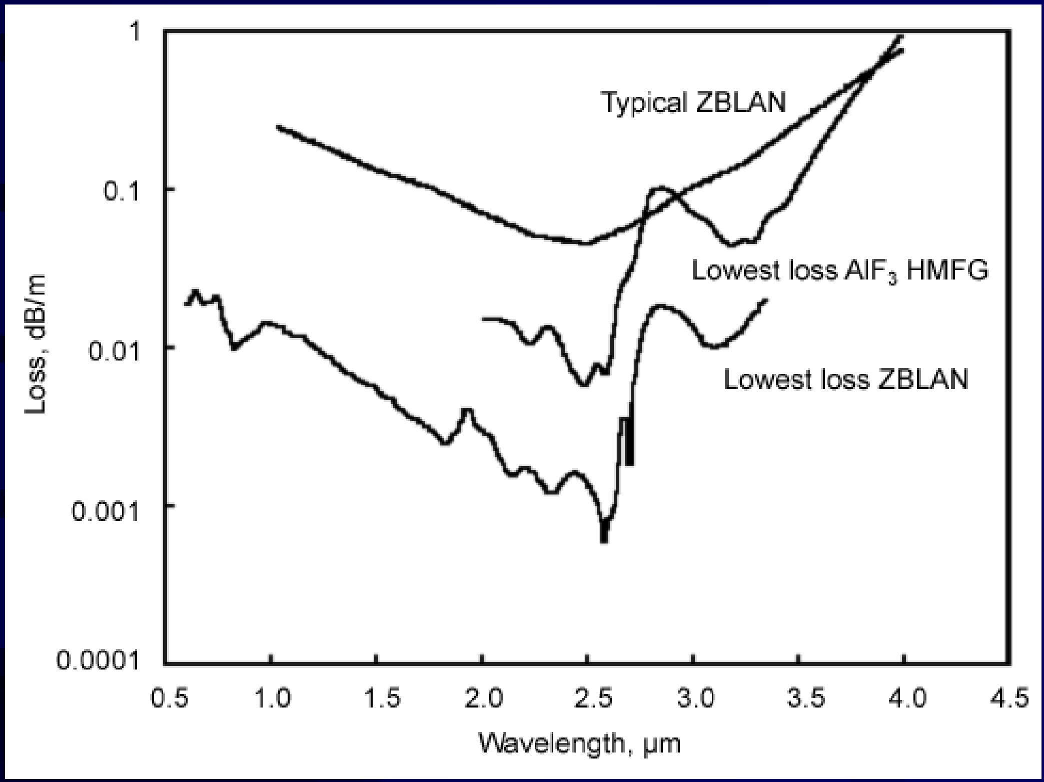
Typical Core and Cladding Diameters (µm)

Materials? (visible)



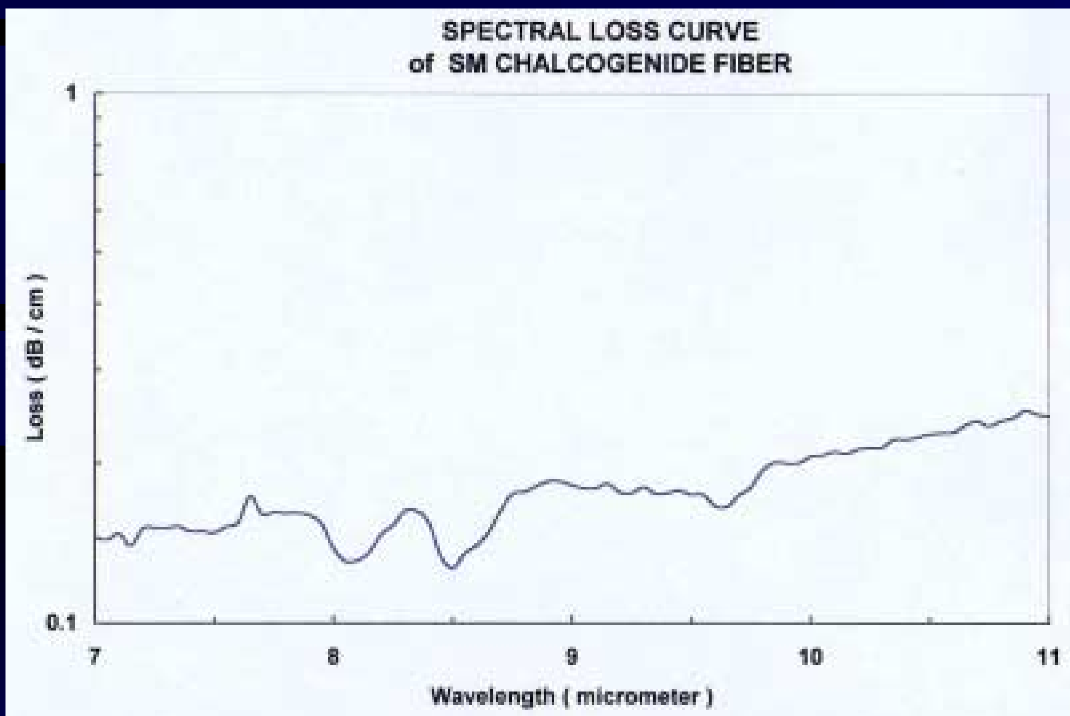
- Fused ultrapure silica for $\lambda<2\mu m$
  - Minimum absortion 0.2dB/km @ 1.55μm
  - The power of telecoms…

Materials? (mid-IR)



- Fluoride glasses for λ<5µm
- Minimal losses @ 2.5µm, equivalent to silica
- More artisanal production (especially SM)

Materials? (thermal IR)



- Halogenides
  - Polycrystals: AgCl or AgBr or mix
  - Potential transmission up to λ=30µm
  - Theoretical absorption minimum 10^{-3}dB/km
- Chalcogenides
  - Glass materials Se, S, Te + cations

- Single-mode structures still experimental

Single-mode waveguides
Fundamental parameters

Numerical aperture

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

Core radius

$$a$$

Wavelength

$$\lambda$$

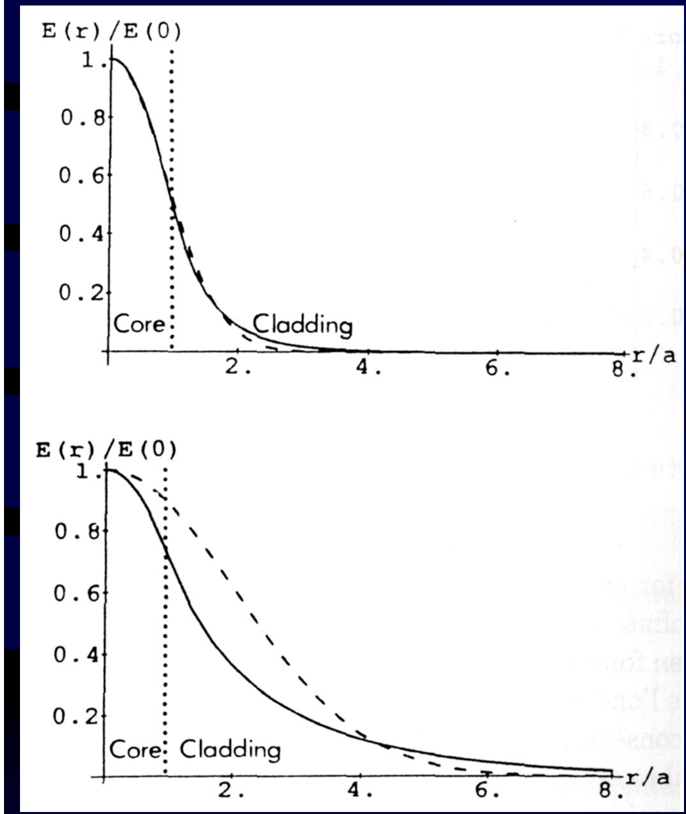
Normalized frequency

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

- 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

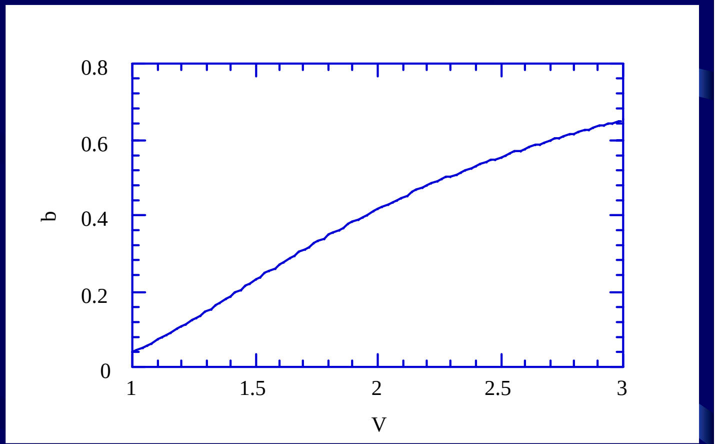


Cutoff wavelength

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

LP_{01} mode velocity effective index

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



- Beam étendue $S\Omega \sim \lambda^2$
- 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

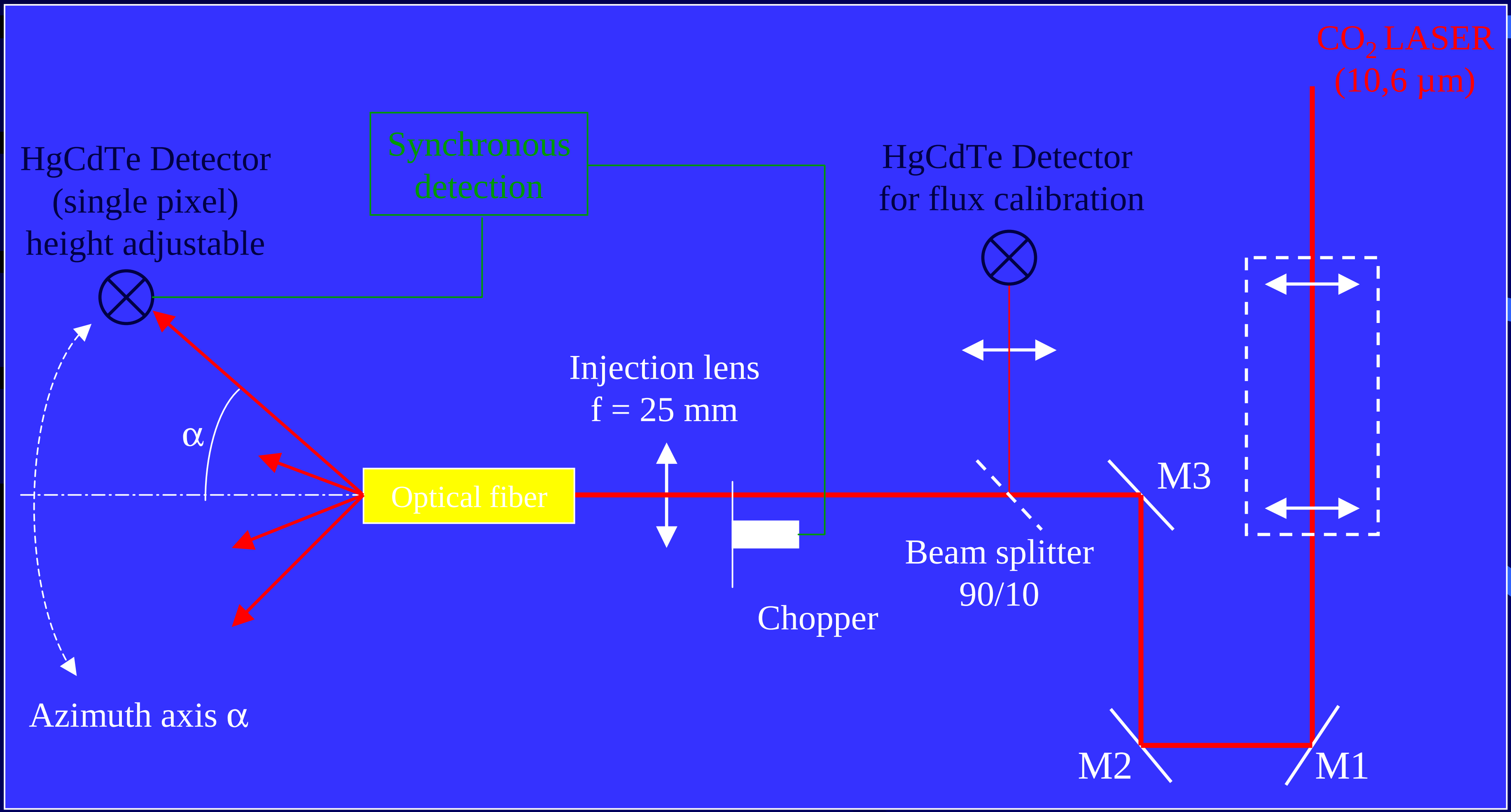
(modal filtering or "amnesia effect")

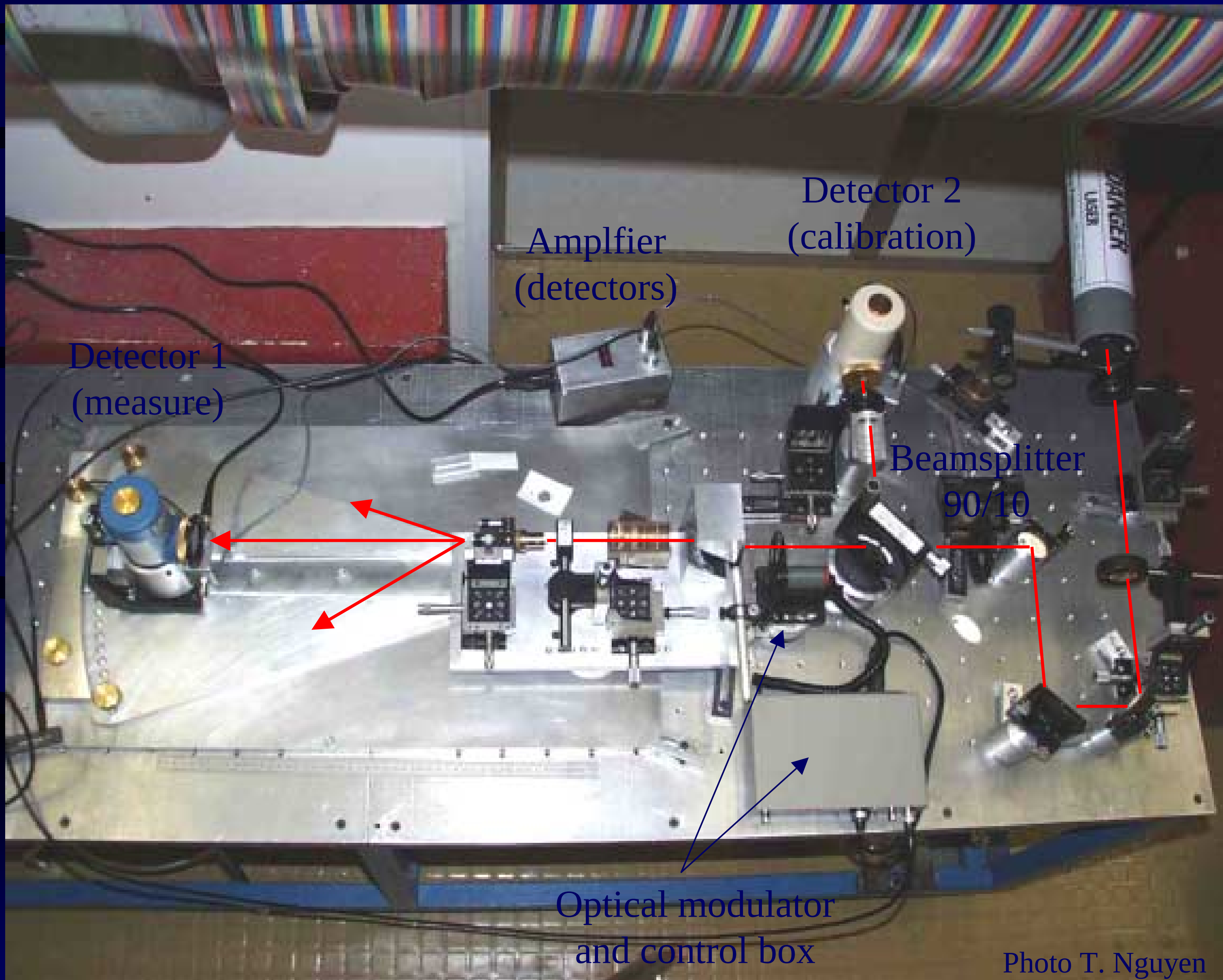
If single-mode,
the beam profile depends on the structure
of the waveguide only,
not on the injection conditions!

Example :
Thermal IR SM fiber verification

• Core diameter :	40 µm
• Core material :	As_2Se_3
• Cladding diameter :	210 µm
• Cladding material :	$GeSeTe_{1,4}$
• Numerical aperture :	0.15
• Cut-off wavelength :	8.1 µm
• Length :	8 cm
• Transmission :	0,2 dB/cm (~70% for 8 cm)

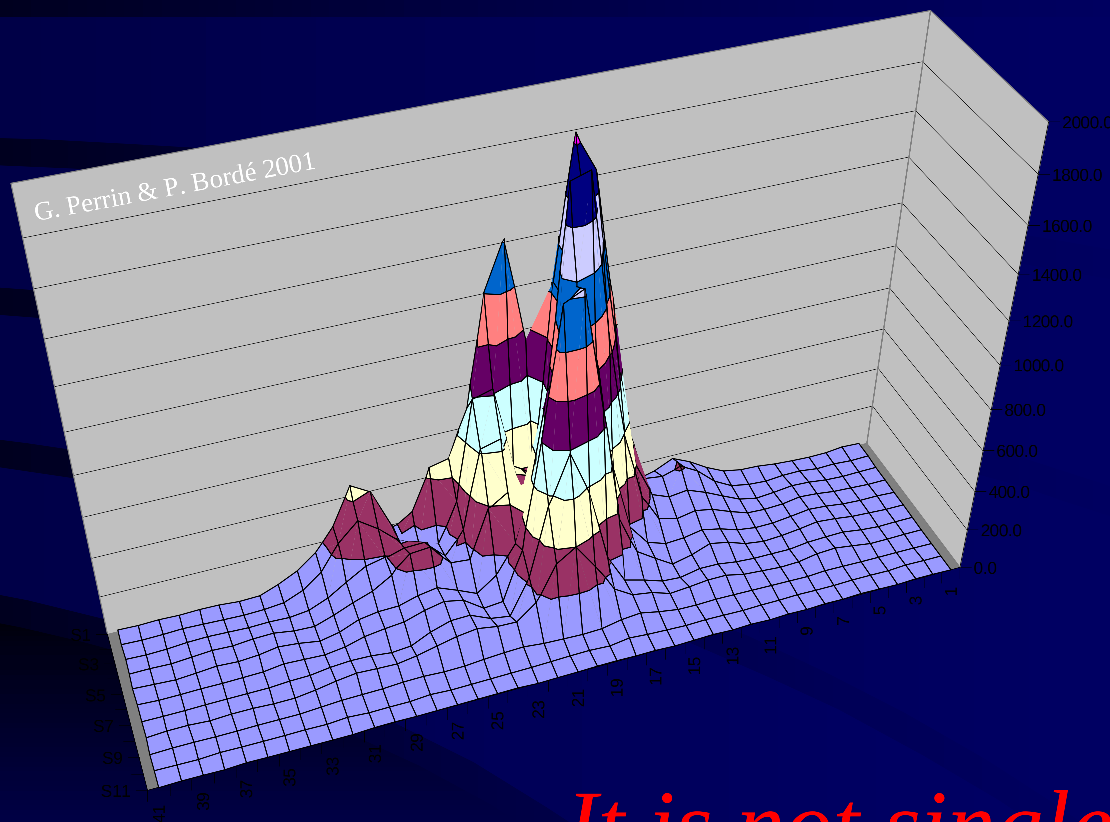
Test experiment





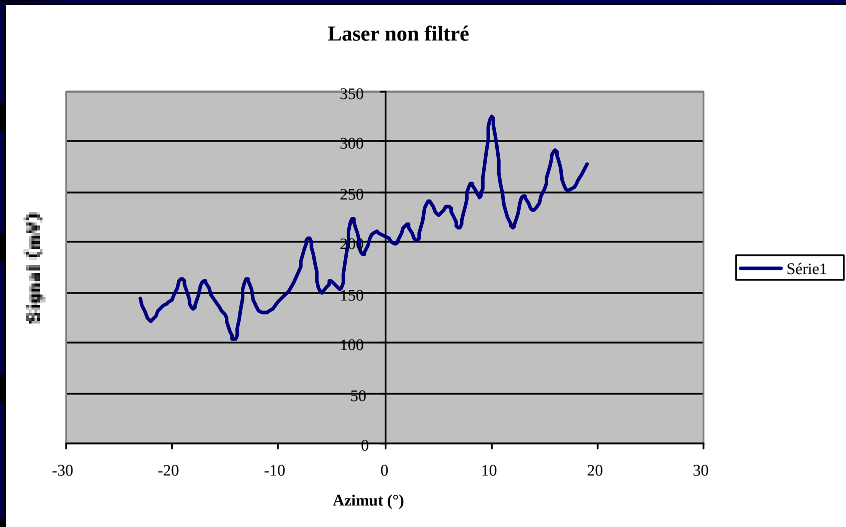
Detector 2
(calibration)
Amplfier
(detectors)
Detector 1
(measure)
Beamsplitter
90/10
Optical modulator
and control box
Photo T. Nguyen

First results (example)

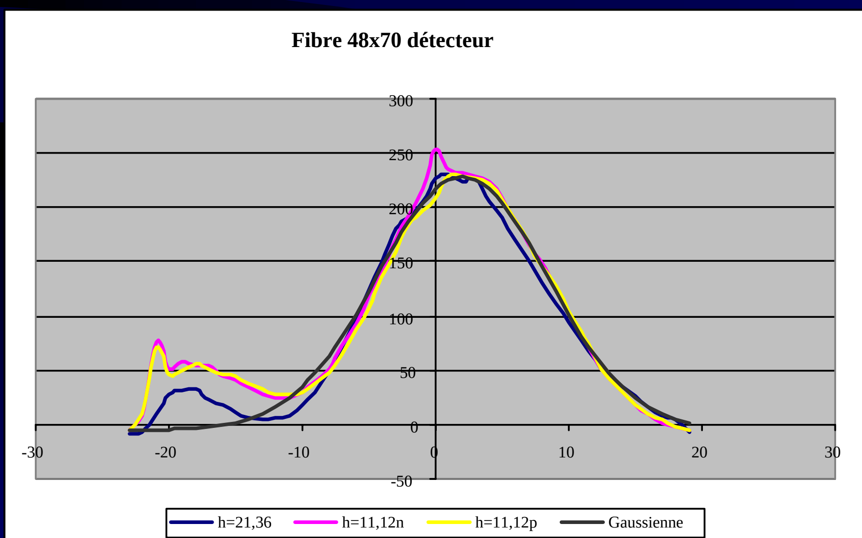


It is not singlemode !!!

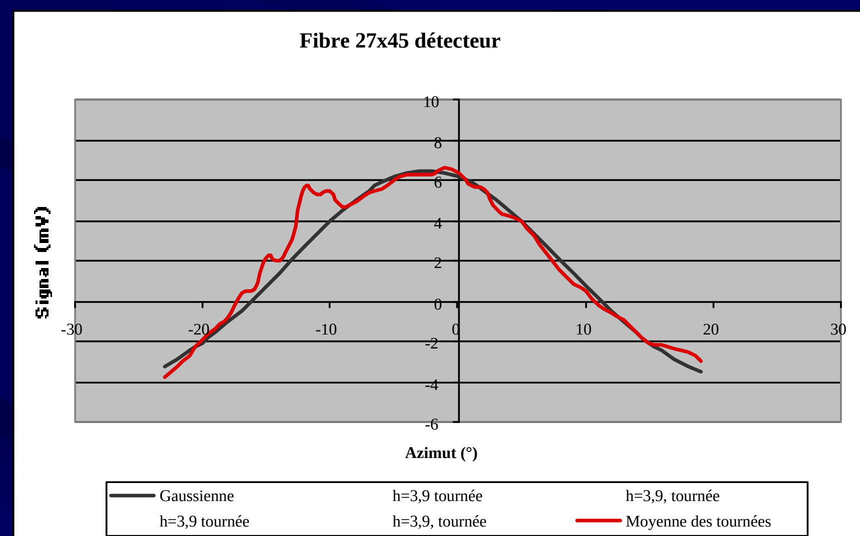
Second generation samples



Input dirty laser beam



Output 48µm fiber



Output 27µm fiber

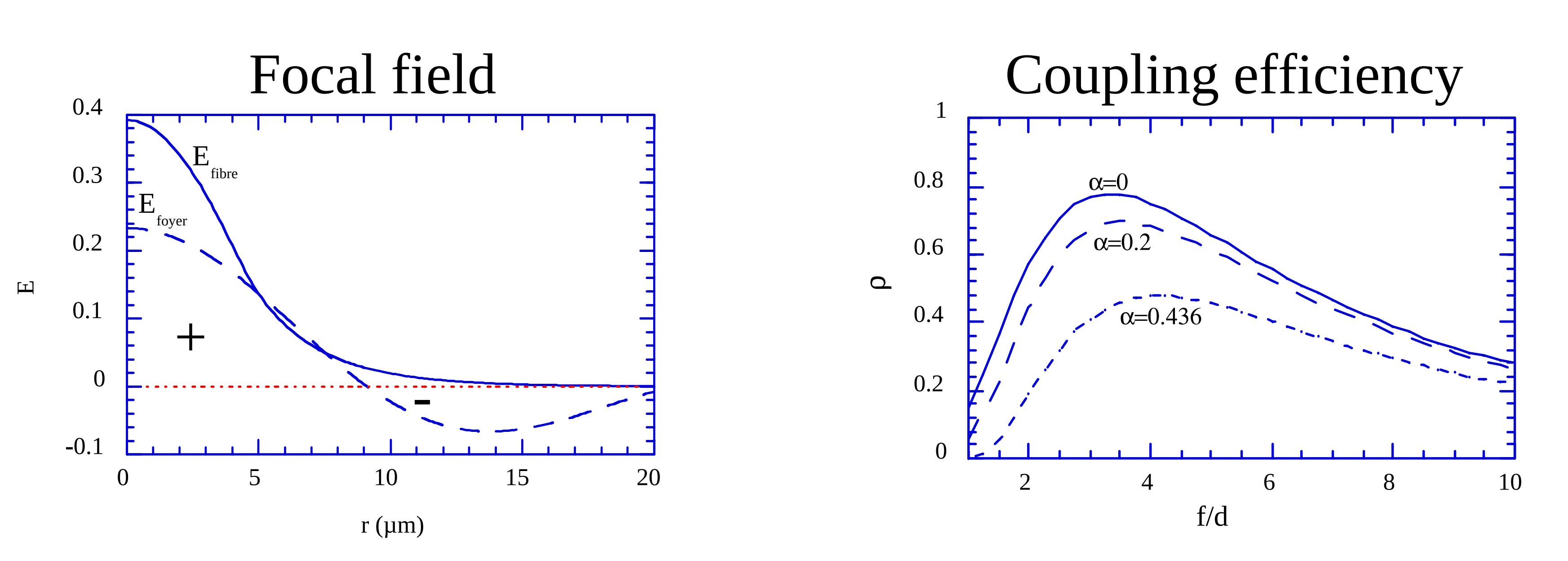
Injecting starlight into a SM fiber

- 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 :

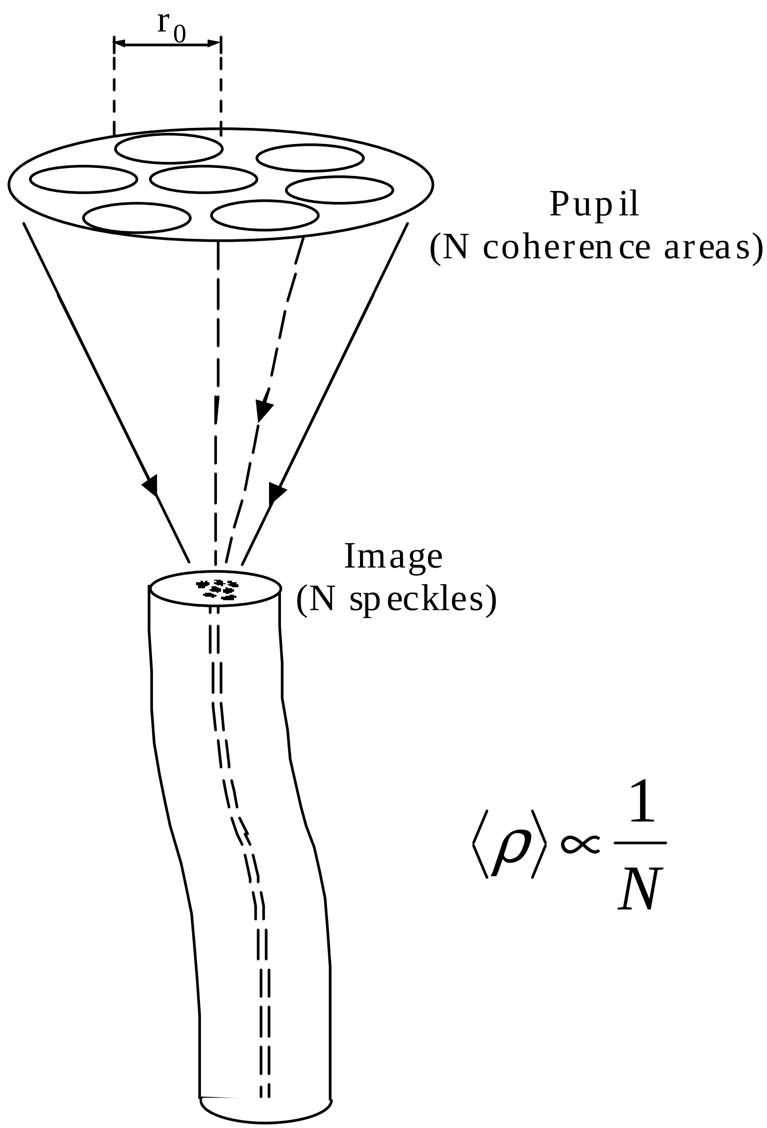
$$\rho = \left| \int \int E_{tel} \; E^{*}_{fibre} \right|^{2}$$

- The overlap integral can be interpreted as the Strehl ratio of the apodized pupil

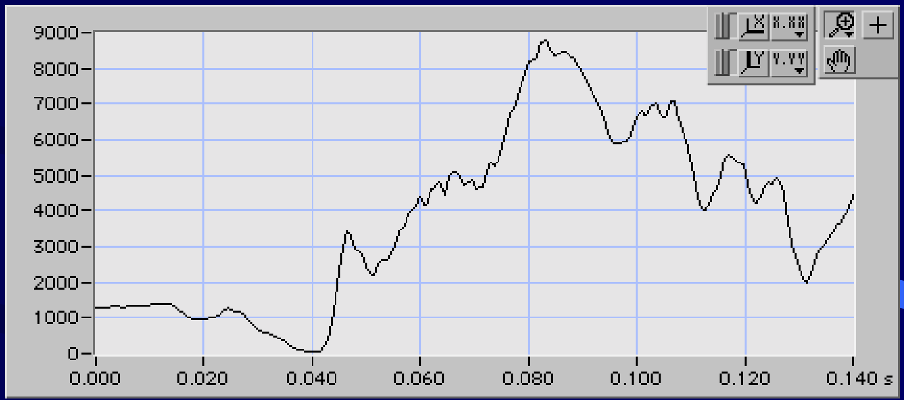
Diffraction limited case



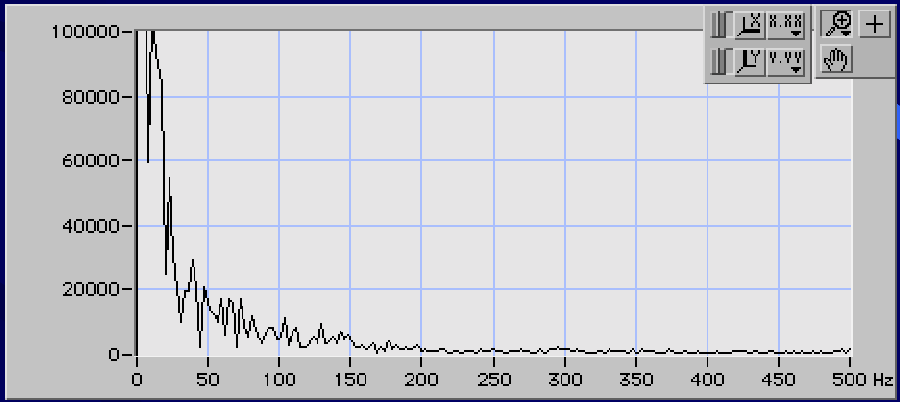
Coupling to turbulent starlight
(uncorrected VLT UT example)



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



Sample time sequence



Amplitude spectrum

With adaptive optics

- SM fibers as fast strehlmeters

V. Coudé du Foresto et al. 2000

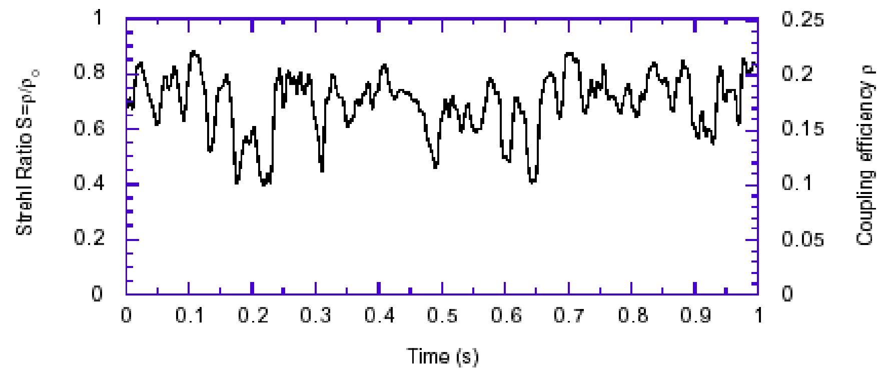


Fig. 5. Strehl ratio and injection efficiency for a stellar source (GM Lup) in a circular core fiber (VF 1078), at the 3.60 m telescope in La Silla corrected by ADONIS. Note the presence of a modulation with a 0.04 s period (25 Hz) induced by a vibration of the telescope tube. The seeing was excellent and very slow (r_0 = 65 cm and τ_0 = 0.4 s in K). The reference efficiency for this setup was ρ_0 = 0.25 and was calibrated on the internal, artificial point source

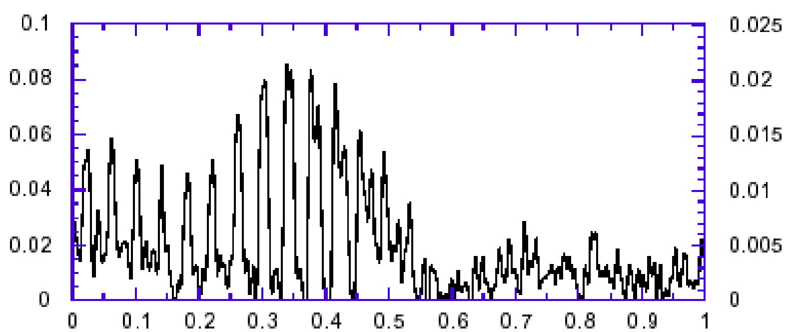


Fig. 7. Strehl ratio and injection efficiency for a stellar source (GM Lup) in a circular core fiber (VF 1078), at the uncorrected 3.60 m telescope in La Silla

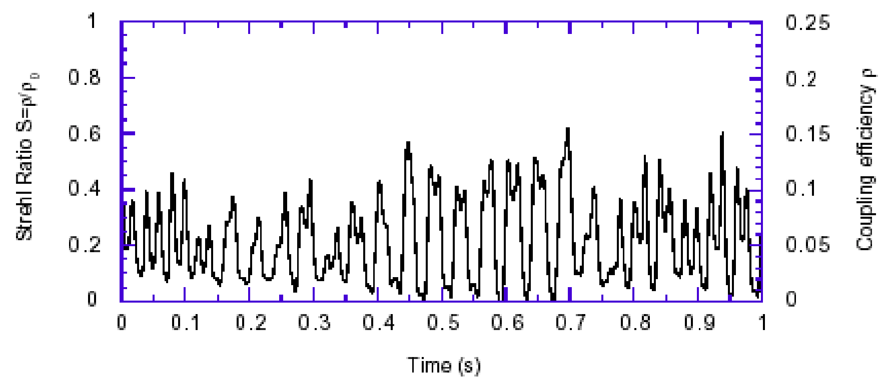


Fig. 6. Another recording of the coupling fluctuations, in identical experimental conditions. The 25 Hz modulation of the injected energy is now total

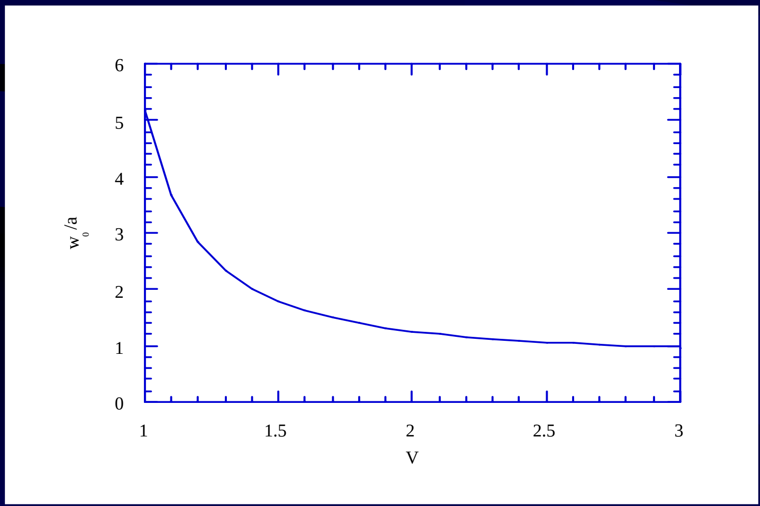
Uncorrected

Corrected

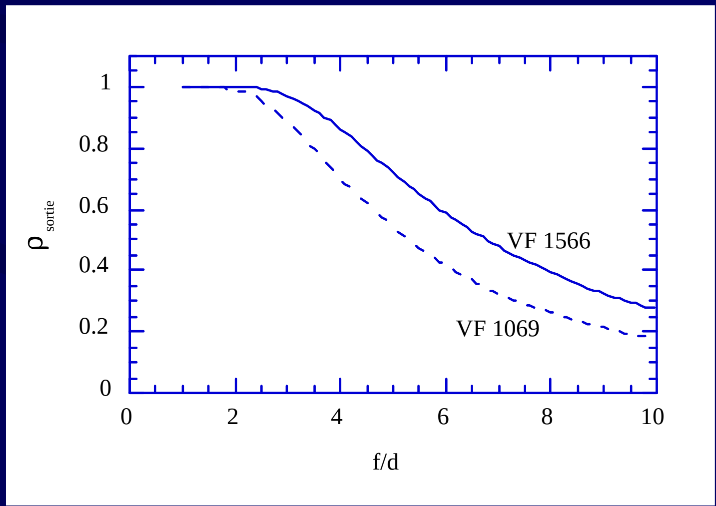
Fiber output

- Beam profile stable and constant
- First order (Gaussian) approximation : mode diameter proportional to λ or 1/V

=> Size of far field diffraction spot independent of λ



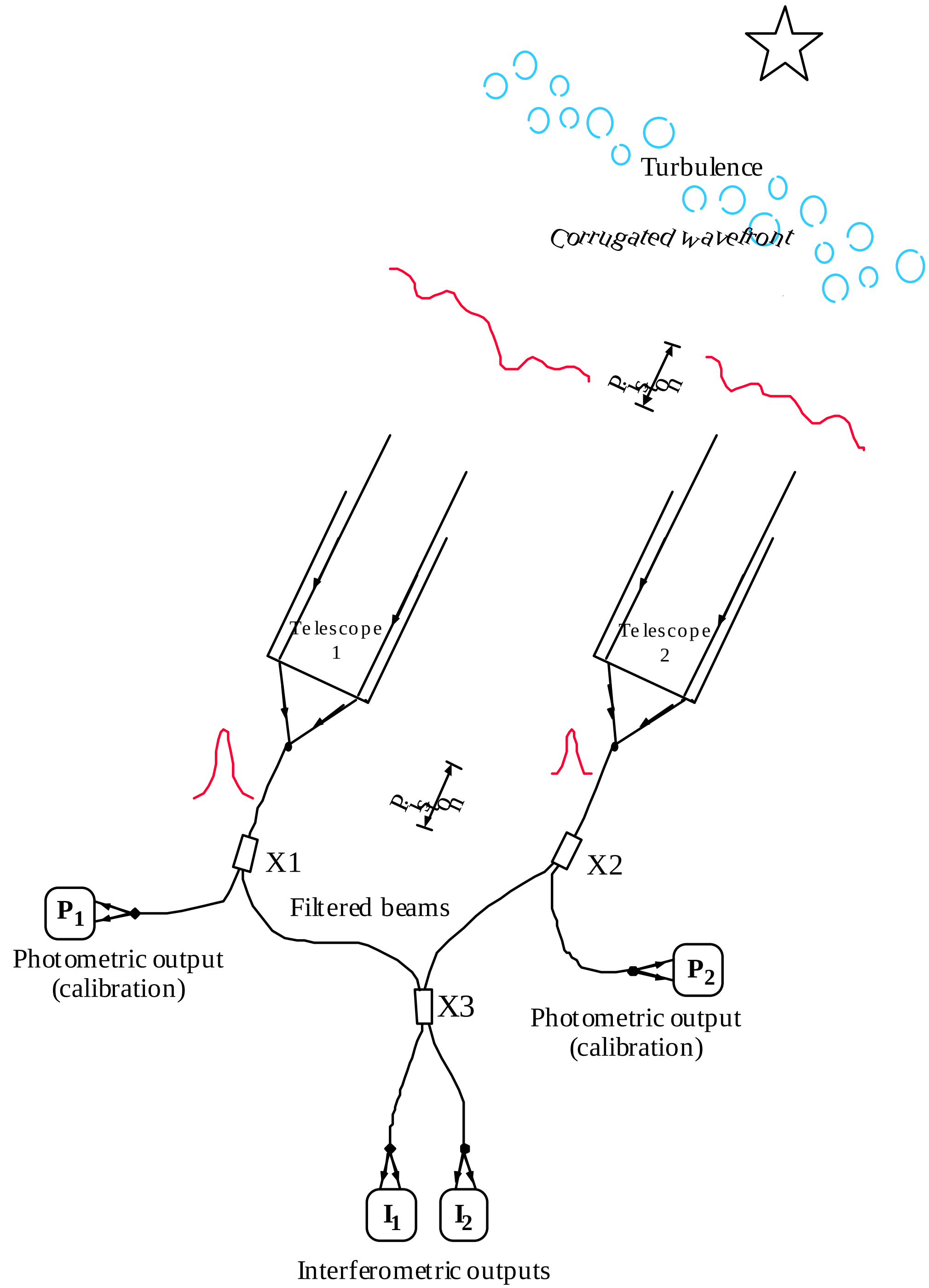
Mode waist vs. normalized frequency



Output coupling of two K band fibers

Taking advantage of modal filtering (FLUOR concept)

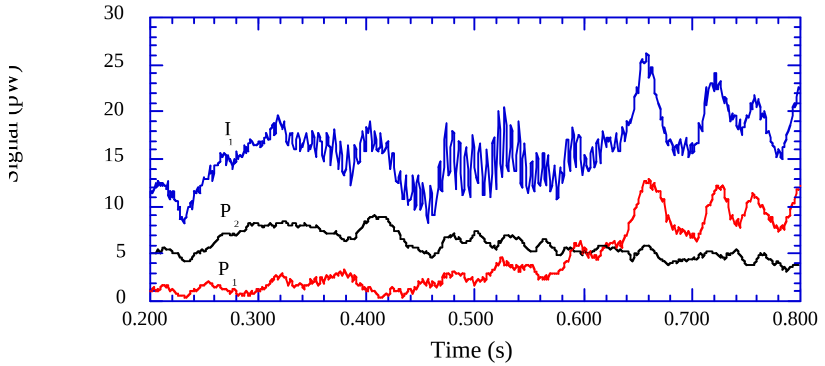
- Two inputs:
  - Beam 1 and Beam 2
- Pupil phase corrugations
  - ⇒ intensity fluctuations
  - ⇒ easier calibration
- Two-stage, triple X-coupler
  - X_1 and X_2 photometric calibration
  - X_3 beam combination
- Four outputs:
  - I_1, I_2, P_A and P_B
- Piston *not* filtered

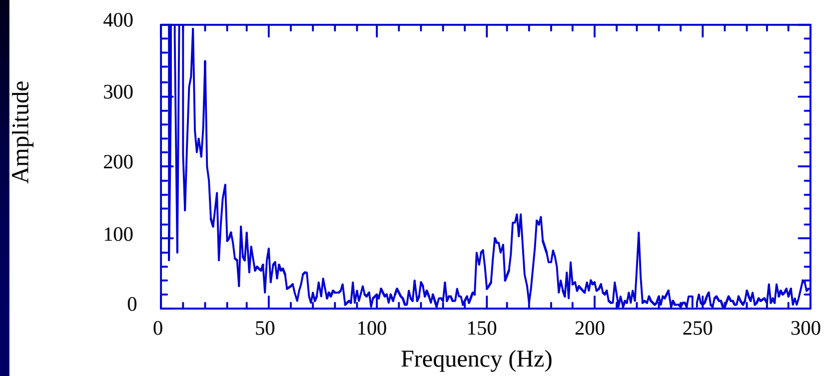


Raw interferogram

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

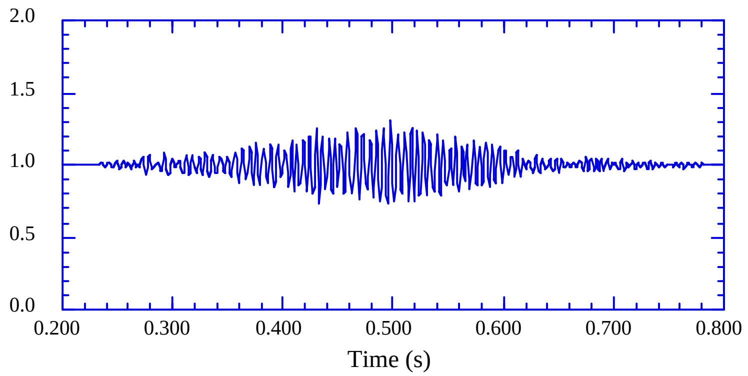
γ_{12} complex degree of coherence between the two beams

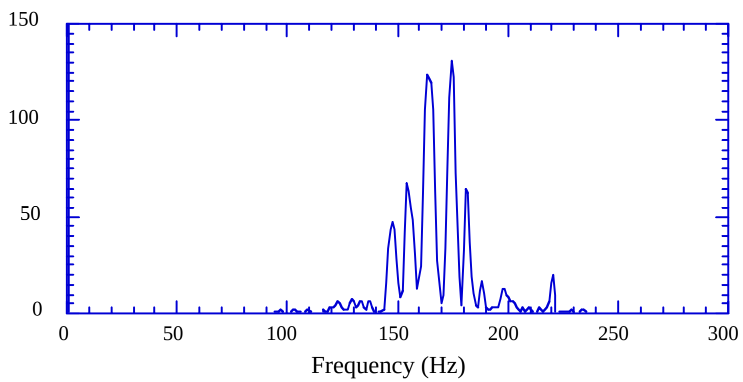




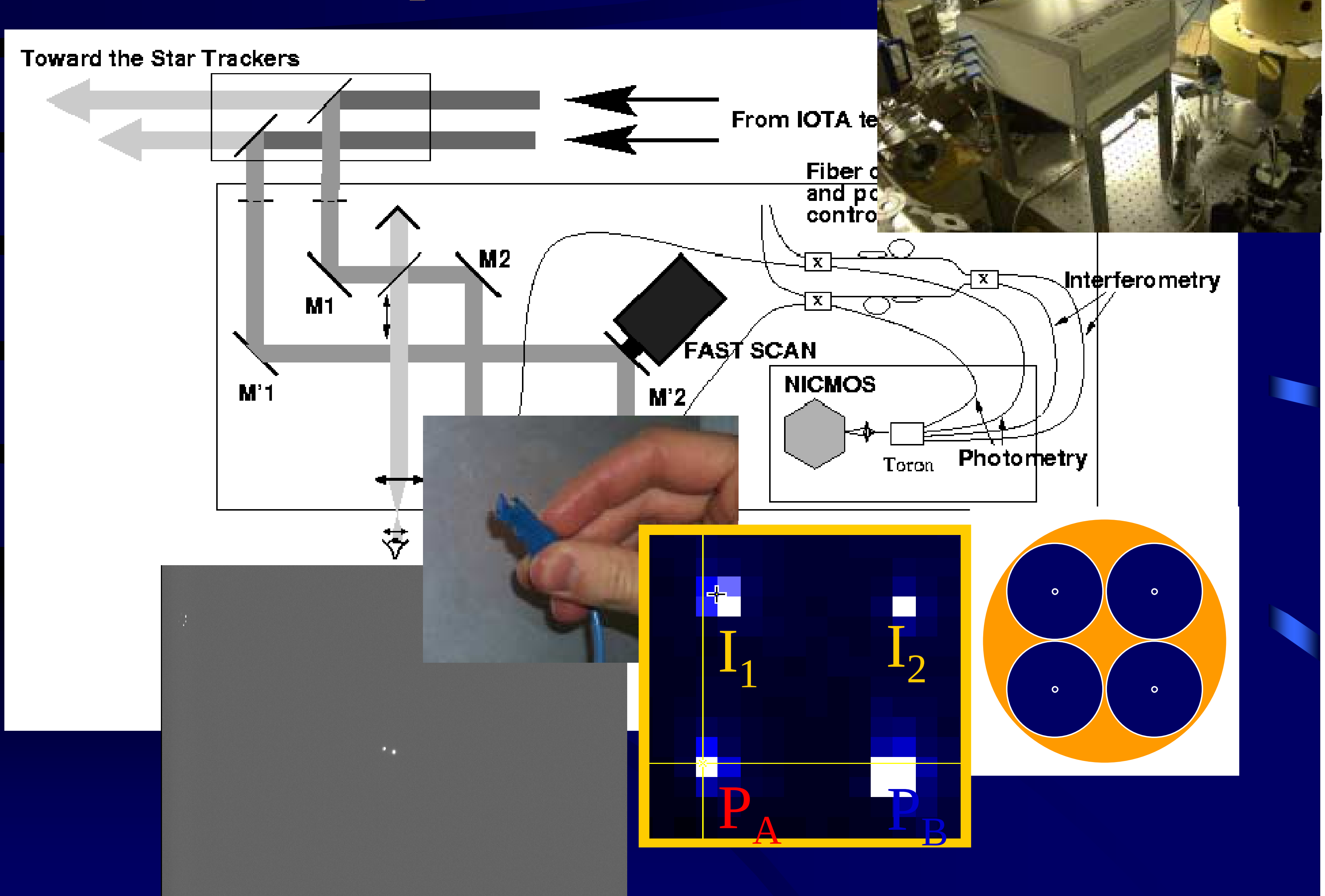
Corrected interferogram

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



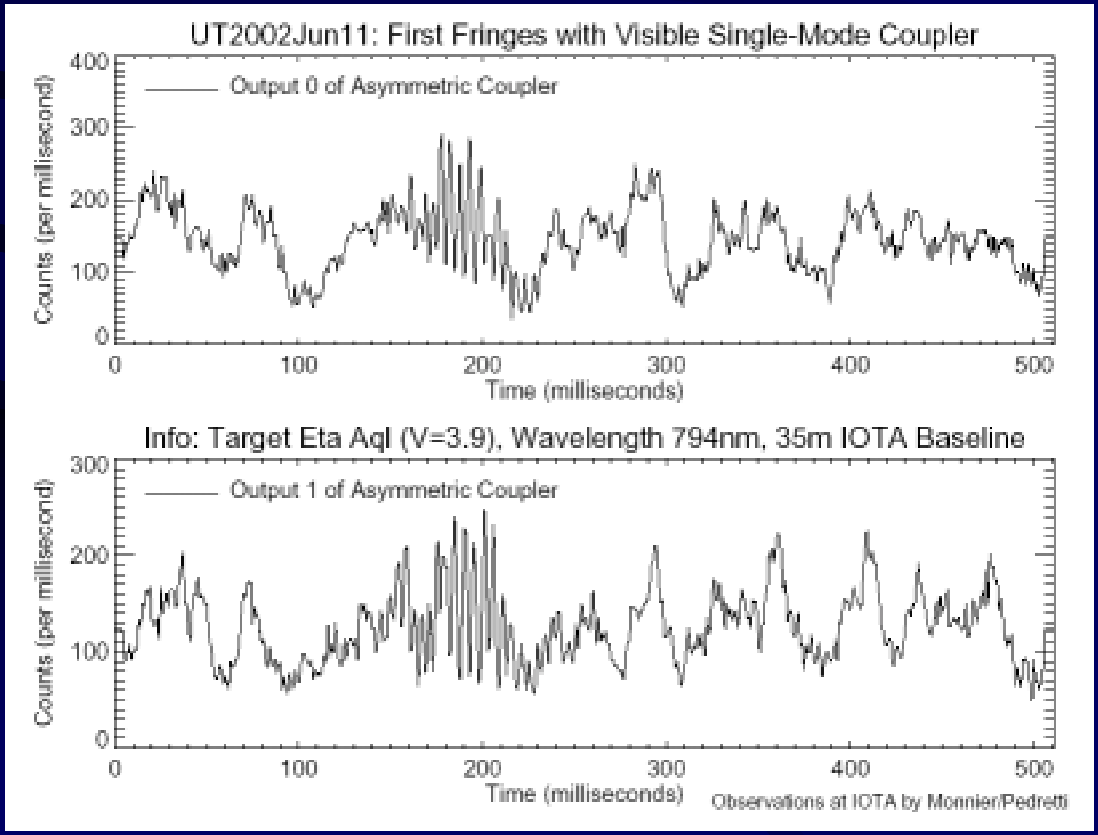


Practical implementation



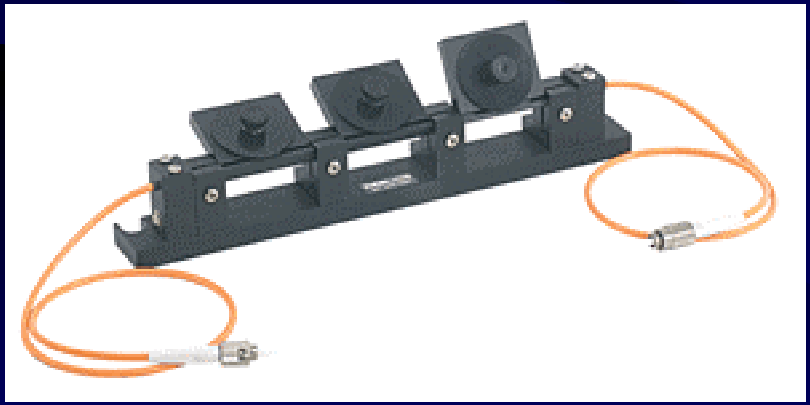
Alternate solutions (to avoid photometric beam extraction)

- Spatio-temporal modulation (G. Perrin, unpublished)
- Asymetric beam combiner (J. Monnier 2001, PASP 113)

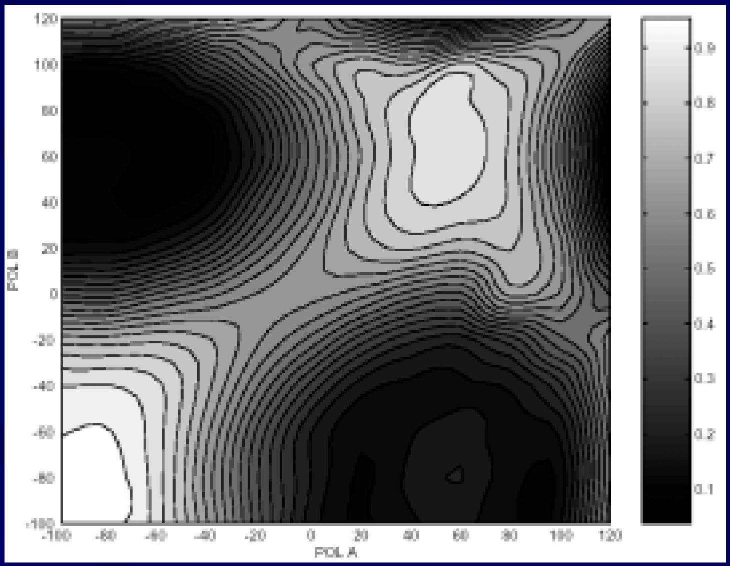


Polarization control

- Optimal contrast only obtained if polarizations match at recombination
  - Same orientation
  - Same delay
- Therefore use polarization preserving fibers…
  - Highly birefringent fibers
  - In effect two separate interferometers
- …or polarization controllers

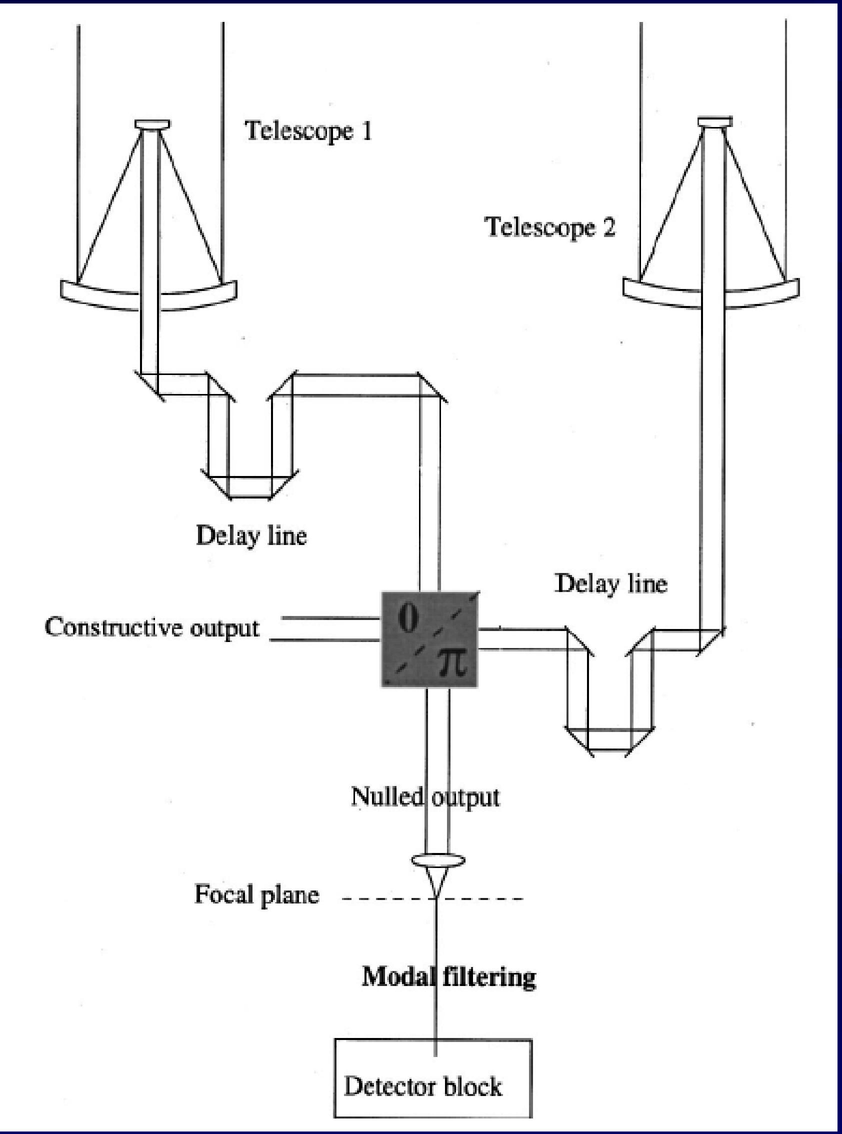


Instrumental visibility map on VLTI/VINCI



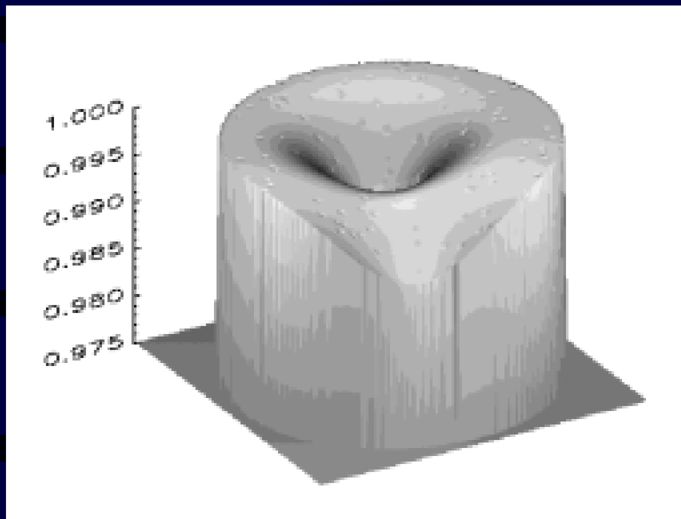
Modal filters for nulling interferometry

M. Ollivier & J.-M. Mariotti, Applied Optics 36 (1997)

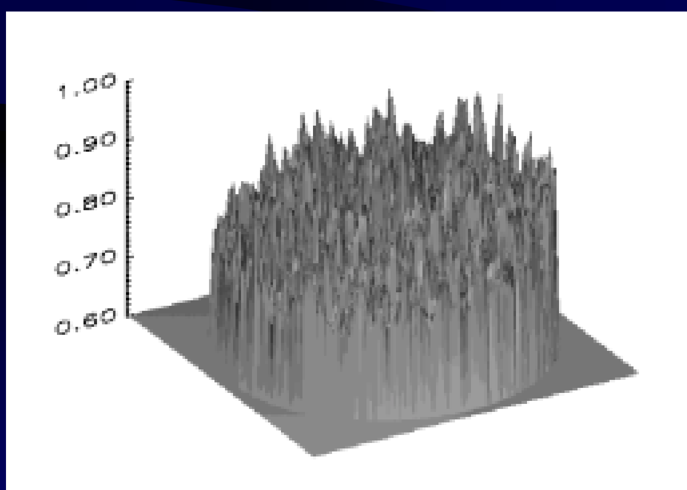


- Wavefront errors impact the performance of a nulling interferometer
- Without spatial filtering, to maintain a 10^{-5} null at 10µm:
  - Polishing defects and path difference errors should be kept smaller than $\lambda_{IR}/2000$ rms, i.e. $\lambda_{vis}/100$rms
  - Pointing errors should remain within 1/80th of an Airy disk

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

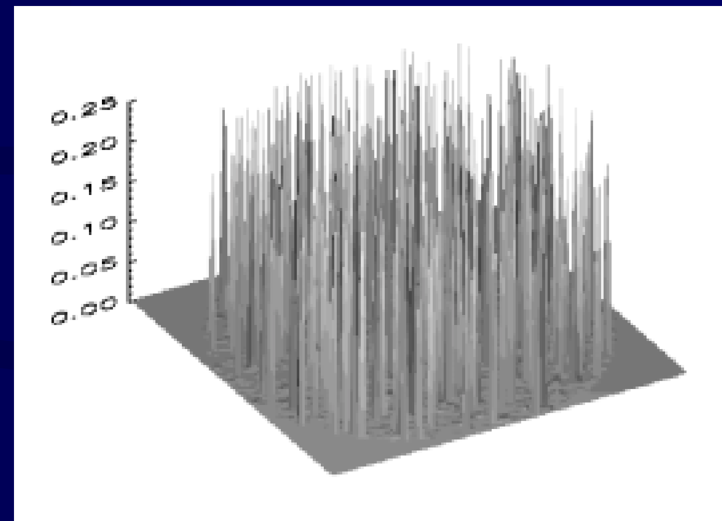


Amplitude

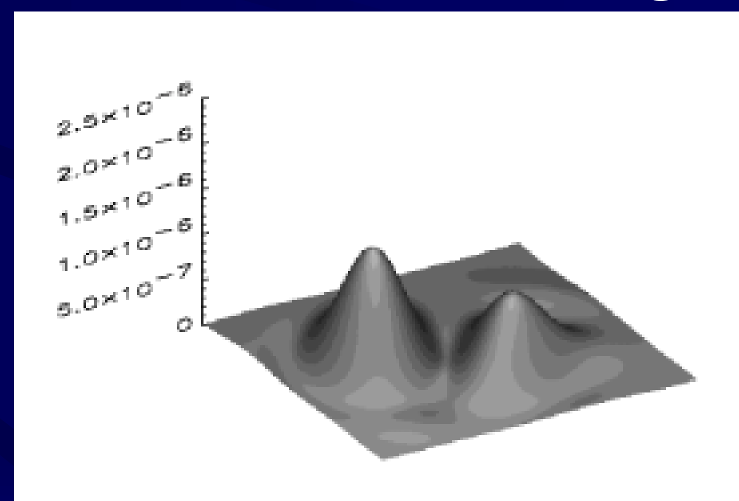


Phase

Substractive recombination



Without modal filtering



With modal filtering

Modal filtering for nulling
Remarks

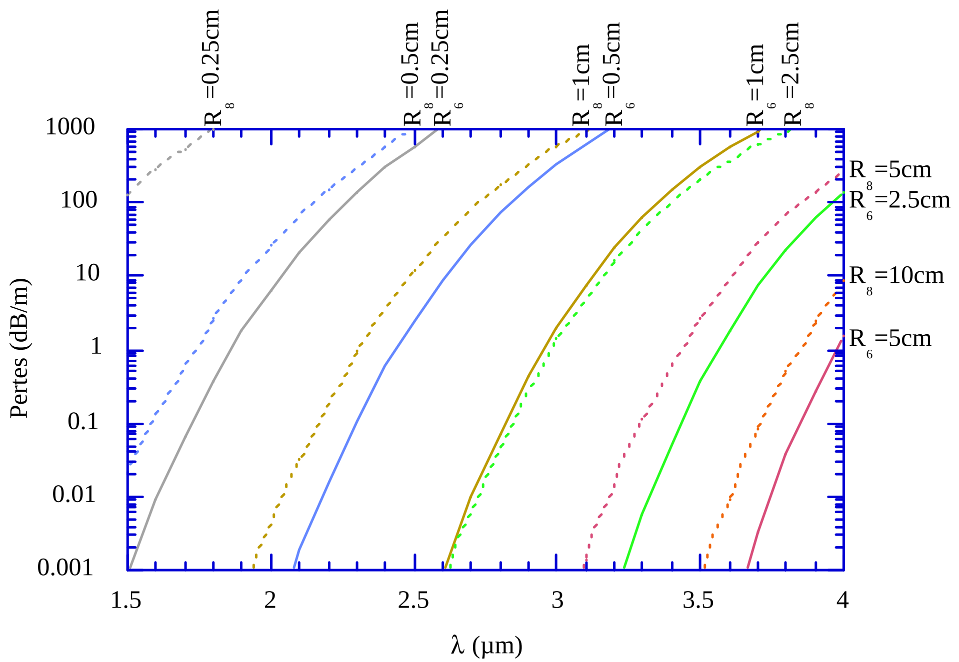
- Spatial filtering is a linear process, like pupil substraction
  => The spatial filter can be placed *before* or *after* the beam combiner
- The spatial filter will block all the more light as the pupil is corrugated :
  ⇒ Need an active control of intensity balance (at 10^{-3} level)
  ⇒ Overall,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

Perspectives : What can fibers be used for?

- Modal filtering
- Polarization control
- Beam combination
- Optical path modulation
- Background reduction
- Low bandpass filter
- Beam transportation

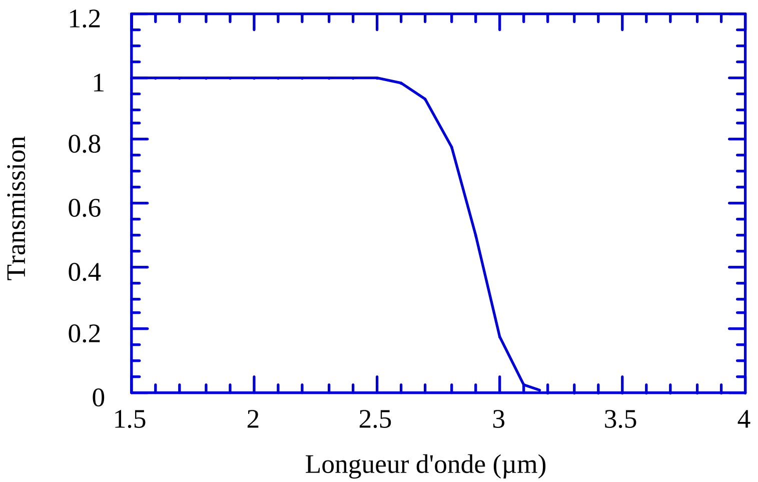
See also integrated optics (Pierre Kern, next…)

Macrocurvature losses and lowpass filtering

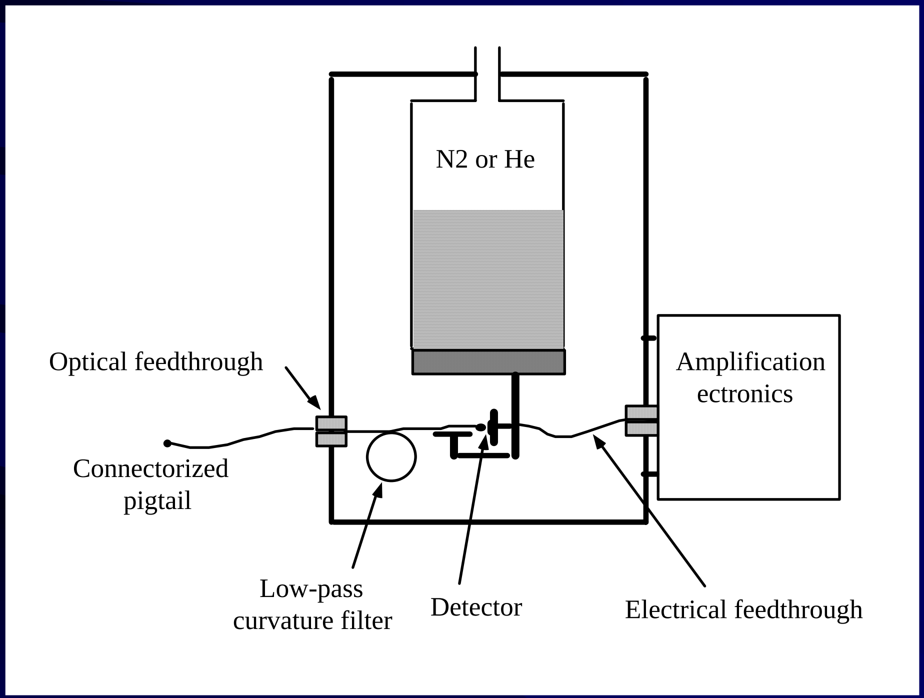


Macrocurvature losses

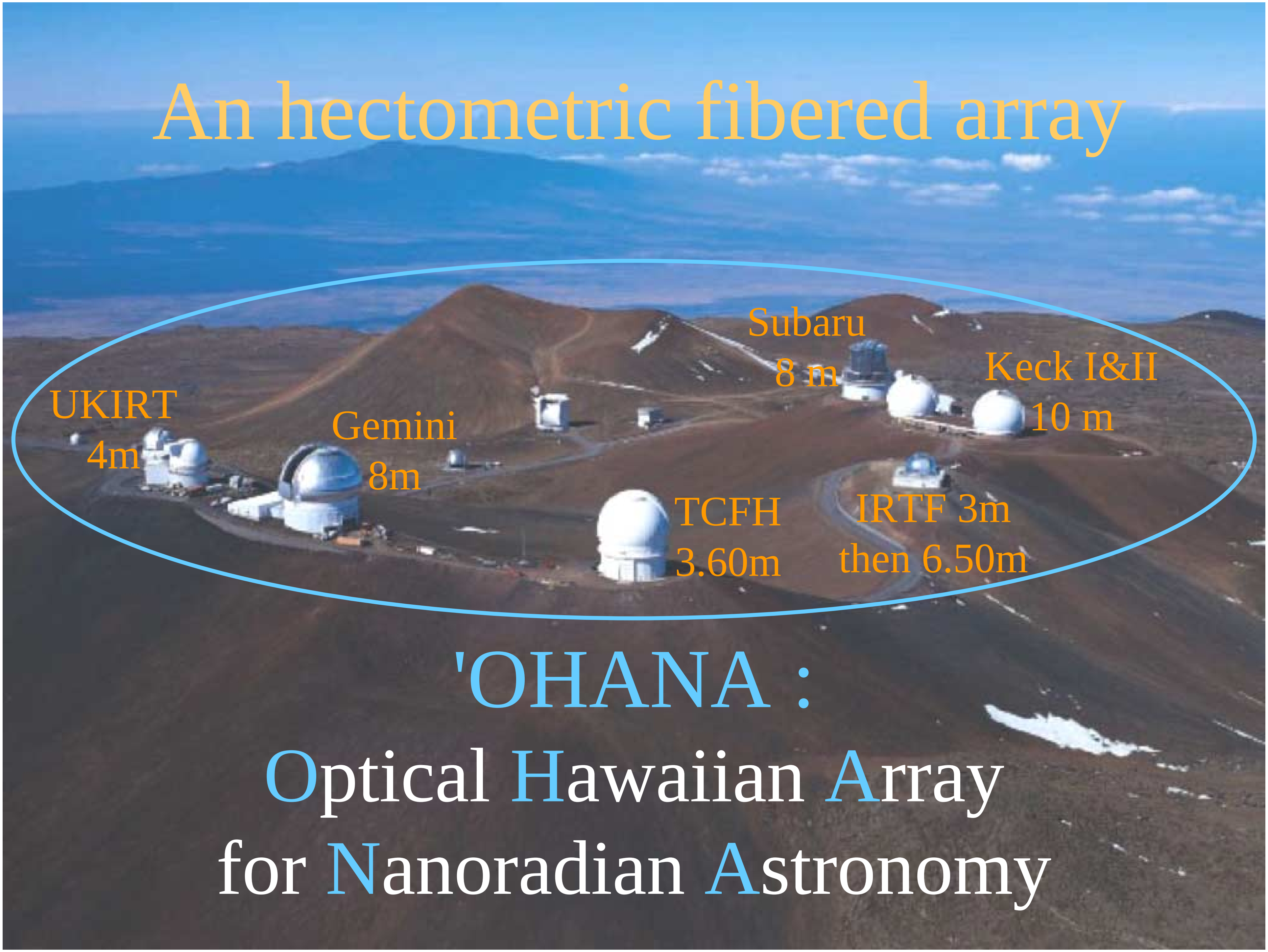
Lowpass filter



A concept for a fibered cryostat

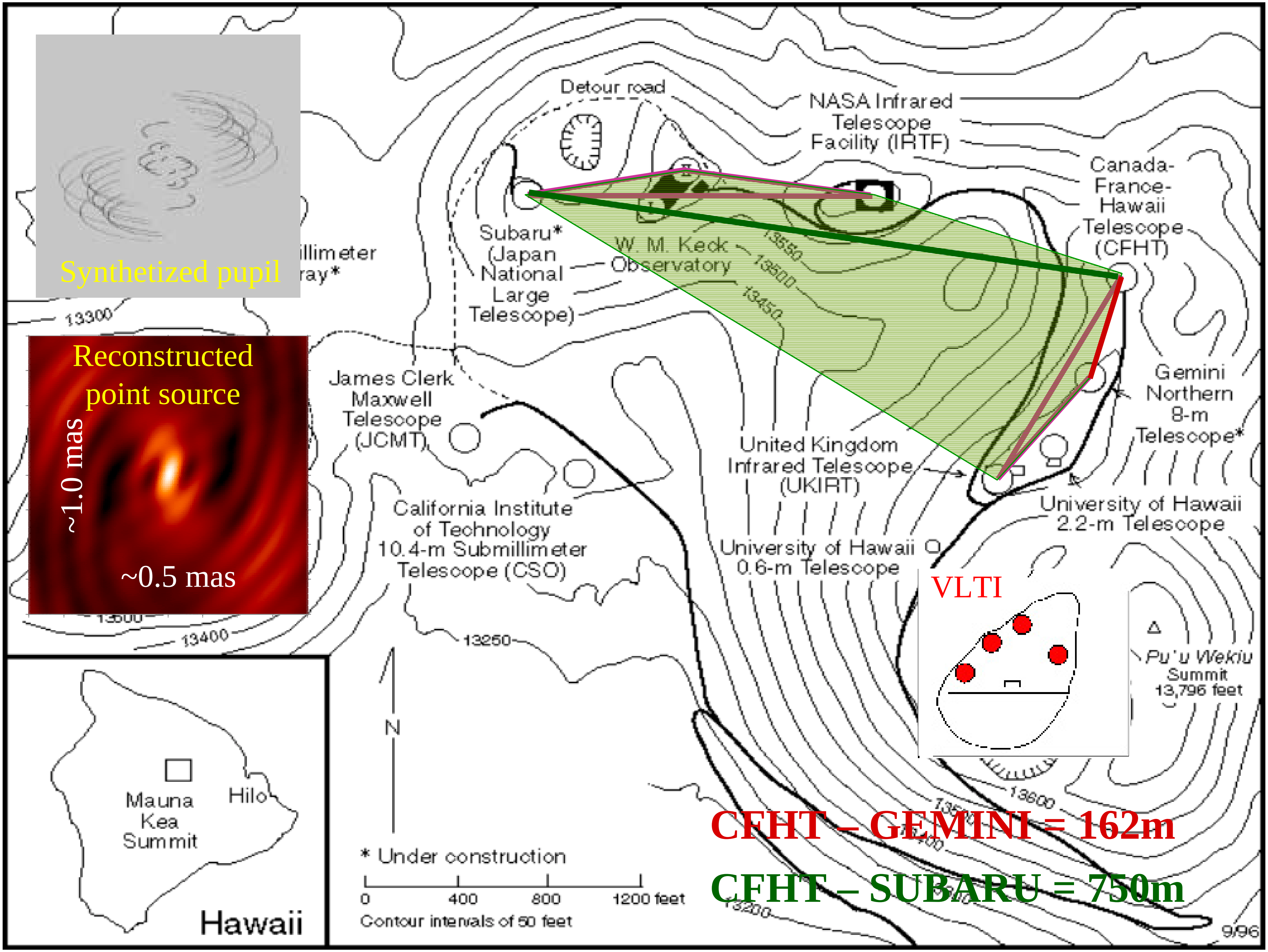


An hectometric fibered array

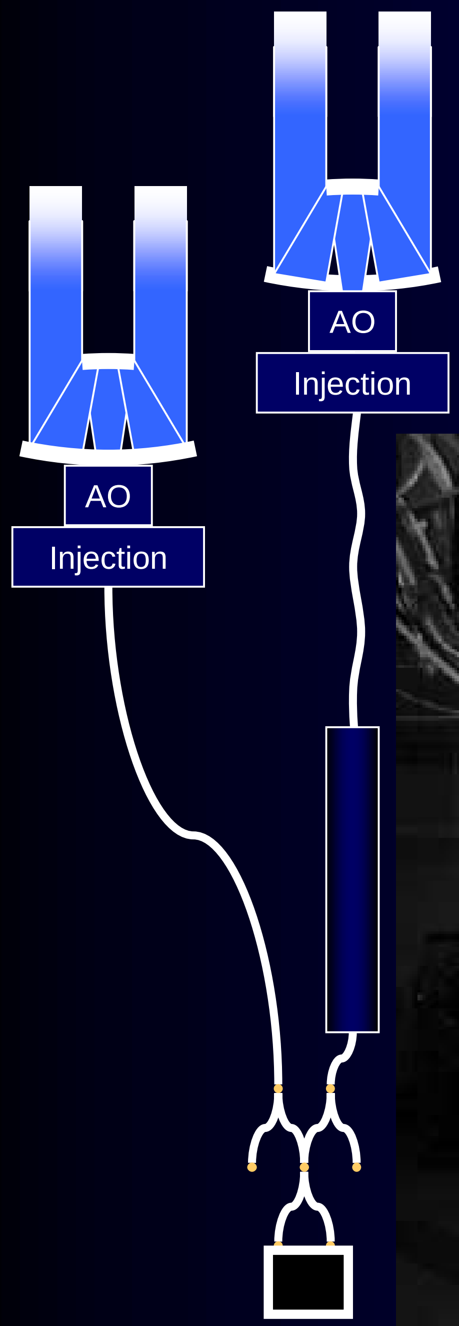


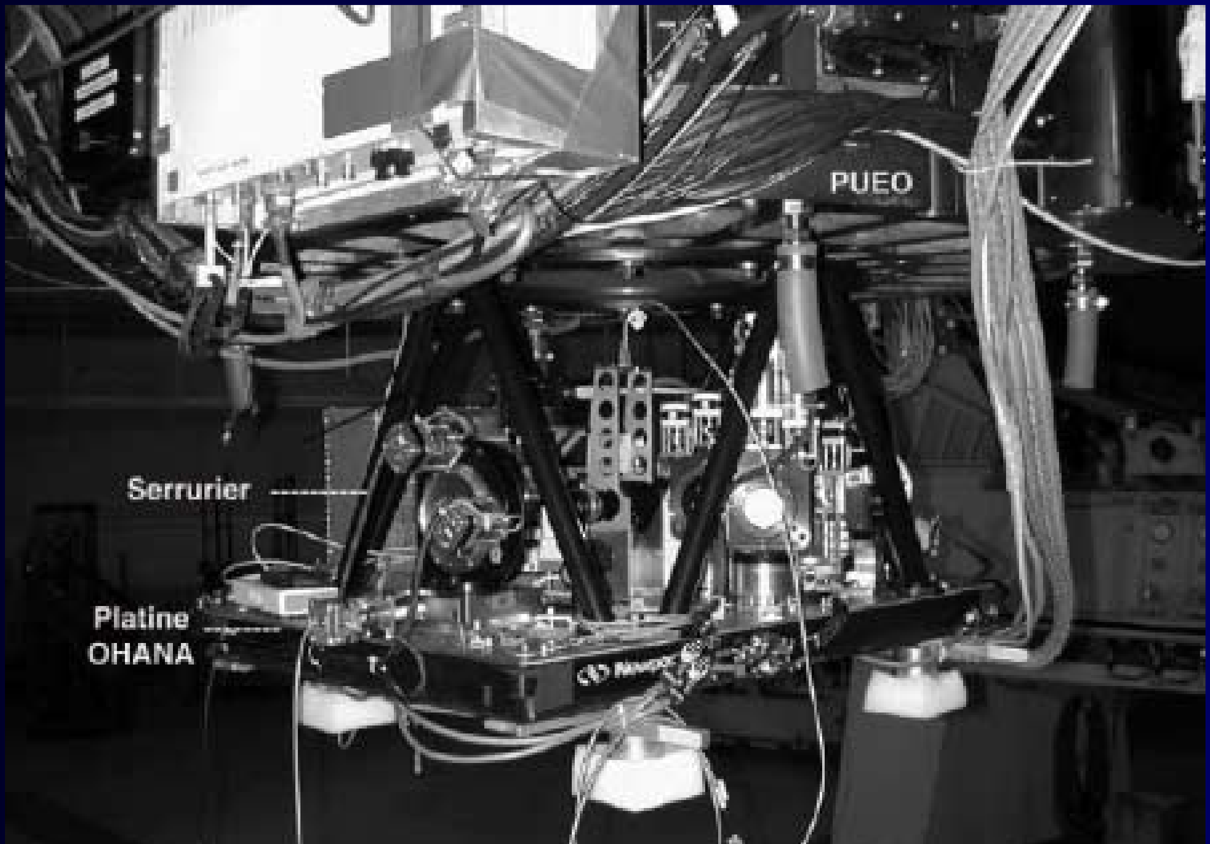
'OHANA :

Optical Hawaiian Array
for Nanoradian Astronomy


Synthetized pupil
Reconstructed point source
~1.0 mas
~0.5 mas
Detour road
NASA Infrared Telescope Facility (IRTF)
Canada-France-Hawaii Telescope (CFHT)
Subaru* (Japan National Large Telescope)
W. M. Keck Observatory
illimeter
ray*
13300
13550
13500
13450
James Clerk Maxwell Telescope (JCMT)
California Institute of Technology 10.4-m Submillimeter Telescope (CSO)
United Kingdom Infrared Telescope (UKIRT)
Gemini Northern 8-m Telescope*
University of Hawaii 2.2-m Telescope
University of Hawaii 0.6-m Telescope
VLTI
Pu'u Wekiu Summit 13,796 feet
13400
13250
N
13600
* Under construction
0 400 800 1200 feet
Contour intervals of 50 feet
13200
9/96
Mauna Kea Summit
Hilo
Hawaii
CFHT – GEMINI = 162m
CFHT – SUBARU = 750m

'OHANA concept





Platine d'injection OHANA sur l'optique adaptative PUEO du CFHT (01/2002)

ALIRA
Atacama Large InfraRed Array

- A fibered array reusing ALMA's infrastructure at 5–30µm
- 64 x 12m telescopes on Chajnantor plateuau
- Surface quality 2λ @ 12µm + $D/r_0 \sim 1$ => low order AO
- Challenge: kilometric, thermal IR waveguides