Appendices

Appendix A

Notes on the History of Stellar Interferometry

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In the following I discuss what influences Michelson may have had relating to his early work on stellar interferometry, and I also include a timeline of interferometry from 1868 to the present day.

A.1 Fizeau and Michelson

Hippolyte Fizeau (1819–1896) was the first to suggest that it might be possible to measure the angular diameters of stars through observations of interference fringes produced from starlight (Fizeau, 1868). Based on this suggestion, and through subsequent correspondence, Edouard Stéphan, the director of the Marseilles Observatory, conducted the first interferometric measurements of stars between 1872 and 1873. Stéphan published his initial thoughts on this technique and his subsequent results in the Proceedings of the French *Academie des Sciences* (Stéphan, 1873, 1874).*

Albert Michelson (1852–1931) was the first to fully describe the mathematical foundations of stellar interferometry and the first to measure a stellar diameter (Michelson, 1890; Michelson and Pease, 1921). His earliest work in this field took place around 1890, 17 years after

*The telescope that Stéphan used was the largest reflecting telescope then in existence, built by Foucault. The history of Foucault's 80 cm reflector, described by Tobin (1987), is interesting in its own right and is well worth reading. Biographical material concerning Stéphan's life and work may be found in his own history of the Marseille Observatory (Stéphan, 1914).

Stéphan's observations in Marseille. Although Michelson appears to have invented stellar interferometry independently, because he never once refers to the prior work of Fizeau, Stéphan, or others, the obvious question arises: to what extent was Michelson influenced by Fizeau? In the following section I will attempt to address this question. For more on the history of Michelson's interest in stellar interferometry, the reader is encouraged to read the paper by de Vorkin (1975) and the biography by Livingston (1973).

A.1.1 American References to European Work in Stellar Interferometry

Michelson's early work in stellar interferometry, and in particular his measurement of the satellites of Jupiter (Michelson, 1891), soon became known to European astronomers, as can be seen in the preamble of papers by Hamy (1893) and Schwarzschild (1896). However, European work in stellar interferometry, including the pioneering observations by Stéphan, only begins to appear in scientific papers in English around 1928.

The French work on stellar interferometry seems to have been unknown to Michelson and his collaborators until sometime after the measurement of the diameter of Betelgeuse (Michelson and Pease, 1921). Anderson seems to be ignorant of anything but Michelson's work when he describes his own binary star interferometer (Anderson, 1920). He states that

> In view of the great beauty and simplicity of the method, it is surprising to find that the only application it has had up to the present time is to the determination of the diameters of Jupiter's satellites, and this was done by Professor Michelson himself.

Neither Michelson nor Pease (Michelson, 1920; Michelson and Pease, 1921) make any reference to prior work by others, apart from the work of Anderson.

Only in 1928, when Henroteau reviews measurements of double and multiple stars, do we find what I believe to be the first references in English to Fizeau, Stéphan, and Hamy (Henroteau, 1928). The references that Henroteau cites are exhaustive, and to my knowledge cover all sources of work in this field up to 1928, and further include some obscure theoretical work and early work on double star interferometry.[†‡]

It is perhaps not surprising then that in 1931 when Pease writes about the 50-ft interferometer (Pease, 1931) he now reviews previous work citing Fizeau and Stéphan:

> Stephan had already shown that fringes were conspicuous in the 80-cm Marseilles refractor, but his results were hidden in the volumes of the Comptes Rendus...

[†]The history of work on double star interferometry prior to the invention of speckle interferometry is covered in detail by Finsen (1971).

[‡]Henroteau's description of Michelson is as follows: "In the Philosophical Magazine for July 1890, Michelson, carrying both theory and application further, describes his method for measuring the angular magnitude of celestial objects when these are beyond the powers of the largest telescopes." This seems to be worded to avoid the issue of whether Michelson was aware of Fizeau's work.

> It remained for Michelson in 1890, then at Clark University, to work out this idea independently and to add to it an essential element which led to the construction of the modern stellar interferometer.

The simplest conclusion is therefore that Michelson independently invented stellar interferometry, and that (taken in context with the rest of his career) it was simply one of the many applications he invented for his interferometer.

Notwithstanding the above, in my own opinion it is entirely possible that Fizeau's scientific career was an inspiration to Michelson, as they both shared an interest in the measurement of the speed of light and the detection of relative motions of the ether. Moreover, it is likely that the two met in Paris long before Michelson elaborated his thoughts "On the application of interference methods to astronomical measurement" (Michelson, 1890).[§]

A.1.2 Could Michelson Have Been Influenced by Fizeau Prior to 1890?

It is certainly possible that Michelson met Fizeau at a period where Michelson was still establishing his career.* The earliest opportunity would have been during Michelson's stay in Europe, beginning in the fall of 1880. Michelson had previously conducted experiments on the speed of light at the Naval Academy, and was given a year's leave of abscence to take courses at the University of Berlin and study under Hermann von Helmholtz.[†] During this period he also visited France, a visit that is described by Michelson's daughter in *The Master of Light* (Livingston, 1973):[‡]

> In the interim, Michelson turned his mind to opportunities at hand. He was well aware that the French were making important strides in the field of optics, and Paris was becoming the center of important work in several scientific fields. He had long been anxious to meet with the eminent Frenchmen whose work had originally brought him to a career in physics, and he made arrangements to leave for a winter's study in the French capital.
>
> Foucault was dead, but there were others who had carried on the study of optics. Michelson felt that he could learn much from a winter of study at the College de France and the Ecole Polytechnique. There were three men in particular with whom he wished to study: Cornu, Mascart, and Lippmann.
>
> ...When Michelson arrived in Paris in the fall of 1881 he found that his reputation had preceded him. His accurate determination of the speed of light, followed by his daring challenge to the received theory of astronomical aberration as Fresnel had established it, made his French colleagues eager to meet him. When he presented himself at the Ecole Polytechnique, he was asked if he were by chance the son of the famous Michelson.

[§]In 1881 Michelson would have been 29 years old and Fizeau 62.

*Fizeau became a member of the *Academie des Sciences* in 1860 In 1863 he was also appointed Inspector of Physics at the *Ecole Polytechnique*. He died in Nanteuil, France, in 1896.

[†]In Berlin he put together the earliest version of what would later be known as the Michelson-Morley experiment. In 1881 the Michelsons moved to Heidelberg where he studied as well.

[‡]Dorothy Livingston was Michelson's youngest daughter from his second marriage. She had not yet been born at the time of these events.

Table A.1: Events in Early Stellar Interferometry

Year	Event	Authors and Reference
1868	Stellar interferometry suggested	H. Fizeau, C. R. Acad. Sci. **66**, 932 (1868)
1872–73	Stellar diameters need be $\ll 0.158$ arcsec	E. Stéphan, C. R. Acad. Sci. **78**, 1008 (1874)
1890	Mathematical theory of stellar interferometry	A.A. Michelson, Phil. Mag. **30**, 1 (1890)
1891	Satellites of Jupiter measured	A.A. Michelson, Nature **45**, 160 (1891)
1896	Binary star measurements	K. Schwarzschild, Astron. Nachr. **139** 3335 (1896)
1920	Orbit of Capella measured	J.A. Anderson, Astrophys. J. **51**, 263 (1920)
1921–31	First stellar diameter measured	A.A. Michelson, F.G. Pease, Astrophys. J. **53**, 249 (1921)
1931–38	50-ft interferometer	F.G. Pease, Erg. Exakt. Natur. **10**, 84 (1931)

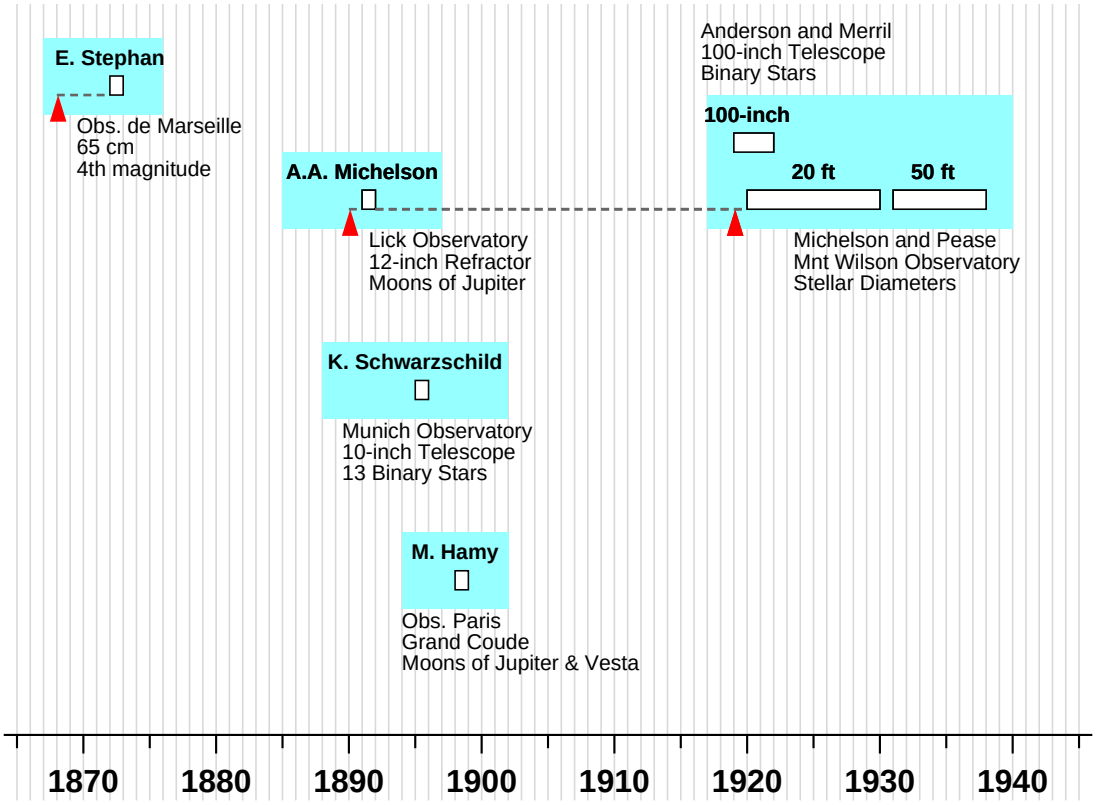

Figure A.1: Stellar Interferometry from 1868 to 1940.

> When he laughingly replied that he was himself that Michelson, invitations were pressed upon him to meet the other professors of the science faculty. Discussions soon turned to the instrument he had devised.
>
> ...M. Andre Potier, a former pupil of Cornu, called Michelson's attention to an error in his calculations in neglecting the effect of the earth's motion on light travelling in the arm of the interferometer at right angles to that motion, which Potier said would reduce the fringe shift to zero. Michelson acknowledged his error at the February 20, 1882 meeting of the Paris *Academie des Sciences* but pointed out that the fringe displacement would be reduced only by half, not to zero.

Fizeau was actively involved in the *Academie des Sciences*, and could possibly have been present at the meeting Michelson attended. Seeing as Michelson had improved upon Fizeau's measurement of the speed of light, it would be surprising if Michelson did not seek him out to introduce himself, although no meeting is specifically mentioned in the biography.[†*]

It is clear that Michelson admired Fizeau and was indeed influenced by him. Michelson wrote that Fizeau's measurement of the speed of light in moving water was "in my opinion one of the most ingenious experiments that have ever been attempted in the whole domain of physics" and "on this account, and also for the reason that the experiment was regarded as one of the most important in the entire subject of optics, it seemed to me that it was desirable to repeat it..." (Michelson 1902, pp. 152 and 155). Although it is tempting to believe that a connection existed between these two, and despite the similarity of their work and their many shared professional interests, there does not seem to be any clear evidence that Fizeau guided Michelson in his work in stellar interferometry.

A.2 A Timeline of Stellar Interferometry: 1868–2000

I now include two timelines of stellar interferometry, shown in Figures A.1 and A.2, to illustrate the development of the field through its early years, up until about 1940, and from the period beginning with the invention of intensity interferometry up until the present day. Tables A.1 and A.2 provide comments and references to accompany the figures. A more detailed account of the history of stellar interferometry can be found in the introduction to *Selected Papers on Long Baseline Stellar Interferometry* (Lawson, 1997).

In the figures I have attempted to group together projects where there has been a unified effort, or where several interferometers have been strongly associated. I have started each

[†]Labeyrie (1982) has written that "Years after H. Fizeau's 1868 suggestion, the American physicist A.A. Michelson went to work with him in Paris and also became interested in stellar interferometry." When I asked Prof. Labeyrie for further information, he could not remember where he had read about the meeting, and so I believe he was instead referring to Michelson's time in Paris, as described above.

[*]After Fizeau's death, the *secrétaire perpétuelle* of the *Academie des Sciences*, wrote a biography of Fizeau (Picard, 1924) citing Fizeau's original role in stellar interferometry, but without any mention made of a meeting with Michelson.

Table A.2: Milestones in Long Baseline Stellar Interferometry

Year	Milestone	Authors and Reference
1956	Fringes with the prototype intensity interferometer	R. Hanbury Brown and R.Q. Twiss, Nature **177**, 27 (1956)
1970	Invention of speckle interferometry	A. Labeyrie, Astron. Astrophys. **6**, 85 (1970)
1972	10-micron heterodyne fringes	J. Gay and A. Journet, Nature Phys. Sci. **241**, 32 (1973)
1974	10-micron heterodyne fringes with separated telescopes	M.A. Johnson et al., Phys. Rev. Lett. **33**, 1617 (1974)
1974	Direct detection visible fringes with separated telescopes	A. Labeyrie, Astrophys. J. **196**, L71 (1975)
1979	Phase tracking stellar interferometer	M. Shao and D.H. Staelin, Appl. Opt. **19**, 1519 (1980)
1982	Fringe measurements at 2.2 microns	G.P. Di Benedetto and G. Conti, Astrophys. J. **268**, 309 (1983)
1985	Measurement of closure phase at optical wavelengths	J.E. Baldwin et al., Nature **320**, 595 (1986)
1986	Fully automated interferometer for astrometry	M. Shao, M.M. Colavita et al., Astron. Astrophys. **193**, 357 (1988)
1991	Use of single-mode fibers with separated telescopes	V. Coudé du Foresto and S.T. Ridgway, ESO Proc. **39**, 731 (1992)
1995	Optical synthesis imaging with separated telescopes	J.E. Baldwin et al., Astron. Astrophys. **306**, L13 (1996)

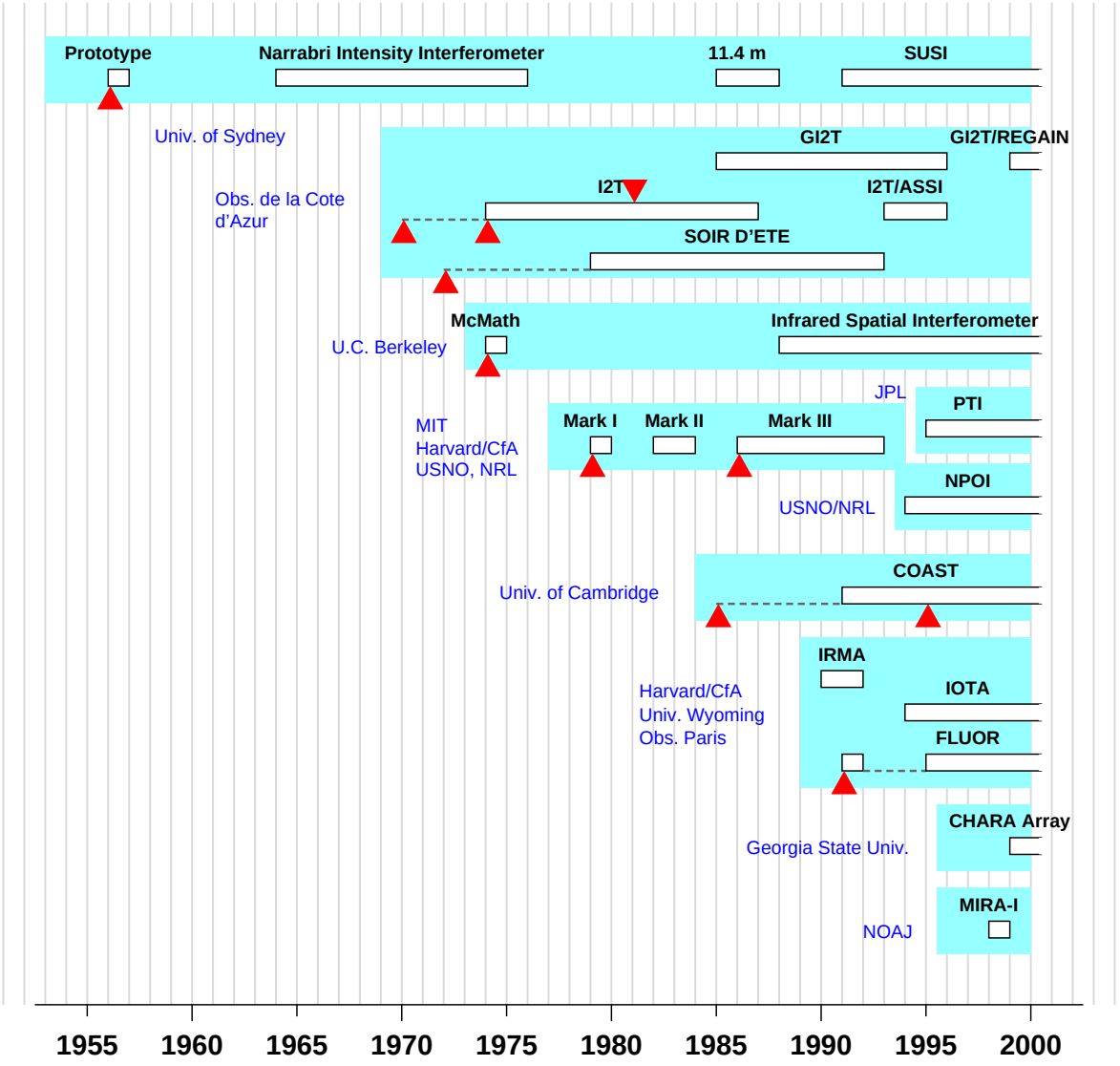

Figure A.2: Stellar Interferometry from 1950 to 2000.

interferometer in the year it first acquired fringes and ended it (if applicable) in the year it ceased observations. Some of these groupings are subjective: for example, three quite separate interferometer projects have existed at the Observatoire de la Côte d'Azur—although here I group them together. What I consider to be milestones in the timeline are indicated by the triangles and described in the Tables.

Acknowledgments

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H. Fizeau, "Prix Bordin: Rapport sur le concours de l'année 1867," C. R. Acad. Sci. **66**, 932–934 (1868).

M. Hamy, "Sur la mesure des faibles diamètres," Bulletin Astronomique **10**, 489–504 (1893).

F.C. Henroteau, "Double and multiple stars," in *Handbuch der Astrophysik 6*, 299–468 (Berlin, Germany: Julius Springer, 1928).

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E. Picard, *Les Theories de l'Optique et l'Oeuvre d'Hippolyte Fizeau* (Paris, France: Academie des Sciences, 1924).

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E. Stéphan, "L'Observatoire de Marseille: histoire depuis la révolution," in *Encyclopédie des Bouches du Rhône* **6** (1914). http://www-obs.cnrs-mrs.fr/patrimoine/histoire-f.html.

W. Tobin, "Foucault's invention of the silvered-glass reflecting telescope and the history of his 80-cm reflector at the Observatoire de Marseille," Vistas in Astronomy **30**, 153–184 (1987).

D.H. De Vorkin, "Michelson and the problem of stellar diameters," Journal for the History of Astronomy **6**, 1–18 (1975).

Appendix B

Suggested Reading

B.1 General References

Engineering and Technology for Stellar Interferometry

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M. Shao and M.M. Colavita, "Long-baseline optical and infrared stellar interferometry," Ann. Rev. Astron. Astrop. **30**, 457–498 (1992).

V. Coudé du Foresto, "Integrated optics in astronomical interferometry," in *Very High Angular Resolution Imaging*, J.G. Robertson and W.J. Tango, eds., IAU Symp. **158** (Kluwer Academic: Dordrecht, Netherlands, 1994), pp. 261–271.

Recent Conferences and Workshops on Stellar Interferometry

Interferometry in Optical Astronomy, P.J. Léna and A. Quirrenbach, eds., Proc. SPIE **4006** (SPIE Press: Bellingham, WA, 2000). Munich, Germany, 27–29 March 2000.

Working on the Fringe: Optical and IR Interferometry from the Ground and Space, S. Unwin and R. Stachnik, eds., ASP Conf. Ser. **194** (Brigham Young University Press: Provo, UT, 1999). Dana Point, California, USA, 24–28 May 1999.

Catching the Perfect Wave: Adaptive Optics and Interferometry for the 21st Century, S. Restaino, W. Junor, and N. Duric, eds., ASP Conf. Ser. **174** (Brigham Young Univ. Press: Provo Utah, 1999). Albuquerque, New Mexico, USA, 28 June – 1 July 1998.

Astronomical Interferometry, R.D. Reasenberg, ed., Proc. SPIE **3350** (SPIE Press: Bellingham, WA, 1998). Kona, Hawaii, USA, 20–24 March 1998.

Astrophysics with Stellar Interferometers

Fundamental Stellar Properties: The Interaction Between Observation and Theory, T.R. Bedding, A.J. Booth, and J. Davis, eds., IAU Symposium No. 198 (Kluwer Academic : Dordrecht, 1997).

Complementary Approaches to Double and Multiple Star Research, H.A. McAlister and W.I. Hartkopf, eds. IAU Colloquium 135, ASP Conf. Ser. **32** (San Francisco: Astronomical Society of the Pacific, 1992).

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K.J. Johnston, "Reference frames in astronomy," Ann. Rev. Astron. Astrophys. **37**, 97–125 (1999).

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A.R. Thompson, J.M. Moran, and G.W. Swenson, Jr., *Interferometry and Synthesis in Radio Astronomy* (John Wiley and Sons: New York, 1986).

P.F. Goldsmith ed., *Instrumentation and Techniques for Radio Astronomy*, an IEEE volume of collected reprints (IEEE Press: New York, 1988).

G. B. Taylor, C. L. Carilli, and R. A. Perley, eds., *Synthesis Imaging in Radio Astronomy II*, ASP Conf. Ser. **180** (Brigham Young Univ. Press: Provo Utah, 1999)

E.B. Fomalont and M.C.H. Wright, "Interferometry and aperture synthesis," in *Galactic and Extra-Galactic Radio Astronomy* (Ist edition), G.L. Verschuur and K.I. Kellermann, eds., (Springer-Verlag: New York, 1974), pp. 256–290.

J.L. Yen, "Image reconstruction in synthesis radio telescope arrays" in *Array Signal Processing*, S. Haykin ed., (Prentice-Hall: Englewood Cliffs, NJ, 1985), pp. 293–350.

Resources on the Web

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

Optical Long-Baseline Interferometry Newsletter, P.R. Lawson ed., (Jet Propulsion Laboratory, Pasadena, California).

B.2 Long Baseline Stellar Interferometers

In this section are listed references for the interferometers that have been mentioned in these course notes. In each case the first reference is a paper that describes the engineering of the interferometer and the other references are papers that describe astrophysical results.

Mark III Interferometer

http://www.mtwilson.edu/Tour/NRL/

M. Shao, M.M. Colavita, B.E. Hines, D.H. Staelin, D.J. Hutter, K.J. Johnston, D. Mozurkewich, R.S. Simon, J.L. Hershey, J.A. Hughes, and G.H. Kaplan, "The Mark III stellar interferometer," Astron. Astrophys. **193**, 357–371 (1988).

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Grand Interféromètre à 2 Télescopes (GI2T)

http://www.obs-nice.fr/fresnel/gi2t/en/

D. Mourard, I. Tallon-Bosc, A. Blazit, D. Bonneau, G. Merlin, F. Morand, F. Vakili, and A. Labeyrie, "The GI2T interferometer on Plateau de Calern," Astron. Astrophys. **283**, 705–713 (1994).

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Infrared/Optical Telescope Array (IOTA)

http://cfa-www.harvard.edu/cfa/oir/IOTA/

W.A. Traub, "Recent results from the IOTA Interferometer," in *Astronomical Interferometry*, R.D. Reasenberg ed., Proc. SPIE **3350**, 848–855 (1998).

H.M. Dyck, J.A. Benson, G.T. van Belle, and S.T. Ridgway. "Radii and effective temperatures for K and M giants and supergiants," Astron. J. **111**, 1705–1712 (1996).

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Infrared Spatial Interferometer (ISI)

http://isi.ssl.berkeley.edu/

D.D.S. Hale, M. Bester, W.C. Danchi, W. Fitelson, S. Hoss, E.A. Lipman, J.D. Monnier, P.G. Tuthill, and C.H. Townes, "The Berkeley Infrared Spatial Interferometer: a heterodyne stellar interferometer for the mid-infrared," Astrophys. J. **537**, 998–1012 (2000).

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http://ad.usno.navy.mil/npoi/

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Palomar Testbed Interferometer (PTI)

http://huey.jpl.nasa.gov/palomar/

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