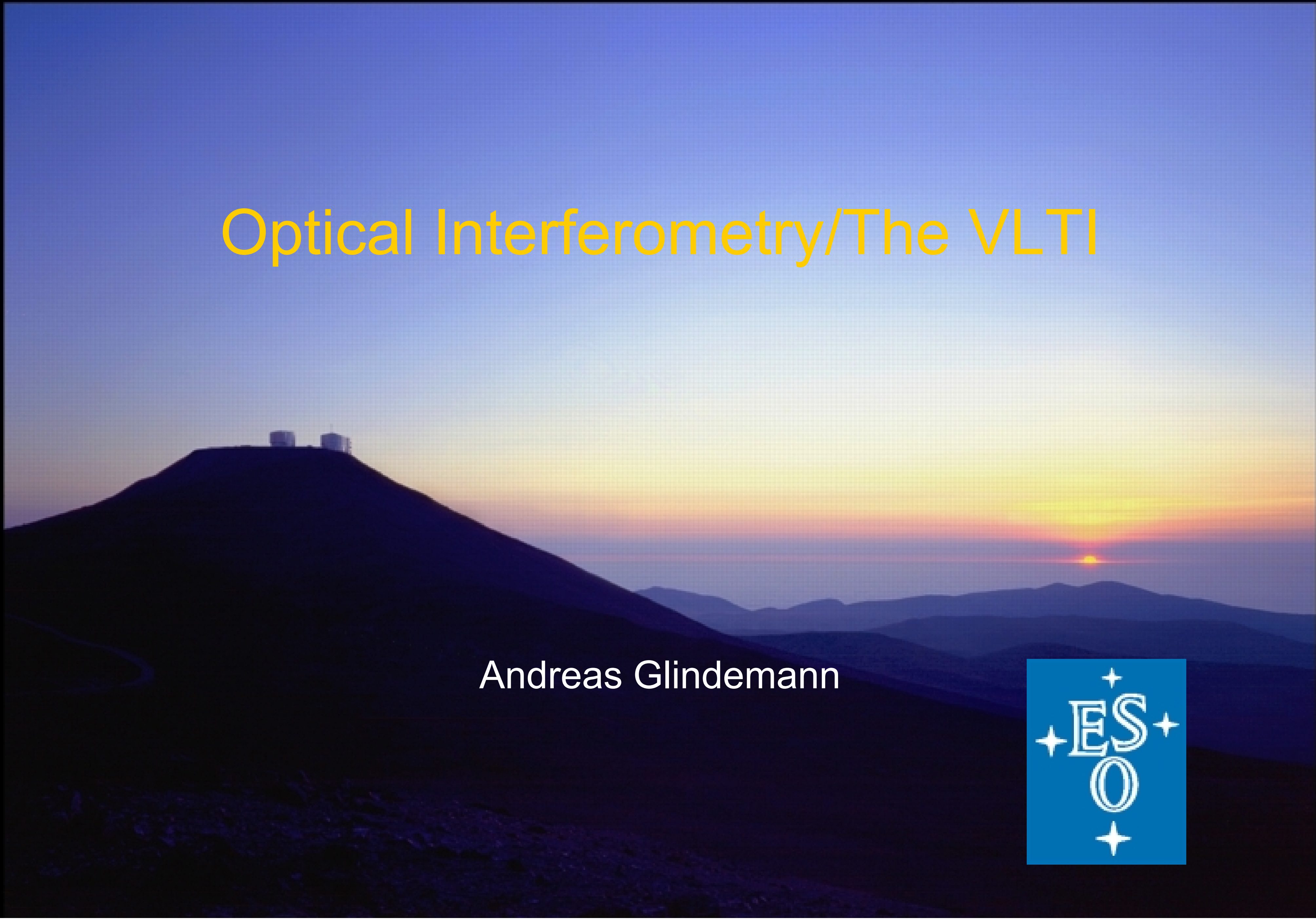
Optical Interferometry/The VLTI

Andreas Glindemann



Optical vs mm interferometry – a reminder

- mm (and Radio) interferometry:
  mm waves are first detected and amplified,
  then combined
  (heterodyne detection)
- Optical interferometry:
  Light waves are first combined,
  then the intensity is detected
  (Exception: 10μm heterodyne interferometer, ISI)
- Problems for heterodyne detection at lower wavelengths:
  - Number of photons
  - Atmospheric turbulence

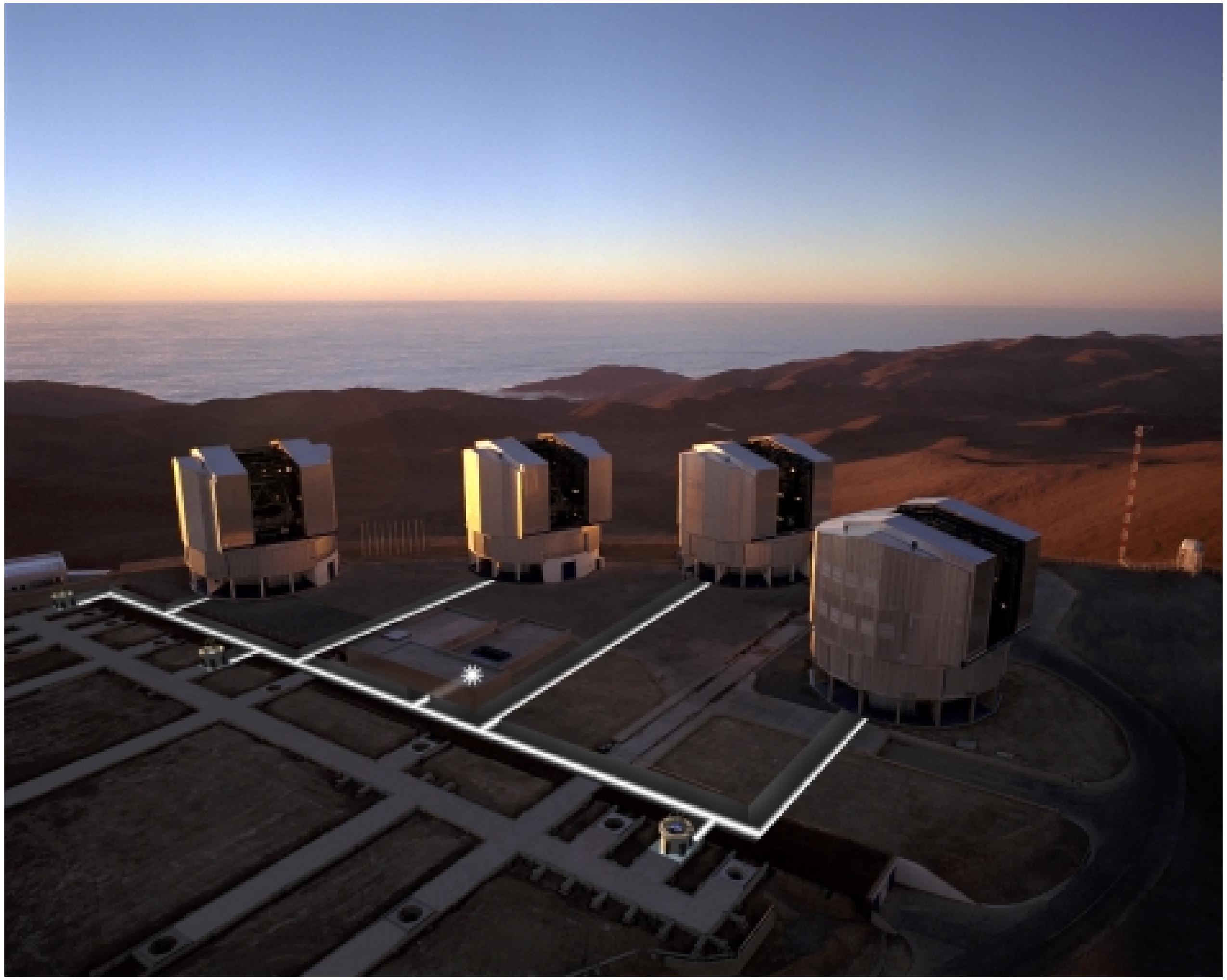
Outline

1. Introduction: Basic requirements for an optical interferometer
2. Atmospheric turbulence:
   - Basic characteristics
   - What does AO do for interferometry
   - Fringe tracking
3. The visibility function
4. Types of Interferometers: Michelson and Fizeau, Homothetic mapping, measurement of the visibility
5. VINCI
6. Interferometric imaging

Outlook, Conclusions

The VLT Interferometer

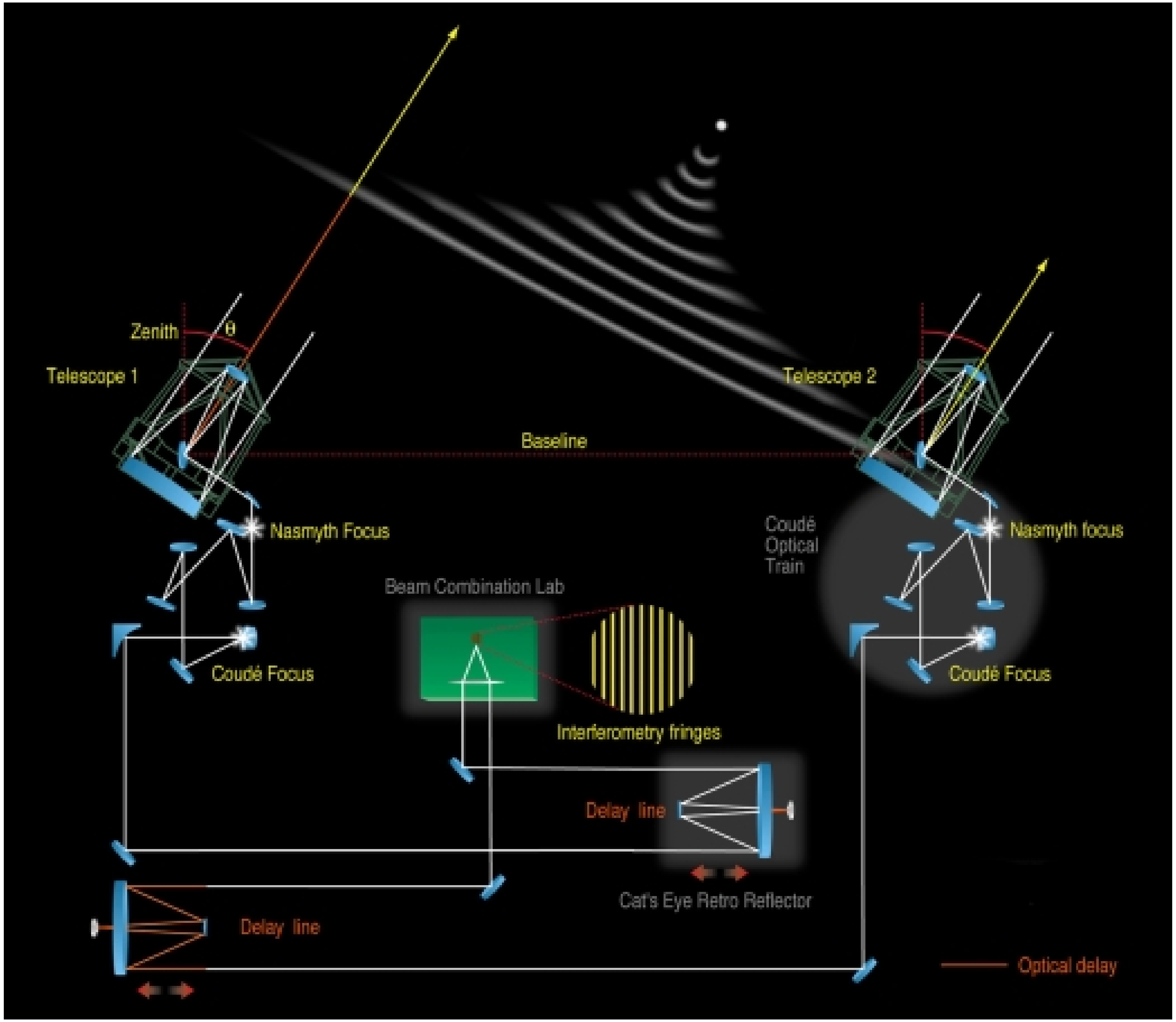
- Four 8-m Unit Telescopes
  Max. Baseline 130m
- Three 1.8-m Auxiliary Telescopes
  Baselines 8 – 200m
- Near IR to MIR (angular resolution 1-20 milli arcsec)
- Dual Feed Facility
- Excellent uv coverage



Optical Layout and Sub-systems

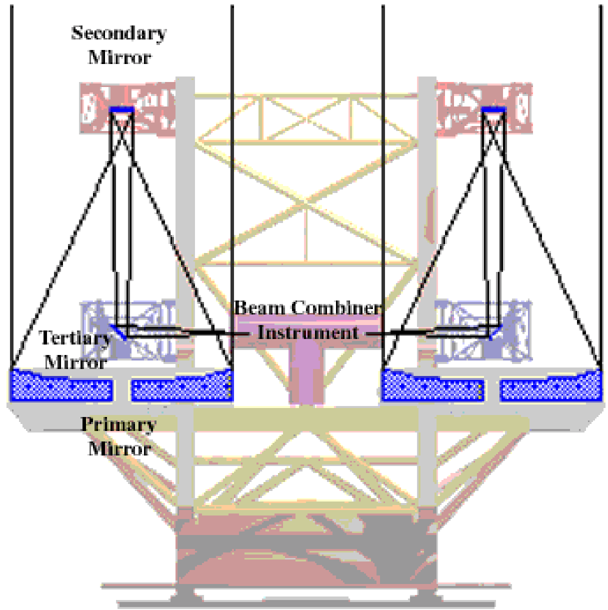
- Field of view in Coudé focus: 2 arcmin
- Field of view in VLTI lab: 2 arcsec
- Fringe Tracker
- Adaptive optics with 60 actuator DM

Strehl >50% in K
Guide Star $m_V < 16$



Large Binocular Telescope (LBT)

- The LBT consists of two 8.4m mirrors on a common mount (!)
  - Baseline 14.4 m
  - AO for >70% Strehl (K band)
  - Angular resolution 17mas (at 2μm)
- The LBT is a joint project of the
  - University of Arizona + others
  - MPG + others
  - Italian community (Arcetri etc.)



Error budget

Error budget quantified in visibility (contrast) loss $\Delta V/V$ at 2.2μm

- Largest contributor is atmospheric turbulence:
  - $\Delta V/V = 24\%$ (residual of adaptive optics correction)
  - $\Delta V/V = 2\%$ (with fringe tracker)
- Optical aberrations contribute $\Delta V/V = 6\%$
- Differential incident angles and/or coatings on mirrors affect polarisation and cause $\Delta V/V = 6\%$
- Unequal beam intensities $\Delta V/V = 1 - 2\,(\sqrt{I_1} \times \sqrt{I_2})/(I_1 + I_2)$

  The exact figures depend on the beam combination scheme

Total loss: $\Delta V/V \sim 40\%$

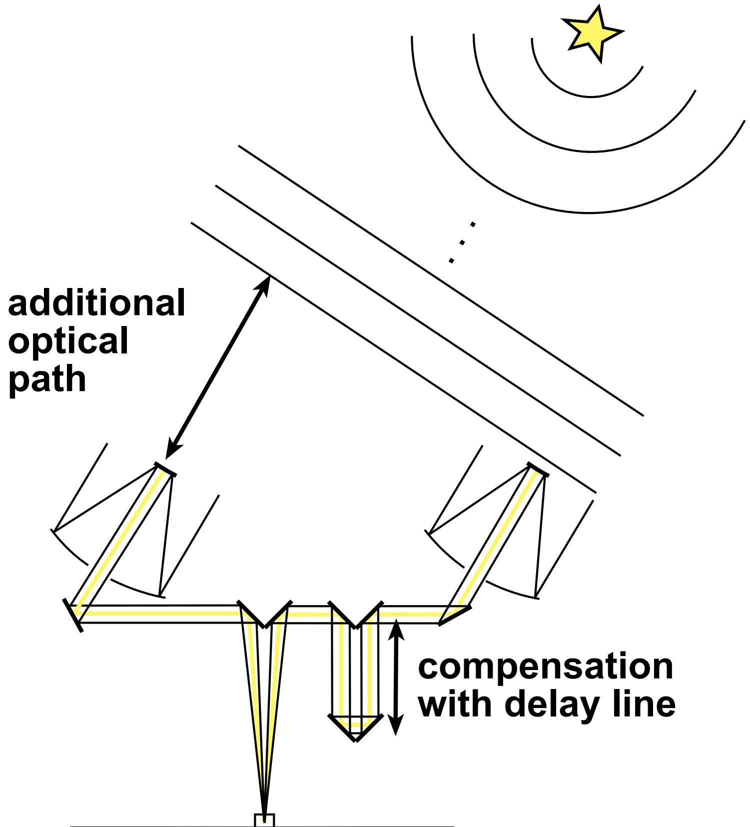
Delay Line Tunnel

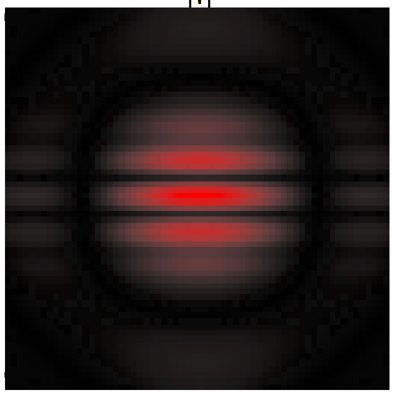
- ‘Wine cellar approach’
- Flatness of rails better than 25μm over 65m.
- Cat's Eyes v_{max} = 0.5m/sec
- Beam tilt < 1.5 arcsec
- Absolute position accuracy 30μm
- Rel. position error about 20nm
- Optical system with VCM on a piezo mount
  - Reimaging of telescope pupil
  - Fast adjustements of OPL

Video at http://www.eso.org/outreach/press-rel/pr-2001/phot-04-01.html

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 <100µm
- Observations executed by BOB

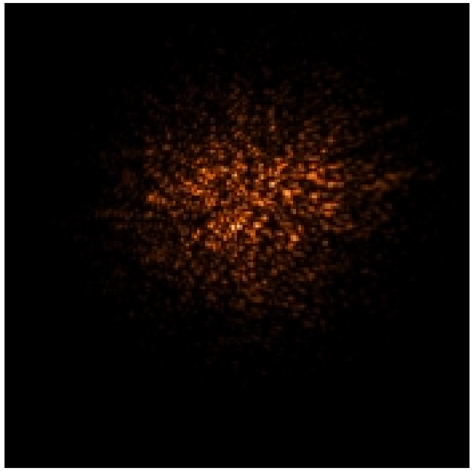


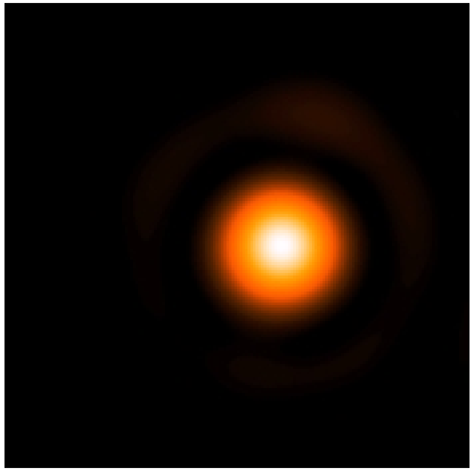


(Movie with fringes moving in)

2. Atmospheric turbulence

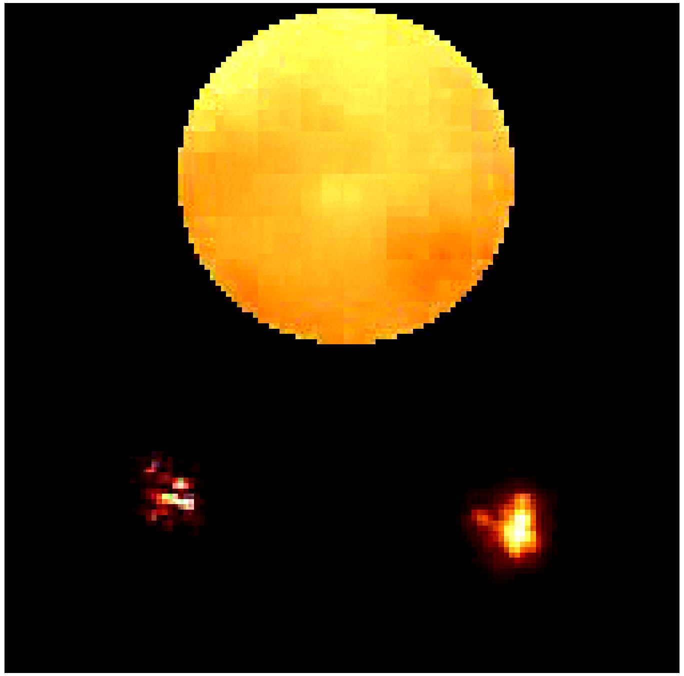
Images in single telescopes show more (small λ) or less (long λ) speckle.



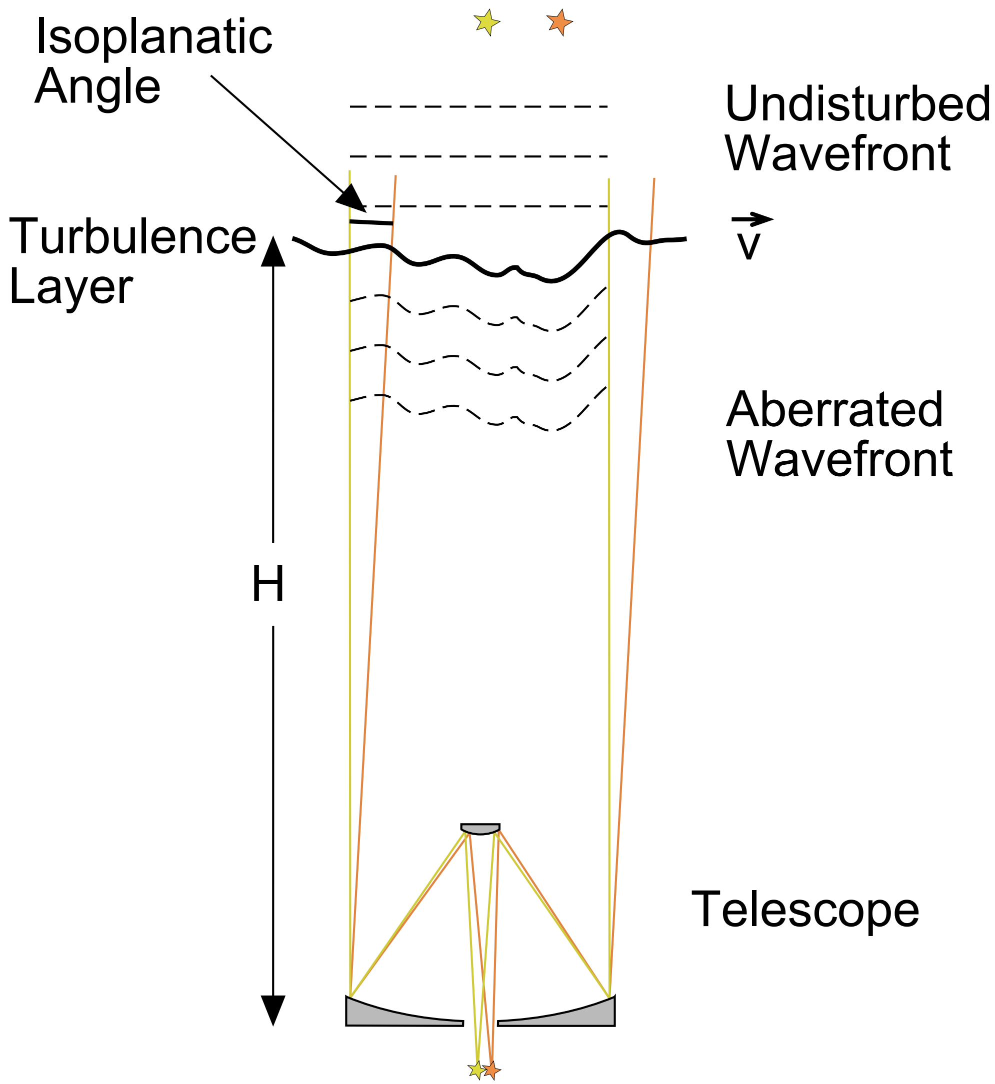


Seeing is the temporal average of the speckle pattern

Fried Parameter, r_0, is the diameter of a ‘flat’ part of the turbulence. r_0 is proportional to $\lambda^{6/5}$

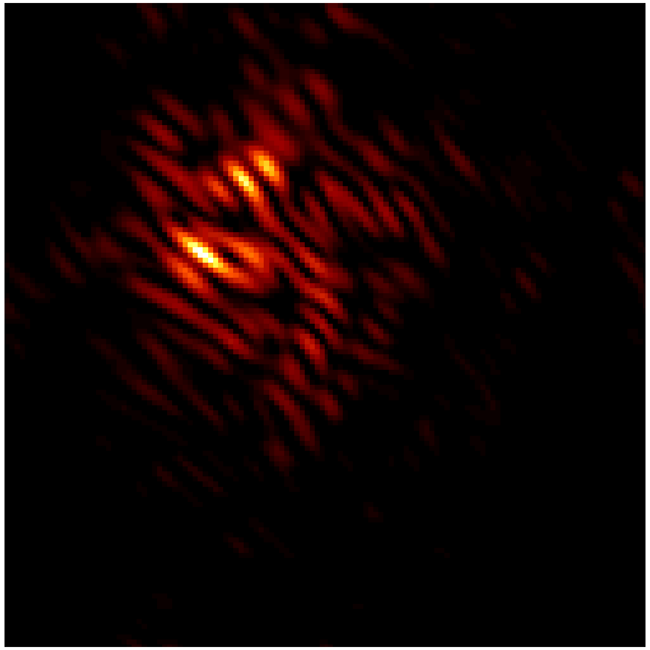


Isoplanatic Angle and Coherence Time



- Isoplanatic angle
  $\theta \sim r_0/H$, $H \sim 10$km
- Coherence time
  $\tau \sim r_0/v$, $v \sim 30$m/sec
- $\lambda = 2.2\mu$m with $r_0 = 90$cm:
  $\theta \sim 18''$, $\tau \sim 30$msec

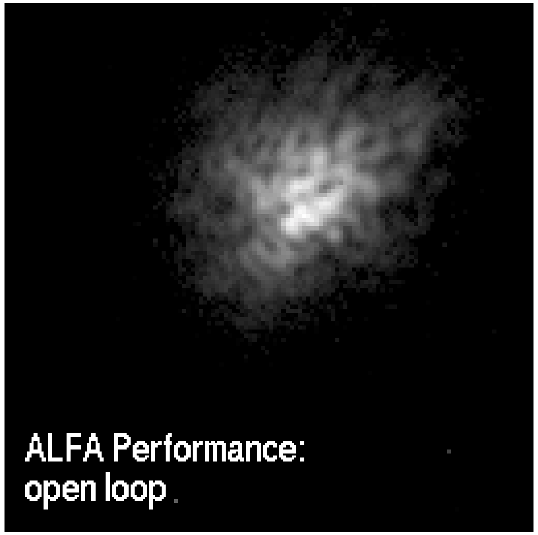
Speckle and fringes

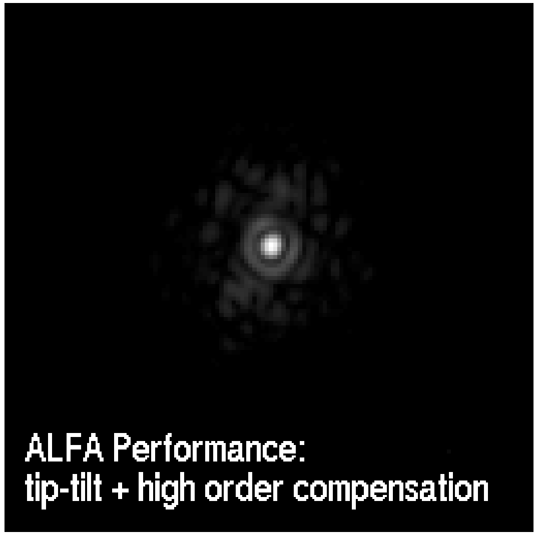


Spatial fringe pattern of 2 UTs at 2.2 μm in 0.5” seeing

- 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

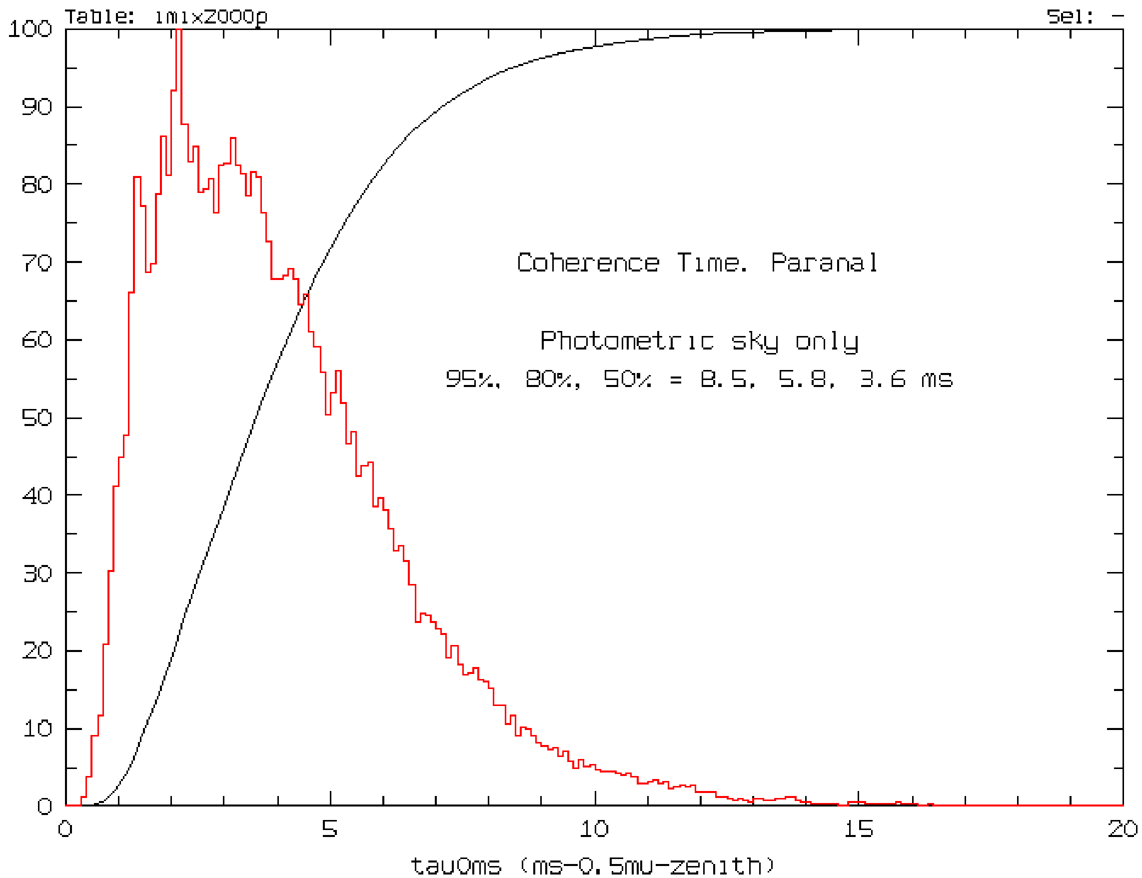
Calar Alto 3.5m telescope
MPIA Heidelberg

(Movie with real data)

Atmospheric Coherence Time

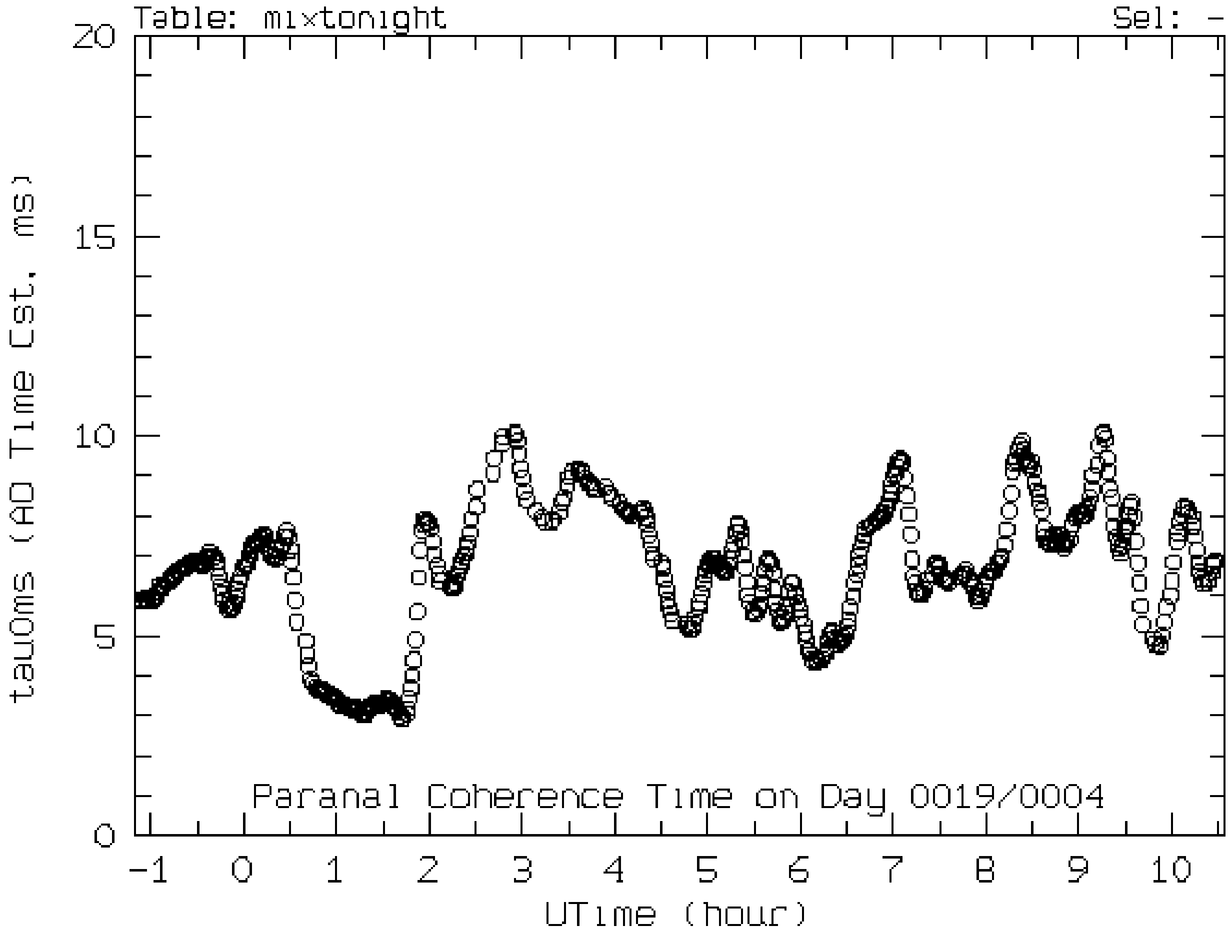
Statistics for 2000 from DIMM seeing measurements

Median value 22 msec at 2.2μm



http://www.eso.org/gen-fac/pubs/astclim/paranal/seeing/adaptive-optics/

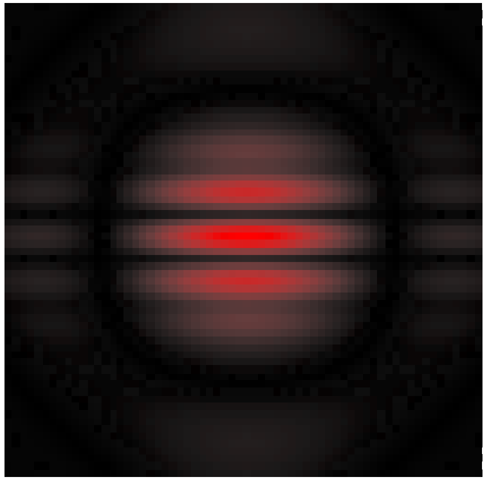
Atmospheric Coherence Time (II)



Daily variations are easily ±10msec

Fringe tracking

- Remaining atmospheric piston causes fringe wobble
  $\Rightarrow$ 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!

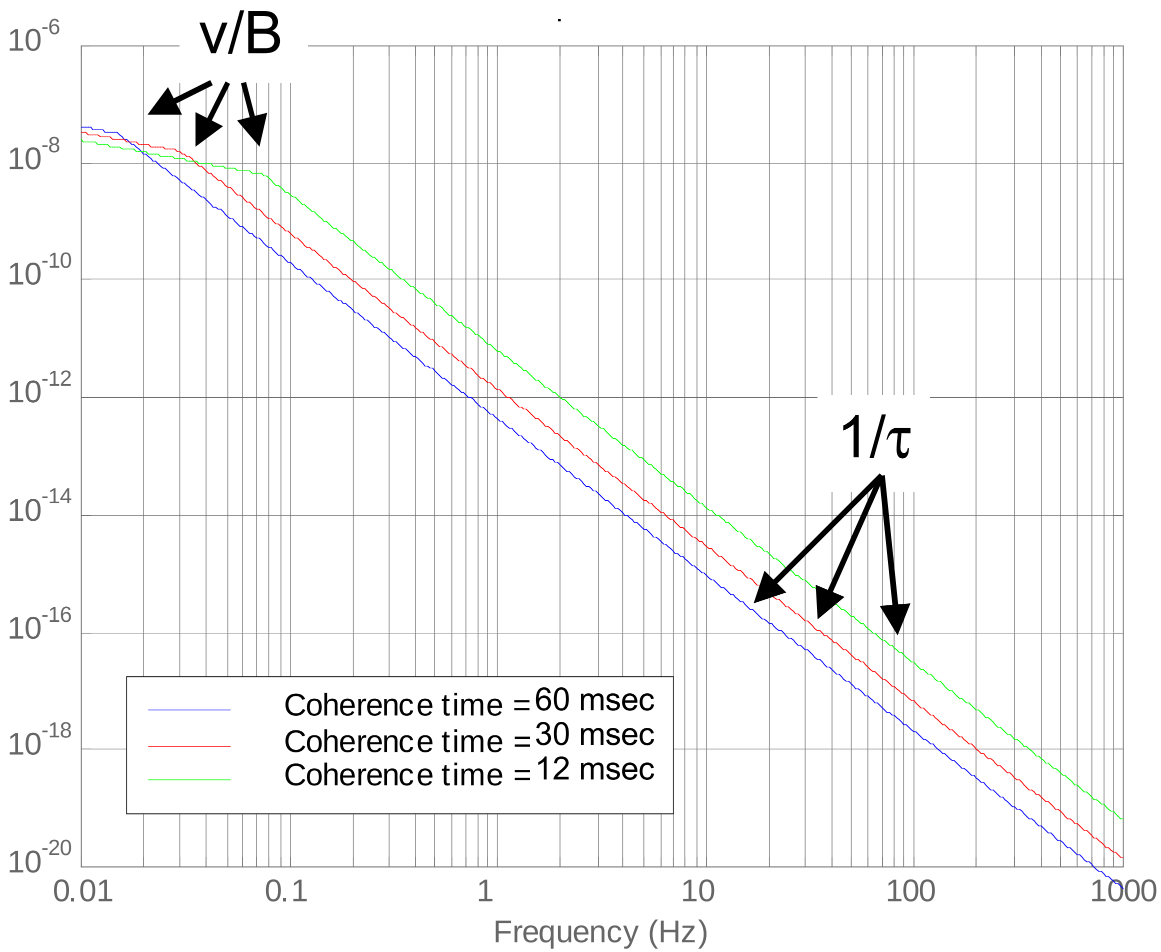


(Movie showing fringe wobble)

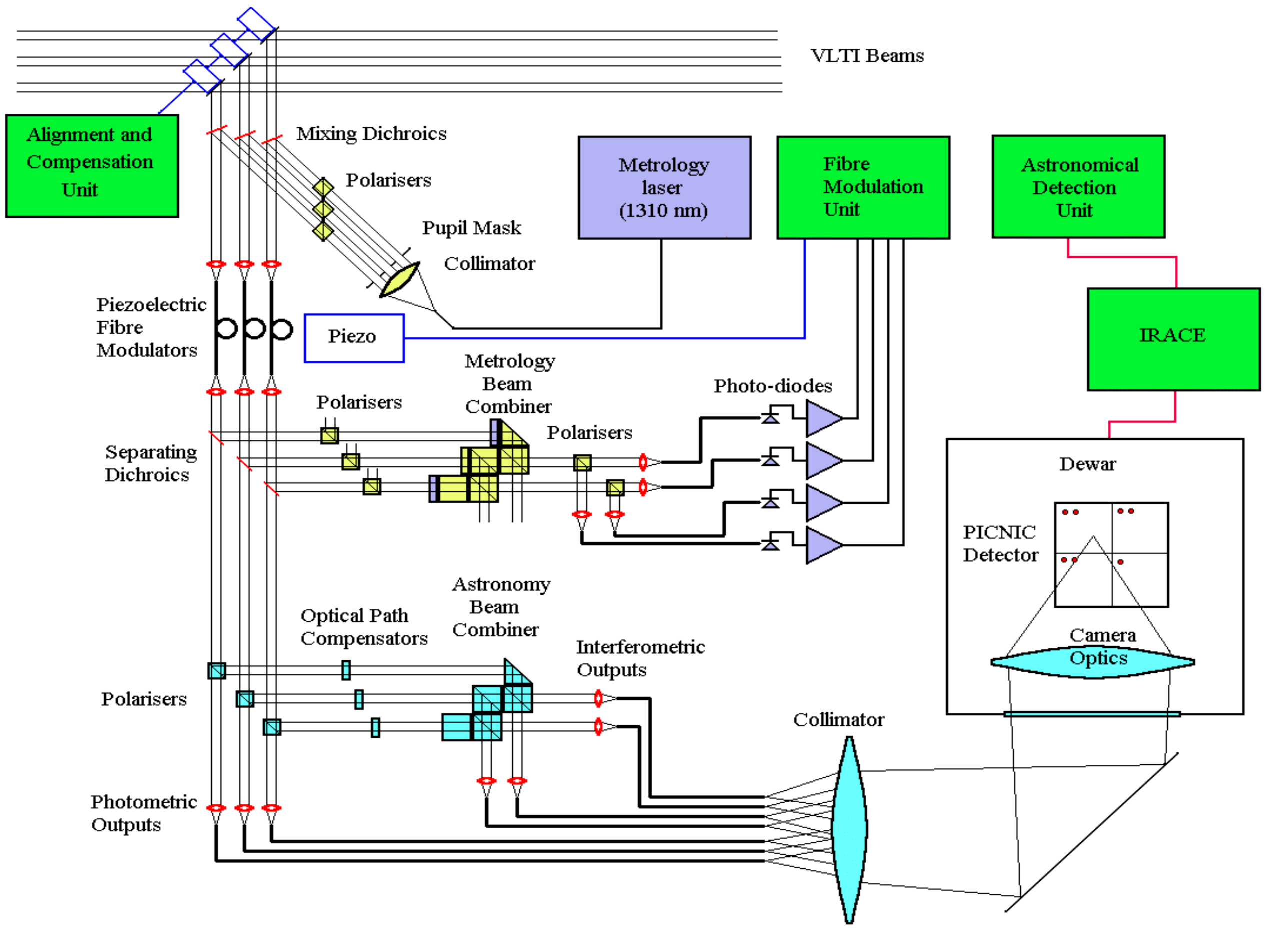
Spatial fringe pattern
(multi-axial beam combination)

Atmospheric OPD Noise

- Power spectrum of OPD variations
- τ is defined such that remaining OPD variations are smaller than ~150nm (*i.e.* ΔV/V < 10%)
- Uncorrected OPD stroke is ~50μm



FINITO – Schematic Layout



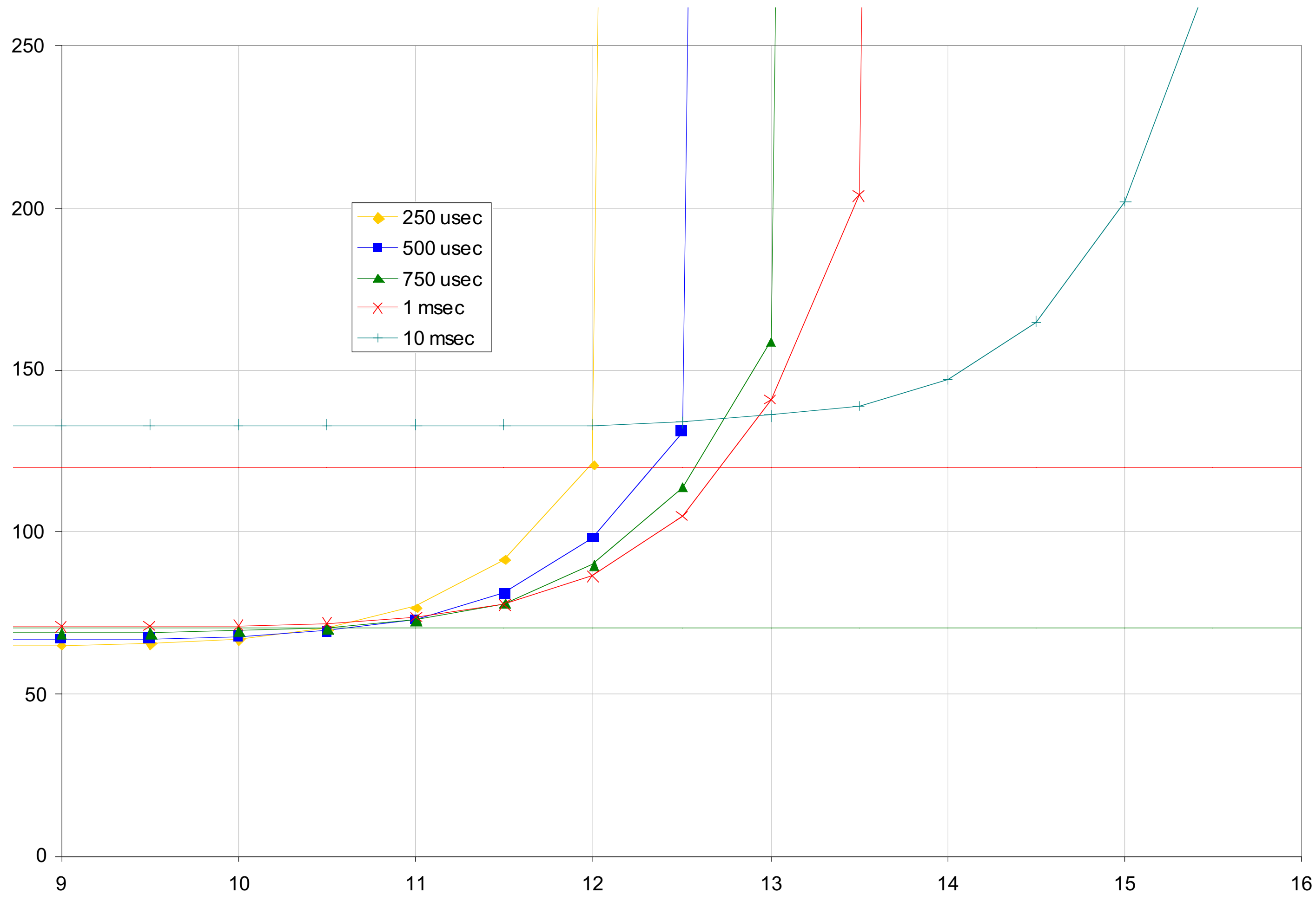
FINITO – Fringe-Tracking Instrument of Nice and Torino

FINITO – Expected Performance

Residual OPD

OPD = 75nm corresponds to $\Delta V/V$ =2%

τ = 50 msec at 2.2μm

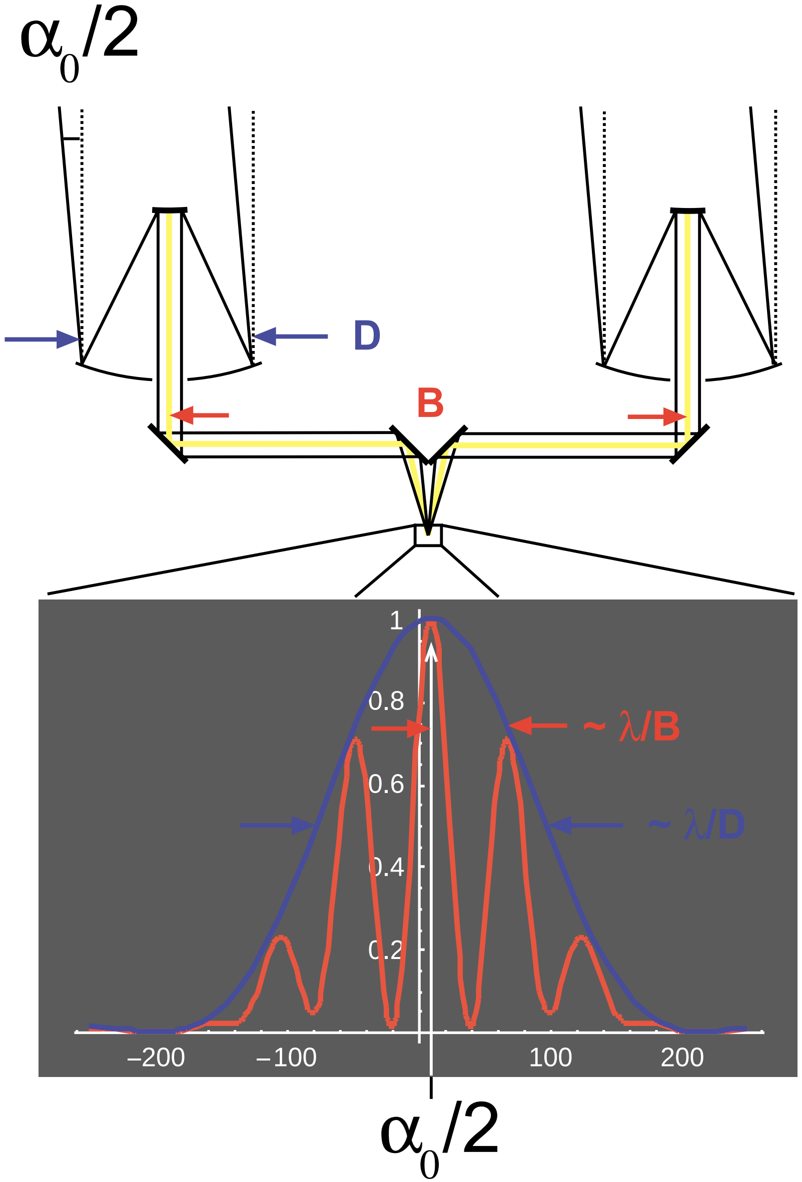


H Magnitude

Summary atmospheric turbulence

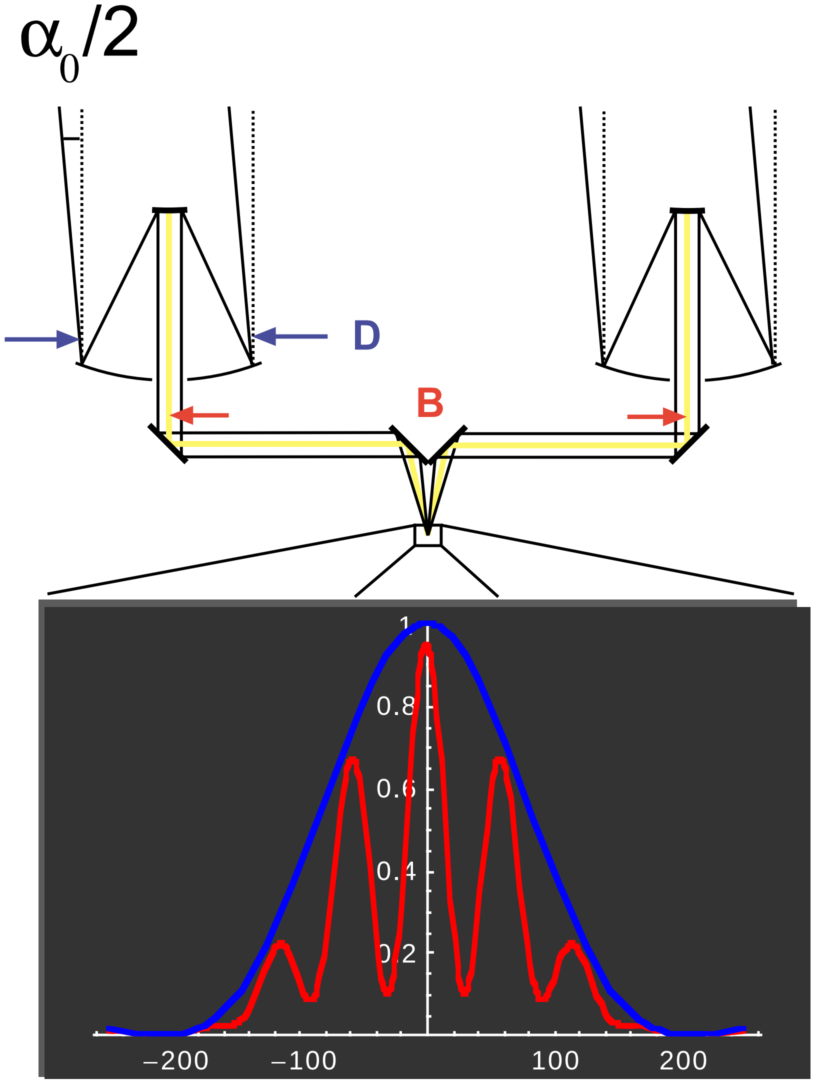
- Adaptive Optics is required to increase the sensitivity
- With a perfectly corrected Airy disk, the sensitivity is limited by the fringe motion, reducing the exposure time to some 10msec
- Remaining fringe motion has to be removed by fringe tracker

3. Our measurable: the visibility function

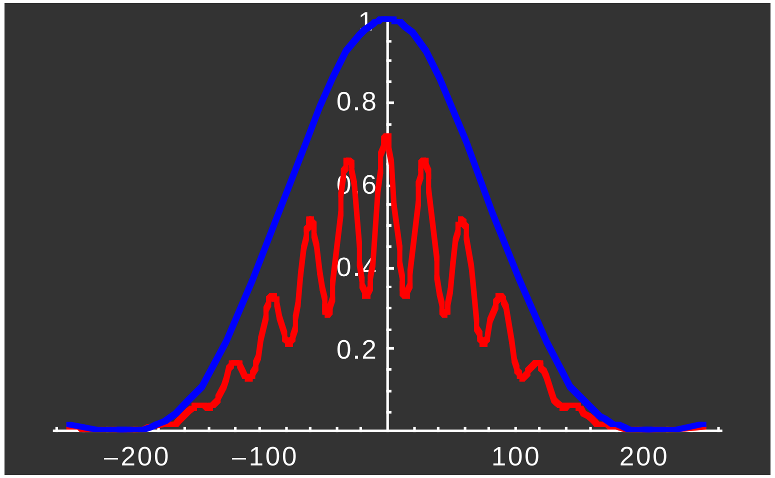


- Stellar source with angular size α_0
- Add fringe patterns (i.e. intensities) between $\pm\alpha_0/2$

3. Our measurable: the visibility function



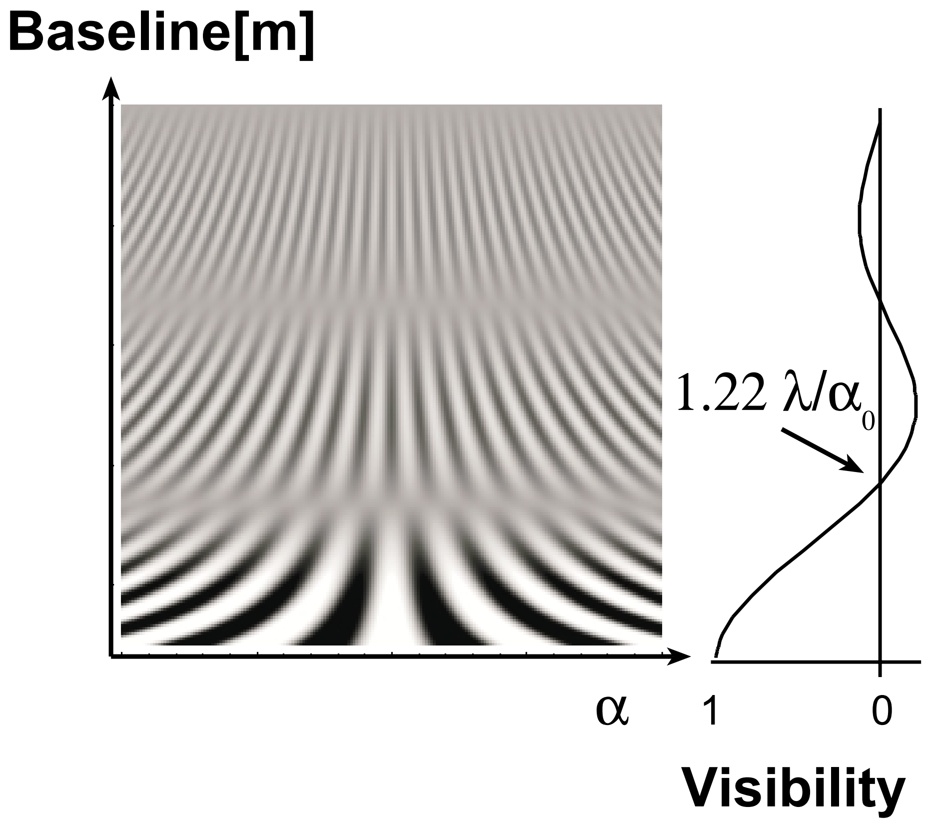
B_1 and α_0 (Movies used for illustration)



$B_2 > B_1$ 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 $I(\alpha) = Circ(\alpha/\alpha_0)$ $Vis(B) = Besinc(\pi\alpha_0 B/\lambda)$

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.

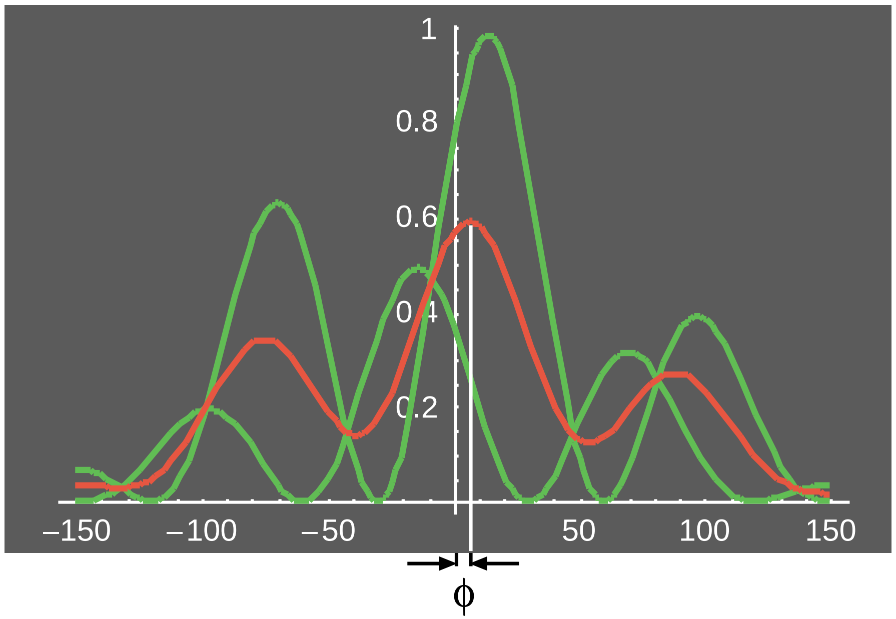
- γ is the degree of spatial and temporal coherence, also called the visibility
- γ is a function of $u_1 - u_2$, the difference vector
- for a point source the spatial coherence is 1, and
  the contrast is determined by the temporal coherence

Phase of the 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 binaries, spots on the stellar surface, dense clusters etc.

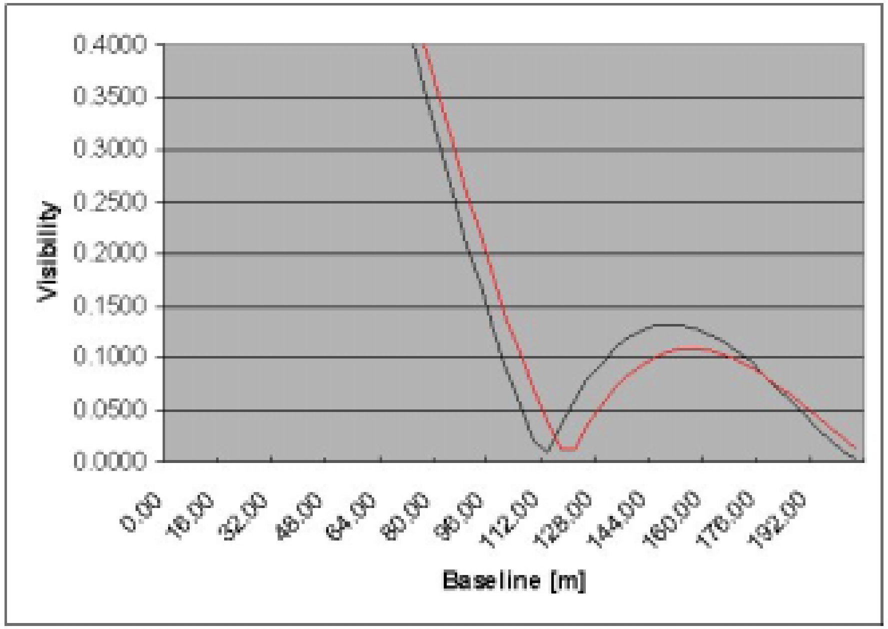
The phase is vital for imaging!

Note: This is not the phase of the electromagnetic wave!

Examples of visibility functions

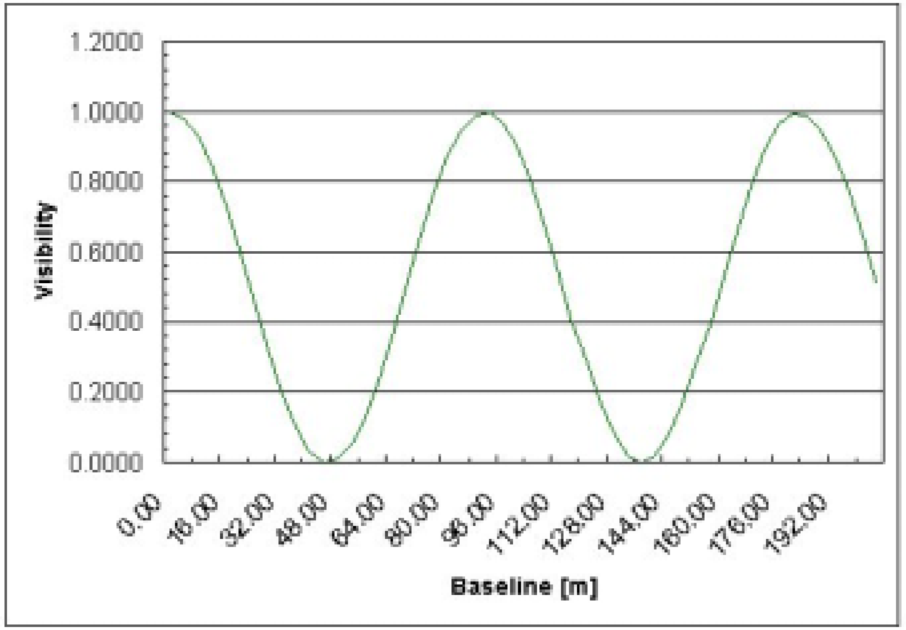
Uniform disk + limb darkening:

(UD diameter 5 milliarcsec)



Binary star:

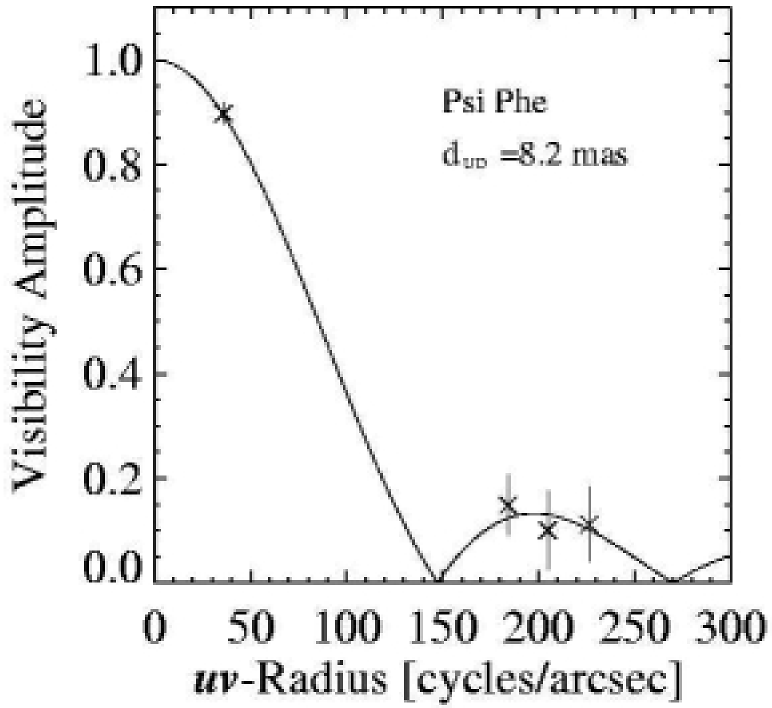
(separation 5 milliarcsec)



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

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

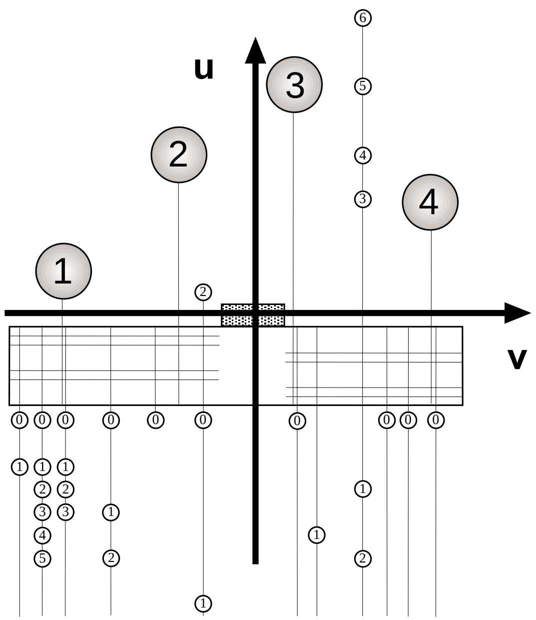


Interferometric imaging

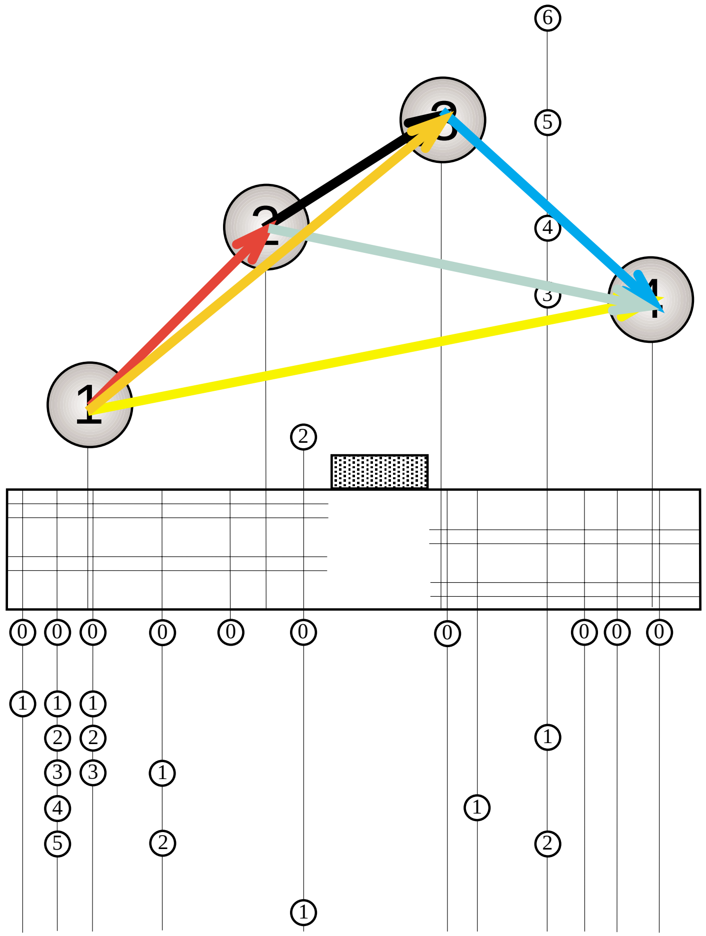
Image intensity $I_{im}(\alpha) = \mathcal{F}(\Gamma(u_1 - u_2))$, with $u_1 - u_2$ = Baseline vector

Fill factor in the uv plane determines ‘smoothness’ of the image

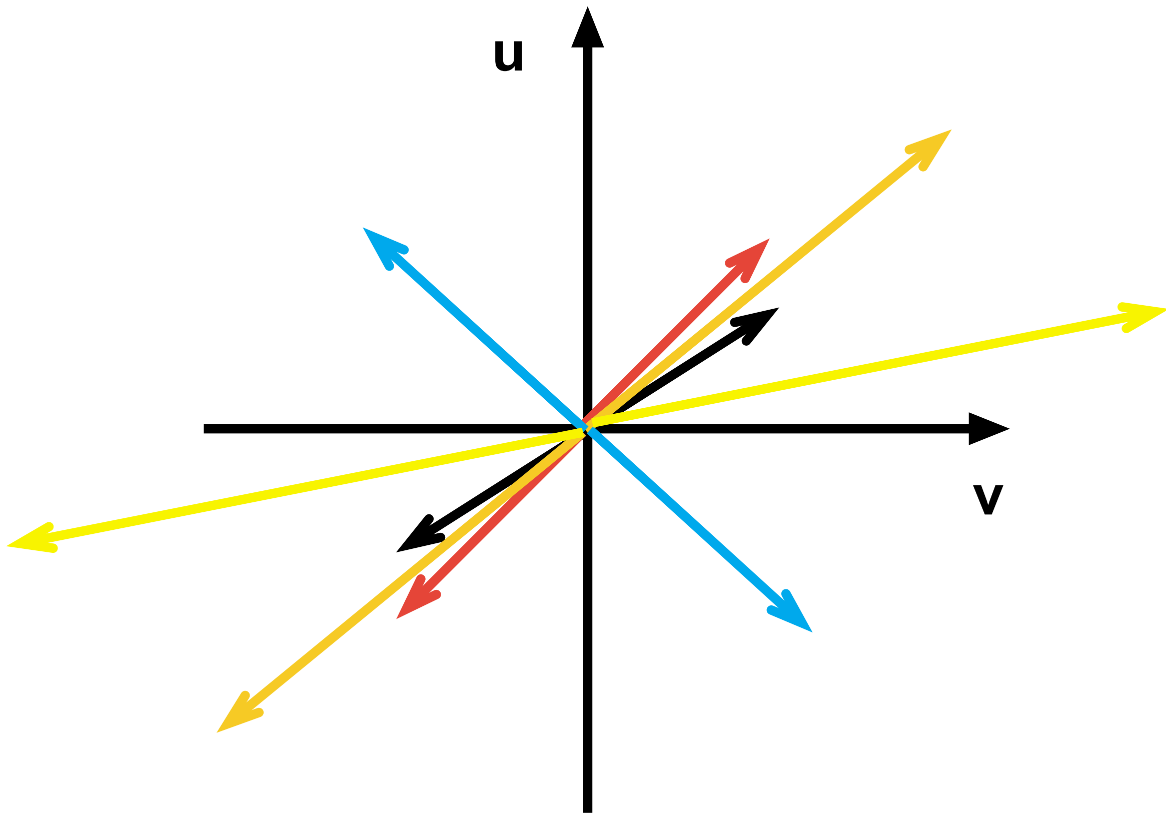
Measure Visibility and Phase for many baselines in the uv plane.

Note: This  is not the uv plane!

The uv-plane

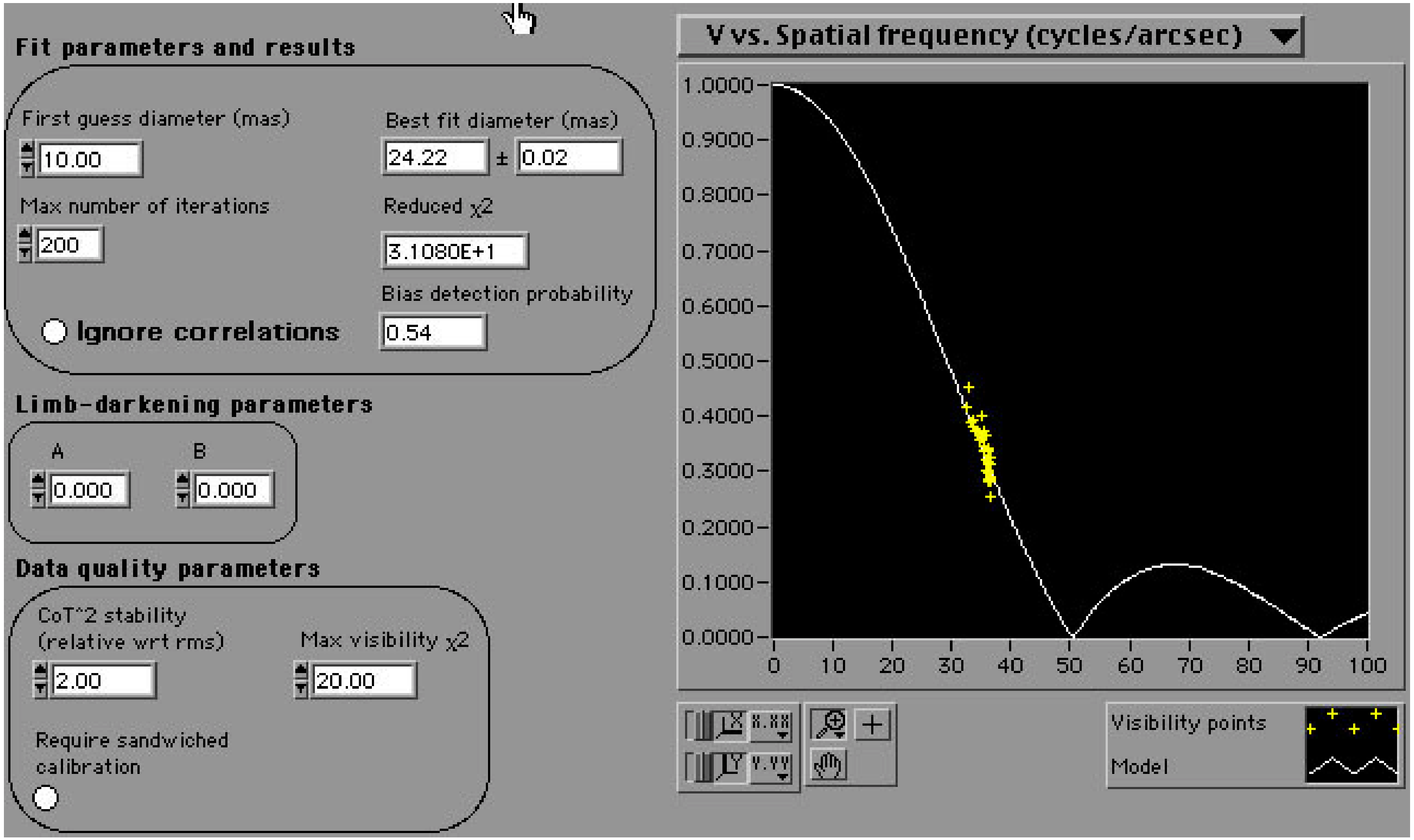


This is the uv-plane:



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

R Leo over several nights (April 1-3, 2001)

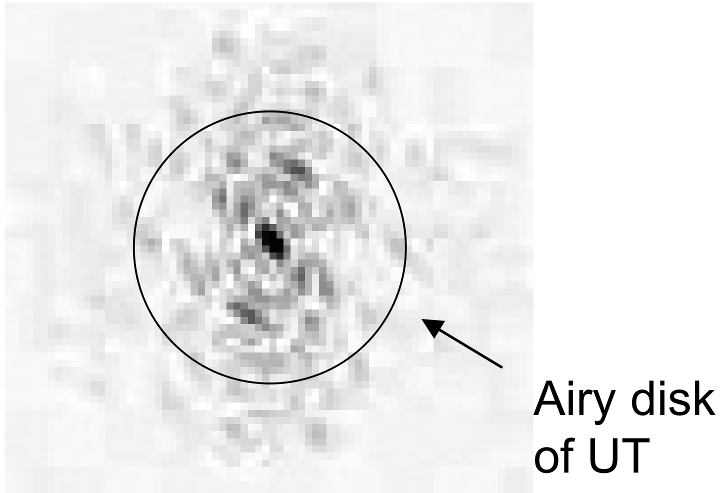


Data analysis software from Observatoire de Paris

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)

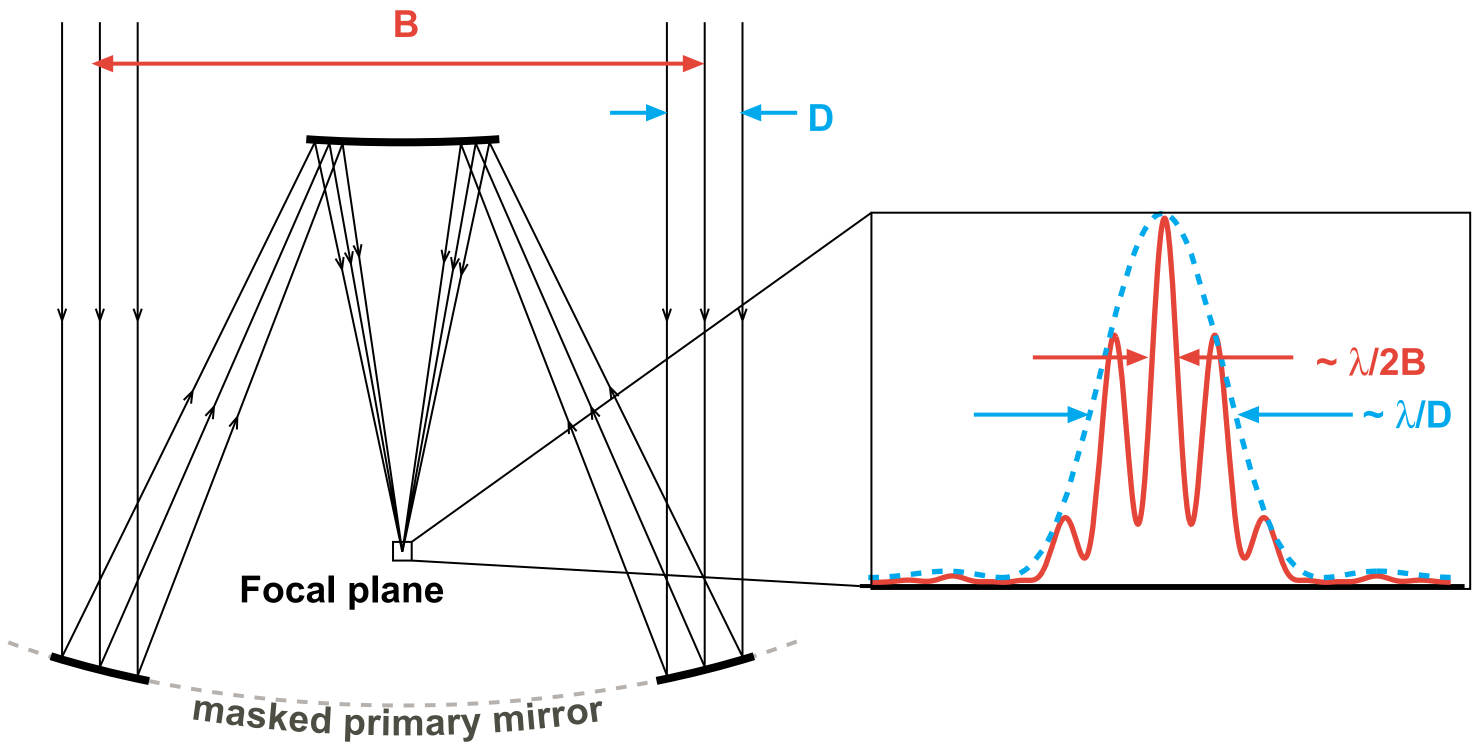
Summary of visibility function

- The Visibility is the Fourier Transform of I(α), 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(α) (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.

4. Types of interferometers, The measurement of the Visibility function

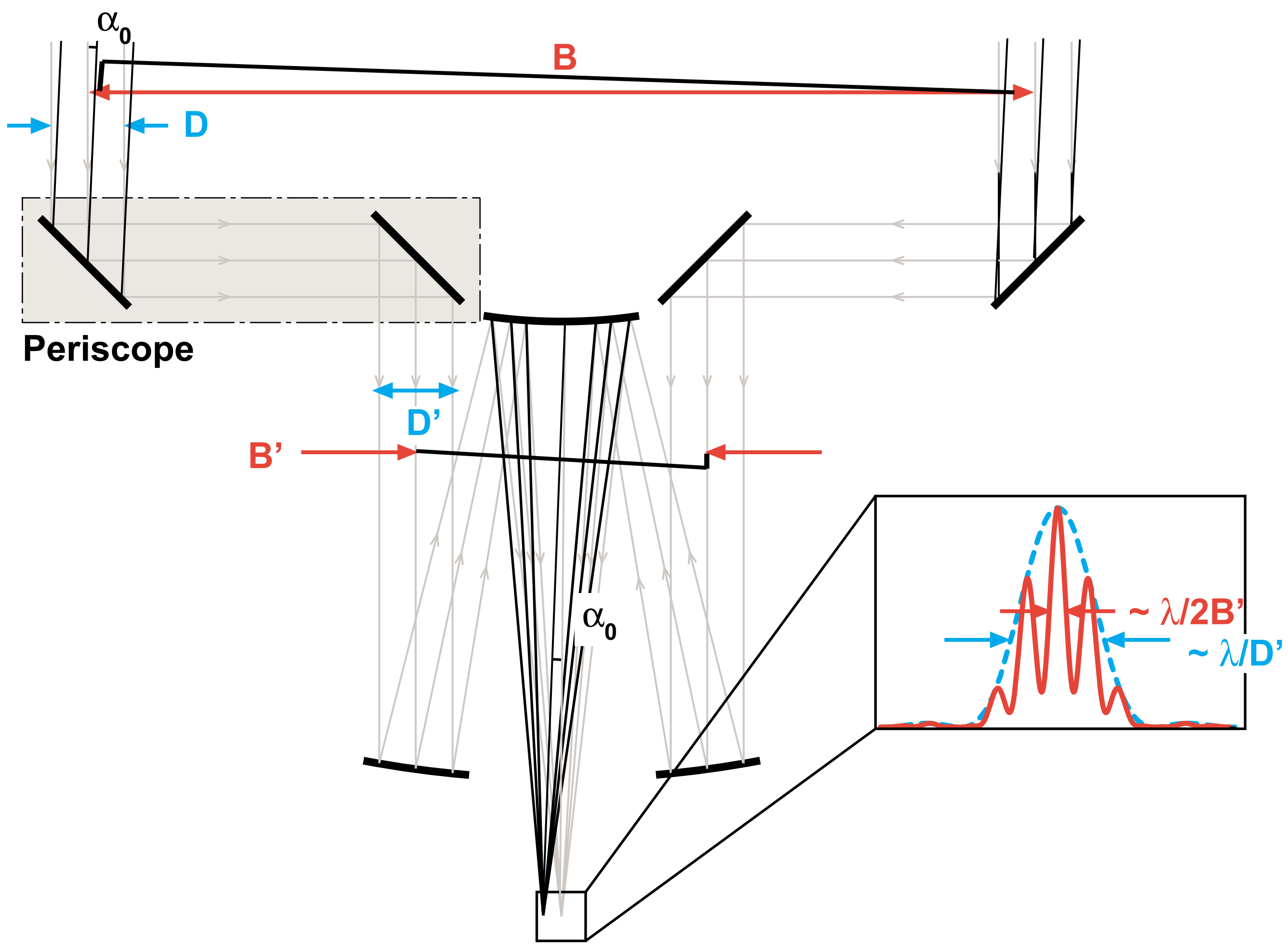
- Two major types: Michelson and Fizeau
- Main difference between the two: size of field of view
  $\Rightarrow$ homothetic mapping
- Three way beam combination
- Measurement principles
- Multi-axial vs co-axial beam combination

Masking a telescope



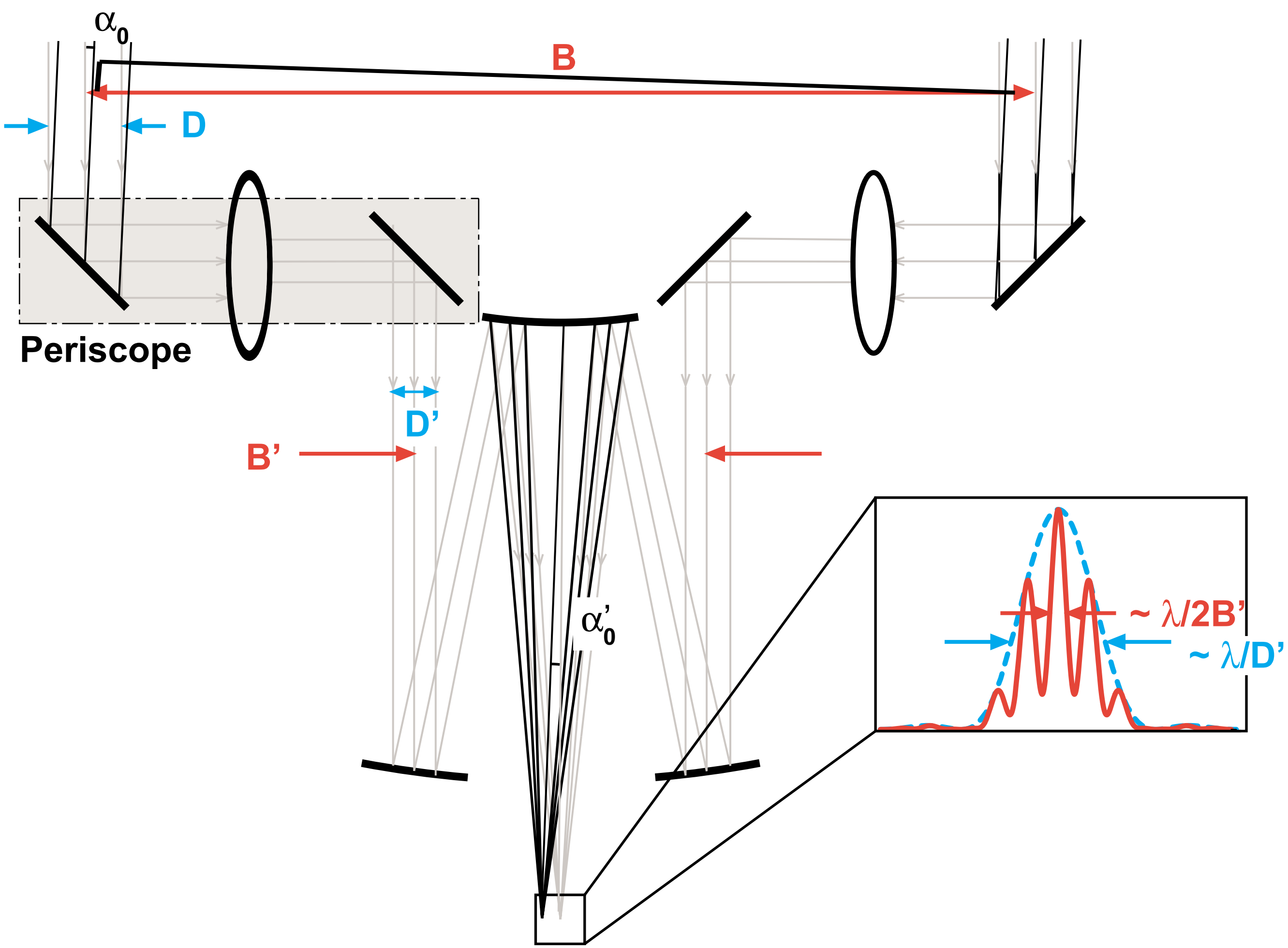
- The imaging process in a telescope is the superposition of fringe pattern from all combinations of baselines in the telescope pupil
- Masking the pupil, one can select one particular baseline
- Every star in the field of view has fringes

Michelson interferometer



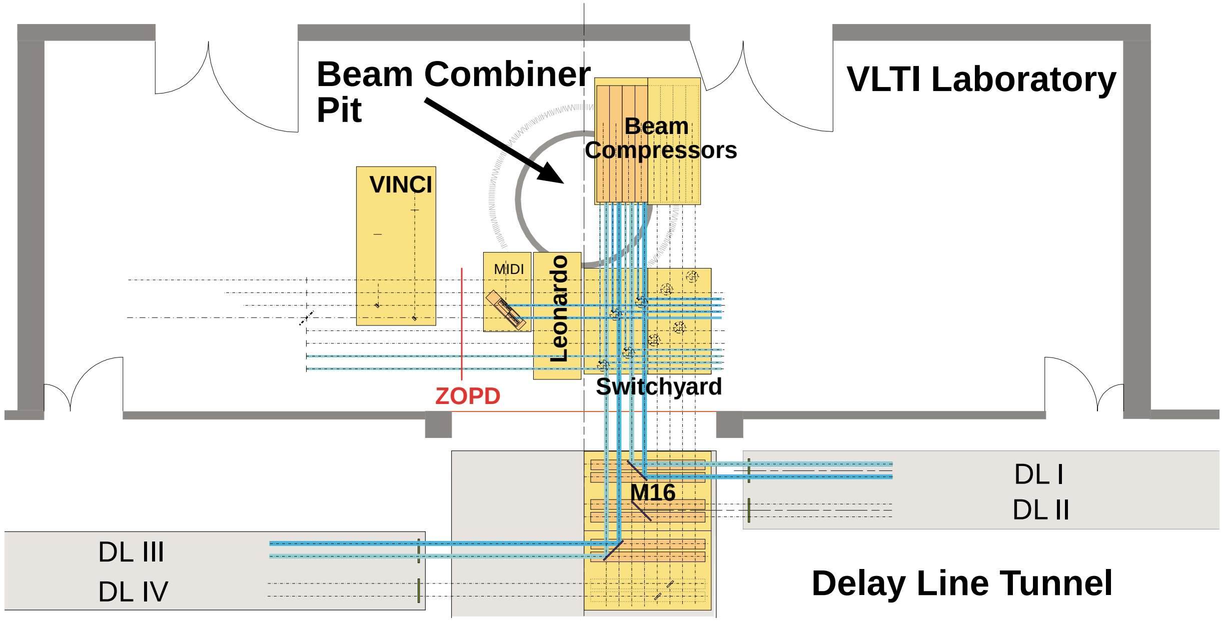
- Image at position α_0 (if D' = D)
- Left beam with delay α_0 B , right beam with delay α_0 B' $\Rightarrow$ OPD = α_0 B - α_0 B' ≠ 0 at image position α_0

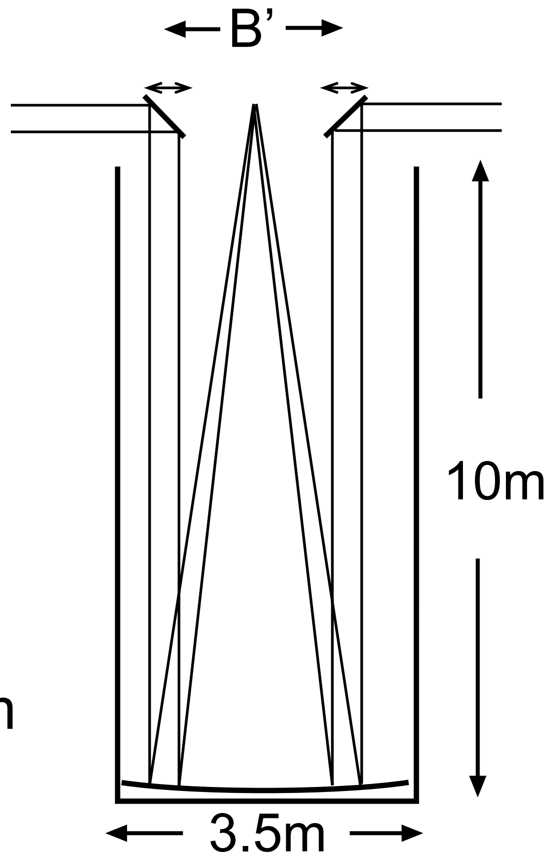
Fizeau interferometer



- 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

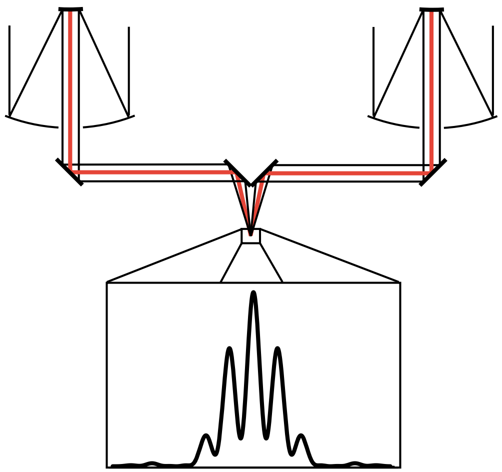
Option: Homothetic mapping with the VLTI





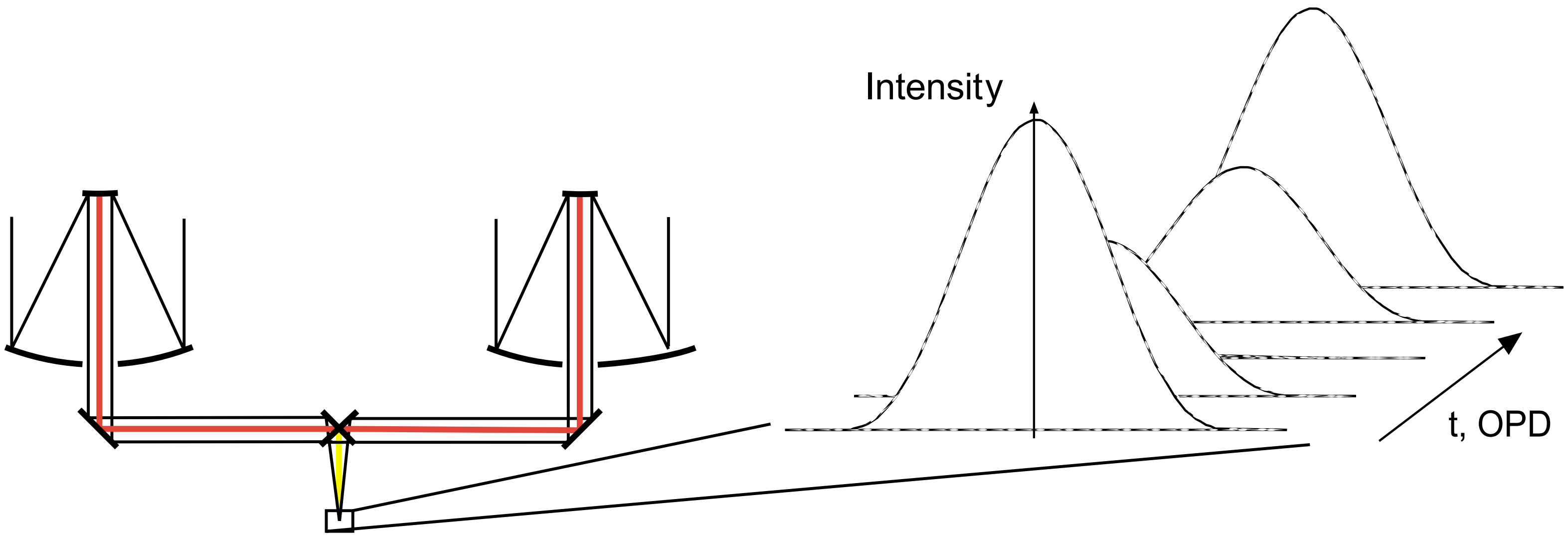
- Cylindric hole with parabolic mirror on the bottom
  - reimaged telescope pupils in front focal plane,
  - spatial fringe pattern in the focus
- Dynamic adjustment of pupil mirrors with µm precision required
- Precise (10^{-5}–10^{-7}) knowledge of individual scale plates required
- 2 arcsec field at 2µm, 200m baseline ⇒ 2kx2k detector required

Spatial vs temporal fringe patterns



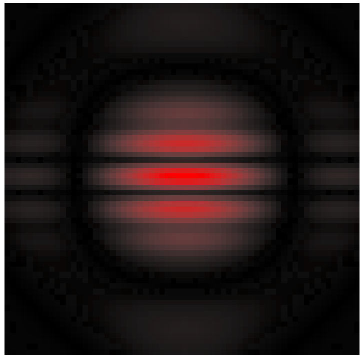
- The Michelson and Fizeau interferometers discussed so far have spatial fringe pattern (multi-axial beam combination)
- Co-axial beam combination produces Airy disk without fringes.
- Temporal OPD modulation produces I(t)

(Compare to Michelson Fourier Spectrometer)

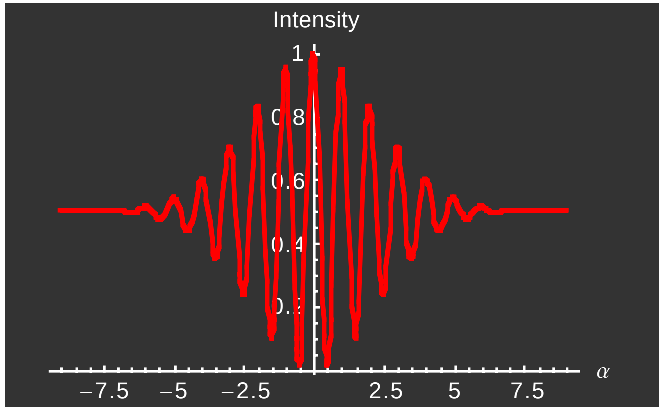


Spatial vs temporal fringe patterns

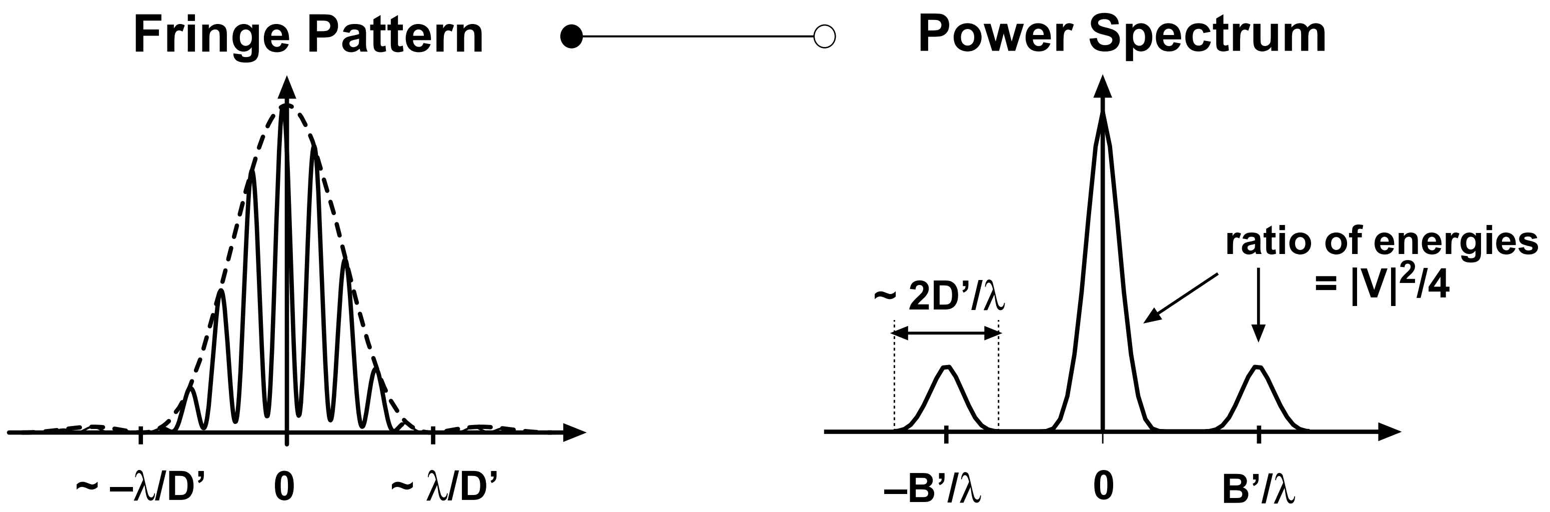
- A spatial fringe pattern is a 2D signal as a function of the image coordinates with fringes along one coordinate enveloped by an Airy disk



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

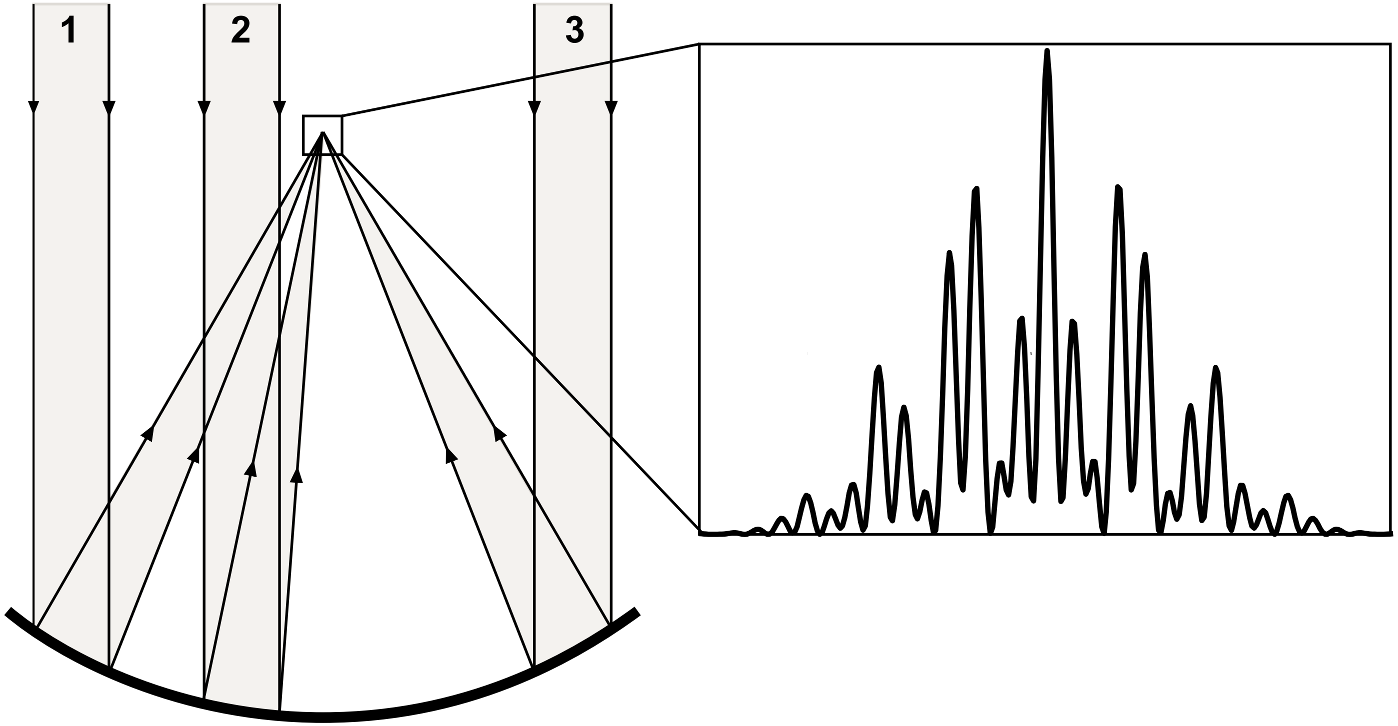


Visibility measurement in the power spectrum



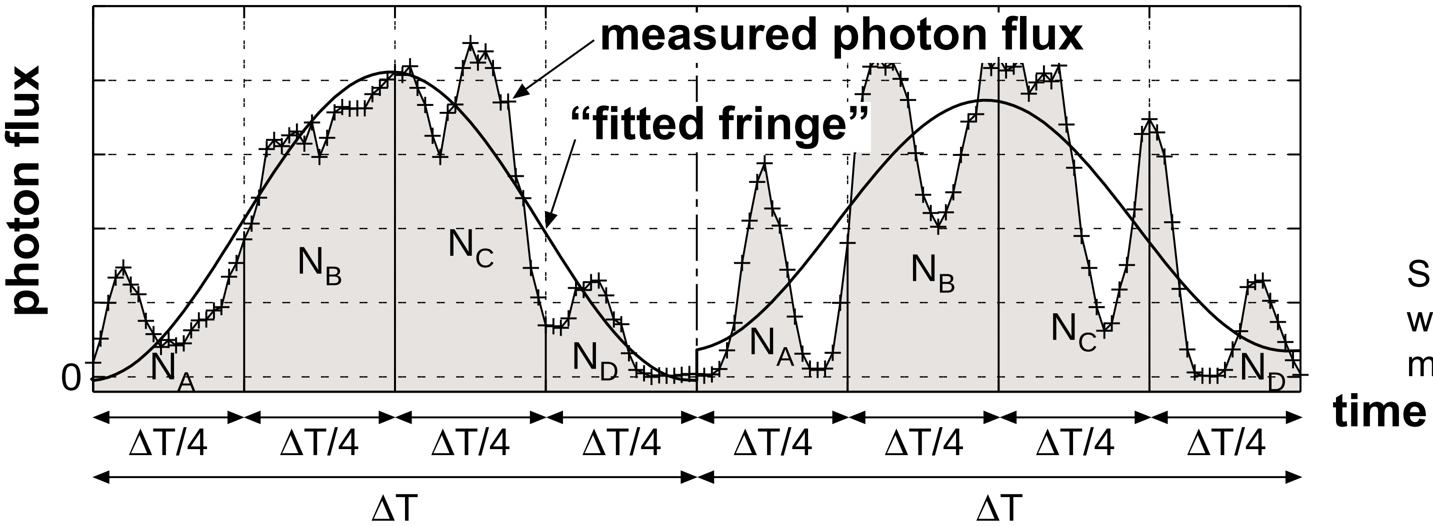
- Both spatial and temporal pattern can be analysed in the power spectrum
  - Spatial power spectrum is shown above
  - Temporal power spectrum shows intensity spectrum G(ν) multiplied by the modulus V^2 of the spatial coherence (VINCI)
- Three beam combination produces sidelobes at each of the three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

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
- Possible with AMBER

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

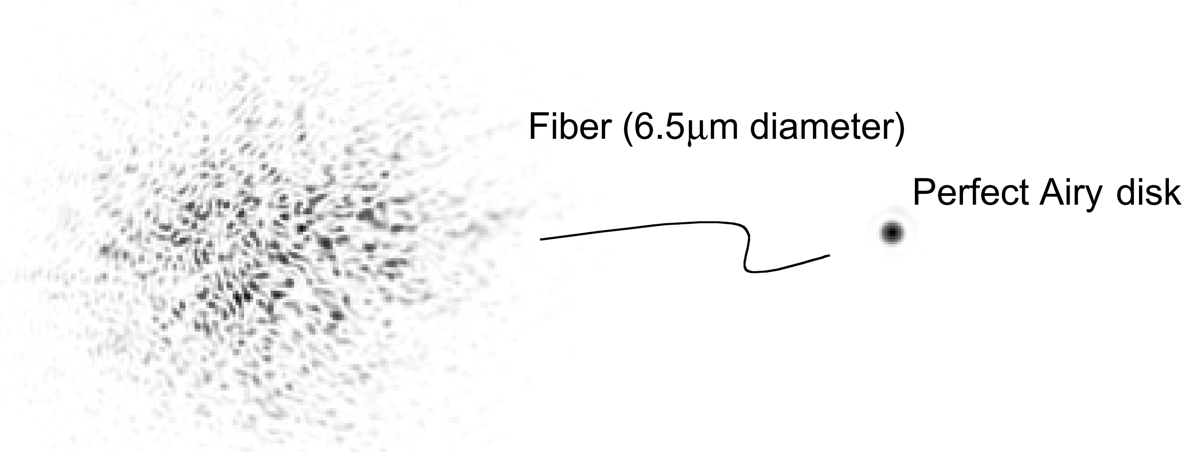
Note that $|V|^2$ is actually averaged because of treatment of photon bias

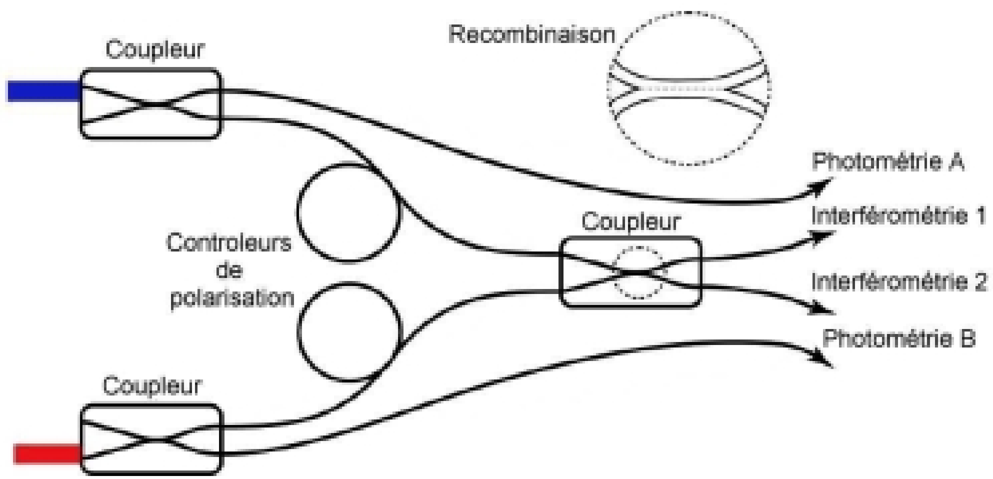
Summary of interferometer types

- 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 (~Airy disk)
  - Exit pupils imaged on top of each other
    $\Rightarrow$ Co-axial beam combination with 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

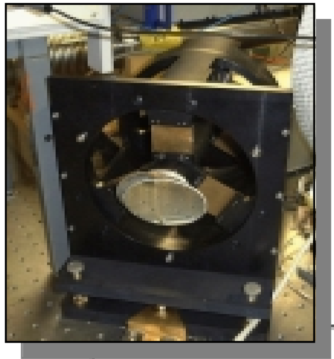
5. VINCI – The VLTI test instrument

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



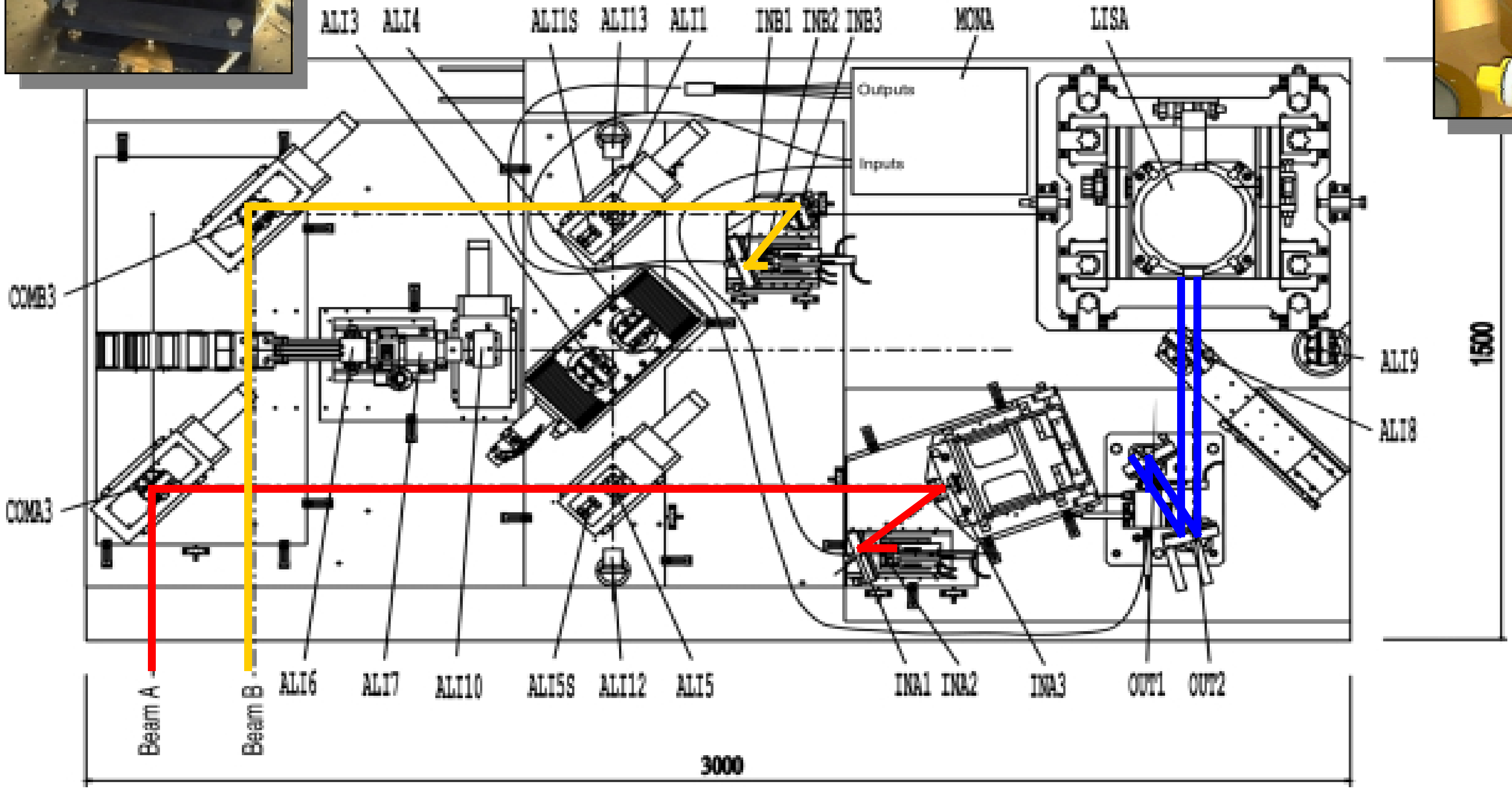


VINCI - Optical Setup

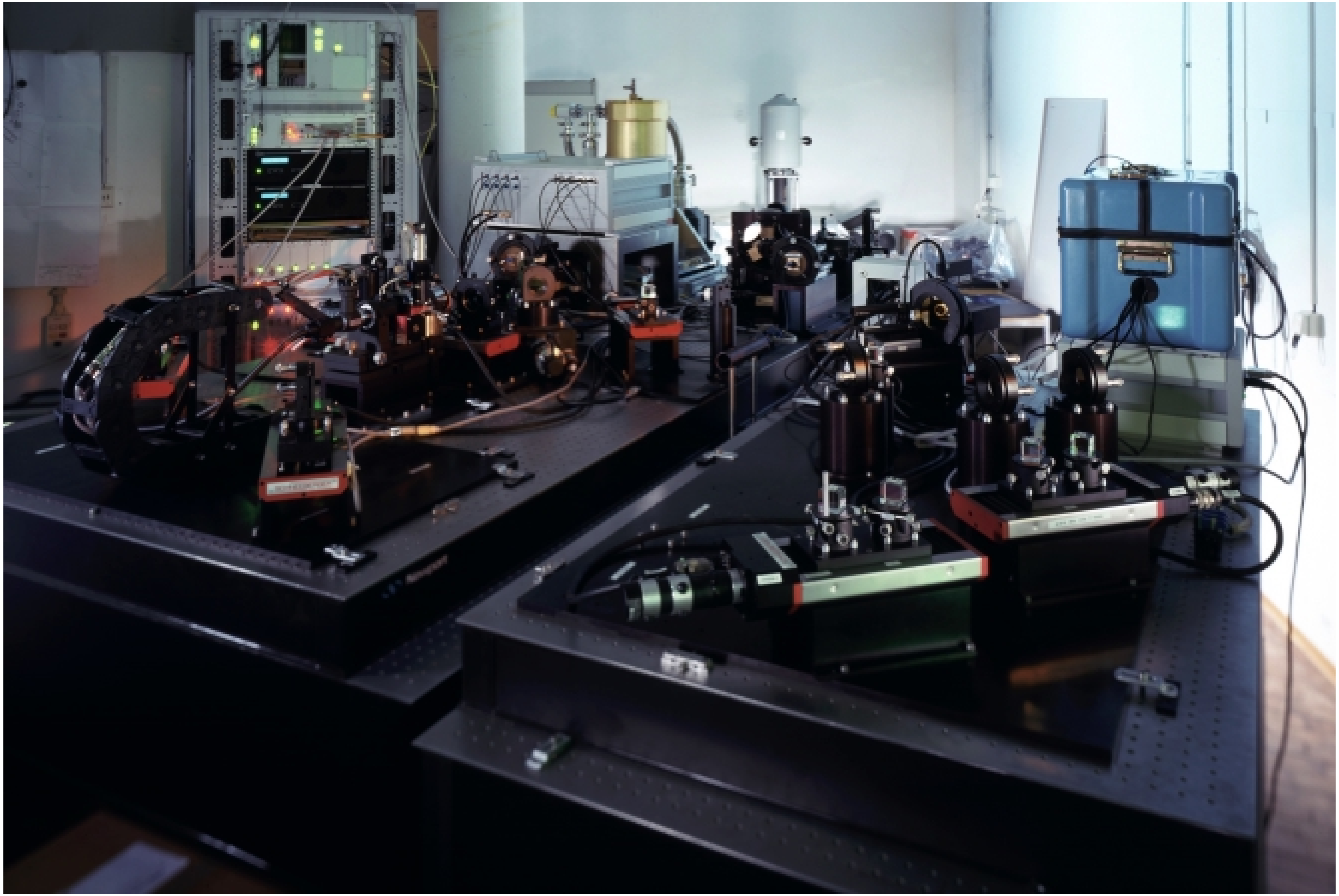


MONA

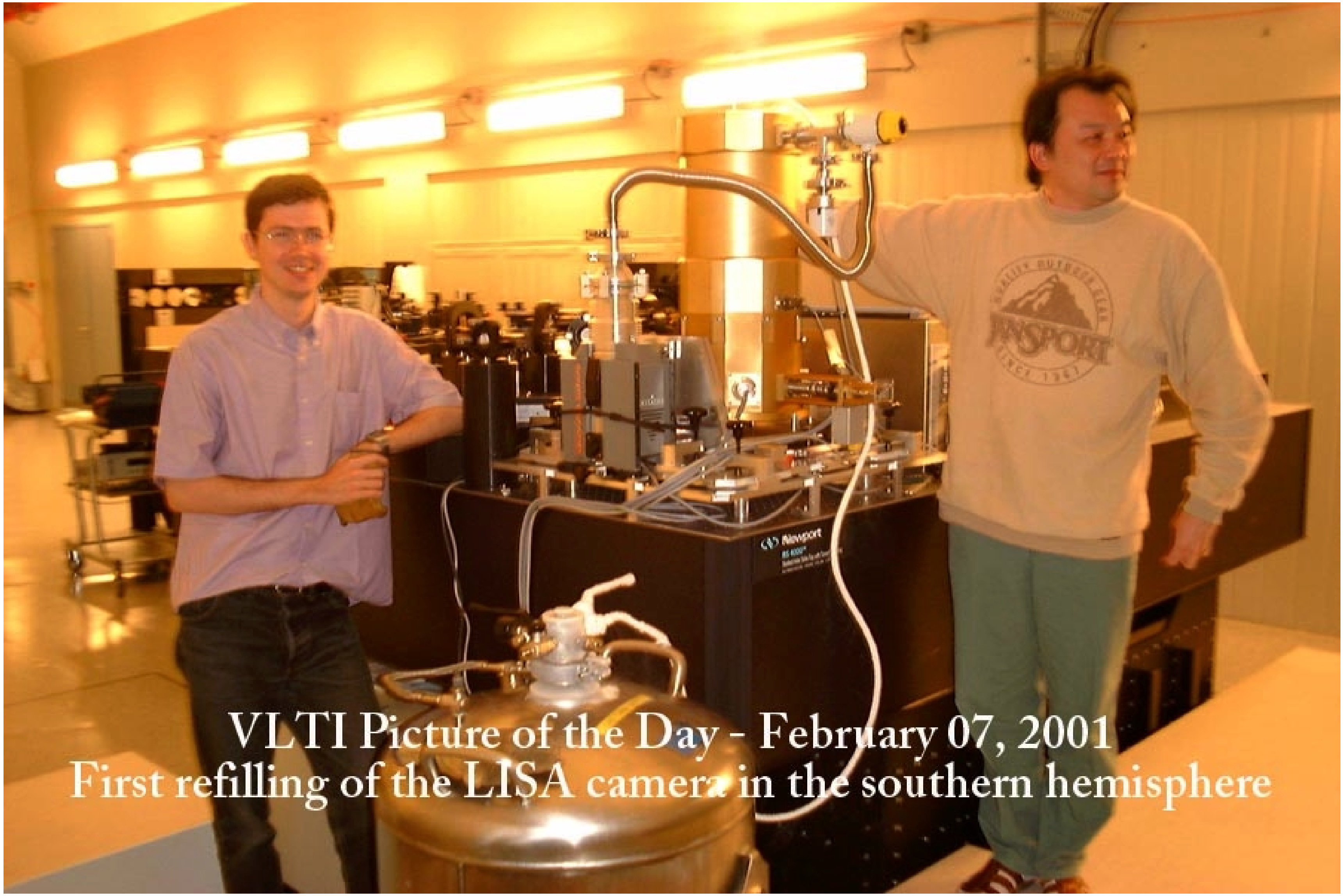
LISA



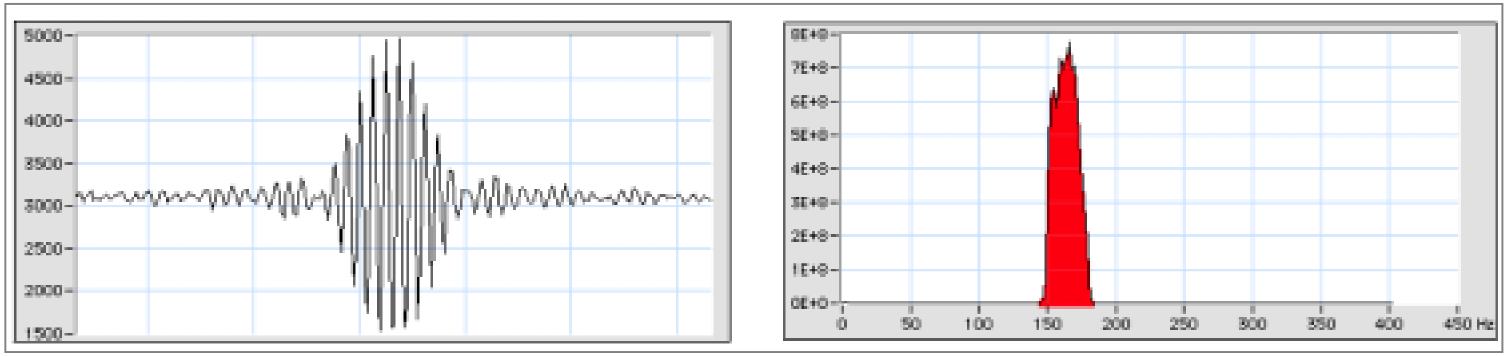
VINCI assembled in Garching



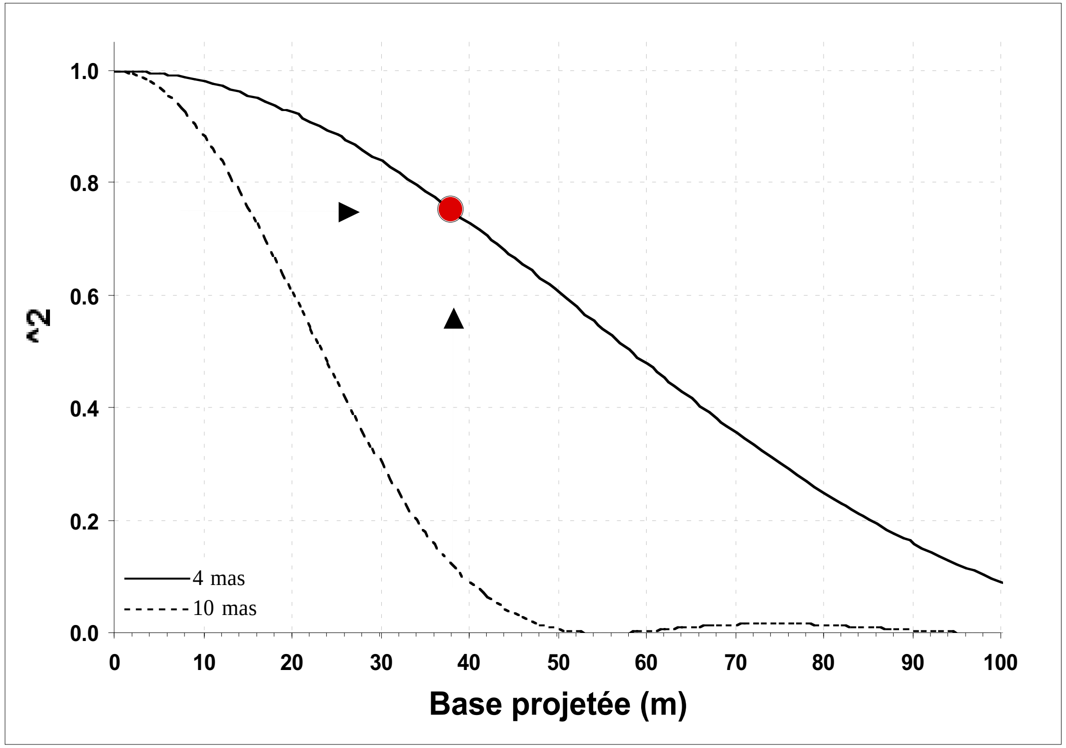
VINCI in the Beam Combination Lab



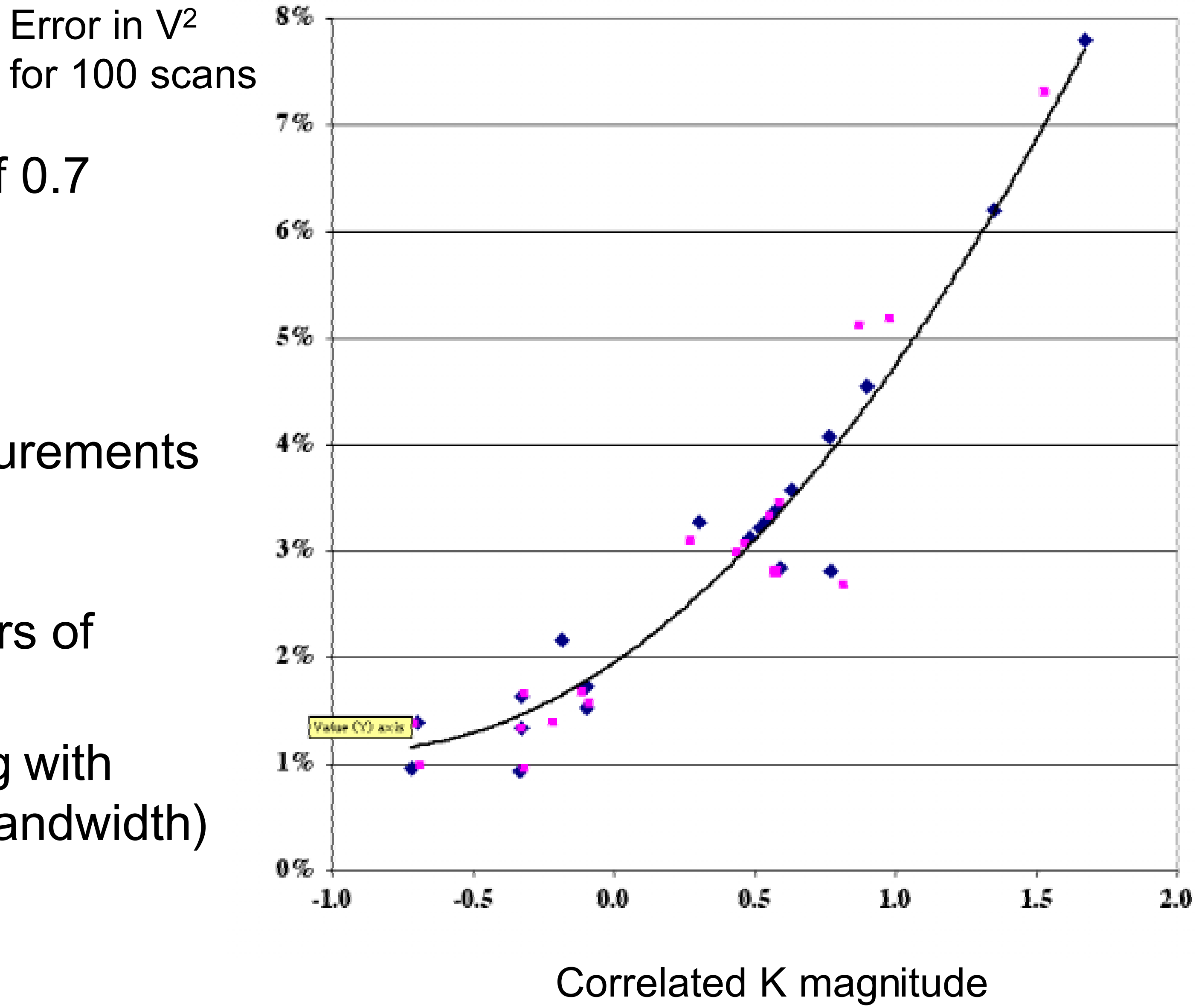
Measurement of the Visibility function with VINCI



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

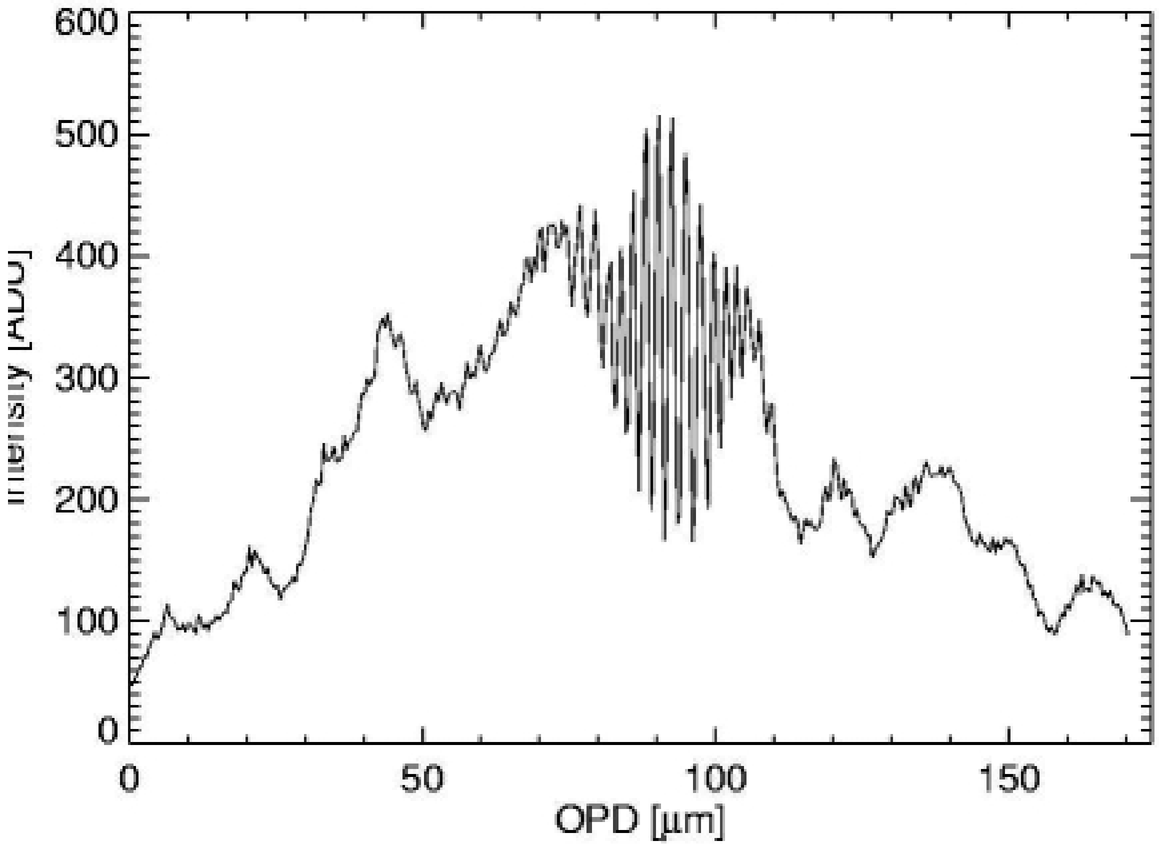


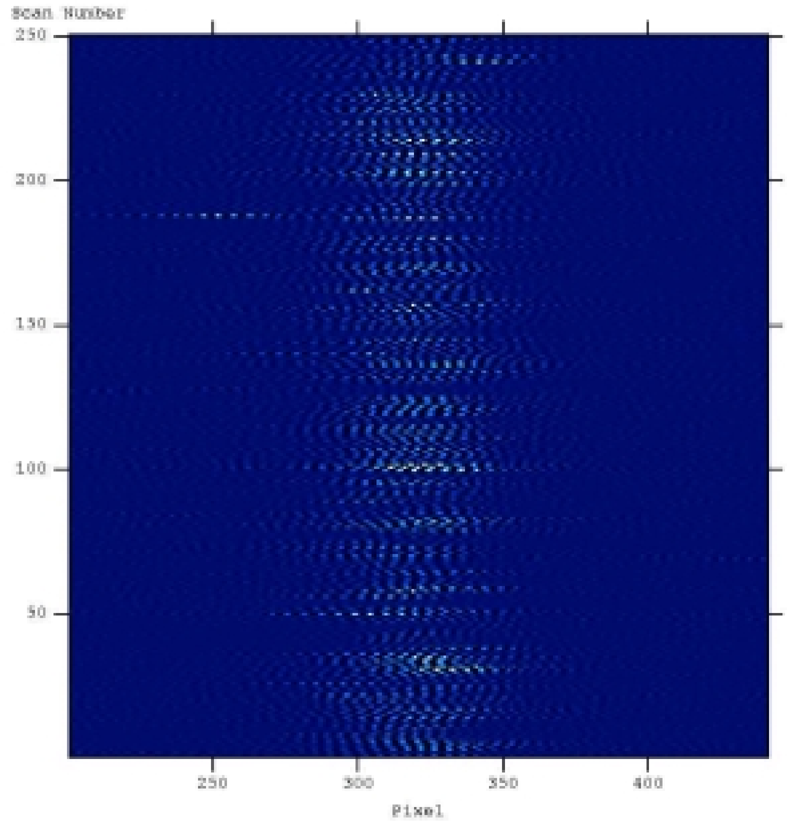
VLTI Performance



- Transfer function of 0.7 (V^2=0.5)
- Stability: 0.7±0.04
- Smallest $V^2=0.08^2$
- Accuracy for measurements of star diameter: <± 0.5 milli arcsec (on typical diameters of 10–25 milli arcsec)
- Slow fringe tracking with VINCI (max 4 Hz bandwidth)

First Fringes with the UTs





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

6. Interferometric imaging – Measurement of the visibility phase

- So far, the measurement of the contrast of the fringe pattern has been discussed
- Two methods for imaging:
  - Three telescope measurements of closure phase
  - Phase referenced imaging
- Closure phase observations will be possible with AMBER
- Phase referenced imaging requires a hardware extension – called PRIMA – of the VLTI
- PRIMA allows for astrometry
- PRIMA opens the door to faint object science

Closure phase

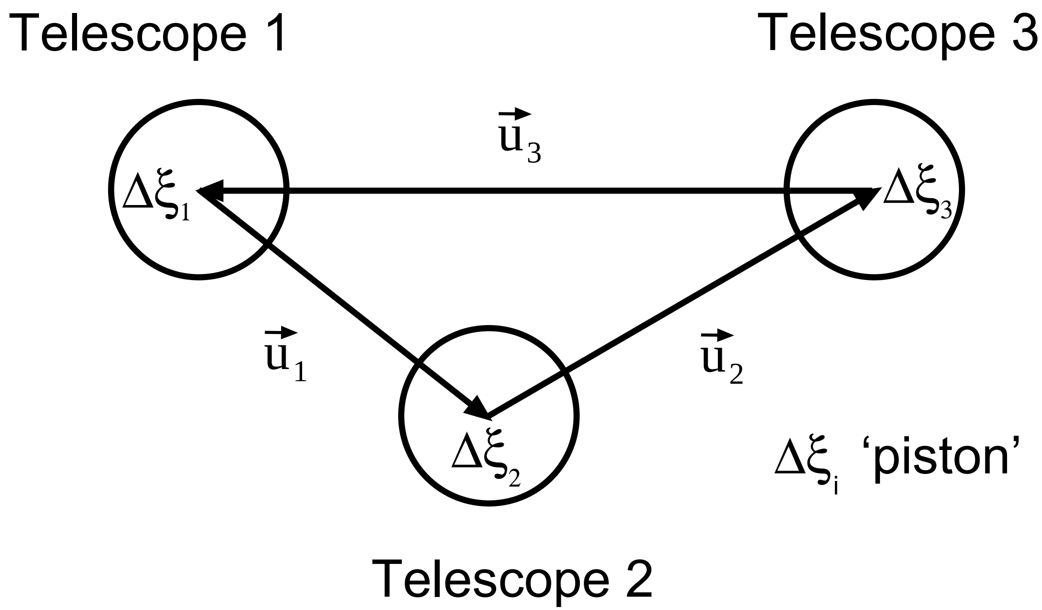
- In the sum of the three phases the random fluctuation is eliminated:

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

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

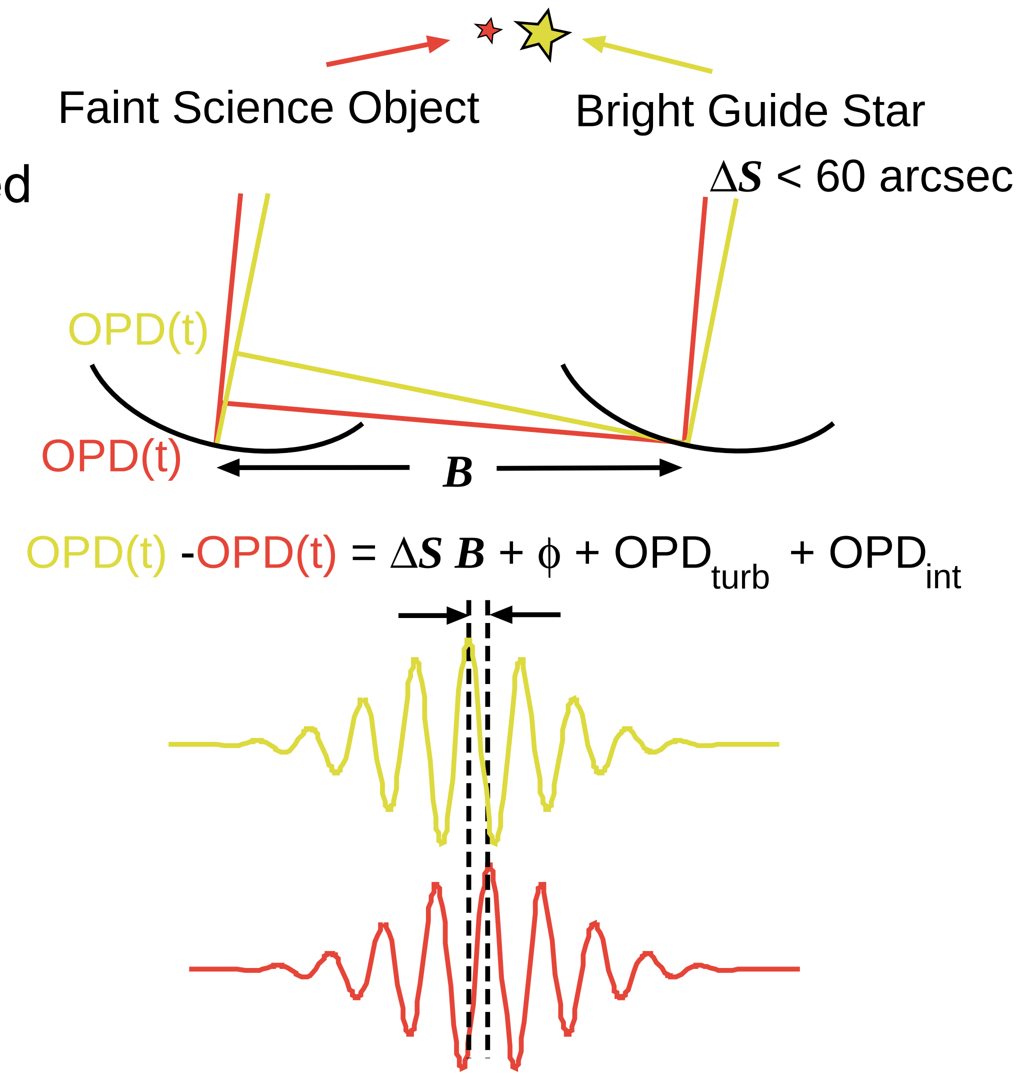
  $\psi_3(u_3) = \phi_3(u_3) + \Delta\xi_3 - \Delta\xi_1$

  $\psi_1 + \psi_2 + \psi_3 = \phi_1 + \phi_2 + \phi_3$
- Many baselines required to determine individual phases.
- The exposure time is limited, again by the individual fringe motion, i.e. some 10msec



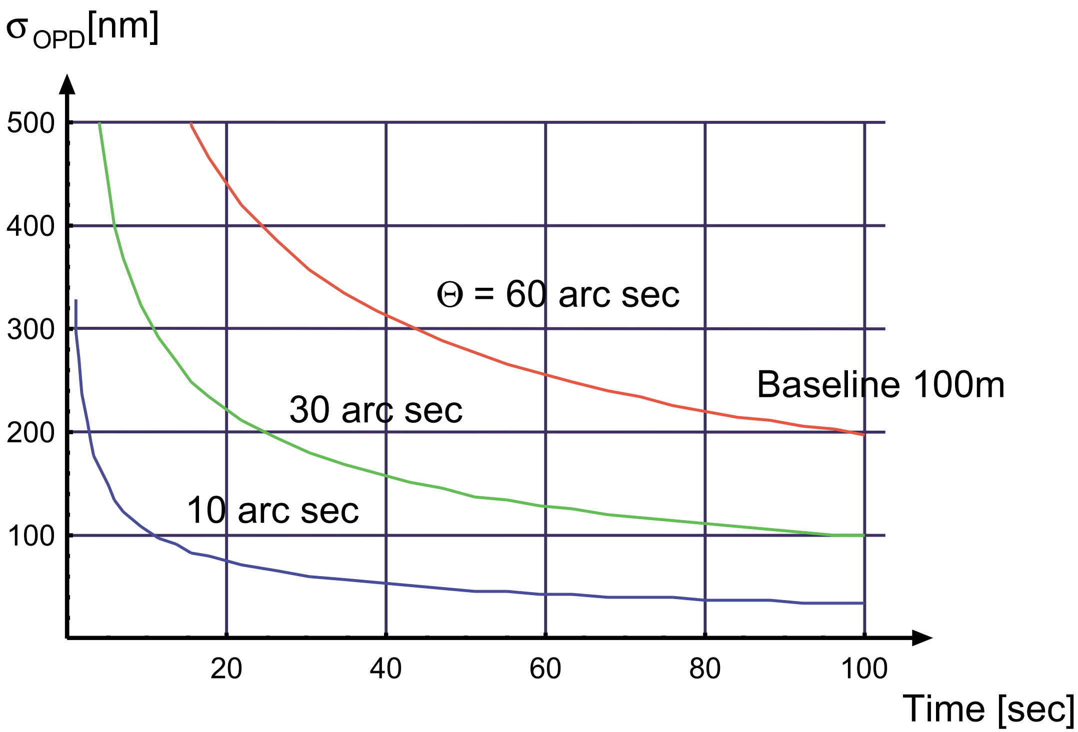
PRIMA – the VLTI dual feed facility

- Tracking the fringes on the guide star
  $\Rightarrow$ Fringes of science object are stablised
- PRIMA picks two stars in the Coudé, feeds it into the Delay Lines



- 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



$$\sigma_{OPD} \sim \theta/\sqrt{t}$$

- The rms OPD error is reduced to <200nm even if the separation is 1 arcmin
- After 30min the error is small enough (<5nm) to allow for 10 μarcsec astrometry

The VLTI + PRIMA

Standard Components

+ PRIMA Subsystems

- Star separator

  Complex opto-mechanical system
  at Coudé focus of UT's/AT's
  Two fields of 2'' separated by up to 1'

- Laser metrology system

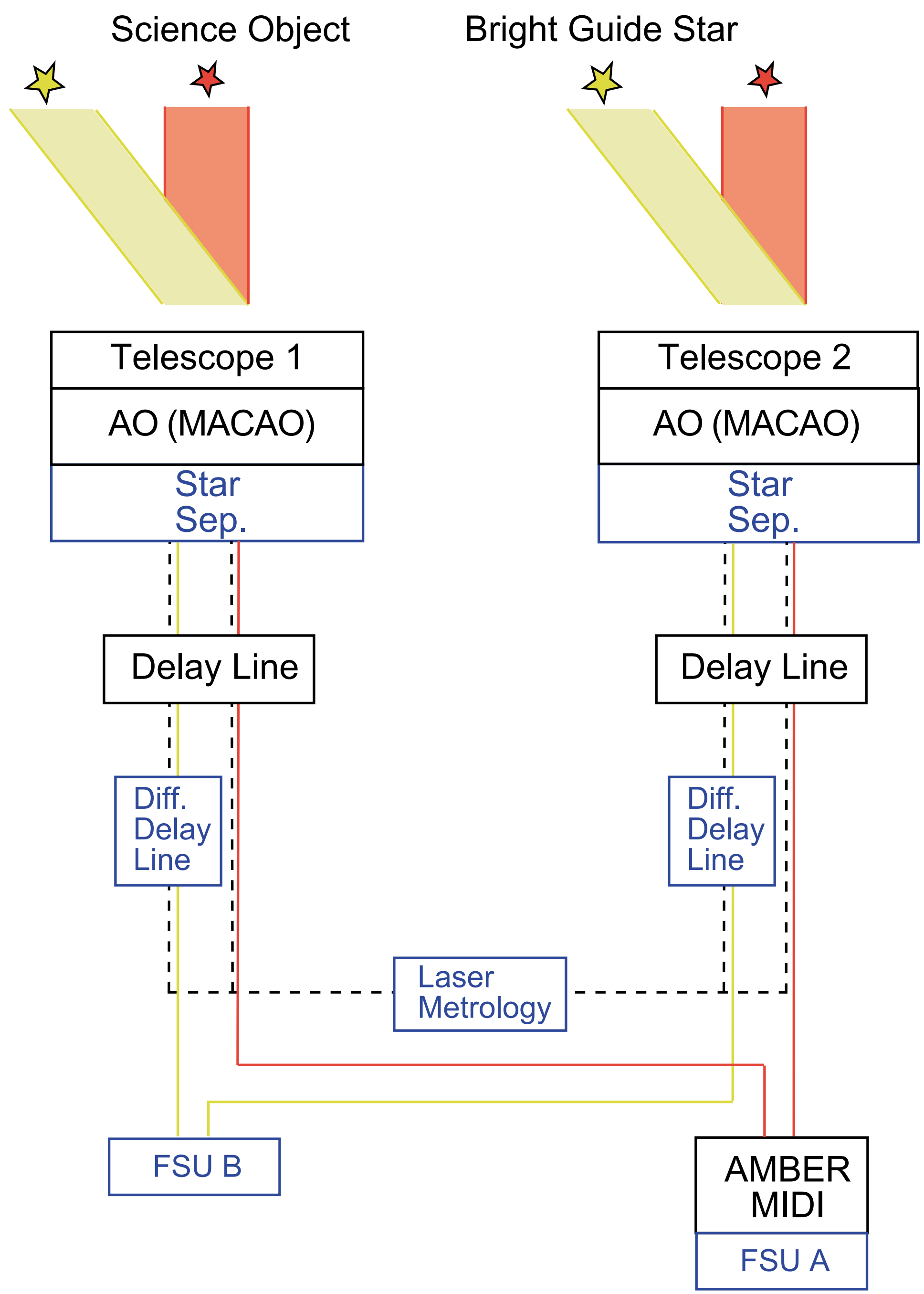
  Monitor internal OPD
  with 5 nm rms over 30 min

- Differential delay lines

  Provide differential delay with
  5nm rms, maximum stroke 65mm

- Fringe sensor unit

  Measure fringe position
  with 30 nm rms on H = 13 (UTs)



PRIMA – The VLTI Dual Feed Facility

- Observations of faint objects (K ~ 20) with MIDI and AMBER
- Imaging of faint objects (UTs and ATs) with MIDI and AMBER
- Astrometry on ATs (10 μarcsec) with dedicated camera

Requirement: K~12 guide star within 60arcsec

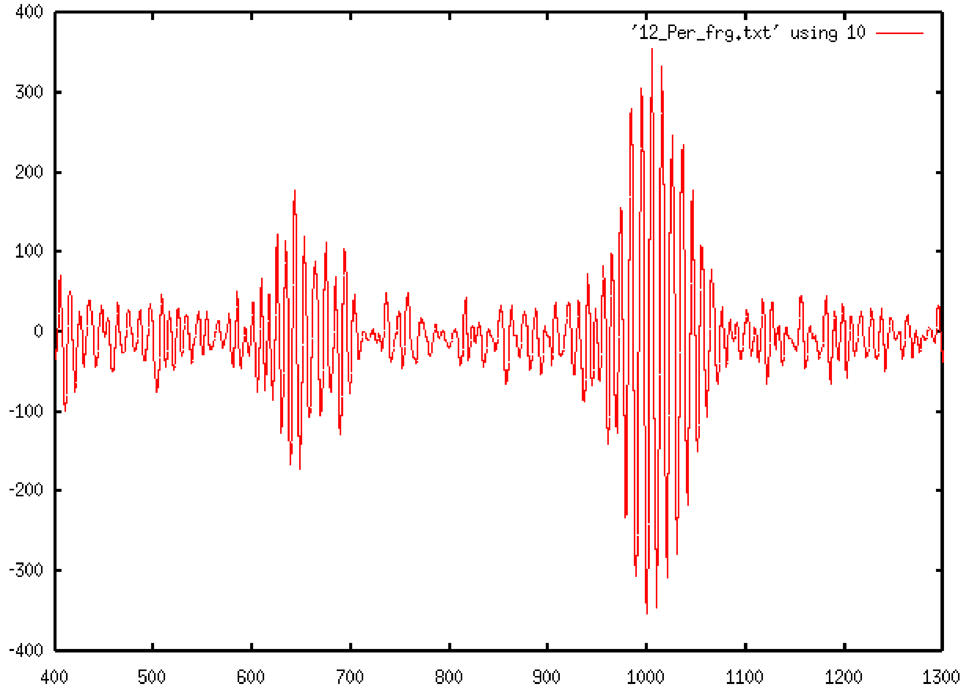
Science Instruments:

- MIDI and AMBER with PRIMA
- Dedicated PRIMA Astrometry Camera

Binary observation in a co-axial fringe pattern

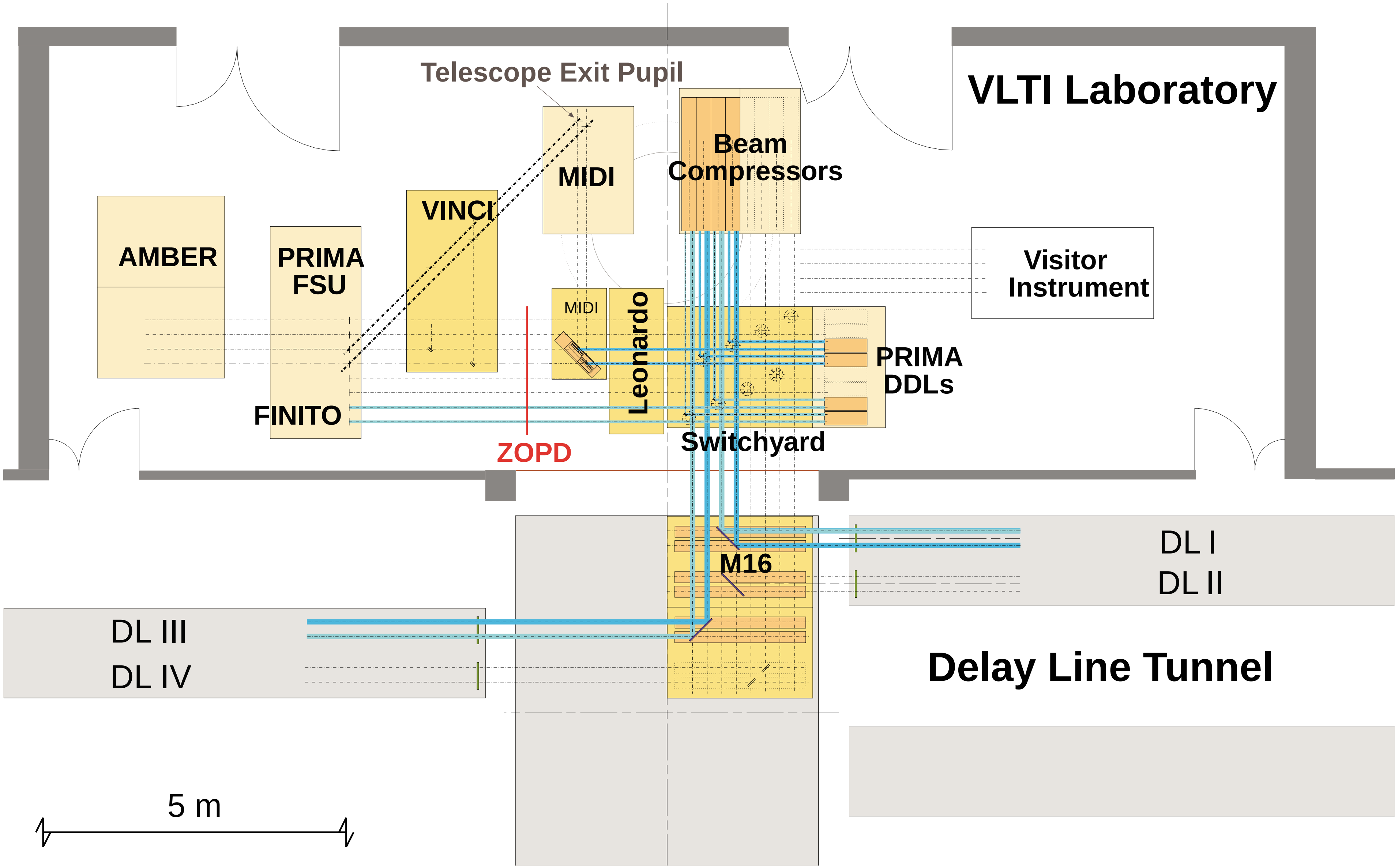
The two fringe pattern are completely separated
due to separation δ times baseline B > coherence length

The separation is determined directly by the distance of the white light fringes, or by the reduced contrast described by the visibility function!



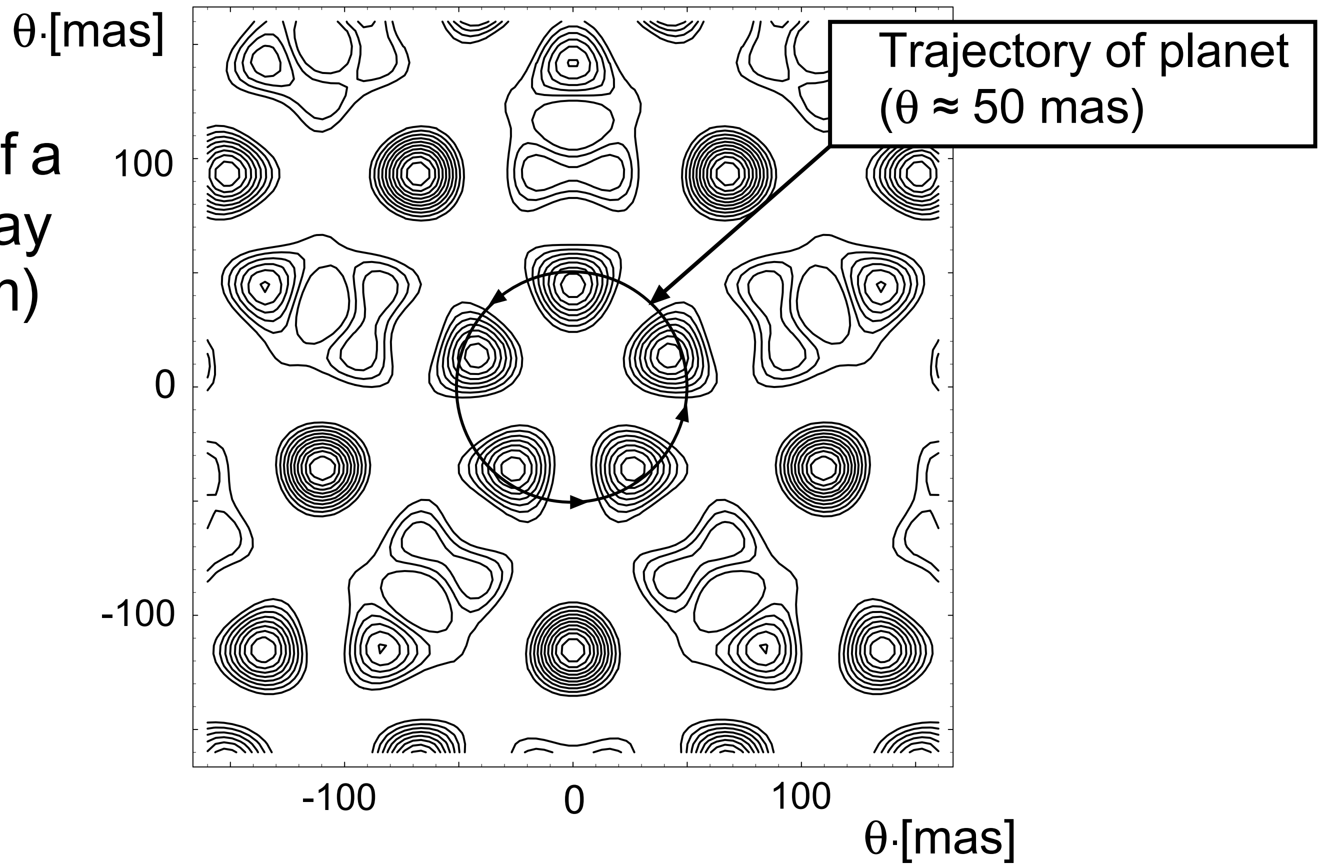
12 Persei observed on Oct 9, 2001 with the CHARA Array,
K'-band, 330m baseline, separation 40 marcsec

VLTI Laboratory



Nulling Interferometry

- Transmission map/PSF of a Nulling interferometer array on a 50m circle (λ = 10µm) as proposed by Mennesson/Mariotti.
- GENIE (DARWIN ground experiment) is a VLTI science instrument to be built by ESA
- Problems:
  - Background at 10µm
  - Quality of AO required



Outlook

- Fibers and integrated optics for
  - Beam transport with coherent amplification (!)
  - Beam combination with integrated optics components (Experiment with IONIC planned for Q2 2002)
  - Fringe detection with integrated optics and STJs
- Field of view 1 Airy disk (50-250marcsec) - mosaicing fields? (however: 1.8-m ATs with 200m baselines ~200x200 ‘pixels’)
- Simple multi baseline beam combination
- Bulk opto-mechanics only for Delay Lines
- Instruments in ‘shoeboxes’

The Overwhelmingly Large Array - La OLA

- Baselines of km
- Delay Line Tunnels of km or
  use integrated optics for fast beam switching
  => short(ish) Delay Lines for tracking
- Boot strapping for fringe tracking?
- 8+ m telescopes or
  use OWL production line to produce a ‘few’
  more 8m telescopes?
- Go to ALMA site or
  build la OLA in VLTI style (2-4 OWLs + a dozen
  ATs of 8m)?

Conclusion

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