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Using Atmospheric Cherenkov Telescope arrays as Intensity Interferometers

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The Narrabri intensity interferometer was successfully used until 1974 to observe 32 stars [1], all brighter than B=+2.5, among which some were found to have an angular diameter as small as 0.41+/-0.03 milli-arc-seconds (mas). The technique was then abandoned in favor of Michelson interferometry [2, 3]. Here we consider the technical feasibility and scientific potential of implementing intensity interferometry on Imaging Air Cherenkov Telescope arrays. The scientific motivations are varied, including stellar diameter measurements and investigations of the circumstellar environment. Long baselines and short wavelengths are easily accesible to this technique, making it uniquely suited for some applications.

1. Intensity Interferometry

In a stellar intensity interferometer[4], the light from a star is received by two separated photoelectric detectors through a narrow-band filter. The technique relies on the fact that the current output fluctuations Δi_1 and Δi_2 of the two detectors are partially correlated. The principal component of the fluctuation is the classical shot noise which does not show any correlation between the two detectors. In addition, there is a smaller component, the wave noise, that shows some correlation. Because of this correlation, the product of the fluctuations in each detector will be positive, and provide a measurement of the square of the degree of coherence $\gamma_{\rm d}$ of the light at the two detectors. $\gamma_{\rm d}$ is equivalent to the fringe visibility measured with a Michelson interferometer. It depends upon the angular diameter θ of the star, the wavelength λ and the distance between the two detectors d . In the case of a star modeled as a uniform disk it reaches zero when $\mathrm{d} = 1.22\lambda/\theta$. In fact, according to the van Citter-Zernike theorem, $\gamma_{\rm d}$, the complex degree of coherence is the normalized Fourier transform of the source intensity distribution projected on a line parallel to the line joining the two detectors. Measuring $|\gamma_{\rm d}|^2$ provides information on the angular structure of the source.

The shot noise from both channels is responsible for most of the correlator output fluctuations to which the wave noise correlation has to be compared for the sensitivity of a specific experiment to be estimated. The signal to noise ratio can be expressed as $(S/N)_{RMS} = A\alpha n|\gamma_d|^2(\Delta fT/2)^{1/2}$ where A is the collection area of each telescope, α the photo-detector quantum efficiency, Δf the bandwidth of the electronics including the photo-detector, T the integration time, n the intensity of the source in photons per unit optical bandwidth, per unit area and per unit time. Using 100 m^2 telescopes with 30% quantum efficiency photo-detectors, 1 GHz electronics during a full 10 hours night would permit to measure the diameter of stars with magnitude less than 8.

1.1 Comparison with Michelson Interferometry

After decades of development, a number of world-class instruments for long-baseline optical interferometry are currently operating or soon to come online (VLTI, Keck interferometer). These are, without exception, based upon the Michelson technique for interferometry. The advantages of this method are clear. As it relies on the visibility of fringes produced by the amplitude interference formed by the light collected by two telescopes, it permits measurements of stars much dimmer than intensity interferometry with same size telescopes. Furthermore, with intensity interferometry, only the modulus of the coherence is measured and the two-dimensional image can only be reconstructed up to a central symmetry.

Unfortunately, Michelson interferometry is also a very challenging technique as the relative lengths of the light paths have to be controlled to an accuracy smaller than the wave length of the light being measured. This requires high optical quality and high precision tracking. The situation is further complicated by the effects of atmospheric turbulence which must be actively compensated for. These difficulties have constrained Michelson interferometry to small baselines (most interferometers provide baselines of less than 100m) and long wavelengths (most interferometers work at more than 1μm) while the maximal angular resolution is proportional to the base line and to the inverse of the wavelength.

Intensity interferometry, on the contrary, only requires control of the light paths to an accuracy fixed by the light coherence time ($\sim$ 100ns). It is therefore insensitive to atmospheric fluctuations and easy to implement at shorter wavelengths. In addition, as the correlation is made *after* the photons are detected, intensity interferometry also permits simultaneous measurement of $|\gamma_d|^2$ between any two-telescope pair of an array, while with Michelson interferometry this is impossible without a loss in sensitivity. The major drawback associated with intensity interferometry is the need for very large quantities of light. The necessary large light collectors do not however need to be of optical astronomy quality as they are only required to isochronally concentrate the light on a photo-detector.

2. Possible Implementations

The Narrabri interferometer consisted of two telescopes 6.5m in diameter with an 11m focal length. The telescopes were carried on trucks running on a circular railway track 188m in diameter. This allowed for a baseline from 10m to 188m to track any star while keeping the line joining the two telescopes perpendicular to the direction of the star in such a way that no delay was required to bring the signals in time. At the focus of each telescope, the converging light was collimated and passed through an interference filter centered on 443nm with a passing bandwidth of 10nm. The measured light intensity was converted to a currant by a photomultiplier tube of 25% quantum efficiency at 440nm and 60MHz effective bandwidth. The signals were sent to the control building where the correlator, a transistor based linear multiplier, was located.

While the Narrabri instrument was successful, significant sensitivity improvements can be achieved by observing the same star with a full array of telescopes providing measurements over several baselines simultaneously [5]. The number of baselines is proportional to the square of the number of telescopes in the array. This could be combined with the technological developments during the last 30 years which provide higher quantum efficiency photo-detectors, higher bandwidth photo-detectors and electronics and the possibility of processing digitized signals at high speed.

Modern ground-based γ-ray observatories (CANGAROO, HESS, MAGIC and VERITAS) consist of arrays of IACTs which satisfy many of the specifications for an intensity interferometer. The characteristics of several IACT arrays are summarized in Table 1. We have included HESS-16 in order to illustrate the benefits of a large array. IACT arrays typically extend over $\sim$ 200m making them comparable to the Narrabri interferometer in terms of the angular resolution they could achieve. The telescopes have diameters ranging from 10 m to 17 m providing a gain of a factor of 2.8 to 8.0 in sensitivity (1 to 2.3 magnitudes) when compared to the Narrabri interferometer. Furthermore, these arrays, with one exception, are made up of 4 telescopes and so permit measurements over up to 6 baselines simultaneously (120 in the case of HESS-16). For the measurement of a symmetric object this corresponds to a sensitivity gain of $\sim$ 2.5 or one magnitude ($\sim$ 10 or 2.5 magnitudes for HESS-16). Figure 1 shows $|\gamma_\mathrm{d}|^2$ as a function of baseline for stars of different angular diameters. Measurements at only two points along this curve enable θ to be measured unambiguously.

Table 1. Characteristic of the major IACT arrays compared to the Narrabri interferometer. N is the number of telescopes, A is the collection area of each telescope, Δt is the dime dispersion introduced by the optics, $n \times d$ indicate the number and the length of available baselines for n observation at zenith, θ_{Min} is the corresponding angular resolution ($\gamma_{\mathrm{d}} = 0.5$) for observations at 400 nm and V_{Max} is the magnitude of the faintest non resolved star ($\gamma_{\mathrm{d}} = 1$) that can be measured in one night using all available baselines.

Array	N	A (m^2)	Baselines
MAGIC	2	227	$1\times \sim 85$m
CANGAROO	4	78	$5\times \sim 100$m 1×184m
VERITAS	4	113	3×80m 3×140m
HESS	4	113	4×120m 2×170m
HESS16	16	113	$120 \times$ from 120m to 510m
Narrabri	2	30m^2	$1 \times 10m \rightarrow 188m$

IACTs can be used for gamma-ray observations only during Moonless nights. Stray light from the Moon will only marginally reduce the sensitivity of an intensity interferometer and telescope time allocation could be set according to the Moon visibility, leaving almost half the night time available for interferometry measurements.

Conversion of an IACT into an intensity interferometer receiver would require the installation of a narrow-band filter in front of only one of the photo-multipliers of the camera. In one possible implementation, signals from this channel could be transferred to a central location via an analog optical fiber. After being digitized at high rate, the signals could be duplicated and aligned in arrival time for each pair in the array before being multiplied and integrated over time. Field programmable gate arrays seem to be the ideal tool for implementing such a system.

Existing IACT arrays have the inconvenience of not having at least one pair of telescopes close together to allow the measurement of the degree of coherence from a non resolved source. This could be compensated for by splitting each optical channel in two in such a way the degree of coherence at each telescope can be measured. Another important difference between the Narrabri interferometer and IACT arrays is the fact that in the latter, telescopes are at fixed locations while at Narrabri, the two telescopes could be moved along tracks to keep the signals aligned in time and to maintain the fixed baseline as a star was tracked for long periods of time. While with fixed telescopes the baseline will unavoidably change during an observation, analog or even digital programmable delays can be used to align the signals in time and the varying baseline can be used to our advantage, providing additional coverage of the phase space.

3. Science

Astrophysics which can be addressed covers many of the areas currently being explored by Michelson interferometers (e.g. [6]). The catalog of directly measured stellar diameters is still limited to hundreds, and only a few measurements of have been made of lower-mass dwarf stars and hot main sequence stars. Such direct measurements are important for models of stellar atmospheres and stellar evolution, and can be used to calibrate surface brightness relations. Figure 1 shows the magnitude-diameter relationship for stars at different distances, indicating the wide range of stellar types within the sensitivity range of a modern intensity interferometer.

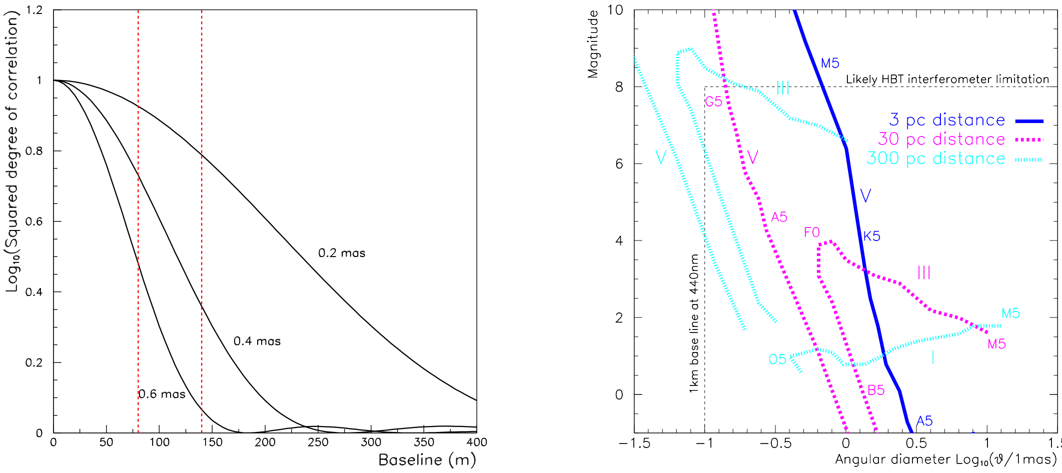

Figure 1. Left: $|\gamma_d|^2$ as a function of baseline for three different stellar angular diameters. The vertical lines indicate the two baselines available to VERITAS. **Right:** Visual magnitude angular diameter relationship for the main sequence, the giant and the super-giant branches for distances of 3 pc, 30 pc and 300 pc.

Other applications include measuring the parameters of binary systems, measurements of the circum-stellar environment - particularly in the case of variable stars (e.g. Cepheids or Mira variables) or stars with high mass loss (e.g. Be stars). It may even be possible to resolve simple features on the surface of giant stars such as Betelgeuse. The specifics of the technique make certain applications more attractive; long baseline measurements at short wavelengths are very difficult for Michelson instruments but relatively easy for intensity interferometers, as are long term monitoring of sources and studies over a wide range of wavelengths.

4. Conclusion

We discussed the feasability of Implementing a modern-day intensity interferometer on Imaging Air Cherenkov Telescope arrays. Developments in fast digital signal processing technology now make such an instrument relatively easy to construct, as well as improving the sensitivity. Measurements at short wavelength ($<$ 400nm) with long baselines ($\sim$ 1000 m) which are still very challenging for Michelson interferometers could be made. Such a project could operate during bright moon periods, providing valuable scientific output for relatively small expense and no impact on the gamma-ray observing schedule.

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