Ground-based Optical/Infrared Interferometry: High Resolution, High Precision Imaging

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Summary

Over the past decade, optical interferometry has demonstrated that its combination of high resolution and high precision can make unique contributions to astrophysics. Interferometers have grown in aperture size, baseline length, number of apertures, and spectral resolution. At the same time, methods to circumvent the limitations of interferometry are being introduced. Further increases in sensitivity through larger apertures and adapative optics, improved imaging flexibility through baseline bootstrapping, improved beam combination/fringe detection systems, and advances in reduction and analysis software to extract the maximum of information from the fringe data will allow us to realize the potential of optical interferometry for fainter and more-complex sources.

1. Introduction

In the past decade, ground-based optical/infrared interferometry* (OI) has demonstrated its potential by producing important astrophysical results at an increasing pace, as detailed in the white paper "Science at Very High Resolution" by Creech-Eakman. (See, e.g., http://olbin.jpl.nasa.gov/papers/index.html for lists of publications, Monnier 2003 for a tutorial and survey. The OLBIN website also has links to introductory material.)

These recent results demonstrate that OI is capable of more precise imaging than filled apertures, in addition to its more obvious advantage in angular resolution, even though most observations have been done with four or fewer apertures. These results include measuring the sizes of AGNs, imaging accretion disks in interacting binary stars, mapping the temperature distribution on the surfaces of rapidly rotating A stars, measuring Cepheid pulsations—and limb darkening, and imaging disks around YSOs and Be stars. The fundamental reason for OI's advantage in precision is that interferometric data are simple, with one separately measured complex number for each pair of apertures (see section 2)

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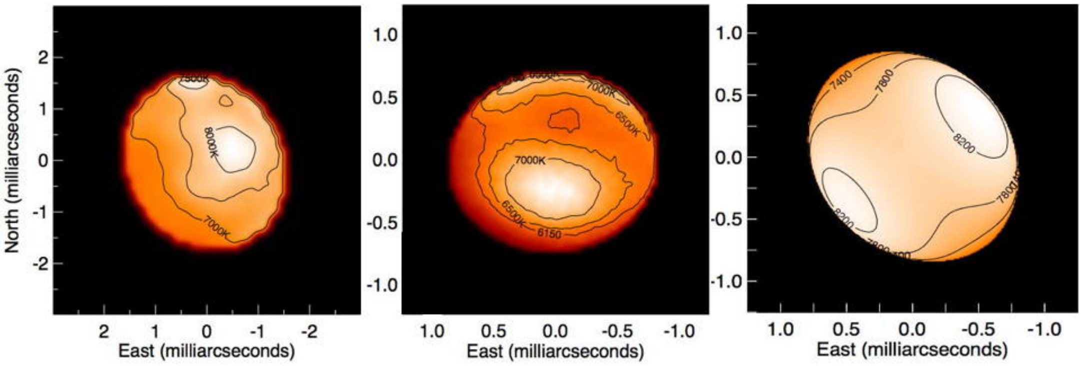
* For brevity, "optical interferometry" refers to interferometry over the visual and infrared bands.



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Rapid rotators observed with CHARA: Model-independent images of Altair (Monnier et al. 2007) and α Cep (Zhao et al. 2009), and a Roche-von Zeipel model α Oph (Zhao et al. 2009).

The factors that limit the sensitivity of OI are the same as those for adaptive optics (AO): both are problems of detecting and servomechanically removing the effects of the atmosphere. As the techniques of OI mature, the field of regard and sensitivity of OI will become comparable to those of AO. Mature OI will come to dominate high-precision, high-resolution imaging, much as radio interferometry now completely dominates radio astronomical imaging.

The science white papers for this Decadal Review demonstrate that OI can make contributions to astrophysics that are unavailable by any other means. To mention only a few, Aufdenberg points out that combining interferometric angular diameters, accurate parallaxes, and asteroseismology data can provide masses of single stars to within a few percent, and Giampapa's asteroseismology white paper cites the example of a 1.6% uncertainty in the mass of τ Ceti (Teixeira et al. 2009). Both Millan-Gabet and Mundy point out that the geometry of the inner few AU of planet-forming disks can be determined only with interferometry. Sahai anticipates observing the launch regions of collimated outflows in AGB stars. For a larger perspective on the growing relevance of interferometry, we note that 18% of the 354 white papers mentioned O/IR interferometry either as an enabling or supporting technique.

Existing interferometer technology is adequate for moving forward to a next generation array facility. However, there are numerous technology areas, including low loss methods of transferring light over long distances, high efficiency beam combiners with high spectral resolution, and data reduction techniques to extract maximum information from the detected photons, that are ripe for significant advances. These advances will significantly enhance the arrays in operation today and will enable substantially more ambitious facilities of the future.

2. Fundamental advantages of interferometry

It is well known that interferometry is capable of angular resolutions that no other technique can match, simply because it is always easier to move the array elements further apart than to build a bigger single telescope.

Interferometry has a second powerful advantage over single telescope observations that is not as widely appreciated: the ability to generate highly precise images. This potential has been realized in radio interferometry; some VLA images of radio galaxies such as Cygnus A (Carilli & Barthels 1996) have a dynamic range exceeding 10^5. Recent optical interferometry images have also reached high precision binary star separations with uncertainties ~10 mas (e.g., Muterspaugh et al. 2008), and contrast of ~200 between debris disks and stars (Absil et al. 2008).

This advantage stems from the simplicity of the data that interferometry generates: one complex number (the fringe amplitude and phase) for each baseline (pair of apertures). Under some very weak assumptions, the calibration of these data depends only on atmospheric and instrumental effects at the apertures involved, not on the length or orientation of their separation. When this is true, the calibration involves determining one number for each of the N apertures. Since the number of baselines, or pairs of apertures, grows as N^2, the data set contains information about the source, independent of perturbing effects, that can be used to self calibrate the data. This self-calibration is the key to radio interferometry's fantastic images. Although OI does not yet have enough apertures to produce equally stunning images, the best phase measurements, precise to a part in 500 (Zhao et al. 2008), point in this direction.

With adaptive optics on a big telescope, the point spread function tends to be a diffraction-limited core superimposed on a large halo. It is extremely difficult to calibrate that halo to a similar precision. To understand why, think of the telescope's primary mirror as composed of a large number of sub-apertures. Each pair of sub-apertures produces an independent measurement of a fringe amplitude and phase. The telescope optics Fourier transforms those fringes to form an image, while an interferometer measures the fringes separately, then does the Fourier transform with a computer. The problem with full-aperture imaging is that all but the largest separations are measured multiple times. These redundant observations all have different phases that are never completely corrected by AO. Since these measurements are combined before detection, the fringe amplitude is reduced by a term that depends on the phase variance. The lack of self-calibration information, the coupling between amplitude and phase errors and the dependence of the calibration on higher-order statistics all make for more difficult calibration for full-aperture imaging.

3. . . . and its disadvantages

The disadvantages of OI stem from the fact that, like AO, an optical interferometer is a servo-controlled system, and as such, it is subject to the same limitations as an AO system. In the case of OI, the need to detect a signal within the coherence time of the atmosphere imposes a set of interrelated constraints.

A first approximation is that the signal must be strong enough to detect within ~t_0, the atmospheric coherence time, typically a few to a few tens of milliseconds, using apertures limited to 1 – 3 times r_0, which is typically ~10 cm at visual wavelengths or ~40 cm at K band. The Fried length, r_0, is the diameter of the patch over which the rms of the atmospherically induced wavefront errors is less than a radian. This constraint has two consequences. First, the target must be bright enough to provide enough photons. Second, the target must have enough compact structure to produce detectable fringes, where "compact" means no larger than the fringe spacing, λ/B. Otherwise, data collection slows to unacceptably low rates.

But we now have techniques that stretch the space, time, and structure constraints. Adaptive optics can enlarge the effective Fried length by removing low-order wavefront errors, allowing us to observe fainter targets. Baseline bootstrapping—using fringes on shorter baselines to keep the longer baselines phased—allows us to take data on long baselines even when fringes there are too faint to detect. Coherent averaging in data post-processing, again using the short-baseline data to generate corrections for long-baseline data, gives us the ability to integrate over times longer than t_0.

4. State of the Art

Optical interferometry technology worldwide has significantly pushed back the limits of sensitivity and image complexity over the past ten to fifteen years with a combination of larger facilities (bigger apertures and more of them), better beam combiners and observing techniques, and improved software. In the European community, much of this progress has taken place in the context of a shared facility, VLTI, which numerous teams have used to develop a variety of techniques in the $\lambda = 1 - 10$ μm range. These groups have used VLTI in a wide range of areas, from measuring Cepheid pulsations to resolving the dust disk around a Seyfert nucleus. The VLTI, which uses up to four 1.8 m telescopes and sometimes up to four 8.2 m telescopes, has a maximum baseline length of 200 m.

Optical interferometry in the US is divided among several small groups, most led by one or two institutions, with the Keck Interferometer (KI) as an exception. These groups draw funding from different agencies, which has discouraged consolidation. Table 1 lists seven US optical interferometers, including LBTI and MROI, both of which are under development, and PTI, which was closed recently. Table 2 lists various instrumental characteristics, including angular resolution (calculated as $\lambda/B_{\max}$, where $B_{\max}$ is the maximum baseline length of the array) and sensitivity or limiting magnitude.

Sensitivity

Current arrays reach magnitudes of 5 to 10 in various visual to near-IR bands. This sensitivity allows us to reach the brightest targets in many categories: the brightest 10 to 15 Cepheids, a handful of interacting binaries, ten Hyades binaries, a handful of YSOs and a few AGNs. The primary limitation on sensitivity, as discussed above, is that most of the current arrays use apertures between one and a few times r_0. KI has used adaptive optics since 2003 (Colavita et al. 2003).

Table 1: US Optical Interferometers

Array	Institution	Funders	Status
ISI	UC Berkeley	JPL/ NExScI	Operating since 1988
NPOI	USNO/NRL	ONR, CNMOC	Operating since 1994
CHARA Array	Georgia St. Univ.	NSF, GSU, Keck	Operating since 1999
KI	Keck Obs/ NExScI/JPL	NASA	Operating since 2001
MROI	New Mexico Tech	ONR	Expect fringes 2010
LBTI	Steward Observatory	NASA	Expect completion 2010
PTI	MSC, CalTech, JPL	JPL, NExScI	Operated 1995 – 2009

ISI=Infrared Spatial Interferometer NPOI=Navy Prototype Optical Interferometer CHARA=Center for High Angular Resolution Astronomy KI=Keck Interferometer MROI=Magdalena Ridge Observatory Interferometer LBTI=Large Binocular Telescope Interferometer PTI=Palomar Testbed Interferometer

Angular resolution and spatial frequency coverage

The raw angular resolution of current arrays, which results from observing on the longest baselines with the shortest wavelengths, is one aspect of optimizing spatial frequency coverage. The longest baseline now in operation is 331 m at CHARA, corresponding to a resolution of 0.3 mas at visual wavelengths, roughly the diameter of a 4th magnitude B star, or 0.1 times the diameter of a 4th magnitude K star. The arrays with large apertures (VLTI, KI) have significantly shorter baselines: 200 m for VLTI, 85 m for KI. The fixed positions of the CHARA telescopes were chosen to give an even distribution of baseline lengths, while ISI, NPOI, and MROI were designed to be reconfigurable.

But for most imaging, the raw angular resolution of the array is not the only issue. The second is phasing an array that includes a range of baseline lengths. As discussed in Section 3, a stellar disk that is large compared to $\lambda/B_{\max}$ lacks adequate V^2 on that baseline. Two techniques are available for using long baselines under these circumstances. The first is “wavelength bootstrapping,” in which fringes are tracked at the red end of the instrumental bandpass, making it possible to integrate data taken simultaneously at the blue end. One of the first applications of this technique is described by Quirrenbach (1996) in observations of Arcturus.

The second technique, “baseline bootstrapping,” in which fringes are tracked on short baselines AB and BC, keeping the longer baseline AC properly phased, was first suggested by Roddier (1988). This mode is in current use; however, it has not yet been used to its fullest extent, e.g., a five baseline (six array element) chain at NPOI or CHARA.

Table 2: US Optical Interferometer Characteristics

Array	Resolution	Sensitivity	Apertures, Diameters	Wave band	Baselines
ISI	27 mas	50 Jy/hr$^{-1/2}$	3 x 165 cm	mid IR	5 – 80 m
NPOI	1.2	R = 5.5	6 x 12 cm	Visual	7 – 98 m
CHARA Array	0.9	K = 6.5	6 x 100 cm	Visual, near IR	31 – 331 m
KI	3.9	K = 10	2 x 10 m	near-mid IR	85 m
MROI	0.75	H = 10 (est)	10 x 140 cm	Visual, near IR	7 – 340 m
LBTI	3.3	0.1 mJy (est)	2 x 8.4 m	Visual, IR	23 m
PTI	3.0	K = 7.5	3 x 40 cm	H, K bands	85, 110 m

CHARA and NPOI both have feed systems that can accommodate six array elements, but they have usually observed with four or fewer due to beam combiner limitations. The MIRC combiner on CHARA has recently been upgraded to accept six input beams. The NPOI combiner can also accept six beams, but its six-beam mode suffers from crosstalk between baselines and has been used infrequently.

Multi-beam observations are important because they maximize the fraction of phase information recovered by the closure phases. A closure phase ϕ_{cl} is the sum of the baseline phases around a triangle of array elements. The contribution to the baseline phase of the turbulent atmosphere above each element appears in the sum once with a positive sign and once with a negative sign, so calculating ϕ_{cl} recovers a fraction of phase information about source structure unaffected by the atmosphere. The cost is the loss of a fraction $2/N$ of the phase information originally carried by the baseline phases, where N is the number of array elements.

Spectral resolution

Ten years ago, most near-infrared and visual OI observations were done at spectral resolutions below ~100, insufficient to isolate spectral lines. Moderate spectral resolutions are now available at CHARA—up to a few hundred on the MIRC combiner and 30,000 on the VEGA combiner—and a resolution of ~3000 is available at KI. At mid-infrared wavelengths, ISI uses much higher resolution, a reflection of its heterodyne detection system. The MIDI backend at VLTI uses resolutions up to ~500, while Amber has modes with R ~ 20, 1500, and 12000.

Backend development

The most advanced backends—beam combination and fringe detection systems—have started to use single-mode fibers as spatial filters, and in some cases integrated optics to combine multiple beams. The idiosyncrasies of these techniques are now being explored. These developments have been driven by two issues: the complexity of multi-beam combiners based on bulk optics, and the desire for improved calibration based on greater backend stability. Fringe amplitude calibration has benefited from the advent of spatial filters for the incoming beams. Spatially filtering the beams converts wavefront curvature into photometric fluctuations, which can be monitored separately in order to produce a correction and calibration to better than 1%. Fringe phase calibration, however, is the biggest beneficiary of spatial filtering, with the MIRC combiner at CHARA showing stability well below 0.1 deg.

Data reduction

It has been known for some time that closure phase is not the only source of phase information. There is also differential phase referencing, in which the difference in visibility phase between two wavelengths is measured. In recent observations of β Lyrae with the NPOI, the phase difference between the Hα emission channel and the continuum on either side indicated an offset of 1 mas between the two (Schmitt et al. 2009).

At visual wavelengths, it is sometimes possible to determine and remove the atmospheric contribution to the phase. Self-calibration methods adopted from radio interferometry can often be applied. When these efforts succeed, the format in which the data are usually analyzed, i.e., as V^2 on each baseline plus ϕ_{cl} on each triangle, is replaced by complex visibilities, to which decades of radio interferometry experience can be applied.

A complementary technique for maximizing the signal-to-noise ratio uses fringe modeling in multiple spectral channels to infer the fringe motion that remains after the fringe-tracking system has done its best. Compensating phase corrections are added to the data, which are then averaged (Jorgensen et al. 2007, 2008).

5. Technical development

The technology development discussed here is designed to address the particular challenges of optical interferometry discussed above—increasing sensitivity in the face of r_0 and t_0 constraints, and keeping an array phased while increasing angular resolution—while exploiting the angular resolution and imaging precision unique to OI.

Increase sensitivity: larger apertures, adaptive optics, efficient beam transport

Larger apertures and adaptive optics. Increasing aperture size is the most fundamental means for improving sensitivity, but to avoid the loss of fringe contrast while making use of the additional photons, larger apertures require adaptive optics beyond tip-tilt correction. CHARA already has 1 m telescopes, corresponding to ~10r_0 at visual wavelengths. NPOI is acquiring a 1.4 m telescope built of carbon-fiber-reinforced polymer (CFRP) for testing. Its weight, ~100 kg including mount, is well suited to reconfigurable array. In addition, USNO plans to acquire the four 1.8 m Keck outriggers and install them at NPOI if funds can be found. MROI is in the process of acquiring its first telescopes, 1.4 m in diameter.

While adaptive optics systems have been used at both the Keck Interferometer and VLTI since 2003, AO has not yet been applied to the three long-baseline interferometers, CHARA, NPOI, and MROI. At an earlier stage in the development of OI, some researchers felt that adding adaptive optics to an interferometer would not lead to a significant increase in sensitivity (e.g., Armstrong et al.1998, Baldwin & Haniff 2002). More recent work has suggested that the benefits are likely to be significant (Bharmal 2004; Ting et al. 2006; Mozurkewich et al. 2007), and that low-order AO, perhaps up to five Zernike polynomials, should be implemented on at least some apertures in order to begin confirming these results. All three of the long-baseline interferometers have programs to implement AO (e.g., Ridgway et al. 2008), and would benefit from technology support.

Beam transport over hundreds of meters or kilometers. Free-space beam propagation (in vacuum) proves suitable for distances of hundreds of meters. For kilometer distances, diffraction makes free-space transport increasingly difficult and costly. Transmission in single mode, polarization preserving optical fibers has now been demonstrated in hundred meter increments for the OHANA project (interferometric connection of Mauna Kea telescopes) where free-space transport is impossible owing to irregular terrain and environmental protection controls. (Perrin et al. 2006). Fiber is a natural technology to extend to much longer baselines. Development and production of fiber will continue in the telecom industry. Support is needed on technologies of efficient beam injection and extraction, dispersion control and correction, and phase stabilization. NPOI, CHARA, MROI, and the OHANA experiment are all suitable sites for a study of these issues.

Improve imaging flexibility: baseline bootstrapping, longer baselines

Without bootstrapping, using the longest baselines requires the presence of some structure in the source that remains only partly resolved by the interferometer. A program to implement a baseline bootstrapping capability on one or more of the long-baseline arrays should be supported. For the current configurations, this implementation would involve changing the delay line control algorithm, while for NPOI and MROI, which are both designed to be reconfigurable, it includes commissioning the appropriate telescope locations. Stellar surface imaging in particular would benefit from baseline bootstrapping on an equal-spacing array.

Improving sensitivity will eventually lead to a need for longer baselines; in fact, the maximum baselines of both CHARA (331 m) and NPOI (437 m when complete) are already too short to fully resolve stars earlier than about mid-A that are at their respective faintness limits. Both NPOI and MROI have enough space to expand to perhaps 1 km, an option that should be explored.

Improve the backends

The outlines of a modern general-purpose visual/near-IR beam combination system are in place. Each of these features has been implemented on one or more instruments, but no combiner has put them all together. Such a backend should separate fringe tracking and data taking functions so that both could be optimized. It should spatially filter the input beams, probably with single-mode fiber.

In order to provide the data needed to apply self-calibration methods and extract phase information, the data taking component should correlate as many simultaneous baselines as possible, should have moderate to high spectral resolution, and should also photometrically monitor the input beams to create a correction for flux imbalances. The need for mechanical and optical stability may mean that integrated optics should be developed and used.

The fringe tracker should use pairwise combination of a minimal subset of inputs, in order to maximize sensitivity. The science camera should accept multiple beams; the most successful technique at present seems to be to combine them in a focal plane illuminated by a non-redundantly spaced set of input beams.

Get the most out of the data: phase referencing, coherent averaging, imaging software

The recent developments in software deserve further support. They include phase referencing and related methods for reconstructing baseline phases using coherent integration. Closure phases produce inferior SNR to baseline phases and cannot be used at low SNR such as on faint targets or at high spectral resolution (Jorgensen et al., in preparation, 2009). Maximum entropy based imaging algorithm methods such as MACIM (Ireland et al., 2006) must also be developed.

Summary and estimated costs of technology areas endorsed

We envision that supporting the technology development described here could be accomplished with $18M over ten years. The breakdown of this estimate is shown in

Table 3: Suggest interferometry program costs	
Sensitivity	
Optimized telescopes (e.g., lightweight mirrors)	\$ 5 M
Adaptive optics for interferometry	\$ 3 M
Beam transport	
Fiber transport development	\$ 2 M
Free-space optics transport development	\$ 2 M
Backend development	
Backend development	\$ 2 M
Baseline bootstrapping capability	\$ 2 M
Fringe detection software development	\$ 2 M
TOTAL over 10 years	**\$18 M**

Table 3. Support for hardware support would fall naturally under the ATI program of NSF and similar programs. We would ask that NSF designate funds against which proposals for interferometry technology development could be written. We call attention to the fact that software development is not currently funded by NSF.

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