VLTI Tutorial

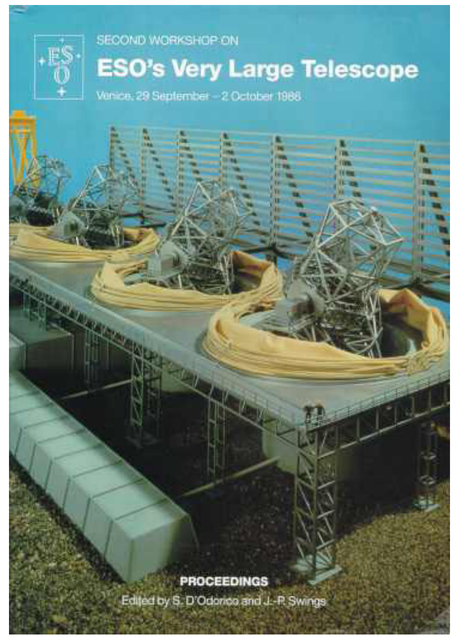
The VLTI conceptual design

VLTI Concept...The birth

From a 16m telescope (1980)

VLT
Very Large Telescope Project

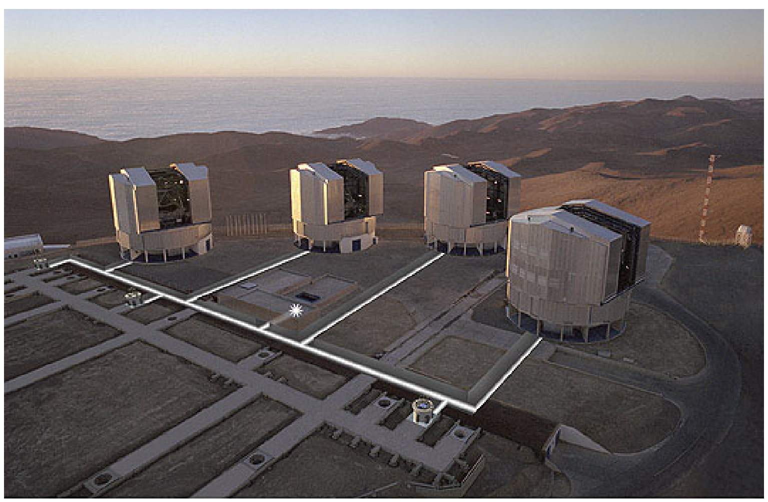
…nice dream, but no interferometry …



…to a linear array of four 8m telescopes... (1988)

…the baby was born! …

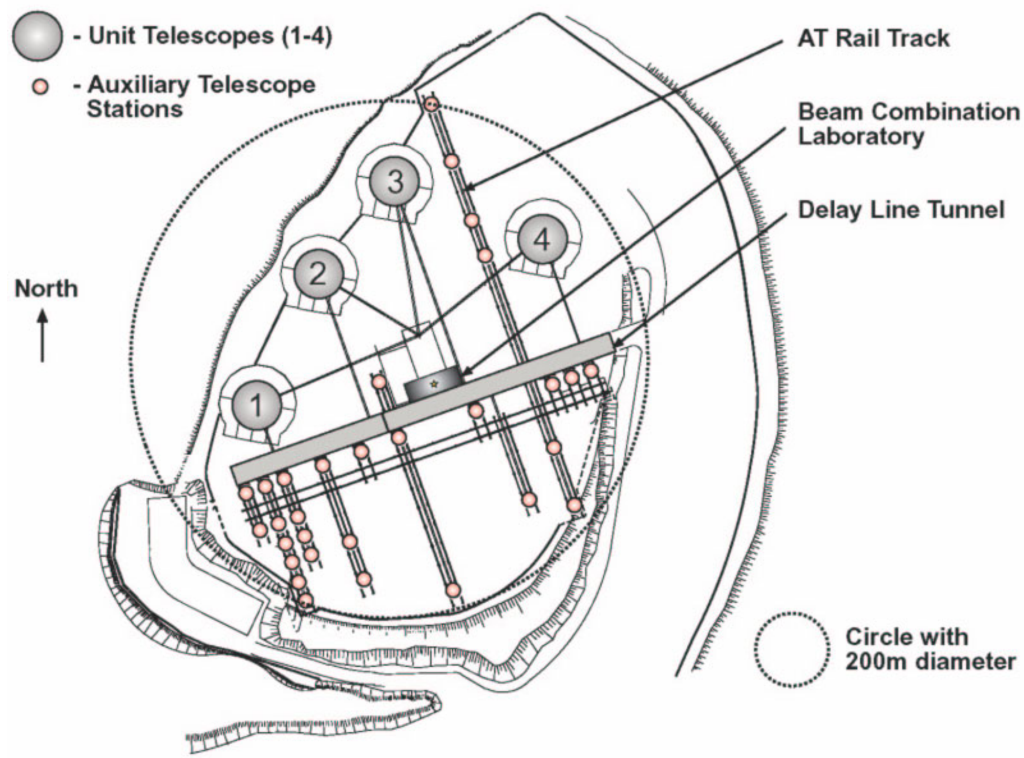
…to a mature VLT Interferometer layout (1990)



…the troubles could start! …

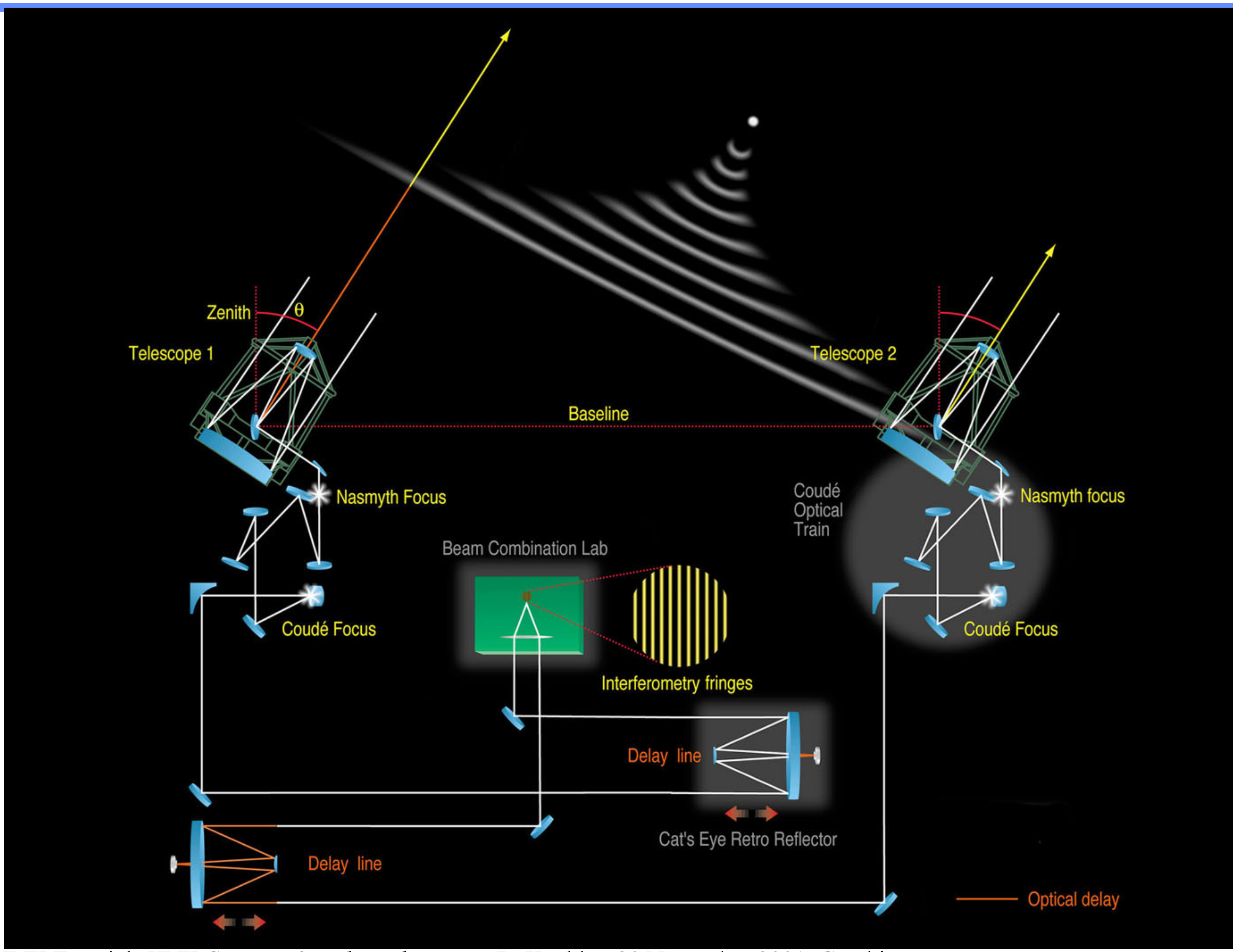
The Final VLTI Array Layout

- 4 UT's as 'trapezoidal' as possible (wind shadow, ground quality)
  - Baselines 47 – 130m ⇒ 1.5 milli arcsec
- 30 Stations for AT's
  - Baselines 8 – 200m ⇒ 1 milli arcsec
- Delay Line Tunnel (160 x 8m) positioned to minimize path differences. Can house 8 DL's



- Central combining Lab (20 x 7m) with specific VLTI building / control room
- All elements are located on an 8m grid
- Light travelling underground for high thermal stability (vacuum alternative not selected for cost reasons)

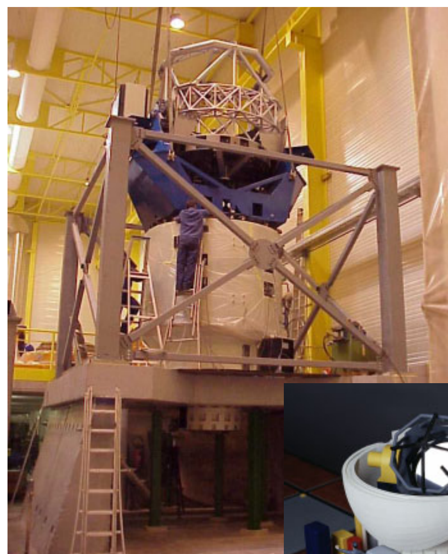
The VLTI Optical Layout

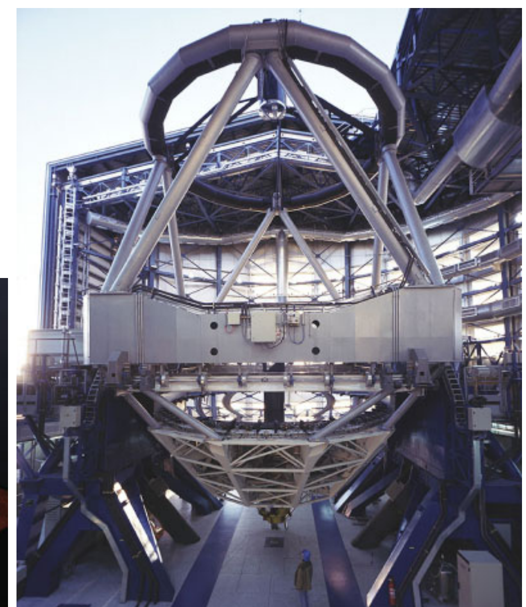


VLTI Tutorial: *VLTI Concept & technical aspects*, B. Koehler, 20 November 2001, Garching

The telescope family

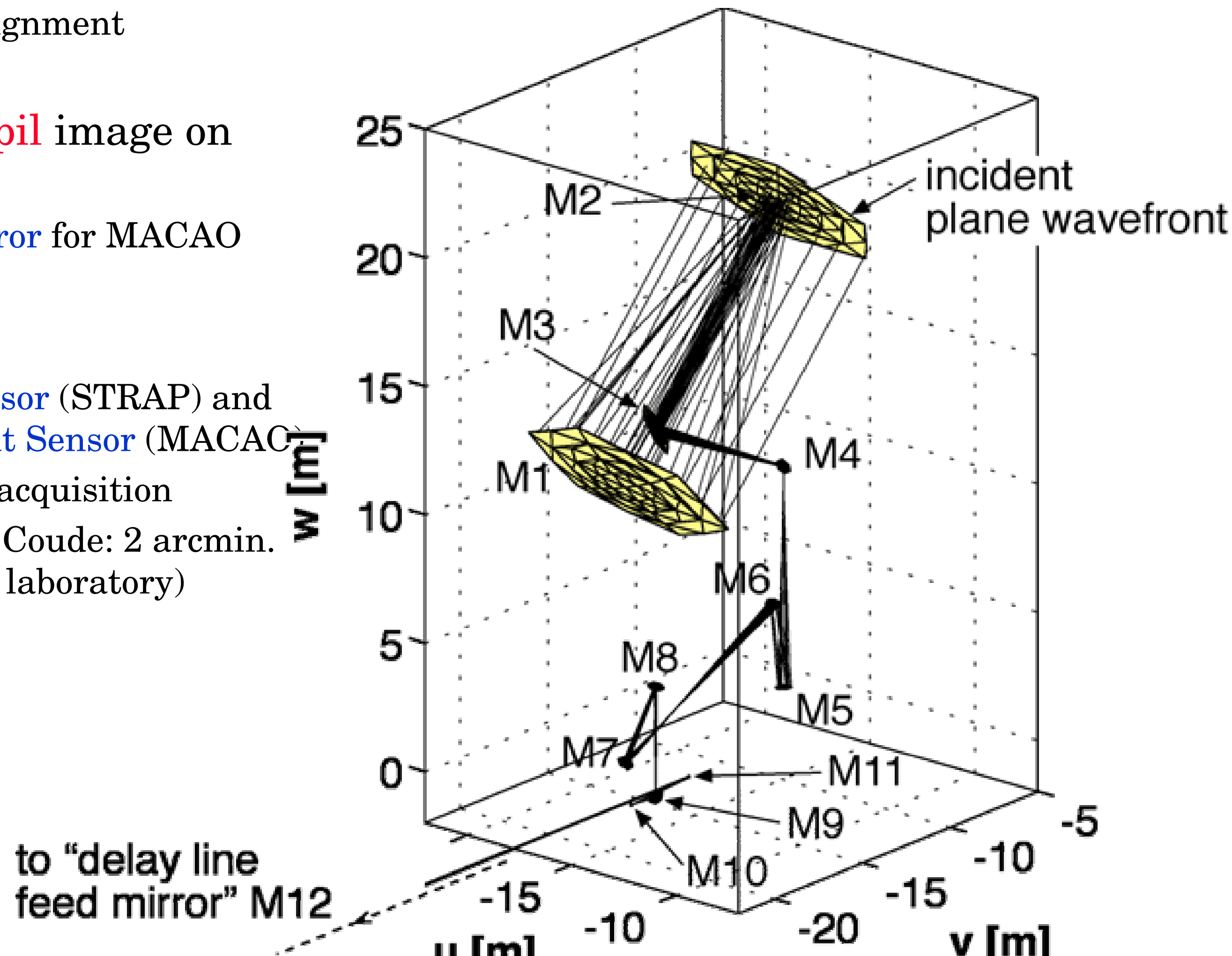
- The ‘Appetizers’ (2 Siderostats)
  - Installed early 2001
  - Relocatable in day(s)
  - Primary: 0.4 m
  - Autoguiding only
  - Airy disk (in K): 1.1”
- The ‘Workhorses’ (3 Auxiliary Tel.)
  - Relocatable in 3h
  - Primary: 1.8m
  - Fast Tip-Tilt
  - Limited Chopping
  - Airy (in K): 0.25”
- The ‘Kings’ (4 Unit Tel.)
  - Fixed position!
  - Primary: 8 m
  - Adaptive Optics
  - Airy disk (in K): 0.06”



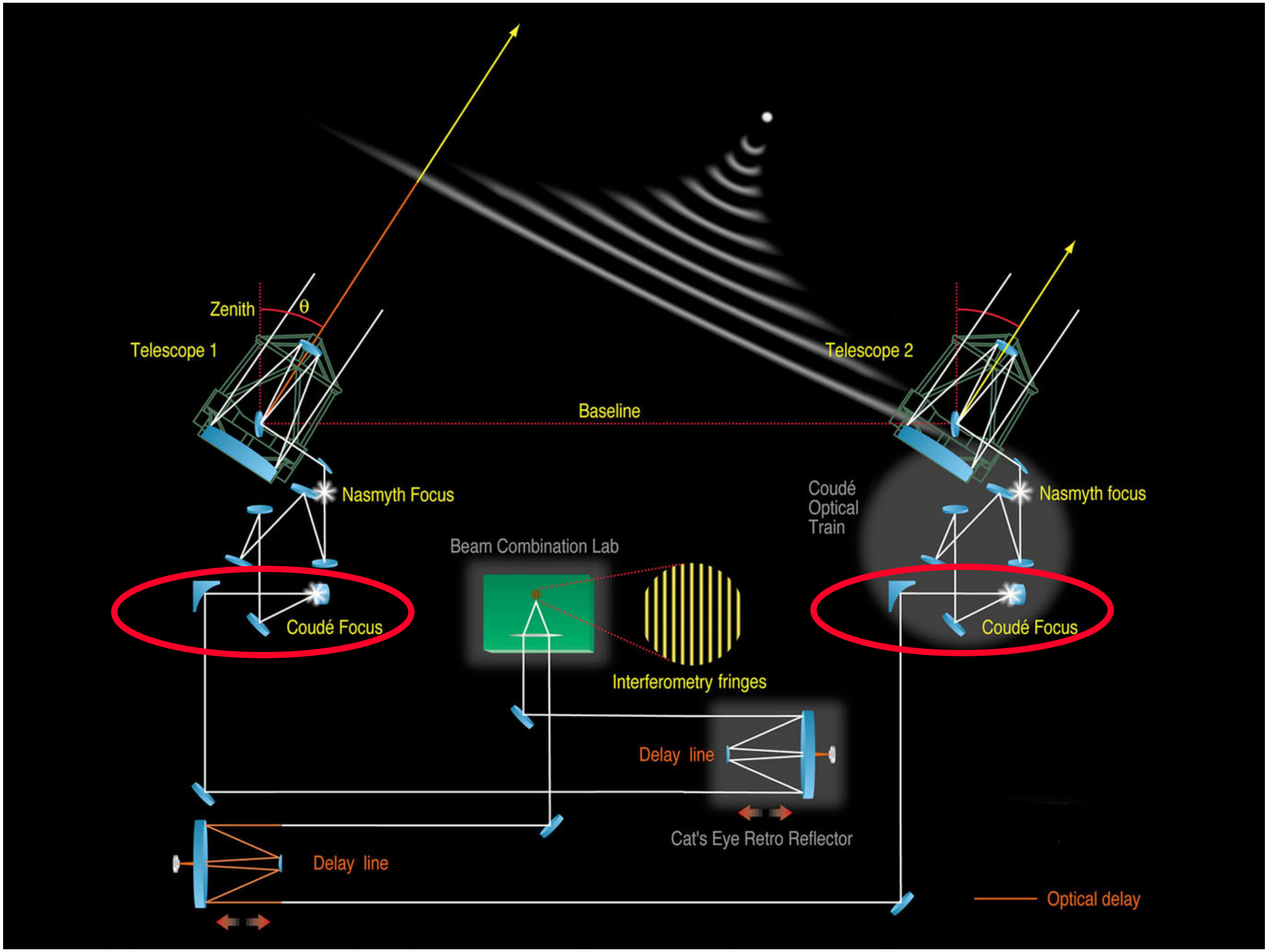


Telescope Optical Design

- Intermediate Focus below M4:
  - Various artificial light sources for calibration & alignment
- Intermediate pupil image on M8:
  - Deformable mirror for MACAO
- Coude Focus:
  - Fast Tip-tilt sensor (STRAP) and later Wave Front Sensor (MACAO)
  - TCCD for Field acquisition
  - Field of View at Coude: 2 arcmin. (FoV 2 arcsec in laboratory)



Relay Optics



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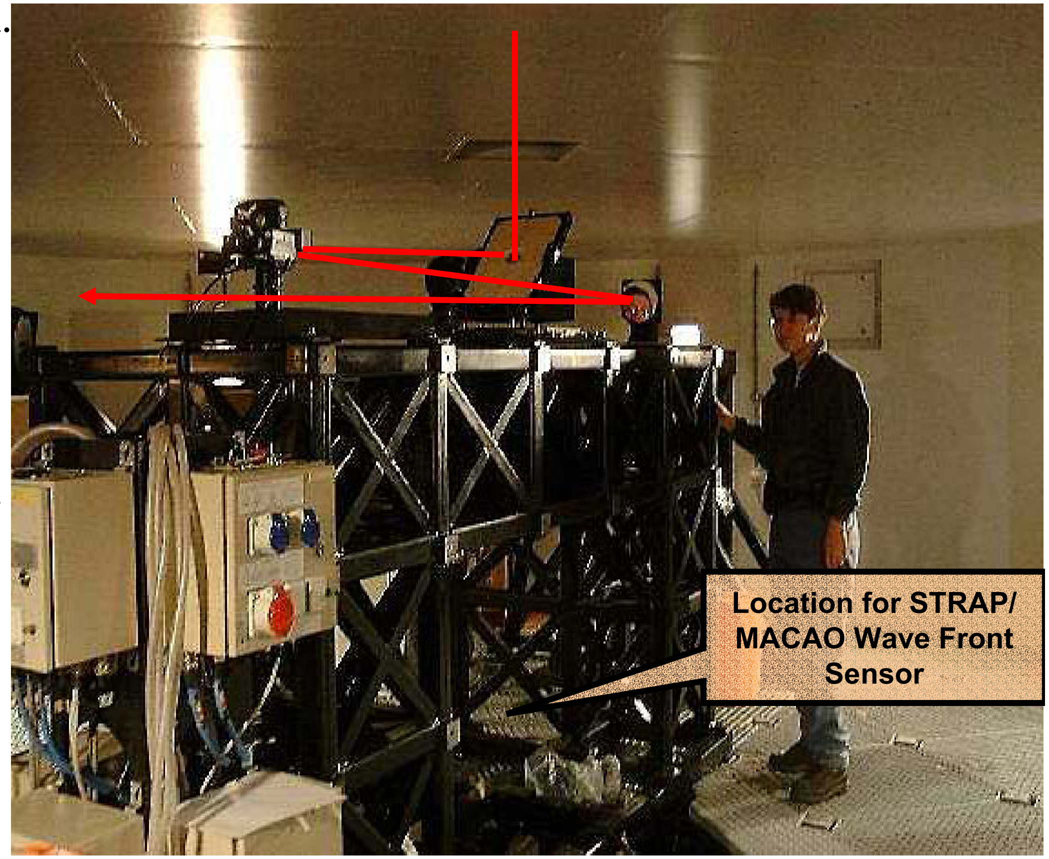
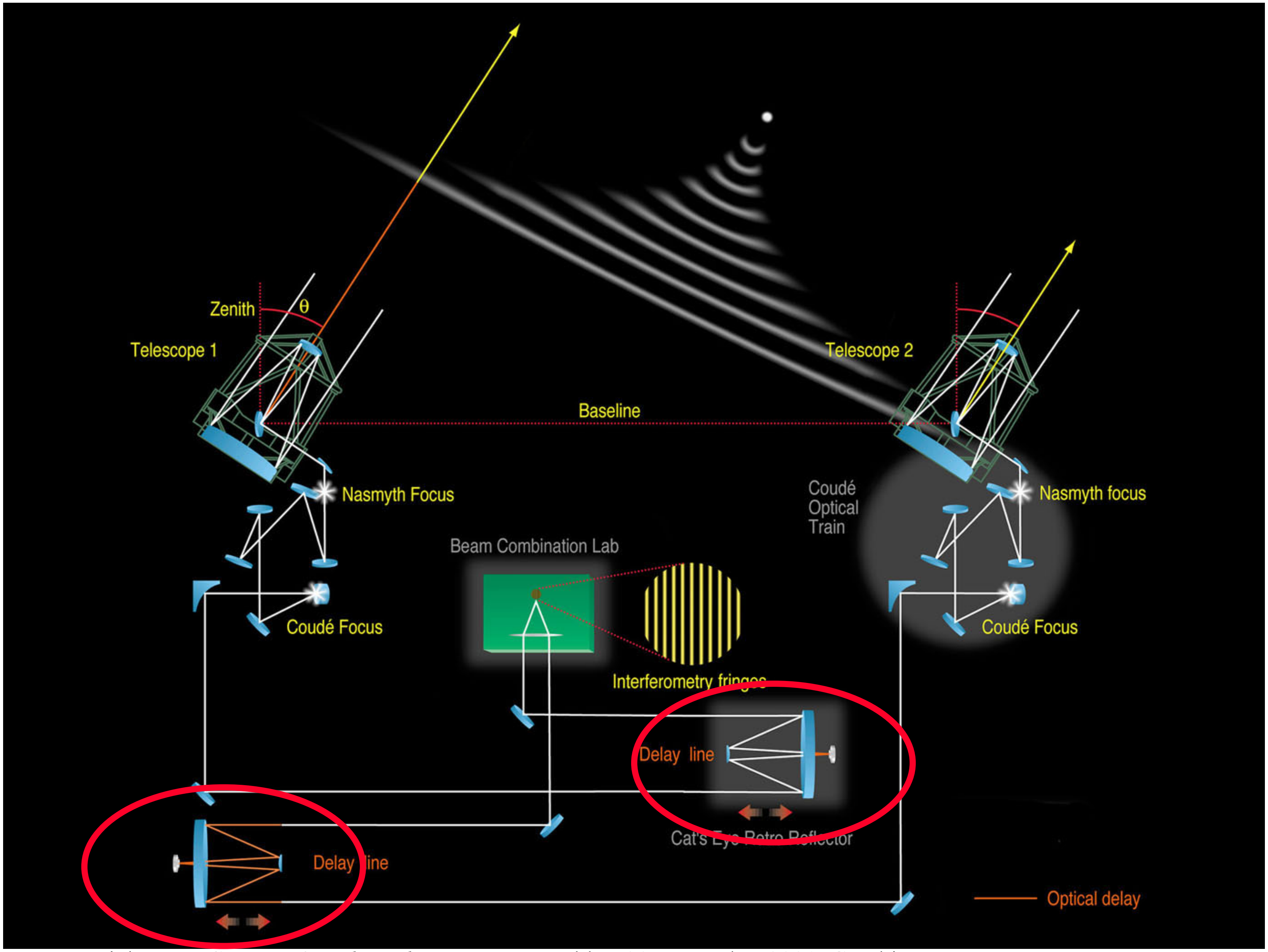
Relay Optics

- ‘Grasping’ the UT-photons
  - M9: large dichroic.
    - Reflects IR to VLTI
    - transmits Visible to STRAP and later MACAO Curvature sensor.
    - Optimized for polarization.
  - M10: convex spherical.
    - Re-image telescope pupil (M2) in Tunnel center.
    - Articulated mount to adjust lateral pupil position in Lab.
  - M11: off-axis parabola.
    - Collimates beam and send it into light duct towards M12 in DL Tunnel



The Relay Optics (M9, M10, M11) inside UT Coude room)

The Delay Lines



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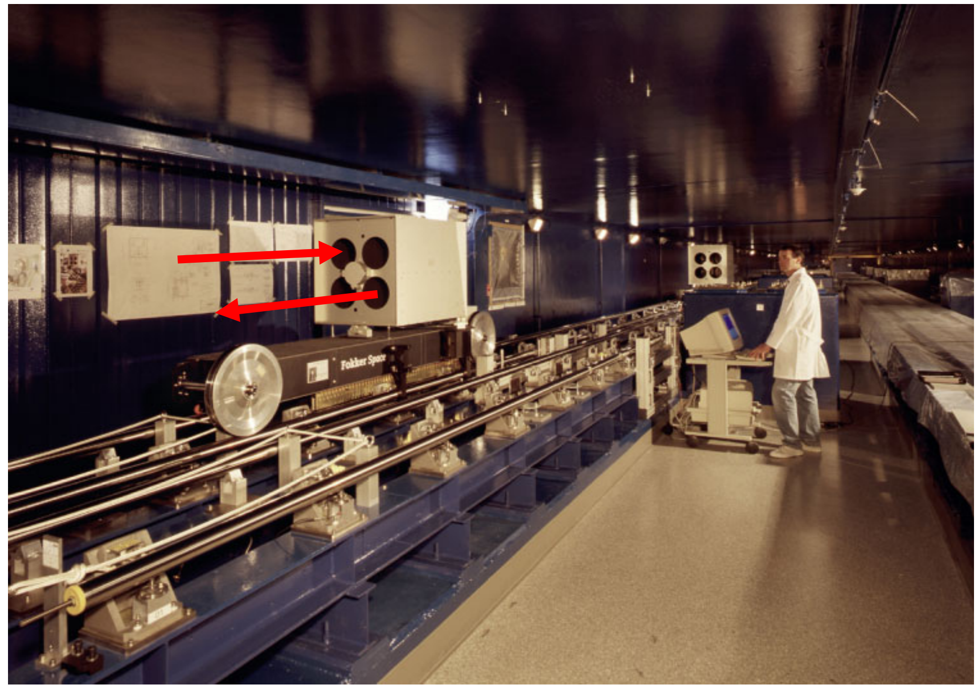
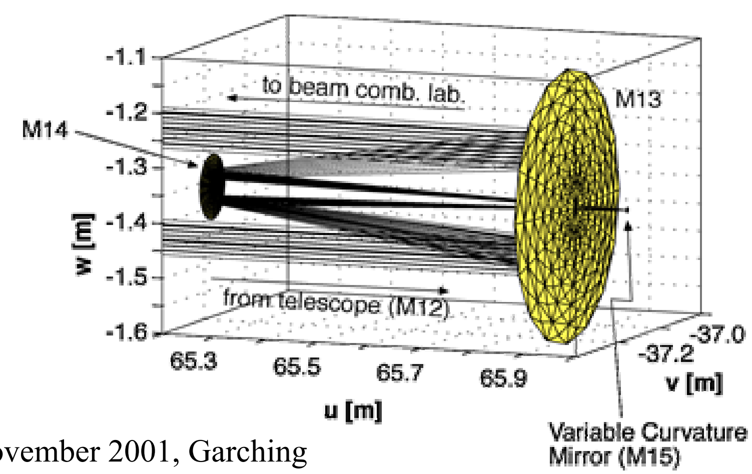
The Delay Lines

- The 'Paranal-Express'
  - Stroke: 60 m (120m in OPL)
  - Resolution: <5nm
  - Max. velocity: 0.5 m/s
  - Stability (jitter): <14nm rms
  - Power dissipation: <15W

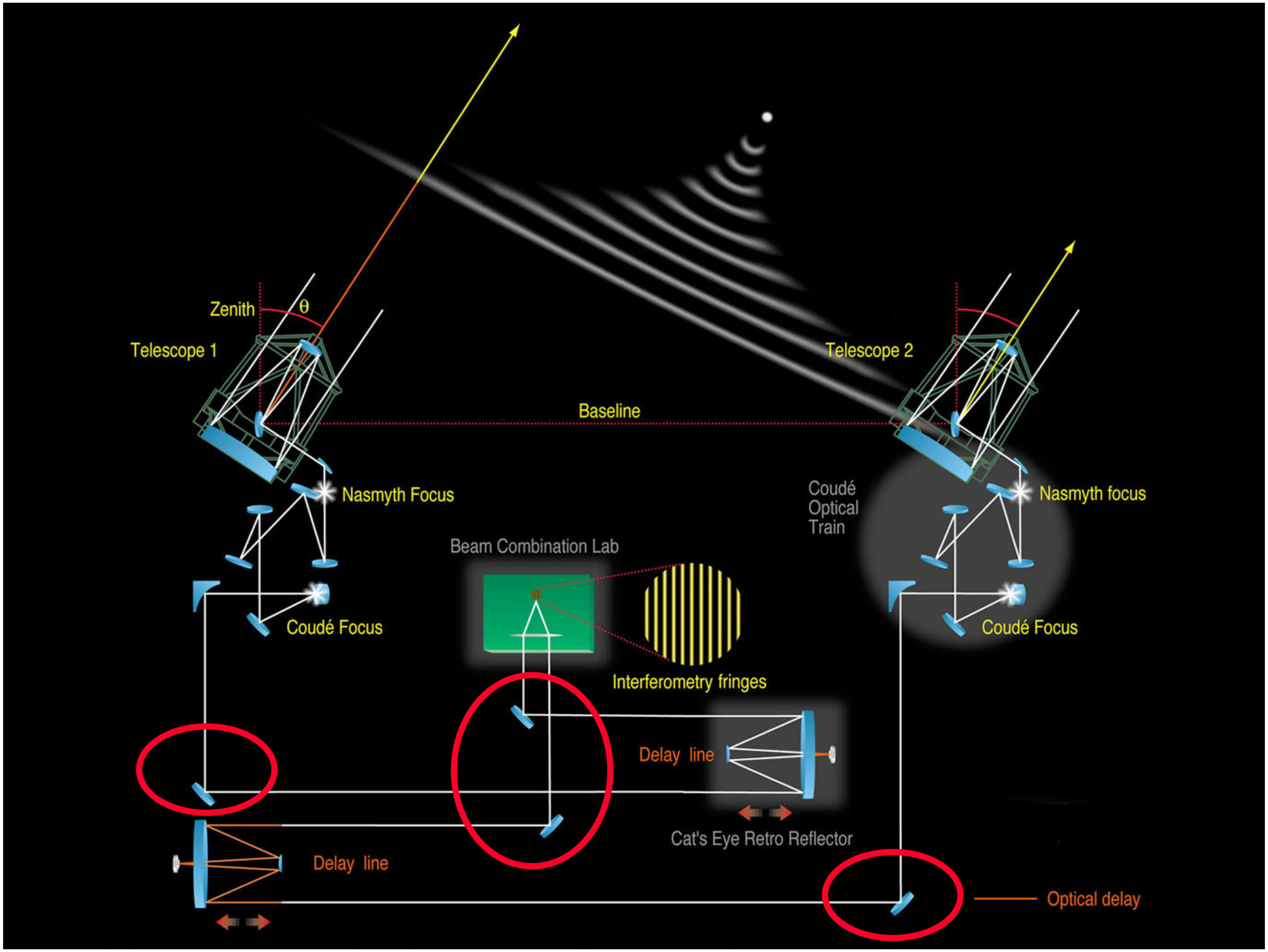


The first two Delay Lines (#I & II) inside the tunnel

- Variable Curvature Mirror (VCM)
  - re-image pupil inside the Laboratory
  - mounted on piezo translator for fast OPD correction

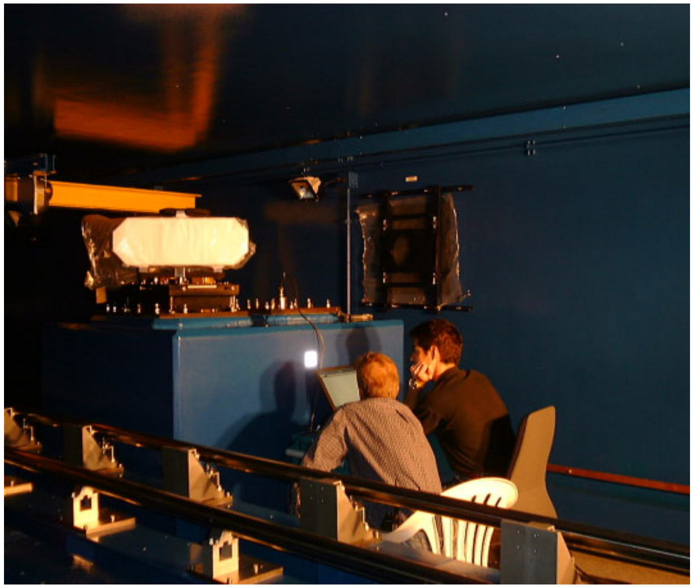


Transfer Optics



Transfer Optics

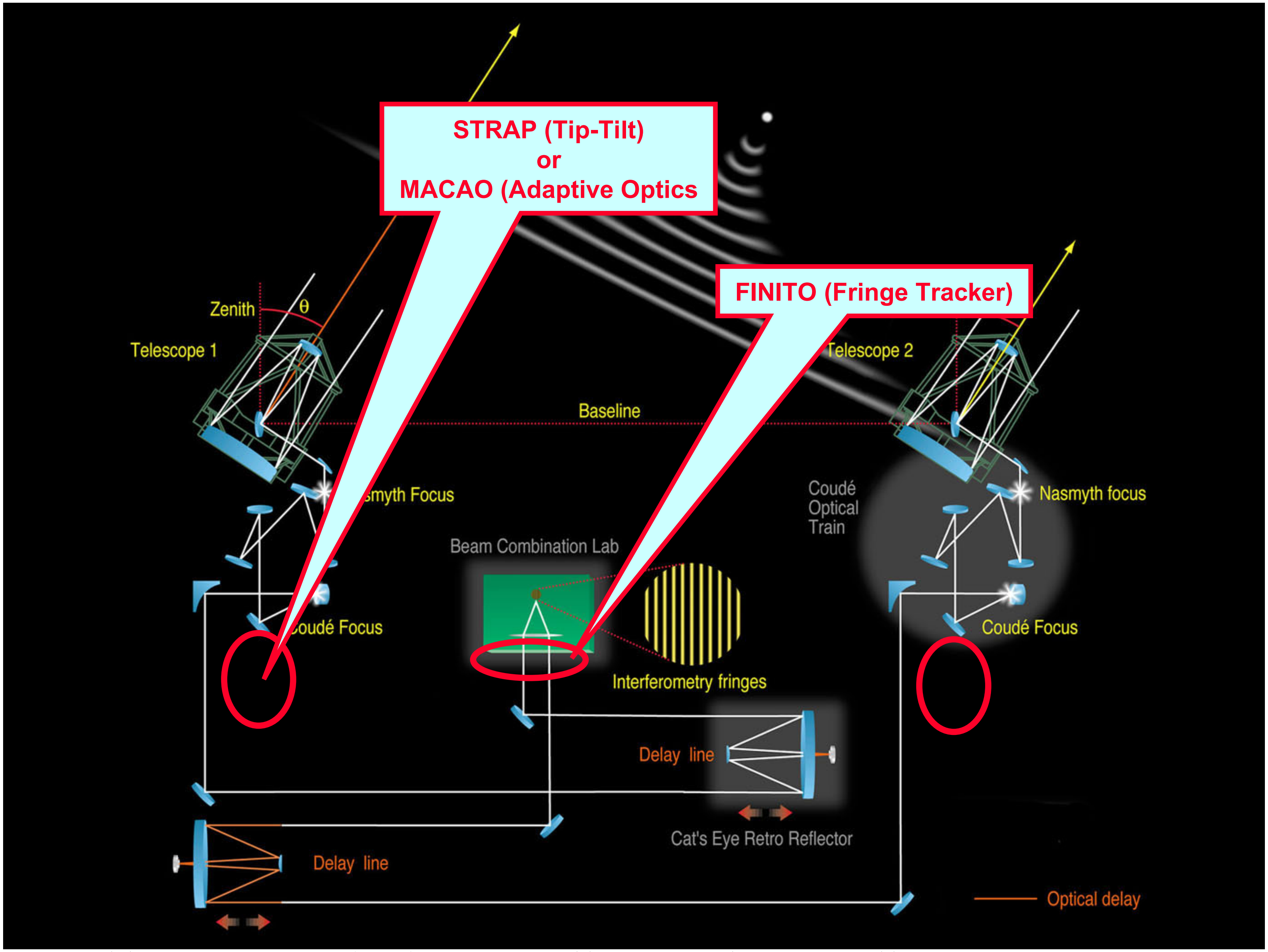
- The beam bending 'gadgets'
  - Very high optical quality flats (λ/60 surf.)
  - Coating optimized for transmission and polarization (45° incidence)
  - Very stiff mounts and tables for immunity to μ-seismic noise
  - M12 eventually on robotic arm for automatic array reconfiguration
  - M16 on translation stages for beam switching inside lab.
  - Support future dual-feed (PRIMA)



The M12 flat folding mirror

The M16 flat folding mirror

Beam Make-up

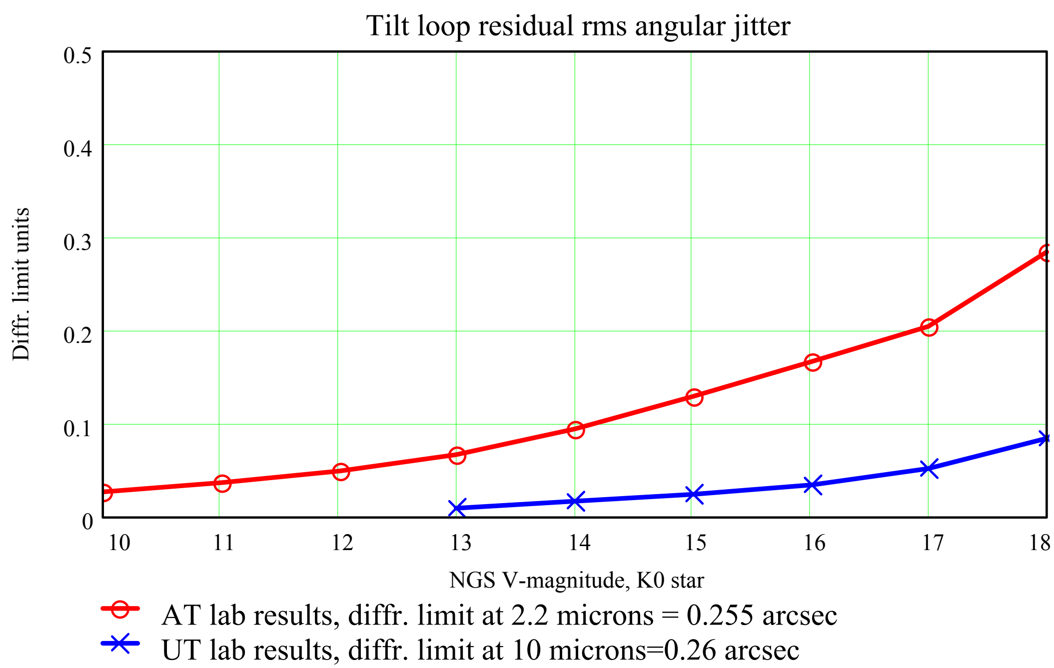


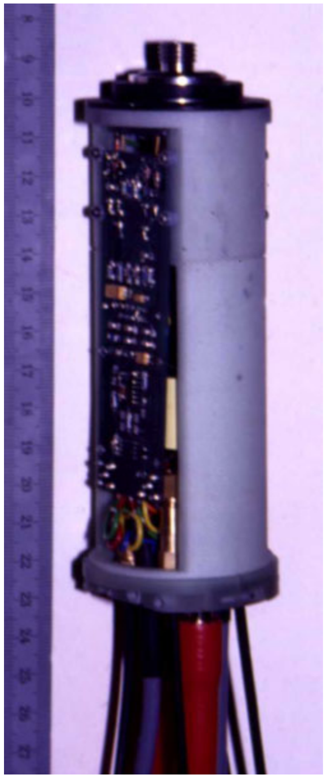
STRAP (Tip-Tilt)
or
MACAO (Adaptive Optics
FINITO (Fringe Tracker)
Zenith
θ
Telescope 1
Telescope 2
Baseline
smyth Focus
Nasmyth focus
Coudé
Optical
Train
Beam Combination Lab
oudé Focus
Coudé Focus
Interferometry fringes
Delay line
Cat's Eye Retro Reflector
Delay line
Optical delay

STRAP (Tip-Tilt)

- Quad-cell detector with APD at telescope Coude focus

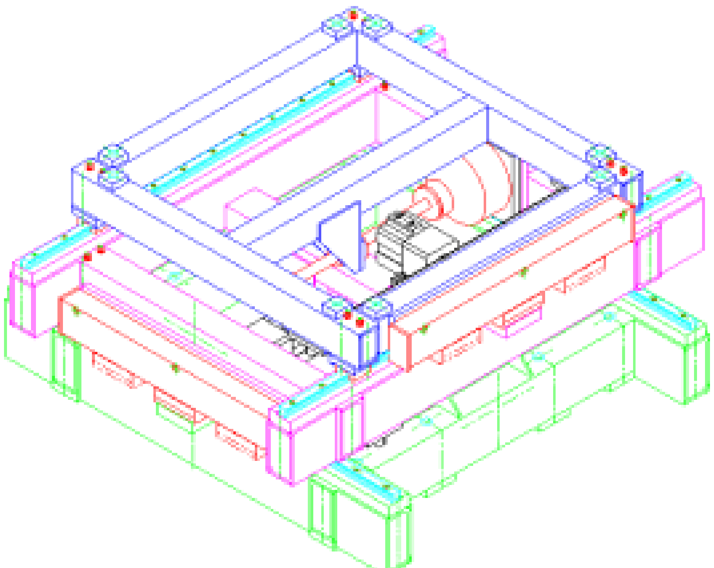
- Pure tip-tilt correction is optimal when $D/r_0<4$, i.e. UT/10µm (MIDI) or AT/2 µm (VINCI,AMBER, MIDI)
- Gain on Strehl up to 5.
- Will be used on UT till MACAO is available
- Will be resident on AT

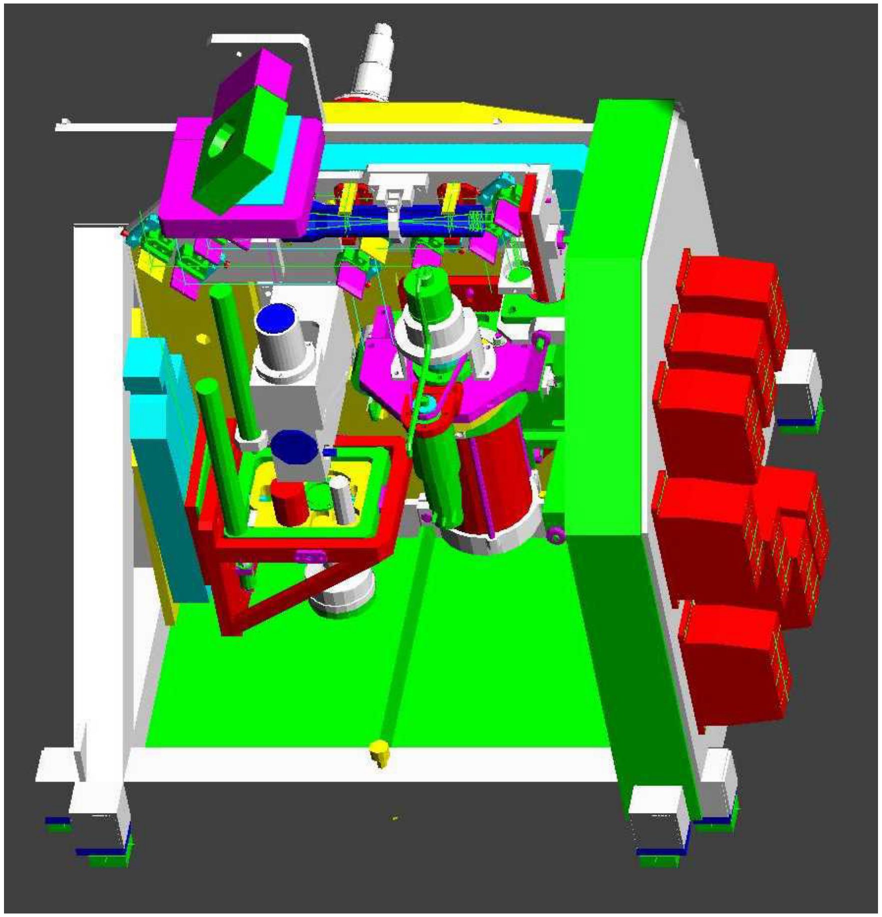




MACAO (Adaptive Optics)

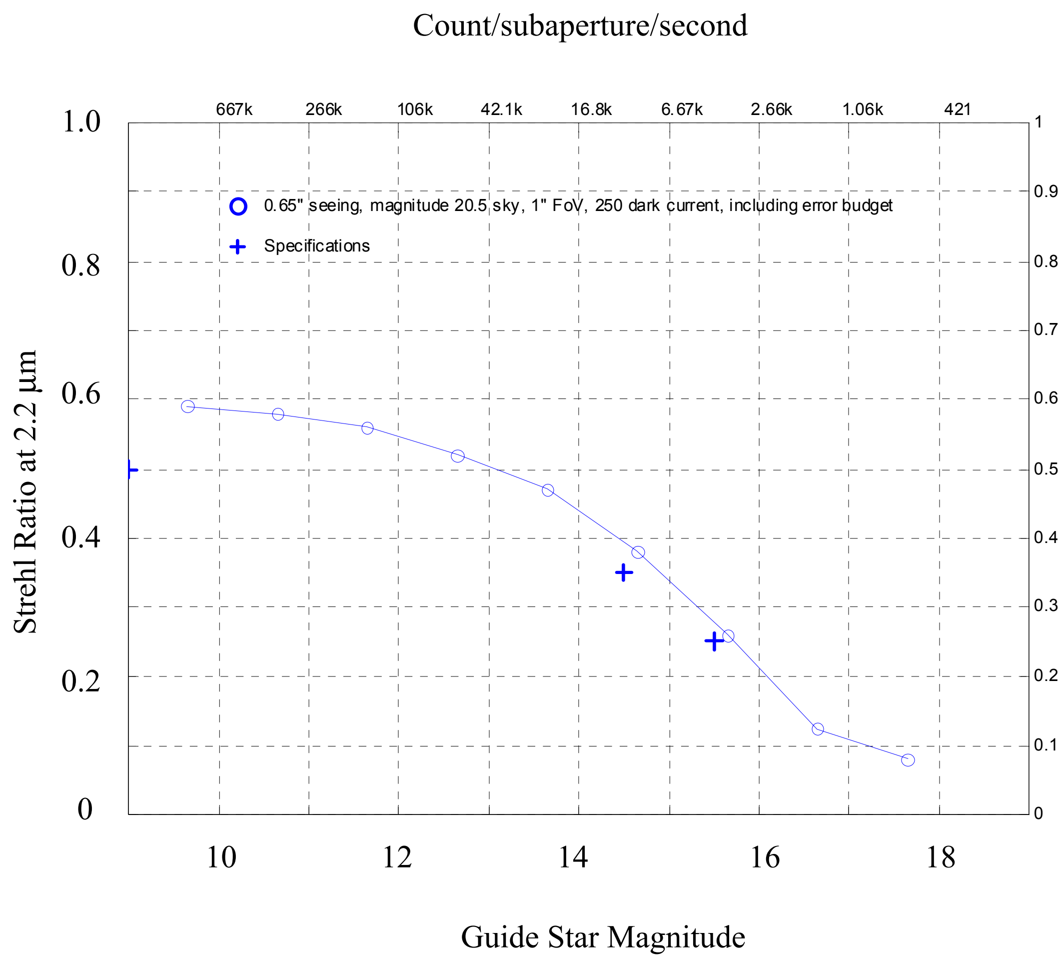
- A must for UT in K-band (AMBER). Gain in coherent flux ≈100
- 60 elements Curvature System at telescope Coude
  - WaveFrontSensor using APD coupled with optical fibers
  - Bimorph Deformable Mirror on Tip-Tilt mount
  - vibrating membrane,
  - radial geometry micro-lenses,
- X-Y Table allows reference source different from target



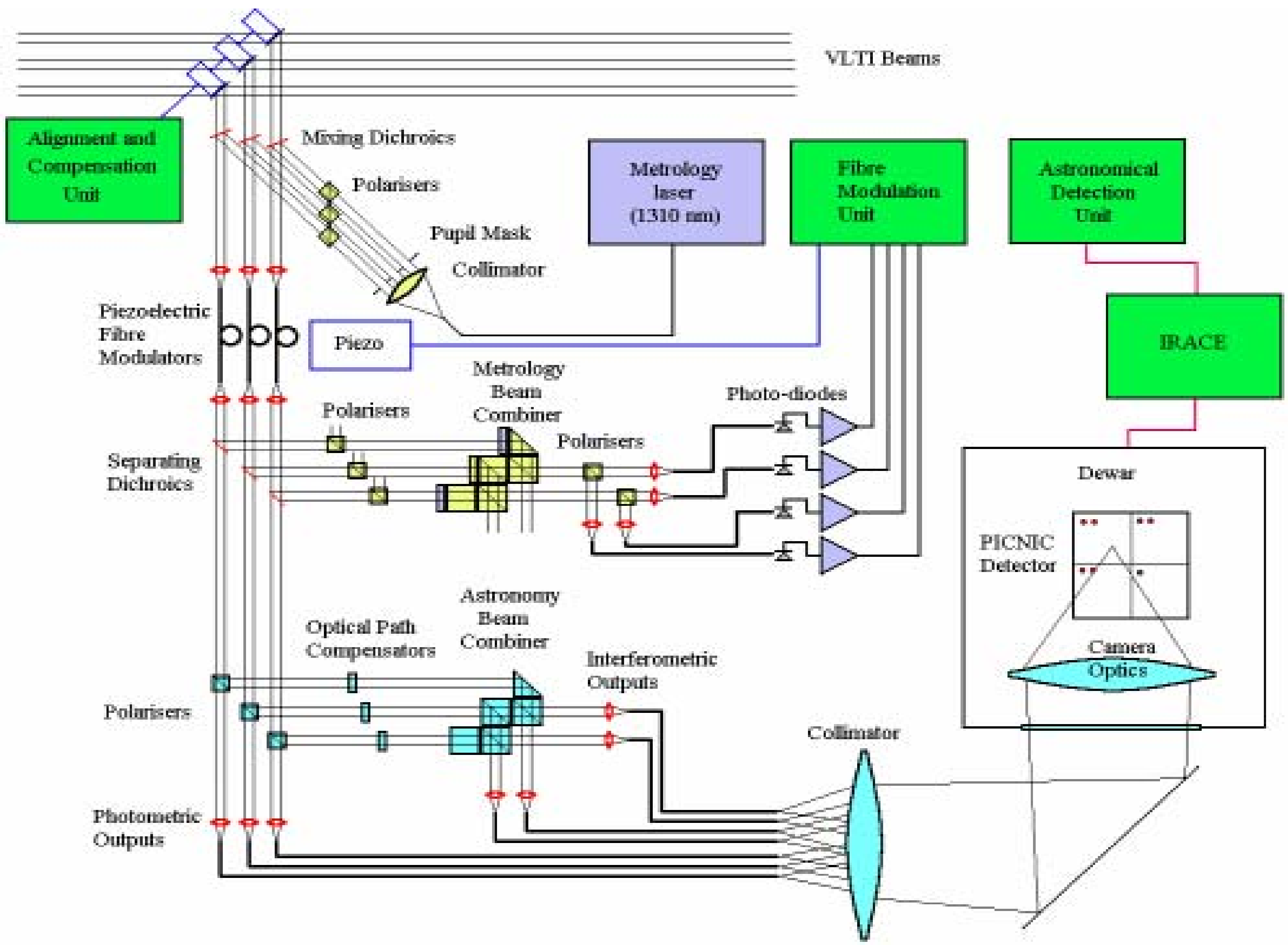


MACAO performance

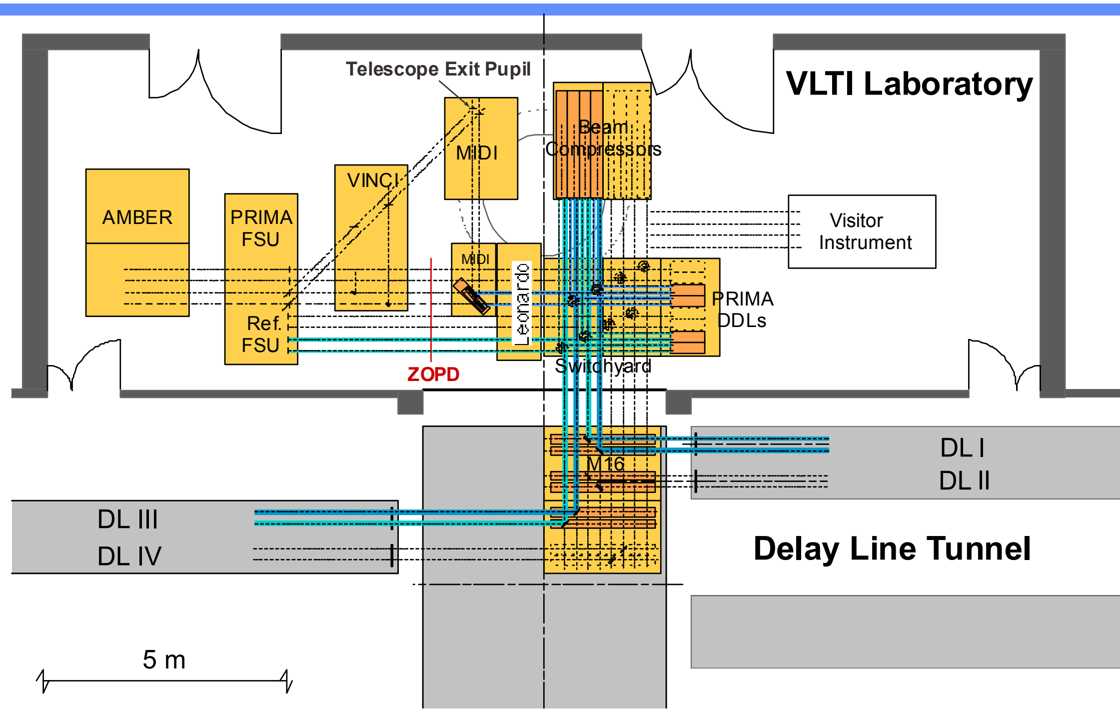
0.65” @ 500 nm,
τ_o~4ms,
V=20.5 sky background



FINITO (Fringe Tracker)



The VLTI Laboratory

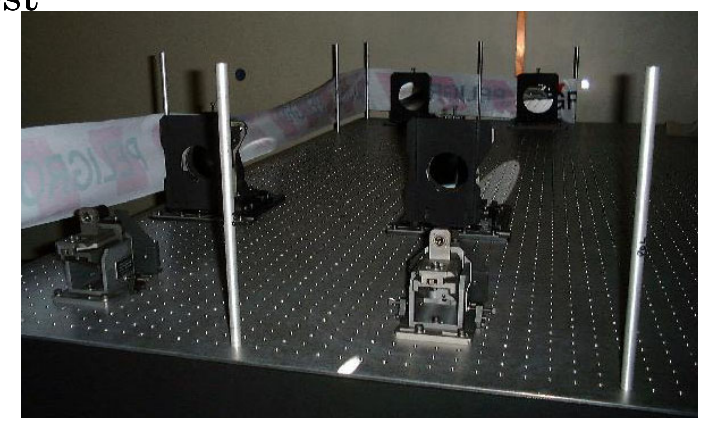


- High thermal stability; limited access, low power dissipation
- Telescope Exit Pupil re-imaged into instruments
- Optical design for up to 8 beams (4 UTs with dual feed)

Inside the Laboratory

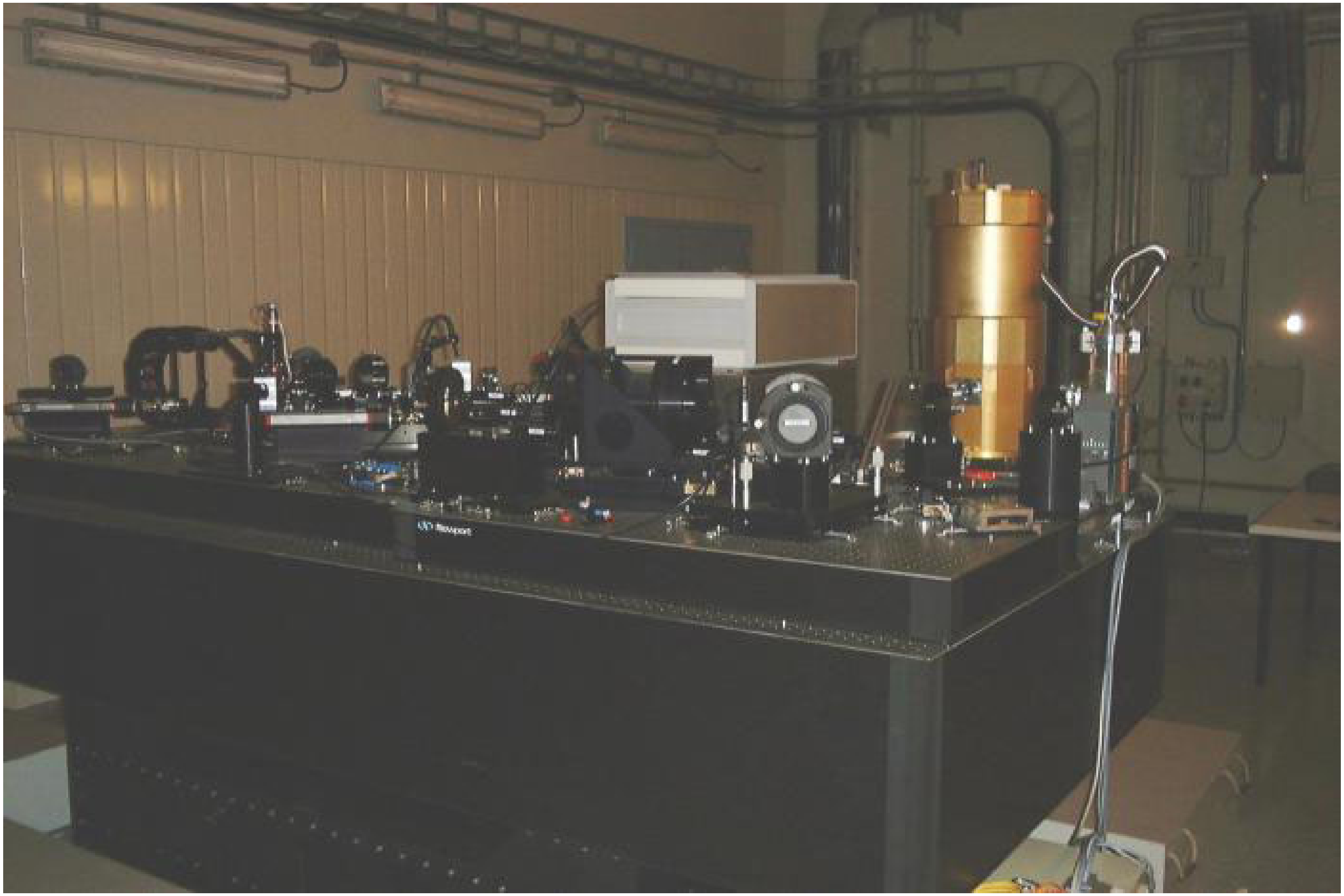
- The Beam Switchyard
- The Beam Compressors
  - 3-mirror design (compress 80 ➔ 18 mm)
  - High optical quality off-axis parabolas (surface error 7 rms)
- LEONARDO Reference sources
  - Laser and white-light sources
  - Light can be sent to any instrument or backwards to telescope
  - Provide reference axis for each beam and reference OPD between beams
  - Enable instrument to obtain fringes in ‘autotest’
- VINCI Test Instrument
  - Used for VLTI commissioning & later as reference for performance tracking.
- Fringe Tracker FINITO
  - Co-phases (3 beams) to allow long exposures
  - mH<12 (UT)

The Switchyard &
***Leonardo* reference source**



The Beam Compressors (3 mirrors each)

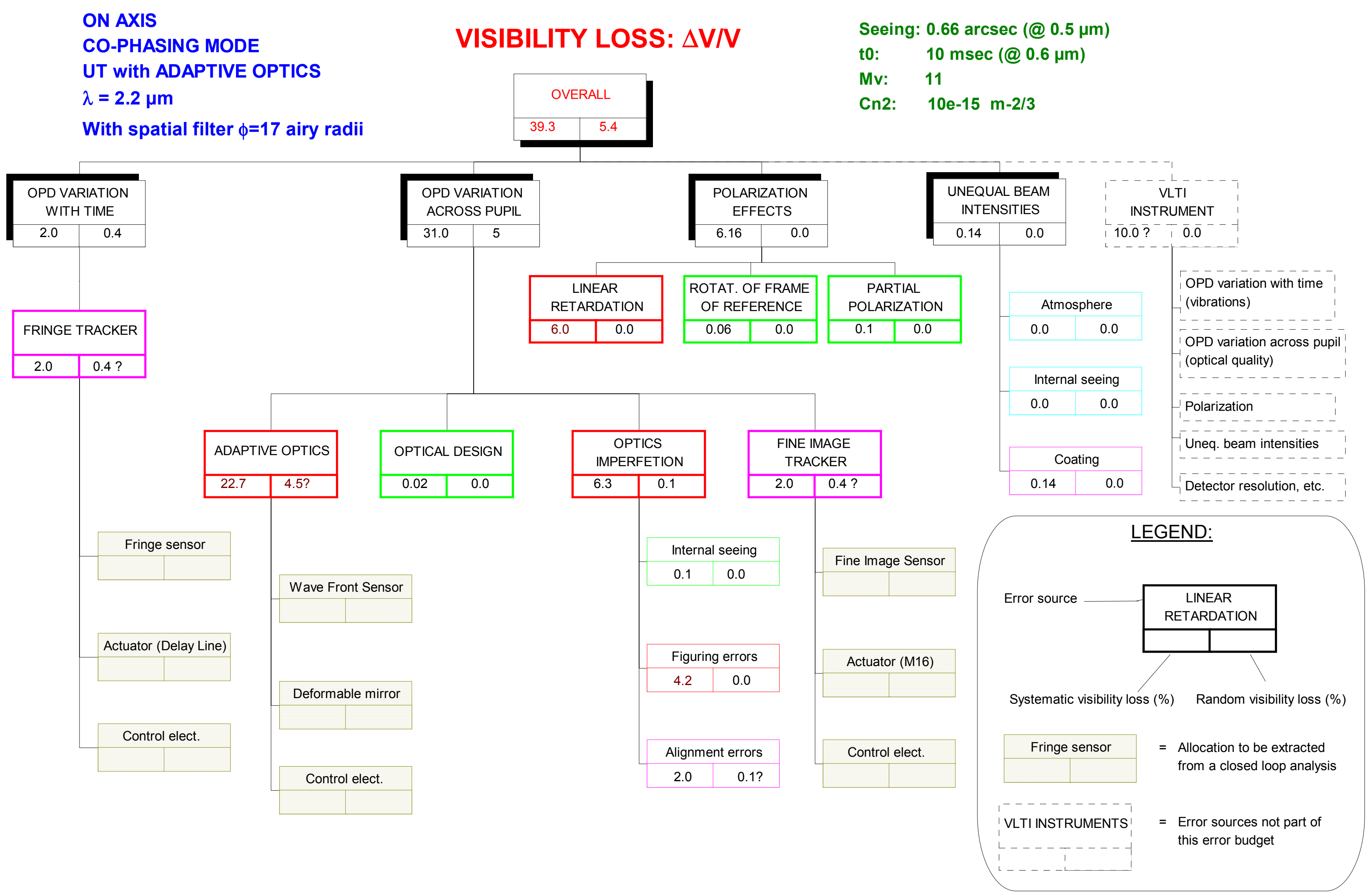
VINCI



VLTI Tutorial

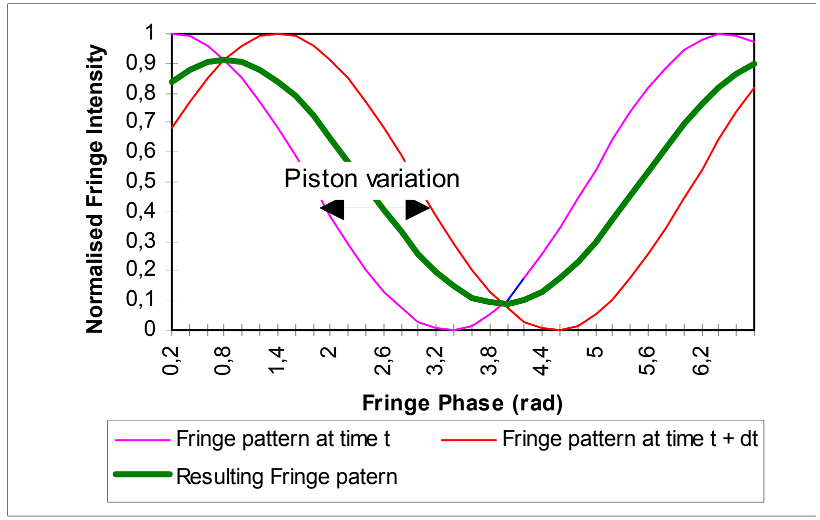
The VLTI
selected critical technical aspects

VLTI Error Budget



OPD variation with time (Piston errors)

- Error sources:
  - Atmosphere
  - Internal seeing
  - Vibration (wind, natural & man-made seismics, acoustics, pumps, etc.)
- Compensated (Partially) by fringe tracking.

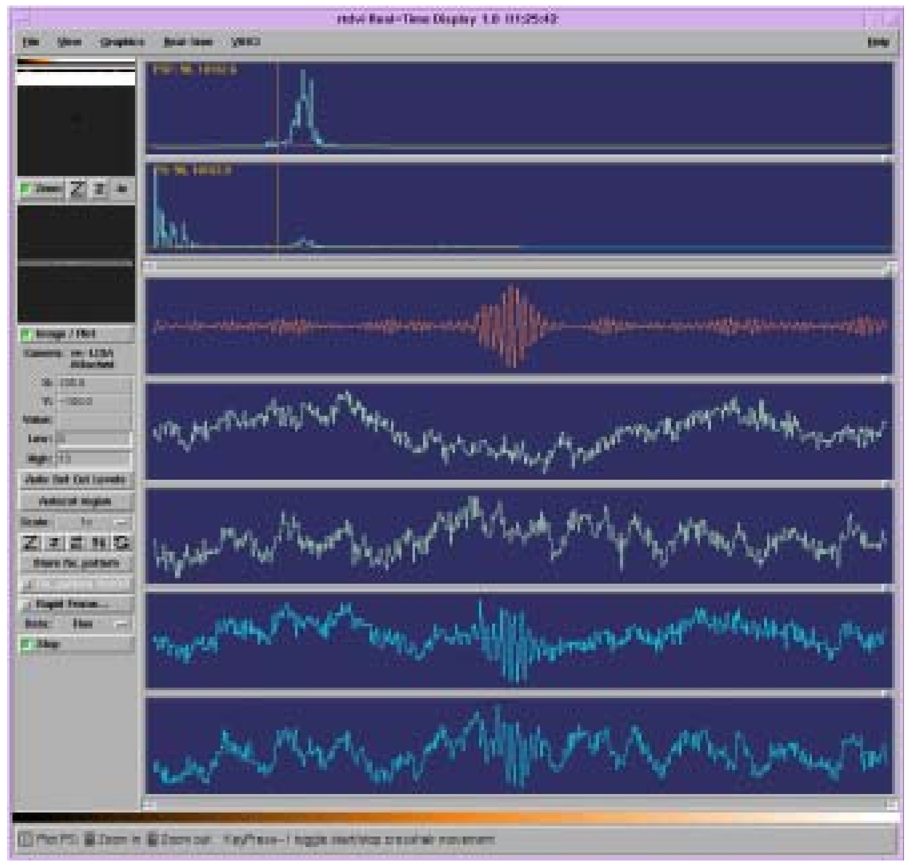


- Top Level requirement:
  Instrumental errors (internal seeing & vibrations) < atmosphere

Wavelength	0.6 µm	2.2 µm
Exposure time	10 msec	48 msec
OPL requirement (each arm) in **[nm]**	21	75
Telescope (UT or AT, each)	**14**	**50**
Delay Line (each)	**14**	**50**
Beam Combiner	**6**	**21**
Transfer Optics	**3**	**10**
Internal Seeing	**3**	**10**

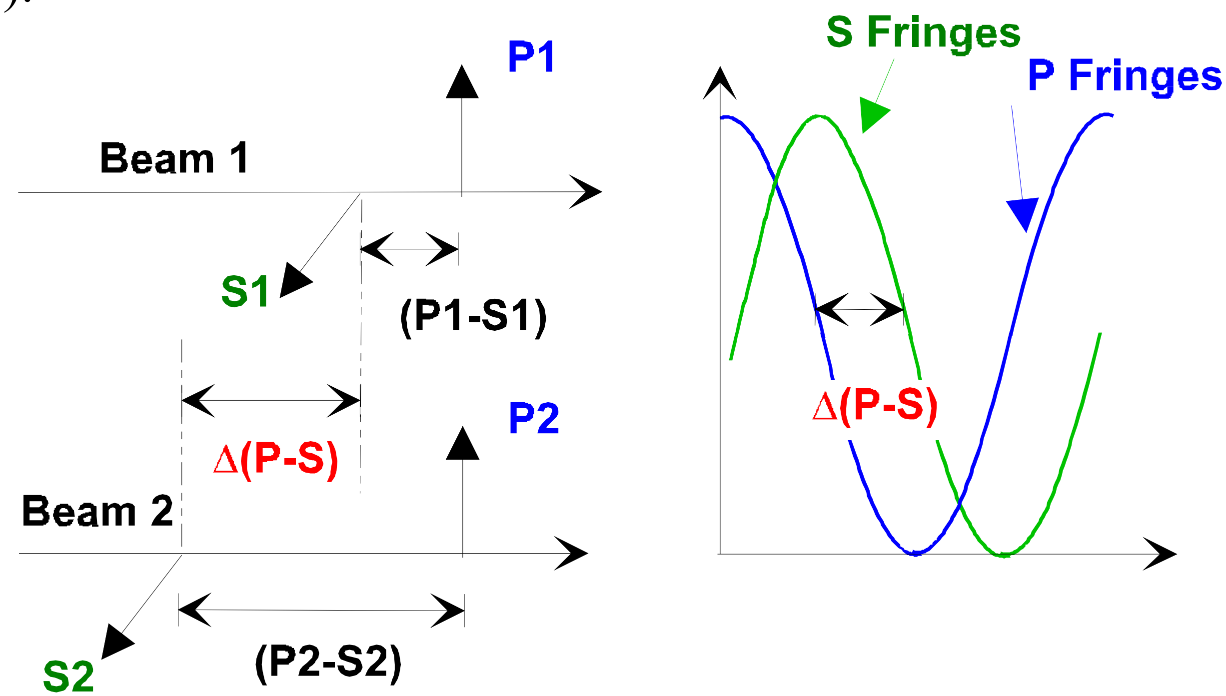
Unequal beam intensity

- Visibility loss due to intensity mismatch: $$\frac{\Delta V}{V} = 1 - 2.\frac{\sqrt{I_1}.\sqrt{I_2}}{I_1 + I_2}$$
- Error sources:
  - Atmospheric scintillation (negligible)
  - Coatings (small)
  - For fiber-fed instrument (large):
    - Tip-tilt errors
    - Instantaneous Strehl fluctuation
- VINCI measure I1 & I2 (photometry channels) to correct for this effect. $\Rightarrow$



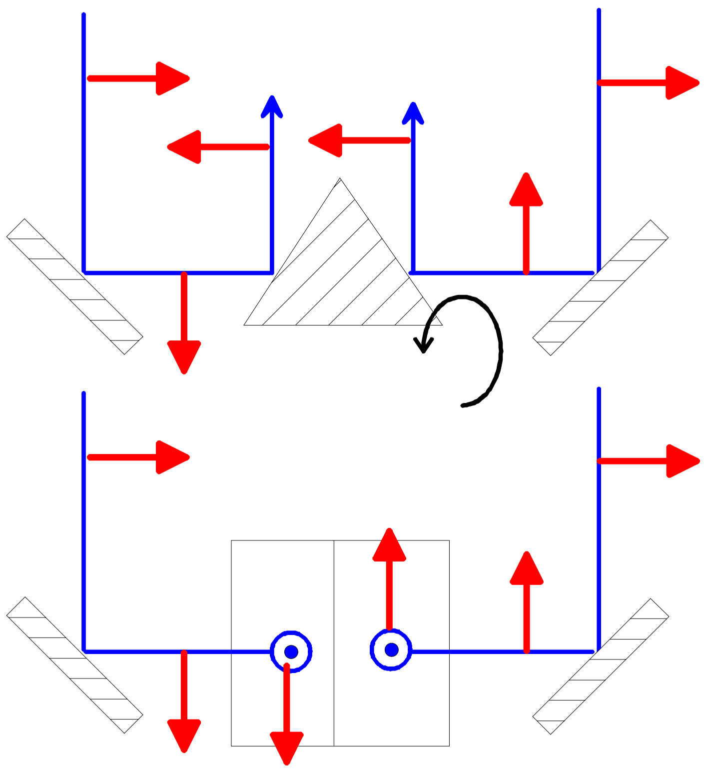
Polarization Effects

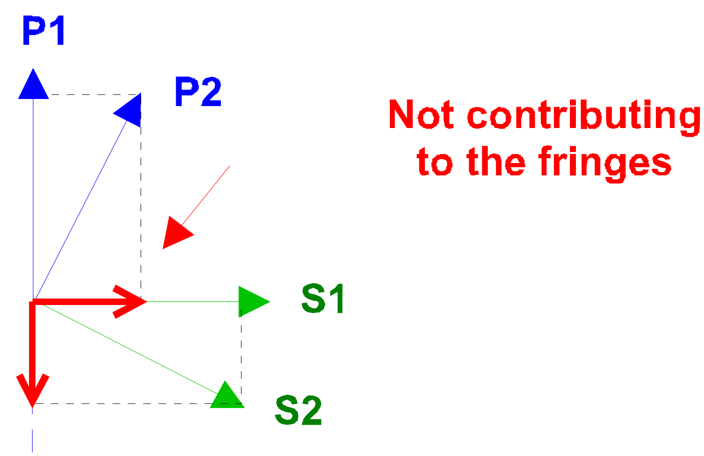
- Linear Retardation
  - Error sources: Coatings
    - Different coatings in the two arms
    - Differential incidence angles (between arms)
    - Differential coating characteristics (e.g. thickness of the protecting layer)
  - Can be very critical in Near IR/Visible and for multi-dielectric coatings (M9).



Polarization Effects

- Rotation of polarization frame
  - Error sources:
    - Differential frame-of-reference/pupil rotation due to optical design and/or misalignment
  - Can be avoided by proper optical design and alignment.

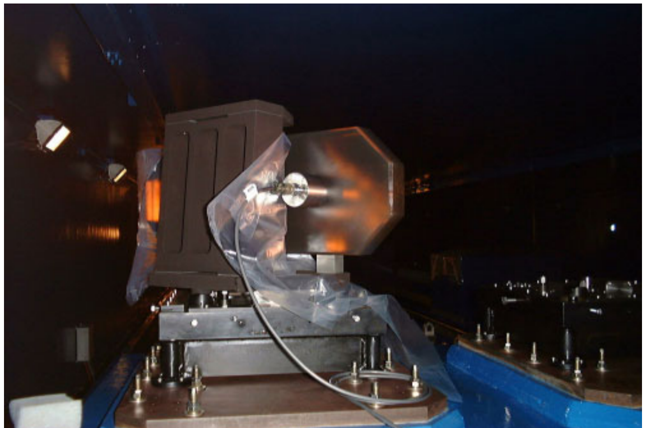




VLTI Tutorial

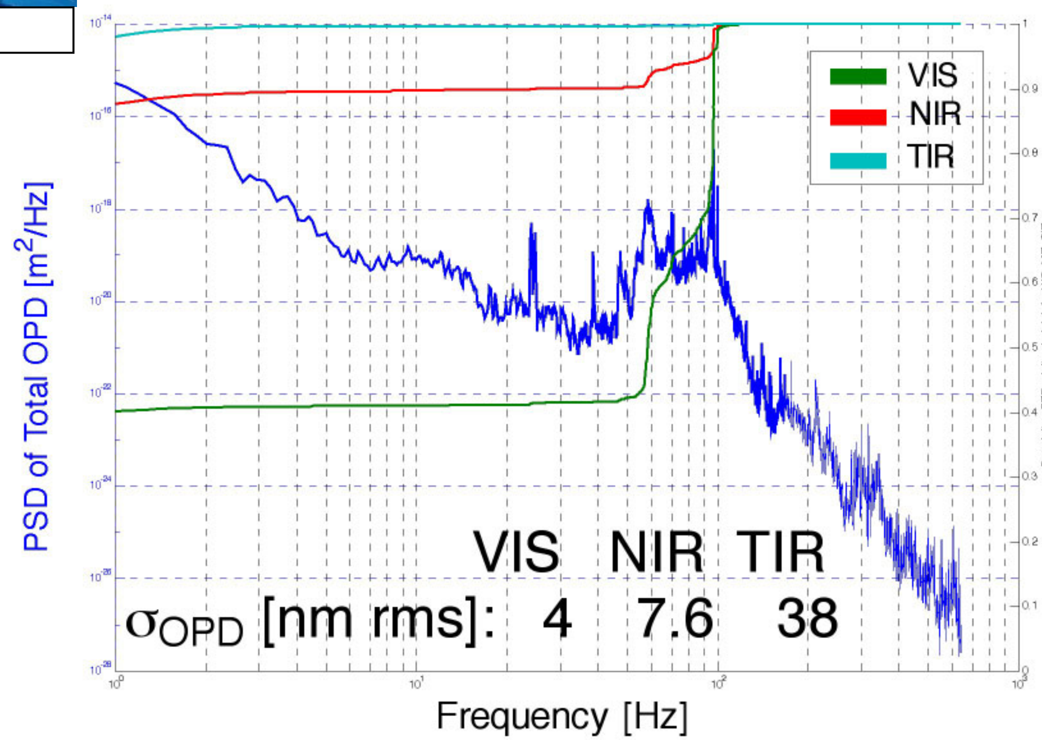
Some results from on-going VLTI commissioning

Measured micro-seismic vibration



Accelerometer on back of M12-G0 mirror

- OPD as measured with accelerometers at the back of Transfer Optics mirrors (*M12, M16, Switchyard, Beam Compressor*)

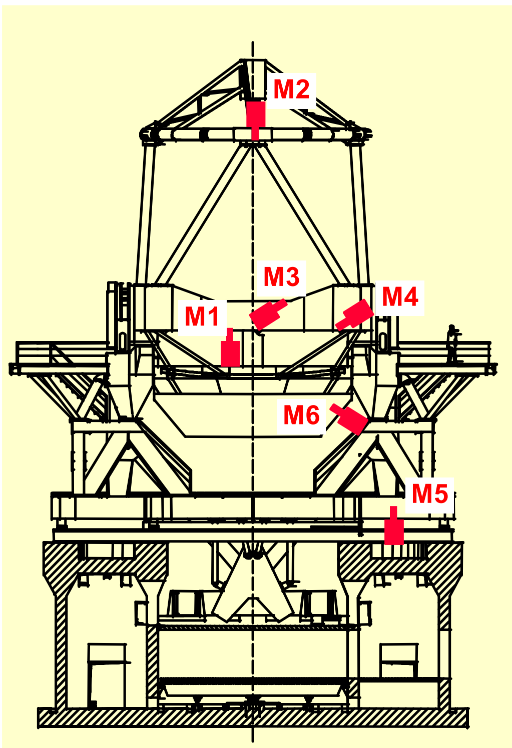


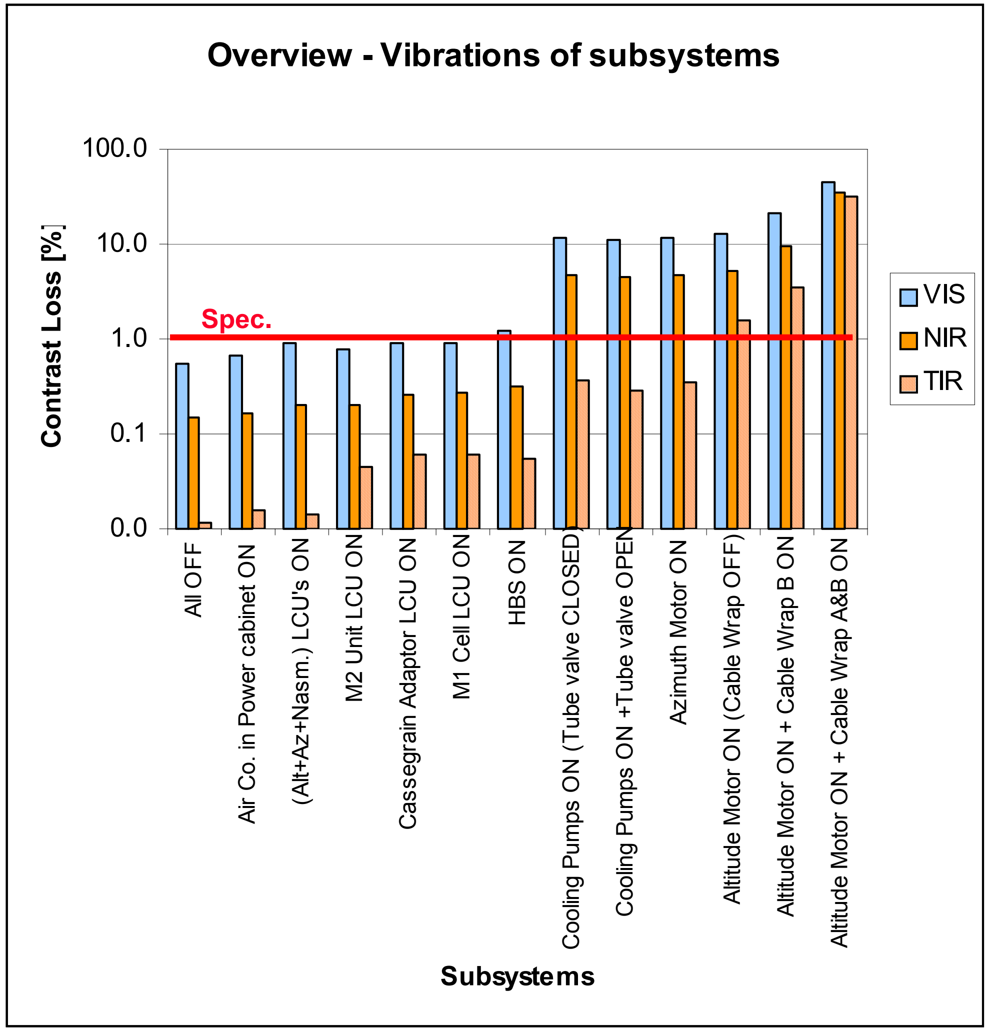
- Error budget:

Wavelength	VIS	NIR	TIR
Transfer Optics	**3**	**10**	**45**

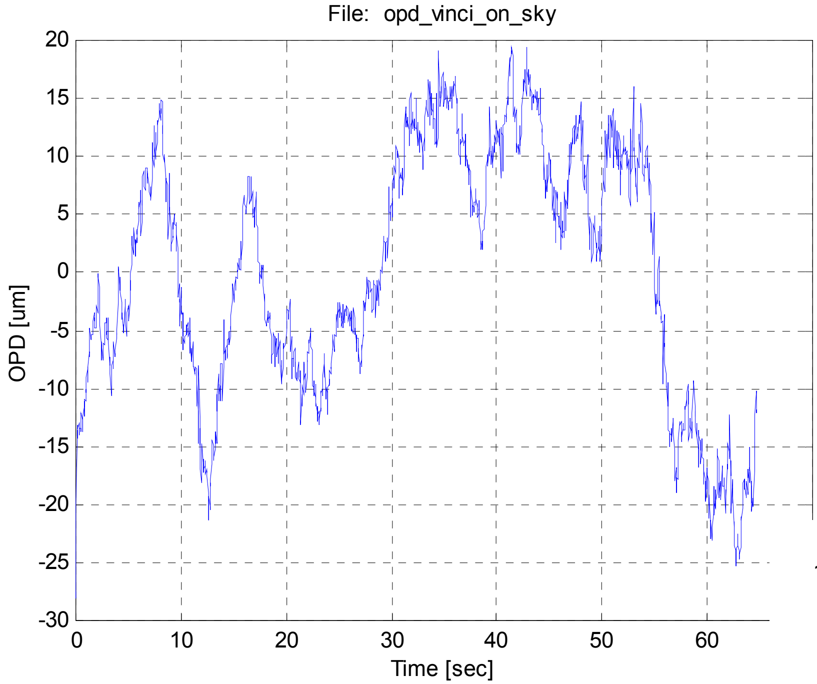
OPD stability inside UT

- Measured with high sensitive accelerometers on UT#1&3
- Few improvements on sub-system identified and on-going
- Overall stability excellent

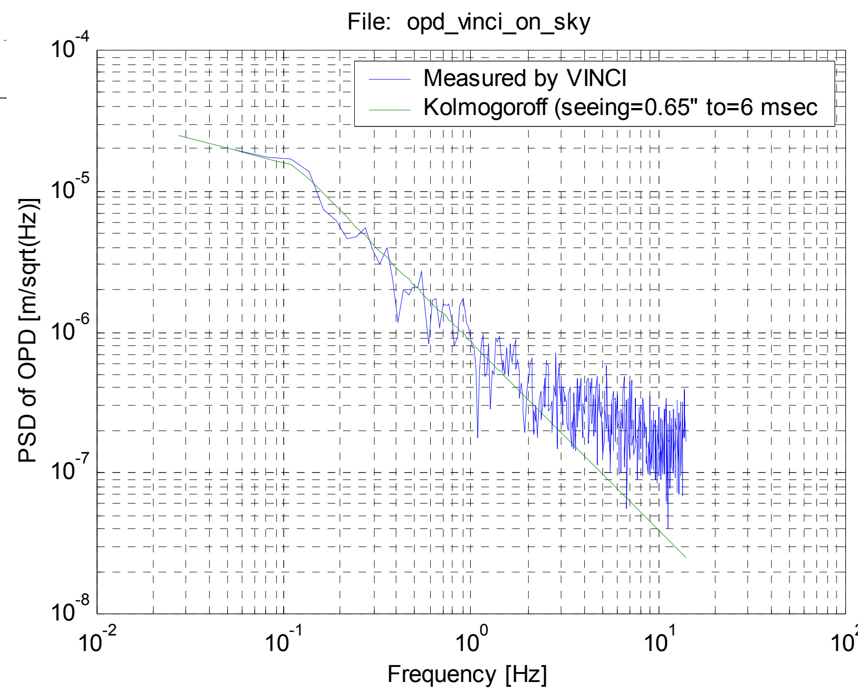




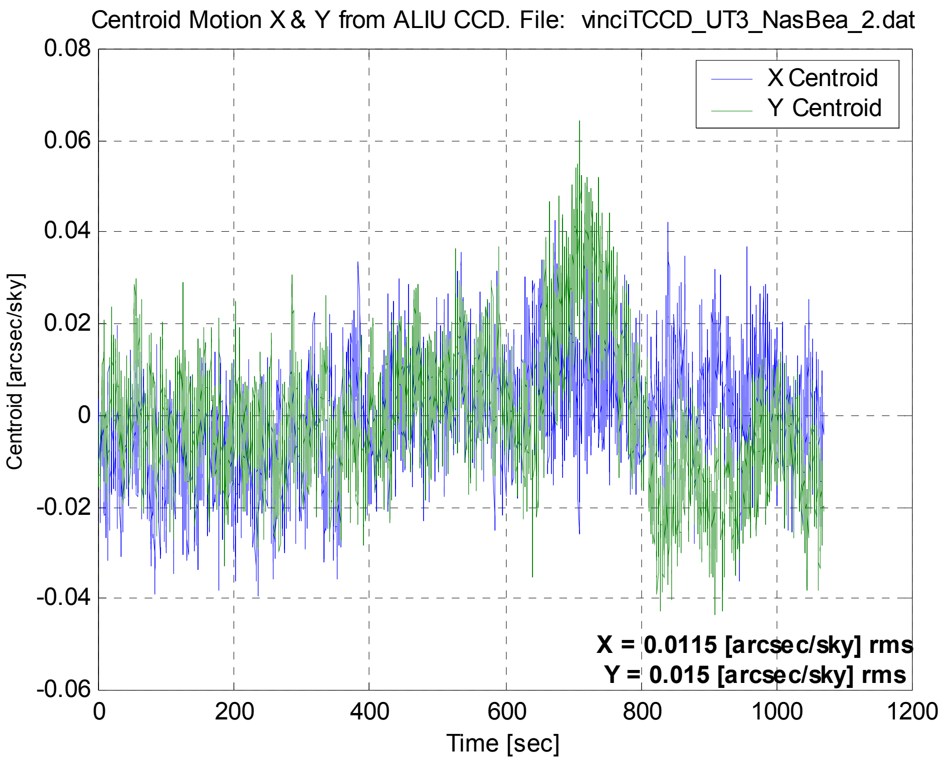
Measured OPD spectrum



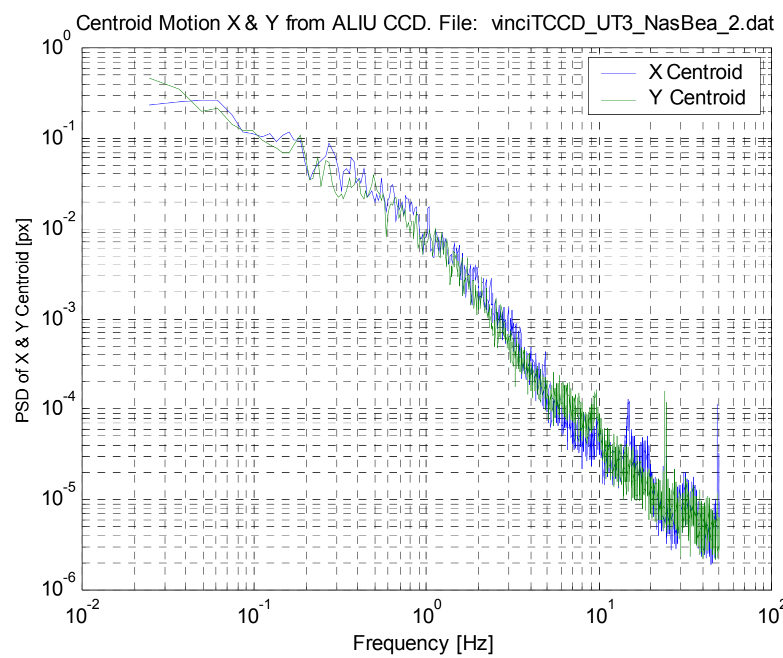
- OPD as measured on a star by VINCI with Siderostats



Measured Internal seeing (tip-tilt)



- Nasmyth laser beacon (UT3) imaged on VINCI CCD *(after 25 mirrors and 200m distance)*



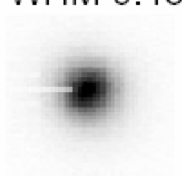
Measured Image Quality

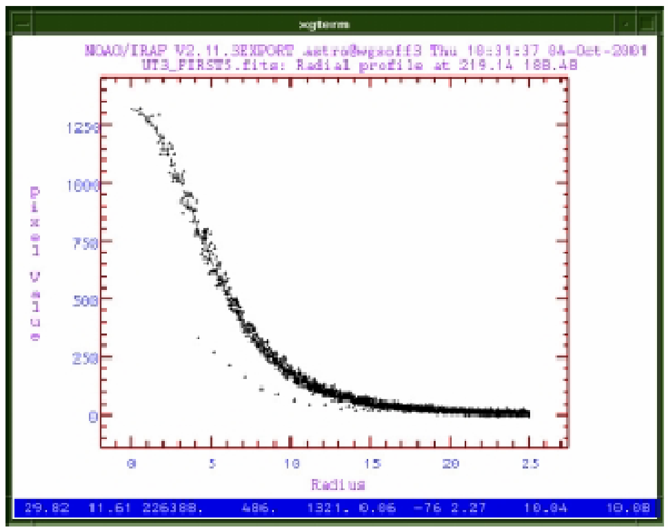
First UT Light in VINCI

Airy disk

Radial Plot

FWHM 0.45''





(Note: the light reaches VINCI after 25 reflections and 200m travel)

- Image Quality from UT Nasmyth laser beacon to VINCI CCD:

FWHM < 0.040" (limited by pixel size)

Conclusion

- Specific and stringent error contributions need to be taken into account for an Interferometer:
  - OPD stability (vibrations from equipment, wind buffeting, micro-seismic noise, residual atmospheric piston,...)
  - Polarisation (optical layout, coatings)
  - Image Quality (mirror figuring, alignment, internal seeing,...)

- The two major technical risks have been:
  - OPD stability within the UT
  - The internal seeing
- Both proved to be according (or very close) to the required performance

- Ready for the next step: PRIMA + ...