Optics in Astronomy
- Interferometry -

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- Concepts of interferometry (contd.)
  - Differential delay tracking
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- Practical interferometry
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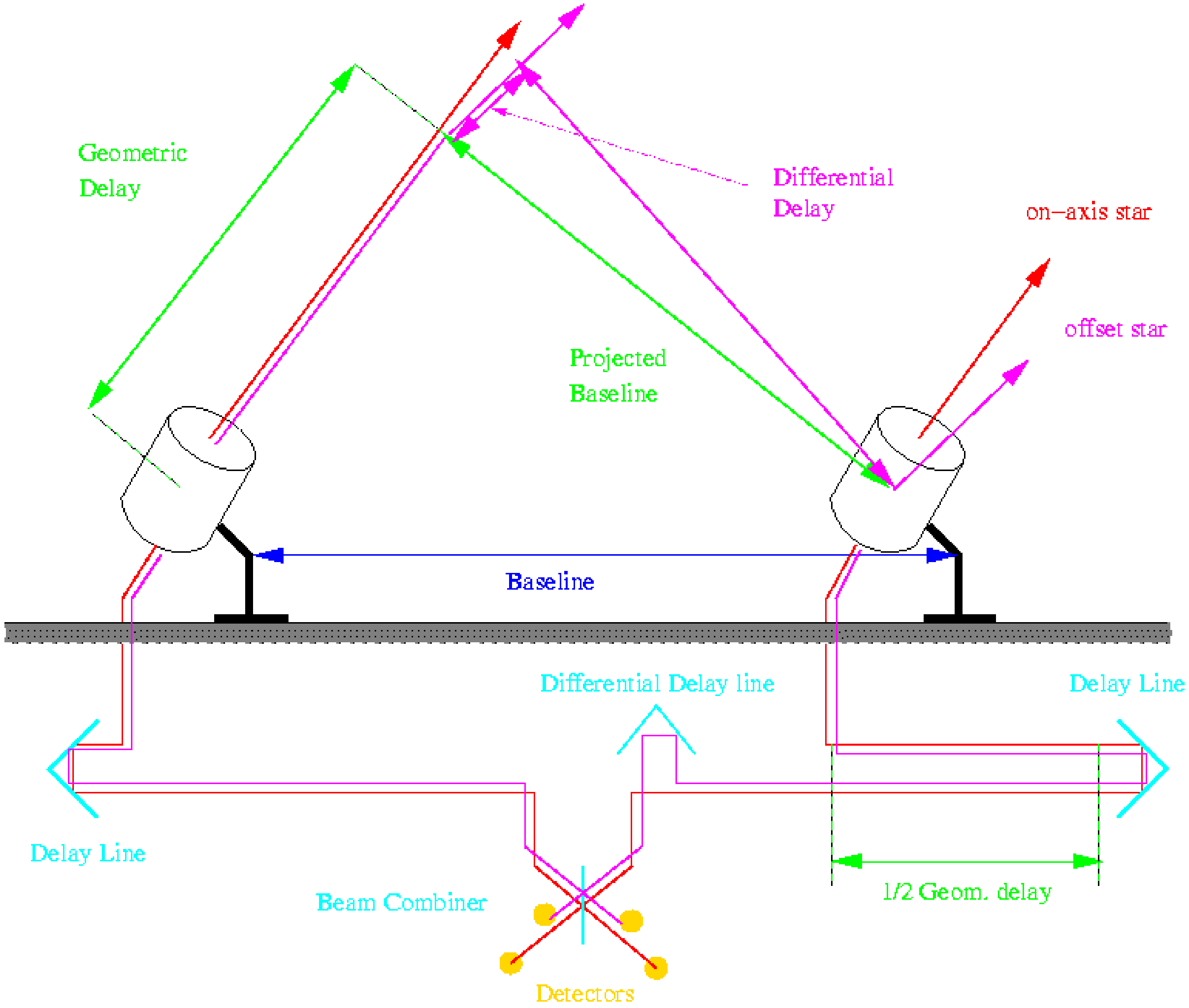
Differential delay tracking

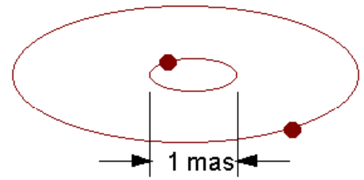


Differential delay tracking

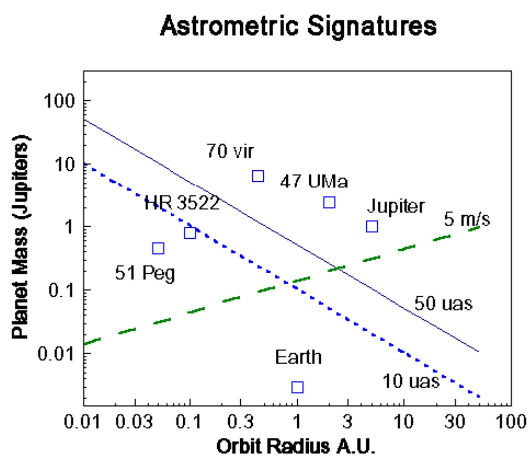
Goals of DDT:

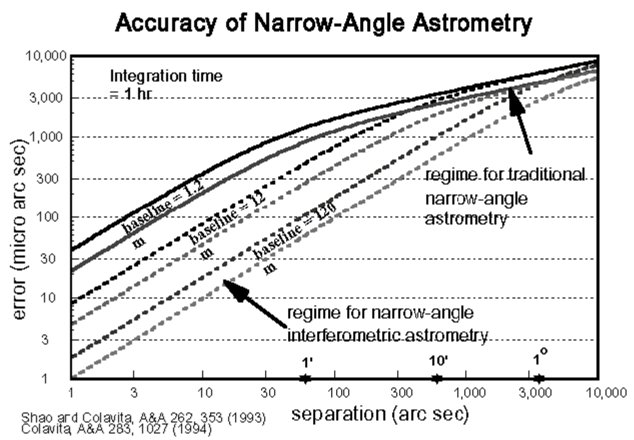
- off-source phase referencing
- narrow-angle astrometry

Typical star ~ 10 parsec from Earth
Jupiter mass planet 5 AU from star



Mass ratio Sun/Jupiter ~ 1000:1
Motion of Planet ~ 1000X stellar motion
Star's motion ~ 0.001 arcsec peak to peak
1 mas (milliarcsec) is angular size of an astronaut standing on the moon as seen from Earth





Source of figures: PTI

Measured Quantities and Observables

The measured quantity of interest is the correlated flux at wavelength λ and angle frequency $\vec{u}_{ik} = \vec{B}'_{ik} / \lambda$

Fourier component of source intensity:

$$\hat{I}_\lambda(\vec{u}_{ik}) = \iint_{FOV} I_\lambda(\vec{\alpha}) \exp(2\pi j \vec{\alpha} \cdot \vec{u}_{ik}) d\vec{\alpha}$$

Complex visibility:

$$V_{ik} = \frac{\hat{I}_\lambda(\vec{u}_{ik})}{\hat{I}_\lambda(\vec{0})} = \frac{\iint_{FOV} I_\lambda(\vec{\alpha}) \exp(2\pi j \vec{\alpha} \cdot \vec{u}_{ik}) d\vec{\alpha}}{\iint_{FOV} I_\lambda(\vec{\alpha}) d\vec{\alpha}}$$

Observables I

Group Delay $\Delta_{0,ik}$ **:**

Delay for which interference contrast is maximised

Group delay depends on

- baseline
- instrumental fixed delays
- source position
- delay errors: optics, vibrations, atmosphere

High precision measurement of $\Delta_{0,ik}$ permit relative position measurements with 1mas accuracy over wide angles (many degrees) and with ~10µas accuracy over narrow angles (arcminutes): **Mark III, PTI**

Calibration with reference stars or optical truss anchored to earth crust: **NPOI**

⇨ Astrometry!

Observables II

Visibility Amplitude $|V_{ik}|$**:**

- **maximum contrast in interferogram**
- visibility as function of delay Δ_{ik} depends on spatio-spectral content of source and system throughput
- essential for imaging with photometric fidelity
- calibration through rapid switching between program and reference sources with known visibility, monitoring of system parameters

⇨ Maps, Images!

Observables III

Referenced phase φ_{ik} :

- argument of complex visibility: $|V_{ik}| \exp j \varphi_{ik}$
- can be referenced to off-set calibrator source by differential delay measurements
- can be referenced to program source at different wavelength: **GI2T**
- essential for imaging
- Raw visibility phases are no good observables due to uncontrolled errors: $\varphi_{ik} = \varphi_{0,ik} + \varepsilon_k - \varepsilon_j$
- Visibility phase can be re-transformed by changing origin of coordinate system without affecting the morphology of the reconstructed image

⇨ Maps, Images!

Observables IV

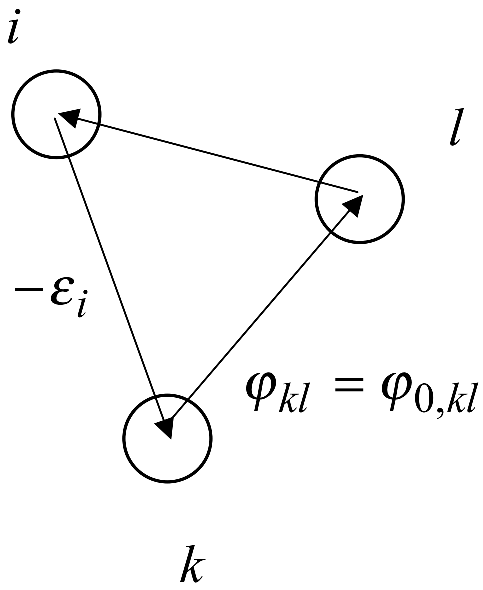
Closure phase ψ_{ikl} **:**

- triple product of complex visibility: $$\psi_{ikl} = \varphi_{ik} + \varphi_{kl} + \varphi_{li}$$ $$= \varphi_{0,ik} + \varphi_{0,kl} + \varphi_{0,li}$$
- good observable provided there are no baseline-dependent error sources
- insensitive to source position
- fewer independent closure relations than baselines:
  $$\left(\tfrac{N}{2} - 1\right)(N-1) \quad \text{vs.} \quad \tfrac{N}{2}(N-1)$$
- essential for imaging if there are no referenced phases

⇨ Maps, Images!

Phase closure

$$\varphi_{ik} = \varphi_{0,li} + \varepsilon_i - \varepsilon_l$$



$$\varphi_{ik} = \varphi_{0,ik} + \varepsilon_k - \varepsilon_i$$

$$\varphi_{kl} = \varphi_{0,kl} + \varepsilon_l - \varepsilon_k$$

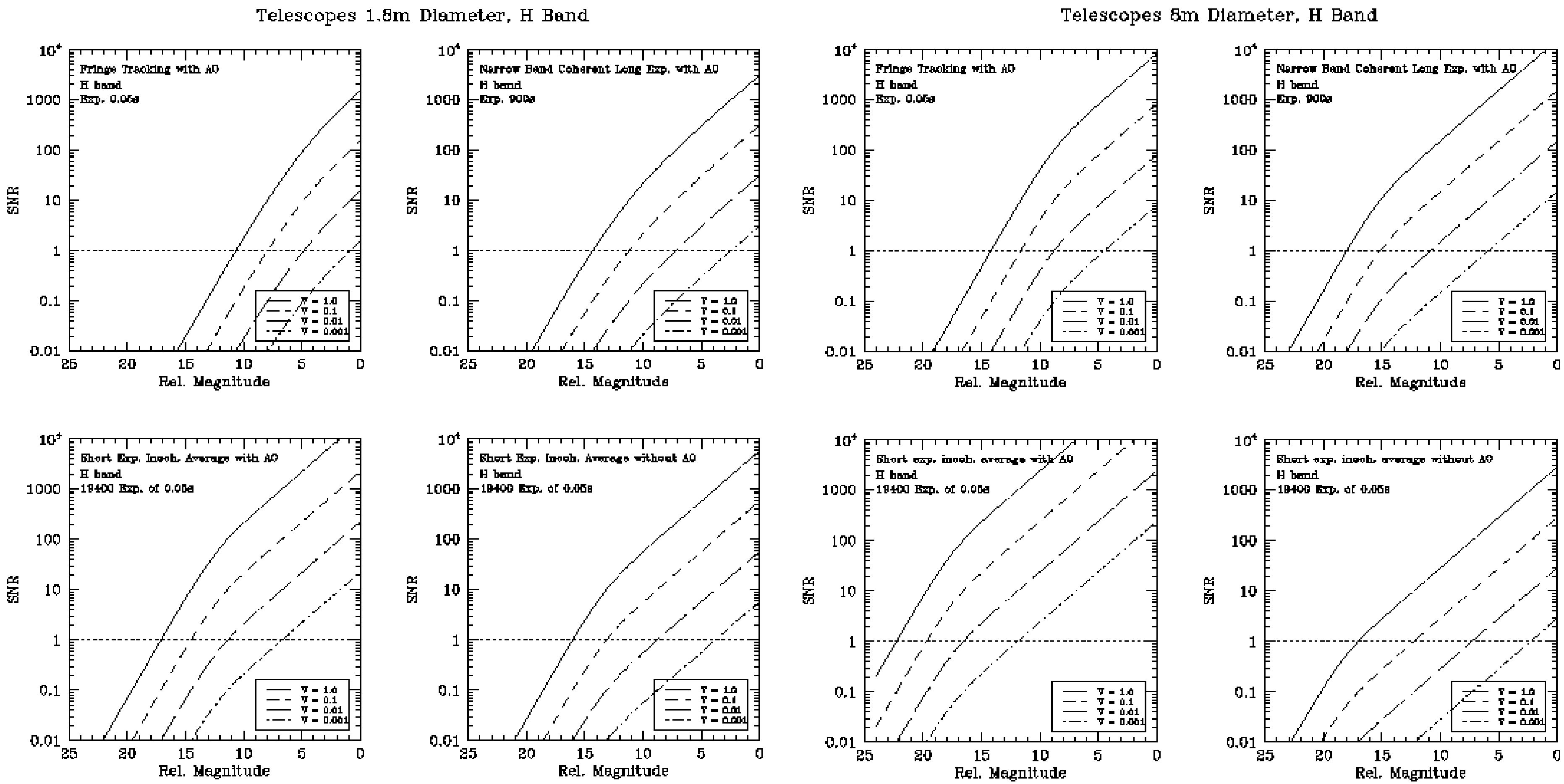
$$\begin{aligned}\psi_{ikl} &= \varphi_{ik} + \varphi_{kl} + \varphi_{li} \\ &= \varphi_{0,ik} + \varepsilon_k - \varepsilon_i \\ &\quad + \varphi_{0,kl} + \varepsilon_l - \varepsilon_k \\ &\quad + \varphi_{0,li} + \varepsilon_i - \varepsilon_l \\ &= \varphi_{0,ik} + \varphi_{0,kl} + \varphi_{0,li}\end{aligned}$$

Signal-to-noise ratio of a visibility measurement

$$SNR = \frac{S N_p}{\sqrt{1 + S^\kappa N_p + N_b + N_d^2}} \cdot \frac{N_{red} V}{N_{tel}} \cdot \sqrt{K}$$

S	system Strehl, $\kappa = 1$ with mode stop, $\kappa = 0$ w/o mode stop
N_p	detected number of source photons
N_b	detected number of background photons
N_d	detector noise, expressed as equivalent *rms* no. of photons
N_{red}	redundancy of baseline considered
N_{tel}	total number of telescopes in array
V	intrinsic visibility of source
K	number of incoherently averaged visibility measurements

Signal-to-noise ratio of a visibility measurement



Milestones in Optical Interferometry

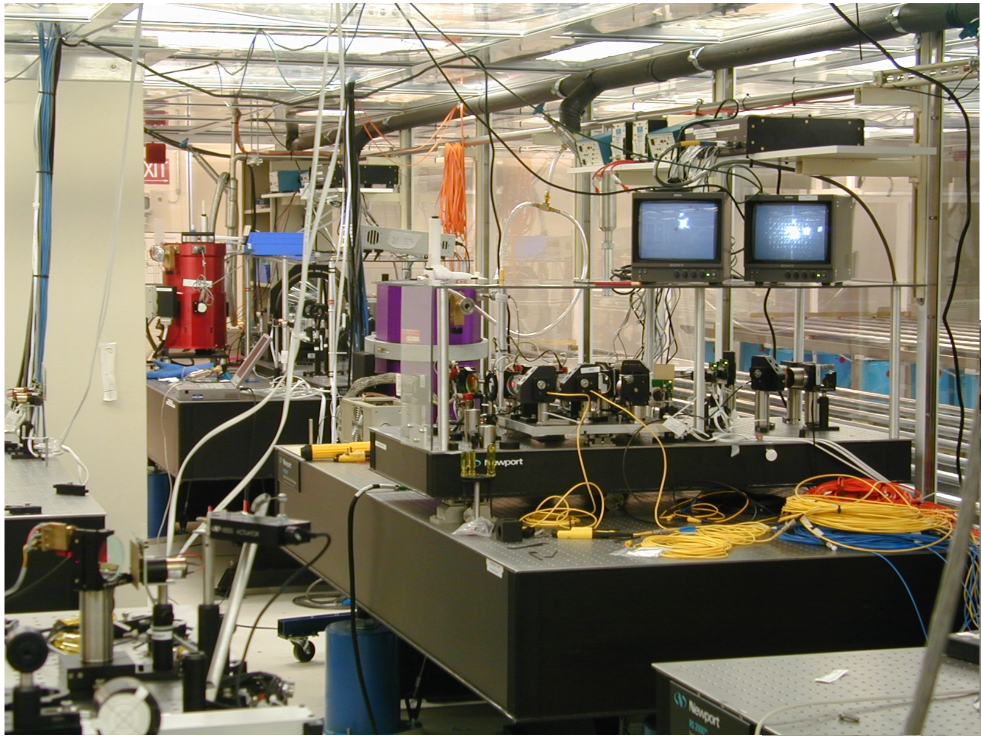
Year	Scientist	Remarks
1868	H. Fizeau	Proposal to use masks to increase telescope resolution
1870	E. Stephan	Marseille 80cm reflector with strip mask
1890	A. Michelson	Diameters of Jovian satellites (Lick)
1921	A. Michelson, F. Pease	Diameter measurement of α Ori with 20 ft. interferometer on Mt. Wilson Hooker telescope
1935	F. Pease	Mt. Wilson 50 ft. interferometer (unsuccessful)
1956	R. H. Brown, R. Twiss	Intensity Interferometer
1970	A. Labeyrie	Stellar Speckle Interferometry
1973-1975	A. Labeyrie	Interferometry w. independent telescopes (24cm)
1974	M. Johnson et al.	Heterodyne interferometry at 10 µm
1985	A. Labeyrie	Interferometry w. independent telescopes (150cm)
1988-1993	M. Shao et al.	Production-line interferometry
1990	J. Baldwin et al.	Phase-closure imaging of α Ori surface
1995	J. Baldwin et al.	Multiple telescopes imaging of Capella
2001	M. Shao et al.	"First fringes" with Keck Imaging Interferometer Array
2001	A. Glindemann et al.	"First fringes" with VLT Interferometer siderostats

Today's Interferometers

Program (Nation)	No. of. Baselines	Max Baseline [m]	Element Diameter [m]	Year of Operation
GI2T (F)	3	65	1.52	1985
ISI (USA)[1]	1	35	1.65	1988
COAST (GB)	6	100	0.40	1992
SUSI (AUS)	1	640	0.14	1992
IOTA (USA)	3	45	0.45	1993
NPOI (USA)	3 (6, 15)[2]	250	0.35	1995
PTI (USA)	1	110	0.45	1996
MIRA-I (JN)	1	4	0.20	1998
CHARA (USA)	10	350	1.00	2000
VLTI (EUR)	6 / 3 / 6[3]	128 / 200[4]	8 / 1.8	2001
KIIA (USA)	1 / 6 / 15[3]	75 / 180[4]	10 / 1.5	2001
Magellan (USA)	1	60	6.5	2005
LBT (USA/I/D)[5]	1	20	8	2005

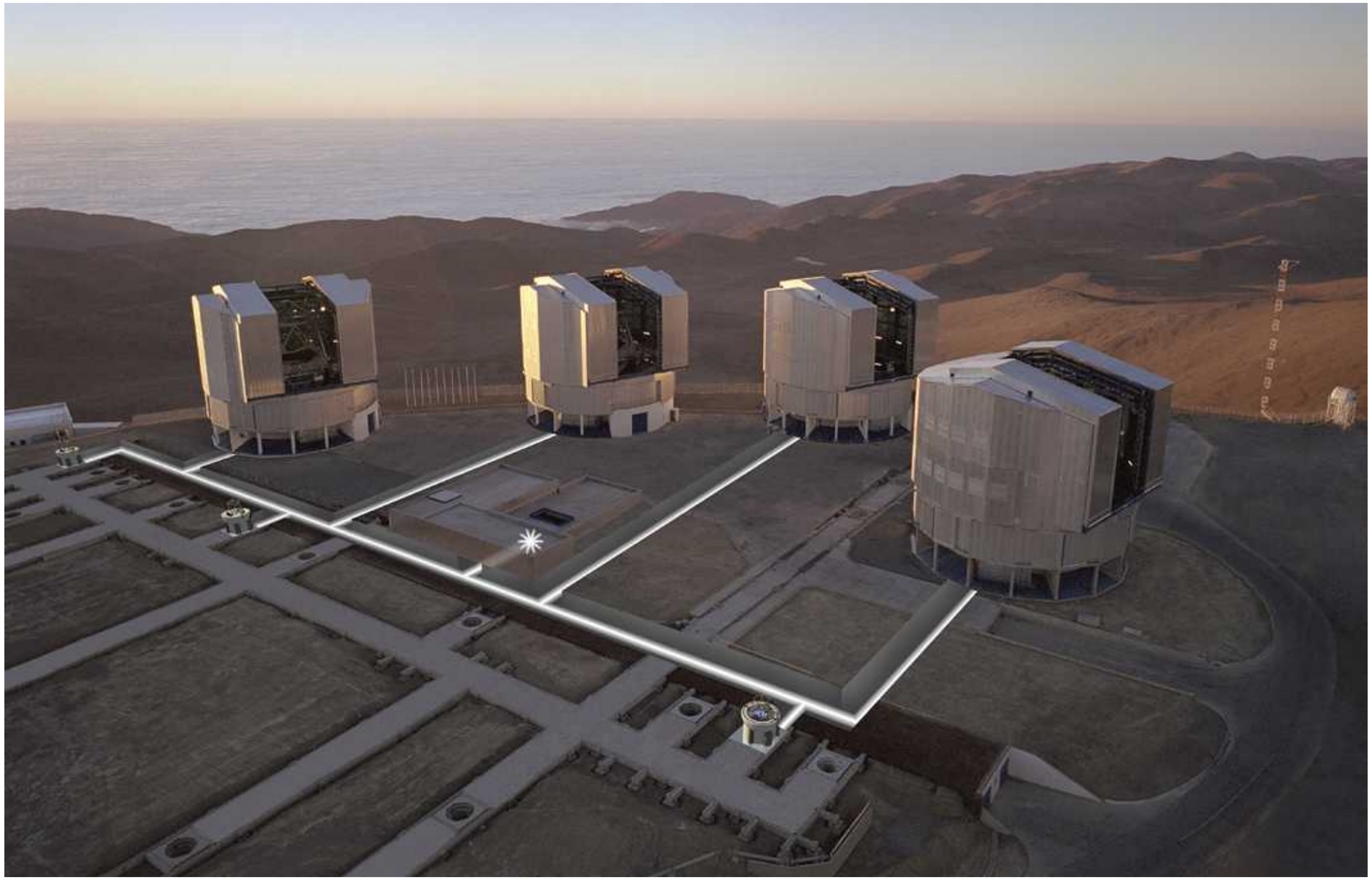
Keck Interferometer Array, USA

image courtesy Bertrand Koehler

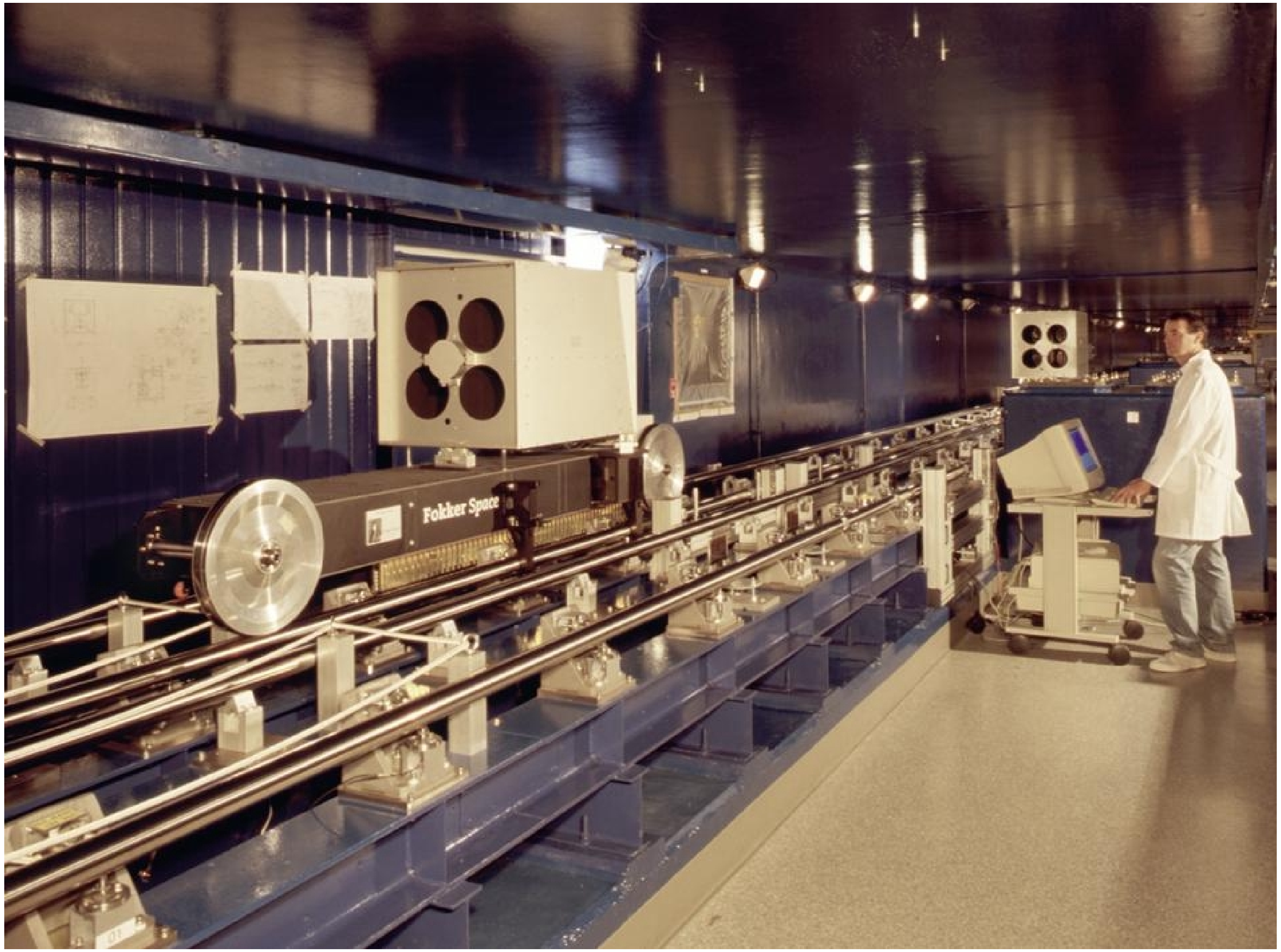


images courtesy Keck Observatory

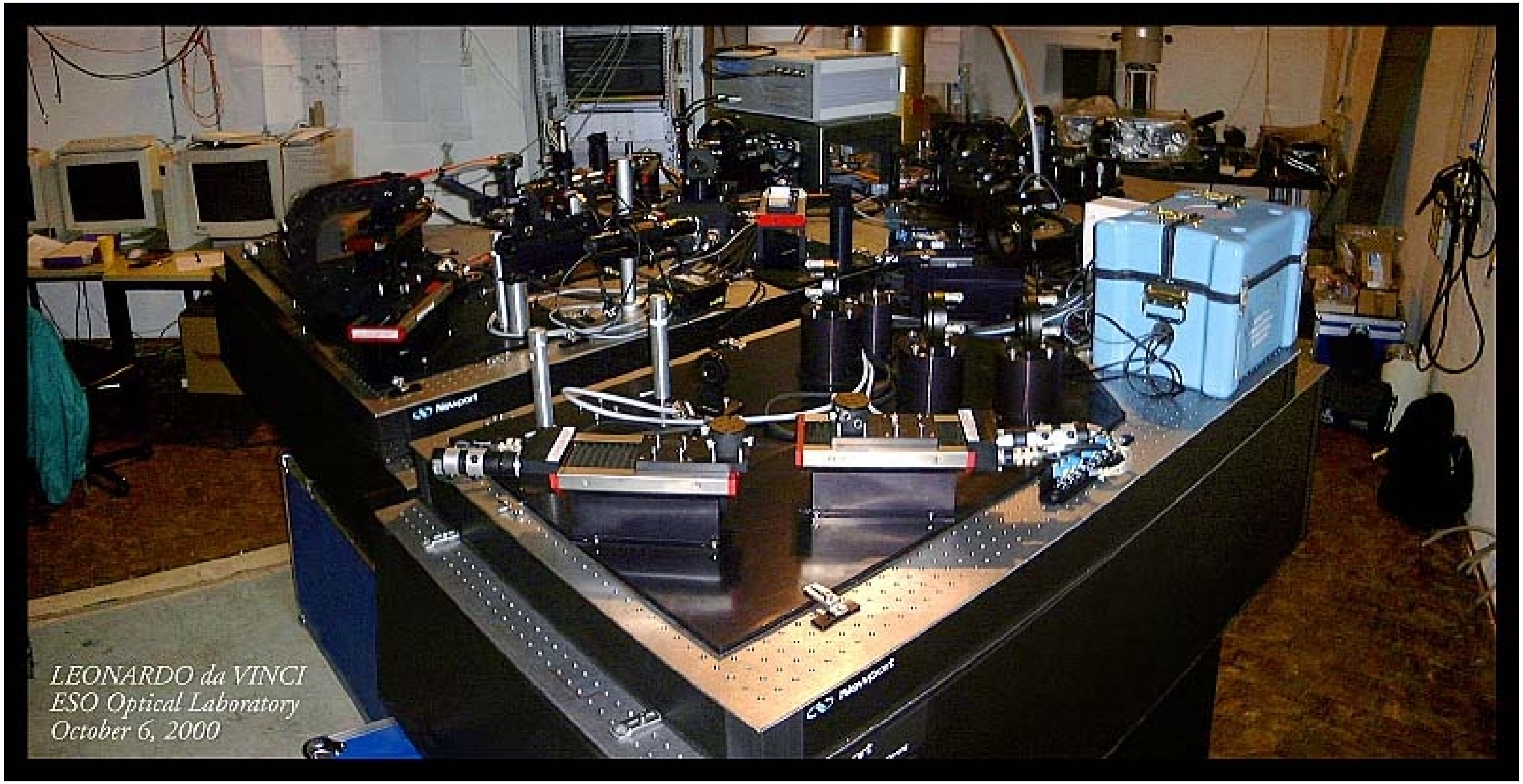
VLT Interferometer, EUR



VLTI Delay Lines

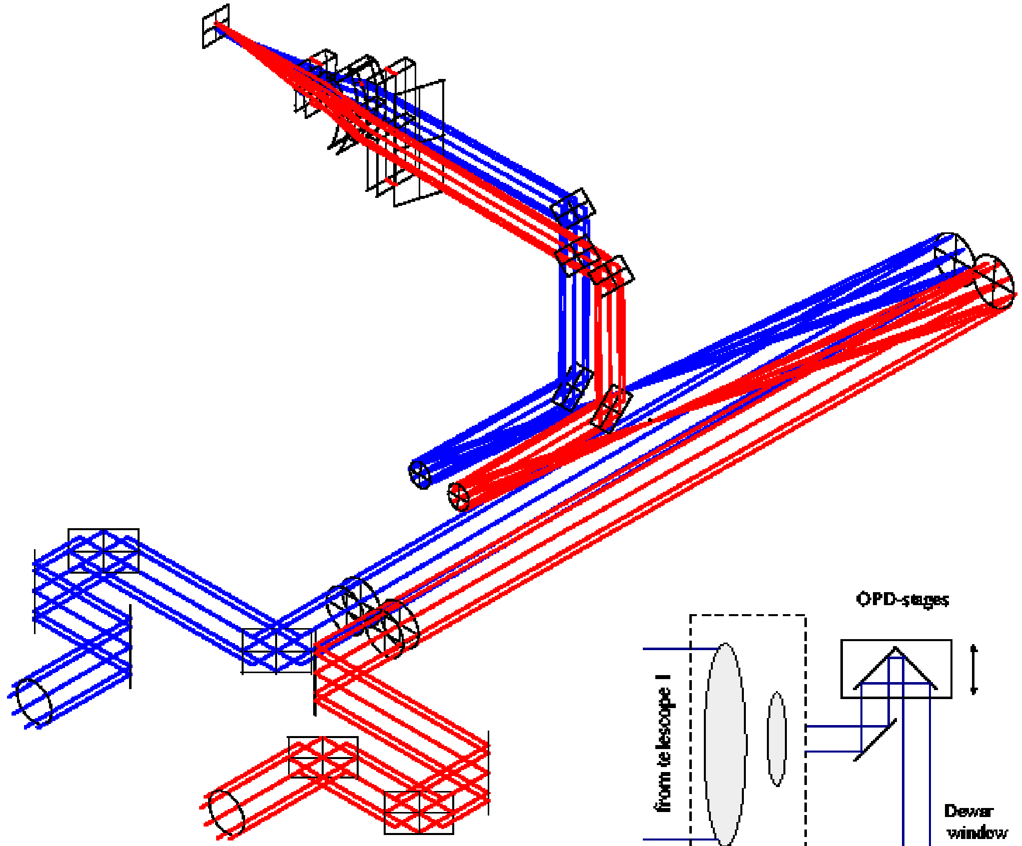


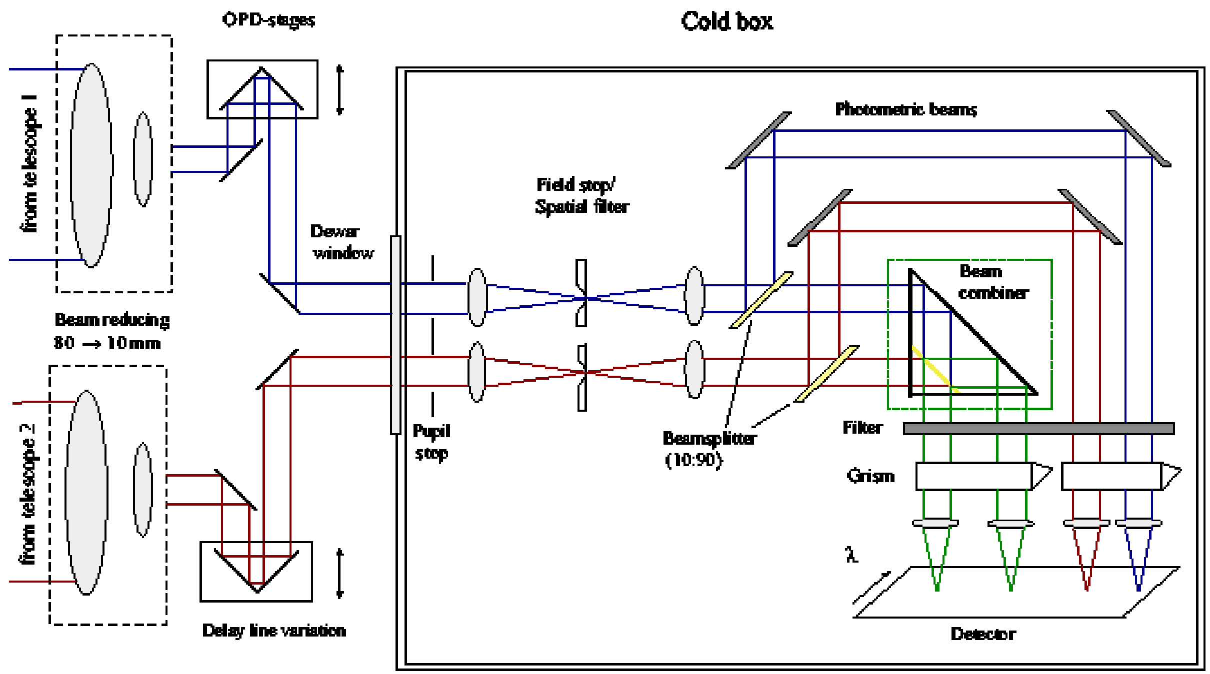
VINCI - VLTI Commissioning Instrument



VLTI - Mid-Infrared Instrument (MIDI)

MIDI principle and optical design





Fundamental Stellar Parameters

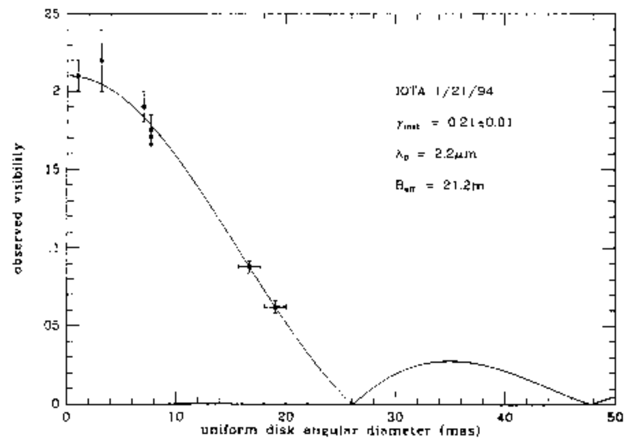
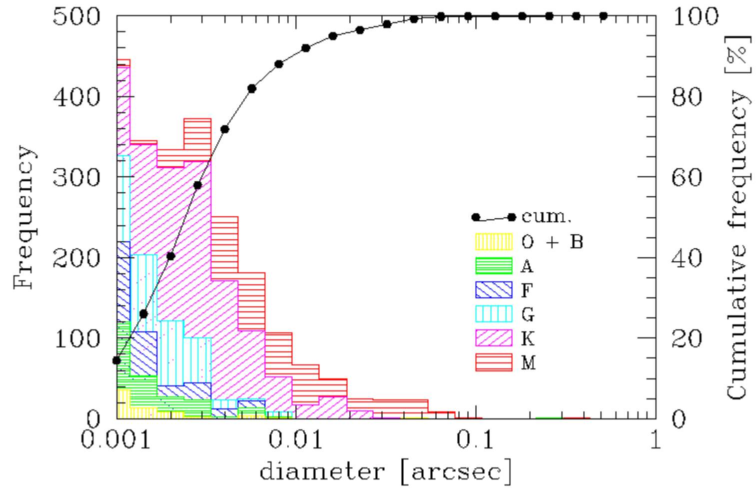


Figure 4. Visibility vs θ_{ud}; reference stars (< 8 mas), RS Cnc (16.6 mas), RX Boo (19.0 mas).



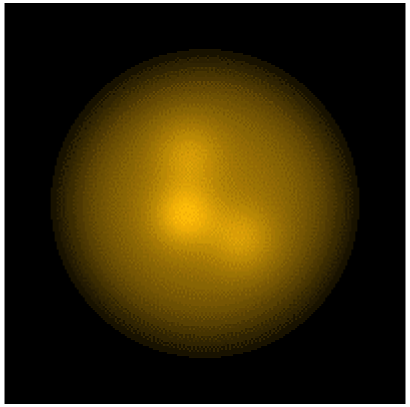
Fringe contrast as function of apparent diameter

Distribution of apparent diameters for various spectral classes for stars seen from Paranal, Chile

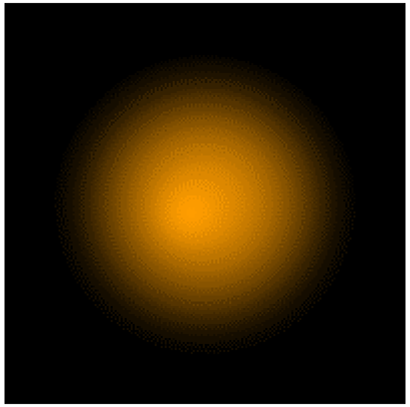
SUSI, Narrabri, Australia, IOTA, Mt. Hamilton, USA

Stellar Surfaces

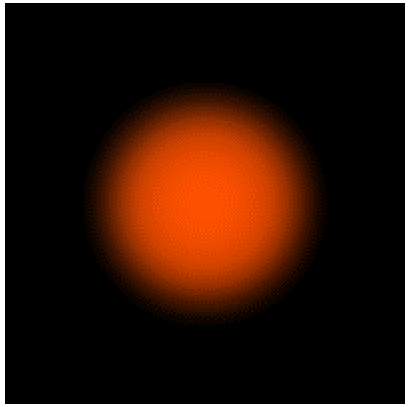
Three maps of α Ori (Betelgeuse) taken in Nov. 1997



700 nm (WHT)



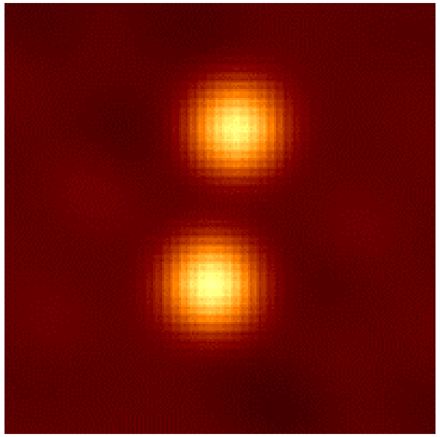
905 nm (COAST)

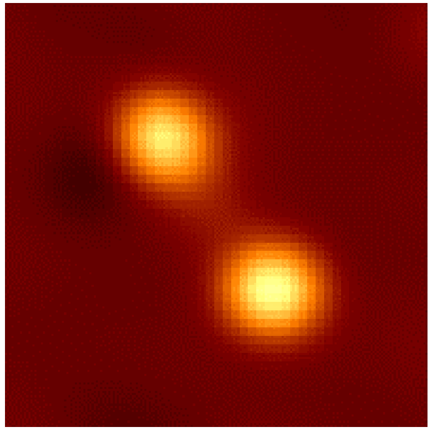


1290 nm (COAST)

pictures courtesy COAST

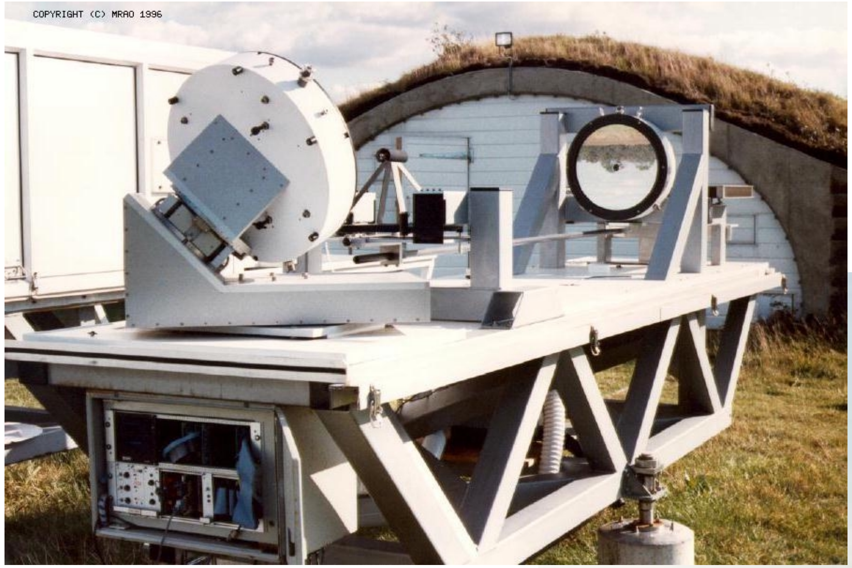
Multiple Stars



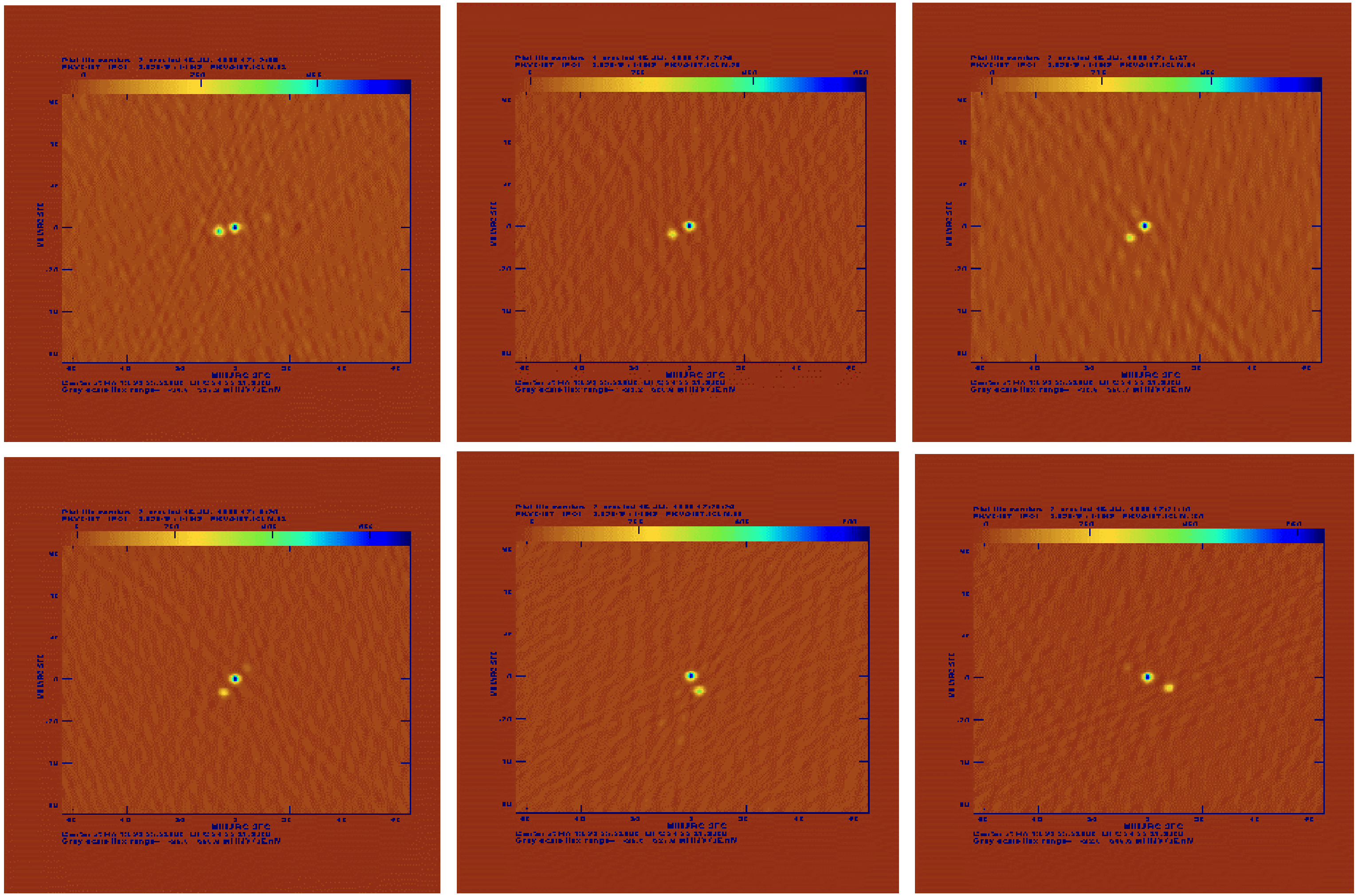


Maps of Capella taken 15 days apart

COAST, Cambridge, UK

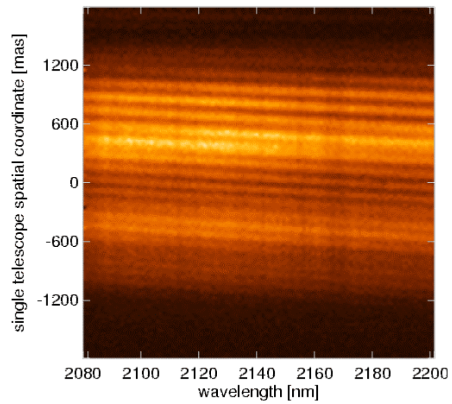


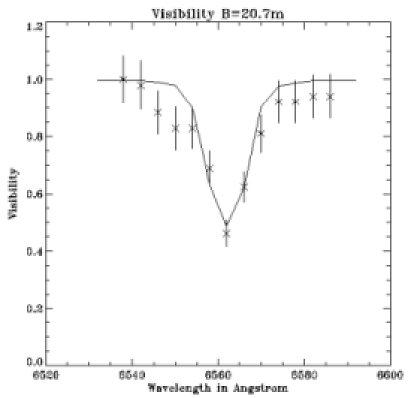
Observations of Mizar with **NPOI** on May 1 - 4, 29, June 1, 1996

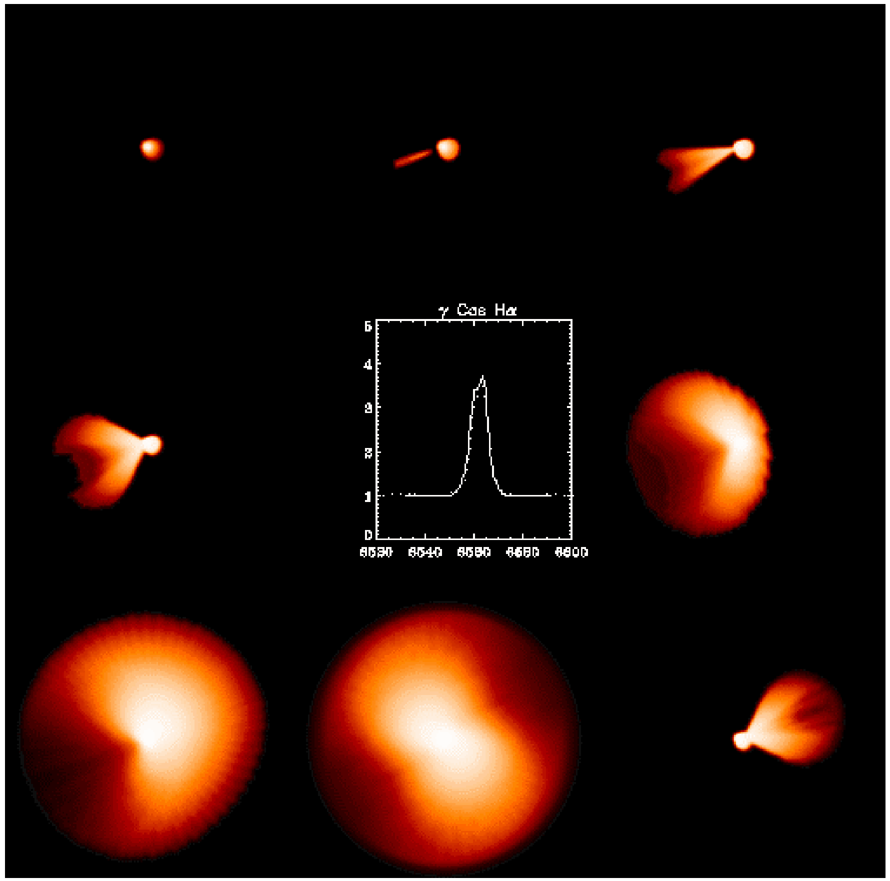


NPOI, Flagstaff, USA

Stellar Environments





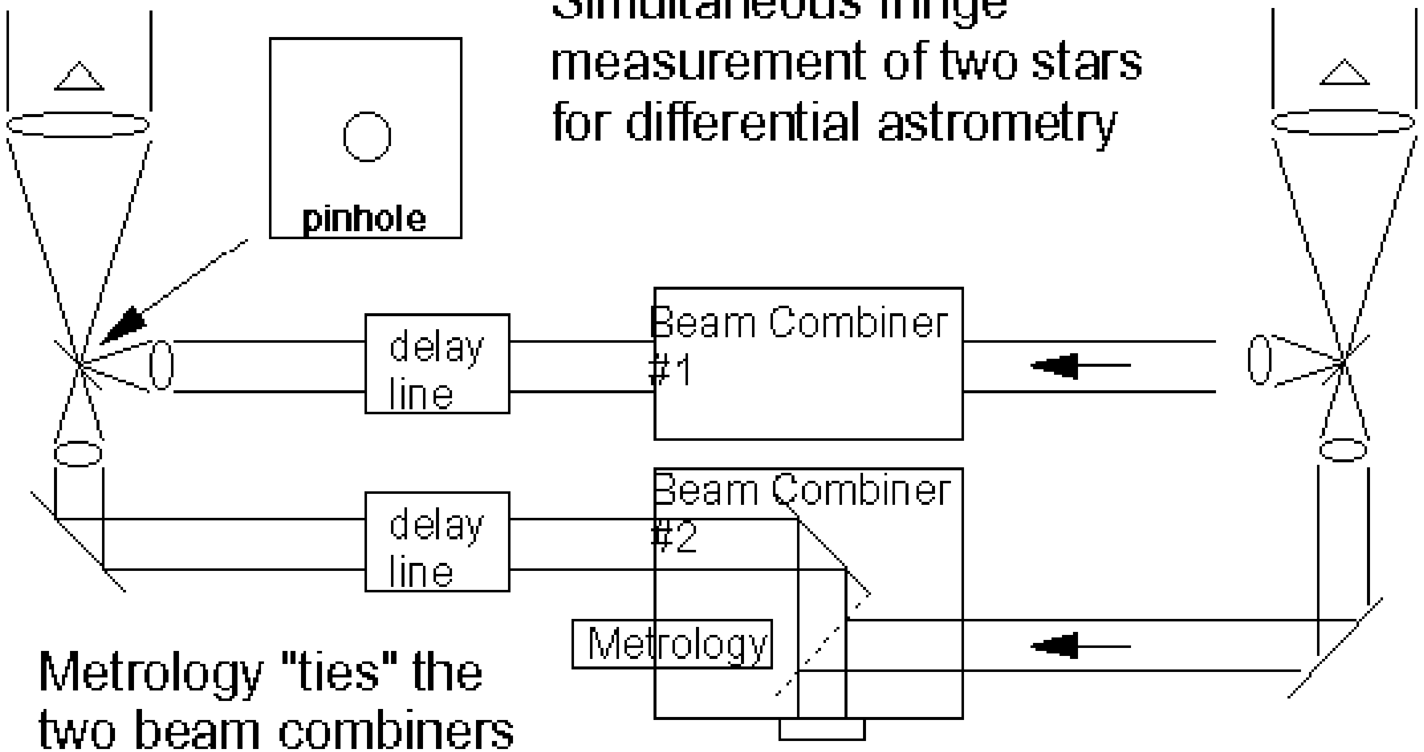


GI2T, Calern, France

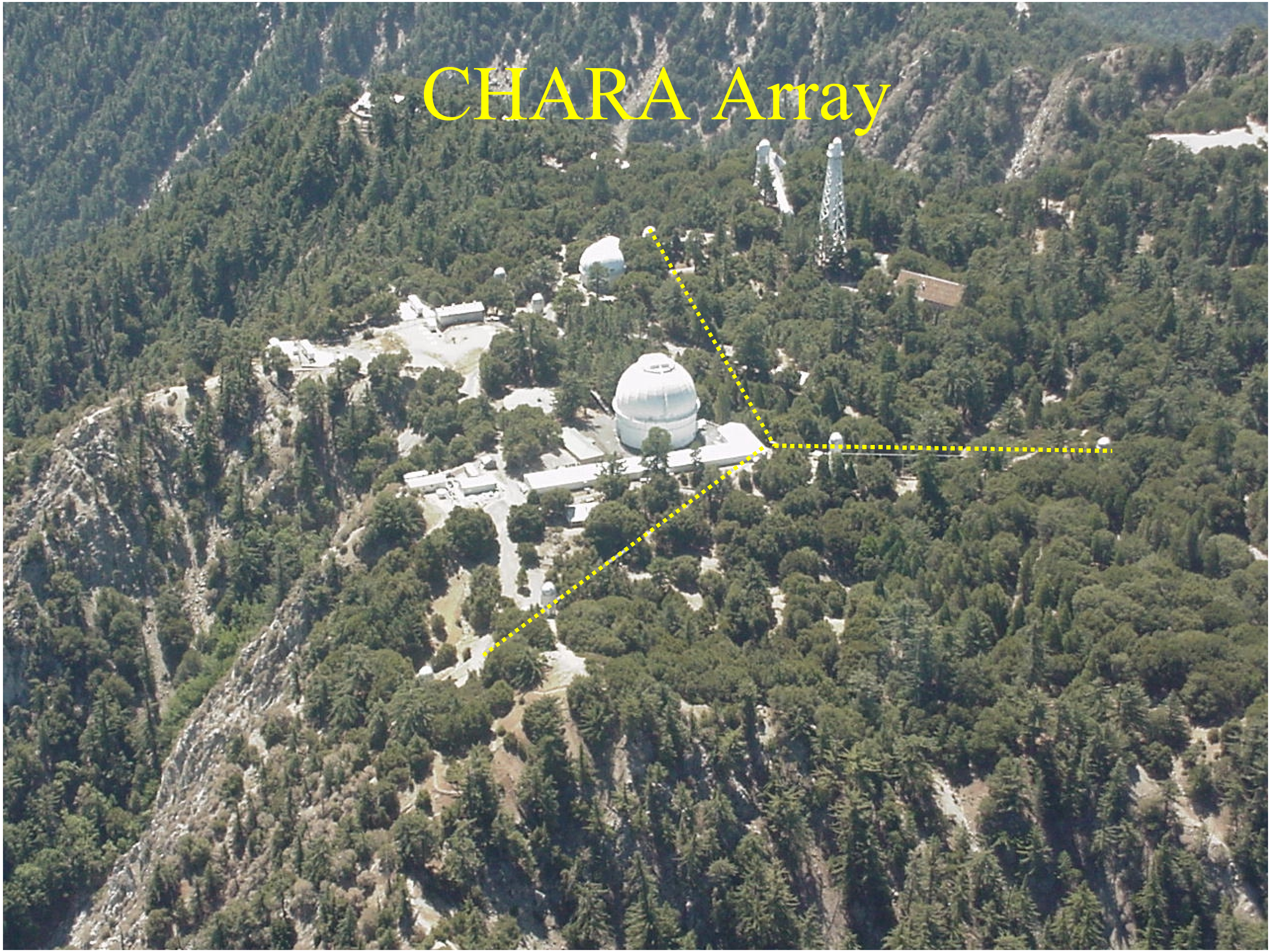
Palomar Testbed Interferometer (PTI), USA

Dual Object Interferometry

Simultaneous fringe measurement of two stars for differential astrometry



Metrology "ties" the two beam combiners together (~10 nm)


CHARA Array

Conclusions

- **Optical interferometry has matured and becomes a regular tool for astronomy**
- eight interferometers with apertures up to 1.5m operational on regular basis
- three arrays involving 10m class telescopes nearing completion
- unique science being produced