Infrared Interferometric techniques and the VLTI

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Overview

Elements of an interferometer

Telescopes

Delay lines

Beam combination

Adaptive optics, spatial filtering, fringe tracker and variable curvature mirror

Optical path, array layout, alignment and interferometer control

The Very Large Telescope Interferometer

Some acronyms

- OPL - optical path length
- OPD - optical path difference
- ZOPD - zero optical path difference
- UT - Unit Telescope (8.2m)
- AT - Auxiliary Telescope (1.8m)
- MACAO - Multi Application Curvature Adaptive Optics
- STRAP - System for Tip-tilt Removal with Avalanche Photo diodes
- VINCI - VLT INterferometer Commissioning Instrument
- AMBER - Astronomical Multiple BEam Recombiner
- MIDI - MID Infrared interferometric instrument
- FINITO - Fringe sensing Instrument NIce TOrino
- IRIS - InfraRed Image Sensor
- ISS - Interferometer Supervisor Software
- VCM - Variable Curvature Mirror

Elements of an interferometer

Telescopes
Delay lines
Beam combiner

Optical trains
Tip/tilt sensor
Adaptive optics
Fringe tracker

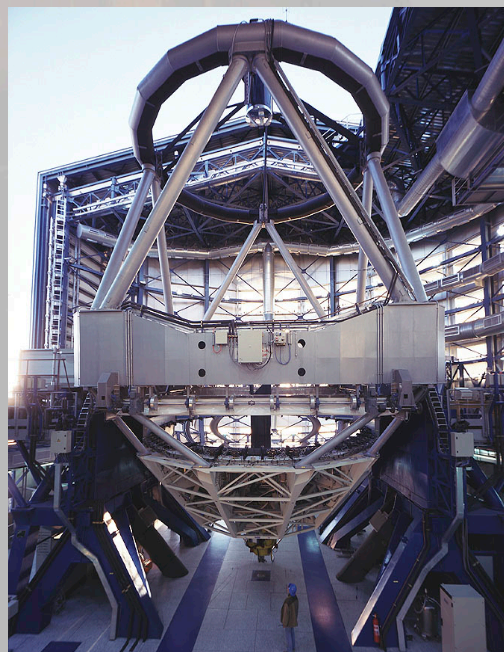
Interferometric telescopes

Collect photons

Rigid design to avoid any introduction of optical path difference due to vibrations

Use the same telescopes with the same orientation of mirrors and the same coatings to control differential polarization

Interferometric telescopes



OPD variations

Vibrations coming from:

- MACAO cabinets (50Hz)
- acoustic waves from pumps through cooling circuits (96Hz)
- M1 cell Eigenmodes
- M3 tower Eigenmodes
- UT instrument cryocooling systems (e.g. CRIRES on UT1)
- new: FLAMES (OzPoz) pump
- …

Possible solutions:

- damp vibrations
- determine vibrations with accelerometers
- determine vibrations with other sensors, ie MACAO and FINITO

Delay lines

Cancel the optical path difference (OPD) for all baselines in the interferometer

Follow the siderial delay while the object moves across the sky

Delay line types

Delay line schemes per beam

- One fast tracking DL with a wide range of OPL (e.g. VLTI)
- One fast tracking DL with a short range of OPL and adaptation of the telescope positions (e.g. GI2T)
- One fast tracking DL plus one fixed DL (e.g. KeckI)

Delay line optics

- Cat’s eye
- Roof mirror

Number of delay lines

- N moving
- (N-1) moving plus one fixed

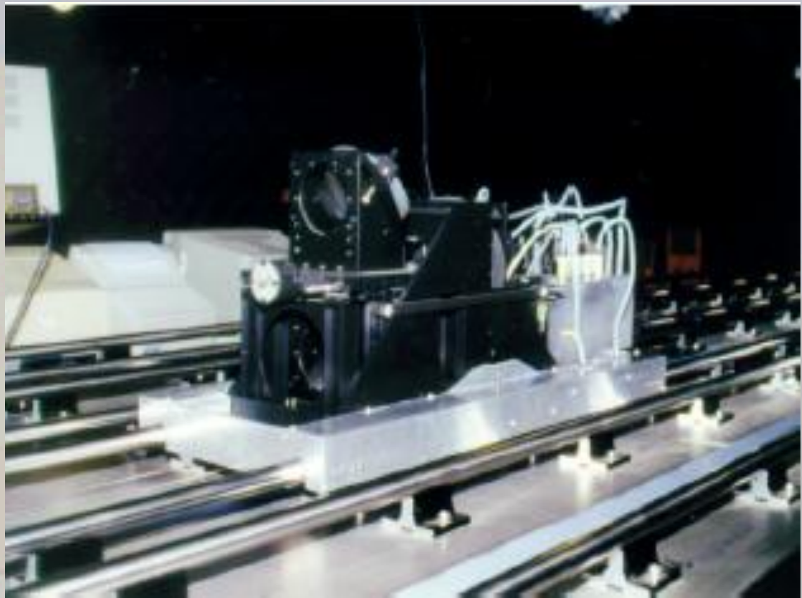
Delay line controls

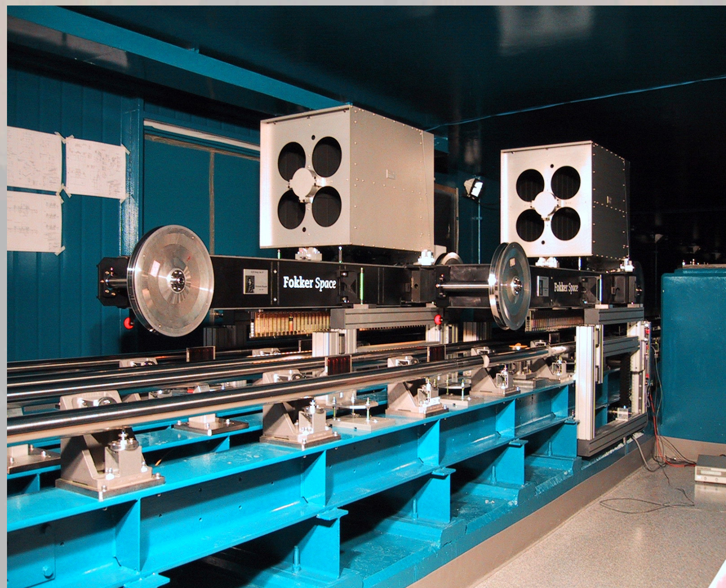
- Linear motor
- Voice coil
- Piezo

Delay line stages

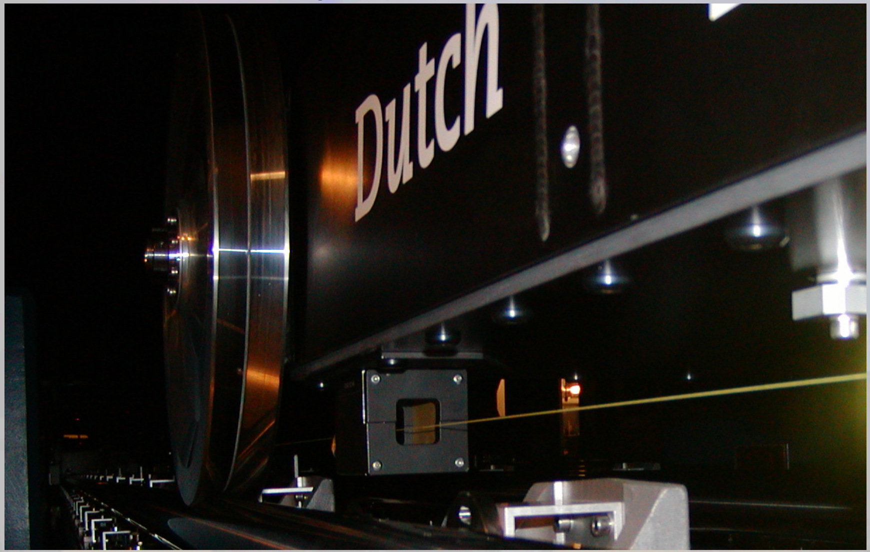
- e.g. two for VLTI (LM and piezo)
- e.g. three for KeckI (LM, voice coil, piezo)

Delay lines





Delay Lines : DELIRIUM on VLTI DLs 1-6



Two 2D capacitive sensors

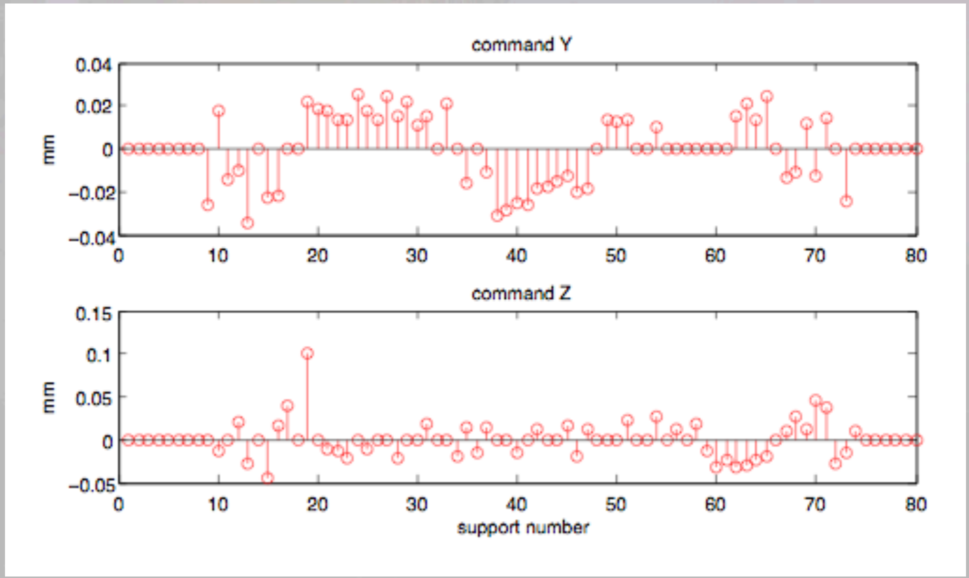
One inclinometer for roll measurement

Metrology (laser or coarse)

Complete trajectory reconstruction

Closed loop control based on global reconstruction

- Influence function measurements (on one support)
- Construction of IM / CM (assuming same response on all supports)
- Scan results multiplied by CM to produce correction sequence (control gain = 1)
- Corrections clipped to 10% of max error (or 7 microns ~ limiting accuracy)



Carried out daily by Maintenance Department.

Variable curvature mirror (VCM)

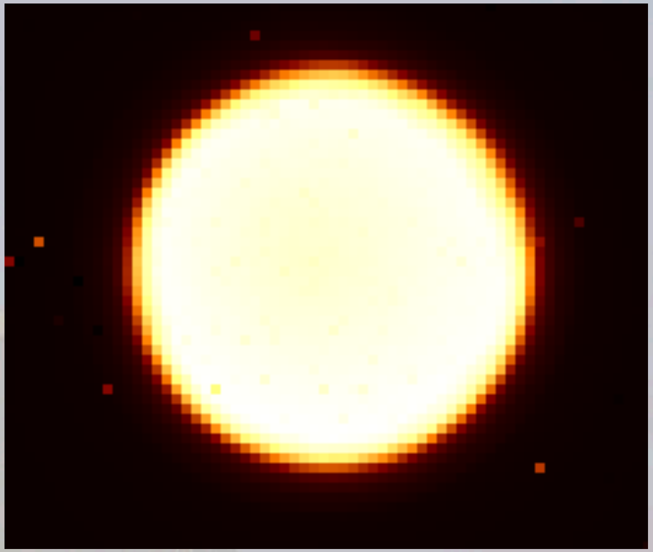
Distance from telescope entrance pupil to beam combination instrument variable due to moving delay line

Without active element in optical train no pupil imaging (e.g. on a cold stop) possible

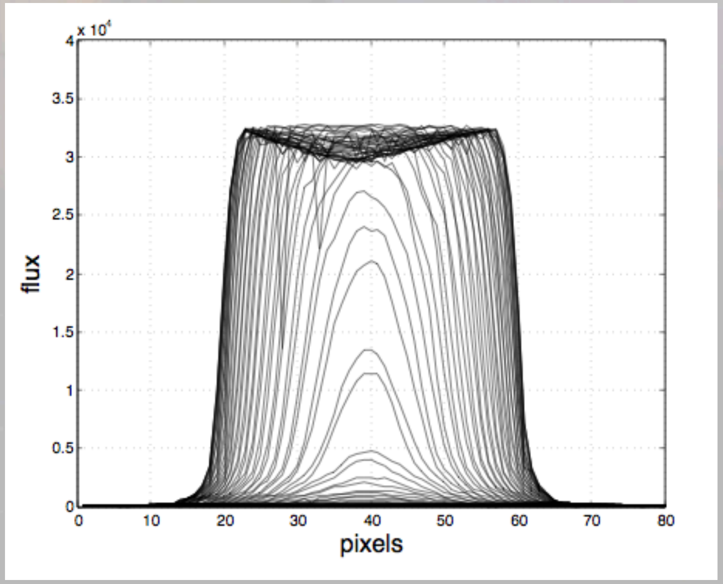
Variable curvature mirror sits in image plane and changes its radius of curvature so pupil is relayed to a given position

VCMs

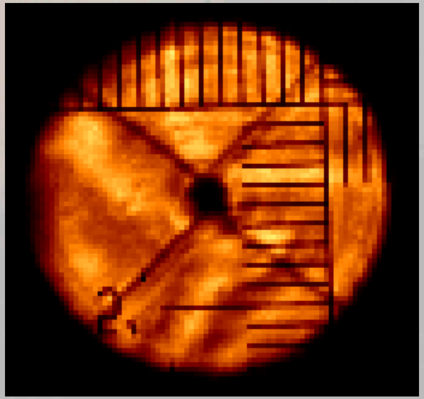
Without the VCMs functioning the field of view of the ATs is limited to about an arcsecond (approx the diffraction limit of a 1.8-m telescope at 10 microns).



J moon in IRIS

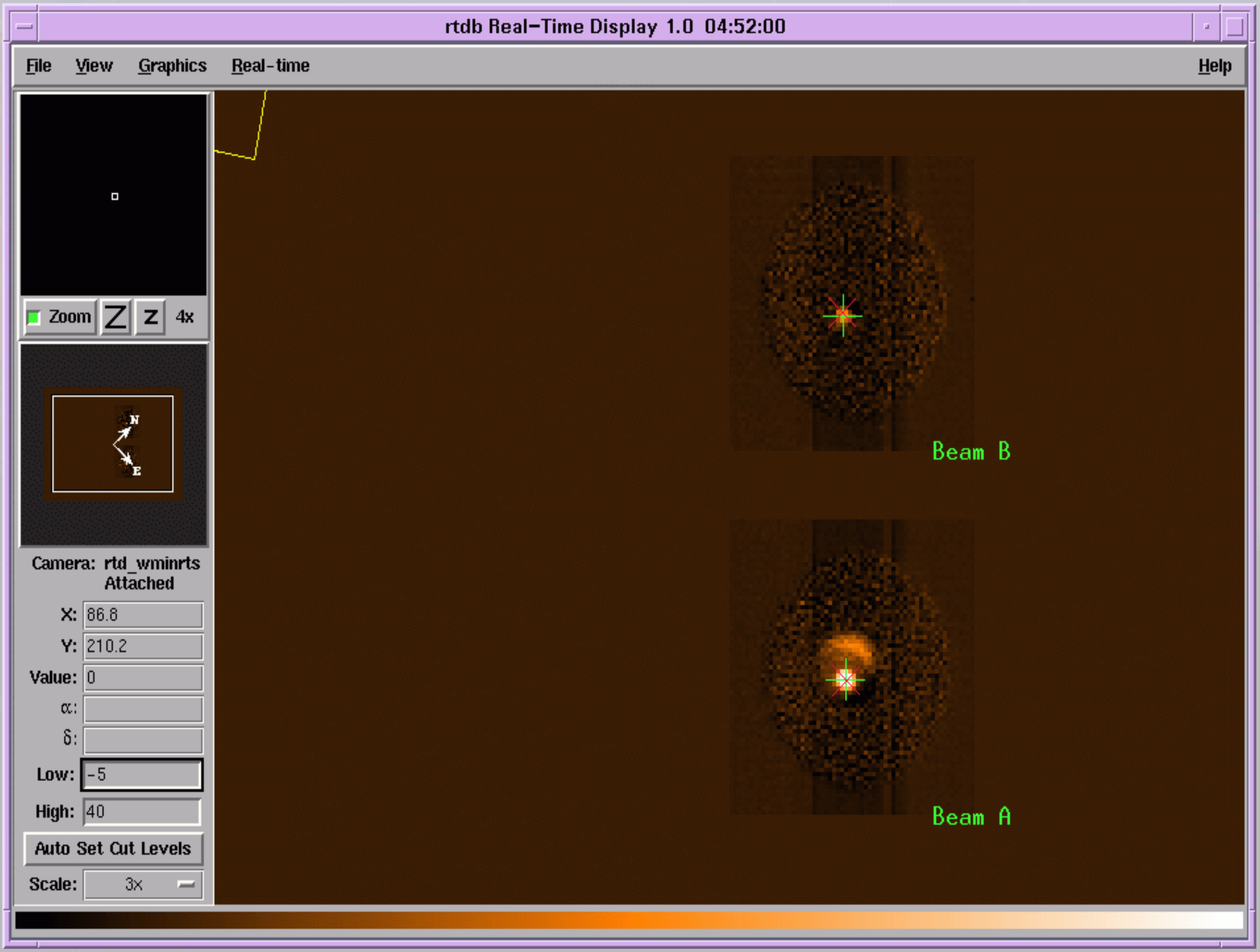


FWHM = 7.6 arcsec



AT2 pupil on ARAL through DL6

AT field of view on MIDI



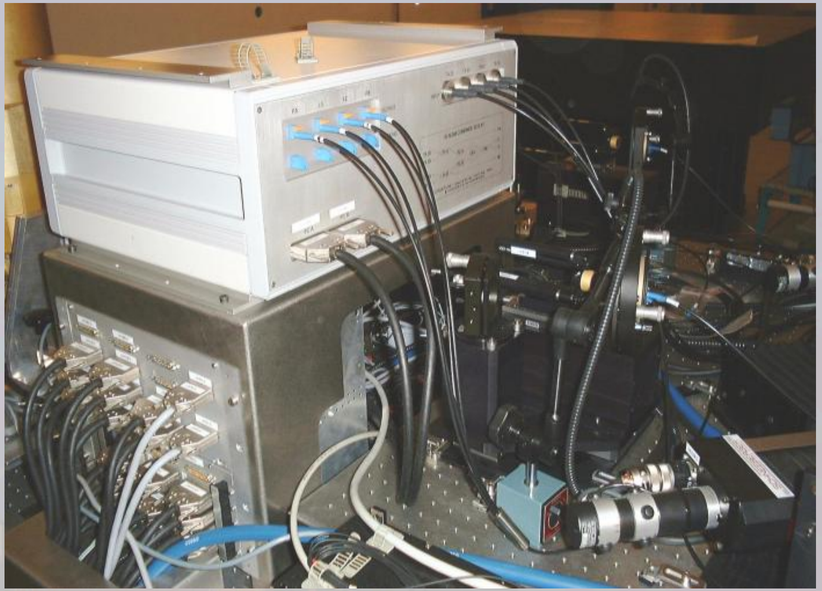
Beam combiner

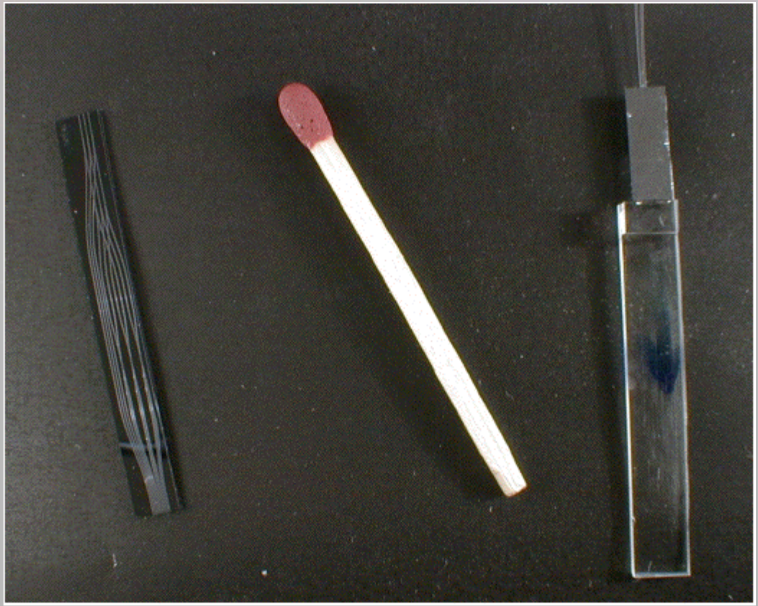
- Optics to bring the beams from the telescopes close enough together so they can interfere
- Modulator if coaxial beam combiner
- Detector to record data

Beam combiner types

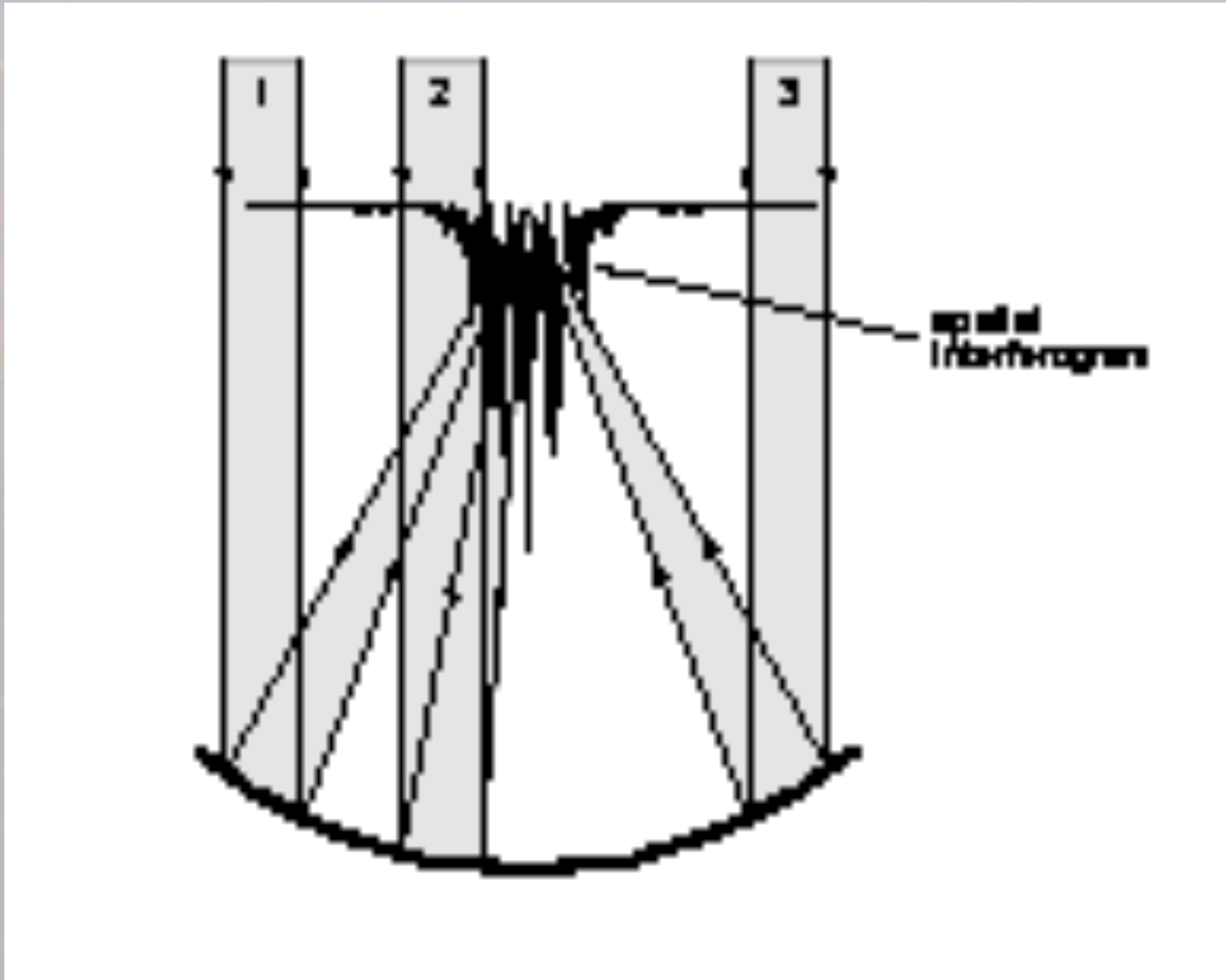
- Combination geometry
  - Coaxial
  - Multiaxial
- Technology
  - Bulk optics
  - Fiber optics
  - Integrated optics
- Combination scheme
  - All on one
  - Pairwise

Beam combiner

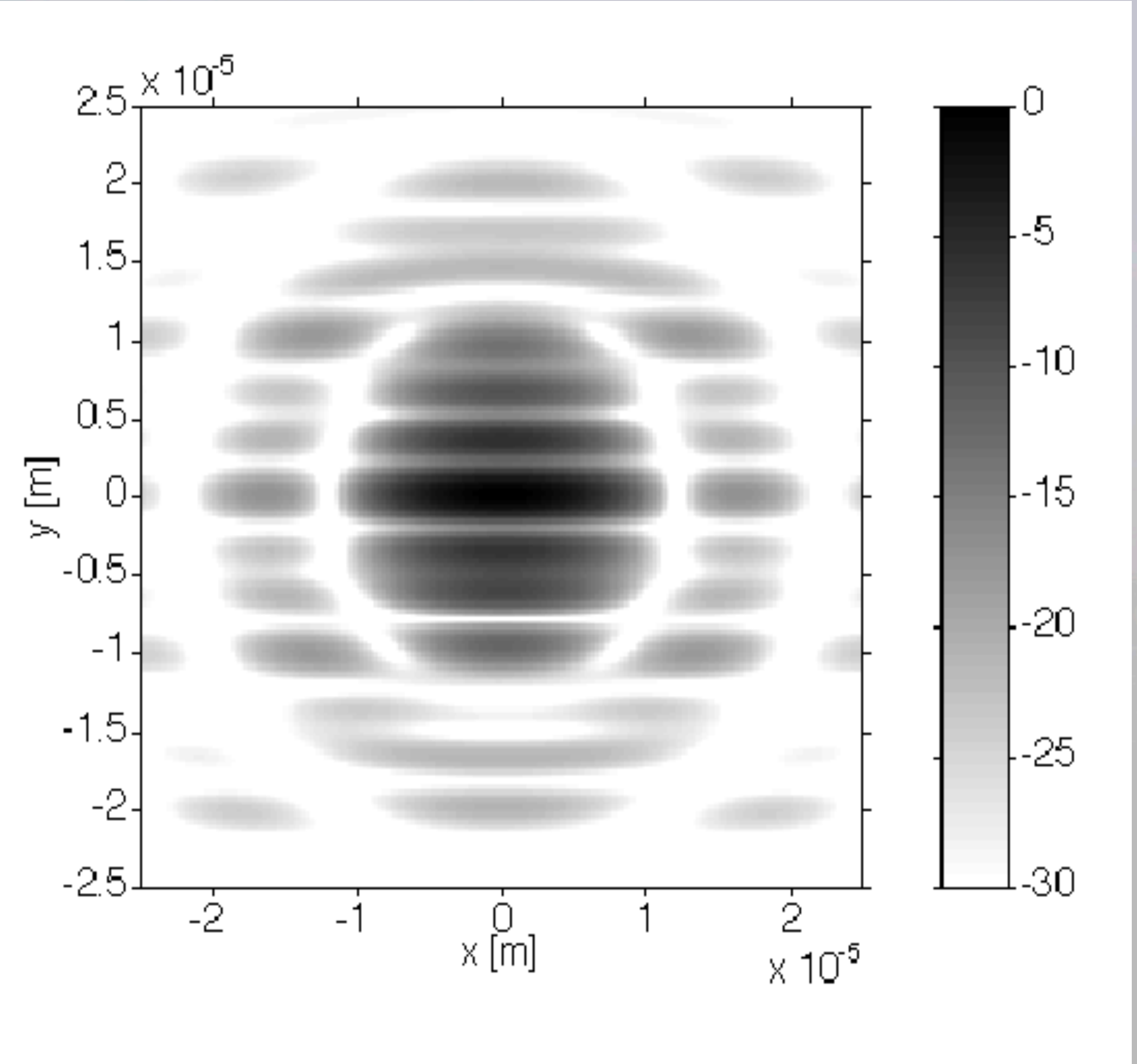




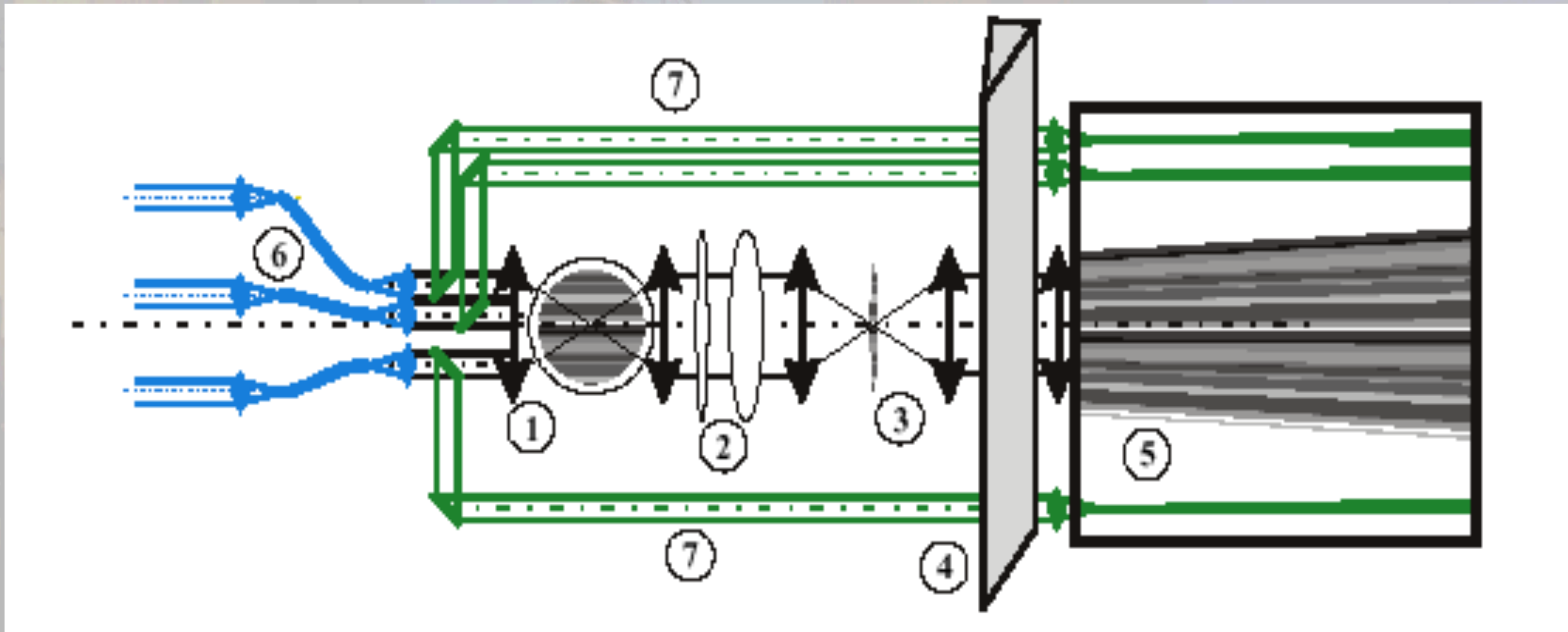
Multiaxial beam combination



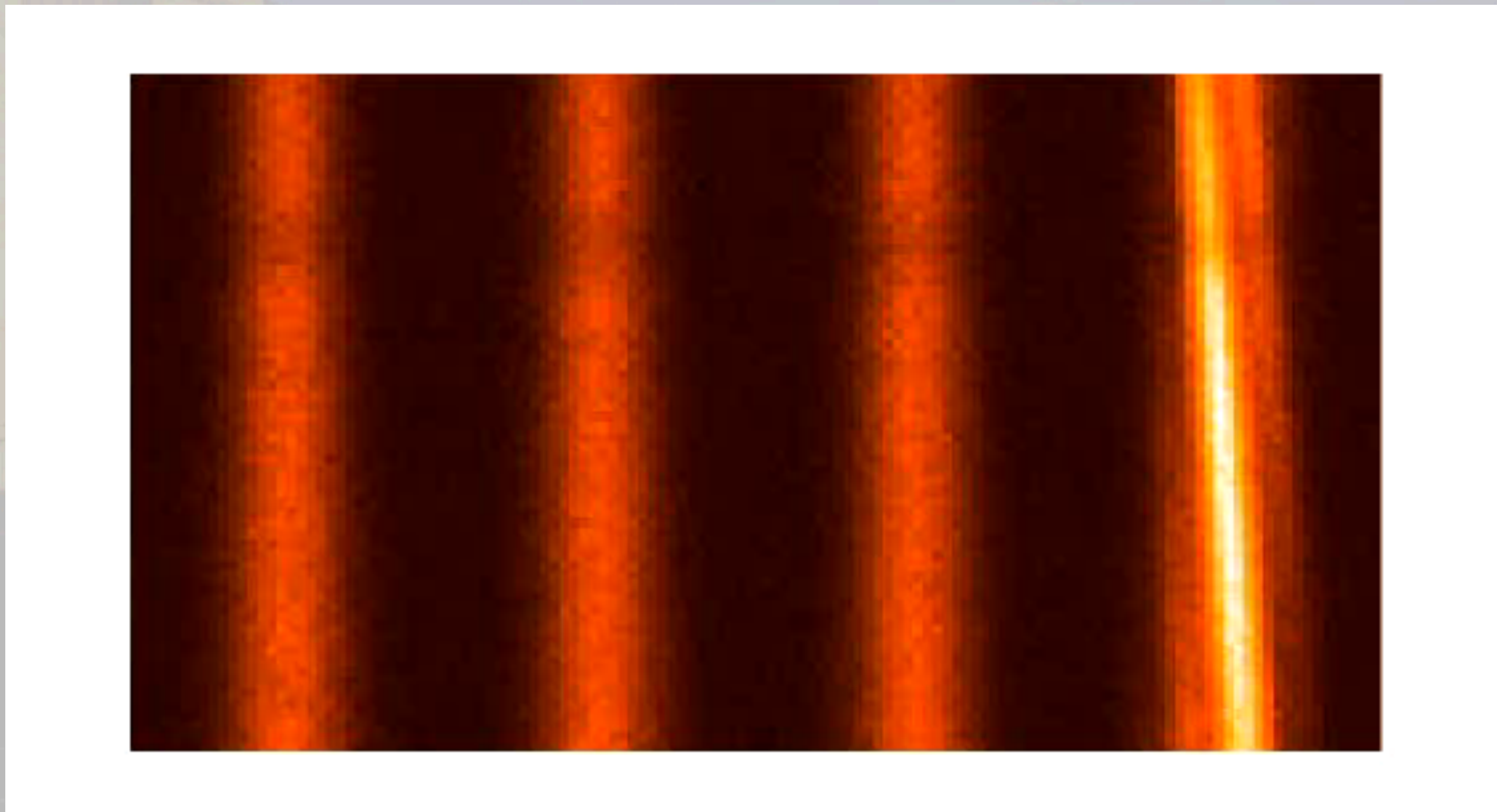
Simulated AMBER PSF



AMBER beam combination

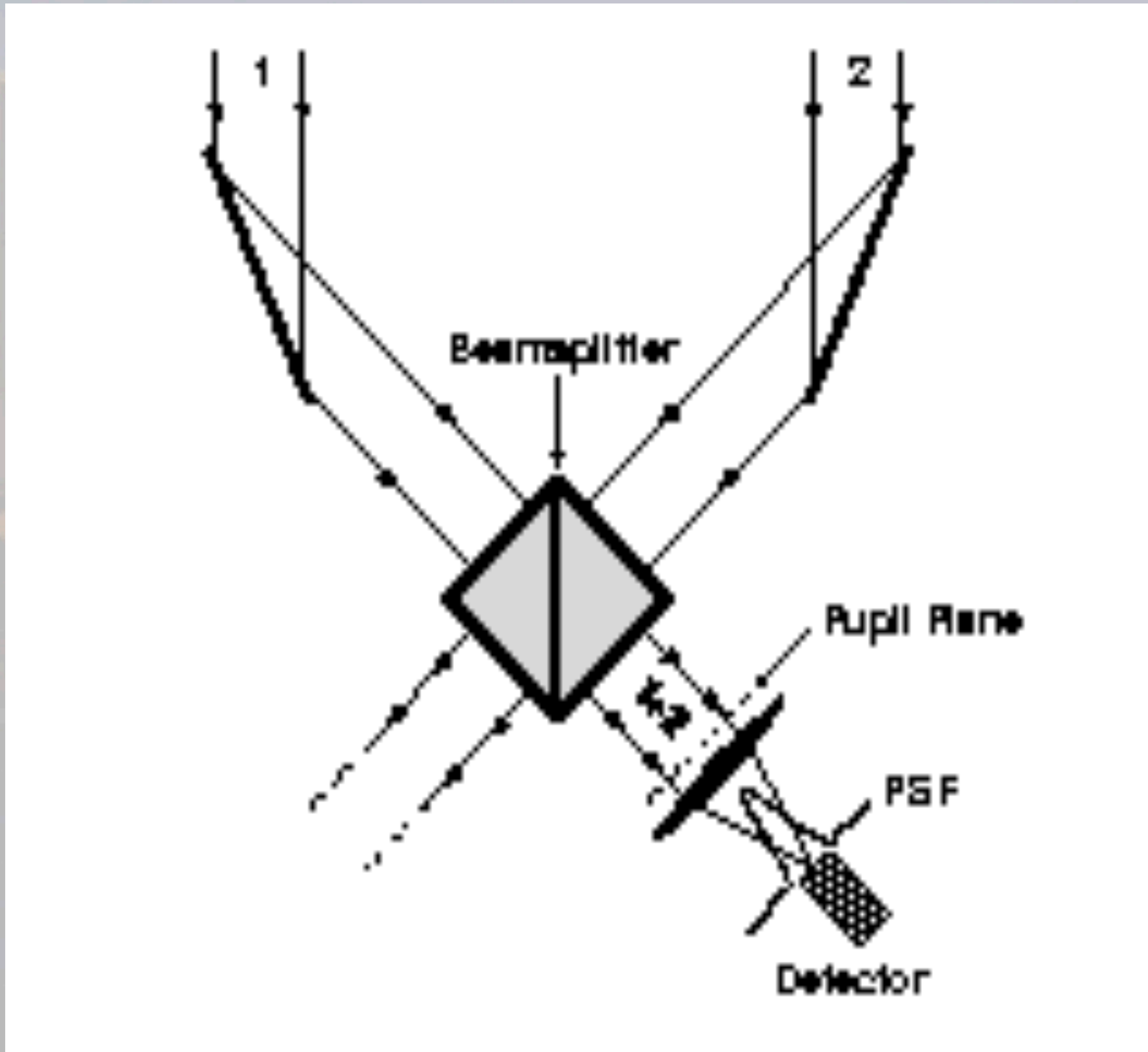


Movie of simulated AMBER fringes

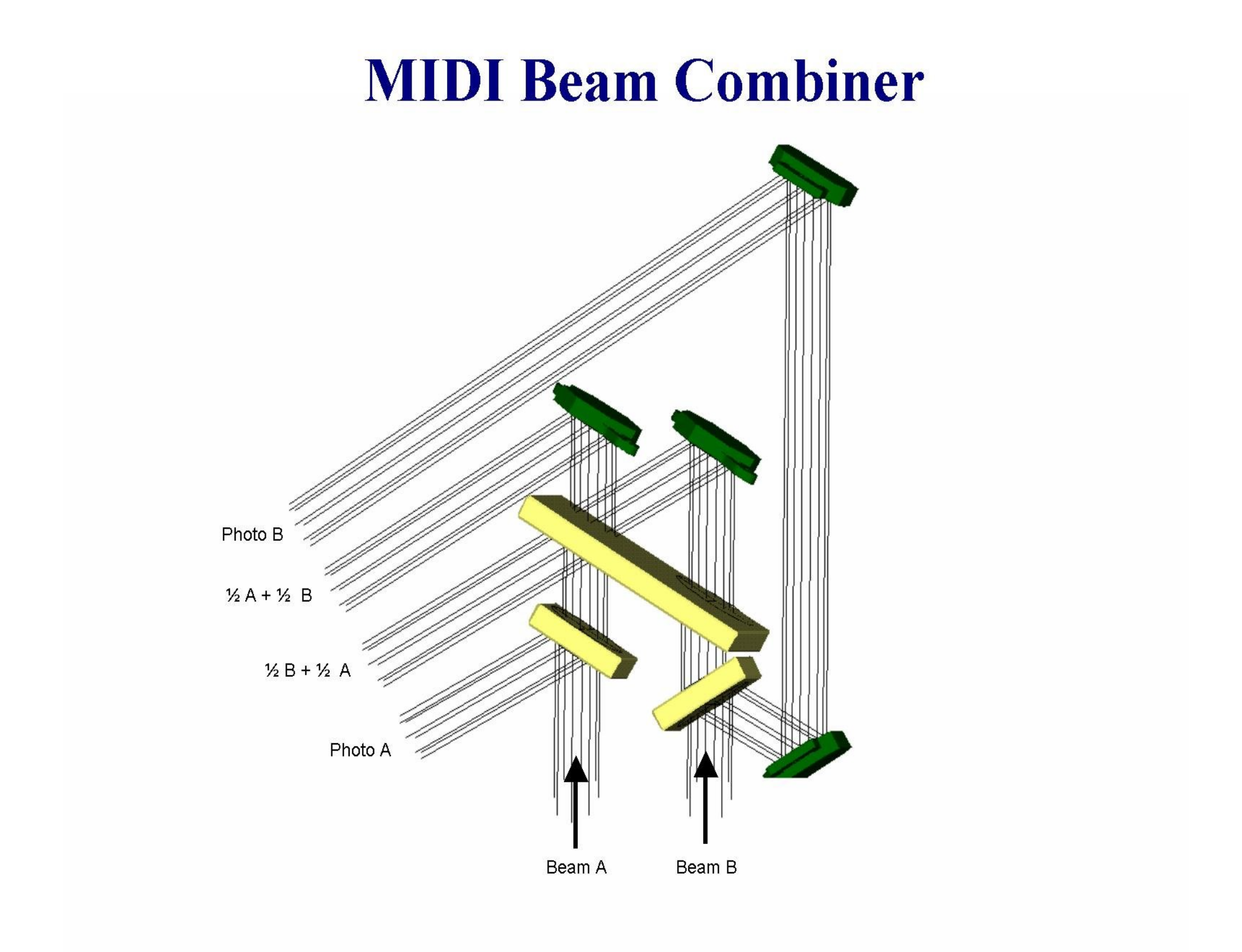


Beam arrangement and MTF

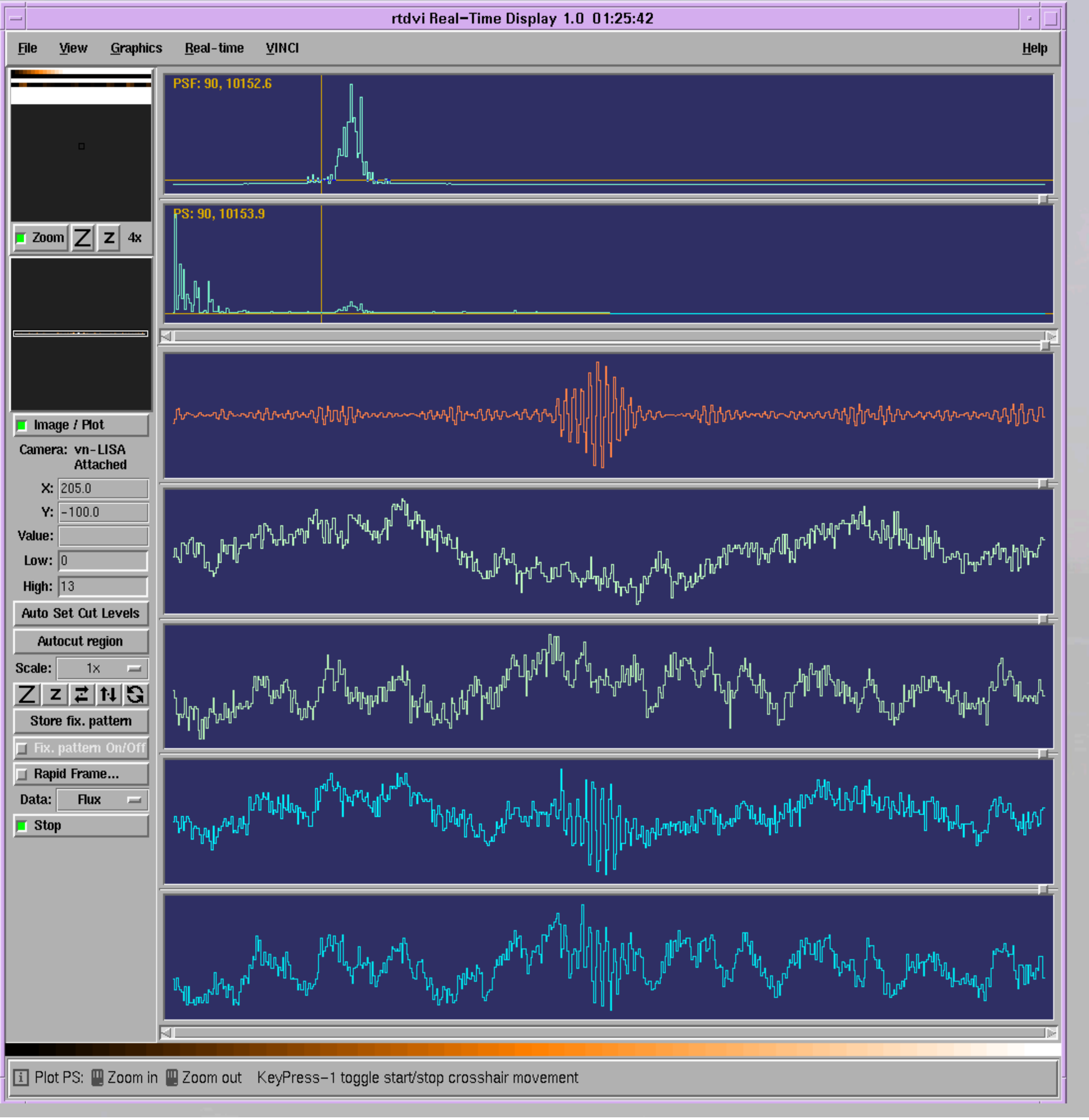
Coaxial beam combination



MIDI beam combination



VINCI fringes



Tip/tilt and Adaptive Optics

Tip/tilt: stabilize the image, e.g. on a spatial filter

AO: enhance number of photons which are interfering

Tradeoff:

- AO sensor at the telescope: no correction of wavefront errors from the optical path
- AO sensor in the laboratory: sensitivity loss and possible alignment problems

Possible solution: AO at the telescope and slow tip/tilt in the laboratory

Spatial filtering

Wave front errors lead to degradation of the measured visibility.

A spatial filter ideally removes the inhomogenities of the wave front while reducing the amount of light available for beam combination.

A spatial filter is a low pass filter for the wavefront.

Implementations:

- Pinhole
- Single mode fiber

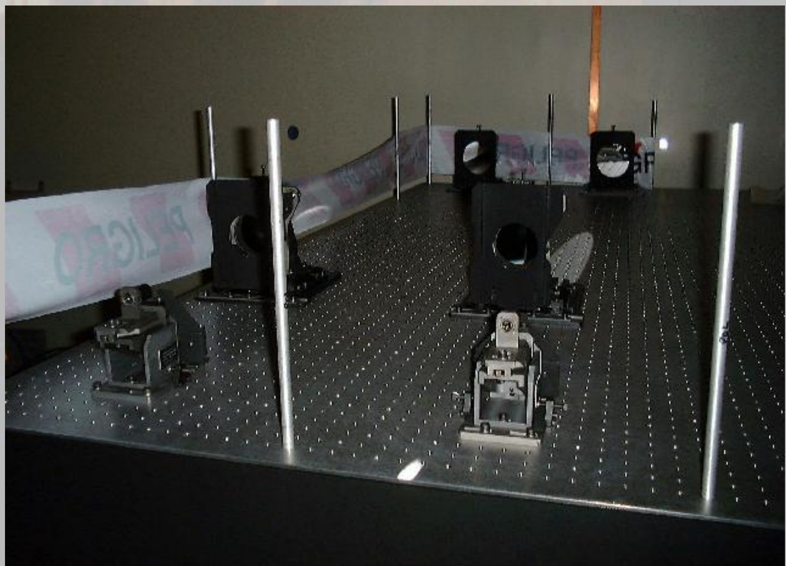
Fringe Tracking

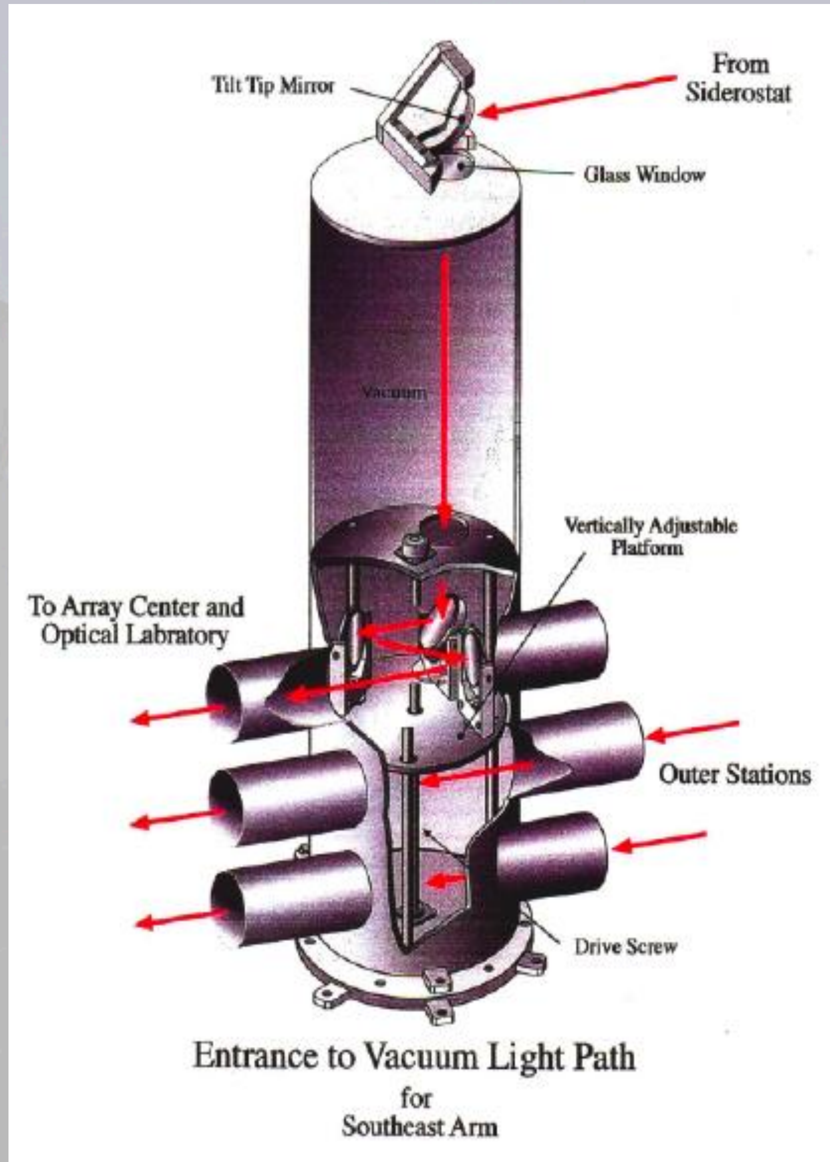
A fringe tracker stabilizes the fringes within a fraction of a wavelength so the scientific instrument can integrate much longer than the coherence time of the atmosphere would allow.

Possible scenarios:

- Fringe tracking in wide band while science instrument uses high spectral resolution
- Source can be tracked at the fringe tracker wavelength while not at the scientifically interesting wavelength
- Fringes are tracked on two shorter baselines while the science instrument is integrating on a long baseline (baseline bootstrapping)
- Fringes are tracked on another source in dual feed mode

Lots of optics





Beam transport

In air:

- Additional wave front errors due to turbulence
- Requires stable environment (wine cellar or building-in-building)

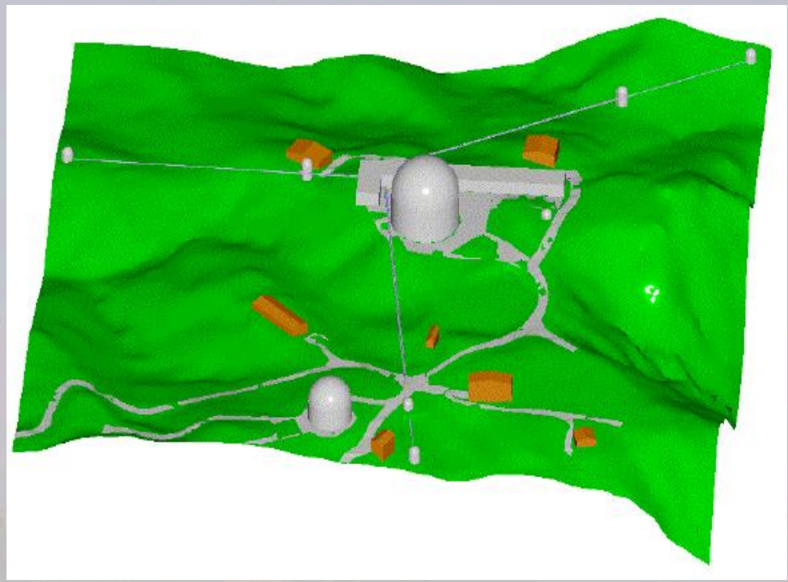
In vacuum:

- Necessary when beams travel over ground
- Entrance windows
- Optics not easily accessible

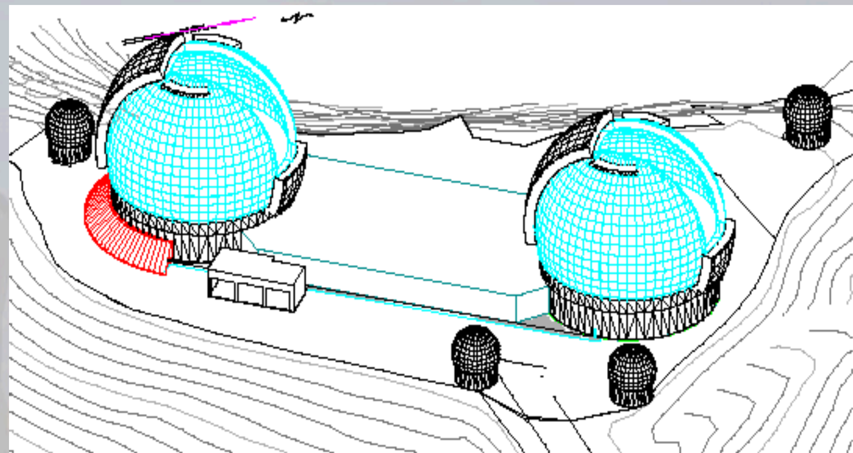
Beam transport - vacuum

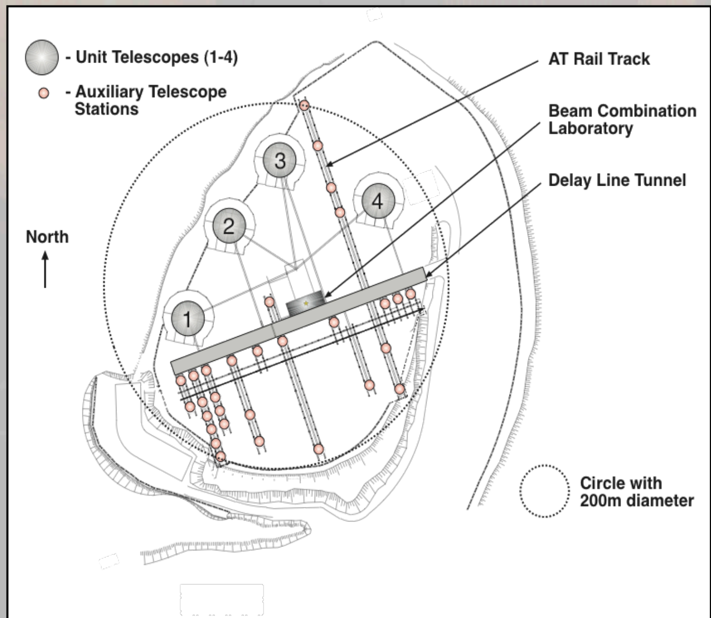
Beam transport - air

Interferometer layouts - Y



Interferometer layouts - other concepts





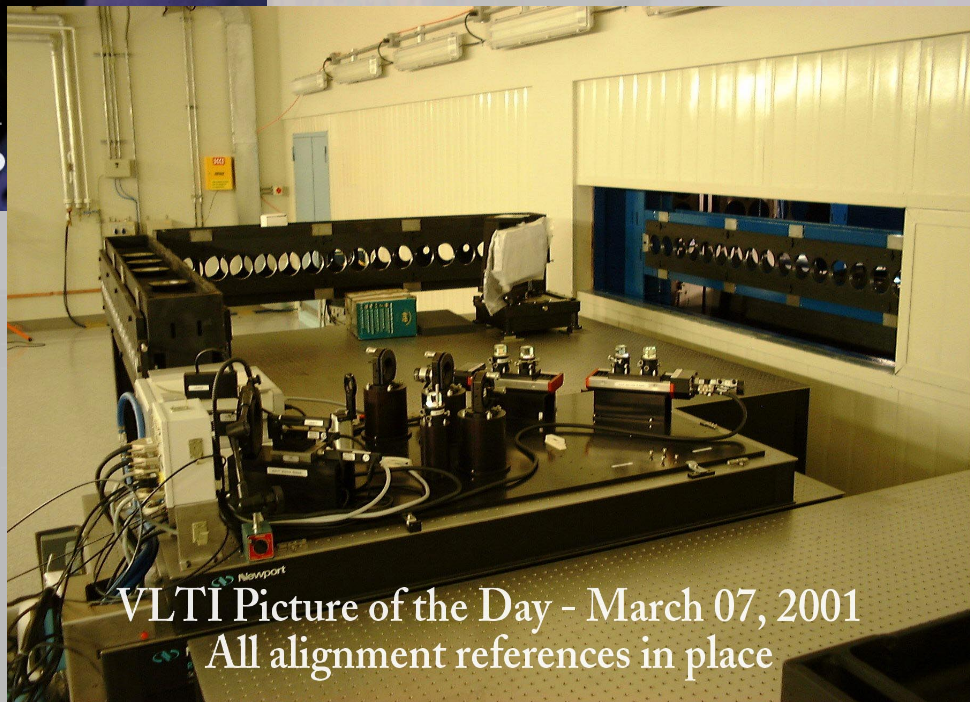
Aligning

Strategies:

- Have light sources and degrees of freedom everywhere to be able to align the optical system
- Have an undisturbed and well engineered system which does not require frequent alignment

A well designed interferometer has an image alignment and a pupil alignment device and everything else is static

Aligning tools



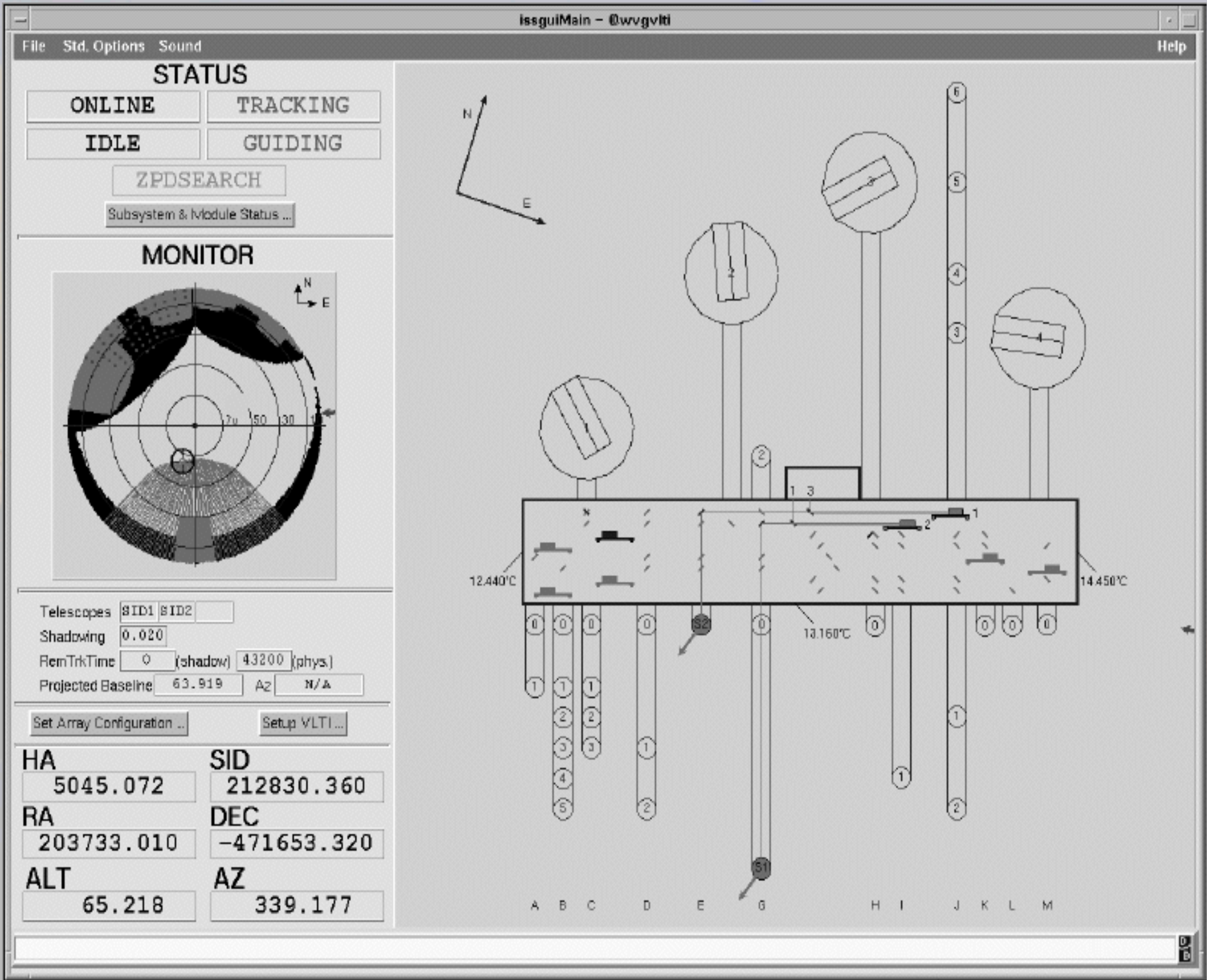
Controlling an interferometer

Since interferometers tend to be highly complex systems, one has to invest some effort into the software and hardware which ties the pieces together.

Example: MIDI with fringe tracker on VLTI 8m and chopping

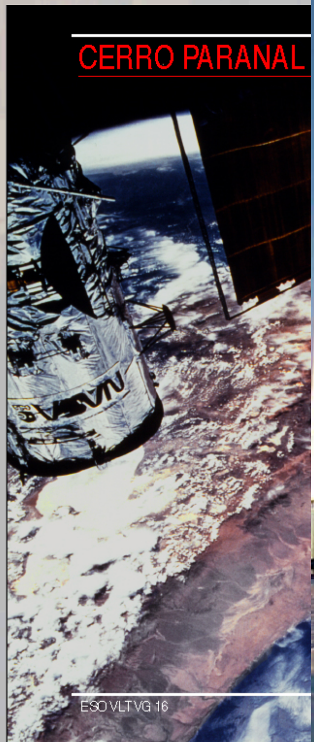
- MIDI and fringe tracker on source, integrating
- Fringe tracker opens loop, AO opens loop
- Telescope chops off source, MIDI integrates a sky fringe
- Telescope chops back on source
- AO closes loop
- Fringe tracker closes loop
- MIDI integrates on source
- Repeat with about 2Hz for the full cycle

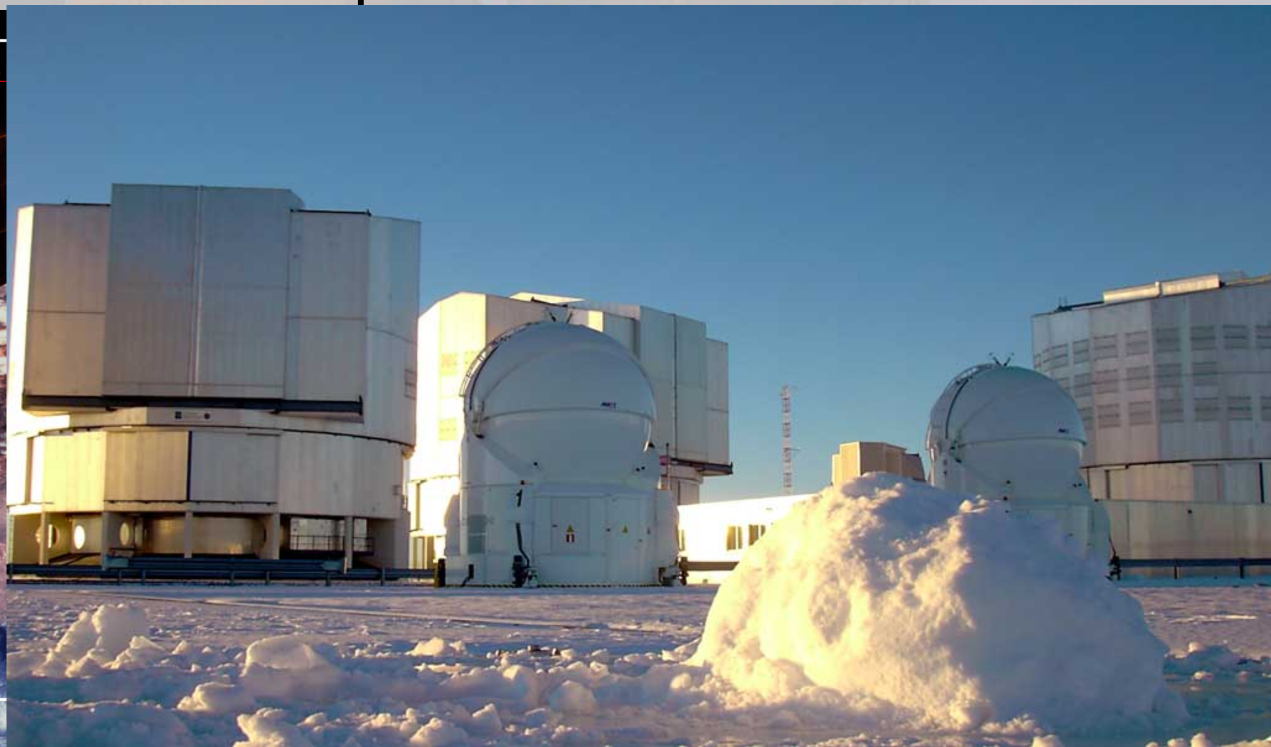
Interferometer Supervisor



ESO - The “European Southern Observatory”

European Organisation for Astronomical Research in the Southern Hemisphere

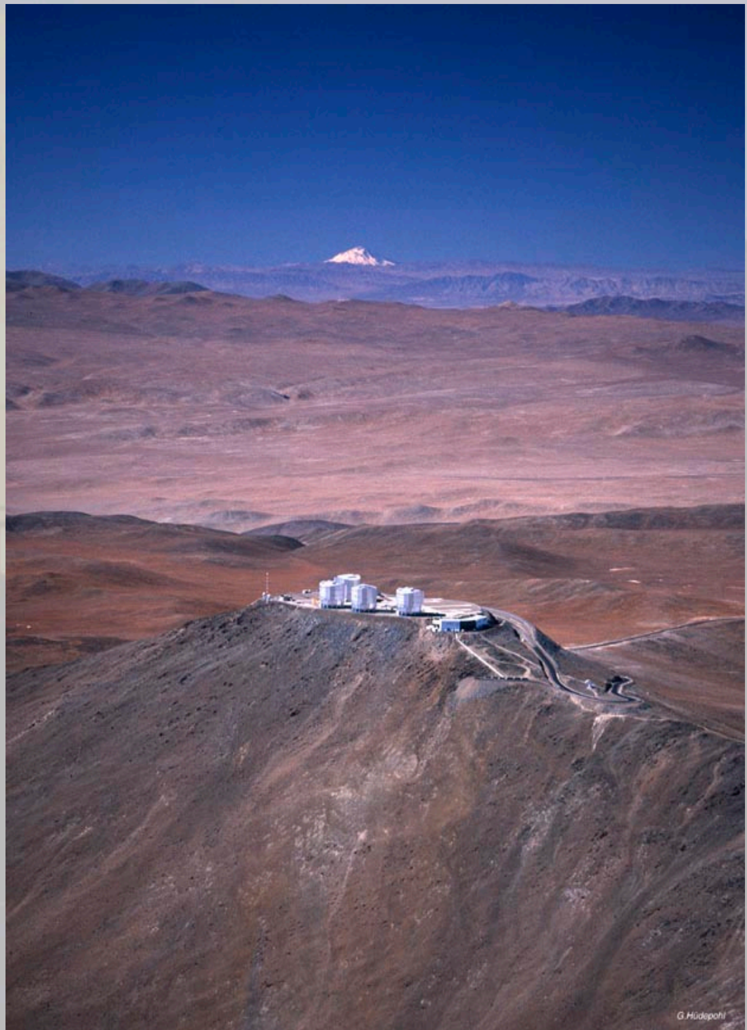




A brief history of VLTI

- 1980s - Interferometry integral part of the VLT project, early linear array design for UTs goes to trapezium structure
- Early 1990s - engineering of the general layout
- 1993 - council stalls the VLTI, infrastructure implementation (light ducts, tunnel, lab) continues
- 1996 - MPG/CNRS/ESO tri-partite agreement for third AT
- 1997 - MIDI and AMBER proposed by community
- 1998 - contracts for ATs and Delay Lines awarded, MIDI and AMBER instruments started
- 2000 - start of implementation on Paranal (siderostats and delay lines)
- March 2001 - first fringes with VINCI on siderostats

VLTI

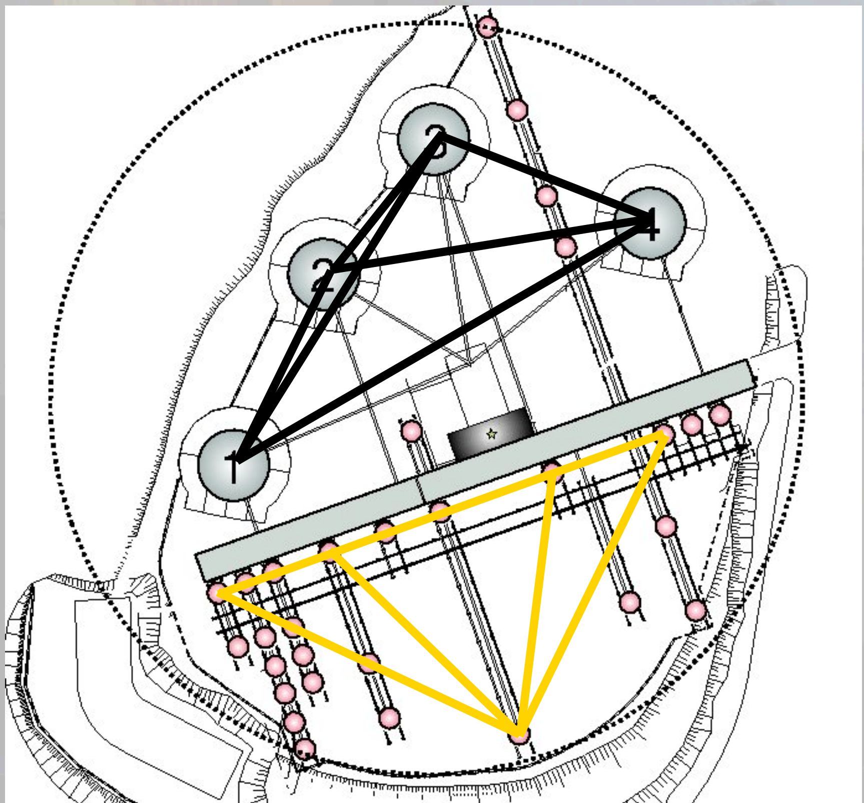


Four 8.2m telescopes (UTs)
All equipped with AO (MACAO)
Six Baselines 47m-130m

Four 1.8m telescopes (ATs)
Movable to 30 stations
Baselines 8m-202m

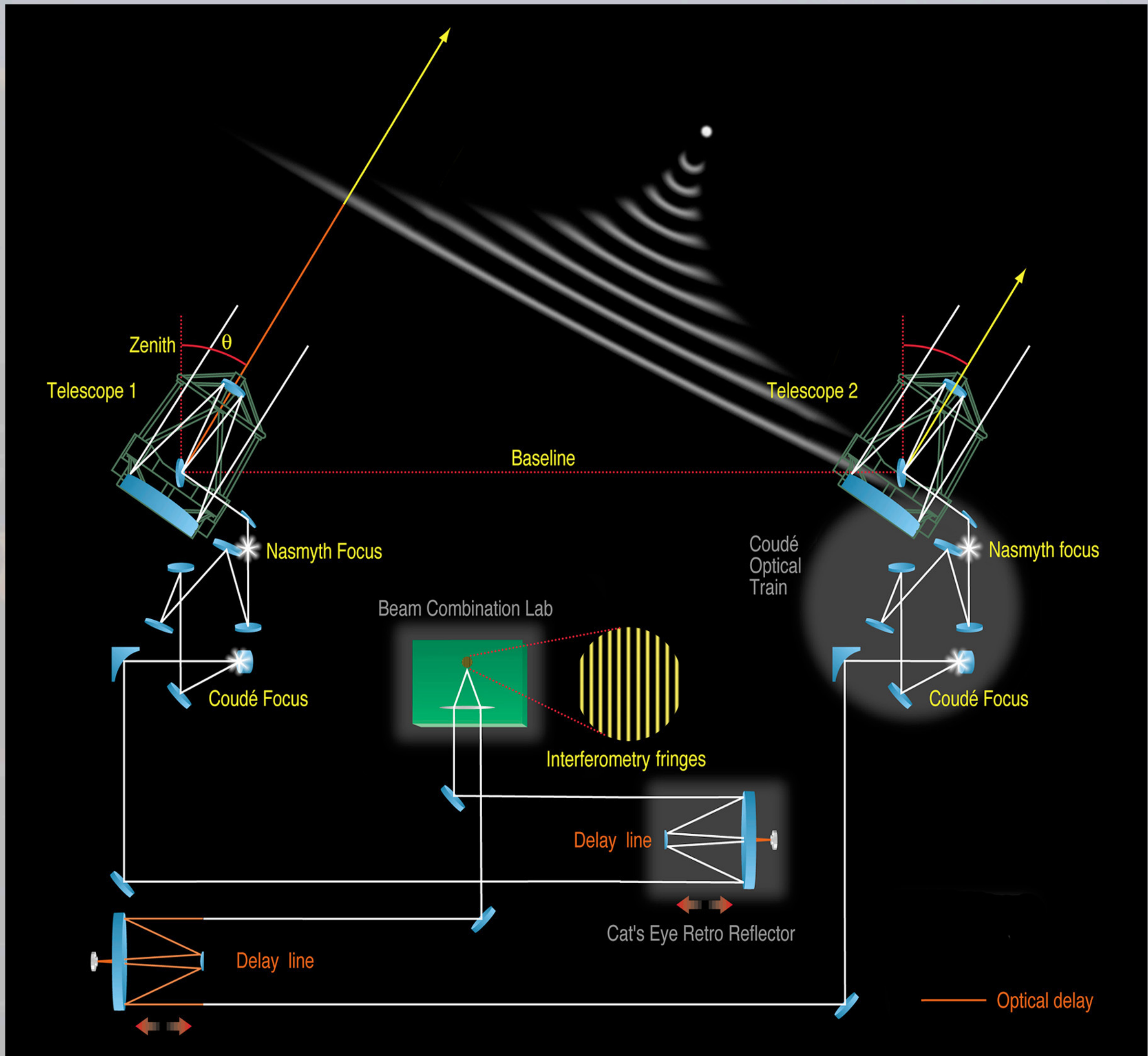
Six delay lines
PRIMA dual feed facility
IRIS lab tip/tilt tracker
FINITO fringe tracker
MIDI/AMBER/VINCI

Status



- All UTs operational with full AO, all six baselines and all four baseline closures used for science
- AT1-4 in operations on four baseline triples
- 4 Delay Lines in operations for UTs, 3 Delay Lines for ATs (all 6 with VCM)
- MIDI offered since April 2004 on UTs and October 2005 on ATs
- AMBER offered on UTs since October 2005 and ATs since April 2007
- FINITO offered on ATs and UTs
- ~50% of nights used for VLTI science operations
- Five operations astronomers, three fellows, numerous TIOs to run VLTI
- 100+ refereed papers

VLTI Scheme - Subsystems



What does the VLTI infrastructure do?

"Put the light in the one place at the one time."

- Inject the image plane into the lab
- Make the pupils coincide
- OPD variations should only be atmospheric or their residuals

How does VLTI do it?

Each UT has a MACAO system that concentrates the bulk of the photons within the Airy ring.

The beam is propagated via the relay optics to the delay lines

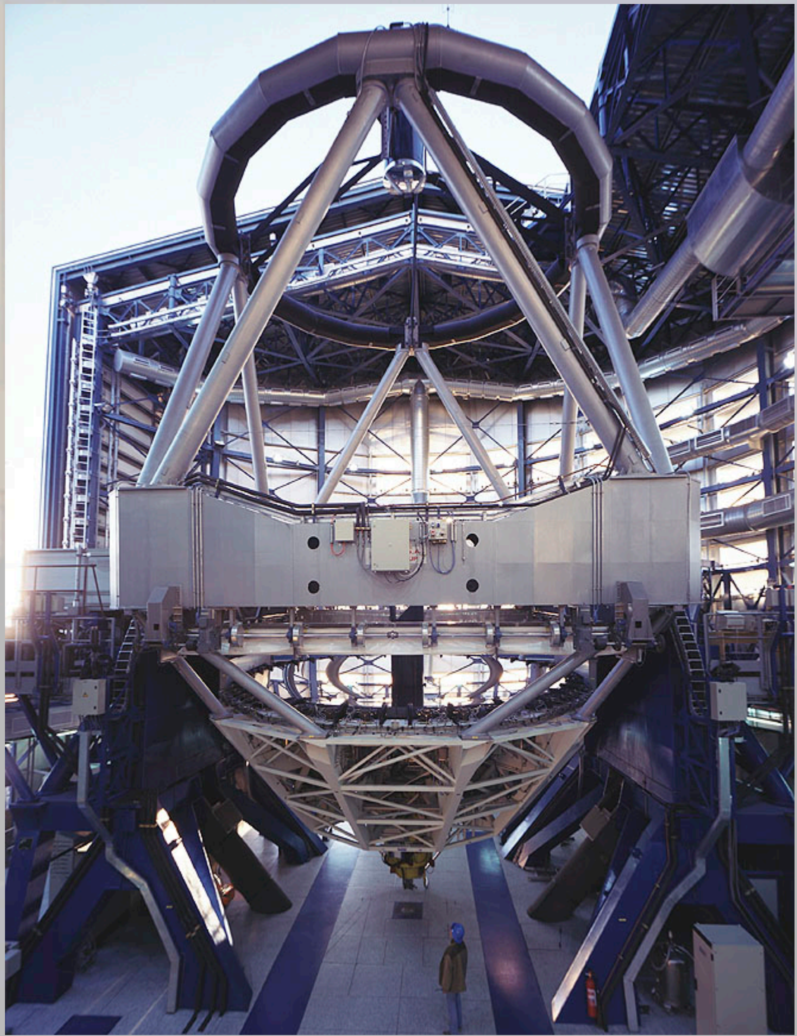
The delay lines correct in ‘open loop’ geometric OPD (telescope and star locations)

The VCMs on the delay lines move the pupil in the ‘axial’ direction.

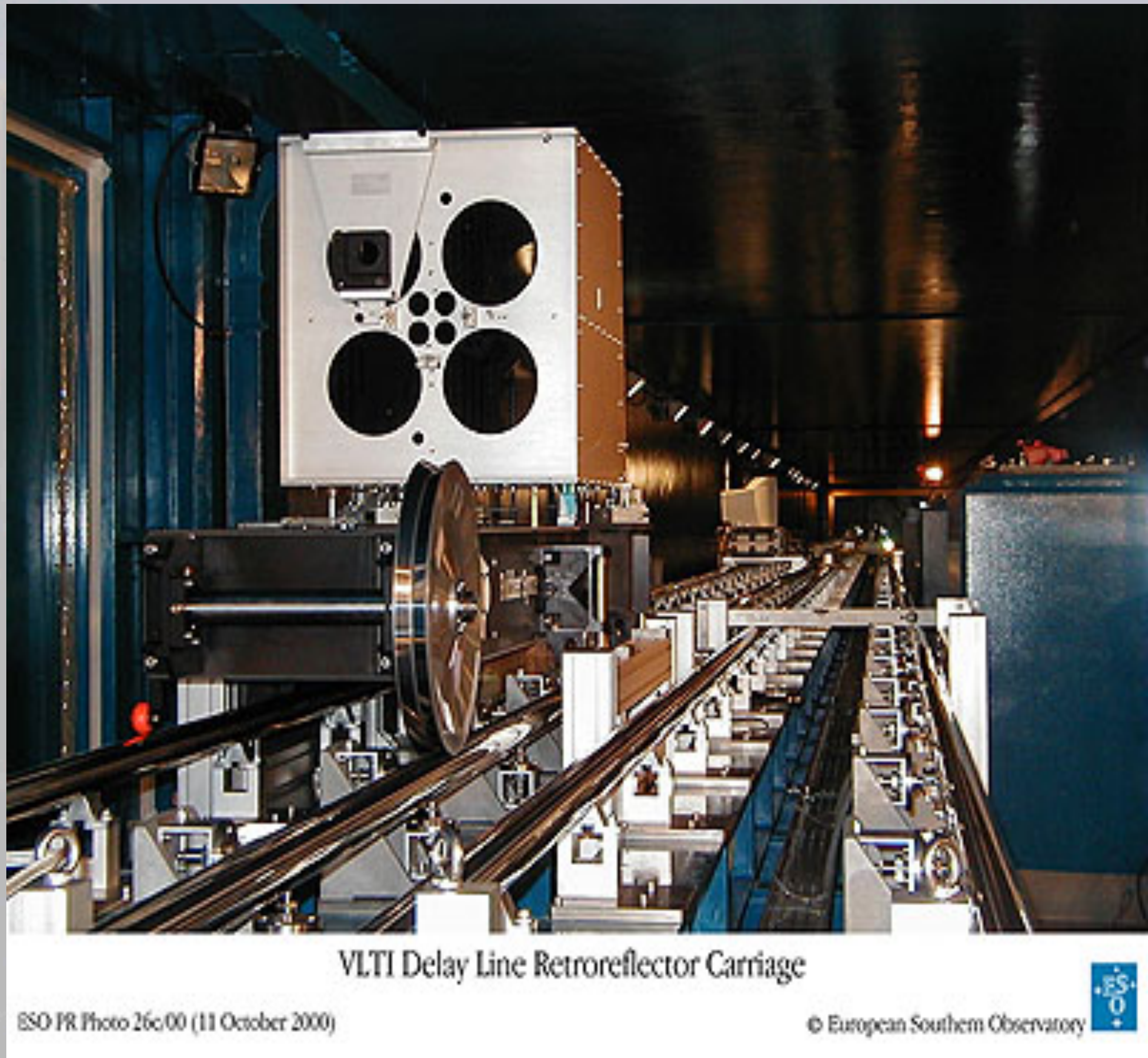
IRIS corrects for drifts in the conjugation between the MACAO reference and the lab reference

FINITO corrects for atmospheric OPD variations through the delay lines

The VLTI Telescopes



Delay Lines


VLTI Delay Line Retroreflector Carriage
ESO PR Photo 26c/00 (11 October 2000)
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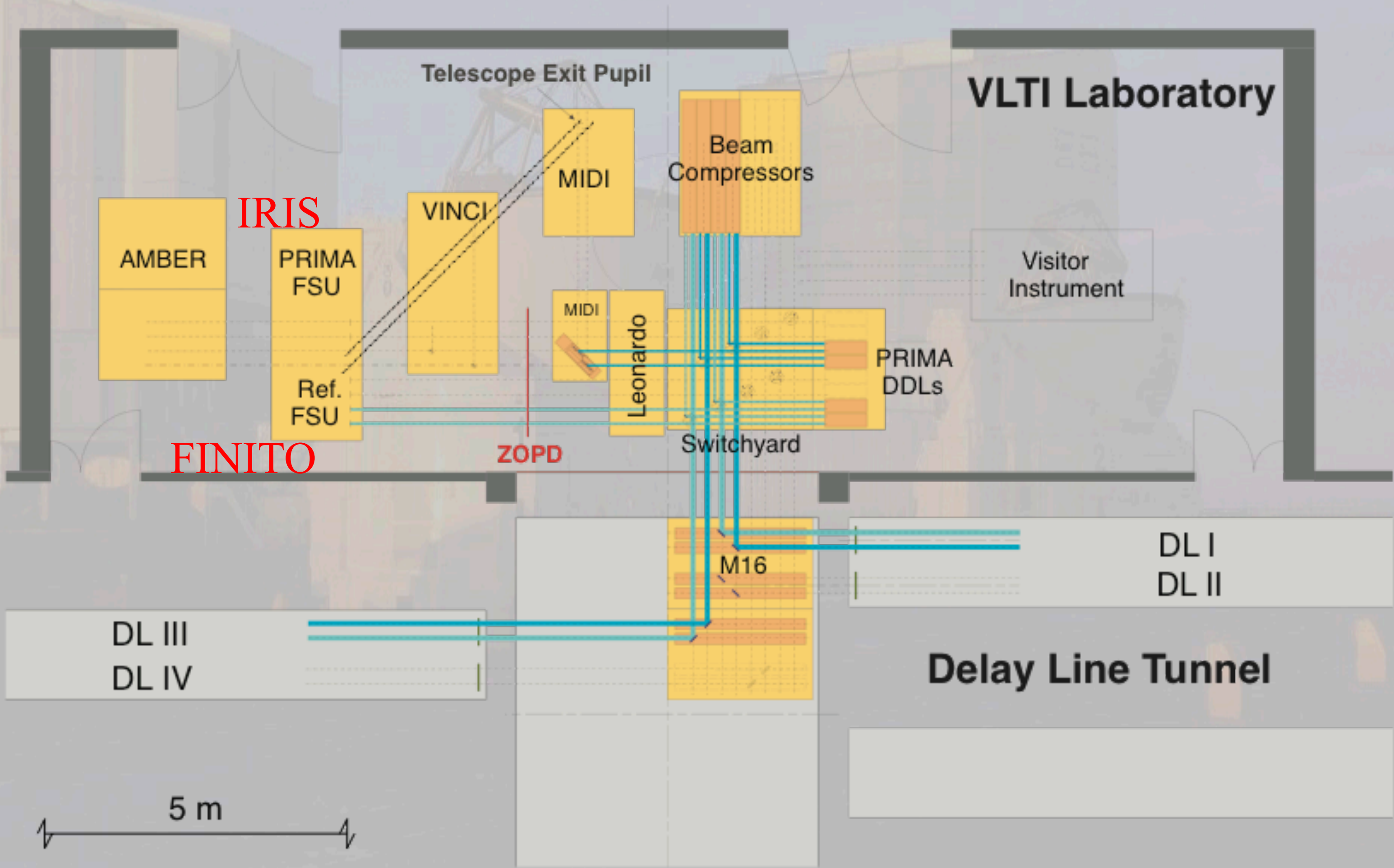
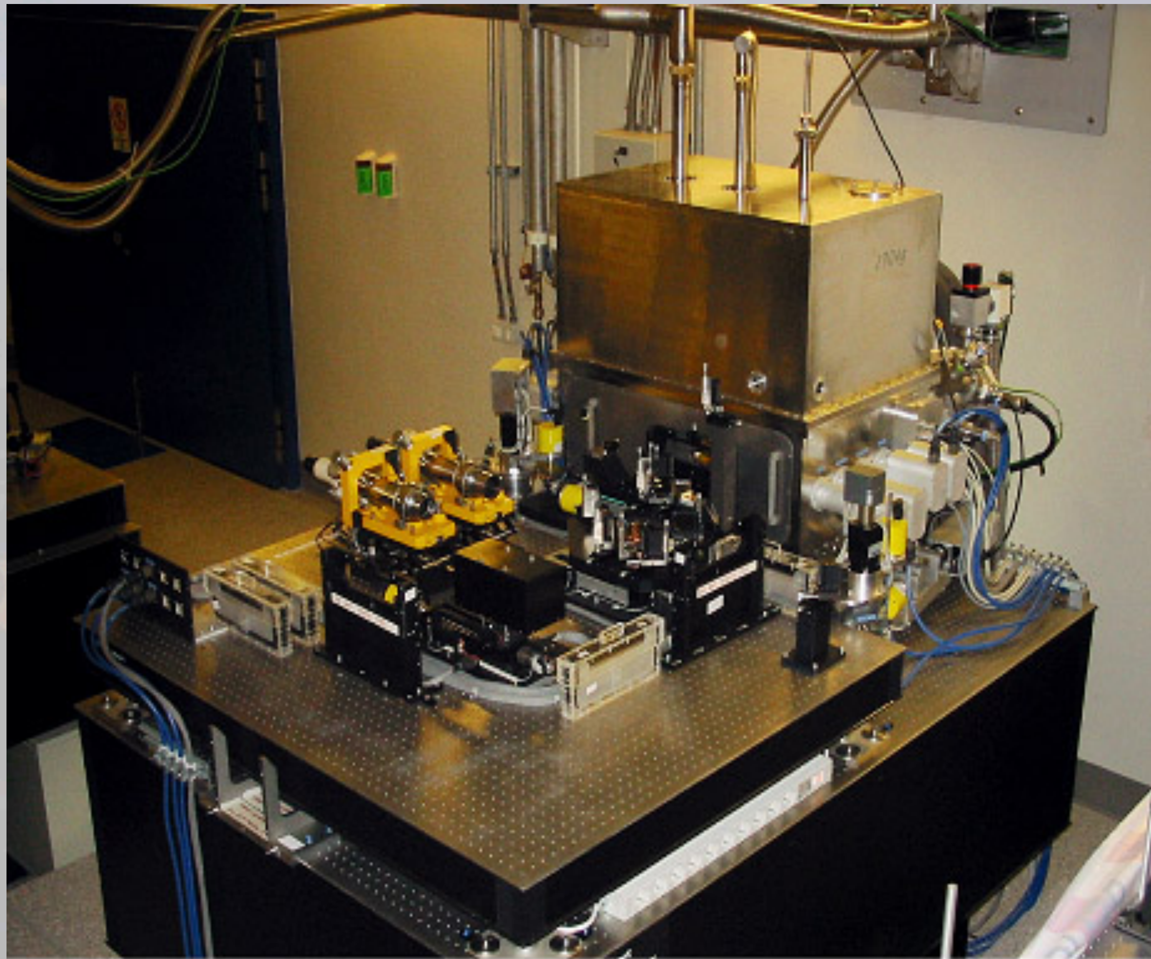
The interferometric laboratory



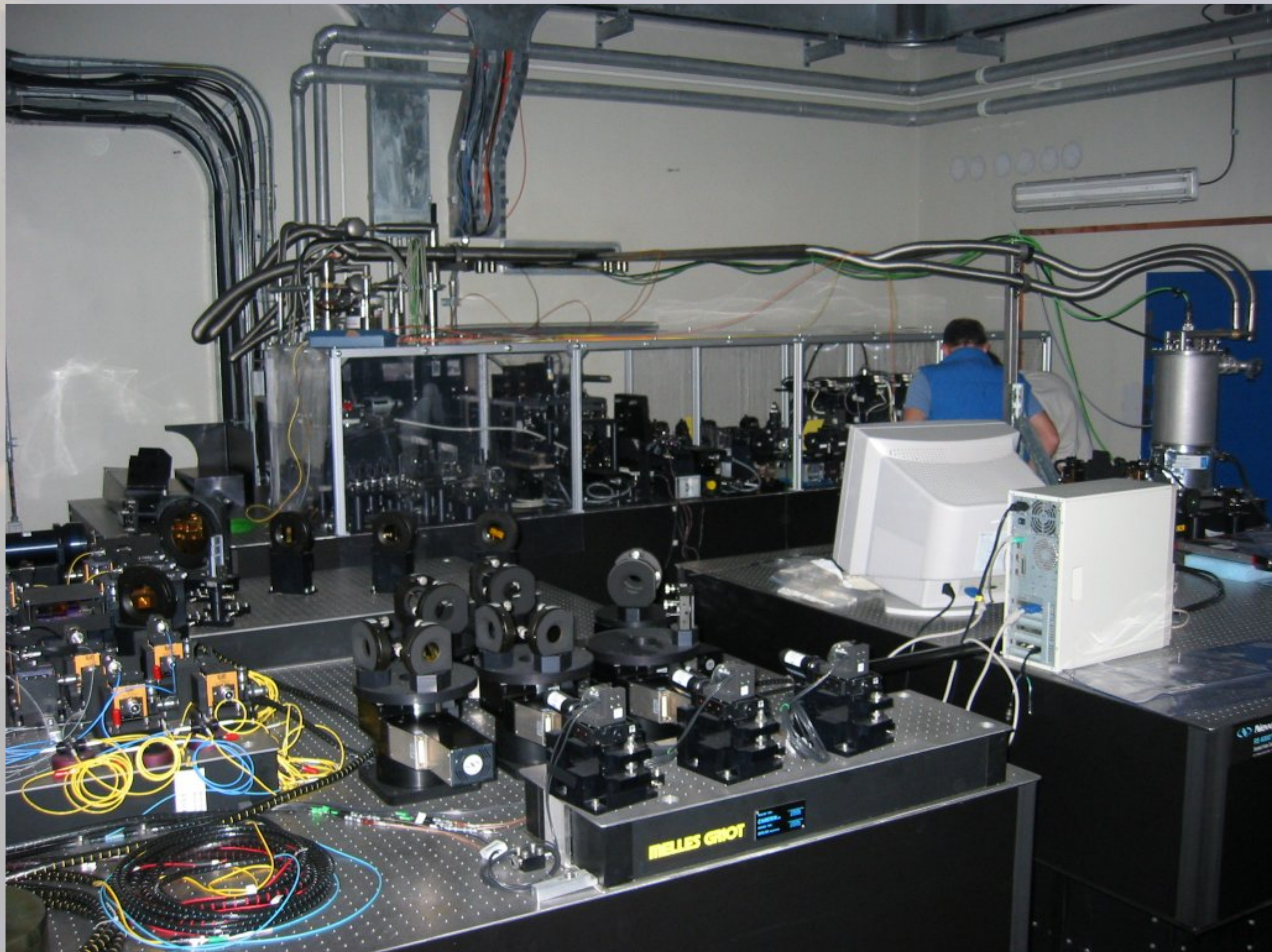
MIDI in the VLTI lab



The MIDI Instrument at the VLT Interferometric Laboratory on Paranal

ESO PR Photo 30c/02 (18 December 2002)

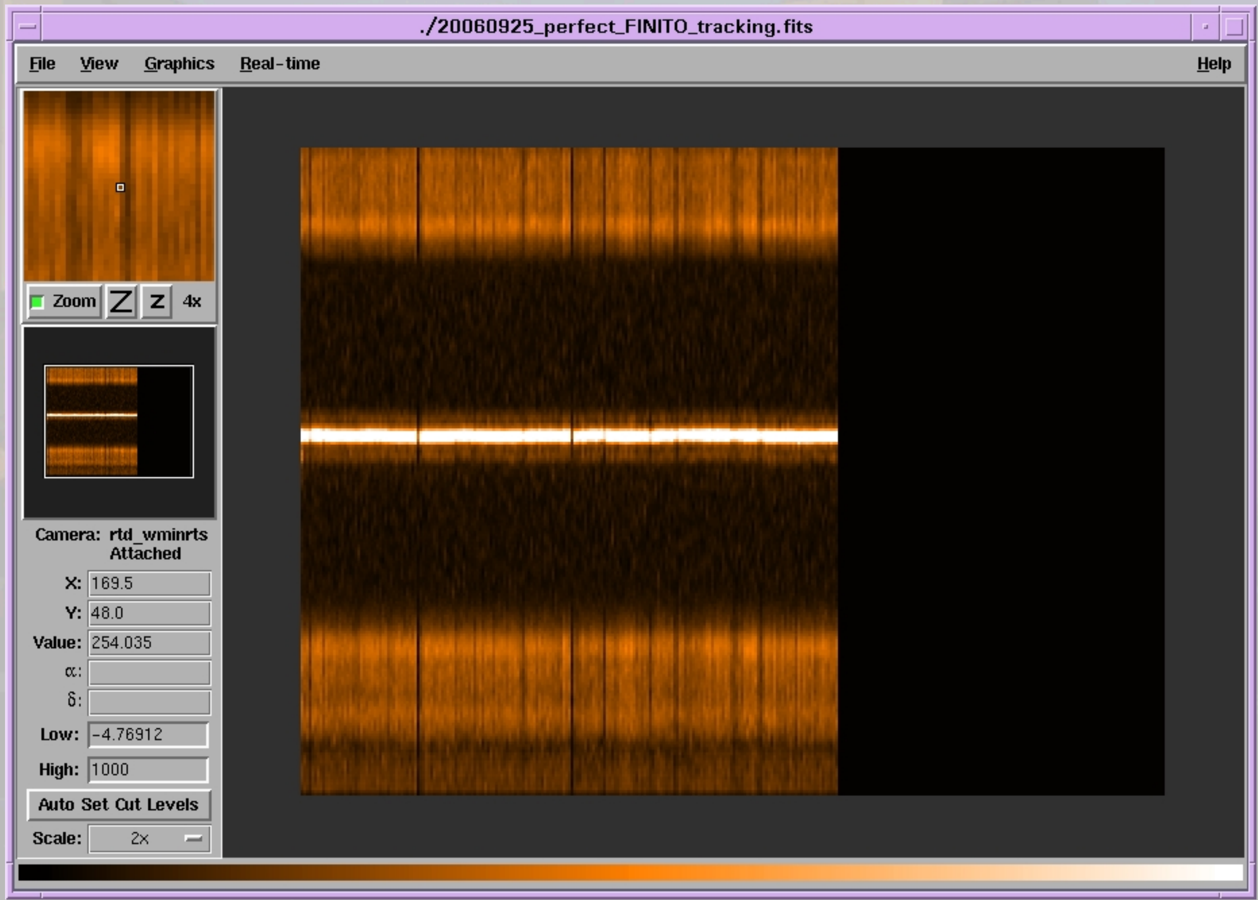
AMBER in the VLTI Lab

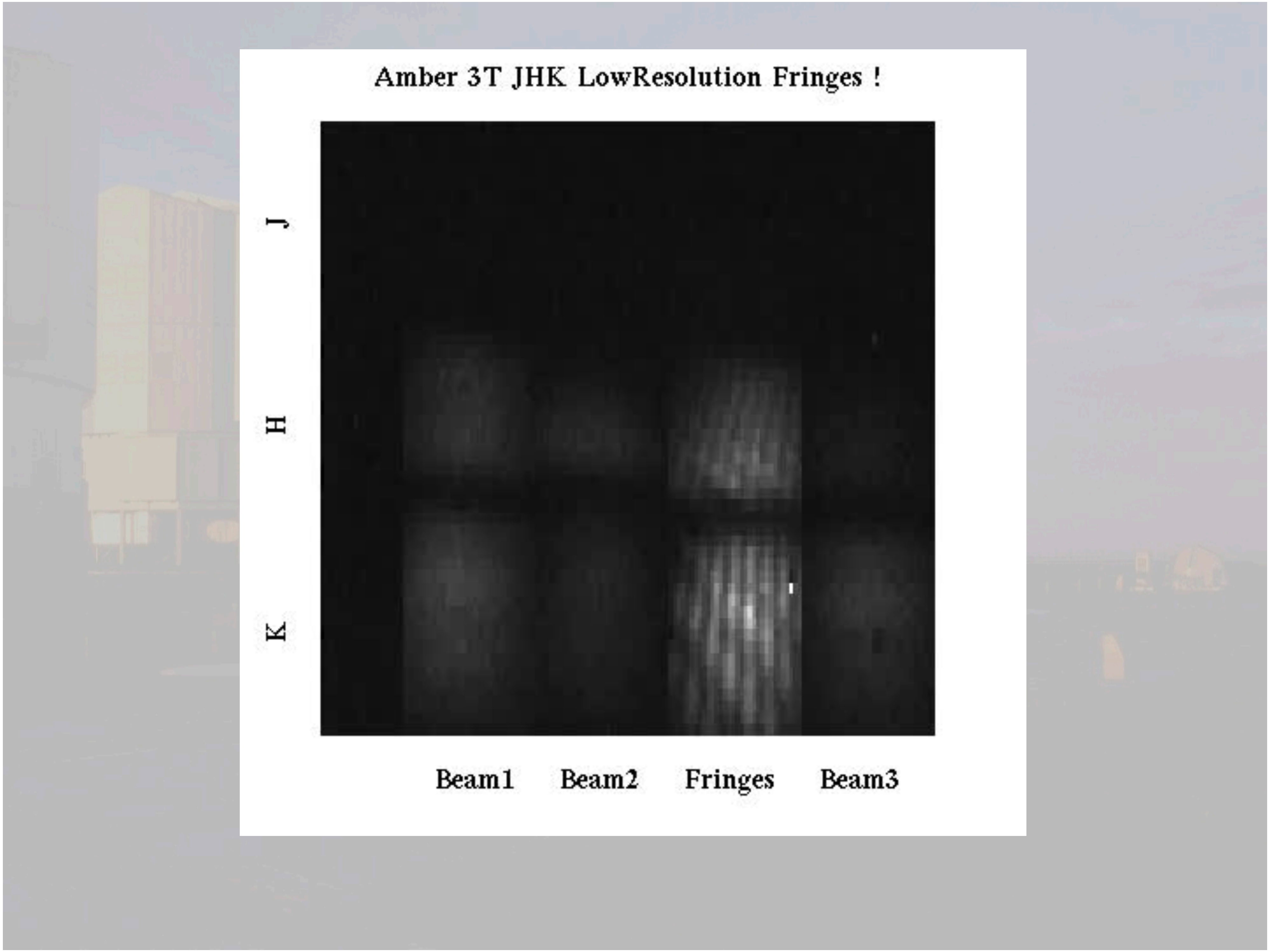


VLTI Science Instrumentation

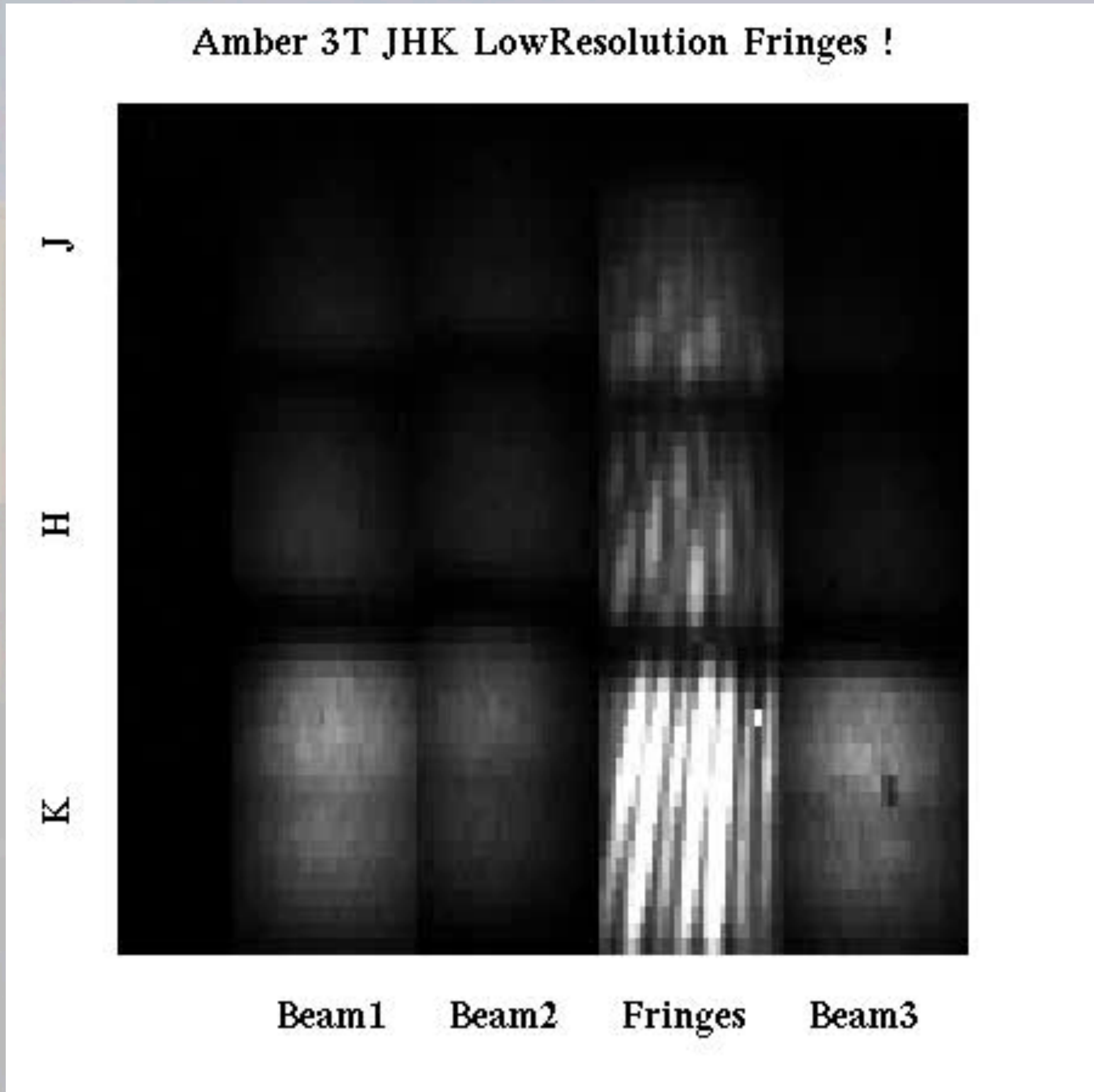
	Bands	# telescopes	spectral resolution	limiting magnitude (UTs/ATs)
AMBER	J,H,K	3	35, 1500, 12,000	7,4,1.5/ 5.1,1.6,-
MIDI	N	2	30, 230	4 (1Jy), 2.8/ 0.7,0.3

Stabilized fringes on MIDI (Sep 06) - Running from template




Amber 3T JHK LowResolution Fringes !
J
H
K
Beam1
Beam2
Fringes
Beam3

Nov 06


Amber 3T JHK LowResolution Fringes !
J
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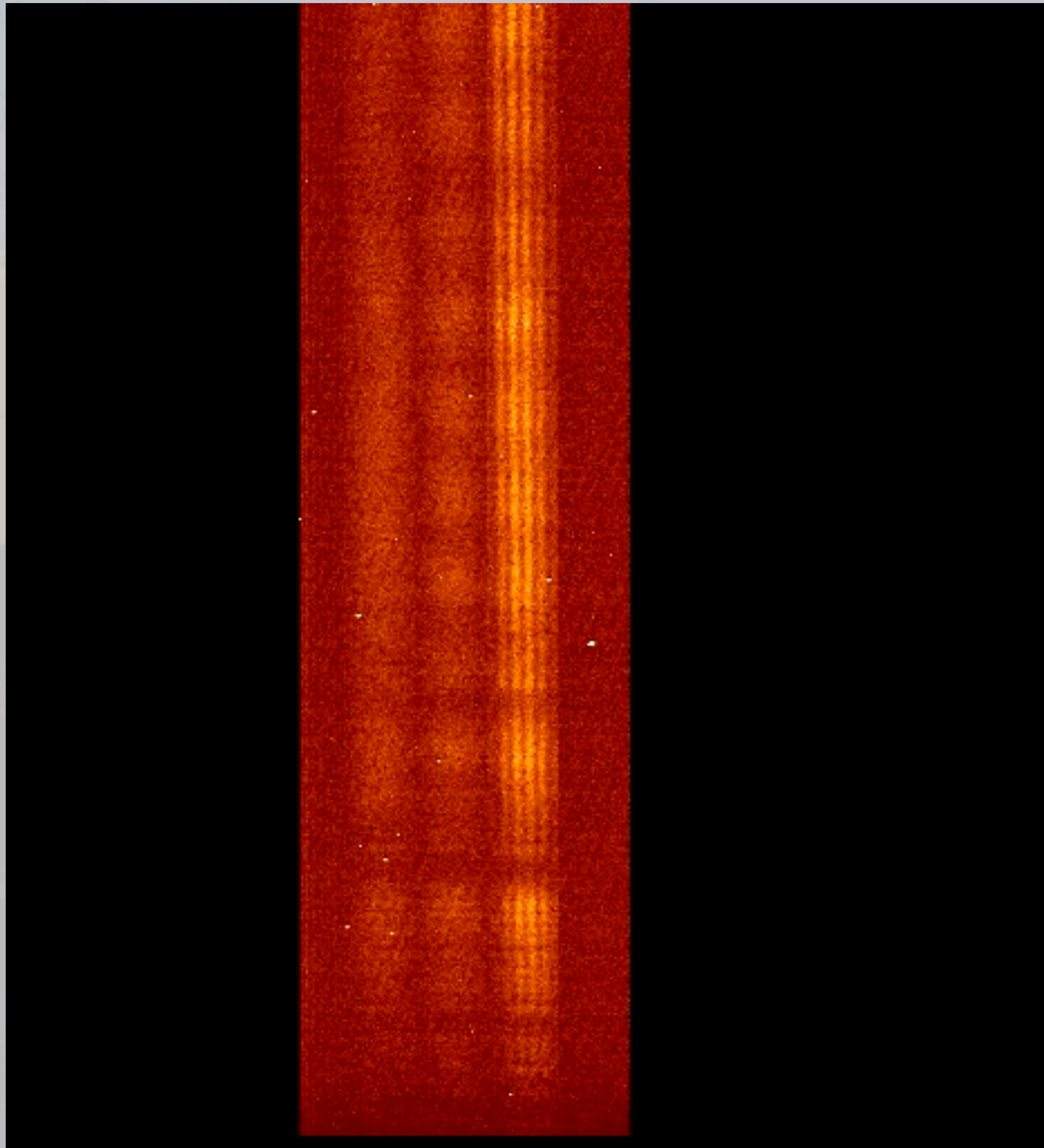
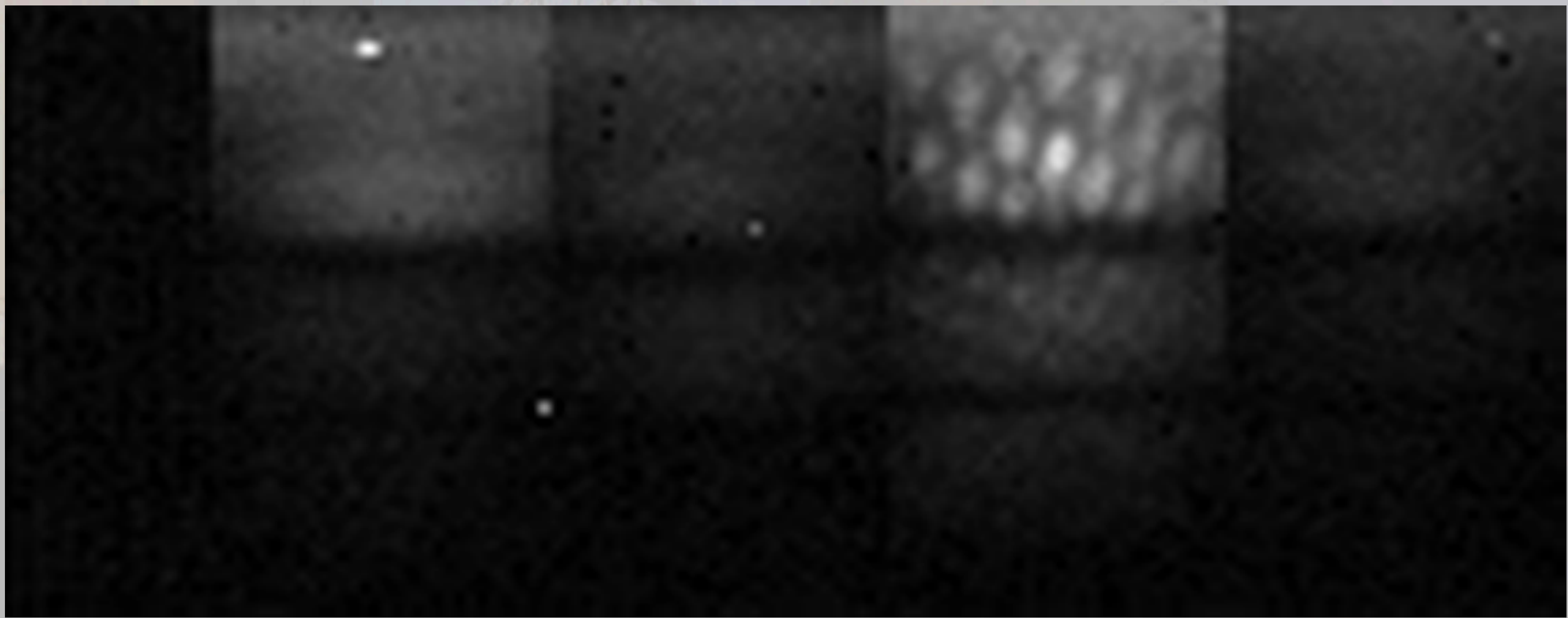
Beam1
Beam2
Fringes
Beam3

Jan 07



AMBER MRK

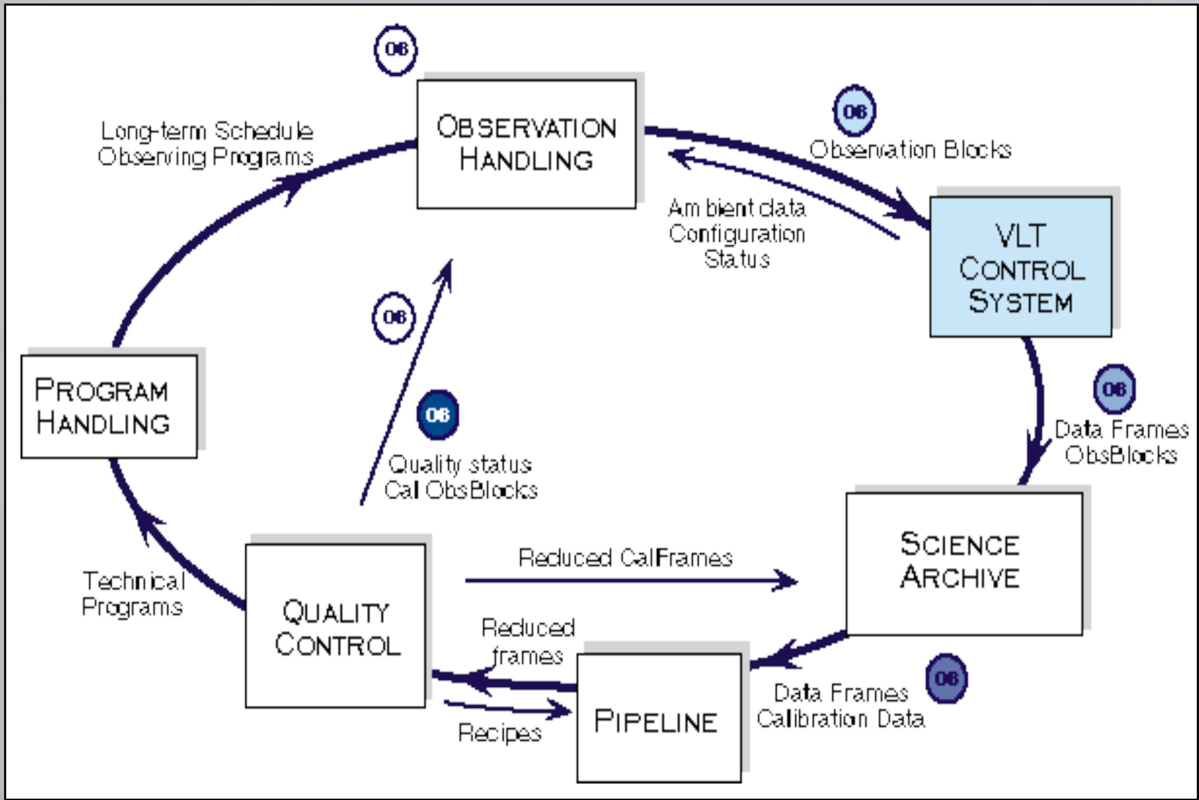
Apr 2007



VLTI Science Instrumentation

	Bands	# telescopes	spectral resolution	limiting magnitude (UTs/ATs/ UTs+FINITO/ ATs+FINITO)
AMBER	J,H,K	3	35, 1500, 12,000	7,4,1.5/ 5.1,1.6,-/ 7,7,6/ 5,5,5
MIDI	N	2	30, 230	4 (1Jy), 2.8/ 0.7,0.3

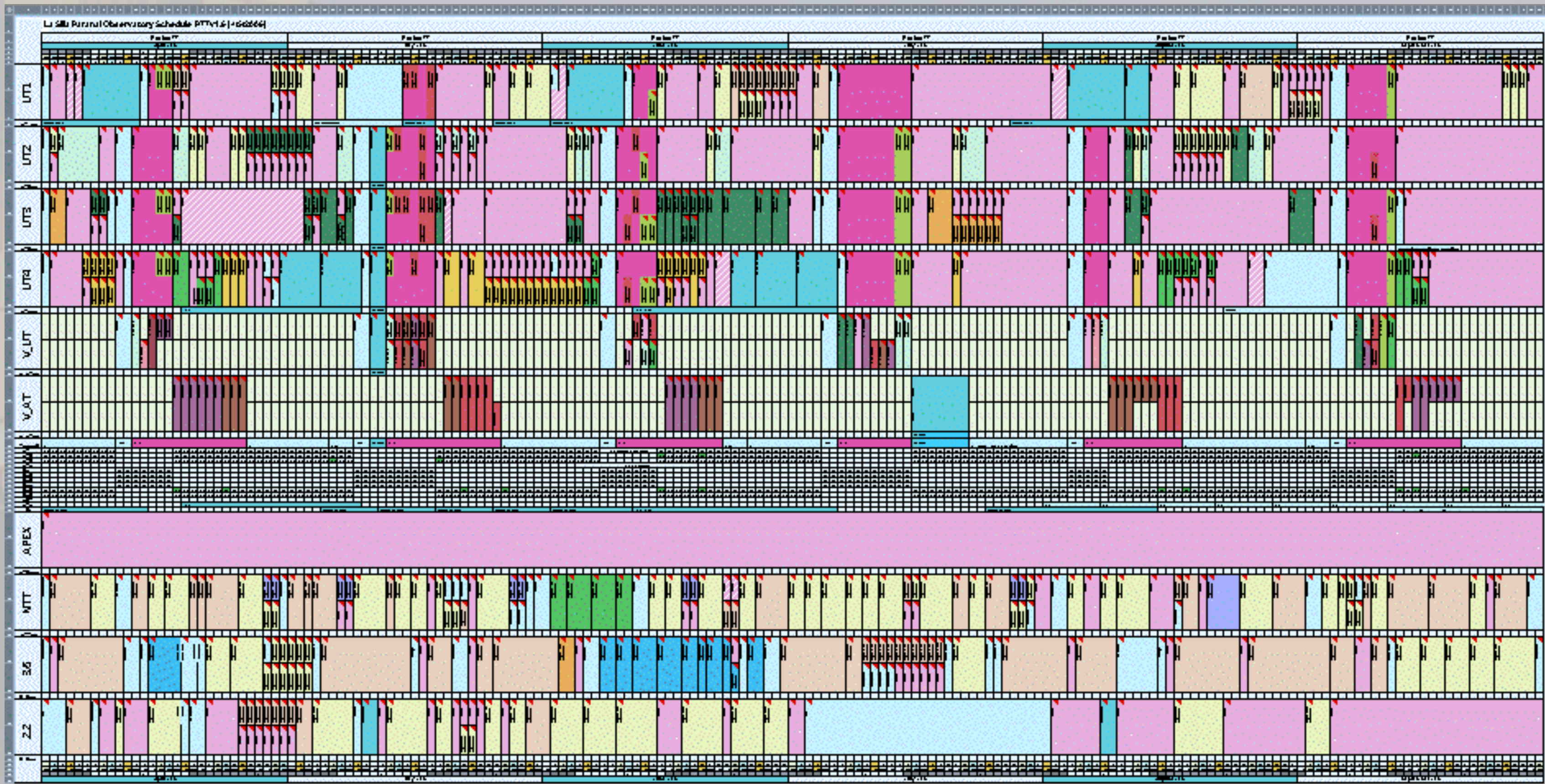
VLTI Operations



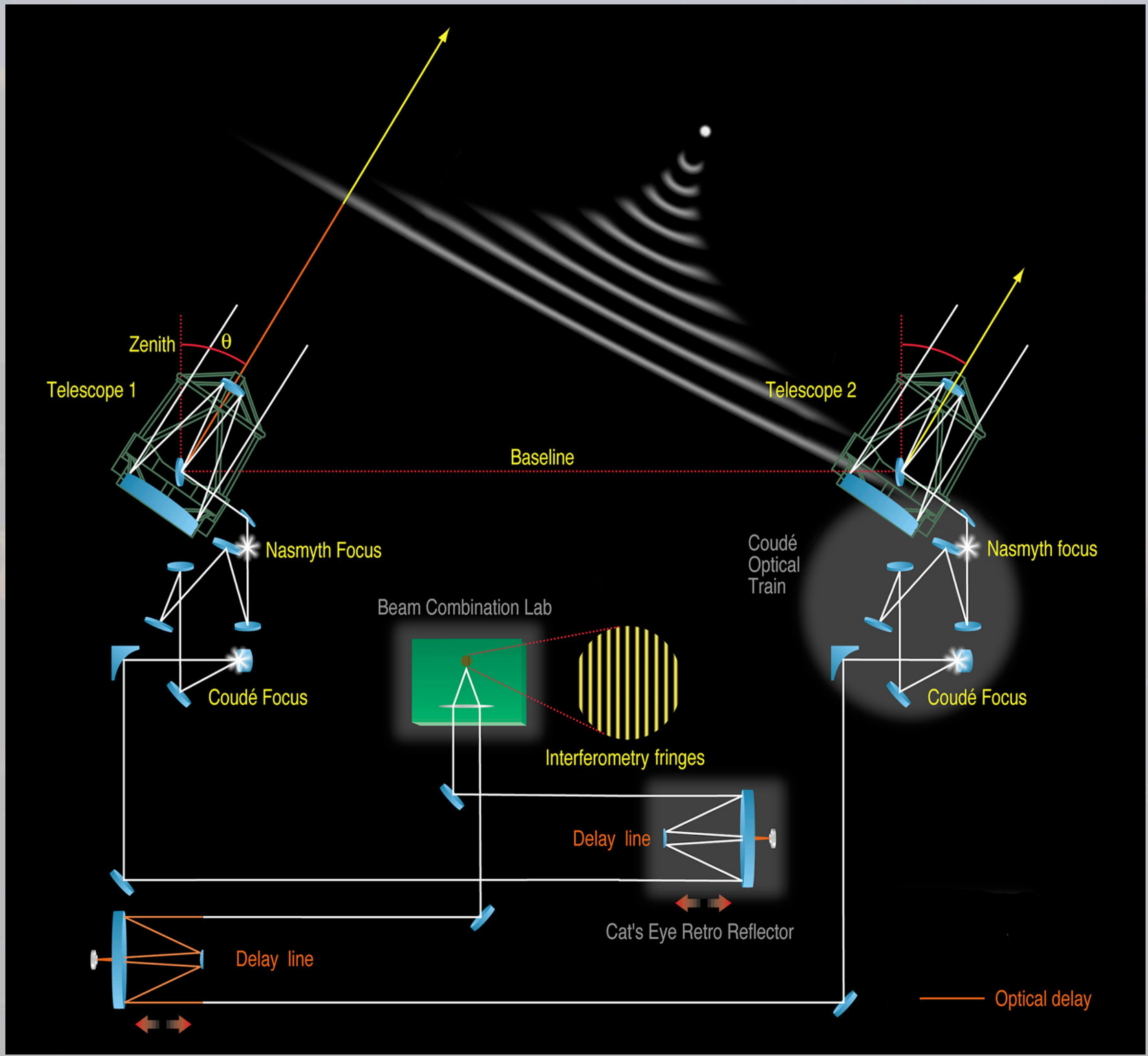
VLTI follows the VLT data flow: proposal form, OB preparation and execution, FITS data, archive

Observations performed in Visitor and Service Mode

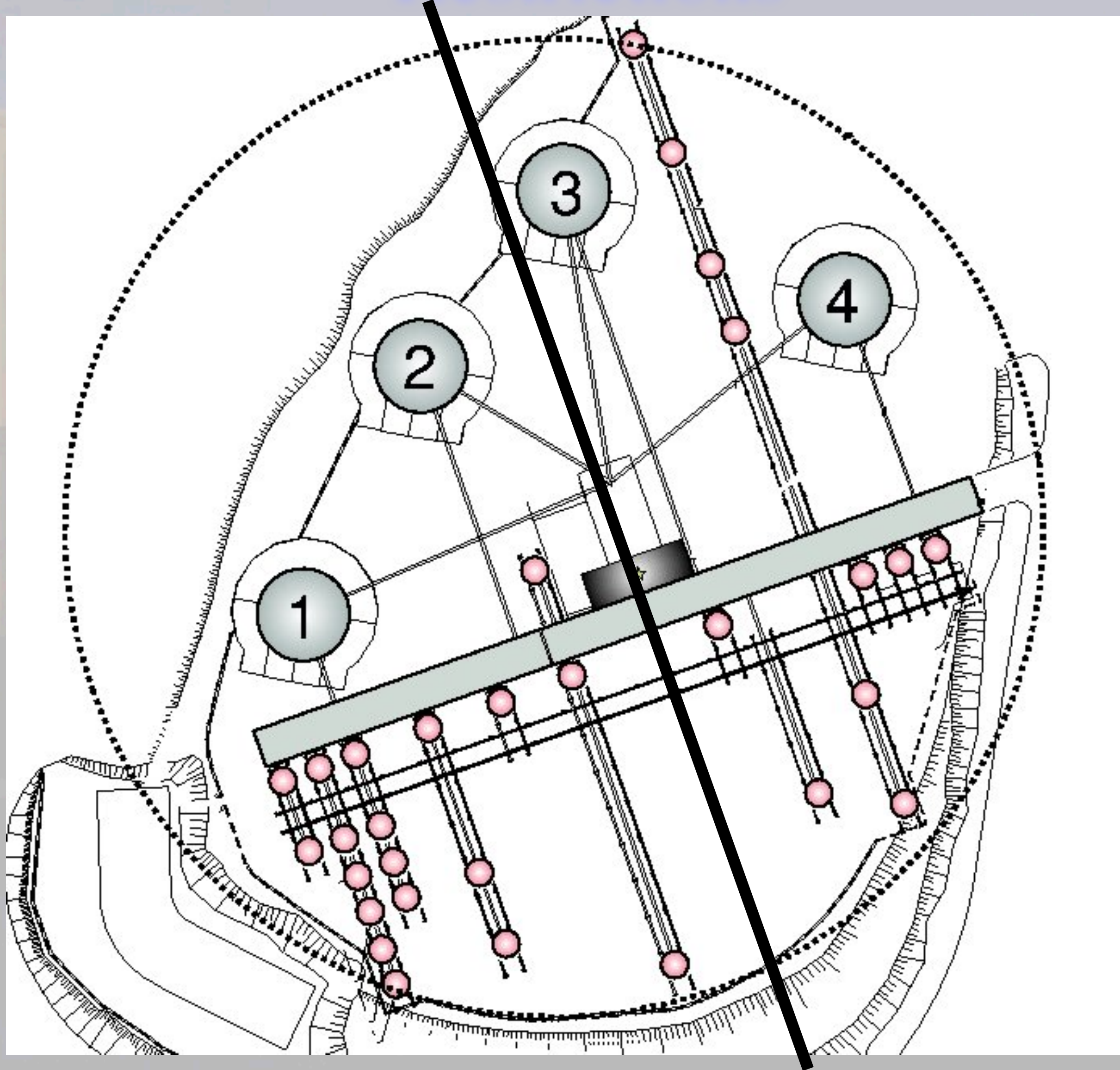
La Silla/Paranal schedule P77 (now)



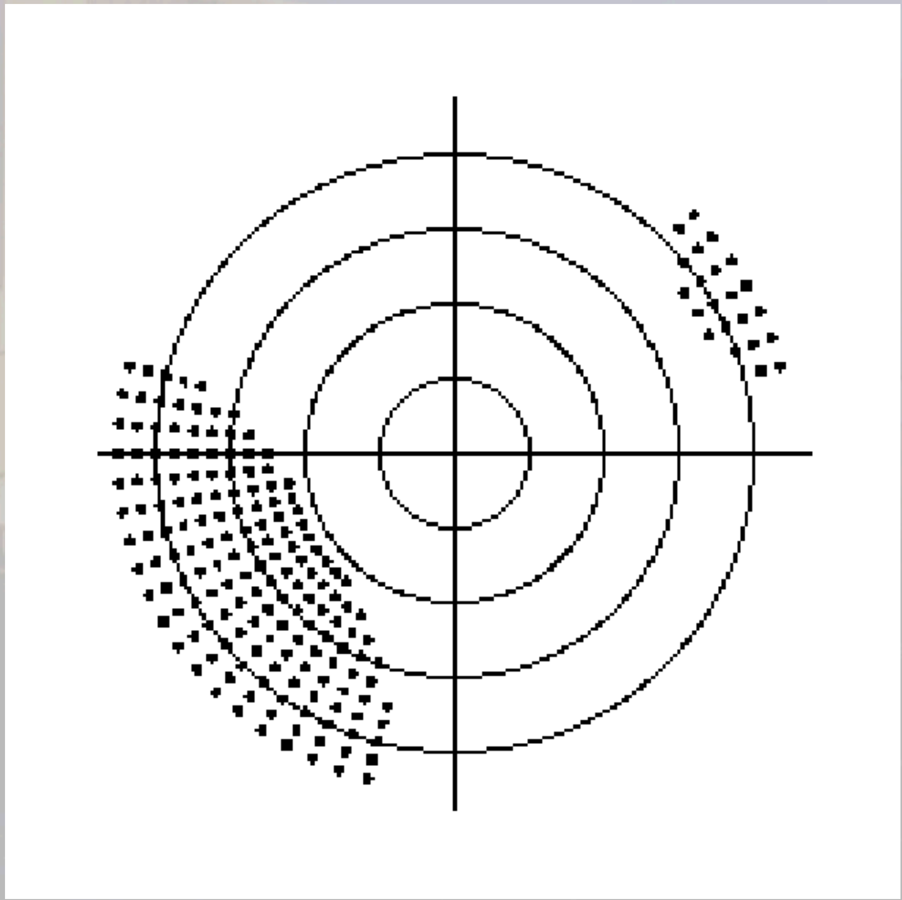
VLTI Scheme - Constraints

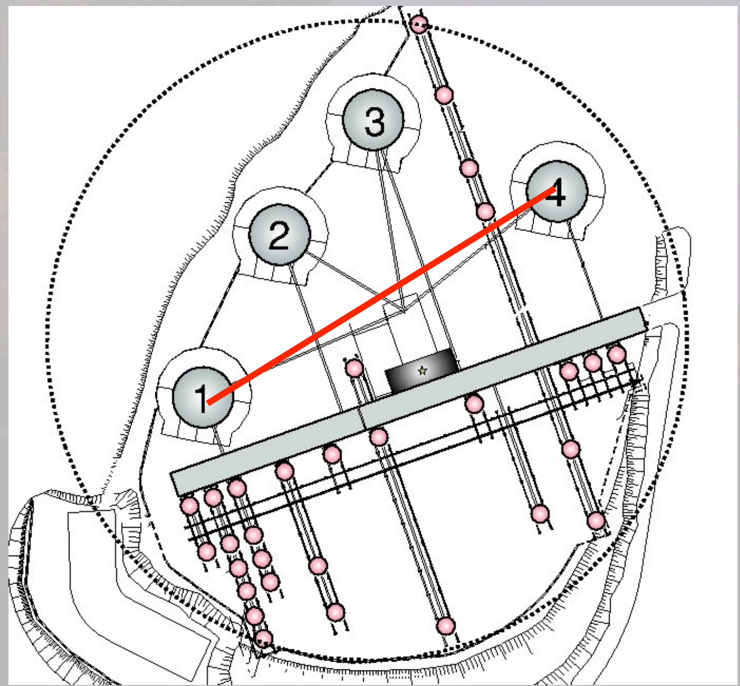


Restrictions

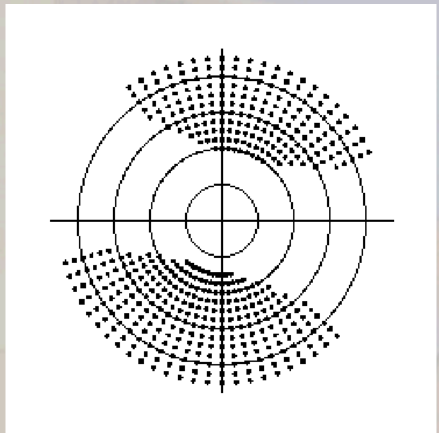


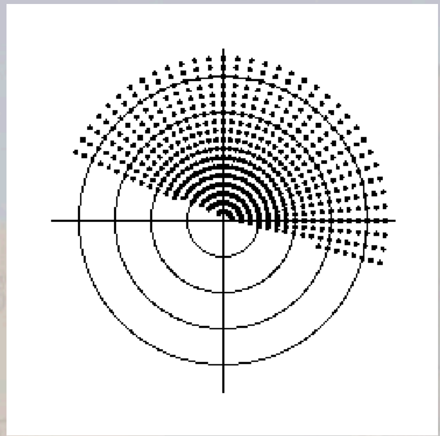
DL restrictions on UT1/4

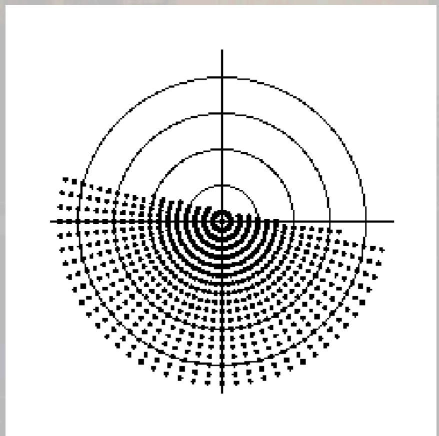


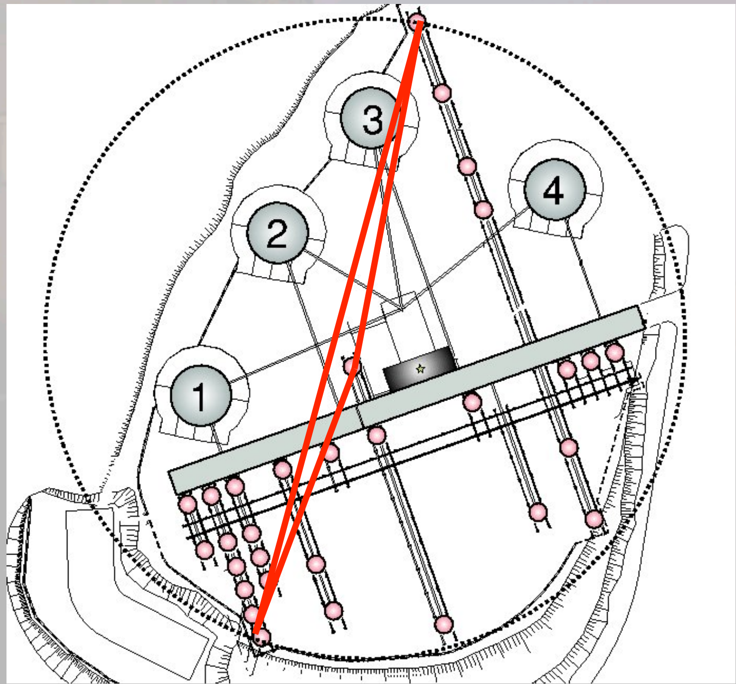


DL restriction on ATs

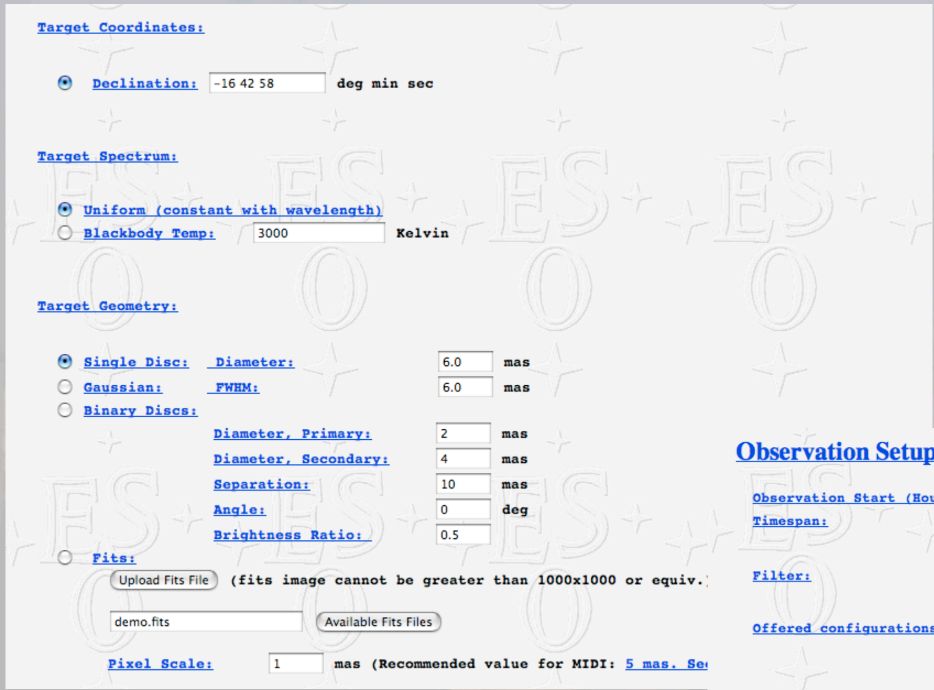


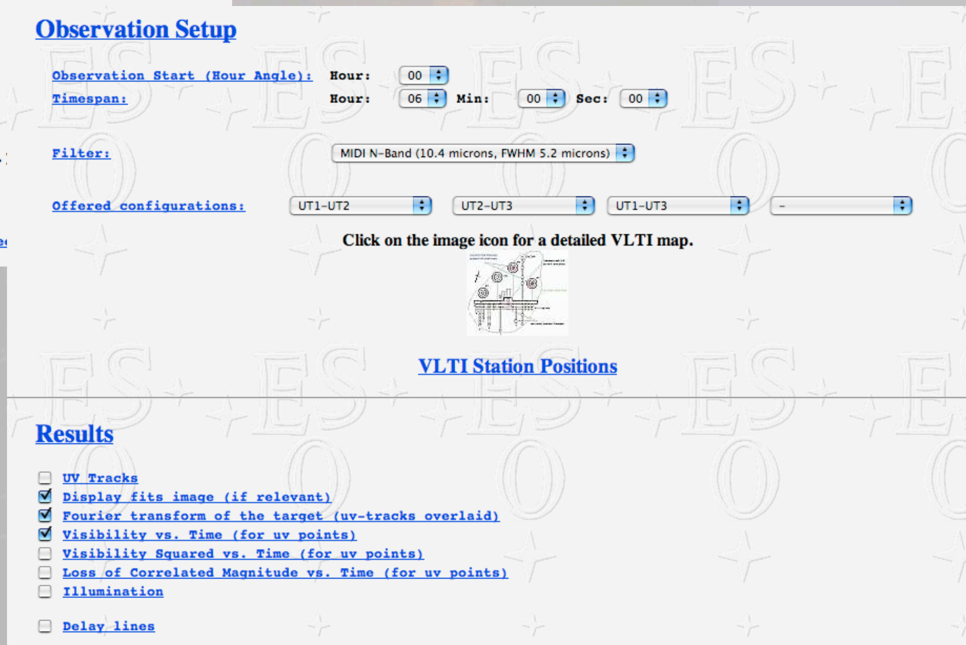






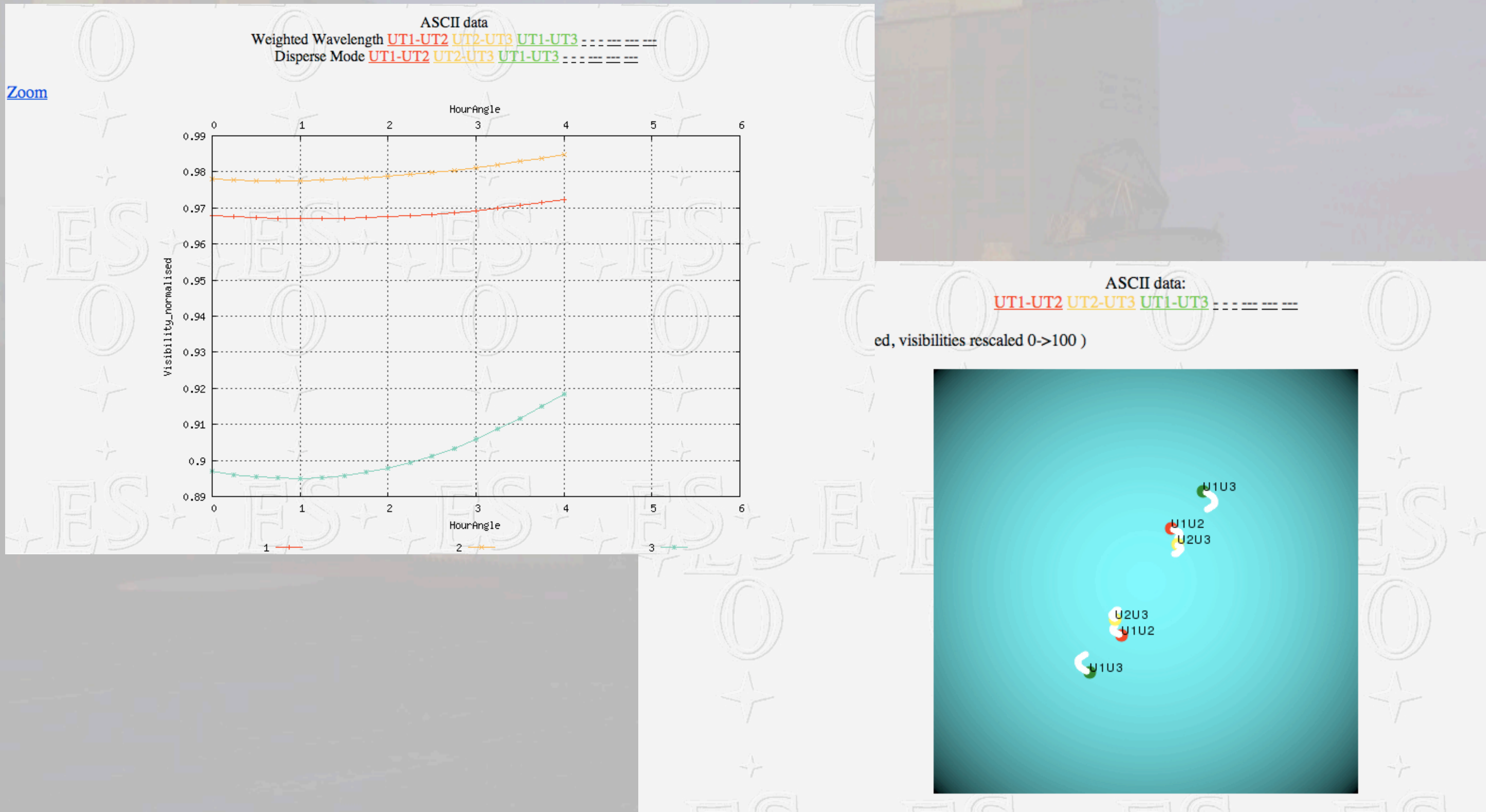
Observation preparation - VisCalc





http://www.eso.org/observing/etc/

VisCalc output



Selecting calibrators - CalVin

Comparative graphs for *Target* vs. 7 calibrators:- Normalized Visibilities Loss of Correlated Magnitudes Target Altitudes Shadow

No.	Name	R.A. (h,m,s)	Dec. (d,m,s)	Ang. Dist. (deg°)	Ang. Diam. (mas)	Mag_K	Spec. Type	Lum. Class	Qual. Flag	Normalized Visibility ave ± err range	Loss of Correlated Magnitude ave ± err range	RiseTime SetTime Duration	Culmination MaxAltitude	Shadowing
1 (0)	*Target*	6 45 8.90	-16 42 58.00	0.0	6.00 ± 0.00					0.08 ± 0.000 0.08-0.08 graph ascii	5.58 ± -0.00 5.58-5.58 graph ascii	35.50UT 35.50UT 0.00hrs	35.50 UT max = 17° graph ascii	max = 0% graph ascii
2 (1578)	hd51054_M04	6 55 12.02	-15 42 12.54	2.6	0.91 ± 0.01	3.69	K2/K3III	III	1	NOT VISIBLE	NOT VISIBLE	NOT VISIBLE	NOT VISIBLE	NOT VISIBLE
3 (1584)	hd51546_M04	6 57 3.17	-17 5 54.83	2.9	0.87 ± 0.01	3.89	K2III	III	1	0.97 ± 0.001 0.97-0.97 graph ascii	0.07 ± 0.00 0.07-0.07 graph ascii	22.25UT 22.25UT 0.00hrs	22.25 UT max = 15° graph ascii	max = 0% graph ascii
4 (1509)	hr2450_B02	6 39 16.72	-14 8 44.75	2.9	2.56 ± 0.04	1.53	K2III	III	1	0.65 ± 0.010 0.65-0.65 graph ascii	0.93 ± 0.03 0.93-0.93 graph ascii	35.50UT 35.50UT 0.00hrs	35.50 UT max = 17° graph ascii	max = 0% graph ascii
5 (1497)	nu.02cma_B02	6 36 41.04	-19 15 21.16	3.2	2.38 ± 0.03	1.56	K1III+...	III	1	0.67 ± 0.006 0.67-0.67 graph ascii	0.86 ± 0.02 0.86-0.85 graph ascii	35.25UT 35.50UT 0.25hrs	35.50 UT max = 20° graph ascii	max = 0% graph ascii
6 (1467)	hd46308_M04	6 31 55.65	-18 3 44.14	3.4	1.14 ± 0.01	3.17	K3III	III	1	0.92 ± 0.002 0.92-0.92 graph ascii	0.18 ± 0.00 0.18-0.18 graph ascii	35.25UT 35.50UT 0.25hrs	35.50 UT max = 20° graph ascii	max = 0% graph ascii
7 (1485)	hd46853_M04	6 34 51.18	-19 38 47.97	3.8	0.95 ± 0.01	3.71	K4III	III	1	0.94 ± 0.002 0.94-0.94 graph ascii	0.13 ± 0.00 0.13-0.13 graph ascii	35.25UT 35.50UT 0.25hrs	35.50 UT max = 20° graph ascii	max = 0% graph ascii
8 (1596)	hd52436_M04	7 0 38.60	-15 23 55.31	3.9	1.20 ± 0.02	3.32	K5III	III	1	0.94 ± 0.002 0.94-0.94 graph ascii	0.13 ± 0.00 0.13-0.13 graph ascii	22.25UT 22.25UT 0.00hrs	22.25 UT max = 15° graph ascii	max = 0% graph ascii

Further prospects

- PRIMA commissioning ongoing since second half of 2008
- 2nd gen instruments (MATISSE and Gravity) going for PDR in 2009

Some acronyms

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- OPL - optical path length
- OPD - optical path difference
- ZOPD - zero optical path difference
- UT - Unit Telescope (8.2m)
- AT - Auxiliary Telescope (1.8m)
- MACAO - Multi Application Curvature Adaptive Optics
- STRAP - System for Tip-tilt Removal with Avalanche Photo diodes
- VINCI - VLT INterferometer Commissioning Instrument
- AMBER - Astronomical Multiple BEam Recombiner
- MIDI - MID Infrared interferometric instrument
- FINITO - Fringe sensing Instrument NIce TOrino
- IRIS - InfraRed Image Sensor
- ISS - Interferometer Supervisor Software
- VCM - Variable Curvature Mirror