Towards a diffraction-limited square-kilometer optical telescope: Digital revival of intensity interferometry

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ABSTRACT

Much of the progress in astronomy follows imaging with improved resolution. In observing stars, current capabilities are only marginal in beginning to image the disks of a few, although many stars will appear as surface objects for baselines of hundreds of meters. Since atmospheric turbulence makes ground-based phase interferometry challenging for such long baselines, kilometric space telescope clusters have been proposed for imaging stellar surface details. The realization of such projects remains uncertain, but comparable imaging could be realized by ground-based intensity interferometry. While insensitive to atmospheric turbulence and imperfections in telescope optics, the method requires large flux collectors, such as being set up as arrays of atmospheric Cherenkov telescopes for studying energetic gamma rays. High-speed detectors and digital signal handling enable very many baselines to be synthesized between pairs of telescopes, while stars may be tracked across the sky by electronic time delays. First observations with digitally combined optical instruments have now been made with pairs of 12-meter telescopes of the VERITAS array in Arizona. Observing at short wavelengths adds no problems, and similar techniques on an extremely large telescope could achieve diffraction-limited imaging down to the atmospheric cutoff, achieving a spatial resolution significantly superior by that feasible by adaptive optics operating in the red or near-infrared.

Keywords: astronomical intensity interferometry, air Cherenkov telescopes, stellar surface imaging, quantum optics

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1. THE QUEST FOR MICROARCSECOND IMAGING

Our local Universe is teeming with stars, but despite 400 years of telescopic observations, astronomy is still basically incapable of observing stars as such! Although we can observe the light radiated by them, we do not (with few exceptions) have the capability to observe the stars themselves, i.e., resolving their disks or viewing structures across and outside their surfaces (except for the Sun, of course!). One can just speculate what new worlds will be revealed once stars no longer will be seen as mere point sources but as extended and irregular objects with magnetic or thermal spots, flattened or distorted by rapid rotation, and with mass ejections monitored in different spectral features as they flow towards their binary companions. It is not long ago that the satellites of the outer planets passed from being mere point sources to a plethora of different worlds, and one might speculate what meager state extragalactic astronomy would be in, were galaxies observed as point sources only.

1.1 The new stellar physics

A limited number of (mostly supergiant) stars actually already now can be (at least marginally) resolved by present large telescopes and interferometers, showing a tantalizing richness of features (e.g., they may not have the smooth and round shape of our Sun but rather appear like fluffy clouds, their diameter being grossly different when seen in chromospheric or photospheric spectral features); longer-baseline interferometers resolve the flattened shapes of rapidly rotating stars, and periodically changing sizes of pulsating ones. Recent studies indeed hint at the richness of this new stellar physics:

Rapidly rotating main-sequence dwarf stars naturally take on an oblate shape, with an equatorial bulge that for stars rotating close to their break-up speed may extend into a circumstellar disk, while the higher effective-gravity regions near the stellar poles become overheated, driving a stellar wind. If the star is observed from near its equatorial plane, an oblate image results, as for the B3 Ve star Achernar[1], or the A7 V star Altair[2]; if the star instead is observed from near its poles, one sees a radial temperature gradient, as in the case for the A0 V star Vega[3]. Possibly, stars with rapid and strong differential rotation could take on weird shapes, midway between a donut and a sphere[4].

Going to supergiant stars, it becomes feasible to study atmospheric structures. The red supergiants Betelgeuse (α Ori) and α Her show different diameters at different wavelengths, probably due to warm envelopes of water molecules[5]. Surface structures are predicted from three-dimensional and time-dependent models of large-scale stellar convection[6], and multi-wavelength studies of α Ori have found a strong variation in the asymmetry of the stellar brightness as a function of wavelength, including three bright spots interpreted as unobscured areas of elevated temperature, shining through the upper atmosphere at the shorter wavelengths[7]. (Naturally, at shorter wavelengths the contrast between features at differing temperatures becomes elevated.)

Although the smaller convective surface features on dwarf stars cannot be directly imaged, predictions from three-dimensional stellar atmospheric models can still be tested from limb-darkening curves observed at different wavelengths; examples include Procyon (F5 IV-V)[8] and α Cen B (K1 V)[9]. For some classes of active dwarf stars with suitably rapid rotation, Doppler imaging enables the inferring of spotted stellar surface structure[10].

Long-period (radially and/or non-radially) pulsating variables of the Mira type not only show substantial distortions from circular symmetry, but different appearances in different spectral features (e.g., the molecular atmosphere seen in TiO bands, as opposed to the photospheric continuum)[11,12]. Further, the stellar diameters undergo huge cyclic variations on the order of 50%[13], and the combination with infrared and radio data reveals intricate relationships between the photosphere, molecular layer, dust shell, and SiO maser emission[14,15]. Although the pulsational amplitudes in Cepheid variables are smaller, the changing stellar size is now seen by interferometers[16].

Even more extreme objects are represented by exceptionally luminous and highly variable objects such as η Carinae, where interferometric observations suggest that the very rapid stellar rotation causes enhanced mass loss along the rotation axis (rather than from the equatorial regions, as might be intuitively believed), resulting from the large temperature difference between pole and equator that develops in rapidly rotating stars[17].

These examples show how we are on the verge of starting to view stars as the vast diversity of objects that they really are, and a great leap forward will be enabled by improving the angular resolution by just another order of magnitude from the present, then resolving very many different types of stars of often several milliarcseconds across (Table 1). The required resolutions are thus in the hundreds of microarcseconds, corresponding to interferometer baselines of some hundreds of meters in the optical.

Table 1. A dozen bright stars, prime targets for imaging. Sizes for giants vary as function of wavelength or pulsational phase. The value for γ^2 Vel denotes the orbital separation. (Adapted from Carpenter et al.[18])

STAR	TYPE	SIZE [mas]	Comment
α Cen A	G2 V	8.5	Solar near-twin
α Cen B	K1 V	6.0	Binary component
β Hyi	G2 IV	1.7	‘Old Sun’
α Boo	K1 III	21	Arcturus; ‘ancient Sun’
α CMi	F5 IV-V	5.5	Procyon
α CMa	A1 V	6.0	Sirius
α Tau	K5 III	~ 20	Aldebaran; red giant
α Ori	M2 Iab	~ 50	Betelgeuse; supergiant
α Aur	G1 III	5.8	Capella primary
o Ceti	M7 III	~ 8	Mira
R Leo	M8 III	~ 40	Mira-type
γ^2 Vel	WC8+O8 III	5.4	Nearest Wolf-Rayet

1.2 Kilometric phase interferometry

Although impressive advances have been made in phase (Michelson-) interferometry, baselines much longer than some hundred meters encounter serious issues in both atmospheric turbulence and in atmospheric physics that make ground-based observations very challenging or simply not practical. As a possible remedy, space-based telescope clusters flying as phase interferometers have been proposed to attain baselines up to kilometers (*Stellar Imager*[18–20] and *Luciola hypertelescope*[21]), which would be capable of imaging stellar surface details even in the ultraviolet. Of course, at shorter wavelengths the contrast of any thermal feature – a cool starspot or a hot convective element – will normally be greater, so that observations at shorter wavelengths are always the most sensitive. However, despite their scientific appeal, the considerable complexity and probable expense of these large-scale space missions makes the timescale for their realization somewhat uncertain, prompting searches for alternative approaches. One promising possibility is ground-based intensity interferometry.

2. INTENSITY INTERFEROMETRY

The stellar *intensity interferometer* was developed already long ago by Hanbury Brown and Twiss for the original application of measuring stellar sizes[22]. At the time of its design, the understanding of its functioning was the source of considerable confusion, whose eventual solution led to the development of the quantum theory of optical coherence, acknowledged with the 2005 Nobel Prize in physics to Roy Glauber. Today this is considered the first quantum-optical instrument, and its concept has found numerous applications for studying both optical light in the laboratory, and other classes of high-energy particles having the same type of integer quantum spin as photons, and therefore sharing the same type of Bose-Einstein quantum statistics[23–25]. However, following the pioneering experiments by Hanbury Brown et al., there seem to have been no further applications to astronomy.

The intensity interferometer is an instrument whose functioning is challenging to intuitively comprehend. To begin with, the name itself is sort of a misnomer: there actually is nothing interfering in the instrument; rather its name was chosen for its analogy to the ordinary [phase-] interferometer, whose scientific aims the original intensity interferometer was replicating (in measuring stellar diameters). In an intensity interferometer, two telescopes are simultaneously measuring the random and very rapid [quantum] fluctuations in the intensity of light from some particular star. When the telescopes are placed sufficiently close to one another, both measure the same signal, but when they are moved apart, the fluctuations gradually become different and de-correlated: how rapidly this occurs gives a measure of the spatial coherence of starlight, and thus the angular extent of the star. The signal observed is thus the *correlation* between the intensity fluctuations electronically measured in each of the two telescopes, and how this correlation gradually changes as the telescopes are moved apart from one another. The signal is a measure of the second-order spatial coherence, from which the first-order coherence follows, and the size and shape of the source along the projected baseline is obtained.

The functioning of the intensity interferometer is now well documented, including details of the original instrument[26,27], and retrospective overviews by Hanbury Brown[22,28,29]. The principles are well explained in various textbooks and reference publications[30–33].

The quantity measured by an intensity interferometer is the second-order correlation function of light $G^{(2)}$ with the time-variable intensity $I(t)$:

$$G^{(2)}(\tau) = \frac{\langle I(t)I(t+\tau)\rangle}{\langle I(t)\rangle^2} \tag{1}$$

where τ denotes the correlation time delay, t is time, and $\langle\ \rangle$ denotes long-term averaging.

For ordinary light with a 'random' distribution of photons in time (such as thermal emission from stars), simple relations exist between the [modulus of the] first-order coherence function (the visibility measured in ordinary phase interferometers) and the second-order functions: $G^{(2)} = |G^{(1)}|^2$, so that the modulus of the visibility $G^{(1)}$ can directly be deduced, yielding stellar shapes and sizes from intensity-correlation measurements.

2.1 Advantages (and disadvantages) of intensity interferometry

The great observational advantage of intensity interferometry is its lack of sensitivity to either atmospheric disturbances or to imperfections in telescopic optical quality. This comes about from the electronic (rather than optical) connection of telescopes, from which follows that the noise budget relates to the relatively long electronic timescales (nanoseconds, and light-travel distances of centimeters or meters) rather than those of the light wave itself (femtoseconds and nanometers): the control of atmospheric path-lengths and telescope imperfections needs only to correspond to some reasonable fraction of this electronic resolution. For a realistic time resolution in the electronic correlation function of 10 ns, say, the corresponding light-travel distance is 3 m, and optical errors of maybe one tenth of this can be tolerated, enabling coarse flux collectors to be used (rather than precise telescopes), and avoiding any sensitivity to atmospheric seeing (thus enabling very long baselines).

There is, however, a price to be paid in that large photon fluxes (and thus large telescopes) are required even to observe brighter stars; already the 6.5 meter flux collectors of the original intensity interferometer at Narrabri, Australia, were larger than any other optical telescope at that time. However, the signal is almost independent of the spectral passband, and can be improved if using multiple spectral channels, as foreseen already in the proposed (but never realized) successor to the original Narrabri instrument[34]. Although the signal-to-noise ratio can be enhanced by improving the electronic time resolution, faster electronics can only be exploited up to a point since there is a matching requirement on the optomechanical systems. A timing improvement to, say, 100 ps, would require mechanical accuracies on mm levels, going beyond what is achieved in flux collectors, and beginning to approach the levels of fluctuations in atmospheric path-length differences. Another limit is set by the significant skylight background if using coarse flux collectors.

A two-telescope system such as originally used by Hanbury Brown et al. provides the angular size and shape of the source but, since phase information is not retained in the modulus of the visibility, does not permit a full (possibly asymmetric) image to be reconstructed. This limitation, however, is possible to circumvent in systems with a larger number of telescopes, where sampling across all possible pairs and triples of baselines (possibly measuring also higher-order intensity correlations) may actually permit a full reconstruction of the source image[35–41].

Although, for one single pair of telescopes, phase interferometry has superior sensitivity, the balance rapidly shifts towards intensity interferometry when the number of telescopes and the ensuing number of baseline pairs grows (roughly as the square of the number of elements). In any larger array, phase interferometry suffers loss of signal since it becomes awkward to split the available light among all the elements, while there is no corresponding loss of the electronic signals in intensity interferometry. Not only does the signal increase monotonically with the number of flux-collecting apertures, but since a large number of differently oriented baselines can readily be handled, an extensive coverage of the interferometric (u,v)-plane results, yielding a superior coverage of projected orientations across the source image.

2.2 Optical *e*-interferometry

Electronic combination of signals from multiple telescopes has recently been established as a technique in long-baseline radio interferometry, electronically joining remote radio antennas to a common signal-processing station via optical fiber links in so-called *e-VLBI*. This is feasible due to the relatively low radio frequencies (MHz-GHz); a corresponding optical phase-resolved signal (THz-PHz) would not be doable but the much slower intensity-fluctuation signal (again MHz-GHz) is realistic to transmit, thus enabling an electronic connection also of optical telescopes in digital software.

The original intensity interferometer at Narrabri used analog electronics and telescopes that were moved along a circular rail to preserve the relative timing while tracking stars across the sky. Modern high-speed digital electronics now allow a revival of intensity interferometry with new and much broader possibilities. Using two or multiple telescopes (or telescope apertures), a precise electronic timing of arriving photons within intense light fluxes, combined with digital signal storage and handling, now enables digital intensity interferometry with degrees of freedom not available in the past. Further, the telescopes no longer need to be mechanically movable but may be fixed, their mechanical displacements replaced by continuously changing electronic delays that enable the tracking of stars across the sky.

Several authors have noted this potential of reviving intensity interferometry, and a number of suggestions exist in the recent literature. Discussions of such *e*-interferometry by Dravins et al.[42,43] point at the potential of electronically combining multiple subapertures of extremely large telescopes, in particular for observations at short optical wavelengths. Ofir & Ribak[44–46] evaluate concepts for multidetector intensity interferometers, and even space-based intensity interferometry has been proposed[47,48], exploiting the possibility to combine signals off-line from each component telescope, rather than real-time combination of phase-stable optical beams, thus greatly relaxing the requirements for spacecraft orientation and orbital stability. With a reference star within the field of view, intensity interferometry might even be used for astrometry, possibly in searches for exoplanets[38].

2.3 Air Cherenkov Arrays

A particularly fortunate development is the recent establishment of optical telescope arrays for studying high-energy gamma rays from cosmic sources through the Cherenkov radiation that is produced by secondary air-shower particles in Earth's upper atmosphere. The success of this concept has prompted the construction of several arrays with large flux collectors, including CANGAROO in Australia, H.E.S.S. in Namibia, MAGIC on La Palma, and VERITAS in Arizona.

These Air Cherenkov Telescopes (ACTs) need to be large (12 m diameter for VERITAS, 17 m for MAGIC, and for H.E.S.S. even one 28 m dish is under construction) because the Cherenkov light is very feeble and the flash lasts only a few nanoseconds, also demanding correspondingly fast photon-counting detectors. The image seen by any one telescope shows the track of the air shower, but a single telescope is insufficient for any more precise reconstruction of the air shower geometry, and thus the precise direction to the source. This is the reason for having multiple telescopes, offering a stereoscopic view. Telescope separations are set by the beaming of the Cherenkov light, which typically illuminates a ground spot of a few hundred meter diameter, prompting telescope separations on the order of 100 m. For imaging the air shower, a modest optical imaging quality is sufficient (typically 3-5 arcminutes), but possibly diverse path-lengths within the optics must not temporally smear out the Cherenkov pulse more than a few nanoseconds.

These parameters are amazingly similar to the requirements for intensity interferometry, and the compatibility is made even greater when it is realized that the faintness of the Cherenkov light precludes the use of these telescopes during brighter moonlight, a condition that does not inhibit interferometric observations of brighter sources. The potential of using ACT arrays for intensity interferometry has now been detailed by LeBohec et al.[49–51].

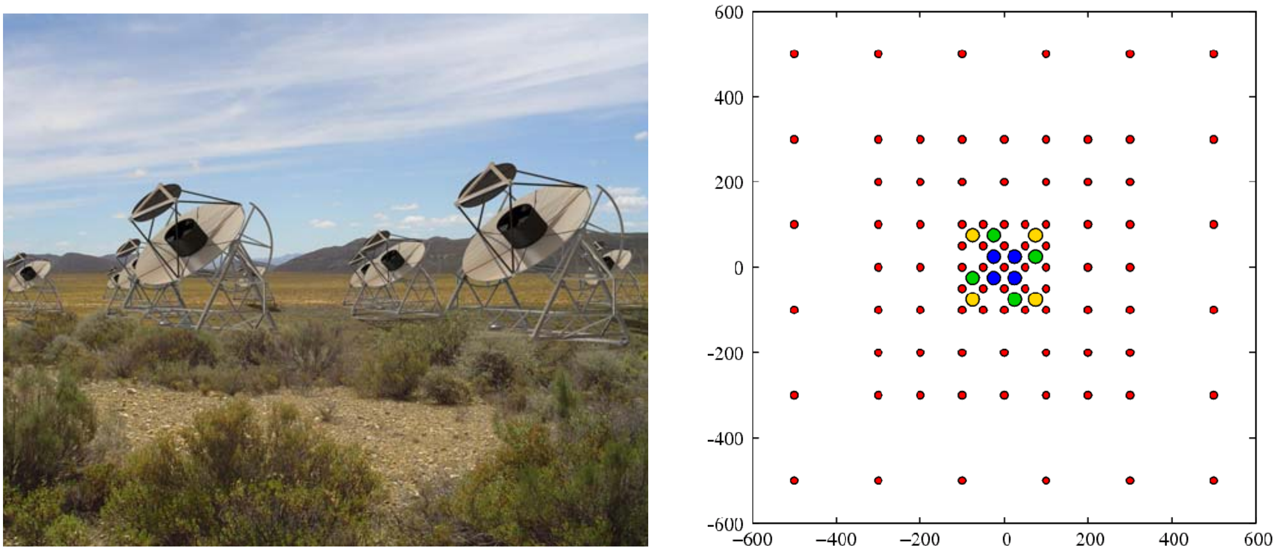

Fig 1. Left: Artist's vision of a possible layout of the proposed *AGIS* (Advanced Gamma-ray Imaging System; image courtesy of J.Buckley and V.Guarino). Right: One possible layout (with scale in meters) of the proposed *CTA* (Cherenkov Telescope Array) with 97 telescopes of which 3×4 have collecting areas of 600 m² each, and 85 others have 100 m² (figure by K.Bernlöhr[52]).

The most remarkable potential, however, comes from planned future ACT facilities which aim at improving both the gamma-ray flux sensitivity and the angular resolution by having between maybe 50–100 flux collectors spread out over an area on the order of one square kilometer, offering thousands of baselines. Projects led by European and American groups include the *CTA*[52] (Cherenkov Telescope Array) and the *AGIS*[53] (Advanced Gamma-ray Imaging System). Although these projects are still in their preparatory phases, their proposed concepts permit to estimate the potential for intensity interferometry. Figure 1 shows an artist's vision, and one possible layout. Although the layout geometry might not primarily be optimized for interferometry[54], very many baselines would be available in such an array which, when used as an interferometer, would allow to probe angular scales between milli- and microarcseconds (Figures 2 and 3).

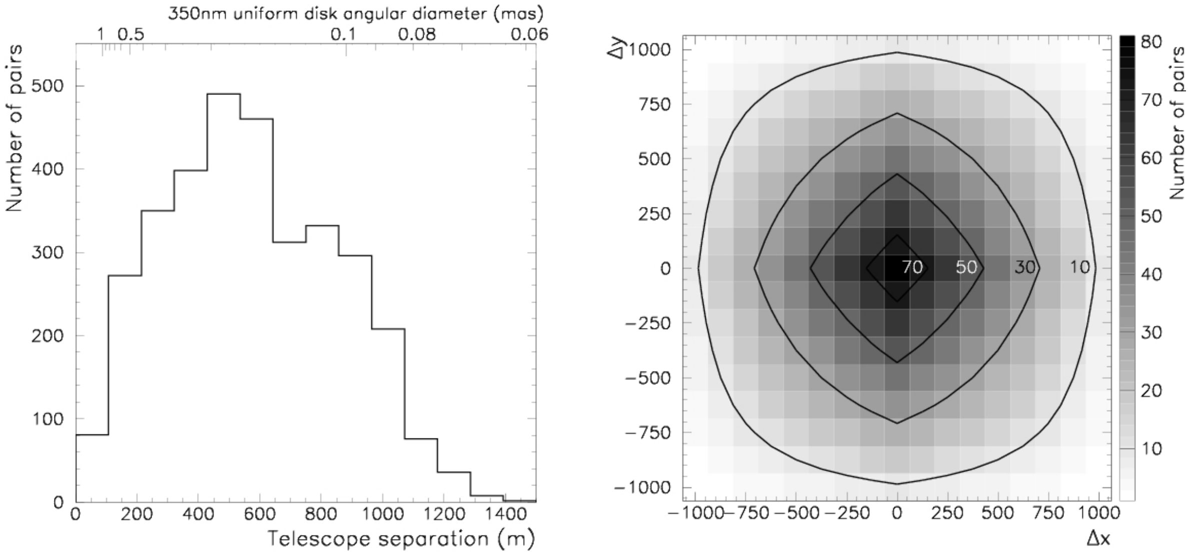

Fig. 2. Left: Distribution of interferometer baselines in one possible large-scale array of 81 telescopes placed in a 1 km^2 square grid with 125 m spacing. The upper scale indicates the baseline for the first interferometric minimum for a uniform stellar disk observed at 350 nm. Right: The two-dimensional baseline distribution, with scales in meters.

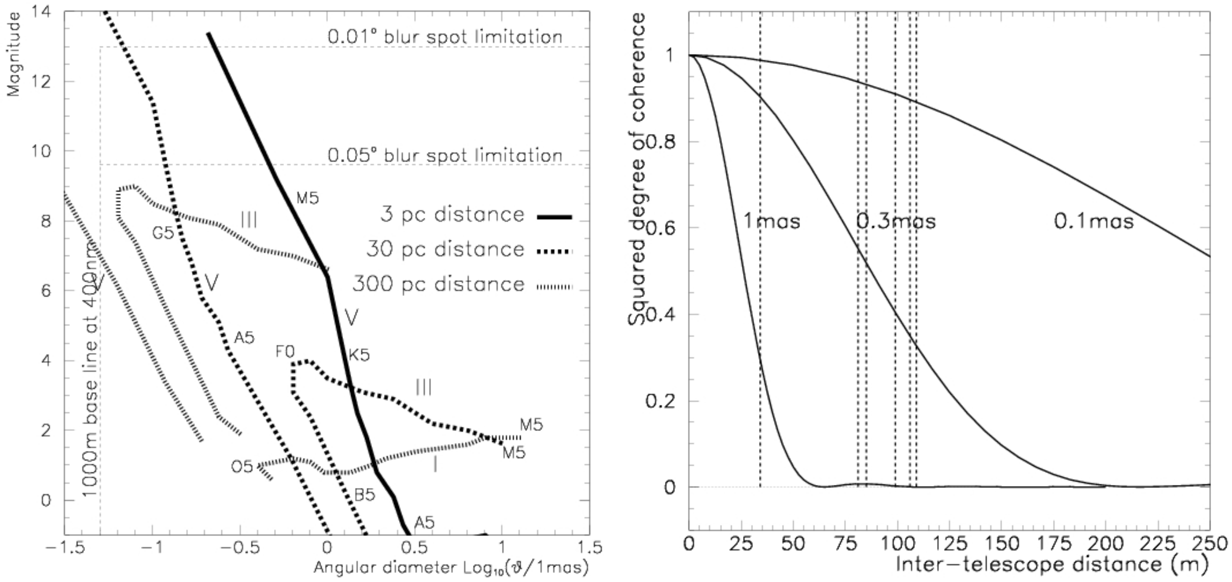

Fig.3. Left: Large Cherenkov telescope arrays would permit to measure or even image main-sequence stars within 3 parsecs, giant-branch stars as far as 30 pc and supergiants out to more than 300 pc. Right: The second-order spatial coherence (the signal measured in intensity interferometry) at λ 440 nm, for uniform stellar disks of various diameters, as function of baseline. Vertical lines indicate baselines presently available at VERITAS for observations in the zenith.

2.4 First full-scale observations with VERITAS

As steps towards future kilometric-scale optical interferometry, a number of laboratory-scale experiments in intensity interferometry were set up during the last few years, both at Lund Observatory, and at the University of Utah, leading to the first full-scale observational test of digital intensity interferometry measurements on stars during two weeks in October 2007, using pairs of the 12-meter diameter telescopes of the VERITAS array on Mt.Hopkins in Arizona. The baselines between different pairs of its four telescopes range between 34 and 109 meters.

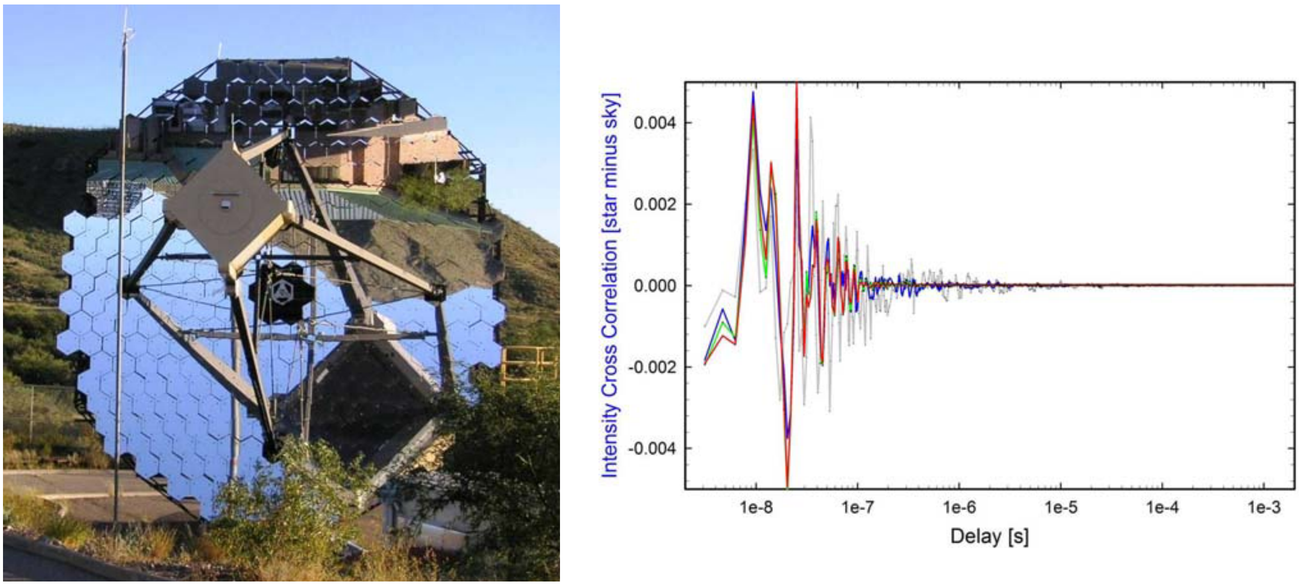

Fig. 4. Left: One of the four 12-m telescopes of the VERITAS array, used as a flux collector in the present experiments. The reflection of the photomultiplier matrix camera is seen. Right: Example of nanosecond-scale intensity cross correlations measured between one particular pair of VERITAS telescopes for the star 28 Cep (A2m; $m_V = 5.8$). The four curves illustrate how the signal converges as the integration times increase in the steps of 1-10-100-1000 seconds.

For these observations, starlight was detected by a photon-counting photomultiplier in the central pixel of the regular Cherenkov-light camera, the outgoing photon pulses were digitized using a discriminator, pulse-shaped to a width down to some 5 ns, and then transmitted from each telescope via an optical cable to the control building where they entered a real-time digital correlator (manufactured by *Correlator.com*), computing the cross correlation function for various time delays, with a time resolution of 1.6 nanoseconds. Continuous count rates up to some 30 MHz were handled, limited by the digitization and signal-shaping electronics. Actually, to limit the count rates, the detectors on each telescope were masked down to admit only some percent of the incoming starlight so that, in a future optimized setup, the stellar signal can be of very much higher fidelity than achieved here (Figure 4). Even if the present data were not processed for full time-delay normalization, and may be affected by unidentified noise sources, we believe these experiments represent the first case of optical astronomical telescopes having been connected for real-time observations through *e*-interferometry by digital software rather than by optical links (in some sense following the lead of radio *e-VLBI*).

2.5 Intensity interferometry on extremely large telescopes

Although the baselines offered by extremely large telescopes are rather smaller than the hundreds of meters discussed above, also ELTs offer good possibilities for intensity interferometry, provided they are outfitted with a suitable high-speed photon-counting instrument. This potential was recognized in the design study of the *QuantEYE* instrument[42,55,56]. There, the ELT entrance pupil was optically sliced into a hundred segments, each feeding a separate photon-counting detector. Different means of electronically combining the signal in software would yield either a photometric signal of very high time-resolution using the collecting area of the entire telescope or – by suitable cross correlations – intensity interferometry between various pairs of telescope subapertures. Since intensity interferometry is immune against atmospheric turbulence, such observations would normally be made when seeing conditions are inadequate for adaptive-optics operations, and would be practical already with the main mirror being only partially or sparsely filled with mirror segments (a situation likely to last for several years during the ELT construction phase, given the huge number of mirror segments that will make up its primary). And last (but not least!), since intensity interferometry has no limitations to operate at short wavelengths (other than detector sensitivity and the atmospheric cutoff), the achievable spatial resolution will be superior by a factor of 2-3 to that feasible by adaptive optics, given its current limitation to operate in the red or near-infrared.

2.6 The nearest future

Our various laboratory experiments, as well as the recent full-scale experiments at VERITAS, have been able to confirm the promising capabilities of digital intensity interferometry, but they have also shown the need to better understand various noise sources and systematic effects before embarking on larger-scale observing programs. In order to have a more permanent setup to test out and verify various detectors, electronics, correlators, and observational modes, two 3-meter telescopes are being installed on an east-west baseline as a dedicated interferometric facility in Grantsville, Utah[50]. Preparatory work is in progress towards an ELT instrument for very high time-resolution astrophysics and quantum optics, in that a smaller version of the *QuantEYE* concept has now been realized as *AquEYE*[57], incorporating photon-counting avalanche photodiodes with very precise timing, and already tested in observing runs on a 1.8 m telescope at Asiago, Italy.

The intensity interferometer was the first instrument in quantum optics, but there exist other applications of photon correlations and photon statistics. One related method is photon-correlation spectroscopy which essentially is an intensity interferometer, but in the temporal (not spatial) domain. By measuring the changing correlation between fluctuations in light intensity as function of time delay, the temporal (rather than spatial) coherence is deduced. Measuring temporal coherence times of nanoseconds enables spectroscopy with spectral resolution several orders of magnitude beyond that feasible with optical spectrometers, reaching $R = \lambda/\Delta\lambda \approx 10^8$, and beyond. While such resolutions have not yet been realized in optical astronomy, such actually would be required to resolve the theoretically predicted very narrow emission lines from natural cosmic lasers, such as those in η Carinae, and in other luminous stars[43,58].

Thus, long after the pioneering experiments by Hanbury Brown and Twiss, the development of high-speed electronics has caught up with the requirements inherent in intensity interferometry, bringing the promise to achieve a simple but difficult goal: to finally be able to view our neighboring stars not only as mere unresolved points of light but as the extended and most probably very fascinating and diverse objects that they really are.

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