HISTORY of Stellar Interferometry

Optical Interferometry Motivation and History

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Overview

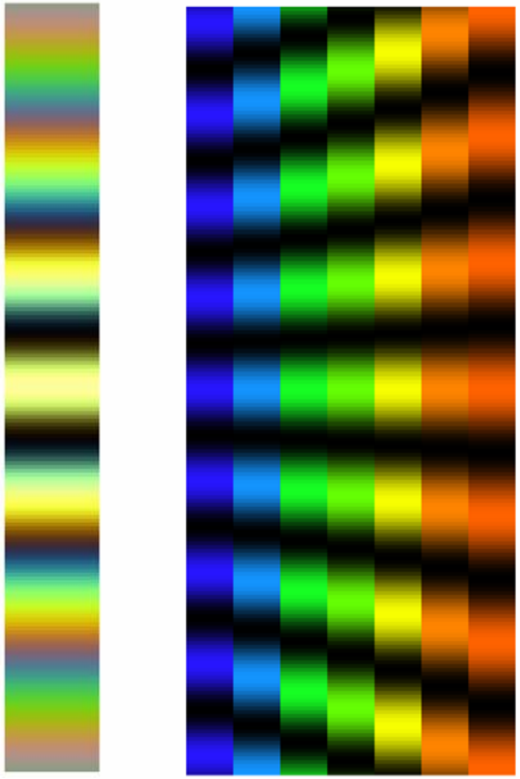
- First notions of interference and interferometry
- Early stellar interferometry
- Michelson's life work
- Development of modern optical/infrared interferometry
- Current developments and selected science results

On Tides, Organ Pipes, and Soap Bubbles

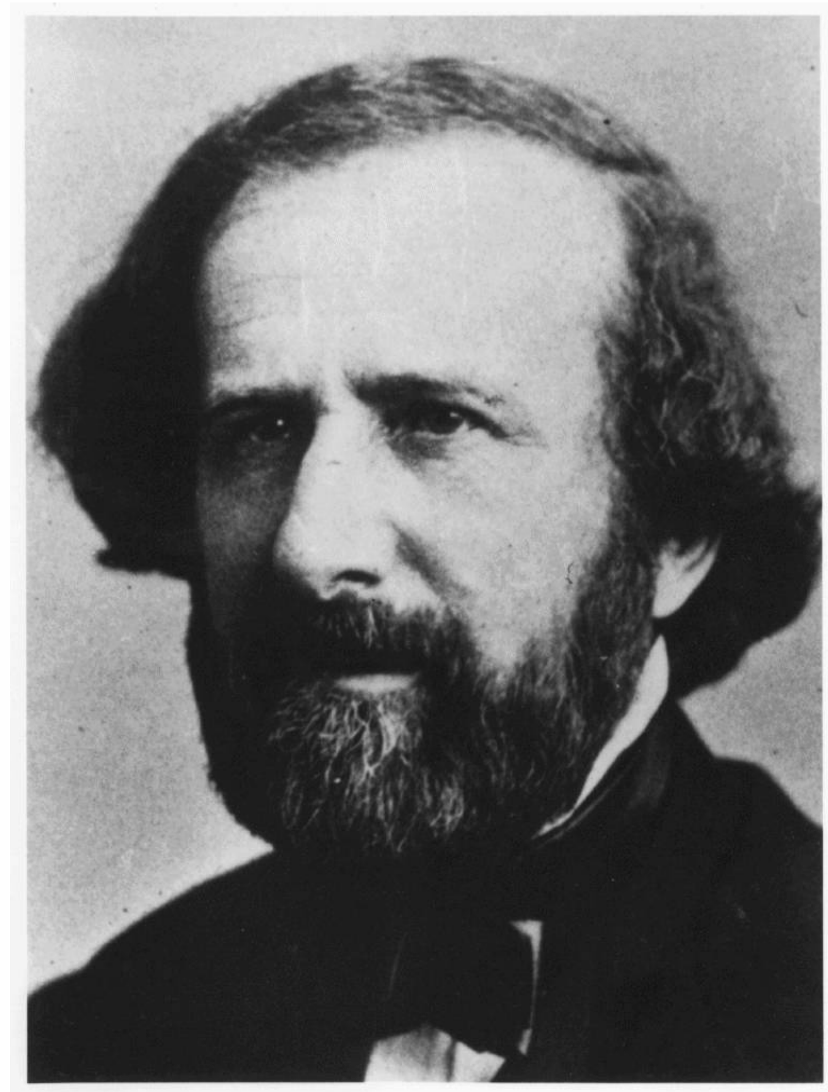
HISTORY of Stellar Interferometry

- Tides at Batsha (1684)
- Newton's *Principia* (1688)
- Thomas Young (1773-1829) and uncle Brocklesby
- General Law of interference
- Two slit experiment (1802)

Armand Hippolyte Fizeau (1819-1896)



- 1845 Fizeau and Foucault describe fringes in dispersed light



Fizeau Suggests Stellar Interferometry 1867

HISTORY of Stellar Interferometry

PRIX BORDIN.

QUESTION PROPOSÉE EN 1865 POUR 1867.

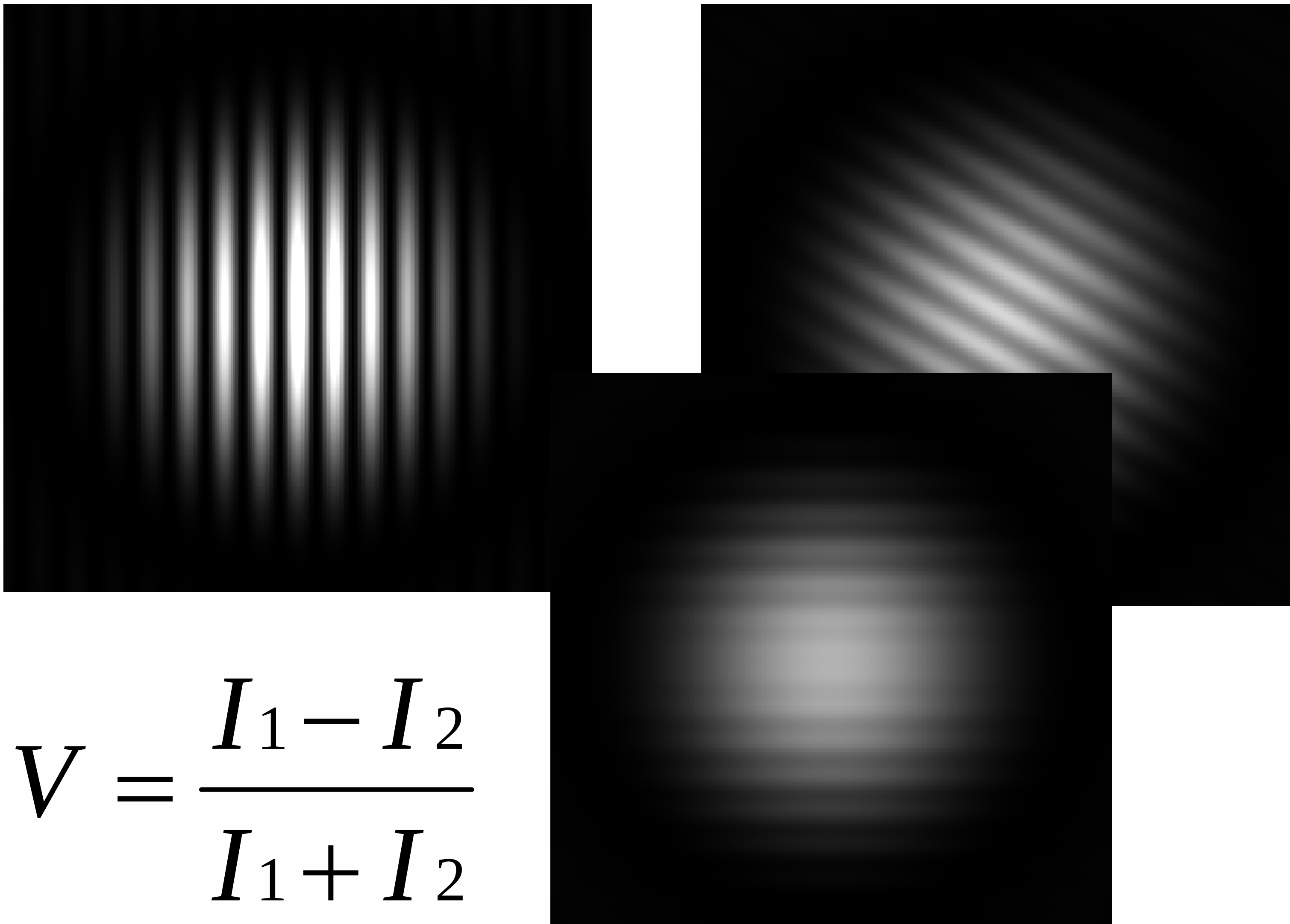
(Commissaires : MM. Duhamel, Pouillet, Regnault, Bertrand, Edmond Becquerel, Fizeau rapporteur.)

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.* »

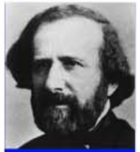
Il existe en effet pour la plupart des phénomènes d'interférence, tels que les franges d'Yung, celles des miroirs de Fresnel et celles qui donnent lieu à la scintillation des étoiles d'après Arago, une relation remarquable et nécessaire entre la dimension des franges et celle de la source lumineuse, 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.

What is a fringe? Visibility?



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

Edouard Stephan (1837-1923)



- 1874 E. Stephan uses the Foucault refractor at the Marseilles Observatory to observe most stars down to 4th magnitude.
  - 65 cm aperture separation.
  - All stars produce distinct fringes.
  - Concludes stars must have diameters much smaller than 0.158 arcseconds.

Foucault Refractor

HISTORY of Stellar Interferometry

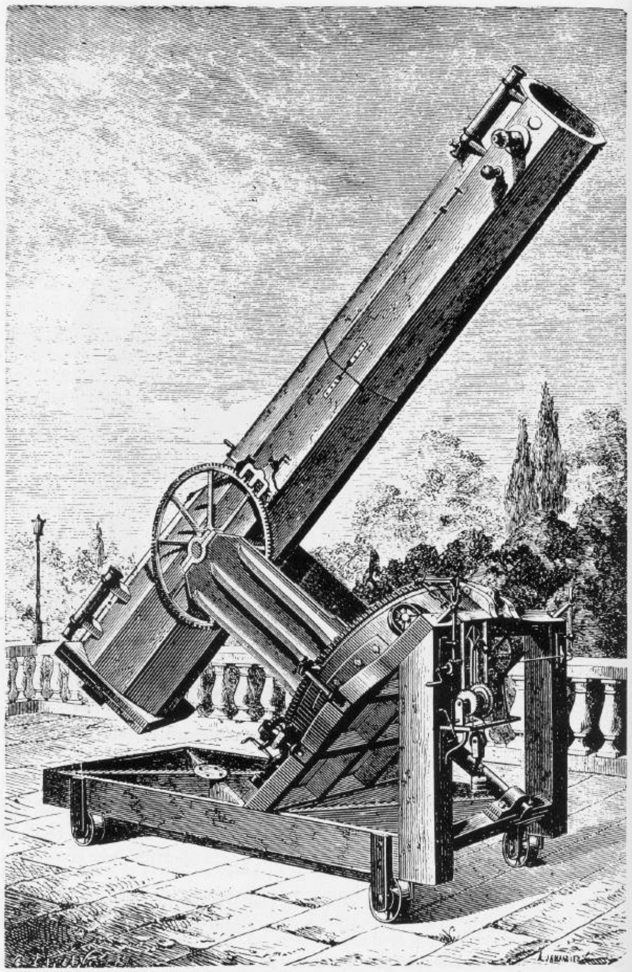
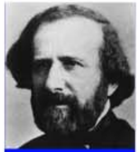


Fig. 5.8. Foucault's largest (80 cm) silver-on-glass reflector, completed in 1862 (reproduced from King [5.2])

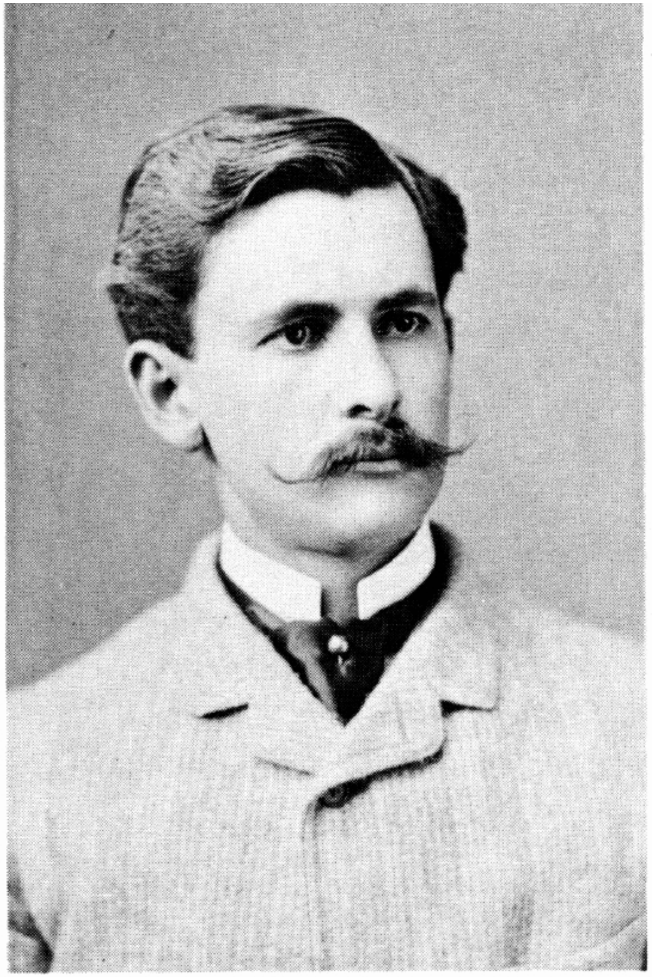
Albert A. Michelson (1852-1931)



HISTORY of Stellar Interferometry

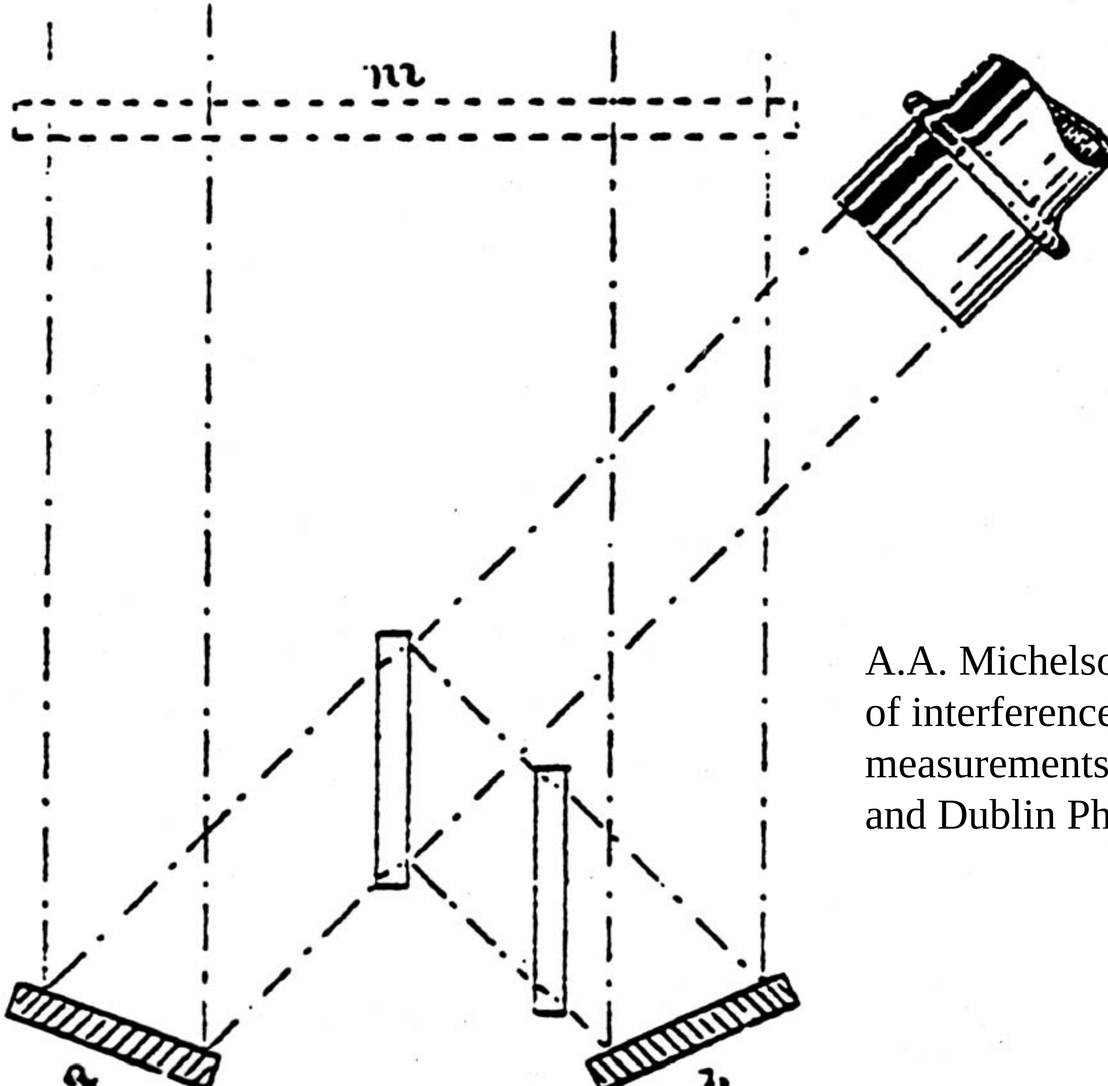
- 1878. Measures speed of light 200 times more accurately than previous measurements.
- 1880. Invents *Interferential Refractometer* in Berlin while on leave from Naval Academy.
- 1887. Michelson-Morley experiment.
- 1890. Describes mathematical basis of stellar interferometry

...and proposes an approach to long-baseline optical interferometry



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

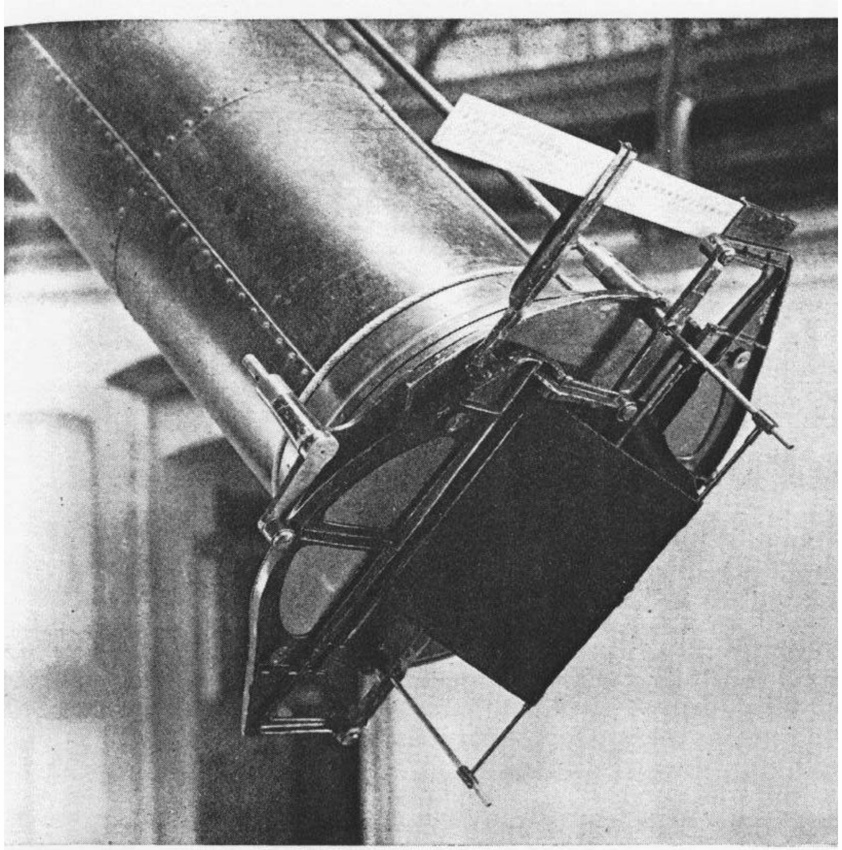
On the Application of Interference Methods to Astronomy (1890)



A.A. Michelson, “On the application of interference methods to astronomical measurements,” London, Edinburgh, and Dublin Phil. Mag. 30, 1-21 (1890)

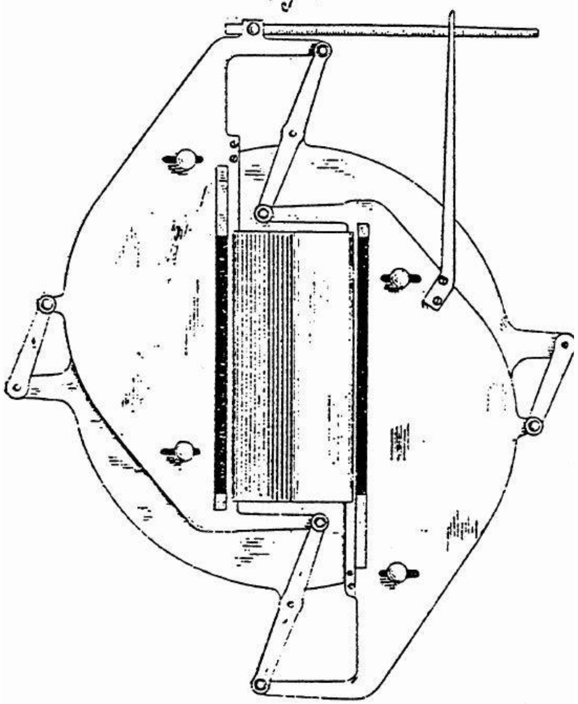
Moons of Jupiter (1891)

HISTORY of Stellar Interferometry



Interferometric mask used on the 12-inch refractor at Lick Observatory to measur
the angular diameters of the Jovian satellites. The rod adjacent to the telescop
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.

Fig 3



With this apparatus the satellites of Jupiter were measure
ith 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	

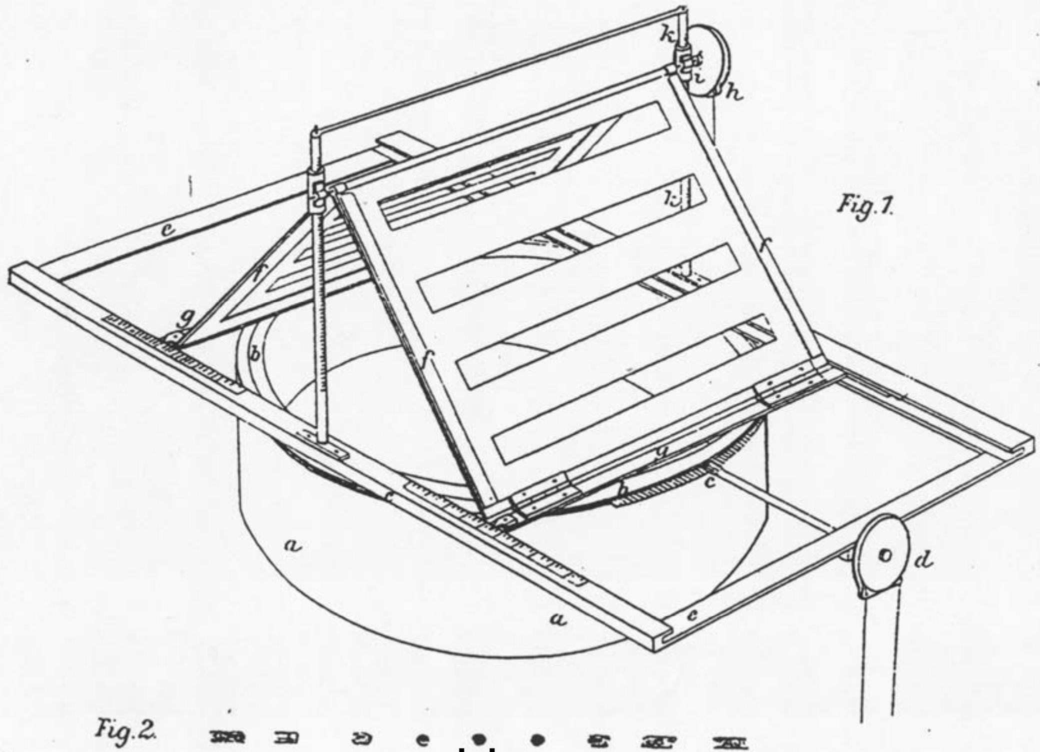
A.A. Michelson, "Measurement of Jupiter's satellites by interference,"
Nature **45**, 160-16 (1891)

Other Applications in 19th Century

HISTORY of Stellar Interferometry

- First use of interferometry to measure binary stars (1895)

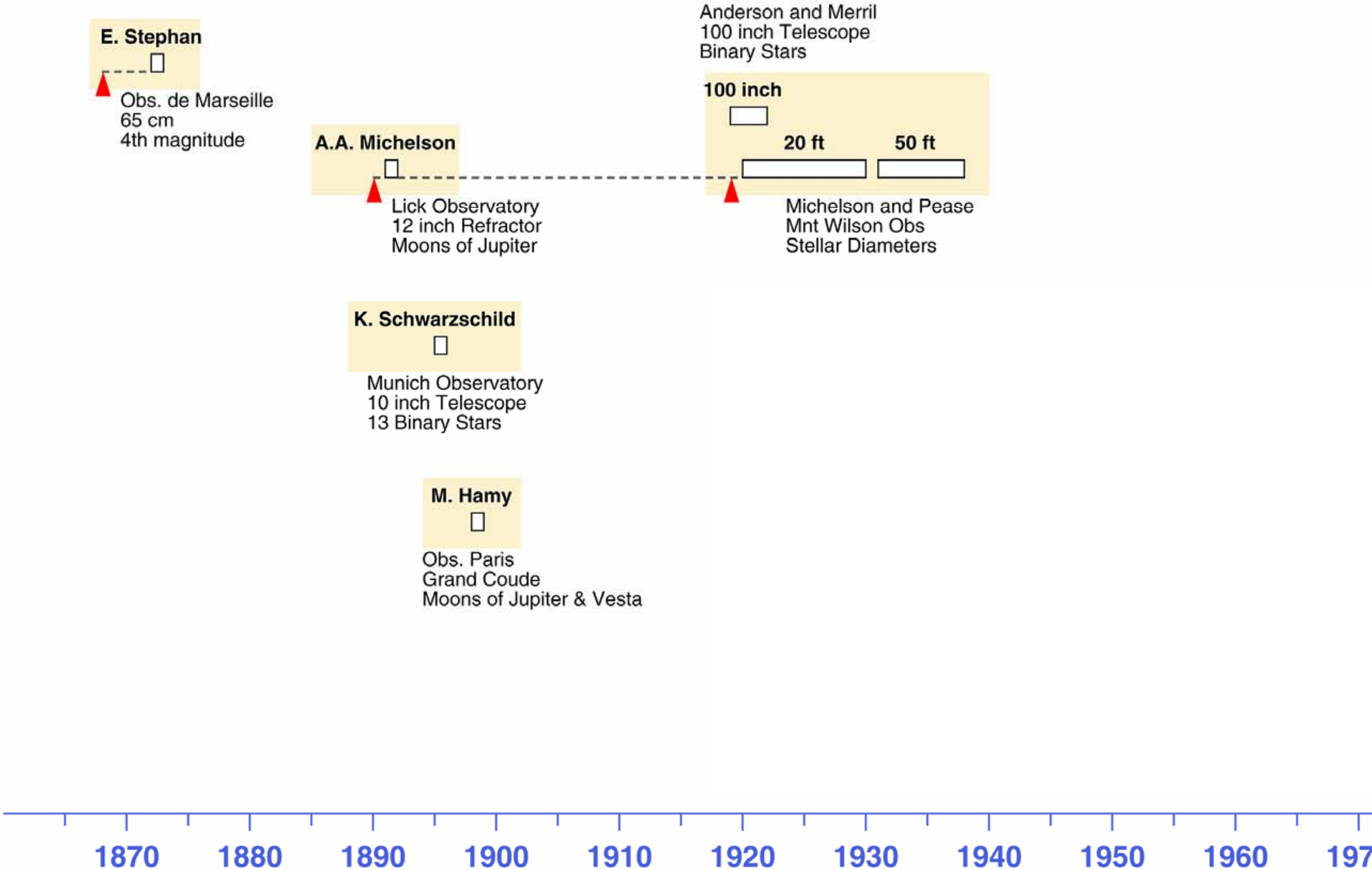
Karl Schwarzschild
Born: 1873, Frankfurt/Main,



- 1896 M. Hamy performs aperture masking measurements at the Observatoire de Paris, repeating work by Michelson

Timeline of Interferometry to 1938

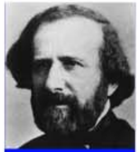
HISTORY of Stellar Interferometry



30 years goes by...

- Michelson’s measurements of the Moons of Jupiter was a feasibility test. Why didn’t he follow it up?
- Work had been planned with the 32-inch at Lick, but Michelson left for Europe.
- He never followed up with the observations at Lick
- Perhaps there was no point. Stars were obviously too small to measure with single telescopes
- ...stellar interferometry was only a footnote in Michelson’s extremely productive career
- Depression in Chicago in 1890s (little money)
- World War I

Mount Wilson Observatory



- 1914 Russell proposes two classes of red stars
- 1919 Michelson funded to measure diameters
- Much confusion over predicted sizes of stars
- 25 ft rotatable interferometer proposed to George Elliot Hale

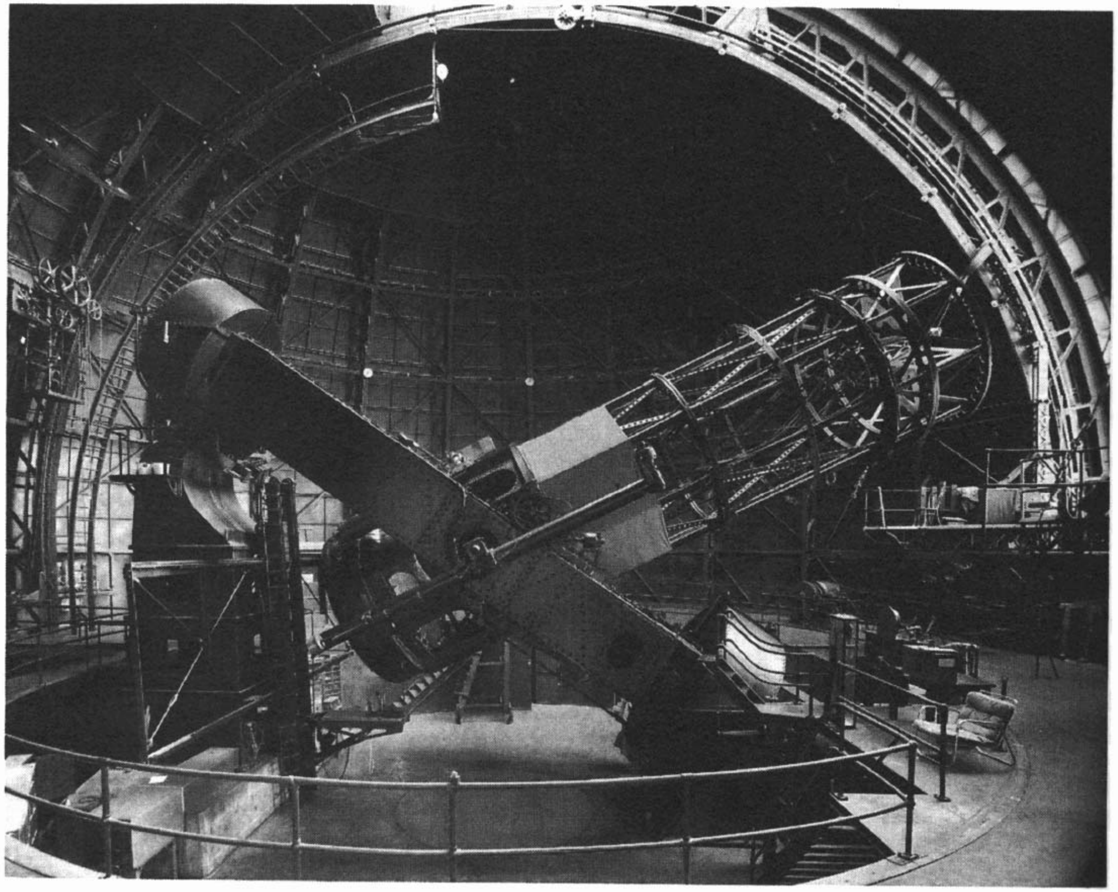
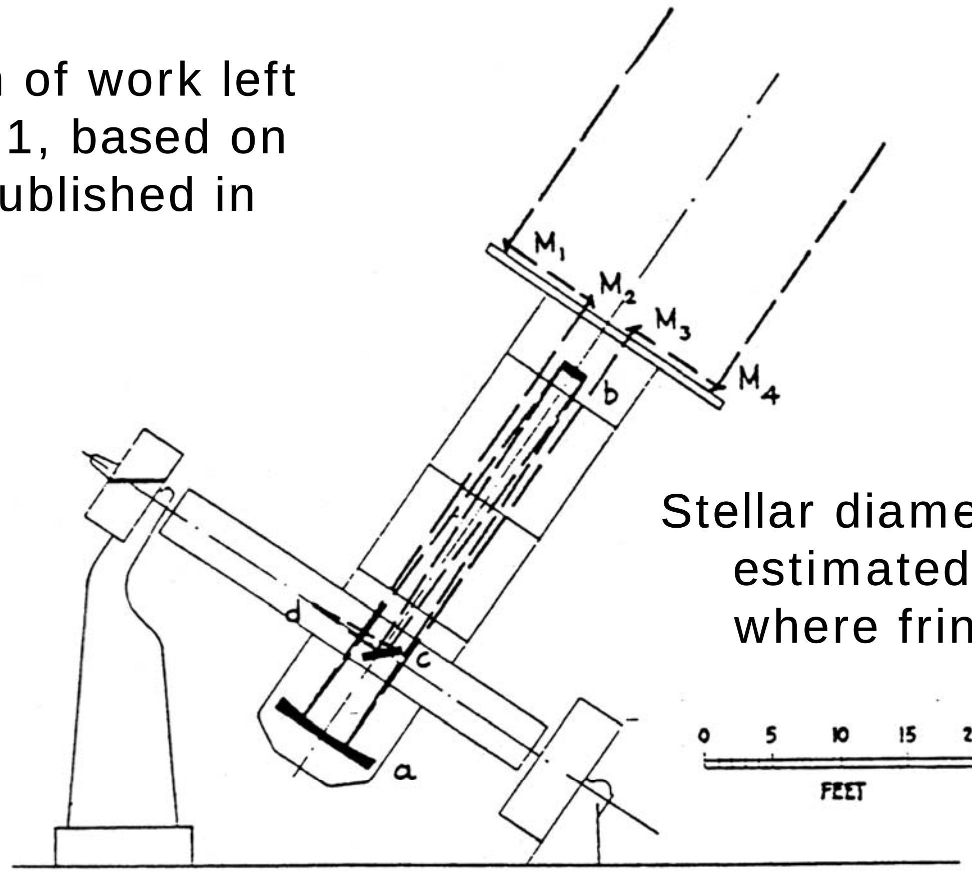


Figure 13.5 *The 100 inch (2.5 m) Hooker reflector on Mount Wilson, completed in 1917. (Courtesy* The Observatories of the Carnegie Institution of Washington.*)*

Michelson's 20 ft Interferometer

HISTORY of Stellar Interferometry

Continuation of work left off in 1891, based on an idea published in 1890



Stellar diameter estimated at baseline where fringes vanish

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.

I 1920

HISTORY of Stellar Interferometry

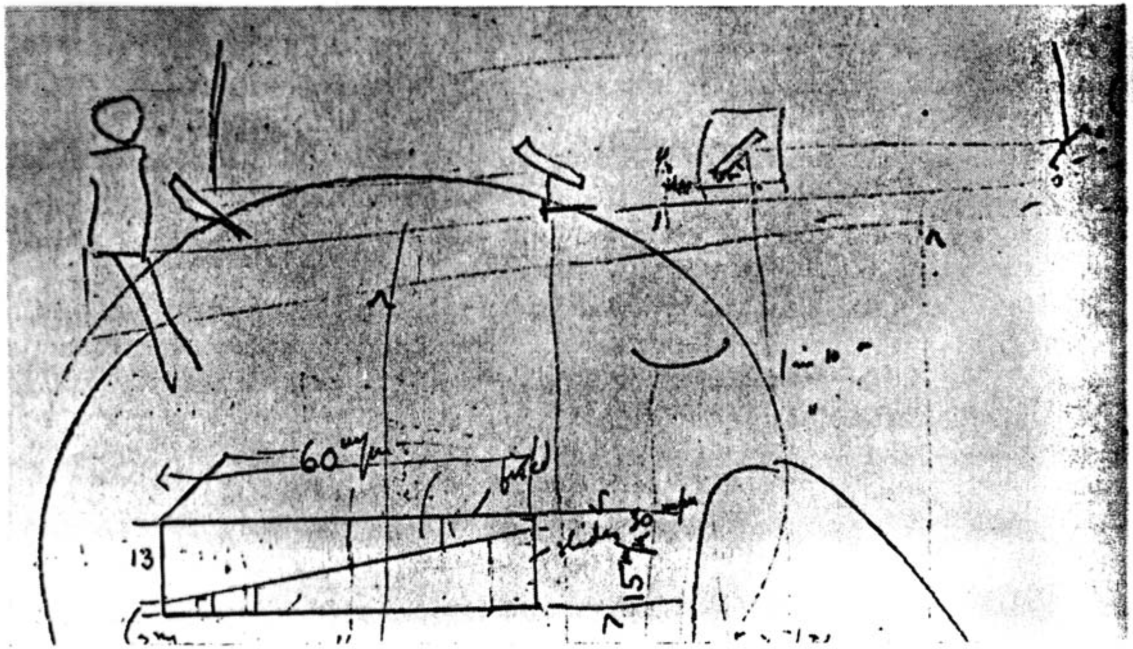
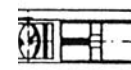


FIG. 3. From F. G. Pease, Notebook 1, sheet 42; approximate date 14 July 1920 (Hale Observatories, copy in Michelson Museum). Crude drawings of the optical wedge used to equalise path length. Note the superimposed sketch illustrating how the night assistant must be perched to move the mirrors on the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



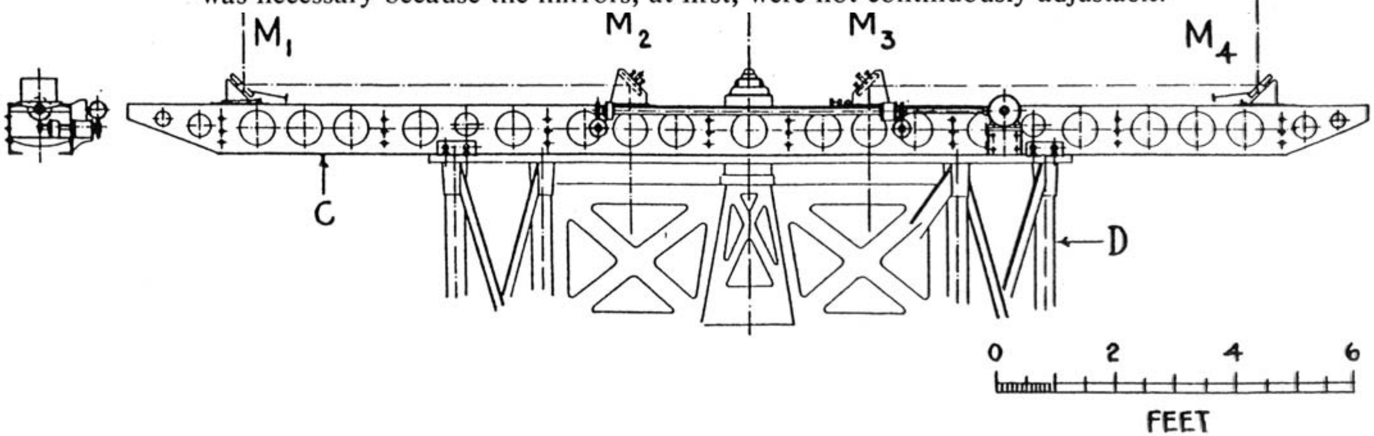
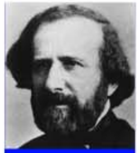


FIG. 2.—Diagram of 20-foot interferometer beam. M_1, M_2, M_3, M_4, mirrors; B, B, 10-inch channels; C, steel plate; E, E, screws to move outer mirrors; F, motor drive for screws; D, Cassegrain cage.

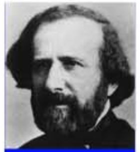
Was Michelson Influenced by Fizeau?



- Yes
- No

Albert A. Michelson, about 1928

...Work Continues in the 1920s and 30s



HISTORY of Stellar Interferometry

- Observations of Betelgeuse and other stars in 1921
- A small number of other targets observed in the 1920s
- Francis Pease plans a more ambitious instrument
- Michelson dies in 1931

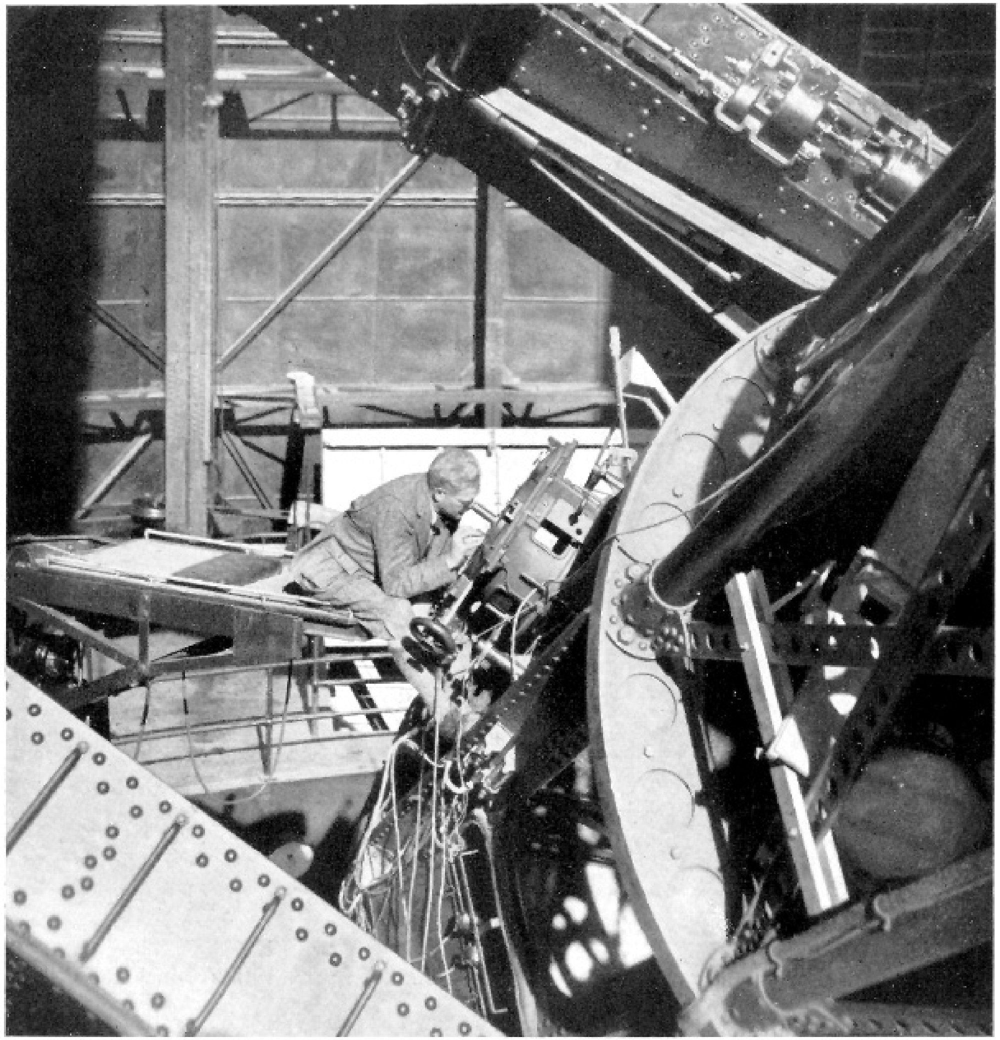
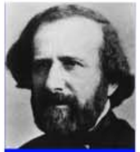


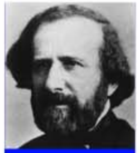
Abb. 3. Showing observer at eyepiece of 20 foot interferometer.

50 ft Interferometer (1931-1938)

HISTORY of Stellar Interferometry



Light Paths in the 50 ft Interferometer



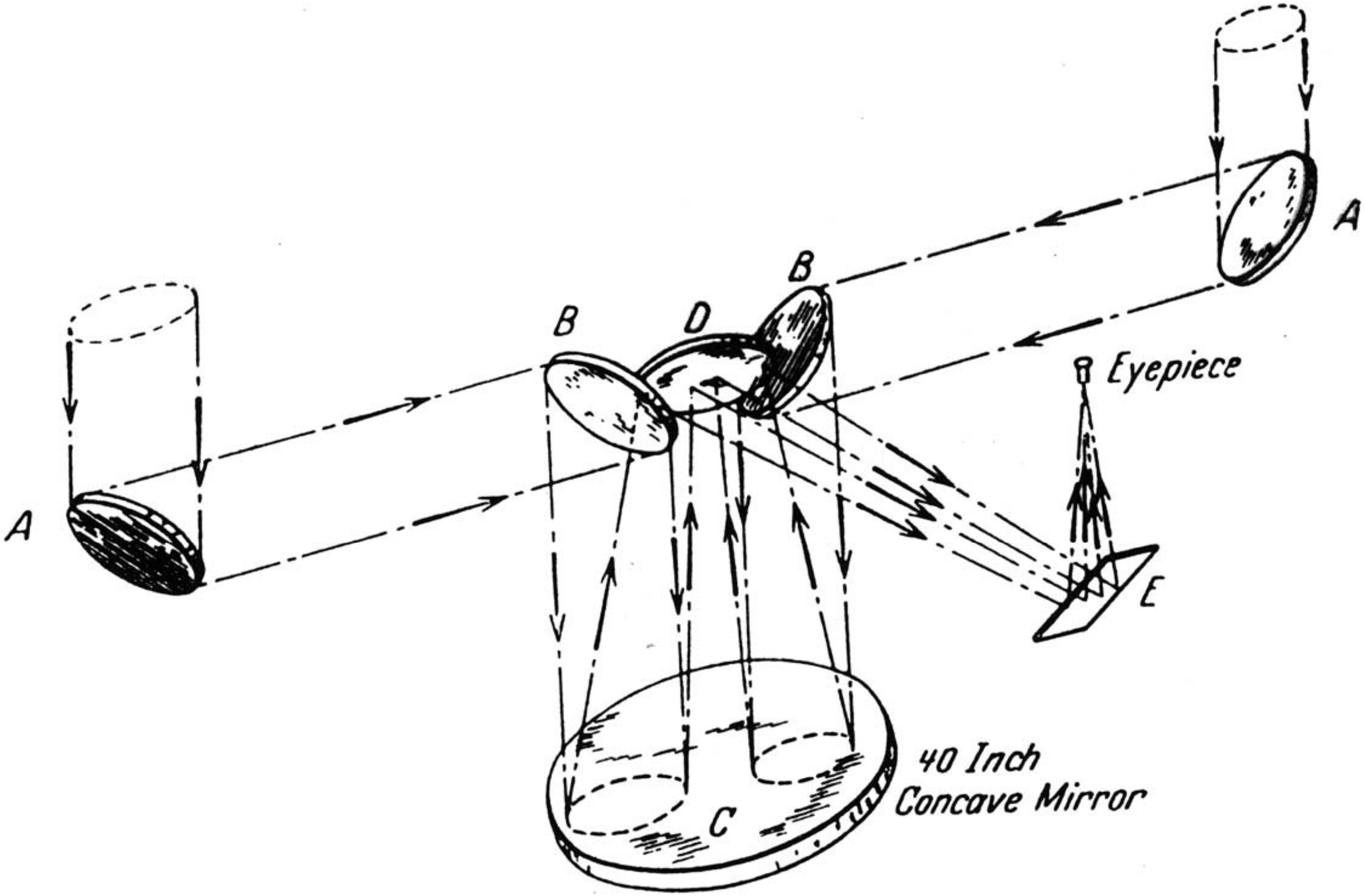


Abb. 8. Diagram of light path in 50 foot interferometer.

HISTORY of Stellar Interferometry

F.G. Pease (1881-1938)

HISTORY of Stellar Interferometry

- Designed and built by F.G. Pease (1931).
- Probably subject to numerous problems
  - 38 cm mirrors produced speckled images
  - Increased fringe motion at longer baselines
  - Excessive vibrations
  - Polarization mismatch between arms
- Produced results of questionable value
  - Accuracies estimated at 10 - 20%

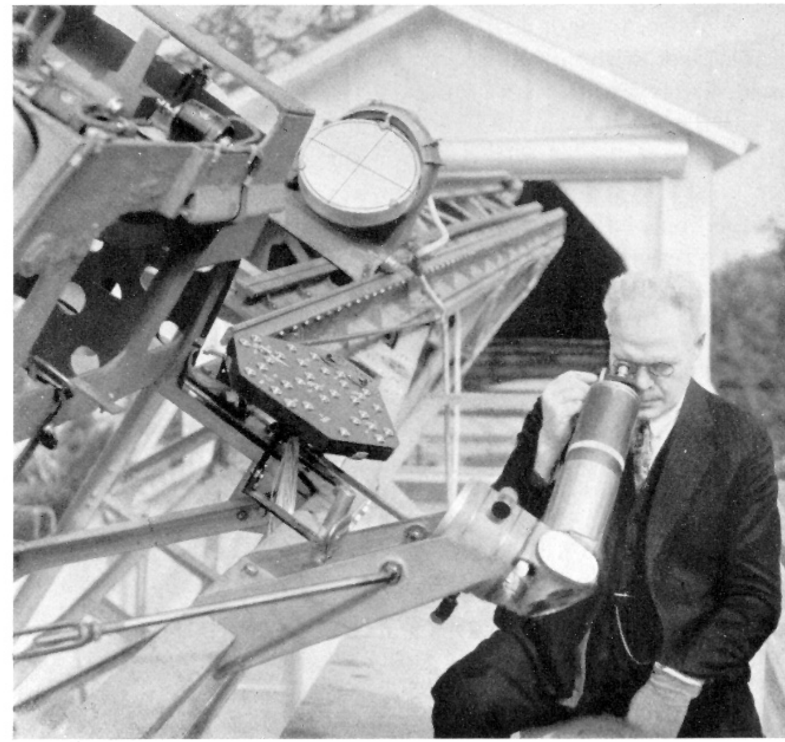
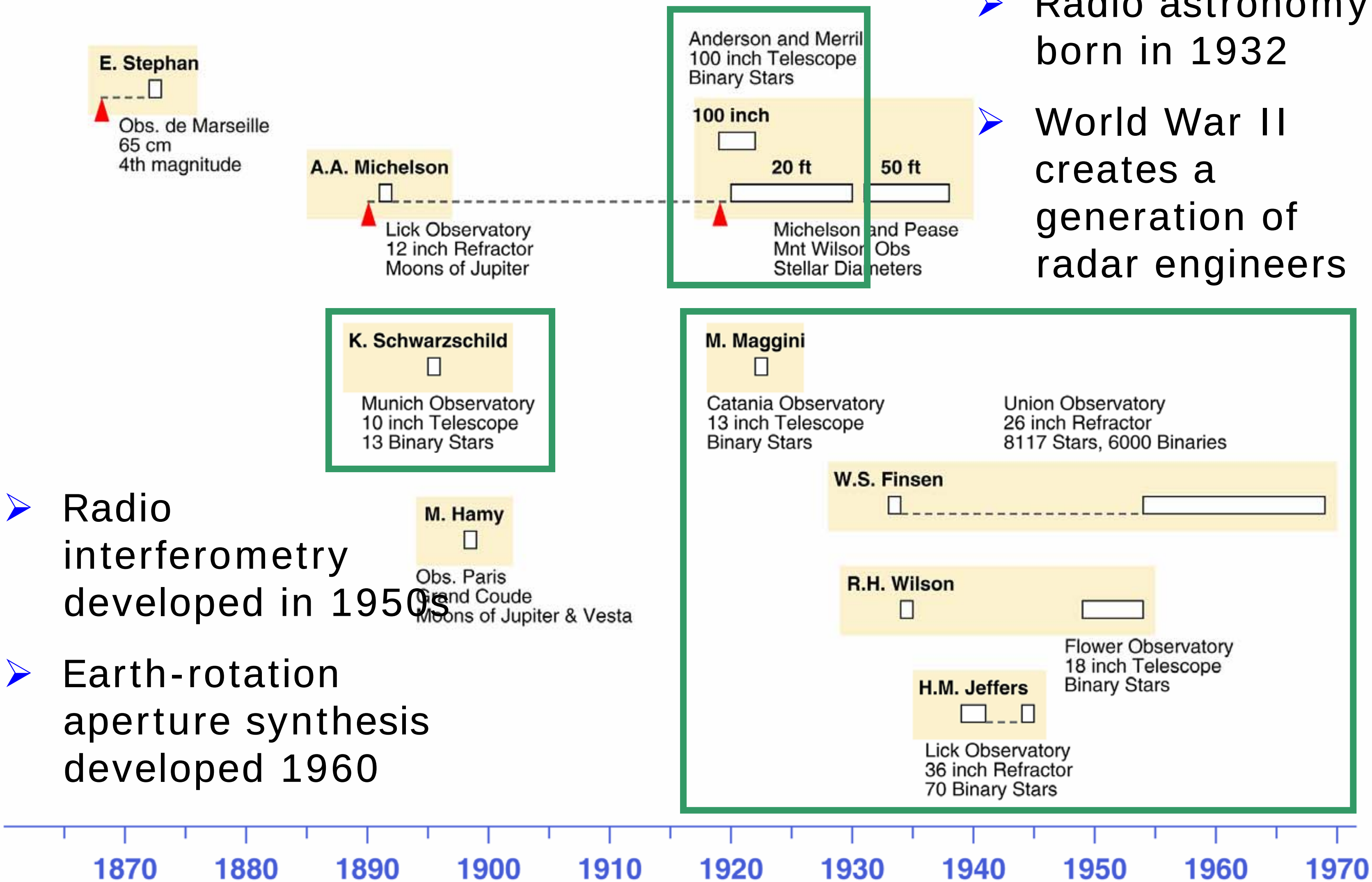


Abb. 9. Upper part of interferometer showing control board and observer at eyepiece.

- Observations ceased in 1938
- ...at the limits of technology

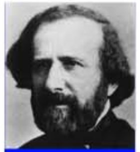
Timeline of Optical Interferometry to 1970

HISTORY of Stellar Interferometry

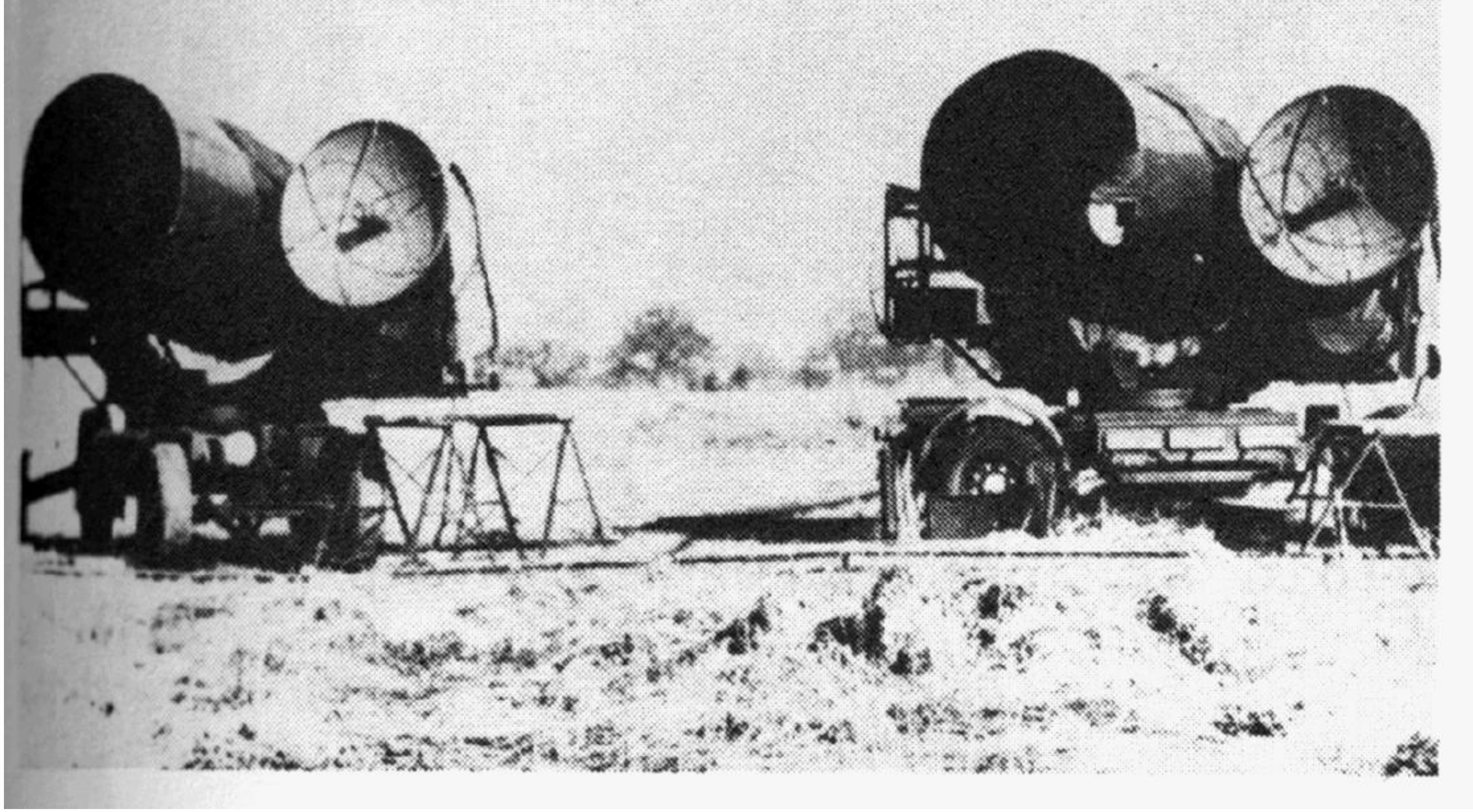


- Radio astronomy born in 1932
- World War II creates a generation of radar engineers
- Radio interferometry developed in 1950s
- Earth-rotation aperture synthesis developed 1960

A New Type of Stellar Interferometer (1956)



- R. Hanbury Brown and R.Q. Twiss (1956).
- Diameter of Sirius estimated from experiments at Jodrell Bank, UK (1956).



Intensity Interferometer (1963-1976)

- Manchester University and Sydney University build the *Intensity Interferometer* at Narrabri, NSW, Australia (starting 1961)
  - Initially under the guidance of Twiss
  - Hanbury Brown established as Professor at Sydney University

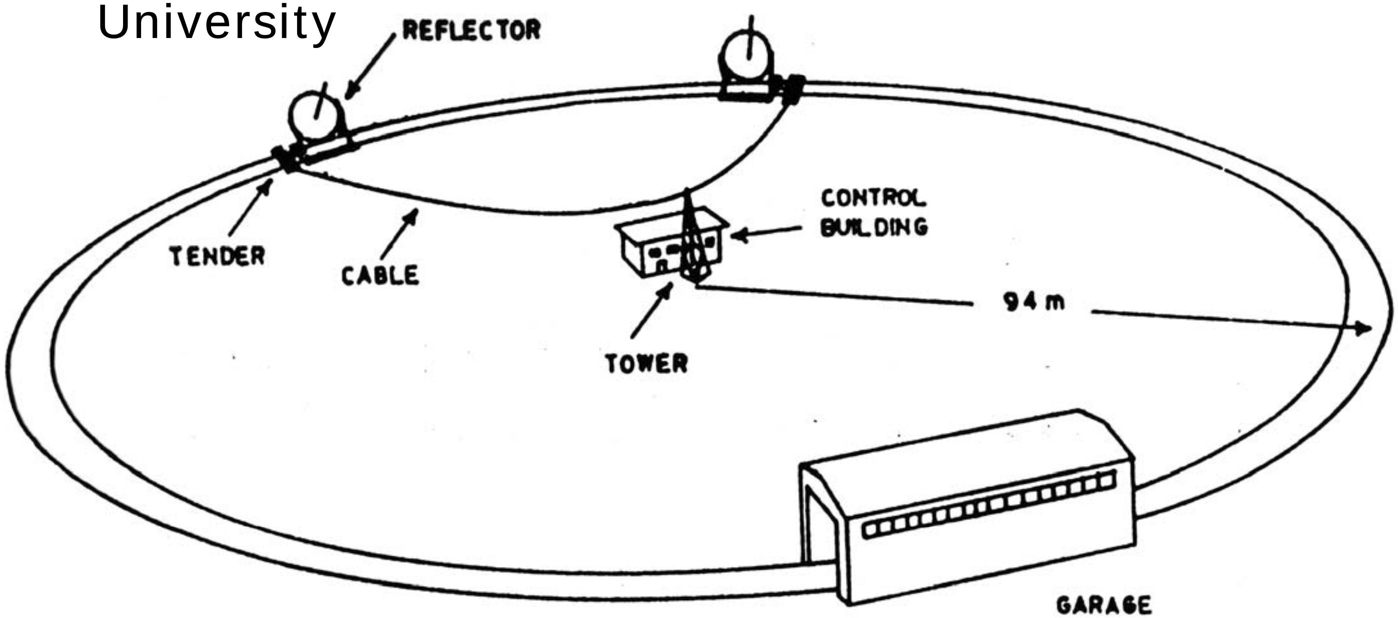
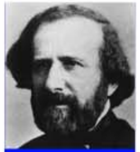


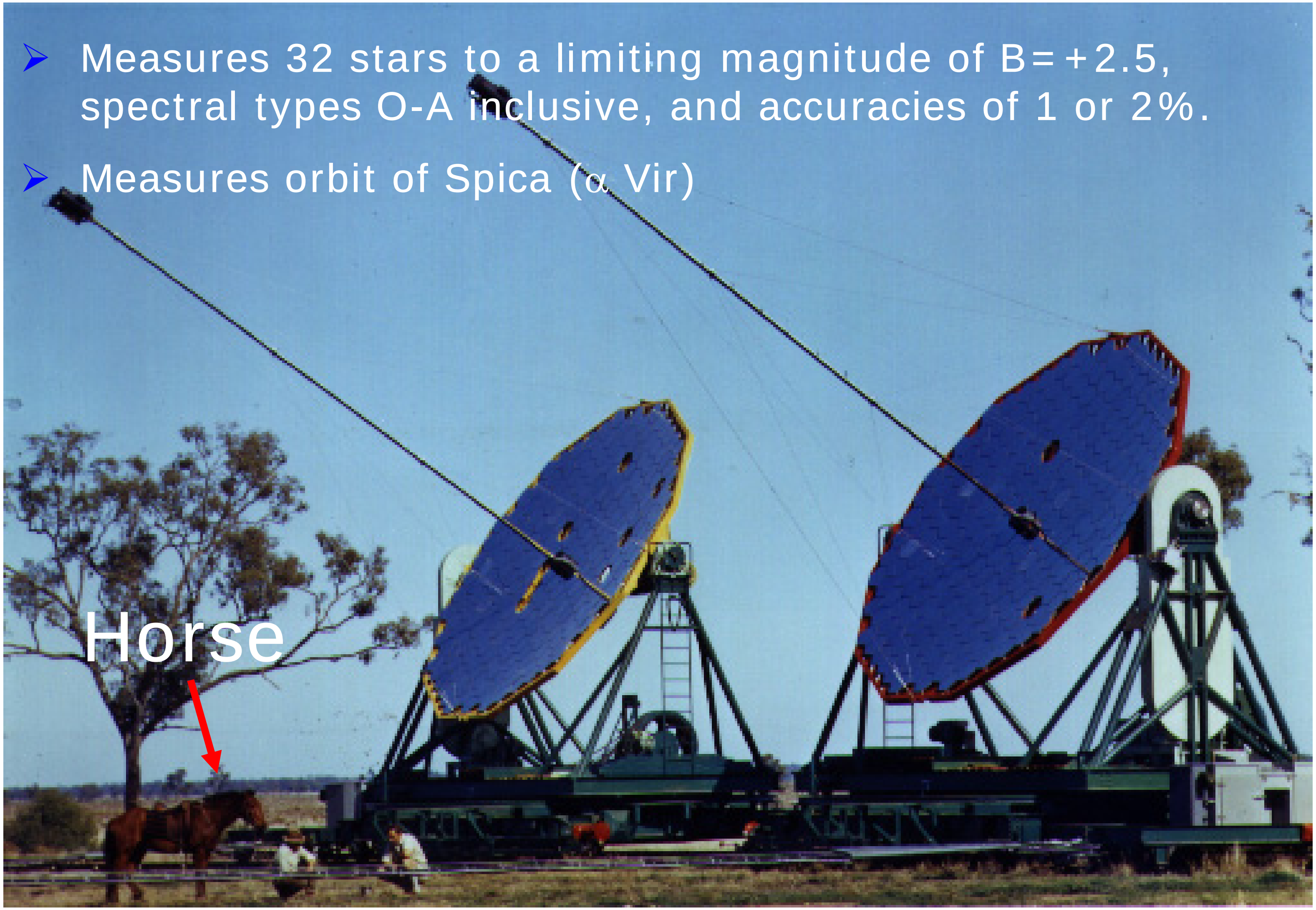
FIG. 7. The general layout of the interferometer at Narrabri Observatory.



HISTORY of Stellar Interferometry

Intensity Interferometer (1963-1976)

- Measures 32 stars to a limiting magnitude of B=+2.5, spectral types O-A inclusive, and accuracies of 1 or 2%.
- Measures orbit of Spica (α Vir)



Interest in Optical Interferometry in the 1960s

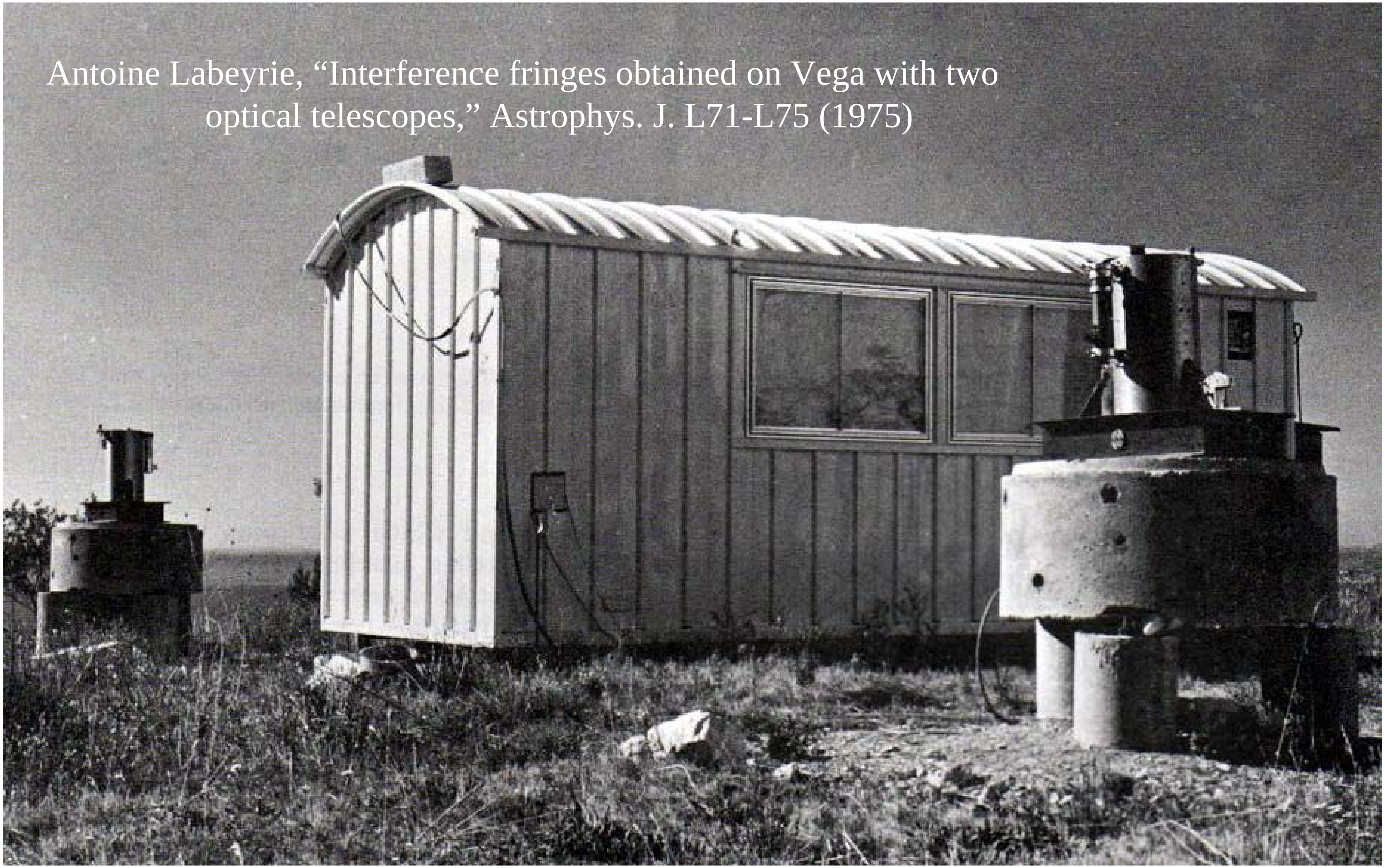
- W.I. Beavers , “Modern Stellar Interferometry” ***Astron. J.*** 68 (1963)
- R.H. Miller, “Measurement of Stellar Diameters” ***Science*** 153 (1966)
- 1967 Woods Hole Summer Study on *Synthetic Aperture Optics* **-** Advisory Committee to the Air Force Systems Command
  - Closure phase proposed by Rogstad for optical arrays
  - D. Currie and the University of Maryland (1967)
  - H.A. Gebbie, R.Q. Twiss, W.J. Tango and the Monteporzio Interferometer
  - Goodman proposes aperture masking imaging with closure phase information
- E.S. Kulagin, Pulkovo Observatory, measures Capella 1970

Interferometry in the Early 1970s

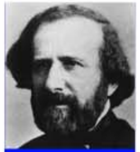
- Speckle interferometry invented 1970
- Lunar occultation measurements ongoing
- 10 micron heterodyne demonstrated by J. Gay at the Observatoire de Paris 1972.
- “Amplitude Interferometer” (aperture masking) by Currie et al. June-December 1972
- First long-baseline observations at 10 microns by Johnson et al. (1974) at MacMath Solar Observatory using the planet Mercury
  - Observations in late July and Early August 1974

First directly detected fringes with separated telescopes (1974)

HISTORY of Stellar Interferometry



First Fringes



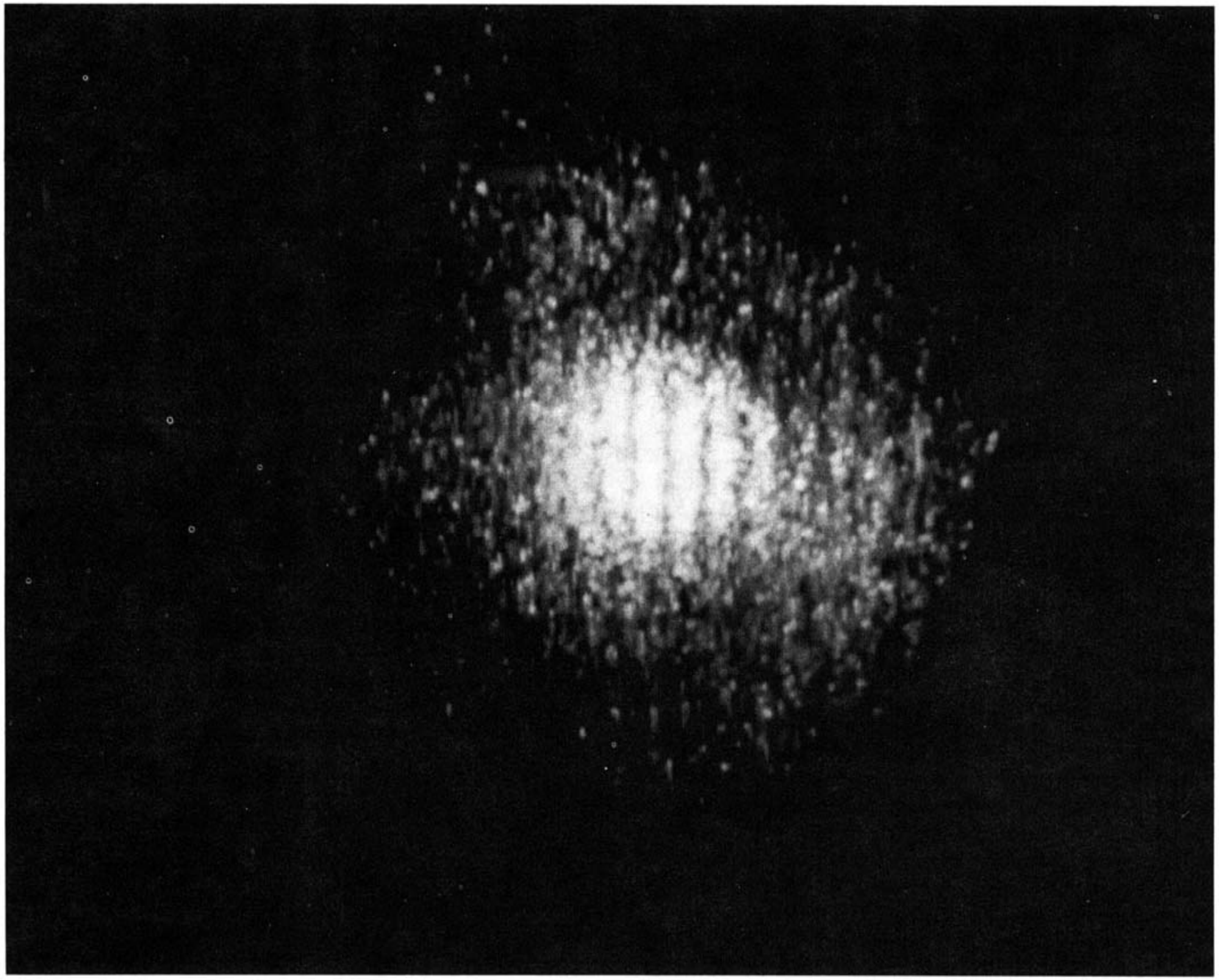


FIG. 4.—Interference fringes (photographed from a television sequence), obtained in the image of Vega with 500 Å bandwidth. In this case, the photon-counting camera is operating at reduced gain in the analog mode. Individual photon events are nevertheless visible as bright points.

Antoine Labeyrie's IT2

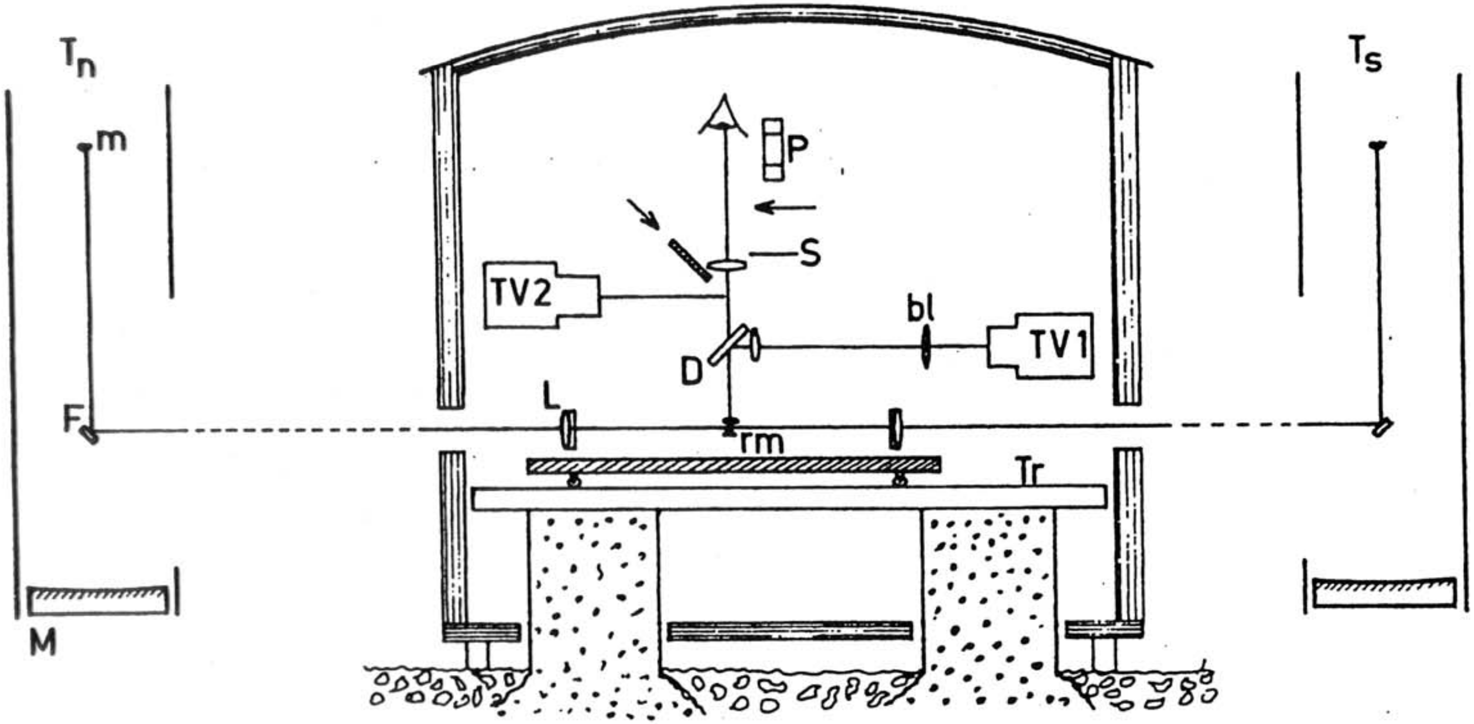


FIG. 1.—Optical layout of the two-telescope interferometer: Tn,Ts: north and south telescopes; M: 250-mm primary mirror (f = 850 mm); m: Cassegrain secondary (f = 7.5 mm); F: coudé flat; L: field lens; rm: roof mirror in pupil plane; D: dichroic mirror; TV1: guiding camera; bl: bi-lens serving to separate the two guiding fields; S and P: slit and direct view prism used for fringe acquisition; TV2: photon-counting camera (tunable filter not represented); Tr: tracks on which table moves (programming mechanism not represented).

Inside the I2T

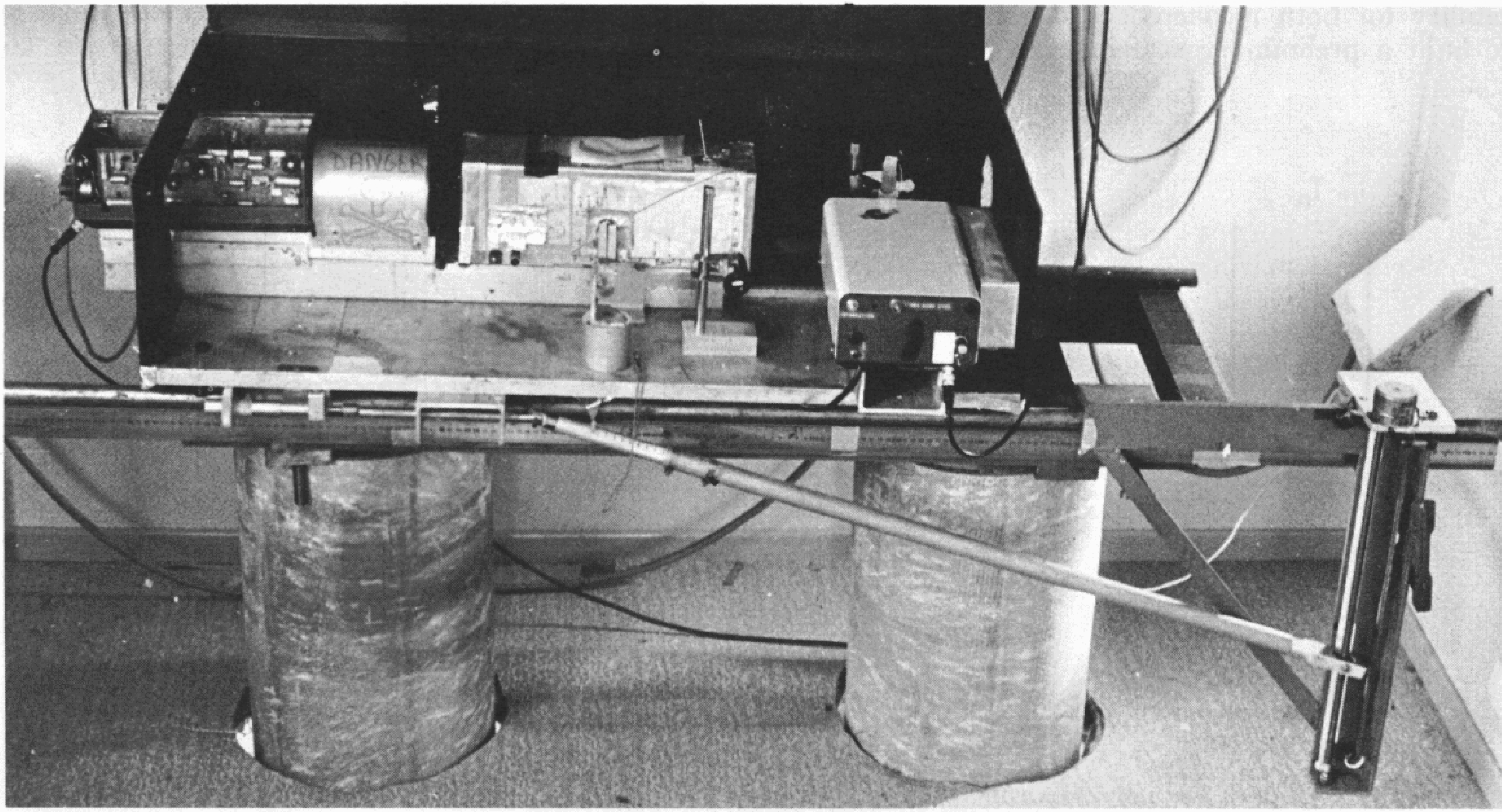
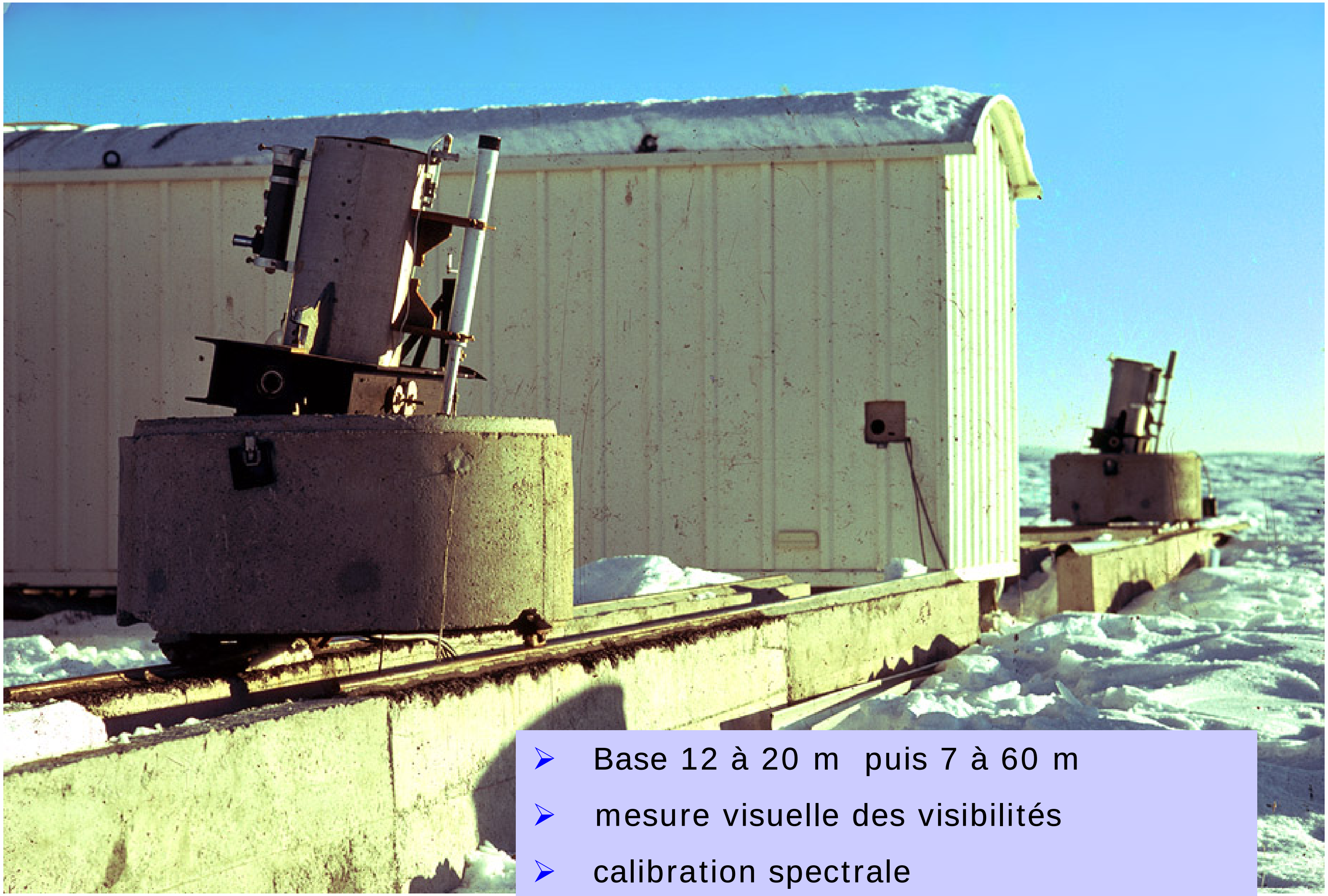


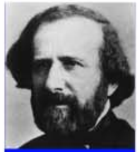
FIG. 3.—Central station, showing the optical table with its tracks, and the fringe-tracking mechanism which approximates the required cosine H displacement law. The concrete piers independent from the building are also visible, as well as the micrometer screw which allows for fine fringe tracking.

1976 on a nearby mountain plateau



- Base 12 à 20 m puis 7 à 60 m
- mesure visuelle des visibilités
- calibration spectrale

(Courtesy of Laurent Koechlin)



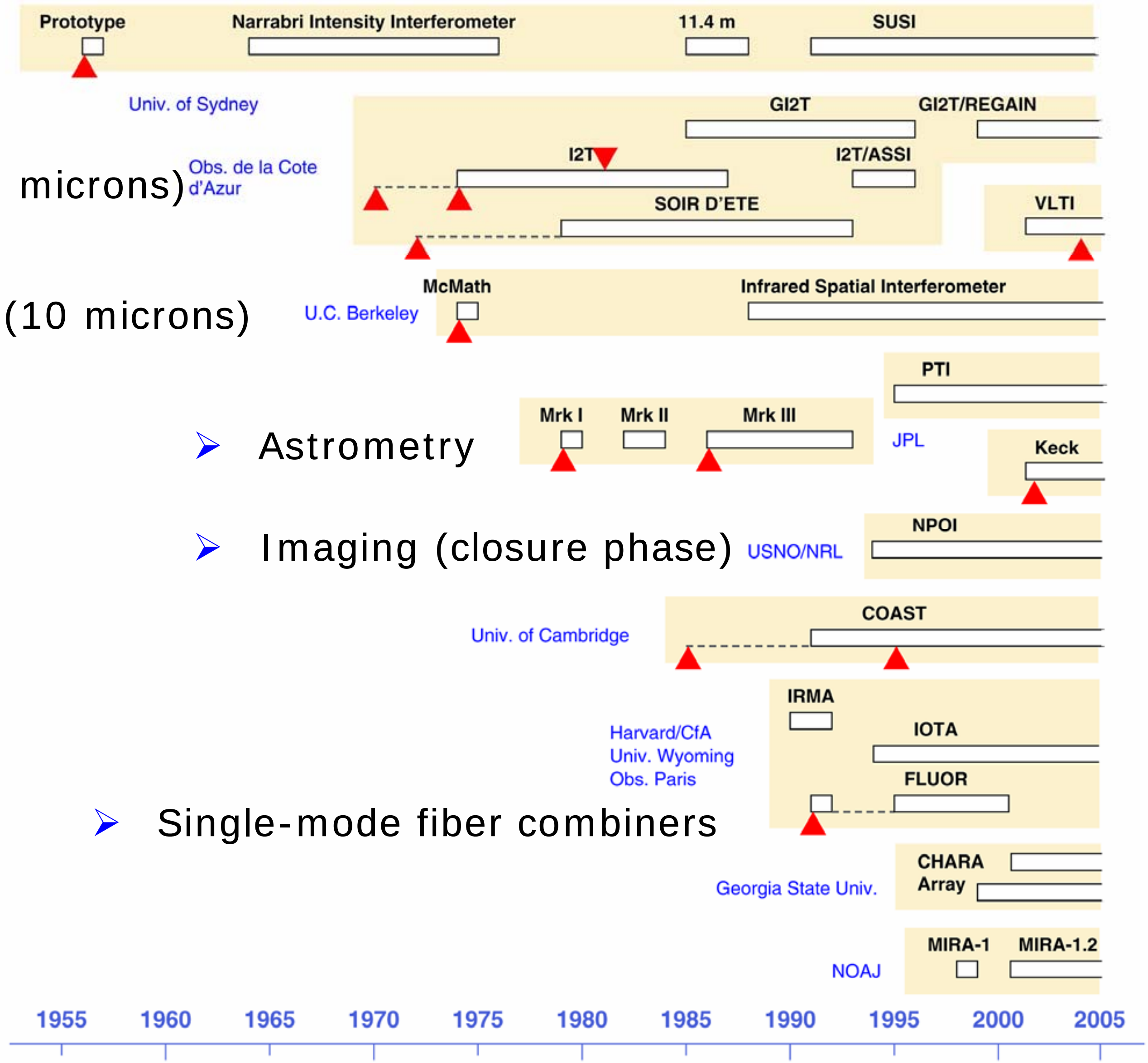
Part II

1974-2006

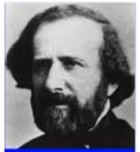
Advances in Technology 1974-2006

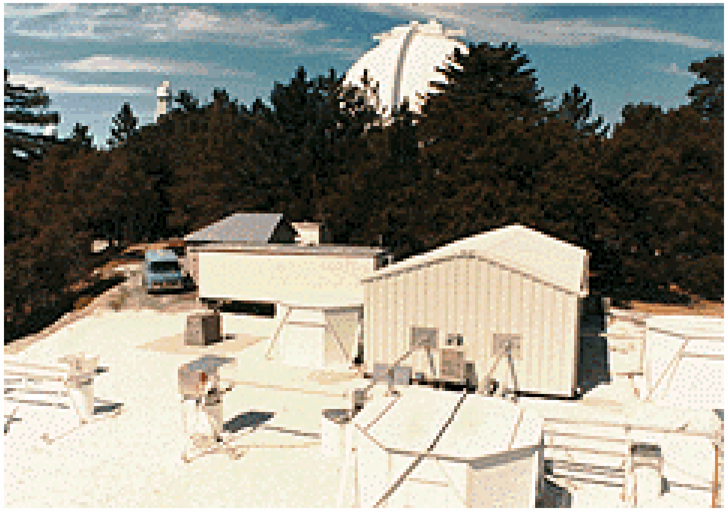
HISTORY of Stellar Interferometry

- Infrared (2.2 microns)
- Mid-infrared (10 microns)
- Astrometry
- Imaging (closure phase)
- Single-mode fiber combiners

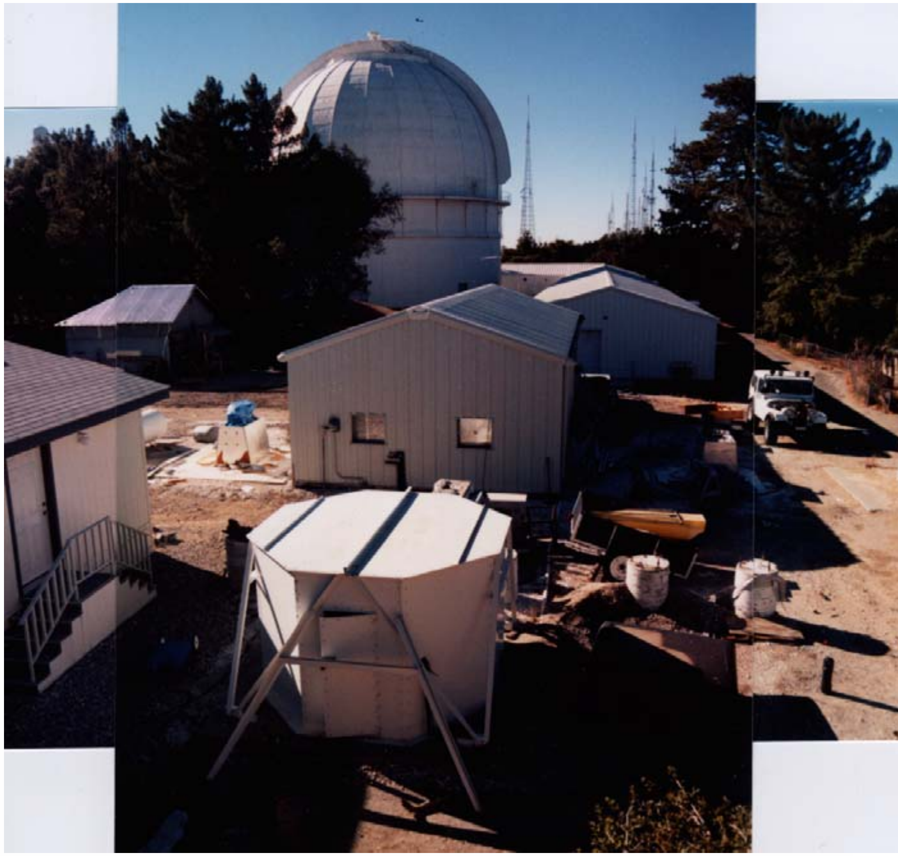


The First Modern Stellar Interferometer (1986)





Mark III
Stellar Interferometer

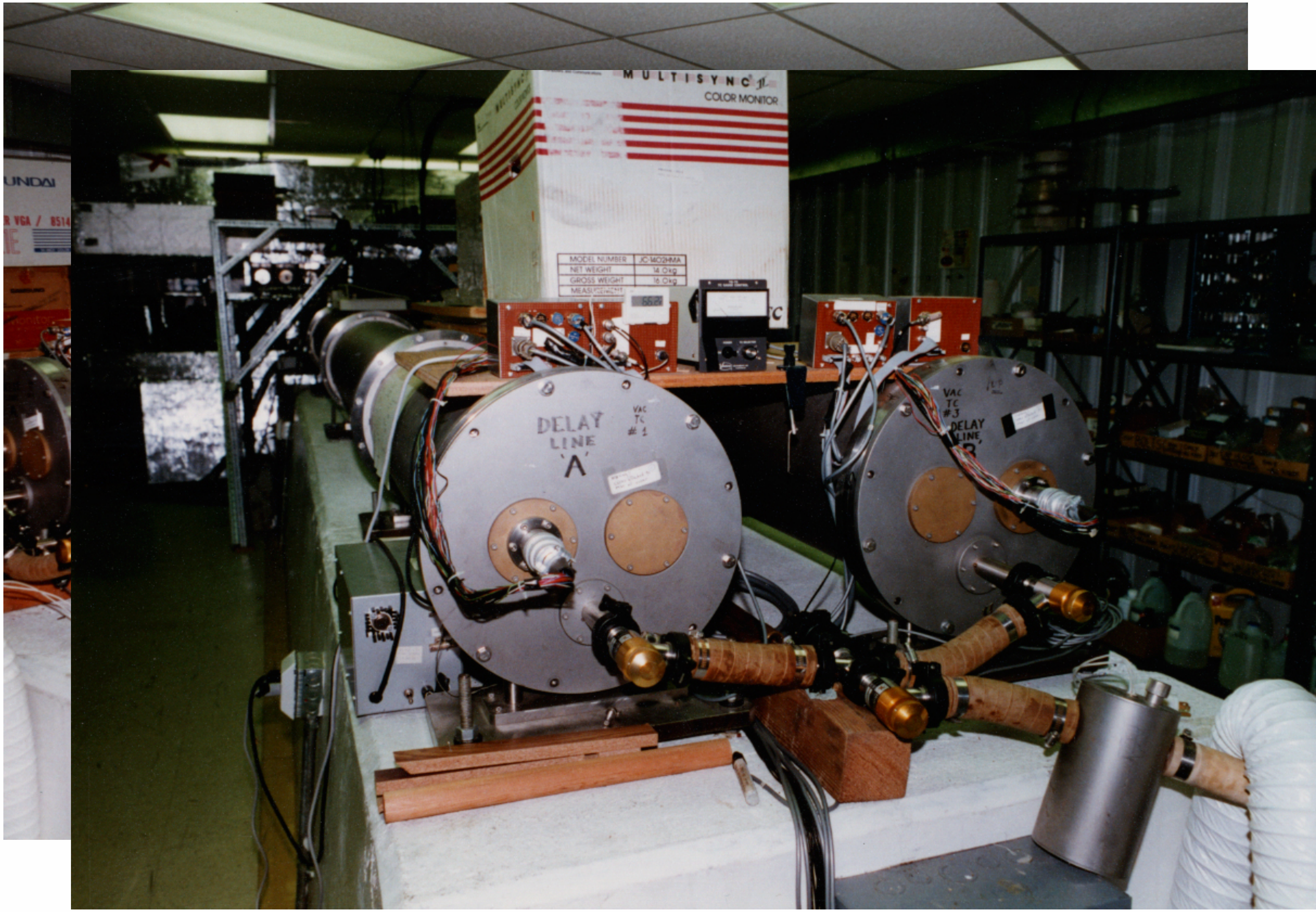


- Fringe tracking (Mark I, 1979)
- Delay lines (Mark II, 1982)
- Automated observing

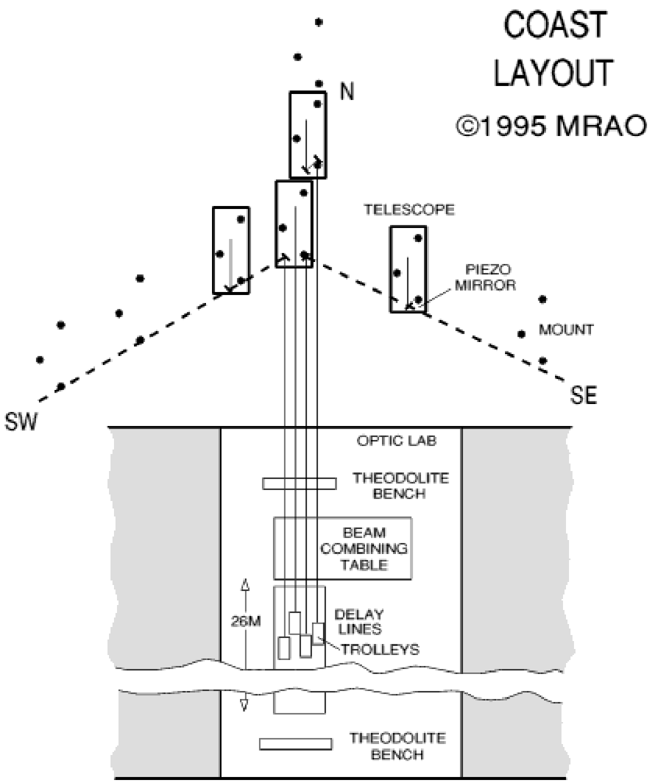
M. Shao et al. "The Mark III stellar interferometer," Astron. Astrophys. 193, 357-371 (1988)

HISTORY of Stellar Interferometry

Delay Lines of the Mark III (Photographed 1997)

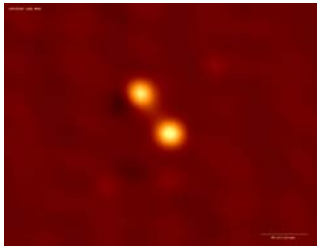


Interferometric Imaging

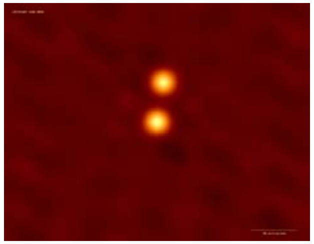


Cambridge Optical Aperture Synthesis Telescope (COAST)

Optical Synthesis Images of Capella



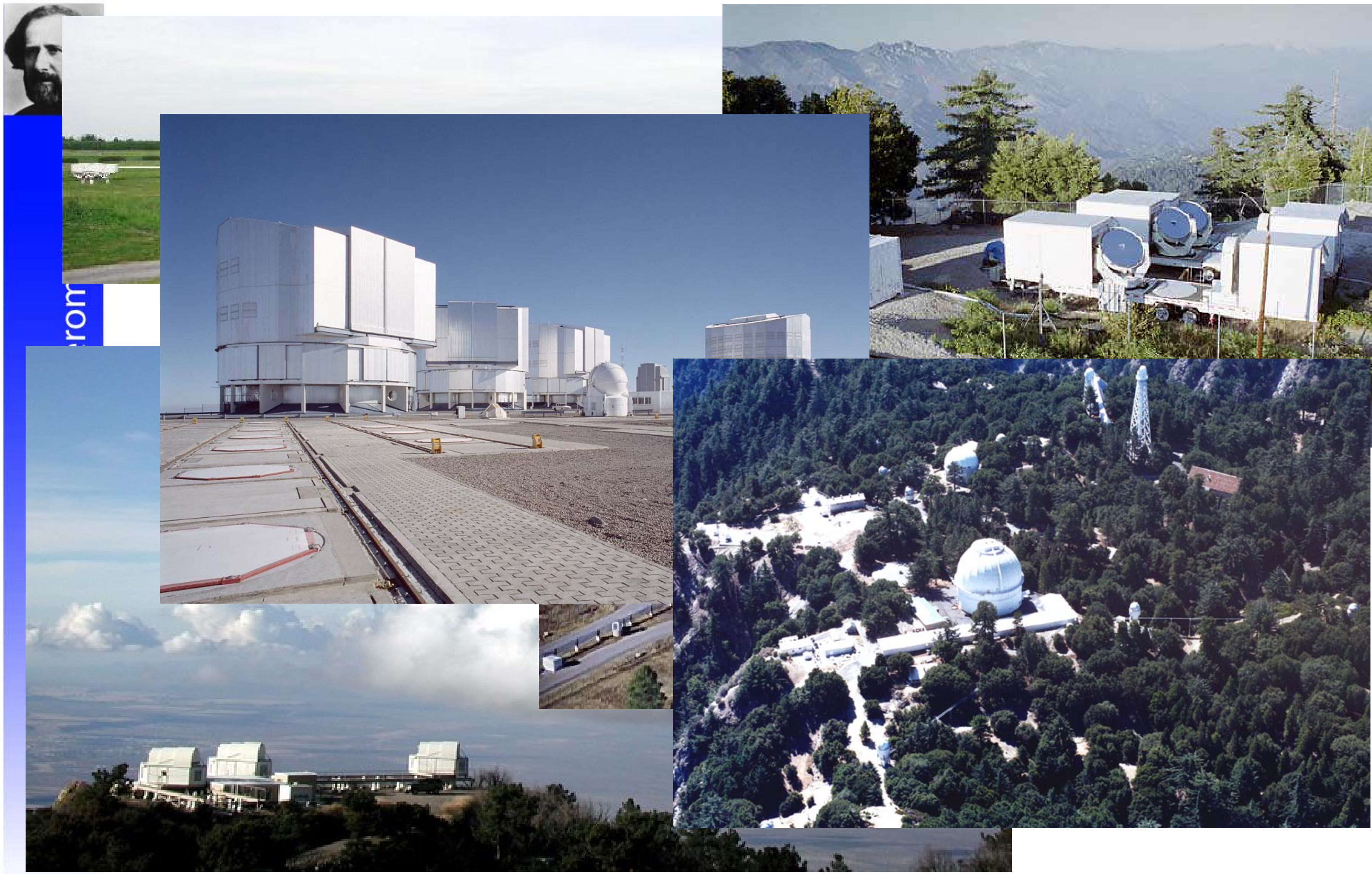
13 Sept. 1995



28 Sept. 1995

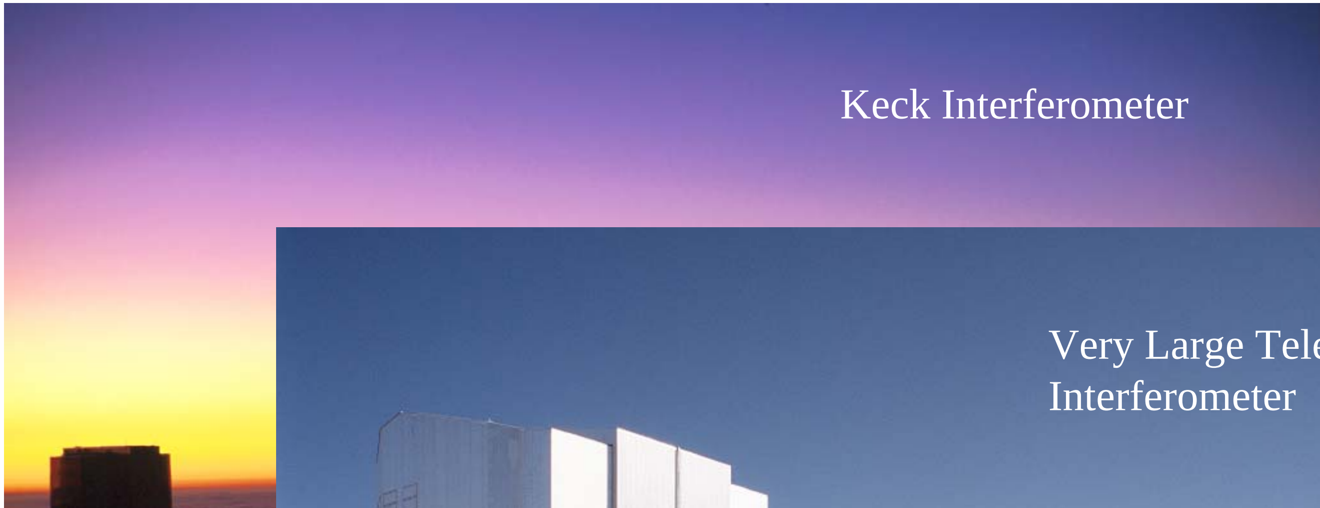
J.E. Baldwin et al., “The first images from an optical aperture synthesis array: mapping of Capella with COAST at two epochs,” Astron. Astrophys. 306, L13-L16

Imaging Interferometers (1995-2006)



2001: World-Class Observatories

HISTORY of Stellar Interferometry



Mark III to Astrometry and Planet Finding

HISTORY of Stellar Interferometry

Advanced telescope searches for Extrasolar Planets and habitable environments.

• Primary Goals

— Detect and characterize Earth-like exo-planets
— Understand the formation, history and distribution of planetary systems in our Galaxy.

• Secondary Goal

— Understanding of the formation and evolution of stars, planets and galaxies.

KECK

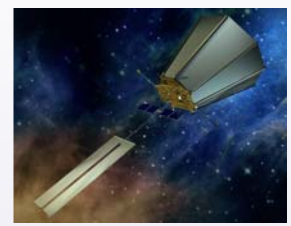
- Characterize inner exo-zodiacal dust environments
- Identify long-period planets, "warm-Jupiters"

LBTI

- Characterize outer dust environments
- Observe giant planets

SIM PlanetQuest

- Search for terrestrial planets
- Characterize planetary systems
- Determine planet mass

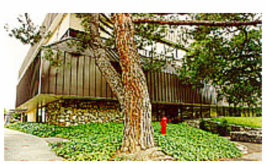


TPF-C

- Detect Earth-like planets in visible light
- Characterize planet atmospheres
- Assess habitability

TPF-I

- Detect Earth-like planets in infrared light
- Characterize planet atmospheres
- Search for indicators of life

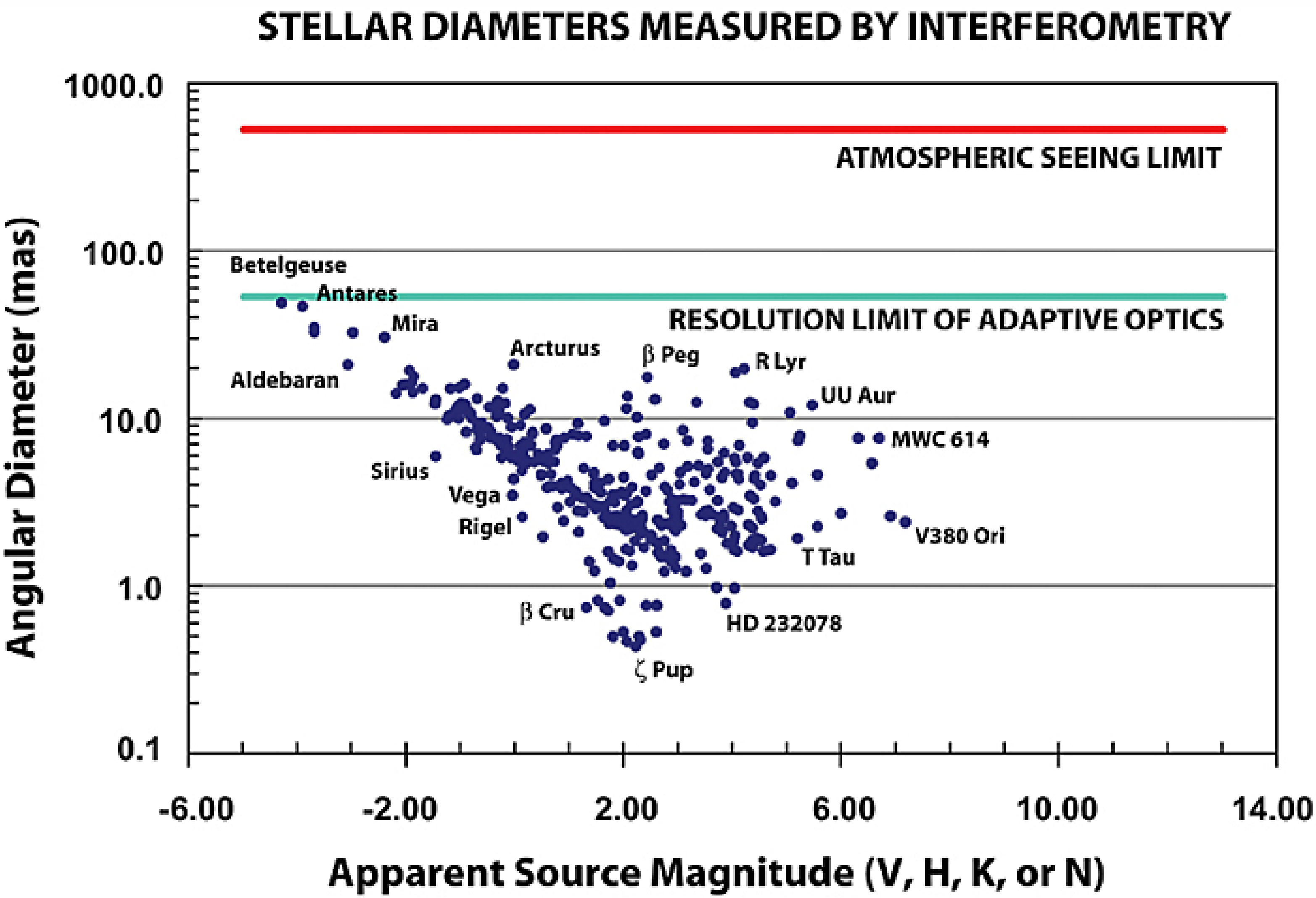


Michelson Science Center

- Science community development
- Science operations for Navigation missions
- Multi-mission tools and science data archives to support Navigation Program projects and science community.

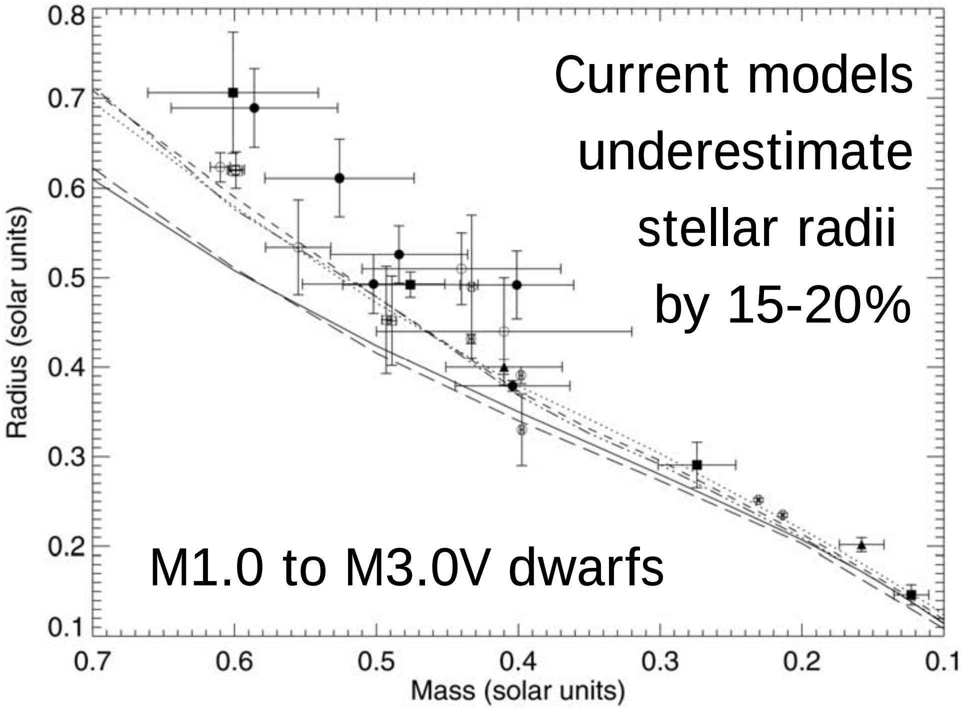
Angular Diameters of Stars

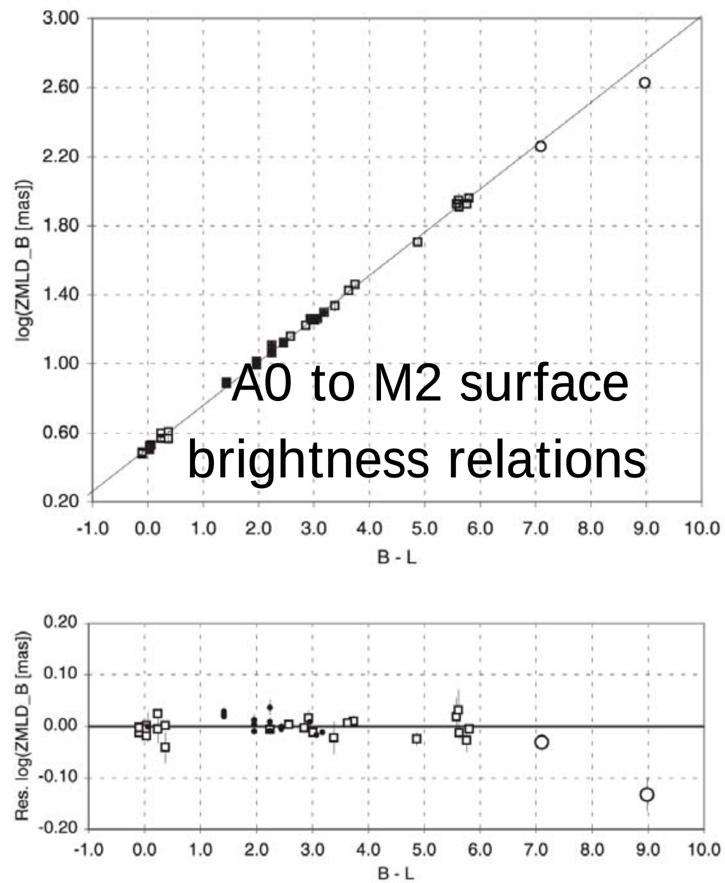
HISTORY of Stellar Interferometry



Dwarf and Subgiant Stars

HISTORY





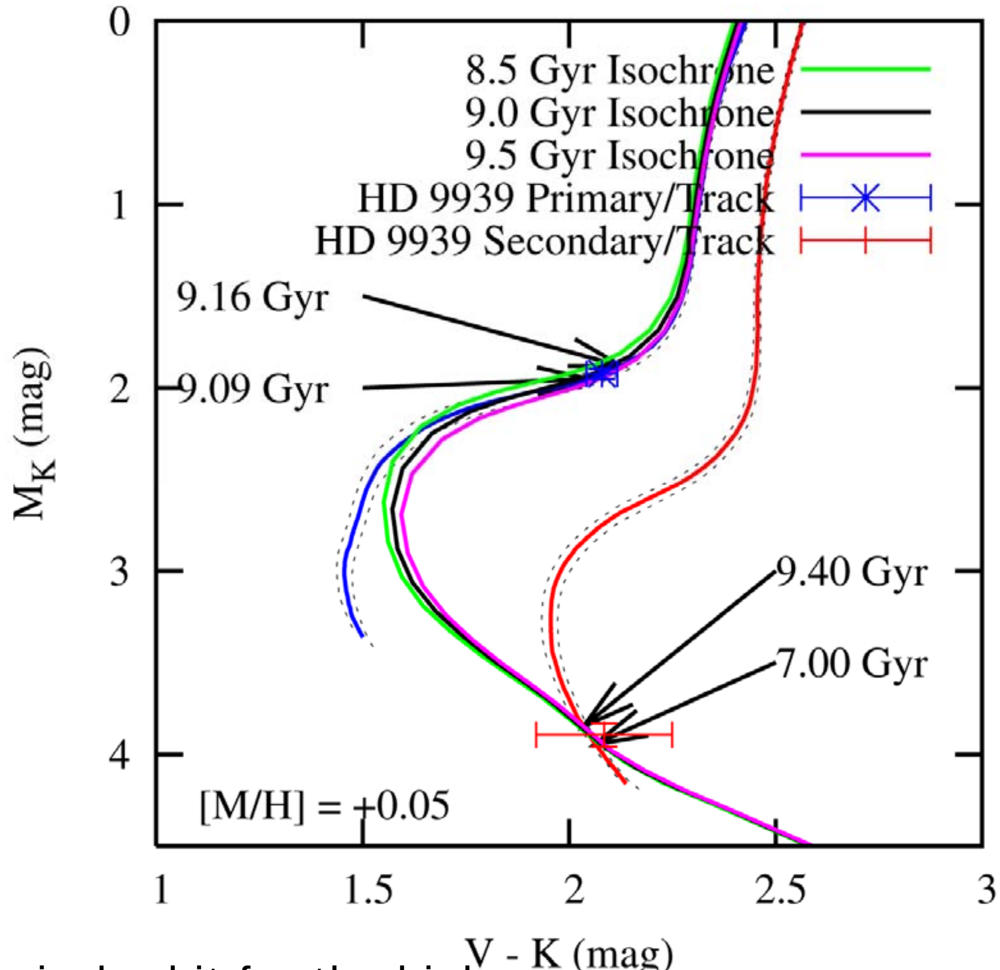
- D. Berger *et al*. "First results from CHARA Array IV. The interferometric radii of low-mass stars," Astrophys. J. in press (2006)

- P. Kervella *et al*. "The angular sizes of dwarf stars and subgiants," Astron. Astrophys. 426, 297-307 (2004)

Binaries & Stellar Evolution

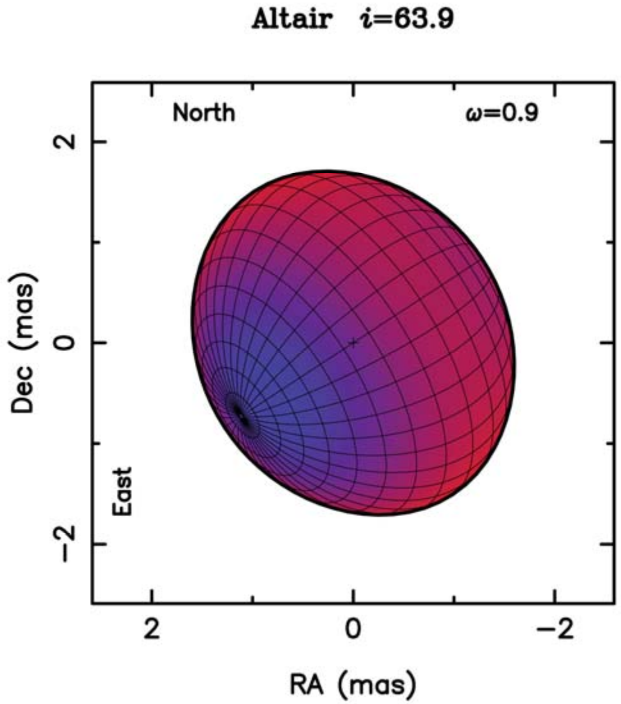
HISTORY of Stellar Interferometry

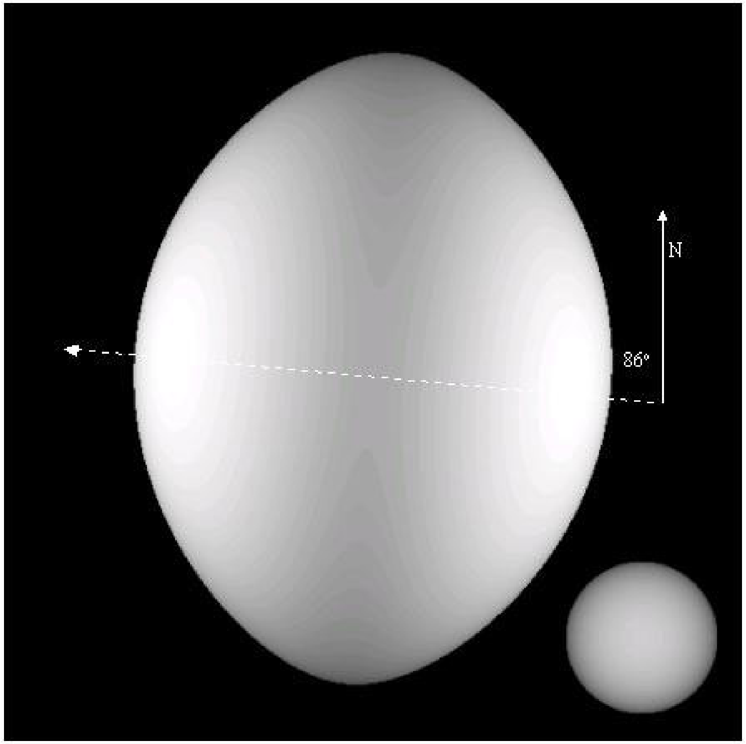
- HD 9939 has evolved off the main sequence approaching red giant phase
- Age of primary 9.12 ± 0.25 Gyr



- A. Boden *et al*. “A physical orbit for the high proper motion binary HD 9939,” Astrophys. J., in press (2006)

Rapidly Rotating Stars



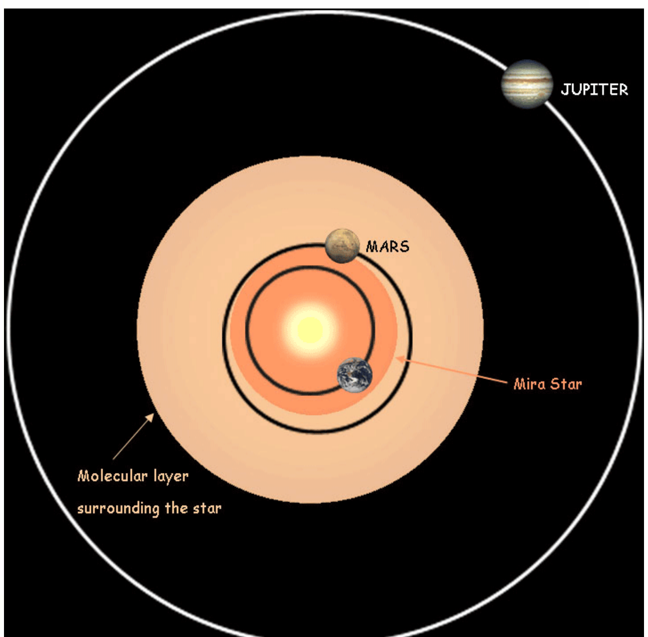


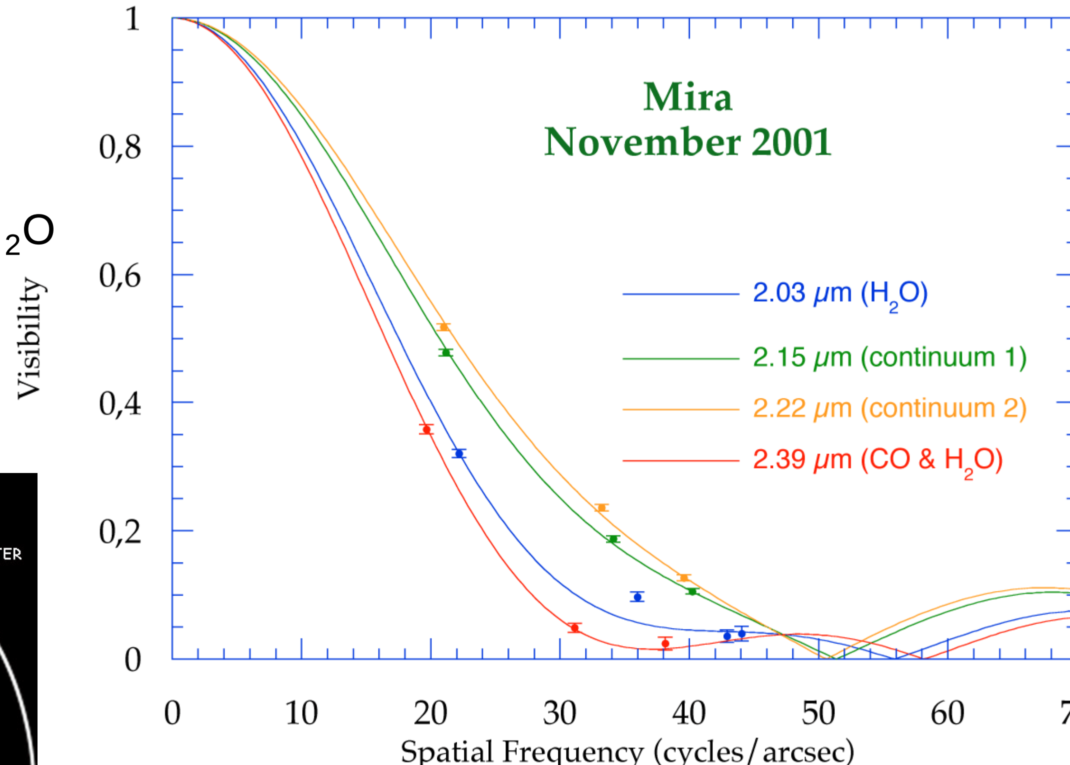
- A. Domiciano de Souza *et al*. “Gravitational-darkening of Altair from interferometry,” Astron. Astrophys. 442, 567-578 (2005)
- D. Peterson *et al*. “Resolving the effects of rotation in Altair with long-baseline interferometry,” Astrophys. J. 636, 1087-1097 (2006)
- H.A. McAlister *et al*. “First results from the CHARA Array. I. An interferometric and spectroscopic study of the fast rotator a Leonis (Regulus),” Astrophys. J. 628, 439-452 (2005)

Water around Miras and Supergiants

HISTORY of Stellar Interferometry

- J. Weiner "Mira's apparent size variations due to a surrounding semiopaque H_2O layer," Astrophys. J. 611, L37-L40 (2004)

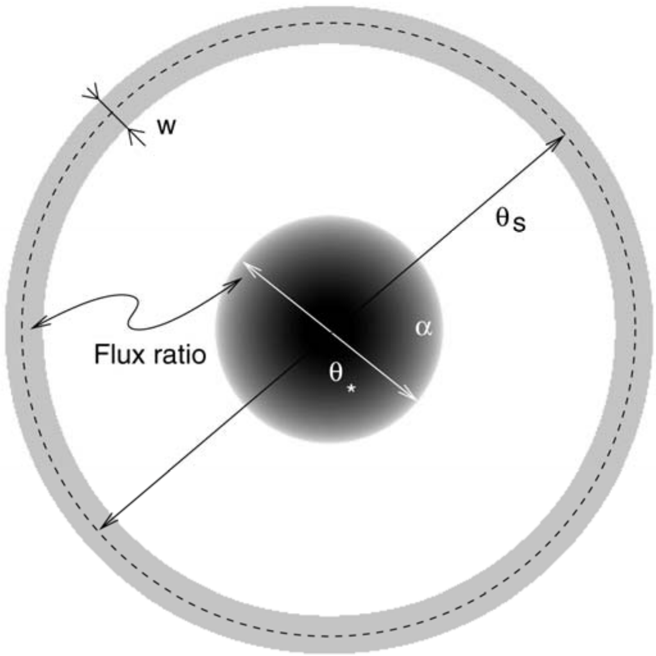


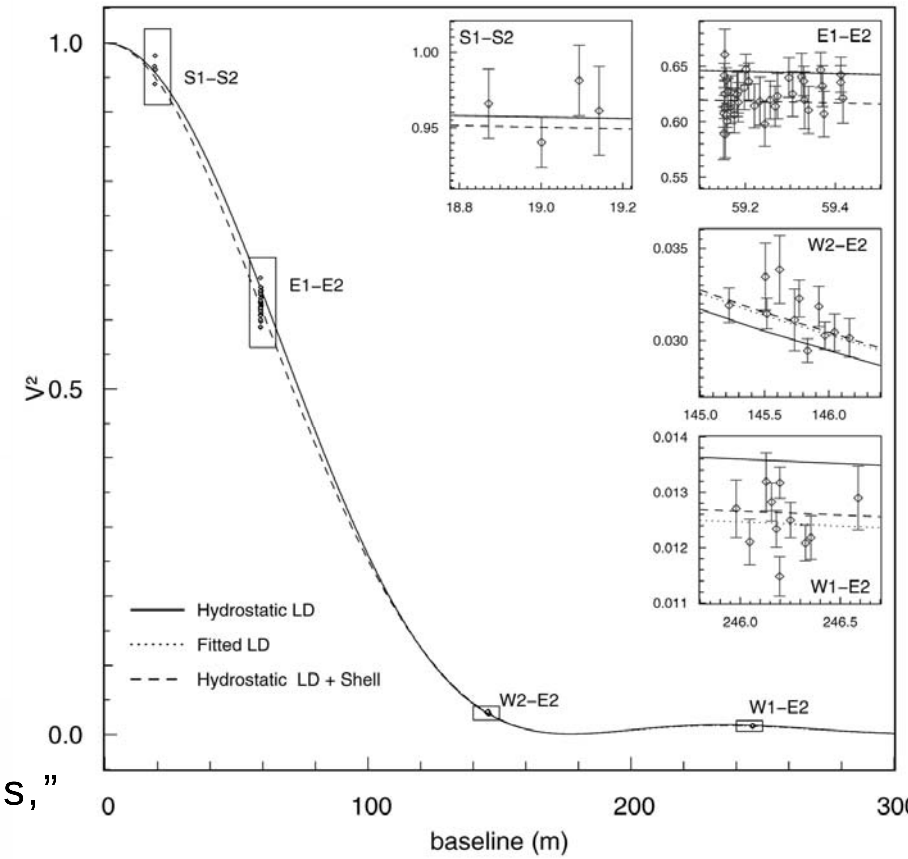


- G. Perrin *et al*. "Unveiling Mira stars behind the molecules," Astron. Astrophys. 426, 279-296 (2004)
- G. Perrin *et al*. "Study of molecular layers in the atmosphere of the supergiant star u Cep by interferometry in the K band," Astron. Astrophys. 436, 317-324 (2004)

Envelopes around Cepheids

HISTORY of Stellar Interferometry

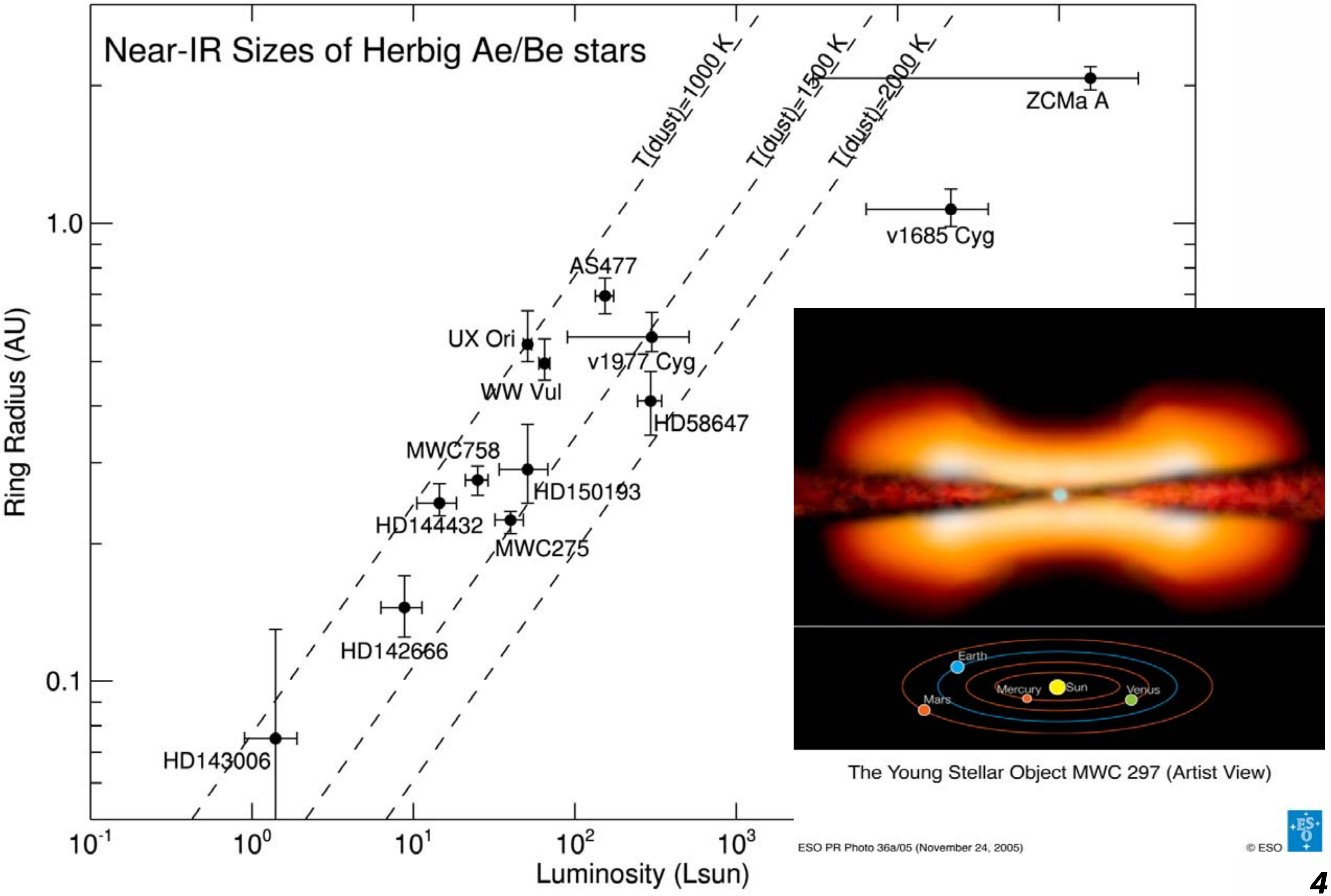




- P. Kervella *et al*. “Extended envelopes around galactic Cepheids,” Astron. Astrophys. 448, 623-631 (2006)
- A. Merand *et al*. “Entended envelopes around galactic Cepheids,” Astron. Astrophys. In press (2006)

Models of Young Stellar Objects

HISTORY of Stellar Interferometry



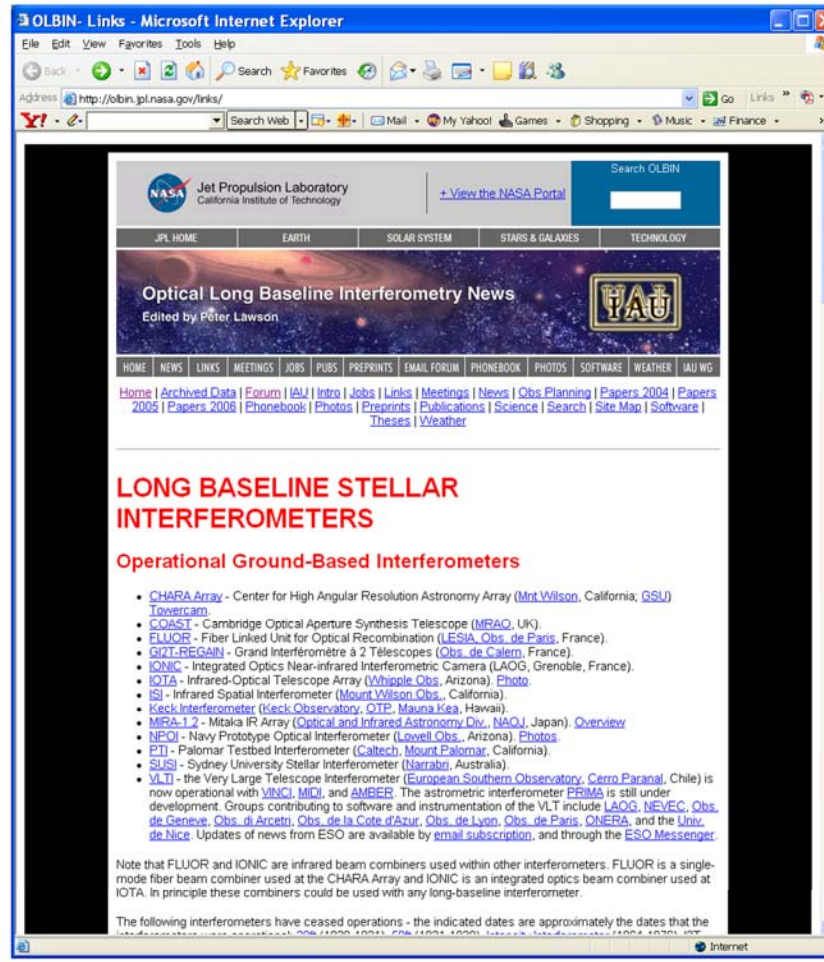
The Young Stellar Object MWC 297 (Artist View)

ESO PR Photo 36a/05 (November 24, 2005)

Acknowledgments

HISTORY of Stellar Interferometry

- Work by PRL was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.



- http://olbin.jpl.nasa.gov/

Additional Reading

- D. H. De Vorkin, “Michelson and the problem of stellar diameters,” Journal for the History of Astronomy **6** (1), 1-18 (1975).
- Selected Papers on Long Baseline Stellar Interferometry P.R. Lawson, editor (SPIE Milestone Series, MS **139**) SPIE Press, 1997
- P.R. Lawson, “Optical Interferometry Comes of Age,” Sky and Telescope, May 2003.
- P.R. Lawson, “Advances with Stellar Interferometers 2004-2006,” SPIE Conf. **6268** *Advances with Stellar Interferometers* (2006).