VLTI Tutorial

Introduction to Stellar Interferometry

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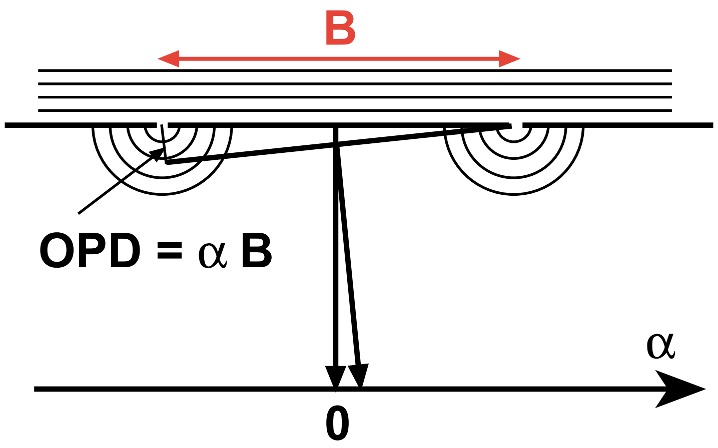
Project ‘VLTI Tutorial’

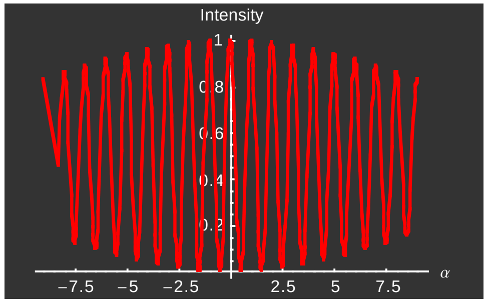
Milestones:

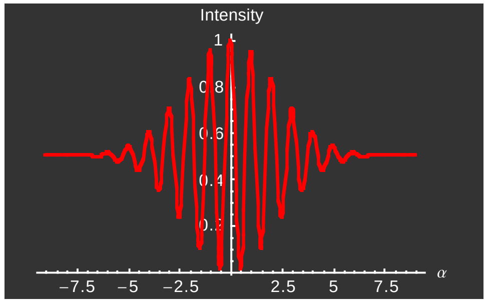
- Principle of Interferometry: concept of coherence length and spatial coherence, van Cittert-Zernike Theorem
- Types of Interferometers: Michelson and Fizeau, Homothetic mapping, measurement of the visibility
- Atmospheric turbulence: What does AO do for interferometry, why do we need a fringe tracker and PRIMA?
- Interpretation of VINCI data

Young's Two-Pinhole Experiment



1st Min: OPD = $\lambda/2 \Rightarrow \alpha_{min} = \lambda/(2B)$



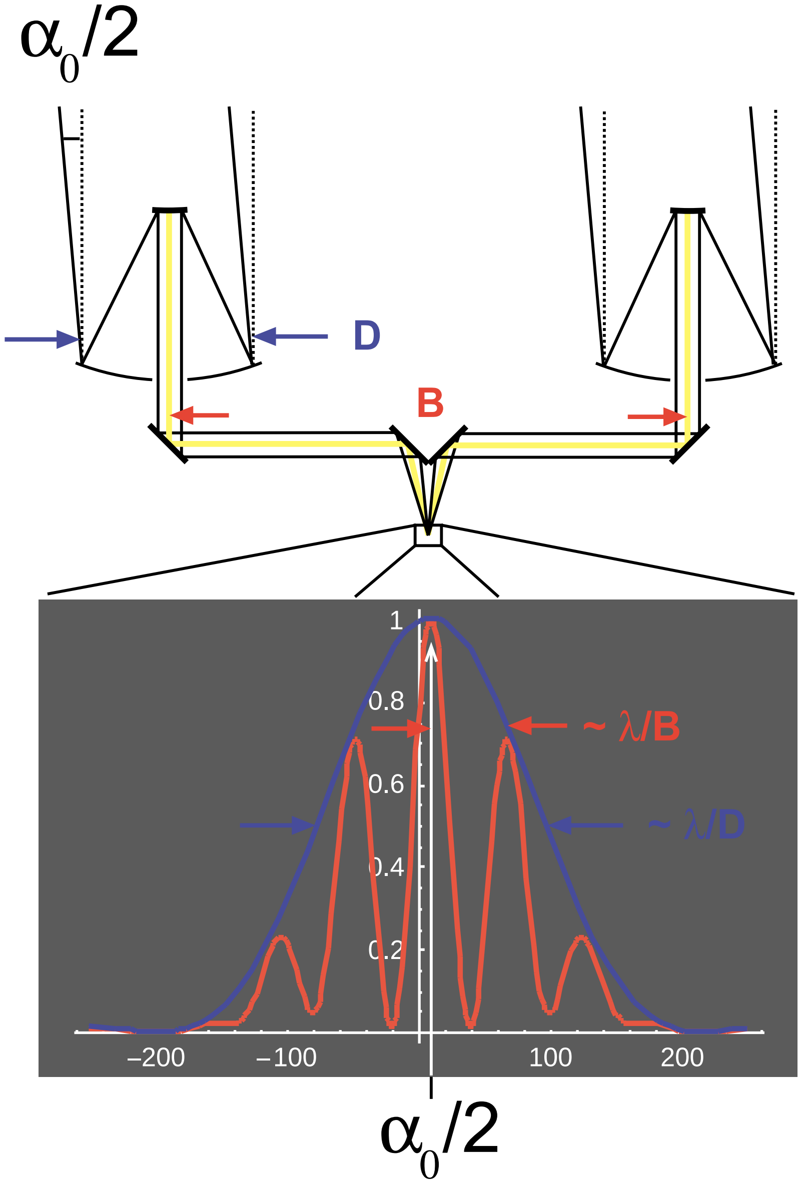


(First and last picture of a movie)

- Light source at infinity at $\alpha = 0$
- Intensity pattern ~ 1+cos as a function of α, period length: λ/B
- OPD > coherence length $\Rightarrow$ fringes disappear

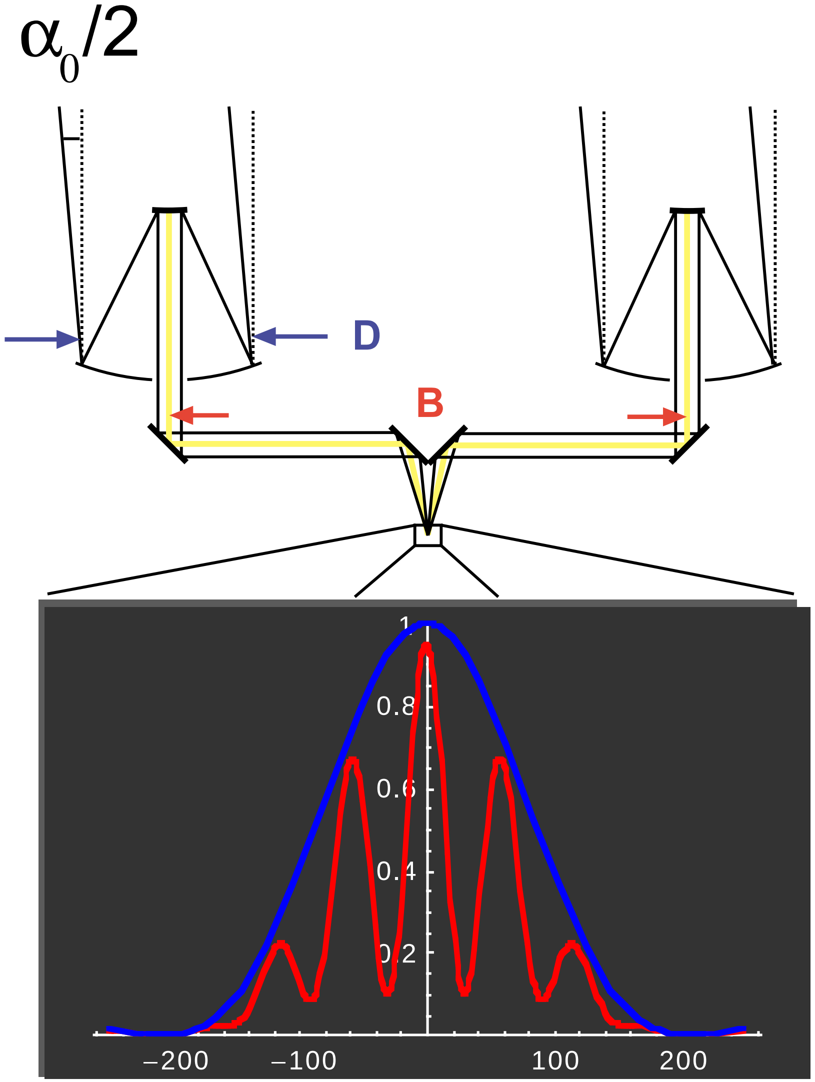
Light source at angle α_0
$\Rightarrow$ fringe pattern shifts accordingly

Michelson stellar interferometer

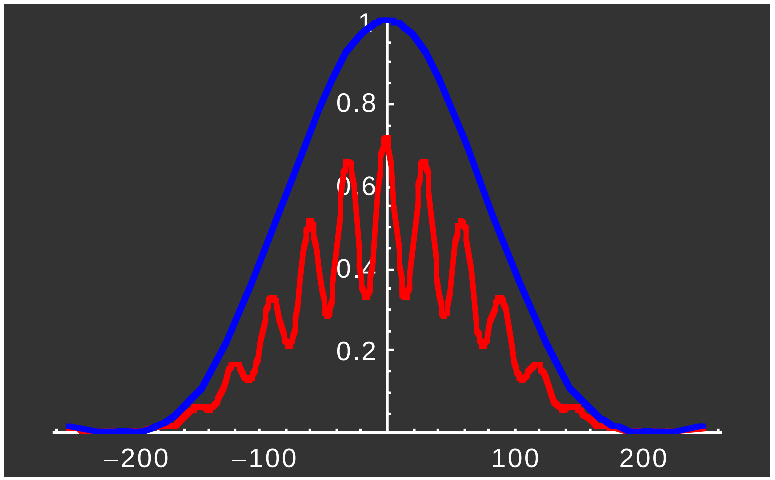


- Stellar source with angular size α_0
- Add fringe patterns (i.e. intensities) between $\pm\alpha_0/2$

Michelson stellar interferometer



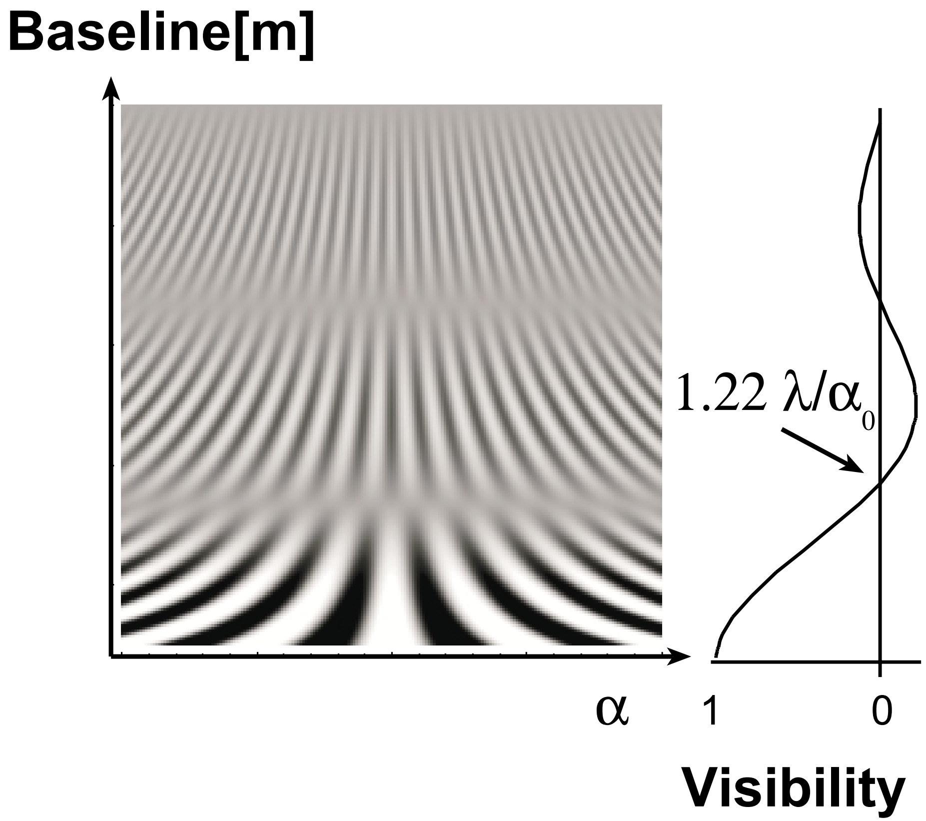
B_1 and α_0 (Movies used for illustration)



$B_2 > B_1$ and α_0

- Stellar source with angular size α_0
- Add fringe patterns (i.e. intensities) between $\pm\alpha_0/2$
- Resulting fringe pattern shows reduced contrast
- Reduced contrast depends on B – and on α_0

Visibility Function



- Analysing the resulting fringe pattern as a function of B and α_0 one finds that

  Visibility(B) = $\mathcal{F}(I(\alpha))$

- If $I(\alpha) = \mathrm{Circ}(\alpha/\alpha_0)$

  $\mathrm{Vis}(B) = \mathrm{Besinc}(\pi\alpha_0 B/\lambda)$

Van-Cittert-Zernike Theorem

Definition of the coherence function: $\Gamma(\alpha_1, \alpha_2, \tau) = \langle\Psi(\alpha_1, t+\tau)\, \Psi^*(\alpha_2, t)\rangle$

Split spatial and temporal terms: $\Gamma(\alpha_1, \alpha_2, \tau) = \Gamma(\alpha_1, \alpha_2)\, \mathcal{F}^{-1}(G(\nu))$

Propagation in space: $\Gamma(u_1, u_2) = \int \Gamma(\alpha_1, \alpha_2) \exp(ik(r_1 - r_2))\, d\alpha_1 d\alpha_2$

Incoherent source (Star): $\Gamma(\alpha_1, \alpha_2) = I(\alpha_1)\, \delta(\alpha_1 - \alpha_2)$

Degree of coherence: $\gamma(u_1, u_2, \tau) = \int I(\alpha) \exp(ik(u_1 - u_2)\, \alpha)\, d\alpha \;\; \mathcal{F}^{-1}(G(\nu))$

This is the measured quantity in a stellar interferometer.

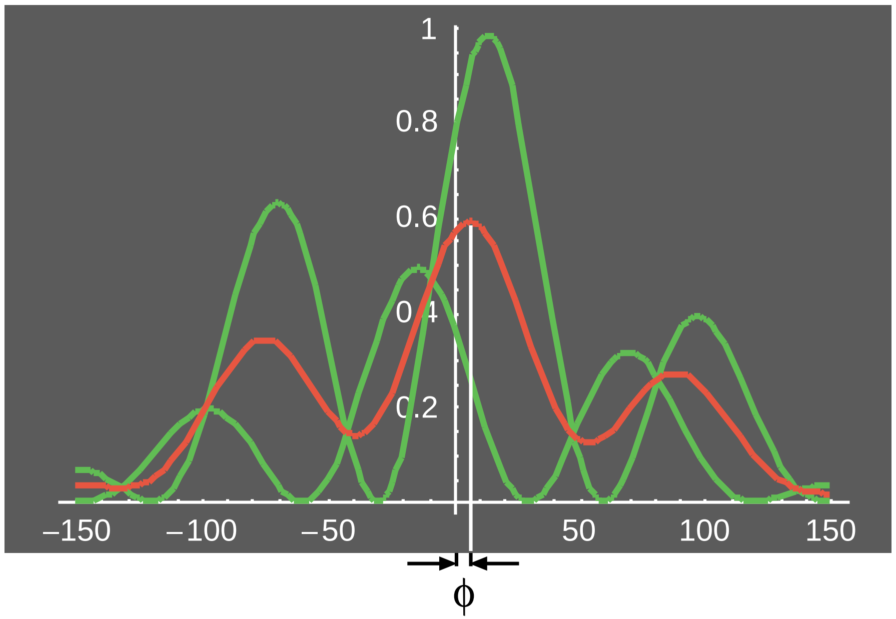
- γ is the degree of spatial and temporal coherence, also called the visibility
- γ is a function of $u_1 - u_2$, the difference vector
- for a point source the spatial coherence is 1, and
  the contrast is determined by the temporal coherence

Visibility function

The visibility function γ is complex, with:

Modulus V: contrast of the fringe pattern

Phase ϕ: Position of white light fringe with respect to OPD = 0



With $\gamma = \mathcal{F}(\ I(\alpha))$ it is

$\phi \neq 0$ if $I(\alpha)$ is non-symmetric

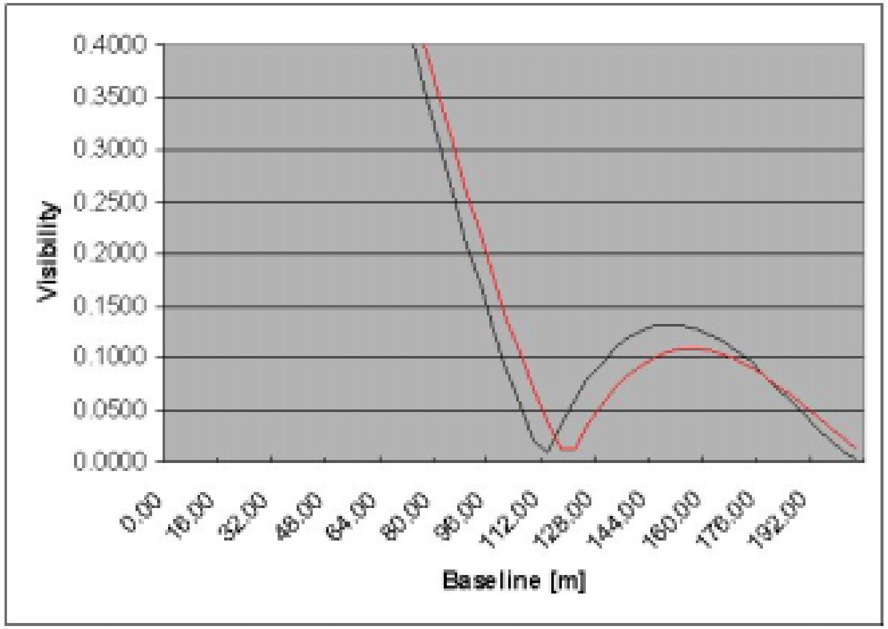
eg spots on the stellar surface, dense clusters etc.

The phase is vital for imaging!

Examples of visibility functions

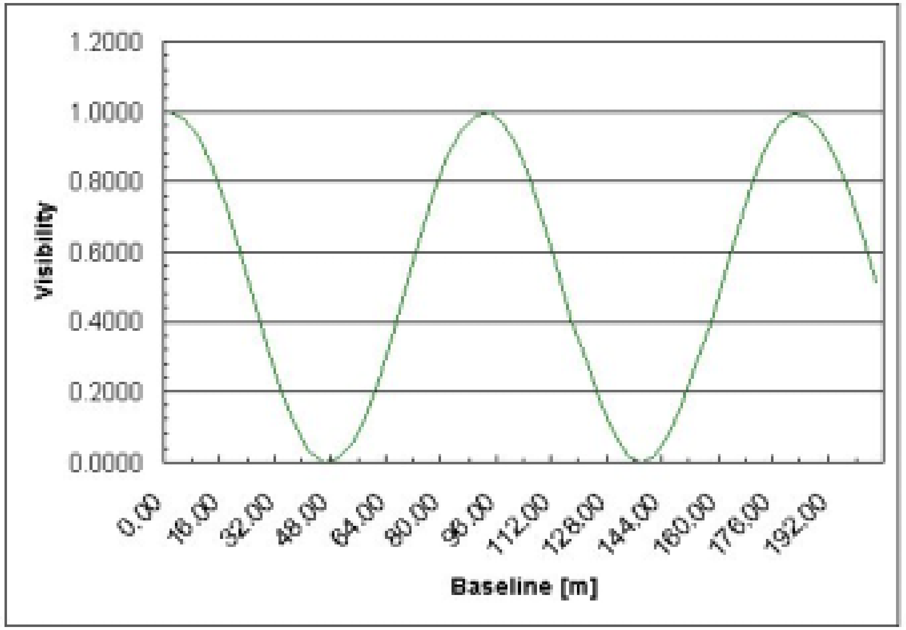
Uniform disk + limb darkening:

(UD diameter 5 milliarcsec)



Binary star:

(separation 5 milliarcsec)



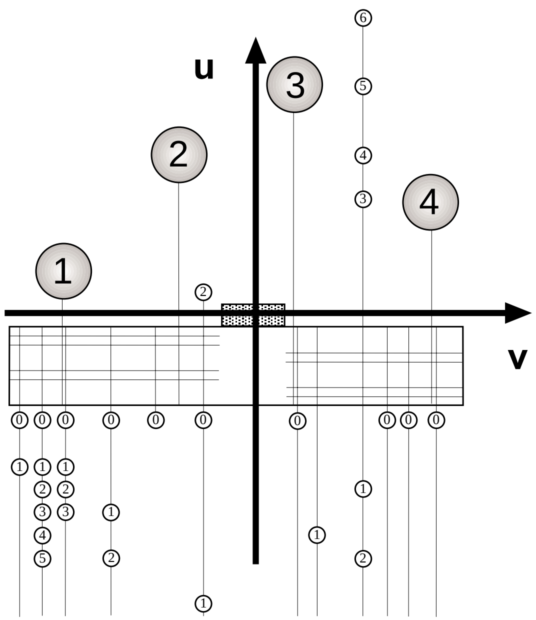
Note: Do not confuse a binary's visibility function (~cos) with the fringe pattern (~cos) of an interferometer

Interferometric imaging

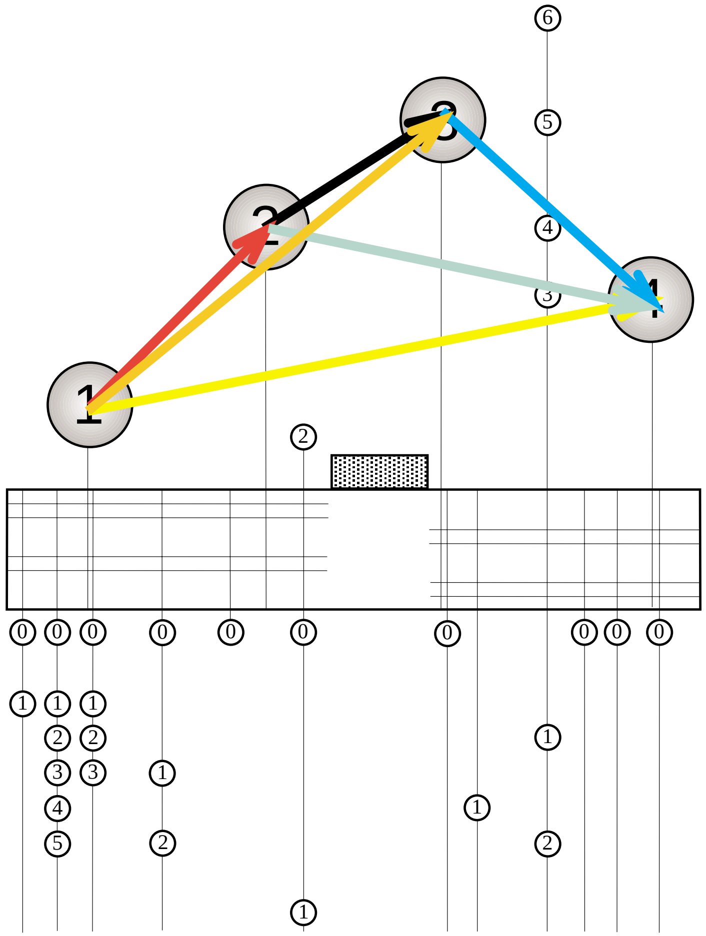
Image intensity $I_{im}(\alpha) = \mathcal{F}\,(\,\Gamma(u_1 - u_2)\,)$, with $u_1 - u_2$ = Baseline vector

Fill factor in the uv plane determines 'smoothness' of the image

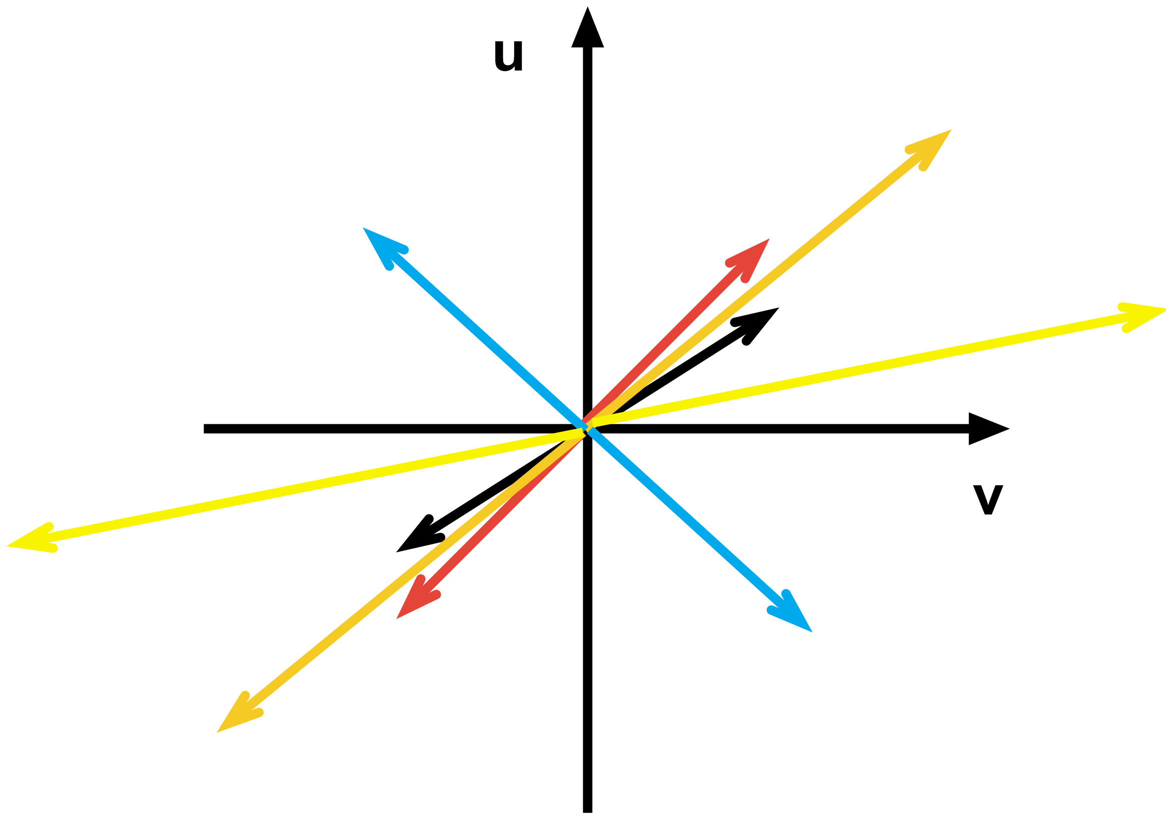
Measure Visibility and Phase for many baselines in the uv plane.

Note: This  is not the uv plane!

The uv-plane

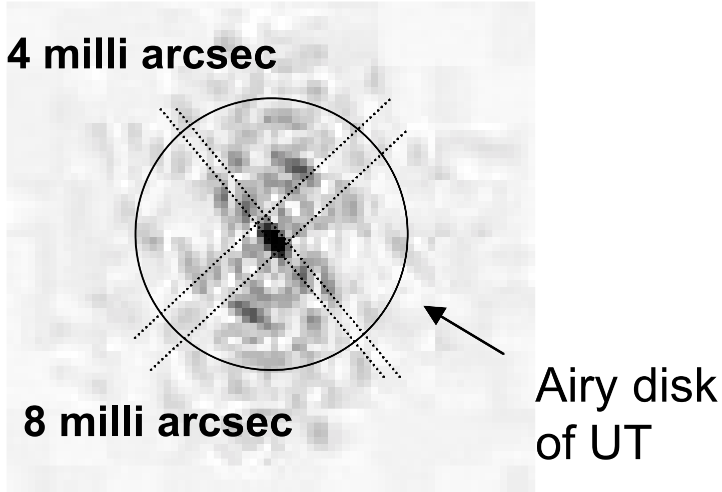


This is the uv-plane:



Note: This is the uv-plane for an object at zenith.
In general, the projected baselines have to be used.

The uv-plane with the UTs



uv coverage for object at -15°

8 hour observation with all UTs

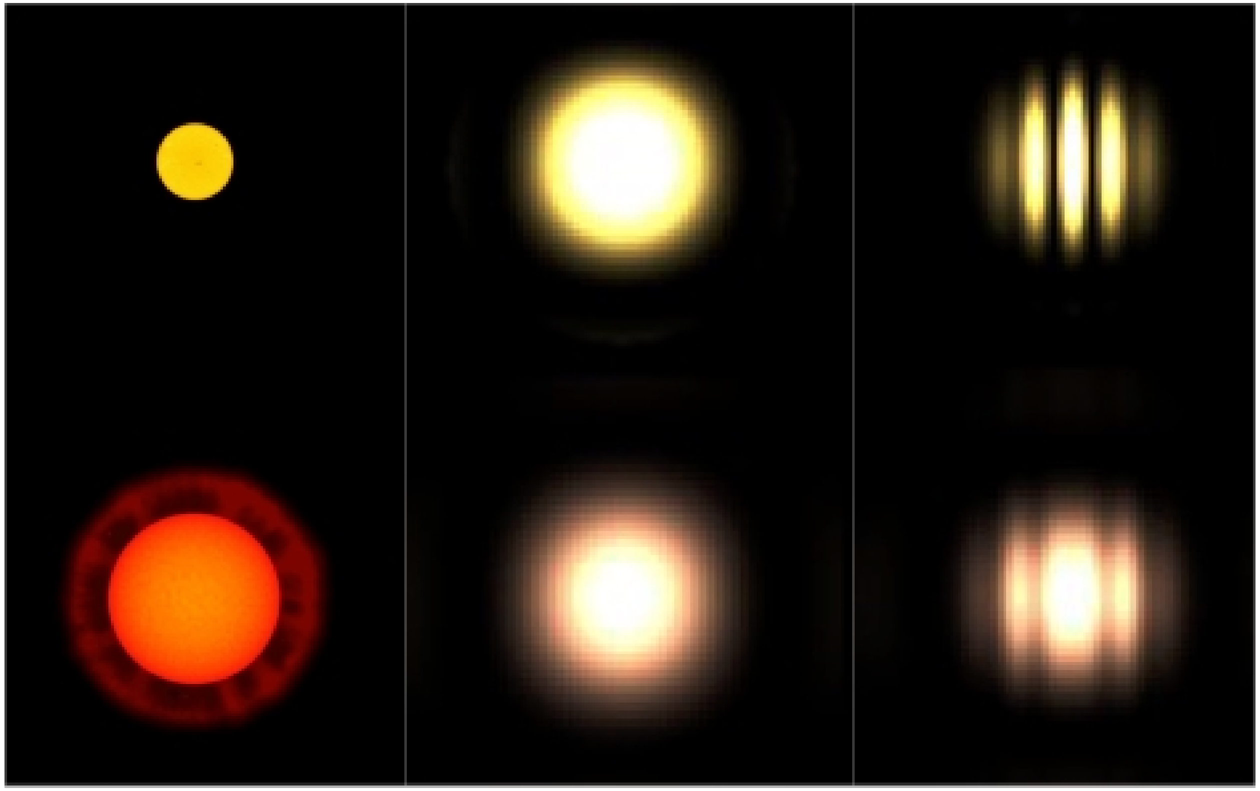
Resulting PSF is the Fourier transform of the visibilities

λ = 2.2μm (K-band)

Why is interferometric imaging better?

Small star

Big star



Objects	Single Telescope	Interf. Fringes
	$I_{im}(\alpha) \sim \mathcal{F}(\,D\,)$	$I_{im}(\alpha) \sim \mathcal{F}(\,B\,)$
Angular Resolution: $\sim \lambda/D$		$\sim \lambda/B$

Summary of concept

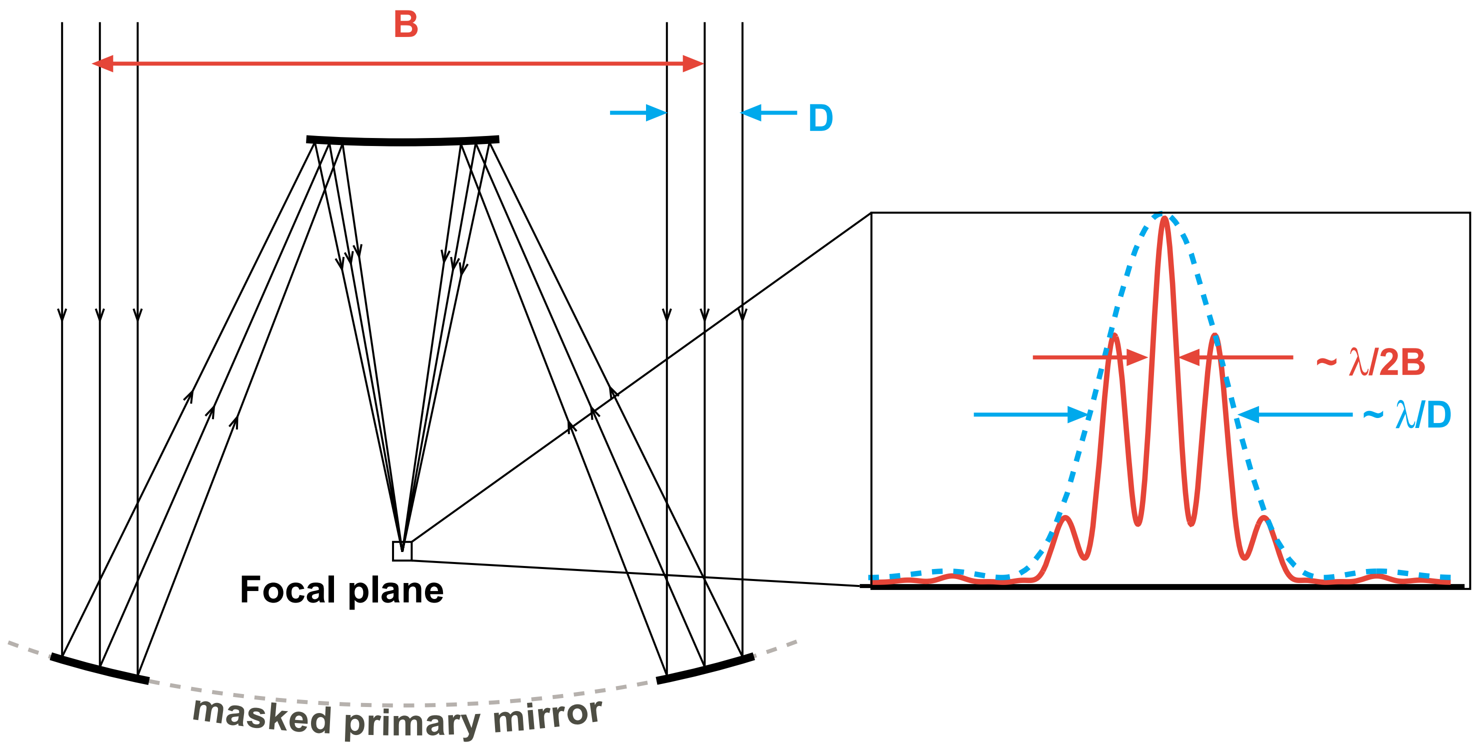
- The Visibility is the Fourier Transform of $I(\alpha)$, a complex function,
  the modulus is the contrast of the fringe pattern,
  the phase is the position of the white light fringe (wrt OPD = 0).
- A stellar interferometer measures the Visibility function at individual points in the uv plane, i.e. (projected) baseline vectors.
- Smooth reconstruction of the intensity distribution $I(\alpha)$ (i.e. imaging) requires visibility measurements with many baselines.
- Angular resolution determined by the longest baseline and not by the diameter of the individual telescopes.

- Conclusion: Concept is good, CDR passed

Second Part: Types of interferometers, the measurement of the Visibility function

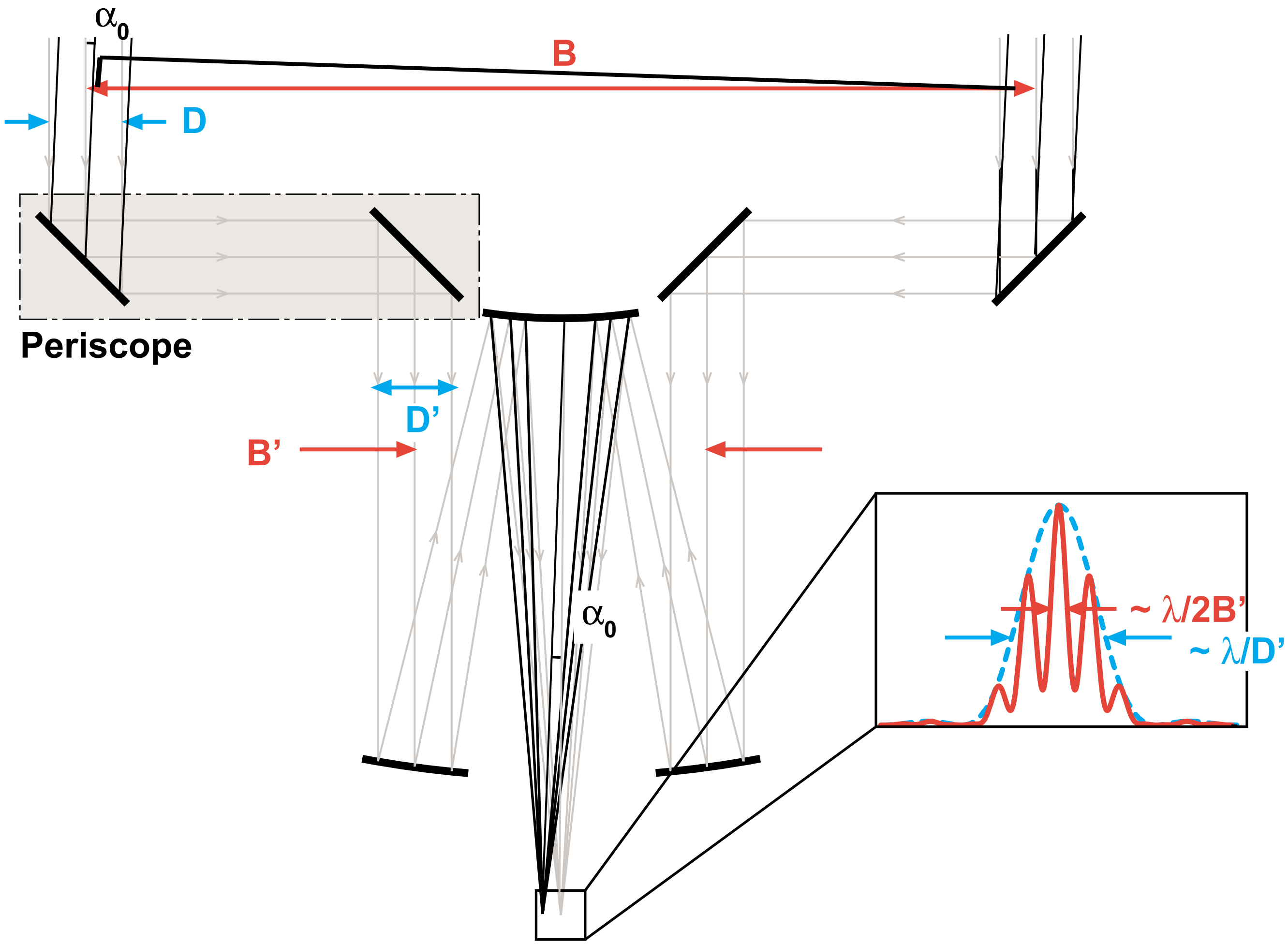
- Two major types: Michelson and Fizeau
- Main difference between the two: size of field of view
  $\Rightarrow$ homothetic mapping
- Three way beam combination
- Measurement principle types
- Multi-axial vs co-axial beam combination

Masking a telescope



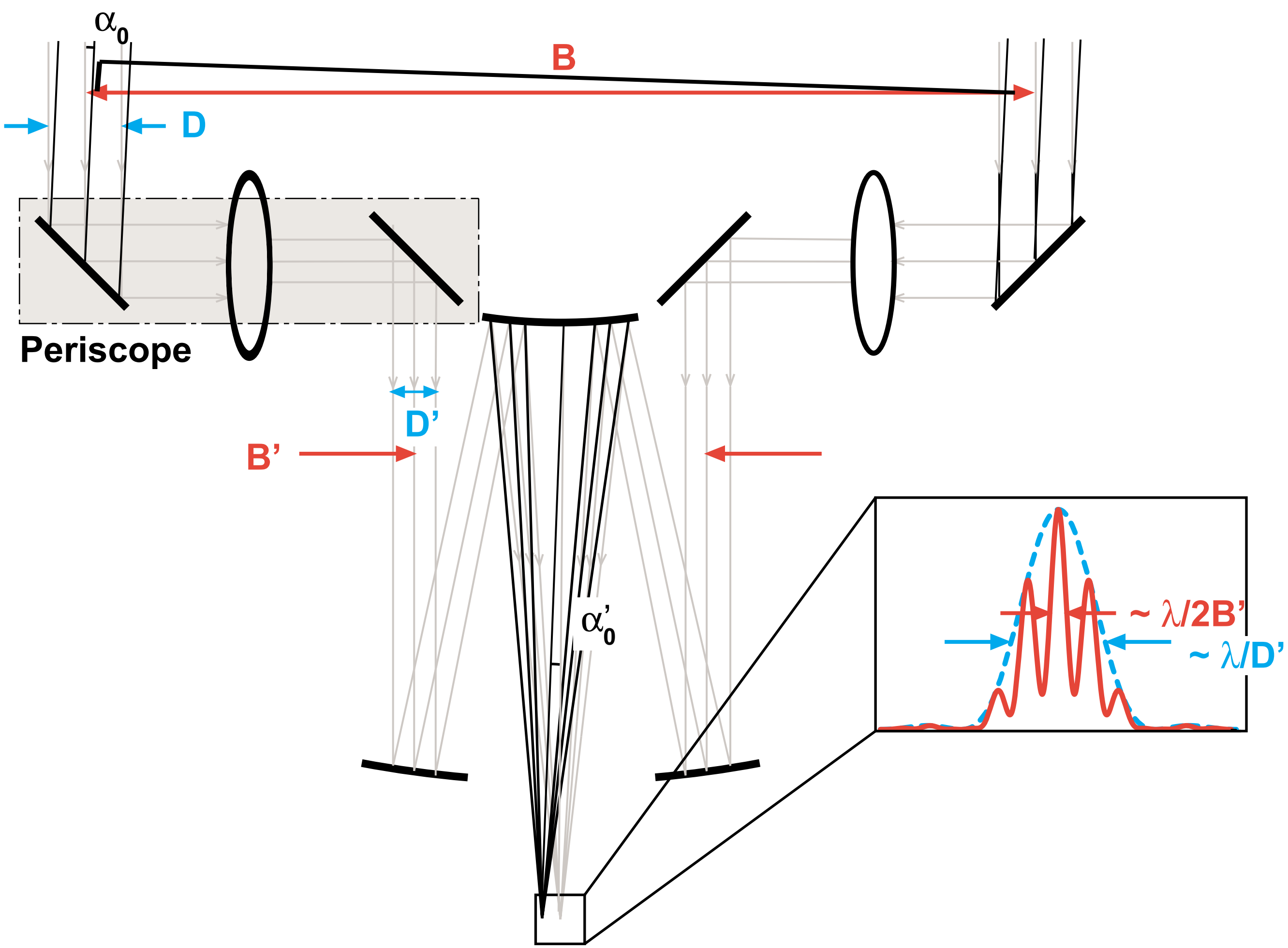
- The imaging process in a telescope is the superposition of fringe pattern from all combinations of baselines in the telescope pupil
- Masking the pupil, one can select one particular baseline
- Every star in the field of view has fringes

Michelson interferometer



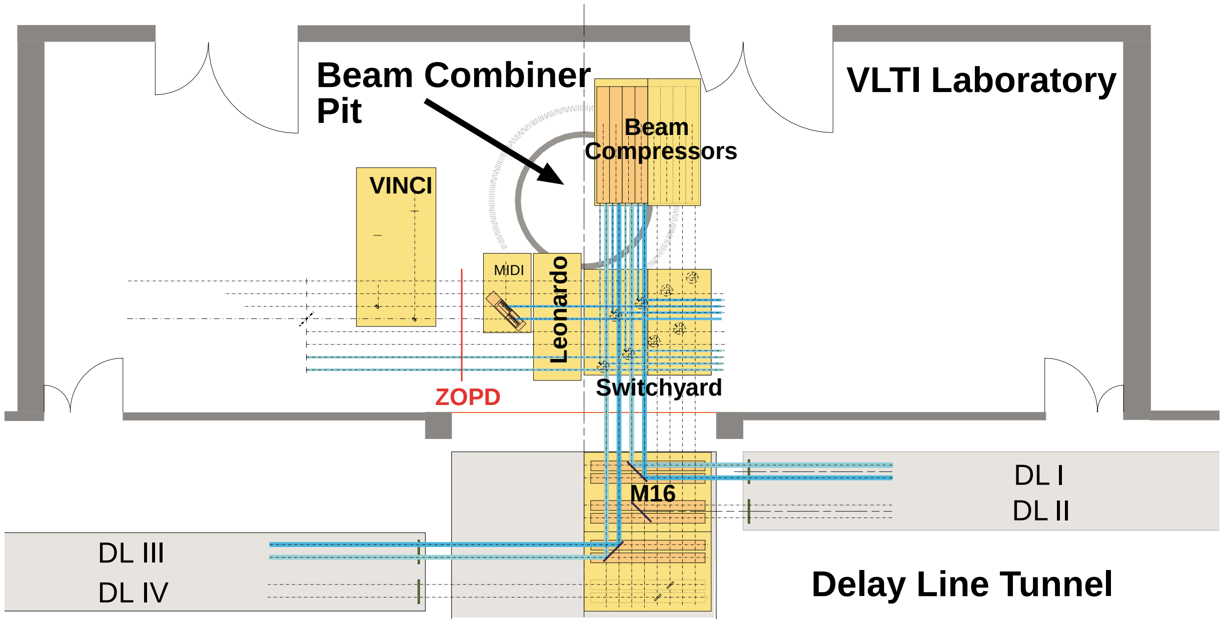
- Image at position α_0 (if D' = D)
- Left beam with delay α_0 B , right beam with delay α_0 B' $\Rightarrow$ OPD = α_0 B - α_0 B' $\neq$ 0 at image position α_0

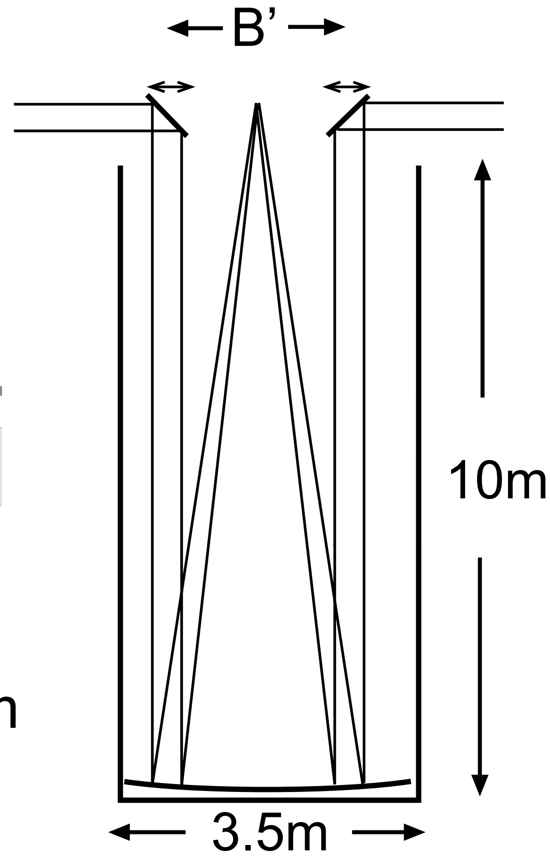
Fizeau interferometer



- If D' ≠ D the image position is $\alpha_0' = \alpha_0$ D/D'
- If D/D' = B/B' one finds OPD = α_0' B' = α_0 D/D' B' = α_0 B/B' B' = α_0 B
- This kind of reimaging of the telescope pupils is called homothetic mapping

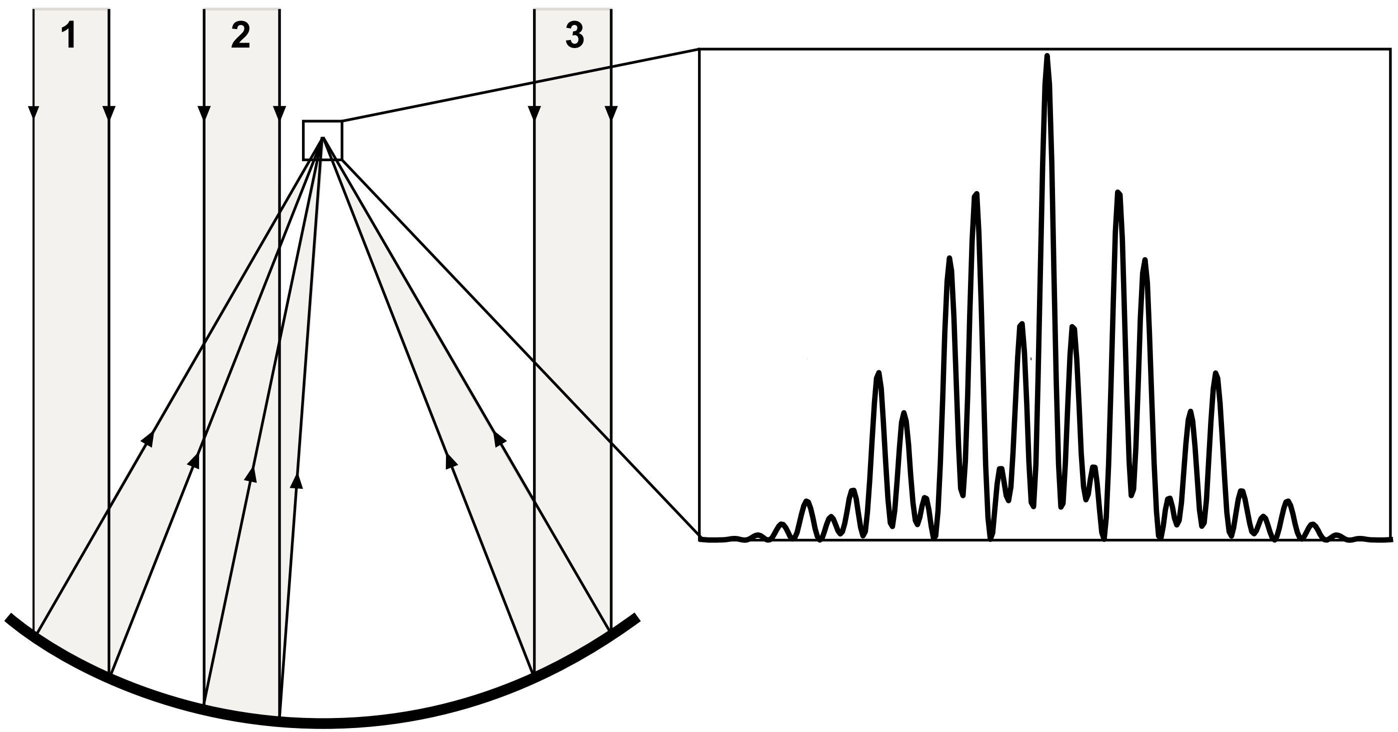
Option: Homothetic mapping with the VLTI





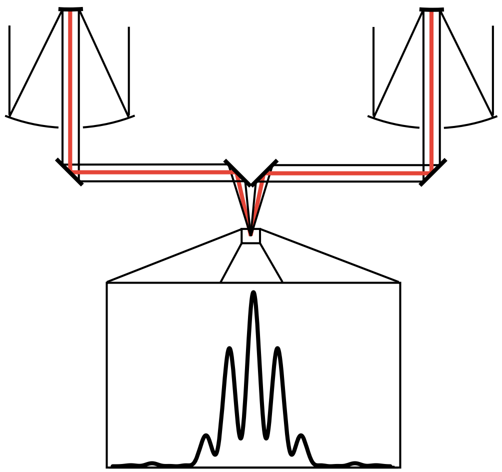
- Cylindric hole with parabolic mirror on the bottom
  - reimaged telescope pupils in front focal plane,
  - spatial fringe pattern in the focus
- Dynamic adjustment of pupil mirrors with µm precision required

Three beam fringe pattern



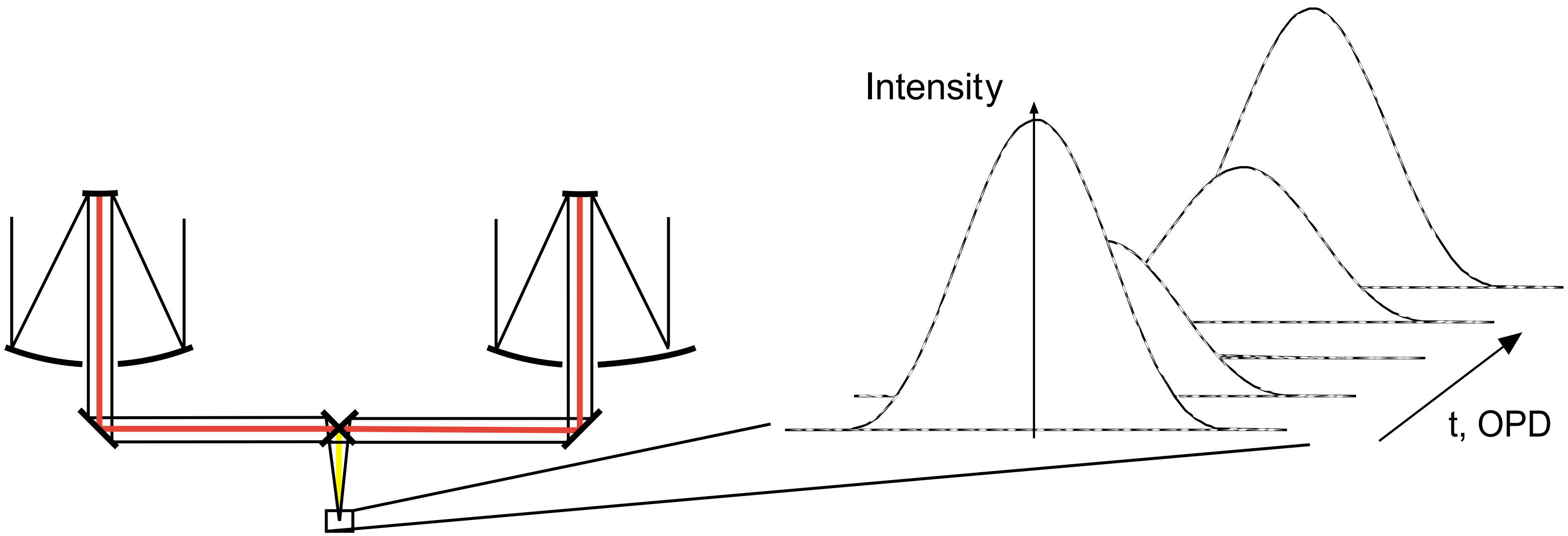
- Three baselines (B'_{12}, B'_{23}, B'_{13}) with relation 1:2:3 produce three different spatial frequencies in the fringe pattern
- Disentangle the individual visibilities in Fourier space
- Planned in AMBER

Spatial vs temporal fringe patterns



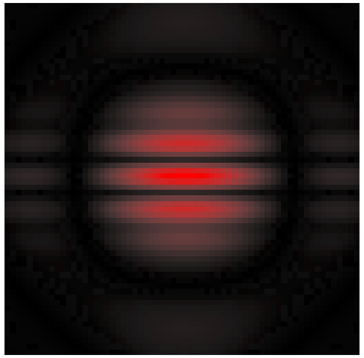
- Michelson and Fizeau interferometers discussed so far produce spatial fringe pattern (multi-axial beam combination)
- Co-axial beam combination produces Airy disk without fringes.
- Temporal OPD modulation produces I(t)

(Compare to Michelson Fourier Spectrometer)

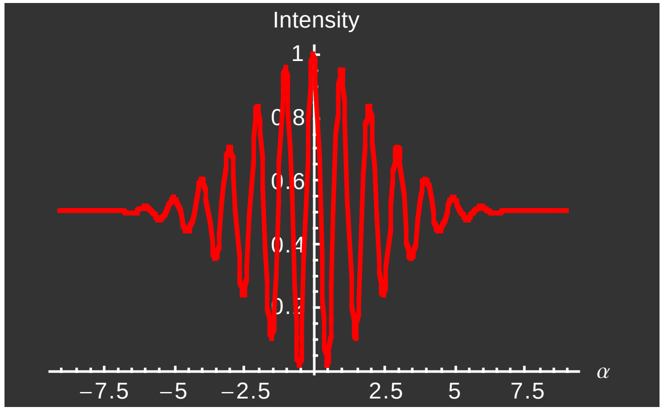


Spatial vs temporal fringe patterns

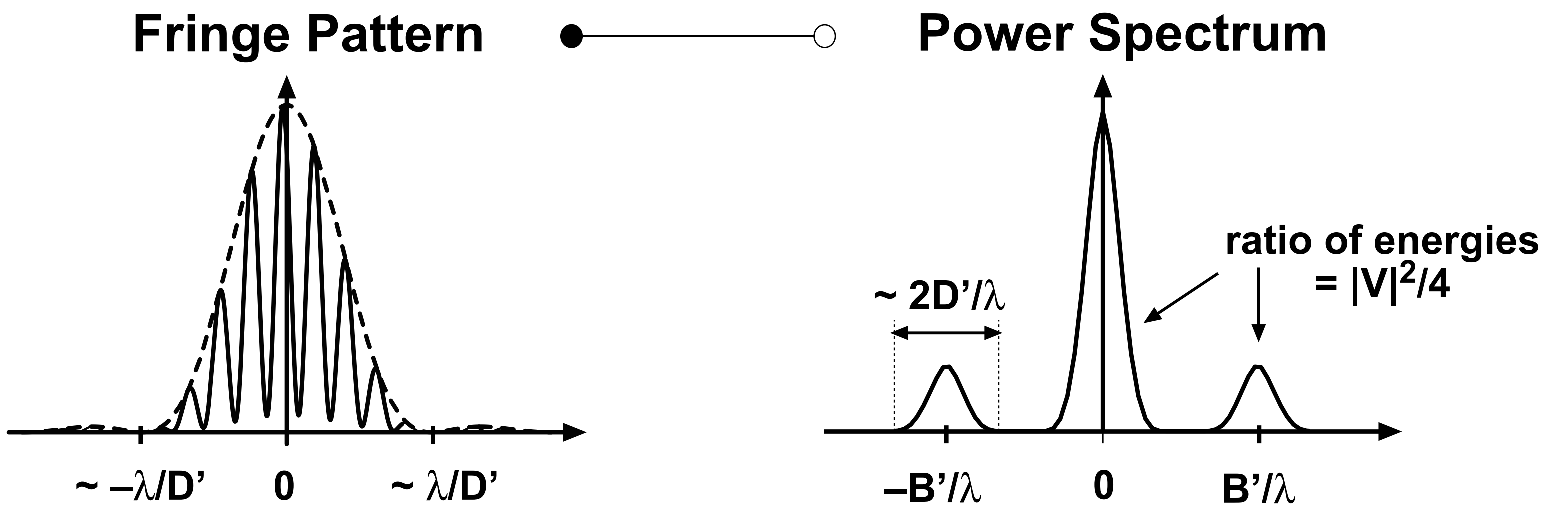
- A spatial fringe pattern is a 2D signal as a function of the image coordinates with fringes along one coordinate enveloped by an Airy disk



- A temporal fringe pattern is a 1D signal as a function of OPD enveloped by the Fourier transform of the spectrum G(ν)

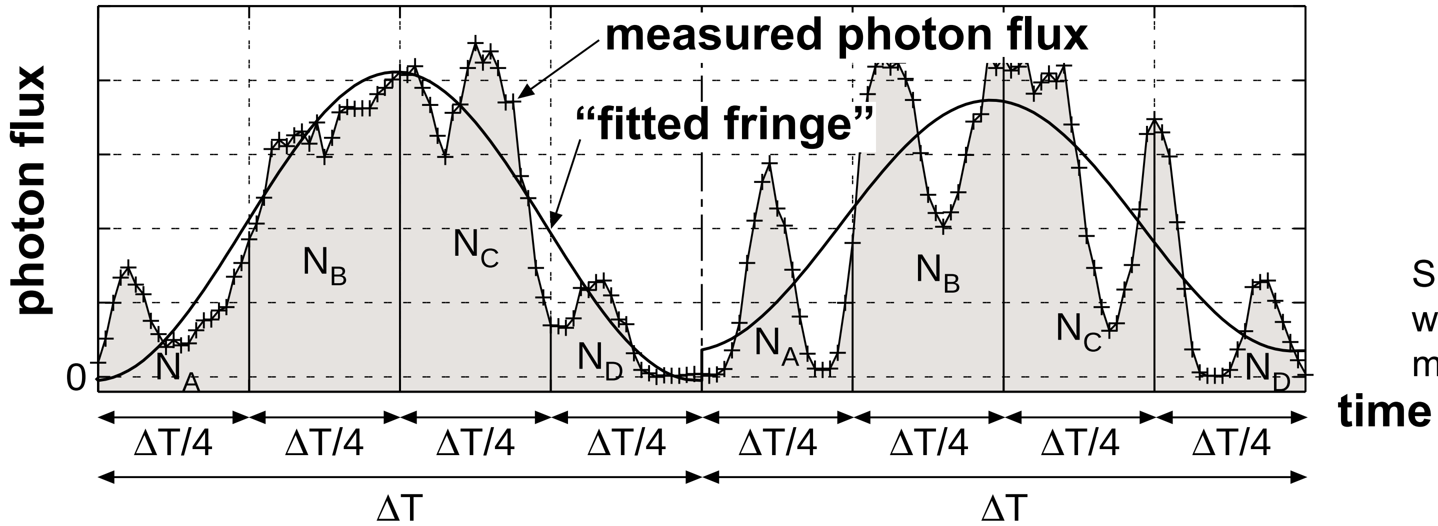


Visibility measurement in the power spectrum



- Both spatial and temporal pattern can be analysed in the power spectrum
  - Spatial power spectrum is shown above
  - Temporal power spectrum shows intensity spectrum G(ν) multiplied by the modulus V^2 of the spatial coherence (VINCI)
- Three beam combination produces sidelobes at each of the three frequencies.
- Weak or noisy signal eventually shows up in the averaged power spectrum.

Visibility measurement - ABCD method



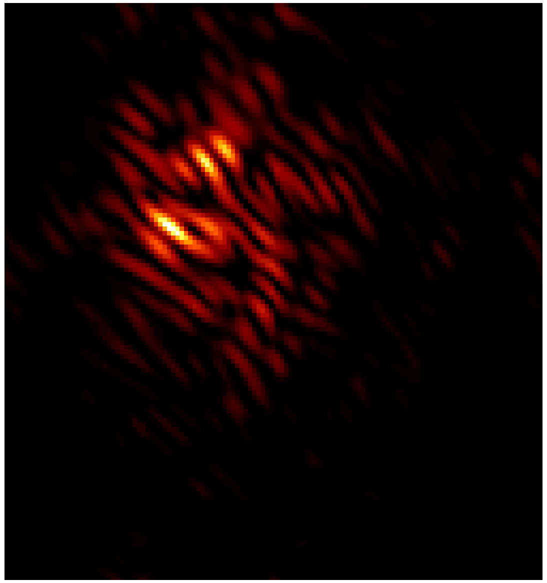
Simulation done with End-to-End model

- Principle: Measure intensity at four points spaced by $\lambda/4$
  - Temporal pattern shown above
  - Spatial pattern awkward, first integrate along the fringes in the Airy disk, then normalise with Airy disk intensity. Error prone.
- Fitting $(1+|V| \cos(\alpha + \phi))$ determines modulus and phase
- Averaging is less efficient than using the power spectrum

Summary of designs

- The position of the reimaged telescope pupils determine the interferometer type:
  - Exit pupils form scaled down model of interferometric array
    $\Rightarrow$ homothetic mapping, Fizeau type, ‘unlimited’ field of view
  - Exit pupils are placed to have convenient fringe spacing
    (e.g. to match detector pixels)
    $\Rightarrow$ Michelson type, very limited field of view
  - Exit pupils imaged on top of each other
    $\Rightarrow$ Co-axial beam combination producing temporal fringe pattern
- Visibility measurements in space/time or in Fourier space
  - ABCD method determines directly modulus V and phase ϕ
  - Fourier spectrum determines modulus and phase,
    averaged power spectrum can be used to measure weak signals
- Conclusion: preliminary design is ok, PDR passed

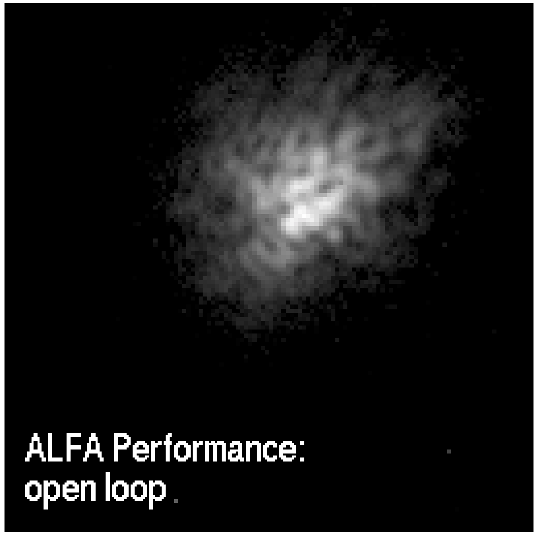
Excursion: Atmospheric turbulence and PRIMA

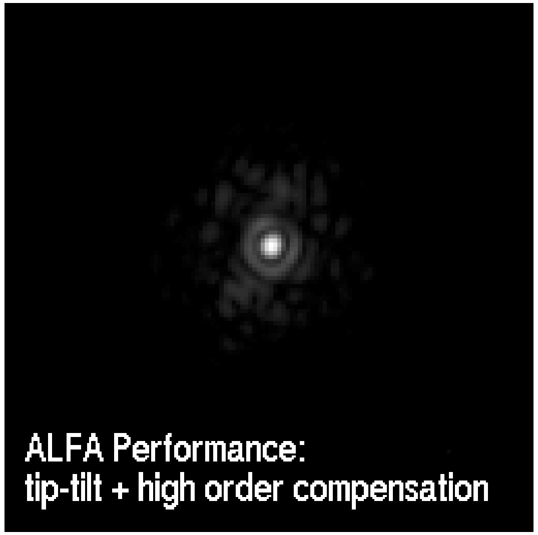


Spatial fringe pattern of 2 UTs at 2.2 μm in 0.5” seeing

- Goal: Measurement of fringe contrast and fringe position
- Requirement:
  Small pixel size (1- 10 milli arcsec) + Short exposure time (~10 msec)
- Note:
  The angular resolution depends only on the length of the baseline. Any improvement of the ‘image quality’ only affects the sensitivity.

Adaptive optics and interferometry





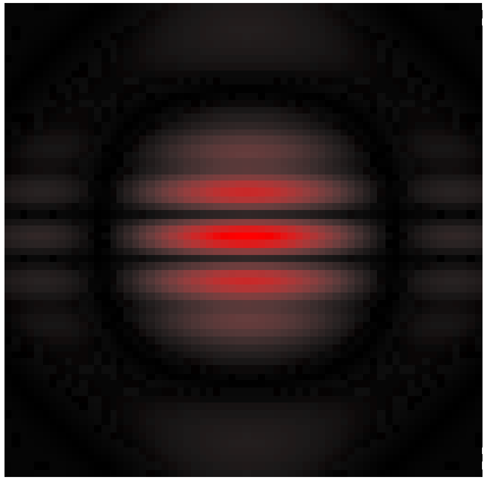
- Turbulences cause speckle pattern in individual telescope
- ‘Fishing’ for intensity with monomode fibers or using an area detector both loses sensitivity
- Perfect Airy disk has all aberrations removed, except for piston

Calar Alto 3.5m telescope
MPIA Heidelberg

(Movie with real data)

Fringe tracking

- Remaining atmospheric piston causes fringe wobble
  ⇒ exposure time limited to some 10msec depending on λ
- Solution:
  Bright guide star for fringe tracking
  Integrate fringes on science object
- Concept similar to Adaptive Optics
- Note: Individual Telescopes can observe faint stars without AO,
  Interferometers cannot go faint without a fringe tracker!

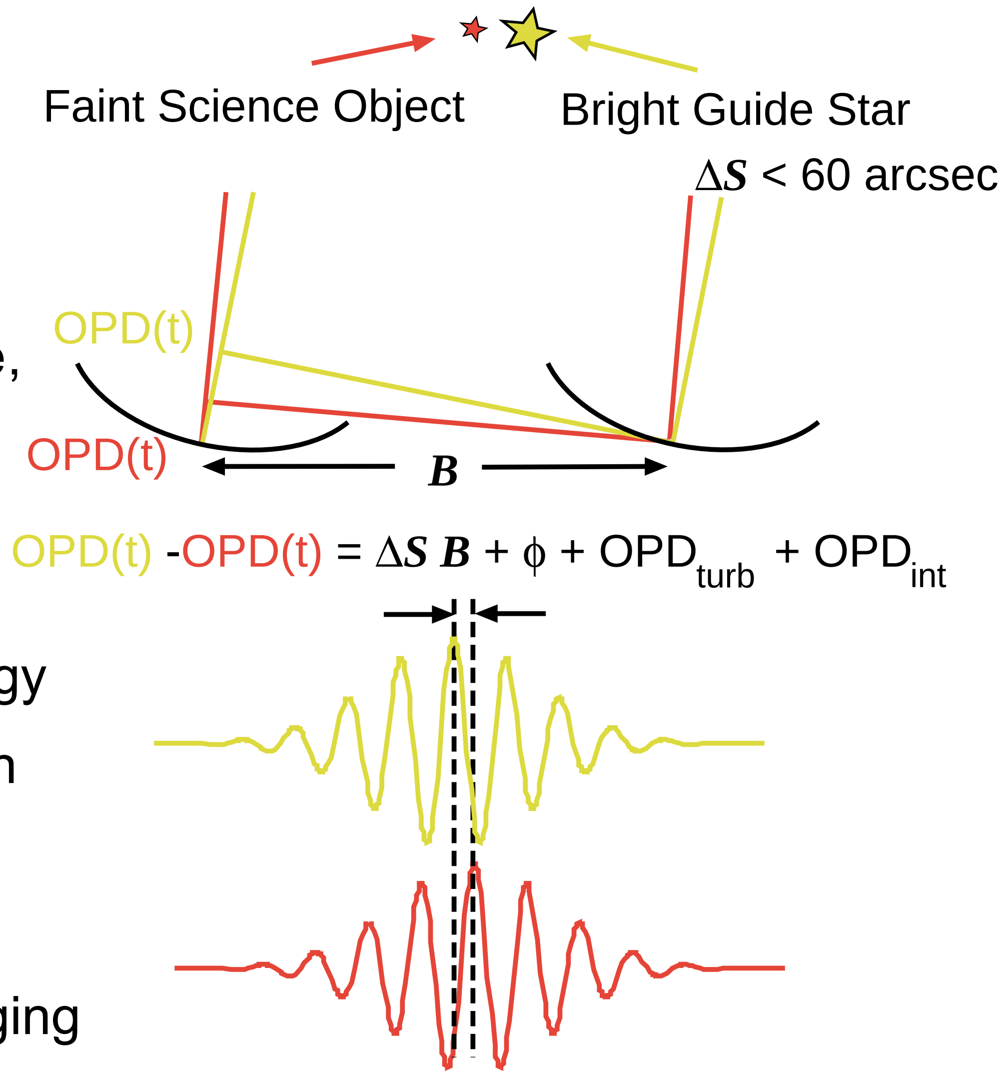


(Movie showing fringe wobble)

Spatial fringe pattern
(multi-axial beam combination)

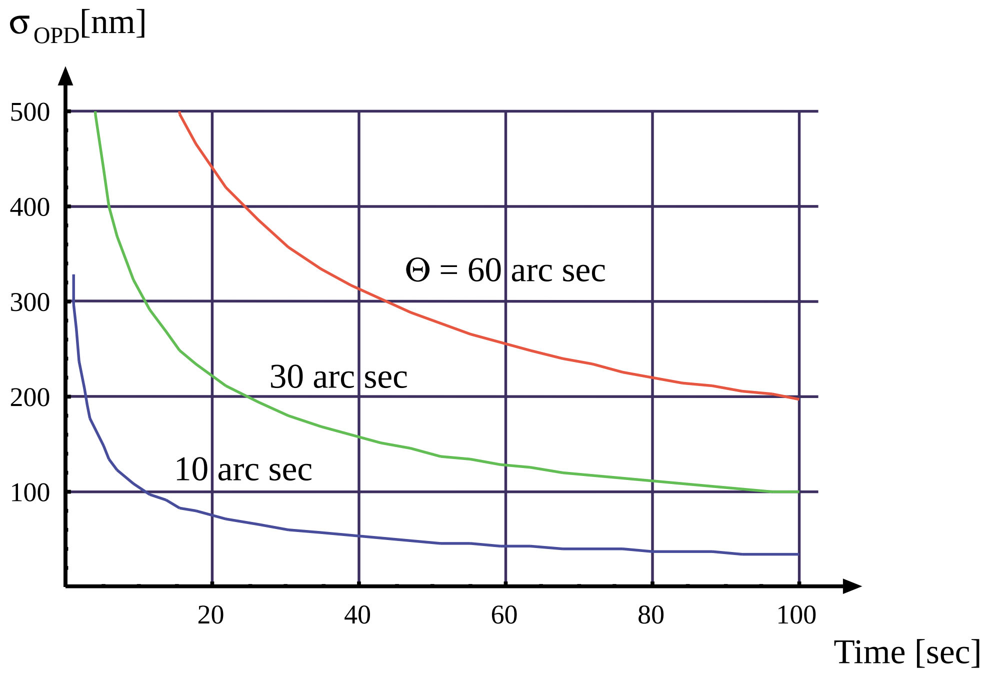
PRIMA – the VLTI dual feed facility

- VLTI field of view 2 arcsec
- Coudé focus (in UTs and ATs) field of view 2 arcmin
- PRIMA picks two stars in the Coudé, feeds it into the Delay Lines and produces the fringes in the VLTI Laboratory
- OPD_{int} measured with laser metrology
- OPD_{turb} averaged by long integration
- $\Delta S\ B + \phi$ determined by interferometric instruments
- ΔS gives the astrometry, ϕ the imaging



Isoplanatic angle

- The rms OPD error is reduced to <200nm even if the separation is 1 arcmin
- After 30min the error is small enough to allow for 10 μarcsec astrometry
- Even individual exposures of ~10sec have ~100 more signal and increase the limiting magnitude by 5



Closure phase

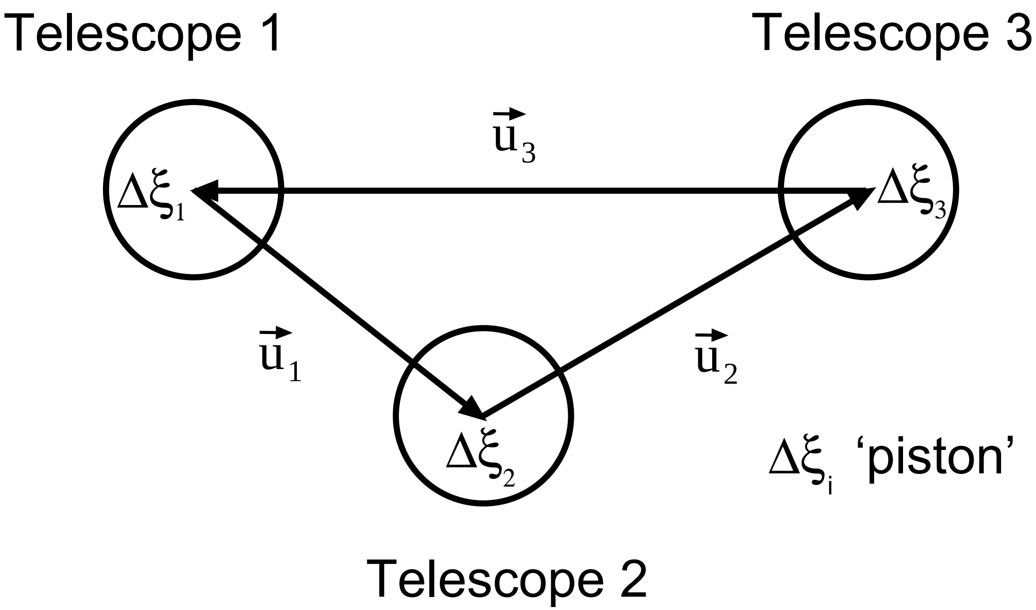
- In the sum of the three phases the random fluctuation is eliminated:

  $\psi_1 (u_1) = \phi_1 (u_1) + \Delta\xi_1 - \Delta\xi_2$

  $\psi_2 (u_2) = \phi_2 (u_2) + \Delta\xi_2 - \Delta\xi_3$

  $\psi_3 (u_3) = \phi_3 (u_3) + \Delta\xi_3 - \Delta\xi_1$

  $\psi_1 + \psi_2 + \psi_3 = \phi_1 + \phi_2 + \phi_3$
- Many baselines required to determine individual phases.
- The exposure time is limited, again by the individual fringe motion..



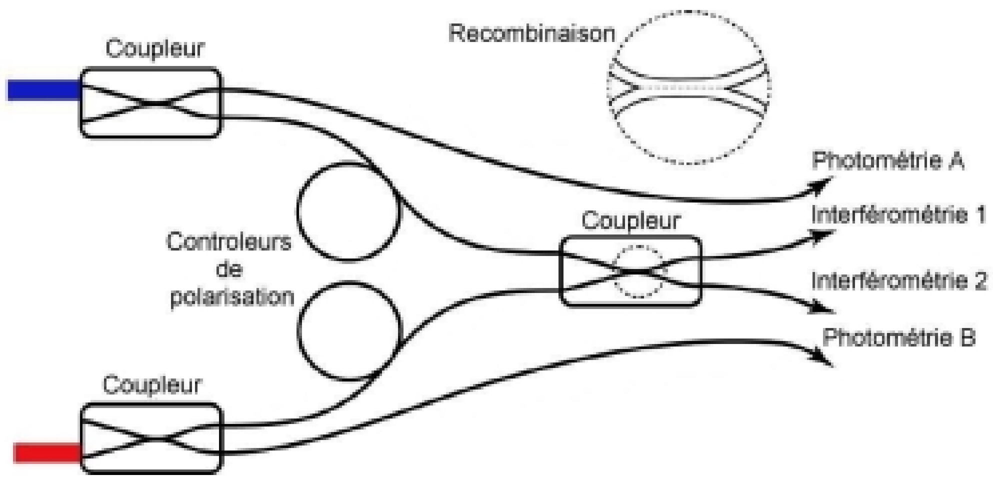
Summary atmospheric turbulence

- Adaptive Optics is required to increase the sensitivity
- With a perfectly corrected Airy disk, the sensitivity is limited by the fringe motion, reducing the exposure time to some 10msec
- Remaining fringe motion has to be removed by fringe tracker
- PRIMA allows to go as faint as K~20 with bright guide star (K~12-16 depending on required accuracy) within <1 arcmin

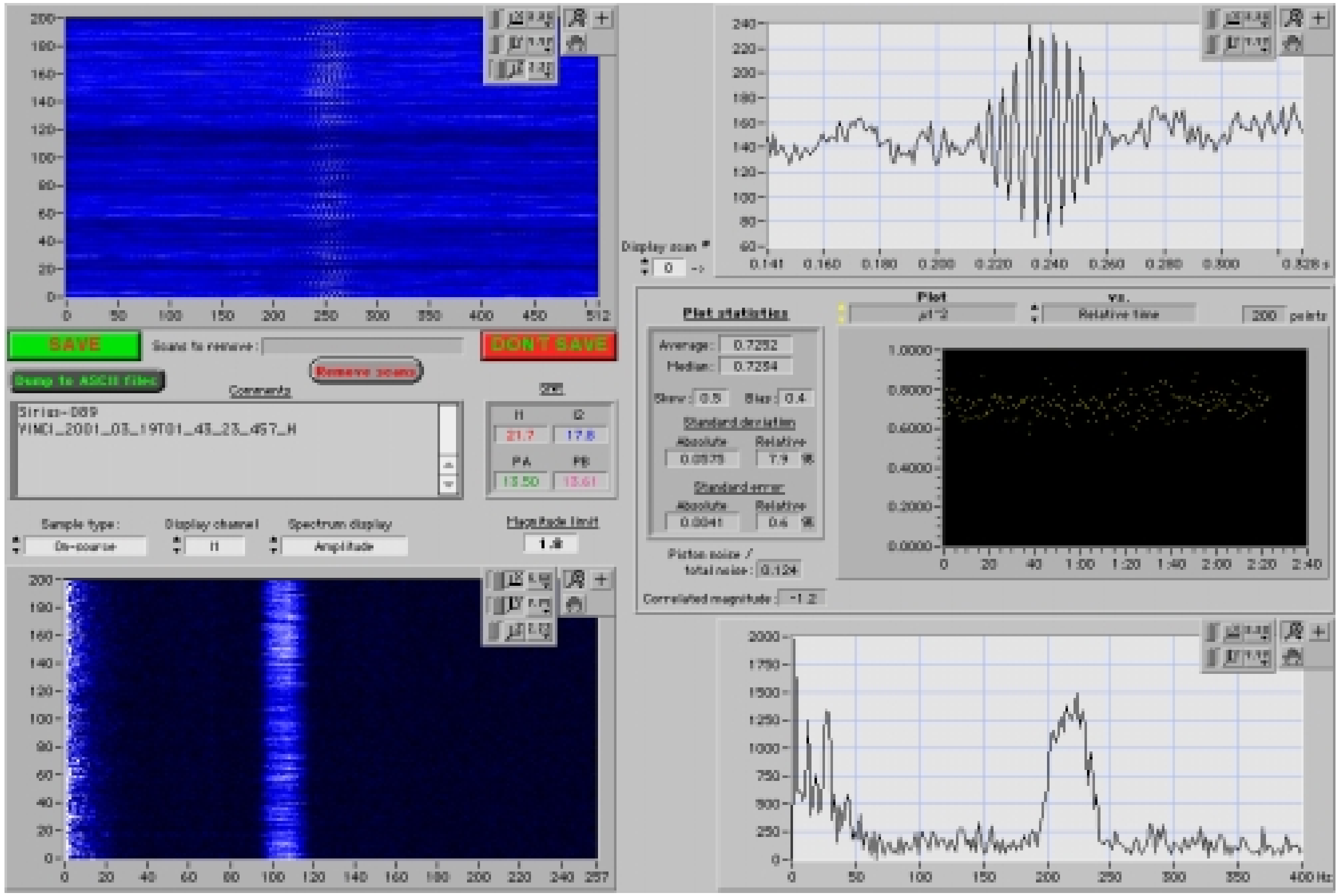
- Conclusion: Atmospheric turbulence can be controlled,
  FDR is passed $\Rightarrow$ VINCI

VINCI - Measurement principle

- Light is fed into two monomode fibers (Concept adopted from FLUOR at IOTA)
- Fiber coupler adds as beam combiner for coaxial beam combination
- Temporal fringe pattern measured in I1 and I2
- Modulation performed at fiber feed



Data analysis software from Obs. de Meudon

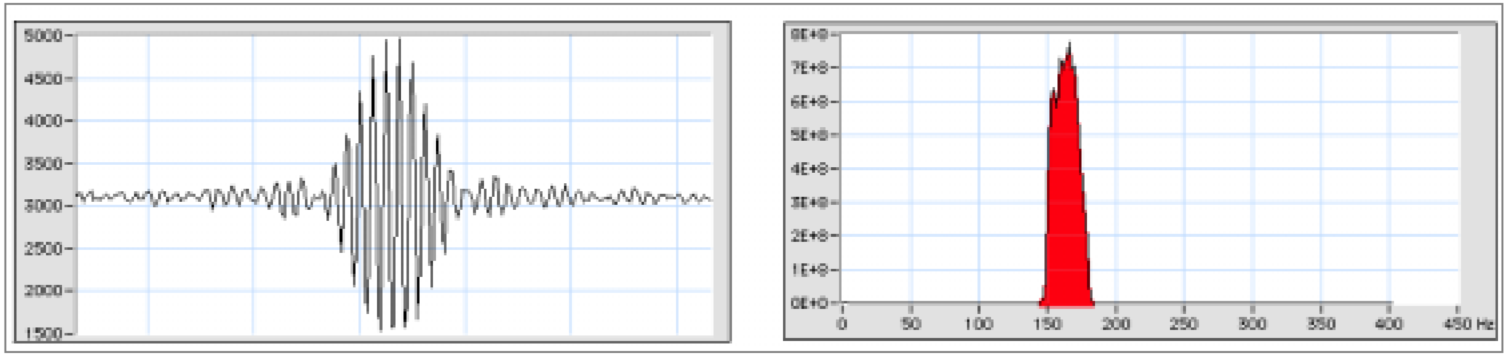


- Temporal fringe pattern left: 'waterfall display', right: individual scan

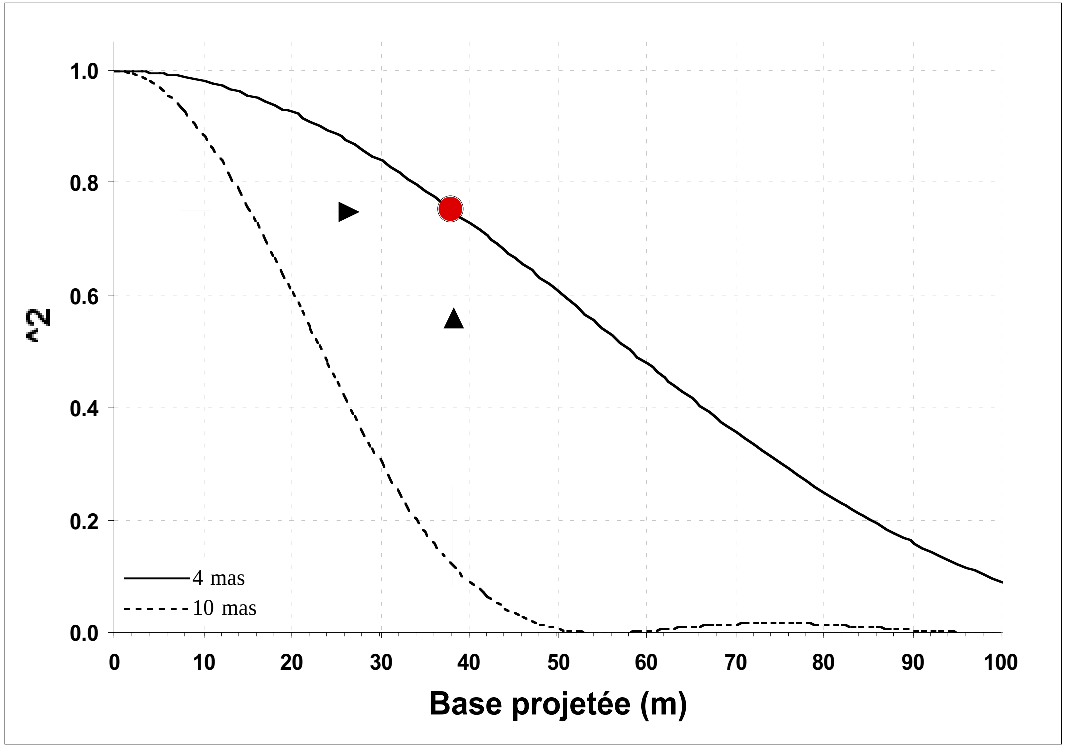
- Power spectrum with noisy DC term and K-band spectrum left: 'waterfall display', right: individual scan

Note: In the meantime, a similar package has been written for the ESO pipeline

Measurement of the Visibility function with VINCI



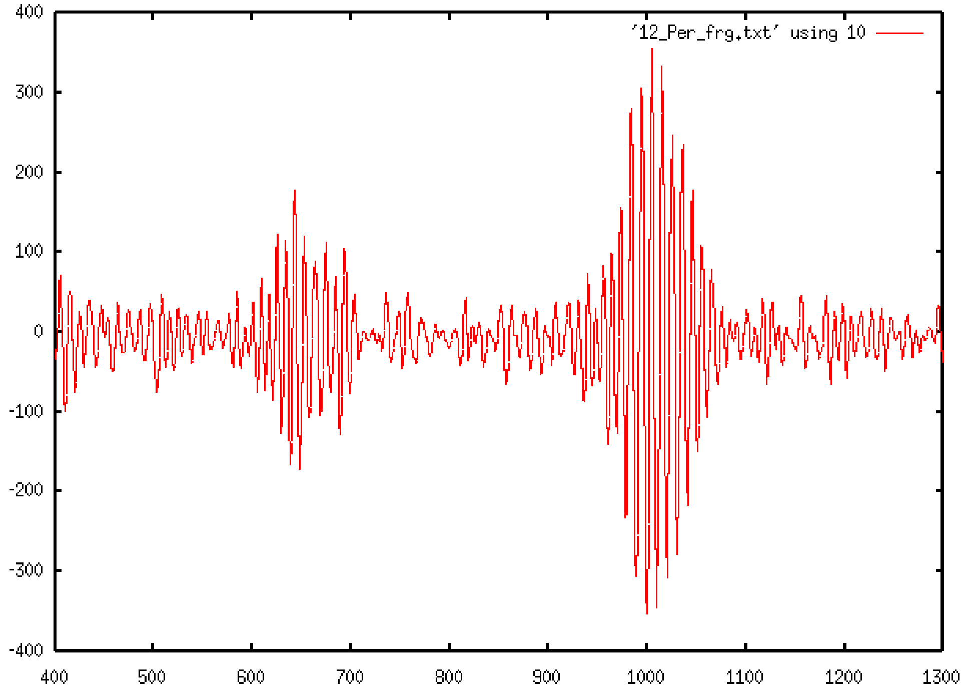
- The power spectrum is masked with the K-band spectrum
- The integrated power determines V^2 the square of the visibility



Binary observation in a co-axial fringe pattern

The two fringe pattern are completely separated
due to separation δ times baseline B > coherence length

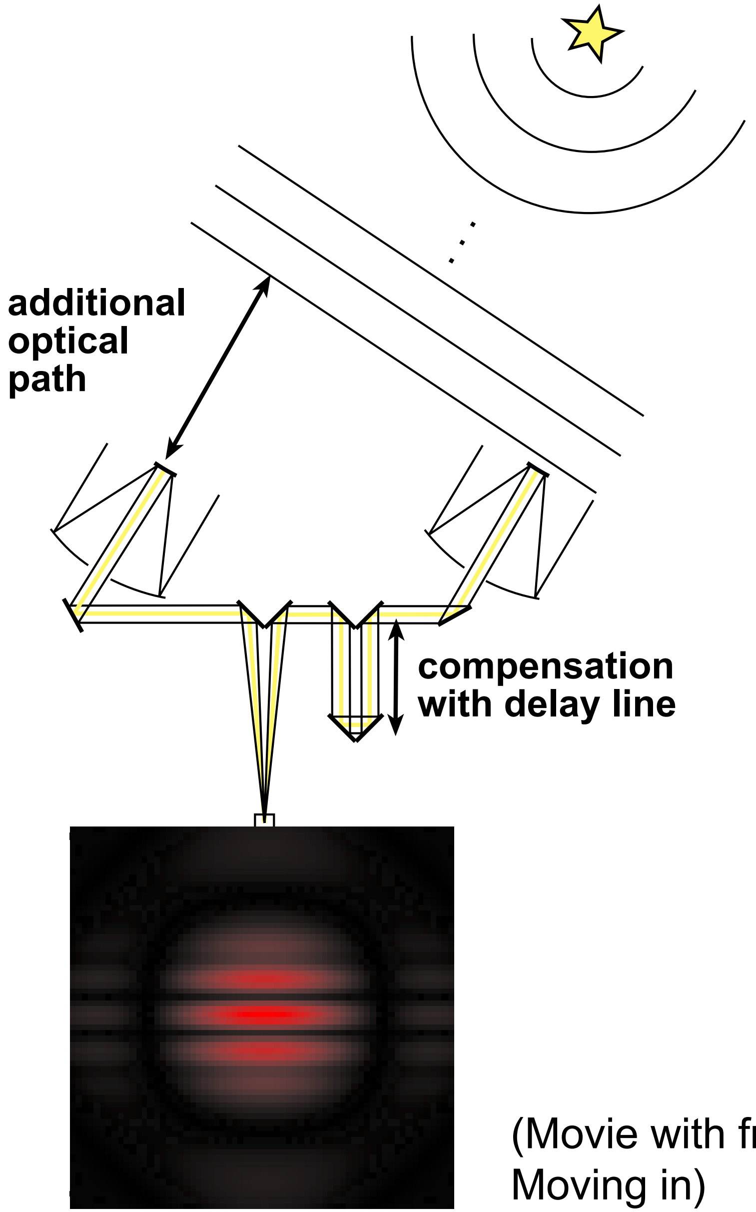
The separation is determined by the distance of the white light fringes,
not by the reduced contrast described by the visibility function!



12 Persei observed on Oct 9, 2001 with the CHARA Array,
K'-band, 330m baseline, separation 40 marcsec

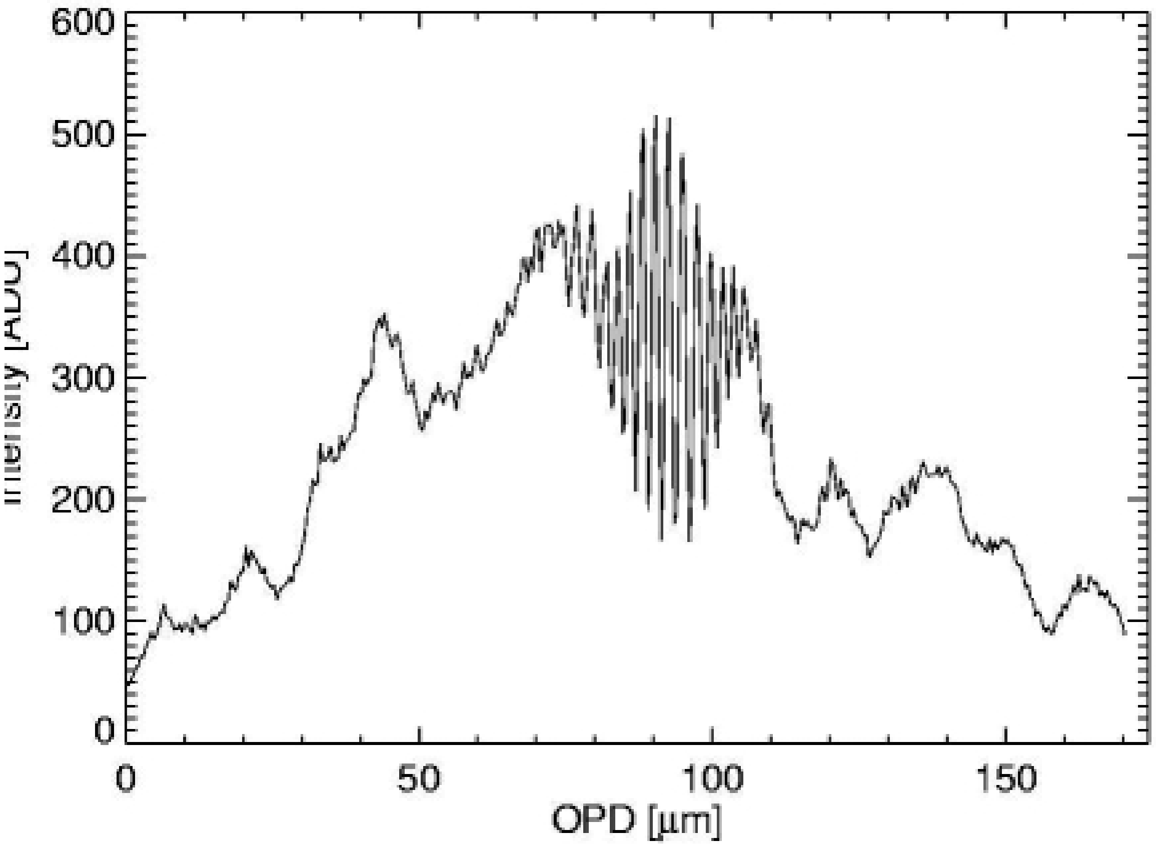
Finding fringes

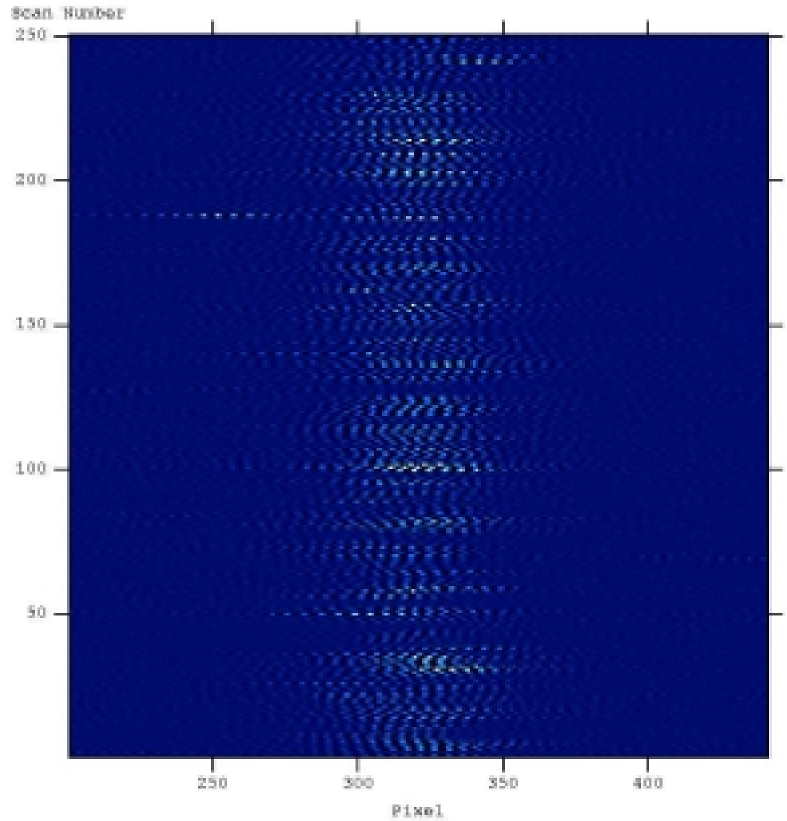
- Adjust star on fiber
- Follow trajectory with Delay Lines
- Scan starts, sweeping around calculated 0 OPD position (scanning 10mm takes about 5min)
- After first few observations calculate new OPD model
  ⇒ Fringes found within <1mm
- Observations executed by BOB



(Movie with fringes
Moving in)

First Fringes with the UTs

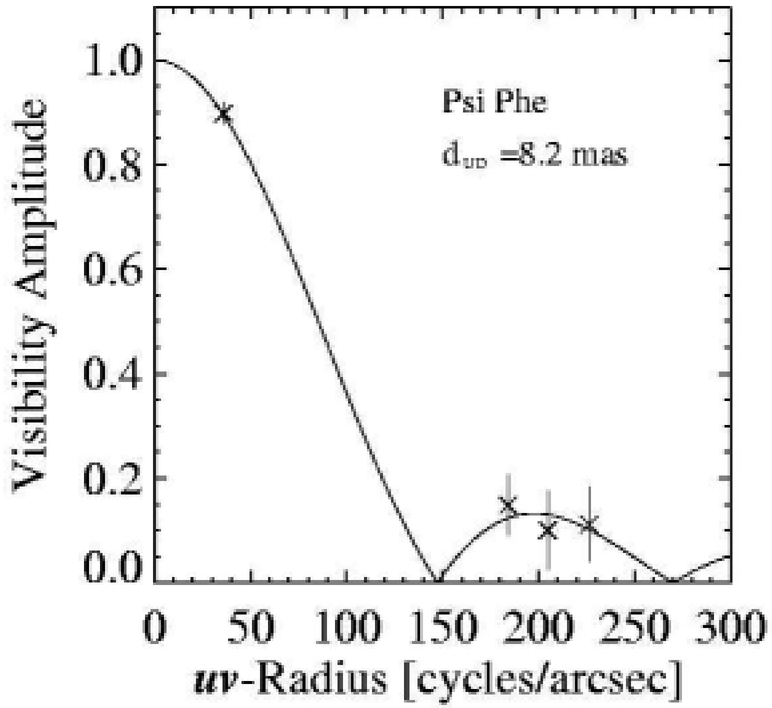




Achernard on Oct 30, 2001, at 1 am,
scan on the left chosen from 'waterfall' display on the right

The diameter of a red giant

- Psi Phoenicis observed with siderostats (baseline 16m), and with UT1 and UT3 (baseline 102m)
- Differences in projected baselines provide different baseline vectors
- Preliminary result for diameter: 8.21 marcsec



Conclusion

- Stellar interferometry is not (that) complicated
- Manifold of interferometer types is limited
- Measurement principles allow to go (rather) faint, large and detailed

- VLTI started working in its literal sense, as the

  Very Large Telescope Interferometer