Workshop on the Future Directions for Ground-based Optical Interferometry

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Objectives - A major program goal of the AURA New Initiatives Office is to develop an understanding of the scientific potential and technical drivers for an Optical/Infrared interferometer. The goal of this workshop was to shape and inform NIO discussions of the future of interferometry for the next decadal survey.

Context and Themes - Since the Bahcall Committee gave optical interferometry a priority for technology development in 1990, prototype experiments have led the way to the first generation of user facilities. As Optical Interferometry comes of age (more than 100 science papers in the last 2 years) it is becoming clear that high spatial resolution is leading toward a revolution in stellar physics. At the same time, filled aperture technology is approaching its limits with an ELT[1] or an OWL, yet still falling short of fully relieving confusion in crowded regions, and still very far from resolving main structure in compact and/or distant sources. Hence it is timely to look beyond the capability of today's optical arrays, to consider what performance may be possible in the future, and what science opportunities may be enabled.

The workshop was oriented around four themes:

- Science opportunities with a next-generation optical array
- Array concepts
- Candidate sites
- Today's arrays and tomorrow's technologies—a roadmap toward the future

The following workshop synopsis and attached documents provide detailed recommendations on science opportunities, technical rationale, and roadmaps.

Workshop Conclusions

1. Optical interferometry offers a unique and powerful resource for astrophysics.
2. The workshop had identified two significant opportunities. One is for very high angular resolution studies of compact sources. The highest priority science objective is the detailed study of circumstellar material related to star and planet formation. A second high priority objective is the study of energetic and interacting systems, including AGN's, relativistic stellar systems, and binary systems with mass transfer.
3. A second opportunity is for high angular resolution over extended fields with high sensitivity. The highest priority objectives include deep imagery and photometry of stellar fields in distant galaxies that are confusion limited with ELT's.
4. The scope of a next-generation facility requires national coordination, and international collaboration may be essential.
5. Vigorous programs with current generation arrays will clarify and assure the scientific motivation and technical foundation for a significant future project.

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[1] Most acronyms are listed in Appendix 4.

Workshop Recommendations to NOAO

Near term

1. Support or otherwise facilitate community access to existing U.S. optical interferometer facilities under competitive, peer reviewed guest observer programs.

2. Support Antarctic site studies to characterize them for interferometer operation.

3. Collaborate with current facilities to begin to address the high leverage elements in the technical roadmap – beam transport and optical delay for kilometric distances.

4. Organize follow-on workshops and conferences from time to time with the objectives of monitoring progress on the technical and scientific roadmaps, and further clarifying the scientific potential of both classical and compact array concepts.

5. Investigate developments in optical and mechanical technology that may facilitate significant cost reductions in major interferometric systems such as telescopes and adaptive optics, for example by collaborative instrument programs.

Long Term

1. Select one or more array concepts for further study.

2. Work with the interferometry and broader astronomy communities to prepare a concept and plan.

3. Investigate potential international collaborations and develop partnerships.

4. Engage in an appropriate program to ensure and support the development of a strong array concept, design study, proposal, implementation and operation.

Workshop Recommendations to NSF

1. Assist the interferometry community in its integration into the Ground-based Optical Infrared System, for example by invitation to the OIR System planning meetings.

2. Authorize interferometry facility access to the NSF Telescope Systems Instrumentation Program (TSIP), in which agency support for major instrumentation is made available to private observatories in exchange for astronomer access to the observatories through the NOAO Telescope Allocation process.

3. Provide competitive opportunities for support of research with interferometric facilities and data, for example through PI grants and fellowships.

4. Provide competitive opportunities for support of interferometry technology development.

Workshop Recommendations to the Interferometry Community

1. Carry out vigorous scientific programs, with wide-ranging exploratory measurements and focused projects that exploit the unique advantages of high angular resolution.

2. Provide reliable and routine observing capabilities useable by guest observers.

3. Engage specialists from outside the interferometry community in interferometric science programs.

4. Work together to educate other astronomers and to foster support. Distribute information about current and next generation array capabilities. Participate in topical conferences and planning processes.

5. Work toward accomplishment of the recommended technical and scientific milestones, and publicize appropriately their completion.

6. Prepare recommendations to the Decadal Review for the further development of Interferometry facilities.

Workshop Report

THE STATUS OF OPTICAL INTERFEROMETRY TODAY

Optical interferometry has a significant international infrastructure of private and public facilities, particularly including the ESO Very Large Telescope Interferometer (VLTI), the Keck Interferometer (KI), the CHARA Array, and the Navy Prototype Optical Interferometer (NPOI), and the Magdalena Ridge Optical Interferometer (MROI) which is under construction. These observatories are designed to carry out high angular resolution measurements (~few milliarcseconds) of bright[2], compact sources, and are now delivering on their promise, with break-through measurements of stars and stellar environments. Improvements in progress will extend the operation of some facilities to faint sources.

The Large Binocular Telescope (LBT) will explore and demonstrate the potential of compact interferometric arrays for high-resolution imagery of faint sources over an extended field of view.

All of the basic technology of optical interferometry, including wavefront compensation, beam transport, optical path control, beam combination, and post-detection image reconstruction, have achieved operational state. Further significant developments in each of these areas can be expected, paving the way to simpler and less costly interferometric facilities of the future.

Major Science Opportunities

STELLAR PHYSICS

Currently operating optical interferometers routinely achieve, for stellar studies, angular resolutions 30X greater than is possible with the largest current filled-aperture telescopes. When today's arrays were in development, it was predicted that such resolution would enable precision determination of certain obvious stellar model parameters, such as limb darkening, angular diameters, pulsations and binary orbits. In fact, experience has shown that virtually no simple model withstands the test of such a gain in observational power. The first years of array facility operation have produced one surprise after another. Here is a list from just 2006.

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[2] By convention, a *bright* source is one for which the interferometric phase can be determined from the source photons alone, within the atmospheric coherence time, while a *faint* source requires additional wavefront phase information, such as from an offset reference source. An analogous limit applies for AO systems for bright targets that are self-referenced or faint targets that are off-axis referenced.

Recent Progress in Stellar Physics from Optical Interferometry

- Cepheids
    - Calibration of Baade-Wesselink
    - Detected envelopes
- Mira stars
    - High opacity of the upper atmosphere
    - Dust too close to the surfaces
    - Asymmetries and temporal irregularities in mass loss
- High molecular layer in supergiants too
- Dust differentiation in η Car
- Granulation (convection) in Procyon
- Polar mass loss from a classical Be Star
- Hot dust shell resolved in α Lyr
- Unexplained irregularity in the shape of α Boo

Looking to the future, we can forecast with confidence that interferometry will continue to drive a revolution in stellar astrophysics. Straight-forward enhancement of current array facilities, with the increasing imaging power (including snapshot imaging) of improving U-V coverage, and the combination of interferometric spatial resolution with high spectral resolution, will provide increasingly detailed views of stellar surface and circumstellar environments and their evolution with pulsation and orbital phase.

High priority Objectives in Stellar Physics

- Imaging of stellar surfaces
- Determination of fundamental parameters with sub-percent accuracy
- Interacting binaries and the disk-jet connection
- Dust and mass loss in varying stellar environments
- Asteroseismology and stellar interiors
- Challenging and calibrating stellar evolutionary models

YOUNG STELLAR OBJECTS AND EXOPLANETARY SYSTEMS

As in the case of stellar physics, interferometry is already returning model-breaking surprises in the study of young stars. Here is a short list from the same year as the list above in the stellar physics section.

Recent Progress in YSO Physics from Optical Interferometry

- Tests of active accretion theories in FU Ori stars
- Size and detailed structure (puffing up) of inner dust disk for young stars
- Continual replenishment of dust grains in TW Hya

YSO environments are rich with exciting and important phenomena. Central stars exhibit a wide range of energetic activity. Accretion disks have unknown and likely complex structures, with associated outflows or jets, possible hydrodynamic instabilities, disk-protoplanet interactions, residual post-planet-formation debris disks, and the exoplanets themselves. Imaging resolved spectral emission and absorption lines in circumstellar material uniquely combines spatial measurements with kinematic and excitation information. The ultra-precision astrometric capability of interferometry over narrow angles offers an approach to exoplanet studies that will be otherwise available only from specialized space missions.

Objectives for Optical Interferometry of YSO's and Exoplanets

- Masses/diameters of young stars
- Stellar accretion process/geometry
- Stellar magnetic field structure and rotation
- Detailed dust chemistry vs. location in the disk and time evolution in young circumstellar disks
- Observe the dynamics of the gas disk near the star
- Resolve the star-disk interface, determine the jet launching region (star or disk?)
- Structure of planet forming disks
- Exoplanet dynamics
- Exoplanet mass, orbital radius
- Structure of debris disks.

GALAXY SCIENCE

Stellar Populations

A high science priority for ELT's is the study of crowded stellar fields enabled by the combination of high sensitivity and Adaptive Optics supported angular resolution of a large aperture. However, some of the most interesting targets will remain confusion limited at ELT sensitivity/resolution. Study of stellar populations in a range of galaxy types requires ELT collecting apertures, with greater than ELT spatial resolution. Improved resolution will provide both improved photometric precision in measurement of color-magnitude diagrams, and an improved capability for astrometric study of galaxy internal kinematics.

Challenging problems in stellar populations for the next decade

- Unraveling the formation histories of spiral bulges and disks
- and of elliptical galaxies
- Measuring the Initial Mass Function in dense star forming regions
- Measuring the internal space motions in galaxies

Galactic Nuclei

Adaptive Optics has dramatically advanced our knowledge of the stars in the core of the Milky Way. Interferometric measurements promise to extend such studies to local group galaxies. Interferometric resolution and astrometric precision will track the orbits of fainter, more numerous stars in the Milky Way, providing sensitive probes of General Relativistic orbital effects. Interferometry and spectroscopy can employ spatially resolved velocity dispersion measurements to infer black hole masses in more distant galaxies, contributing to an understanding of the Maggorian relation. Interferometry may offer the best leads on evidence for the importance of black hole multiplicity in galaxy evolution, study of merged black hole systems, and stellar merger rates. Detection of gravitational microlensing by massive black holes may be possible from the relative apparent background star densities

Optical interferometry is well suited for study of Active Galactic Nuclei. Initial measurements of the AGN's NGC 1068 and NGC 4151 have already shown the capability of the simple first generation facilities to determine characteristic sizes of these sources, and are beginning to reveal sufficient structure to motivate empirical structural models.

Recent Progress in AGN Physics from Optical Interferometry

- Direct evidence supporting the unification scheme of AGNs for Seyfert 2 galaxies
    - Detection of a torus
    - Unresolved cores
- Low temperatures for dust favor clumping scenario rather than uniform distribution
- Directly testing models for torus organization and support

For the future, one can foresee study of the nature of the Broad Line Region possibly in 3D (tomography) by combining interferometry and reverberation mapping. Depending on the real size of the accretion disk, 1 km - 10 km baseline interferometers should have enough resolution to resolve both the BLR and the external part of the disk in Seyfert 1 galaxies.

Distant Galaxies and Cosmology

Interferometry can directly support improved distance determinations. Angular diameter measurements at the VLTI and the CHARA Array, combined with HST parallaxes, have already produced the first direct calibration of the critical p factor, which relates the line-of-sight pulsation to the plane-of-the-sky pulsation, directly addressing the importance of the second order effect in the Cepheid distance scale. Interferometry can in the future support geometric distance determinations with direct measurement of supernova shells, light echoes from Gamma Ray Bursts. Interferometry can support measurement of surface brightness fluctuations.

Interferometric measurements in support of microlensing measurements can aid the interpretation of the events, by directly measuring the deflection, or by resolving the lens from the star after the event.

Interferometry may offer the best method for resolving sub-structure in the earliest galaxies, and may give the best answer to the question of what these early objects look like.

ASTROMETRY

While astrometry is mentioned in several specific science topics above, the topic deserves discussion on its own merits. The astrometric potential of interferometers, both on ground and in space, is truly unique and surpasses other potential approaches. For ground-based facilities, narrow and very-narrow angle astrometry offer the most exciting possibilities. Tests at the Mark III and at the PTI have confirmed the predicted performance for theses facilities. The combination of interferometric astrometry with the atmospheric conditions attributed to Antarctic sites is expected to deliver errors of less than 10 microarcseconds in one hour of measurement for differential measurements over separations of less than 30 arcseconds. This measurement capability can detect exoplanets with longer periods than are accessible via RV measurements, and can provide masses and orbital inclinations, greatly reducing the degeneracy of the orbital solutions.

The potential for study of exoplanets in binary systems is quite remarkable, perhaps surpassing even SIM in these particular measurements. Each star produces distinct fringe packet and their relative locations in delay space can be monitored very accurately, yielding a very precise relative astrometric measurement with which to detect a possible planet-induced wobble

Interferometric astrometry can be expected to improve on AO studies of the galactic center stellar orbits by a factor of about 10. This will give access to general relativistic effects including orbital precession, dark matter, flares (believed to represent the ingestion of matter into the black hole), and frame dragging due to the black hole spin.

ARRAY CONCEPTS

The science opportunities lead naturally to two concepts for future arrays. One concept would extrapolate current experience with dilute arrays to higher resolution, higher sensitivity, and better UV coverage, with a next generation dilute array, which might be called a Classical Array, since it would consist of a significant number of free-standing telescopes. A second concept would extrapolate forward from the LBT concept in a configuration which might be viewed either as a compact array, or as a dilute ELT.

The classical and compact concepts are quite distinct in their configuration and capabilities, and highly complementary in their functionality. Both concepts could be implemented as parts of a single larger facility. In this case, the compact array would provide fast, complete, high signal-to-noise UV coverage of low spatial frequencies, significantly improving the imaging performance of a classical array, while a classical array could provide precise characterization of sources unresolved by the compact array, permitting improved photometry and astrometry.

A Classical Array

The success of the current generation array facilities assures us that a promising direction for a future array would be a project with enhanced performance in one or more parameters. A larger number of telescopes with longer baselines would ensure higher resolution and improved imaging capability. A suggested baseline concept description follows.

A Classical Array

Number of telescopes	>15
Aperture	~8 m
Aperture (if in Antarctica)	~2 m
Maximum baseline length	1-2 km minimum
Preferred baseline length	10 km
Spectral resolution	Up to R=100,000
AO features	IR wavefront sensing
Imaging capability	~ 20x20 pixel images
Development needed	Beam transport and optical delay for multi-km baselines

An array such as described above could of course be implemented as a space-based facility. A space interferometer would have advantages in access to spectral ranges in which the atmosphere is opaque or difficult to compensate and in simplicity of design (no long delay lines are needed since the array can be tilted to equalize path lengths to "off-axis" targets, and reconfigurations of the array are relatively easy), but disadvantages are cost and accessibility.

A Compact Array

In expectation of successful demonstration of wide field interferometric imaging at the LBT, an extension of the concept to a larger facility would be a natural approach to enhancing the imaging capability of ELT's with a modest loss in sensitivity. (Quantitatively, the relative sensitivity of a partially filled aperture to a filled aperture is given approximately by the square root of the filling factor.) As this area is technically less well developed than classical arrays, the suggested concepts span a larger range of parameters. An LBT-like concept could be considered, with a linear array of telescopes (probably non-redundant) as large as 100 m or more. A partially independent mounting of telescopes should also be considered (for example, the "20-20" ELT concept with two telescopes, each of 20m aperture, on a circular track, operating as an interferometer). The two approaches would involve significantly different design and performance trades.

Compact Array Concepts

Linear Compact Array	
Baseline	100-300 m
Sub-apertures	8 m (non-redundant)
Pros	Rapid UV plane coverage
Cons	Flexure
Development needed	Mechanical & optical design; LBTI implementation
20/20 Style	
Baseline	100-300 m
Sub-apertures	20 m (circular track)
Pros	Greater sensitivity
Cons	Slower UV filling
Development needed	Mechanical & optical design

Concepts for compact arrays in space include some relatively exotic layouts that do not have a strong heritage in astronomy. An example would be an array of a large number of small free-flying sub-apertures feeding a common focus.

INTERFEROMETRY FROM THE ANTARCTIC

The performance of ground based interferometers is a strong function of the atmospheric conditions. Differences between conventional outstanding astronomy sites (Mauna Kea, Cerro Paranal, Cerro Pachon) are important, but not enabling. However, it appears that the atmosphere above favorable Antarctic sites offers a unique potential for interferometry.

It is estimated that an optical array in the Antarctic, composed of 2-3 m telescopes, could be phased for interferometric observations over the entire visible sky, by reference to offset stars. The corresponding requirement at a conventional site would be 8-10 m sub-apertures. This enormous difference follows directly from the gains listed below.

Dome C (above 30 m) Versus Conventional Sites

- Fried parameter r_0* 2 – 3x better
- Isoplanatic angle* 2 – 3x larger
- Coherence time* 2.5x longer
- Scintillation 3 – 4x less
- IR background* 20 – 100x less
- Aerosols up to 50x lower

* Most relevant parameters for interferometry

This estimate is based on monitoring programs at Dome C - superior sites might exist.

While an observatory in the Antarctic has some disadvantages with respect to conventional sites, they are fewer and less severe than commonly believed. Work is in progress to mitigate known challenges such as the boundary layer seeing, particularly including measurement of boundary layer characteristics and elevation of telescopes to the required height.

INTERFEROMETRY FROM SPACE

Space seems to be a natural environment for interferometry, with free-flying spacecraft offering array reconfiguration and adjustable UV coverage with no delay lines and no atmosphere. Since the mid-1980's, both NASA and ESA have studied interferometric missions in space. A dozen or more concepts have been developed to some degree.

And yet today, we still seem far from the first major space interferometer. As long as the first step requires a Great Observatory class mission, it will be very difficult to take that first step. The Space Interferometer Mission, SIM, is closest to flight, having nearly completed Phase B before ramping down development to a risk reduction program with an indefinitely deferred launch. A Terrestrial Planet Finder Interferometer is in early formulation at NASA, though no launch date is currently specified. However, the current, relatively dismal, situation for such new space missions, will improve; thus, concepts for numerous other space-based interferometers, covering a broad range of wavelengths from the x-ray to the far-IR continue to be developed. These range from modest facilities with a few elements and baselines of 10-50 m (e.g., FKSI, PEGASE, SPIRIT, and the SI and MAXIM Pathfinder missions) to the true, direct imaging "Vision Missions" with many elements and very large baselines of 0.5 to many km (e.g., SPECS, SI, BHI/MAXIM, LF, and PI). Numerous ground-based testbeds exist and are being utilized to develop the technologies needed to support these missions. One or more great general purpose interferometric observatories in space will surely be eventually achieved, but it seems unlikely that serious development of at least the large "Vision Missions" will occur in the next decade, and in any event they will be costly enough that very careful comparison with ground-based options will be inevitable. Thus, while coordination between ground and space interferometry planning and technology development is important, neither should preclude the other, and each should proceed as priorities and resources allow.

PLANNING IN EUROPE

First, it should be emphasized that the U.S. lags significantly behind Europe in optical interferometry. There is nothing existing or planned in the U.S. that can compare to the VLTI, especially in the areas of consistent planning and development with a long-term vision directed toward general astrophysics.

In Europe, optical interferometry enjoys wide international support. Expertise centers in Leiden (NEVEC), Grenoble (Jean-Marie Mariotti Center) and Heidelberg (FRInGe), bring together scientists and engineers with common interests and objectives in interferometry instrumentation and science. The European Interferometry Initiative (EII), which includes partners from 14 countries plus ESO and ESA, sponsors joint research activities including development of VLTI instrument concepts, software and technology, as well as educational opportunities and programs. The ARENA network (7 countries plus ESO) is specifically focused on fostering optical and infrared astronomy in Antarctica, including possible interferometer concepts. Major facilities in the U.S., including the LBT and the Magdalena Ridge Observatory Interferometer, benefit from participation by European partners.

Planning in the European community is several years advanced over similar efforts in the U.S. Two conference/workshops have been held in the last two years. The results have been published as:

- Proceedings of the 37th Liège International Astrophysical Colloquium (23-26 August 2004): “Science cases for next generation optical/infrared interferometric facilities (the post VLTI era)”, 2005, eds. J. Surdej, D. Caro, A. Detal http://www.astro.ulg.ac.be/colloques/2004/meeting2.html

- Proceedings of the Liège International Workshop (6-8 July 2005, JENAM2005): “Technology roadmap for future interferometers", 2006, eds. J. Surdej, D. Caro, A. Detal, in press, http://www.astro.ulg.ac.be/RPub/Colloques/JENAM/

These discussions have led to the concept of a Next Generation Optical Interferometer (also known as the Overwhelmingly Large Array - OLA) consisting of nominally 12 large (8 to 12-m) telescopes. This concept has been offered as a reasonable goal for a 15-year planning horizon, and awaits institutional support for preliminary study.

ROADMAPS

The 1990 Decadal Review for Astronomy and Astrophysics recommended a national investment in interferometry of $100M during the 1990’s. While the resources did not reach this full amount, they did suffice to carry out an important series of prototype developments (The JPL Mark III interferometer, the Wyoming Infrared Michelson Array, the CFA Infrared Optical Array, the JPL Palomar Testbed Interferometer, the USNO Prototype Optical Interferometer), and important developments in France and Australia contributed correspondingly. These programs have given interferometry the technical momentum and scientific strength which has carried it forward to the current major operational facilities (CHARA, KI, VLTI). These resources enable strong paths forward. We would like to distinguish three of these. The Technology Roadmap describes high priority technical developments and demonstrations which will enable or facilitate future generation array facilities. The Scientific Roadmap describes science-oriented work which will strengthen, clarify and elaborate the science opportunities of current and future facilities. The Current Facilities Roadmap suggests how one can capitalize on the great opportunity of existing facilities to carry forward the technical and scientific programs.

Technology Roadmap

The Technology Roadmap group recommends that NOAO establish a Technology Roadmap with well defined technology milestones, maintain community engagement in the Roadmap, and communicate progress. The group provides the following list of topics for high priority development.

Technical Topics

- Beam transport and delay for > 1 km baselines
    - Dispersion compensation
    - Fibers, fiber couplers, switching schemes, throughput
    - Diffraction, pointing for free-space transport; beam size
    - How does LISA do it?
- AO
    - MCAO
    - Laser guide stars
    - Sensing in the infrared
- Co-phasing, fringe tracking for faint sources
    - Dual feed needed?
- Beam combiner technologies
    - Beam combination strategies for 12 or more telescopes
    - Local oscillators for IR interferometry
    - Intensity interferometry?
- High-dynamic-range imaging
    - Starlight suppression
    - Precision visibilities, phases
- Detectors
    - Zero read noise photon-counting infrared detectors (for co-phasing)
- Telescopes
    - Strategies for reducing cost
- Site selection
    - Multi-site, multi-year information needed
- Metrology over long paths
- Site Testing [Antarctica and others] for Next-Gen Array
- Operational and efficiency development
    - Queue Scheduling/Automated/Efficient Operation/Non-Expert
    - Data Archiving Demonstrated
    - User-Friendly Operations
    - Software Tools & Data Standards

The Technology Roadmap Group recommended candidate milestones for tracking progress in some of these areas.

Milestone Candidates

- Baseline bootstrapping with 4 telescopes
    - Quantify with, e.g., phase jitter on bootstrapping baselines
- ‘OHANA fringes on 800 m baseline
- Dynamic range of 10^4
    - In an image, or on a single baseline?
- Target fringe-tracking faintness limits for each wavelength band
- List of candidate sites
- Path length metrology of 500-1000 meters
- Beam transport
- Laser guide star on an interferometer.
- Right-priced “large” telescope for an array

Finally, the Group recommends specific technology priorities.

Technology Priorities

- Roadmap: Priorities for technology demonstration:
    - High-quality imaging on existing arrays
    - Increase sensitivity of existing arrays
    - Combine AO with interferometer*
    - Demonstrate baseline bootstrapping
    - Fiber links between existing telescopes
- Roadmap: Priorities for technical development
    - Metrology over 1 km lengths
    - Guided optics for beam transport
    - Site identification and testing
    - Low-loss beam combiners for large number of telescopes

*AO equipped large telescopes (VLT, Keck) have been used for interferometry, but AO matched to current generation arrays has not yet been demonstrated or implemented.

The topics of beam transport and optical delay compensation deserve special mention.

Integrated Optics and Fiber Linked Arrays

The topic of integrated optics is of course covered in the technology roadmap. While integrated optics is not required for optical interferometry, and has already been the subject of impressive demonstrations, it was nevertheless judged to deserve special focus in this report. Fibers have the potential to provide higher throughput than classical optical trains. Integrated optics offers enormous simplification and enhanced stability in beam combination. These may be enabling technologies for large and complex interferometric systems.

For beam transport over long distances, free propagation may be problematic. Beam shaping and reimaging has considerable potential, but the simplicity of propagation by optical fibers has a strong attraction. Fiber linkage of interferometric arrays with 300m fiber segments has been demonstrated. Current technology provides acceptably low propagation losses for baselines up to several kilometers - for longer fiber linked baselines, further development is required. Dispersion control and compensation, also deserve further study. A short white paper on integrated optics and fiber technologies is appended to this report.

Interferometry Science Roadmap

The Interferometry Science Roadmap Group examined the target performance requirements for future optical arrays, organized these in a series of science-oriented target demonstrations, and considered which existing facilities could contribute significantly to each, and noted specific high priority science objectives that could serve as benchmarks for significant progress in each.

Science Roadmap – Requirements and Milestones

Required Capability	Scientific Milestones
Improved Sensitivity • Phase Referencing/Coherent Fringe Tracking • Throughput/Optimization of Current Facilities • Address technical limitations of existing facilities • Address issues of quiet big apertures • Wavefront sensing & control	Survey of 20 active galactic nuclei
Imaging (& Dynamic Imaging) • “Complex” scenes (~ 100s of pixels over a narrow field) • Phase-referenced/high-sensitivity imaging	Imaging of the inner 1 AU of a T Tauri disk at 300:1 dynamic range
High Spatial Freq/Long Baseline • ~1 km	Resolve the apparent sizes of the nearest T Tauri stars
Fizeau Image-plane beam combination • LBT	Image GM Aur & AU Mic disks at K, L, and M
Nulling • 1000:1 starlight suppression from ground	Survey of 10 potential TPF targets at 1000:1 contrast and of 50 at 200:1 (at 10 μm)
Astrometry Program • 30 μarcsec precision narrow angle • 10 μarcsec ultra-narrow angle	Monitor 200 solar neighborhood stars over 5 years
Adaptive optics • Cost effective AO on 1-2 m class telescopes • Visible to mid-IR operation • Source brightnesses V<10-12	Survey of 100 YSO disk sources in Taurus
Mid-infrared operation • 3-5 μm (L ~9)	
Greater-US Community Access to existing facilities • TSIP or similar program • Competed through NOAO TAC	Open competition for 500 interferometer observing hours per year

Roadmap for Current Interferometry Facilities

The Science Roadmap Breakout Group first took stock of the situation with respect to the current state of Ground-based Optical Interferometry sites. It offered the following prospective - where future closures are estimates.

Probable Status of Interferometry Facilities in 2016

COAST (closed)
GI2T (closed)
IOTA (closed)
PTI (probably closed)
ISI (uncertain)
SUSI (probably closed
MIRA (probably closed)
CHARA (open)
NPOI (open)
KI (open)
VLTI (open)
LBTI (open)
MROI (open)

This inevitable shakeout of resources, with older prototype and demonstration projects closing and newer, more ambitious and more broadly-based facilities coming on-line, is inevitable and in the long term healthy. In the short term, significant rebalancing of resources and activities will be necessary in order to maintain steady progress and innovation.

In an interesting exercise, representatives of several on-going facilities were asked how they would dispose of additional resources ($25M over 10 years) if available to their program. The answers were as follows.

> CHARA - double staff, improve mirror coatings, improve delay lines, add automation, add detectors, data analysis software, add telescopes, add turnkey AO systems.
>
> NPOI - add staff, mechanical engineering support, real time systems, beam combiner upgrades, more and larger apertures.
>
> Keck Interferometer - Negotiate with Keck observatory for additional observing time.

The Breakout group prepared a series of recommendations (to NOAO, and to funding agencies) for activities and opportunities that would enable existing facilities to contribute effectively to interferometry technology development and demonstrations.

- Create a mechanism which allows "open time proposals" on the U.S. optical interferometric facilities. (example milestone schedule: 10% in 2010, 25 % in 2015, etc.)

- Create incentives for non-interferometric astronomers to work with optical interferometric data. (example: fellowships to collaborate, buy observing time, …)

- Make current facilities part of the technology roadmap for a new facility. (example: demonstrate fringe tracking at H=14 by 2010)

- Continue a conference series with targeted topics to provide exposure of optical interferometry results to main stream astronomy. (example: MSC conference series with European partners)

INTERFEROMETRIC FACILITIES - LESSONS LEARNED

While astronomers have centuries of experience with conventional observatories, and decades of experience with radio arrays, they only a few years experience with optical arrays. What lessons have been learned about facility construction issues and operations costs?

A survey of operating interferometer facilities for which funding information was available led to some very interesting observations. For CHARA, GI2T, NPOI, PTI and SUSI, the average annual operating budget per telescope (that is the total operating budget divided by the number of telescopes) was $91K. The corresponding figure for PdBI, BIMA, OVRO, and SMA was $657K. This suggests that the optical interferometer facilities mentioned are operating at an unrealistically low level.

Beyond this, the Lessons Learned group offered the following advice for future facilities:

- Make the operation (and array!) as simple as possible.
- Develop an automatic seeing monitor in parallel to the array.
- Provide automated data and environment logging.
- Plan on full testing and characterization.
- Provide a mode of operation for more experienced "black belt" interferometry groups.
- It will cost much more than you estimate!
- Build solid and quiet systems which do not require frequent realignment.
- Equip your array with pupil and image actuators and monitors.

EXTREMELY LARGE TELESCOPES (ELT'S)

Current planning for a future large optical array takes place in the shadow of the much larger effort to plan for one or more ELT's. Work in the U.S. has settled on apertures in the range 20-30 m, while ESO has recently committed to a design study at 40 m aperture. The priority of these programs is appropriate considering the importance of sheer sensitivity to astronomy and the broad utility of an ELT, as recognized by the strong recommendations of the 2000 Decadal Review. At the same time, it is widely recognized that with an ELT of 30, or perhaps 40, or even 80-100 m, the filled aperture telescope concept will reach the point of diminishing returns. At a certain telescope aperture size, a compact array will become more cost effective for given science objectives. Without knowing the precise transition point, we can nevertheless understand the wisdom in preparing the alternate path.

Optical interferometry will have a tight and complementary relation with ELT facilities. Experience with current generation large telescopes has shown that interferometric imaging with a filled aperture (non-redundant sub-pupils and phase closure imaging) can achieve higher dynamic range and ultimately higher image quality than the AO corrected full aperture with current generation AO equipment.

Classical arrays, typically emphasizing good UV coverage of large baselines in order to adequately characterize high spatial frequency structure in images, can be strongly supported by accurate measurement of low spatial frequency information, which will be more quickly and more accurately accessible with a filled aperture ELT than with an array of telescopes operating on comparably short baselines.

Interferometers and ELT's will directly compete in few areas. The topic of crowded fields has been mentioned above - up to the confusion limit, ELT's will offer superior sensitivity, while beyond the confusion limit, arrays may be the only option for progress. Interferometric arrays can support ELT imaging by providing characterization of the bright point sources in a low brightness extended field.

Another area of competition is in the study of exoplanets. Here, the measurements are extremely difficult for both ELT's and for interferometers. It appears that ELT's, especially with the larger possible aperture sizes, are likely to be superior for isolating planetary photons (extremely narrow PSF core), in particular cases, for direct spectroscopic study of some massive exoplanets. Interferometers promise superior astrometric performance (long baseline) . Differential closure phase measurement is a very powerful interferometric imaging technique, with potential for detection of exoplanets. In techniques based on nulling, perhaps it is premature to draw conclusions on the comparison between the different approaches.

Appendix 1. The Workshop Story

The U.S. has had few venues for discussion of long term objectives and planning in optical interferometry. In addition to the decade reviews, we recall the Socorro Workshop, *Imaging with Ground-based Optical Interferometers*, organized by NSF (http://www.chara.gsu.edu/CHARA/WorkshopReport.pdf).

The planning for this workshop began as a response to the 2004 *Report of the OIR Long Range Planning Committee - A Roadmap for National Facilities*, in which optical interferometry was identified as a candidate future initiative for NOAO. In particular, the description of such a facility included the following words:

> **INFRARED INTERFEROMETER**
>
> This will also be a special-purpose, stand-alone facility with large collecting area and large baseline. One concept involves construction around an existing large telescope or telescopes. Each telescope within the array will need to be equipped with adaptive optics and a robust opto-mechanical system. A 100 m – ~1km baseline at 1 micron will produce milliarcsecond to sub-milliarcsecond resolution, greater than Very Long Baseline Interferometry and the Space Interferometry Mission, and with considerably greater sensitivity. Studies of extrasolar planets and disks, active galactic nuclei, close binaries, astrometry, kinematics of the local group, and so on are likely to figure prominently in its science case. Recent studies of atmospheric properties at the Dome C site in Antarctica suggest this site may also be well suited to the next generation of infrared interferometers.

In preliminary response to this recommendation, NOAO invited a number of community scientists who had previously shown interest in long range planning to form an ad hoc Committee for Optical Ground Based Interferometry (COGBI). The participants in COGBI were:

William Danchi
John Monnier
Peter Lawson
Charles Townes
Michelle Creech-Eakman
David Buscher
Chris Haniff
Mark Swain
Tom Armstrong
Hal McAlister
Wesley Traub
Deane Peterson (chair)
Stephen Ridgway
Rachel Akeson

The AURA New Initiative Office, in its 2006-2010 Long Range Plan, proposed as follows:

> AURA New Initiatives Office Major Program Goals:
>
> Develop an understanding of the scientific potential and technology drivers for next generation O/IR facilities (e.g., a 50m–100m single aperture telescope; O/IR interferometer; South Pole science) via small, structured community workshops. The goal is to develop the background material needed to shape and inform discussion for the next decadal survey.

The COGBI discussed a range of science drivers and array concepts, and recommended a series of activities to advance the planning process and to engage the community. This led to planning and organization of a special ground-based interferometry session at the January 2006 AAS, and of a special Interferometry Planning discussion session at the 2006 Orlando SPIE meeting.

Plans for the Interferometry Workshop were developed in discussion with COGBI. The Scientific Organizing Committee for the Workshop consisted of:

Rachel Akeson
Stephen Ridgway
Ken Johnston
Hal McAlister
Josh Eisner

The Interferometry Workshop was announced at the January 2006 AAS meeting, at the 2006 Orlando SPIE meeting, and in the NOAO WEB pages.

At the Orlando SPIE meeting, a special discussion session on “The Future of Optical Interferometry” drew approximately 100 attendees. Most attendees remained for a following “rump” session whose objective was to harvest input for further development, including at this workshop. Topic discussed included: science directions, facility concepts, how to build consensus, develop a strategic plan, and devise a technology roadmap.

The original concept was for a small meeting with participation “by invitation”. However, as word of the meeting spread, it became clear that a small meeting would not satisfy the community desire to participate. Hence the venue was moved from NOAO to a local hotel. Eventually, approximately 65 people participated.

At first the intention was to have a 5 day workshop, but it quickly became apparent that this was unrealistically long for many participants, so the length was reduced to approximately 2.7 days. In order to promote a high level of participation within the workshop format and the limited duration, the following model was adopted. A number of major topics were identified. For each topic, an invitation was issued to a participant to present a review and recommendations. The charge was to develop an overview, working with other members of the workshop. In order to register interests, each participant was invited to identify on a list of topics those to which they wished to contribute. This list was a resource to the reviewers. Thus a considerable level of interaction and iteration occurred before the workshop began (though admittedly a lot of this took place in the last weeks or days).

The following table identifies the topics, the reviewers, and the contributors that we could identify (an imprecise list at best, and not reflecting the extensive contributions that were made during discussions at the workshop).

Topic	**Reviewer**	**Contributors**
Introductions and information	Stephen Ridgway	SOC
NOAO Longe Range Planning, Interferometry, and the Decade review	Todd Boroson	Mould
Status of Interferometry Planning in Europe	Andreas Glindemann	Foresto, Haniff, Herbst, Perrin, Surdej
Space Interferometry in the 2020+ Era	Ken Carpenter	Allen, Benson, Ciardi, Danchi, Foresto, Karovska, Mighell, Monnier, Mould, Mourard, Surdej, Swain, Leisawitz
ELT Perspectives	Bruce Macintosh	Graham, Hickson, Larkin, Davidge, Tuthill, Monnier, Lloyd
Stellar Physics	Doug Geis	Armstrong, ten Brummelaar, Carpenter, Ciardi, Lane, Mighell, Millan-Gabet, Monnier, Mourard, Perrin, Quirrenbach, van Belle
YSO's	Josh Eisner	Akeson, Ciardi, Gies, Lane, Lloyd, Macintosh, Mighell, Millan-Gabet, Monnier, Probst, Swain
Exo-planets	Mark Swain	Akeson, Armstrong, Ciardi, Guyon, Lane, Macintosh, Mighell, Monnier, Quirrenbach
Crowded Field Imaging	Knut Olson	Allen, Ciardi, Guyon, Mourard, Probst
Normal Galactic Nuclei & Massive Black Holes	Tod Lauer	Allen, Eisner, Elvis, Perrin, Peterson, Surdej
AGN's & QSO's	Martin Elvis	Allen, Perrin, Quirrenbach, Swain
Distant Galaxies and Cosmology	Stephen Serjeant	
Current Generation Arrays - Current Status, Getting the Most of them, and their Further Development	Rachel Akeson	ten Brummelaar, Eisner, Haniff , Karovska, Monnier, Mourard, Perrin, Surdej, Tycner
Astrometry	Ben Lane	Eisner
Classical Array, Possibly Fizeau	Andreas Quirrenbach	
Compact Fizeau Array as an ELT alternative	Olivier Guyon	Angel, Quirrenbach, Nelson, Labeyrie, Lardiere, Le Coroller, Martinache, Macintosh, Coude du Foresto
LBT Sequel - Compact Array of Large apertures (20-20)	Roger Angel	

Sky Coverage of Interferometry and the Antarctic	John Storey	Coude du Foresto, Lloyd, Petrov, Swain, Tokovinin
Integrated Optics and a Fiber Linked Array	Guy Perrin	Berger, Labadie, Monnier
Array Facilities Operations - Lessons Learned	ten Brummelaar	Akeson, Monnier, Mourard
Future Technologies for Interferometry	Wes Traub	
Cost modeling for Arrays	Dan Eklund	Rajagopal
Working Lunch - invited talk "Science from the CHARA Array"	Hal McAlister	CHARA Staff and collaborators
Working Lunch - invited talk "Science from PTI and Keck Interferometer"	Andy Boden	MSC, PTI and KI staff and observers

In addition to the overviews, a number of breakout sessions were scheduled. Each of these had volunteers who served as "moderators and scribes", leading the discussion and bringing the recommendations back to the plenary session. The following table lists the participants in these break sessions as best they could be determined (again, imprecise at best). Each breakout session provided a set of slides with conclusions and recommendations to NOAO.

Topic	**Moderators/Scribes**	**Participants**
Stars	Hutter/Danchi	List not available
YSO's & Exo-Planets	Najita/Swain	List not available
Galaxies	Boroson/Herbst	List not available
Crowded fields	Allen/Mighell	Christou, Olsen
Future Array concepts - bright targets	Millan-Gabet/ Kervella	Carpenter, Haniff, Allen, Quirrenbach, Armstrong
Future Array concepts - faint targets	Herbst/Karovska	Glindemann, Guyon, Perrin, Olsen
An Antarctic Interferometry Program	Stencel/Foresto	Christou, Elvis, Lynds, Mighell, Rajagopal, Serjeant, Storey, Swain, Tokovinin
Current generation facilities	van Belle/Bakker/Gies	Hutter, Tycner, Akeson, Boden, Benson, Mourard, Horch, McAlister, Creech-Eakman, Monnier
Technology Roadmap	Armstrong, Bakker, Lawson	Lawson, Quirrenbach, Guyon, Creech-Eakman, Lynds, ten Brummelaar, Labadie
Science Roadmap	Monnier, Perrin, Boden	List not available

Finally, Steve Ridgway served as master of ceremonies for the workshop, and later as editor, collecting the conclusions and recommendations, formatting them into the current document, with advice and contributions from the reviewers and the breakout group leads, and finally an email review by the plenary workshop participation.

Appendix 2. Integrated Optics and Fiber-Linked Arrays (Draft 2.0)

Contributors: Jean-Philippe Berger, Lucas Labadie, John D. Monnier, Guy Perrin

Introduction: two functions for a single class of components

The idea of using single-mode fiber optics in astronomical interferometry was first introduced by Froehly (1981). Fibers are useful to transport the beams from a collecting point to a beam combiner. But spatial coherence needs to be preserved along the path, hence the use of single-mode fibers. Aside from beam transportation, single-mode fibers (and more generally single-mode waveguides, including integrated optics) also perform a perfect spatial filtering of the beams thus restoring full spatial coherence of beams at a single telescope pupil scale. The use of single-mode fiber optics was investigated by several groups in the late 80s – early 90s. The implementation of single-mode fibers in interferometers as spatial filters was successful first, beam transportation turned out to be more difficult. In the late 90s, first integrated optics components were produced for astronomical interferometry and quickly tested on the sky.

Single-mode waveguide structures

There are different geometries of single-mode fibers:

- Step-index fibers: the index of refraction is constant in the cladding and in the core (it is always larger in the core to counter the defocusing effect of diffraction) ;
- Graded-index fibers: the index of refraction varies across the core (according to a Gaussian law for example to obtain a perfectly Gaussian mode intensity distribution) ;
- W fibers: the high refraction index core is surrounded by a low-order index of refraction second core. In the same vein more complex structures are possible ;
- Photonic Cristal Fibers: the variation of index across the waveguide section is produced by structures of different refraction index (air holes or lower refraction index cylinder assemblies).

All geometries can come in two different flavors:

- Polarization maintaining fibers: a high level of birefringence is introduced in the material either with a stress or through a departure from circular symmetry for the refraction index distribution (elliptical symmetry is the most common case). The two axes of linear polarization have different propagation velocities and cannot mix (like a man would fail jumping from one train to another with a too different speed).
- Standard fibers: the birefringence is not large enough and axes of polarizations cannot be defined. For fibers with residual birefringence, linear polarizations cannot be separated and fringe contrast is degraded. It is better to use fibers which

are not birefringent or for which the birefringence beat length is far much longer than the length of fiber used. In this case, polarization planes can be rotated with Lefevre loops to align polarizations in all interferometer arms.

Most integrated optics components do not necessarily have a step-index structure. Ion exchanged on silica combiners are not step index which is one of the difficulties since the index profile is not easy to get. IO technologies span all ranges of birefringence, low and high, but are still polarization maintaining (because of the mechanical stiffness of the structure) while standard fibers have low birefringence but are not polarization maintaining.

Single-mode optics for spatial filtering and beam combination

1.1 spatial filtering: pros and cons

The purpose of spatial filtering is to clean the wavefronts collected by each telescope of an array. Wavefronts emitted by point-like sources at infinity and corrugated by atmospheric turbulence are perfectly restored by this technique ensuring maximum fringe contrast: phase fluctuations are traded against intensity fluctuations which can be monitored to calibrate interferograms. Studies of beam combiners using spatial filtering have concluded to their superiority in terms of interferometric data quality.

At the end of the data processing pipeline, interferometers produce images which are reconstructed from the visibility data. The dynamic range of the images depends partly on the accuracy of measured visibilities. Without spatial filtering, fringe contrasts are not very precise (except at low visibility since errors and biases produced by atmospheric turbulence scale with visibility amplitude) and therefore dynamic range is limited (like in speckle interferometry). This is the number one reason why spatial filtering is useful. However, one major consequence is that the instantaneous field of view is limited to a one-telescope diffraction limit angle. A larger field of view could be reconstructed by 2D-mapping of the sky as is performed at radio wavelengths but at the cost of telescope time. Another disadvantage is that single-mode interferometers may be photometrically less sensitive than unfiltered interferometers. « Incoherent photons » are filtered out by the spatial filter and are not collected. But anyway these would not contribute to the fringe pattern and the photometric sensitivity must be weighted against the usefulness of the visibilities.

An alternative to single-mode components is the classical pinhole spatial filter. It is far simpler to produce and therefore cheaper. However, it is not perfect as low order wavefront aberrations are not filtered (unless the size of the pinhole is only a fraction of the diffraction limit but then sensitivity drops). Besides, its size is fixed and does not match the diffraction pattern size inside an astronomical band, a nice property of single-mode waveguides. Filtering performances are therefore wavelength dependent.

1.2 Single-mode fibers for beam combination

There are two ways to use single-mode fibers in beam combiners. Either use the fibers to filter the beams only and feed a beam combiner (free-space/bulk optics beam combiner or integrated optics beam combiner) or use the fibers for both spatial filtering and beam combination. The second type only is discussed here as it includes functions/architectures for the first type.

Two types of fibers can be used: polarization maintaining (PM) fibers or standard fibers. Because it is hard to synchronize the two axes of polarization interferograms when using PM fibers (with a Soleil-Babinet compensator), polarizations need to be split before or after beam combination not to lose fringe contrast, even if the polarization properties of the source are not to be measured. With standard fibers, polarization planes need to be matched in all interferometer arms. This can be done by twisting fibers with Lefevre loops.

Beam combination can be performed with single-mode fiber components called directional X-couplers. X-couplers are equivalent to classical optics beam splitters. Because of the conservation of energy, the two outputs of X-couplers are $\pm\pi/2$ phase shifted. Photons are exchanged by putting fiber cores near each others along the interaction length. The splitting ratio of the coupler (usually chromatic) depends on the interaction length. X-couplers come in two flavors (although another technique is possible but losses are much larger):

- Fused couplers: fibers are twisted then heated to be fused. The mixing ratios are adjusted by monitoring exit powers and tapered is stopped when specifications are met. They have excellent thermal and mechanical stability.
- Polished couplers: claddings are polished almost down to the cores. Cores are then mechanically set close to each others and the splitting ratios can be adjusted by varying the distance between cores and the length of interaction over which the distance between cores is minimum.

Both types have excellent transmissions (few 0.1 dB losses).

X-couplers can be used for beam combination but also to sample the beams to perform an instantaneous monitoring of the beam photometry.

Other components exist: 1-to-3 couplers, fiber switches …

The simplest 2-telescope beam combiner is realized with a single X-coupler. In order to measure fluxes for visibility calibration, two X-couplers are required upstream the beam combiner coupler (FLUOR set-up). For a larger number of telescopes, several strategies can be chosen with X-couplers. Either recombine telescopes by pairs. In this case photometric couplers are no longer required as photometric signals can be recovered from interferometric signals (at least as many equations as unknowns for more-than 3-telescope interferometers, example: the IONIC beamcombiner at IOTA). Or perform an all-in-one recombination with all interferograms on a same coupler output. In this case photometric couplers are required because there are less equations than unknowns.

X-couplers are a few centimeters to about 10 cm in size. Since the complexity of a beam combiner increases with the number of telescopes squared for co-axial beam combination, the size of beam combiners based on X-coupler technology dramatically increases with the number of telescopes. In this respect, integrated optics technology is very promising for large interferometric arrays.

Since fibers are intrinsically dispersive, differential dispersion needs to be cancelled in the beam combiner. For short fiber lengths, this is equivalent to matching fiber lengths. However, fibers and couplers may not be homogeneous and an interferometric measurement is required. Dispersion can be matched alternating lab interferogram measurements and fiber polishing. Excellent performances are obtained with this method (differential dispersion-free beam combiners).

Another drawback of fiber couplers for beam combiners is the potential internal OPD drifts (need for temperature stabilization) which change the zero point of closure phases and require regular calibrations.

1.3 Integrated optics for beam combination

There is no fundamental difference between integrated optics (IO) and step-index fiber optics waveguides. The difference is about the functions that can be performed with IO and the compactness of components hence their smaller space envelope and increased stability.

IO components are much more versatile than fibers. Basically all functions that can be designed with classical optics can have an IO version. Therefore, all beam combination geometries are *a priori* possible with IO components :

- Co-axial with X (2 inputs, 2 outputs) and Y-couplers (2 inputs, 1 output, 50% loss), either pair-wise or all-in-one combinations ;
- Multi-axial: the fringe pattern is formed at the focus of a camera ;
- Co-axial with fringe pattern phase spatial multiplexing (e.g. ABCD samples can be simultaneously read at the output of the beam combiner) ;
- Multimode interference structures which allow a static (i.e. without modulation) encoding of the complex visibilities (same family as ABCD but very different principle).

Up to now 2-telescope and 3-telescope beam combiners have been successfully tested on the sky. 4 to 8-telescope beam combiners have been produced or are being designed. Multi-axial beam combiners for a large number of telescopes are easier to design compared to co-axial beam-combiners. However, for more than 8 beams mixed concepts (fibers feeding a focusing optic) such as the Michigan InfraRed Combiner could be interesting compromises a IO will probably never follow more than 8 beams. For the co-axial beam combiner type, difficulties are twofold. First, waveguide lengths have to be matched to ensure zero differential dispersion in wide band which is a strong constraint in a limited space. Paths can be equalized to a precision of the order of a micron. Second, as a consequence, crossing of waveguides cannot be avoided causing cross talks between channels. Cross-talk is minimized by imposing large angles at waveguide intersections. For these reasons, the design of components for a large number of telescopes is difficult and multi-axial beam combiners may be preferred in this specific case. To ensure maximum transmission of the IO component, the design has to be as compact as possible.

Currently sky-tested IO beam combiners are silica-based. There are two technologies using silica substrates : ion exchanged (gradient index) and doped silica etching. These are industrially mature but different technologies. An alternative technology for near-infrared wavelength ranges, especially longward of 1.8 μm, is lithium niobate. Complex circuits are available but tests for astronomy are still in their infancy and R&D is on-going.

In practice, IO chips are fed with single-mode fibers glued at the waveguide input. The fiber mode and the IO mode are well matched and injection losses are very low. Current transmissions in the H band are as good as 70-80% for the whole beam combiner (respectively 4 and 2 way beam combiners).
IO components may be birefringent. But polarization splitting is not absolutely necessary since the phase difference between the two linear polarization interferograms can be made very small with highly symmetric beam combiners and since the birefringence property of the chip is very stable. Polarization splitting may be safer to ensure high level and high stability contrasts if (polarization maintaining) fibers are used to launch light in the OI component since the relative phase between polarization axes in the fibers are likely to be temperature dependent.

Compared to near-IR components, integrated optics for λ above 5 μm is only emerging. Single-mode planar structures and channel waveguides have been successfully tested at 10 μm and seem promising. They are based on hollow waveguides (Hollow Metallic Waveguides, HMW) and on chalcogenide glasses. The concept of HMW is more promising at $\lambda \geq 10$ µm since the attenuation factor theoretically decreases when the cut-off wavelength increases (and thus the waveguide transverse dimension), but the average propagation losses remain nevertheless high, which makes this solution more suitable for modal filtering only. Although no beam combination capability with mid-IR IO has been demonstrated so far (Dr Winnick's successful attempt to design lithium niobate combiners operating at 3 microns ?), it is likely that a future IO combiner will rely more on dielectric materials. For instance, chalcogenide-based solutions offer a better perspective in terms of transmission despite the cut-off of the material is below 20 μm. Channel rib-waveguides etched on telluride chalcogenide films have been successfully characterized at 10 µm and their development is encouraging. Single-mode planar structures (1-D waveguide) in ZnSe/ZnS (zinc selenide) have been manufactured too, but the technology to etch channel waveguides is less mature than for the chalcogenide solution. The option of using silver halide substrates to manufacture IO has not been considered so far.

1.4 Wavelength coverage

Apart from hollow waveguides whose transmission is essentially limited by the roughness of the cavity, the transmission of single-mode material waveguides is limited by :

- Absorbers
- Raleigh scattering
- Micro cracks
- Core inhomogeneities
- Bends

Absorbers and scattering are intrinsic to the material. Micro cracks, core inhomogeneities and bends are more a process and use issue. Bend losses can be reduced by either imposing waveguide straightness or a wavelength range close to the cut-off wavelength above which the waveguide is single-mode (in practice the range is [λ_{cut}-2λ_{cut}] for waveguide lengths of a few meters).

A limit on transmission can be set to 50% (considering it is an acceptable level of throughput for beam combiner). Fiber based beam combiners need on the order of 5 m of fibers at most. The fiber transmission requirement is therefore 0.6 dB/m. IO beam combiners have characteristic lengths of 5 cm and the average transmission requirement is 0.6 dB/cm (most losses are due to complexity as pure propagation losses at H are more 0.05 dB/cm).

The attenuation of silica from the blue to 1.8 μm is better than 10 dB/km and this material can be used for both integrated optics and fiber technologies with the 50% transmission criterion. Plastic fibers are available in the visible domain (0.5 dB/m for multimode fibers at 650 nm) but need to be evaluated for astronomical interferometry. It is likely that silica be a better material anyway.

Above 1.8 μm, attenuation increases dramatically in silica. Although silica can still be used for IO (but components need to be short in length), better transmissions are likely to be obtained with lithium niobate IO components (0.2-0.4 dB/cm). fluoride glass fibers are required for fiber beam combiners. Fluoride glass has a transmission better than 0.1 dB/m up to 7 μm.

Above 7 μm (up to 30 μm), special glasses and technologies are required for fibers. Depending on the material, these samples could partially or fully cover the M and/or the Q band in addition to the N band. Single-mode fibers based on chalcogenide and silver halide materials present transmissions of few dB/m, with increasing experience on the fabrication technology in the last years. Silver halide materials can transmit up to 30 μm. Chalcogenide glasses can transmit up to 18 μm, depending on the material composition (selenide, telluride, AMTIR…). Those materials also present a good transmission below 5 μm and could thus also be considered for M band applications. Single-mode photonic crystal fibers are also investigated for spatial filtering, but the fabrication technology is only emerging. Hollow waveguides are another possible solution: hollow waveguides are already commercially available with core sizes of about 300 µm, but single-mode behavior requires core sizes of the wavelength scale (~10-20 µm) and the technology is only emerging too. Metallic waveguides present interesting properties of polarization maintaining due to their rectangular or square shape but their propagation losses, which are practically due to the roughness of the metal, are high and they can likely be used only over very short distances for spatial filtering. Concerning fiber Y-couplers, successful attempts to produce silver halide samples operating at 10 μm were obtained by assembling and pressing half-shaved unclad AgClBr. The technique was implemented with 900-µm core fibers (multimode in the mid-IR), and becomes thus more difficult when transferred to single-mode fibers.
In summary, some first basic questions on the technological feasibility side have been

positively answered for both mid-IR fibers and IO and further work should help in improving the performances.

As a general concluding remark, materials with intrinsic low attenuations may be available for a wavelength range but the process to make a single-mode waveguide is very likely to degrade this intrinsic performance. The quoted attenuations above are usually for single-mode waveguides, not for the material.

Beam transportation with single-mode fibers

The specifications on fibers for beam transportation are quite simple:

- High throughput over several tens of meters: a minimum can be set to 10% (attenuation of 10 dB) between the telescope focus and the delay line input point (the global efficiency of long baseline interferometers is about 1% or less);
- Very low differential dispersion to obtain high contrast fringes (set to 70% as SNR scales as V^2) ;
- Very low differential polarization to obtain high contrast fringes (set to 70%);

1.5 Wavelength coverage

Only two types of fibers can be used to meet the above specifications, silica and fluoride glass fibers:

- Silica fibers in the 400 nm – 1 μm range: attenuation decreases from 100 dB/km down to 2 dB/km (exponential decrease towards the ultraviolet edge) ;
- Silica fibers for the J and H bands: minimum attenuation of about 1 dB/km
- Fluoride glass fibers for K (and L band): potential attenuation of 3 dB/km (current ‘OHANA fibers: 9 dB average attenuation across the K band) ; no real data for the L band.

Kilometric baselines in the visible are not possible except for the very upper end of this wavelength range and with theoretical transmissions of 10% at best. Hectometric baselines are possible even at short wavelengths.

Kilometric baselines are possible at near-infrared wavelengths (J, H and K bands). A 10 km baseline is a limit at J and H and not possible with current characteristics of fluoride glass fibers at K.

1.6 Polarizations

The same conclusions as for beam combiners apply here. The safer solution is clearly to use polarization maintaining fibers for polarization splitting at the output. Use of standard fibers is possible (and demonstrated with ‘OHANA between the two Kecks). However, the beat length of birefringence has to be much larger than the length of the fiber cables. In practice, for kilometric baselines, beating lengths of at least 3 kilometers are required ($2\pi/3$ phase shift between two polarizations over a kilometric distance and a 50% contrast loss).

1.7 (Differential) Dispersion

Dispersion is a shorter form for chromatic longitudinal dispersion, i.e. a wavelength dependence of the zero optical path difference. There are two major sources of dispersion in a fiber: material dispersion (the dispersion of the glass) and waveguide dispersion, a third source of dispersion is negligible in practice. In some instances, material and waveguide dispersions have opposite signs across a given astronomical band. Theoretically, intrinsic dispersion could therefore be cancelled but this requires a very accurate adjustment of fiber parameters (for example the core diameter needs to be adjusted to nanometric precision). The same theoretical prospect exists with PCF fibers but the constraints are as stringent as for classical fibers.

Nowadays fibers are therefore intrinsically dispersive. The consequence on the design of fibered interferometers is that dispersions of all fiber arms must be matched. A corollary is that all fiber lengths have to be roughly equal even if baseline lengths are different if all baselines are to be measured simultaneously.

Dispersion matching would be easy if fibers were homogeneous. Unfortunately, fiber cores are slightly conical along a long fiber length. Or fiber core diameters may be oscillating along the fiber cable. Length matching is therefore not enough although it provides a very good starting point for dispersion matching. The technique to match dispersion is therefore to compensate the residual differential dispersion by adding a few centimeters to tens of centimeters of fiber (compensation cables) to the less dispersive fiber and cut/polish until dispersion is minimum. Excellent results have been obtained over 300 m with fringe contrasts larger than 96% in the K band with single-mode fluoride glass fibers. The same fibers used in autocollimation (propagation length is doubled) still provide contrasts larger than 90%.

Although intrinsic dispersion is an issue, differential dispersion can be cancelled. The issue however still holds if unequal lengths of fibers are required to build delay inside fibers.

1.8 Sensitivity to temperature and vibrations

Single-mode fibers are well-known as … high sensitivity sensors ! They are indeed extremely sensitive to temperature and mechanical stress.

Sensitivity to temperature has been measured in the framework of the ‘OHANA project for both silica and fluoride glass fibers. Measured characteristics are very close. The fibers expand at the rate of 2 mm/°C/150 m in OPD. The change of fiber length with temperature induces both a shift of the ZPD and differential dispersion. Differential dispersion and OPD shift can both be compensated by mechanically expanding a fiber wrapped on a variable diameter cylinder. Another counter measure consists in servoing the fiber temperature.

Sensitivity to vibrations has also been measured during ‘OHANA tests at Keck. The elasticity limit of a fiber ranges between 0.1 and 1% meaning that every millimeter of fiber may vary in length by a few microns even at rather high frequency. In this respect, a fiber is a mechanical antenna. A solution to this issue is mechanical insulation. Another solution is to servo the fiber length with a high band pass metrology system.

This should not be an issue for future interferometers for which fibers could be integrated in the design right from the beginning.

1.9 Metrology and astrometry

Differential astrometry can be performed with a fibered interferometer as long as fiber lengths are monitored with a metrology system. There is no particular drawback to do this with fibers. A dual beam module is required to feed the two fibers with two different objects, a reference source and a target source. Two independent fibers can then be used. An alternative solution is to multiplex the two source signals in a single fiber either using two orthogonal polarization axes or two half bands in a given astronomical band. The second solution may suffer from difficulties to properly calibrate chromatic dispersion effects.

The same system can be used to servo the science target fringe position using the reference source fringe pattern to allow for long integrations.

Delaying beams with single-mode waveguides

1.10 Fast fringe modulation

Short delays (up to a hundred microns) are easy to achieve with single-mode fibers without damaging the fringe contrast (~ $5x10^{-5}$ fringe contrast loss). Wrapping the fiber on a piezo cylinder, a fast fringe modulator can be built (kHz fringe modulation in the near-infrared).

Lithium niobate modulators can be used for at least 10 μm modulation and probably more. With modulation frequencies can be higher than 1 Mhz.

1.11 Long stroke delay lines

Long stroke delay lines are currently not within reach in wide astronomical bands. Differences of 50 mm and 200 mm in fiber lengths induce fringe contrast losses of respectively 10 and 50% with realistic fluoride glass fibers in the K band. Zero intrinsic dispersion fibers are therefore mandatory for this purpose. Or another trick needs to be discovered…

Fiber linking existing and future telescope arrays

Current telescope sites are at most kilometric in size. Technology is mature for interferometric linkage of telescopes with fibers. A first result was achieved in the K band with the two Keck telescopes linked with 2x300 m of fiber (as if they were ~ 500 m apart with the beam combination station in the middle). However, classical delay lines are required and it is necessary to get out of fibers before beam combination thus causing sensitivity losses. One of the difficulties with current facilities is to use existing conduits which may be subject to vibrations and temperature vibrations. Also, using telescopes not specified for interferometry and not identical may cause extra difficulties such as extra dispersion due to different transmissive optics that has to be compensated. Using fibers for future interferometric facilities should be easier as the design of these facilities can be made compliant with the use of fibers.

The prospect of PCF fibers is interesting in both contexts. First, a single PCF fibers can cover several astronomical bands as long as this is compliant with transmission specifications. Second, if non-zero dispersion PCF fibers are produced an all-fiber solution will be possible potentially making interferometers far more sensitive.

Conclusion and recommendations

1.12 What has been achieved so far

The field has been very successful with beam combination and with the demonstration of the gain brought by spatial filtering techniques : 2-, 3- and 4-telescope single-mode beam combiners are (or have been) operated on the sky at visible and near-IR wavelengths from 0.8 through 4 μm.

Linking telescopes with fibers is still in its infancy with a first result using the two Keck telescopes in the K band.

Single-mode components for spatial filtering are commercially available in the visible and in the near-infrared domains. Nice efforts have been made in the thermal infrared to provide such components in the framework of the NASA and ESA programs to detect and characterize exoplanets by interferometry.

1.13 Prospects

1.13.1 Technology

Some progress need to be made with the technology for astronomical applications. Most components have been produced for the telecom industry for which specifications on transmission and photometric band pass are far less stringent than for the more photon-starved astronomy.

1.13.1.1 Spatial filtering

Some new windows have been opened for astronomical needs towards mid-infrared wavelengths for fibers, integrated optics (at least attempts) and hollow waveguide technologies. Some progress is clearly to be made to improve the throughput at these wavelengths so that transmission should not be a concern for the use of these components. For both mid-IR fibers and IO, future work should also help in gaining a more global understanding of specific issues like polarization properties, crosstalk, and sensitivity to external constraints. These effects, that play a role at a higher level in the performances of the component, should be investigated once the manufacturing technology is completely mastered.

1.13.1.2 Beam combination

The main challenges are the extension of the number of telescopes at visible and near-infrared wavelengths (4 to 10) and the design of beam combiners at mid-infrared wavelengths. Directional coupler-based solutions are an alternative to integrated optics up to 5 μm. Design of compact solutions should be contemplated to reduce the space envelope of instruments and allow for cryogenic use (the number of couplers scales as the squared number of telescopes). Integrated optics may be preferred in general as instruments are necessarily more compact and more stable. The multi-axial design for beam combination may a priori turn out to be an easier path to achieve large number of telescope combinations. However, beam sampling for photometric calibration requires as many couplers as the number of telescopes. Although the scaling law is more favorable than for co-axial designs, cross-talk issues and therefore the component size issue should not be overlooked. These same conclusions apply for the co-axial design.

The design of dichroic components should be investigated to merge beam combination and metrology. Higher sensitivity (through reduction of complexity) and higher astrometric accuracy are at stake here. The main issue, besides component complexity, is the high crosstalk between the metrology channel and scientific channels as the metrology signal may be far more powerful at the launching point than the incoming science signal. The issue is not easy to solve as the metrology wavelength needs to be in the single-mode domain of the component. Very selective components are therefore needed with chromatic attenuations of several hundred or thousand dBs.

Another potentially interesting lithium niobate IO component feature is electro-optics phase modulation for fast fringe tracking without any moving part in the interferometer. OPDs of 10 μm have been generated and frequencies larger than 1 Mhz can be achieved.

1.13.2 Beam transport - transmission

The use of fibers for beam transport is primarily limited to the near-infrared and the upper part of the visible domain. Silica fibers could potentially have attenuations as low as a few 0.1 dB over a kilometer (pure material transmission). Some efforts should be attempted to improve the current attenuations to this level to either increase the transmission of kilometric interferometers or to allow contemplating 10 km interferometers and reach a few tens of μas angular resolution (current goal of millimetric VLBI). Fluoride glass fibers can also be improved to the same level of transmission (reach at least 1 dB/km). In either cases, actions have to be taken with the industry to improve the transmission of fibers. It is primarily a homogeneity and quality issue of waveguides and better control procedures must be developed in the fabrication process. Development of PCF fibers should be continued for astronomy as they potentially would allow to decrease the number of fibers for a wide wavelength range utilization of the interferometer (currently one fiber cable is required per astronomical band).

1.13.3 Beam Delay - dispersion

Long delays are currently impossible because of dispersion. Should fibered beam delay be the solution to long baseline interferometry, close cooperation with industry is required here. Non dispersive fibers exist in theory. But the realization process is not accurate enough for such components: the nanometer level in waveguide structure accuracy is required over hectometric to kilometric lengths, be it with classical step-index fibers or with PCF fibers.

This requirement may turn out to be very difficult to achieve in the end and alternative strategies may be investigated that would be compliant with the use of dispersive fibers. These strategies may include the use of free-space delay lines. But progress has to be made on the design of these to increase their transmission (vacuum operation and minimum number of reflective optics).

1.13.3.1 Signal amplification

The telecom industry has developed repeaters to amplify signals in single-mode fibers. These would of course be of interest for astronomical interferometry if applicable. They work in very narrow band passes (laser) and not in wide astronomical bands. Besides, they (probably) require large numbers of photons and are not efficient in amplifying few photon signals (TBC). Recommendations on this are difficult to make since there may be little hope for success. C. Townes demonstrated that heterodyne interferometry was only relevant longward of 10 μm.

1.13.4 Instruments

The main question here is: should a fibered interferometer be considered a serious option for a future large facility ? The transmission of current interferometers is quite low (~ 1% at most for the coherent flux of an unresolved source). Single-mode fiber links potentially have higher throughputs (first ‘OHANA tests at Keck were very promising in this respect with transmissions of the same order despite cloudy conditions and far too long fibers). But transmission of free-space propagation interferometers may be improved with better designs with far less mirrors and with vacuum beam transport. If transmissions are comparable in the end, fiber links still require less infrastructures. The two designs must therefore be compared in terms of sensitivity, infrastructures, data quality and wavelength coverage.

The issue of building delay in fibers has to be seriously considered as it is currently a splinter for all-fiber solutions. But it may not be a show-stopper as alternative solutions exist.

Linking existing telescopes with fibers in the ‘OHANA way may be considered as a shorter term option

Appendix 3. Current generation arrays: current status, getting the most out of them and future development,

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Executive summary

The scientific and technical success of the current generation of optical/infrared interferometers is an essential step in the road map to the next major facility. We make specific recommendations in the areas of efficient observations, data tools and archives, collaborations and attracting new users. The overall conclusion is that in balancing the division of resources over the next several years, sufficiently funding the current arrays must be a high priority.

1 Introduction

This paper describes the status of currently operating optical and infrared long-baseline ground- based interferometers, estimates their current usage, discusses how to get the most from existing facilities and the priorities for further development. One of our specific goals was to identify the most pressing issues and questions for the larger community to address. Where specific examples are given, there is a bias towards facilities that the authors are familiar with and no slight is intended toward other facilities or groups. A related set of issues on lessons learned from the current facilities is addressed in the working group led by T. ten Brummelaar. In this paper, we do not attempt to survey the current technical status and planned upgrades to existing arrays; we refer the reader to the literature, in particular the most recent SPIE proceedings (vol. 6268), and the facility websites, for this information.

2 Status of existing and upcoming facilities

For the purposes of this paper, we define existing facilities as those which have produced a peer- reviewed paper and are still operating (or were operating within the last 2 years) and we define upcoming facilities as those expected to be operational within 5 years. The last column indicates the level of community access to the facility, where “collaboration” indicates that a single or multiple groups operate the facility and community members generally gain access through collaboration and “open”, which designates that at least one large community can propose through a widely advertised, open call for proposals, with no contribution, other than observing, required. In general, the collaboration facilities offer more opportunities for direct instrumentation involvement, while the open facilities offer more observing opportunities to the wider community, but both types are important for the future of the field.

Current Arrays

Short Name	Long Name	References	Access
CHARA Array	Center for High Angular Resolution Astronomy Array	ten Brummelaar et al. 2005 (ApJ, 628, 453)	Collaboration
COAST	Cambridge Optical Aperture Synthesis Telescope	Baldwin et al. 1996 (A&A, 306, L13)	Collaboration
GI2T	Grand Interférometre á deux Télescopes	Mourard et al. 2001 (C.R.Acad.Sci. Paris, t2, S. IV, 35)	Closed
IOTA	Infrared Optical Telescope Array	Dyck et al. 1995 (AJ, 109, 378)	Closed
ISI	Infrared Spatial Interferometer	Bester et al. 1990 (Proc. SPIE, 1237, 40)	Collaboration
KI	Keck Interferometer	Colavita et al. 2003 (ApJ, 592, L83)	Open
MIRA-I.2	Mitaka IR Array	Yoshizawa et al. 2006 (Proc. SPIE, 6268, 08)	Collaboration
NPOI	Navy Prototype Optical Interferometer	Armstrong et al. 1998 (ApJ, 496, 550)	Collaboration
PTI	Palomar Testbed Interferometer	Colavita et al. 1999 (ApJ, 510, 505)	Collaboration
SUSI S	ydney University Stellar Interferometer	Davis et al. 1999 (MNRAS, 303, 773)	Collaboration
VLTI	Very Large Telescope Interferometer	Schöller et al. 2006 (Proc. SPIE, 6268, 0L)	Open

Upcoming Arrays

Short Name	Long Name	References	Access
LBT	Large Binocular Telescope	Hill & Salinari 2004 (Proc. SPIE, 5489, 603)	Open
MROI	Magdalena Ridge Observatory	Creech-Eakman 2006 (Proc. SPIE, 6268, 1V)	TBD
OHANA	Optical Hawaiian Array for Nanoradian Astronomy	Perrin et al. 2006 (Science, 311, 194)	TBD

3 Getting the most out of them

The current arrays have many individual goals, but their success is vital for the continuation and expansion of optical interferometry. Here we discuss several areas that we can address as a community.

3.1 Efficient operations

With multiple telescopes, electro-optic servos, and control systems that all interact, optical interferometers present a big maintenance challenge. Combine this with the constant pressure to upgrade systems and performance and there is the potential for conflicts between science operations, maintenance and development. Within science operations, there exists a range of user needs – from the expert observer who needs the basic systems working so that the facility can be pushed in other ways, to the new user, who needs the system to be reliable.

While systems that break down or develop problems must be fixed, it is important to build engineering time into the observing schedule explicitly, rather than in an ad-hoc manner. This helps ensure that science time is not lost to new and incompletely tested systems, and also that engineering teams have focused goals and test schedules.

For the interferometers run by smaller groups, many of the operations inefficiencies are the result of a shortage of staff, both during the day and during the night. For an array to operate with a minimum of down time there needs to be adequate day and night staff. If daytime staff are required to spend most of their time repairing systems when they break down, or are constantly required to change configurations, little new development work will take place. Similarly, inadequate night (i.e. observing) staffing will severely hamper the scientific productivity of the facility.

Recommendations:

1. Current and planned facilities should aim for and (where possible) budget for adequate staffing levels for both day and nighttime operations.
2. There should be a dividing line between science using existing capabilities and engineering time used to develop new capabilities. This must be explicitly built into the schedule and into the user expectations.
3. The observing schedule needs to take into account array configuration changes that may be necessary between projects.

3.2 Data tools

Here we briefly review the tools available to the optical/infrared interferometry community, concentrating on those tools that are sufficiently generalized for use at more than one facility. This list is not complete and many other useful packages exist and are in use.

3.2.1 Planning

This category covers a range of tasks, from selecting calibrators to detailed planning of observations within a night. Selecting calibrators is sufficiently detached from instrument details that a general package can be used at many facilities. Two such packages are widely distributed: SearchCal and getCal. SearchCal (Bonneau et al. A&A, 456, 2006) is distributed by the Jean Marie Mariotti Center[3] (JMMC) and identifies potential calibrators from requests to online catalogs, accurate estimations of angular diameters and use of various selection criteria (magnitude, angular distance, variability…) and then predicts visibility quantities from the target properties and interferometer configuration. getCal is distributed by the Michelson Science Center[4] (MSC) and uses the Hipparcos catalog and a strategy of selecting calibrators based on matching location, flux and estimated angular size, using the Hipparcos astrometric information to select against stars likely to be problematic at milliarcsec size scales. There are also single facility packages such as CHARA_PLAN[5]. It should also be noted that a community effort already exists for the maintenance of a 'bad calibrator' database[6].

3.2.2 Data reduction and calibration

There are several required steps in processing raw fringe data to completely calibrated visibility products that can be used for astrophysical modeling. Here we will describe these steps as reduction (removal of detector characteristics, performed on individual sources) and calibration (removal of instrument and sky characteristics, performed between sources), although we recognize that many packages perform both these steps.

Due to substantial differences in hardware and operational procedures, the reduction of raw data into fringe amplitudes is generally done by software written specifically for that instrument and observatory. These differences also mean that it is unlikely that standard programs for the first level of data processing are likely to be developed or widely utilized.

For the data calibration step, there are currently packages distributed for the VLTI instruments[7] (MIDI and AMBER) and for KI and PTI by the MSC. In both cases, the calibrated data can be output in the OI-FITS format[8] (Pauls et al, 2005) which greatly facilitates data exchanges between groups. The input formats are also sufficiently well documented that it is possible to use them on data from other observatories.

3.2.3 Imaging

Several of the existing arrays produce data that can be used for imaging. Although this area of optical interferometry is only just beginning, it may be one of the keys for expanding the user community as astronomers not interested in learning the details of the technique are probably willing to work with even limited imaging if it has bearing on

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[3] http://www.mariotti.fr
[4] http://msc.caltech.edu
[5] http://www.noao.edu/staff/aufdenberg/chara_plan/
[6] http://www.astro.lsa.umich.edu/~monnier/calib.html
[7] http://www.eso.org.vlti
[8] http://www.mrao.cam.ac.uk/~jsy1001/exchange

their areas of research.

Unlike radio and millimeter interferometry, a standard software package for imaging has not yet been adopted by most of the optical interferometry community, but progress has been made, as can be seen in the "Beauty contests" organized by P. Lawson and presented at the 2004 and 2006 SPIE conferences (Lawson et al., 2006, SPIE vol. 6268; Lawson et al., 2004, SPIE Vol. 5491). These references contain a description of the groups involved and the deconvolution methods used.

3.2.4 Data modeling and visualization

The astrophysical modeling of calibrated visibilities is an area where common packages would be most useful as at this point, all instrument characteristics should have been removed by the calibration step. Several groups are developing packages and this area has good potential for collaborations. An example of a general package to visualize data in the OI-FITS format is described by Thureau et al (2006, SPIE vol. 6268).

3.3 Data availability and archives

The advent of easily searchable databases of astronomical data greatly facilitates the use of data not only by the original investigator, but also by other astronomers, often for other scientific goals. However, establishing a database requires significant effort in data standardization and documentation and is most useful to the wider community if data are publicly available. To date, two groups have archives with data accessible to the community, ESO's VLTI archive and the MSC's KI and PTI archive. An additional resource is the CHARM catalog of angular size measurements, many of which were obtained with interferometric observations (Richichi et al, 2005). Some published, calibrated data is available in OI-FITS format7.

Recommendations (Data tools and archives)

1. Whenever possible, data tools should use existing standards for input and output formats.
2. All user tools should have documentation adequate for new users.
3. The community should examine ways to collaborate on new tools that can be used with data from many facilities.
4. Create a central list of available tools and data.
5. More current arrays should consider making older data available to the general community.
6. Compile a list of speakers available to give science talks.

7 http://olbin.jpl.nasa.gov

3.4 Fostering collaborations between groups

Besides the obvious scientific advantages such as UV, temporal and wavelength coverage, there are many good reasons why there should be more collaborations between groups. Many of the existing facilities are under staffed and over subscribed, and it could be that collaborations will help alleviate these problems. Furthermore, in an environment of reduced funding, collaborations can help spread the financial burden of developing new subsystems and observing techniques. It is interesting then, that while they are becoming more common, these sorts of collaborations have not, in the past, been very numerous. Perhaps if we can find out why we have been unwilling, or unable, to form these collaborations we can work out how to move forward. In order to foster collaboration, we need to find ways to get the best leverage out of existing facilities by finding good matches between each group's needs and resources. That is, we need to identify what expertise or equipment each group has that may help move another group forward.

There are many good examples of collaborations throughout the community; here we discuss a few with which the authors are familiar. One example of collaboration is the agreement between the MSC and CHARA. MSC is able to provide some financial support, and a great deal of hardware and operational experience. For example, the MSC has been contributing to development of a second camera (originally in service at IOTA) that would have been very expensive in either man power or money, and will result in doubling the observing efficiency of the CHARA Array. This in turn frees up more observing time for both groups. We need to identify other ways for us to share existing resources, and in particular identify skills and resources available in each group and what each group may lack.

Collaborations are also an ideal way for university groups, which play a vital role in bringing students into the field, to become involved at existing arrays. These collaborations could involve contributions of instruments, other technical expertise, personnel or financial resources, software or strictly scientific work. Now that many interferometrists have spread beyond the group where they learned interferometry, many more universities have knowledgeable resident faculty. Once facilities are fully functional and most of the time is scheduled for observing, the collaboration possibilities may evolve from mainly technical to mainly scientific, but the scientific collaborations are equally valuable.

There has also been what one may call a healthy amount of competition between the existing groups. Each wishes to be the first to achieve a new observing mode, wavelength regime, sensitivity, or baseline length. This can be said to have lead to a reluctance to join forces with those whom you regard as your competition. At some level, competition can help push the pace of development, but often it is not productive. Images have been made, large baselines are operational and wavelengths from 440 nm to 11 microns have been successfully used to produce scientific publications. Clearly, there are still many improvements to be made, but we need to find a way to get over any "us and them" feelings that still exist.

With the exception of the VLTI and KI, interferometry groups have tended to be small and built around a group at a single institution. This has meant that there is often a core group of scientists working for many years to fund, design and build an instrument, resulting in an understandable desire to keep the best science targets to themselves once the machine is operational. This is only fair, but eventually these feelings have to be overcome at some level.

Collaborations work best when each party brings value to the table, and each party feels they have adequate access to the scientific output of the facility. This can be a difficult balance to achieve, but not impossible. In the end, the management and structure of the collaboration will determine, to a large extent, its success. We should identify successful existing, or past, collaborations and see if that model has more general application in the community.

Recommendations

1. The community should construct and maintain a list of existing facilities, resources and expertise in the hope of identifying how best to bring these together.
2. Competition between groups will not cease, but we need to remind ourselves to look beyond that towards how we might improve the field in general.
3. A balance must be found between our obligations to our individual institutions and those to the community at large.
4. Existing successful collaborations may provide a good model for how to proceed and manage future, possibly larger, groups.
5. The larger and better-funded arrays such as KI, VLTI and the arrays under construction should consider providing the capability to host visitor instruments, with well defined interfaces and operational guidelines, which would allow smaller groups to participate directly in these facilities.

3.5 Attracting new users

There are many reasons for the limited community of optical interferometry users and there are many levels of users, from those who construct and operate facilities and instruments, to expert observers, to scientific investigators who have specific astrophysical questions and are not interested in how the technique works. To survive and expand, optical/infrared interferometry must attract all categories of users. In this section, we address the non-expert users. Here we list some of the more common reasons given by our astronomical colleagues as to why they don’t use optical interferometry.

- The instruments are not sensitive enough. This is probably the most fundamental barrier and will only be solved with future development and facilities. However, in the near- term we can focus on astrophysical problems where the current facilities are relevant.

- Optical interferometry is inefficient and the observations are too complex. This relates back to several issues discussed above: operations need to be efficient to maximize the science programs and there need to be tools available for non-expert users. The ability to make even limited images would attract more users by potentially removing much of the data complexity for the end users (if the tools are adequate).

- The perception that optical interferometry has not produced major results, only confirmed existing theories. While “major results” may be in the eye of the beholder, there are certainly many results that test between theories or contradict standard ones.

Recommendations

1. Develop imaging capabilities where possible and publicize current imaging results.
2. We must continue to interact with our colleagues at scientific meetings (not just technical ones) to make them aware of outstanding interferometry results.
3. Construct a downloadable database of high profile science results that speakers can use.
4. Existing facilities should consider making a small portion of observing time available to users from outside their “normal” user group if there is a strong chance for interesting science results, even if the new users do not become expert observers.

4 Further development

In addition to deciding on a long-term direction and strategy, the community needs to consider the medium term (5-10 years) and what facilities will be available for technical pathfinding and scientific use. The arrays listed in Table 1 are a mix of recently completed, nationally and internationally supported facilities with planned lifetimes of decades and smaller, university or collaboration run facilities that may only operate for a few more years. We assume that many of these facilities will continue to develop new capabilities and extend their sensitivity and resolution, but it is not the purpose of this document to list or guide those developments.

4.1 Trade-offs between support of existing facilities and developing new ones

This is a critical issue for the community over the next few years. We need to balance support of the existing facilities, which produce scientific results and attract new users to the field, with development of new technologies and facilities, which will expand the scientific questions which can be addressed. We recognize that in many cases, these decisions are driven by the realities of different goals of the funding agencies but it is still useful to consider the big picture.

1. What is the appropriate number single institution/collaboration and national/international facilities which should be supported? If we judge from the comparison to millimeter interferometry (see below) the answer to this question is fewer than are currently operational. However, as a community we should be careful that any closures result in more resources for the remaining facilities, rather than just fewer facilities available for use.

2. To increase the visibility of optical interferometry, how should efforts and

resources be divided between producing unique astrophysical results, operating current facilities for existing and new users and developing new capabilities at current and new facilities? More resources for the existing facilities may be tied to open access for the astronomical community as the most likely sources for significant operational funding would desire or require this. However, this would help both operations and science results.

3. Where are the best opportunities for collaborations between groups within the optical interferometry community and with other astronomy groups: hardware development, joint operations, software development. To best use the limited resources available, the existing groups should agree on a set of milestones necessary to achieve the goal of next large facility. Existing facilities and groups can contribute to these milestones as their expertise and resources allow, trying not to duplicate too much effort between groups.

5 Summary

In this white paper, we have tried to identify the relevant issues for the current optical/infrared interferometers in discussions of what comes next for the field. In several areas, we have direct recommendations. As we look forward to the next level of development in our field, it is instructive to consider millimeter interferometry, which was in a similar position many years ago, but now is constructing a major international facility (ALMA) with broad community support. For many years there were several, mostly university-based interferometers with somewhat overlapping capabilities, but each with its own strength. Each facility worked to expand their technical capabilities, but also worked to expand the millimeter community through support of student work and a substantial amount of time made available to the broader community through open proposal calls. Gradually the community expanded and millimeter interferometry became recognized as a crucial technique for the study of many astrophysical fields, from our own solar system to cosmology. Some important differences between the millimeter arrays then and the optical arrays now are: only 4 millimeter arrays were fully operational previous to the approval of ALMA, each of these facilities was considerably better funded than most optical arrays (see lessons learned report), each gave substantial observing time to the general community, and even at the earliest development stages, these arrays produced images which non-experts in the astrophysical community felt competent to interpret. The optical and infrared arrays are in the position to address the last two points immediately: we can open more facilities to all users and we can emphasize imaging development.

In order to convince our colleagues in the broader astronomical community that optical/infrared interferometry is worthy of major investment of resources in the environment where resources are becoming more scarce, we must be viewed as successfully completing and operating the current generation of interferometers. This success does not necessarily mean that interferometry can address every topic of astrophysical research, but that we contribute substantially to a number of areas in proportion to the resources currently used. Over the next 5-10 years if the current generation of arrays are not well funded in order to finance future project, the overall effect on optical/infrared interferometry will be detrimental. The interferometry community needs to work together to increase the scientific output of the current arrays through better operations, further development and increasing the interest in the community. One important attribute of optical interferometry that we should continue to remind our colleagues of is: Even in the era of twenty to thirty meter telescopes, long-baseline optical and infrared interferometry observations will provide the highest angular resolution and that in the past, whenever a jump in sensitivity or resolution is achieved, many unpredicted discoveries have been made.

Appendix 4. Acronyms

AGN -Active Galactic Nuclei
AO - Adaptive Optics
BIMA - Berkeley Illinois Maryland Association millimeter-wave interferometer at Hat Creek in California
BLR – Broad Line Region (a site of energetic activity in AGN's)
CHARA - Center for High Angular Resolution Astronomy of Georgia Statue University
COGBI - committee on Ground-Based Interferometry
ELT - Extremely Large Telescope, generally >20m aperture equivalent collecting area
ESA - European Space Agency
ESO - European Southern Observatory
GI2T - Grand Interferométre á 2 Telescopes (interferometer in southern France, now closed)
HST - Hubble Space Telescope
IMF – Initial Mass Function
JPL - Jet Propulsion Laboratory operated by Cal Tech of NASA
KI - Keck Interferometer on Mauna Kea in Hawaii, consisting of the two Keck telescopes
LBT - Large Binocular Telescope on Mt Graham in Arizona
LBTI - Interferometric instrumentation of the LBT
MCAO - Multi-Conjugate Adaptive Optics
MROI - Magdalena Ridge Observatory Interferometer of New Mexico Tech
NPOI - Navy Prototype Optical Interferometer, operated by the Navy in Arizona
OHANA - Optical Hawaiian Array for Nanoradian Astronomy
OIR - Optical/Infrared
OVRO - Owens Valley Radio Observatory near Bishop in California
OWL - OverWhelmingly Large Telescope - ESO telescope concept under study, currently for 40m aperture
PdBI – Plateau de Bure Interferometer (a millimeter facility)
PTI - Palomar Prototype Interferometer at Mt Palomar in California
SMA - Sub-Millimeter Array on Mauna Kea in Hawaii
TSIP - Telescope Systems Instrumentation Program - An NSF funding opportunity
VLT - Very Large telescope (4 telescopes of 8-m aperture operated by ESO)
VLTI - VLT Interferometer, consisting of VLT 8-m telescopes and a number of 1.8m auxiliary telescopes
YSO - Young Stellar Object (young stars)