Enabling CTA for intensity interferometry
and high time-resolution astrophysics

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Enabling CTA for intensity interferometry

- **Aim 1:** Optical imaging of disks and surfaces of hot and bright stars with unprecedented, sub-milliarcsecond, angular resolution. With a great light-collecting area, spread out over some km², CTA holds great potential for also optical stellar astronomy, in particular as a multi-element intensity interferometer. Second-order coherence of starlight can be measured by electronically correlating nanosecond-scale intensity fluctuations between pairs of telescopes, creating a kilometric-scale telescope in software, somewhat analogous to long-baseline radio interferometry. This technique is insensitive to atmospheric turbulence and also permits the use of coarse flux collectors. Detector and telescope requirements are very similar to the nominal CTA ones, the main difference being the treatment of data. Further, observations of brighter stars – as opposed to feeble Cherenkov-light – are feasible in full moonlight. While various futuristic concepts have been proposed to realize kilometric-scale amplitude/phase interferometers in space or on the ground, their complexity places them much further into the future than CTA, which thus could become the first kilometric-scale optical imager in astronomy.

High time-resolution astrophysics

- **Aim 2:** Searching for optical variability on extremely short timescales (micro-, or even nanoseconds, such as already observed in radio) from relativistic and compact objects such as neutron-star binaries, pulsars, or black-hole candidates. Despite CTA’s limited image sharpness (and the ensuing night-sky background), its huge collecting area distributed over many telescopes makes such searches more sensitive than with any existing large telescope since the study of microsecond phenomena requires correspondingly high photon fluxes to be recorded.
Highest spatial resolution in optical astronomy

The science cases for constantly higher angular resolution in astronomy are overwhelming, indeed driving much of the world-wide instrumentation developments from gamma rays through long-wavelength radio. This is the current state of the art:

**Left:** Actual near-infrared image of the pulsating Mira-type star T Leporis, obtained by combining hundreds of phase-interferometric measurements with *VLTI*, ESO’s *Very Large Telescope Interferometer*. The central disk is the stellar surface, surrounded by a shell of expelled molecular material. The resolution is 4 milli-arcseconds. (J.-B. Le Bouquin et al., *Astron. Astrophys.* **496**, L1, 2009).

**Right:** Artist’s vision of the 100-meter equivalent-size telescope (red circle), obtained by reconfiguring small movable telescopes at ESO’s Paranal observatory. (ESO)

Even without full imaging, longer-baseline optical interferometry gives great insights into 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 (P. Kervella, *New Astron. Rev.* **51**, 706, 2007), or the A7 V star Altair (J.D. Monnier et al., *Science* **317**, 342, 2007); if the star instead is observed from near its poles, a radial temperature gradient is seen, as in the case for the A0 V star Vega (D.M. Peterson et al., *Nature* **440**, 896, 2006). Possibly, stars with rapid and strong differential rotation could take on weird shapes, midway between a donut and a sphere (K.B. MacGregor et al., *Astrophys. J.* **663**, 560, 2007).

Examples of exceptional stars as prime candidate targets for intensity interferometry (H. Jensen; presented at the workshop on Stellar Intensity Interferometry, Salt Lake City, January 2009).
Even more extreme objects are represented by exceptionally luminous and highly variable objects such as \( \eta \) 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 (R.van Boekel et al., *Astron. Astrophys.* **410**, L37, 2003).

These examples show how we are on the verge of starting to view stars as the vast diversity of objects 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. Bright stars in the sky typically have angular sizes of a few milliarcseconds, requiring interferometry over hundreds of meters to enable any stellar surface imaging. The science case was summarized by Dravins & Le Bohec (*SPIE Proc.* **6986**, 698609, 2008):

*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.*

**Longer-term alternatives**

Current interferometers for highest-resolution optical astronomy are exemplified by ESO’s *VLTI* in Chile, and the *CHARA* array in California. These are of the Michelson (amplitude/phase) -type, combining optical light from separate telescopes, having it interfere in a common focus location. However, their required optical precision and atmospheric stability to within a fraction of an optical wavelength, become very challenging for baselines much longer than 100 m, and at shorter visual wavelengths.

With an overwhelming science case, the challenge of microarcsecond imaging is limited entirely by technological possibilities. Several – more or less futuristic – kilometric-scale interferometers in space, or

**The Stellar Imager (SI) “Vision Mission”: Imaging the UV/Optical Universe with Sub-milliarcsecond Resolution**

![Image of Stellar Imager](image1)

A comparable space mission, the *Luciola hypertelescope*, was proposed for the ESA Cosmic Vision 2015-2025 plan. The *Luciola* flotilla of many small collector mirrors would operate like one giant diluted mirror, with focal beam-combiners exploiting the sky image formed at the focal surface (A.Labeyrie et al., *Exp.Astron.* 23, 463, 2009):

![Image of Luciola hypertelescope](image2)

Despite the challenges of atmospheric turbulence, very-long-baseline optical aperture synthesis might be feasible also from the Earth. The probably best atmospheric conditions are in Antarctica, and an imaging synthesis optical array has been proposed near the Concordia base at Dome C. The many individual telescopes of this *KEOPS* array (*Kiloparsec Explorer for Optical Planet Search*) would be grouped around an optical recombiner (F.Vakili et al., *EAS Publ.Ser.* 14, 211, 2005).

All these proposals of kilometric-scale optical imagers appear physically feasible, and when ultimately realized, promise to transform our view of the Universe. However, they are also technologically very challenging: these visionary projects were reviewed for the recent *ASTRONET* roadmap in defining priorities for a strategic plan of European astronomy, but only “considered but not ranked” because their obvious complexity and cost seems to place them well beyond the *ASTRONET* time horizon.
The CTA Alternative: The first kilometric-scale optical imager?

CTA will have many telescopes distributed over at least some square km. Besides its prime task of observing Cherenkov light from gamma rays, the unprecedented optical collecting area spread over a large area forms an excellent facility for ultrahigh angular resolution (sub-milliarcsecond) optical imaging through long-baseline intensity interferometry (different from amplitude/phase interferometry), enabling a digital revival of a method originally developed by Hanbury Brown et al. already back in the 1960’s.

Advantages of intensity interferometry

Although not a replacement for the envisioned flotillas of future, much more general-purpose, phase interferometers in space, for some specific classes of brighter objects – such as hot stars – comparable imaging could be realized very much sooner by ground-based intensity interferometry, measuring the second-order (i.e., intensity-, not phase-) coherence of light.

The great observational advantages of intensity interferometry are 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: the noise budget relates to electronic timescales of 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 thus needs only to correspond to some reasonable fraction of this. For realistic time resolutions of 1–10 ns, the corresponding light-travel distances are 0.3–3 m, and optical errors of maybe one tenth of those can be tolerated, enabling coarse flux collectors to be used (rather than precise telescopes), and avoiding sensitivity to atmospheric seeing (thus enabling both very long baselines and observations at short optical wavelengths). Also, objects may be observed near the horizon, accessing a greater part of the sky from any given observatory location.

Electronic real-time combination of signals from multiple telescopes has recently been established as a technique in very-long-baseline radio [phase] interferometry in so-called e-VLBI. In a way, this method of electronic intensity interferometry may be seen as the optical equivalent to e-VLBI, essentially synthesizing an optical telescope in digital software.
However, since a second-order physical quantity is measured, the method is expensive in terms of the signal required, and both large photon fluxes (thus large telescopes) and very high time resolution are required, even to observe brighter stars. Already the 6.5 m flux collectors of the original intensity interferometer set up at Narrabri, Australia, were larger than any other optical telescope at that time.

The original intensity interferometer at Narrabri observed one star simultaneously with two 6.5 m flux-collecting telescopes whose mutual distance was gradually changed by moving them on railroad tracks. (University of Sydney)

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 opto-mechanical systems. A timing improvement to 100 ps, say, would require mechanical accuracies on mm levels, going beyond what is achieved in Cherenkov telescopes, and beginning to approach the levels of turbulence fluctuations in atmospheric path-length differences (on order 10 ps).

**What is measured in an intensity interferometer?**

The intensity interferometer was originally developed for measuring stellar diameters. At the time of its design, 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 it is seen as 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 (bosons), and therefore sharing the same type of Bose-Einstein quantum statistics. However, following the pioneering experiments by Hanbury Brown et al., there have been no further applications to astronomy.

The intensity interferometer is an instrument whose functioning is indeed somewhat 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 interferometer, whose scientific aims the original intensity interferometer was replicating. Two telescopes simultaneously measure the random and very rapid [quantum] fluctuations in the intensity of light from some particular star. With the telescopes sufficiently close to one another, both measure the same signal, but when moved apart, the fluctuations gradually become de-correlated: how soon this occurs gives a measure of the spatial coherence of starlight, and thus the angular extent of the star. The second-order spatial coherence is thus
obtained from the \textit{correlation} between the intensity fluctuations measured in each of the two telescopes, and how this correlation gradually changes as the telescopes are moved apart from one another.

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

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

where $\tau$ 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), a simple relation exists between 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 be deduced, yielding stellar shapes and sizes from intensity-correlation measurements.

A retrospective overview of the original intensity interferometer is in a monograph by R.Hanbury Brown: \textit{The Intensity Interferometer} (1974), while the optical and physical principles are explained in various textbooks, e.g., A.Labeyrie et al.: \textit{An Introduction to Optical Stellar Interferometry} (2006).

\textbf{Reconstructing images from intensity interferometry}

A two-telescope system, such as originally used by Hanbury Brown et al., provides the angular size and shape of the source but – since only few Fourier components of the image brightness distribution are measured, and phase information is not retained in the modulus of the visibility – does not permit a full source image (possibly asymmetric and complex) to be reconstructed. This limitation, however, may be circumvented in systems with many telescopes, sampling across all possible pairs of baselines, applying mathematical relations between the magnitudes of the Fourier components and their phases:

Numerical reconstructions of source images from simulated intensity interferometry observations. True images of oblate stars and of a star crossed by a dark circumstellar disk are shown yellow on black; reconstructed images are at bottom. The grayscale image at upper right is the two-dimensional Fourier transform of the source image. (P.Nuñez, et al.; presented at the workshop on Stellar Intensity Interferometry, Salt Lake City, January 2009)
With an assumed model for the CTA arrangement of telescopes, the number of baselines and their length distribution is obtained, and the resulting interferometric resolution can be computed. The resolution at short optical wavelengths now reaches microarcseconds, more than two orders of magnitude higher than possible with, e.g., the Hubble Space Telescope! (S.Le Bohec; P.Nuñez et al; Salt Lake City workshop, January 2009)

Limiting magnitudes and primary targets

For intensity interferometry, the signal-to-noise ratio is proportional to: detector quantum efficiency; geometric mean of the areas of the two telescopes; photon flux per unit optical frequency bandwidth; square root of the integration time; and square root of the electronic bandwidth. A realistic magnitude limit seems to be around $m_V \approx 9$ (but depending on night-sky background and other circumstances):

Single-telescope mirror sizes needed to achieve $S/N = 3$ in 1h, 2h, or 3h, at a given visual V magnitude. The inset highlights capabilities of current large astronomical telescopes (VLT and LBT), and of the 17-m MAGIC. The HBT arrow indicates what was achieved by the original Narrabri interferometer. $S/N$ denotes the excess counts of coherent intensity fluctuations over the fluctuations of the random coincidences. These estimates appeared in a design study towards the European Extremely Large Telescope (D.Dravins et al., QuantEYE. Quantum Optics Instrumentation for Astronomy. OWL Instrument Concept Study, ESO, 2005)
The S/N ratio, however, is independent of the optical passband (and can thus be improved by observing in multiple spectral channels). This may appear strange since it implies that the S/N in measuring a small photon flux in a single spectral line is the same as that from a large flux in white light. The explanation is that, for any realistic instrumentation, one always measures only a partial [temporal] coherence of light. Increasing the spectral passband decreases this coherence by the same factor as the greater photon flux permits its more precise determination. Ultimately, the S/N depends only on the [brightness] temperature in the source. For stars with the same angular diameter but decreasing temperature (thus decreasing fluxes), telescope size must successively increase to maintain the same S/N. When the mirrors become so large that the star is resolved by a single mirror, the S/N drops. Therefore, for stars cooler than a given temperature, no gain results from larger mirrors, indicating that the technique is most powerful in studying hotter targets, including in their individual spectral lines. As first targets for early observations one would therefore naturally select some group of particularly interesting hot stars:

Hot and bright stars as examples of primary targets for intensity interferometry: *The Bright Star Catalogue* contains 34 stars that are either both very bright (m_V < 2) and hot (T_eff > 9,000 K), or very hot T_eff > 25,000 K. For reference, the hottest known white dwarf was added at top right. Circle sizes indicate relative angular diameters where available. (H.Jensen, presented at the workshop on Stellar Intensity Interferometry, Salt Lake City, January 2009)

**High-time-resolution astrophysics with CTA**

Further uses of CTA in optical astronomy include searching for very rapid variability (on micro-, or even nanoseconds, such as already observed in radio from pulsar bursts) from relativistic and compact objects such as neutron-star binaries, pulsars, or black-hole candidates. Despite CTA’s limited image sharpness (and the ensuing contribution from the night-sky background), the very large collecting area distributed over several independent telescopes (not only minimizing atmospheric influences but also permitting to check noise transients), would make such searches more sensitive than with any existing large telescope. Although the number of photons per second in the background skylight may be very great, their number per microsecond is modest and the sensitivity for detecting the very shortest fluctuations becomes mainly a function of light-collecting area:
Comparison of one H.E.S.S. 100 m² Cherenkov telescope with a “normal” optical telescope for high-time-resolution photometry. For a given duration of an optical flare $\tau$, the diameter of an optical telescope free from any night-sky-background (NSB) was calculated to achieve the same sensitivity as H.E.S.S. For the most rapid phenomena, the large collecting area becomes of dominant importance. (C.Deil et al., Astropart.Phys. 31, 156, 2009).

Simulated observations of the optical Crab pulsar with a MAGIC 17-m telescope illustrate the potential of large Cherenkov telescopes for high-speed astrophysics. The intensity profile (top), folded with the pulsar 33 ms period, only hints at the main pulse around 0.006 s. In the temporal autocorrelation (bottom), each peak reveals some variability timescale. The peak at 33 ms (and its harmonics) is the pulsar period; those around 13 and 20 ms are the times between the main and secondary, and between the secondary and main peaks, etc. Although the pulsar signal is only some $10^{-6}$ of the background, a good signal can be retrieved down to microsecond resolutions within reasonable integration times. The flux ratios between the pulsar, the Crab nebula, and the sky background were taken from E.Oña-Wilhelmi et al., Astropart.Phys. 22, 95, 2004. (Ricky Nilsson, Lund Observatory).

Requirements on CTA design

Some details in the CTA design should be considered to enable its efficient use also as an intensity interferometer. Actually, the required amendments appear to be minimal since the signals to be measured are very similar to those of Cherenkov flashes: nanosecond timescales and relatively short optical wavelengths. Most probably, the same types of very fast photon-counting detectors can be used, with very similar data transmission to some computing location, the main difference being the later signal handling in either hard- or software. A number of issues are essential, while some further ones are desirable.
**Essential: Detectors**

An important issue is the detectors. At existing Cherenkov telescopes, two different approaches have been taken for enabling optical non-Cherenkov observations: either a central, possibly specialized, portion of the camera (“pixel”), or a separate, additional camera. Each option has its advantages and disadvantages:

**Central pixels?**

A central “pixel” implies that some central part of the camera (imaging the point in the sky that is tracked by the telescope), i.e., a photomultiplier or detector module, can be [at least] electronically accessed, irrespective of the rest of the Cherenkov camera. The advantage is that it will be readily available, can use standard power supplies, signal cables, etc., thus allowing experiments to be carried out quickly with a minimum of additional investment, perhaps searching for high-speed variability in a just discovered optical afterglow gamma-ray burst. It would permit [short] experimental measurements where it would not be realistic for observers to provide additional equipment, especially if many telescopes are involved. On the negative side, however, the different electronic requirements in observing, e.g., bright stars (rather than feeble Cherenkov light) could lead to conflicts in the adjustments or calibrations of the detectors unless the central pixel is mechanically and electronically independent from the rest of the camera. Also, detector replacement could be complex if one has to mechanically intrude among all other detector units.

This option also requires a provision to [manually?] mount some small optical element(s) immediately in front of this central pixel. In case of, e.g., a 25-mm diameter photomultiplier, that element could be a 25 mm diameter color filter of a few mm thickness plus a similar-sized optical lens for focusing on stars at “infinity” (rather than on those heights in the atmosphere where most Cherenkov light originates), in case the telescope itself has no such re-focusing capability. The filter would both select some particular optical region, and decrease the stellar flux to a manageable level (white-light photon flux for a bright star in a large telescope is much higher than existing photon-counting detectors can handle). Since the mount for such filters would only be the diameter of the photomultiplier housing (not protruding onto neighboring pixels), these color filters can only be of the dye type, selecting relatively broad spectral regions.


**Right:** Schematics of the *MAGIC II* modular camera, consisting of 163 detector clusters with 7 photomultiplier pixels in each (F.Goebel, Proc.30th ICRC 3, 1485, 2008).
Dedicated cameras?

Even if central pixels permit some initial experiments, the further optimization of intensity interferometry or high-speed optical astrophysics is likely to involve experiments with different detectors, color filters, polarizers, or other components which might be awkward to mechanically and electronically [re]place inside the Cherenkov camera. Narrow-band color filters (required to isolate individual spectral lines) will probably be of interferometric type and may have to used in parallel light, requiring collimating optics with beam diameters much in excess of single-pixel dimensions. All such items could be integrated into an independent unit which, to minimize any disturbances to the Cherenkov camera, should be mounted on the outside of the camera shutter lid. This option comes with the requirement to accept an extra mass (tbd kg), with size up to tbd×tbd×tbd cm, an electric power supply (tbd W), and signal cables to/from this location. Since some consortium will have to provide this instrumentation, finite resources could limit the number of telescopes thus equipped. In any case, CTA should have a provision to mechanically mount such equipment on the outside of all camera lids. One such construction is a 7-pixel unit on H.E.S.S.:

![7-Pixel-Camera](image)

A 7-pixel camera mounted onto the lid of the Cherenkov camera of a H.E.S.S. telescope, using a plane secondary mirror to put it into focus. Its central pixel records the light curve of the target, while a ring of six ‘outer’ pixels monitors the sky background and acts as a veto system to reject atmospheric background events (C.Deil et al., Astropart.Phys. 31, 156, 2009)

**Essential: Timing of photon-pulse train within < 1 ns to computing location**

Already current correlators, used in photon-counting laboratory experiments preparing for stellar intensity interferometry, have time resolutions reaching 1.4 ns, and comparable time resolutions (but not much higher) are expected to be used in CTA observations. Not to compromise the signal of temporal photon statistics, the error budget should not have components in excess of about 1 ns. In particular, the timing precision of the photon-pulse train from the detector to a central computing location should be assured to no worse than one nanosecond (this applies to the timing of a leading edge; the pulse-width may be wider). Such performance can be achieved by signal transmission in optical fibers, and presumably will be implemented for CTA in any case (e.g., the present MAGIC data flow has a trigger jitter of 1.25 ns).
Desirable: Telescopes with isochronous optics ($\Delta t < 1$ ns)

For intensity interferometry, the signal-to-noise ratio is proportional to the square root of the electronic bandwidth (the [inverse] time resolution at which stellar intensity correlations are measured). Therefore, it is preferable to have a maximally isochronous design for the telescope optics, i.e., photons striking any part of the entrance aperture should arrive to the focus at the same time. Among existing Cherenkov telescopes, this is satisfied by parabolic designs but not by the Davies-Cotton concept. Since foreseen correlators have resolutions approaching 1 ns, it is desirable that the error budget should not have components in excess of such a value. (But, since the time dispersion in any case should not exceed the intrinsic spread of the Cherenkov wavefront of a few ns, a performance adequate for intensity interferometry is guaranteed anyway, but the signal-to-noise ratio will improve with better isochronicity.)

Large Cherenkov telescopes are usually parabolic (e.g., MAGIC and H.E.S.S. II) and thus in principle isochronous – apart from minute effects caused by individual mirror facets being spherical rather than parabolic (e.g., for the 17 m diameter MAGIC I telescope, the intrinsic time spread is stated as 400 ps). Smaller telescopes (such as foreseen to be grouped in the outer parts of the CTA array, thus spanning the longest baselines) more often have the Davies–Cotton layout (e.g., H.E.S.S. Phase I and VERITAS), giving smaller aberrations off the optical axis compared to a parabolic design. Here, all reflector facets have the same focal length $f$, arranged on a sphere of radius $f$, causing the structure to be not isochronous: e.g., for the H.E.S.S. Phase I telescopes, the photons spread over $\Delta t \approx 5$ ns, with an rms width $\approx 1.4$ ns.

Of course, there exist many aspects in selecting the telescope design. Here, we just recall that there exist alternative designs which satisfy high demands on isochronicity, such as a Schmidt-type one (M.I.Mirzoyan & M.I.Andersen, *Astropart.Phys.*, 31, 1, 2009, or the Schwarzschild-Couder two-mirror type (V.Vassiliev et al., *Astropart.Phys.* 28, 10, 2007).

Desirable: Good optical quality – sharp images limit the sky background

Any stellar measurements will have contributions from the background light from the night sky. Although this background does not contribute any net intensity-correlation signal, it increases the photon-counting noise and also takes in other sky events (meteors, lightning, etc.). Telescopes with good optical quality will generate less background (especially noticeable when observing under moonlight conditions):

Any reasonable optical quality will be adequate for intensity interferometry as such, but the magnitude $m_v$ of the faintest stars that can be studied will depend on the optical point spread function. The numbers give the equivalent stellar magnitudes for different image sizes, and for different sky brightness conditions.
Desirable: Telescopes on a somewhat irregular grid offer more baselines

The placement of telescopes in interferometers can be optimized for the best coverage of the (u,v)-plane, i.e. the plane of the Fourier transform of the object image. As the star gradually crosses the sky during a night, the projected baselines between pairs of telescopes change, depending on the angle under which the star is observed. If the telescopes are placed in a regular geometric pattern, e.g. a repetitive square grid, the baselines that are “seen” by the star are similar for many pairs of telescopes, and only a limited region of the (u,v)-plane is covered, limiting the spatial frequencies that can be sampled, and thus the sharpness in the reconstructed image. Since stars rise in the east and move towards west, baselines between pairs of telescopes that are not oriented exactly east-west will trace out a wider variety of patterns, and improve the (u,v)-plane coverage. Because of such considerations, existing phase interferometers (both optical and radio) locate their component telescopes in some optimal manner (e.g., in a Y-shape, or in logarithmic spirals), while placements at some observatories are constrained by local geography:

*Left:* The *ESO Very Large Telescope* and interferometer on Cerro Paranal in Chile. The four large telescopes were placed in a pattern for best interferometric coverage, given the topographic constrains of the site; small movable telescopes can be moved to supplementary locations. *Right:* Telescope placement can be optimized using different criteria (L.M.Mugnier et al., *J.Opt.Soc.Am.A* 13, 2367, 1996).

In CTA, its smaller telescopes will be very numerous, and their exact placement is not essential for interferometry (except that an exact east-west grid should be avoided). However, the situation is different for the fewer medium-size, and the very few large telescopes. Avoiding placing them on a regular grid (such as a square) will offer a wider variety of baseline lengths, give a better coverage of the (u,v)-plane, and permit better image reconstruction. (Also, it is understood that the stereoscopic reconstruction of Cherenkov-light trails in the atmosphere is improved by not having telescopes in repetitive patterns.)

**Impact on CTA operations**

The impact of intensity interferometry on other operations is likely to be very modest. An important aspect is that – while brighter moonlight may preclude observations of the feeble atmospheric Cherenkov light – measuring brighter stars is no problem, enabling CTA operations during both bright- and dark-Moon periods. (Of course, all observations desire a minimum of background light, and at some point there might be issues if observing faint stars; however there are thousands of observable stars in the sky brighter than the moonlit sky background.)
Synergy with other projects: Intensity interferometry at the E-ELT?

The completely dominant cost in realizing intensity interferometry stems from establishing a grid of large light collectors spread over a significant area, hence the advantages of the synergy with CTA. Another facility with a synergy potential is E-ELT, the planned European Extremely Large Telescope. Although its 42-m mirror aperture is much smaller than the CTA baselines, its performance may permit unique measurements. Likely timelines suggest the completion of E-ELT to be several years later than that of CTA, and intensity interferometry techniques developed at CTA might later be applied also at the E-ELT.

Like in all large ground-based telescopes, imaging with the E-ELT will be limited by atmospheric turbulence. Diffraction-limited performance in the [near-]infrared (with partial seeing improvements also at shorter wavelengths) is to be achieved using adaptive optics with laser guide-stars. However, such performance is unlikely to result more than some fraction of the time, and also not in the beginning of E-ELT operations. Since effects of atmospheric turbulence follow a steep function of wavelength, adaptive optics are rather inefficient at shorter visual wavelengths, so any method to reach diffraction-limited performance in the blue or violet will improve the angular resolution by a significant factor.

At present, no E-ELT instrument is foreseen that would be capable of intensity interferometry; however such an option was considered in the design study of QuantEYE, an instrument for very high time resolution astrophysics, quantum optics, and intensity interferometry (D.Dravins et al., OWL Instrument Concept Study, ESO, 2005; D.Dravins et al., MPIA 106, 85, 2006; C.Barbieri et al., J.Mod.Opt. 54, 191, 2007). Comparing to other E-ELT auxiliaries, such an instrument would hardware-wise be extremely small and simple, just a photometer which internally images each mirror segment onto a separate photon-counting ultrahigh-speed detector (the complexity instead coming in the ensuing data handling).

One cannot yet foresee how the E-ELT construction will advance, e.g., the commissioning of all its 984 mirror segments that make up its 42-m primary mirror could well last for several years, during which the main mirror will be only partially filled but combinations of mirror segments might perhaps already then be considered for intensity interferometry, if the technique had been proven and appropriate (visitor?) instrumentation available. The main differences relative to CTA would be the much better point-spread function (seeing-limited to about ≈ 1 arcsecond; reaching fainter sources thanks to lower sky background) and the shorter, but much more numerous, baselines (a thousand independent mirror segments imply hundreds of thousands of interferometric pairs!). Comparable imaging would be impossible with either the standard E-ELT (diffraction limited only in the infrared), nor by CTA (incapable in imaging over tens of meters), and nor by space telescopes (too small apertures), thus offering a niche of unique science.

Outstanding issues for future studies

The above discussion has concerned requirements on the CTA design to enable intensity interferometry and optical high-speed observations. Obviously, several issues have to be tackled to develop and demonstrate intensity interferometry as a reliable technique for high-resolution astronomy. While perhaps not very important already for the present CTA design study, those issues include topics such as: developing prototype instrumentation to carry out test observations; evaluating the alternatives of real-time hardware-, or off-line software correlation; understanding noise sources of alternative detectors; understanding noise sources in the sky; feasibility of simultaneous observations in different wavelengths; understanding the physical information content in also third- and higher-order correlation functions;
demonstrating a full image reconstruction from simulated CTA observations; selecting the most promising astrophysical targets and their spectral features; etc. Further, there is considerable experience in somewhat related fields, with which collaborations should be developed. These include long-wavelength radio [phase] interferometers (LOFAR, MeerKAT), which are handling data whose electronic radio-frequency passbands (on order 100 MHz) are very comparable to the electronic passbands in our optical intensity fluctuations. Although intensity interferometry has not recently been used in astronomy, it has broad applications in high-energy particle physics since the basic quantum processes are analogous for kaons, pions, and other bosons, particles which like photons have integer quantum spin, and display enhanced intensity correlations whenever a small source is observed.

At “Starbase Utah” near Grantsville outside Salt Lake City – http://www.physics.utah.edu/~lebohec/StarBaseWeb/, two 3-m telescopes were recently set up as a testbed for developing techniques in intensity interferometry and Cherenkov-light studies. This photo of some among the participants from the workshop on Stellar Intensity Interferometry (January 2009) includes several task contributors to this report.

Selected references

Historic retrospective on astronomical intensity interferometry

Physical principles of astronomical intensity interferometry

and texts like:
Potential of intensity interferometry with Cherenkov telescope arrays

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Optical observations with Cherenkov telescopes


High time resolution optical astrophysics


Intensity interferometry in high-energy particle physics


SUMMARY: Desiderata in enabling CTA for optical intensity interferometry

Overall, the required CTA design amendments appear to be minimal since the signals to be measured are very similar to those of Cherenkov flashes, the main difference being the later data handling in either hard- or software. However, for maximum versatility, the following aspects should be considered:

**Detectors**
At existing Cherenkov telescopes, two different approaches have been taken for enabling optical non-Cherenkov observations: either (1) a central detector pixel (e.g., MAGIC I), or (2) an additional camera mounted outside the normal Cherenkov camera (e.g., H.E.S.S.):

1. A central “pixel” means that the central part of the Cherenkov camera is electronically accessible, independent from the rest. The advantage is that it would be readily available, also for improvised observations of suddenly emerging optical targets. A disadvantage is that modifications to this detector unit imply a mechanical intrusion into the camera.

2. Irrespective of whether (1) is offered, provision is needed to mount small dedicated cameras (provided by external groups), on the outside of the Cherenkov camera shutter lids. This would enable optimized detectors to be developed while minimizing disturbances to the main camera.

**Timing of photon-pulse train to computing location**
Timing analysis is foreseen with resolutions approaching 1 ns, and the timing precision of the photon-pulse train from the detector to a central computing location should therefore be no worse.

**Telescopes with isochronous optics**
Since the signal-to-noise ratio improves if more rapid stellar intensity fluctuations can be measured, a maximally isochronous design for the telescope optics is desired, i.e. photons striking any part of the entrance aperture should arrive to the focus at the same time, ideally within about 1 ns.

**Good optical quality**
Telescopes with a narrow point spread function limit the contributions from the night sky background.

**Telescopes on a somewhat irregular grid offer more baselines**
As a star crosses the sky, the projected baselines between pairs of telescopes change, depending on the angle under which the star is observed. Avoiding placing telescopes on a regular and repetitive grid offers a wider variety of baselines. Since stars rise in the east, moving towards west, baselines between pairs of telescopes that are not oriented exactly east-west trace out a wider variety of baselines.

**CTA operations**
While brighter moonlight may preclude observations of feeble Cherenkov light, measuring bright stars for intensity interferometry is no problem, enabling operations during both bright- and dark-Moon periods.

**Issues for future studies**
Outstanding tasks include: prototype instrumentation and test observations; evaluating alternative real-time hardware-, or off-line software data handling; understanding noise in detectors and in the sky; simultaneous observations in different wavelengths; understanding physical information content in also higher-order optical correlation functions; demonstrating full image reconstruction from simulated CTA observations; selecting the most promising astrophysical targets and their spectral features; and assessing experiences from radio phase interferometry, and intensity interferometry in high-energy particle physics.