The VLTI Interferometer

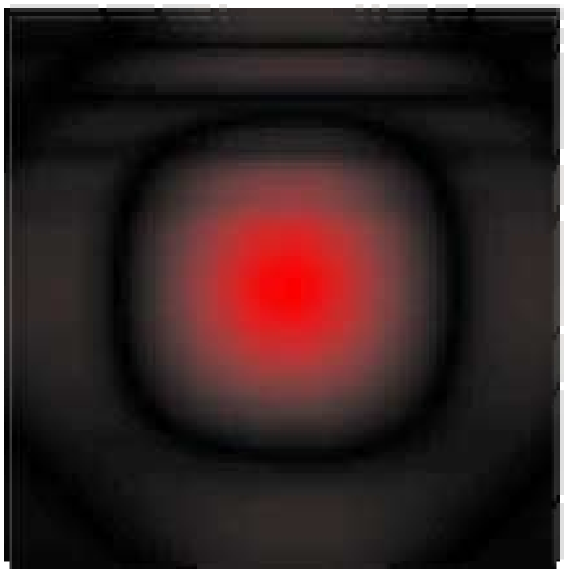
Part I: context, description, operations.

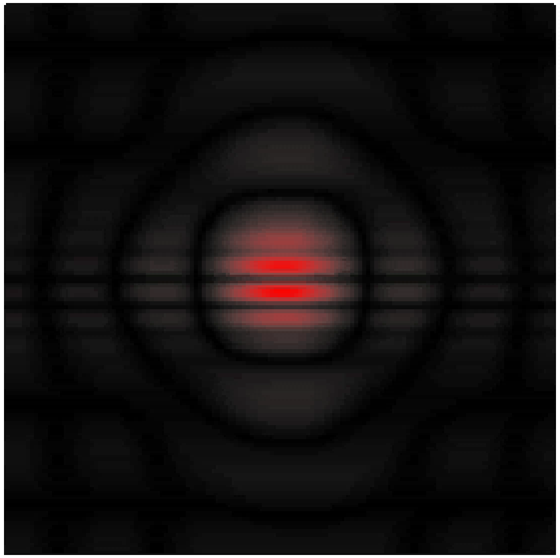
A. Richichi (ESO Garching)

Scuola Nazionale di Tecnologie Astronomiche

Napoli 23 - 28 September 2002

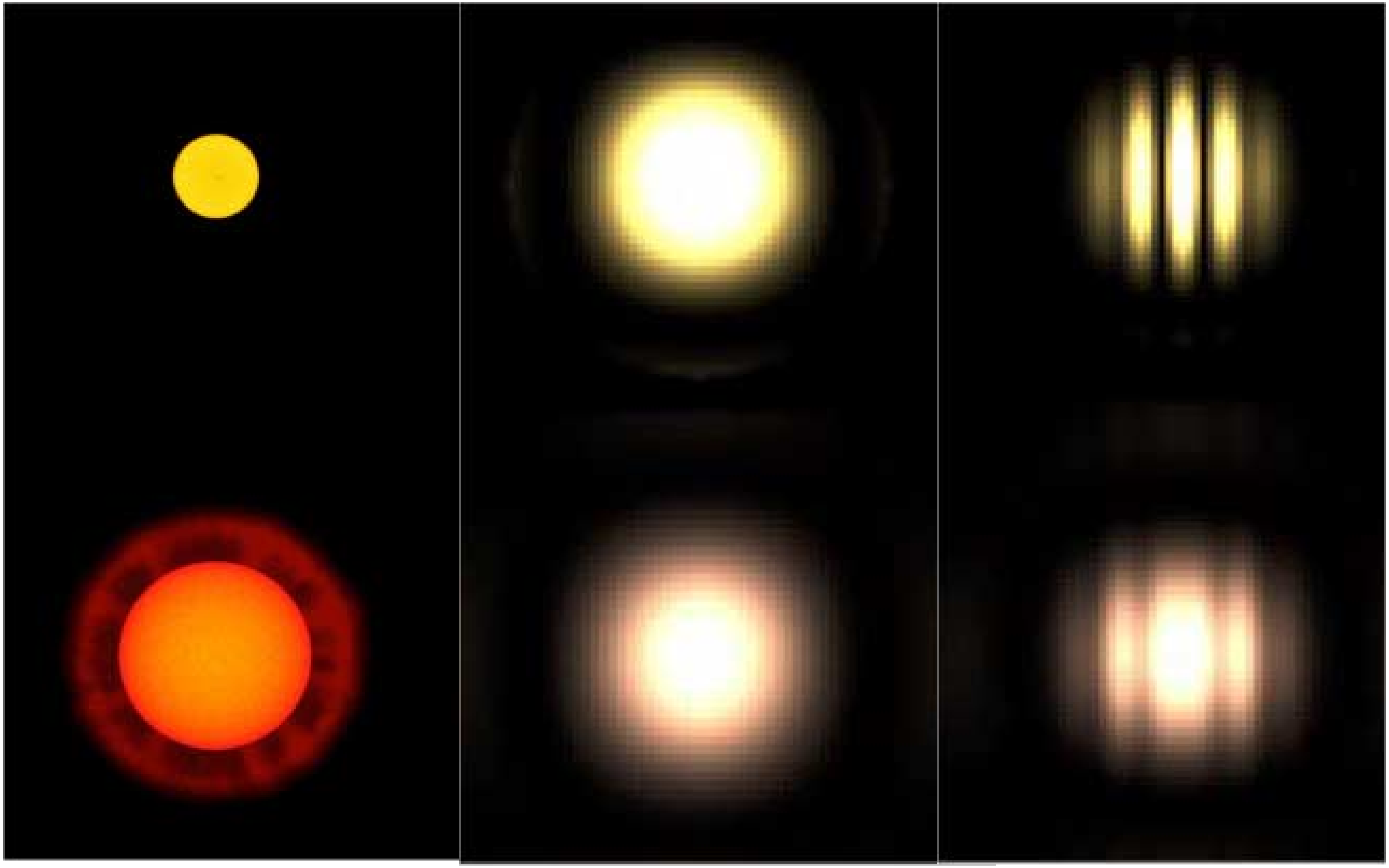
Interferometry at work - I





Very nice. And now what?

Interferometry at work - II



Objects **Single Telescope** **Interf. Fringes**

Design vs. Science

<u>Baseline Length</u>

- Resolution improves with Baseline
  - "correlated" magnitude decreases
  - relative errors increase
- Calibrators
  - accuracy vs baseline
  - magnitude vs baseline
  - density
  - boot-strapping

Wavelength vs. Science

Wavelength

- Angular Resolution
  - resolution $\propto \lambda^{-1}$
- Atmospheric Turbulence
  - phase errors $\propto \lambda^{-1}$
  - isoplanatic patch $\propto \lambda^{6/5}$
  - seeing $\propto \lambda^{-1/5}$
  - coherence time $\propto \lambda^{6/5}$
- Source Spectrum
  - many (but not all!) sources are red
  - spectral features

Geometry vs. Science

Telescopes

- Number of telescopes
  - number of baselines $\propto$ N(N-1)
  - number of closure phases $\propto$ (N-1)(N-2)/2
- Beam Combiner
  - complexity drives cost (and size)
  - efficiency decreases with number of telescopes
  - new approaches
- Array Geometry
  - non-redundancy
  - configuration
  - NS vs. EW orientation
  - relocation of telescopes

Overview of current Interferometers

facility	funding	location	n. of apertures	apertures (m) primary	apertures (m) secondary	baseline max (m)	year of first fringes	wavelength range
CHARA	USA	Mt. Wilson	6	1.0		350	1999	vis
COAST	UK	Cambridge	5	0.4		48	1991	vis
GI2T	F	Calern	2	1.5		65		vis, NIR
IOTA	USA, F	Mt. Hopkins	2-3	0.45		38	1993	VRI, JHKL
ISI	USA	Mt. Wilson	2-3	1.65		75	1988	M
KECK	USA	Mauna Kea	2(4)	10	1.8	85(140)	2001	IR
LBT	USA, D, I	Mt. Graham	2	8.4		23	in constr.	vis, NIR
MIRA-I.2	J	Tokyo	2	0.30		6	2001	vis
MRO	USA	New Mexico	3	2.4		100	funded	vis, NIR
NPOI	USA	Arizona	3-6	0.35		64	1994	vis, NIR
PTI	USA	Mt. Palomar	3	0.40		110	1995	K
SUSI	AUS	New South Wales	2	0.14		640		B
VLTI	ESO	Paranal	4(3)	8.2	1.8	130(205)	2001	JHK, NQ

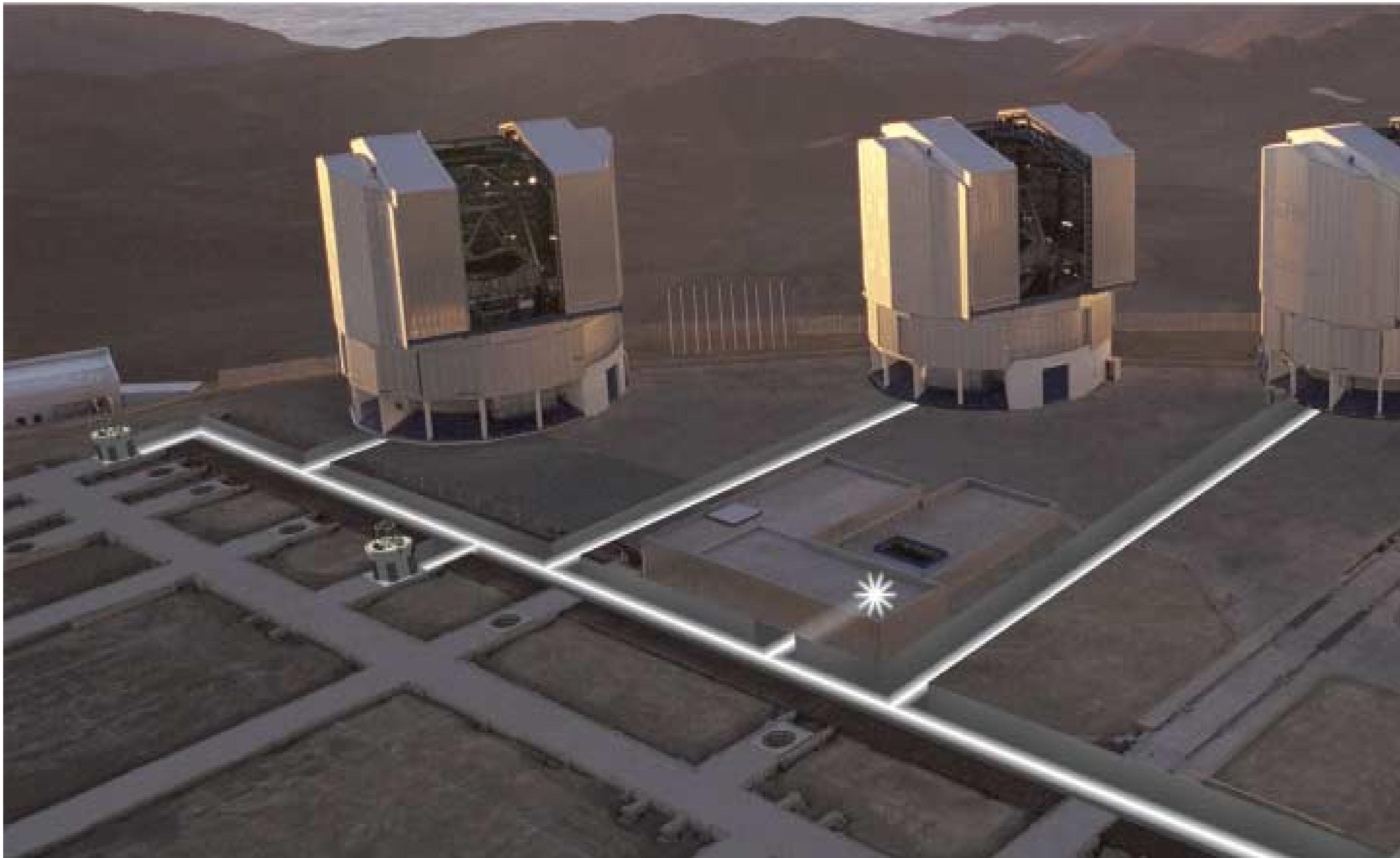
Interferometers on the WEB

facility	URL
CHARA	http://www.chara.gsu.edu/CHARA/array.html
COAST	http://www.mrao.cam.ac.uk/telescopes/coast/index.html
GI2T	http://wwwrc.obs-azur.fr/fresnel/gi2t/gi2t.htm
IOTA	http://cfa-www.harvard.edu/cfa/oir/IOTA/
ISI	http://isi.ssl.berkeley.edu/
KECK	http://huey.jpl.nasa.gov/keck/
LBT	http://medusa.as.arizona.edu/lbtwww/lbt.html
MIRA-I.2	http://tamago.mtk.nao.ac.jp/mira/MIRA-I_2/mira_1_2.html
MRO	http://www.physics.nmt.edu/research/MRO.html
NPOI	http://ftp.nofs.navy.mil/projects/npoi/
PTI	http://huey.jpl.nasa.gov/palomar/
SUSI	http://www.physics.usyd.edu.au/astron/susi/
VLTI	http://www.hq.eso.org/projects/vlti/

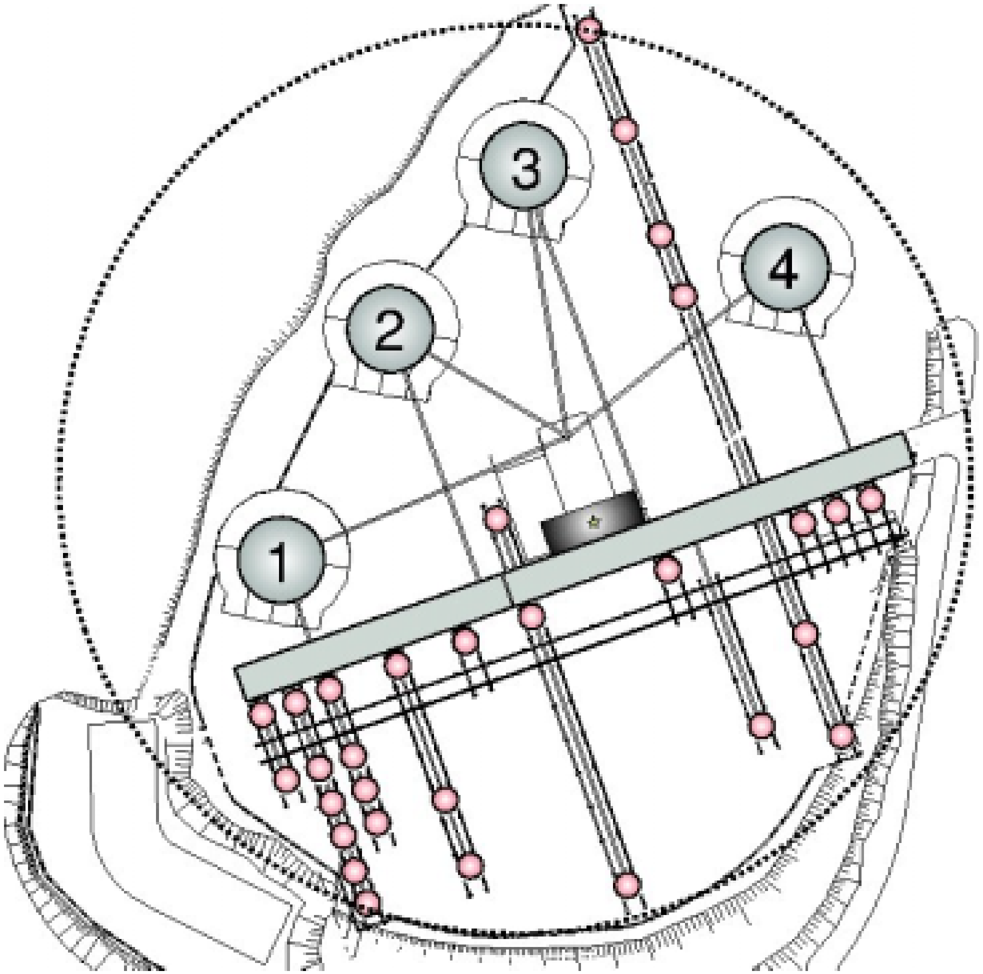
The VLT Interferometer

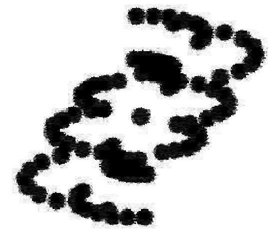
- Four 8.2-m
  Unit Telescopes
  Baselines up to 130m
- Four 1.8-m Auxiliary Telescopes.
  Baselines 8 – 200m
- Field of view: 2 arcsec
- near-IR to MIR (angular resolution 1-20 mas)
- Excellent uv coverage
- Fringe Tracker
- Dual-Feed facility
- Adaptive optics with 60 actuator DM (Strehl >50% in K - Guide Star $m_V < 16$)

The VLT Interferometer - close up

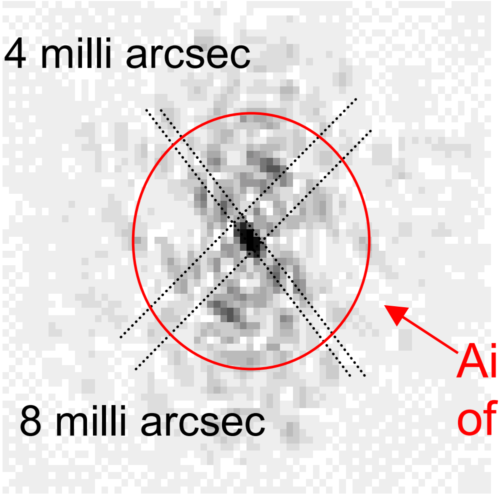


VLTI Main Characteristics



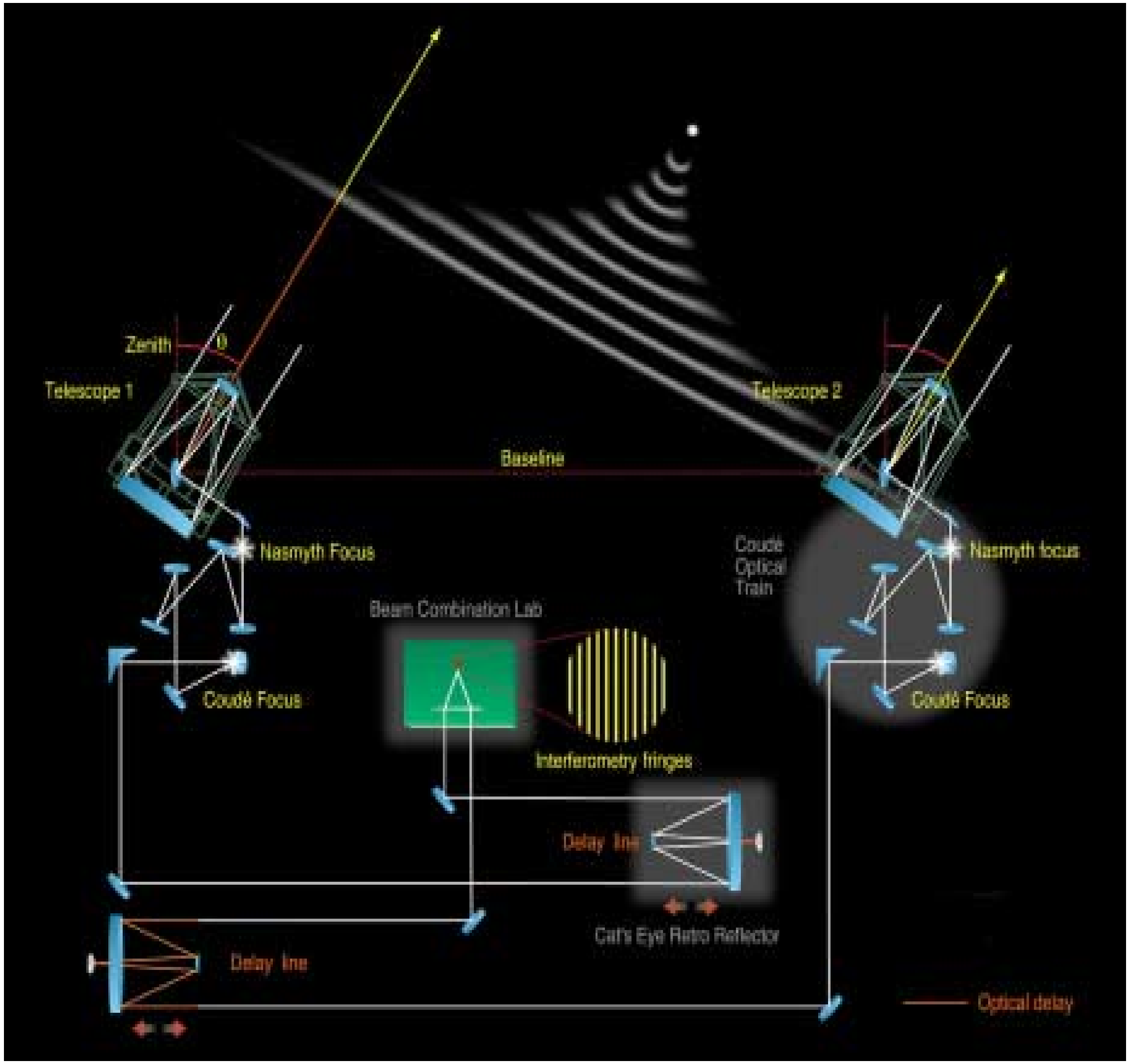


uv coverage after 8 hour observation with all UTs (object at -15^{o})

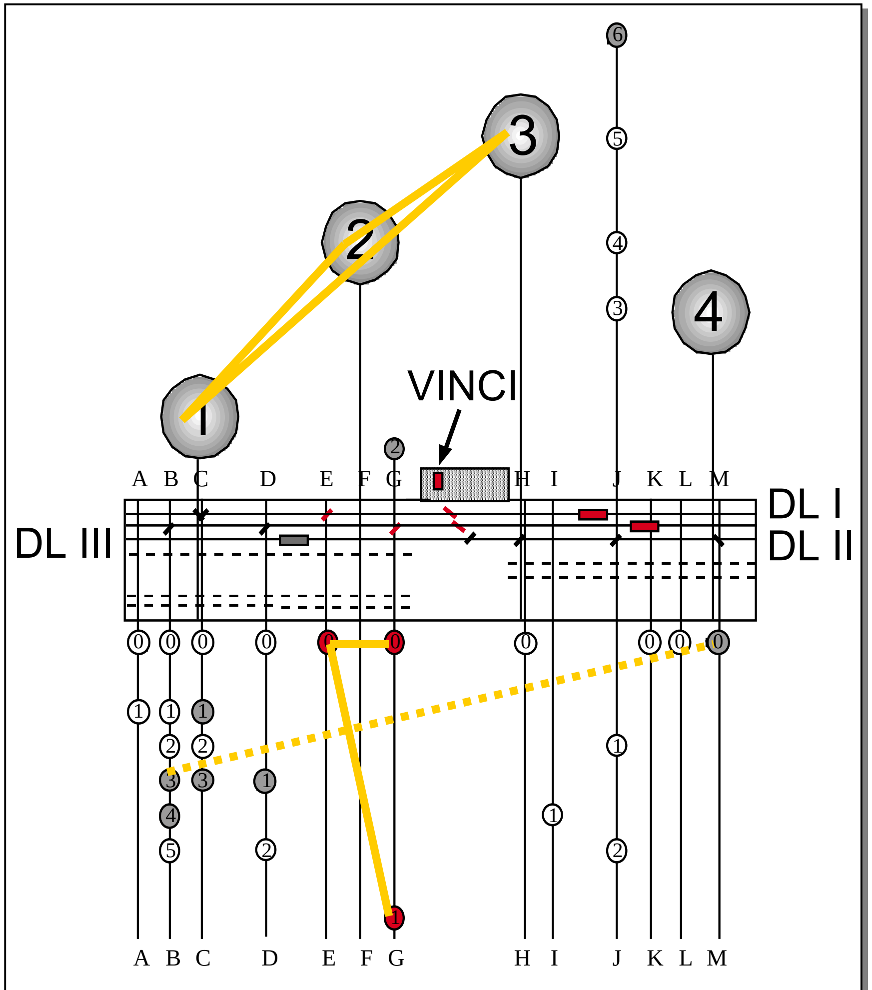


Resulting PSF is the Fourier transform of the visibilities at λ = 2.2μm (K-band)

VLTI Scheme


Zenith
θ
Telescope 1
Telescope 2
Baseline
Nasmyth Focus
Nasmyth focus
Coudé Optical Train
Beam Combination Lab
Coudé Focus
Coudé Focus
Interferometry fringes
Delay line
Cat's Eye Retro Reflector
Delay line
Optical delay

VLTI Layout and Main Components



- 3 (+3) Delay Lines
- 4 Coudé optical trains in Unit Telescopes
- 2 Siderostats
- 3 (->4) 1.8 ATs

1.8-m Auxiliary Telescopes

- Manufactured by AMOS, Liège
- All optics completed for all three ATs, except for M1/M2 for AT2 and M1-M3 for AT3
- Final system tests for AT1 95% finished
- AT1 and 2 ready for interferometry in November 2003
- Fully automatic movement on rails. Relocation and alignment in few hours' daytime operation.

Auxiliary Telescopes Enclosures

The AT Stations

- 30 stations
- baselines from 8m to 205m
- wide range of PA
- provide extensive uv coverage
- quick relocation

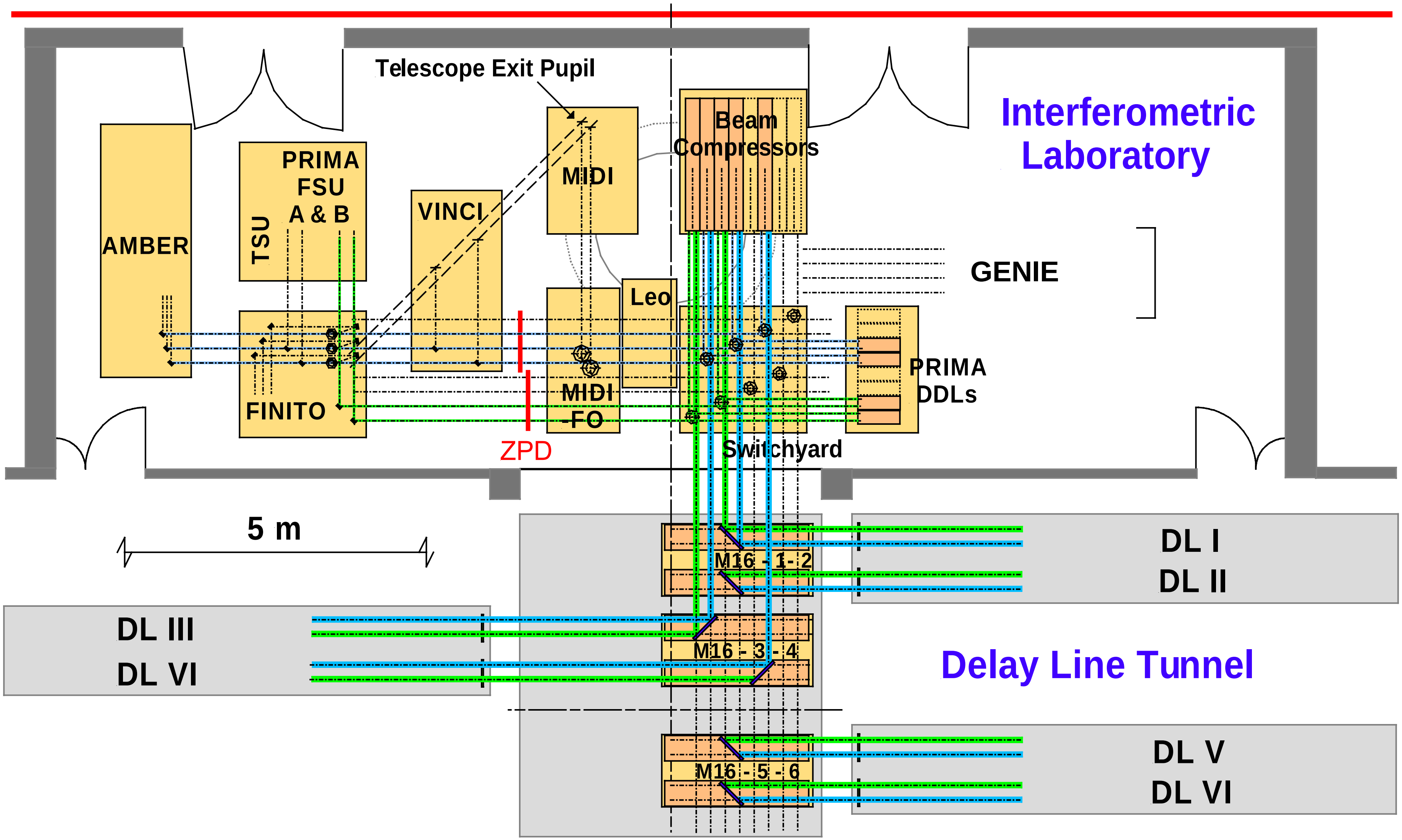
Observing Stations for VLTI Auxiliary Telescopes

ESO PR Photo 10g/01 (18 March 2001)

© European Southern Observatory

The Siderostats at the AT stations

VLTI Laboratory



The Delay Lines

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

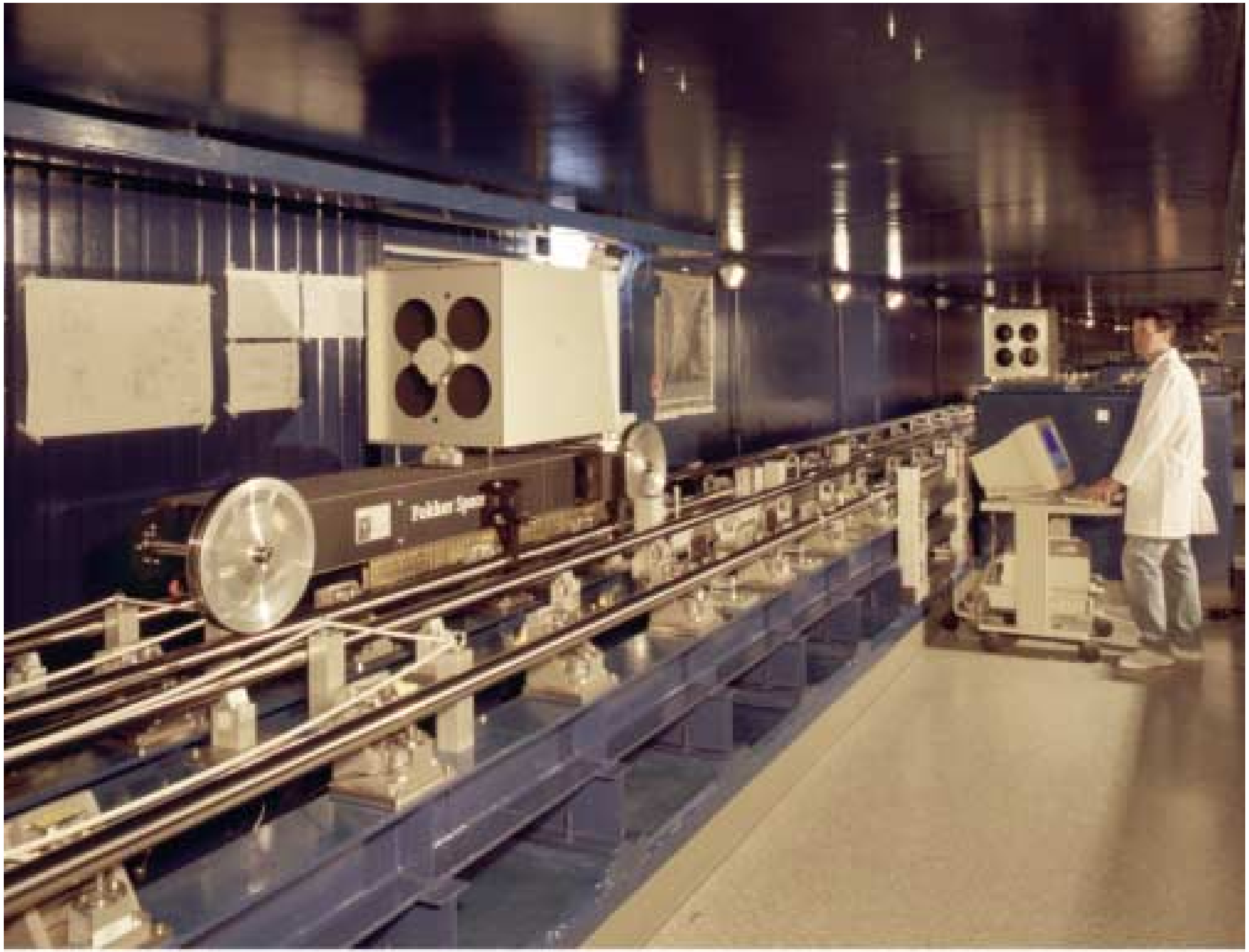
The Delay Lines Tunnel

VLTI Delay Lines in the Interferometric Tunnel

ESO PR Photo 26a/00 (11 October 2000)

© European Southern Observatory

The Paranal Express



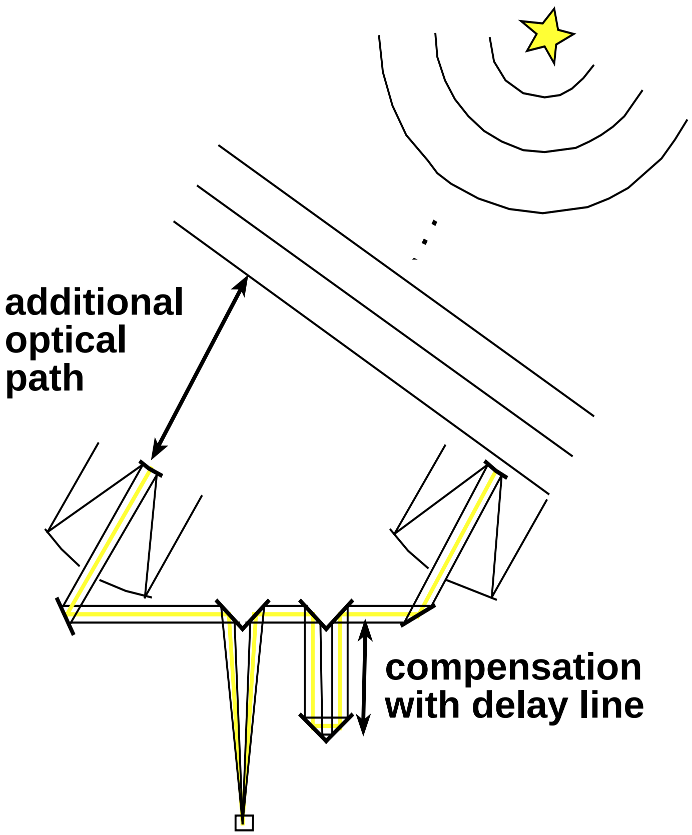
Delay Line Carriage in VLTI Tunnel

ESO PR Photo 10j/01 (18 March 2001)

© European Southern Observatory

Finding fringes

- Adjust star on detector
- 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



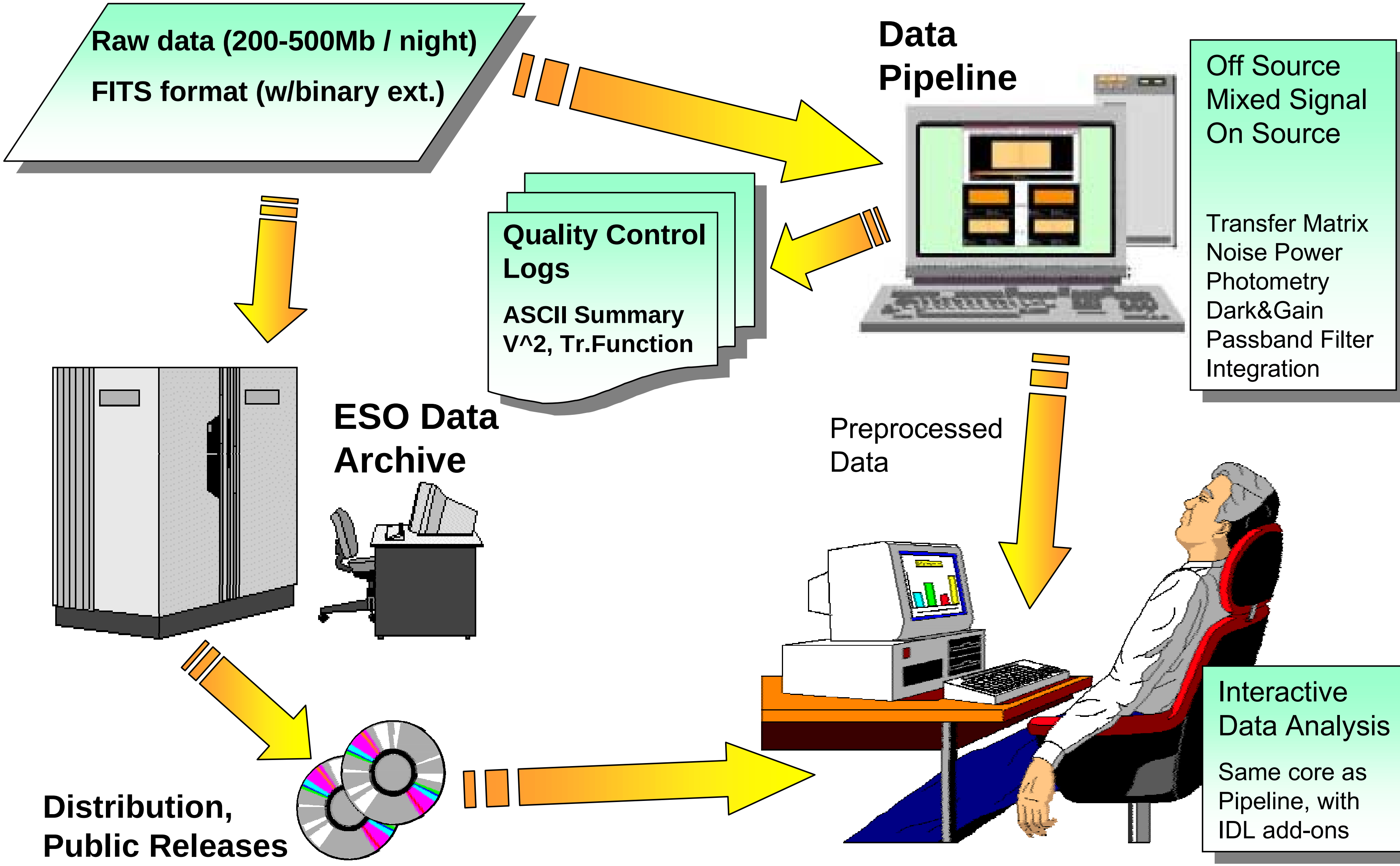
Control and operations

- Remote control
- OB in VLT style
- Data Pipeline
- Data Archive
- Interferometric FITS format

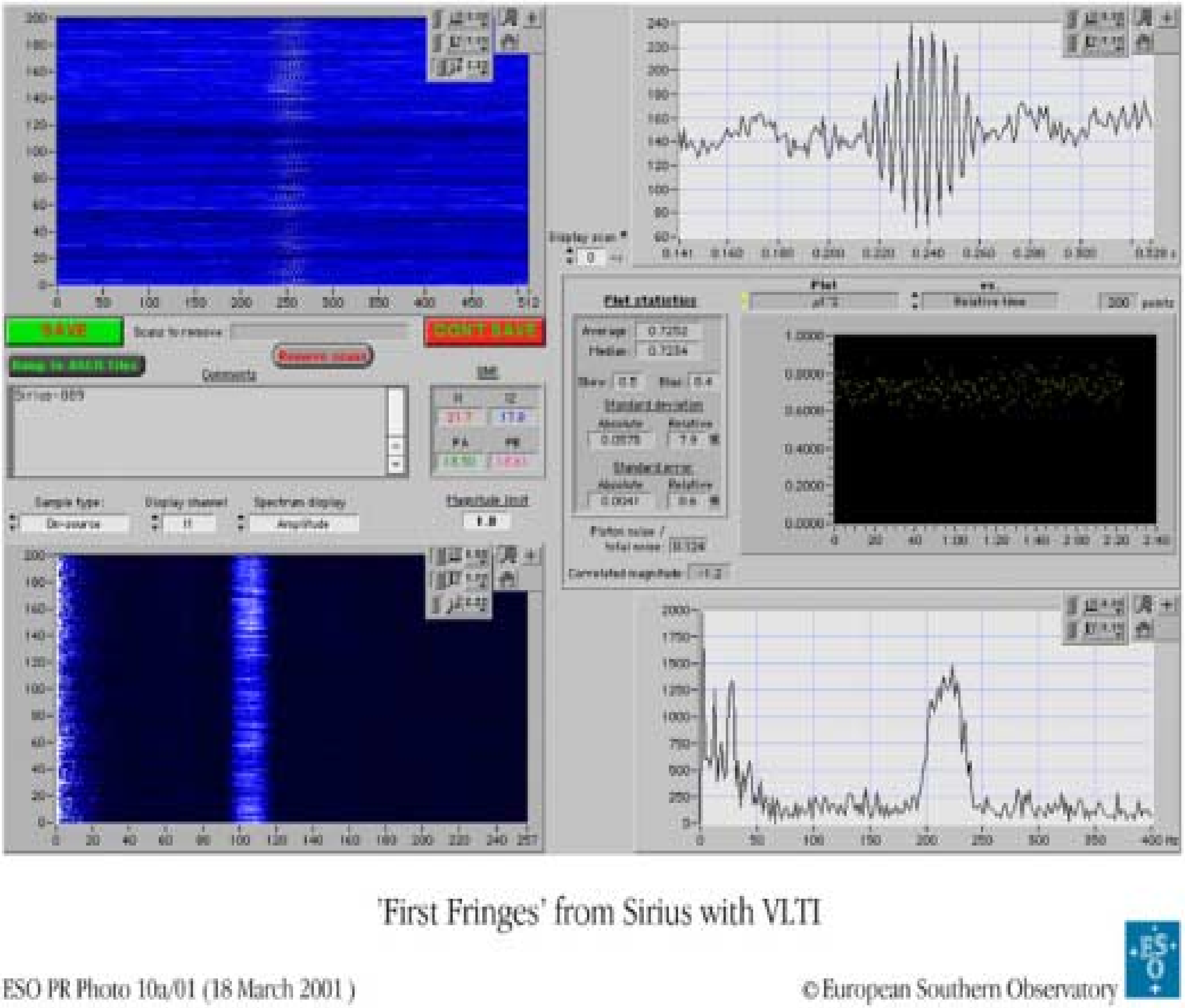
The VLTI Control Consoles

ESO PR Photo 10/01 (18 March 2001) © European Southern Observatory

VLTI Data Flow and Analysis



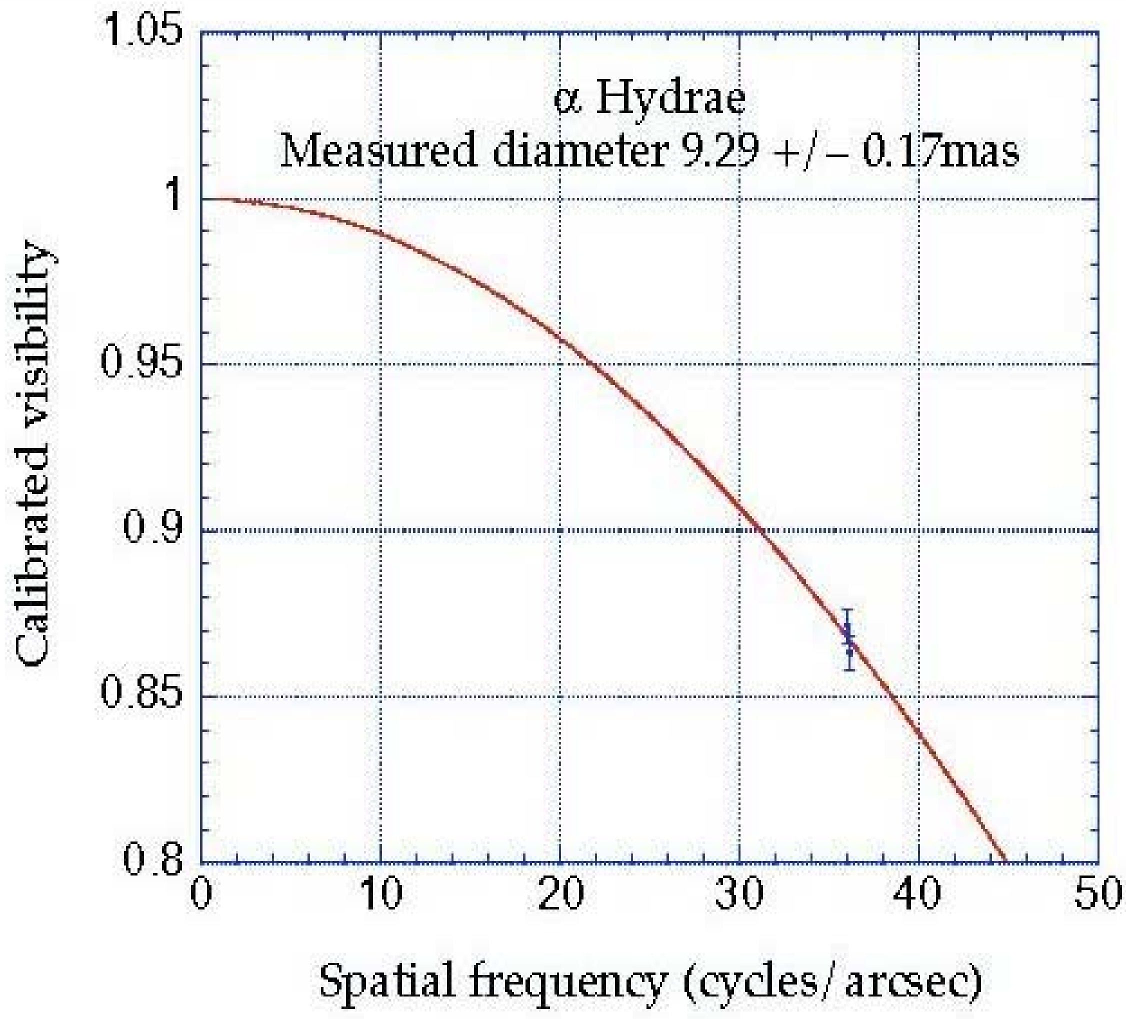
First Fringes Milestone 16 March 2001



March 18, 2001: First Scientific Result

Angular diameter of α Hya from two independent measurements

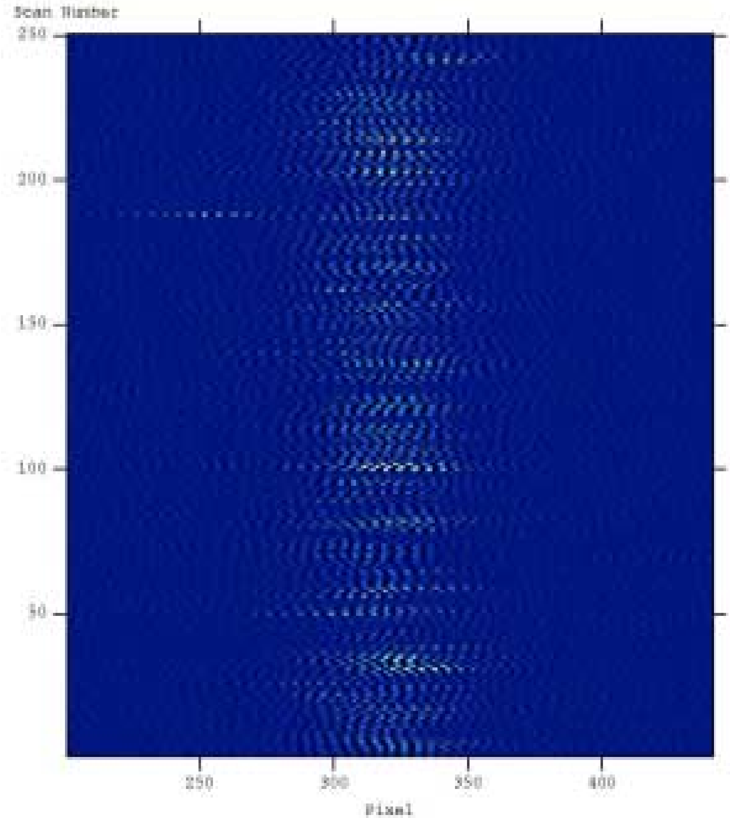
The interferometric efficiency was measured to be 87% and stable to within 1.3% over several days.



First Fringes with the UTs

- Achernar on Oct 30, 2001, UT1-3
- Fringes move less than one period length (2.2 μm) between scans
- Every scan shows a fringe, i.e. there is always light in each fiber

First fringes with UT2/UT3 on June 20, with UT1/UT2 on Aug 1.



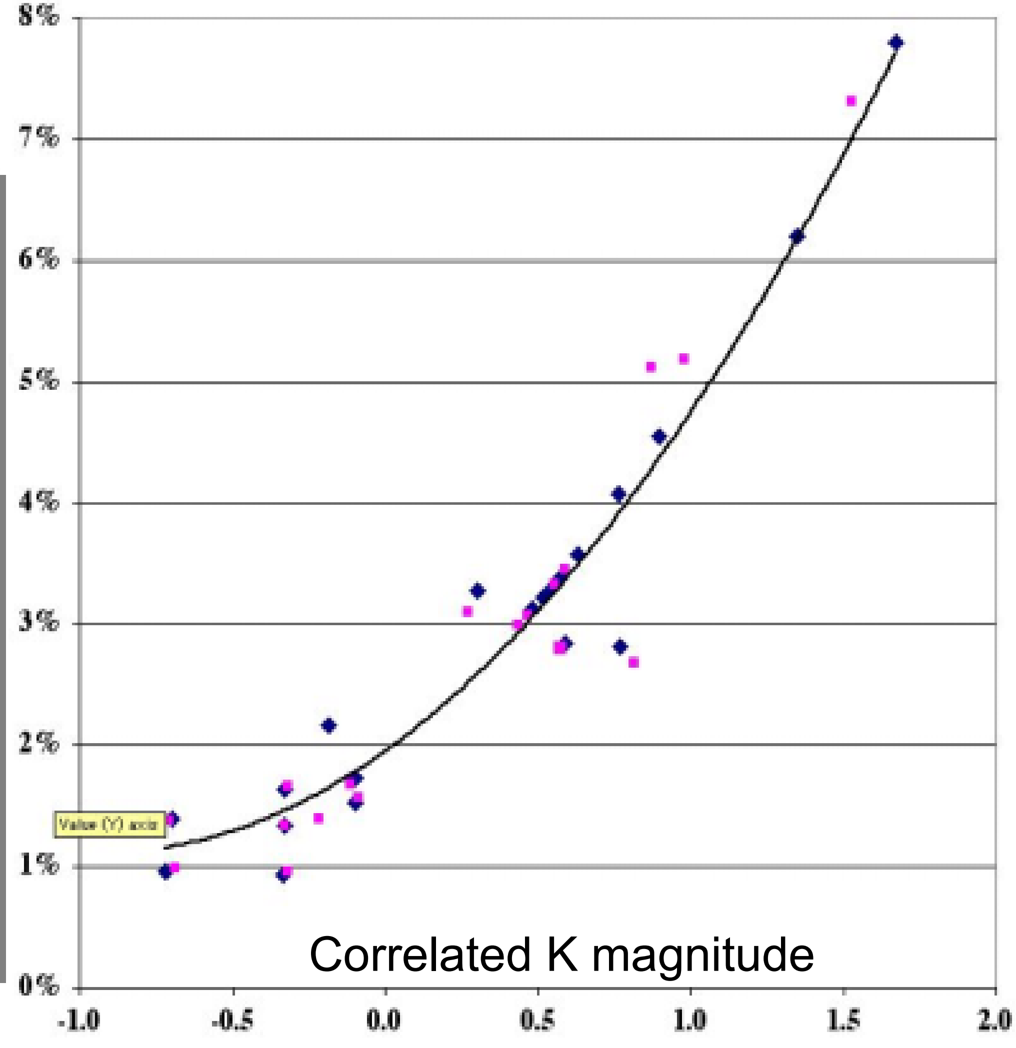
Commissioning Activities

- Commissioning team on Paranal
- Long-term plan with 80 tasks in 2001, 19 tasks in 2002 (structure, subsystems, telescopes, etc.)
- Priority over science
- Intensive SW development and upgrades
- Ensure user-friendly and reliable facility
- Interface Control Document regularly updated
- Public release of on-sky data at regular intervals
- ~180 Objects, ~4000 measurements, ~270 nights, 15 Gb of data

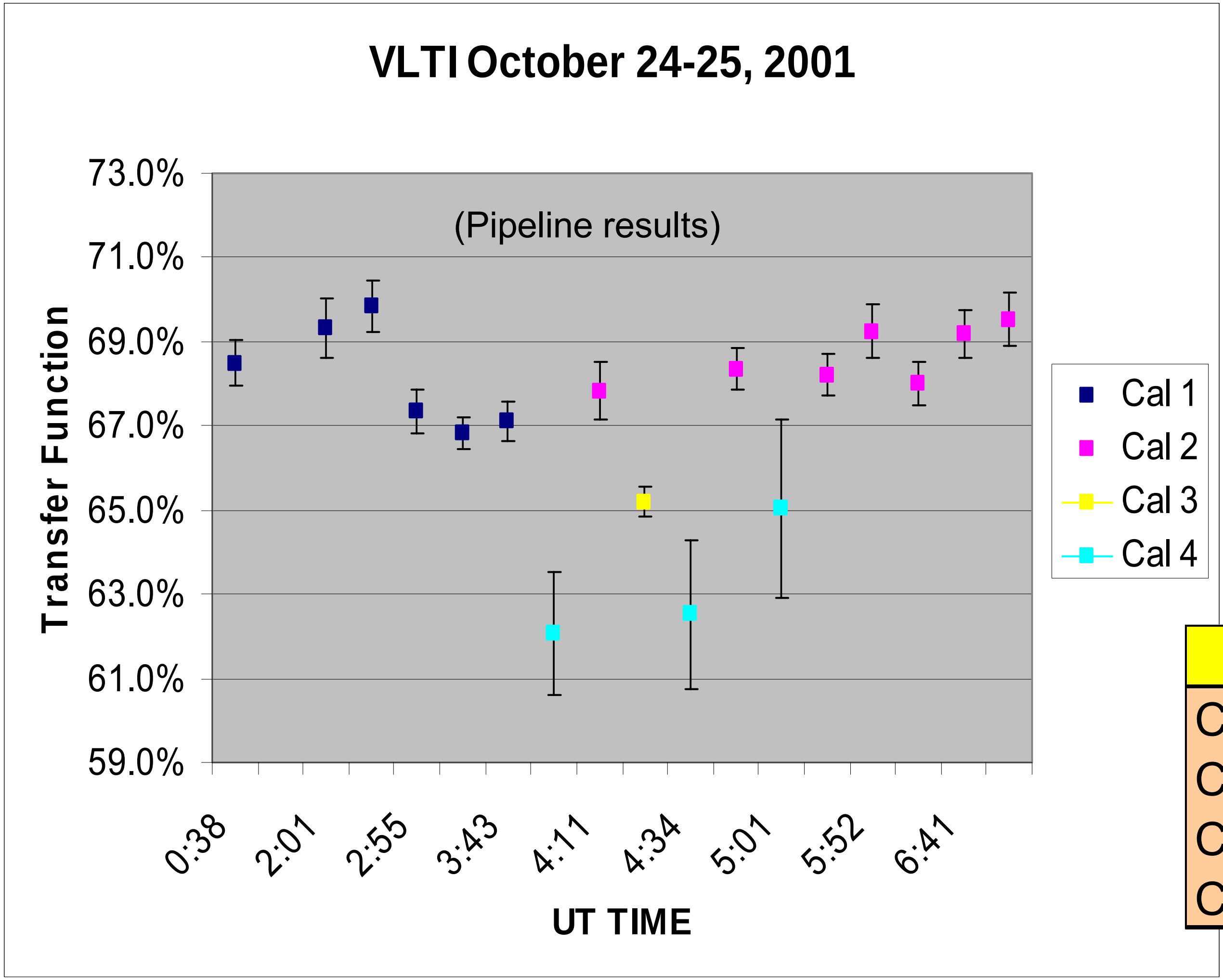
VLTI Performance

- Transfer function of 0.7 (V^2=0.5)
- Stability: 0.70±0.04
- Smallest V=0.08
- 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)

Error in V^2
for 100 scans



Calibrators



$V_{m,1} = \alpha V_{o,1}$

$V_{m,2} = \alpha V_{o,2}$

α=transfer f.

Aver.	**67.3%**	**2.3%**
Cal 1 w.m	**67.7%**	**0.2%**
Cal 2 w.m.	**68.6%**	**0.2%**
Cal 3	**65.2%**	**0.4%**
Cal 4 w.m.	**62.8%**	**1.0%**

End of Part I - The VLTI Team

The VLTI Interferometer

Part II: instruments, access by the community, practical aspects.

A. Richichi (ESO Garching)

Scuola Nazionale di Tecnologie Astronomiche

Napoli 23 - 28 September 2002

Phased Implementation Plan

Date	Instrument	Tel.	Subsystem	What you can do
Today	VINCI (H,K-band, 2 beams)	SID (UT)	STRAP	Commissioning
2002/12	MIDI (MIR, 2 beams)	(SID) UT		Possible Call for Proposals March 2003
2003/05			FINITO Fringe Tracker, 3 beams	Extend limiting mag of MIDI & AMBER
2003/07	AMBER (NIR, 3 beams)	SID (UT)		Possible Call for Proposals September 2003
2003/07			MACAO UT2, UT4	Use AMBER with 2 UTs
2003/08		AT1, AT2		Dedicated to Interf.
2004/01		AT3		Closure phases
2004/03			MACAO UT1	Use AMBER with 3 UTs
2004/08			MACAO UT3	All UT with AO
TBC		more ATs	PRIMA	Astrometry, Extragalactic

Instrument Overview - VINCI

VINCI

(ESO, France)

Paranal: January 2001

K-band, 2-beam

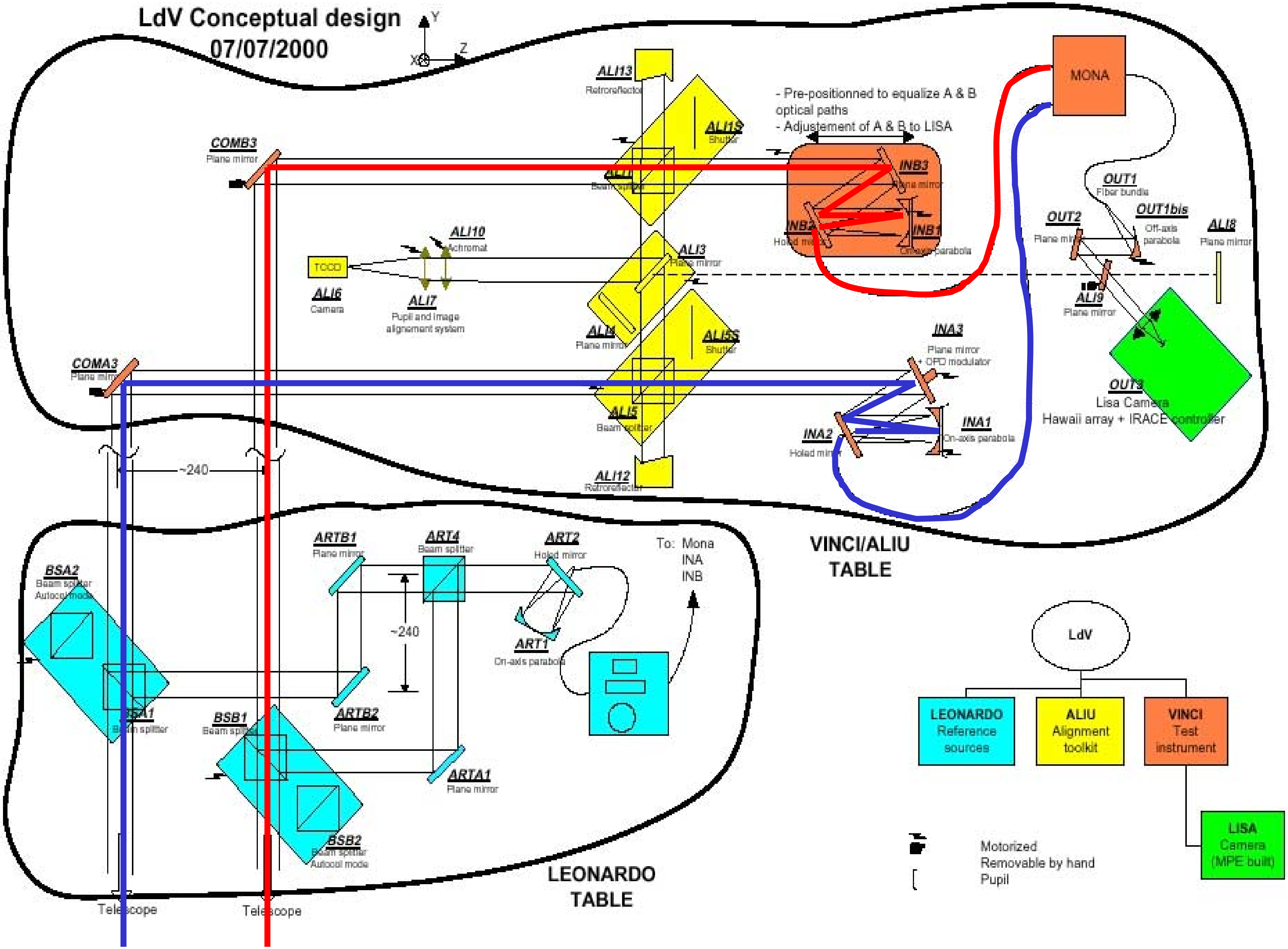
Visibility Accuracy:	0.1% (so far in commissioning with SID)
	0.01% (goal)
Limiting Magnitude:	goal K=6 with SID, K=11 on UT without FT

First Fringes with Siderostats achieved March 2001

First Fringes with UTs achieved October 29, 2001

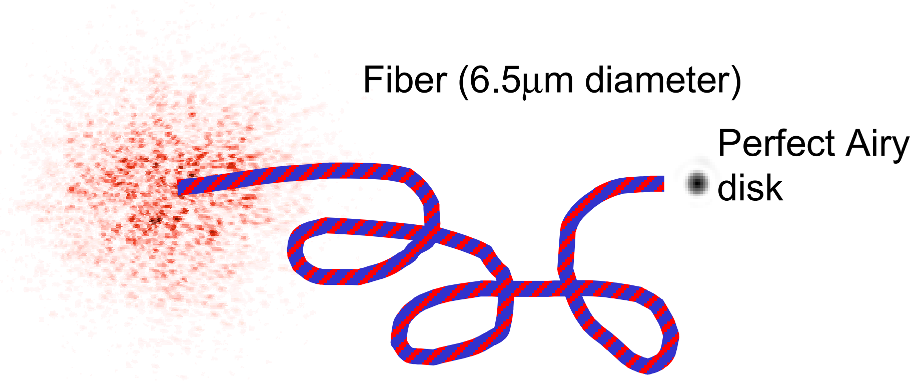
Main purpose: commissioning, test instrument

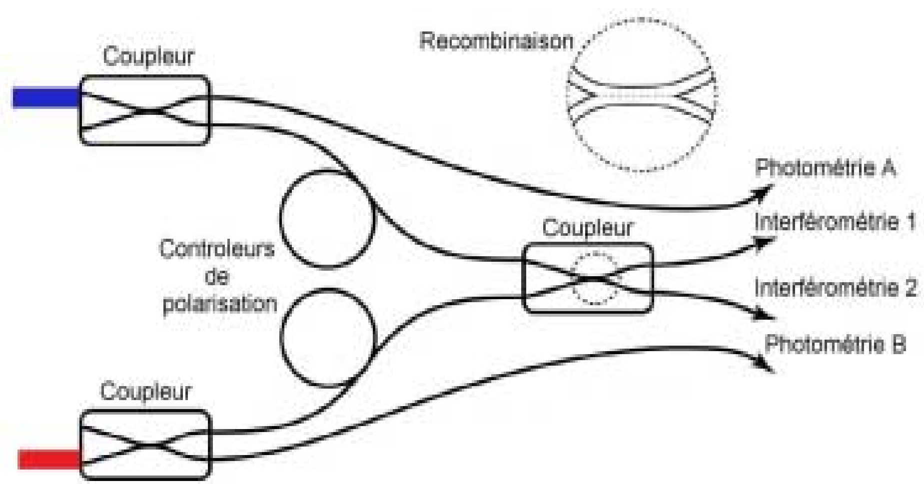
LdV Conceptual design 07/07/2000

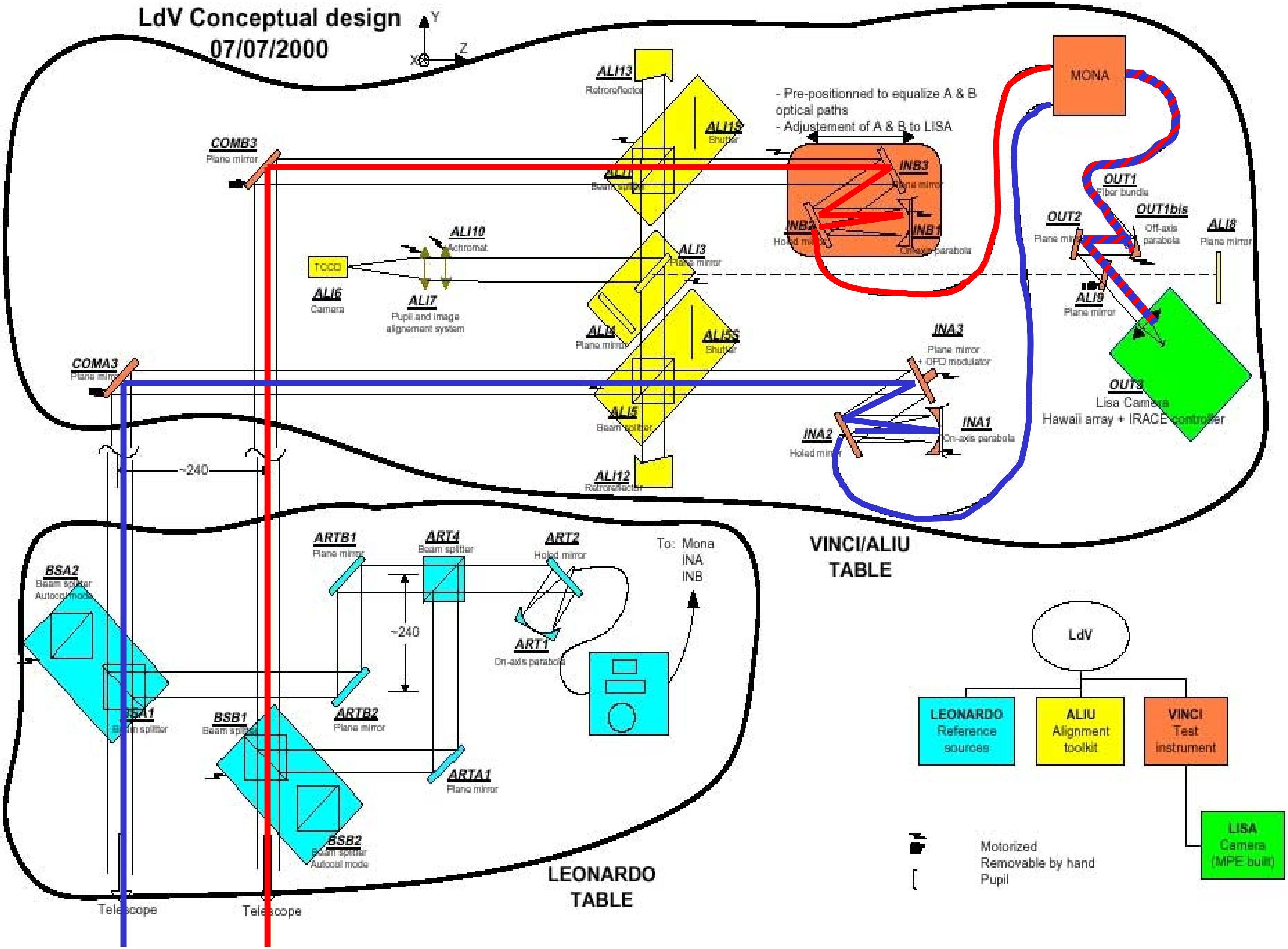


MONA – the fiber beam combiner

- 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



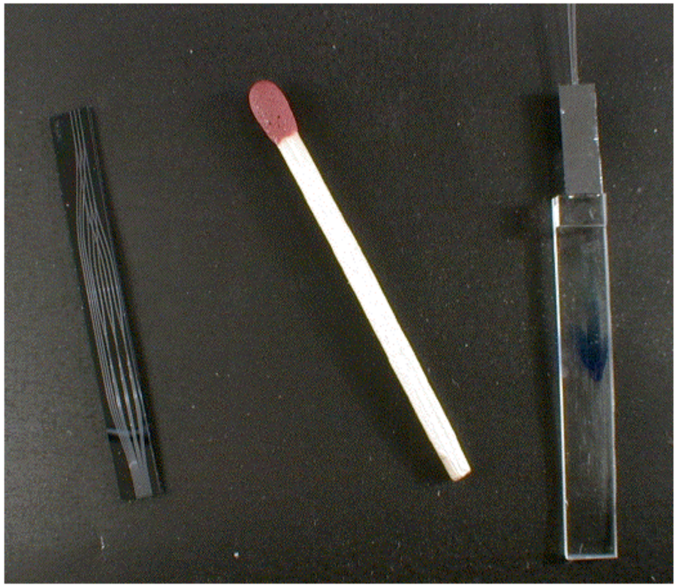



LdV Conceptual design
07/07/2000
Y
X
Z
ALI13
Retroreflector
ALI15
Shutter
- Pre-positionned to equalize A & B optical paths
- Adjustement of A & B to LISA
MONA
COMB3
Plane mirror
ALI1
Beam splitter
INB3
Plane mirror
INB2
Holed mirror
INB1
On-axis parabola
OUT1
Fiber bundle
OUT1bis
Off-axis parabola
OUT2
Plane mirror
ALI8
Plane mirror
ALI10
Achromat
TCCD
ALI6
Camera
ALI7
Pupil and image alignement system
ALI3
Plane mirror
ALI9
Plane mirror
ALI4
Plane mirror
ALI5S
Shutter
INA3
Plane mirror
+ OPD modulator
COMA3
Plane mirror
OUT3
Lisa Camera
Hawaii array + IRACE controller
ALI5
Beam splitter
INA1
On-axis parabola
INA2
Holed mirror
~240
ALI12
Retroreflector
VINCI/ALIU
TABLE
ARTB1
Plane mirror
ART4
Beam splitter
ART2
Holed mirror
To: Mona
INA
INB
BSA2
Beam splitter
Autocol mode
~240
ART1
On-axis parabola
LdV
BSA1
Beam splitter
BSB1
Beam splitter
ARTB2
Plane mirror
LEONARDO
Reference
sources
ALIU
Alignment
toolkit
VINCI
Test
instrument
ARTA1
Plane mirror
LISA
Camera
(MPE built)
BSB2
Beam splitter
Autocol mode
Motorized
Removable by hand
Pupil
LEONARDO
TABLE
Telescope
Telescope

VINCI in the integration lab

Integrated Optics at the VLTI

- University of Grenoble presented first results of integrated optics beam combiner IONIC at IOTA
- Closure phase results obtained in Feb 2002
- Successful VLTI test run with IONIC in July – (plug-and-play!)



3-way (left) and 2 -way(right) beam combiners

The MIDI Instrument

- fringes in the lab in Oct 2001
- Hardware 99% procured
- SW was critical item (ESO standards & manpower), largely completed
- PAE tests completed
- AIV and commissioning plans.

The Team

D: Heidelberg, Freiburg, Jena

NL: Amsterdam, Leiden, Dwingeloo

F: Meudon

PI: C. Leinert (MPIA)

PM: U. Graser (MPIA)

http://www.mpia-hd.mpg.de/MIDI/

MIDI Overview

Mid IR instrument for 10&20* μm , 2-beam, optical beam combiner*

Spectral Resolution: 30-260 (filters, prism, grism)

Limiting Magnitude N ~ 4 (1.0Jy, UT with tip/tilt, no fringe-tracker) (0.8 AT)

N ~ 9 (10mJ, with fringe-tracker) (5.8 AT)

Visibility Accuracy 1%-5%

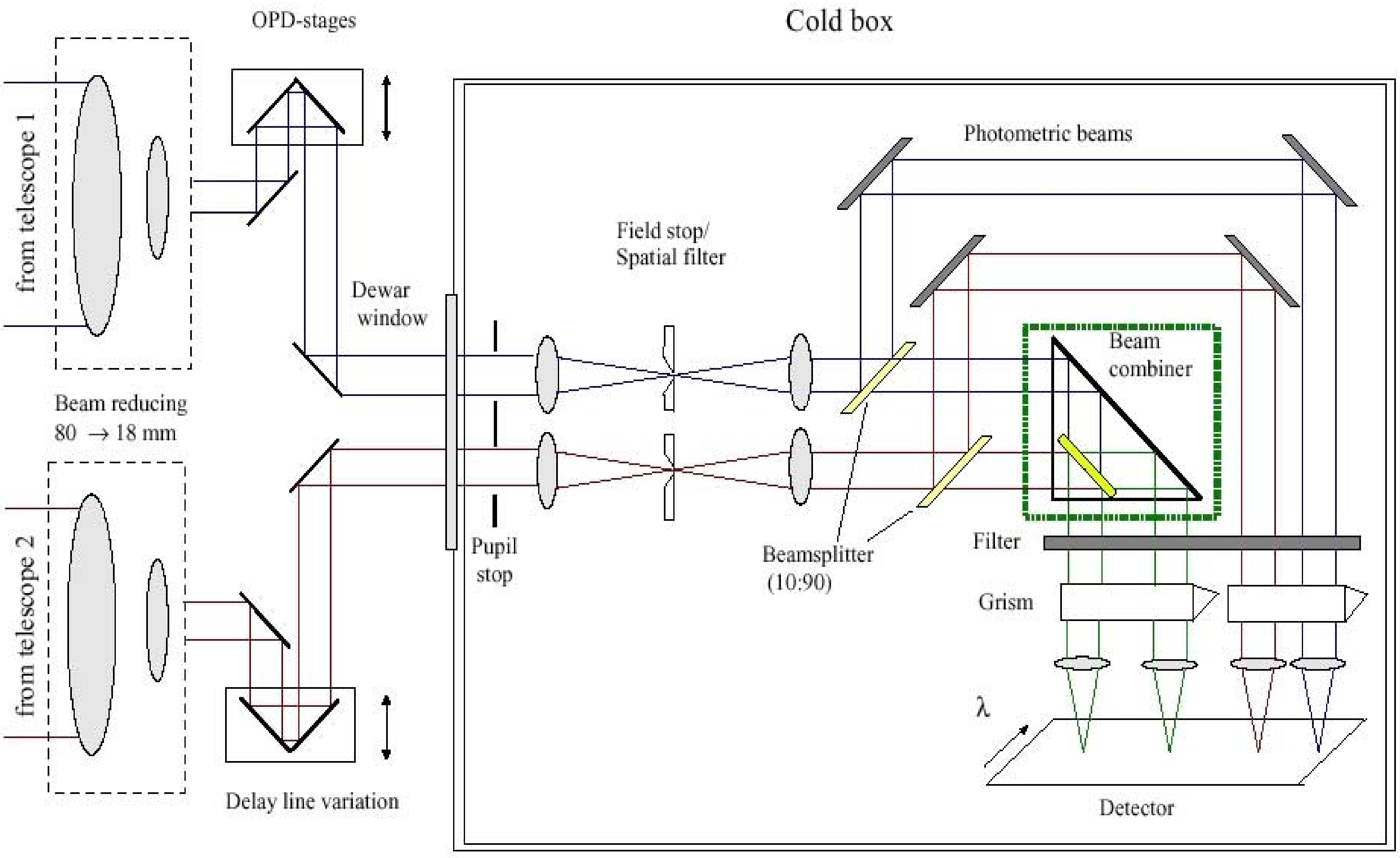
Airy Disk 0.26" (UT), 1.14" (AT)

Diffraction Limit [200m] 0.01"

GTO Program includes: Dust Tori in AGN; Inner disks of low-mass and intermediate mass YSO and MS stars; massive YSO; dust around hot stars; late-type stars; extrasolar planets and brown dwarfs.

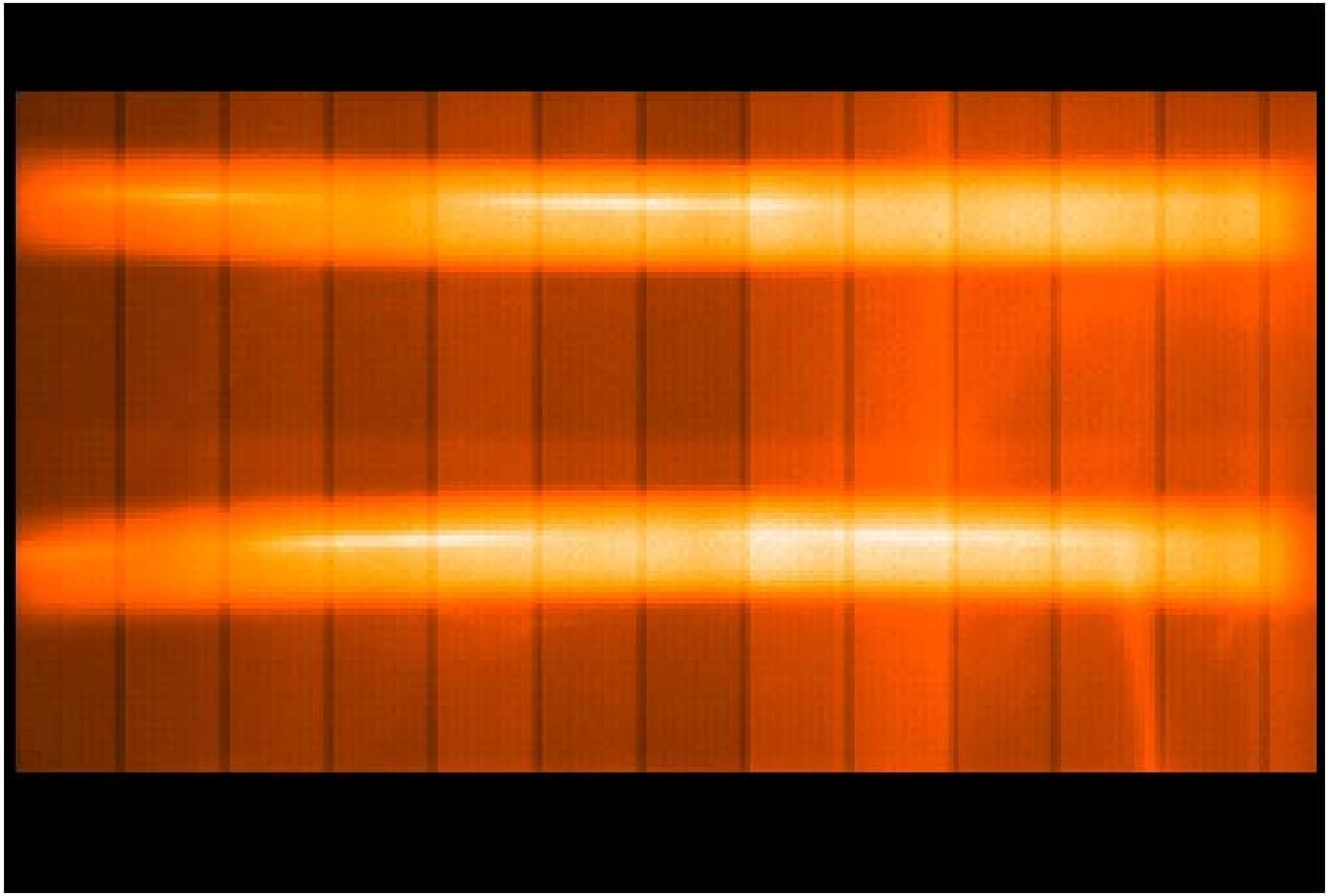
* to be implemented later: 20 μm; 10 μm fiber beam-combiner

MIDI scheme


OPD-stages
Cold box
from telescope 1
Photometric beams
Field stop/
Spatial filter
Dewar
window
Beam
combiner
Beam reducing
80 → 18 mm
Filter
Pupil
stop
Beamsplitter
(10:90)
from telescope 2
Grism
λ
Delay line variation
Detector

MIDI in Heidelberg

MIDI: first fringes in the lab

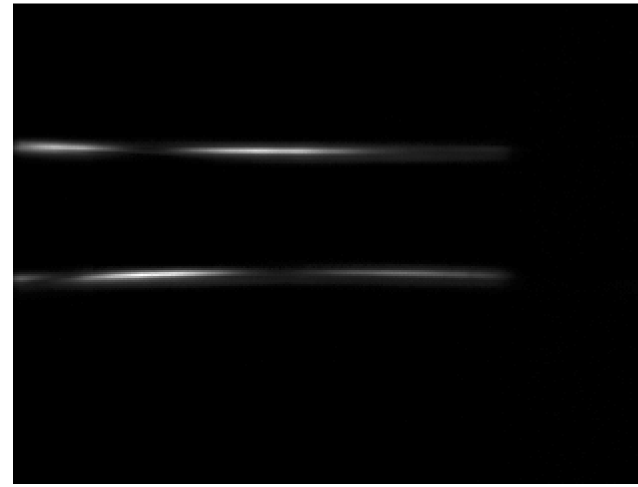


7.5 μm 13.0 μm

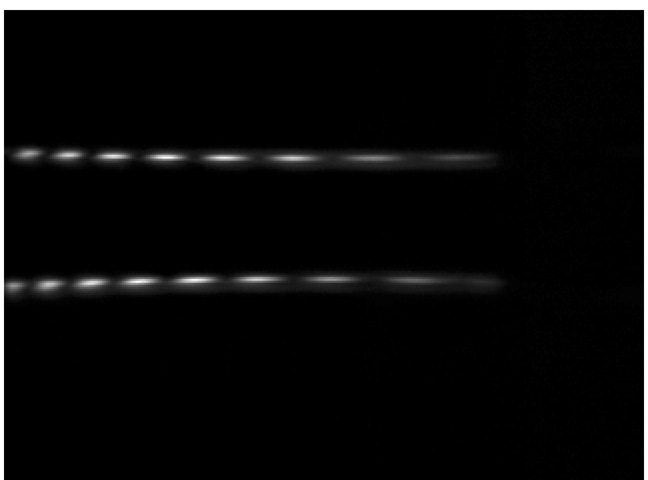
MIDI: first fringes in the lab (movies)

undispersed fringes

dispersed fringes



dispersed fringes (small step)



MIDI Schedule

MIDI	
SW PAE	07-Aug-02
PAE in Heidelberg	10-Sep-02
Shipment	10-Oct-02
Arrival in Paranal	01-Nov-02
AIV	5 weeks
First Fringes	15-Dec-02
First commissioning	14-17 Feb 03
Second Commissioning	March/April 03
PAC with 2 modes, w/o FT	Jul-03
2 other CR in 2003, 2 in 2004	

Several observing modes, not all to be implemented. 2 modes in first commissioning.

The AMBER Instrument

- Hardware 80% procured
- optics from industry are critical item
- start of integration in Europe by end of July 2002
- PAE Feb/Mar 2003
- Paranal April/May 2003

The Team

F: Nice, Grenoble, others

D: Bonn

I: Florence

PI: R. Petrov (Nice)

http://buz.obs-nice.fr/amber/

AMBER Overview

Near IR Instrument (1–2.5 μm) , 3-beam combination (closure phase)

Spectral Resolution: 35-14000 (prism, 2 gratings)

Limiting Magnitude K =11 (specification, 5 σ, 100ms self-tracking)

J=19.5, H=20.2, K=20 (goal, FT, AO, PRIMA, 4 hours)

Visibility Accuracy 1% (specification), 0.01% (goal)

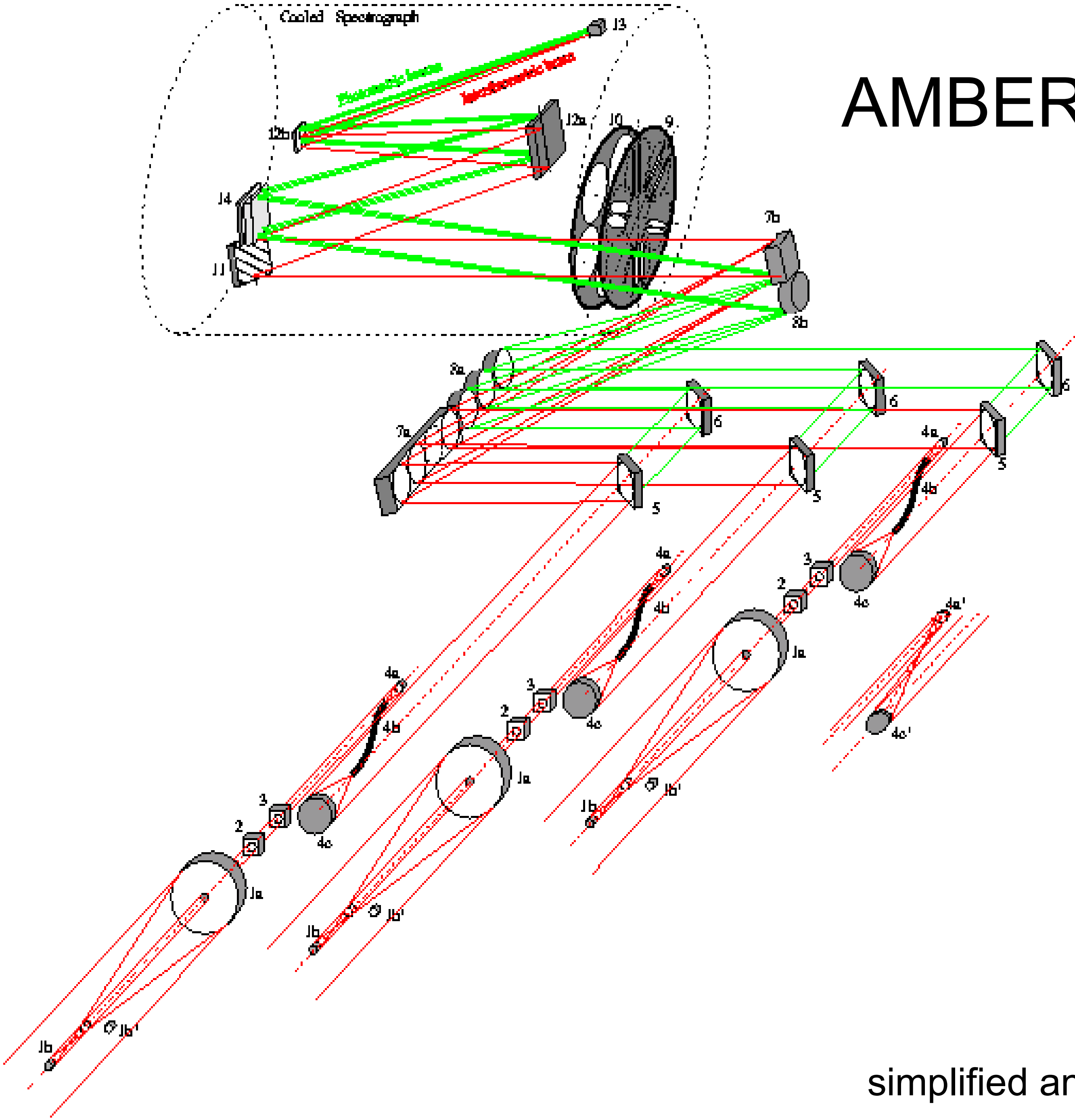
Airy Disk 0.03”/0.06” (UT), 0.14”/0.25” (AT) [J/K band respectively]

Diffraction Limit [200m] 0.001” J, 0.002” K

GTO not yet published. Key programs include: AGN; exoplanets; young stars; fundamental stellar quantities; binaries; circumstellar matter; etc.

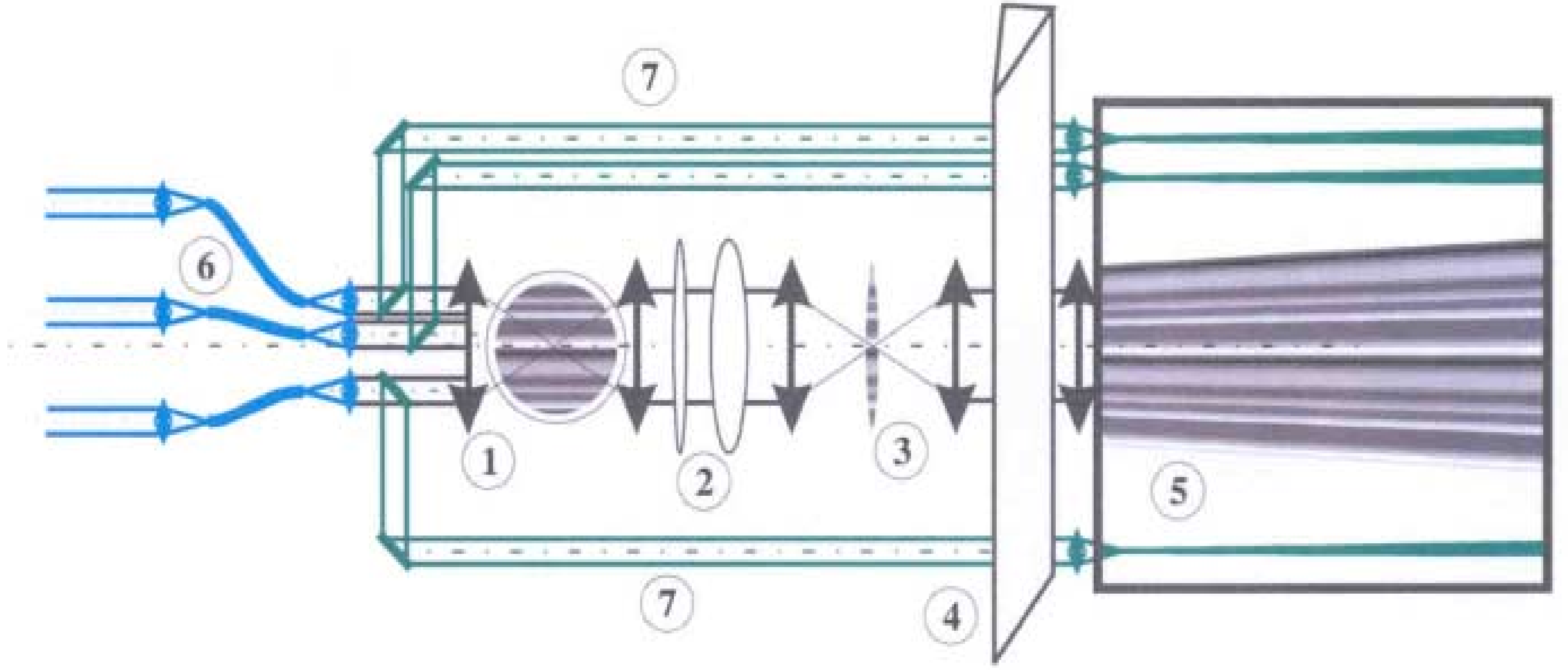
First large interferometer with closure phases

AMBER scheme

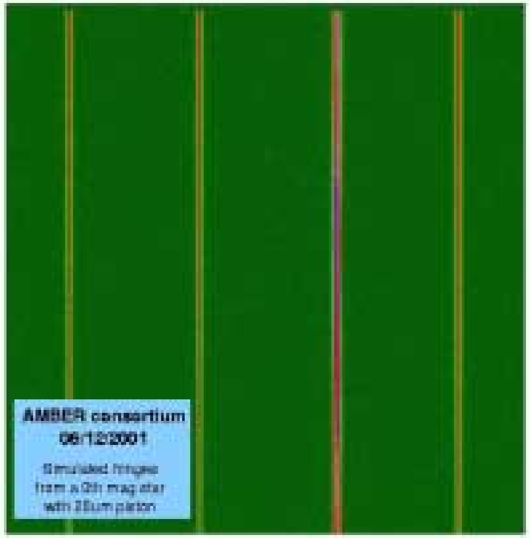


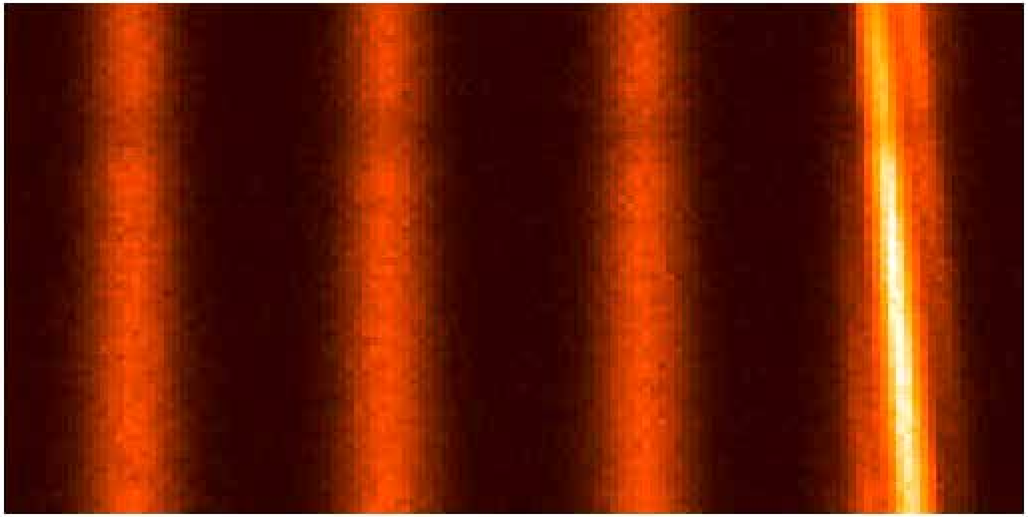
simplified and … outdated!

AMBER beam combination



AMBER fringes (simulated)





AMBER Schedule

AMBER	
Beginning of assembly	Nov-2002
PAE in Grenoble	Jun-2003
Arrival in Paranal	July-2003
AIV	4 weeks
First Fringes	Aug-2003
First commissioning	Nov-2003?
Second Commissioning	Feb-2004?

Schedule of other subsystems

FINITO	
PAE Electronics	Nov-02
PAE Garching	Feb-03
Start AIV in Paranal	Mar-03
Delivery to VLTI	Apr-03

Auxiliary Telescopes	#1	#2	#3	#4
Provisional Acc. Europe	12-Dec-02	18-Mar-03	24-Jul-03	
Start AIV in Paranal	06-Feb-03	13-May-03	14-Oct-03	
Delivery to VLTI	29-May-03	05-Aug-03	06-Jan-04	TBD

MACAO-VLTI	#1	#2	#3	#4
TAE	Dec-02	May-03		
Release to Observatory	Apr-03	Jul-03	Mar-04	Aug-04

Idiosyncrasies of interferometry

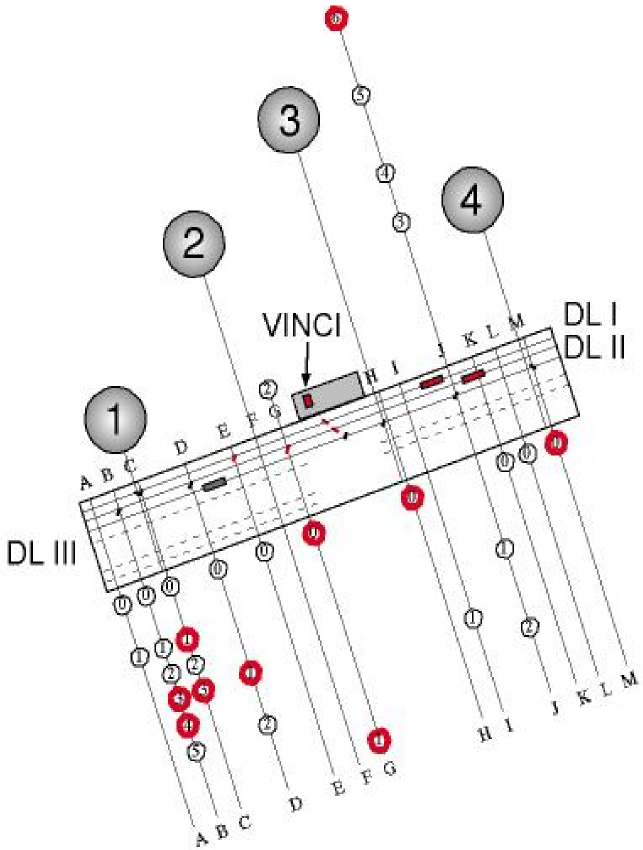
- ☼ two telescopes do not point as one
- ☼ night shadows on Paranal
- ☼ left is right, up is down, 30 = 435 = 254 = 10!
- ☼ magnitudes are not magnitudes
- ☼ integration time and Earth rotation
- ☼ living in Fourier space
- ☼ calibrate, calibrate, calibrate

VLTI preparation tools - Demo

- choosing an object
  - VisCalc
    - Calvin

Shared risk science operations in 2002

- Call for proposals for VLTI:
  "During Period 70, part of the VLTI commissioning time will be open for shared risk observing programmes with VINCI and the siderostats. About 150 hours will be available for these observations. The observations will be carried out by the commissioning team."
- Offered performance:
  - K_{corr} = 3 (confirmed after siderostat upgrade)
  - 1-5% accuracy
  - 4-5 baselines between 8 and 200m
- ESO will deliver:
  - output of data pipeline (visibility and accuracy)
  - raw data
  - data reduction software
- 39 proposals received
  almost 10% of all VLT proposals!
  600 hours requested, pressure of 4x



Access Opportunities

- Application form for interferometry
  Ready for P71. Extra page dedicated to interferometry. Requires calibrators.
- Shared-risk VINCI proposals P71 (April-October 2003)
  Similar strategy as for Period 70. K-band only, SID only, about 6-7 baselines offered. Access rules as for normal ESO proposals. Data will be released to the community after validation (at the same time as to the PI).
- Access to MIDI
  1st/2nd commissioning in P70. It is foreseen to have two modes demonstrated by April 2003. GTO and SDT to start in 2003. Could be included in a call for P72, with an early start around August 2003. Proposals would be due in March 2003.
- Access to AMBER
  Either P73 or P74.
- Long term
  Applications, selection, operation of instrument (visitor or service), data release: will be the same as for other VLT instruments

Fringes on the WEB

ESO VLTI:

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

AMBER and MIDI:

http://buz.obs-nice.fr/amber/

http://www.mpia-hd.mpg.de/MIDI/

This presentation:

http://www.eso.org/~arichich/download/snta-na2002/

Students welcome!

Thanks to A. Glindemann for some of the material used in this presentation.