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Technology for Future Interferometric Facilities: Conclusions and Perspectives

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Abstract: The science case for a future large optical / infrared interferometer is strong. The prospects for such a facility depend critically on a number of key technologies, including optical fibers with low transmission losses and very small dispersion, and affordable telescopes with sizeable apertures. The overall array and instrument design, and the choice of a suitable site play equally important roles. Addressing these issues in the context of a systematic technology roadmap will be an important step towards the realization of a large interferometric array.

1 Introduction: Science Requirements for Future Interferometric Facilities

A next-generation interferometric facility with sub-milliarcsecond resolution, high sensitivity, and good imaging capability would enable many types of unique astronomical observations that are not possible with any other technique. Amongst the drivers of such an instrument are:

- Imaging of Jupiter-size objects (e.g., brown dwarfs) at a distance of $\sim 10\,\mathrm{pc}$;
- High-quality imaging of stellar surfaces;
- Detailed imaging of young stellar objects and pre-main-sequence disks;
- Measuring Baade-Wesselink distances of pulsating stars, novae, and supernovae;
- Detailed imaging and imaging spectroscopy of broad-line regions in active galaxies, and geometric distances of quasars.

These are just a few examples of what interferometry could do; many other topics of current interest could be addressed as well (see e.g. Ridgway & Roddier 2000, Quirrenbach 2004, Surdej et al. 2005 and Absil & Mawet, these proceedings).

The most important requirements set by the astronomical drivers for future interferometers revolve around two main parameters: angular resolution and sensitivity. Additional factors such as wavelength coverage, spectral resolution, imaging performance (e.g., coverage of the *uv* plane), and field of view, also have an important impact on the capabilities of an interferometer. These will be discussed one by one in the following sections.

2 Technical Questions

2.1 Angular Resolution

The scientific goals listed above, and many others, seem to share a common requirement, namely an angular resolution of order 100 μas or better, corresponding to a baseline length of several kilometers. In principle, the difficulty of doing interferometry is rather independent of the length of the baseline, but longer baselines imply a larger area needed for the facility, and beam relay and pathlength compensation systems that are longer and have a larger diameter (because of diffraction effects and the need to transmit a non-zero field). At first glance this looks mostly like a solvable engineering problem, but by extrapolating from current facilities one may as well conclude that an array with kilometric baselines based on traditional bulk optics will not be affordable within any reasonable budget. This would imply that the development of optical fibers for beam relay and delay compensation (see Sect. 2.5) is a crucial enabling technology for a large next-generation array.

2.2 Sensitivity

Present-day optical and infrared interferometers suffer from a rather low sensitivity, compared with single telescopes. This is probably the largest single impediment for a wider use of interferometry by the general astronomical community. The fundamental sensitivity limit is related to the need to co-phase the array; it is set by the requirement that several photons need to be observed per atmospheric coherent area (circle with diameter r_0) within the coherence time τ_0. The first imperative of interferometry therefore is to use an efficient fringe tracking scheme (see e.g. le Poole & Quirrenbach 2002; Gai et al., these proceedings).

There exists at least one possibility, however, to beat this coherence limit. One can equip each telescope in the array with a laser guide star system, and use adaptive optics to flatten the single-telescope wavefronts. The fringe-sensing sensitivity thus depends on the telescope diameter, not on r_0. With sufficiently large telescopes one can obtain a limiting magnitude good enough to find a star within each isoplanatic patch on the sky; the array could thus be co-phased for observations of arbitrary targets. In practice, one could obtain a very respectable sky coverage if each array element is an 8 m or 10 m telescope (Quirrenbach 2004). The point-source sensitivity of an array co-phased in this way would come close to the sensitivity of single 10 m class telescopes.

2.3 Field-of-View

Essentially all present-day interferometers provide a very small field-of-view; in many cases the radius of the useful area is only a few resolution elements. Observations of extended objects and of fields containing many point sources, such as clusters of stars, would benefit tremendously from a larger coherent field. There are many possible technical solutions to this problem, but usually they involve a trade-off between field and sensitivity (Quirrenbach, these proceedings).

In direct imaging interferometers (frequently called hyper-telescopes) there is a natural densification factor that matches the size of the imaged field to the *uv* coverage of the array. The number of independent pixels in the image is then about equal to the number of telescopes in the array (Martinache & Lardière, these proceedings), which makes this concept attractive in particular for arrays with many elements. One should note, however, that this approach does not take advantage of Earth rotation synthesis or wavelength synthesis, which can improve the *uv* coverage and the synthesized field.

It appears at present that there is no single "optimum" way of enlarging the field in interferometric arrays. It is quite reasonable to presume that a multi-purpose facility should support a variety of beam combination schemes optimized for different wavelengths, resolutions, fields, and astronomical applications.

2.4 Telescopes

Building telescopes for an interferometric array does not seem to be a particular technological problem — one has to pay careful attention to the stability, but there are few other very demanding specifications. The main challenge is finding a way of producing a large number of telescopes for a rather low price, especially if large diameters are wanted (see Sect. 2.2). In this context one should pay attention to efforts aimed at building extremely large single telescopes for relatively low cost, which seek to take advantage of mass-production techniques; a similar approach might also be applicable to the production of telescopes for an interferometric array (Quirrenbach 2004).

A challenge that is unique to interferometry comes from the desire to reconfigure the array by moving telescopes around (see Sect. 2.7). This is done routinely at the VLTI with the 1.8 m Auxiliary Telescopes, but seems to be scary proposition for 10 m class telescopes. However, many solutions exist for transportation systems that can carry comparable masses very reliably (Kraus, these proceedings). The experience that has been gained with the VLA and that will also be generated soon by ALMA should also lend some plausibility to the notion that moveable telescopes with apertures comparable to the VLT Unit Telescopes should be feasible. One will of course have to pay proper attention to the telescope foundations and piers, and to the interfaces between the moveable telescopes and the fixed infrastructure.

A completely different set of complications is associated with a potential location in Antarctica (see Sect. 2.9). In addition to engineering the telescopes for the harsh environment, reliability issues play an even larger role than at more traditional locations. Again, it appears likely that the telescopes should not present show stoppers, at least up to a size in the 2 m class (Pirnay et al., these proceedings).

2.5 Optical Fibers and Integrated Optics

Many interferometric instruments that are operational or being planned now use relatively short single-mode optical fibers for functions such as spatial filtering, pupil rearrangement, or delay modulation (e.g., Kern et al. and Patru et al., these proceedings). In the 'OHANA experiment, much longer fibers are used for the beam transport from the individual telescopes to the central facility (Perrin et al. 2002). This has been made possible by advances of fiber technology over the past few years, which have led to dramatic reductions of the transmission losses. For arrays with baselines of several kilometers, however, further improvements of the fiber transmission will be required.

To minimize dispersion effects, one usually takes great care to make the fibers in all interferometer arms equally long. In an interferometer with kilometric baselines, it would be highly desirable, however, if not only the beam transport, but also the delay compensation could be accomplished with optical fibers — this would circumvent the difficulty of building very long delay lines with large optical systems. In principle, it should be possible to provide a set of fibers with different lengths, and to use fiber switches to send the light through a chain of these. If the fibers have lengths of 1 m, 2 m, 4 m, ..., for example, it is obviously possible to take out the delay up to a residual of ± 0.5 m. (The residual delay could then be compensated with a separate mechanical delay line.) The big difficulty with this concept is the fact that the interferometer arms now have fiber lengths that differ by amounts that are of the order of the baseline lengths. It is presently not clear whether essentially dispersion-free fibers or dispersion compensation schemes can be developed that would provide a useful bandwidth under these circumstances.

The complexity of bulk-optics beam combiners grows rapidly with the number of telescopes in the array that are to be combined simultaneously. Even three-telescope instruments such as AMBER at the VLTI consist of many optical components whose alignment needs to be maintained precisely. Extrapolating this approach to ~ 20 beams seems to be completely unrealistic. Integrated optics that provides many waveguides, beam splitters, and beam couplers on a single chip (Kern et al., these proceedings) may therefore be the only viable beam combination technology for many-telescope arrays.

One has to keep in mind that single-mode propagation in fibers or integrated optics components implies a restriction of the field-of-view to no more than the size of the single-telescope point spread function. While this may be tolerable in very dilute arrays (where the shortest baseline is still much longer than the telescope diameter), more compact configurations call for a larger field. This can be achieved with parallel systems using fiber bundles and / or multiple integrated optics components on the same chip.

2.6 Detectors

Like in many other fields of astronomy, progress in interferometry is closely linked to improvements in detector technology. It is probably fair to say that modern interferometry would not have been possible without fast electronic detectors, and the recent shift towards longer wavelengths has been enabled by the development of low-noise infrared detectors. There clearly is room for further improvements, which would help boost the sensitivity of future interferometers and simplify the design of interferometric instruments. Photon-counting detectors with good quantum efficiency based on low light level CCD technology (L3CCDs) or on image intensifiers (Blazit et al., these proceedings) could serve as workhorse detectors in interferometers working at visible wavelengths.

Detectors with intrinsic energy resolution such as kinetic inductance detectors (KIDs, see Baselmans et al., these proceedings) could open paths to completely new instrument designs. One could for example use “dispersed fringe” techniques without dispersive elements, or use the information on the photon energy to benefit from a broad observing band and a long coherence length simultaneously. Unlike most other astronomical instruments, many fringe sensors need only a small number of pixels, and may thus provide an ideal application of super-conducting detectors, which are difficult to produce in large arrays.

2.7 Imaging Capability and Array Geometry

The quality of interferometric images increases dramatically with the number of telescopes in the array. Furthermore, in arrays with more than two telescopes, it is possible to use the signal on the short baselines for the fringe tracking servo, while data are taken on the long baselines (Armstrong et al. 1998). This baseline bootstrapping works best if long chains of baselines with similar lengths can be formed (see Buscher, these proceedings). A next-generation facility with good imaging capability should probably consist of 20 to 30 telescopes.

The geometric arrangement of the telescopes does not seem to be a particularly critical issue. Examples of array layouts that provide good *uv* plane coverage and baseline bootstrapping capability are circular and Y-shaped configurations. The latter has substantial practical advantages when traditional bulk optics are used for the beam relay; for fiber-coupled arrays the differences between these two possibilities are less important.

An interesting alternative to these and similar "standard" array configurations is a geometry in which the optical pathlength is the same for all interferometer arms, so that long delay lines (or long unbalanced fibers, see Sect. 2.5) are not necessary. One way in which this can be achieved is arranging fixed reflectors on a spherical surface (for example, in a large crater), and suspending the beam combiner from a balloon (Borkowski et al., these proceedings). In this "Arecibo-like" arrangement, the beam combiner must include a corrector for the spherical aberration, and it must track the target by moving along the focal surface. A second concept for a zero-delay geometry employs telescopes that move continuously during the observation, such that they are always located on the ellipse that is the intersection of the observatory platform with a large parabola whose axis points towards the target and whose focal point is at the location of the beam combiner (Lardière et al., these proceedings). It remains to be seen whether the advantage of not having to build a delay compensation system will offset the complications of either of these schemes (suspended beam combiner and continuously moving telescopes, respectively).

2.8 Interferometric Astrometry

Precise narrow-angle astrometry would be another interesting application of an interferometer with very long baselines. The astrometric error scales with $\theta L_0^{1/3}/B$, where θ is the angle between the target and an astrometric reference star on the sky, L_0 the outer scale of atmospheric turbulence, and B the baseline length (Shao & Colavita 1992). L_0 is generally believed to be of order 100 m (e.g., Quirrenbach 2002), which means that it should be possible to achieve an accuracy considerably better than $1\,\mu$as, which would allow the detection of terrestrial planets through the reflex motion of their parent stars, and to measure their masses dynamically.

2.9 Possible Sites

Finding a good site for a large interferometric array is not a trivial task at all. It is obvious that one needs a reasonably flat plateau of considerable size, and such plateaus tend to have poorer seeing than the best mountain tops. One candidate site, for which data from a systematic site evaluation campaign are available, is Llano de Chajnantor, the location of the ALMA millimeter array at an altitude of 5000 m in the Chilean Andes. Typical values in the range $1''$ to $1\farcs5$ have been reported for the seeing at the Chajnantor plateau itself, with substantially better seeing at a location 100 m above the plateau (Giovanelli et al. 2001). This indicates that a rather large fraction of the turbulence occurs in the boundary layer just above the plateau, probably due to katabatic winds off the surrounding mountain slopes. The boundary-layer seeing is easier to correct with adaptive optics than high-altitude seeing, and it does not significantly contribute to anisoplanatism. This leads to the conclusion that Llano de Chajnantor should offer acceptable (although not excellent) seeing conditions.

Dome C in Antarctica has recently emerged as an attractive alternative site for a next-generation interferometer. The interest in this location has been spurred by measurements of excellent seeing conditions above a ~ 30 m thick surface layer (Agabi et al. 2005, Aristidi et al., these proceedings). If one can deal with this surface layer, either through placing telescopes on 30 m high towers, or through optical means analogous to ground-layer adaptive optics, Dome C should provide very substantial advantages for interferometry over any known non-Antarctic site. A number of studies are therefore underway to assess the viability and cost of imaging, astrometric, and nulling interferometers at Dome C (e.g., Lloyd et al. 2002, Swain et al. 2004, Coudé du Foresto et al. and Valat et al., these proceedings).

2.10 Single Telescopes and Interferometers

There are many possible synergies between large single telescopes and interferometer arrays (Delplancke, these proceedings). Both types of telescopes are very complementary scientifically, with very distinct science cases (see Sect. 1). Nevertheless, the sensitivity of an extremely large telescope and the resolution of an interferometer will frequently work in tandem to further our understanding of important astrophysical phenomena, for example in the realm of the formation and evolution of planetary systems.

Technical synergies are also possible, in particular in the application of mass production techniques for mirror segments and other structural elements. The cross-fertilization of single-telescope instrument concepts and interferometric techniques in the field of high-resolution high-dynamic range imaging is also quite obvious (see e.g. Quirrenbach 2005a and Lacour & Perrin, these proceedings).

Whether or not an interferometric array should be co-located with an extremely large telescope is a more complex question. The possibility of sharing infrastructure (access roads, maintenance facilities, expert staff, ...) is an argument in favor, the differences in the required site characteristics an argument against co-location.

2.11 Ground and Space

The discovery and characterization of Earth-like planets in the Solar neighborhood, and the search for biospheres on them, will be among the most important goals of space astronomy for the coming decades. The implementation of this component of ESA's Cosmic Vision 2015-2025 program and of possible follow-up missions will depend heavily on interferometry (Quirrenbach 2005b and Fridlund et al., these proceedings). There will certainly be a strong technical and scientific interdependency between the development of space interferometers and that of a large ground-based array. One can hardly imagine that key interferometric technologies could mature sufficiently for space applications without having been tested on the ground, and conversely one should expect that ground-based interferometry should benefit tremendously from the influx of funds required for bringing interferometric components and technology to the level necessary for space missions. Furthermore, the vitality of the community developing interferometric instrumentation and techniques will depend strongly on the interplay between ground-based and space-borne efforts. For all these reasons, a healthy ground-based interferometry program in Europe will also be of vital importance for the success of European space science.

2.12 Crossing the t's and Dotting the i's

An important aspect of building a good interferometer that is easily overlooked is the complexity of the overall system, which calls for exceptional attention to detail. The two main aspects of this issue concern the optical and the operational efficiency. Present-day interferometers are notorious for having a fairly low overall optical throughput, due to the many optical surfaces in their beam trains. Reducing the transmission losses is clearly an important step towards faint-object interferometry. Improvements are certainly possible through the use of optimized optical components and coatings, and by keeping all optical surfaces exceptionally clean. Guided beam transport and beam combination would drastically reduce the number of reflections in the system, but then the beam coupling efficiency and the bulk fiber transmission losses become the critical numbers. In this context one must not forget that coherence losses (i.e., a reduction of the system visibility from the ideal value of unity) are even more detrimental than transmission losses. Good wavefront quality and identical polarization properties between the interferometer arms are the keys to a high system visibility.

Making an interferometer operationally efficient is important for two reasons: the first and trivial point is that the scientific output increases when the overheads are reduced, the second and even more important issue is the drastic improvement of the calibration that can be achieved when many dozens of observations (or even a couple of hundred) are possible during each night (see e.g. Buscher, these proceedings). Being able to slew to and acquire a new target within one minute or at most a few minutes is a formidable task for the systems engineering in view of the many control loops that must be activated and optimized. It is clear that full automatization of the array operations is absolutely necessary.

3 Towards a Next-Generation Interferometric Array

3.1 Organization

The design and construction of a large interferometric array is a task that far exceeds the resources available at individual research institutions, and perhaps even those of established national and international observatories. It seems therefore clear that some form of cooperative structure is needed for the planning of such a facility. One could start with a rather informal association of interested institutions, with an "open door" policy regarding membership. This embryonic organization could later evolve into a more formal project office for the management of the design and construction phases.

The variety of concepts described in the contributions to these proceedings clearly indicates that there is no consensus yet about the "best" way of building a future interferometric facility. It is quite plausible that such an "optimum" design does not even exist — there may well be several plausible ways of achieving the same goals, and emphasis on different aspects of the potential science case certainly imply different design solutions. Nonetheless, it may be prudent to establish an "interferometer array" project under the umbrella of an international consortium rather sooner than later; decisions about core science program, design, and site could then be deferred to a later time.

3.2 Funding

The cost of an interferometric facility far more capable than that of any present instrument will certainly be several hundred million Euros. The scope of such a project calls for international, perhaps world-wide collaboration. At present, however, a large optical / infrared interferometer is not included in the financial planning of national funding agencies or international organizations. This is not necessarily an immediate problem, because the definition phase will not require a substantial amount of money. Establishing a project office as suggested in Sect. 3.1, developing the science case, setting up a realistic development plan, and performing initial architecture trade-offs, can certainly be done with minimal funding. But within this framework, one then also has to look for ways in which the much more expensive next phase, which comprises the facility design and any necessary technology development, could be organized and financed. One should expect that this phase would cost of order 10% of the total construction budget, i.e., a few tens of millions of Euros. Obtaining such an amount of money will only be possible on the basis of an exciting science case, and a solid technology plan.

3.3 Technology Roadmap

From these considerations it follows that the definition of a credible technology roadmap for a large interferometric array is an immediate important task. A rather systematic approach will be needed for this essential next step. A comprehensive plan should consider at least the following aspects:

- Consolidation of the design ideas that have been discussed into a few "strawman concepts";
- Comparison of the scientific capabilities of these concepts;
- Identification of the critical technology needs for each strawman concept, and of cross-cutting technologies;
- Assessment of the readiness of each technology identified, and of a realistic further development plan;
- Prioritization among the potential technology development lines;
- International cooperation and coordination of the technology development;
- Organizational and financial framework and boundary conditions.

Integrating all these considerations into a coherent and comprehensive technology roadmap for interferometry will be an interesting and challenging task for the near future. The workshop in Liège, on which the present proceedings are based, was a good first step in this direction. It is to be hoped that the process started here will lead to the construction of a truly ground-breaking facility with stunning capabilities, which will provide the remarkable scientific opportunities alluded to in the introduction of this paper.

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