Astro2020 Activity and State of the Profession
White Paper

Revitalizing the Optical/Infrared Interferometry Community in the U.S.
Advocacy from Members of the U.S. Interferometry Community (MUSIC)

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Abstract:
Long baseline optical/infrared interferometry (LBOI) has produced groundbreaking results in stellar astrophysics and is essential for the future of high-resolution observations. We describe capabilities and recent results, discuss the development of LBOI in the U.S., and make recommendations for the support and growth of U.S. interferometry.

URL: http://chara.gsu.edu/wiki/doku.php?id=usic:home
1 Key Issues and Overview of Impact on Astrophysics

1.1 Recent results and current capabilities

Current interferometric capabilities provide the opportunity for unmatched, detailed studies of the nearest stars. Here, we give a brief summary of recent innovative interferometric results and their associated Astro2020 Science White Papers1.

Significant contributions to fundamental stellar astrophysics are already possible through interferometric observations measuring just the angular stellar diameters (Baines et al., 2018; van Belle et al., 2019). Based on interferometrically measured angular diameters, we may construct an empirical Hertzsprung-Russell Diagram (HRD) and constrain the relationship between stellar temperatures and radii (e.g., von Braun & Boyajian, 2017). Detailed measurements of stellar diameters improve the constraints on stellar ages for co-evolving systems (e.g., the Ursa Major moving group, Jones et al., 2015), as well as providing the means to calibrate evolutionary models and zero points for stars across many regions of the HRD (e.g., Boyajian et al. 2015; Mann et al. 2015). Direct observations of Cepheid pulsations, combined with radial velocities and other data, elucidate Cepheid distances and radial velocity projection factors (e.g., Kervella et al., 2017).

The angular resolution of long-baseline optical interferometry (LBOI) allows for the mapping of visible binary orbits. When these orbits are combined with spectroscopic radial velocity curves, high precision masses of the stars can be determined (e.g., Mourard et al., 2015; Schaefer et al., 2016, 2019). Not only is interferometry able to resolve close binaries, but it can directly detect companions with large flux ratios (e.g., Gallenne et al., 2015; Roettenbacher et al., 2015). Current efforts aim to push the observational limits further in order to detect the micro-arcsecond reflex motion caused by a planet on binary star systems (Gardner et al., 2018). With the significantly larger apertures of the VLTI Unit Telescopes and the GRAVITY beam combiner, the Gravity Collaboration was able to resolve the orbits of stars at the center of the Milky Way Galaxy (Gravity Collaboration et al., 2018).

Beyond diameter and orbital observations, stellar surface imaging has continued to develop and improve over the last decade. Recent results include an assortment of oblate, rapidly-rotating massive stars that serve as tests of gravity darkening (Che et al., 2011; Zhao et al., 2011). The distortion of the components of interacting binary systems (Baron et al., 2012) and of the disk around a Be star in a binary system (Che et al., 2012) have also been imaged. Ground-breaking images of a supergiant star undergoing eclipse by a disk-enshrouded companion have been obtained

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1For the collection of the Astro2020 Science White Papers in support of long-baseline optical interferometry, see http://chara.gsu.edu/wiki/doku.php?id=usic:astro2020
Figure 2: Stars interferometrically imaged in the last decade represent a wide range of astrophysics. a. Rapidly-rotating, main-sequence stars with radiative envelopes provide tests for gravity darkening (see review by Zhao et al., 2011). b. First image of convective cells on the asymptotic giant branch star $\pi^1$ Gruis (Paladini et al., 2018). c. Aitoff projection of the entire surface of the giant star $\zeta$ Andromedae shows starspots caused by stifled convection due to strong magnetic fields (Roettenbacher et al., 2016, for an animation of the rotating stellar surface, see https://rmroettenbacher.github.io/Roettenbacher2016-CAPTION.gif). d. Images of the expanding ejecta from the Nova Del 2013 (Schaefer et al., 2014). e. A series of images of the disk of a companion eclipsing the surface of the supergiant star $\epsilon$ Aurigae (Kloppenborg et al., 2010) f. One phase of the interacting binary system, Algol (Baron et al., 2012).
with the current interferometric capabilities (Kloppenborg et al., 2010). The size of the expanding shell of ejecta from Nova Del 2013 was measured with interferometry, and the early stages of the expansion were imaged (Schaefer et al., 2014). The temperature differences of features due to convective cells and starspots have been captured with interferometric images (Roettenbacher et al., 2016, 2017; Paladini et al., 2018; Rau et al., 2019; Roettenbacher et al., 2019). Images of the disks and winds surrounding young stellar objects (YSOs; e.g., Kraus et al., 2012; Setterholm et al., 2018; Labdon et al., 2019) have begun to reveal the structures of the innermost regions of star and planet formation. For an assortment of the images possible with LBOI, see Figure 2.

The results of the community’s studies have impacted fundamental stellar astrophysics, and those results are widely used by the general astronomical community. For example, the Boyajian et al. (2012) study of stellar diameter and temperature of main sequence K- and M-stars is a popular resource among the exoplanet community aiming to improve planetary constraints. A number of the results listed above have been published in high-impact journals in the last decade and have been groundbreaking in their respective fields (using CHARA: Kloppenborg et al., 2010; Derekas et al., 2011; Schaefer et al., 2014; Roettenbacher et al., 2016). Our community will continue to push observational boundaries with the unique ability of interferometry to reveal stars as they are.

The number of targets that are accessible by the current interferometric capabilities are limited. Advances to the current technology and resources are needed in order to study even more exciting and far-reaching science. With the next generation of upgrades and new interferometers, it will be possible to investigate planets forming in their disks, resolve active galactic nuclei, and obtain interferometric observations of a sufficiently large sample of stars so that astrophysical theories of planet and stellar evolution, stellar magnetism, galaxy formation, and more can be improved and constrained.

1.2 Where Do We Come From? What Are We? Where Are We Going?

Optical interferometry for astronomy became a reality when Albert Michelson, the quintessential American physicist/inventor, measured the diameter of Betelgeuse with a two-aperture extension of the Mt. Wilson 100” telescope (Michelson & Pease, 1921). The modern era of optical interferometry in astronomy began in 1975 when Antoine Labeyrie, working in the French tradition of innovative optical physics, followed his invention of speckle interferometry with a demonstration of optical interferometry between two independent telescopes (Labeyrie, 1975). The subsequent extension, by Labeyrie’s students, developed a productive demonstration facility in southern France (Koechlin, 1988). Very soon after this, the Hanbury Brown team in Australia revised their plan for a next generation intensity interferometer, and began developing it as an amplitude interferometer, conceding the superiority of direct interference. In the same 1990’s time frame, Charles Townes’s Berkeley group extended the radio technology of heterodyne interferometry to the thermal IR. Heroic technical accomplishments produced a few unique measurements, but owing to the compromise of ultra-limited sensitivity, the method was not pursued beyond the pioneer experiments (Hale et al., 2000).

In the U.S., these activities triggered considerable interest, reflected in the formation of an “Interferometry Panel” for the 1990 Decadal (National Research Council, 1991). The Decadal recommended an investment of $45M for “Optical and Infrared Interferometers”. Multiple groups were ready and waiting for the opportunity. By the mid-1990s, there were several prototype university PI facilities in operation - the Infrared Michelson Array at University of Wyoming, which gave
way to the Infrared Optical Telescope Array at Mt. Hopkins (U. Wyoming, Harvard-Smithsonian, and U. Massachusetts). The US Naval Observatory and Naval Research Laboratory, hosted by Lowell Observatory, built the Navy Prototype Optical Interferometer (NPOI) with the mission objectives of precision astrometry for Navy purposes and of developing interferometric imaging. NASA funded the Palomar Testbed Interferometer (PTI) as a technology demonstrator for exoplanet oriented mission development. As the names imply, these were considered prototypes or experiments and were not expected to serve as facility-class observatories. By the mid-1990’s, the U.S. held a commanding lead in implementation of optical interferometry.

Concurrent with PTI, NASA developed the Space Interferometry Mission (SIM), to pursue astrometric studies. Although SIM technology achieved marvels of measurement and control, the discovery component of its mission was eclipsed by the progress in radial velocity techniques. SIM was ended by the 2010 Decadal Review. In an overlapping study, NASA pursued the Terrestrial Planet Finder (TPF) mission—a thermal wavelength optical interferometer—a concept also vigorously pursued by ESO as Darwin. Interest in TPF faded owing to projected costs associated with the required baseline for thermal IR operation, and NASA interests turned to visible optical coronagraphy, with the possibility of doing important work with a single aperture general purpose telescope. This direction continued with vigor for review in the 2010 and 2020 decadal surveys.

In the late 1990’s, NASA took the decision to pursue a very ambitious ground-based interferometry facility - the Keck Interferometer Array (KIA). The second Keck telescope was purpose-built (and NASA funding partially justified) for beam combining of the two telescopes. This concept was enabled by the expected imminent extension of adaptive optics and laser beacon technology to large apertures. The NASA plan for the KIA included interference between the Kecks in the thermal IR for study of exo-zodiacal light (information essential for designing sensitive space exoplanet missions). It also included four “outrigger” telescopes with 1.8-m diameters, which were to be used in beam combination with each other and with the Kecks; the outriggers were to be optimized for narrow-angle astrometric detection of planets. Interference between the Kecks was accomplished and measurements made, setting limits on the exo-zodi in the targets observed, but the goals were not fully achieved and the exo-zodi mission was passed to the Large Binocular Telescope Interferometer. The KIA auxiliary telescopes were fabricated, but never broke ground, as the project ran afoul of the developing island resistance to Mauna Kea development. NASA canceled the project. Thus the investment recommended by the 1990 decadal (and more) was made, and lost, in the Keck Interferometric Array.

The impact of this cancellation is not widely appreciated outside the interferometry community. The NASA-funded KIA was understood to be the U.S. national facility for optical interferometry, with planned open community access via NASA-moderated peer review. There were other facility-scale interferometer concepts at the time, but they were essentially frozen out—how could they compete with NASA, and why would the community support two large programs?

The ESO Very Large Telescope Interferometer (VLTI) concept was similar in a programmatic sense to the KIA. Starting several years later, it was considerably behind KIA. However, with KIA cancelled, VLTI took the lead in large facility interferometry, and retains that lead today.

Meanwhile, another small array project was developing - the Center for High-Angular Resolution Astronomy (CHARA) Array. The CHARA Array was conceived as an instrumental extension

For targets smaller than the single aperture Airy disk, telescopes of different aperture size can be combined, with a sensitivity equivalent to the geometric mean of the aperture sizes.
to the GSU binary star observing program. It was modestly funded ($5M in public money) to carry forward this plan, on a scale more ambitious than the several prototype arrays mentioned above, but still a program of limited objectives. However, when the NASA ambitions for KIA faded, CHARA became by default the U.S. flagship interferometry project. CHARA staff took on this challenge, and augmented the intellectual and financial resources with a multiplicity of partners. CHARA continues to operate, with a mix of Georgia State, NSF and collaborator support.

There are now two new and substantial optical interferometry programs under development in the US. The NPOI (now the Navy Precision Optical Interferometer) is undergoing an expansion to larger telescopes, longer baselines, and more extensive general science use. NPOI builds on the existing, extensive facility infrastructure and many years of successful Navy-focused operation, with some modest scientific use including multi-spectral measurements of stellar angular diameters. The Magdalena Ridge Observatory Interferometer (MROI) is the newest project. Thanks to its recent start, it has been developed from the ground up so it benefits from many years of prototype experience elsewhere, the latest technology, and no burden of aging infrastructure. The MROI philosophy insists on exceptional performance, both for sensitivity (high throughput) and imaging (multiple movable telescopes).

The Planet Formation Imager (PFI), now in science planning and conceptual design, illustrates a new stage of maturity in our community. Elevating a specific science objective over general purpose function, multiple design decisions are driven to optimize the performance for that science.

Although NASA truncated its early space and ground efforts, interferometry remains prominent for NASA’s future. The NASA Astrophysics Roadmap Enduring Quest, Daring Visions (Kouveliotou et al., 2014) reports that “All notional missions in the Visionary Era are interferometers.” This is understandable - extracting the surface features of habitable zone planets, for example, is a task that only future interferometry can plausibly address. Meanwhile, our ground-based observatories mature the technology, pursue the science, and nurture the expertise.

CHARA, NPOI, MROI and PFI are presented in separate project white papers. In this broad overview, we emphasize that no one of these projects is the equivalent of, or a substitute for, any other. An optical interferometer has multiple design decisions that determine the performance parameters and the optimum science applications. The various arrays currently in operation virtually never overlap in science programs. Even scientists with access to the massive VLTI facility work with U.S. projects to benefit from different capabilities, and for opportunities to pursue technical and scientific innovation in a PI rather than institutional environment.

We have a lot to be proud of. The U.S. operates the longest interferometer baselines. In the last decade, our modest organizations have successfully competed head to head with the largest observatory in the world. We have improved sensitivity by a factor of 10 over the decade. We have competed successfully for funding of new telescopes, AO, instruments and detectors. Open community time through the NSF Mid-Scale Innovations Program is a success. Next generation array planning is maturing. The synergies of interferometry with Kepler, TESS and GAIA are supporting a new appreciation of the opportunities in stellar physics.

Our objective here is to emphasize to the decadal committee that a multiplicity of vigorous projects is essential to a healthy astronomy ecosystem. The projects represented by MUSIC are contributing a mix of strong and unique science, developing the technology and and concepts for a next generation array, and passing to young astronomers the vision and skill sets to build it.
2 Strategic Plan

In order to maintain the community and grow capabilities needed for future facilities beyond the 2020 decade, a reinvestment in LBOI is required in all development areas. Background and a suggested approach are proposed below for each area. This strategic plan has been endorsed by all participants in the Members of the U.S. Interferometry Community (MUSIC) Consortium.

2.1 Community Development

Summer schools provide a way to train and inspire the next generation of interferometrists. As compared with other efforts such as the VLTI summer schools and the NRAO Synthesis imaging summer schools, the U.S. has fallen behind in its development of young people interested in the data reduction techniques, instrumentation, and science associated with LBOI facilities. For example, the VLTI summer schools began in 2002 and were hosting their 9th school in 2018. Each school hosts approximately 100 new investigators, meaning nearly 1,000 people have been introduced to the technique and facilities in Europe over about 2 decades. The NSF-NRAO Synthesis Imaging summer schools, now biannually, began in 1982 and held their 16th school in 2018. They bring in approximately 110 investigators each cycle, meaning nearly 1,800 people have been trained to use radio interferometric facilities in the past 3.5 decades.

In the U.S. optical interferometric community, the Michelson summer schools began in 1999 and were initially traded among institutions including Caltech, Berkeley, Harvard-CfA, and Lowell, but eventually were hosted primarily by the NASA Exoplanet Science Institute (NExSci) at Caltech-IPAC. In 1999-2003 and 2006, the schools were specifically focused on long-baseline optical interferometry. Those schools typically covered most of the costs of attendance for the young investigators, keeping the schools smaller and focused, but training about 50-60 people each time. There has not been a U.S.-based summer school on optical interferometry since 2006; U.S. students attend the VLTI schools in lieu of that opportunity, but many cannot due to the expense of a trip abroad. The lack of training and support impacts the number of new investigators in the U.S. and is visible in the publication rates (see Fig. 3.).

Recruitment and training of students and postdocs in the U.S. interferometry community over the last decade has mainly occurred at universities which have institutional access to LBOI fa-
cilities; many of these students and postdocs have gone on to fellowships and jobs in science, technology, and engineering. In 2017, the CHARA Array began offering 50-60 nights per year of community access time through NOAO as part of an NSF-supported program. Concurrently CHARA offered half-day workshops at several institutions across the U.S. to generate interest in the program. The over-subscription rate for the community access time is \( \sim 2.4 \), indicating a strong interest from the broader astronomical community when resources are available. In order to develop a core base of young people capable of working with future interferometric facilities on all fronts including instrumentation, data reduction and science, it is imperative to increase training opportunities.

**Recommendation:** We recommend that the professional development of the community be rejuvenated by restarting optical interferometry summer schools and that community access to interferometric facilities is key to a vibrant community.

Although this could take on many forms, one option would be to reinstate the NASA-sponsored Michelson Summer Schools that were previously administered quite effectively by NExScI. The inclusion of experts from a variety of institutions as well as focus on instrument technology, data reduction methodologies and science, including financial support for young investigators, especially from underrepresented groups, will be key to growing the community. Growing the attendance size of the schools will be key to developing the community today.

### 2.1.1 Diversity

Within the LBOI community, diversity is a known problem with marked underrepresentation of individuals identifying as non-white, non-cisgender-male astronomers. The LBOI community neither reflects society nor astronomy as a whole. Within the worldwide LBOI community, researchers are developing Visibility in Interferometry (VII\(^3\)), an initiative for better representation among those underrepresented in the community. VII is developing a network of support for underrepresented interferometrists by providing opportunities to connect with each other at conferences and resources helpful with research. For the LBOI community, VII collects the contact information and research areas of underrepresented minorities that are willing to represent the field. The list is available to those interested in, for example, diversifying invited speaker lists.

**Recommendation:** We recommend that the astronomical community explicitly invest in supporting underrepresented minorities in optical interferometry through providing travel funds to relevant conferences, workshops, and schools.

VII would benefit from the support of the Astro2020 Decadal Survey. While endorsements are morale-building and increase exposure, concrete support recommendations for funds for underrepresented minorities to travel to and attend (e.g., covering registrations fees, accommodations, meals, and incidentals) conferences, workshops, or the rejuvenated summer school series suggested in this white paper, would be beneficial to strengthening the diversity of the community by supporting current and welcoming new members.

\(^3\)https://visibilityininterferometry.github.io/
Figure 4: Table of U.S. facilities. Anything noted with an asterisk has not yet been demonstrated on-sky but is under development.

### 2.2 Operational Facility Development

As noted in the introduction, each of the major US facilities is highly complementary to the others, with each still being singularly unique in terms of capabilities—in much the same way that large single aperture telescopes in the astronomical community co-exist with each other. As with more traditional telescopes, each of these facilities has a pressing need for operational funding and ongoing development. Each of these facilities has prepared its own Astro2020 White Paper, documenting their science capabilities and how they relate to the Astro2020 Science WPs, and their associated needs for resources.

**Recommendation:** As articulated in the individual facility Astro2020 APC White Papers, we recommend that these facilities be operationally and developmentally supported over the 2020-2030 time frame as ‘medium’ to ‘large’ scale ground-based projects.

### 2.3 Technology Development

Non-specialists, or those who do not closely monitor our technology, may be amazed at the technical base now available for optical interferometry. There are many demonstrated ways of providing telescopes for interferometers, including conversion from previous use, massive new fixed hardware, truck-mounted transportable, and lightweight moveable by transporter. Adaptive optics have been deployed to all the telescopes of arrays. Beam transport over many hundreds of meters has been done in air, vacuum, and optical fibers. Multi-stage optical delay lines are well established, utilizing selectable combinations of fixed and continuously variable segments. Sophisticated beam combiners accept discrete beams from multiple telescopes, divide them by wavelength, amplitude or polarization, produce signals for calibration, visibility amplitude and phase detection, with appropriate modulation to facilitate measurement.

Optical interferometers lead in automation and remote operation, with the possibility of a single scientist either on site or remote. The remarkable reliability of electro-optical technology enables systems with literally hundreds of optical components and many tens of electro-mechanical widgets to perform year after year with rare failures. A major interferometer utilizes multiple CPUs operating within interconnected networks, measuring, monitoring, controlling, and responding to...
operator demands. Early on, there was concern for the possibility of complexity failure due to
unpredicted timing or subtle logic errors. Experience has shown that this is not a problem. In fact,
interferometers are remarkably robust against down-time. Even in the case of sub-system down-
time, consider that a facility with $n - 1$ telescopes operating instead of $n$ is still capable of doing
a lot of science.

While the technology described above suffices to build exciting observatories, there are mul-
tiple technical directions that can make those observatories more powerful and/or less expensive;
many of these areas, ripe for technology development, are strategic milestones necessary for a
mature proposal of PFI to the 2030 Decadal and potential future facilities in space.

Our field is on the cusp of even greater things as shown e.g. by the recent VLTI measurement of
rotation in the galactic black hole accretion disk. Factors of 2 in sensitivity and baselines are rela-
tively easy and still low hanging fruit left. We have identified plausible paths to improve sensitivity
a further $x10$ over next decade. **Recommendation: Technology development of optical interfer-
ometry should be pursued as a stand-alone ‘medium’ scale effort.** Aspects of this technology
development will have direct benefit for the general astronomical community. Specific technology
development areas of emphasis can include:

**Large, low-cost telescopes:** Efforts are being made in the LBOI and DoD communities to de-
velop low-cost ($< $2M), large (> 2m) apertures suitable for optical interferometry. These would
be AO-corrected and relocatable, but achieve low cost through use of thin, lightweight mirrors that
are diffraction limited only over very narrow fields-of-view ($< 2 – 3$ PSFs) appropriate for LBOI.
This one development has striking implications not just for economically enabling the next gener-
tional of LBOI, but could have significant impacts in application elsewhere in the astronomical
community.

**Advanced beam transport:** The anticipated kilometer-scale baselines from expansion of the
CHARA and NPOI arrays will potentially require new approaches to relaying the beams to the
central beam combination facilities. Possible solutions include fibers, improved vacuum beam
pipes, or AO-corrected free air propagation.

**Next-generation beam combiners:** One bright area for the U.S. interferometry community is
its leadership in operational six-way beam combiners, including the MIRC instrument at CHARA
(Monnier et al., 2012) and VISION instrument at NPOI (Garcia et al., 2016). Recent advances
in newly-available fast, low-noise near-infrared detectors have led to a dramatic improvement in
sensitivity for these combiners (Anugu et al., 2018). Additionally, eight-way (or more) beam
combination is being considered at some of the U.S. facilities, which would improve the imaging
capabilities there. As demonstrated at VLTI, advanced new combiners in the form of the Gravity
and MATISSE facility instruments are delivering breathtaking results.

3 Organization, Partnerships, and Current Status

The U.S. interferometry community is substantial (>100 facility operators and users), but closely
connected and cooperating in technology, science and planning. MUSIC (Members of the U.S.
Interferometry Community) is the current forum for that connection, and this white paper repre-
tsents our consensus high-level views on paths forward. Our common ground is expertise in the
methods of interferometry and confidence in its potential for astronomy. Facility-specific white
papers present NPOI, CHARA, MROI and PFI status and programs.
4 Schedule

The investments recommended in our facility white papers are mostly short to medium term (within the decade), with return in science production, array sensitivity, imaging, open access, and student participation. In the longer term, we follow the road to a future large optical array. It will notionally feature an ambitious observatory concept optimized for interferometry, with number and size of apertures appropriate to the ambitions of the national community. The technology is nearly in place for a 3rd generation optical array, as exemplified by the PFI concept.

5 Cost Estimates

We present here suggested investments in several cross-discipline areas that would greatly benefit the state of the profession. These estimates are based upon the recommendations described in §2.

- Summer workshops, conducted on a semiannual basis, notionally attended by 50 students, 10 instructors: $350K/ea (or half that on an annualized basis)
- Interferometry-oriented technology, especially telescopes, long distance beam transport, and beam combiners: $2M/yr
- VII travel support grants for underrepresented minorities, 10 grants annually: total $30k/yr
- Fellowships for graduate and postdocs - 3 year terms, funding one new fellow at each professional level per year (for a total of 6 rotating slots). For postdocs at a cost of ~$150k/ea/yr, graduate students at ~$100k/ea/yr, and a first-year startup instrumentation stipend of ~$75k/ea, we project the annual cost to be roughly ~$900k/yr

In total, these particular community building and supporting activities are on the order of ~$3M/yr for each of the years in the 2020 decade. **This level of support is commensurate with the immediate scientific benefit to the greater astronomical community, and developing technical and intellectual capital to meet the future demands for optical interferometry on the ground and in space.**

Project support cost estimates for the individual facilities – PFI, MROI, CHARA and NPOI – at a range of levels, are included in their separate white papers. It is vital that support opportunities extend throughout the decade. Note that in 2010, the decadal recommendations did not call out individual small/medium scale programs. Decadal mention of these, as a group or preferably by name, is a powerful tool of community resource prioritization available to the decadal and valuable to funding agencies as they set priorities.
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