Interferometry and Stellar Interferometers

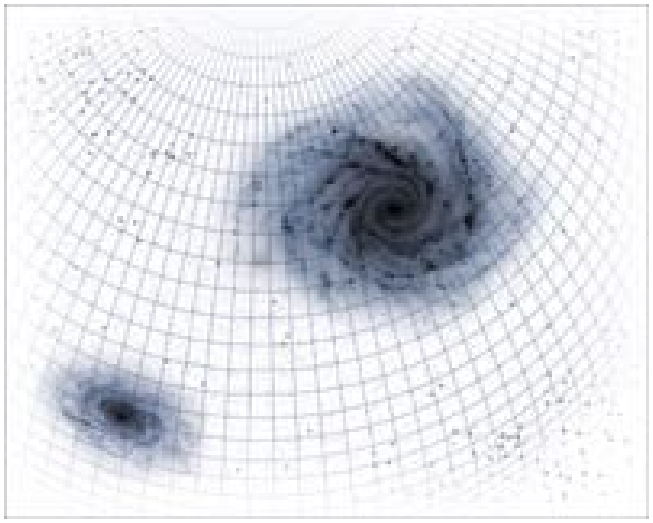
Theo A. ten Brummelaar

Center for High Angular Resolution Astronomy
Georgia State University
Atlanta, GA 30303

Peter R. Lawson

Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA 91107

Overview



- **Introduction to the lecture series**
- **Brief History of Stellar Interferometry**
- **Fundamentals of Interferometry**
  - Physics and mathematics
- **Design of Modern Stellar Interferometers**
  - Fringes and fringe measurement at optical wavelengths
  - Engineering and practical considerations
  - Examples of current ground-based instruments
- **Approaches to Observation and Data Reduction**
  - Source modeling
  - Synthesis imaging
  - Astrometry
- **Future Prospects from the ground and space**

Why Build a Stellar Interferometer?

- **To overcome the resolution limitations of conventional telescopes**
- **To measure the brightest and nearest stars**
  - Angular diameters
  - Binary star orbits
  - Limb-darkening
  - Stellar surface structure
  - Stellar positions and proper motions
  - Indirect detection of planets
- **To constrain theoretical models that describe stellar astrophysics.**

Interferometry and Stellar Interferometers

PRIX BORDIN.

QUESTION PROPOSÉE EN 1865 POUR 1867.

(Commissaires : MM. Duhamel, Pouillet, Regnault, Bertrand, Edmond Becquerel, Fizeau rapporteur.)

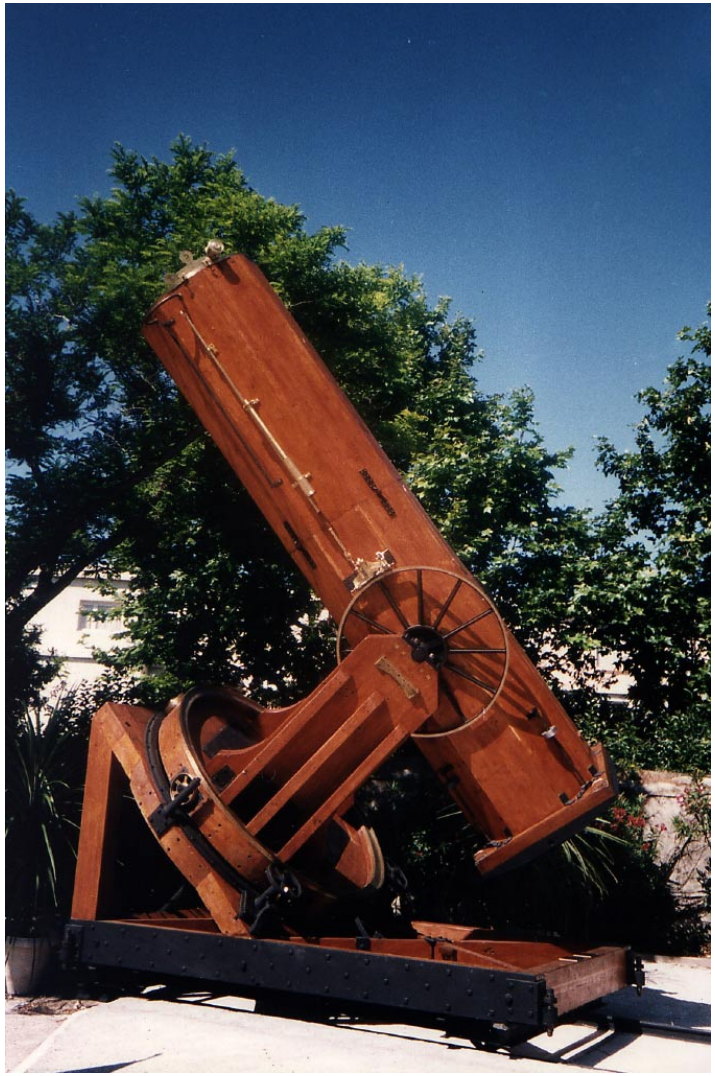
Rapport sur le Concours de l'année 1867.

« *Le prix sera décerné au savant qui aura exécuté ou proposé une expérience*
» *décisive permettant de trancher définitivement la question déjà plusieurs fois*
» *étudiée de la direction des vibrations de l'éther dans les rayons polarisés.* »

Il existe en effet pour la plupart des phénomènes d'interférence, tels que les franges d'Yung, celles des miroirs de Fresnel et celles qui donnent lieu à la scintillation des étoiles d'après Arago, une relation remarquable et nécessaire entre la dimension des franges et celle de la source lumineuse, en sorte que des franges d'une ténuité extrême ne peuvent prendre naissance que lorsque la source de lumière n'a plus que des dimensions angulaires presque insensibles; d'où, pour le dire en passant, il est peut-être permis d'espérer qu'en s'appuyant sur ce principe et en formant par exemple, au moyen de deux larges fentes très-écartées, des franges d'interférence au foyer des grands instruments destinés à observer les étoiles, il deviendra possible d'obtenir quelques données nouvelles sur les diamètres angulaires de ces astres.

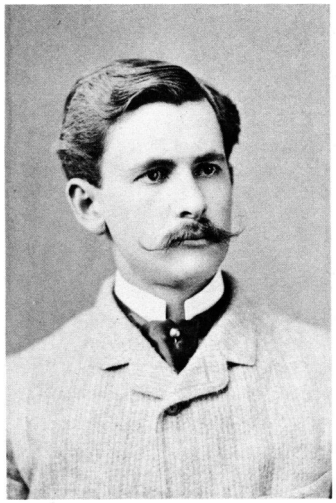
Interferometry and Stellar Interferometers

Edouard Stephan (1837-1923)



http://www-obs.cnrs-mrs.fr/dynamique/pap/compact.html

Interferometry and Stellar Interferometers



Michelson in 1887, at the time of the Michelson-Morley experiment (COURTESY CLARK UNIVERSITY ARCHIVES)

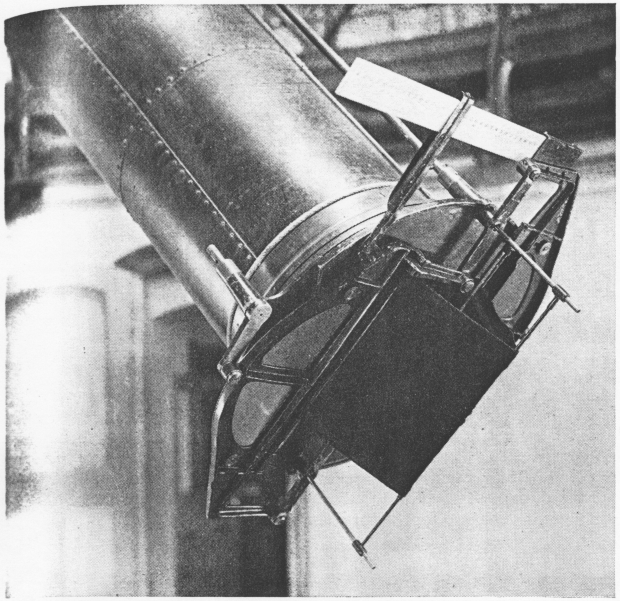
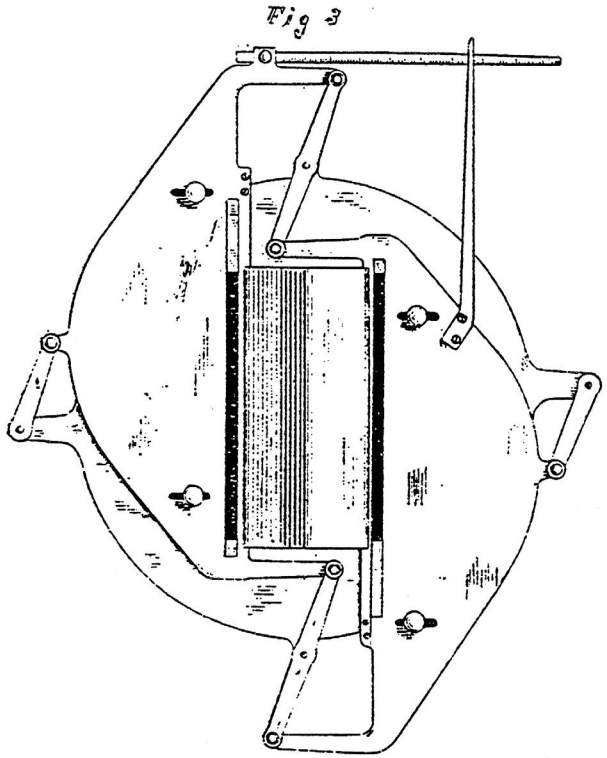


FIG. 1. Interferometric mask used on the 12-inch refractor at Lick Observatory to measure the angular diameters of the Jovian satellites. The rod adjacent to the telescope tube is turned by the observer, which in turn rotates a lever connecting the two slits immediately exterior to the pictured objective shroud. Photograph courtesy University of California at Santa Cruz Library.



With this apparatus the satellites of Jupiter were measured, with results as given in the following table :—

TABLE I.

No. of Satellites.	I.	II.	III.	IV.	Seeing.
August 2 ...	1″·29 ...	1″·19 ...	1″·88 ...	1″·68 ...	Poor.
August 3 ...	1·29 ...	— ...	1·59 ...	1·68 ...	Poor.
August 6 ...	1·30 ...	1·21 ..	1·69 ...	1·56 ...	Poor.
August 7 ...	1·30 ...	1·18 ...	1·77 ...	1·71 ...	Good.
Mean...	1·29	1·19	1·73	1·66	

Interferometry and Stellar Interferometers

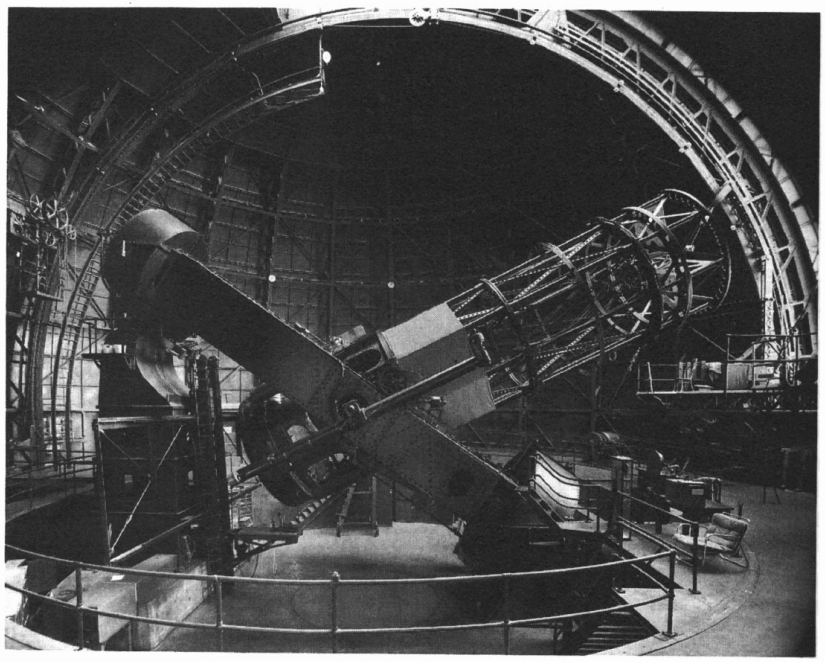


Figure 13.5 *The 100 inch (2.5 m) Hooker reflector on Mount Wilson, completed in 1917. (Courtesy* The Observatories of the Carnegie Institution of Washington.*)*

Albert A. Michelson, about 1928

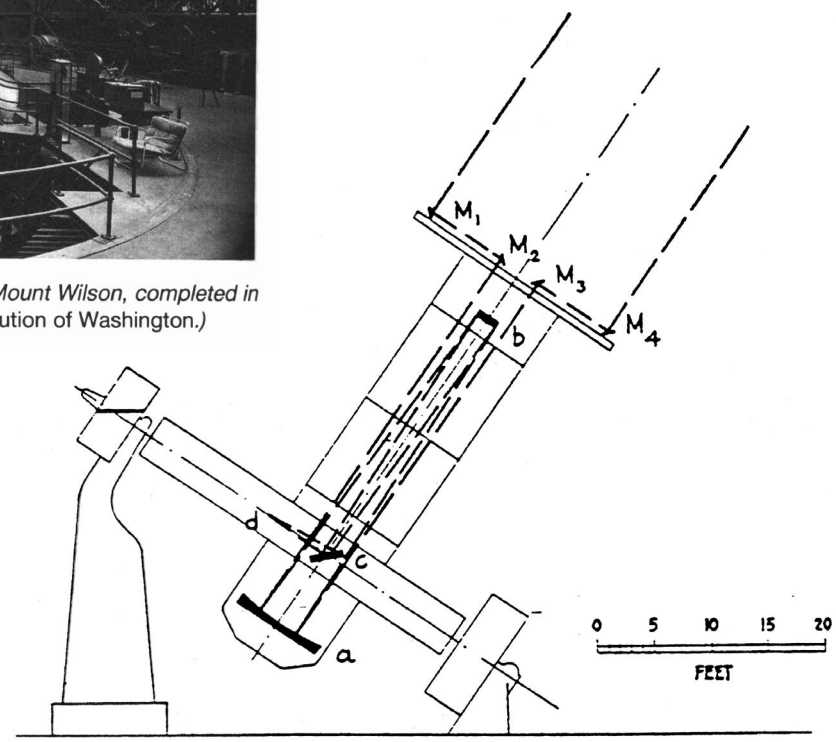


FIG. 1.—Diagram of optical path of interferometer pencils. M_1, M_2, M_3, M_4, mirrors; *a*, 100-inch paraboloid; *b*, convex mirror; *c*, coudé flat; *d*, focus.

Interferometry and Stellar Interferometers

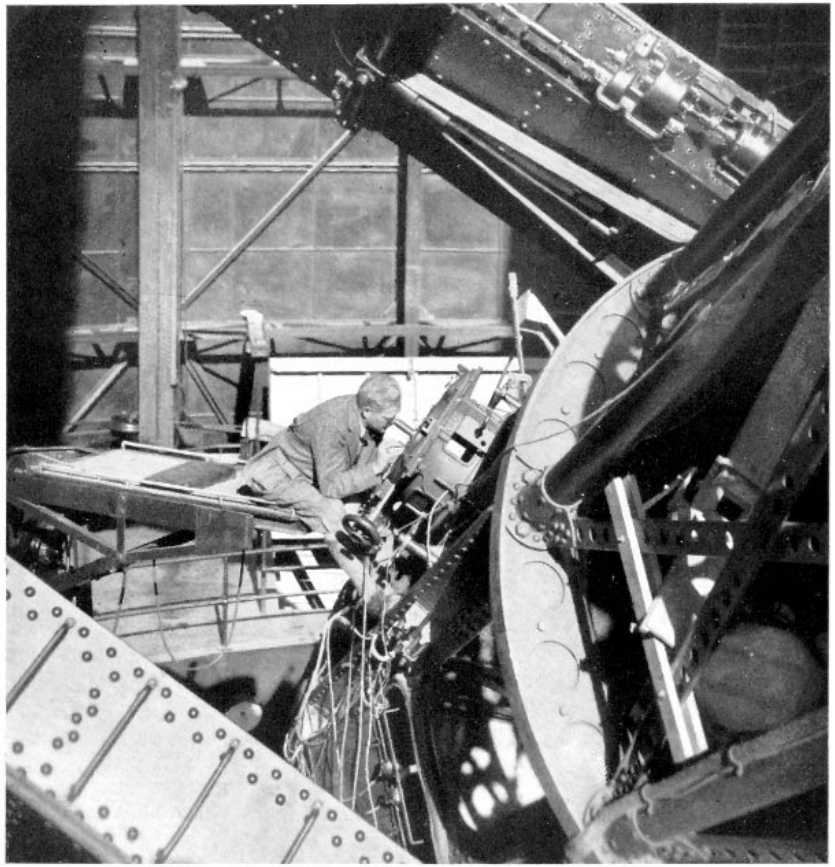


Abb. 3. Showing observer at eyepiece of 20 foot interferometer.

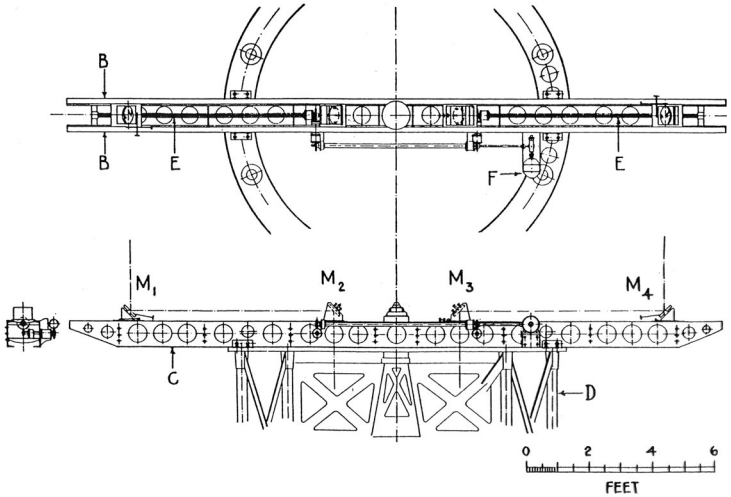


FIG. 2.—Diagram of 20-foot interferometer beam. M_1, M_2, M_3, M_4, mirrors; B, B, 10-inch channels; C, steel plate; E, E, screws to move outer mirrors; F, motor drive for screws; D, Cassegrain cage.

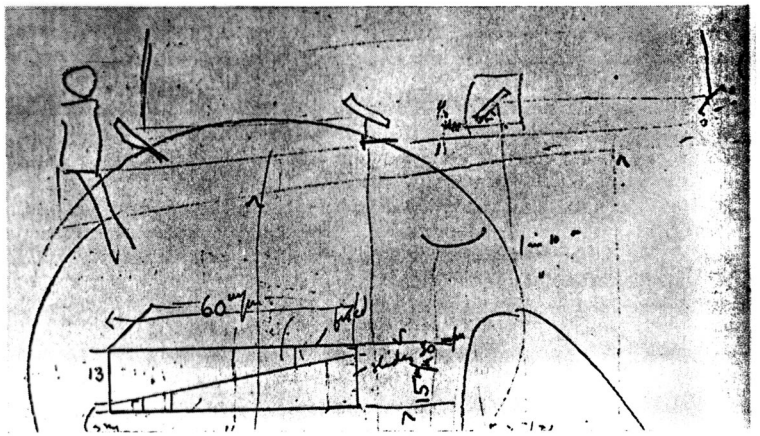


FIG. 3. From F. G. Pease, Notebook 1, sheet 42; approximate date 14 July 1920 (Hale Observatories, copy in Michelson Museum). Crude drawings of the optical wedge used to equalise path length. Note the superimposed sketch illustrating how the night assistant must be perched to move the mirrors on the beam. This situation was necessary because the mirrors, at first, were not continuously adjustable.

Interferometry and Stellar Interferometers

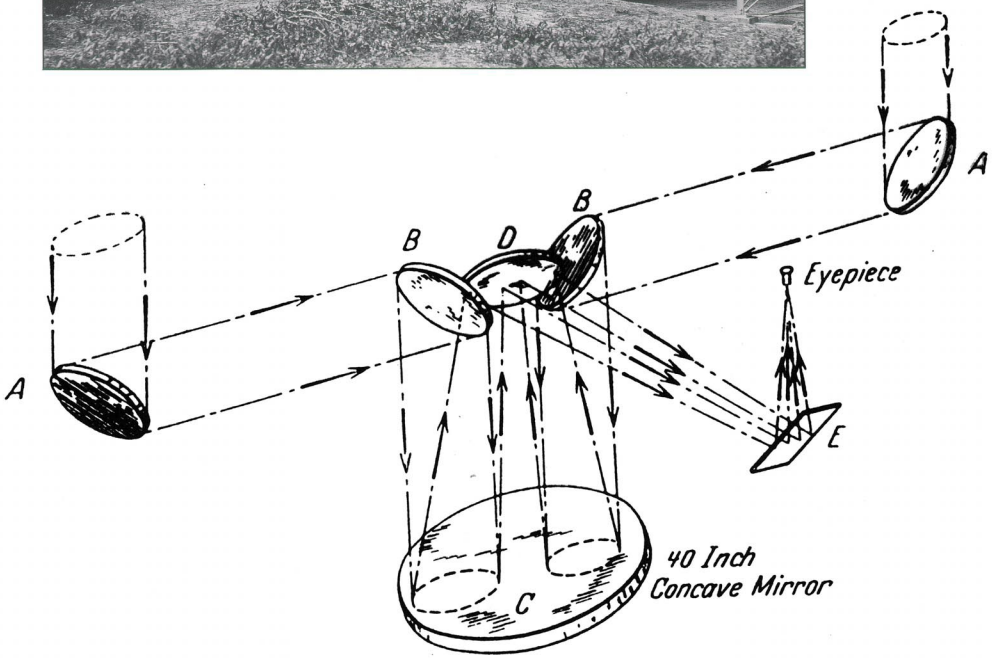


Abb. 8. Diagram of light path in 50 foot interferometer.

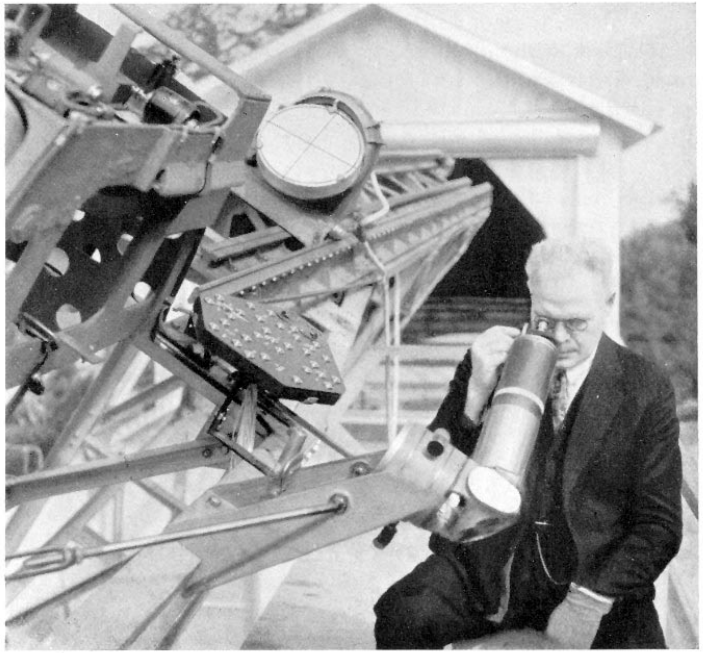
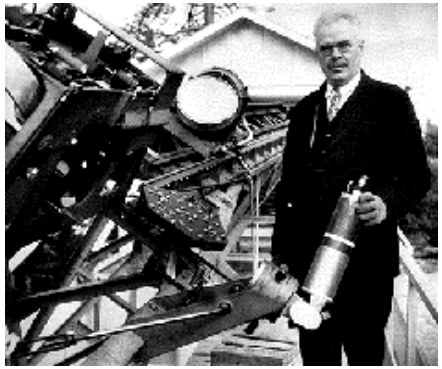
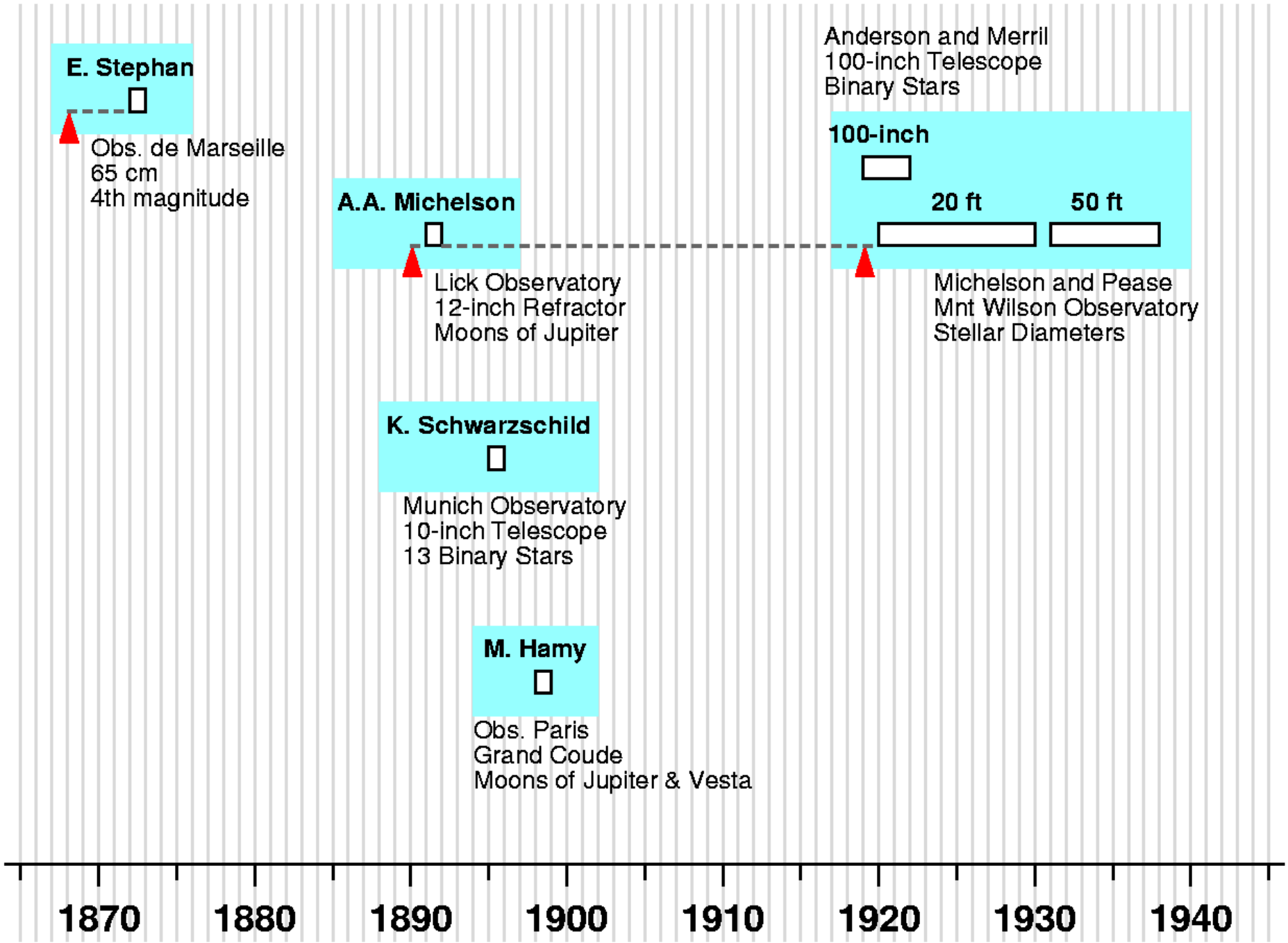


Abb. 9. Upper part of interferometer showing control board and observer at eyepiece.




E. Stephan
Obs. de Marseille
65 cm
4th magnitude
A.A. Michelson
Lick Observatory
12-inch Refractor
Moons of Jupiter
K. Schwarzschild
Munich Observatory
10-inch Telescope
13 Binary Stars
M. Hamy
Obs. Paris
Grand Coude
Moons of Jupiter & Vesta
Anderson and Merril
100-inch Telescope
Binary Stars
100-inch
20 ft
50 ft
Michelson and Pease
Mnt Wilson Observatory
Stellar Diameters
1870
1880
1890
1900
1910
1920
1930
1940

Interferometry and Stellar Interferometers

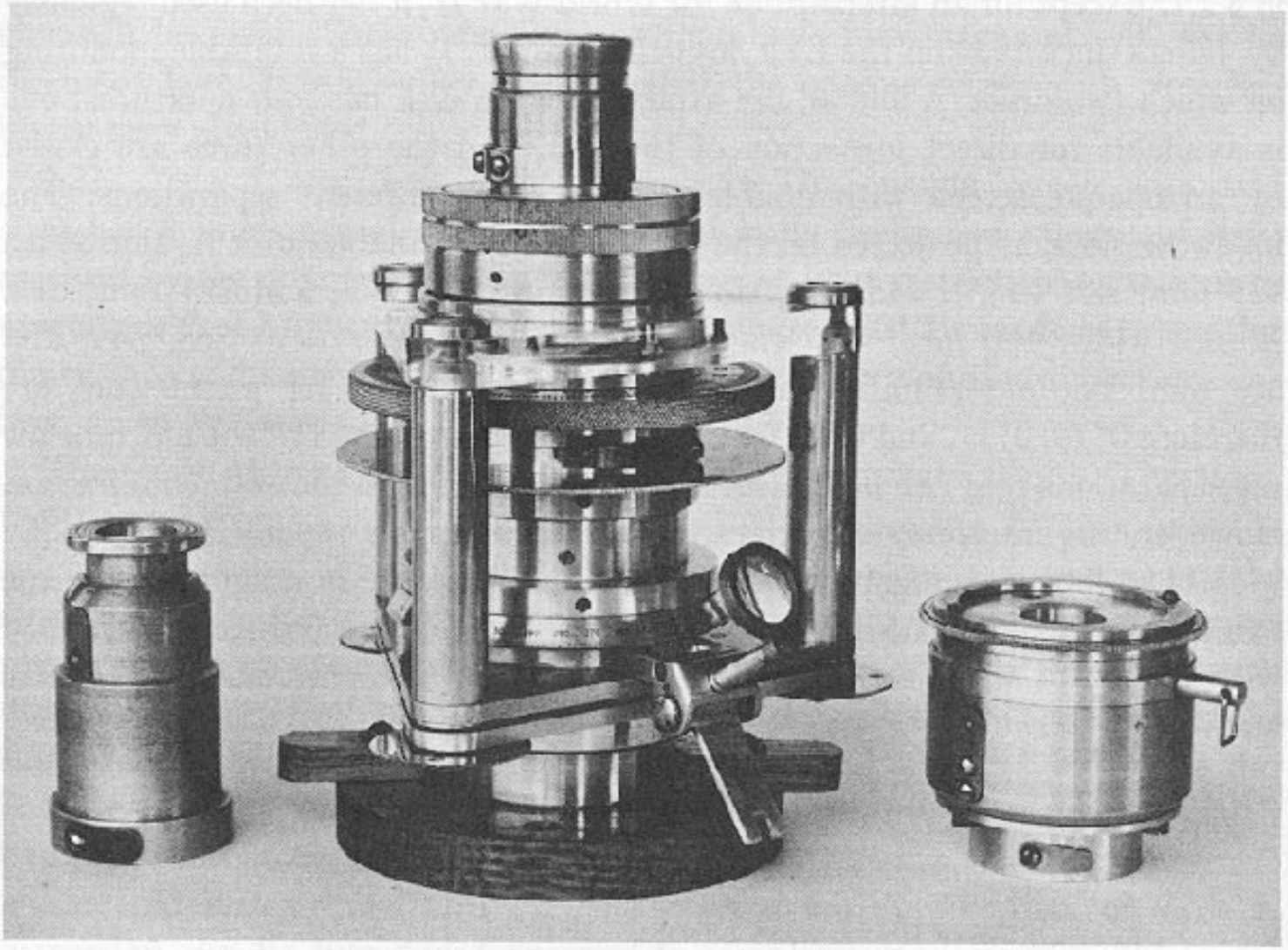
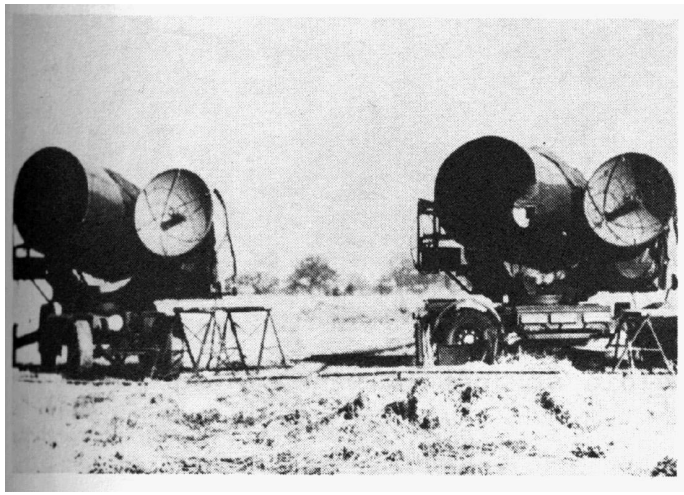
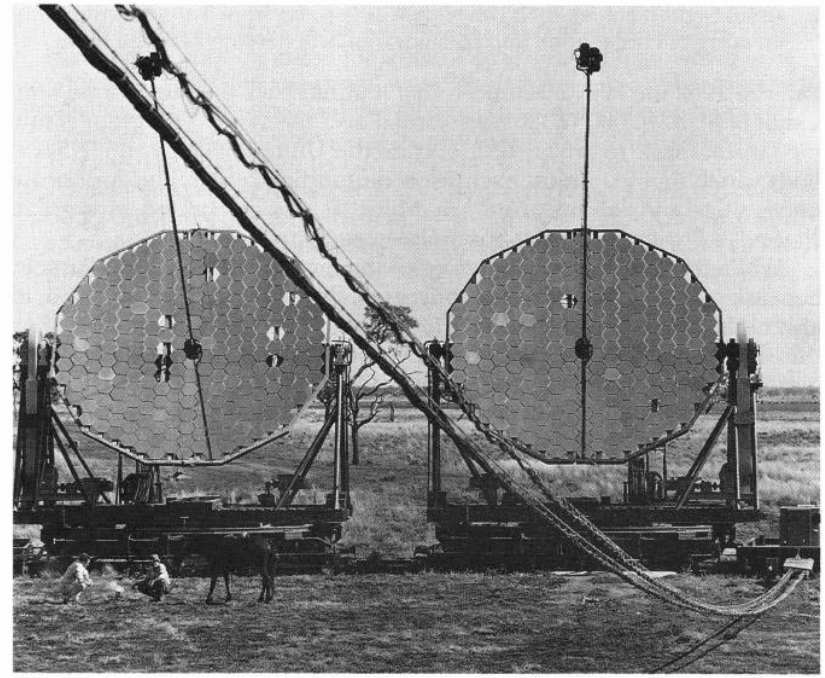


FIG. 9.—The eyepiece interferometer of the Union Observatory

Interferometry and Stellar Interferometers





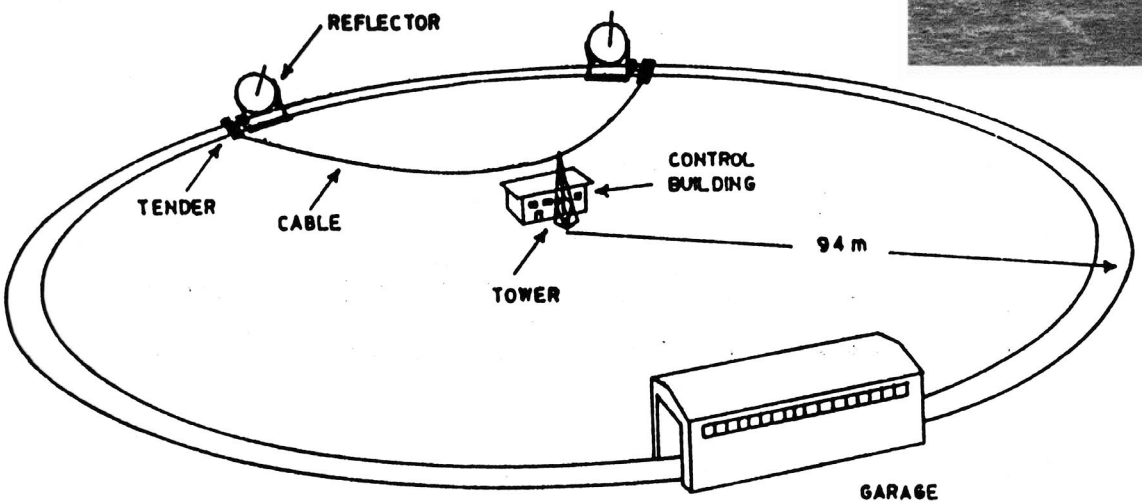
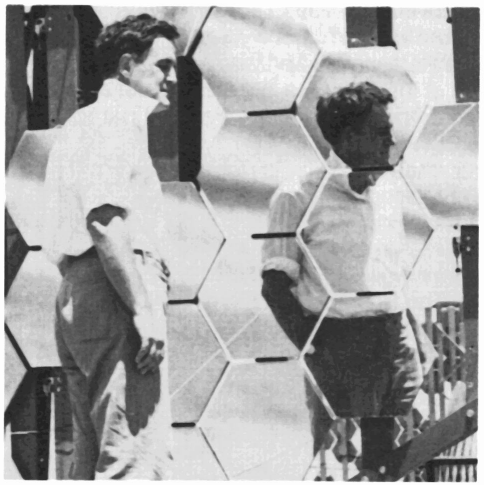


FIG. 7. The general layout of the interferometer at Narrabri Observatory.



Interferometry and Stellar Interferometers

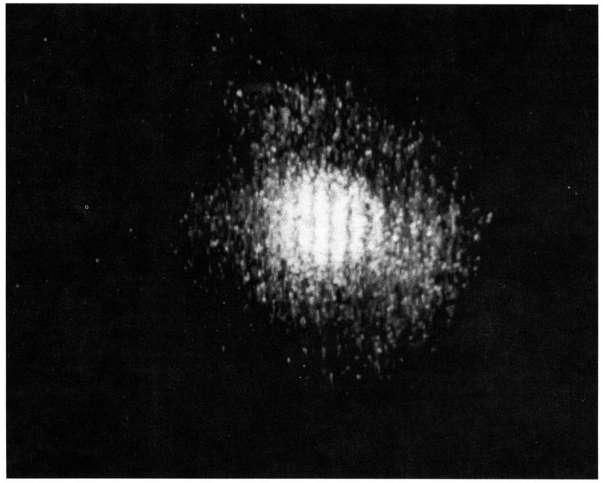


FIG. 4.—Interference fringes (photographed from a television sequence), obtained in the image of Vega with 500 Å bandwidth. In this case, the photon-counting camera is operating at reduced gain in the analog mode. Individual photon events are nevertheless visible as bright points.

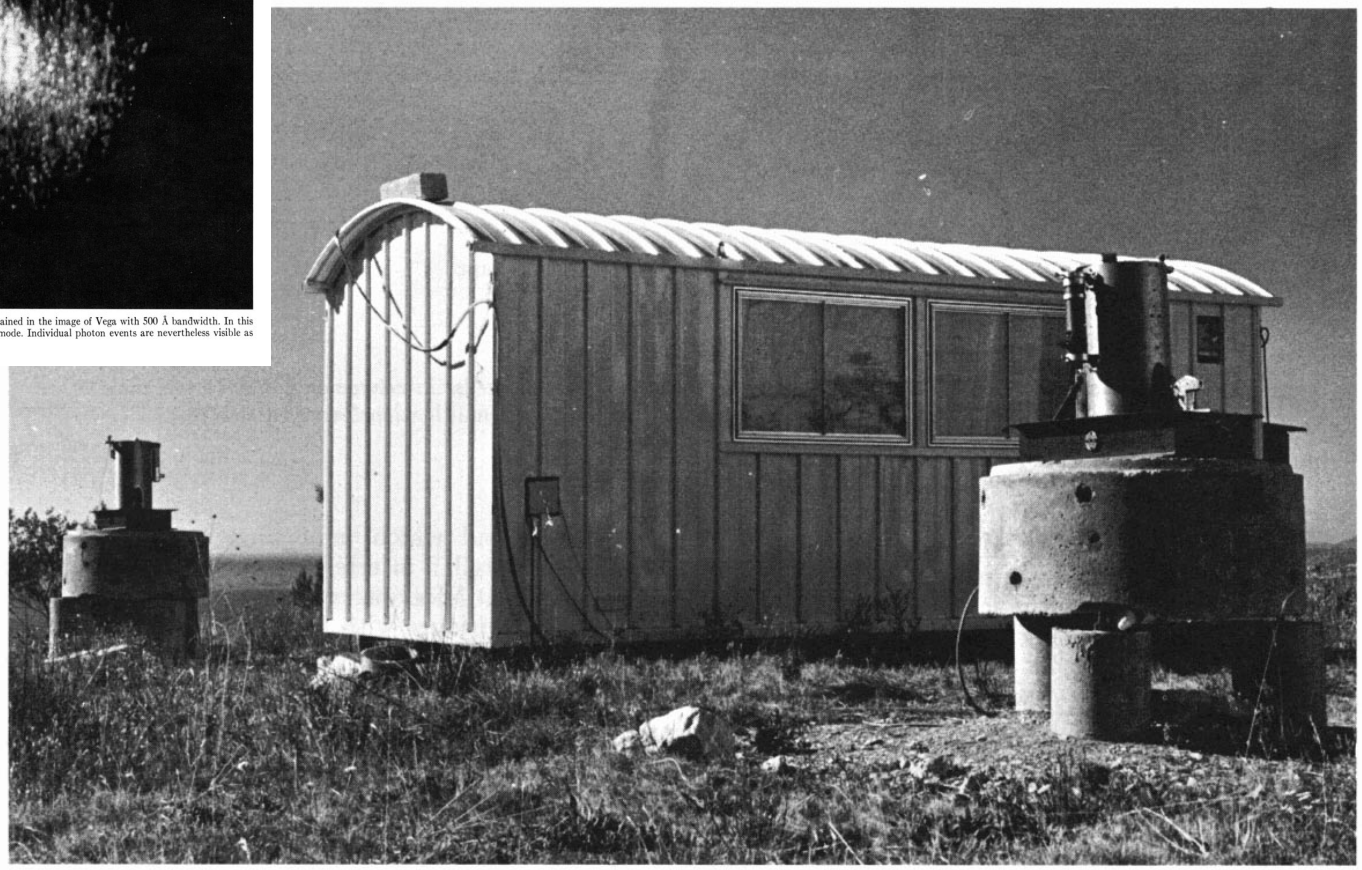
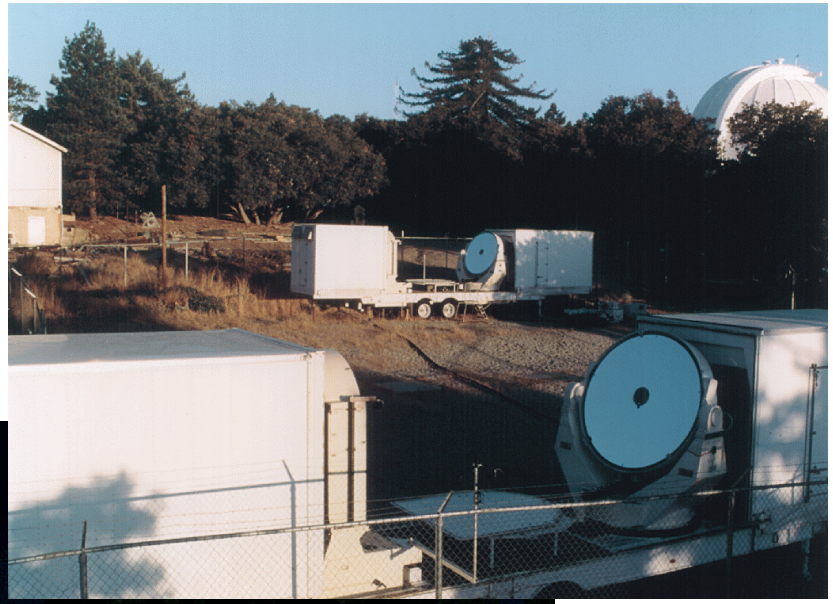


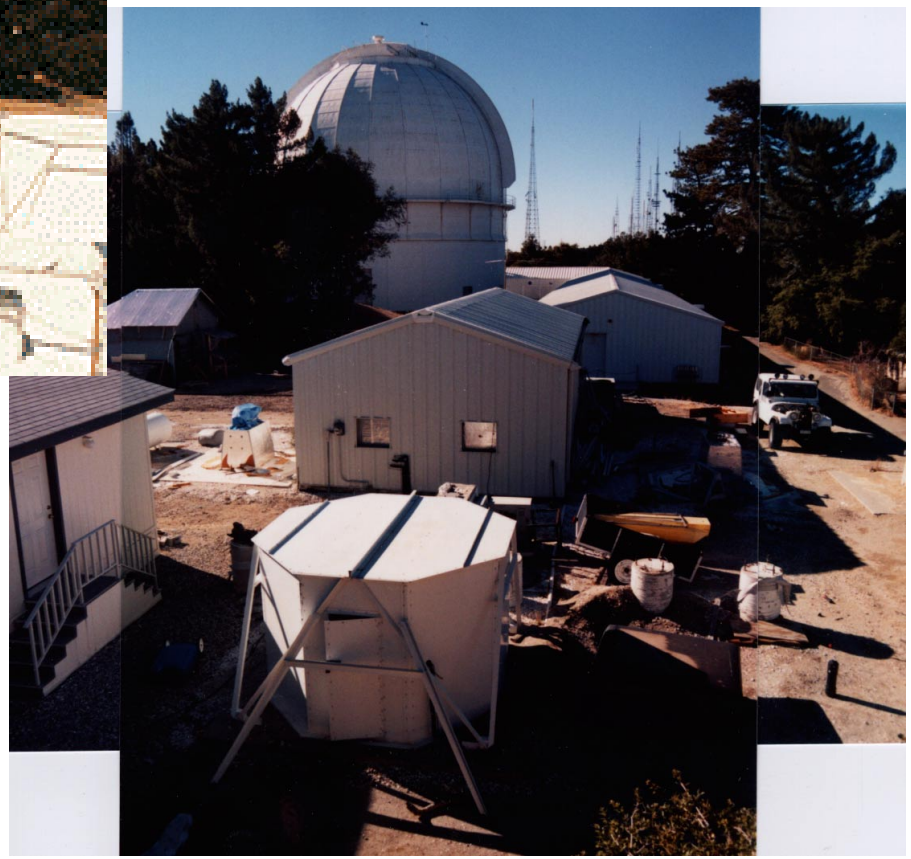
FIG. 2.—Interferometer at Nice observatory, showing the heavy alt-alt yoke mounts with their servo drives. The large concrete elements are commercial pipe sections providing a stable but movable substrate. Not visible is a mechanism which rotates the coudé mirror at half the declination rate, thus providing a fixed coudé output. The construction of 60-m tracks is currently undertaken for a variable baseline.

Interferometry and Stellar Interferometers



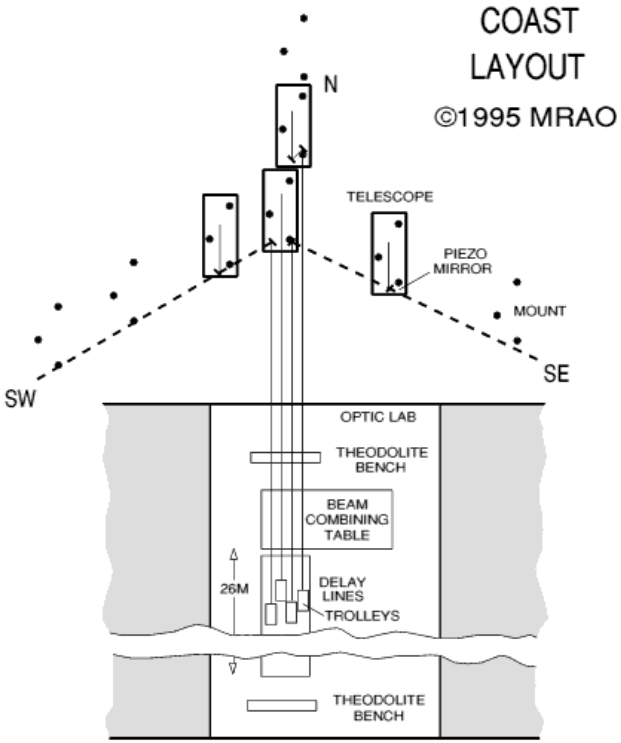
Infrared Spatial Interferometer (ISI)

Interferometry and Stellar Interferometers



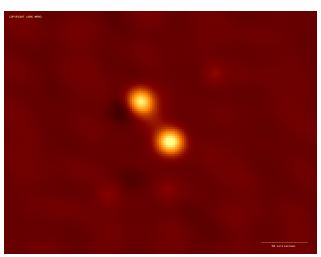
Mark III
Stellar Interferometer

Interferometry and Stellar Interferometers

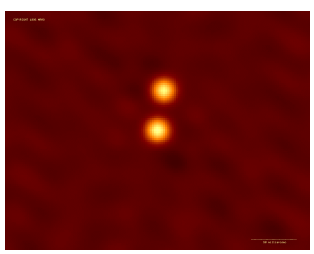


Cambridge Optical Aperture Synthesis Telescope (COAST)

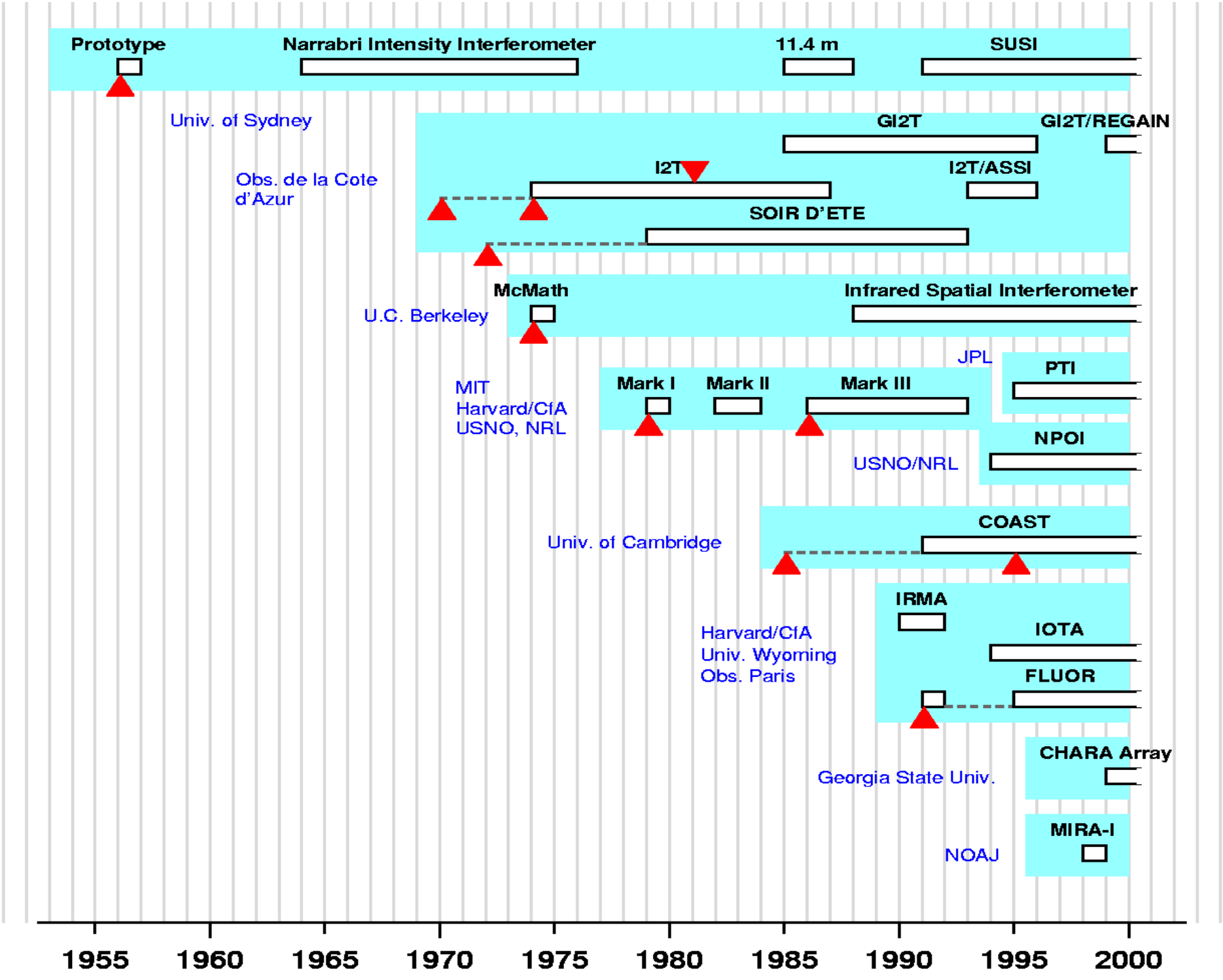
Optical Synthesis Images of Capella



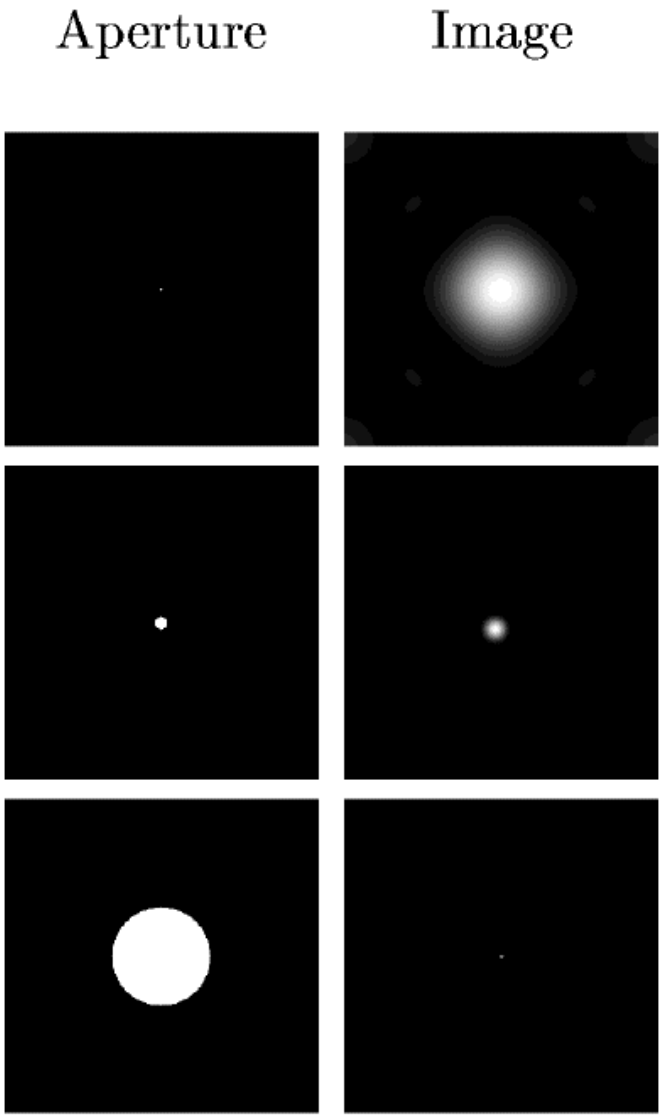
13 Sept. 1995



28 Sept. 1995


Prototype
Narrabri Intensity Interferometer
11.4 m
SUSI
Univ. of Sydney
GI2T
GI2T/REGAIN
I2T
I2T/ASSI
Obs. de la Cote d'Azur
SOIR D'ETE
McMath
Infrared Spatial Interferometer
U.C. Berkeley
JPL
PTI
MIT
Harvard/CfA
USNO, NRL
Mark I
Mark II
Mark III
NPOI
USNO/NRL
COAST
Univ. of Cambridge
IRMA
IOTA
Harvard/CfA
Univ. Wyoming
Obs. Paris
FLUOR
CHARA Array
Georgia State Univ.
MIRA-I
NOAJ
1955
1960
1965
1970
1975
1980
1985
1990
1995
2000

Examples of Diffraction: Apertures and Images



Angular Resolution $\approx \lambda/D$

The Fourier Transform

The Fourier transform $F(\vec{s})$ of a function $f(\vec{r})$ is defined

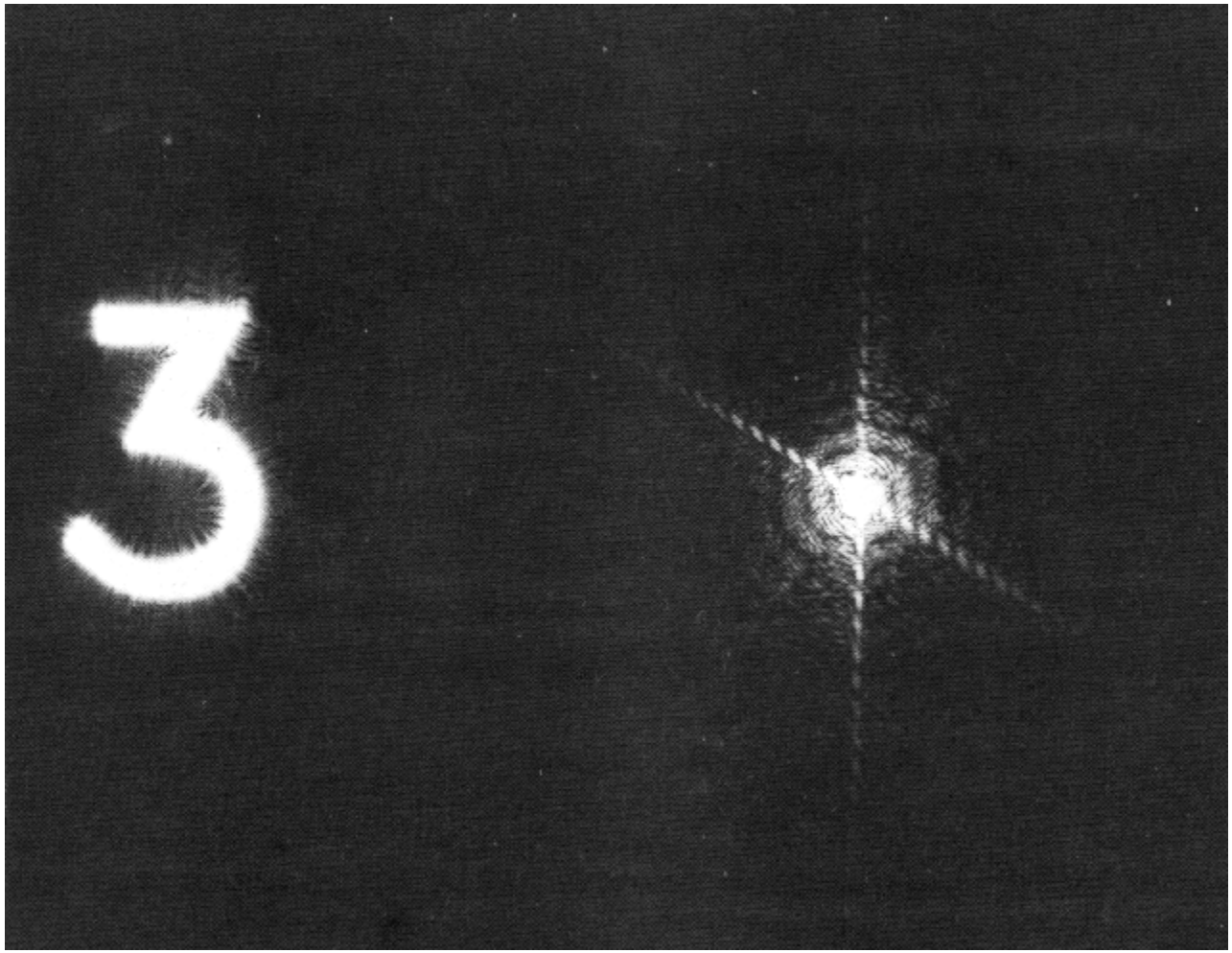
$$F(\vec{s}) = \int_{-\infty}^{\infty} f(\vec{r}) e^{-2\pi i \vec{s}.\vec{r}} d\vec{r}$$

This transform is your friend, it allows you to solve a problem either in linear space or in spatial frequency. This is like breaking up sound into a sum of pure sine waves. The transform is reversible using the equation

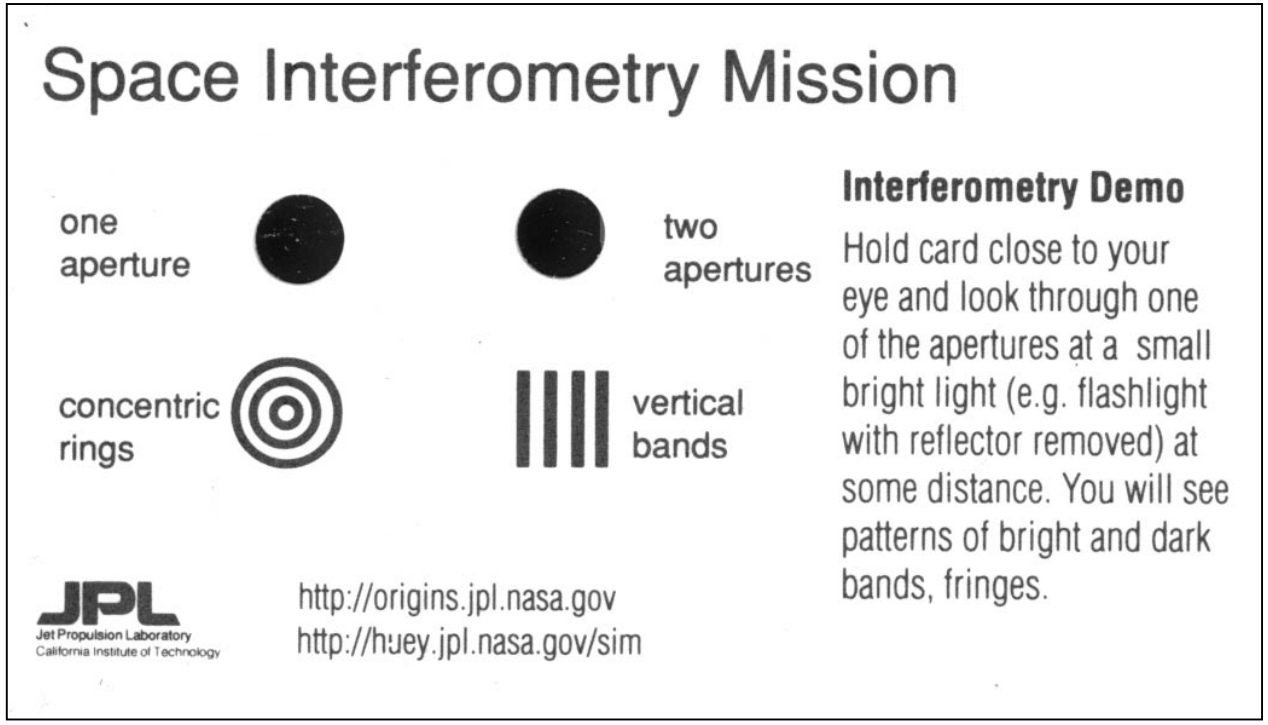
$$f(\vec{s}) = \int_{-\infty}^{\infty} F(\vec{r}) e^{2\pi i \vec{s}.\vec{r}} d\vec{s}.$$

Note the symmetry. This transform can be performed by hand, by computers and by optics: a telescope is a Fourier transform device.

Optical Fourier Transform of “3”

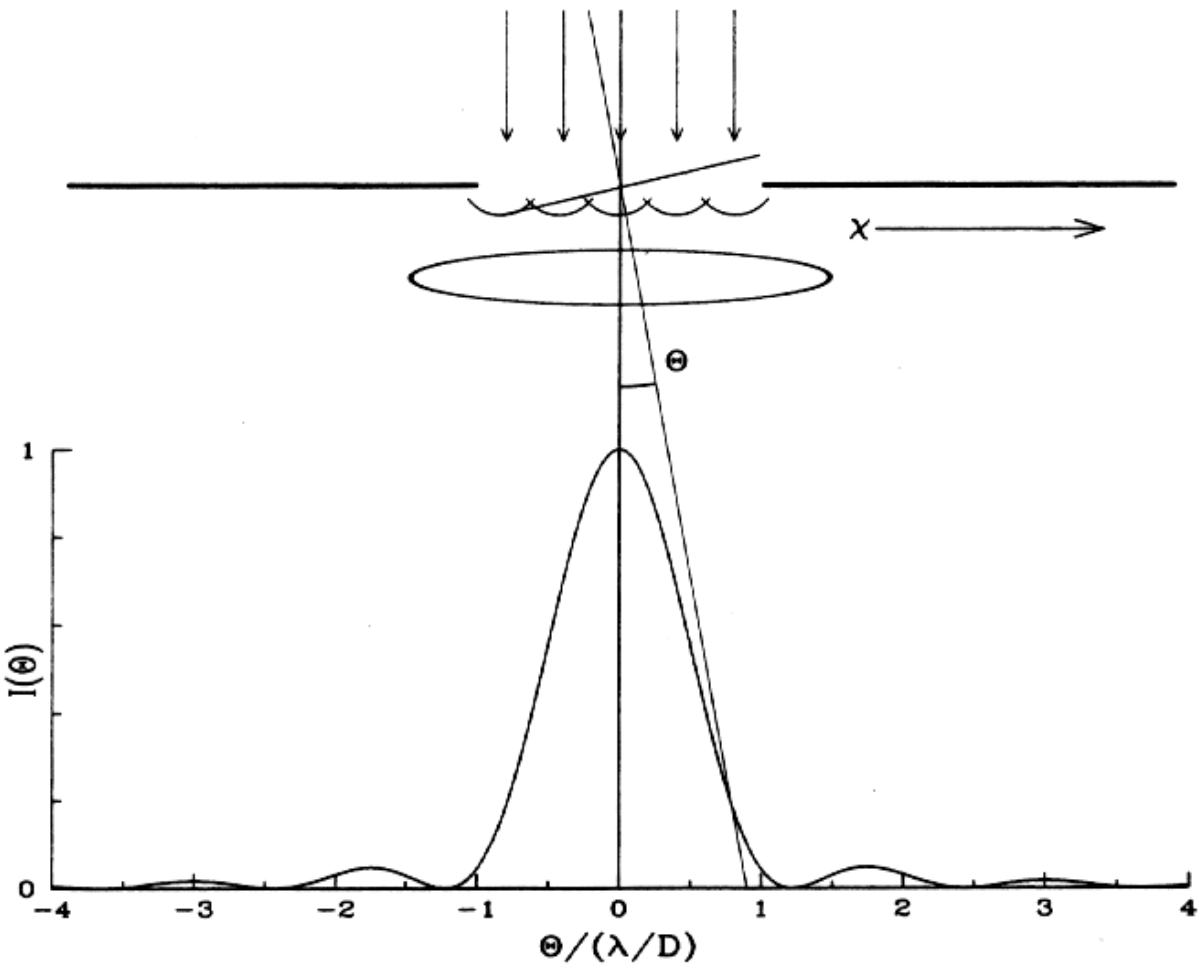


How does interferometry give us high-angular resolution?

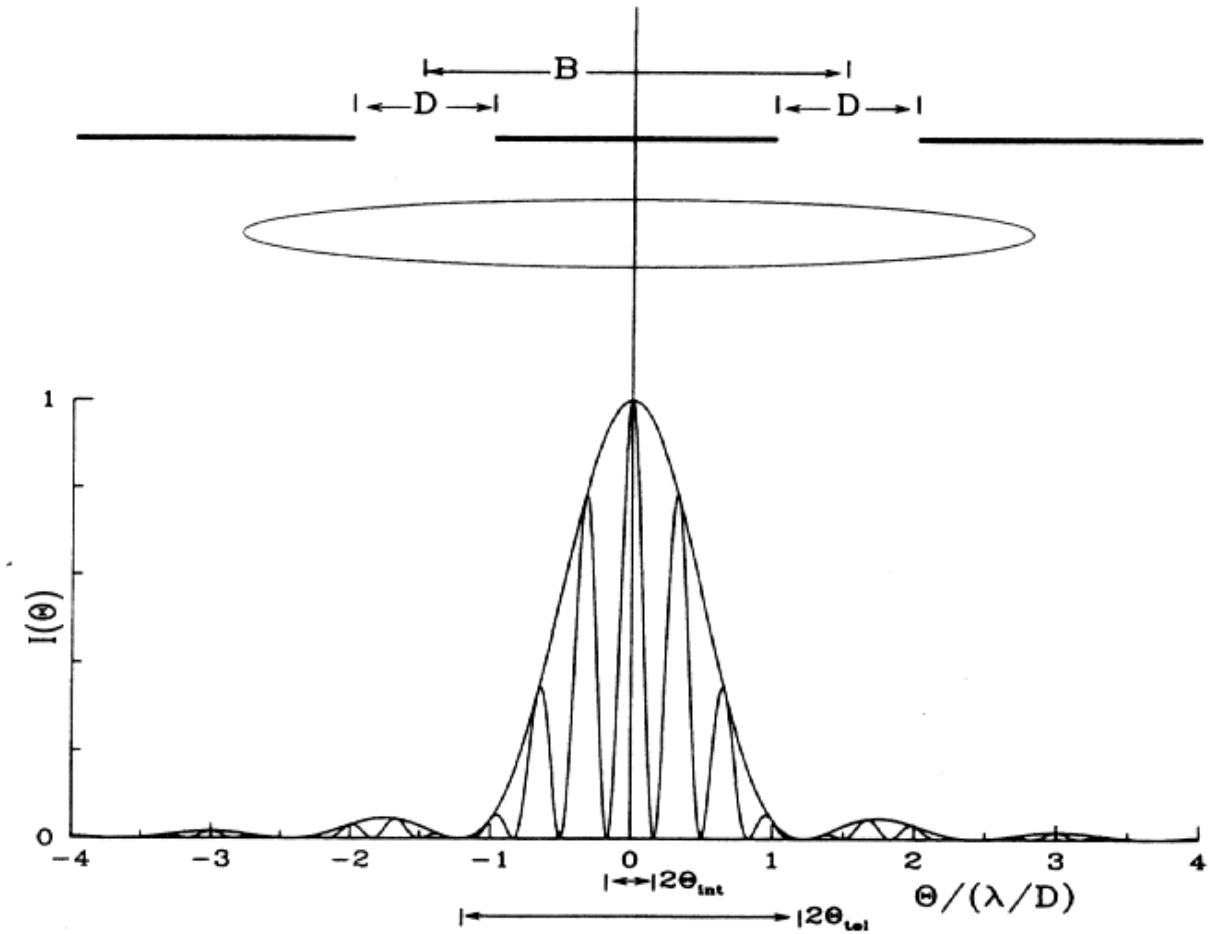


- **Imaging and Astrometry explained.**

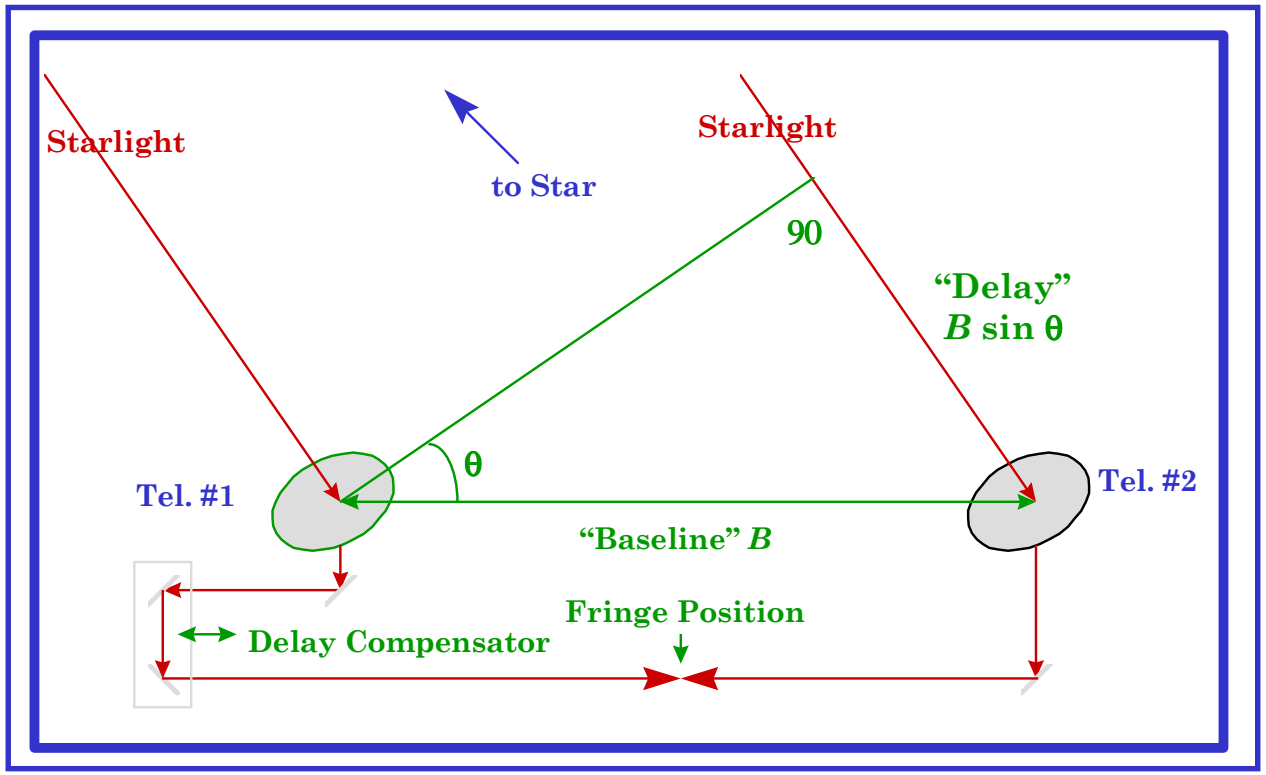
Single Aperture and a Point Source



Two Apertures and a Point Source



"Simple" Long-Baseline Interferometer



Long Baseline Stellar Interferometer

Fringe Equation

$$I(t,\nu) = 1 + V(t,\nu) \times \frac{\sin(\pi\, x(t,\nu)\, \Delta\nu)}{\pi\, x(t,\nu)\, \Delta\nu} \times \cos\left(2\pi\, x(t,\nu)\, \nu + \Phi_{\mathrm{obj}} + \Phi_{\mathrm{atm}}(t)\right)$$

$$V(t,\nu) = V_{\mathrm{obj}} \times \eta_{\mathrm{atm}}(t) \times \eta_{\mathrm{inst}}$$

$$x(t,\nu) = B\cos\left(\theta(t)\right) + x_{\mathrm{vac}}(t) + n_{\mathrm{air}}(\nu) x_{\mathrm{air}}(t) + n_{\mathrm{glass}}(\nu) x_{\mathrm{glass}}(t)$$

Fringe Visibility Defined

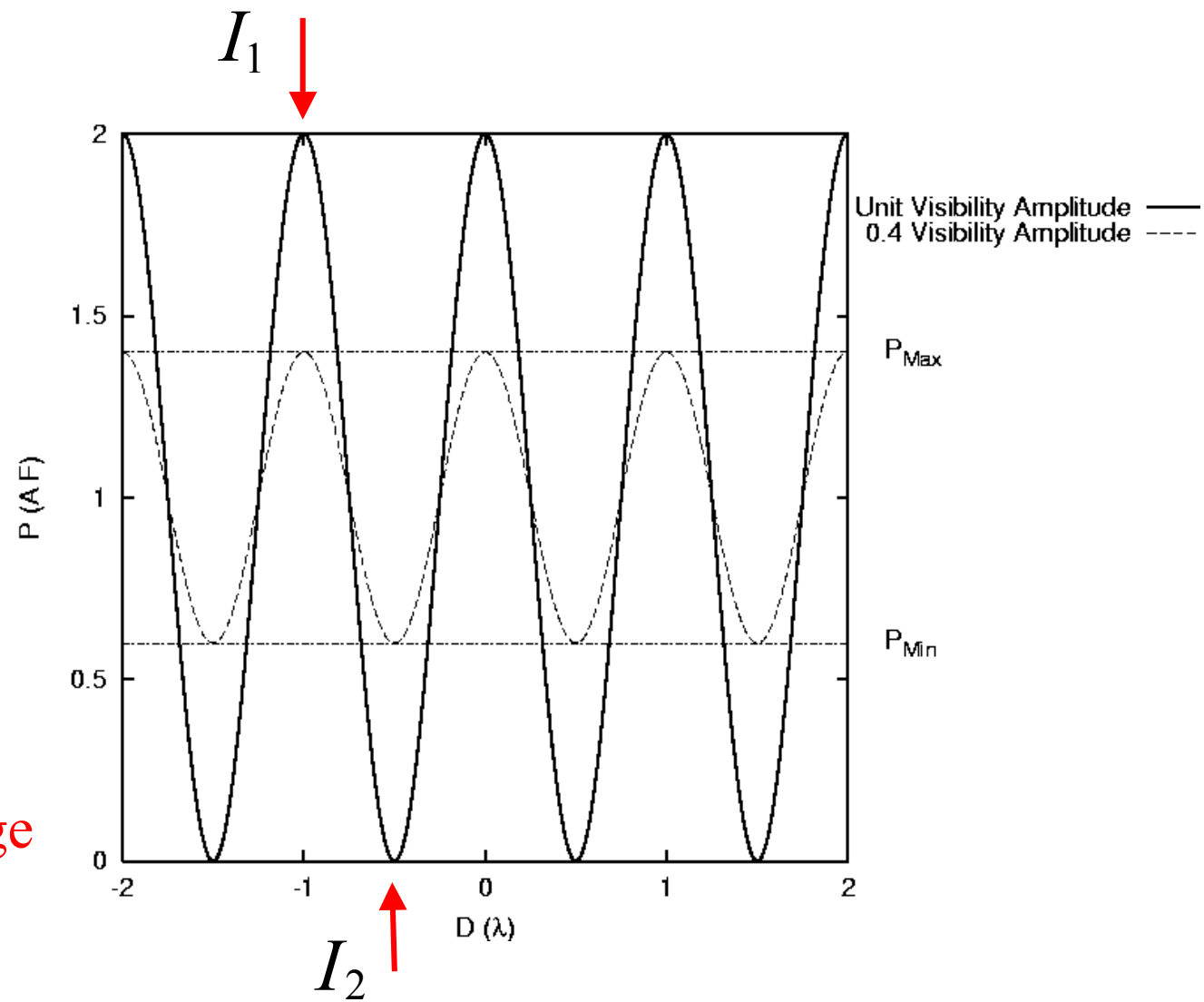
Visibility:

$$V = \frac{I_1 - I_2}{I_1 + I_2}$$

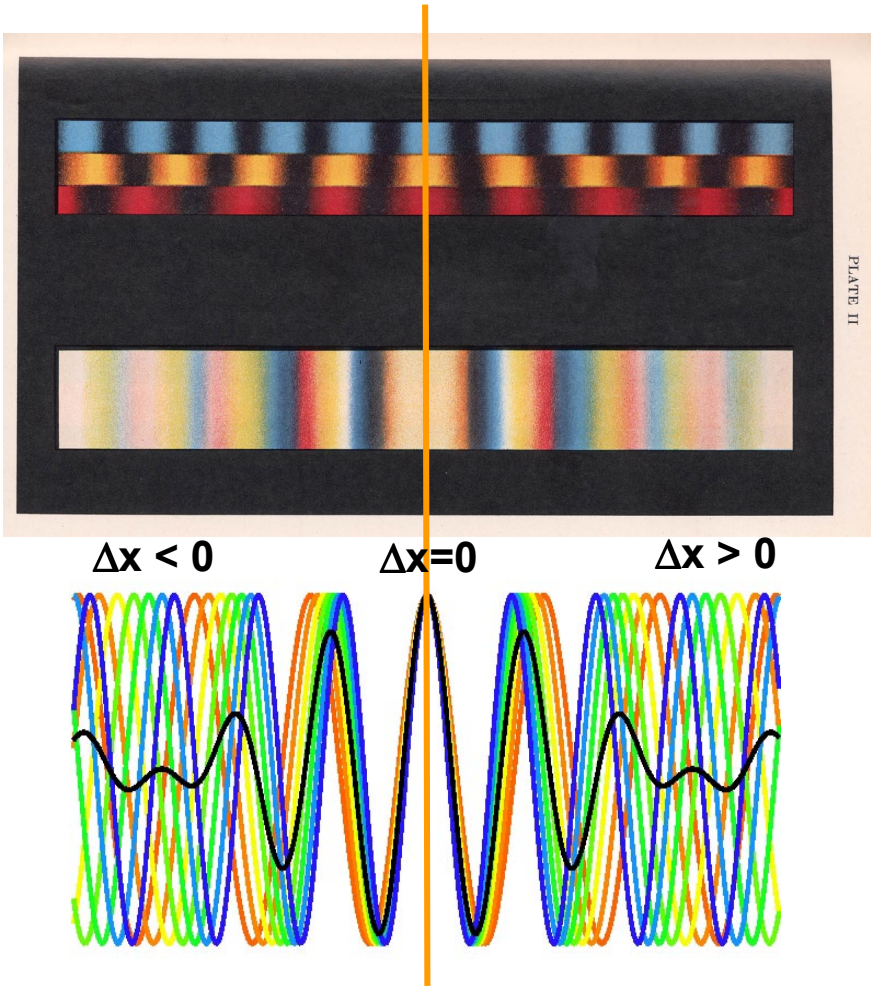
$I_1 =$ bright fringe

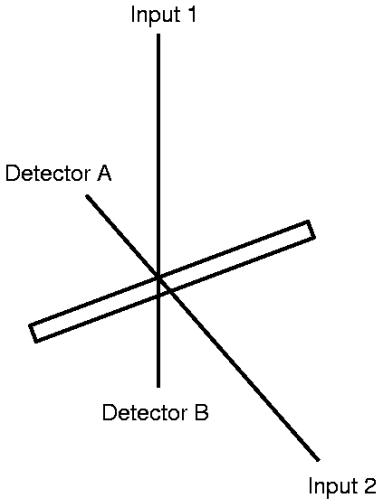
$I_2 =$ dark fringe

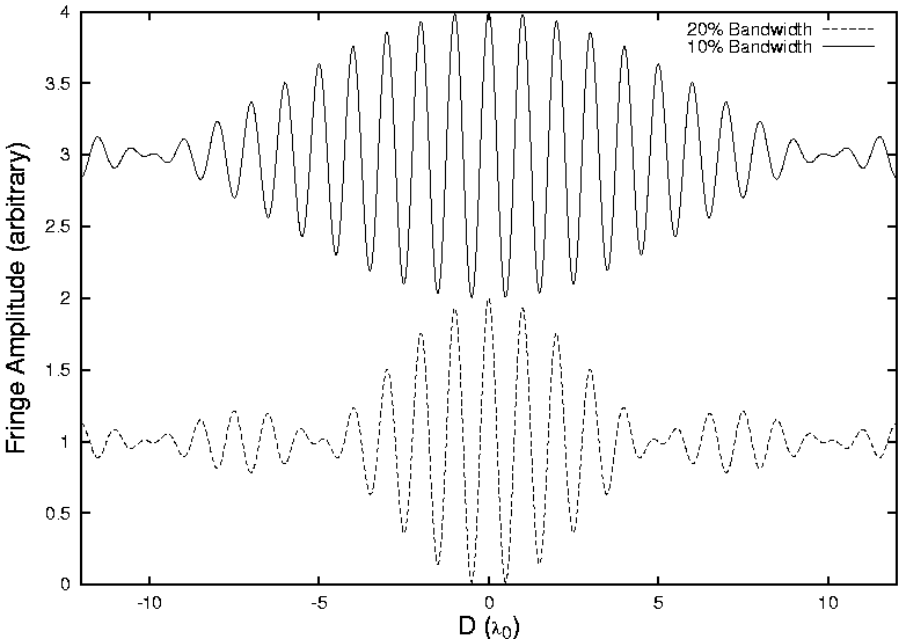
The visibility is a measure of the fringe contrast



Coherence Envelope of Fringe







Delay Lines for Long Baseline Stellar Interferometry

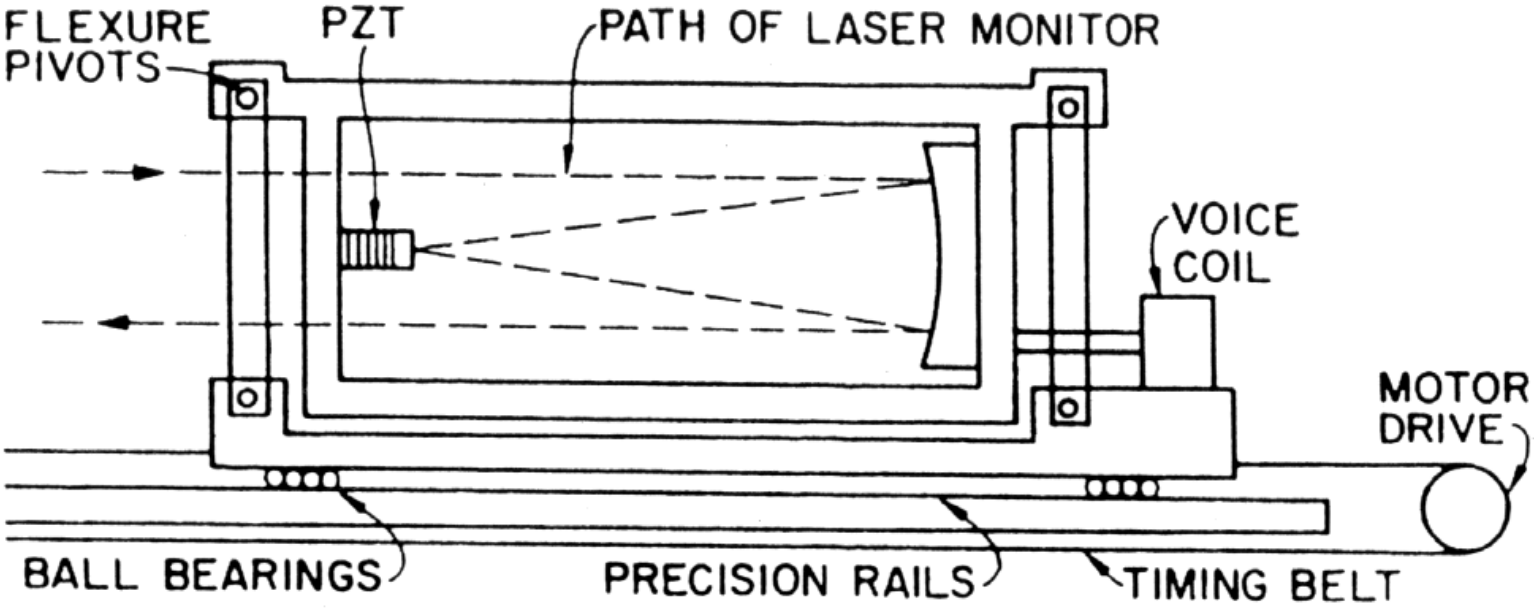
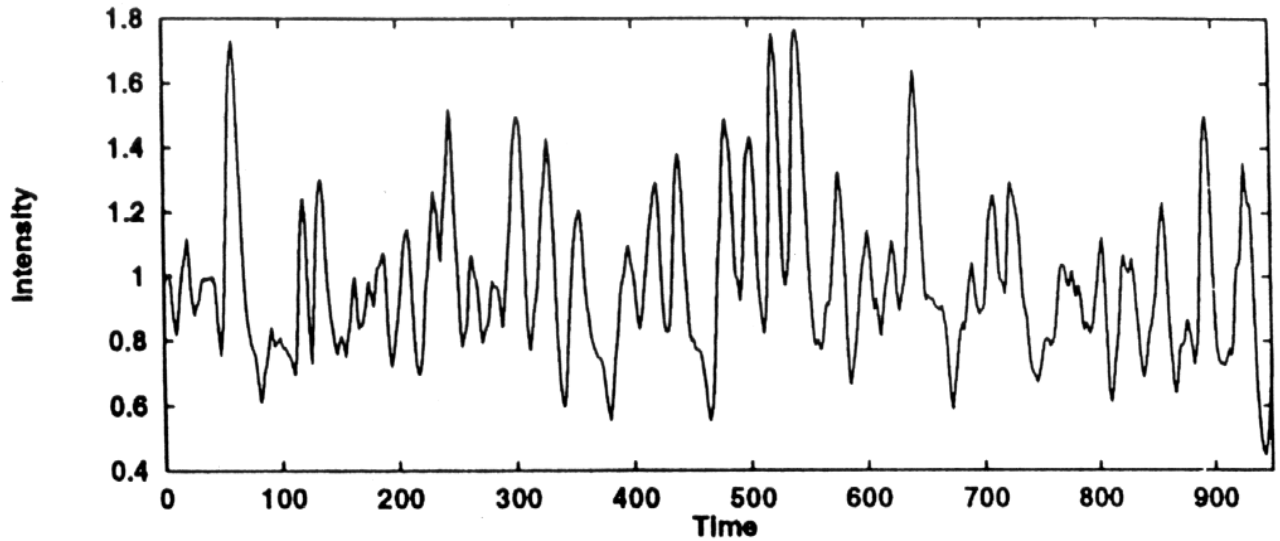


Fig. 4. Three stage (PZT, Voice Coil, Motor) optical delay line

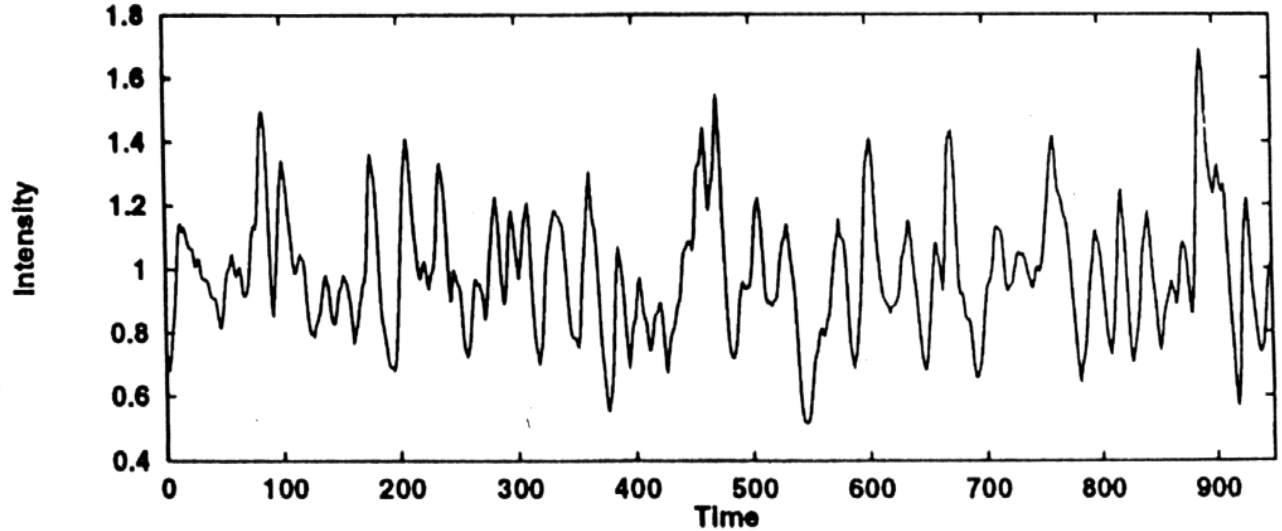
Atmospheric Turbulence: r_0 and t_0

Simulations of Scintillation

Beam 1



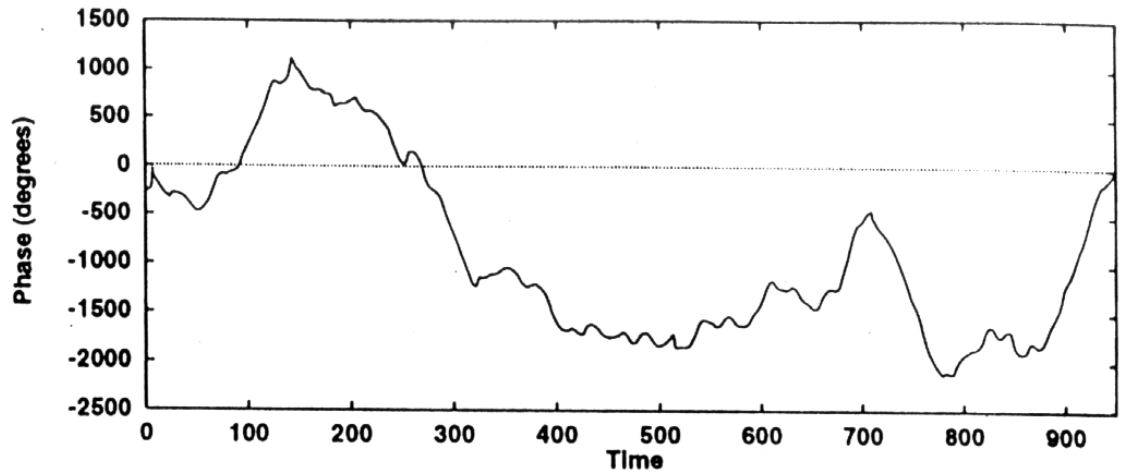
Beam 2



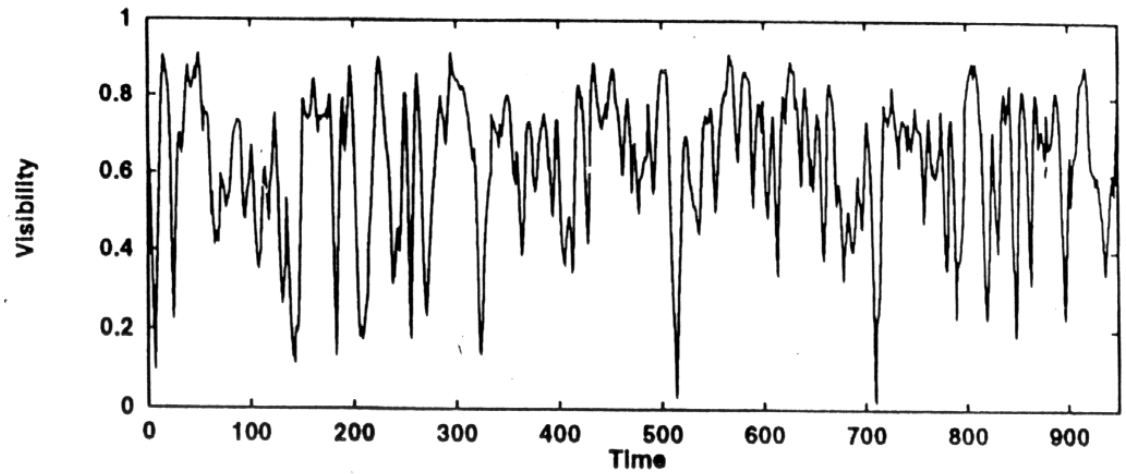
Atmospheric Turbulence (continued)

Simulations

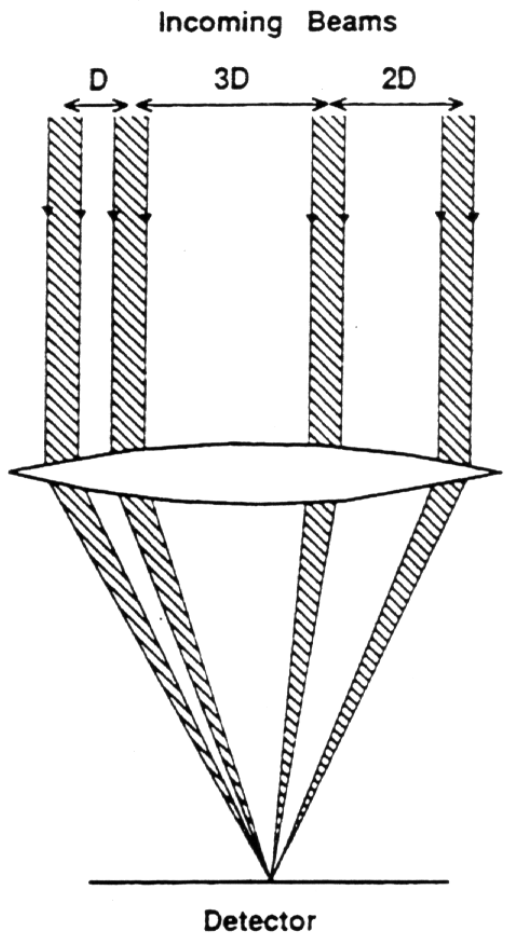
Phase variations



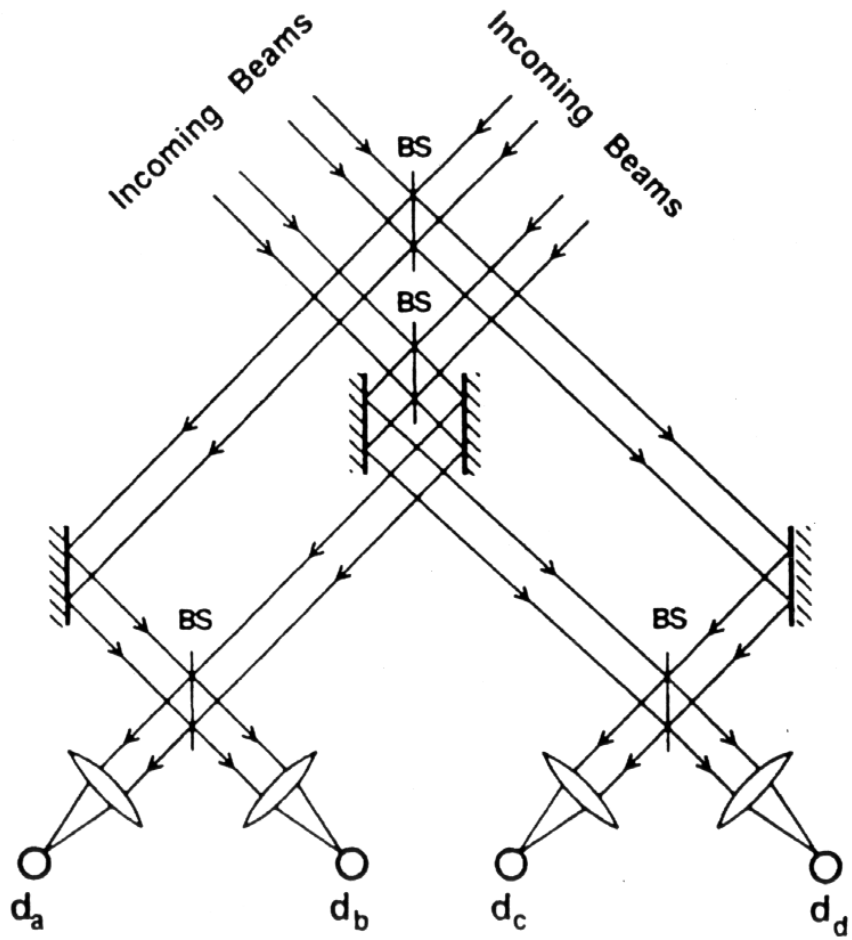
Visibility Fluctuations



Measurement of Fringe Parameters

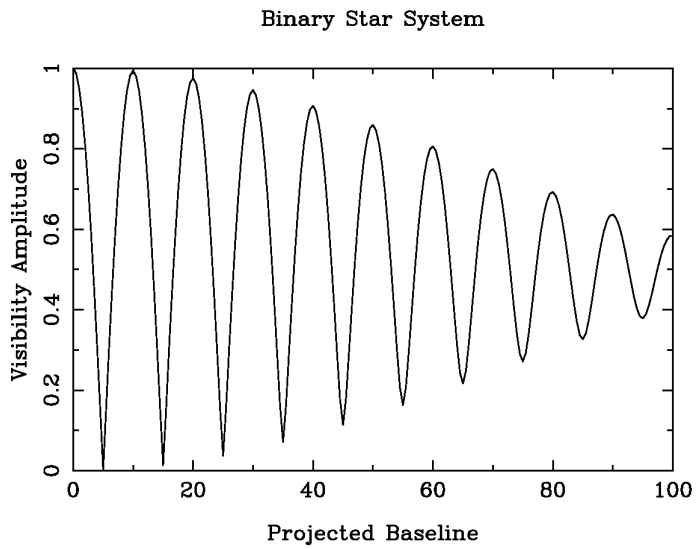


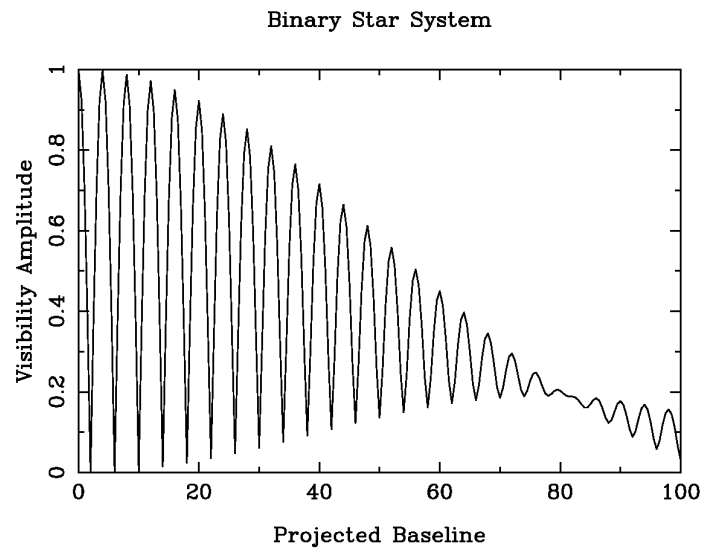
Spatial Modulation



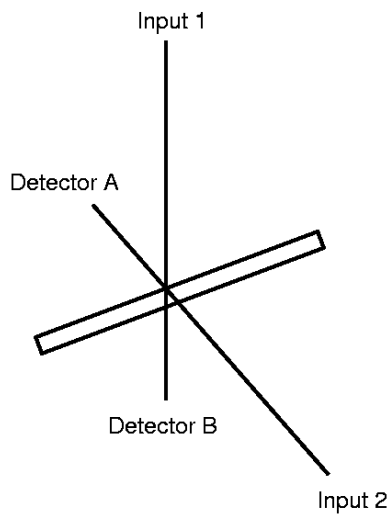
Temporal Modulation

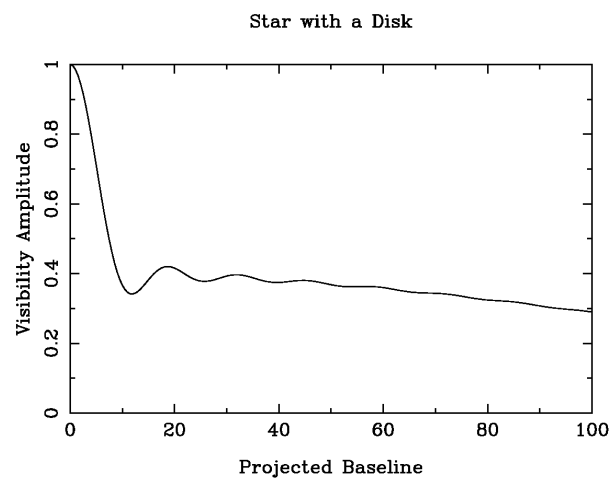
Sources with High Visibility



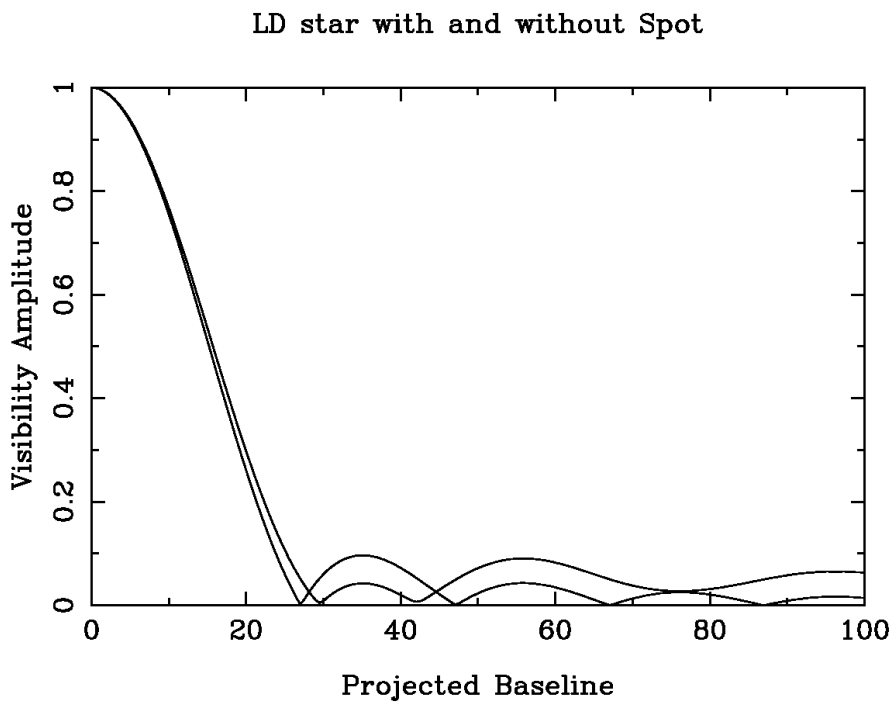


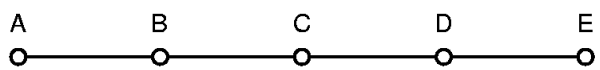
Two-input
beam combiner



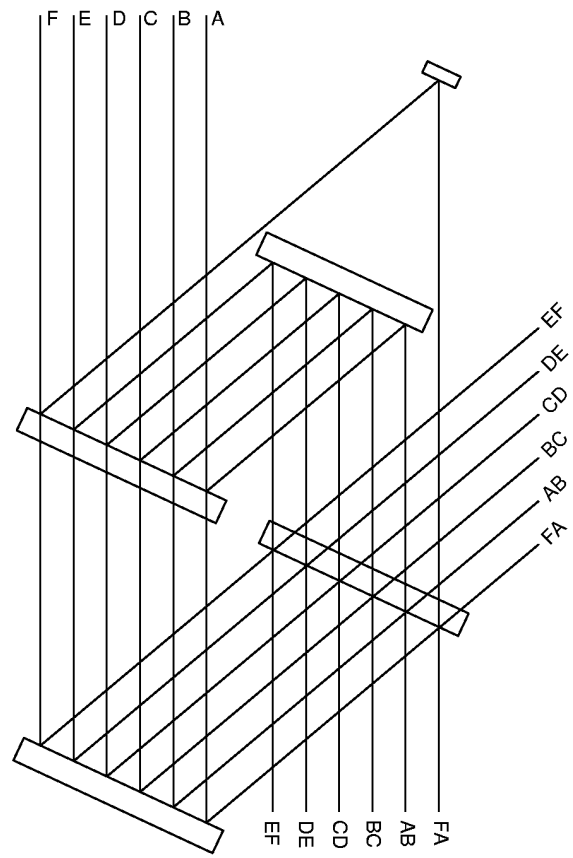


Detecting Fine-Scale Stellar Structure



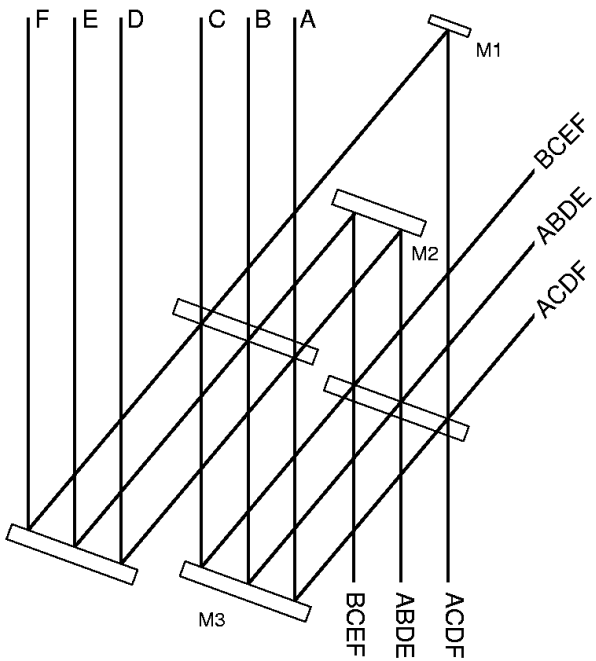


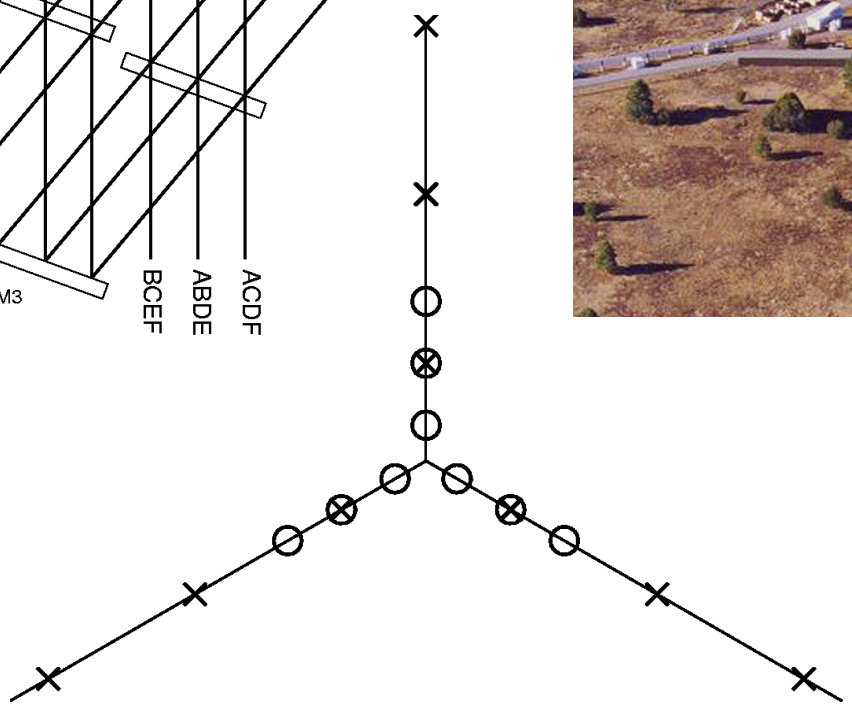
Baseline "bootstrapping"

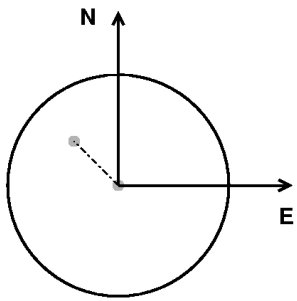


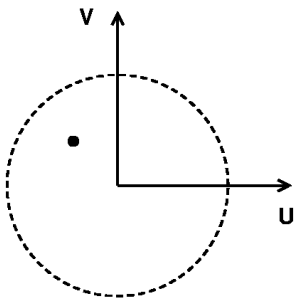
Partial pairwise beam combiner

Beam Combination for Synthesis Imaging

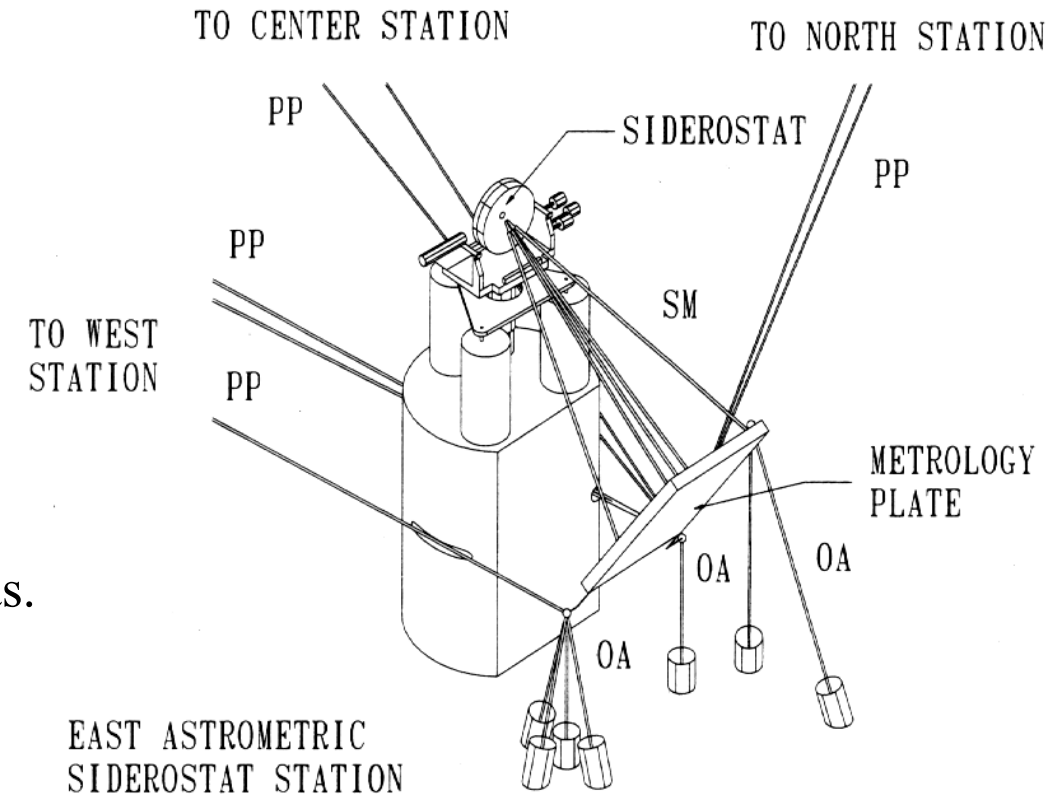






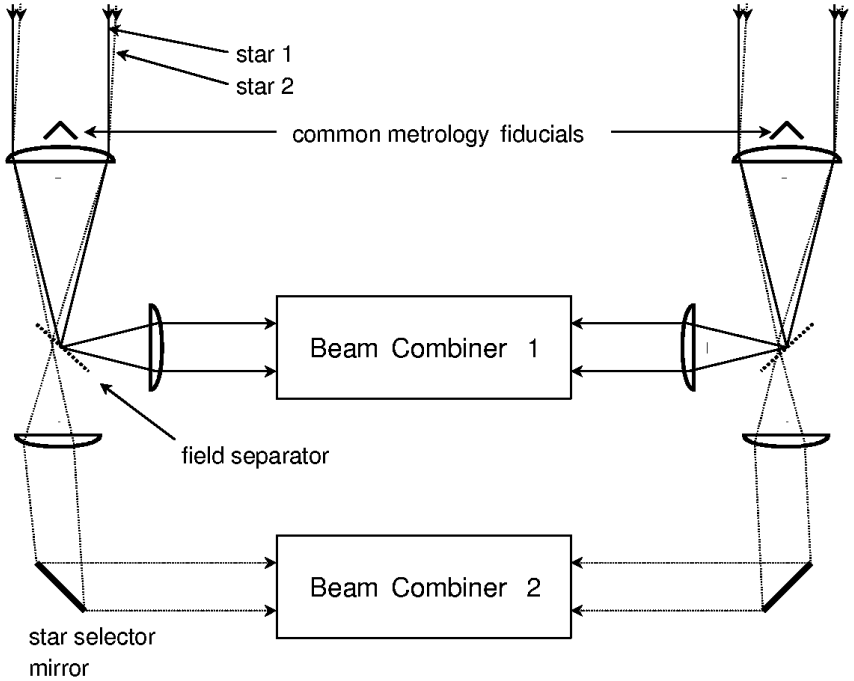


Wide-Angle Astrometry



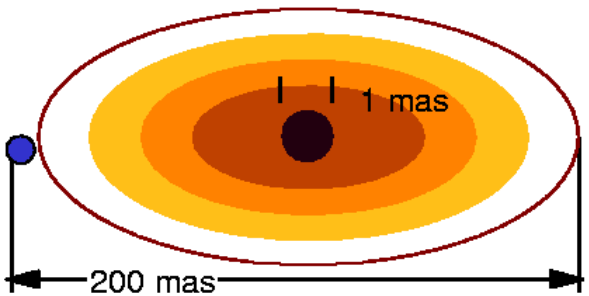
- Catalog of ~1000 Hipparcos stars with internal accuracy of 1 - 3 mas.
- Update and correct for rotation in Hipparcos reference frame.

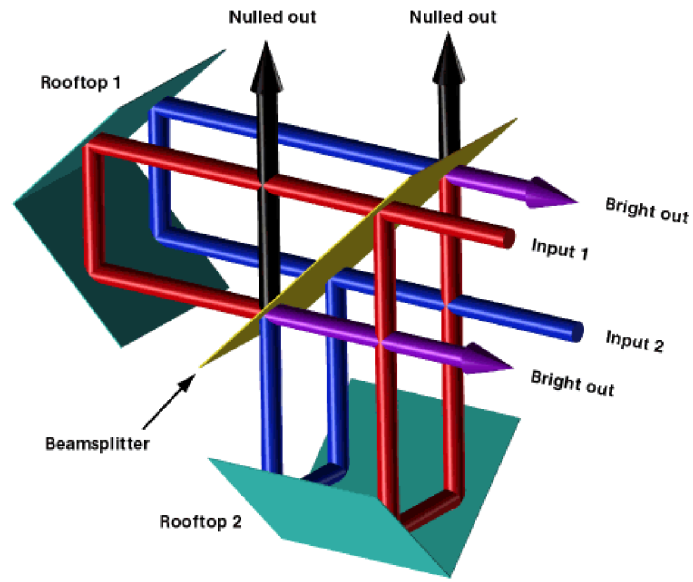
Narrow Angle Astrometry

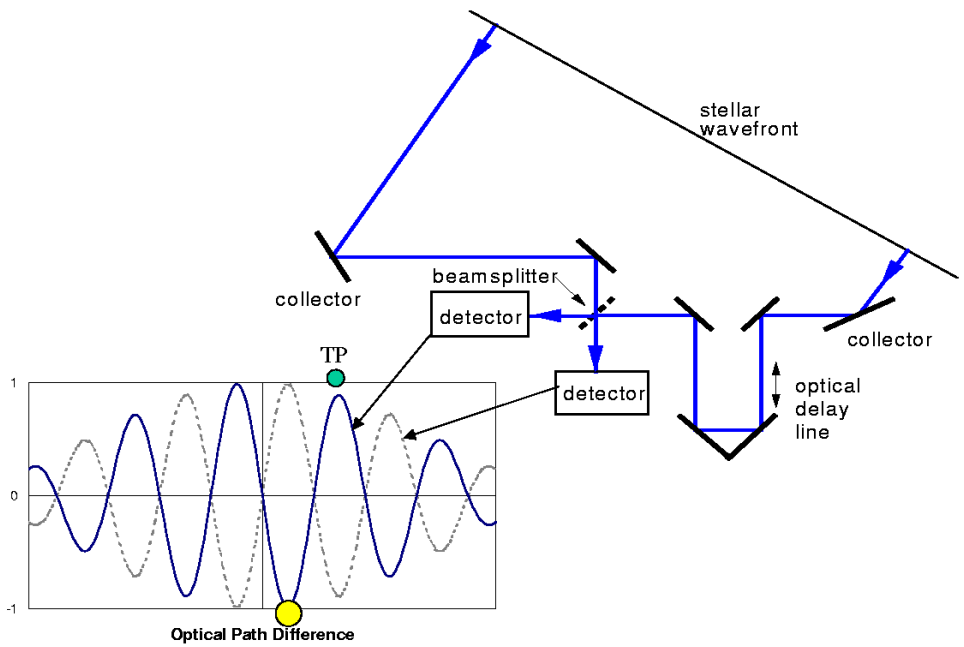


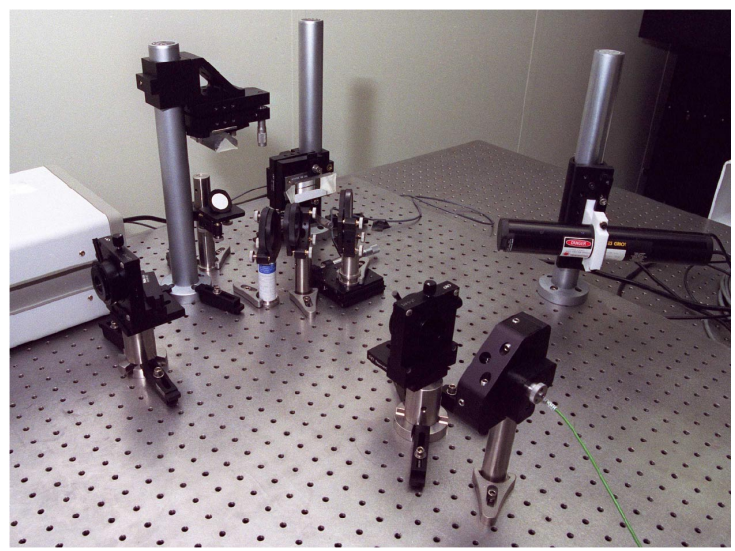
- Planet detection: "Jupiter" at 10 pc produces a 1 mas peak-to-peak star wobble.
- 20 μas astrometry possible from the ground over narrow angles.

Nulling Interferometry





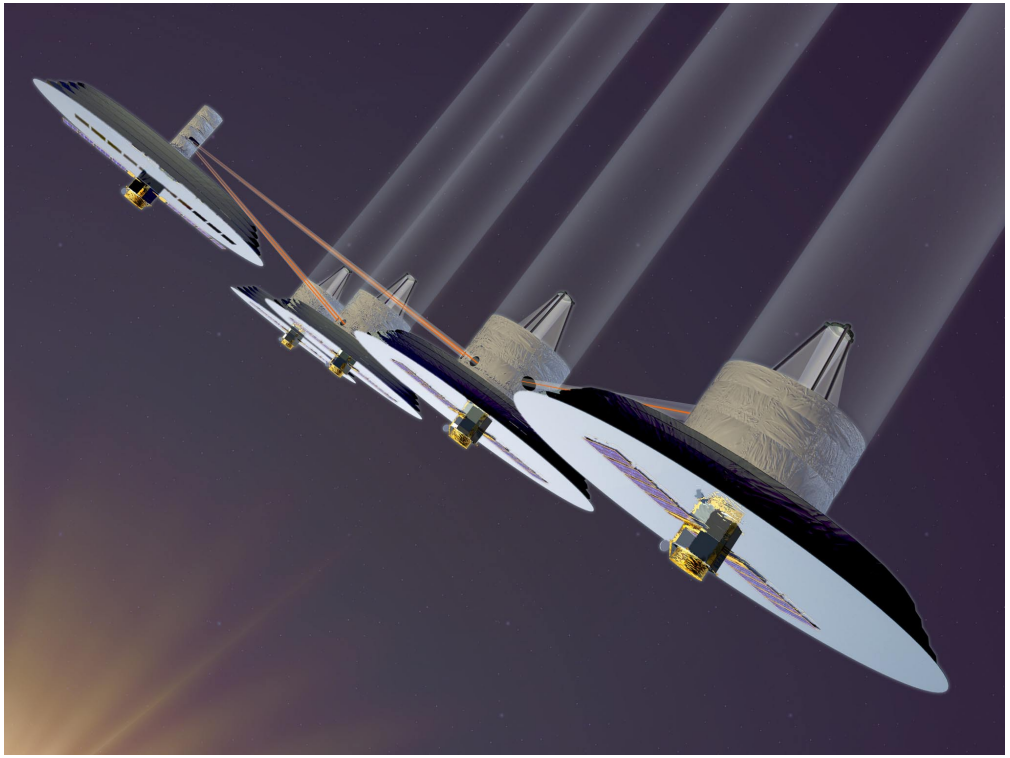




Space Interferometry Mission (SIM)

Wide angle astrometric accuracy	4 μas (5 yr)
Narrow angle astrometic accuracy	1 μas (1 hr)
Instrument field of regard	15 degrees
Instrument throughput (V=16 star)	5.8 μas (10 min)
Synthesis Imaging Resolution	10 mas
Nulling Depth	10^{-4}

Terrestrial Planet Finder (TPF)

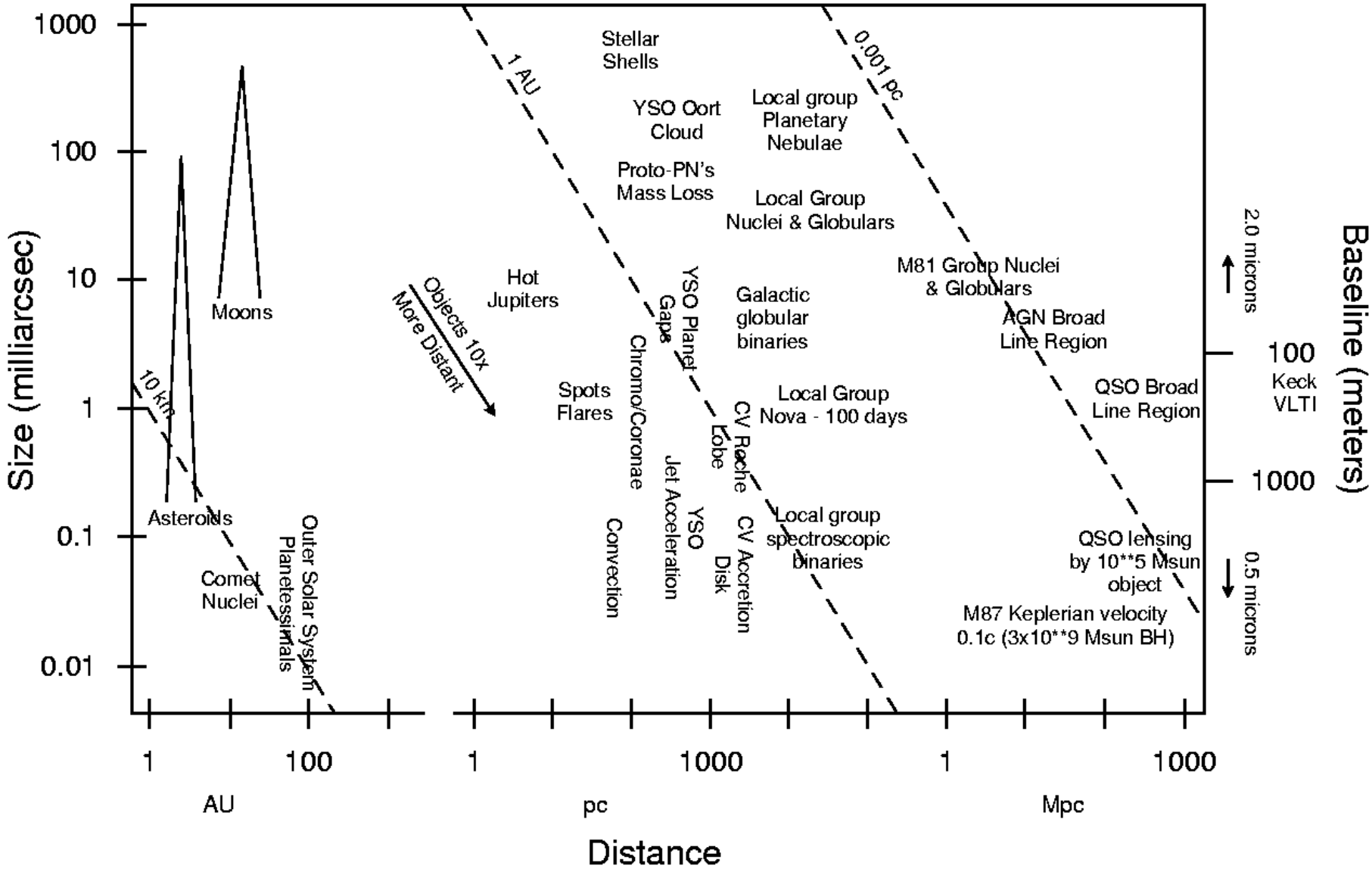


Characterize ~150 planets within 10 pc
Wavelength range: 3 - 20 microns
Baselines 75 - 1000 m
Launch 2011

Infrared Very Large Array (IRVLA)

Large baseline	1000 m
Many telescopes	27
Large unit telescope apertures	3-4 m
Adaptive optics equipped	Curvature sensing based
Dual beam operation	Similar to PTI/Keck
Reconfigurable	Telescopes on rails
Dedicated facility	
Multi-national collaboration	

Interferometry and Stellar Interferometers

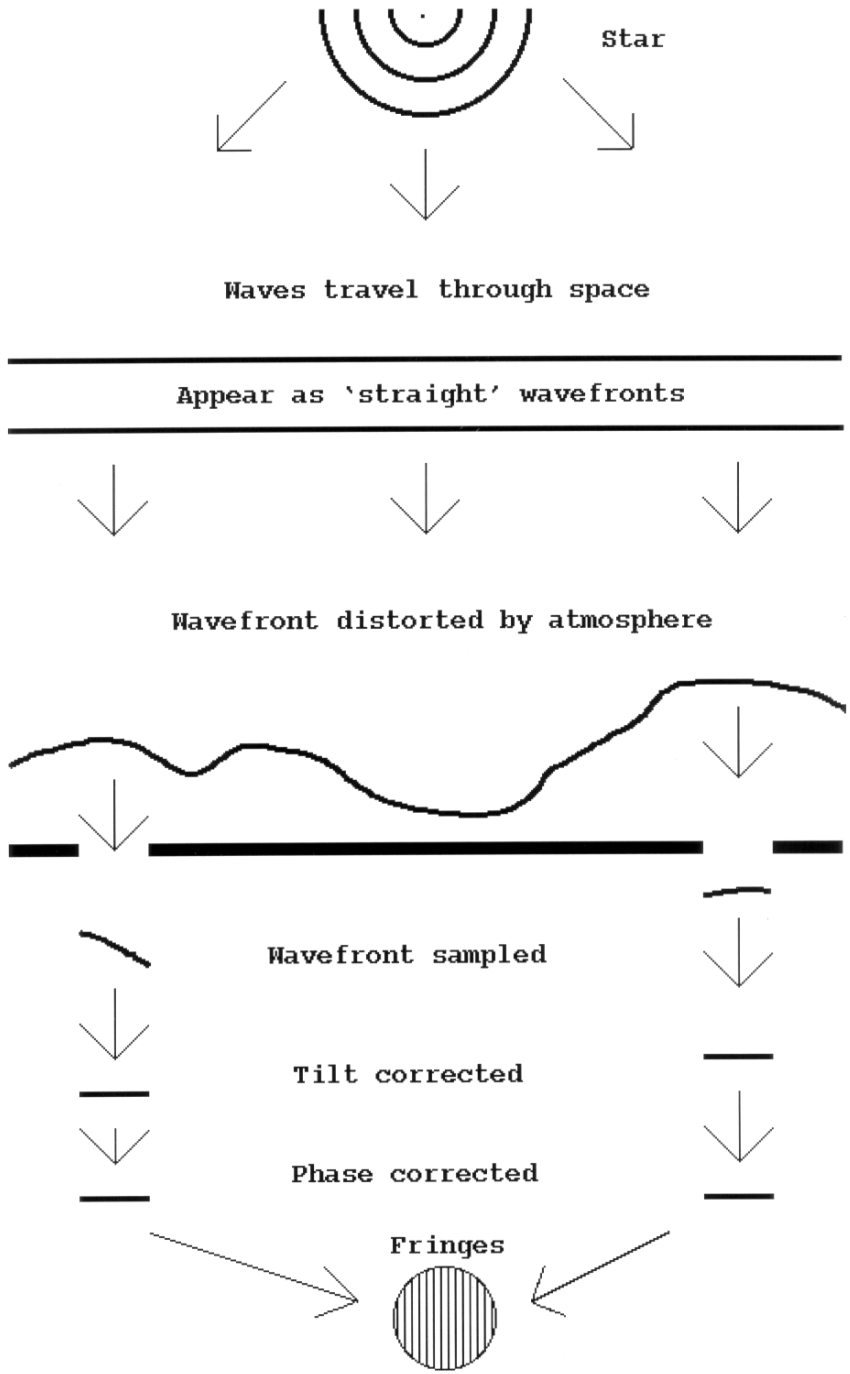


Interferometry Science
In Perspective

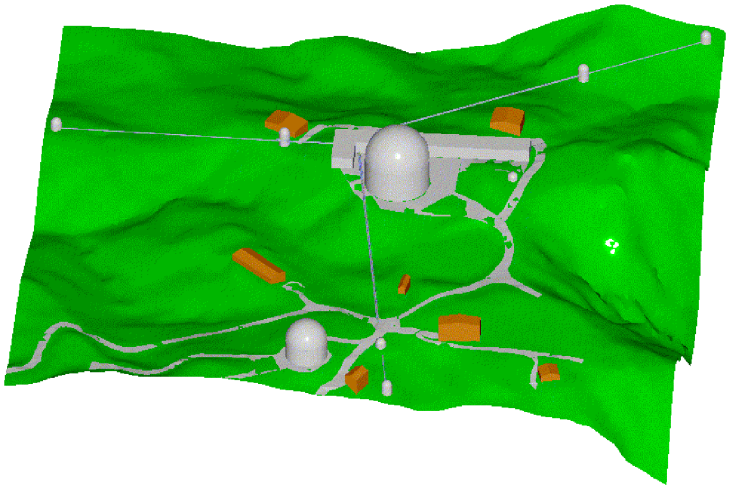
- **Presently Sensitivity Limited**
  - **Low Throughput is Inevitable**
  - **Adaptive Optics May Help**
- **Stellar Stellar Science**
- **Little or No Extragalactic Science**

Current Ground-Based Interferometers

Name	Institution	Site	Number of Elements	Element Aperture (cm)	Max. Baseline (m)	Operating Wavelength (microns)	Operating Status
GI2T	CERGA	Calern	2	150	35	0.4 - 0.8 & >1.2	since 1985
COAST	Cambridge U	Cambridge	4	40	100	0.4 - 0.95 & 2.2	since 1991
SUSI	Sydney U	Narrabri	13	14	640	0.4 - 0.66	since 1991
IOTA	CfA	Mt. Hopkins	3	45	38	0.5 - 2.2	since 1993
ISI	Berkeley U	Mt. Wilson	3	165	30(+)	10	since 1990
NPOI	USNO/NRL	Anderson Mesa	6	60	435	0.45 - 0.85	since 1995
PTI	JPL/Caltech	Mt. Palomar	2	40	110	1.5 - 2.4	since 1995
CHARA	Georgia St. U	Mt. Wilson	6	100	350	0.45 - 2.4	initial 1999
Keck	CARA	Mauna Kea	2(4)	1,000(150)	165	2.2 - 10	initial 2001?
VLTI	ESO	Cerro Paranal	4(3)	840(250)	200	0.45-12	initial ??

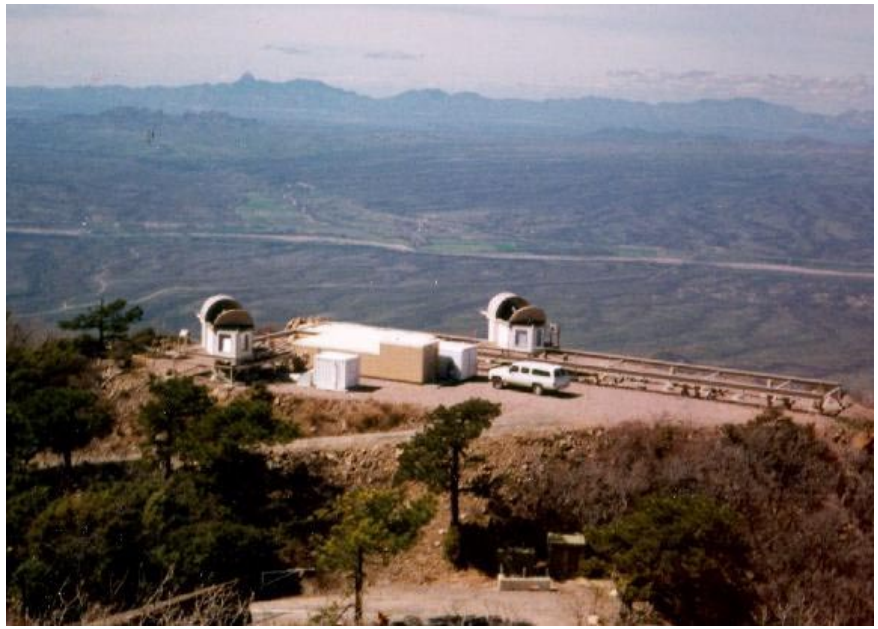

Star
Waves travel through space
Appear as 'straight' wavefronts
Wavefront distorted by atmosphere
Wavefront sampled
Tilt corrected
Phase corrected
Fringes

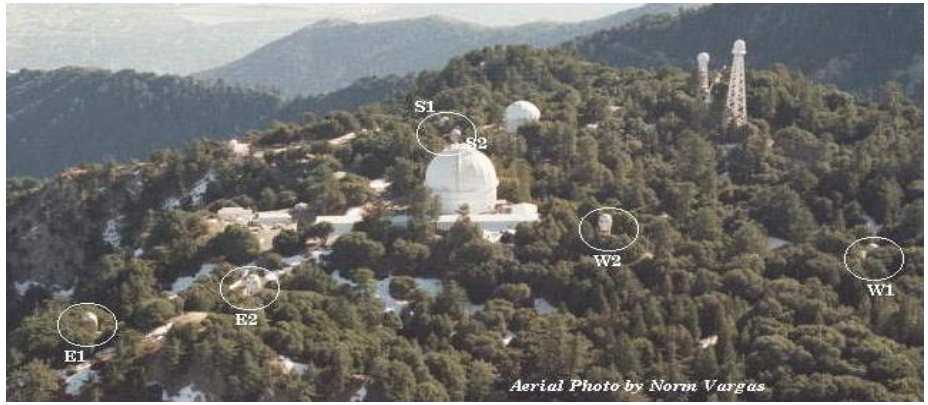
Interferometers tend to all look very similar



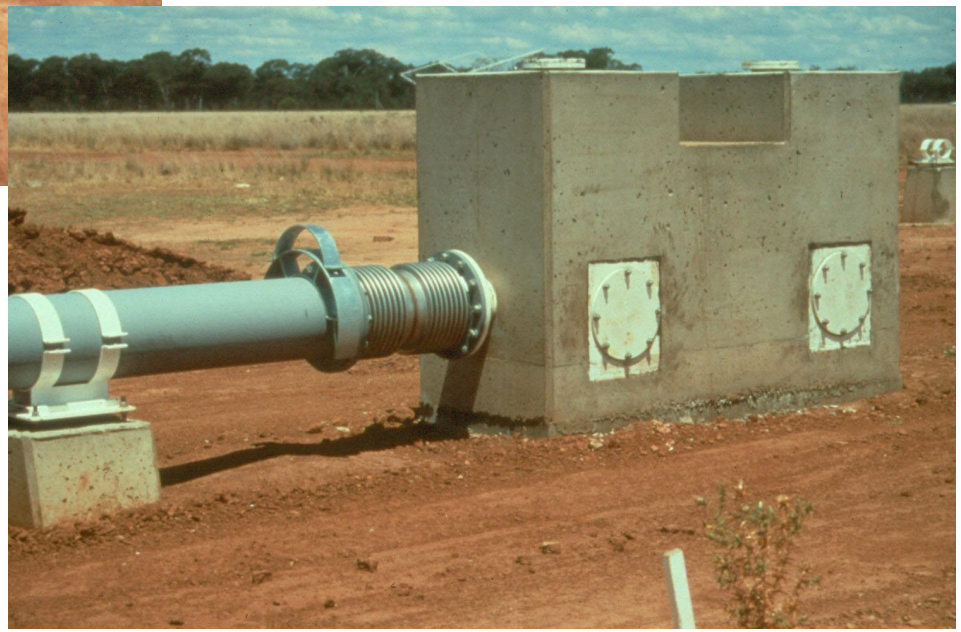
...usually located at an existing facility

…not always a flat site, but often large



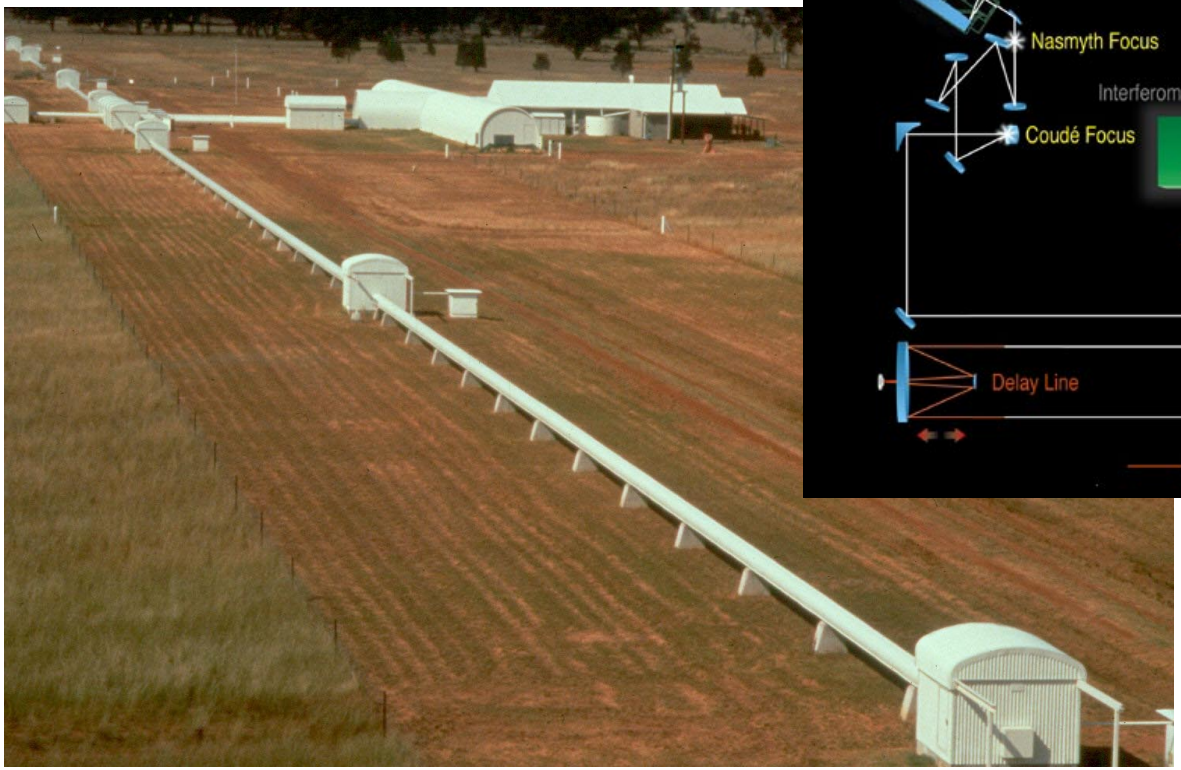


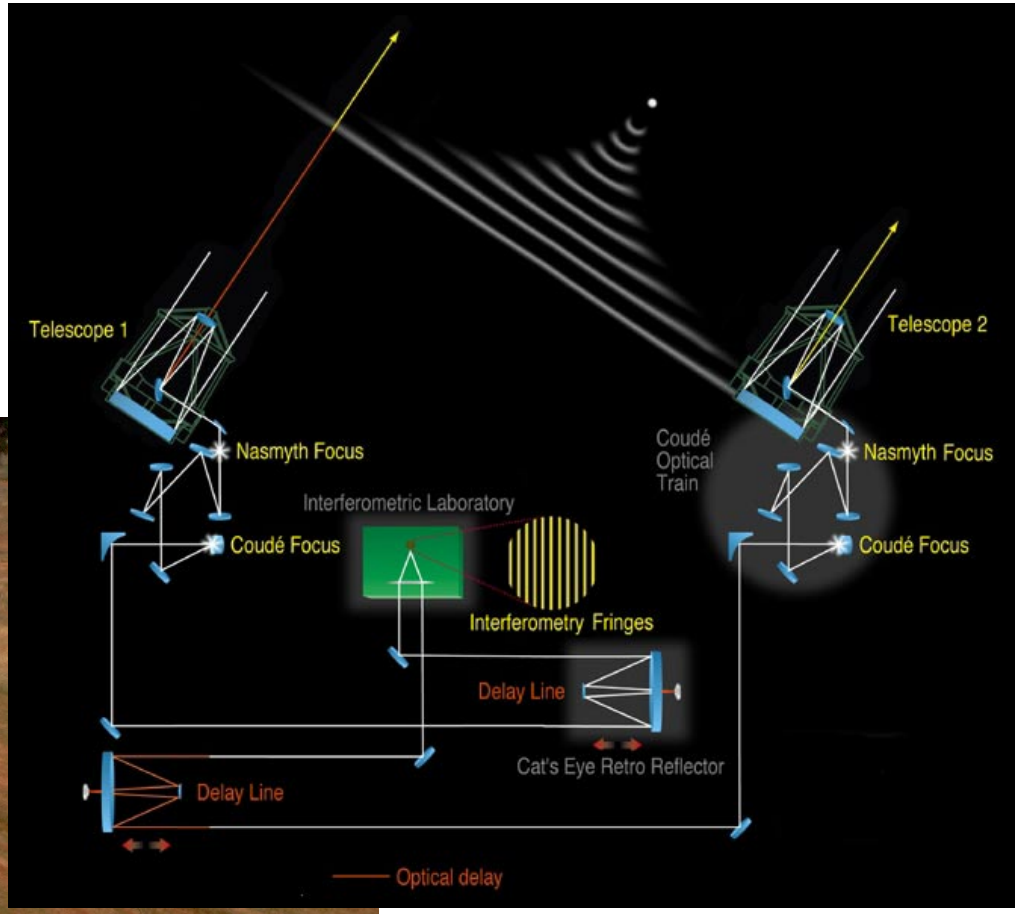
Lots of reinforced concrete required...



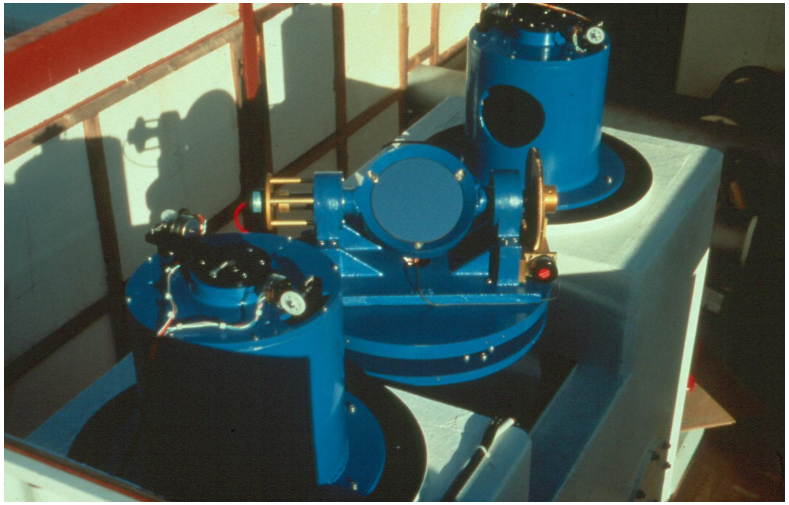
... and steel, of course

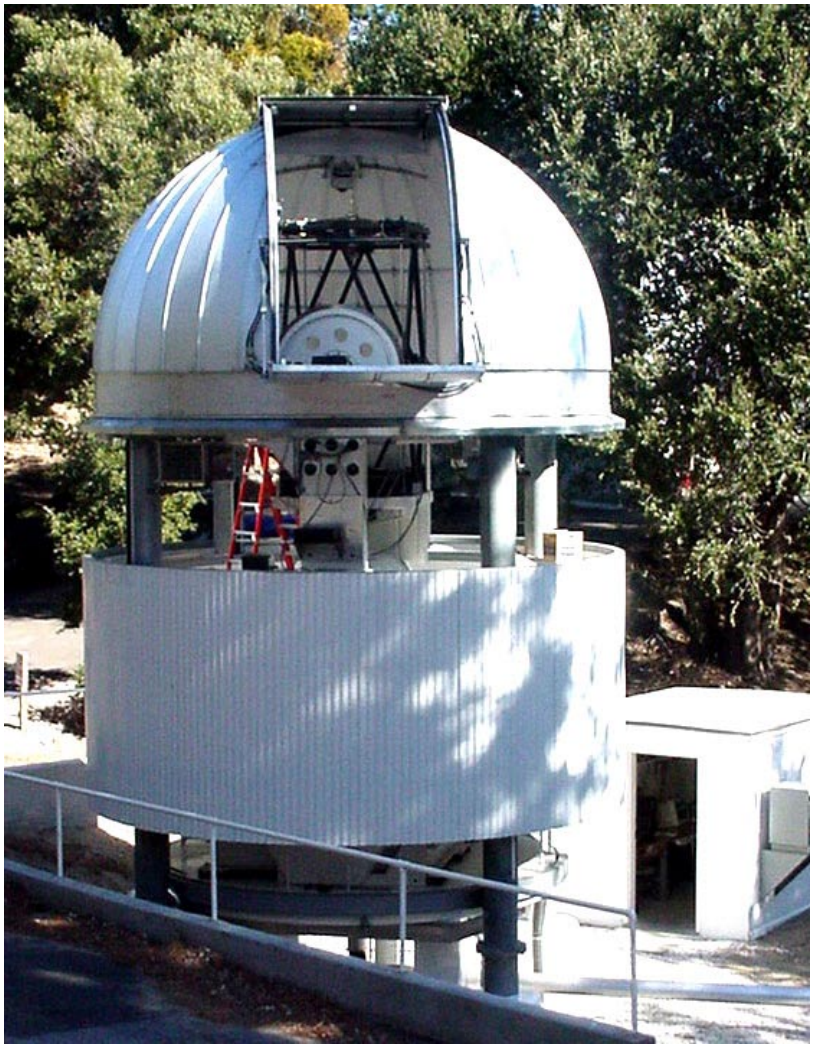
Interferometry and Stellar Interferometers



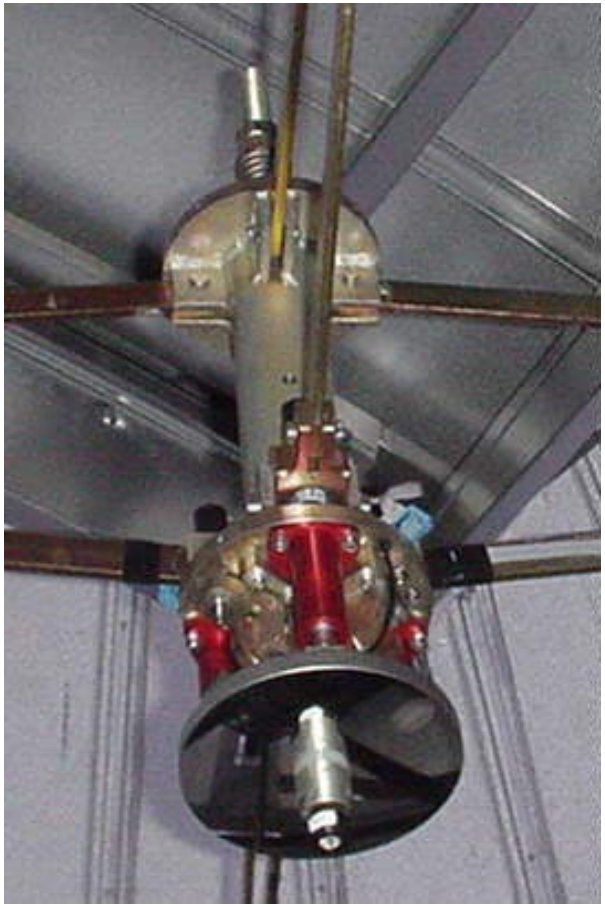


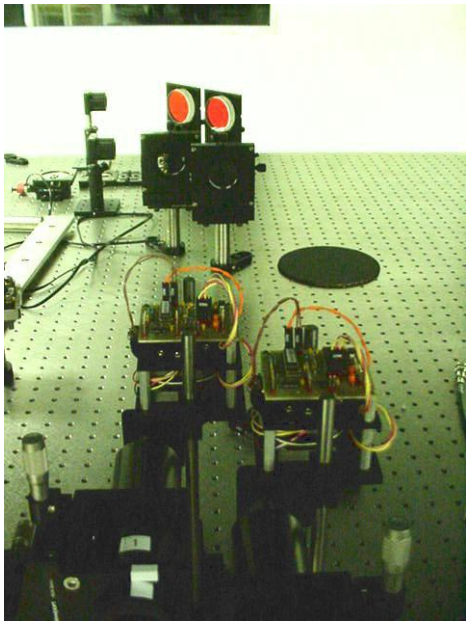
The light must get in…

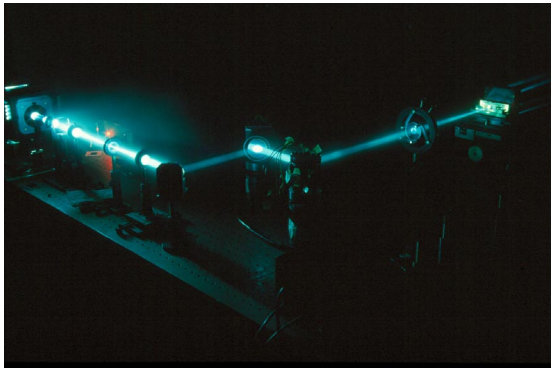


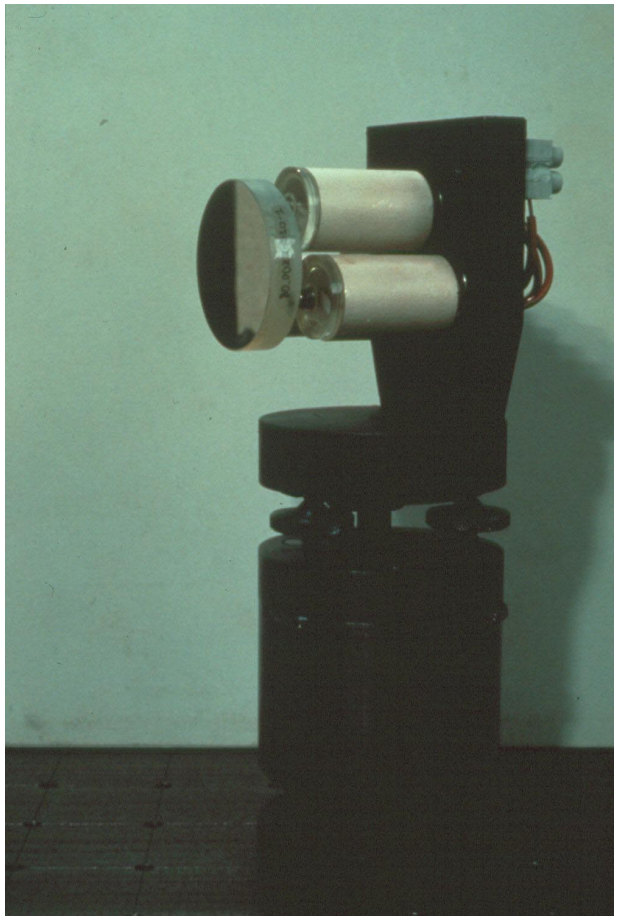


… be stable

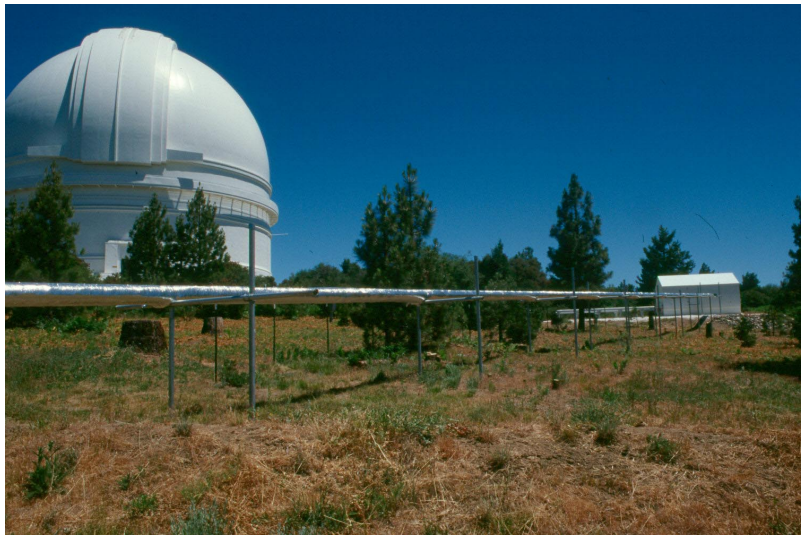








… and make it to the central facility

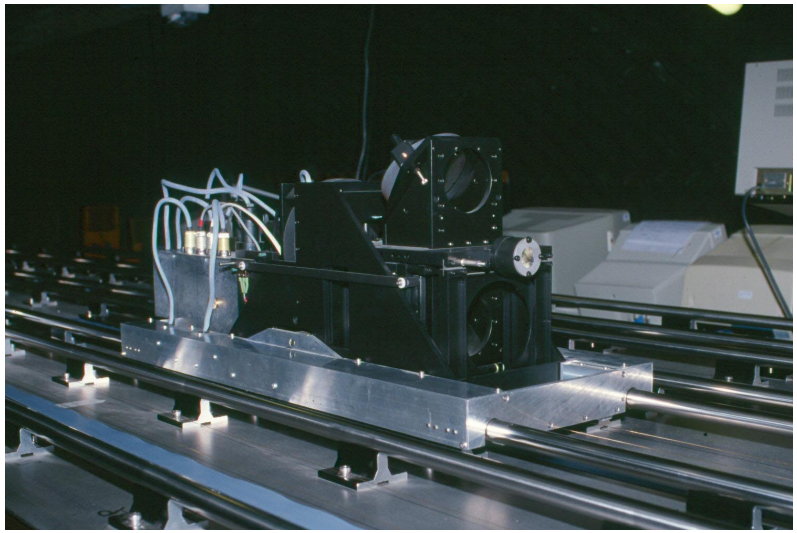


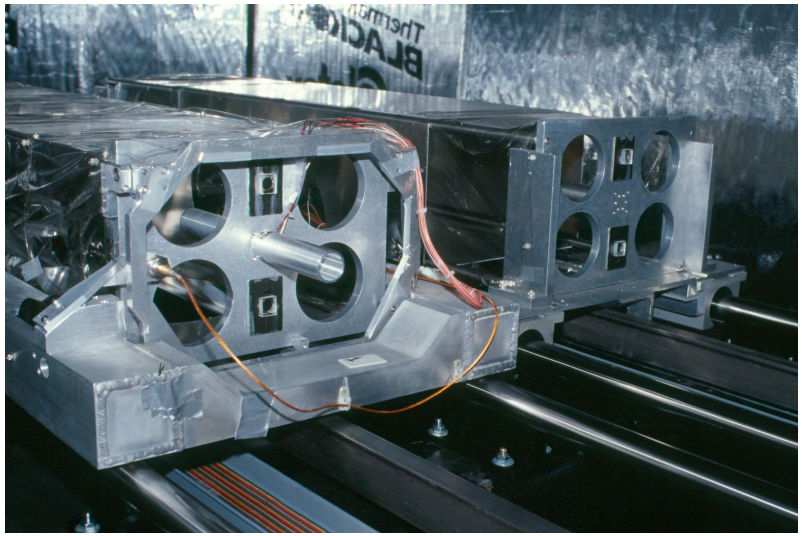
The instruments need enclosing … (not buildings)

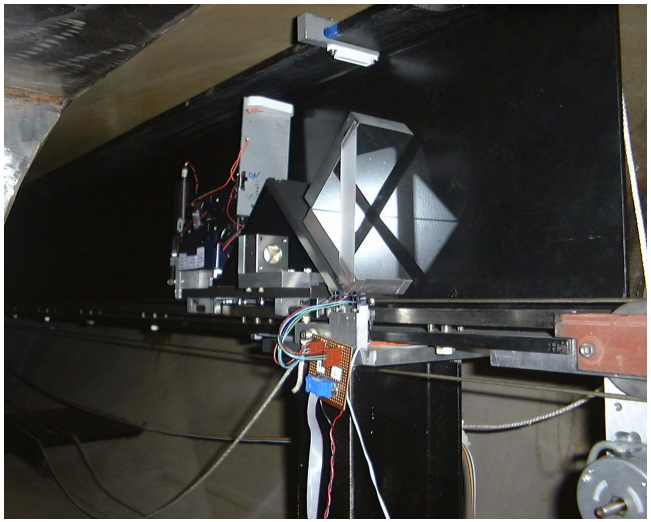
… and thermal stability.

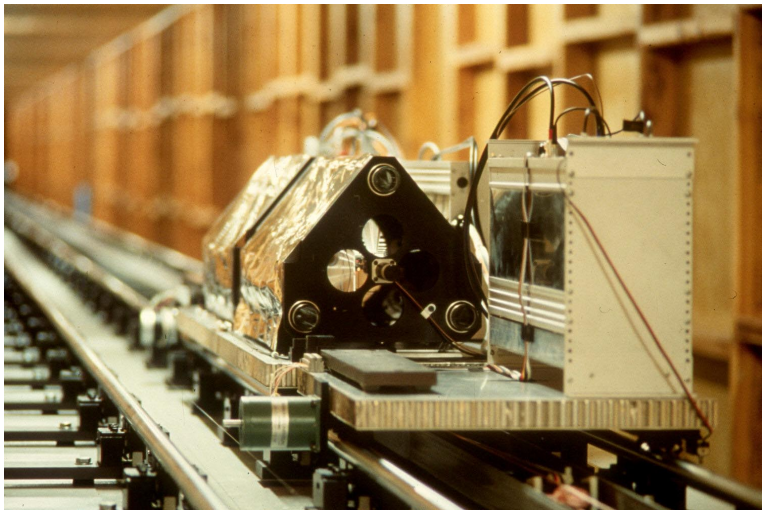
Delay lines sit on rails…

… and delay the light

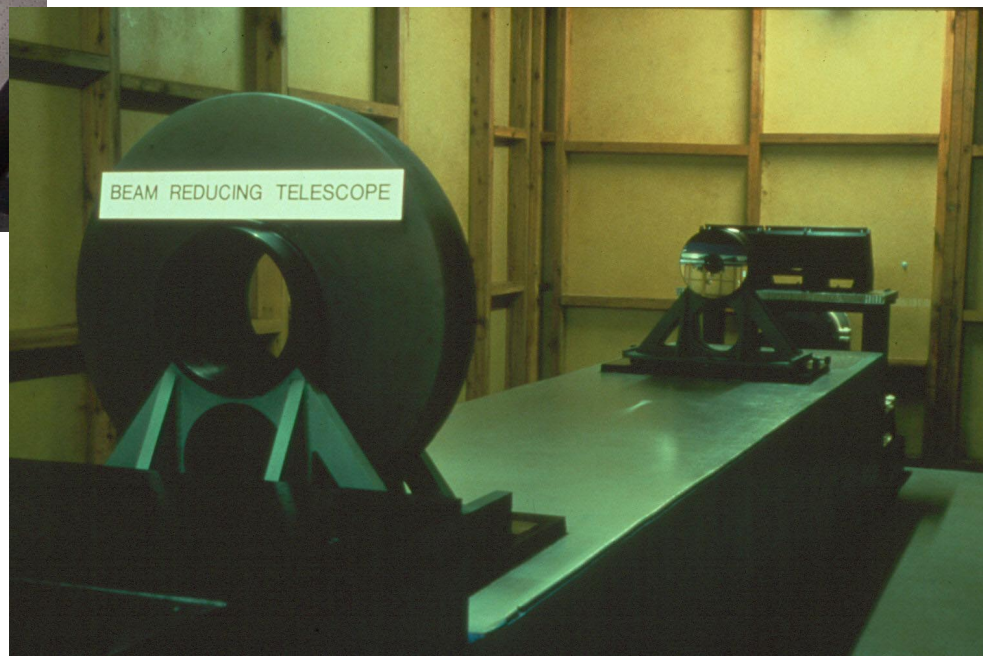




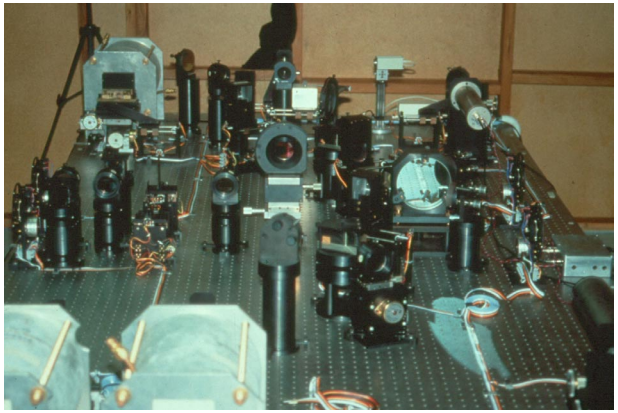


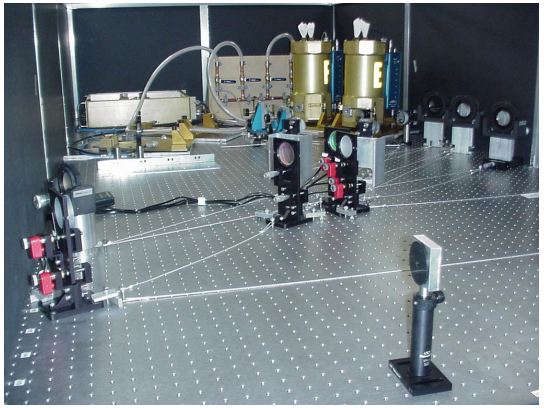


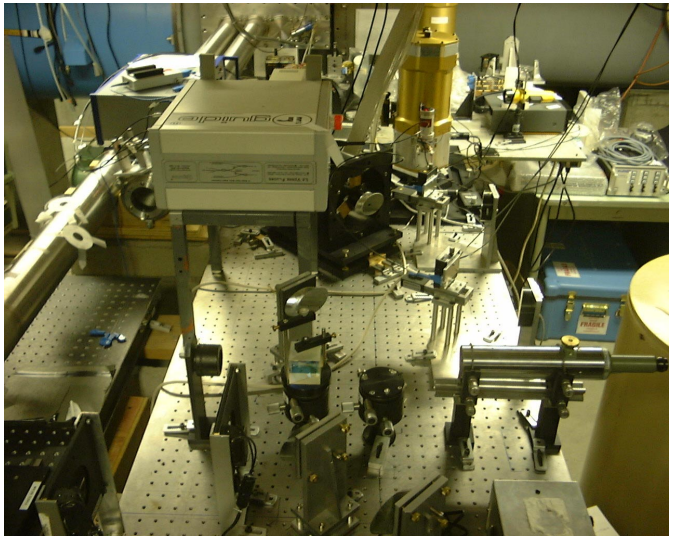
Beams need to be the right size…



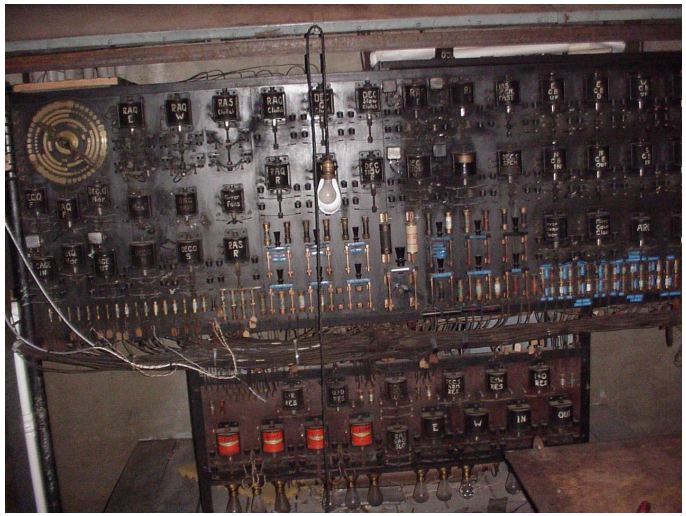
…and combined with other beams.

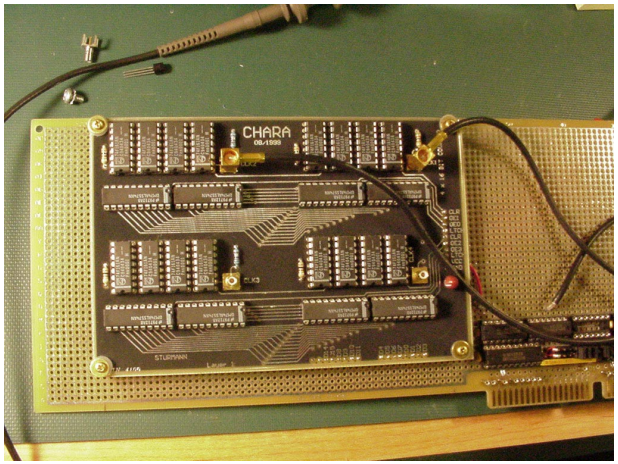


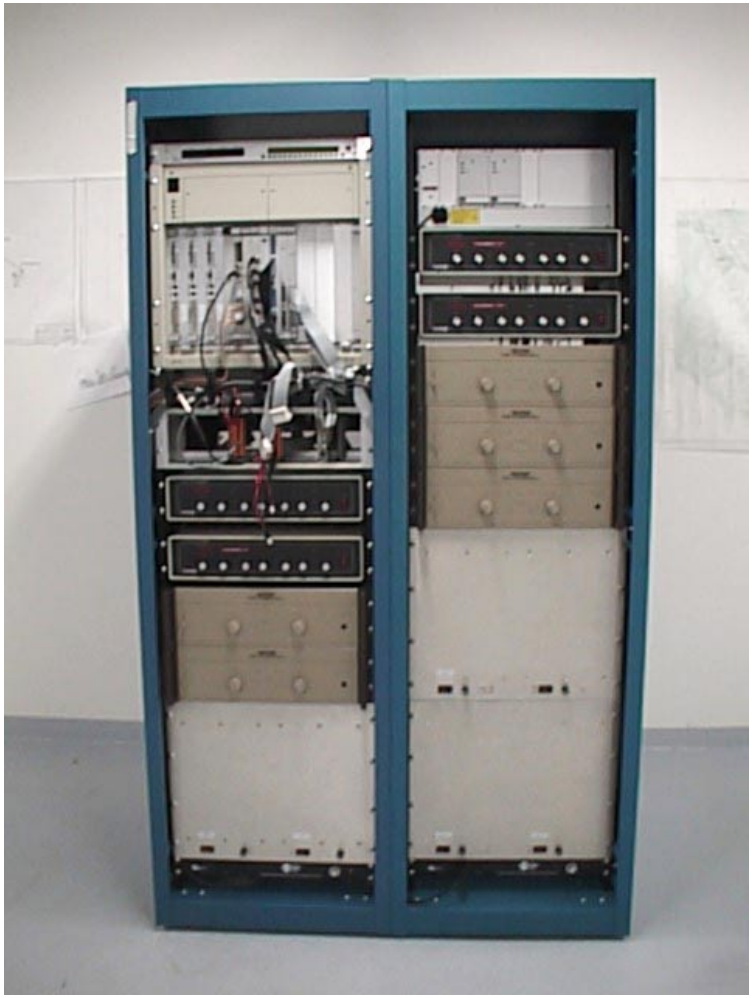




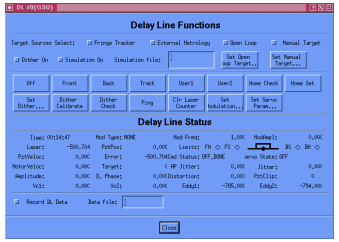
Controllers made by DIY Electronics, Inc.

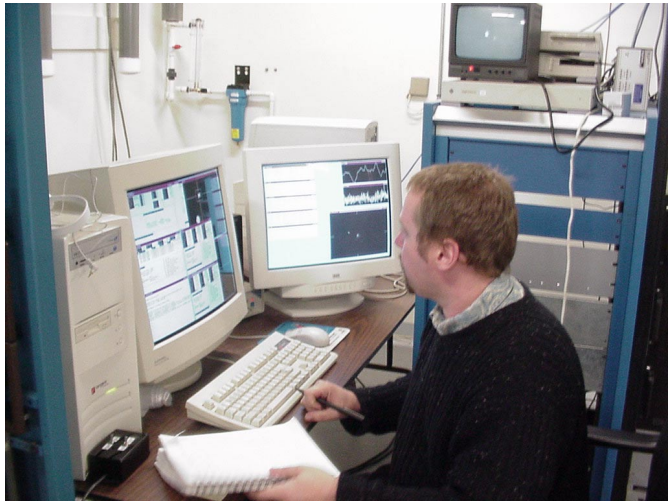


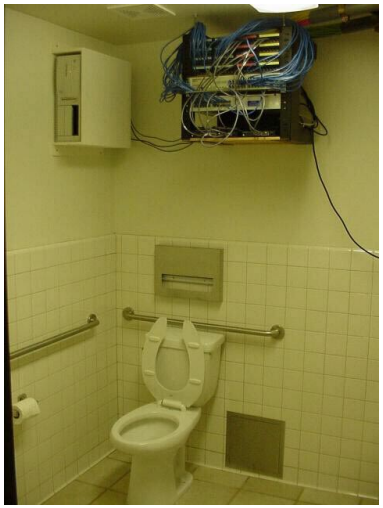


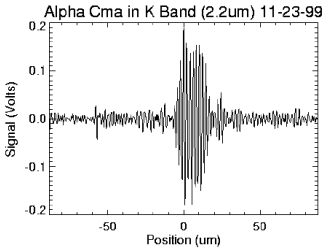


…with a well trained sequencer

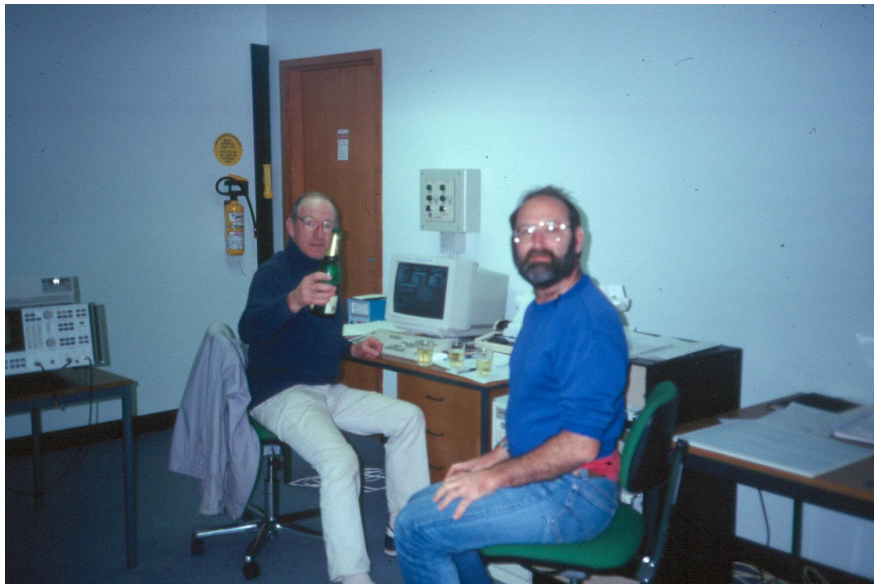


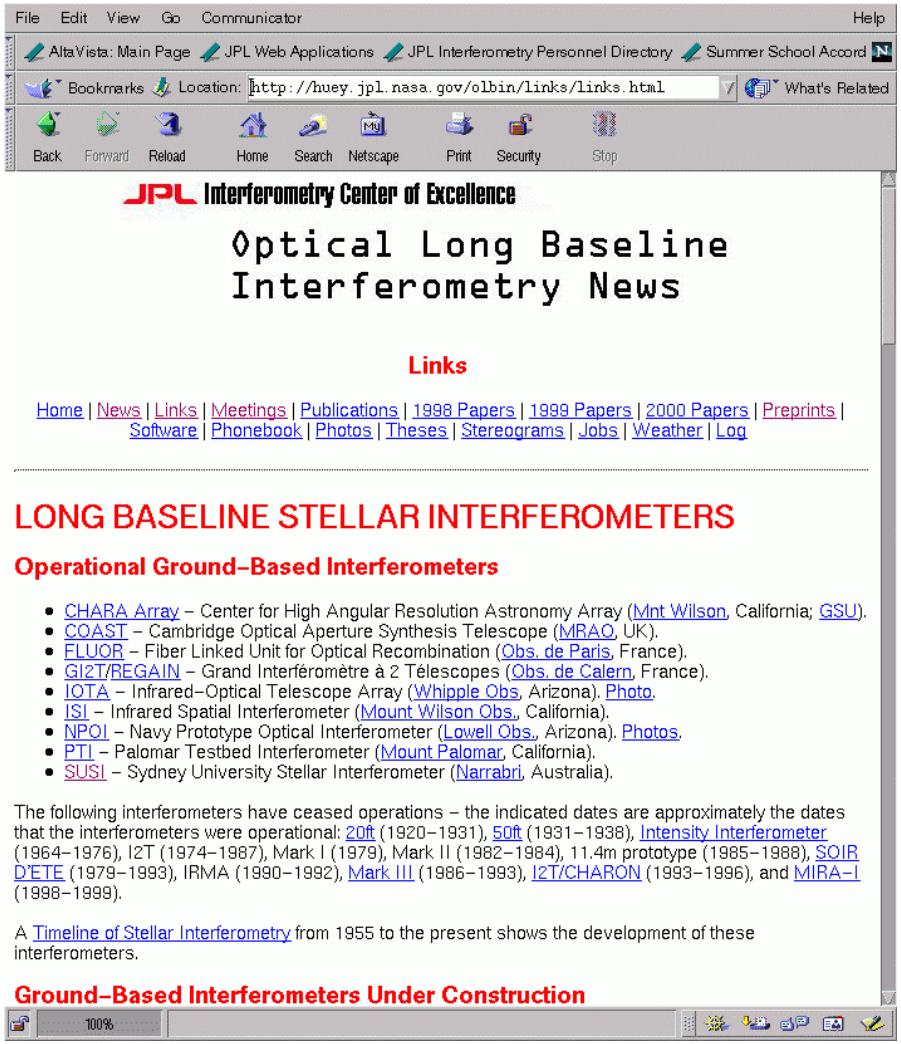






All resulting in fringes… you hope.



Optical Long Baseline Interferometry Newsletter

- http://huey.jpl.nasa.gov/olbin/
- Contains links to all existing and proposed optical/IR interferometer projects.
- News
- Papers and preprint information
- Upcoming meetings
- Contact information
- Translations of selected papers
- List of PhD and Masters theses
- Photographs and resources
- Job listings