Interferometry in the USA

History of interferometry in the US and recent developments

Wesley A. Traub

Jet Propulsion Laboratory,
California Institute of Technology

"Ten Years of VLTI" Conference
Garching
24-27 October 2011

Timeline of Interferometers in the US

- A. Michelson: Lick Obs. 12-inch, 1890; Mt. Wilson 100-inch, 1920-30

- Mark I/II/III, MIT/Harvard/CfA/USNO/NRL, Mt. Wilson, 1979/1982-84/1986-93

- Infrared Spatial Interferometer (ISI), UC Berkeley, Mt. Wilson, 1987-present

- IRMA, U. Wyoming, Laramie, 1990-92

- Navy (Prototype) Optical Interferometer (NPOI$\rightarrow$ NOI), USNO, Flagstaff AZ, 1994-present

- Infrared Optical Telescope Array (IOTA), CfA/UMass, Mt. Hopkins, AZ, 1994-2006

- Palomar Testbed Interferometer (PTI), JPL, Mt. Palomar, 1995-2008

- CHARA, Georgia State U./NSF, Mt. Wilson, 2001-present

- Keck Interferometer, JPL, Mauna Kea, HI, 2001-present

- Large Binocular Telescope Interferometer (LBTI), U. Arizona/JPL/UVa/UMinn, Mt. Graham, AZ, 2011…

- Magdalena Ridge Observatory Interferometer (MROI), NM Tech, Socorro, NM, ~2013…

Note: Years are "first fringes" to "last fringes", approximate.
Ref.: P. Lawson, Notes on the history of Stellar Interferometry, Appendix A, in Principles of Long Baseline Stellar Interferometry, P. Lawson, Ed., 1999.
Ref.: C. Townes, M. Creech-Eakman, P. Hinz, personal communications; also relevant web sites.

A. Michelson: Mt. Wilson 100-inch, 1920-30

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.
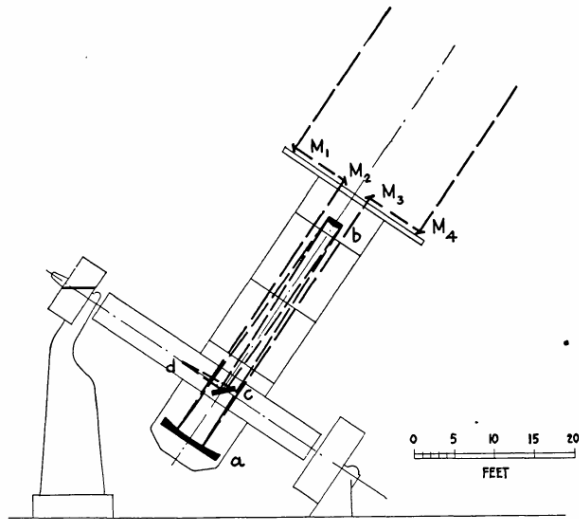

Fig. 2.—Diagram of 20-foot interferometer beam. M_1, M_2, M_3, M_4, mirrors; B, B, 10-inch channels; C, steel plate; E, E, screws to move outer mirrors; F, motor drive for screws; D, Cassegrain cage.

Fig. 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.
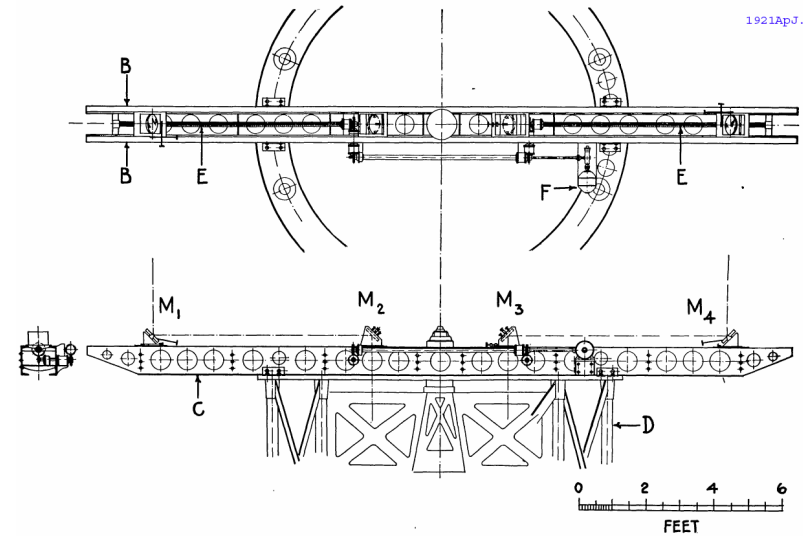
Assuming that the effective wave-length for α Orionis is λ 5750, its angular diameter from the formula $\alpha = 1.22\, \lambda/b$ proves to be 0″.047; and with a parallax[1] of 0″.018 its linear diameter turns out to be 240×10^6 miles, or slightly less than that of the orbit of Mars. This value corresponds to a uniformly illuminated disk, while for one darkened at the limb, this result, as mentioned above, would be increased by about 17 per cent. The uncertainty of the measurement of the angular diameter is about 10 per cent.
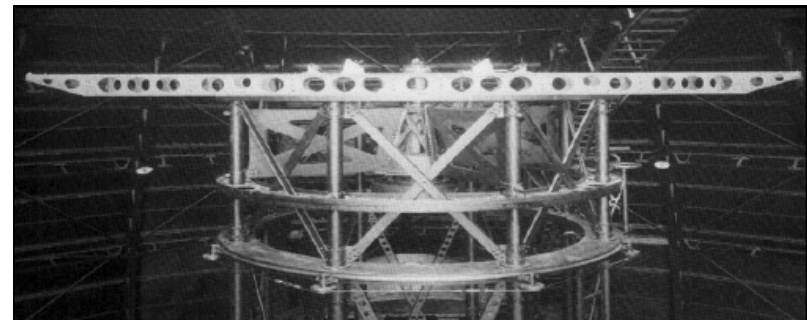

Ref.: Michelson and Pease, ApJ, 53, 249 (1921)
And http://www.chara.gsu.edu/CHARA/Slides/CHARAoverview.pdf

A. Michelson: Lick Obs. 12-inch, 1890

MEASUREMENT OF JUPITER'S SATELLITES BY INTERFERENCE.

IT has long been known that even in a telescope which is theoretically perfect, the image of a luminous point is composed of a series of concentric circles with a bright patch of light at the common centre. This system of circles can easily be observed by examining any bright star with a telescope provided with a circular diaphragm which diminishes the effective aperture. The appearance of the image is shown in Fig. 1, a. In the case of an object of finite angular magnitude the image could be constructed by drawing a system of such rings about every point in the geometrical image. The result for a small disk (corresponding to the appearance of one of the satellites of Jupiter as seen with a 12-inch telescope whose effective aperture

Fig 1

a b c
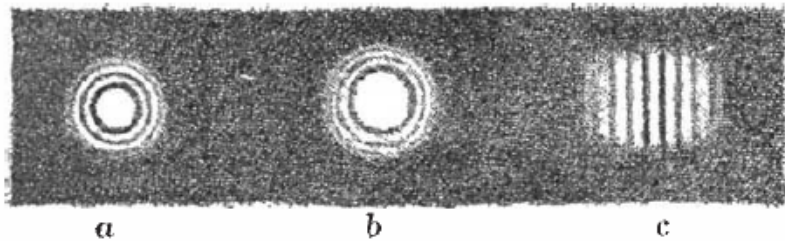
The general theory of these fringes may be found in the *Philosophical Magazine* for March 1891. The general equation showing the relation between the *visibility* of the fringes and the distance between the slits is

$$V^2 = \frac{\left[\int \phi(x) \cos kx\, dx\right]^2 + \left[\int \phi(x) \sin kx\, dx\right]^2}{\left[\int \phi(x)\, dx\right]^2} \quad . \ (1)$$
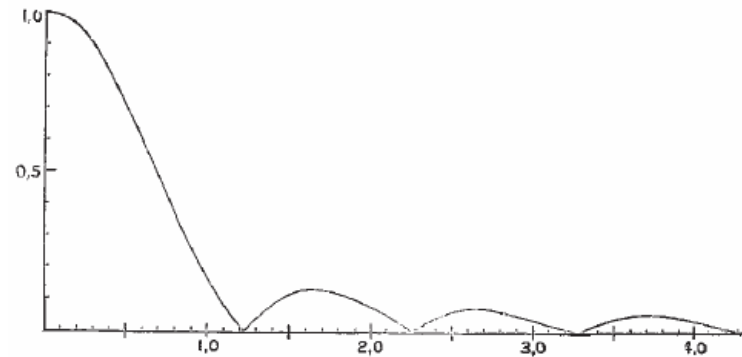
FIG. 2.

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	

Mark I/II/III, MIT/Harvard/CfA/USNO/NRL, Mt. Wilson, 1979/1982-84/1986-93

Mark III Interferometer c. 1985

First fringe measurements with a phase-tracking stellar interferometer

Michael Shao and David H. Staelin

A prototype two-telescope stellar interferometer with a 1.5-m base line has been used to track the white-light fringes, 0.4–0.9 μm, from Polaris. Continuous fringe phase and amplitude measurements were made with ~220-photon/4-msec integration time and 1.27-cm^2 collecting area under 2-arc sec seeing conditions. The same control algorithm should be able to track fringes from an 8.7-mg star using the light from two 13-cm (5-in.) telescopes and a 10-msec integration time under 1-arc sec seeing conditions. When tracking, the servo maintained equal path lengths to 0.1-μm rms in the two arms of the interferometer, thus cancelling the path-length variations caused by earth rotation and atmospheric turbulence. In the future, two-color phase measurements will make optical aperture synthesis and optical very long-base-line astrometry possible.
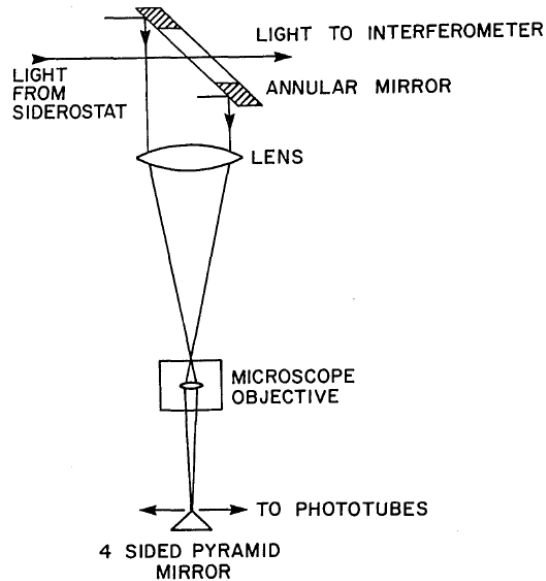
Fig. 3. Fringe detector phototube output.

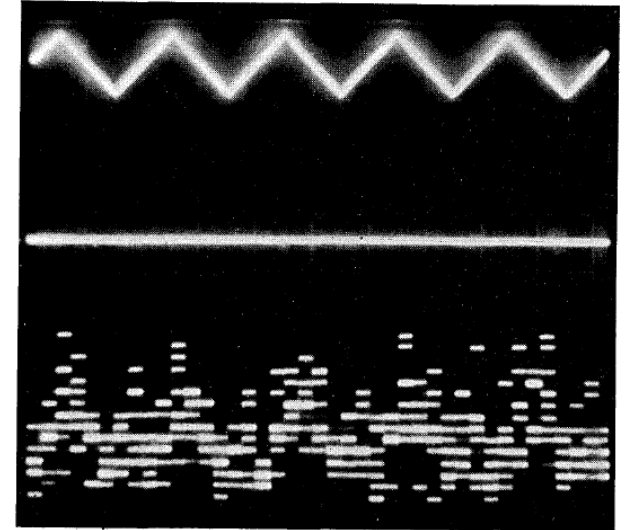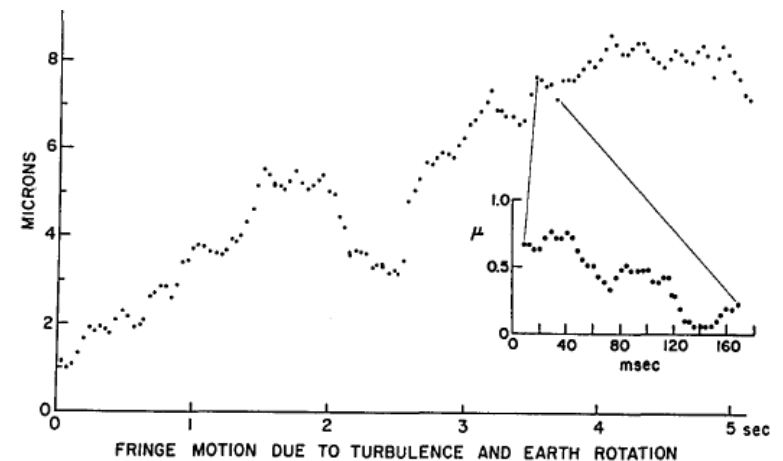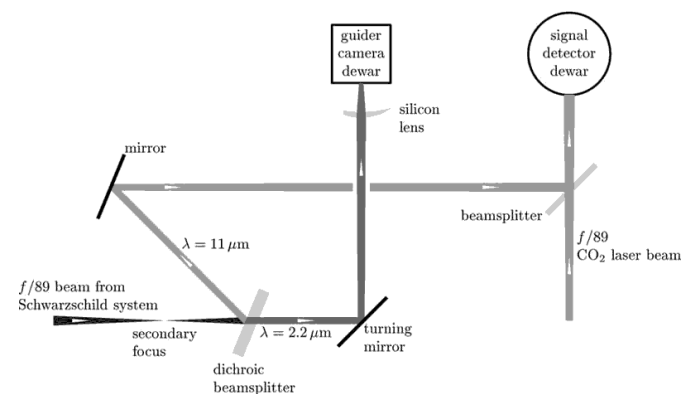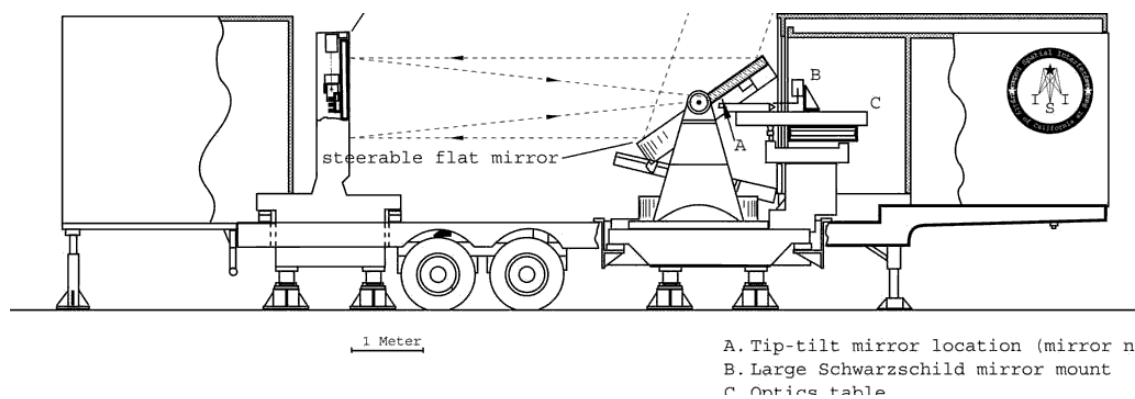

Fig. 2. Optical schematic of star trackers.

Fig. 4. Fringe motion due to turbulence observed 7 March 1979.

Infrared Spatial Interferometer (ISI), UC Berkeley, Mt. Wilson, 1987-present

steerable flat mirror

B
C
A

ISI

1 Meter

A. Tip-tilt mirror location (mirror n
B. Large Schwarzschild mirror mount
C. Optics table

guider camera dewar

signal detector dewar

silicon lens

mirror

beamsplitter

$f/89$ CO_2 laser beam

$\lambda = 11\,\mu m$

$f/89$ beam from Schwarzschild system

secondary focus

$\lambda = 2.2\,\mu m$

turning mirror

dichroic beamsplitter

Ref.: http://isi.ssl.berkeley.edu/system_overview.htm

Infrared Spatial Interferometer (ISI), UC Berkeley, Mt. Wilson, 1987-present

HIGH SPATIAL RESOLUTION 10 MICRON IMAGING OF IRC +10216

E. E. BLOEMHOF[1]
Harvard-Smithsonian Center for Astrophysics

W. C. DANCHI[1] AND C. H. TOWNES[1]
Department of Physics, University of California, Berkeley

AND

R. A. MCLAREN
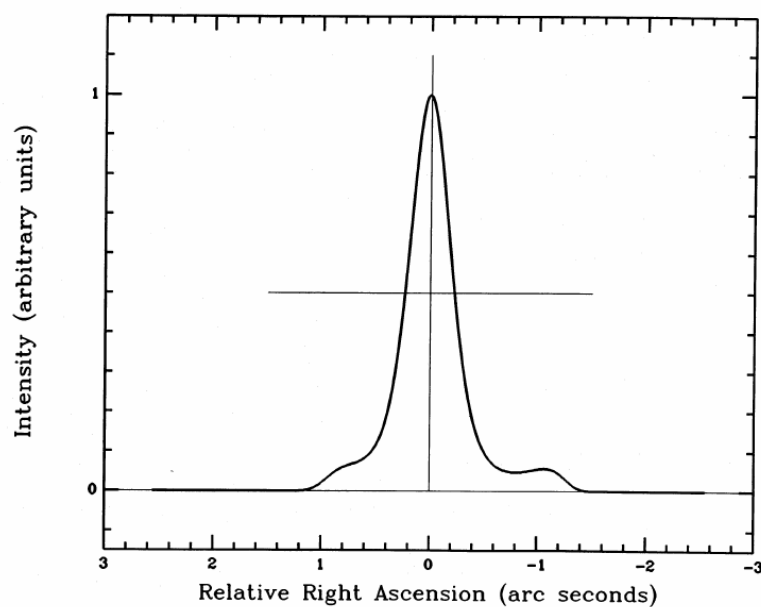Canada-France-Hawaii Telescope Corporation

FIG. 2.—Deconvolved east-west profile of IRC +10216. The Richardson-Lucy iterative algorithm was applied to the data of Fig. 1, using the α Boo profile as the telescope point-spread function; this map is the result of 60 iterations. The central peak has FWHM ~ 0″46, indicating that the true width of the central component is ~0″40 when the residual point-spread width of the deconvolution procedure is removed (see discussion in text).

Refs.: Bloemhov, et al, ApJ, 333, 300 (1988); Ravi et al, arXiv:1012.0377v1, (2010)

The many faces of Betelgeuse

Vikram Ravi[1], Ed Wishnow[1], Sean Lockwood[1], Charles Townes[1]

[1]Space Sciences Laboratory and Department of Physics, University of California, Berkeley, CA 94720, USA

Abstract.
The dynamics of the surface and inner atmosphere of the red supergiant star Betelgeuse are the subject of numerous high angular resolution and spectroscopic studies. Here, we present three-telescope interferometric data obtained at $11.15\,\mu m$ wavelength with the Berkeley Infrared Spatial Interferometer (ISI), that probe the stellar surface continuum. We find striking variability in the size, effective temperature, and degree of asymmetry of the star over the years 2006−2009. These results may indicate an evolving shell of optically thick material close to the stellar photosphere.
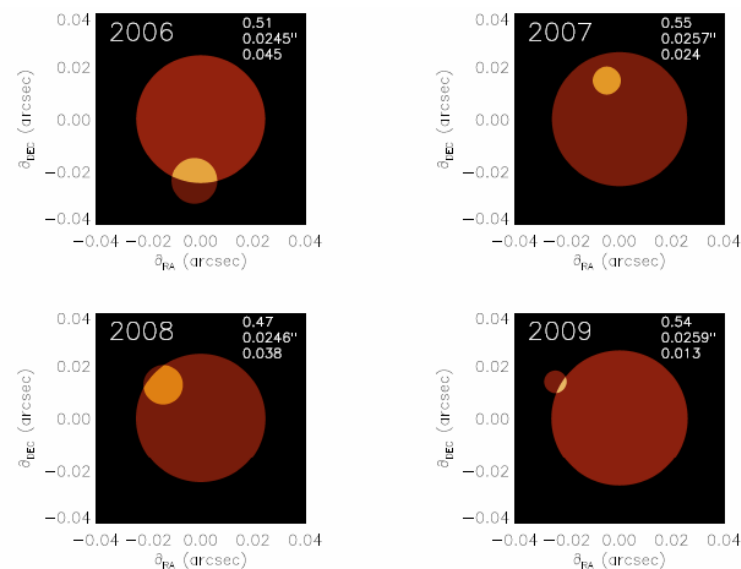
Figure 2.   Depictions of the best-fit image models for Betelgeuse during each of the 2006, 2007, 2008 and 2009 epochs. Each figure includes the fit parameters: the fraction of the total flux from the star, the stellar radius in arcseconds, and the fraction of the total flux from the point. The point sources have been given the uniform disk sizes that they would have if they represented regions at a temperature of 7200 K. Our upper limit on the point source diameter is 20 mas.

Infrared Michelson Array (IRMA), U. Wyoming, Laramie, 1990-92

THE INFRARED ANGULAR DIAMETER OF ALPHA HERCULIS MEASURED WITH A MICHELSON INTERFEROMETER

J. A. BENSON AND H. M. DYCK

Department of Physics and Astronomy, University of Wyoming, Laramie, Wyoming 82071

S. T. RIDGWAY

National Optical Astronomy Observatories, Tucson, Arizona 85726

D. J. DIXON[1]

Department of Physics, Colorado College, Colorado Springs, Colorado 80946

W. L. MASON AND R. R. HOWELL

Department of Physics and Astronomy, University of Wyoming, Laramie, Wyoming 82071
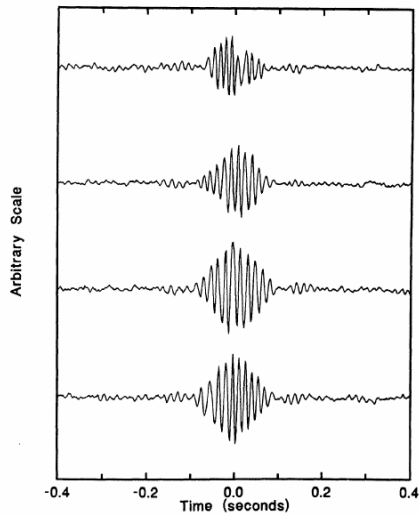Received 3 June 1991; revised 16 August 1991

IRMA: A Prototype Infrared Michelson Stellar Interferometer

H. M. DYCK AND J. A. BENSON

Department of Physics and Astronomy, P.O. Box 3905, University Station, University of Wyoming, Laramie, Wyoming 82071
Electronic mail: meldyck@noao.edu

S. T. RIDGWAY

National Optical Astronomy Observatories, P.O. Box 26732, Tucson, Arizona 85726
Electronic mail: ridgway@noao.edu
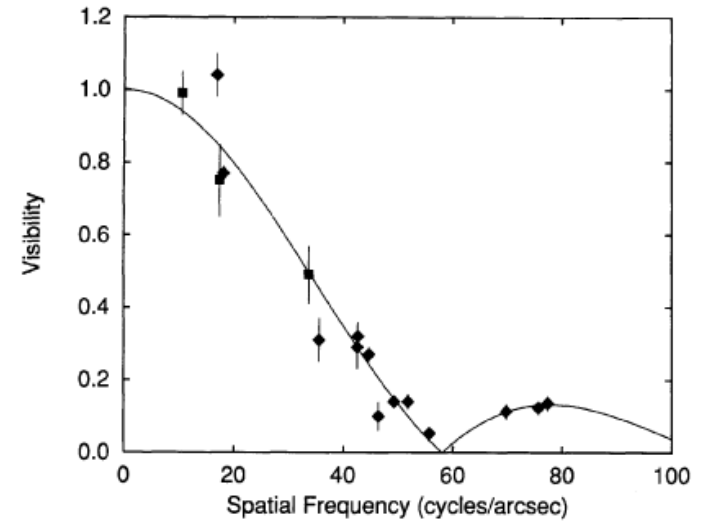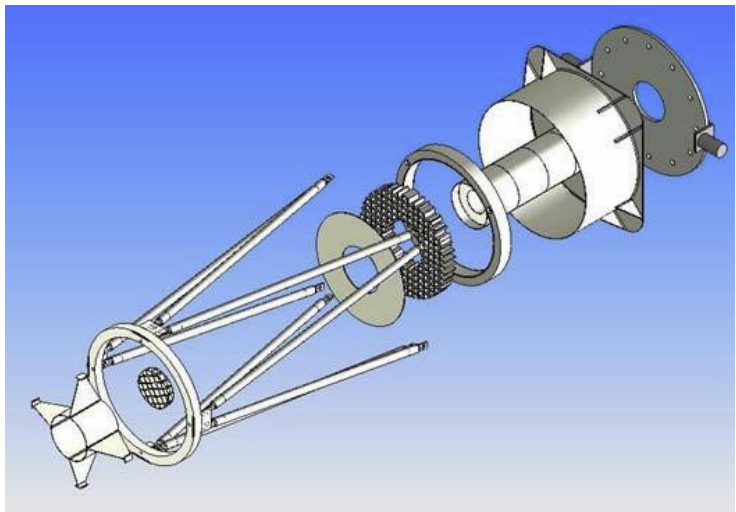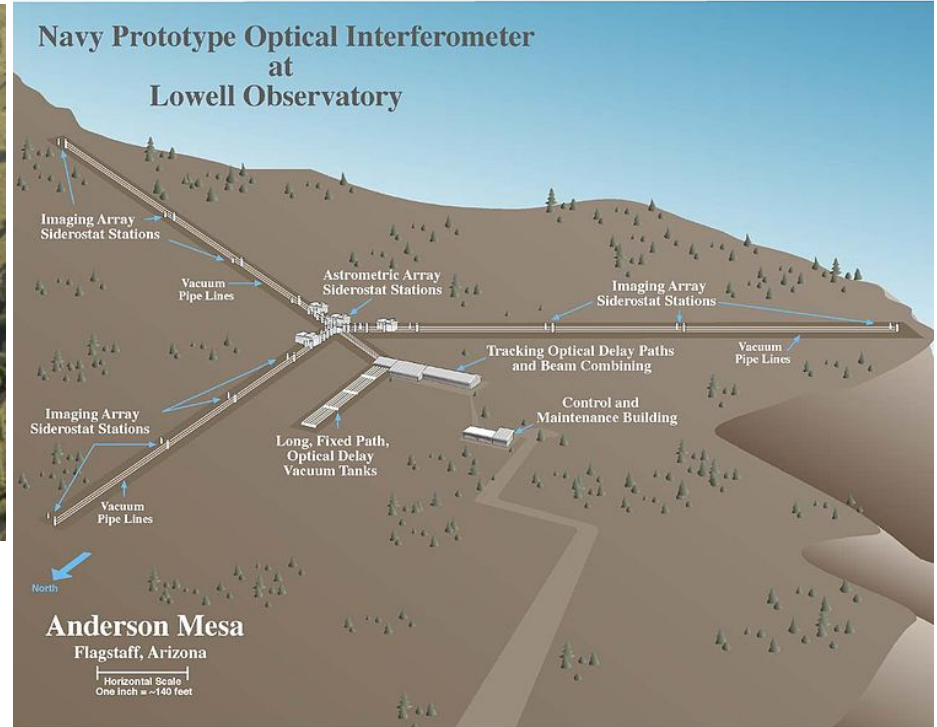Received 1992 October 19; accepted 1993 March 9

FIG. 1. Sequential examples of difference signal fringe packets.
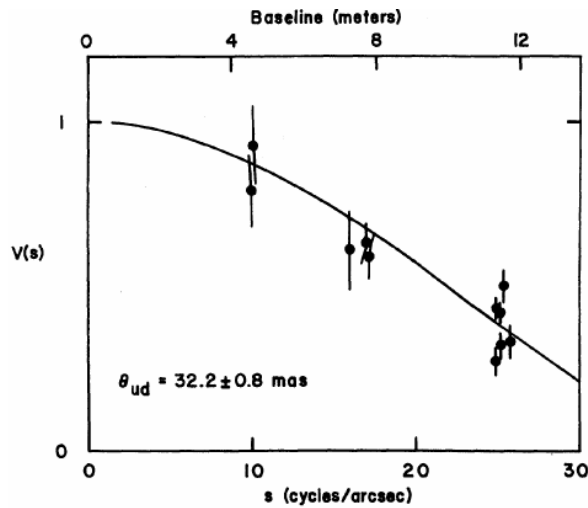
FIG. 2. Calibrated visibilities for α Her fit with a uniform disk model.

$\theta_{ud} = 32.2 \pm 0.8$ mas

FIG. 6—Visibility data for α Boo. The filled squares (■) were obtained with IRMA and the filled diamonds (♦) were obtained with CERGA. The solid curve is a uniform-disk visibility function for an angular diameter $\theta_{ud} = 0.021$ arcsec.

Refs.: Benson et al, AJ, 102, 2091 (1991); Dyck et al, PASP, 105, 610 (1993)

Navy (Prototype) Optical Interferometer (NPOI→ NOI), USNO, Flagstaff AZ, 1994-present

Navy Prototype Optical Interferometer at Lowell Observatory

Imaging Array Siderostat Stations
Vacuum Pipe Lines
Astrometric Array Siderostat Stations
Imaging Array Siderostat Stations
Tracking Optical Delay Paths and Beam Combining
Vacuum Pipe Lines
Control and Maintenance Building
Imaging Array Siderostat Stations
Long, Fixed Path, Optical Delay Vacuum Tanks
Vacuum Pipe Lines
North

Anderson Mesa
Flagstaff, Arizona
Horizontal Scale
One inch = ~140 feet

Ref.: http://en.wikipedia.org/wiki/Navy_Prototype_Optical_Interferometer

Navy (Prototype) Optical Interferometer (NPOI→ NOI), USNO, Flagstaff AZ, 1994-present

THE NAVY PROTOTYPE OPTICAL INTERFEROMETER

J. T. ARMSTRONG,[1,2] D. MOZURKEWICH, AND L. J RICKARD
Naval Research Laboratory, Code 7210, Washington, DC 20375; tarmstr@fornax.usno.navy.mil, mozurk@rsd.nrl.navy.mil, rickard@rsd.nrl.navy.mil

D. J. HUTTER, J. A. BENSON,[3] P. F. BOWERS,[3] N. M. ELIAS II,[3] C. A. HUMMEL,[2] AND K. J. JOHNSTON
US Naval Observatory, 3450 Massachusetts Avenue NW, Washington, DC 20392; djh@fornax.usno.navy.mil, jbenson@nofs.navy.mil,
bowers@sextans.lowell.edu, nme@sextans.lowell.edu, cah@fornax.usno.navy.mil, kjj@astro.usno.navy.mil

D. F. BUSCHER,[4] J. H. CLARK III,[1,5] AND L. HA[1]
Universities Space Research Association, 300 D Street SW, Washington, DC 20024; David.Buscher@durham.ac.uk, jhc@fornax.usno.navy.mil,
longha@fornax.usno.navy.mil

L.-C. LING[2]
Photonics Industry and Technology Development Association, Fifth Floor, No. 9, Roosevelt Road, Section 2, Taipei, Taiwan; lcl@www.PIDA.org.tw

N. M. WHITE
Lowell Observatory, 1400 West Mars Hill Road, Flagstaff, AZ 86001; nmw@lowell.edu

AND

R. S. SIMON[6]
National Radio Astronomy Observatory, Edgemont Road, Charlottesville, VA 22903; rsimon@nrao.edu
Received 1997 June 5; accepted 1997 October 30

THE REVISED ORBIT OF THE δ Sco SYSTEM

C. TYCNER[1], A. AMES[1], R. T. ZAVALA[2], C. A. HUMMEL[3], J. A. BENSON[2], AND D. J. HUTTER[2]
[1] Department of Physics, Central Michigan University, Mount Pleasant, MI 48859, USA
[2] US Naval Observatory, Flagstaff Station, 10391 West Naval Observatory Road, Flagstaff, AZ 86001, USA
[3] European Southern Observatory, Karl-Schwarzschild-Str. 2, 85748 Garching bei München, Germany
Received 2011 January 17; accepted 2011 January 21; published 2011 February 8
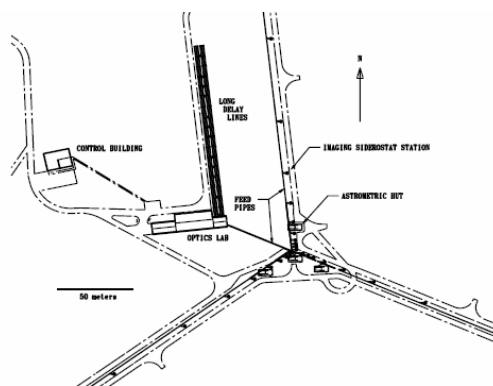
FIG. 4.—Plan view of the NPOI layout, showing imaging siderostat locations (filled circles), astrometric siderostat huts, roads, feed pipes, the optics laboratory, and the control building. The array arms extend beyond the area of the figure to a distance 250 m from the array center. The Lowell Observatory telescopes are just beyond the left edge of the figure.
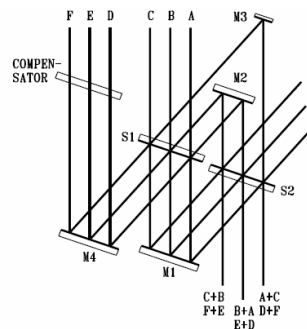
FIG. 9.—Schematic view of the beam combiner. Currently, the combiner works with three beams and combines them pairwise. The input beams (A, B, C) are split at beamsplitter S1. The reflected beams from S1 are shuffled by mirrors M2 and M3 and combined at S2 with the beams transmitted by S1 and reflected from M1. The combined beams (A + C, B + A, and C + B) transmitted by S2 are sent to the spectrometers. At present, the reflected beams from S2 are not used. The combiner will be converted to six-beam use by adding mirror M4. Six input beams (A, B, C, D, E, and F) will be combined into three output beams, each containing contributions from four inputs (A + C + D + F, B + A + E + D, and C + B + F + E). The compensator before M4 equalizes the optical paths in glass for all six input beams.
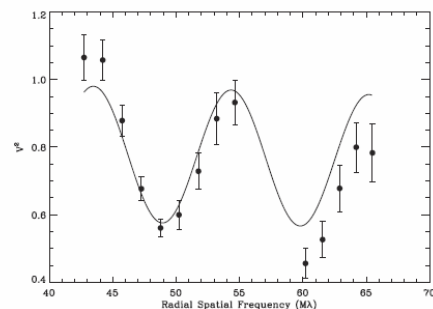
Figure 1. Squared visibility data obtained for δ Sco on 2006 June 5 across 14 spectral channels plotted as a function of radial spatial frequency. Data from only one scan and one baseline are plotted for clarity to illustrate the interferometric binary signature in the form of a cosine (solid line) that is used to obtain the angular separation and orientation of the binary components.
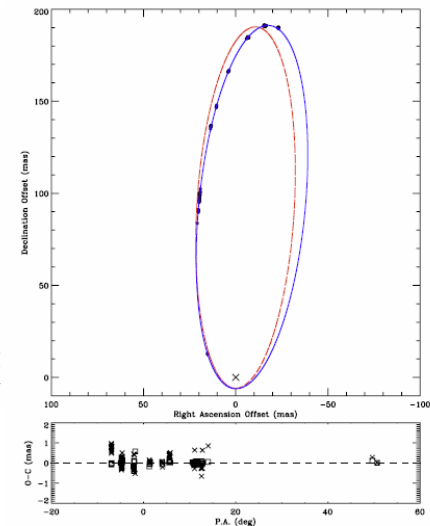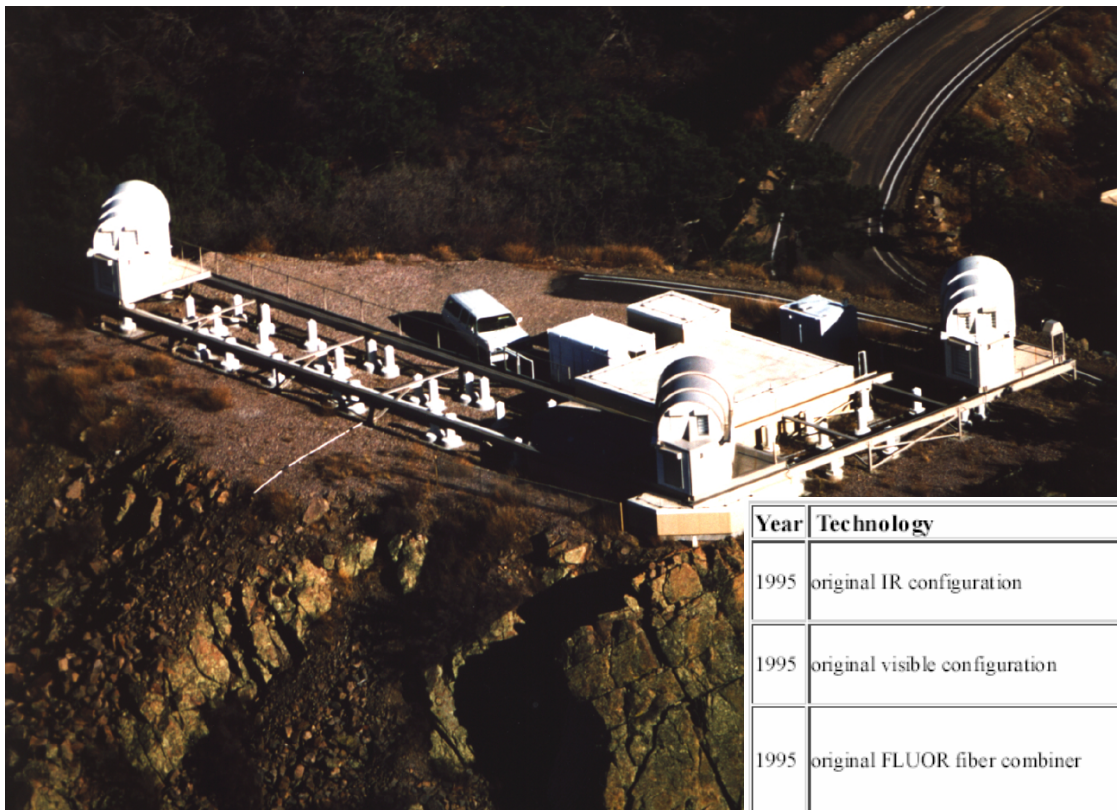
Figure 2. Top panel: binary orbits based on the parameters from Table 2 based on the best-fit parameters from this study (solid line) and those based on Tango et al. (dashed line) plotted with the astrometric results (filled circles) of Table 1. The uncertainty ellipses of the astrometric data are generally smaller than the size of the plotted symbols and were omitted for clarity. The location of the primary is marked with an "×." Bottom panel: the east–west (squares) and north–south (crosses) components of the O − C vectors as a function of the P.A. of the secondary.

Refs.: Armstrong et al, ApJ, 496, 550 (1998); Tycner et al. ApJL, 729, L5 (2011)

Infrared Optical Telescope Array (IOTA), CfA/UMass, Mt. Hopkins, AZ, 1994-2006

Ref.: http://tdc-www.harvard.edu/IOTA/

Year	Technology	Characteristics	Science examples
1995	original IR configuration	InSb discrete detector slow scan (0.03 Hz) K-band	Mira diameters (10%, K=3) effective temperature of K,M giants
1995	original visible configuration	4 parallel channels. VRI bands 512x512 SITe CCD	binary separation (V=7)
1995	original FLUOR fiber combiner	single-mode image fiber beam-combination discrete detector K-band	Mira diameters (1%, K=1) Teff to M8 (+/-50K) L-band (2%, L=-2) M-band tests
1997	NICMOS3 camera with classical beam combination	low read noise co-added reads 2 pixels, 2 beams JHK bands	HAeBe star disks (+/-5%, J,H=7, K=6) Miras (+/-5%, J,H=7, K=6) copy to CHARA
1998	rapid scan, classical beam combination	fast scan (10 Hz) stroke 60 micron VRI, JHK bands	CI Cam diameters (+/-4%, H,K=4) M dwarf masses (+/- 1%)
1999	NICMOS3 camera and FLUOR combination	low read noise 4 pixels, 4 beams slow (0.2 Hz) scan K-band	SW Vir, asym. diameters (+/-2%) zeta Gem, Cepheid (phi = 2 +/- 0.1 mas) R Leo diameters (+/- 0.2%)
2000	3rd telescope	3 simultaneous baselines, phase-closure	....

Infrared Optical Telescope Array (IOTA), CfA/UMass,
Mt. Hopkins, AZ, 1994-2006

R. MILLAN-GABET AND F. P. SCHLOERB
Department of Physics and Astronomy, University of Massachusetts, Amherst, MA 01003; rmillang@comet.phast.umass.edu
W. A. TRAUB
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138
F. MALBET AND J. P. BERGER
Laboratoire d'Astrophysique, Observatoire de Grenoble, Grenoble Cedex 9, F-38041, France
AND
J. D. BREGMAN
NASA Ames Research Center, Moffet Field, CA 94035
Received 1998 December 15; accepted 1999 January 14; published 1999 January 28
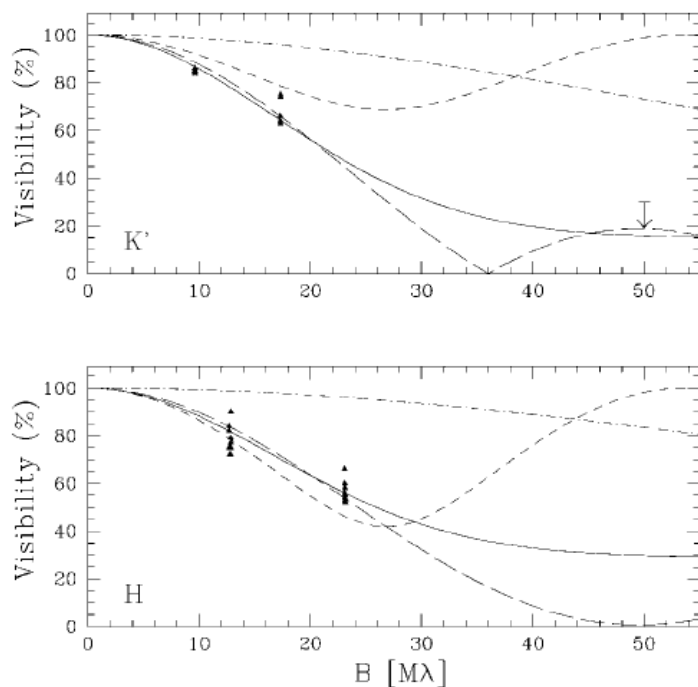
FIG. 1.—Visibility of AB Aur as a function of baseline length data and comparison with models of the source brightness distribution described in the text. The bottom panel shows the H-band data, and the top panel shows the K'-band data. The K' panel also shows the upper limit corresponding to the PTI observation. The models are plotted as follows: Gaussian (*solid lines*); ring (*long-dashed lines*); binary (*dashed lines*); and accretion disk (*dash-dotted lines*). The Gaussian and ring models provide an acceptable fit to the visibility data.

Hot exozodiacal dust resolved around Vega with IOTA/IONIC

D. Defrère[1], O. Absil[2], J.-C. Augereau[3], E. di Folco[4,6], J.-P. Berger[5], V. Coudé du Foresto[6], P. Kervella[6],
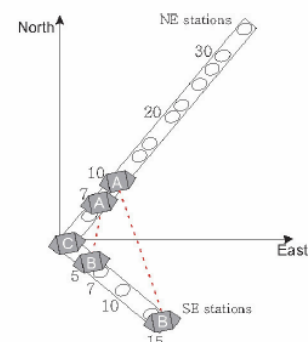J.-B. Le Bouquin[3], J. Lebreton[3], R. Millan-Gabet[7], J. D. Monnier[8], J. Olofsson[9], and W. Traub[10]
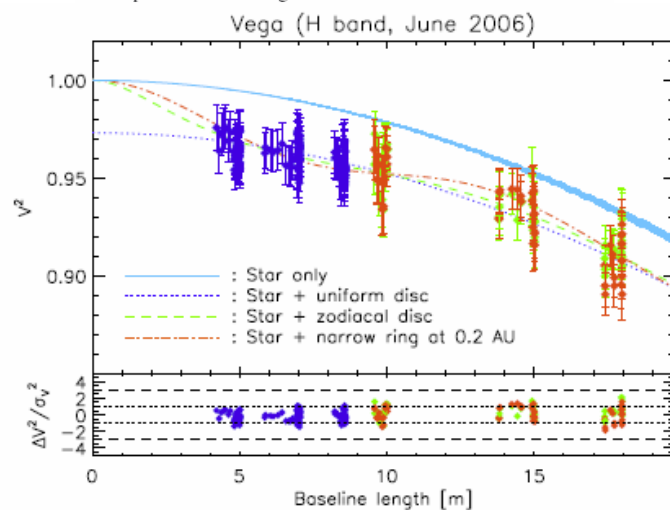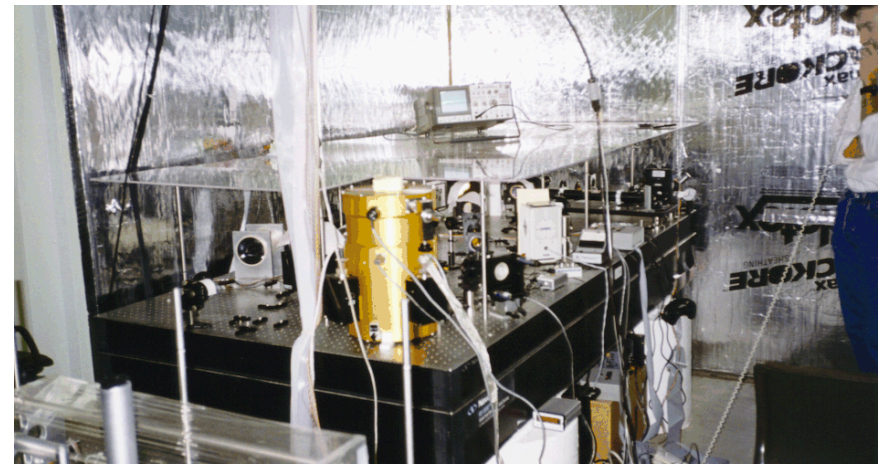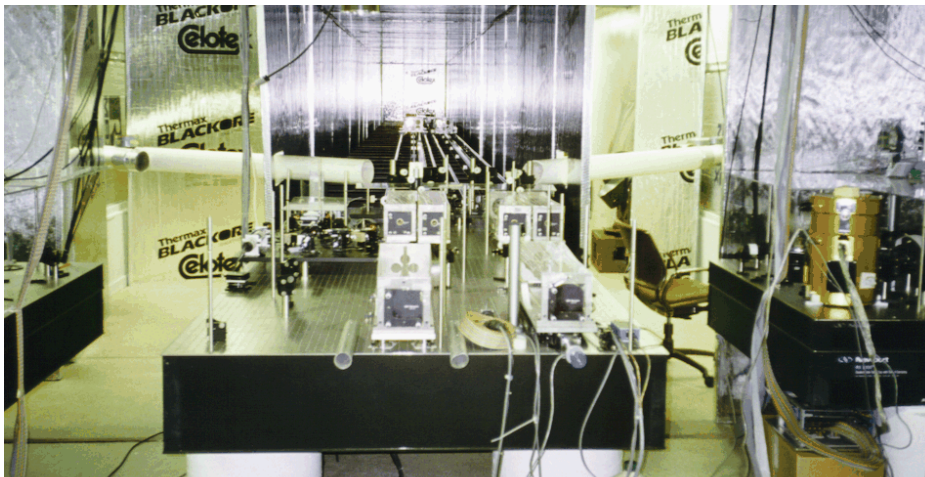
Fig. 1. Array geometry given with the available stations. Stations used during the observations are marked with a letter. Telescopes A and C can move on stations located along the 35 m north-eastern arm, while telescope B can move along the 15 m south-eastern arm.

Ref.: http://tdc-www.harvard.edu/IOTA/

Palomar Testbed Interferometer (PTI), JPL, Mt. Palomar, 1995-2008

Refs.: http://nexsci.caltech.edu/missions/Palomar/tour2.html
http://en.wikipedia.org/wiki/Palomar_Testbed_Interferometer

Palomar Testbed Interferometer (PTI), JPL,
Mt. Palomar, 1995-2008

RADII AND EFFECTIVE TEMPERATURES FOR G, K, AND M GIANTS AND SUPERGIANTS

G. T. van Belle and B. F. Lane
Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, MS 306-388, Pasadena, CA 91109

R. R. Thompson
Department of Physics and Astronomy, University of Wyoming, Laramie, WY 82071

A. F. Boden, M. M. Colavita, P. J. Dumont, D. W. Mobley, D. Palmer, M. Shao, G. X. Vasisht, and J. K. Wallace
Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, MS 306-388, Pasadena, CA 91109

M. J. Creech-Eakman, C. D. Koresko, S. R. Kulkarni, and X. P. Pan
California Institute of Technology, 4800 Oak Grove Drive, MS 306-388, Pasadena, CA 91109

AND

J. Gubler
Department of Physics, and Center for Astrophysics and Space Sciences, C 0424, University of California, San Diego, La Jolla, CA 92093-0424
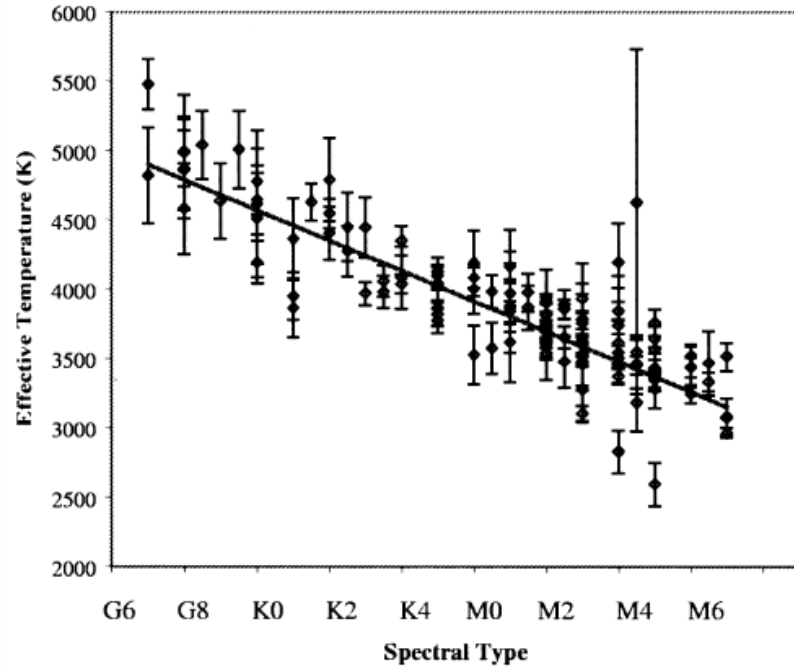Received 1998 June 12; accepted 1998 September 17

FIG. 1.—Temperature and radius as a function of spectral type. Data fr
and radii derived (Dyck et al. 1996, 1998) are plotted in all the figures.

HIGH-PRECISION ORBITAL AND PHYSICAL PARAMETERS OF DOUBLE-LINED SPECTROSCOPIC
BINARY STARS—HD78418, HD123999, HD160922, HD200077, AND HD210027

Maciej Konacki[1,2], Matthew W. Muterspaugh[3,4], Shrinivas R. Kulkarni[5], and Krzysztof G. Hełminiak[1]
[1] Nicolaus Copernicus Astronomical Center, Polish Academy of Sciences, Rabianska 8, 87-100 Torun, Poland; maciej@ncac.torun.pl
[2] Astronomical Observatory, A. Mickiewicz University, Sloneczna 36, 60-286 Poznan, Poland
[3] Department of Mathematics and Physics, College of Arts and Sciences, Tennessee State University, Boswell Science Hall, Nashville, TN 37209, USA
[4] Tennessee State University, Center of Excellence in Information Syste3500 John A. Merritt Blvd., Box No. 9501, Nashville, TN 37203-3401, USA
[5] Division of Physics, Mathematics and Astronomy, California Institute of Technology, Pasadena, CA 91125, USA
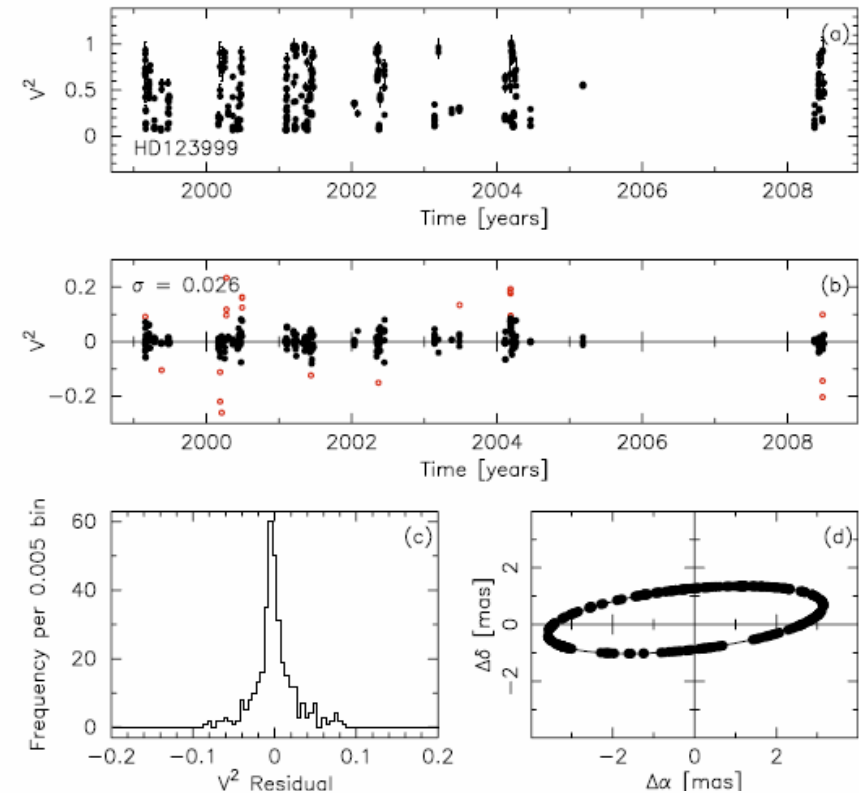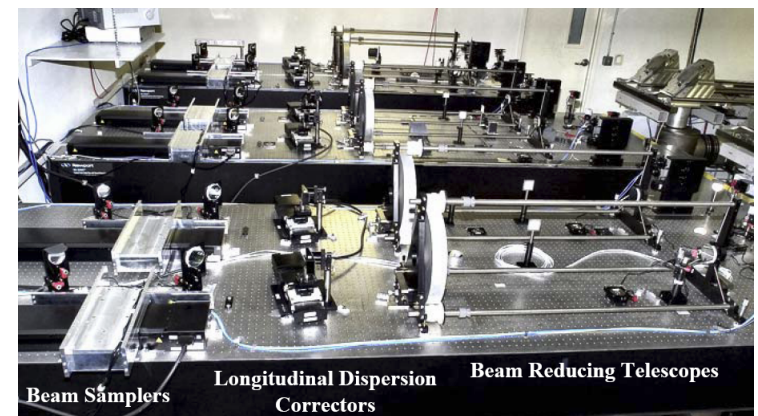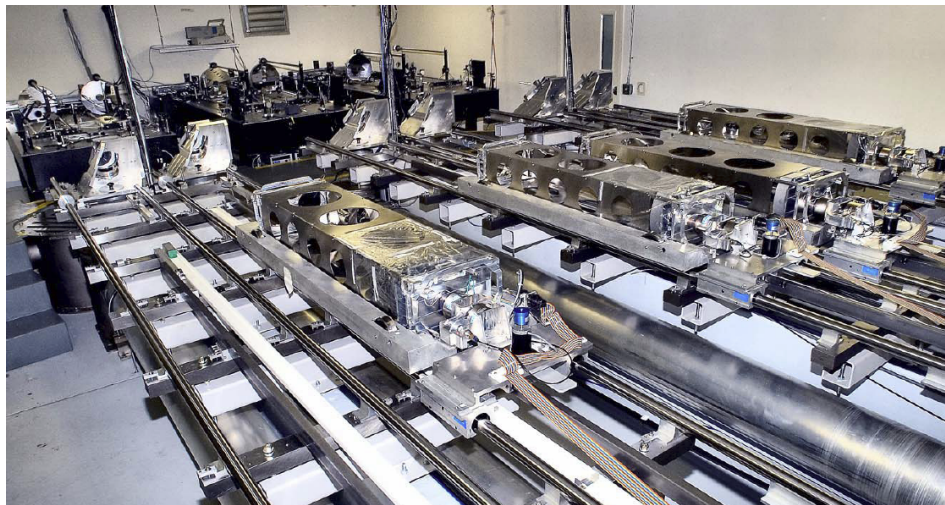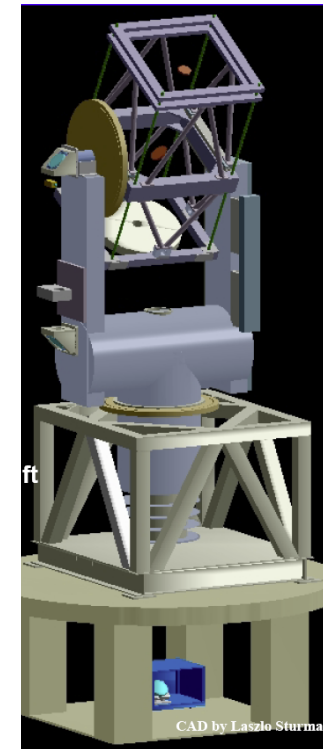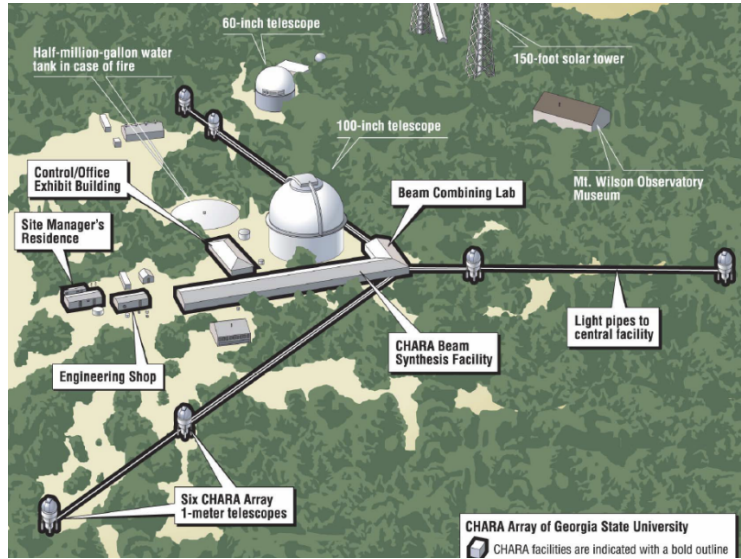Received 2009 October 23; accepted 2010 June 16; published 2010 July 28

Figure 11. Visibility measurements of HD123999 as a function of time (a), their best-fit residuals as a function of time (b) and histogram (c). The measurements used to determine the best-fit orbital solution are denoted with filled circles. The corresponding orbital coverage and the relative orbit are shown in panel (d).

Refs.: Boden et al, AJ, 117, 521 (1999);   Konacki et al, ApJ, 719, 1293 (2010)

CHARA, Georgia State U./NSF, Mt. Wilson, 2001-present

Refs.: http://www.chara.gsu.edu/CHARA/Slides/CHARAoverview.pdf

CHARA, Georgia State U./NSF, Mt. Wilson, 2001-present

FIRST RESULTS FROM THE CHARA ARRAY. V. BINARY STAR ASTROMETRY: THE CASE OF 12 PERSEI

WILLIAM G. BAGNULO, JR., STUART F. TAYLOR, HAROLD A. McALISTER, THEO TEN BRUMMELAAR, AND DOUGLAS R. GIES
Center for High Angular Resolution Astronomy and Department of Physics and Astronomy, Georgia State University,
Atlanta, GA 30303-3083; bagnulo@chara.gsu.edu

STEPHEN T. RIDGWAY
National Optical Astronomy Observatory, 950 North Cherry Avenue, Tucson, AZ 85719; ridgway@noao.edu

JUDIT STURMANN, LASZLO STURMANN, NILS H. TURNER, AND DAVID H. BERGER
Center for High Angular Resolution Astronomy Array, Mount Wilson, CA 91023; judit@chara-array.org,
laszlo@chara-array.org, nils@chara-array.org, berger@chara-array.org

AND

DONALD GUDEHUS
Center for High Angular Resolution Astronomy, Georgia State University, Atlanta, GA 30303-3083; gudehus@chara-array.org
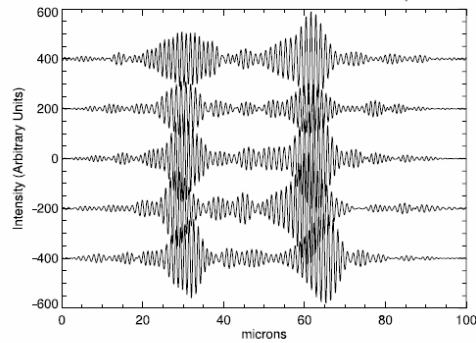Received 2005 October 7; accepted 2006 January 13

Toward Direct Detection of Hot Jupiters with Precision Closure Phase: Calibration Studies and First Results from the CHARA Array

M. Zhao[1], J. D. Monnier[2], X. Che[2], E. Pedretti[3], N. Thureau[3], G. Schaefer[4], T. ten Brummelaar[4], A. Mérand[5], S. T. Ridgway[6], H. McAlister[4], N. Turner[4], J. Sturmann[4], L. Sturmann[4], P. J. Goldfinger[4], C. Farrington[4]

FIG. 1.—Five consecutive fringe scans of 12 Per, after filtering.

Telescope Triangle: S1-E1-W1

Fig. 3.— Closure phase vs. Azimuth for six calibrators in 2008 August. The first, middle and the last wavelength channels of MIRC are shown from top to bottom. The data were taken with telescope S1-E1-W1. The red line shows the linear fit of closure phase as a function of azimuth. Different colors indicate different targets. The slope of the linear fit and the reduced χ^2 are also labeled in each panel.
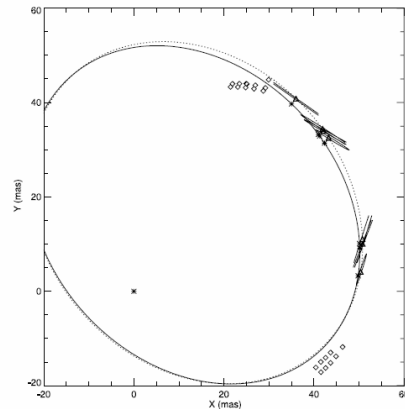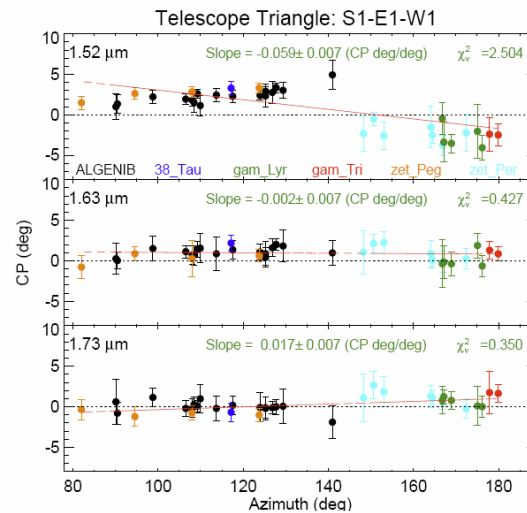

FIG. 5.—12 Per separations for all seven nights. The solid line represents the BSF98 orbit, and asterisks represent the standard locations during the nights. The dotted line represents the new orbit fit to the data, and the triangles represent the new orbit locations on the observing nights. The diamonds represent all the projected separations (21) derived from the seven nights. The error ellipses are plotted for each night's observation, as described in the text.
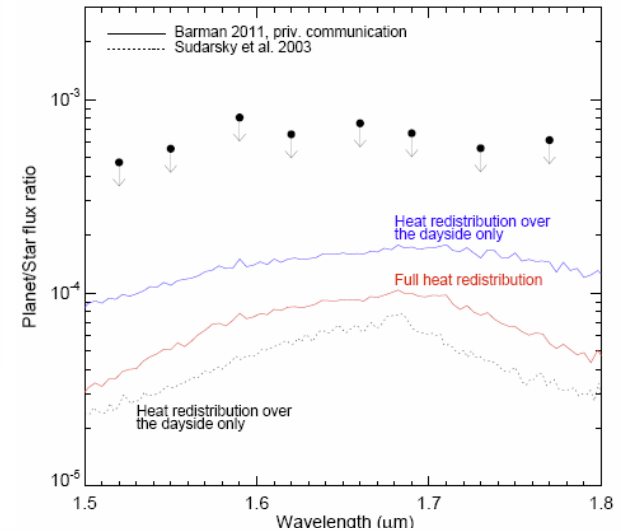

Fig. 9.— Upper limits with 90% confidence levels for the planet/star flux ratios of v And b in the H band, using the newly calibrated CHARA/MIRC data from multiple nights. The average upper limit level is 6×10^{-4}. The best channel at $1.52 \mu m$ shows an upper limit flux ratio of 4.7×10^{-4}. The solid lines show the latest model based on Barman et al. (2005) (Barman 2011, private communication), assuming a typical radius of 1.3 R_j for the planet. The blue line shows the model with incident flux uniformly distributed over the dayside of the planet only, while the red line shows the model with full heat redistribution over the entire sphere. The dotted line shows the model prediction from Sudarsky et al. (2003), assuming a radius of 1 R_j with heat redistribution over the dayside only.

Refs.: Bagnulo et al, AJ, 131, 2695 (2006);   Zhao et al, arXiv:1109.5183v1 (2011)

Keck Interferometer, JPL, Mauna Kea, HI, 2001-present
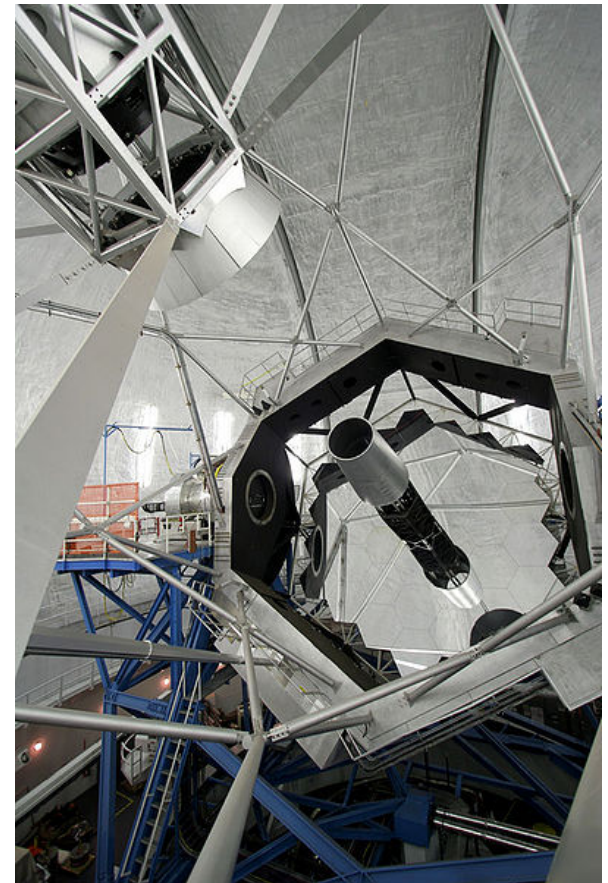
Ref.: http://en.wikipedia.org/wiki/File:Kecknasa.jpg
http://planetquest.jpl.nasa.gov/Keck/keck_intro.cfm

Large Binocular Telescope Interferometer (LBTI),
U. Arizona/JPL/UVa/UMinn, Mt. Graham, AZ, 2011…

Ref.: http://lbti.as.arizona.edu/LBTI-Main/Project.html
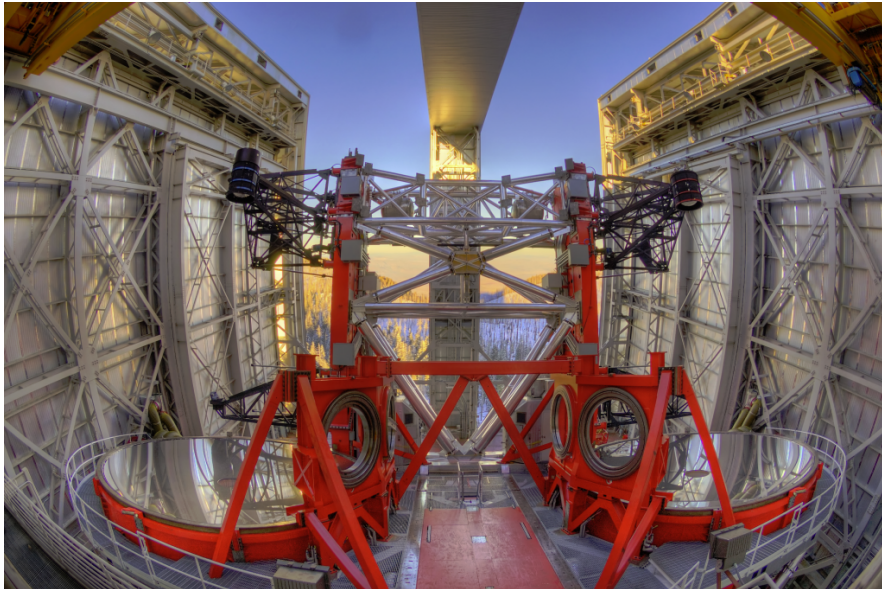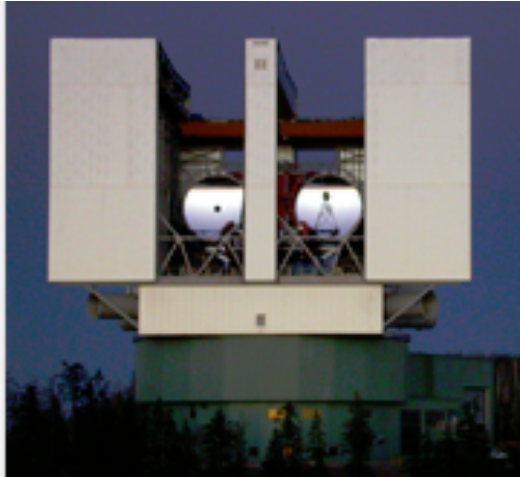
Magdalena Ridge Observatory Interferometer (MROI),
NM Tech, Socorro, NM, ~2013...

A Few Significant Conferences

- **IAUC 50, High Angular Resolution Stellar Interferometry, U. Maryland, 1978**

  - Connes, Dainty, Davis, Fried, Hanbury Brown, Koechlin, Low, Mertz, Ridgway, Roddier, Shao, Tango, Townes, Twiss, Weigelt, Worden, …

- **Optical and Infrared Telescopes for the 1990s, KPNO, Tucson, 1980**

  - Angel, Greenaway, Labeyrie, Meinel, Townes, Vakili, Woolf

- **Michelson Summer School, Caltech, 1999**

  - Lawson's book: McAlister, Boden, Townes, Quirrenbach, TenBrummelaar,, Colavita, Hutter, Dyck, Monnier, Mozurkewich, Armstrong, Serabyn, Ridgway

- **Interferometry for Optical Astronomy II, Waikoloa, HI, 2002**
- **New Frontiers in Stellar Interferometry, Glasgow, 2004**

  - 2 SPIE conferences, 5 volumes, 3308 pages of interferometry

Personal Epiphanies: 1/6

- **One photon at a time**

Personal Epiphanies: 2/6

- One photon at a time

- **"Golden Rule"**

Personal Epiphanies: 3/6

- One photon at a time

- "Golden Rule"

- **(Pupil densification, A. Labeyrie, violates rule)**

Personal Epiphanies: 4/6

- One photon at a time

- "Golden Rule"

- (Pupil densification, A. Labeyrie, violates rule)

- **Sums of wavefront patches are the key to understanding**

Personal Epiphanies: 5/6

- One photon at a time

- "Golden Rule"

- (Pupil densification, A. Labeyrie, violates rule)

- Sums of wavefront patches are the key to understanding

- **Same reflections for each wavefront patch**

Personal Epiphanies: 6/6

- One photon at a time

- "Golden Rule"

- (Pupil densification, A. Labeyrie, violates rule)

- Sums of wavefront patches are the key to understanding

- Same reflections for each wavefront patch

- **Radio ≠ optical, owing to induced emission**