Revival of Intensity Interferometry

White Paper

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ABSTRACT

Intensity interferometry removes the requirements on mechanical precision and atmospheric corrections that limit amplitude interferometry, at the cost of limited sensitivity. Since it was introduced in the 1960s much progress has occurred in detectors, analogue and digital electronics, and analysis methods. Novel ideas and simple technical advance suggest that the idea still has its power, especially where amplitude interferometry is lacking. An astronomical facility, on the ground or in space, will be able to provide information, even image, a celestial field in several optical bands. Other quantities are spectra and photometric light curves, polarization and temperatures. A number of objects from various astrophysical fields is proposed which can only be measured by this technique.

1. INTRODUCTION

Amplitude interferometry is today's mainstream technique for high angular resolution astronomy, mainly in the infrared regime. In principle, amplitude interferometers combine the electromagnetic waves from two or more separate locations to produce a high-resolution brightness distribution, or image, of the source. Intensity interferometry, on the other hand, combines the *intensities* of the electromagnetic wave via the correlation of the electrical currents generated by the already-detected intensities. For astronomical purposes, the main advantage of intensity interferometry is its mechanical and atmospheric robustness: the required accuracy depends on the electrical bandwidth of the detectors, and not on the wavelength of the light. This opto-mechanical robustness also means that the atmosphere does not influence the performance of the instrument, and wave-length sensitivity only comes in as a second order limitation. The main disadvantages of intensity interferometry are its very low intrinsic sensitivity and the fact that the classical, two-detector intensity interferometer cannot reconstruct the phase of the complex degree of coherence, and thus can't be used to produce true images [Hanbury Brown 1974].

In astronomy, intensity interferometry was initially used in the radio part of the spectrum [Hanbury Brown *et al.* 1952]. Hanbury Brown and Twiss demonstrated that it would also work at visible wavelengths [Hanbury Brown and Twiss 1957a, Hanbury Brown and Twiss 1957b] and subsequently the Narrabri Stellar Intensity Interferometer (NSII) was constructed and operated from 1965 to 1976. The NSII was the first instrument to successfully measure the angular diameter of main sequence stars, and a total of 32 angular diameters were measured by the NSII [Hanbury Brown 1974]. The low sensitivity implied a limiting magnitude of m_b=2.5 despite the fact that NSII used a pair of large reflectors, 30m^2 each. In essence, this low sensitivity is due to the fact that intensity correlation is a second-order effect.

The three-detector intensity interferometer, which correlates the intensities from three separate detectors (and so is a third order effect), was first proposed by Gamo [1963] as a way to reconstruct the phase of the complex degree of coherence, and this technique was subsequently proved in the laboratory by Sato *et al.* [1978]. A holographic method was also proposed by Kurashov and Khoroshkov [1976]. Since then, many other algorithms were proposed for the full reconstruction of the complex degree of coherence from amplitude-only measurements [Bartelt *et al.* 1984, Lohmann and Wirnitzer 1984, Marathay *et al.* 1994, Barakat 2000, Mendlovic *et al.* 1998, Holmes and Belenkii 2004]. Classical two-detector intensity interferometry [Hanbury Brown 1974] was abandoned in the mid seventies due to its low sensitivity. Higher-order intensity correlations were never observed for astronomical sources, although the method was used in amplitude or speckle interferometry [Lohmann and Wirnitzer 1984].

2. PRACTICING INTENSITY INTERFEROMETRY

NSII employed on-line correlators, and these are still the state of the art today. However, there is much to say for advancing to off-line processing. Fontana [1983] generalized intensity interferometry to *N* detectors correlating all *N* currents to form a single output. Ofir and Ribak [2006a,b] examined a linear array of many detectors with a uniform spacing. This highly redundant configuration, when coupled with off-line processing, can be used to effectively increase the overall signal to noise ratio of the instrument (or alternatively, its sensitivity). For example, a 0^{th} magnitude source was simulated with a 100-element array of ~100m dishes, for one hour. The data, processed as an intensity interferometer array using NSII's 1960s technology, will have a signal-to-noise ratio (SNR) of more than $1.2\cdot10^6$. Most of this performance is due to the very large active area of the array, but this is also more than 190 times better than what one would expect if one used the previously known scaling laws alone, and is due to the high redundancy of the uniform linear array and the proposed algorithm, different from what was done in radio telescopes such as Westerbork [Yang 1988]. This high redundancy can be divided to two types: translational symmetry, which does not decrease for dimmer sources and contributes a five-fold improvement, and higher order correlations, which are very dependant on the source's spectral photon flux density and contribute the rest of the improvement. Therefore, the earlier type of redundancy will still contribute to the performance of the instrument for faint sources, whereas the later type will not. If we define the limiting magnitude of that simulated array as the magnitude where we only get SNR of 3 after one hour of integration, then the limiting magnitude will be slightly more than the 10^{th} magnitude using the NSII-old technology, and about 14.4 magnitudes when conservative technological improvements are considered. A "coronagraphic" effect of intensity interferometry to increase the dynamic range of the instrument [Ofir and Ribak 2006a,b] was not included in these computations.

The issue of dish size is important. While providing more flux and contributing to the redundancy and SNR, it also limits the size of observed objects: they must not be resolved by the dish, or else the signal will drop accordingly. Thus one should consider extremely distant (or small) astronomical targets, such as globular clusters, stars orbiting black holes, jets or fireballs formed by accreting matter, and so on. These objects are more amenable to higher order correlation as it depends on their higher visibility moments.

The SNR also scales with the number of optical channels $p^{½}$ and electrical bandwidth $b_v^{½}$ of the detectors [Hanbury Brown 1974]. Observations of several targets in a sparse field can be made simultaneously by having a sparse two dimensional detector array mounted on each reflector (similar to atmospheric Čerenkov telescopes), with each point-like source illuminating a different detector where all the j detectors onboard each of the N reflectors point at the same source. The detectors will be further apart then the reflector's point spread function (which will be quite wide, given the crudeness of the reflector).

Recording and offline processing all of data will enable a very productive scientific facility that will measure other observables simultaneously, on top of all quantities derived from precise astrometry:

1) Information from all reflectors is gathered simultaneously. The entire correlation function (N-1 points) will be measured in a single observation run (on p optical bands). The many (tens and up) baselines will create a dense Fourier plane coverage in a single run, without the need to fit a model to the data. Phases could be recovered by one of the already known and somewhat redundant algorithms. Imaging will be possible by having sufficient (u, v) coverage (see also §2.2).
2) Averaging individual reflectors over relatively long periods (seconds) will provide high quality photometry of each target on each of the p optical bands on the same run (N redundant times). This is actually a spectrum with a low, p point, resolution but high quality (high SNR) due to the very large collecting area. Observing several targets simultaneously will enable differential photometry.
3) Simultaneous observations in several optical channels will also enable differential interferometry [Vannier *et al.* 2001] to extend even further the dynamical range of the instrument.
4) High resolution spectra (within each optical band) of each source can be recovered (N redundant times) by correlation spectroscopy [Fontana 1983].
5) Multi-detectors intensity interferometers have an independent capability to measure the distance to each source by searching for the maximum signal [Fontana 1983]. This measurement will also give results on the same run. It is interesting to compare the statistical significance of 1 earth-orbit parallax measurement ($3\cdot10^8$ km baseline) and many 1km baseline measurements – which happens at $(3\cdot10^8)^2$ individual measurements, or after using all relevant subgroups of an array with just 58 elements. Theoretically, a 100-element array with a 1km typical baseline will measure distances with the same statistical significance as a single measurement with a baseline of 84 light-years. Unfortunately, this is too optimistic since this computation assumes we can detect the distance measurement signal from *each individual* subgroup - which is very difficult already at the 3^{rd} order correlation and quite impossible at the 50^{th} order correlations (as explained in [Ofir and Ribak 2006a,b], even for the ~100m diameter reflectors the *total* of all 3^{rd} order correlations is negligible for sources dimmer than magnitude 3, when using NSII technology).
6) The high sampling rate of an intensity interferometer, all the way to the GHz scale, will enable the use of the residual timing technique for appropriate sources (for example: pulsars, stellar scintillation, eclipsing objects).

7) NSII was already used to measure directly the emergent flux of the source, the source's effective temperature and effect of polarization [Hanbury Brown 1974]. These observables will also be available to the multi-detector intensity interferometer.
8) Multi-photon experiments may uncover thermodynamic information of how the light was originally created or how it has been scattered since its creation [Dravins 1994]. A multi-detector intensity interferometer may bring this type of information to the measurable range.
9) As a by product, an intensity interferometer can operate as an atmospheric Čerenkov camera. Alternatively, out-of focus Čerenkov detectors can be used for intensity interferometry [LeBohec and Holder 2006]. Čerenkov radiation will not contaminate long baselines (>300m).
10) When used for bright sources (astronomical or not), this technique can by used as a probe to quantum optics via the pronounced multi-correlation (photon bunching) effect.

Building a completely non-redundant (or only partially redundant) array, in contrast to a fully-redundant array, will only affect the SNR of the reconstructed correlation function, and not the other observables. There are other proposed algorithms related to intensity interferometry improvement:

- Improving the contrast between different parts of the image, and enlarging it without any limitation and, in spite of this enlargement, without any distortions of objects borders caused by discreteness of the initial image [Telyatnikov 1997].
- Implementation of an eigenfunction method to the problem of correlation function restoration from the photocurrent data [Kurashov *et al.* 1997].

Very advanced technology might be required for digitization, computation power and storage. The full analysis of an observation run by an intensity interferometer will be computer intensive. One way this problem may be addressed is with a distributed computing platform such as BOINC (Berkeley Open Infrastructure for Network Computing), which successfully runs several distributed computing projects, of which one is SETI@home [Korpela *et al.* 2003].

Ofir and Ribak [2006a,b] suggested a linear (and rotated linear) array with its unique (u,v) coverage. Herrero [1971] suggested that a *V*-shaped array will be the optimal configuration for an intensity interferometer array. It seems that it is advantageous that the reflectors are mobile in order to keep the projected separations constant in spite of Earth’s rotation, since fixed reflectors would force short integration periods and would render the instrument impotent. Indeed, for this very reason the two NSII reflectors moved on circular tracks during the observations [Hanbury Brown 1974]. Further simplification may come about by using any of these: mobile focal collector concept employed in radio astronomy, rotating liquid mirrors or the Carlina hypertelescope [Le Coroller *et al.* 2004]. The crude reflectors adversely affect the ability to focus such large reflectors on the relatively small active area of the detectors. This disadvantage may be mitigated by using non-imaging concentrators [Gleckman *et al.* 1989], provided that the total path difference after these additional optical elements is not more than the specified tolerance (1cm in our example). Beyond these, different realizations exist [Ofir and Ribak 2006a,b and LeBohec and Holder 2006]:

1) Central tower, as in STACEE (Solar Tower Atmospheric Čerenkov Effect Experiment [Covault *et al.* 2001]): a field of “dumb” mirrors will simply reflect light to a central tower where all light will be detected and processed [Hanbury Brown 1974]. Advantages: Inexpensive, probably feasible by modifying or nearly replicating a solar tower experiment. The detectors are not mounted on the reflectors, so all the sensitive electronics of the entire instrument are fixed, protected and easily accessible, almost flat reflectors; Shorter electrical leads from detection to recording. Disadvantages: Due to the poor optical quality of the reflectors and the large distance to the tower, probably only one target per observation will be possible, Atmospheric extinction of the signal and scintillation along the way from the mirrors to the tower.

2) No central tower, as in NSII: every reflector will carry all its detectors onboard. Advantages: The short reflector-detector distance enables multi-targeting, No atmospheric extinction or scintillation from the reflectors to detectors. Disadvantages: Cannot be realized on any existing array (including astronomical arrays observing at the mm or longer wavelengths), without major modifications, and probably would have to be a dedicated instrument, Will create a need to protect the detectors from the elements on many separate and mobile platforms.

3) A cross of the two may be possible: instead of placing a detector on every reflector on the NSII-like configuration, a light guide is positioned at the focus, for example, a multimode optical fiber or a bundle thereof, bringing the signals all the way to a central, fixed, lab. A direct transmission of the signal through air is also conceivable, turbulence being a small error compared to others. Advantages: it eliminates all the disadvantages of the two configurations above, except the need to build it probably as a dedicated facility. It might be relatively inexpensive. Disadvantages: the poor optical quality of the reflector may require non-imaging optics to collect the light into the light guide.

4) As in radio astronomy, the signals might be taped and transferred to a central station for later correlation, with time stamps to verify simultaneity. Advantages: it simplifies communications. Disadvantages: the technology is limited in temporal response and requires accurate path equalization.

5) Synergies with high energy and radio arrays. Air Čerenkov detector arrays and mm radio interferometer arrays share many features with intensity interferometers: many low-quality, shiny reflectors, spaced over large distances, fast photon detectors, relay and delay lines, fast parallel correlators. Sharing the design and planning in advance would be beneficial to all sides. Divisions between lunar phases, focal reliefs and wave-lengths allow having one to three modalities observing the same object at the same time. Advantages: reduced costs. Disadvantages: more complex design and scheduling.

6) Space interferometry was proposed by Klein *et al.* [2007], essentially in the context of formation flight. Advantages: this is the simplest kind of interferometer to place in space in terms of optical requirements. It is perfect for regions where the atmosphere is opaque, especially in the ultraviolet with its improved resolution. Disadvantages: station communications and signal correlations need to have a high band width, space complexity, long-term realization.

3. ASTRONOMICAL INTENSITY INTERFEROMETERS

There are many possible astronomical targets, and here is a very partial list for utilizing the capabilities of intensity interferometry to the fullest:

1) Fast repeaters (such as pulsars): as in boxcar averaging, binning the few-GHz of samples into millisecond bins, synchronized with the pulsar's period, will provide a way to create a "movie" of the different phases of the Pulsar. The cost: observing time will scale by the number of frames in the "movie".
2) Gamma repeaters and supernovae: the intensity, spectrum and delay between the spectrally-remote events and their inexplicable energy have been long puzzling. In a model, slowly being adopted by the community, these are relativistic plasma fireballs in which directionality sets all these observed parameters [Dado, Dar and De Rujula 2003] (This complex model might also explain the origin of energetic cosmic rays). These unresolved, hot spots (which seem to us like jets) are a perfect target for intensity interferometry.
3) Close binaries and multiples, including bright compact objects and extra-solar planets: these will be found and characterized by astrometry (from interferometry and imaging), radial velocity (from high resolution spectra), photometry (transits and lensing events), and residual timing, all independently and in the same observational run.
4) Gravitational lenses and astronomically coherent sources [Borra 1997, 2008, Dravins *et al.* 1994, Johansson and Letokhov 2005].
5) Distance and parallax measurements using signal correlations [Fontana 1983, Jain and Ralston 2008].
6) Hot spots in accretion systems, features on hot white dwarfs [Dravins, private communication].

One of the appeals of the proposed instrument is that no new technology needs to be developed and all the components (besides the reflectors themselves) are off-the-shelf products. Yet, we can say what kind of technological advance would further promote this kind of instrument significantly: since the only uncontrolled parameter is the spectral flux density, then theoretically one would want to have a device that optically amplifies the intensity of the source before it is electronically detected, in front of every detector. The difficulty is that this device needs to operate at high speed, uniformly (for all detectors) and while keeping all the statistical properties of the light to allow for post-processing of the data. We note that amplification of an optical signal always involves its absorption first, and thus the above advantages can currently only be realized at much longer wavelengths ($\lambda > 10\mu$m), where off-line amplitude interferometers, with their superior sensitivity, might be feasible.

We note that such a large facility may have other uses during the daytime that may generate revenues and thus help to finance its construction. These uses include uses usually associated with concentrating solar power plants, for example - power generation and garbage disposal by high temperature incineration.

4. DISCUSSION

Major improvement is made possible by the offline processing of the data, allowing utilization of each photon several times and thus overcoming the low intrinsic sensitivity of intensity interferometers. Offline processing of the data will also enable measuring a variety of other observables, including photometry, spectroscopy, distance and timing.

Construction of a new facility, well within current technical capabilities as all of the requirements are already well-exceeded by different currently operating or already-planned instruments: STACEE is already using some of the 220 digitally-controlled 37m^2 heliostats for optical detection at 1 GHz, The Green Bank Telescope is a single aperture that already boasts 7853m^2 of collecting area, accurate to better than 0.22mm rms [Jewell and Langston 2000], compared to 7680m^2 accurate to 1cm that we used in our calculations, and the total scale of the proposed instrument (768,000m^2 active area) is smaller than the proposed 10^6 m^2 of the Square Kilometer Array at comparable mechanical accuracy [Carilli and Rawlings 2004]. The cost will be a major issue for such a huge facility.

Using all of these properties will enable the relatively simple construction of a ground based facility able to transform a 2*D* field of point-like sources to a 3*D* distribution of micro-arcsec resolved systems. Each of the systems will be truly imaged in *p* optical bands without a need to fit the visibility curve to some model, and it will also have its high quality spectra (inside each optical band), photometry, emergent flux, effective temperature, high resolution residual timing and polarization effects measured. All of these can be achieved in a single observation run of such a dedicated facility. The facility will not need adaptive optics, beam combiners, delay lines, precision optics and mechanics of almost any kind. In addition, due to their mechanical and atmospheric robustness intensity interferometers are far more amenable to use in shorter wavelength, and indeed NSII already operated at the blue band at 438.4nm. However, at longer wave lengths where photons are more plentiful, intensity interferometry suffers less from noise.

Contemporary astronomy is plagued by the need to have optical surfaces smooth, and distances fixed to a fraction of the wavelength. Multi-detector optical intensity interferometry offers a way out of this restriction, even if not for the faintest of objects, offering:

1. Ease of construction since mechanical accuracy depends on electrical bandwidth, and not on wavelength. Using mobile focal collectors may significantly reduce the moving mass of each reflector.
2. All reflectors are identical and are not connected optically to the others. Furthermore, reflectors will probably be segmented, enabling "industrialized" parts manufacturing.
3. Relatively easy to obtain very long baselines of many kilometers at 1cm mechanical accuracy.
4. No new technological development is needed.

Results obtained with intensity interferometry are still the state of the art, even decades later. This is important especially in the blue, where amplitude interferometry is lacking. The main drawback of intensity interferometry is sensitivity, but using all of the proposed improvements and scaling laws improves the limiting magnitude from 2.5 at NSII to 14.4 of the proposed instrument. It seams that multi-detector intensity interferometry could be used as a present day technique answering present day questions, and indeed deserves another review.

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