Report of the Workshop On Imaging with Ground-based Optical Interferometers

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Sponsored by:
National Science Foundation

Co-chaired by:
T. Cornwell, National Radio Astronomy Observatory
H. McAlister, Georgia State University

Participants & Presentations

The participants in the workshop were:

Andrew Boden[S]	*California Institute of Technology*	bode@ipac.Caltech.edu
Wim Brouw[A]	*Australia Telescope National Facility*	wbrouw@atnf.csiro.au
Theo ten Brummelaar[H]	*Georgia State University*	theo@mtwilson.edu
David Buscher[H]	*University of Cambridge*	dfb@mrao.cam.ac.uk
Tim Cornwell[A]	*National Radio Astronomy Observatory*	tcornwel@cv3.cv.nrao.edu
Robert Fiete[A]	*Eastman Kodak*	rfiete@Kodak.com
Chris Haniff[S]	*University of Cambridge*	cah@mrao.cam.ac.uk
Mark Holdaway	*National Radio Astronomy Observatory*	mholdawa@cv3.cv.nrao.edu
Athol Kemball[A]	*National Radio Astronomy Observatory*	akemball@cv3.cv.nrao.edu
Richard Lyon[A]	*Goddard Space Flight Center*	lyon@jansky.gsfc.nasa.gov
Charles Matson[A]	*Air Force Research Laboratory*	matson@plk.af.mil
Harold McAlister[S]	*Georgia State University*	hal@chara.gsu.edu
David Mozurkewich[H]	*Naval Research Laboratory*	dm@gemini.usno.navy.mil
Thomas Pauls[A]	*Naval Research Laboratory*	pauls@atlas.nrl.navy.mil
Richard Paxman[A]	*Veridian/ERIM*	paxman@erim-int.com
Andreas Quirrenbach[H]	*University of California, San Diego*	qui@cassir.ucsd.edu
Francois Roddier[H]	*University of Hawaii*	roddier@IfA.hawaii.edu
Wesley Traub[H]	*Harvard-Smithsonian Center for Astrophysics*	wtraub@firs2.harvard.edu
Charles Townes[S]	*University of California, Berkeley*	cht@sunspot.ssl.berkeley.edu
Peter Tuthill[S]	*University of Sydney*	gekko@physics.usyd.edu.au
Glen Tyler[A]	*The Optical Sciences Company*	gatyler@tosc.com
David Westpfahl[S]	*New Mexico Institute of Mining and Technology*	dwestpfa@kestrel.nmt.edu

S=Science Panel A=Algorithms & Software Panel H=Hardware Panel

The following thirty-minute presentations were made on the first day of the workshop:

From Passive to Active (Adaptive) Interferometric Imaging	F. Roddier
Imaging Results from Aperture Masking	P. Tuthill
Optical Imaging Requirements	H. McAlister
COAST Overview	D. Buscher
ISI Overview	C. Townes
NPOI Overview	T. Pauls
IOTA Overview	W. Traub
Keck Interferometer Overview	A. Boden
CHARA Overview	T. ten Brummelaar
Experience from Radio Imaging	T. Cornwell
Imaging Algorithms and Software	A. Kemball
Array Layout Design	M. Holdaway
DoD Imaging Efforts	R. Paxman
Experience at Kodak	R. Fiete
NASA/GSFC Imaging Efforts	R. Lyon

Kneeling in front: R. Lyons, C. Haniff, T. ten Brummelaar, W. Traub, D. Buscher
Standing: T. Cornwell, J. Breckinridge, H. McAlister, F. Roddier, R. Paxman, G. Tyler, D. Mozurkewich, A. Quirrenbach, C. Townes, A. Kemball, R. Fiete, P. Tuthill, T. Pauls, A. Boden, W. Brauw

Introduction

Significant investments have been made during the past decade in ground-based instrumentation for long-baseline, optical/infrared interferometry. While important scientific goals will be met through the analysis of fringe visibilities alone, it is the promise of image reconstruction from distributed telescope arrays that will enable a revolutionary new window for observational astronomy.

But, the imaging of complex, extended objects using more than three telescopes is a significant challenge to existing facilities. Many relevant questions have not yet been definitively answered. Among these are: What kinds of scenes will be encountered? How will the distributions of spatial frequencies and contrasts within these scenes affect the resulting image? How do the number of light-collecting telescopes and their distribution affect the image? What levels of imaging fidelity can we anticipate when dealing with quasi-monochromatic light? How can the great successes of imaging at radio wavelengths benefit optical interferometry? What are the inherent limitations on imaging imposed by atmospheric turbulence? How important is adaptive optics, with and without laser guide stars, to interferometric imaging?

With these questions in mind, a small group of representatives from existing ground-based interferometers along with scientists with experience in complementary areas was convened at the Array Operations Center of the National Radio Astronomy Observatory in Socorro, New Mexico on 13/14 June 2000. The purpose of the workshop was to begin framing a "roadmap" outlining a sequence of research and technology efforts that must be accomplished before we can expect to have reliable methods for interferometric imaging at optical wavelengths. This advice will aid the Division of Astronomical Sciences within the National Science Foundation in fostering the development of interferometric imaging during the coming decade. Funding for this meeting was provided through the NSF Astronomy Division's Advanced Technology and Instrumentation, directed by Dr. James Breckinridge, who represented the NSF at the workshop. It is anticipated that this technology planning process will be a continuing exercise with annual meetings and updates.

The first day of the workshop was filled with presentations, several of which were intended to provide a general familiarization with existing ground-based interferometers and their capabilities and plans for imaging. NRAO staff astronomers, who have themselves been major contributors to the development of imaging with radio arrays, presented several talks imparting lessons learned from the radio experience. The complete program of talks is listed on page 2 above.

On the basis of areas of interest and expertise, the workshop participants divided themselves on the second day into three groups representing the general areas of *science*, *algorithms & software*, and *hardware*. These groups spent the morning in separate discussions of issues within their areas of consideration that they considered as being important to the development of optical interferometric imaging. The three groups were charged with developing specific recommendations to be incorporated in the roadmap. The results of the group discussions were presented to the plenary session after lunch by McAlister (science), Cornwell (algorithms & software) and Mozurkewich (hardware). A distillation of those reports is presented here.

Summary of Panel Discussions

Science - The Science Panel defined and then quantified a list of "instrument parameters" considered to be critical to the imaging performance of an interferometric array. These parameters were developed with existing facilities in mind and formed a starting framework to judge the applicability of these instruments to interferometric imaging. The performance parameters are:

1. *Baselines* – Currently available baseline dimensions are in the range of a few 10s to 500 meters (640 m in the case of SUSI). This corresponds to resolution limits (λ/D) of 4 to 0.2 mas at 0.6 μm and 15 to 1 mas at 2.3 μm. A wide range of important science goals, ranging from solar system to extragalactic astronomy, is accessible at these resolution limits.
2. *Number of Elements* – The number of light collecting telescopes n determines the number of baseline pairs $n(n-1)/2$ and independent closure phase triplets $(n-1)(n-2)/2$. Six elements

was considered to be the minimal starting point for imaging relatively simple objects. The imaging of complex objects will require doubling this number.

3. *Field of View* – The field of view of an interferometer is nominally determined by the diffraction-limited resolution of an individual light-collecting element. Thus, an array with 50 cm aperture elements has a maximum field of view radius of 300 mas at a wavelength of 600 nm, a limit within which extensive science can be accomplished. Larger fields of view, however, are important in many astrometric applications (e.g., proper motions in globular clusters, planets within binary star systems.) and must be accommodated with special techniques such as dual-beam interferometry. Adaptive optics may provide a better venue for certain wide field of view applications than interferometry.

4. *Sensitivity* – The limiting magnitude reachable by an array strongly determines the astronomical sub-fields to which the instrument can contribute. Achieving magnitude limits of +10 to +13 in the applicable pass band provides significant scientific opportunities, including applications to active galactic nuclei. Interferometers are not presently performing to this level, and are limited to applications in stellar astrophysics. Superficially, sensitivity is tied to the aperture of the collecting elements. However, because of the very large number of reflective and transmissive optical elements required to relay light from collecting telescopes to final beam combination, sensitivity is also largely determined by instrumental throughput, given by f^n where f is the efficiency of a reflective surface and n is the number of relay reflections. For a system with 15 reflections, the throughput decreases from 54% to 3% when f degrades from 0.96 to 0.80. Thus ways to improve sensitivity through enhancing the performance and lifetimes of coatings, across a broad range of spectral response, is critical to the success of optical interferometers. Other contributors to sensitivity are improved signal-to-noise of detectors and the use of adaptive optics. While the latter would allow long integration over the whole aperture of a light collector to improve S/N and limiting magnitude, it comes at the expense of diverting a significant fraction of the available light to wave front sensing.

5. *Dynamic Range* – Interferometers have achieved a modest dynamic range of 100:1, at least in the sense of detecting companions to stars five magnitudes fainter than the primary object. Dynamic range is associated with the precision of visibility measurements and the accuracy with which they can be calibrated.

6. *Spectral Resolution* – Spectral resolutions ($\lambda/\Delta\lambda$) in the range of 10 to 100 are essential for most science goals and increase to about 10^5 for detecting certain surface and circumstellar features in absorption for dwarf stars.

7. *Critical Time Scales* – At the limits of resolution achievable by optical interferometers, many phenomena are changing on timescales that limit the ability of the instrument to integrate for arbitrarily long periods of time. Behavior such as orbital motions in short-period spectroscopic binaries, stellar pulsations, expanding gas and dust shells, evolving features on stellar surfaces, gravitational lensing events, etc. lead to critical timescales of hours to months. The shorter time scales constrain the ability of an interferometer to build up (u,v)-plane coverage through earth rotation aperture synthesis or repositioning of light collectors, and strategies must be developed to optimize performance against these constraints.

The Science Panel attempted to create an initial list of science goals and characterize them against these basic performance parameters. This list is highly incomplete due to the very restricted time available for this discussion, and the quantities inserted in the table below are arguable. But, this limited exercise did point to aspects of the performance parameters listed above that require development. This initial list is given below for those science goals for which the Panel had time available for discussion. Following the table is a list of additional science goals that could be added to this table.

Class of Object	Single Stars	Single Stars	Evolved Stars	Dwarf Stars	Single Stars
Science Goal	Diam/Eff. Temp	Pulsations	Surface Structure	Surface Structure	Circumstellar
Wavelength Range	all	all	vis - nearIR	vis - nearIR	vis - midIR
$\lambda/\Delta\lambda$	~100	~100	~100	100 to 100,000	100 to 100,000
Characteristic Scale (mas)	50 - 0.5	50 - 0.5	5	1.0 - 0.1	50 - 0.1
FOV	small	small	small	small	small
Timescale Limited	no	hours - months	weeks	hours	weeks
Magnitude	<13	<13	<10	<13	<10
Dynamic Range	100:1	100:1	100:1	100:1	100 to 1000:1
Imaging Required	phaseless	phaseless	yes	yes	yes
Presently Feasible	yes	yes	yes	somewhat	yes
Special Observing Requirement	no	no	no	no	no
Polarization	no	no	yes	yes	yes

Additional science goals identified by the panel were:

1. Single Stars
    a. Mass Loss
    b. Solar Analogs
2. Young Stars
    a. Disks (Including Relics)
    b. Outflows/Jets
3. Binary Stars
    a. Mass Determinations
    b. Faint Companions
    c. Astrometric Companions
    d. Nulling
    e. Differential Phase (Center of light)

4. Novae/Supernovae Imaging
5. Active Galactic Nuclei
    a. Dust Torus Imaging
    b. Broad-Line Region Imaging
6. Gravitational Micro-Lens Imaging
7. Solar System
    a. Small Body Imaging
    b. Planetary Surface Imaging
8. Solar Surface Imaging

The Science Panel concluded that a very large parameter space of science awaits existing interferometric arrays. Much of this science can be accomplished by measurements of visibility, but imaging is crucial to important scientific areas that are also likely to attract attention to the field from non-specialists. While the investment made to date has poised optical interferometry quite favorably, major future resources will by strongly correlated with the success of the present facilities.

The interferometric facilities sponsored by NASA and NSF are largely complementary rather than redundant in nature. In particular, NASA funded instruments are directed towards specialized instrumental modes (astrometry, differential phase, nulling, etc) in pursuit of NASA Origins goals of detecting and imaging extrasolar planets. NSF facilities are more directed to broad science programs with less immediate need for pushing beam handling and combination toward new techniques. This complementarity is healthy and important to the development of the field.

Because of present limitations in sensitivity, current instruments are likely to revolutionize stellar astrophysics but will have little impact on major other fields, especially extragalactic astronomy, until advances in sensitivity are achieved. Ultimately, images of interesting objects are critical to the long-term success and to the flowering of interferometry into mainstream observational astronomy.

Hardware – Optical interferometry will flourish in the forthcoming era of 30 to 100 meter full aperture telescopes if it can produce important scientific results that cannot be obtained with full aperture telescopes. Interferometers do work better than full aperture telescopes when a high dynamic range result near the diffraction limit of the instrument is needed. Interferometry also does extremely-narrow angle astrometry better than full apertures. As long as we continue to build longer baselines interferometers, full apertures will never achieve the high angular resolutions that optical interferometers can achieve. We should consider optical interferometry to be a tool complimentary to full aperture telescopes and we should develop and exploit those capabilities that demonstrate that complementarity. With the baselines now available, optical interferometry is well poised to make this demonstration on compact objects such as stellar surfaces, circumstellar material, clusters of stars and active galactic nuclei.

In order to connect interferometric *capabilities* to their enabling *technologies,* the panel produced a list of desirable capabilities. To the right of each capability are listed those contributing technologies which are elaborated below.

Capability	*Technology*
Image Dynamic Range	*ACEFKM*
Image Accuracy	*ABCEFLM*
Astrometric Accuracy	*DEGKLO*
Resolution	*CDF*
Sensitivity	*ACDEFGHJK*
Field of View	*ADEFGLMO*
Dual Feed	*DFO*
Sky Coverage	*ACF*
Wavelength Coverage	*ABCDFHJN*
Observing Efficiency	*CGIKMO*

The relevant technologies are:

A. Detectors – Detectors play critical roles in instrument control and in the collection of science data. In the area of control, detectors need to have high speed, broad spectral response, low-noise, and high quantum efficiency in both discrete devices (like APDs) and arrays. All of these properties are available, but, unfortunately, not in one detector. The cost for the ideal control detector seems to be prohibitive. For science detectors, linearity and excellent statistics must be added to this list.

B. Spatial Filtering - Using either a single mode fiber or a pinhole as a spatial filter eliminates wavefront aberrations but introduces intensity changes. A fluctuating wavefront causes calibration problems whereas intensity fluctuations do not affect the standard V^2 estimator. The use of single mode fibers has already demonstrated an increase in V^2 and an improvement in calibration. However, poor coupling into the fibers, polarization effects, narrow bandpass and the lack of long wavelength fibers hinder their usefulness. It is unclear how much of an improvement (if any) we should expect from a fiber over a pinhole. Spatial filters quench any prospect of extending the field of view beyond the diffraction limit of the subapertures.

C. *Single Telescope Adaptive Optics* - AO promises two potential benefits for optical interferometry. First, for faint stars, AO can increase the sensitivity of an interferometer since both the wavefront sensing and correction can be performed at the telescope, thereby avoiding the pre-detection light loss currently inherent in long optical trains. This way, the AO can be made to work on fainter objects than the fringe detection. With a working AO system, the aperture can be increased until there are enough photons for fringe detection. It is necessary to point out that the gain for fringe detection is more than just an increase in the number of available photons. Adaptive optics allows longer fringe integration times because the piston time constant increases with aperture diameter. This application requires AO comparable in performance to current systems, but because one system is needed for each interferometer element, the systems must be lower cost and more turn-key. The system also has to be robust enough to allow us to move it from a temperature controlled optics lab to the telescope. Second, on bright stars we need an AO system that produces a very high Strehl ratio (>0.95). This requires more actuators per D/R_o than for conventional telescopes, but in principal can significantly improve fringe calibration.

D. *Beam Transport* – Pupil management is required for wide field of view and for applications in the thermal IR. While vacuum systems are typically used in current systems for transporting beams from telescopes into delay lines, single mode fibers might be applicable for very long baselines. In this regard, issues such as polarization, dispersion over wide spectral bandpasses, optical path difference monitoring, and bending efficiency/attenuation must be considered.

E. *Beam Combination* – Imaging interferometers require the combination of light from a large number of collectors. The optimum way of doing this has not yet been determined, and the correct approach may well depend on the spatial frequency content of the source. Existing beam combiners for three or more array elements are large and already fill optical tables. Integrated optics holds the potential of reducing the size of the beam combiner to a manageable level. Smaller systems also usually have better stability.

F. *Site Selection* – Excellent interferometric sites require good seeing as measured by the parameters r_o, τ_o, θ_o and L. Interferometers also require large flat areas, thus the optimum interferometric sites will not necessarily correspond to sites already developed for large, single-aperture telescopes. Site exploration and selection is a very long-term effort that needs to be started in the near term if we are going to be ready to advocate a large array a decade from now.

G. *Delay Compensation Improvements* – Current methods work quite well, but their large number of reflections is a primary source of reduced throughput.

H. *Coatings* – Improved performance of coatings is a major potential contributor to improved throughput and hence improved sensitivity. Current pressing needs in this area include broad spectral bandwidth beam splitters, improved dichroic phase properties, and durable enhanced coatings with good far-field reflectivity.

I. *System Control* – Improvements in this area include automation (eventually to the extent compatible with remote operation), rapid and accurate alignment procedures, better sequencing of control events, and the ability to rapidly recover from error fault conditions.

J. *Thermal Infrared Operation* – Emissivity control in the presence of diffraction over long path lengths is a challenge. To improve performance, interferometric usage of chopping on and off source needs to be developed.

K. *Fringe Measurement and Control* – There are many choices for measuring fringes and for using them for instrument control. Different choices are better in different applications. Relevant questions involve the optimum use of scarce photons, coping with non-isoplanatism in dual-feed or wide field of view systems, and the development of custom hardware, and software for fringe computation and data storage. We advocate terminology that distinguishes a 2x2 matrix of possible situations: measurement and control of fringe packet (e.g., at the one to few wavelength level), and measurement and control of an interference fringe (e.g., at the sub-wavelength level).

L. *Instrument Characterization* – This includes characterization of the atmosphere where a better understanding leads to better calibration. A key is the recording of all relevant observational parameters during observation (including r_o, τ_o and possibly θ_o). Accurate differential astrometry demands the knowledge of optical surfaces to very high accuracy.

M. *Configurability* – Some existing arrays rely on fixed collecting telescopes, whereas other arrays have moveable telescopes. Next generation arrays are very likely to demand easily reconfigurable arrays to match object-imaging requirements. Thus investigations of the design and performance of movable telescopes need to be carried out. The number and configuration of telescopes need to be traded against the resolution requirements of imaging targets recognizing that some targets require good (u,v) coverage in a snapshot mode due to changing morphologies on timescales competitive with Earth rotation aperture synthesis.

N. *Spatial/Temporal Interferometry* – Attaining high spectral resolution at high angular resolution is an interesting challenge to existing interferometers.

O. *Metrology* – Astrometry places heavy demands on full aperture metrology and is stressed by such things as dispersion and slew speed. The use of active optics to improve cumulative aberrations should be explored.

Algorithms and Software – The Panel discussed software issues in the context of data exploration and reduction, design testing and performance evaluation, instrument control/observing/scheduling, and science analysis. "Reduction" software has the broadest range of uses including instrument commissioning, post-commissioning instrumental exploration, data reduction with and without policy, algorithm development and exchange, and verification and validation.

Of immediate concern to the Panel was the possible proliferation of a wide variety of data formats. This would significantly inhibit the joint development of community-wide tools and effectively isolate the various groups from each other by preventing the easy exchange of data, algorithms. Ultimately, non-standard data formats will discriminate against scientific collaborations between groups and force the development of redundant but non-interchangeable software packages. It is therefore strategically important for the optical interferometry community to define and adopt a common data format as quickly as possible.

The feasibility and desirability of consolidating data exploration/reduction software into a single package was considered. The advantages of such a consolidation include the ability to concentrate on what is new and important rather than re-inventing basic software infrastructure and tools. This is particularly important considering the ever-increasing cost of writing code. A consolidated approach also easily permits the exchange, prototyping and preservation of newly developed algorithms. On the other hand, consolidation comes at the cost of additional overhead in developing and maintaining a community package and requires users to invest time in understanding and mastering toolkits that are initially foreign to them. The interferometry community could buy in at various levels of complexity ranging from sharing a common toolkit to subscribing to a community-wide measurement model.

While the panel asserted the importance of developing common practices in the areas of design testing and performance validation, it recognized the likelihood of non-commonly shared software packages for instrument control, observing and scheduling. It the area of scientific analysis of fully reduced and calibrated data, it is also highly likely that individual investigators will develop their own analysis procedures and codes. However, commonly used tools for data modeling, such as for limb darkening, kinematic modeling and the analysis of periodic phenomena do provide opportunities for sharing.

Recommendations to the NSF

From the Science Panel:

1. In comparison with NASA and DoD funded interferometers, NSF funded facilities are significantly understaffed. For full realization of the potential of these instruments, additional scientific and technical staff is needed to complete them and operate them in a timely and productive manner.
2. Interferometer projects should increase cross-group collaborations on technical and scientific issues and reach out to non-interferometrists, particularly theoretical astrophysicists, to provide complementary scientific expertise.
3. The most significant near-term technical needs center around achieving gains in sensitivity with an emphasis on improving photon throughput. Thus advances in enhanced coatings and low-noise, high-speed detectors are important, as is the development of adaptive optics for interferometers.
4. Desirable longer-term developments should emphasize the achievement of very high dynamic range (>>100) and very faint imaging (<+18).

From the Hardware Panel:

1. The panel strongly recommends supporting the existing arrays to improve the quantity and quality of their scientific output. In particular:
   a. Support efforts to understand and model the performance of existing arrays. (e.g. we all know that mirror coatings affect throughput, but what can be done to improve them?)
   b. Support the development of innovative beam combination and control techniques, especially those stressing: *i.* compactness through the use of single-mode fibers and integrated optics; *ii.* broad bandpass; *iii.* application to systems involving more than three telescopes; and *iv.* optimization of detection and control techniques for fringe packets and fringes.
   c. Support the development and implementation of control systems that give increased automation of current interferometers, including automated startup and good error handling.

   - d. Encourage increased interchangeability of hardware and software among current interferometers.
2. Prepare for a next-generation optical interferometric array by:
   - a. Studying optimum methods for deploying arrays of telescopes;
   - b. Exploring beam combination from arrays of more than three telescopes;
   - c. Initiating, as soon as possible, a site survey to determine where a next-generation optical array should be built.
3. We recommend support of projects that integrate adaptive optics into existing interferometric arrays. These efforts should develop the key methods of wavefront control, make them spectrally broadband and polarization independent, and provide this technology at modest cost. It is apparent that a next-generation array will require adaptive optics, and it is imperative that we develop an understanding of how AO systems interact with an optical interferometer before designing that array.
4. Improved, accessible detectors are a priority, and we recommend a program whereby:
   - a. Faster, lower-noise, efficient detectors, both discrete and in small arrays, are developed for interferometers;
   - b. Useful detectors be made available at affordable prices to interferometer groups;
   - c. Optimum methods of electronic read-out of these detectors be developed and successful techniques be disseminated to other interferometer groups.

From the Algorithms and Software Panel:

1. The Panel placed its number one priority on defining a common data format to which all optical interferometry programs must subscribe and utilize. A distinction between data exchange and instrument archive should be established. The activities of Tom Pauls at NRL are commended and may form the means for rapid evolution to a formal, community-wide working group with representatives appointed by each active project. The "data format working group" should then establish and maintain a standard, documented format that is updated on a known and agreed-upon basis. The need for such agreement is immediate and should be reached on the timescale of a few months.
2. In the areas of data exploration and reduction software, the working group described above should consider the feasibility of adopting a community-wide software architecture. This process would include an assay of existing possibilities that may represent enormous reductions in coding efforts with the desirable goal of selecting a specific package for community exploitation.
3. In support of design testing and performance validation, the Panel recommends the development of shared metrics to reflect science drivers and shared software tools for connecting designs to metrics. These tools should incorporate error trees and error budgeting and use simulations, hardware tests, prototypes, analysis, etc. In this regard, there is a significant existing knowledge and experience base from radio interferometric imaging.

Current Ground-Based Optical Interferometers

Name	Institution	Site	Number of Elements	Element Aperture (cm)	Max. Baseline (m)	Operating Wavelength (microns)	Operating Status
GI2T[4]	CERGA	Calern	2	150	35	0.4-0.8 & >1.2	since 1985
COAST[4]	Cambridge U	Cambridge	5	40	100	0.4-0.95 & 2.2	since 1991
SUSI[4]	Sydney U	Narrabri	13	14	640	0.4-0.66	since 1991
IOTA[3]	CfA	Mt. Hopkins	3	45	38	0.5-2.2	since 1993
ISI[1]	UC Berkeley	Mt. Wilson	3	165	30(+)	10	since 1990
NPOI[3]	USNO/NRL	Anderson Mesa	6	60	435	0.45-0.85	since 1995
PTI[2]	JPL/Caltech	Mt. Palomar	2	40	110	1.5-2.4	since 1995
CHARA[1]	Georgia St. U	Mt. Wilson	6	100	350	0.45-2.4	initial 1999
Keck[2]	CARA	Mauna Kea	2(4)	1,000(150)	165	2.2-10	initial 2001?
VLTI[4]	ESO	Cerro Paranal	4(3)	840(250)	200	0.45-12	initial ??

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