A Brief History of Astronomical Interferometry in the Optical

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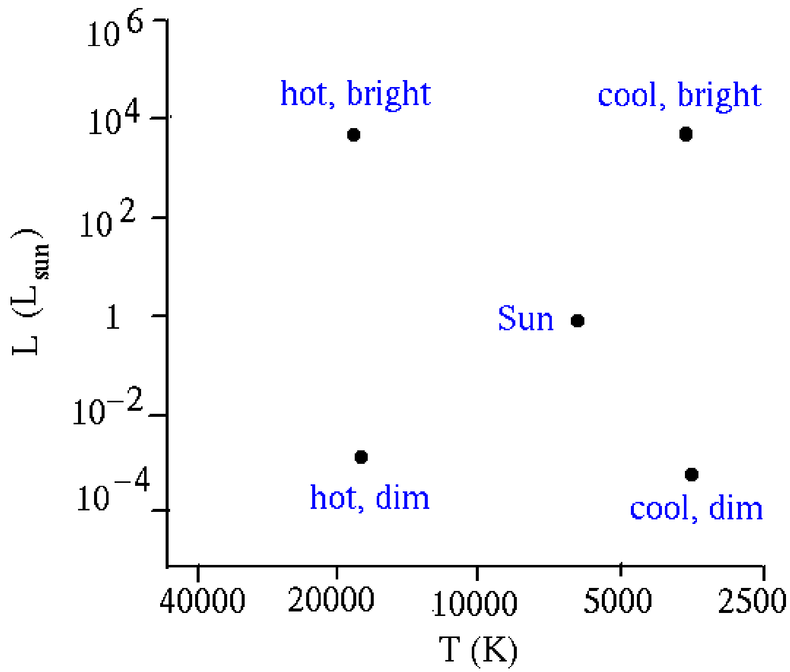
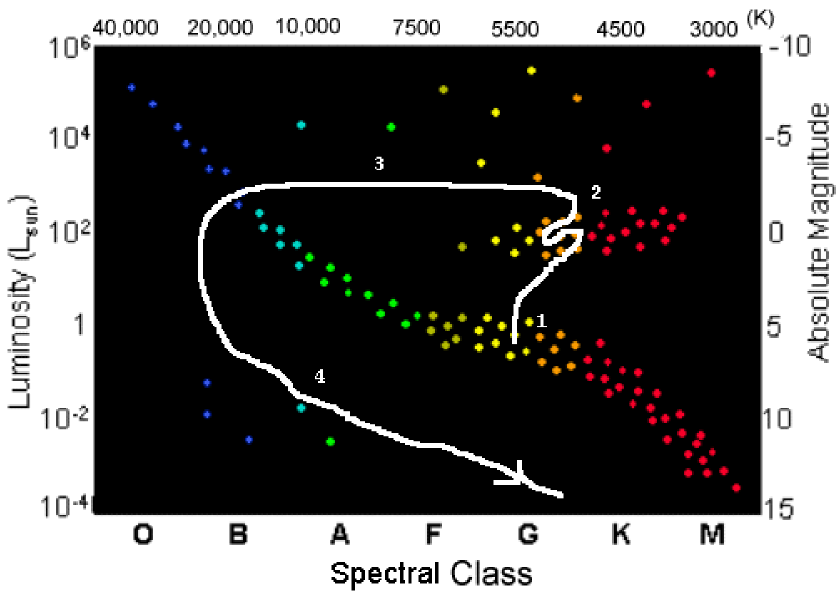
Why Astronomical Interferometry?

- No, really, why?
  - It's hard to do
  - Therefore, it's expensive
  - Its produces limited results
  - As telescopes grow, sensitivity and spatial resolution increase
- Here's why:
  - →But not impossible
  - →Yet there are solutions to that, too
  - →But results you can't get anywhere else
  - →Interferometers allow you to skip the increased sensitivity

Why Astronomical Interferometry?

Which HR Diagram do you prefer?



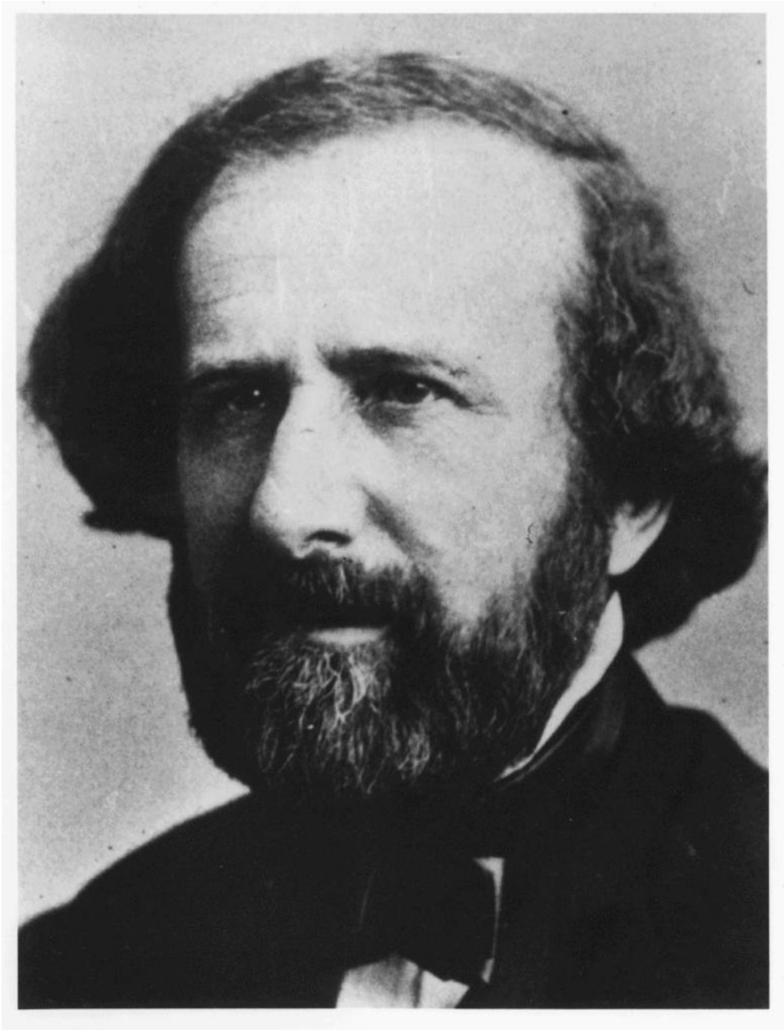


Why the History of Astronomical Interferometry?

- Sporadic development path is rather unusual
  - Clearer understanding of the starts – and stops – useful in avoiding bad outcomes
- "Those who cannot remember the past are condemned to repeat it." (Santayana 1905)
- About as colorful as any niche in astronomy
  - Given astronomy, that's saying a lot

Fizeau

- Armand-Hippolyte-Louis Fizeau (1819-1896)
  - First to develop reliable method for determination of speed of light (1849, with Foucault)



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.

- 1868 – Fizeau suggests the possibility of stellar interferometry.

PRIZE BORDIN.

QUESTION SUGGESTED IN 1865 FOR 1867

(Chiefs: Misters Duhamel, Pouillet, Regnault, Bertrand,
Edmond Becquerel; Fizeau reporting)

Report on the Contest of the year 1867

"The prize will be decreed with the scientist who will have carried out or proposed a decisive experiment allowing definitively to solve the question already several times studied of the direction of the vibrations of ether in the polarized rays"

There exists indeed for the majority of the phenomena of interference, such as the fringes of Yung, those of the mirrors of Fresnel and those which give place to the scintillation of stars according to Arago, a relation remarkable and necessary between the dimension of the fringes and that of the source of light, so that fringes of an extreme tenuity cannot occur due when the source of light has nothing any more but almost insensitive angular dimensions; from where to say it while passing, it is perhaps allowed to hope that while being based on this principle and while forming for example, by means of two broad very-isolated slits, of the interference rings to the hearth of the large instruments intended to observe stars, it will become possible to obtain some new data on the angular diameters of these stars.

- 1868 – Fizeau suggests the possibility of stellar interferometry.

Stephan

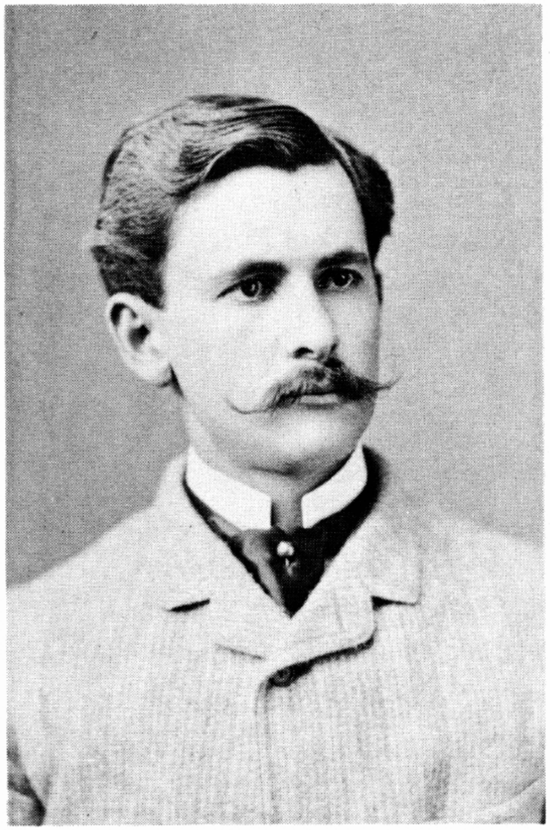
- Édouard Stephan (1837-1923)
  - Followed up Fizeau's idea to measure stellar diameters (1873)
  - Only found upper limit of θ<0.158"

80 cm Foucault Reflector

- Significance of Stephan's work
  - 65 cm aperture separation
  - Observed most stars down to 4th magnitude
  - All stars produced distinct fringes
- 1896 M. Hamy performs similar measurements at the Observatoire de Paris

Michelson

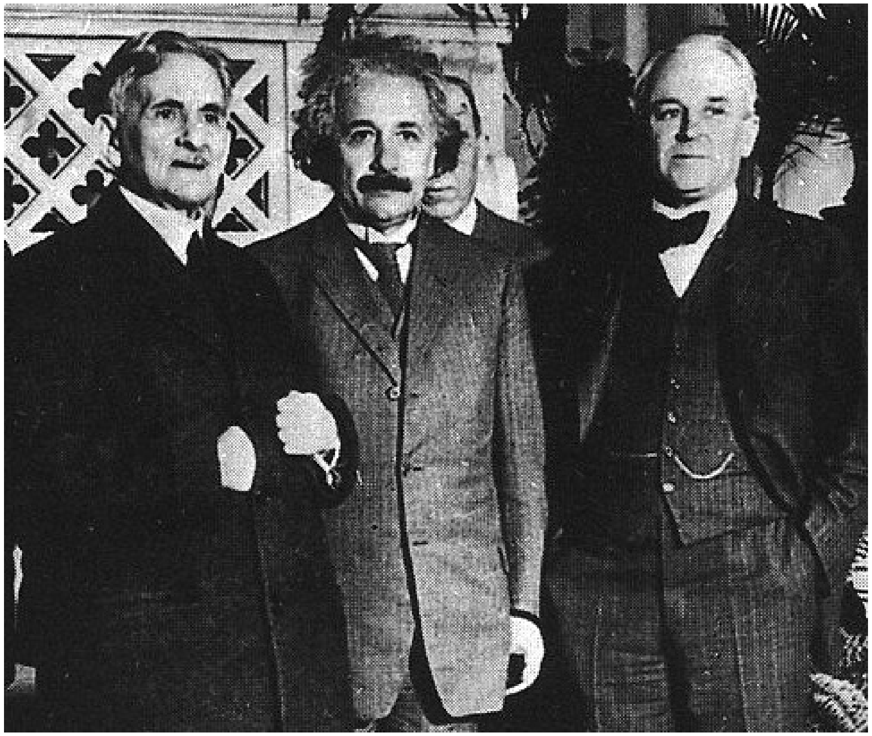
- Albert Abraham Michelson (1852-1931)
- Scientific Achievements
  - Measured speed of light 200 times more accurately than previous measurements (1878)
  - Invented Interferential Refractometer in Berlin while on leave from Naval Academy (1880)
  - Michelson-Morley experiment (1887)



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

Michelson II.

- Scientific Achievements (continued)
  - Described mathematical basis of stellar interferometry (1890)
  - Measured diameters of Jupiter's moons (1891)
  - Received Nobel Prize in physics (1907)
  - Measured diameter of Betelgeuse with the 20 ft Interferometer (1920)



A.A. Michelson, R.A. Millikan and friend

Jovian Moon Diameters

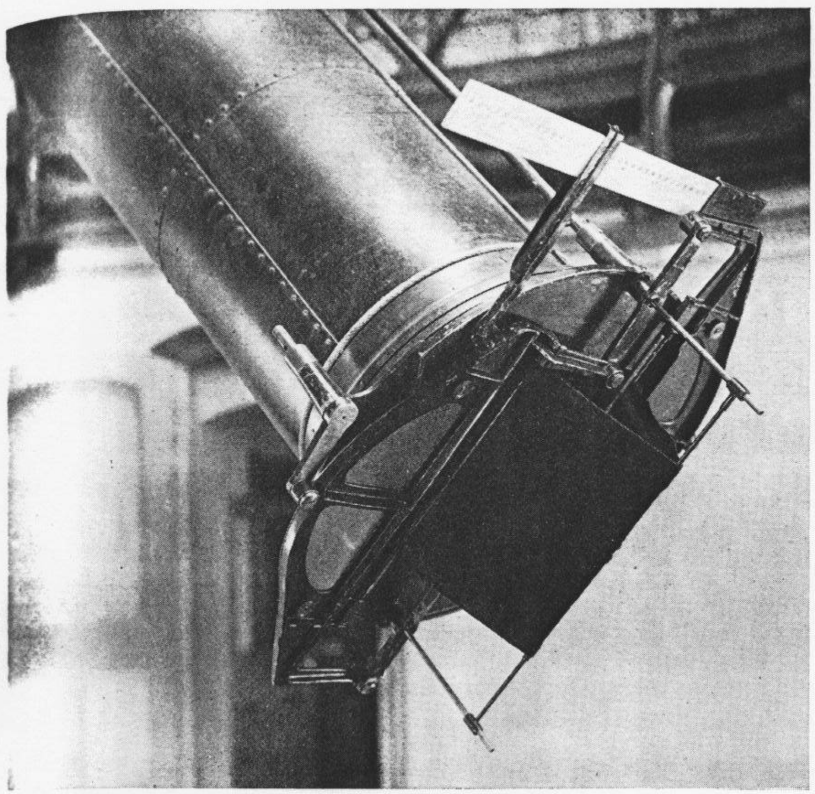
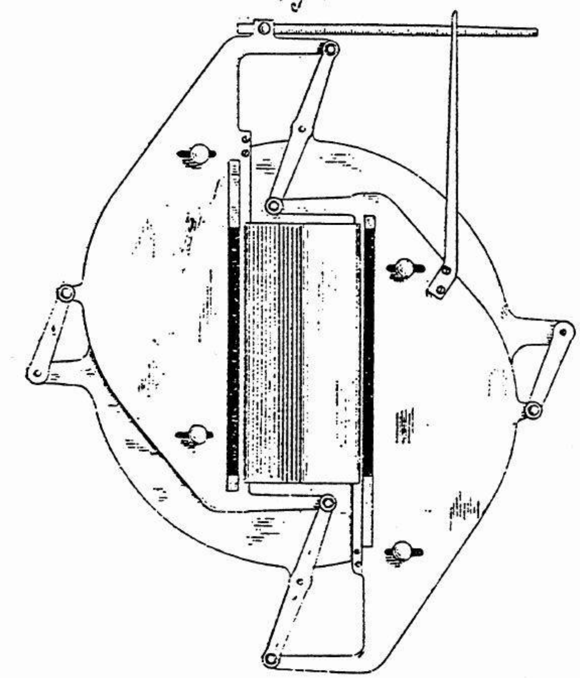


FIG. 1. Interferometric mask used on the 12-inch refractor at Lick Observatory to measure the angular diameters of the Jovian satellites. The rod adjacent to the telescope tube is turned by the observer, which in turn rotates a lever connecting the two slits immediately exterior to the pictured objective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

Fig 3



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	

Hooker Reflector - Mount Wilson

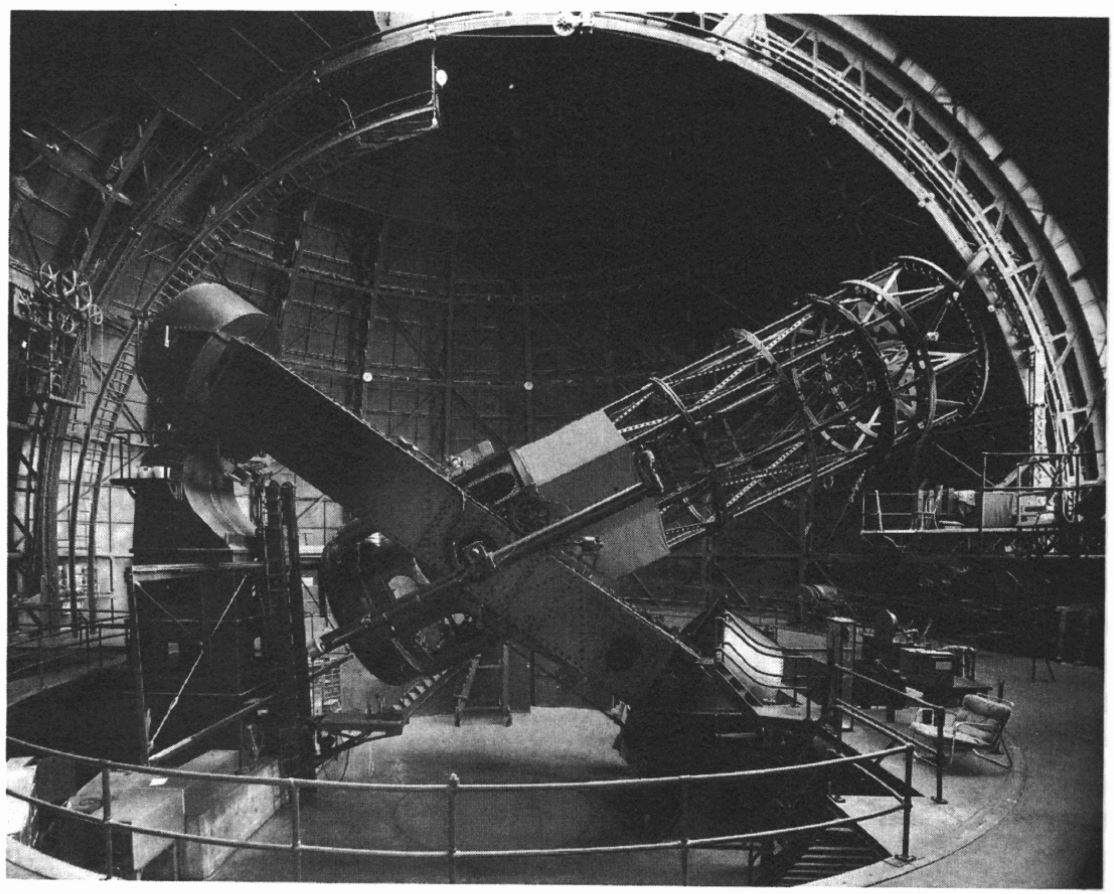


Figure 13.5 *The 100 inch (2.5 m) Hooker reflector on Mount Wilson, completed in 1917. (Courtesy* The Observatories of the Carnegie Institution of Washington.*)*

Experimental Sketch

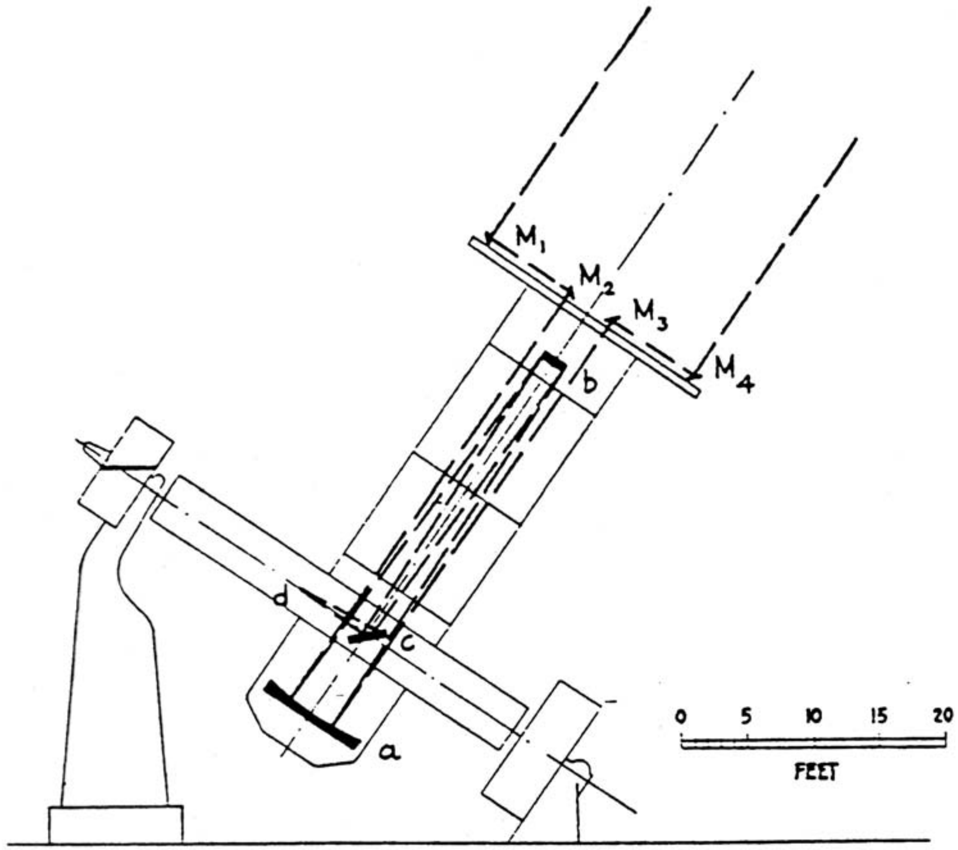


FIG. 1.—Diagram of optical path of interferometer pencils. M_1, M_2, M_3, M_4, mirrors; *a*, 100-inch paraboloid; *b*, convex mirror; *c*, coudé flat; *d*, focus.

20’ Beam Interferometer

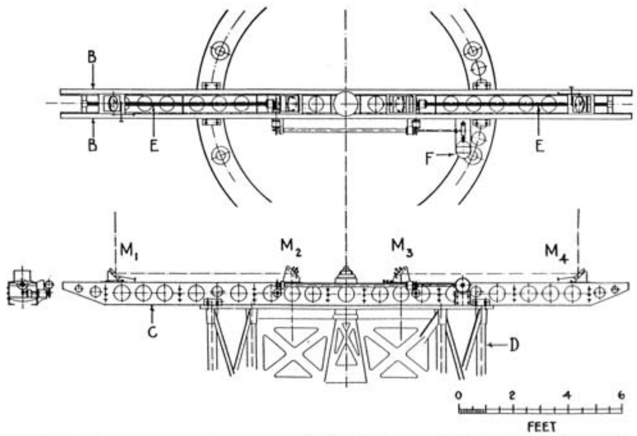
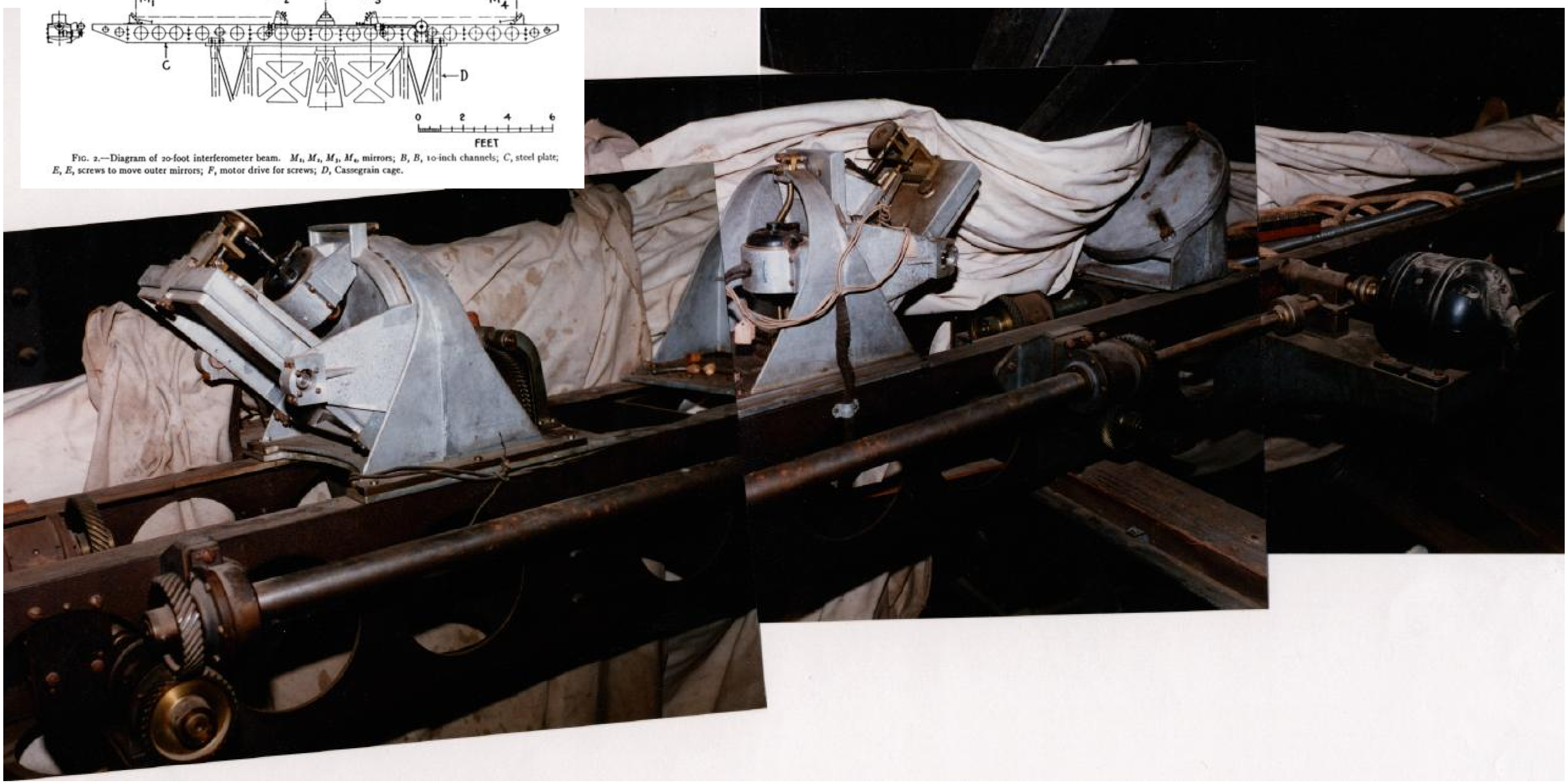


Fig. 2.—Diagram of 20-foot interferometer beam. M_1, M_2, M_3, M_4, mirrors; B, B, 10-inch channels; C, steel plate; E, E, screws to move outer mirrors; F, motor drive for screws; D, Cassegrain cage.



Experimental Notebook

Note Graduate Student

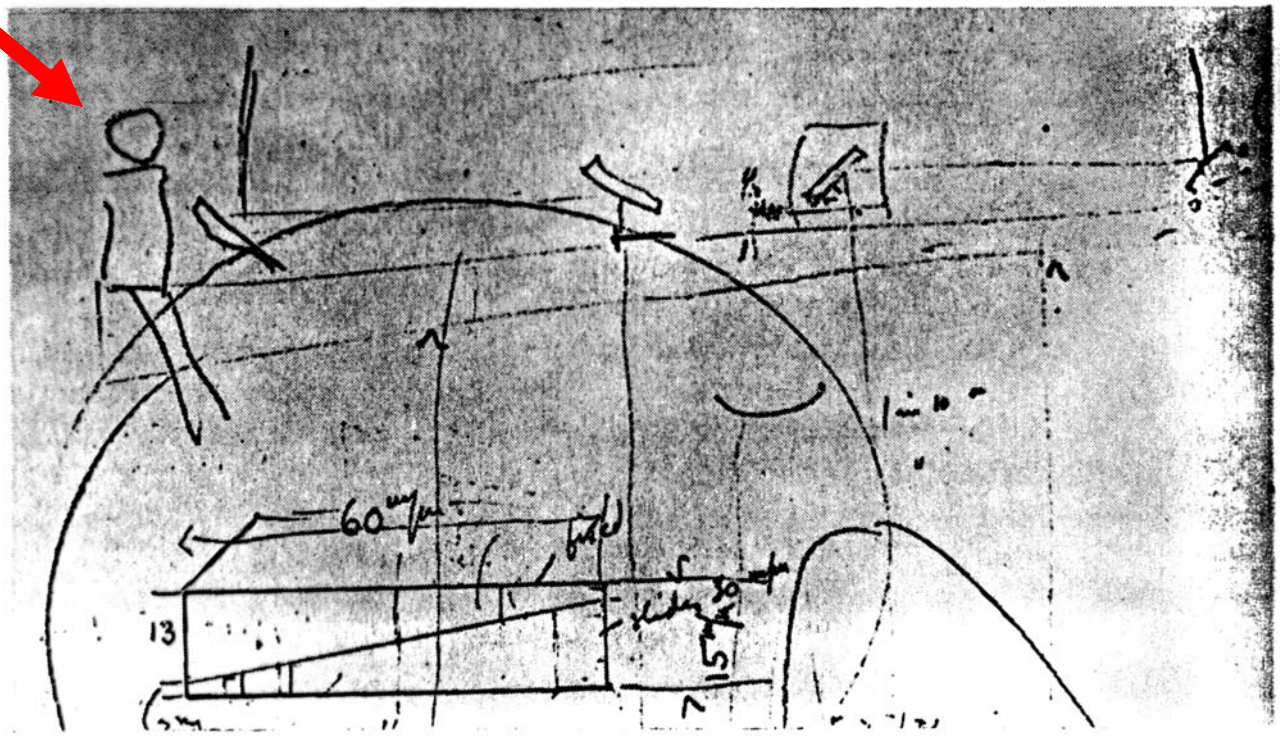
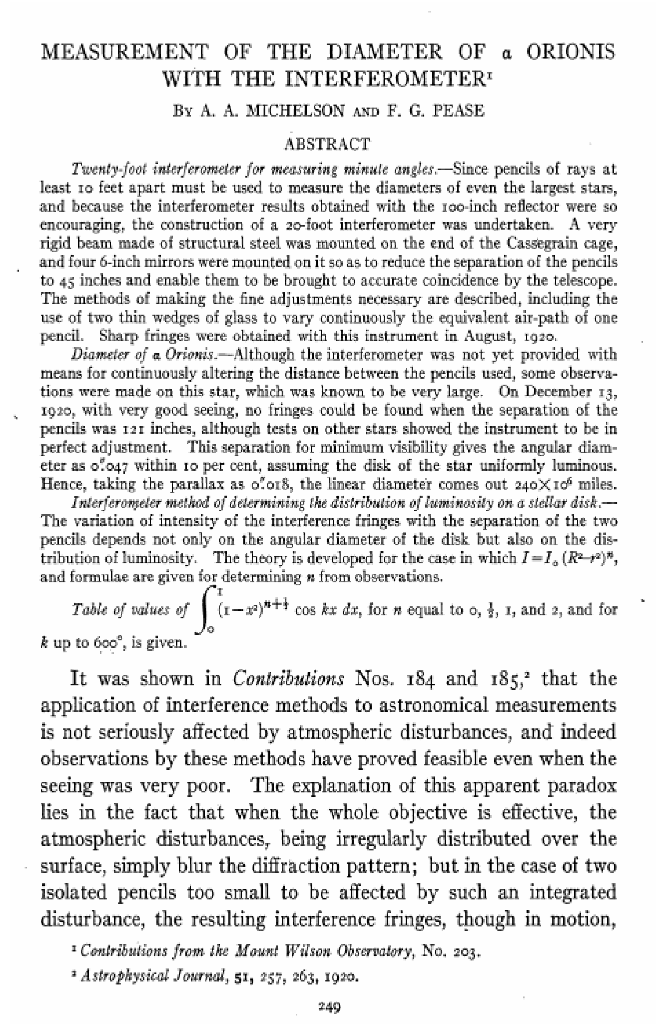


FIG. 3. From F. G. Pease, Notebook 1, sheet 42; approximate date 14 July 1920 (Hale Observatories, copy in Michelson Museum). Crude drawings of the optical wedge used to equalise path length. Note the superimposed sketch illustrating how the night assistant must be perched to move the mirrors on the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

Betelgeuse Result

- Found α Ori to be quite large – ~50mas
- Also measured the diameters of 6 other stars
- Available on the ADS!
  - Michelson & Pease, 1921, ApJ, 53, 249
  - Pease, 1921, PASP, 33, 171 & 204
  - Pease, 1921, PASP, 34, 183 & 346



MEASUREMENT OF THE DIAMETER OF α ORIONIS WITH THE INTERFEROMETER[1]

BY A. A. MICHELSON AND F. G. PEASE

ABSTRACT

Twenty-foot interferometer for measuring minute angles.—Since pencils of rays at least 10 feet apart must be used to measure the diameters of even the largest stars, and because the interferometer results obtained with the 100-inch reflector were so encouraging, the construction of a 20-foot interferometer was undertaken. A very rigid beam made of structural steel was mounted on the end of the Cassegrain cage, and four 6-inch mirrors were mounted on it so as to reduce the separation of the pencils to 45 inches and enable them to be brought to accurate coincidence by the telescope. The methods of making the fine adjustments necessary are described, including the use of two thin wedges of glass to vary continuously the equivalent air-path of one pencil. Sharp fringes were obtained with this instrument in August, 1920.

Diameter of α Orionis.—Although the interferometer was not yet provided with means for continuously altering the distance between the pencils used, some observations were made on this star, which was known to be very large. On December 13, 1920, with very good seeing, no fringes could be found when the separation of the pencils was 121 inches, although tests on other stars showed the instrument to be in perfect adjustment. This separation for minimum visibility gives the angular diameter as 0″047 within 10 per cent, assuming the disk of the star uniformly luminous. Hence, taking the parallax as 0″018, the linear diameter comes out 240×10^6 miles.

Interferometer method of determining the distribution of luminosity on a stellar disk.—The variation of intensity of the interference fringes with the separation of the two pencils depends not only on the angular diameter of the disk but also on the distribution of luminosity. The theory is developed for the case in which $I=I_0\,(R^2-r^2)^n$, and formulae are given for determining n from observations.

Table of values of $\int_0^1 (1-x^2)^{n+\frac{1}{2}} \cos kx\, dx$, for n equal to 0, $\frac{1}{2}$, 1, and 2, and for k up to 600°, is given.

It was shown in *Contributions* Nos. 184 and 185,[2] that the application of interference methods to astronomical measurements is not seriously affected by atmospheric disturbances, and indeed observations by these methods have proved feasible even when the seeing was very poor. The explanation of this apparent paradox lies in the fact that when the whole objective is effective, the atmospheric disturbances, being irregularly distributed over the surface, simply blur the diffraction pattern; but in the case of two isolated pencils too small to be affected by such an integrated disturbance, the resulting interference fringes, though in motion,

[1] *Contributions from the Mount Wilson Observatory*, No. 203.

[2] *Astrophysical Journal*, **51**, 257, 263, 1920.

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50’ Beam Interferometer

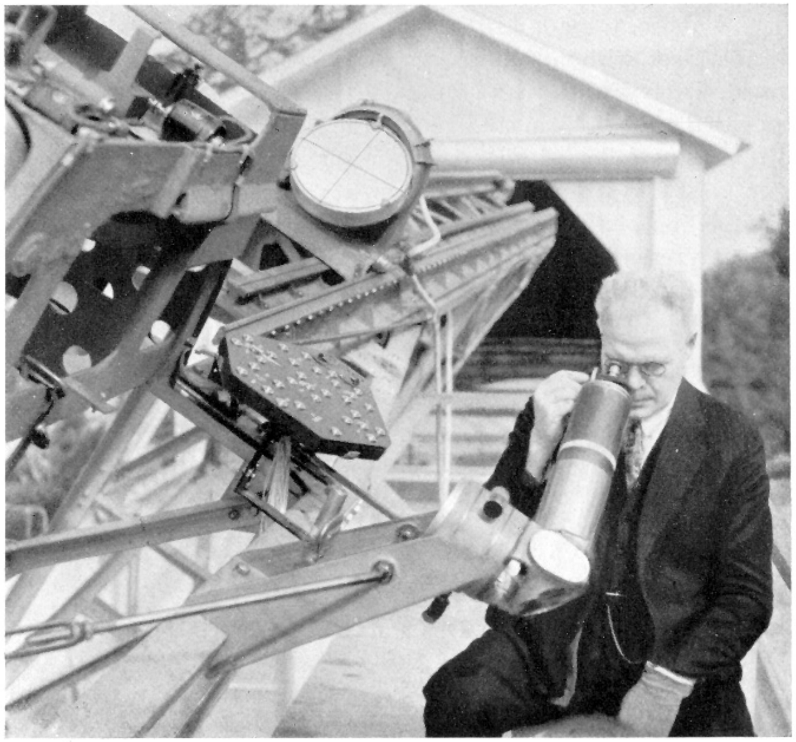


Abb. 9. Upper part of interferometer showing control board and observer at eyepiece.

Francis Pease at the observer’s station

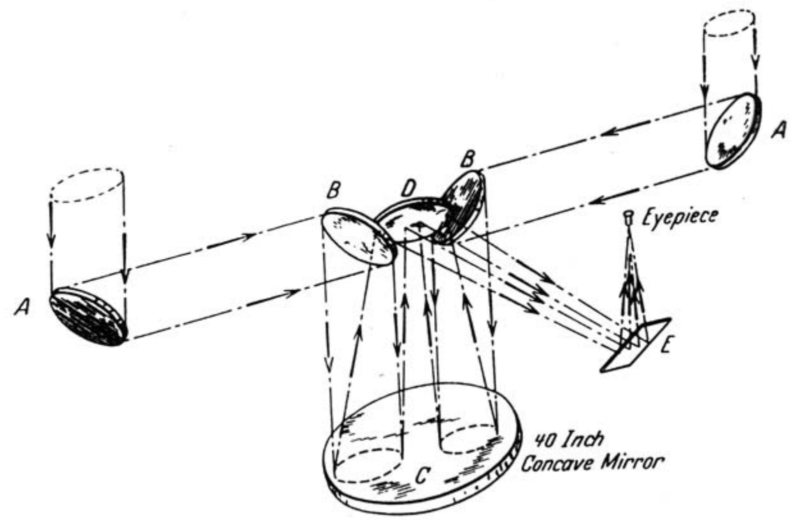
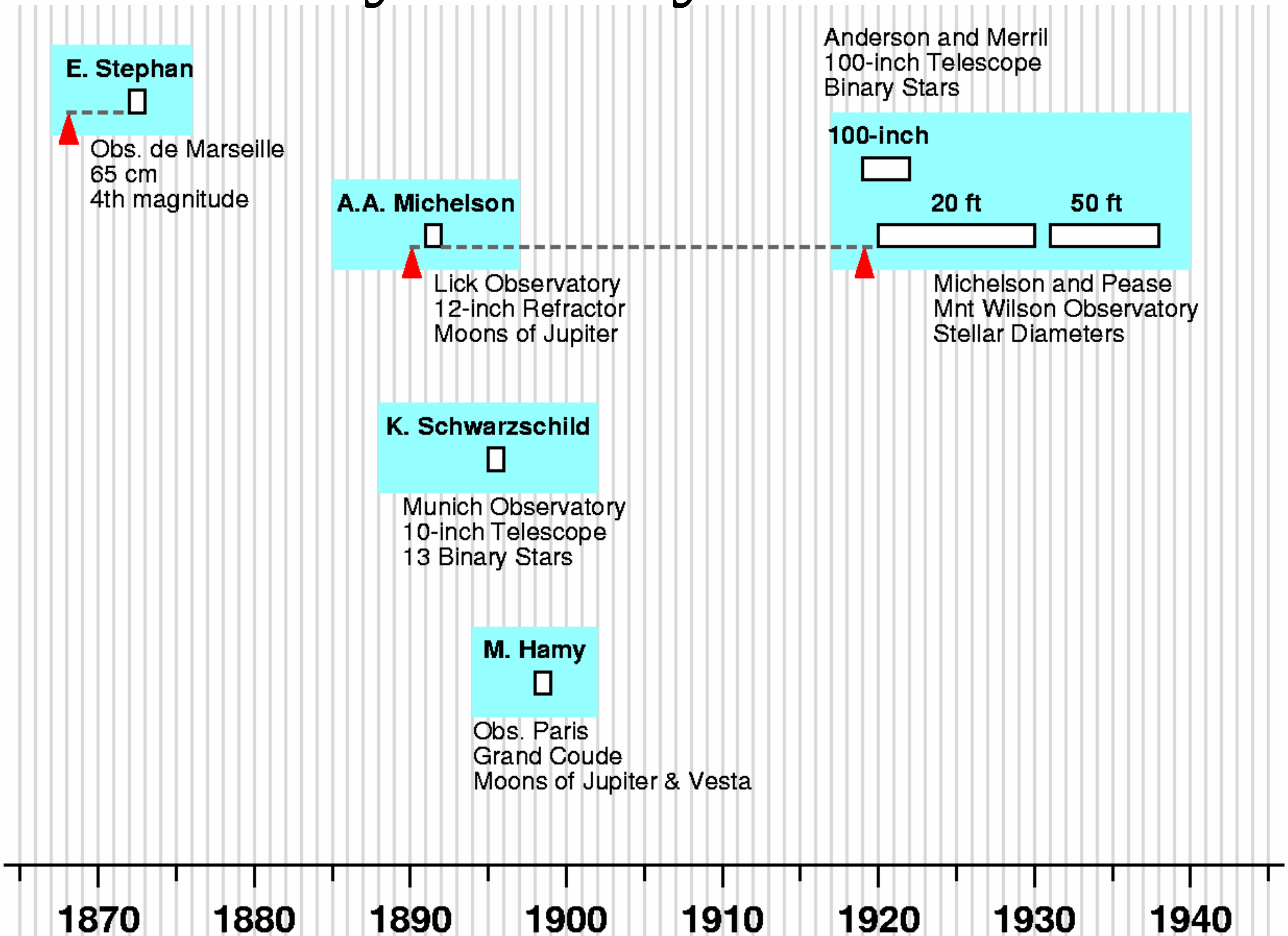


Abb. 8. Diagram of light path in 50 foot interferometer.

Optical layout of the 50’ beam interferometer

Early History Timeline



Hibernation for the Field (1)

- Between 1922 and 1968, virtually nothing published in the field
  - A few unrefereed letters from Pease
  - A few binary stars
- Optical interferometry effectively put into slumber by the 50' instrument

Development of the Intensity Interferometer

- Diameter of Sirius estimated from experiments at Jodrell Bank, UK (1956)
- 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

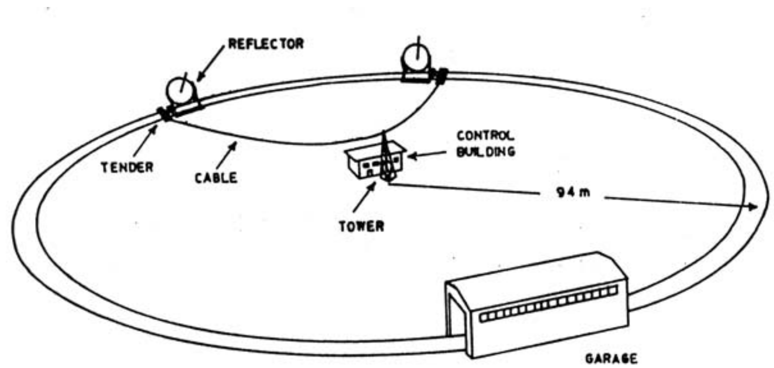
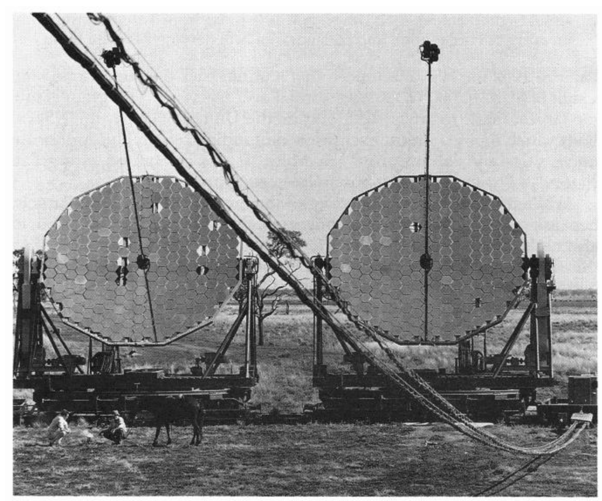
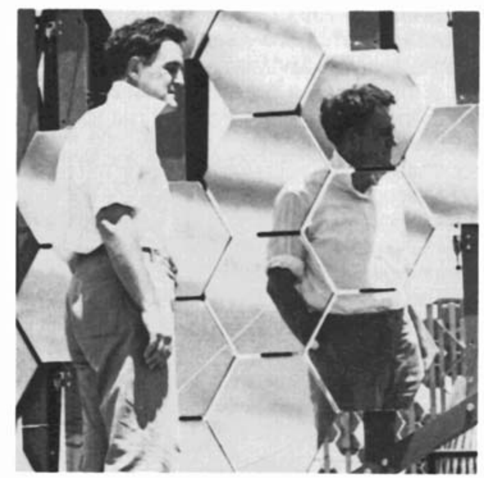


FIG. 7. The general layout of the interferometer at Narrabri Observatory.



The Intensity Interferometer

- Measured 32 stars to a limiting magnitude of B=+2.5, spectral types O-A inclusive, and accuracies of 1 or 2%
  - Remains the seminal paper to this day on main sequence diameters
  - Hanbury Brown, Davis & Allen, 1974, MNRAS, 167 121
- Measured orbit of Spica (α Vir)
  - Herbison-Evans, Hanbury Brown, Davis & Allen, 1971, MNRAS 151 161



Results from Narrabri

No. 1, 1974 *The angular diameters of 32 stars* 133

Table III

The uniform disc angular diameters, true angular diameters and normalized zero-baseline correlations for 32 stars

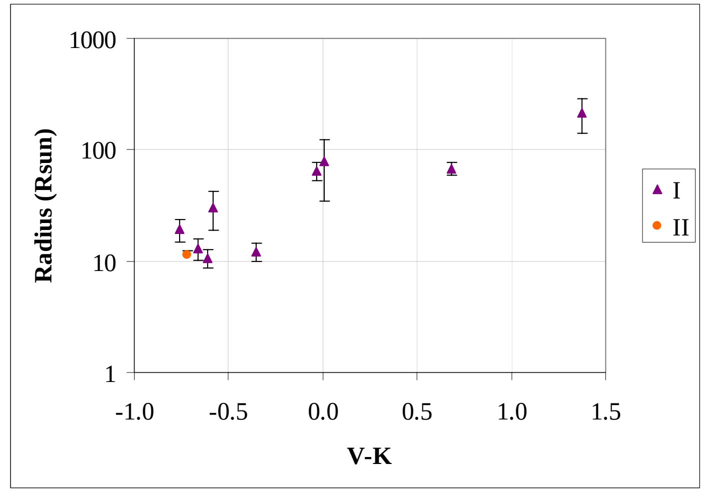
1	2	3	4	5	6
B.S.	Name	MK	$C_N \pm \sigma$ (normalized)	$\bar{\theta}_{UD} \pm \sigma$ (10^{-3} seconds of arc)	$\theta_{LD} \pm \sigma$ (10^{-3} seconds of arc)
472	α Eri	‡B3 Vp	0·98 ± 0·05	1·85 ± 0·07	1·92 ± 0·07
1713	β Ori	†B8 Ia	0·98 ± 0·08	2·43 ± 0·05	2·55 ± 0·05
1790	γ Ori	†B2 III	1·03 ± 0·07	0·70 ± 0·04	0·72 ± 0·04
1903	ε Ori	†B0 Ia	0·86 ± 0·07	0·67 ± 0·04	0·69 ± 0·04
1948	ζ Ori	**O9·5 Ib	0·60 ± 0·06	0·47 ± 0·04	0·48 ± 0·04
2004	κ Ori	†B0·5 Ia	1·18 ± 0·09	0·44 ± 0·03	0·45 ± 0·03
2294	β CMa	*B1 II–III	1·07 ± 0·08	0·50 ± 0·03	0·52 ± 0·03
2326	α Car	F0 Ib–II	0·75 ± 0·22	6·1 ± 0·7	6·6 ± 0·8
2421	γ Gem	**A0 IV	1·17 ± 0·09	1·32 ± 0·09	1·39 ± 0·09
2491	α CMa	A1 V	0·91 ± 0·06	5·60 ± 0·15	5·89 ± 0·16
2618	ε CMa	**B2 II	0·89 ± 0·06	0·77 ± 0·05	0·80 ± 0·05
2693	δ CMa	**F8 Ia	0·93 ± 0·18	3·29 ± 0·46	3·60 ± 0·50
2827	η CMa	†B5 Ia	0·99 ± 0·09	0·72 ± 0·06	0·75 ± 0·06
2943	α CMi	F5 IV–V	0·98 ± 0·10	5·10 ± 0·16	5·50 ± 0·17
3165	ζ Pup	†O5 f	1·04 ± 0·08	0·41 ± 0·03	0·42 ± 0·03
3207	γ^2 Vel	§WC8 + O9 I	—	0·43 ± 0·05	0·44 ± 0·05
3685	β Car	A1 IV	1·01 ± 0·06	1·51 ± 0·07	1·59 ± 0·07
3982	α Leo	**B7 V	1·12 ± 0·07	1·32 ± 0·06	1·37 ± 0·06
4534	β Leo	**A3 V	1·17 ± 0·10	1·25 ± 0·09	1·33 ± 0·10
4662	γ Crv	B8 III	0·97 ± 0·10	0·72 ± 0·06	0·75 ± 0·06
4853	β Cru	‡B0·5 III	0·88 ± 0·03	0·702 ± 0·022	0·722 ± 0·023
5056	α Vir	*B1 IV	—	0·85 ± 0·04	0·87 ± 0·04
5132	ε Cen	‡B1 III	1·02 ± 0·07	0·47 ± 0·03	0·48 ± 0·03
5953	δ Sco	†B0·5 IV	0·75 ± 0·07	0·45 ± 0·04	0·46 ± 0·04
6175	ζ Oph	**O9·5 V	1·01 ± 0·12	0·50 ± 0·05	0·51 ± 0·05
6556	α Oph	**A5 III	0·94 ± 0·09	1·53 ± 0·12	1·63 ± 0·13
6879	ε Sgr	A0 V	1·02 ± 0·06	1·37 ± 0·06	1·44 ± 0·06
7001	α Lyr	†A0 V	0·99 ± 0·04	3·08 ± 0·07	3·24 ± 0·07
7557	α Aql	A7 IV, V	0·94 ± 0·06	2·78 ± 0·13	2·98 ± 0·14
7790	α Pav	‡B2·5 V	1·01 ± 0·07	0·77 ± 0·05	0·80 ± 0·05
8425	α Gru	‡B7 IV	1·11 ± 0·08	0·98 ± 0·07	1·02 ± 0·07
8728	α PsA	†A3 V	1·02 ± 0·08	1·98 ± 0·13	2·10 ± 0·14

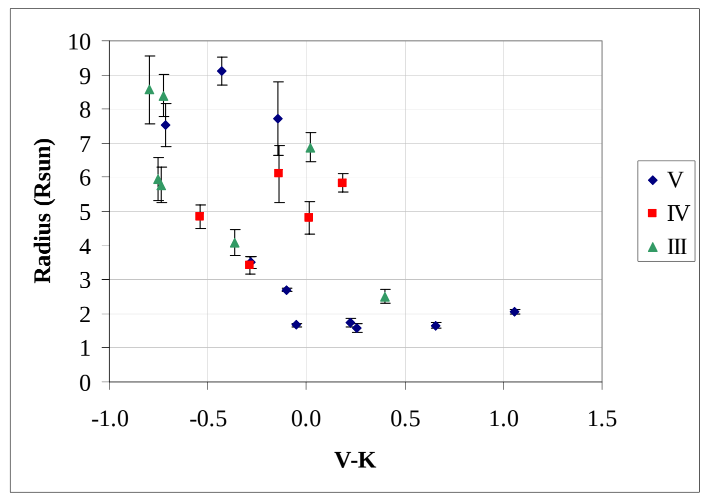
References for MK Spectral Types in order of preference

† Morgan, W. W. & Keenan, P. C., 1973. *A. Rev. Astr. Astrophys.*, in press.
** Johnson, H. L. & Morgan, W. W., 1953. *Astrophys. J.*, **117**, 313.
‡ Hiltner, W. A., Garrison, R. F. & Schild, R. E., 1969. *Astrophys. J.*, **157**, 313.
§ Conti, P. S. & Smith, L. F., 1972. *Astrophys. J.*, **172**, 623.
* Lesh, J. R., 1968. *Astrophys. J. Suppl. Ser.*, **17**, 371.

Remainder from Johnson, H. L., Mitchell, R. I., Iriarte, B. & Wiśniewski, W. Z., 1966. *Communs. lunar planet Lab.*, **4**, 99.

Column 1, number of star in *Catalogue of bright stars* (11); column 2, name of star; column 3, MK spectral classification; column 4, zero-baseline correlation with no partial resolution ($\Delta_\lambda = 1$) normalized by the value expected from a single unresolved star; column 5, weighted mean equivalent uniform disc angular diameter with rms uncertainty; column 6, true angular diameter allowing for effects of limb darkening (see Section 7.2).





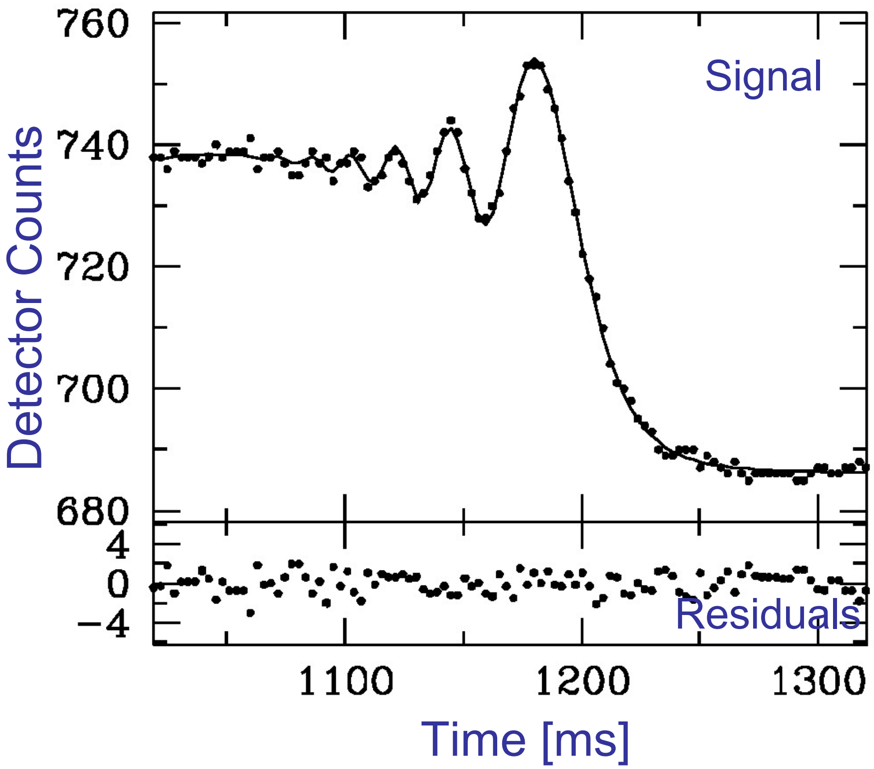
Still Yearning for the Mainstream

"As the method [optical interferometry] can be applied to only the angular largest stars, it is no longer used for the determination of stellar diameters." – Wesselink et al 1972

Hibernation for the Field (2)

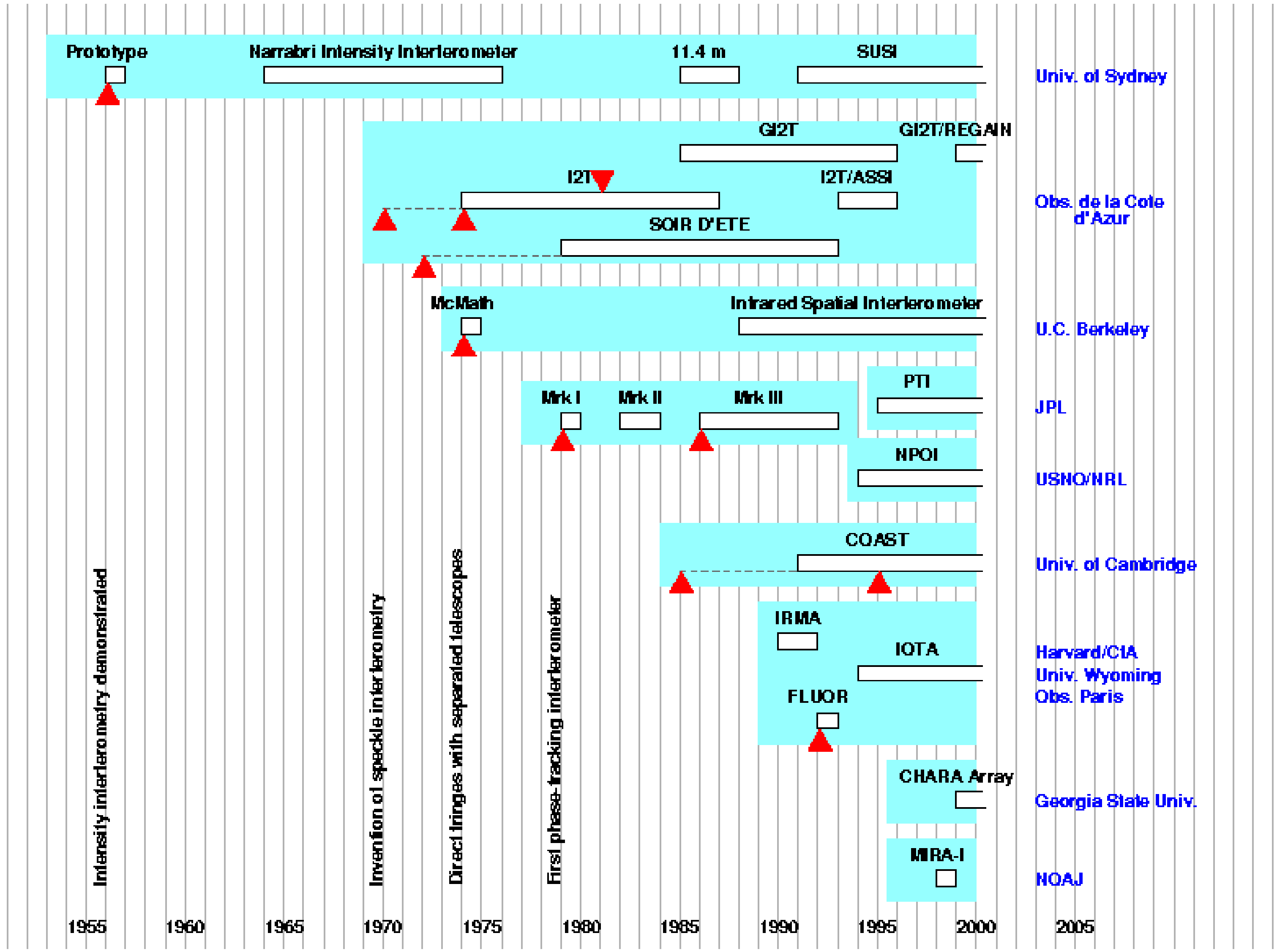
- Spans from 1975-1989
  - This time, only a fitful sleep
  - A few observations published every few years
- Lunar occultations – 1980s
  - The ‘golden era’ for LO – over 300 observations published
  - Urges for high resolution satisfied by this technique
  - Continues to be effectively utilized today

RU Ari



Richichi et al. 1998

The Second Great Reawakening



Significant Events Opening the Field

- 1956: First fringes with the prototype intensity interferometer by Hanbury-Brown and Twiss
- 1970: Invention of speckle interferometry by A. Labeyrie
- 1972: First 10 micron heterodyne fringes by J. Gay and A. Journet
- 1974: First 10 micron heterodyne fringes with separated telescopes by Johnson, Betz, and Townes
- 1974: First direct detection visible fringes by A. Labeyrie
- 1979: First phase tracking stellar interferometer, M. Shao and D.H. Staelin
- 1982: First fringe measurements at 2.2 microns, by G.P. Di Benedetto and G. Conti
- 1985: First measurement of closure phase at optical wavelengths by J.E. Baldwin et al
- 1986: First fully automated interferometer for wide angle astrometry, M. Shao, M.M. Colavita et al
- 1992: First use of single-mode fibers by Coudé du Foresto and S.T. Ridgway
- 1995: First optical synthesis image with separated telescopes, by J.E. Baldwin et al

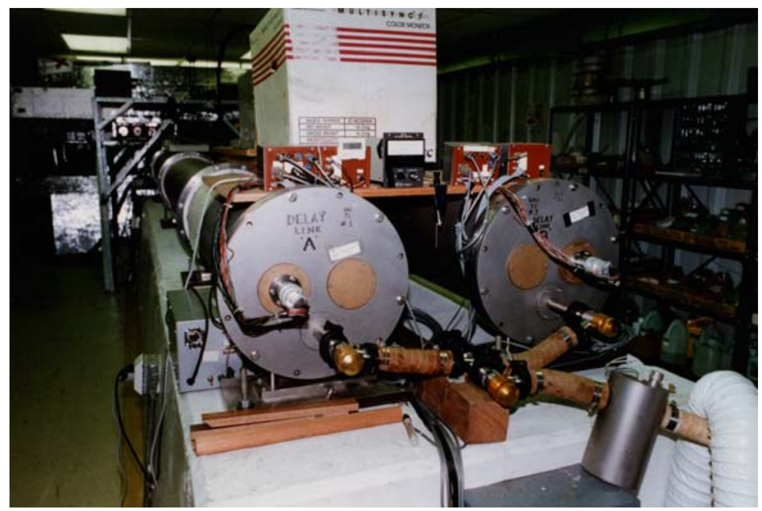
Together, all of these technology stepping stones
pave the path to modern optical/near-IR interferometers

Why the Reawakening?

- Significant advances in technology
  - *Computers & electronics*
  - Detectors
  - Actuators
  - Materials science / microlithography
  - Optics (particularly lasers)
- Significant advances in understanding the atmosphere
  - Tango & Twiss 1980, Prog. in Optics, 17, 239
  - Shao & Colavita 1992, A&A, 262, 353

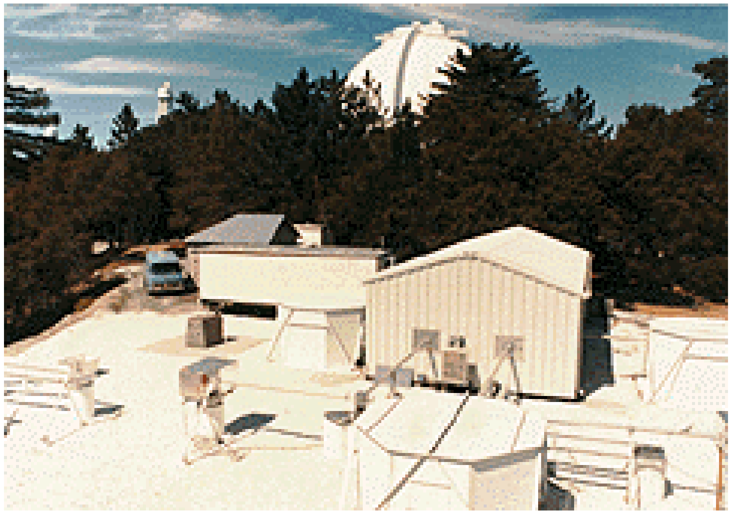
Mark I, II, III

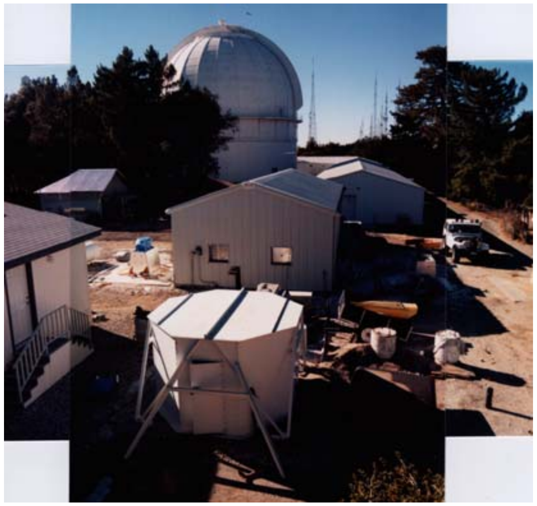
- Mark I: Phase tracking stellar interferometer built by M. Shao and D.H. Staelin (1977-79)
  - Tilt correction + phase tracking
  - No delay line
- Mark II: Technology testbed for astrometry
  - High speed delay line implemented
  - Star-switching automated
  - Astrometric interferometry demonstrated



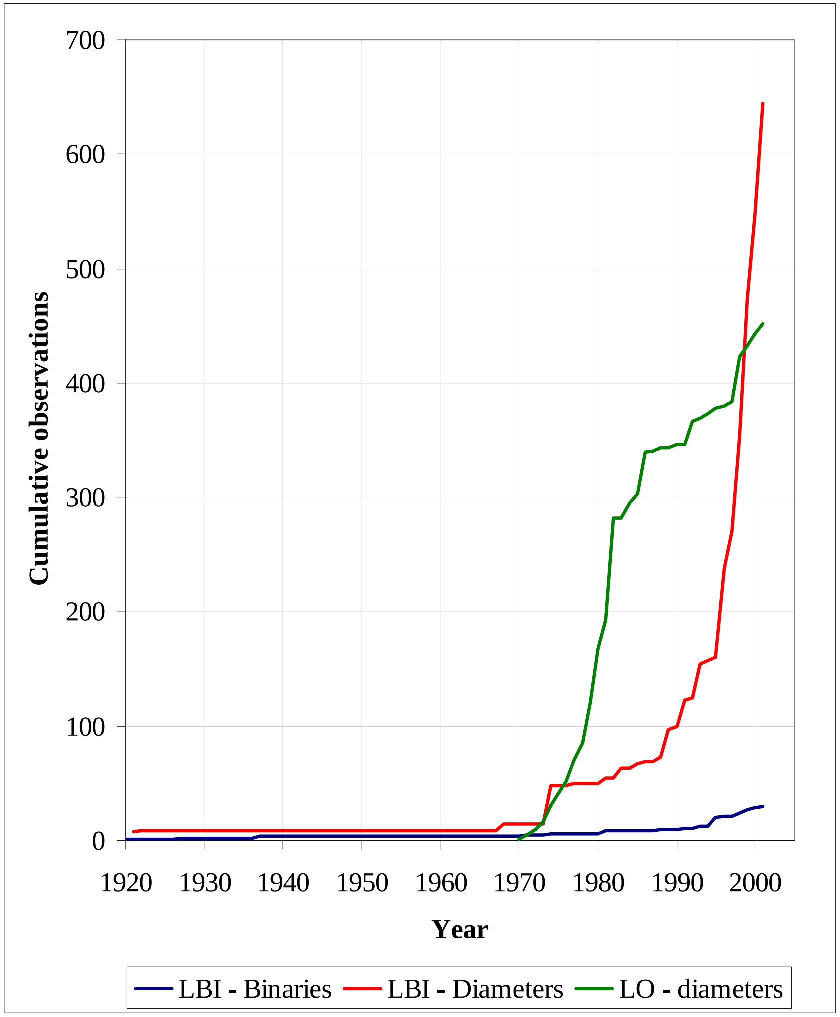
Mark I, II, III

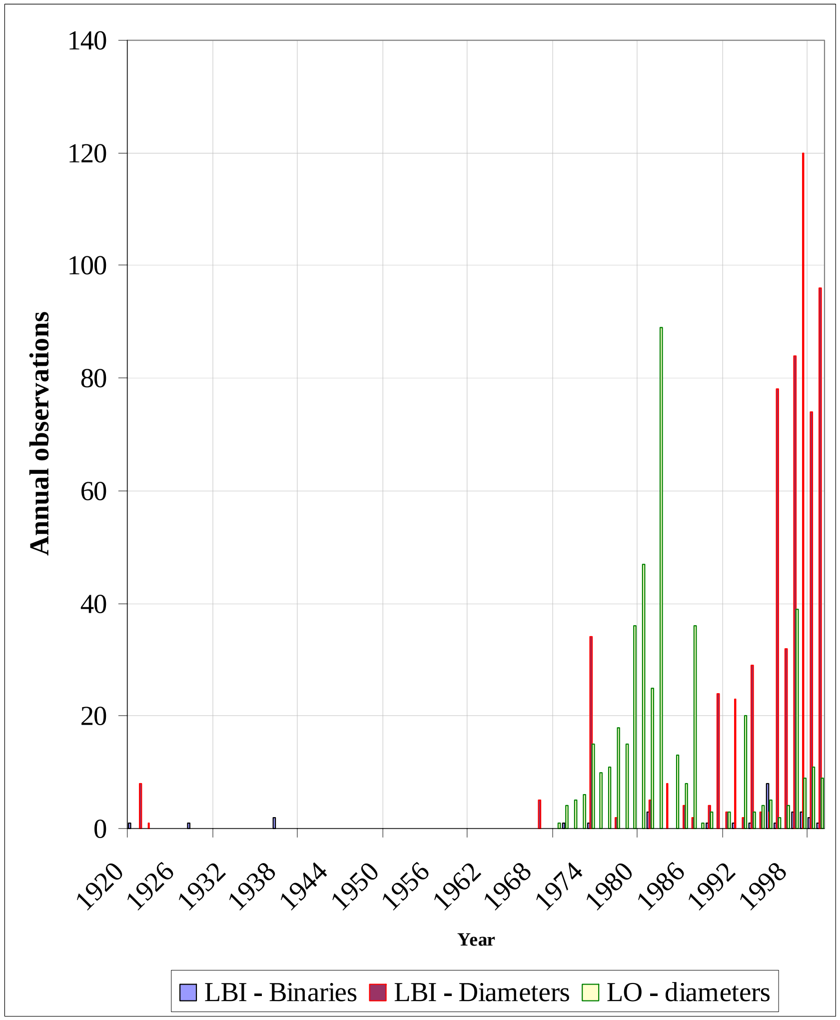
- Mark III: First fringes in 1986
  - Astrometric accuracy of 10 to 20 milliarcseconds
  - Modified for longer baselines (up to 30m) and stellar measurements by NRL/USNO
  - Extensive list of publications (18+ refereed science papers)



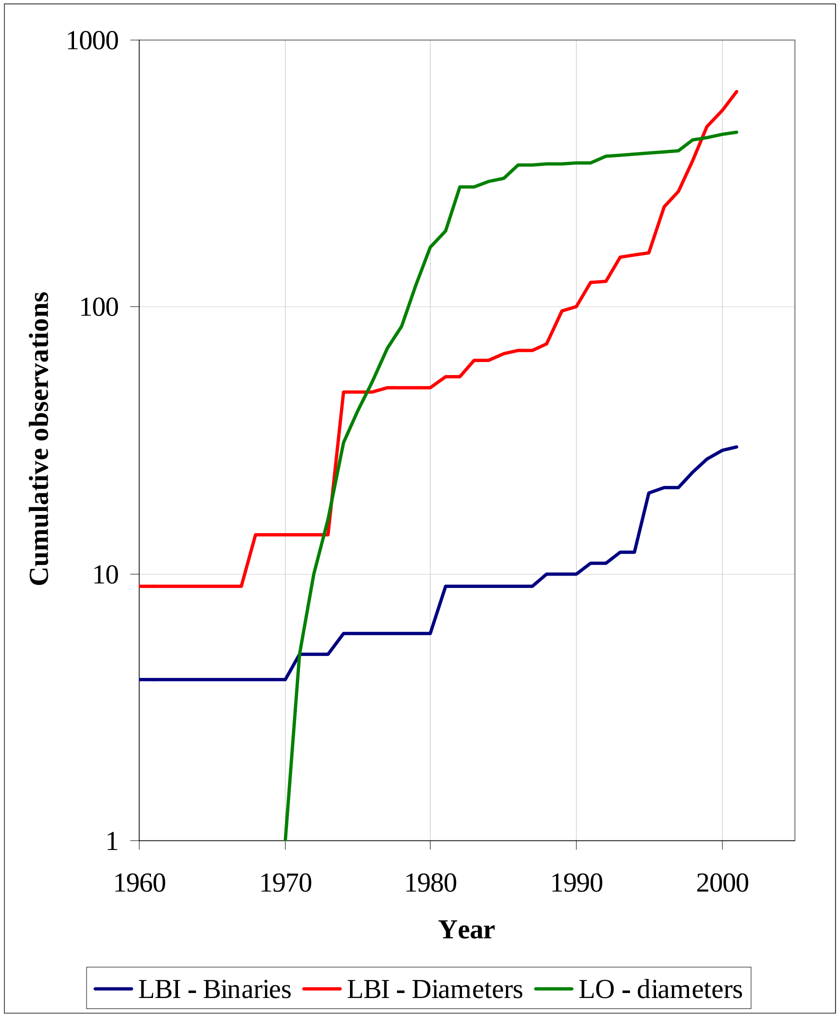


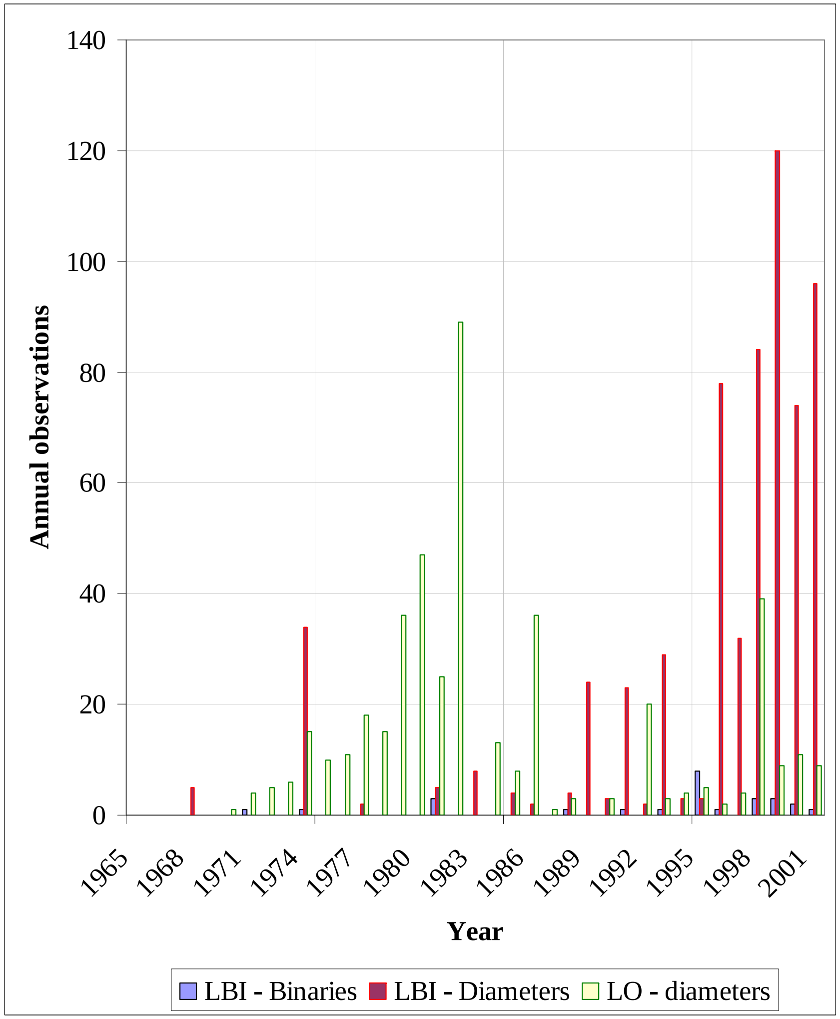
Published Scientific Output by Year





Published Output by Year (1960+)





Current Heavyweights

- Palomar Testbed Interferometer
  - 24+ refereed publications
  - Binary stars, giant diameters, Miras, YSOs
  - First observation of rotational oblateness
- Infrared/Optical Telescope Array
  - 20+ refereed publications
  - Giant stars, Miras, YSOs
  - Large number of PhD students
- Grand Interféromètre à 2 Télescopes
  - Be star observations
  - 11+ refereed publications
- Cambridge Optical Aperture Synthesis Telescope
  - 10+ refereed publications
  - First optical aperture synthesis maps
  - Mira diameters
- Navy Prototype Optical Interferometer
  - 13+ refereed publications
  - First direct detection of stellar limb darkening
  - Closure phase mapping
- Infrared Spatial Interferometer
  - 12+ refereed publications
  - 11μm heterodyne combination

Future Prospects

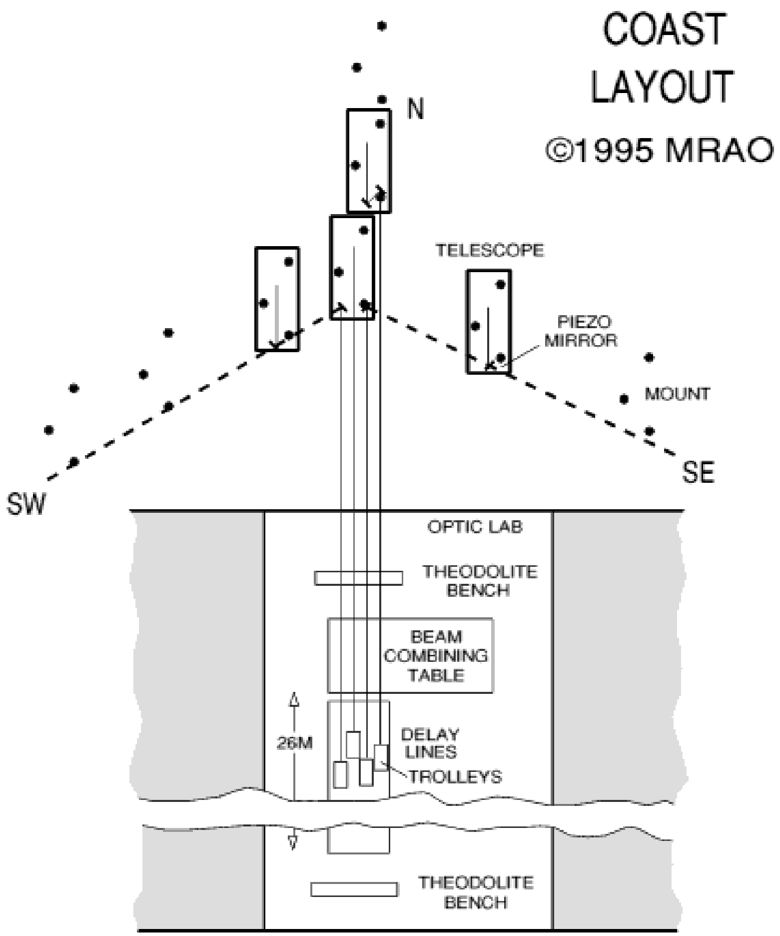
- Up-and-coming contenders
  - Keck Interferometer
  - VLTI
  - CHARA
  - SUSI
- Lurking in the shadows
  - MRO
  - LBTI
  - MIRA

  (See Theo’s talk tomorrow)
- Even further out there

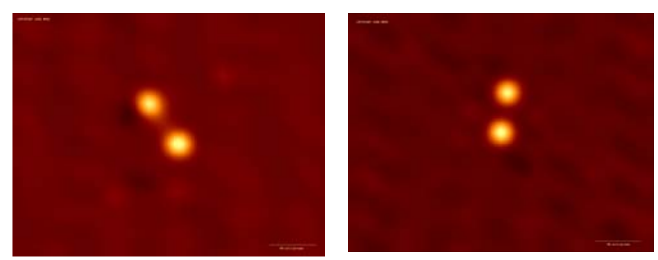
  (see Peter’s talk on Friday)

[redacted]

Cambridge Optical Aperture Synthesis Telescope

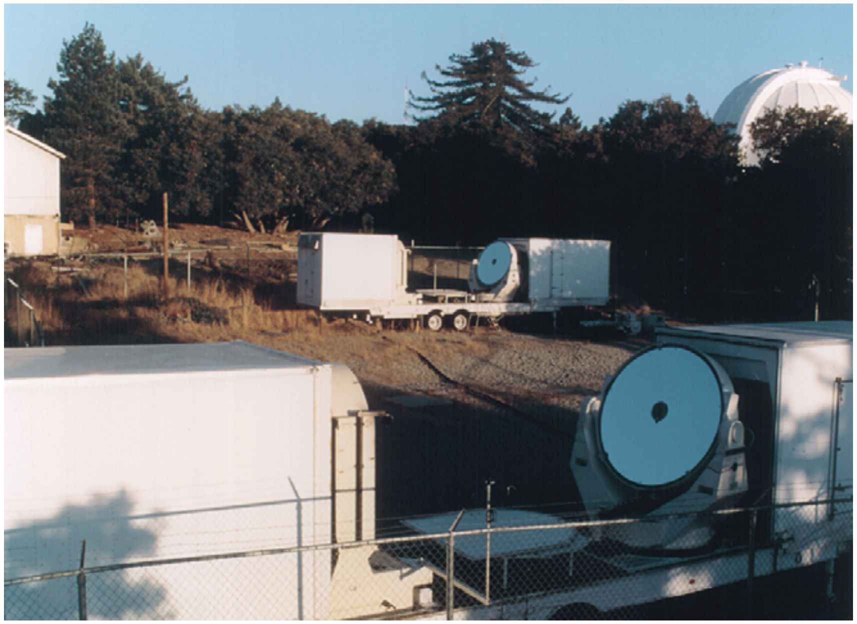


Optical Synthesis Images of Capella



13 Sept. 1995 **28 Sept. 1995**

Infrared Spatial Interferometer



GI2T