# Operational Funding for Optical and Infrared Interferometers

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Contact Author: USIC Chair, Michelle Creech-Eakman, mce@inanna.nmt.edu, phone: 575-835-5809

Contributors: R. Akeson (NExScI), S. Ridgway (NOAO), D. Leisawitz (GSFC), P. Wizinowich (Keck), J. Armstrong (NRL), M. Creech-Eakman (MROI), C. Haniff (Cambridge), P. Hinz (UA), D. Hutter (USNO), H. McAlister (GSU), S. Ragland (Keck), T. ten Brummelaar (GSU), C. Townes (UCB), E. Wishnow (UCB)

## Executive summary

In the last several years, the field of optical and infrared interferometry has reached a level of technical and operational maturity that has enabled many scientific breakthroughs, ranging from the direct measurement of Cepheid pulsations and the first image of the surface of a main sequence star other than our Sun to constraining the central 0.1 pc of active galactic nuclei. These facilities are also ideal environments for hands-on observational astronomy training for students and technical staff. There are four optical/infrared interferometers currently operating in the U.S. and two under development and these facilities now face a new set of challenges in obtaining funding to continue these advances and provide access to the community. We find that the currently available funding opportunities do not allow proposals for supporting the operations of these facilities. We recommend that the State of the Profession committee address this problem and suggest some possible solutions such as creation of a new program similar to the NSF University Radio Observatories (URO) program but for optical and infrared facilities.

## 1 Overview of optical/infrared interferometry

The quest for higher spatial resolution has often been one of the driving forces behind the development of bigger and better telescopes. Experiments in optical interferometry date back to the observations of Michelson and Pease on Mt. Wilson in the 1920's but the technical challenges resulted in limited progress as compared to the proliferation of large single telescopes. After a recommendation in the Bahcall decadal survey for development funding, the 1990's saw a great deal of technical progress in the field and several optical and infrared interferometers were constructed and began operations in the U.S. and Europe. The current facilities span a wavelength range from the optical to the mid-infrared, which enable studies covering a wide range of topics, from stellar properties to the characterization of dust with temperatures of only a few hundred Kelvin. For convenience here, we will refer to all of these telescopes as optical interferometers. Even with the tremendous progress made in adaptive optics and space-based observing, interferometry is still the only technique that allows observations in the optical and near-infrared with resolution better than 10 milliarcsecond (mas). Thus, this technique provides a unique observational capability for many areas of astrophysics.

The technical developments of the last few years have brought new science opportunities that are expanding the scope of optical interferometry. Here we give two examples: higher spectral resolution and phase closure/imaging.

To date, most optical interferometry measurements have been broadband and trace the continuum emission from the stellar photosphere or the dust surrounding stars and AGN. Observations with spectral resolution sufficient to resolve lines from individual atomic or molecular transitions have been made in the mid-infrared for many years and are now possible in the near-infrared and optical. Results from these studies include directly measuring the spatial scale of the outflow in a massive young stellar object (Malbet et al., 2007, A&A, 464, 43) and determining the structure of the molecular shells around evolved stars from ammonia and other molecules (e.g. Perrin et al., 2004, A&A, 426, 279). Resolving the line emission also enables kinematic studies on mas scales.

The second area of recent work is the construction of closure phase and the first images in optical interferometry. Although these techniques are common-place in radio interferometry, they have only recently been implemented at optical interferometers due to the dominance of the atmospheric noise term and other technical challenges. As the closure phase is free of atmospheric noise, it holds great promise for imposing further constraints on source structure and imaging, even with as few as four array elements, and allows model-independent reconstruction of the source brightness distribution. Exciting results in this area include detection of a localized hot spot within the central few AU of a young stellar object disk (Millan-Gabet et al., 2006, ApJ, 645, 547) and an image of the surface of Altair showing the strong effect of gravity darkening on the highly distorted stellar photosphere, which cannot be explained by standard models for a uniformly rotating star (Figure 1).

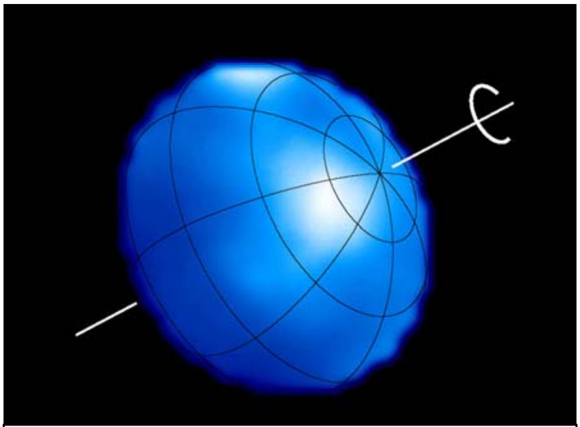

**Figure 1:** Image of the surface of Altair from CHARA observations (from Monnier et al, Science, 2007, 317, 342).

These observational capabilities have resulted in scientific progress on a large range of astrophysical studies. The many areas that benefit from the unique capabilities of interferometry range from direct measurement of fundamental stellar parameters to the environments of young and evolved stars to the physical scales of AGN components. Optical interferometry is relevant to many of the issues raised in the science white papers submitted to ASTRO2010. Several papers (Table 1) focus primarily on science enabled by ground-based optical interferometry. A further 18 papers mention contributions from ground-based optical interferometry while a total of 62 cite the need for ground or space optical/infrared interferometry (see http://usic.wikispaces.com/ASTRO2010+White+Papers for details).

**Table 1:** List of science white papers to ASTRO2010 focused on science enabled by ground-based optical interferometry.

| White paper title | First author | Science panel |
|---|---|---|
| Fundamental Stellar Astrophysics Revealed at Very High Angular Resolution. | Aufdenberg | Stars and Stellar Evolution |
| Science at Very High Resolution: The Expected and the Unexpected. | Creech-Eakman | PSF/SSE/GAN |
| How and When do Planets Form? The Inner Regions of Planet Forming Disks at High Spatial and Spectral Resolution | Millan-Gabet | Planet and Star Formation |
| Quantifying Stellar Mass Loss with High Angular Resolution Imaging | Ridgway | Stars and Stellar Evolution |
| New Frontiers in Binary Stars: Science at High Angular Resolution | Schaefer | Stars and Stellar Evolution |
| New Astrophysical Opportunities Exploiting Spatio-Temporal Optical Correlations | de Wit | PSF/SSE |

The potential of optical interferometry extends well beyond the science applications of current ground-based arrays, offering a solid foundation for the U.S. to extend into the future its role in a vibrant international community. Future progress in astrophysics in a variety of topical areas, extending well beyond those mentioned above, will depend on the successful development and utilization of interferometric techniques. A next-generation ground-based facility could extend capabilities in one or more directions – e.g. sensitivity, image quality, angular resolution. The ground-based interferometers also play a vital role in training the next generation of students and engineers. Over the last four decades, ground-based optical interferometry has produced over 80 MS and PhD theses with at least 10 currently in progress. The current U.S. array facility complement could support open, peer-reviewed access for community researchers, continue opportunities for student involvement, and ensure technical staff training.

Intertwined with the scientific and technical goals of ground-based interferometers is space-based interferometry. During the past decade the astrophysics community proposed a number of new space-based interferometers, each one of which would significantly advance the scientific frontier (e.g., detect and characterize exoplanets, discover the merger history of galaxies and their development over time, probe the event horizons of black holes). These space mission concepts span the electromagnetic spectrum from radio to X-ray wavelengths. Existing ground-based optical interferometers and lab-based interferometry testbeds are the best training ground for a new generation of astrophysics pioneers.

## 2 Summary of current and in-development facilities

Optical interferometry now has a significant international infrastructure of private and public facilities, particularly including the ESO Very Large Telescope Interferometer (VLTI), the Keck Interferometer (KI), Georgia State University's Center for High Angular Resolution Array (CHARA), the Navy Prototype Optical Interferometer (NPOI), and UC Berkeley's Infrared

Spatial Interferometer (ISI) all of which are operational, and the Magdalena Ridge Optical Interferometer (MROI) and Large Binocular Telescope Interferometer (LBTI), which are under construction. These observatories carry out high angular resolution measurements, typically a few mas or better, of bright, compact sources, and are now delivering on their promise, with breakthrough measurements of stars and stellar environments. Improvements currently underway will extend the operation of some facilities to fainter sources than is now possible.

A list of U.S. long-baseline optical interferometers is given in Table 2. These facilities come in different sizes and funding levels: from university-based arrays (ISI) to larger facilities that plan to operate for many years to come (CHARA, NPOI, MROI) to large-aperture interferometers (KI and LBTI) that only operate part of the time at their respective observatories. These facilities each have something unique to offer in wavelength coverage, spatial and spectral resolution or sensitivity.

**Table 2:** List of U.S. long-baseline optical interferometers currently in operation or under development. More details on each interferometer can be found at the links listed at http://usic.wikispaces.com/Interferometry+Web+Resources.

| Short Name | Long Name | References |
|---|---|---|
| CHARA Array | Center for High Angular Resolution Astronomy Array | ten Brummelaar et al. 2005 (ApJ, 628, 453) |
| ISI | Infrared Spatial Interferometer | Hale et al. 2000 (ApJ, 237, 998) |
| KI | Keck Interferometer | Colavita et al. 2003 (ApJ, 592, L83) |
| NPOI | Navy Prototype Optical Interferometer | Armstrong et al. 1998 (ApJ, 496, 550) |
| LBTI | Large Binocular Telescope Interferometer | Hinz et al 2004, (Proc. SPIE, 5491, 787) |
| MROI | Magdalena Ridge Observatory | Creech-Eakman 2006 (Proc. SPIE, 6268, 1V) |

CHARA, ISI, KI and NPOI routinely make scientific observations and MROI and LBTI are under construction and will enter operations in the next few years. Although technical developments are still ongoing, many of the challenges faced by these facilities in the next few years are operational or political:

- How to attract users to a field where the final data product is often not an image.
- How to train the next generation of instrument developers.
- How to balance technical development with scientific operations.
- How to compete for funding within the current NSF and NASA program structure.

Demand has been increasing and will continue to increase as the US community becomes better educated about interferometry, as more interferometer time becomes available to the community, and as the capabilities and performance of interferometers continue to improve and to offer unique and powerful scientific returns. Interferometry is becoming an important part of the scientific toolbox that astronomers use in understanding the universe, and demand to make this tool available will grow as a result.

As an example of the U.S. demand, the 269 CHARA nights scheduled in 2008 were divided among 52 proposals involving 65 investigators. During the second half of 2008, the proposals submitted to CHARA from the six collaborating institutions requested a total of 240 nights compared to the 106 available. At NPOI, two-thirds of the nights are dedicated to a wide-angle astrometry program and the oversubscription rate for the remaining nights is about 2:1. The NASA and NOAO oversubscription rate for KI was 3:1 in the first semester of 2009. About 10% of the respondents to the ALTAIR (Access to Large Telescopes for Astronomical Instruction and Research) survey identified near-IR interferometry from large aperture interferometers as an important capability for their research over the next 2-3 years. In Europe, the facility-class instruments of the VLTI attract ~10% of all proposals to the VLT.

# 3 Current Operational Funding Opportunities

Expanding the opportunities for community use and further technical improvement of the existing and under-development interferometers will require an expanded support structure for several of them. KI is the only one of the existing facilities that has a call for proposals open to the U.S. community (through the NASA and NOAO allocations) and provides fully supported observing, but KI is not a dedicated interferometric facility and the Keck telescopes are also in high demand for non-interferometric science. CHARA, NPOI and ISI are utilized by scientifically vibrant collaborations with active cutting-edge instrumentation programs while MROI and LBTI are currently under construction. Each of these facilities has unique observational capabilities that could be of interest to the community, but would require additional resources to support a broader user community.

Here we review the existing possible funding opportunities and the shortcomings they have for the case of optical interferometers.

**Telescope System Instrumentation Program**: The NSF TSIP program as currently implemented provides funding for new instrumentation or other improvements in return for community access to privately operated telescope facilities. This program is widely viewed as a success in gaining community access to large telescopes; however, the call is limited to aperture sizes greater than 2 meters and CHARA, NPOI, ISI and MROI all have slightly smaller primaries. Awards from this program have ranged from $500k to $6M, but the program has not been funded every year. This program is currently focused primarily on instrumentation development as facilities using the funds for operational costs are penalized a factor of two in their time exchange rate. However, the ALTAIR report recommended increased and stable funding for TSIP as well as a more flexible approach in obtaining community access to capabilities that would otherwise be unavailable.

**Program for Research and Education with Small Telescopes**: The guidelines of the NSF PREST program seem well suited for several of the interferometers under consideration here, particularly concerning the aperture size, however, the focus of this program is access for students and a limited community rather than broad access. In particular, proposals are limited to $50k for operational expenses and the yearly proposal cycle is not geared toward long-term support.  Typical awards are from $100-500k/yr. The PREST program was not offered in 2008 and its future is uncertain.

**Astronomy and Astrophysics Research Grants Program:** This program provides individual investigator and collaborative research grants for observational, theoretical, laboratory and archival data studies in all areas of astronomy and astrophysics and is the main NSF source of PI-based funding.  Both CHARA and ISI have received support from this program.  Although multi-year grants are possible through this program, using PI-based grants has two disadvantages for supporting all or most of the operations budget of a moderate-sized facility.  The first is difficulty in hiring and retaining highly-specialized staff if there are uncertainties in yearly funding levels.  And the second is having to compete against PI's using facilities funded through other programs who only have to cover their own research costs and not those of the facility; e.g., a PI using the Very Large Array radio interferometer.  Awards in the last year from this program range from $50k to $500k.

**University Radio Observatories:** URO is a long-standing NSF program that has provided operational and development funding on a 3-year cycle for both single-aperture and interferometer millimeter and radio telescopes operated by universities.  Awards range from $200k to $5.9M and require open community access to the facility of between one-third and one-half of the available observing time.  This program provided the majority of the operational funding for the Owens Valley Radio Observatory (OVRO) and the Berkeley-Illinois-Maryland Array (BIMA) millimeter interferometers, which were university-run collaborations.  These facilities underwent a period of expansion in the 1990's and the community using them was initially dominated by the university groups operating them.  Open access to these facilities allowed the millimeter interferometry community to grow substantially beyond the groups that operated them and contributed to the community support for much larger projects such as the Atacama Large Millimeter Array (ALMA) and the Combined Array for Research in Millimeter-wave Astronomy (CARMA), the merger of OVRO and BIMA.   The optical interferometers are in a similar situation as the millimeter arrays were several years ago, but an optical equivalent of the URO does not currently exist.

With the exception of KI and LBTI, which can apply to TSIP, the U.S. optical interferometers could only apply for operational funds to the NSF Astronomy and Astrophysics Grants program or the PREST program, which has such a small cap on operational funds that it would be of limited use.  In any case, PREST is not currently active.  We conclude that the existing funding structures in the U.S. do not have an adequate mechanism for supporting operational costs and user support of modest-sized, modest-cost but cutting-edge facilities.

## 4 Recommendations

We believe that this is a crucial time for optical interferometry in the U.S. These facilities are now making cutting-edge discoveries in astrophysics and, as is usually true when a new observational regime is opened up, these discoveries often challenge the existing theoretical framework.  The possibilities for discovery with optical interferometry are explored in the science white paper "Science at Very High Resolution: The Expected and the Unexpected" (http://www8.nationalacademies.org/astro2010/DetailFileDisplay.aspx?id=174 ).  In order for this field to continue contributing, the current and under-development facilities must have a stable resource base to support operations, development and users.

We have made an estimate of the size of such a program based on input from each of the facilities listed in Table 2. The amount of time that could be made available from each facility depends on the nature of the instrument, i.e. whether it is a dedicated interferometer, and the demands of existing collaborations and commitments. The mode of observing, whether PI, service or queue, also varies by interferometer and some facilities support multiple modes that are matched to the needs of the observing programs. The number of nights potentially available to the community at each facility ranges from a few tens of nights to 100 nights a year. A program with an annual budget of $6M would provide sufficient funding for significant community access to all six of these facilities. For comparison, the annual budget for URO was $10M in 2009.

The existing programs at the NSF that come closest to filling the needs of the optical interferometer facilities are TSIP and URO. Only the large-aperture interferometers (KI and LBTI) are eligible for TSIP and there is a factor of two penalty for using the funds for operations instead of for instrumentation. The URO program is only open to radio facilities.

We recommend that the Decadal Survey Committee support the creation of a funding program to which the optical interferometers could apply and we recommend the following attributes:

- Awards cover several years to allow longer-term staffing decisions and support multi-year observing projects.
- Peer-review and competitive selection.
- Flexible program conditions on how much or how little time must be made available to the community, allowing facilities with other operational resources to maintain previous commitments while still having open community access.
- Each proposal could include allocations for operations and/or instrument development, with no financial penalty for operations funding.
- Community access through a convenient and supported mechanism[1].

With modest support these facilities could make their unique capabilities available to the entire astrophysical community, which will lead to new and exciting discoveries throughout the next decade and provide a training ground for the developers of essential new astrophysics measurement capabilities. They can provide the platforms needed for continuing development of O/IR interferometry technology and methodology, and lead the way toward a next generation ground-based array project for a subsequent decade.

[1] CHARA and NPOI are planning trial visitor programs through NOAO, which has expressed interest in fulfilling this role.

March 15, 2009

To: Astro2010

Subject: Funding opportunity for O/IR Interferometric Arrays

We speak for six U.S. O/IR interferometric facilities. Each offers novel and distinct capabilities for ultra-high angular resolution and/or very high contrast imaging and has produced scientific results in many fields of astronomy. Our operational instruments and facilities are setting a high standard of innovation, and those in development promise significant advances in the next few years.

Our facilities are currently used primarily by consortium members and their collaborators. We believe wider community access to O/IR interferometry would expand the scope for astrophysical discoveries and produce the optimum utilization of our facility investment.

At present, it is difficult to foresee a substantial increase in accessibility, as current operations support is marginal to inadequate, and the future of each is in doubt owing to uncertain funding. Operating facilities could close, and facilities in development could remain incomplete.

We endorse the proposal of the U.S. Interferometry Consortium to establish a competitive funding opportunity for operational support of O/IR arrays in exchange for community access to these facilities.

Berkeley Infrared Spatial Interferometer
Prof. Charles Townes, ISI Principal Investigator, UC Berkeley

Center for High Angular Resolution Astronomy Array
Prof. Harold A. McAlister, CHARA Director, Georgia State University

Keck Interferometer
Dr. Taft Armandroff, Keck Observatory Director

Large Binocular Telescope Interferometer
Dr. Richard Green, LBT Director, University of Arizona

Navy Prototype Optical Interferometer
Dr. Kenneth Johnston, USNO Director
Dr. Bob Millis, Lowell Observatory Director
Dr. Richard Bevilacqua, Remote Sensing Division Superintendent, NRL

Magdalena Ridge Observatory Interferometer
Dr. Van Romero, Vice President for Research and Economic Development, New Mexico Tech