MOISAIC: Milliarcsecond Optical/Infrared Science: Access to Interferometry for the Community

Primary Author: M. Creech-Eakman, New Mexico Institute of Mining and Technology, Magdalena Ridge Observatory Interferometer (MROI), 575-835-5809, mce@kestrel.nmt.edu

Co-Authors (United States Interferometry Consortium):

- R. Akeson – NASA Exoplanet Science Institute (NExScI), California Institute of Technology; Keck Interferometer (KI)
- J. T. Armstrong – Naval Research Lab; Navy Prototype Optical Interferometer (NPOI)
- T. ten Brummelaar – Georgia State University; Center for High Angular Resolution Array (CHARA)
- C. Haniff – University of Cambridge, UK; Magdalena Ridge Observatory Interferometer (MROI)
- D. Hutter – Naval Research Lab; Navy Prototype Optical Interferometer (NPOI)
- H. McAlister – Georgia State University; Center for High Angular Resolution Array (CHARA)
- S. Ragland – Keck Observatory; Keck Interferometer (KI)
- S. Ridgway – National Optical Astronomy Observatories (NOAO)
- C. Townes – University of California, Berkeley; Infrared Spatial Interferometer (ISI)
- E. Wishnow – University of California, Berkeley, Infrared Spatial Interferometer (ISI)

Based on feedback and input from more than 100 community members who attended American Astronomical Society special sessions at the Jan. 2008 meeting in Austin, Texas and the Jan. 2009 meeting in Long Beach, California, as well as the Society of Optical Engineers meeting subprogram on Long-Baseline Optical Interferometry held June, 2008 in Marseilles, France.

1 Key Science Goals

1.1 Executive Summary

Optical and infrared interferometry has developed to a level of technical and operational maturity that is enabling scientific breakthroughs. At present, the array facilities offer very limited or no open access. We propose establishment of a funding mechanism to partially support the operation of US ground-based optical/infrared interferometers in exchange for access by a much broader astronomical community. This will leverage the nation's two-decade investment in this technology and allow our whole community to access the highest angular resolution O/IR facilities in the world. Such access will give rise to exciting new discoveries, new observational applications of these systems, and provide training in interferometry and advanced optical technology to a wide group of students and researchers. O/IR interferometry is in its early years, and there are many promising paths for more powerful and more productive facilities. Thus we also recommend funding to support technology development and preliminary planning for a next generation optical array.

1.2 What is Needed in the Broader Community

Optical interferometry is following a pattern of development similarly strong to that of radio interferometry (see Figure 1). As in the early years of radio interferometry, most of the O/IR arrays are PI-scale operations. A vigorous technology program has enabled a strong facility-class interferometry capability in the US, with several operating arrays of up to 6 telescopes. These arrays have different, unique observing capabilities, and most are in full-time operation, carrying out unprecedented sub-milliarcsecond resolution science in stellar, solar system and extragalactic physics. Presently most of these facilities are supported mainly for collaborative or mission-oriented operation. The interferometry community is eager to open these facilities to peer-reviewed open access, but lacks resources to support such access. There is currently no funding opportunity available for this purpose (e.g. optical arrays of mid-sized apertures are not deemed eligible for the Telescope System Instrumentation Program (TSIP), nor are its rules well suited for operations support.)

A 2006 national workshop on ”Future Directions for Interferometry”, organized and sponsored by NOAO, has developed a roadmap for technology development, with the objective of supporting preliminary planning for a next generation optical array in the 2020 time frame. As a community we believe this next decade is ripe both for gaining tremendous insights into many astrophysical phenomena, and developing the technology necessary for a next-generation facility.

Optical/infrared interferometry has made significant strides since its development was recommended by the 1990 Decadal. Currently four (and in two years, six) optical arrays operate regularly in the US. These arrays have made a wide variety of contributions to stellar astronomy and physics, ranging from the structure of young stellar object disks, to the distortion of rapidly rotating stars, debris disks and mass loss.

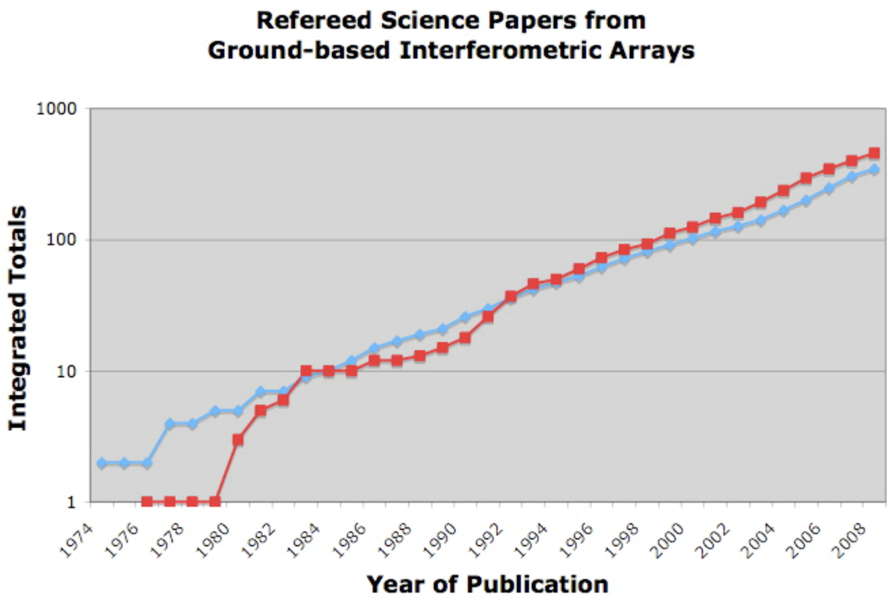

Figure 1. We compare the total number of refereed science papers based on radio interferometry (red line) with those based on O/IR interferometry (blue line) over a thirty-four year period. A shift of 32 years forward has been applied to the radio data. From this, we interpret that the field of O/IR interferometry is developing on a similar trajectory to its preceding radio cousin. However, there is a difference: on this scale, the VLA obtained first fringes in 2008. O/IR Interferometry has made a similar publication footprint without the focus of a dedicated national facility project.

1.3 Review of Recent Results

Optical interferometry has traditionally been associated with precision measurements, and the experience of the last two decades has been fruitful in this regard. It is now straight-forward to measure stellar angular diameters to better than 1%, and binary separation measurements are regularly recorded with errors in the ~20 microarcsecond range. Measurements of limb darkening are now well understood, and the first (somewhat indirect) confirmations of convection and other multi-component atmospheric structures are becoming available.

Less foreseeable are the results of extending interferometry to imaging on milliarcsecond scales. As the USIC (United States Interferometry Consortium) has documented in a Science White Paper by Creech-Eakman et al., the outstanding accomplishment of interferometric imaging has been the abundance of *unexpected* results. These might be described as serendipitous, except that in extending imaging resolution by more than an order of magnitude, the unexpected can scarcely be considered surprising. To first approximation, all very-high resolution measurements are giving new insights that would not have been foreseen by earlier models.

Luminous, cool stars are found to consist of a distinct stellar core and a huge, thin envelope, rather than a continuous smooth distribution. Many main sequence stars have an unexpected warm, rapidly replenished debris disk. Young stellar object disks are both different and more complex than foreseen, having significant gaseous emission interior to the dust disk. Rapidly rotating stars do not seem to follow the von Zeipel law – except that equatorial mass loss complicates the interpretation. Low luminosity star radii vary with metallicity – and not as theorists had predicted.

With most of interferometry today based on small telescopes, it is natural that most interferometric science is in the area of stellar astrophysics, and that is where the future of interferometry is most predictable – the simple forecast is that interferometry will change stellar physics forever. Still, several results suggest broader possibilities. While interferometry is not obviously suited for general solar system programs, a recent measurement recorded the angular structure of an asteroid, establishing that interferometry will have a rich field of application, determining the radii/duplicity of hundreds of asteroids, with resulting constraints on the albedos and in some cases densities. In extragalactic studies, both the Keck Interferometer and European Very Large Telescope Interferometer (VLTI) have been used to study the nuclei of AGN, measuring IR structures associated with the torus or disk structure, at wavelengths from 2 to 12 microns, supporting multi-component empirical models which will eventually be merged with physical modeling efforts. A recent study has provided an interferometric measurement of a stellar envelope in the LMC, extending even direct stellar physics beyond the galaxy.

1.4 Science Impact in the Next Decade

Several areas where the greatest science impacts from O/IR interferometers are expected to be realized in coming years were identified and specifically discussed as part of the suite of Science White Papers for the Astro2010 Decadal survey (c.f. Aufdenberg et al., Barbieri et al., Creech-Eakman et al., Millan-Gabet et al., Ridgway et al. and Schaefer et al.). Further, in reviewing all 300+ science white papers posted on the Decadal website, we find that 18 others specifically mention the value of ground-based O/IR interferometry toward their long-term science goals. Another 46 papers discuss the need to develop space-based UV/O/IR interferometry either in an astrometric (32) or non-astrometric (14) context. In total, almost 20% of the high-impact science areas identified by the US astronomical community include some component of interferometry in their plans to advance their specific science goals.

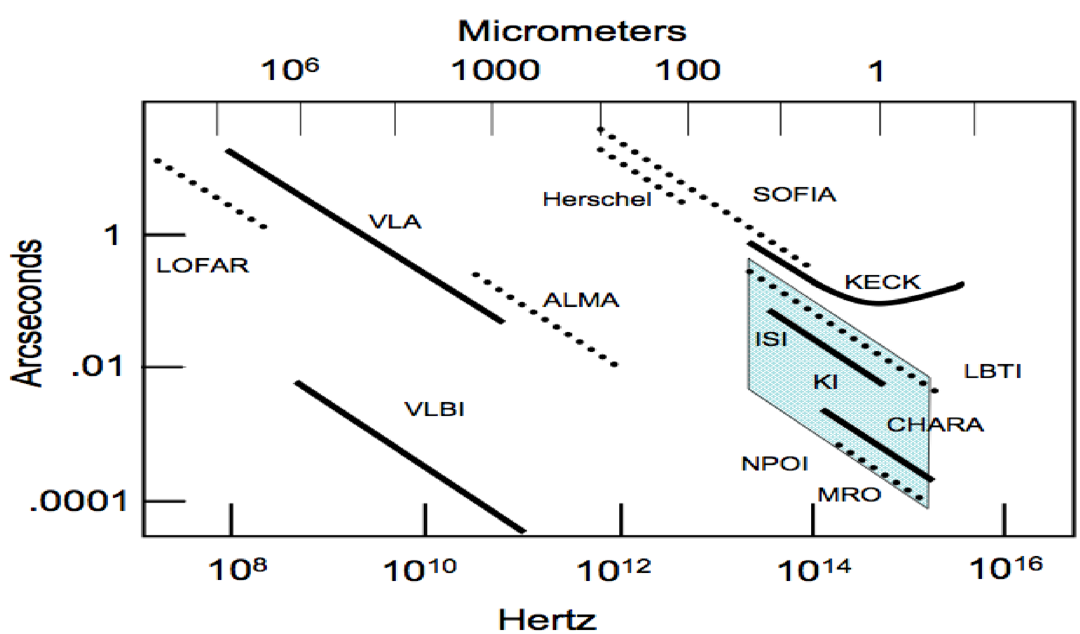

Figure 2: Angular resolution of major instruments in the visible through radio ranges. The solid lines represent operating capabilities, and the dotted lines represent capabilities that are currently in implementation. The hashed and shaded area shows the subset of this parameter space that is addressed by ground-based optical arrays, and which is recommended for support in this proposal. (Figure adapted from P.T. Krichbaum).

Ground-based O/IR interferometers currently occupy a unique niche in the wavelength/spatial resolution phase space of astronomical observations, as can be seen in Figure 2 above. O/IR array interferometry (the shaded area) is seen to currently improve angular resolution by approximately 100x compared to filled aperture facilities (e.g. Keck single-aperture), with additional gains anticipated in on-going development, and still further gains with a possible next-generation array (neither is shown here). This diagram also emphasizes the correspondence of O/IR resolution to the performance of radio/mm arrays (e.g. VLBI, ALMA and the VLA).

1.5 Transformational Science in the 2010 Decade

1.5.1 Young Stellar Objects and Planet Formation

As discussed in the Science White Paper of Millan-Gabet et al. the formation of planets is one of the major unsolved problems in modern astrophysics. Planets are believed to form out of the material in young star circumstellar disks, and are a by-product of the star formation process. Thus the detailed physical conditions in these disks represent the initial conditions under which planets form. The *inner* disk regions (interior to ~10 AU) most relevant in the context of planet formation are very poorly known, primarily because of observational challenges in spatially resolving this region. Recent and future advances in milliarcsecond imaging capabilities will enable direct and fundamentally new measurements of the inner disk: the radial location of the sources of continuum and line emission, gas chemistry and dust mineralogy, and surface brightness. Combined with high resolution spectroscopy and realistic modeling, we can derive:

- The detailed structure and composition of the dust evaporation front, which is fundamental to our knowledge of the terrestrial planet formation zone.
- The disk density/temperature profiles, helping to explain issues such as the location/migration of gas giant planets or disk "dead zones".
- The connection between the disk and the star itself, particularly in regards to angular momentum transportation and disk viscosity.

1.5.2 Mass Loss and Galactic Recycling

As discussed in the Science White Paper of Ridgway et al. stellar mass loss is *key* to understanding the evolution of the universe from the earliest cosmological times to the current epoch, and of planet formation and the formation of life itself. It is crucial in shaping early galaxy formation, pre-main sequence evolution, main sequence lifetime, horizontal branch morphology, formation of planetary nebulae and supernovae shells, and the detailed evolution of interacting binaries and stellar clusters. With the use of optical interferometry over the upcoming decade we can directly determine:

- The detailed spatial extent and density of dust and atomic/molecular components around a wide variety of cool and hot stars.
- The spatio-temporal dependence of mass loss, including details such as the laminar/clumpy nature, and episodic behavior of flows.
- The effects, extent and timing of mass-transfer in binary systems, especially interacting systems such as cataclysmic variables, Algols and SN I progenitors.

1.5.3 Binary Stars and Stellar Astrophysics

As discussed in the Science White Papers of Schaefer et al. and Aufdenberg et al., the essence of stellar evolution lies in the fundamental relationships between stellar mass, luminosity, radius, temperature and intrinsic instabilities (e.g. pulsational, rotational) over a range of metallicities and stellar groupings. Our understanding of this evolution is vital to all areas of astrophysics, and thus it is unfortunate that our knowledge of stellar astrophysics is severely limited by basic measurements such as spectral type and distance. Moreover, second order effects (e.g. rotation, metallicity) are generally ignored. The need for understanding these fundamental stellar properties becomes all the more urgent as we conduct ultra-precise photometric missions (e.g. WIRE, Kepler), distance determinations (e.g. GAIA), and new synoptic efforts (e.g. SDSS, CSS, Pan-STARRS, LSST), all requiring a better understanding of stellar physics than we currently enjoy. These missions, and others likely to be advanced during the next Decade, will only translate to better astrophysical models if they are performed in concert with high angular resolution measurements provided by ground-based O/IR interferometers. With existing O/IR interferometric facilities, we expect over the next few years to:

- Obtain precise radii, temperatures, and parameters on limb-darkening, pulsation, rotation and convection *by direct measurement* of thousands of stars, owing to greater sensitivity and efficiency of the facilities.
- Quantify, at the sub-1% level, masses, angular momenta, and orbital elements in statistical numbers of binary/hierarchical systems across the HR diagram.
- Directly image interacting systems to quantify physics related not only to mass loss and tidal distortions, but also to magnetic fields and chemical compositions.

1.5.4 Beyond Our Galaxy - Active Galactic Nuclei

Perhaps only planets are more successful than supermassive black holes at capturing the general public's curiosity about astronomy. In the Science White Paper by Elvis et al. several compelling questions related to, e.g. the shedding of angular momentum, the origin of gravitational/disk instabilities, and the launching mechanisms for the winds in AGN are presented. Also presented are a concomitant set of technological advances required to make meaningful progress on these questions during the next Decade. One of the fundamental areas pointed out by these authors where such progress will be realized is in high-resolution (sub-milliarcsecond) images of the broad-line region and the torus/disk in these AGN -- measurements which have begun and can only be accomplished with O/IR interferometers.

The topics presented above are only a small fraction of the science areas in which O/IR interferometry can contribute, and most of these are direct contributions addressing the technique at specific questions. There are undoubtedly a larger number of extended effects/insights which will be a consequence of this initial research and which we are unable to predict at this time. Here is where the heart of all scientific investigation lies, and is the fundamental reason we pursue difficult problems – because the pay-off in terms of new insight is so high. In O/IR interferometry, the pay-off is waiting to be harvested as productive facilities already exist and simply need to be exploited by the astronomical community.

2 Technical Overview

2.1 Current Interferometric Capabilities

The burgeoning success in addressing key astrophysical problems using O/IR interferometry has stimulated the development of a number of interferometric facilities within the US. There are now four operational O/IR interferometers and two under development (see Table 1). CHARA, ISI, KI and NPOI routinely make scientific observations whereas LBTI and MROI are still under construction and are likely to realize their “first fringes” within a few years. This multiplicity of facilities hides a scientific and technical complementarity, as well as a wide range of sizes and funding models (e.g. from university-led projects (ISI) through larger “facility” arrays that aim to serve a wider community (CHARA, NPOI, MROI), to large-aperture interferometers (KI and LBTI) that are only available part-time at their respective observatories).

Short Name	Long Name	References
CHARA	Center for High Angular Resolution Astronomy Array	ten Brummelaar et al. 2005 (ApJ, 628, 453)
ISI	Infrared Spatial Interferometer	Hale et al. 2000 (ApJ, 537, 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)

Table 1: The list of U.S. optical/infrared 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.

What these facilities share is the ability to secure photometric and spectroscopic data on angular scales far beyond those attainable with the current generation of space-based and adaptively corrected 10m-class telescopes. Of the six interferometers listed in Table 1, two (ISI and LBTI) are able to study structures with angular scales of a few tens of milliarcseconds, whereas the remaining four permit studies on scales a factor of 10 smaller. In particular, the CHARA, NPOI and MROI arrays – by virtue of their long baselines – have the capability to probe regions as small as 0.5 milliarcseconds in size, i.e. corresponding to physical scales of roughly 0.1 AU in nearby star forming regions, and to detect phenomena (e.g. astrometric perturbations) a further factor of 10 smaller.

One key scientific distinction between these six facilities relates to their wavelengths of operation: the three interferometers using the largest apertures (ISI, LBTI and KI) have a mid-infrared capability – typically within the 3.5-13.5 micron windows – and are therefore very well-suited to studies of cool dust in stellar environments, e.g. in star forming accretion disks and surrounding late-type stars. All of these facilities are able to capitalize on the spectroscopic signatures present in the thermal-infrared for investigating the physical and chemical compositions in these environments. In addition, both the LBTI and KI have so-called “nulling” beam combiners especially designed for studies of extra-solar planets and their zodiacal dust.

The remaining arrays (CHARA, NPOI, MROI) have primarily been designed to operate at visible (RI) and near-IR (JHK) wavelengths (with KI also at HK), where more moderate sized array elements with diameters in the range 0.5m-1.5m offer the optimum balance between sensitivity and the need to operate in the presence of optical turbulence. The impact of seeing is by far the most important factor limiting the fundamental sensitivity of ground-based interferometers and so both the NPOI and CHARA teams have plans to enhance their current sensitivity limits (which are currently around 8^{th} magnitude in the visible and NIR respectively) through the installation of adaptive optics systems on their unit telescopes. The MROI has been designed to deliver a much higher sensitivity (14^{th} magnitude in the H band) through the use of a highly-efficient optical train (mostly in vacuum) and an ambitious error budget for the overall system wavefront errors but without the use of AO. Should this be realized, this would be a very significant step in expanding the scientific capabilities of ground-based instruments.

One final distinction between the six interferometers listed in Table 1 that merits note is the capability to provide images. For ground-based optical/IR interferometers this is critically linked to the ability to secure closure-phase measurements, which in turn relies upon the presence of at least three unit telescopes and a suitable three-beam correlator (the LBTI with its high filling-factor and dense UV coverage, can obtain phase closure between sub-pupils). Furthermore, the ability to probe a wide enough range of spatial frequencies to permit a useful image to be reconstructed is helped significantly if the array can be reconfigured by moving the unit telescopes. However, this is not a requirement, and both the NPOI and CHARA arrays have demonstrated their ability to provide true images at unprecedented angular resolutions, that could not have been interrogated with any other space- or ground-based telescopes currently in operation or planned during the next Decade. (c.f. Science White Papers mentioned above)

2.2 Sustaining Current and Preparing for Future Infrastructure

It is critically important to US O/IR interferometry to sustain the current interferometers and to support the completion of the two facilities under construction. Without these facilities, and in particular the associated expertise, the development of the techniques that will be needed for the next generation of interferometers would be homeless.

Unlike the European interferometry efforts, interferometry in the US is supported by a variety of funding streams, including DoD, NSF, NASA, state funds, foundations, and congressional support, and it is difficult for any of the groups to tap more than one or two of these sources. The result is that US interferometry consists of several relatively small groups and collaborations, each with a different scientific concentration.

One of the purposes of MOISAIC is to circumvent the barriers that this structure raises. We are cooperating to bring in users who are not experts in the technique, and to avoid duplication of effort in technical development. Ultimately, we hope that the US interferometry community will grow and be brought together in a new national facility in the 2020 Decade.

Until that facility becomes a reality, the current interferometry groups, representing more than three decades of experience in the technique, serve as mini-centers for cutting-edge science, test beds for technical development, and as facilities that host/train non-expert users for future efforts both on the ground and in space. In order to play those vital roles, they need national, public support to supplement the very limited private and local operations funding that they have.

There are three areas in which such support is critically needed:

- Updating current facilities as old equipment ages, new technology becomes available, and experience shows us how to improve the facility.
- Supporting outside observers so the strengths of the application of optical interferometry become available to the broad astronomical community.
- Tapping the knowledge at these facilities to guide the development of the next generation ground-based and perhaps future space-based facilities.

CHARA, NPOI, and ISI are all affected by aging equipment. The initial designs for CHARA and NPOI date back 20 years and the origins of ISI are in the 1980s. The design of the Keck telescopes was not optimized for interferometry, though they comprise the largest aperture O/IR interferometer in the world. All these instruments have been updated to some degree to keep up with technical developments and to implement lessons learned, but this is an ongoing and evolving process that requires constant input.

By policy all these instruments support outside users, though in very limited numbers. However, using an optical interferometer—knowing what projects are suitable and how they should be implemented, understanding the strengths and limitations of the arrays, and knowing how to process and interpret the data—can be daunting, and none of these facilities has the resources to introduce more than a handful of users in typically a collaborative fashion into optical interferometry. Although KI provides full user support, only a fraction of the time on the Keck telescopes is used for interferometry, effectively limiting the new users.

Finally, experience with each of the current arrays will influence the design of a new national facility. Sustaining the current instruments will both keep that crucial experience from being lost, and provide facilities for testing and developing elements for a new national interferometer, such as beam combiner designs, implementation of adaptive optics, or innovative methods for retrieving phase information from the observations.

2.3 Community Access

Currently, time allocation is handled differently for each existing facility. For NPOI, CHARA, and ISI this is managed within the collaboration of users. KI time allocation is handled as for all other Keck instruments by the individual time allocation committees (TACs) within the Keck community. Additionally, very limited KI time is made available to the entire US community via open calls supported through NASA and NOAO/TSIP. LBTI's originally anticipated access model resembled KI's, while the current model for MROI looks more like that at CHARA. If funding can be made available to open broad community access to these facilities then we anticipate that a common portal for information, applications and peer-reviewing would benefit both the facilities and the broader community. Currently individual observatories manage their own access and peer-reviewing, and NOAO presently serves as the application gateway for several single-aperture optical facilities in the US system. NOAO also manages peer-reviewed TSIP access that includes the interferometer mode for the Keck observatory, and is in discussions with CHARA for a trial period of open time there as well.

We anticipate that planning for observations and access to low-level data reduction would be made easier for the general user via a common suite of software tools. Several planning packages are already in use at the operational facilities, supported at each observatory's website. The common (to all facilities) aspects of observation planning are typically: baseline selection, spectral resolution and calibrator selection. Some of these packages are already distributed either online (e.g. getCal; http://nexsci.caltech.edu/software/) or to all users of a particular facility (e.g. CHARA, NPOI). Some informal coordination is already in place in the O/IR interferometric community toward maintaining lists of known good and bad calibrators. A concerted effort to centralize these tools and lists would serve as a starting point for general community access.

At a slightly higher level, a user can model anticipated visibilities of their sources based on simple parametric models. In the US, there exists a distributed package (Visibility Modeling Tool; http://nexsciweb.ipac.caltech.edu/vmt/vmtWeb/) which allows users to calculate visibilities for potential sources by using geometric models or a user-specified source brightness profile. Already included basic parameters of the operational interferometers are then used to predict visibilities, allowing users to assess the feasibility of potential observations at different facilities.

Data reduction is highly-dependent upon the instrumental set-up, as the first step in this process always involves removing instrumental terms and calculating the raw visibility. We anticipate that each observatory will have to produce a low-level of calibrated data before any but the most experienced users can further reduce their scientific observations. We believe that some standardization of tools may be possible at the (next) calibration stage (where scientific target and calibrator visibilities are compared) of removing the sky dependencies.

Once the data are completely calibrated, common modeling software can be used on data from any of the facilities (e.g. BSMEM, MAGIC, even AIPS). In particular, the optical interferometry community has been working on producing packages to work with closure phase data and to produce images. Although software to do this has been available for radio interferometry data for decades, the lack of a reference phase creates issues that are best addressed with packages specifically developed for optical interferometry. Several such packages already exist, and have been explicitly compared as part of the "Imaging Beauty Contests" presented at the last three bi-annual SPIE conferences on optical interferometry (c.f. Cotton et al. SPIE, 2008, 7013, 48; Lawson et al. SPIE, 2006, 6268, 59; Lawson et al. SPIE, 2004, 5491, 886).

The first level of calibrated data, often termed raw visibility, natively varies in format and content at each facility. Therefore, the community has defined the standard data format to be at the level of completely (instrument and sky terms) calibrated data. This definition was developed by an IAU Interferometry software working group and resulted in the OIFITS format (http://www.mrao.cam.ac.uk/research/OAS/oi_data/oifits.html). This format has been used to exchange data between facilities and to combine data from multiple interferometers. For the facilities operated by collaborations, the data are generally available within that community. In recent years, public data archives have also become available for KI data (https://nexsciweb.ipac.caltech.edu/ki-archive/secure/main.jsp) and for the no-longer operational Palomar Testbed Interferometer (PTI).

In order for any users to make the most of their observations with optical interferometers, they must have access to software for planning and data reduction. For convenient user support, we suggest, at a minimum, an online clearing house for downloading packages related to the US optical interferometry facilities be established. A clearing house for basic information about world-wide interferometry efforts already exists: (http://olbin.jpl.nasa.gov/) and could serve as a template for this development. However, with a concerted and directed effort, a more robust, purpose-driven system could be established for the community.

2.4 Planning for a New Facility

While we are not proposing a new national interferometer for the current Decadal Review cycle, we must begin during this upcoming Decade planning for such a facility in the subsequent Decade. The "Workshop on the Future Directions for Ground-based Optical Interferometry", sponsored by AURA, NIO, NOAO, and CHARA and held in Tucson in November, 2006 (http://www.noao.edu/meetings/interferometry/) laid out the initial planning stages and identified two complementary concepts: a "Classical Array" of 15 or more large telescopes (up to 8m) with baselines of at least 1 to 2 km, and a "Compact Array" similar to LBTI, but with more apertures and a span of 100 to 300 m.

The workshop also laid out roadmaps:

- Technology demonstrations on existing arrays: High quality imaging; increased sensitivity; addition of adaptive optics; baseline bootstrapping; and fiber links between telescopes.
- Technical development: Metrology over 1 km lengths; guided optics for beam transport; site identification and testing; and low-loss beam combiners for multiple telescopes.

A number of techniques and developments are subsumed in this list, such as backend improvements in spatial filtering, dispersion compensation, photometric monitoring that will lead to better calibration and hence higher dynamic range, or improvements in fringe detection and delay control that will support baseline bootstrapping, which will in turn support improved imaging.

A rough timeline for these tasks would emphasize science productivity with technology development and demonstrations through the decade, technology demonstrations and development and a five year planning cycle in the latter half of the decade to develop a design concept for a national-scale facility.

3 Technology Drivers

The technology of O/IR interferometry is adequate to carry forward a strong science program in the coming decade. However, progress can be expected in numerous areas. These can enhance existing facilities and will enable more powerful observatories in the future. Some of this work is already in progress. At CHARA, back ends that accept four or six beams and include spatial filtering have recently come on-line and are showing promise in increasing calibration accuracy; phase referencing and coherent averaging techniques are improving the imaging capabilities at NPOI; high spectral resolution is in implementation – e.g. 30,000 in the visible at CHARA, and 500,000 in the N-band at ISI.

A Technology White Paper to Astro2010 (Armstrong et al.) describes in greater breadth and detail technology development that is recommended for interferometry. Here, we will mention three technology "tall poles". These are not major challenges that must be resolved to allow progress, but are "poles" of special opportunity, where investment in the coming decade will lead to substantial payoffs in the future. All address in some respect the challenge of utilizing effectively all of the photons that one collects.

Combining adaptive optics and interferometry. Large aperture arrays necessarily employ adaptive optics (VLT, Keck) and are successfully supported with adaptive optics. Other arrays employ telescope apertures which were selected to operate with reasonable efficiency without AO. As high-resolution science progresses, the limited sensitivity of these arrays is felt more and more keenly. AO can serve an important role in improving the performance of small aperture arrays and a recent analysis shows that the gains can be substantial (Mozurkewich et al. 2007, *Appl. Opt*., 46**,** 4413). CHARA, NPOI and perhaps MROI foresee implementation of AO, and preliminary planning is in progress (Ridgway et al. 2008). AO is required for the implementation of a next generation array deploying larger apertures. AO for interferometry does not push component technology as strongly as, e.g., an ELT and planet imaging applications. It does, however, offer different considerations in design issues such as how many photons to invest where in the system to optimally determine fixed optical aberrations, slowly varying internal aberrations, fast aberrations in the atmosphere, while stabilizing phase differences and avoiding potential problems of non-common path error. Other outstanding issues include determining the degree of correction needed, understanding the interaction between the AO and fringe-detection subsystems, and building the automation and reliability necessary to permit simultaneous operation on many telescopes. A period of component evaluation, prototyping, and on-sky demonstration is strongly recommended in order to gain relevant experience and to prove cost-effectiveness. This development can, incidentally, be fed back into the traditional astronomical application of AO on smaller telescopes, and so represents a synergistic development for the broad community.

Beam transport and control over long distances. The throughput of current arrays is low (5% to 10% at best). Contributing factors are diffraction over long distances, coatings, and the large number of optical surfaces. These can be addressed in a variety of ways. Adaptive optics (mentioned above) can reduce diffraction, optimized coatings and controlled environments can reduce other losses. Here we mention particularly the potential of transmitting beams in single mode optical fibers. Wavefronts are not degraded in single mode fibers – in fact they are cleaned.

Fiber can traverse terrain that would be prohibitively rough for bulk optics and free or vacuum transmission. This technique has already been pioneered with the OHANA project to interferometrically link Mauna Kea telescopes (Perrin et al. 2006, *Science*, 5758, 194). Support is needed for technologies of efficient beam injection and extraction, dispersion control and correction, optical path difference balance, and phase stabilization.

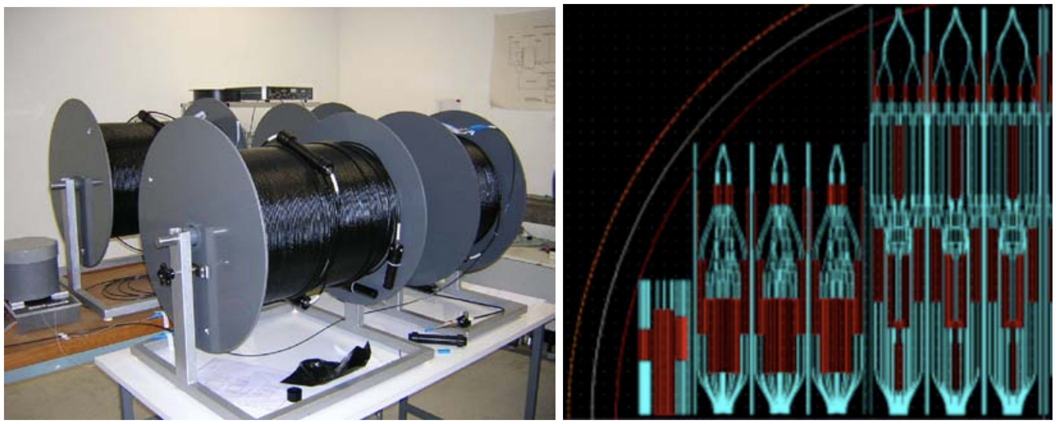

Figure 3: (Left) 100 meter spools of Fluoride fiber spliced and set up in a Mach-Zehnder interferometer for evaluation of phase and dispersion changes with thermal drift (in the LESIA laboratory at Paris Meudon Observatory - author's photograph). (Right) 12 beam combiners, each accepting 2, 4 or 6 inputs, with calibration channels, implemented lithographically on ¼ of an 8-inch disk of silicon (Lacour et al., SPIE, 2008 7013E, 31). One of these devices can replace a table of bulk optics and offer much improved stability.

Multi-beam combiners and spectral resolutions. Combiners currently in operation can combine up to 6 telescopes, can measure fringe visibilities to much better than 1% precision, phases to much less than 1 degree, and record multiple wavelengths at spectral resolutions up to 10^4 and greater – however, no single combiner can currently do all of these things. This is an area of steady progress, as techniques with both bulk optics (mirrors and dichroics on an optical table) and with integrated optics (beam combination on a chip) continue to improve. Integrated optics also suggest novel spectrographic methods which could not be realized in bulk optics (Kern et al, SPIE, 2008, 7013, 30). Optimization of beam combination for many telescopes is in its infancy and deserves continuing study and prototyping.

3.1 R&D and Prototyping at Existing Facilities

Operating array facilities are logical venues, and are staffed by scientific and technical personnel who are highly motivated to develop and implement new technology for immediate science return. Several contemporaneous examples follow.

The NPOI serves as one example of the current efforts to maintain and upgrade an aging facility. Originally conceived as two distinct instruments, one for astrometry and the other for imaging, NPOI became a two-arrays-in-one installation because of costs. The physical infrastructure, including the siderostats and delay lines, dates from the early to mid-1990s, but has aged reasonably well. The electronic infrastructure also dates to the mid-1990s, so replacement parts are increasingly hard to find. USNO and NRL are in the process of updating the siderostat and delay line electronics, but have the budget to support only one FTE in this effort. The limitations are perhaps clearest in the backend: the NPOI was the first array to be designed for group-delay fringe tracking, and the electronics needed to measure fringe positions and relay them to the delay-line control system were designed in-house. Off-the-shelf commercial electronics can now perform the same functions better at much lower cost, but supporting a program to implement replacement of the "fringe engine" is difficult on the current NPOI budget.

Another significant upgrade is found at ISI. ISI is a unique instrument in the world as it operates in the 10 micron band using a heterodyne receiver; as such, it is in some ways more like a radio than an optical interferometer. The heterodyne receiver makes it possible to implement extremely-high spectral resolution. ISI is currently developing a spectroscopic capability with R ~ 500,000 based on a high-speed digital correlator. The work is in collaboration with CASPER, the Center for Astronomical Signal Processing and Electronics Research, an NSF-funded organization.

An important upgrade to the CHARA Array has been provided by collaborating partner University of Michigan, which developed in its laboratories the MIRC imaging beam combiner, and put it into operation for consortium use. Other partners have similarly developed and implemented new beam combiner concepts and technologies, at CHARA and at other arrays.

As a final example, the Keck Interferometer, whose development was funded by NASA for specific mission support tasks, has recently been upgraded with NSF-MRI and university support to provide new capabilities including higher spectral resolution, fainter source modes, and precision narrow-angle astrometry via the ASTRA project.

3.2 Related Technology in Other Areas

It is natural to think of space as the ideal venue for interferometry, with no disturbing/absorbing atmosphere and with easy reconfiguration of free-floating telescopes. USIC represents the U.S. ground-based interferometry community. It does not try to speak for the space intereferometry community, but needless to say, there are many links, technically, scientifically, and in exchanges of scientific and technical personnel. This has been evident and richly exploited by NASA in the simultaneous development of SIM technology and Keck Interferometer, while operating the Palomar Testbed Interferometer. While we have not attempted to forecast the future relation of ground- and space-interferometry technologies, it is reasonable to expect significant transfers, in both directions, of system design, component, and control technologies and we look forward to continued coupling between these activities.

Just in the last few months, an initiative, primarily from the physics community, to develop Intensity Interferometry, has been brought into the Astro2010 discussion. This arose too late in the USIC community process to be included in our head-to-head evaluation with the other ground-based programs described here. Nevertheless, the USIC does wish to acknowledge the past contributions of Intensity Interferometry, the unique features that give it some complementary capabilities to Amplitude Interferometry, and the potential that it may have for the future.

4 Activity Organization, Partnerships and Current Status

The current activities leading to the submission of this and preceding White Papers to various Astro2010 sub-committees have all been done via a self-assembled group of O/IR interferometrists representing all the ground-based facilities in the US, as a direct follow-on to the Nov 2006 NOAO workshop discussions. We call ourselves the United States Interferometry Consortium (USIC) (http://usic.wikispaces.com/) and have taken on the job of responding, on behalf of the community, to this Decadal review. To get community input and support, we have organized special sessions at the 2008 and 2009 Winter AAS meetings, and during the 2008 SPIE meeting special session on Optical Interferometry in Marseilles, France. At these sessions we have presented posters and flyers related to our facilities, have informed the community of our planning activities, and solicited community feedback. We have engaged well-over 100 members of the US community in these activities, including developing our Wiki for announcements, a mailing list for email updates, and in organizing six working groups in mid-2008 (of about 8-10 interferometrists/scientists each) to address key questions related to the following areas (developed in anticipation of this Decadal call):

- Science opportunities for O/IR interferometry in the upcoming decade
- Operational funding requirements and funding models for array facilities
- Science-driven enhancements of array facilities
- US community demand for interferometry
- Models for community access to private facilities
- Roadmap for the future development of interferometry

Our board members (see author list) specifically represent the six arrays listed above in Table 1, all as project/instrument scientists/architects or operational managers, along with a member each from NOAO and NExScI. As a result of these above activities over the past 2 years, we anticipate continuing our collaborative (and occasionally friendly competitive) involvement over the next Decade and into the planning stages for the next facility. We have made efforts, in all these activities, to inform and keep current with the developments of space-based interferometry community, but our main purpose at the USIC is to serve the needs of the existing ground-based facilities. Our charter, and any further information, can be obtained from our Wiki pages or by contacting us directly.

In addition to taking the initiative to organize and support the interferometry workshop, NOAO has encouraged us to organize as we have in order to give the community a unified voice to represent O/IR interferometry and its future prospects. The example of NOAO operation of the TAC process for community access to private facilities serves as a valuable example and a possible path for access to our facilities. Similarly, the extensive experience of NExScI in supporting NASA and Keck interferometry programs is both valuable to current users, and a guide for how to extend such services more widely.

5 Activity Schedule

5.1 MOISAIC Funding for Community Access

Four of the facilities listed in Section 2.1 are currently operating, with the last two expected online in a few years. KI is already available to the US community and the other three could provide open community access as soon as a suitable funding mechanism is available (i.e. by FY2011). Observations at KI are already available to the US community through the NASA and NOAO/TSIP proposal calls. Improvements in user support would occur especially in the first few years of the program once these facilities have funding for staff supporting users. Therefore this portion of the activity can start as soon as a funding mechanism is made available for the current facilities to apply for support.

5.2 Centralized Access

The interferometry community established a solid base for sharing of data and reduction software in 2003 with the release of the interferometry data format standard, OIFITS, discussed above. More recently, the working group has focused on evaluating and comparing (competing) image reconstruction algorithms, with a semi-annual "contest" to correctly invert data sets developed for the purpose. In 2006, IAU Commission 54, Optical Interferometry, was formed (initial officers include U.S. astronomers S. Ridgway as Vice President, and Gerard van Belle as Secretary). Several groups (NExScI, CHARA, ESO, and the JMMC) and individuals have released and in some cases support formally or informally, software for observation planning or analysis. However, it is clear that extending O/IR interferometry to a broad community would be greatly facilitated with user support. This may be provided in part by individual facilities, and another part would be best served by a centralized effort and coordination. Numerous students have gained familiarity with optical interferometry in apprenticeships at optical arrays, including the production of over 80 PhD and Master's theses in the past 3 decades, and skilled personnel could be readily recruited. Ideally, user support should come on-line concurrent with or even somewhat before facility access in FY2011.

5.3 Future Planning and Design Work

The timeline for ongoing design upgrades and determination of new/better infrastructure developments should be ongoing, peer-reviewed, with proposals coming from among the current facilities and their university/national laboratory collaborators. We do not anticipate the need to create new funding mechanisms for these general investigations that will answer questions leading to a new national facility, but we do note that it may be valuable to identify O/IR interferometry developments explicitly in some of the current calls (e.g. NSF MRI or ATI for concepts addressing enabling technologies for O/IR interferometry).

Further, we suggest a working group be assembled in the 2015-2016 timeframe to begin preliminary design and costing studies for the next facility. This working group, which could be fashioned after early GSMT and LSST planning groups, could be developed in cooperation with the IAU Commission 54 and via an open call for interested astronomers and O/IR interferometrists. It would be charged to develop/assemble a science-case, straw-man design(s), timeline and budget as candidate next 2020 Decade facilities. Questions identified at that time may also impact site selection and whether the facility should be national or international in scope. We anticipate intensive, volunteer participation of 15-20 community members over a 2.5-3.0 year period, supported by a small core of scientists and technologists, This should be carried out well-enough in advance of the 2020 Decadal activities to provide meaningful input at that time.

6 Cost Estimates

6.1 Costs for Operations, Maintenance and Basic Upgrades

As described in the White Paper "Operational Funding for Optical and Infrared Interferometers" (Akeson et al.) submitted to the State of the Profession panel, the existing funding structure precludes long-term operational funding proposals from the optical interferometers due to restrictions in the program eligibility criteria and supported costs. This is a major barrier to allowing broad community access.

We recommend that Astro2010 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 some stability in staffing and planning.
- 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, under terms mutually favorable for the facilities and the community.
- Community access through a convenient and supported mechanism.

We have made an estimate of the size of such a program based on input from each of the facilities listed in Section 2.1. Each facility has considered how much time could be made available to the broad community and what costs that would ensue in supporting those users and observations. Some facilities have existing collaboration agreements that provide some operational funding. 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 the NSF program University Radio Observatories (URO) was $10M in 2009.

These funds would be utilized for basic operations costs (staff salaries, infrastructure, maintenance) as well as basic upgrades (mirror re-coatings, newer detectors and beam combiners, more capable computers and electronics) but not for major facility upgrades such as new array elements/beam lines which would be more appropriately targeted to NSF's MRI and ATI programs.

The observational mode would vary from facility to facility, but in all cases users would be given enough support to plan and carry out their observations as well as calibrate the resulting data. Data reduction packages have been developed for all facilities and user support would include access to these. There is no one ideal observation mode (PI observing, service, queue) for all observation types and therefore one of the strengths of the O/IR interferometers is that many support different modes depending on the needs of the observing program. For instance, monitoring Cepheid pulsations every 2 days for a month may be best done through a queue, while pushing the limits of an instrument in a new mode can be done by an experienced PI on dedicated nights.

6.2 Costs for Establishing a Centralized Support Structure

Visitor operations at interferometry facilities will be supported in part by the host institution(s), which will employ some of their new agency funding for this purpose. NOAO has expressed interest in fulfilling the TAC function at its own cost. We do note that a funding mechanism is needed to allow the O/IR community to address upcoming common software needs with regard to data reduction and interpretation, as there is no obvious place to direct such developments in the current US funding infrastructure. We estimate that 4-5 FTE could offer consulting on observation planning and reduction, as well as some software development. Such support is anticipated to be a critical resource in extending interferometry to the wider scientific community in the US. This might be organized as a central resource at NOAO or NExScI, and thus might be supported through their agreement with NSF or contract with NASA, respectively. However, considering the unpredictability of these paths, we recommend providing identified NSF funding available by peer-reviewed competition to provide such support. A funding level of $800K per year is recommended.

6.3 Costs for Technology Development & Planning for Future Facility

Technologies currently in use at array facilities can be extended to substantially more advanced facilities. Nevertheless, there are areas in which technical developments can lead to higher performance and/or lower costs. These are reviewed above and in a separate Technology white paper, "Technical Development of Optical/Infrared Interferometry: High Resolution, High Precision Imaging" (Armstrong et al.). The technologies themselves are not intrinsically expensive, and in some cases leverage off of on-going developments in other areas of the community (AO wavefront sensors) or industry (optical fibers). We expect that the majority of these costs can be directed through existing NSF (ATI) and NASA (APRA) programs if appropriate language is added to those calls to support interferometry developments. We also anticipate that more funding may be required in those calls if an anticipated 1-2 new proposals per year are supported for these efforts, and we recommend an investment of $18M over the decade, as detailed in the Technology White Paper (Armstrong et al.).

A next-generation interferometric facility could evolve in any of several directions: providing higher image quality, higher angular resolution, larger field-of-view, improved sensitivity, better snapshot imaging, etc. We recommend that a small, directed study project should be in operation for several years prior to the Decadal Review in 2020. This will provide an opportunity to incorporate decadal technical progress, and ongoing array operations experience, with an updated view of science opportunities. A modest effort which includes a set of organized workshops and discussion/working groups from within the technical and observing communities can compare several future array options, and present the community with a number of preliminary designs. Potentially there will be need for ancillary studies associated with these efforts including site evaluation (c.f. US sites, international sites, Antarctica, or other locations depending upon design goals and potential partners) and performing specific case-studies (c.f. movable telescope schemes) with industry partners. We recommend a funding opportunity of $2.5M total in the period 2016-2019, funded by NSF AST, sufficient to support several (some part-time) interferometry scientists, technologists, post docs and students in a dedicated study with significant community input and participation.

7 Summary of Funding Recommendations and Closing Remarks

The 1990 Decadal Review recommended $45M in funding for O/IR interferometry over the decade. Allowing for inflation, this is approximately consistent with the non-NASA US rate of investment in this area over nearly two decades, and the ISI, NPOI, CHARA, and MROI facilities/instruments are the legacy of that investment. The Keck interferometer and LBTI are special cases, representing the result of focused development of nulling and other specific capabilities for NASA mission support. [1]

With an exponential increase in publications, and the potential for rapid improvements in sensitivity, imaging performance, and access, the future of interferometry should be shining brightly. However, the fact is that each of our arrays is severely under-funded, and within a small fiscal perturbation of closing its doors. Five smaller interferometric facilities have closed in the past five years, and we may lose one or more before the Astro2010 recommendations can take effect. The national investment in this technology could be lost mainly for lack of operations funding. We ask Astro2010 to endorse a funding profile which will open the doors of existing facilities wide to the community, support the community in its work with this burgeoning technique, pursue technology poles of opportunity, and follow-up later in a few years time with a conceptual design of a next generation array, for discussion and review a decade from now.

A summary of our recommended funding, appropriate agencies/opportunities, and distribution through the decade is shown in Table 3.

Item	**Decadal cost***	**Schedule**	**Agency**	**Mechanism**
Array Operations	$60,000K	2011-2020	NSF	New URO-like program
Interferometry Observer support	$8,000K	2011-2020	NSF	Competition for Support Office
Technology Development	$18,000K	2011-2020	NSF and NASA	MRI, ATI and APRA
Next Generation Array Conceptual Design	$2,500K	2015-2019	NSF	Competition for Project Office
Total	$88,500K	2011-2020		

*FY2009 dollars.

We urge the members of Astro2010 to endorse these moderate funding requirements, and thus ensure continued development and vigorous exploitation of very-high resolution optical/infrared imaging in the United States.

[1] The NASA plan to develop a separate Keck array composed of dedicated auxiliary telescopes was not completed due to non-technical reasons.