A VLTI overview

Andreas Glindemann

Abstract

The VLTI with its subsystems (telescopes, delay lines, adaptive optics, fringe tracker) will be presented as well as the instruments (VINCI, MIDI, AMBER). Imaging techniques - phase closure and dual feed - will be explained and the instrumentation (PRIMA) for imaging will be discussed. The needs for a ground based nulling instrument in the mid infrared will be outlined. An overview over concepts for the second generation instrumentation will be given.

Related publications :

The papers presented at the SPIE conference 25-31 March 2000, provide an excellent overview of the VLTI. Most of them are available as PDF files at:

http://www.eso.org/projects/vlti/publink/

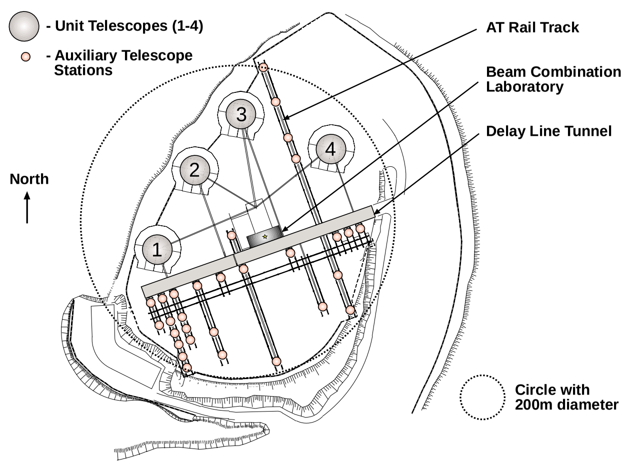
The VLT Interferometer

Andreas Glindemann

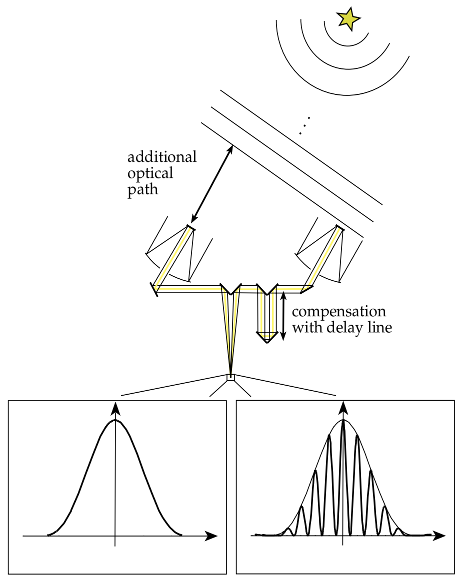
R. Abuter, F. Carbognani, F. Delplancke, F. Derie, A. Gennai, Ph. Gitton, P. Kervella, B. Koehler, S. Lévêque, S. Menardi, A. Michel, F. Paresce, T. Phan Duc, A. Richichi, M. Schöller, M. Tarenghi, A. Wallander and R. Wilhelm

European Southern Observatory
Garching

The VLT Interferometer



- **Four 8-m Unit Telescopes**
  Max. Baseline 130m $\Rightarrow$ 3mas(K) - 15mas(N)
- **Three 1.8-m Auxiliary Telescopes**
  Baselines between 8 and 200m
  $\Rightarrow$ max. resolution 2mas(K) - 10mas(N)
- **Excellent uv coverage**



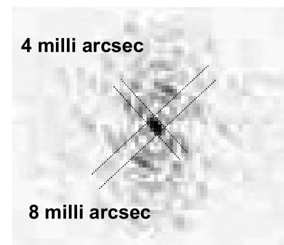
Requirements for Delay Lines:

- `tip-tilt‘ < 1.5 arcsec
- position accuracy < 1μm over 65m travel for a baseline of 200m

The goal

uv coverage for object at -15°

8 hour observation with all UTs

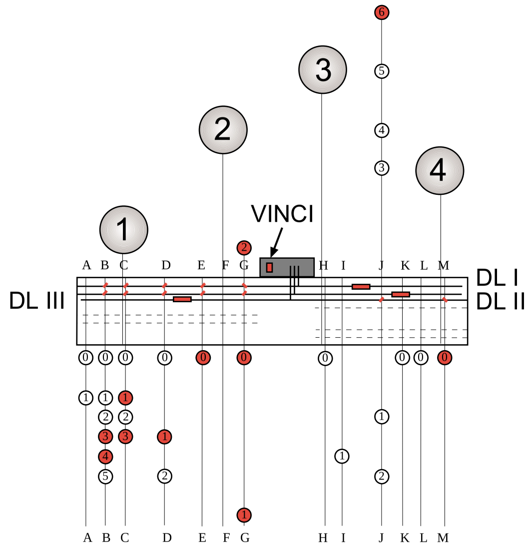


Resulting PSF Fourier transform of visibilities

λ = 2.2μm (K-band)

Magnitude limit K~20

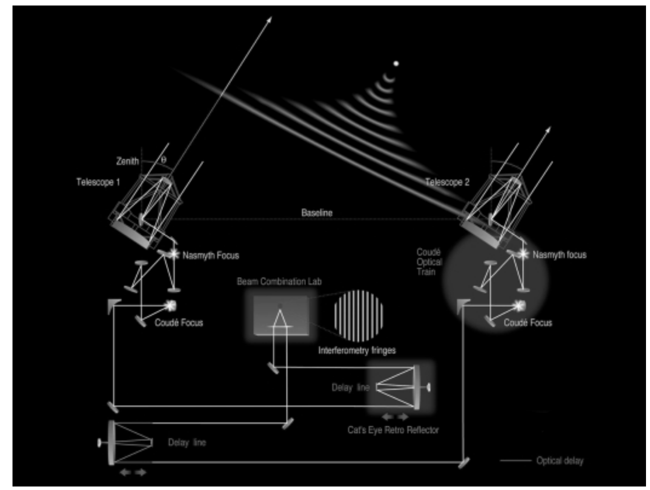
The first steps: Interferometry with Siderostats



Requirements:

- Siderostats ✓
- Delay Lines ✓
- Test Instrument ✓
- Relay Optics (✓)

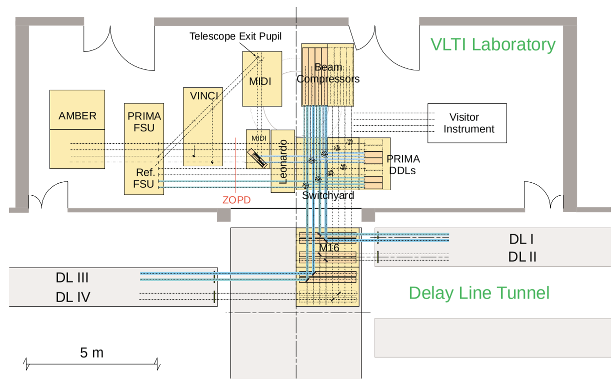
Optical Layout and Sub-systems



- **Field of view: 2 arcsec**
- **Fringe Tracker (m_H ~12)**
- **Adaptive optics with 60 actuator DM**

➜ **Strehl >50% in K-Band**
Guide Star brighter m_V=16

VLTI Laboratory Layout



- Telescope pupil reimaged into instruments
- Zero OPD in a plane across beams
- Provisions for all planned instruments + visitor instrument (Nulling experiment)
- Optical design for up to 8 beams = 4 UTs with dual feed

The first steps: Status of sub-systems

- Siderostats (40 cm)
  - Delivered to Paranal
  - Integration at Paranal — May 2000
- Delay Lines
  - Acceptance Test: — May 2000
  - Integration at Paranal:
  - No. 1 and 2 — June 2000
  - No. 3 — Dec. 2000
- VINCI
  - Test instrument for First Light
  - Operating Wavelength: 2.2 μm
  - Replica of FLUOR (IOTA Instrument)

Goal:
  - Reduce overall risk by using proven technology.
  - Integration at Paranal — Jan. 2001

- Beam Compressor — March 2001
- Transfer Optics for DL Tunnel — Oct. 2000

First Fringes — Feb. 2001

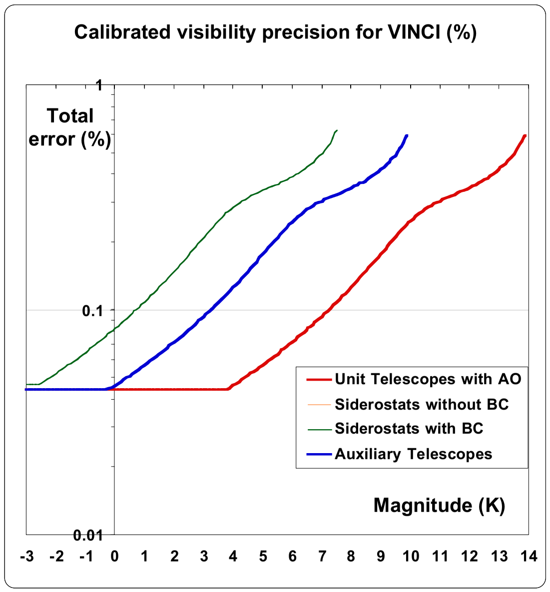
An Interferometry Toolbox

- Artificial star
  - autotest before first light
  - science instruments (AMBER, MIDI)
  - alignment lasers (visible and 2.2 μm)
- Image and pupil alignment sensor
  - Technical CCD detector for alignment
- Beam combiner
  - based on single-mode fluoride glass fibers

VINCI – Instrument Goals

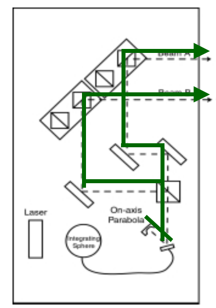
- Commission VLTI subsystems
  - debug the interferometer
  - provide a reference for upgrades
- Perform Measurements
  - baseline vectors, dispersion, Strehl ratio
  - fringe visibility (accuracy <1%, possibly <0.1%)
- Be simple, stable and reliable
  - fully compliant to ESO standards
- Be a training tool
  - can be operated in the lab for demonstrations

Visibility Precision with VINCI

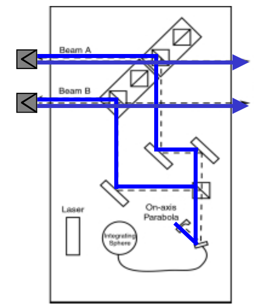


Artificial Star

Autotest



Autocollimation



Band	Flux (W/µm)	Eq. Mag UT	Eq. Mag AT	Eq. Mag Sid.
I (0.9 µm)	3.8e-11	8.2	4.9	1.0
K (2.2 µm)	9.7e-11	4.5	1.2	-2.7
N (10 µm)	4.3e-11	-0.8	-4.1	-8.0

VLTI Instrumentation – MIDI

Arriving at Paranal: Dec. 2001
First Fringes with UTs: Feb. 2002

MIDI Consortium:
- MPIA, Heidelberg
- Astronomical Institute, Amsterdam
- Sterrewacht Leiden
- Observatoire de Paris, Meudon

Mid IR instrument (10 – 20 μm)

Medium spectral resolution

Limiting Magnitude N: 4–9 (UT) 1–6 (AT)

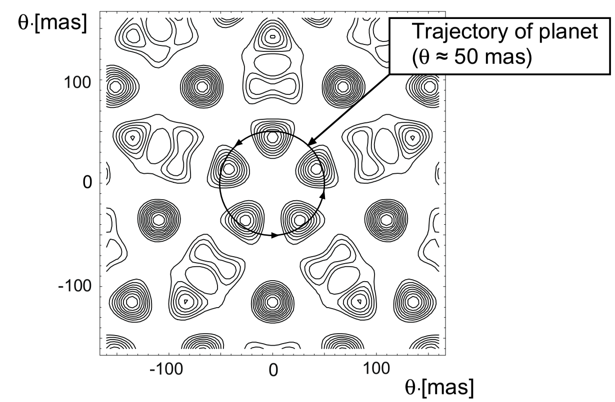
Visibility accuracy 5% (1% bright sources)

Angular resolution 20 milli arcsec

Two beam design

Challenge:
- Signal detection
- Chopping
- New coatings for 10 μm beam splitter

Nulling interferometry – DARWIN



- Transmission map/PSF of a Nulling interferometer array on a 50m circle (λ = 10μm) as proposed by Mennesson/Mariotti.
- DARWIN ground experiment planned for VLTI in collaboration with ESA
- Problems:
  - Background at 10μm
  - Quality of AO required for deep null

Operation Philosophy

- Observing with the VLTI is like remote observing
- Change of configuration is motorised:
  - Relay optics (M12, M16)
  - All optics in VLTI lab (eg switchyard)
  - AT repositioning motorised but needs to be supervised
- Instruments operated remotely
- Detailed operation scheme to be presented in Oct. 2000
- Clean room conditions in DL tunnel and VLTI Laboratory (incl. ante room)
- VLTI adopts successful data management strategy of VLT

VLTI Instrumentation – AMBER

Arriving at Paranal: Feb. 2002
First Fringes with UTs: March 2003

AMBER Consortium:

- Observatoire de la Cote d'Azur, Nice
- Observatoire de Grenoble (LAOG)
- Osservatorio Astrofisico di Arcetri
- MPIfR, Bonn

J, H, K Instrument

Spectral resolution R~10000
Multi-axial beam combination
Limiting Magnitude K: 13–-20(UT) 10–17 (AT)
Visibility accuracy 5%
Angular resolution 4 milli arcsec
Three beam design (closure phase)

Challenge:

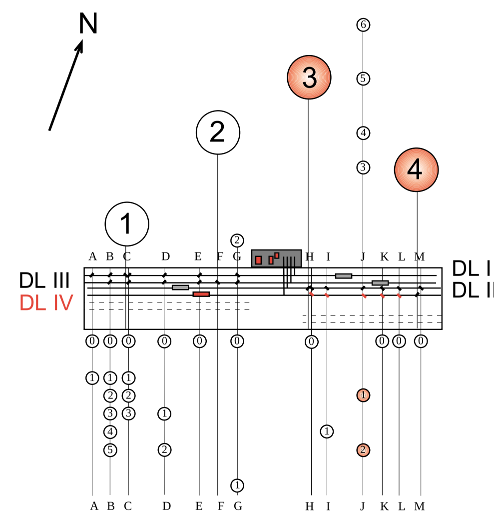
Beam combination (AO mandatory)
Closure phase
Multi-axial beam combination

VLTI Phase A - „Two Telescope Interferometry“

- Auxiliary Telescopes 1 and 2
  - Installed at Paranal — June 2002
- Note: ATs form observatory of their own

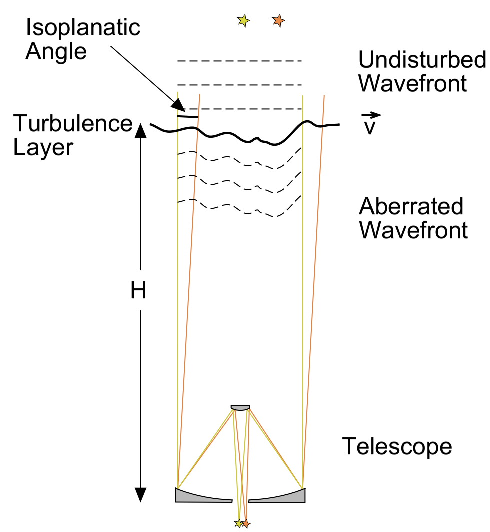
- STRAP
  - Tip-tilt correction on UTs
  - Installed on UT1 and UT3 — June 2001
- MACAO
  - Adaptive Optics for UTs
  - Installed on UT2 and UT4 — Feb. 2003
- FINITO
  - Upgrade of PFSU
  - Three beam design
  - *Fast Track*, Commissioning: Dec. 2001

Interferometry with UTs and ATs - Delay Line No. 4



- Phase A: Two telescope interferometry
  - –UT1+UT3 with STRAP
  - –UT2+UT4 with MACAO
- Phase B: Imaging
  - –Dual Feed Facility
  - –Closure Phase

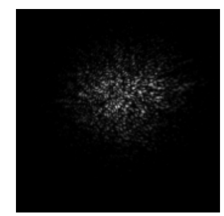
Isoplanatic Angle



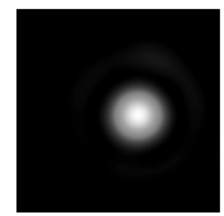
- Isoplanatic angle $\theta \sim r_0/H$, H ~ 10km
- Coherence time $\tau \sim r_0/v$, v ~ 10m/sec
- λ = 2.2μm with r_0 = 60cm : θ ~12", τ ~60msec

Imaging through Turbulence

- No diffraction limited imaging with ground based telescopes
- Images in the telescope show more (small λ) or less (long λ) speckle.



λ = 0.5μm

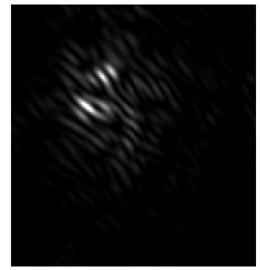


λ = 10μm

With statistical methods diffraction limited images of rather bright stars can be reconstructed (Speckle Interferometry)

The VLT Interferometer - A. Glindemann et al. Leiden Summerschool Interferometry 2000

Adaptive Optics and Interferometry

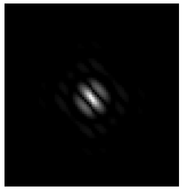


2 UTs
$\lambda = 2.2\ \mu m$
Seeing 0.5 arcsec

Goal: Measurement of fringe contrast and fringe position

Requirement:
Small pixel size (1–10 milli arcsec)
+ Short exposure time (~10 msec)

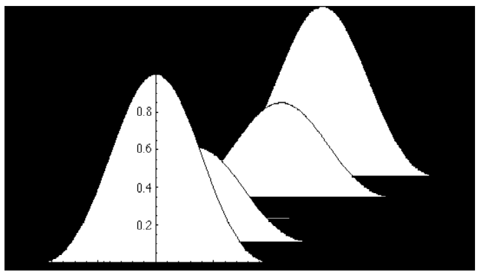
Note: The angular resolution depends only on the length of the baseline. Any improvement of the 'image quality' only affects the sensitivity.



Airy disk of multi-axial interference pattern

Note:
Fringes move within the Airy disk due to atmospheric turbulence

Airy disk of co-axial interference pattern:



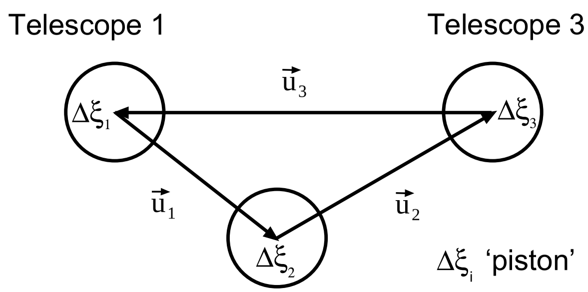
Fringe contrast as a function of OPD

- Fringe motion ('piston' mode) to be eliminated with a Fringe Tracker

VLTI Phase B – „Imaging“
Phase Closure

Auxiliary Telescope No 3	Oct. 2002
MACAO for third UT	Sep. 2003

Science Instrument: AMBER



Closure phase = $\phi_1(u_1) + \phi_2(u_2) + \phi_3(u_3)$

- Imaging of ‘bright’ objects
- Many baseline combinations required to reconstruct individual phases $\phi(u)$

However: Closure phase for object fitting

Fringe Tracking with FINITO

- Collaboration between Torino Observatory and ESO for development of a Fringe Sensor Unit (FSU) for VLTI
- Development: upgrade of Prototype FSU from Observatoire de la Côte d’Azur - Nice
- Key features:
  - Operating spectral band: H [1.5-1.8 μm]
  - combination of upto three beams
  - stabilization of long exposures for the scientific instruments
  - Limiting magnitude: H ~ 4 (siderostats) H~12 (UTs)

(see poster by M. Gai, L. Corcione, D. Gardiol)

VLTI Phase B – „Imaging“
Phase Referenced Imaging – Dual Feed

PRIMA – The VLTI Dual Feed Facility

The Dual Feed Mode enhances the VLTI capabilities in three areas:

- **Observations of faint objects (K ~ 20)**
- **Imaging of faint objects (UTs and ATs)**
- **Astrometry on ATs (10 micro arcsec)**

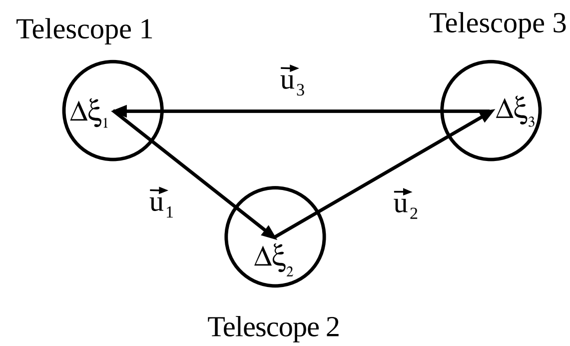
Requirement: K~12 guide star within ~60arcsec

Installation at Paranal 2003

Science Instruments:

- **MIDI and AMBER with PRIMA**
- **Dedicated PRIMA Astrometry Camera**

Phase Closure



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

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

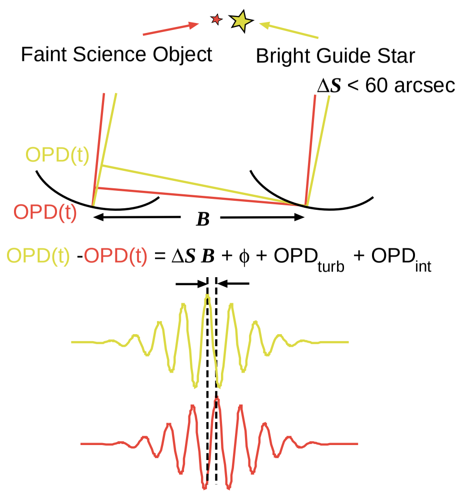
$$\psi_2 (u_2) = \phi_2 (u_2) + \Delta\xi_2 - \Delta\xi_3$$

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

$$\psi_1 + \psi_2 + \psi_3 = \phi_1 + \phi_2 + \phi_3$$

The exposure time is limited, however, by the individual fringe motion..

Dual Feed



- Tracking the fringes on the guide star
  ⇒ Fringes of science object are stablised
- Dual Feed = Feed two stars into delay line

Interferometer Signal

Complex visibilities $V e^{i\phi}$ determined by object shape

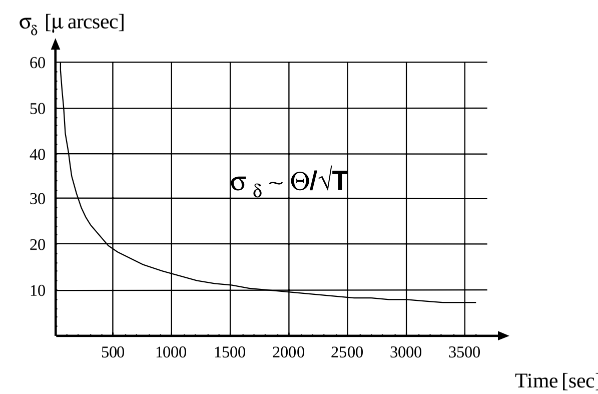
Imaging: Measure ϕ

However: Phase ϕ moves randomly with time due to turbulence

Without further measures:

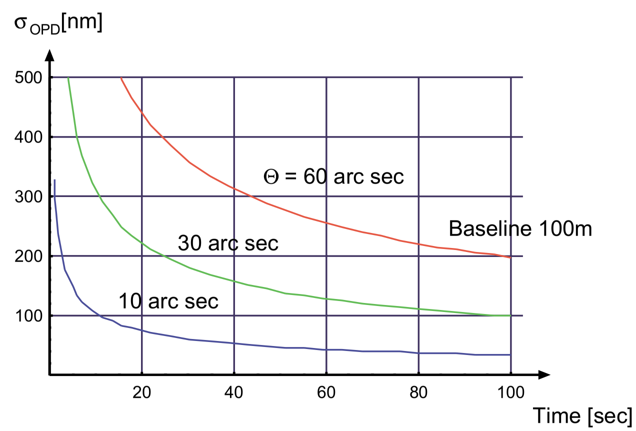
1) No imaging
2) max. exp. Time:
   ~100msec @ 10 μm (N=5)
   ~20 msec @ 2.2 μm (K=10)

Turbulence effects - Anisoplanatism I



Basislinie 200m and $\Theta = 10$ arcsec
$\Rightarrow$ T >30 min for $\sigma_\delta = 10$ micro arcsec

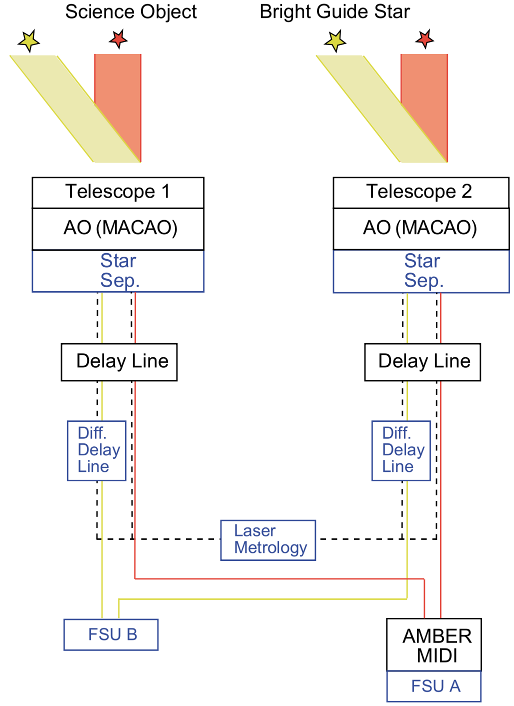
Turbulence effects - Anisoplanatism II



$\sigma_{OPD} \sim \Theta/\sqrt{T}$

Observing time >30 min
for 10 μarcsec accuracy

The VLTI + PRIMA



Standard Components + PRIMA Subsystems

PRIMA

The Dual Feed Mode enhances the VLTI in three areas:

- **Observations of faint objects (Star separator + Fringe sensor unit)**
  - **Exposure time 10-100 sec**
  - $\Rightarrow$ **K = 15-17 and N = 7-9**
- **Imaging of faint objects (Differential delay lines + laser metrology)**
  - **500nm rms over 10min**
  - $\Rightarrow$ **K = 19 with Strehl ~30%and N = 11.5 with Strehl ~80%**
- **Astrometry**
  - **5nm rms over 30min**
  - $\Rightarrow$ **10 micro arcsec astrometry**

Science Programmes

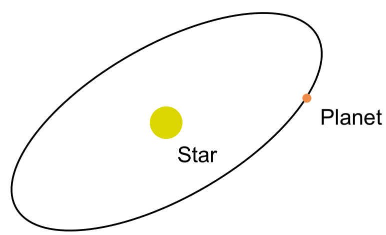
- Search of exoplanets and brown dwarfs:
  - Objects with ~$20M_J$ around nearby stars observable if:
  - N ~ 11 and dynamic range >100
- Extragalactic Studies:
  - AGN's only 'just' observable without dual feed
  - – Resolving broad line region
  - – Detection of dust tori at 10μm
  - – Temperature and density of the torus
- The Galactic Center

...

Sub-System Specs

- 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)

Direct observations



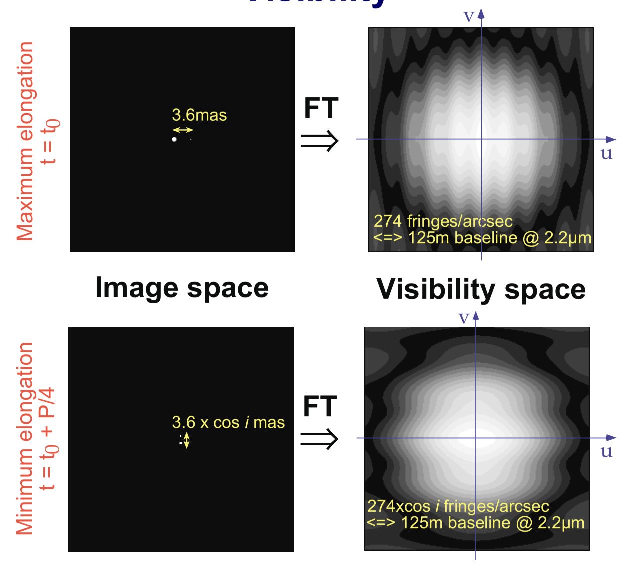
- Challenge: Planet/Star brightness ratio 10^{-9} to 10^{-4} at 5 - 500 milli arcsec
- Solutions:
  - High dynamic range observations
    - Visibility
    - Phase
  - Provide deep null for wide wavelength range with Nulling Interferometer

Extremely high accuracy for visibility and phase measurements required, and thus, elimination of turbulence effects

Interferometry and planet detection

- Interferometry
  - Very high spatial resolution...
  - ...but moderate uv coverage
    $\Rightarrow$ Imaging by model fitting rather than by direct inversion
  - Moderate sensitivity
- Exoplanet detection
  - μarcsec motions or close companions
  - Simple geometry
  - Relatively bright primary sources

Direct observations I: Visibility



(Example given for 51 Peg with *i* =75° and brightness ratio of 20)

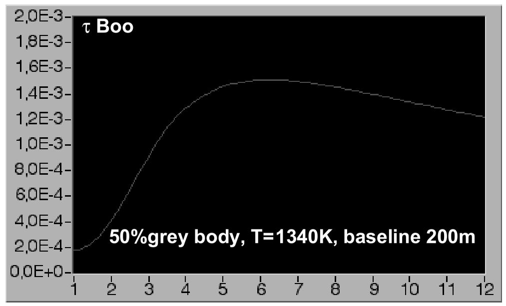
- Visibility varies in the uv plane as a function of brightness ratio and planet position

Figures and idea from V. Coudé du Foresto

Ref: VLT Opening Symposium, March 1999, Ed. J. Bergeron

Direct observations I: Visibility - cont'd.

Visibility modulation

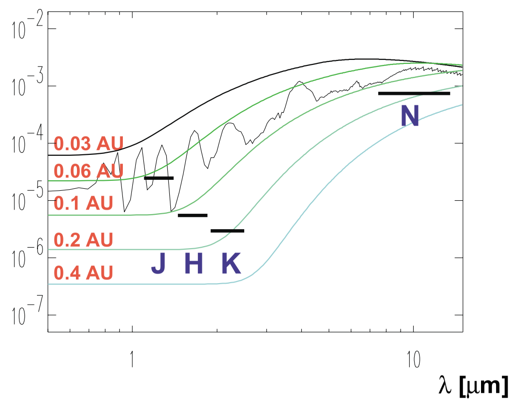


VLTI performance:

- Visibility accuracy (expected for VINCI) seeing limited in 5mn integration
  - All turbulence modes $5\ 10^{-2}$
  - Piston mode only $3\ 10^{-3}$
  - Piston removed ?
- Improvements:
  - Synchronise observations with radial velocity observations
  - Increase observing time SNR =10 possible for τ Boo in 30hrs (on ATs)

Direct observations II: Differential Phase - cont'd

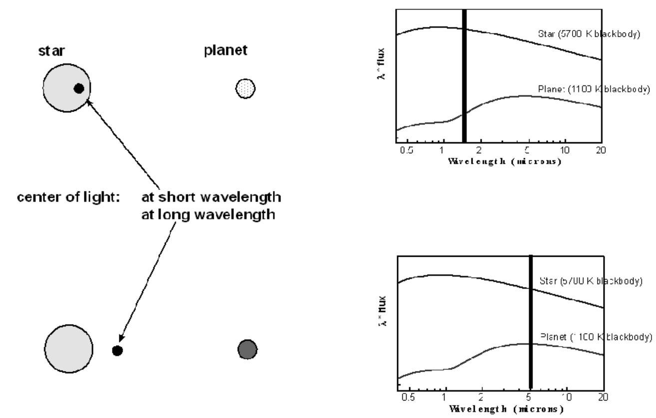
Phase amplitude [rad]



- 1.4 blackbody Jupiters at 0.03- 0.4 AU + synthetic 51 Peg spectr., sun like star at 10pc
- Performance of AMBER (J,H, K) and MIDI (N) for 5 hrs with UTs (baseline 80m) and spectral resolution of 25

Figure and idea from B. Lopez and R. Petrov
Ref: VLT Opening Symposium, March 1999, Ed. J. Bergeron

Direct observations II: Differential Phase



- Apparent star position varies with wavelength since planet is brighter at longer wavelength
- Center of light moves *closer* to star for larger separations δ since planet brightness ~ $1/\delta^2$

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