Evolution in High Spatial Resolution Imaging of Faint, Complex Objects

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The astrophysical community has been working at the task of obtaining image information of the smallest structures in the sky via the use of optical interferometry for well over a century. A richly diverse family of technology architectures has been explored over the years, and yet the current family of facilities are all striking similar. Although there may be other, heretofore undeployed, architectures that support the goal of collecting image information at the highest resolutions, we expect dramatic advances at the component level of long-baseline interferometry to be the best avenue for advancing the technique, rather than entirely new architectures.

1 Introduction

Observing in the visible at the highest resolutions in astronomy has been achieved for well over the past 100 years through the use of interferometry in the visible. First suggested by H. Fizeau in 1868 (Fizeau, 1868), the initial attempts at measures of the sub-arcsecond diameters of stars was reported by E. Stéphan in 1874 (Stéphan, 1874); Albert Michelson successfully used the technique to measure the diameters of the Jovian moons in 1891 (Michelson, 1891). The technique of long-baseline interferometry (LBI) was pioneered by Michelson shortly thereafter, demonstrating that the diameters of the largest stars could be directly measured (Michelson & Pease, 1921) with the technique, though it fell into dormancy until the 1960's because the technical demands of technique outstripped the capabilities of the era. The 60's and 70's saw the useful application of intensity interferometry (IntI) towards astrophysical problems (Hanbury Brown et al., 1970, 1974a,b; Herbison-Evans et al., 1971), though this particular variant of LBI was ultimately a detour that has, for now, fallen into disuse in astronomy, because of its serious sensitivity limitations. [1] The primary approach to LBI in astronomy, through amplitude interferometry, saw developments in the 80's and 90's with facilities such as I2T (Labeyrie, 1981; Faucherre et al., 1983), IRMA (Dyck et al., 1988, 1993) and the Mark III (Shao et al., 1986); followed incrementally by GI2T (Labeyrie et al., 1986; Mourard, 1988), IOTA (Carleton, 1988; Dyck et al., 1995a), SUSI (Davis & Tango, 1985; Davis, 1988), and PTI (Colavita et al., 1994); ultimately leading to operational community facilities such as CHARA Array (McAlister et al., 2005; ten Brummelaar et al., 2005), VLTI (Glindemann et al., 2001), Keck Interferometer (Colavita et al., 2003, 2013), and NPOI (Armstrong et al., 1998, 2013); MROI continues under development towards first light (Creech-Eakman et al., 2016). Use of these facilities in the 90's emphasized two-beam combination; developments of the last 10 years have built on the pioneering multi-beam work of COAST (Baldwin et al., 1994, 1996), seeing the community rapidly developing an increasing dexterity with 4- to 6-way beam combination imaging techniques.

The increasingly operational nature in the past decade of the current, major facilities has allowed the development focus to concentrate on these advanced multi-beam instruments,

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[1] Interestingly, modern developments in electronics have the potential to increase its sensitivity and revive this technique (Dravins et al., 2012). Proposals have been made to utilize IntI on the many large but relative crude apertures of the upcoming Cherenkov Telescope Array (Dravins et al., 2013). For the purposes of this discussion, IntI remains a relatively uninteresting detour, since sensitivities remain insufficient for observation of fainter targets (Nuñez & Domiciano de Souza, 2015).

rather than the facility infrastructure. VLTI's next-generation instruments PIONIER (Berger et al., 2010; Le Bouquin et al., 2011), GRAVITY (Gravity Collaboration et al., 2017) and MATISSE (Lopez et al., 2014) are collectively advancing 4-way imaging for ESO; CHARA is upgrading from MIRC (Monnier et al., 2004) to MIRCx and MYSTIC; NPOI has recently upgraded its next-generation VISION instrument (Garcia et al., 2016) with new EMCCD cameras. Coincident with the new multi-beam instruments is substantial advances in image processing suites for reconstructing images from these instruments.

2 General Concepts

The experience of the astronomical community with current and historic facilities gives compelling guidance on the best architecture for observation of faint targets at spatial resolutions 10-100 times finer than possible with single-aperture 'traditional' telescopes. The current state of the art has been arrived at only after exploring many detours along the way. This architecture is rooted in the simple premise of maximum use of precious photons collected from the faint object of interest in the presence of a turbulent, uncooperative atmosphere. The architecture is best described on its face as arrays consisting of similarly (if not identically) sized telescopes. Arrays of unequally sized apertures suffer from the phenomenon of photon noise of the larger apertures exceeding the signal of the smaller apertures.

The atmosphere imposes strict design considerations. Individual aperture wavefronts are corrupted and need to be corrected with adaptive optics. Without those corrections, the corrugated wavefronts of each aperture will not combine with those of the other apertures provide an interference signal. The time scale of those corrections needs to be of a duration consistent with the atmospheric coherence time, which in the visible is on the order of 1-10ms. Keeping with the premise of preserving the faint object photons, laser guide star adaptive optics can be utilized, although this carries with it significant expense and complication. The overall scale of wavefront corrections must correspond to the atmospheric seeing cell size, which in the visible can range from 1-10cm.

Combining wavefronts from individual apertures must account for an additional insult from the atmosphere: the atmospheric column over each individual aperture is also inducing a varying path length, typically 1-10um, on atmospheric coherence times. As such, tracking of that varying path length must sense and account for atmospheric error. Path length motion associated with the target in the sky relative to the observatory must also be accounted for; in the case of sidereal rate motion, for a 100m separation between apertures, this corresponds to a few cm/s. Path lengths need to meet optical tolerances of 10-50nm.

Between a pair of telescopes, the signal-to-noise (SNR) of path length tracking goes as NV^2 - number of photons N, and the amount of interference contrast, or 'visibility', V. The latter number decreases with increasing separation B between the telescopes, increasing object size θ, and shorter observational wavelength λ. Interestingly, if a pair of telescopes, A and B, have path length tracking ('cophasing') being successfully provided between them, and a third telescope C is pairwise tracking with either A or B, then all three will be cophased. If cophasing is provided at sufficiently high SNR, then the condition is also true at shorter wavelengths.

We can examine these cophasing requirements to divine some essential architecture elements. Of the parameters above, we cannot control N – the object brightness will be what its going to be; we also cannot control its overall size: both of these will simply be limits of the system performance. However, we can control B and λ to increase SNR. For maximum angular resolution, the desire is for values of B that are as large as possible; however, for maximum SNR, the opposite is true. The compromise is to design a chain of telescope stations A-B-C-D-... with each pair having a short separation, but the overall length of the ends of the chain being large; this approach is called 'baseline bootstrapping'. Similarly, cophasing can be carried out at high SNR at long wavelengths, for stabilization of short wavelength interference; this is 'wavelength bootstrapping'. Wavelength bootstrapping is especially powerful if the faint targets are brighter at the longer wavelengths. Together, baseline-wavelength bootstrapping (BWB) is expected to be a powerful technique for cophasing arrays of large numbers of telescope. With a system capable of highly efficient BWB cophasing, shorter wavelength light is then stabilized and can be fed into a multi-way imaging recombiner for capturing the image information.

Two general layouts of telescope arrays immediately present themselves for use with the BWB technique. A traditional 'Y' array, with a slight bend in the arms, can achieve long maximum baselines with a variety of intermediate baselines. A circular array builds a closed loop from short separation apertures along the round circumference. A circular layout emphasizes longer baselines and benefits from 'closing the loop' in providing another cophasing constraint; however, it suffers from needed a larger number of apertures to achieve the same longest baseline as a 'Y' array with identical short spacings.

The number of elements can be estimated with the following shorthand. If the desired image has a certain scale – say, 10×10 pixels – that corresponds to 100 degrees of freedom. An optical interferometer's image information currency is rooted in two flavors. First, each pair of telescopes can provide interference amplitude information – this corresponds to the real part of the Fourier transform of the image upon the sky. For a facility with a number of apertures A, the number of amplitude points will be $A(A-1)/2$. Second, each triangle of telescopes provides a 'closure phase' – this corresponds to the imaginary part of the Fourier transform of the image upon the sky. [2] For A number of apertures, the number of independent closure phases is $(A-1)(A-2)/2$. Following these expressions, we can see that for an 11-aperture system, a 'snapshot' will obtain 55 amplitudes and 45 closure phases – 100 degrees of freedom, satisfying our 10×10 example above.

Additional degrees of freedom can be obtained for an A-element system by treating the wavelengths of imaging as separate elements of spatial information. However, inherent in this approach is the assumption that the observed target is 'grey' – e.g. that there is no compositional information as a function of wavelength. This assumption is known to be false for astrophysical and other faint targets, and as such the astronomical community has typically eschewed this approach as a method by which spatial information is distilled from the observations.

3 Experience of the Astrophysical Community

The experience of the astrophysical community that has led to the general concepts laid out in the previous section is extensive. Cophasing, as provided by the techniques known as

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[2] In a noiseless system – e.g. in space – absolute phases can in principle be measured. However, the atmosphere corrupts individual aperture absolute phases; a mathematical sleight-of-hand (see the discussion in §2.2.3 of Monnier, 2003) shows how sums around triangles of apertures can make that corruption disappear, recovering one phase value per trio.

fringe scanning or fringe tracking, is a basic requirement for all astronomical interferometers. Of the two techniques, fringe scanning is easier and has greater sensitivity, but far less throughput. Dithering path length over the full range of atmospheric uncertainty of cophasing position, typically 50-100um over the course of a fraction of second, ensures capturing of the interference fringe, though along with a lot of incoherent noise. Fringe tracking requires monitoring and following the fringe position every ∼10ms atmospheric coherence time, but also ensures that during that frame, useful data is collected – hence, data rates in this latter case are typically 100 times greater.

The devices themselves that provide the path length control, delay lines (DLs), are not only similar between facilities, but for a large number of those facilities, nearly identical. The DL technology developed by Staelin, Shao & Colavia (Colavita et al., 1991, 1992) for the Mark I, II, and III interferometers promulgated into the DLs of PTI, Keck, NPOI (Clark et al., 1998), and CHARA – the units are part-number interchangable in certain regards. That particular technology is somewhat dated – it reflects the electrical and optomechanical tools available from 20 years ago – but it is also robust, effective, and well-understood.

Instruments such as IOTA, CHARA-Classic are examples of fringe scanning devices (ten Brummelaar et al., 2013); facilities like PTI, Keck, and NPOI are built fully around fringe tracking for all their instruments (Colavita, 1990, 1999; Vasisht et al., 2003; Colavita et al., 2010). Additional examples of fringe tracking include the VLTI trackers FINITO (Gai et al., 2002, 2003), PRIMA (Sahlmann et al., 2009, 2010), and GRAVITY (Choquet et al., 2010); the PRIMA instrument's fringe tracker has been utilized to provide wavelength bootstrapping for the MIDI instrument (Müller et al., 2010, 2014), increasing its sensitivity by a factor of 20×.

Additional experiments have been carried out in the community as efforts to extend the sensitivity and usefulness of fringe tracking. Most notable amongst these efforts have been those relating to two-beam cophasing. The principle is based on the fact that, if a pair of telescopes is cophased along a given line of sight into the sky, the cophasing is valid across the entire seeing disk around that line of sight – the isoplanatic patch. Thus, a faint object can be observed coherently if it is within that on-sky area upon which the facility is being cophased using a brighter object.

Two variations upon this approach have been explored at astronomical facilities. First amongst these is the separated dual beam approach, where two objects are captured by the individual telescopes of the facility, but then relayed to the back end recombination via separate beam paths. The advantage of this approach is that a larger on-sky field of view can be employed – if the size of isoplanatic patch allows. The disadvantage is that two separate beam paths doubles the facility path control infrastructure, and adds the significant complication that telescope beam pairs need to be stable relative to each other. This technique was pioneered for the purposes of narrow-angle astrometry at PTI (Boden & Quirrenbach, 2008), designed into (but never implemented) the Keck Interferometer (van Belle et al., 1998), and then also attempted (but later abandoned) at VLTI-PRIMA (van Belle et al., 2008; Woillez et al., 2014). The PTI and PRIMA experiments were ultimately mothballed because, despite the promise of sensitivity from this approach, it was never achieved, because the inherent system complexity limited that sensitivity.

Dual beam-interferometry that employs a single relay beam path to convey the light of two objects simultaneously has been more successful. An initial demonstration was carried out by Dyck (Dyck et al., 1995b) to capture the separated fringe packets of two stars in a close binary; they already at that time noted the utility of this approach in more elaborate imaging. Binary observing using this technique has been employed at CHARA (Farrington, 2008; Farrington et al., 2010), PTI-PHASES (Muterspaugh et al., 2005, 2010), and now is a core element of the VLTI-GRAVITY program (Gravity Collaboration et al., 2017). Using a single beam relay path greatly simplifies the optical performance, operational considerations (including especially acquisition), but at the price of limited field-of-view (2" versus up to 60" for VLTI-GRAVITY versus VLTI-PRIMA, for example).

The experience of the community with dual-beam approaches provides a cautionary tale to those that might seek to observe faint objects by cophasing on nearby bright objects. It is clearly not impossible but is, at best, tricky, and more limited in its operational flexibility than might appear from the outset.

As noted in the introduction, multi-way beam combination has increasingly become the norm for the mainline instruments at current facilities. There are specialized two-way combiners still in use – e.g. FLUOR/JouFLU (Lhomé et al., 2012) and effectively PAVO at CHARA (Ireland et al., 2008) – but the newest instruments are essentially all 4- and 6-beam combiners.

4 Possible Future Directions

A recent proposal call has presented an interesting question for the astronomical community that uses LBI – namely, how to increase sensitivity of these facilities while reducing cost? Before addressing an answer, it is useful to note that the major facilities currently in use, or in development, in the astronomical community – VLTI, CHARA, NPOI, MROI – all bear striking similarities. Each has telescopes with simple adaptive optics (tip-tilt), with each facility upgrading to more complicated AO. Each facility has beam relay optics and delay lines, along with beam combiners. Image reconstruction software has been embraced as a community-wide common effort (Lawson et al., 2004, 2006; Malbet et al., 2010; Baron et al., 2012; Monnier et al., 2014; Sanchez-Bermudez et al., 2016); this has been particularly facilitated by the adoption of a community-wide data exchange standard for optical interferometry imaging information (OIFITS; Duvert et al., 2017). Despite the broad pallet of exploratory technology efforts over the past three decades, it is remarkable how similar are these major facilities. This suggests there is a 'right answer' when it comes to the architecture of these facilities, in much the same way the largest segmented telescopes (Keck, GTC, TMT, E-ELT) resemble each other.[3]

So an approach to addressing the challenge of increased LBI sensitivity can begin with current facilities as a strawman design, and then choosing between one of two options. First, one may assume a better architecture exists [4] and proceed with fundamentally deviating from that particular architecture. Alternatively, one may assume that the strawman could

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[3] Indeed, the segmented telescopes is a good point of consideration: the diligent reader may recall that there remain a few deviations from that norm in the form of LBT and GMT. However, we would point out that the considerable difficulties in deploying the LINC-NIRVANA Fizeau imager at LBT (Herbst et al., 2016) illustrate the hazards in forging a separate technology path.

[4] Novel thinking is the lifeblood of astronomy, and indeed seems to have a certain essential vitality within the LBI community. But such an assumption carries with it no small measure of hubris in thinking a large number of rather smart people in the astronomical community have inadvertently detoured in a technological dead end with current facilities.

bear some improvements but is, at least in its broad outlines, correct. For a recent exercise in thinking about how to push the sensitivity envelope of LBI facilities, we took the second approach.

Within the constraints of that approach, the most readily apparent improvement is to increase the size of the individual apertures. However, this approach historically has had the consequence of rapidly increasing the cost of a facility. Aperture cost versus size is well understood to scale as diameter, D, to a power somewhere between 2 and 3 – the study of van Belle, Meinel & Meinel (VMM04; van Belle et al., 2004) found cost $\sim D^{2.5}$. This has been attributed to the fact that, while telescope area goes as D^2, two effects impacting the design of ground-based apertures – namely gravity (which necessitates a backing structure that can accommodate varying elevation) and weather (which necessitates a dome) – effectively scale as three-dimensional effects, which increases the value of the exponent in the scaling law towards 3. It is reasonable to expect that, for a given ground-based telescope technology, this scaling law will continue to have an exponent value that lies between the square and the cube.

However, the zero point of the scaling law can be changed with improvements in telescope technology. In VMM04, it was shown that thin-mirror telescopes built since 1980 were fundamentally less expensive than the previous generation of telescopes, built on thicker slab mirrors. Likewise, VMM04 predicted – correctly – that the era of giant segmented mirror telescopes that was beginning at that time, represented a second improvement in the zeropoint of the cost-size scaling power law. Additionally, VMM04 pointed out that speciality purpose-built telescopes – apertures that traded limitations in capability for reductions in cost – could undercut the cost-size scaling law by factors of 10× to 100×.

It is following the guidance of these observations that we feel significant improvements in cost of telescopes for optical interferometry can be obtained. A simple example is field of view: telescopes used in LBI need to be diffraction limited on-axis, but effectively need no diffraction-limited field of view beyond that. A such, simplified optical layouts involving spherical primaries and secondaries can be employed – mirrors which are significantly easier to manufacture. Additional improvements in manufacturing are possible, which we believe will enable telescopes in the 2.5-m class to be operationally commissioned for roughly $1M per aperture.

There is significant demand for these sorts of advances in capability as a function of cost in the astronomical community. Development of the Planet Formation Imager concept as the next-generation facility (Ireland et al., 2016; Kraus et al., 2016; Monnier et al., 2016) to follow VLTI, CHARA, and NPOI, will dictate that a large number ($N > 10$) of large apertures ($D > 2.5$m) be financially feasible. Innovative thinking is continuing to drive advancements in sensitive interferometric imaging in the astronomical community.

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