

White Paper on the Revival of Stellar Intensity Interferometry

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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 morphological and photometric information of celestial objects in several optical bands with unprecedented resolutions. Other quantities are spectra and photometric light curves, parallax, polarization and temperatures. A number of objects from various astrophysical fields is proposed which can only be measured by this technique.

1 General Contents

- Introduction
- Science: Imaging and Temporal Effects
- Intensity Interferometry: Theory, Narrabri, Sensitivity, Background
- Data Analysis
- Implementation: Čerenkov, Collectors, Detectors, Correlators, Improvements
- Conclusions

2 Introduction

In this white paper we deal with the motivation, potential and possible technical approaches for a revival of stellar intensity interferometry (SII). This

document was initiated following the establishment of a working group on Stellar Intensity Interferometry, as a part of the International Astronomical Union Commission 54 on Optical & Infrared interferometry, by G. Perrin. This document is organized as follows. Section 3 presents the science motivation for a modern implementation of SII. After briefly presenting the status of amplitude interferometry, it outlines the potential of SII and the foreseen science applications. Section 4 provides a description of the functioning of the Narrabri Intensity Interferometer and an explanation on intensity interferometry including the sensitivity limitations of the technique. Section 4 also includes a description of the application of Intensity Interferometry in the time domain. Section 5 is dedicated to the analysis of SII observatory data addressing the question of phase recovery, including the potentials and difficulties associated with the exploitation of high order correlations. Section 6 presents ground based and space based implementations being pursued by the SII working group. It also presents consideration on the technical implementation of a modern intensity interferometer, including photo-detection, signal transmission, correlation, and signal processing. The last section concludes and presents an outlook on the ongoing efforts and future developments of SII.

3 Science motivations

3.1 *Successes and challenges of Michelson amplitude interferometry (Volunteers?)*

Michelson or amplitude interferometry relies on the visibility of interferometric fringes to provide a measurement of the mutual degree of coherence between different telescopes. The complex degree of coherence depends on the relative positions of the receivers as the normalized Fourier transform of the source intensity distribution. The original image can then be reconstructed provided the phase can be recovered. After decades of inactivity since A. A. Michelson and F. G. Pease measured the diameter of five stars with their 20 foot interferometer on Mount Wilson in 1920 (45), a number of world-class instruments for long-baseline optical interferometry are currently operating or soon to come online; for reviews see (47; 36). Some real breakthroughs have recently been achieved with in particular the model-independent observations of stellar surface features (46) such as equatorial darkening in fast rotators. More recent interferometric results can be found at the Optical Long Baseline Interferometry News web page (50).

Michelson amplitude interferometry is however a very challenging technique as the relative length of the paths of light have to be controlled within a frac-

tion of the wavelength 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 have to be actively compensated for. These difficulties have constrained Michelson interferometry to smaller baselines (with the exception of CHARA (54) all active interferometers have maximal operational baselines of less than 100 m) and operate at longer wavelengths ($\sim 0.6 - 11\mu\text{m}$) while the angular resolution is proportional to the baseline and to the inverse of the wave-length. Furthermore, because of the small number of telescopes, only simple objects can be measured.

3.2 *Potential of Intensity Interferometry for imaging*

In intensity interferometry the requirements on the control of the relative light path lengths to each receiver are much less stringent than in amplitude interferometry (AI). In particular, SII eliminates the need for adaptive optics and optical delay lines and is essentially insensitive to atmospheric turbulence and seeing conditions. As a consequence, baselines can virtually be arbitrarily large and observing at the shortest wavelength does not result in any extra difficulty. Furthermore, in SII, the received light is not made to interfere directly; rather, detector currents from the various receivers are combined. Electronic signals can be duplicated at will with no penalty and so an arbitrarily large number of receivers, N , can be used together to provide extensive coverage of the interferometric plane with $N(N - 1)/2$ baselines simultaneously available. This improves the coverage of the Fourier description of the object and allows observing more complex targets. In contrast, in AI the number of photons is limited and there are only two main options: split the photons $N - 1$ ways to interfere with the other collectors, and suffer a $\sqrt{N - 1}$ loss in SNR, or interfere only two stations at a time and give up on simultaneity.

On the other hand, SII being a second order correlation, rather than first order correlation as in AI, it suffers from very modest inherent sensitivity which implies the use of very large light collectors (albeit of low optical quality). We consider objects which are thus suitable for interferometry in general, namely of unresolvable details. Within this group, we concentrate on these objects which are not available to AI due to their spectrum, resolution, and complexity. Specific limits on brightness, size, complexity and spectrum are unclear at this stage and extrapolated from the single previous experiment to modern technology and new methodology. Arbitrarily and loosely, they are set at $m_V = 9$, 1 mas features, and the spectrum penetrable through the atmosphere.

In addition, SII was already used to measure directly the emergent flux of the source, the source's effective temperature and effect of polarization (9). These

observables will also be available to the multi-detector intensity interferometer, namely to resolvable objects and parts thereof, similar to AI.

3.3 *Imaging with Intensity Interferometry* (Willem-Jan de Wit, ...)

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

SLB: Interesting, somewhat redundant references for this are (18), (17), (39). Interesting objects are Be stars, eruptive stars. Prototypes that could be cited are γ Cassiopeia, ζ Taurus with the possibility to observe both photospheric activity and circumstellar activity by concentrating on bright emission lines. Close binaries with mutual interactions (β Lyrae or W Ursae Majoris).

- Gamma repeaters and supernovae: the intensity, spectrum and delay between the spectrally-remote events and their inexplicable energy have been long puzzling. Initial models assumed clashes between expanding shells to explain these bright events, and later concentrated on polar shells. Another model tries to explain the effect by assuming relativistic plasma fireballs in which directionality sets all these observed parameters (14). These unresolved, hot spots (which seem to us like jets) are a perfect target for intensity interferometry. Catching a γ ray burst, a nova or a supernova that is bright enough is challenging, but fortunately these events have an advanced early alert system. When a satellite detects one of them, signals are being sent automatically for continued and continuous ground observation. At any rate, if we can lock onto such an event early enough and obtain some spatial and spectral information about it, we might be able to judge different models as to their relevance. Since most of these events are extremely far, only the closest ones will be resolvable. Other sources of directed energy and jets are also interesting, such as AGNs and sources of jets, provided they are bright enough. If we include space SII, then UV and shortward are even more important for understanding these objects.

- Close binaries and solar spots, 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 SII observational run. While the newly discovered extra-solar planets are easier to find in the infra-red, their suns are not necessarily dim. This means that nearby bright stars can be checked for these effects, even if we cannot detect their faint companions. Notice that most of these measure-

ments do not require imaging, allowing SII to use a single dish (but of course, adding more will improve the signal).

SLB: Here again, these topic are very interesting but when it come to extra-solar planets we probably need to be careful to sensitivity issues. How bright are they? In which band? Photometry measurements of faint objects have implications for light collector optical quality requirements. What type of requirement? Are they realistic? If by high resolution spectroscopy here, we mean using SII in the time domain, then what are the width implication for a useable emission line? I do not know the answers to all these questions but I think that if we are to be considered seriously these statements need to be justified in detail.

- Gravitational lenses and astronomically coherent sources (4; 5; 19; 31).

SLB: I would have the same comment here. What are the specific requirements for such observations to be possible?

ER: Do these contain spatial information?

- Hot spots in accretion systems, features on hot white dwarfs (20).

SLB: Great but what is the magnitude of the brightest accretion disk? What about white dwarfs? How many of them are brighter than such and such magnitudes?

3.4 Temporal Effects and Intensity Interferometry (Dainis Dravins)

SLB: Points 4, 5 are fast photometry and low resolution spectroscopy byproducts. A good reference on this is (16). Missing dedicated introduction

Employing N detectors, high resolution spectra (within each optical band) of each source can be recovered (N redundant times) by correlation spectroscopy (21). Multi-photon experiments may uncover thermodynamic information of how the light was originally created or how it has been scattered since its creation (19). A multi-detector intensity interferometer may bring this type of information to the measurable range. When used for bright sources (astronomical or not), this technique can be used as a probe to quantum optics via the pronounced multi-correlation (photon bunching) effect.

- 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).

- 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”. (16)

- Multi-detectors intensity interferometers have an independent capability to measure the distance to each source by searching for the maximum signal (21). It is interesting to compare the statistical significance of 1 earth-orbit parallax measurement (3×10^8 km baseline) and many 1km baseline measurements, which happens at $(3 \times 10^8)^2$ individual measurements, or after using all relevant subgroups of a linear array with 58 elements. Theoretically, a 100-element array with a 1 km 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 of elements, which is very difficult already at the 3rd order correlation and quite impossible at the 50th order correlations. Even for ~ 100 m diameter reflectors the total of all 3rd order correlations is negligible for sources dimmer than magnitude 3, when using earlier SII technology, (48; 49). However, new methods were recently proposed for distance and parallax measurements using signal correlations (29).

4 Intensity interferometry

4.1 The classical picture

An Intensity Interferometer does not rely on actual light interference, instead, the mutual degree of coherence is obtained from the measurement of the degree of correlation between the fluctuations of intensity recorded with a quadratic detector at different telescopes. The principal component of the intensity fluctuation is the classical shot noise which does not show any correlation between two separated telescopes. In addition to the shot noise, there is a smaller component, the wave noise, which can be described as the beating between the different Fourier components of the light reaching the telescopes. The wave noise shows correlation between the two detectors provided there is some degree of coherence between the light they receive. Because of this correlation (Eq. 1) the time integrated product of the intensity fluctuations Δi_1 and Δi_2 in two telescope is positive and provides a measurement of the square of the degree of coherence of the light at the two detectors $|\gamma(d)|^2$, where d represents

the distance separating the telescopes (36).

$$|\gamma(d)|^2 = \frac{\langle \Delta i_1 \cdot \Delta i_2 \rangle}{\langle i_1 \rangle \langle i_2 \rangle} \quad (1)$$

$|\gamma(d)|^2$ corresponds to the fringe visibility in a Michelson interferometer. According to the van Citter-Zernike theorem, $\gamma(d)$, the complex degree of coherence, is the normalized Fourier transform of the source intensity distribution. As a consequence, when the baseline d is too small for resolving the observed object, $|\gamma(d)|^2 = 1$. In the case of a source that can be modeled as a uniform disk with angular diameter θ , the various baselines used in the observation sample an Airy function on the ground. For observations at wavelength λ , the degree of coherence $\gamma(d)$ cancels when $d = 1.22\lambda/\theta$. An interferometer with $d = 1$ km baseline operating at a $\lambda = 400$ nm wavelength, would allow to probe features with angular extension of less than 0.5 nano-radians or 0.1 milli-arcsecond (mas). Equation 1 is valid as long as the source is not partially resolved over a base line corresponding the the light collector diameter.

The important point is that the correlation is a function of the difference in phase between the low frequency beats at the two detectors. This correlation does not depend on the phase difference of the light at the two detectors (see Figure 1). The requirements for the mechanical and optical tolerances of an intensity interferometer are therefore much less stringent than in the case of a Michelson interferometer. 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.

On the other hand, with SII, copious quantities of light, and therefore very large light collectors are necessary for the tiny wave beating to be measurable over the much more dominant shot noise. However, the tolerance of SII to path length differences makes such light collectors relatively inexpensive. An intensity interferometer with 1 GHz signal bandwidth, does not need the optical surface of each collectors to be much more accurate than 3 cm and the pointing does not need to be controlled to better than a few arc minutes for 10 m telescopes. Furthermore, SII appears as the only existing tool for high resolution studies across the entire visible range, including the shorter wavelengths which are not available to amplitude interferometry due to atmospheric turbulence. It is these wavelength regimes which provide better resolution at regions of higher temperatures and give access to bluer and hotter stars.

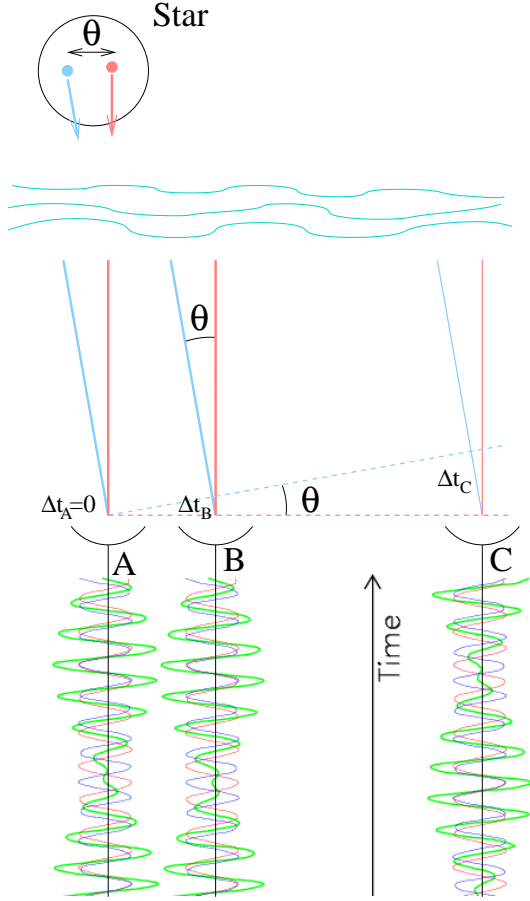


Fig. 1. Considering two harmonic emitting points in the source, with slightly different frequencies, telescopes A and B being close together receive beats almost at the same time. This corresponds to a high degree of correlation. Telescopes A and C being further apart do not receive beats in phase and the degree of correlation is then lower.

4.2 The Narrabri Stellar Intensity Interferometer

In astronomy, intensity interferometry was initially developed in the radio part of the spectrum (6). Hanbury Brown and Twiss demonstrated that it would also work at visible wavelengths (7; 8) and subsequently the Narrabri Stellar Intensity Interferometer (NSII) was constructed and operated from 1965 to 1976 (Figure 2).

The NSII consisted of two telescopes, each 6.5 m in diameter, with an 11 m focal length. The telescopes were carried on trucks running on a circular railway track 188 m in diameter. This allowed the interferometer to operate with a baseline of 10 m to 188 m, and to track any star while keeping the line joining the two telescopes perpendicular to the direction of the star. Having movable telescopes removes the need for additional delay lines to bring the signals in time. At the focus of each telescope, the converging light was collimated



Fig. 2. The two Narrabri Stellar Intensity Interferometer telescopes. Photo from OLBIN (50), courtesy of Prof. John Davis

and passed through an interference filter centered on 443 nm with a passing band width of 10 nm. The light was then focused onto a photomultiplier tube which converted the light intensity to a current with 25% quantum efficiency at 440 nm and a 60 MHz effective bandwidth. The signals were sent to the control building where the correlator was located. The DC component of the signals was measured and recorded for calibration, while the AC components were sent to the input of the correlator, a four transistor based linear multiplier. The DC component to be measured on the output of the multiplier is very small in comparison to the random fluctuations (~ 100 dB). This difficulty was resolved by integrating the output of the multiplier over 100 s time intervals. The drifting effects of small offsets that would have drowned the signal also had to be eliminated. This was achieved by applying the technique of phase-switching, which consists in inverting the phase of the signals on the input of the multiplier at rates of 10 kHz and 10 (0.1??) Hz respectively. On the output of the multiplier, these switching frequencies were amplified and demodulated before the signal was integrated, thus removing any significant contamination due to offsets.

These stages of correlation and lock-in detection were clearly the critical part of the experiment, and great efforts had to be made in order to reduce spurious correlations to acceptable levels. For an unresolved ($\gamma_d = 0$) $m_B = 0$ star observed during one hour, the predicted signal to noise ratio amounts to ~ 130 . The actual signal to noise ratio was degraded by a factor of five because of optical losses and excess noise of various origins. This limited observations to stars brighter than $m_B = +2.5$ despite the fact that NSII used a pair of large reflectors, $30 m^2$ each. In essence, this low sensitivity is due to the fact that intensity correlation is a second order effect. Still, The NSII was the first instrument to allow the successful measurement of angular diameters of main sequence stars. A total of 32 angular diameters were measured with the NSII (9), some as small as 0.4 mas. Classical two-detector intensity interferometry (9), having exhausted the observation list, was abandoned in the mid seventies to the benefit of amplitude interferometry.

4.3 Intrinsic Sensitivity

In a two-receiver intensity interferometer such as the NSII, the shot noise from both channels is responsible for most of the multiplier output fluctuations. The wave noise degree of correlation for the observed object has to be compared to the shot noise to establish whether the sensitivity will allow a significant measurement. R.H. Brown showed the signal to noise ratio can be expressed by equation 2

$$(S/N)_{RMS} = A \cdot \alpha \cdot n |\gamma(d)|^2 \sqrt{\Delta f \cdot T/2} \quad (2)$$

where A is the collection area of each telescope, α the photo-detector quantum efficiency, Δf the photo-detectors and electronics bandwidth, T the integration time and n the the source spectral density in photons per unit optical bandwidth, per unit area and per unit time. This relation does not include signal to noise ratio degradations due to photo-detector and electronics imperfections such as excess noise.

Applying Eq. 2, a pair of 100 m² light collector with 30% quantum efficiency photo-detectors, 1 GHz electronics during a five hours observation would permit measuring a $|\gamma(d)| = 0.5$ correlation with five standard deviations (20% statistical error) for a 6.7 visual magnitude star. In the case of a uniform disk model, this would result in a measurement of the diameter with an accuracy of 14%. The diameter of a magnitude 5 star could be measured with an accuracy of 3% in the same amount of time. Such a capability would already be very valuable but it might seem disappointing in in comparison to the scale of the assumed facility: two telescopes some 11 m in diameter. One should however remember the light collectors do not need astronomical optics quality. For the assumed 1 GHz signal bandwidth, light collecting surface irregularities up to 3 cm would still be very acceptable. If not readily available such large collectors can be relatively inexpensive.

Sensitivity improvement can also be achieved with larger light collector areas A . This however also restricts the range of angular extensions of observed objects: if the light collector is so large it partially resolves the source, the correlation signal drops accordingly. Alternatively, one may be tempted to increase the bandwidth Δf . One must however pay attention to the fact that for the increased bandwidth to be effective, the quality of the light collecting surfaces as well as the control over the relative telescope positions and pointing must be improved accordingly, something that might become rapidly expensive.

Other sensitivity improvement approaches have been proposed. The SNR scales with the square root of the number of optical channels as each pro-

vides and independent measurement of the degree of correlation (9). It should be noted here that the SNR given by Eq. 2 does not depend on the optical bandwidth. This, in principle, allows to take advantage of an arbitrarily large number of optical channels. In practice, attention must however be given to the fact that the limited optical quality of the light collectors optics that may be considered set limits on how narrow an optical bandwidth can be selected. It remains that simultaneous measurements in multiple relatively narrow optical bands benefit observations of the source continuum for sensitivity and permit studies of the wavelength dependence of morphology of bright enough objects. Simultaneous observations in several optical channels will also enable differential interferometry (55) to further extend the dynamical range of the instrument. As a byproduct, averaging individual reflectors over relatively long periods provides high quality photometry on each of optical band providing a low resolution spectrum with high quality (high SNR) due to the very large collecting area.

Sensitivity can also be improved by using more than one pair or receivers. This is particularly efficient. An array of N receivers offers $N(N - 1)/2$ baselines simultaneously available. The measurement of intensity fluctuations within each pair is essentially independent of that within any other pair even when a same telescope is shared between the different pairs. The sensitivity benefit from using an array is therefore close to being proportional to the number of light collectors in the arrays. This is in stark difference from amplitude interferometry, where the few photons available have to be divided between combining stations for any two telescopes. Furthermore, a multi-receiver array can in principle be used for measurements of higher order correlations. Combining many higher order correlations can improve sensitivity (48; 49) as described in section 5 on intensity interferometry data analysis. More importantly, using an array opens the possibility of recovering the phase enabling model independent imaging capability while, in a single receiver pair interferometer, the phase of the complex degree of coherence is lost. Several analysis approaches have been developed for this and some are presented in section 5.

4.4 *Night sky limited sensitivity*

The sensitivity estimation presented above assumes that the only noise is due to the Poisson fluctuation in the light from the observed source. The finite size of the point-spread function of a low quality optics light concentrator implies some amount of night sky background (NSB) light pollutes the signal from the source. The NSB light collected by two telescopes does not produce any correlation signal, but by increasing the shot noise it limits the sensitivity that can effectively be achieved. If $\sim 30\%$ of the collected light is not coming from the star, the time necessary to attain a given significance for the measurement

of the correlation is increased by a factor two. The continuum spectral density from a star of visual magnitude V is approximately $5 \times 10^{-5} m^{-2} s^{-1} Hz^{-1} 2.5^{-V}$ while from the NSB it is close to $5 \times 10^{-3} m^{-2} s^{-1} Hz^{-1} sr^{-1}$ (11). From this, we see that with a 0.05° point spread function of 0.05 ($\sim 6 \times 10^{-7} sr$) 9.6 are the dimmest that could practically be measured. Unfortunately, the only way to circumvent this limitation is to use light collectors of higher optical quality. **ER: add lunar background, for time sharing with Čerenkov detectors.**

4.5 Application of quantum optics in astronomy **Dainis Dravins**

5 Analysis of Intensity Interferometry data

A two-detector intensity interferometer cannot reconstruct the phase of the complex degree of coherence, and thus can not be used to produce true images (9). 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 (22) 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. (52). A holographic method was also proposed by Kurashov and Khoroshkov (34). Higher-order intensity correlations were never observed for astronomical sources, although the method was used in amplitude or speckle interferometry (41). It must be said that no thorough search for such correlations was performed. Many algorithms were proposed for the full reconstruction of the complex degree of coherence from amplitude-only measurements (3; 41; 43; 35; 53; 44; 2; 28?).

Fontana (21) generalized intensity interferometry to N detectors correlating all N currents to form a single output. Ofir and Ribak (48; 49) 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 0th magnitude source was simulated with a 100-element array of ~ 100 m 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 1.2×10^6 . 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 (58). This high redundancy can be divided into two types: translational symmetry, which does not decrease for dimmer sources and con-

tributes 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 10th 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 (48; 49) was not included in these computations.

6 Implementation

The question of revival of SII hinges on practical issues, namely light collection, detection, signal processing software and hardware both for imaging and temporal analysis, and ground and space environment. These will be discussed below.

We assume that SII is (as usual in science) underfunded, and we seek synergies with other devices. The gain for both sides is huge: time sharing is usually possible, and even if not, many astronomical targets are sharable, which calls for simultaneous observations. Thus more funding should be available for general observatories which would yield higher scientific output at lowered price. Below we mention some possible partnerships for future and even existing establishments. It is however worth considering a possible dedicated SII array.

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 37 m² heliostats for optical detection at 1 GHz. The Square Kilometer Array (10) will consist in a 10⁶ m² synthetic aperture. The Green Bank Telescope is a single aperture that already boasts 7853 m² of collecting area, accurate to better than 0.22 mm r.m.s. (30).

6.1 Intensity Interferometry with Imaging Air Čerenkov Telescopes

Imaging Air Čerenkov Telescopes (IACT) are used for γ -ray astronomy at energies greater than 100 GeV. The ACT technique relies on the fact that high energy particles, including γ rays, when entering the atmosphere, initiate extensive air showers of high energy secondary particles, some charged

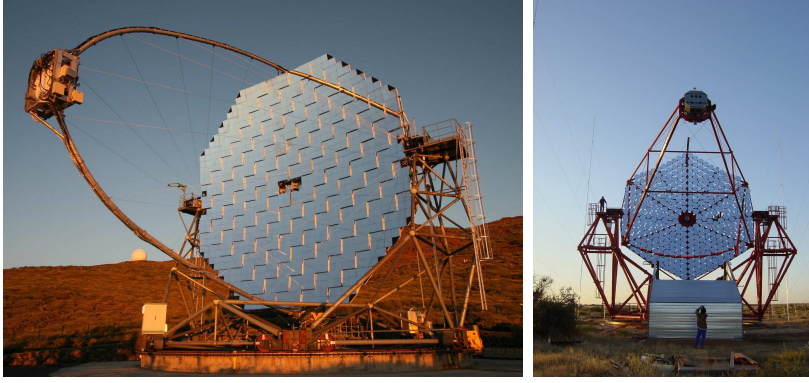


Fig. 3. The two MAGIC telescopes (left) are 17 m in diameter. They are separated by 85 m (42). The four HESS telescopes (right) are 12 m in diameter. They are arranged on a 100 m square (27).

and radiating Čerenkov light. When it reaches the ground, the Čerenkov flash from a shower is very brief: only a few nanoseconds. It is also very faint, ~ 10 photons/m² at 100 GeV and large light collectors equipped with fast electronics are necessary. In order to record stereoscopic views of each shower, ACTs are now generally used in arrays of two to four units with typically 100 m inter-telescope distances, to match the extent of the Čerenkov light pool (57). In fact, the two telescopes of the Narrabri interferometer were also used in a search for astronomical sources of very high energy (E 300 GeV) γ -rays (24; 25). The optical point spread function of IACT is generally close to 0.05° . If used as receives in an SII ((37)), following section 4.4, observations of stars with visual magnitude 9.6 would be possible. Notice that Čerenkov radiation will not contaminate long baselines (≥ 300 m). Figure 3 presents examples of IACT telescopes.

Future projects such as CTA (13) or AGIS (1) aim at improving the γ -ray flux sensitivity by increasing to several square kilometers the area covered by the array with several tens of telescopes. These arrays, when used as an interferometers, would allow to probe angular scales from a few mas to a few hundredths of a mas with a dense coverage of the interferometric plane resulting from the very numerous baselines (Figure 4). IACT arrays have however been designed for high energy γ ray astronomy and the specific design must be taken into account to establish to which extent these large facilities could be used for SII.

With focus to aperture ratio close to unity, minimizing optical aberration has led several collaborations to employ the Davies-Cotton (15) telescope design which does not preserve isochrony (equal optical path from star to detector). For 12m telescopes such as in HESS and VERITAS (56), this results in a limitation of the available signal bandwidth to ~ 100 MHz. With parabolic telescopes such as in MAGIC or AGIS, this limitation does not occur.

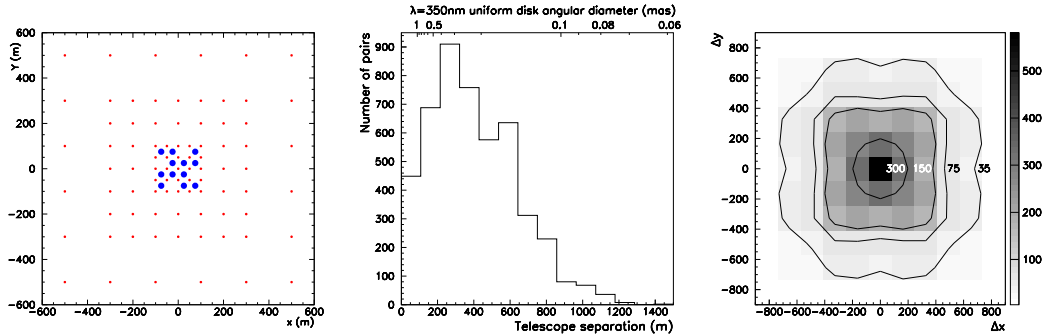


Fig. 4. One of the considered designs of CTA (left) consists of 12 600 m^2 telescope (small points) surrounded by 85 100 m^2 telescopes distributed over a square kilometer. It offers 4656 simultaneous interferometric baselines ranging from 35 m to 1410 m (center) resulting in a unique coverage of the interferometric plane (right)

One might be concerned by the fact that in contrast with what was done in Narrabri, the telescopes in an IACT array are at fixed positions. This has two consequences. First, the signals from different telescopes have to be brought back in time for the correlation to be measured. Programmable delays can be used to accomplish this; an analog delay system with similar requirements has been operated by the CELESTE experiment (51). It should be noted that the accuracy necessary for the timing corrections is fixed by the system bandwidth. For the contribution from the highest frequency preserved by the system to be degraded by less than 10%, the timing must be controlled with an accuracy better than 7% of the corresponding period. For example, a 100 MHz system requires timing corrections to within $\sim 0.7\text{ ns}$. Second, the length and orientation of the effective baseline between two telescopes depends on the position of the star in the sky. This really is not an issue in the case of a large array. At the time of the data analysis, the interferometric (u, v) plane can be binned, with different baselines at different times contributing to the measurement of the degree of correlation for each bin.

The SII dedicated optics, including a collimator, an analyser or a filter, a condenser, a photodetector, and front end electronics, could be mounted in front of the very high energy γ ray cameras. One possibility is to have it mounted in the shutter of the camera so it is out of the way for γ ray observations, as already demonstrated on the HESS telescopes for photometric measurements (16). One possible design of the intensity interferometry hardware is shown in Figure 5

One more question is about the availability of these telescopes for observations that are not related to high energy γ ray astronomy. IACT operation for gamma ray astronomy is limited by moon light. The equivalent of ~ 10 nights each month is free of competition so ~ 800 hours are available each year. Furthermore, future IACT arrays will work as regular observatories. Obtaining telescope time will require the preparation of a proposal. Time requests for

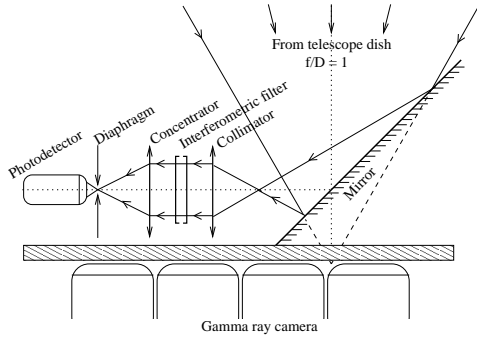


Fig. 5. The light from the mirrors is reflected side way toward a collimator and analyser before being focused on the photodetectors. Such a simple system can be mounted on the shutter of the atmospheric Čerenkov camera so it does not block the view for γ ray observations.

II observations will be considered as long as a competitive science program is presented.

6.2 Intensity Interferometry with other collecting optics

The size, quality, and spread of radio interferometers is so similar to that required for SII that they make a perfect match. Having in the focal plane visible and millimeter wave receivers will allow simultaneous measurements of the same objects. In this case, even the processing (calculation of delays, correlations, data analysis or storage) is rather similar. Radio interferometers can operate during the day time and through bad weather conditions, but some scheduling might be needed for conflicting requirements. Both addition of new stations or construction of new mutual arrays is possible.

Using a central tower, as in STACEE (Solar Tower Atmospheric Čerenkov Effect Experiment (12), a field of “dumb” mirrors will simply reflect light to a central tower where all light will be detected and processed (9). The advantages of this approach are its low price, probable feasibility 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. The main disadvantage is that due to the poor optical quality of the reflectors (0.5° PSF) and the large distance to the tower, probably only one target per observation will be possible, and night sky background contamination will be a limiting factor. Moreover, atmospheric extinction of the signal and scintillation along the way from the mirrors to the tower reduce the signal even further.

Finally, there are now a few 8-10 m class telescopes which are parts of arrays.

Amplitude interferometry is already going on or planned in these arrays, but for some specific applications, mainly in the temporal regime and for vis-uv imaging, one might consider constructing an intensity interferometer between the foci of these behemoths. Moreover, while these telescopes are used for infra-red amplitude interferometry, the shorter wave lengths can be used for simultaneous SII on the same objects. True, the smaller area is a limitation, but a much higher bandwidth can be employed and many more parallel wave length channels be utilised.

6.3 *Other possible implementations and improvements*

- Observations of several targets in a sparse field, or of an extended object, can be made simultaneously by having a 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 corresponding detectors onboard each of the N reflectors point at the same source. The detectors will be further apart than the reflector's point spread function (which will be quite wide, given the crudeness of the reflector). This further requires multiplying the number of correlators by the number of independent detectors.
- 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. It is possible to construct (or adapt) a linear (and rotated linear) array with its unique (u, v) coverage (48; 49). Herrero (26) 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 less effective. Indeed, for this very reason the two NSII reflectors moved on circular tracks during the observations (9). This possibility is especially attractive when sharing collectors with mm-wave interferometers.
- Further simplification may come about by using the fixed mirror with mobile focal collector concept employed in radio astronomy (in Arecibo), and along the same lines, rotating liquid mirrors or the Carlina hypertelescope (40).
- The crude reflectors adversely affect the ability to focus light on the relatively small active area of the detectors. This disadvantage may be mitigated by using non-imaging concentrators (23), provided that the total path difference after these additional optical elements is not more than the specified tolerance (1 cm in our example). Instead of placing a detector on every reflector on the NSII-

like configuration, a light guide may be 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. The poor optical quality of the reflector may require non-imaging optics to collect the light into the light guide, with all the attendant losses.

- Space interferometry was proposed by Klein et al. (32), essentially in the context of formation flight. 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. On the other hand, station communications and signal correlations need to have a high band width, working in space adds complexity to the project and delays its realization.

- Photodetector (**Cedric Foelmi, Jamie Holder, ...**)

- Analog and digital optical fibers for signal transmission (**Joachim Rose, David Kieda, ...**). As in radio astronomy, the signals might be taped and transferred to a central station for later correlation, with time stamps to verify simultaneity. This simplifies communications, but at the same time the technology is limited in temporal response and requires accurate path equalization. Fiber optics may take the electronically detected signal, duly converted into and optical one, and transmit them to the central correlation station.

- Analog correlators can be employed using off the shelf mobile phone technology. Such a correlator can provide the phase difference between two inputs, and that difference drops to zero at zero delay for all frequencies. of course, one can exploit millimeter interferometer correlator technology.

- Digital correlators **Jeter Hall, Dainis Dravins, Stephan LeBohec, ...**

- Offline approaches suffer from the amount of data to be collected. Assuming a 500MHz bandwidth, that is 1 giga-sample per second. In single photon counting mode, that amounts to 3.6 tera-byte of data produced per telescope and per optical channel every 8 hours. Run-length compression can be applied, even if the data are 100% noise. Today this approach can only realistically be considered for very specific measurements with a limited number of optical channels and telescopes, for example for ultra high resolution spectroscopy. 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. Information from all reflectors is gathered simultaneously and the entire correlation function ($N - 1$ points) is 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. 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 (33).

One of the appeals of the proposed instrument is that no new technology needs to be developed now 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.

7 Conclusions and outlook

Using all of these properties will enable the relatively simple construction of a ground based facility able to transform a 2D field of point-like sources to a 3D distribution of micro-arcsec resolved systems. Each of the systems will be 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, optical 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 $438.4 nm$. However, at longer wave lengths where photons are more plentiful, SII suffers less from noise.

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 may improve the limiting magnitude from 2.5 at NSII to 9.5. It seems that multi-detector intensity interferometry could be used as a present day technique

answering present day questions, and indeed deserves another review.

NSII was discontinued after it essentially exhausted all possible observing lists. Similar fate could affect high-energy and mm-wave collectors. Constructing an observatory from collector arrays, with time sharing and time overlapping between SII, γ and mm observations and correlations could produce more results and with higher diversity than each array separately.

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