

Towards the Intensity Interferometry Stellar Imaging System

M. Daniel, W.J. de Wit, D. Dravins, D. Kieda,
S. LeBohec, P. Nunez, E. Ribak
for the Stellar Intensity Interferometry working group
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Contact: David Kieda, University of Utah, Phone: 801 581 6901,
Email: kieda@physics.utah.edu

Abstract

The imminent availability of large arrays of large light collectors deployed to exploit atmospheric Cherenkov radiation for gamma-ray astronomy at more than 100 GeV, motivates the growing interest in application of intensity interferometry in astronomy. Indeed, planned arrays numbering up to one hundred telescopes will offer close to 5,000 baselines, ranging from less than 50 m to more than 1000 m. Recent and continuing signal processing technology developments reinforce this interest. Revisiting Stellar Intensity Interferometry for imaging is well motivated scientifically. It will fill the short wavelength (B/V bands) and high angular resolution (< 0.1 mas) gap left open by amplitude interferometers. It would also constitute a first and important step toward exploiting quantum optics for astronomical observations, thus leading the way for future observatories. In this paper we outline science cases, technical approaches and schedule for an intensity interferometer to be constructed and operated in the visible using gamma-ray astronomy Air Cherenkov Telescopes as receivers.

1 Key science goals

Stellar astrophysics distinguishes itself by the great progress that has been made in understanding the origin and evolution of the basic astrophysical phenomena, despite a physical inability to directly image the stellar surfaces. Nearby stars have maximum angular extent of tens of milli-arcseconds (mas); direct imaging of objects in this angular range requires use of optical interferometry with baselines of one hundred meters or more. Until now, only a handful of stars (in addition to the Sun) have been directly imaged to some extent using interferometric techniques.

Of numerous interferometric methods, two are especially well suited for imaging of stellar surfaces. Stellar amplitude (Michelson) interferometry (SAI) was employed (very simply) in the 1920's to measure a few cool stars, but the technique was strongly control-technology-limited. In the 1960's, stellar intensity interferometry (SII) was employed to measure some 32 stars [13], but it was, at that time, very sensitivity-limited. More recently, SAI has been extensively developed, with several arrays offering telescope apertures in the range 0.5-10 meters and baselines up to ~ 300 meters. Modern amplitude interferometry has achieved sub-mas resolution, with many applications to stellar physics ¹

Amplitude interferometry as currently deployed, however, has significant limitations. In order to image hot stars (typical diameters < 1 mas) SAI would need considerably longer baselines, and would need to operate in the visible (difficult) or blue (very difficult). Intensity interferometry is well matched to blue/visible operation, and scales to long baselines with ease (the atmospheric stability requirements are a factor of a million less stringent for SII than for SAI).

There are excellent technological motivations for renewing interest in SII astronomy. First, the tremendous progress of signal processing technology since the 1960's can improve sensitivity and makes implementation more cost effective and reliable. This opens up the possibility to simultaneously exploit a very large number of baselines to achieve a dense sampling of the interferometric plane (in which the Fourier transform of the image is to be measured). Second, within the next decade, extended arrays of large diameter light collectors are being planned for the next generation of Atmospheric Cherenkov Telescope (IACT) Observatories, such as CTA [2] and AGIS [1]. These projects will involve up to a hundred telescopes distributed over several km^2 area. Such dense sampling of an optical signal over the large area can sample the interferometric u-v plane with close to 5,000 baselines ranging from a few tens of meters to more than a kilometer. The combination of the dense sampling as well as the shorter wavelength measurements can allow the u-v interferometric plane coverage to potentially measure stellar diameters down to the 0.1 mas domain, a capability that will open up a new field of ultra-high precision ground-based astronomical imaging. SII would offer a very complementary functionality to a Cherenkov array, as the SII operation, on relatively bright stars, would be far less sensitive to sky brightness, and could operate under moonlight, during times not useful for Cherenkov studies.

We envision a two-stage development and implementation of modern SII. In the first stage, SII could be implemented on one or more existing Cherenkov arrays, immediately offering the advantages of blue operation and high resolution. In a second stage, SII could be implemented as an augmentation of a next generation Cherenkov array, with an extremely rich range of baselines providing very high resolution and imaging capability unlikely to be matched by SAI in the foreseeable future, and in particular opening the possibility of very detailed imaging of young stars.

The ongoing developments in this direction are presented in the following sections after an outline of the science potential offered by the proposed re-deployment of SII. The capability to address various questions depends on the actual design of a modern intensity interferometer. In the following sub-sections, in order to discuss the value of a few selected science topics which could

¹See the numerous Astro2010 Science White papers <http://usis.wikispaces.com/ASTRO2010+White+Papers>

be advantageously investigated, we adopt a conservative limiting visual magnitude $m_v < 8$ and a resolution of 0.1 mas.

1.1 Pre-main sequence stars (PMS)

Pre-main sequence stars are young stars that are contracting towards the main-sequence, but are powered only by gravitational collapse: core temperature and pressure are insufficient to ignite hydrogen fusion. Key questions relating to the physics of mass accretion and PMS evolution can be addressed by means of very high resolution imaging. Spatially resolved studies will address the absolute calibration of PMS tracks, the mass accretion process, continuum emission variability, and stellar magnetic activity, including the formation of potential jet emission.

Features on the stellar surface may also be directly imaged. Hot spots on the stellar surface deliver direct information regarding rotation via the von Zeipel effect, as well as tracing the accretion of material onto the stellar surface. Cool spots, on the other hand, may cover 50% of the stellar surface; they may be produced by magnetic field effects (sun-spots), or as a product of the slowly decaying rapid rotation of young stars. Measurement of the number, distribution, and then variations of hot and cool spots will constrain the interplay of rotation, convection, and chromospheric activity. It may also provide direct practical application for exploring the anomalous photometry observed in young stars[34]. In addition, the presence of hot and cold features on the stellar surface is not only limited to PMS stars; observation of such features on main-sequence stars may allow detailed study of sun-like transient phenomena on a wider class of main sequence stars. Because the most luminous stars will provide the strongest interferometric signal, U/V band measurements of stellar surface features by SII can provide optimal contrast.

In the last decade, several young, coeval stellar groups have been discovered in close proximity (~ 50 pc) to the sun. Prominent examples of nearby coeval stellar groups include the TW Hydra and β Pic co-moving groups. The proximity of the co-moving groups ensures that their members are bright. The majority of the spectral types within these nearby groups range between A and G-type, and about 50 young stars have $m_v < 8$. Their close proximity renders the co-moving groups relatively sparse making them very suitable, un-confused targets. The relative sparseness also must certainly generate incomplete group membership. As stellar distances continue to be refined, additional members of these groups may be discovered, making it likely that the known number of young, bright stars will continue to increase with time. The ages of the stellar coeval groups lie in the range between 8 to 50 Myr (see [40] for an overview). These young ages imply that a substantial fraction of the low-mass members are still in their PMS contraction phase.

The evolutionary PMS tracks in the Hertzsprung-Russell diagram are usually calibrated using spectroscopic binaries, which do not allow to resolve the individual stellar masses. Statistical methods are used to estimate the inclination angle of the systems and estimate the average masses for an ensemble of stars. By directly imaging the binary orbital parameters, the inclination of the system can be determined, leading to direct measurement of the masses of the binary components. This is a fundamental exercise not only for PMS stars but for all spectroscopic binaries in any evolutionary stage. Measurement of angular sizes of individual PMS stars in combination with a distance estimate (e.g. GAIA) allows a direct comparison between predicted and observed sizes of these gravitationally contracting star on a star-by-star basis, rather than on an average basis over an ensemble of stars.

1.2 Cepheid distance scale

Measuring diameters of Cepheids is a basic method with far reaching implications for determination of the distances of nearby galaxies. Currently, optimum use of a Cepheid distance scale requires

calibration of distances, and correction for Cepheid atmospheric factors. Hipparcos (and in the future GAIA and perhaps SIM) provide precision distances for calibration. SII promises much higher resolution and extension of Cepheid calibration to greater distances with the Baade-Wesselink method [33]. In an exciting development, intensity interferometry was recently proposed as an approach for the measurement of absolute distances by exploiting the time curvature of the observed light wave fronts [32]. Meanwhile, SAI is already providing critical ancillary information, such as the atmospheric p factor, for Cepheids of known distance [25].

1.3 Fast rotating (Be) stars

Classical Be stars are particularly well-known for their close to break-up rotational velocities as deduced from photospheric absorption lines. In addition, they show both IR excess and Balmer line emission due to a gaseous circum-stellar disk. The line emission appears and disappears on timescales of months to years. Photometric observations of Be star disks sometimes provide evidence for evolution of the disk structure into several ring structures, before the gas disappears into the interstellar medium (e.g. [6]). The Be-phenomenon is fairly common (fraction of Be stars to normal B-type peaks at nearly 50% for B0 stars, [39]), and is therefore indicative of a fundamental stellar physics phenomenon. There are about 300 Be stars² brighter than $m_v = 8$, roughly corresponding to a distance limit of 700 pc.

The disk structure, fast rotation, and emission line phenomena in Be stars appear to be related. Although the exact underlying Be mechanism has yet to be identified, the Be phenomenon is probably related to the high rotational velocity of the star. Absorption line studies cannot provide an accurate rotational velocity in these objects due to strong gravity darkening at the equator and brightening at the pole areas. However, direct measurement of the physical shape of the rotating star can provide a direct measure of the rotational speed (see α Eri with the VLTI, [5]). The peak blackbody wavelengths of the Be spectra are in the U/V bands. Since ground-based Michelson interferometry is still restricted to IR wavelengths for imaging, the long-baseline coverage of the interferometric u - v plane is reduced, even for the same physical telescope baseline. In addition, the lower photon flux in the IR tail further decreases the number of observable Be stars.

Since SII is substantially less sensitive to atmospheric turbulence than Michelson interferometry, observations of Be stars in the U/V band can enable high resolution studies of Be stars over substantially longer baselines. A rough estimate of the effective temperatures of the objects in the Bright Star Catalog reveals there are approximately 2600 stars brighter than visual magnitude 7 and hotter than 9000 K. Their typical angular sizes range between 0.5 mas and 5 mas making them observable even with a fairly modest scale intensity interferometer array.

1.4 Other Stellar Physics

Optical interferometry is still in its infancy, but already more than 150 science publications show the dramatic return from high angular resolution studies of stars, ranging from YSO's and pre-planetary disks, to MS stars, debris disks, multiple stars, mass loss in all kinds of systems, and PMS evolution. SII promises to complement and extend such programs to blue/visible imagery with much higher resolution, and at comparatively modest incremental cost. Rather than develop specific science topics further here, we refer to the typically 4-5 SAI publications currently appearing in the literature each month.

²<http://www.astrosurf.com/buil/us/becat.htm>

2 Technical overview

2.1 Intensity Interferometry Technique

The intensity interferometry technique does not rely on the actual interference of light rays as in Michelson interferometry. Instead, the interferometric signal, the degree of mutual coherence, is characterized by the degree of correlation of light intensity fluctuations observed at two different detectors. In practice, the degree of mutual coherence is measured using fast temporal correlations between narrow optical waveband intensity fluctuations observed by two (or more) telescopes separated by a baseline distance.

The principal component of the intensity fluctuation is the classical shot noise which will not demonstrate any correlation between the two separated telescopes. The intensity interferometric signal is related to a smaller noise component: the wave noise. The wave noise can be understood as the 'beat frequency' in optical intensity between the different Fourier components of the light reaching the telescopes. This wave noise will show correlation between the two detectors, provided there is some degree of mutual coherence between the light received at the two telescopes. As per equation 1, this intensity correlation (the time integrated product of the intensity fluctuations Δi_1 and Δi_2 in two telescopes) is positive. The correlation provides a measurement of the square of the degree of coherence of the light at the two detectors $|\gamma(d)|^2$ (the fringe visibility in a Michelson interferometer) where d represents the distance separating the telescopes. [23].

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

According to the van Cittert-Zernike theorem, the complex degree of coherence ($\gamma(d)$) is the normalized Fourier transform of the source intensity angular distribution. 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. As a consequence, when the baseline d is too small for resolving the observed object, $|\gamma(d)|^2 = 1$ and Δi_1 and Δi_2 are maximally correlated. Conversely, when the telescope baseline is sufficient to resolve the Airy disk, $|\gamma(d)|^2 < 1$, and Δi_1 and Δi_1 are still correlated to some extent. For observations at wavelength λ , the degree of coherence $\gamma(d) = 0$ when $d = 1.22\lambda/\theta$. An intensity interferometer with 1 km baseline operating at a 400 nm wavelength should therefore be able to probe features with angular extent less than 0.1 mas.

The important point is that the technique relies on the correlation between the (relatively) low-frequency intensity fluctuations between different detectors, and does not rely on the relative phase of optical waves at the different 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. One strong advantage of intensity interferometry is therefore 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 even in the U and V bands.

The major drawback of SII is that copious quantities of light are necessary to observe the wave noise signal in the presence of the much larger shot noise. Very large light collectors (50 – 100 m² area) are necessary to have sufficient statistical strength to observe non-Poisson fluctuations around the mean photon intensity. 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 the 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. Interestingly, these

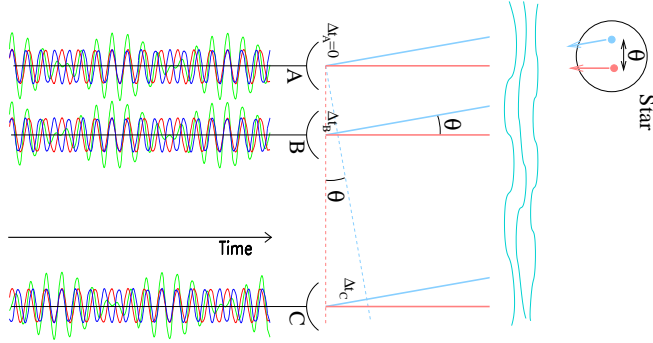


Figure 1: Considering two harmonic emitting points in the source, with slightly different frequencies, telescopes A and B being close together receive beats almost at the same time. This corresponds to a high degree of correlation. Telescopes A and C being further apart do not receive beats in phase and the degree of correlation is then lower [21].

primary design requirements are well matched by Imaging Atmospheric Cherenkov telescopes used for gamma-ray astronomy above 100 GeV. SII also appears to be the only viable tool for high resolution studies through the atmosphere in blue wavelengths. Observations at short wavelengths will provide a higher contrast for measurement of spatial differences in the envelope of hot stars. These wavelengths can potentially extend imaging capabilities of bright stars to larger distances than Michelson interferometry.

2.2 Using Ground-based VHE gamma-ray Telescope arrays for SII

The intensity interferometry technique was initially developed for radio astronomy [17]. Hanbury Brown and Twiss subsequently demonstrated that the technique could also be employed at visible wavelengths [15, 16]. Based upon the success of these initial measurements, the Narrabri Stellar Intensity Interferometer (NSII) was designed and constructed [14]. NSII was located near Narrabri, Australia, 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 two 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. The combination of mirror area, electronic bandwidth, and electronic noise restricted observations to stars brighter than $B = +2.5$. 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, some as small as 0.4 mas [13].

Imaging Air Cherenkov Telescopes (IACT) are used for gamma-ray astronomy at Very High Energies (VHE, energies greater than 100 GeV). The IACT technique relies on the fact that VHE particles and gamma-rays initiate extensive air showers of high energy secondary particles in the atmosphere. Charged shower particles with sufficient kinetic energy will radiate optical Cherenkov light into the atmosphere. This Cherenkov light at ground level is strongly peaked at blue wavelengths, has a duration of only a few nanoseconds, and is also very faint (~ 10 photons/m² at 100 GeV). Large (> 10 m diameter) light collectors with excellent U/V band reflectivity equipped with fast electronics are employed to detect this Cherenkov light. IACTs are typically used in widely-spaced arrays of 2 to 4 telescopes with typically 100 m inter-telescope distances in order to record stereoscopic views of each shower. This telescope separation is chosen to match the extent of the Cherenkov light pool at ground level [38], and is dependent on the altitude of the IACT

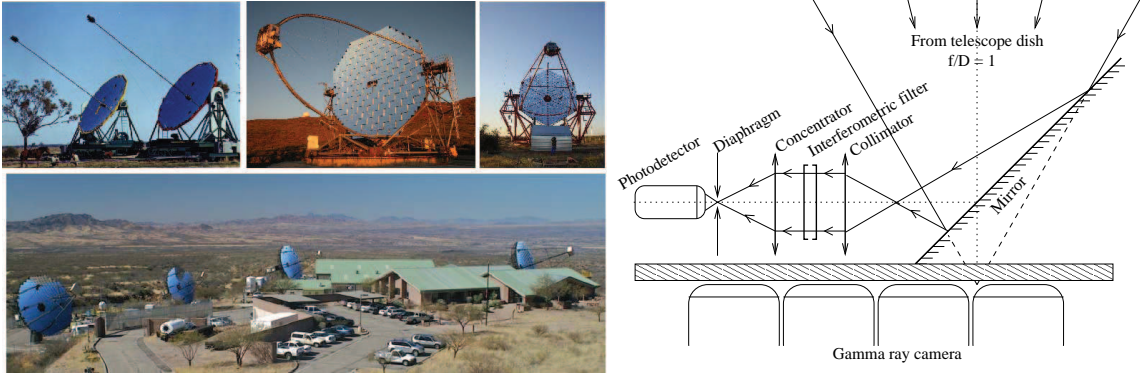


Figure 2: The two 6.5 m Narrabri Stellar Intensity Interferometer telescopes (top left) have many common points with Imaging Air Cherenkov Telescopes such as the two 17 m MAGIC telescopes (center top), the four 12 m H.E.S.S. telescopes (right) or the four 12 m VERITAS telescopes (bottom). On the right is a schematic of a possible implementation of SII on a Cherenkov telescope [22]. The light from the mirrors is reflected side way toward a collimator and analyzer before being focused on the photo-detectors. Such a simple system can be mounted on the shutter of the atmospheric Cherenkov camera so it does not block the view for gamma-ray observations.

observatory, Figure 2 presents examples of current IACT telescopes.

Because the design requirements of IACT arrays and SII arrays are generally similar, these facilities can potentially be used for both types of astronomical observations [22, 20]. Historically, the two SII telescopes of the Narrabri interferometer were subsequently instrumented as air Cherenkov telescopes in a search for astronomical sources of very high energy ($E > 300 \text{ GeV}$) gamma-rays [10, 11].

An existing IACT telescope can be converted into a SII receiver by adding an optical collimator, an interferometric filter, a photo-detector and front end electronics on the focal plane of the IACT telescope. The SII instrumentation could be mounted in front Cherenkov cameras as illustrated on the right side of Figure 2. It is desirable to have the SII instrument package integrated into the camera shutter so that it does not interfere with normal gamma-ray observations. The HESS telescopes have already prototyped such a mounting system for performing photo-metric measurements of stars with a photomultiplier tube [4]. The SII instrument will send the SII signal from each telescope to a central facility to be combined and correlated over various baselines, thereby filling out the u - v interferometric plane. The length and orientation of the effective baseline between two IACT telescopes depends on the position of the star in the sky. At the time of the final data analysis, the interferometric (u, v) plane is binned, taking into account the time-varying baselines from each telescope pair.

Although IACT telescopes can be used for SII, IACT arrays are optimized for high energy gamma-ray astronomy. Optimizations for highest gamma-ray sensitivity with lowest cost will constrain the SII capabilities of these instruments. For example, the signal to noise ratio in an SII instrument depends upon the square root of the correlator bandwidth. IACT telescope designs typically employ a large ($> 3^\circ$ diameter) field of view in order to capture the entire length of the optical Cherenkov signal as well as to efficiently map the night sky for new sources of VHE gamma-rays. The requirement to minimize optical aberration over the wide field of view has led several groups to adopt the Davies-Cotton [3] telescope design. However, this design does not preserve iso-chronicity (simultaneous arrival at the focal plane of all photons collected by single flash of light across the full mirror surface). For 12 m telescopes such as in HESS and VERITAS [36], the telescope optics spreads an optical light impulse out to a duration of several nanoseconds at the focal plane. This

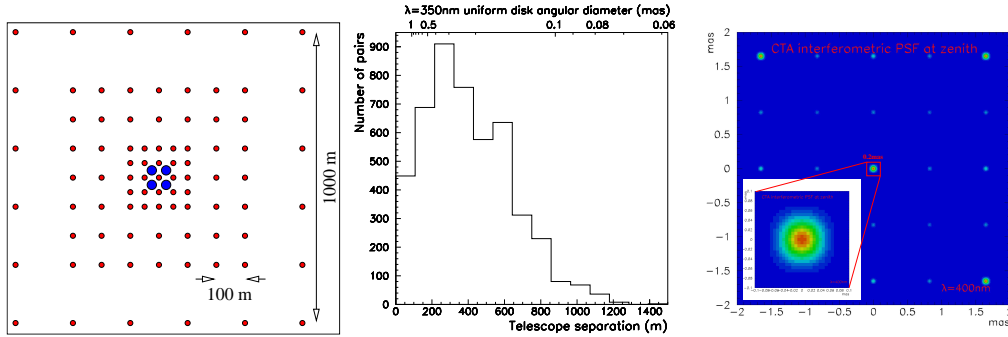


Figure 3: The proposed lay-out for the future CTA (left) includes 85 100 m² dishes (red dots) and four 600 m² dishes (blue dots). It would offer 3,916 baselines [20] ranging from 35 m to 1,414 m (center) and allowing imaging at 400 nm over an aliasing free 1.6 mas field of view with a better than 0.1 mas angular resolution (right).

effectively convolutes any optical signal with an effective filter bandwidth of ~ 100 MHz. With parabolic telescopes such as in MAGIC (17 m) or H.E.S.S. II (29 m), the effective signal bandwidth filter is on the order of 1 GHz.

The optical quality of the IACT telescope will also constrain the limiting visual magnitude for SII applications. The optical point spread function of typical Davies-Cotton IACT design is 0.05° . This point spread function is well matched to the typical angular width of an air Cherenkov light image (0.1°). However, because of the corresponding integration of night sky background light, these telescopes could not be used for SII observations of stars any fainter than visual magnitude ~ 9.6 [22].

In contrast with movable Narrabri SII telescopes, the telescopes in an IACT array are at fixed positions on the ground. The SII signals from different telescopes will have to be brought back in time coincidence for the correlation to be measured; the time delay between arrival of the optical telescopes depends upon their projected path length difference to the star. The path length difference changes as the star transits through the night sky. Electronic signal delays will be added to each photo-detector signal to correct the arrival time, and thereby restore temporal coincidence between intensity fluctuations. The minimum signal delay accuracy is determined by the optical bandwidth of the telescope. To preserve the highest frequency SII correlations between two telescopes with an accuracy better than 10%, the signal time delays must be controlled to an accuracy better than 7% of smallest signal period. For example, a ~ 100 MHz system requires time delay correction accuracy of ~ 0.7 ns. An analog delay system with similar requirements has been operated by the CELESTE experiment [31].

IACT gamma-ray observations are generally limited to dark, moonless nights. During periods when the moon is in crescent phase, IACT telescopes may operate with reduced sensitivity, or they may use this time to perform optical calibrations and alignments. For VERITAS, HESS, and MAGIC, the equivalent of ~ 10 nights each month during near-full moonlight are unused for gamma-ray astronomy, and could be made available for SII observations. This corresponds to ~ 800 hours of SII observation per year. Assured telescope access of this magnitude is more than sufficient for development of a vigorous SII science program. At the same time, the SII program will have minimal impact on existing VHE gamma-ray science programs. If the SII science program is successful using the freely available 800 hours/year on the next generation IACT arrays, it would be advantageous to consider building a future dedicated SII facility with a square kilometer array on varying, non-periodic baselines. The first-light time-frame for a dedicated facility would be in the 2020-2030 decade, or later.

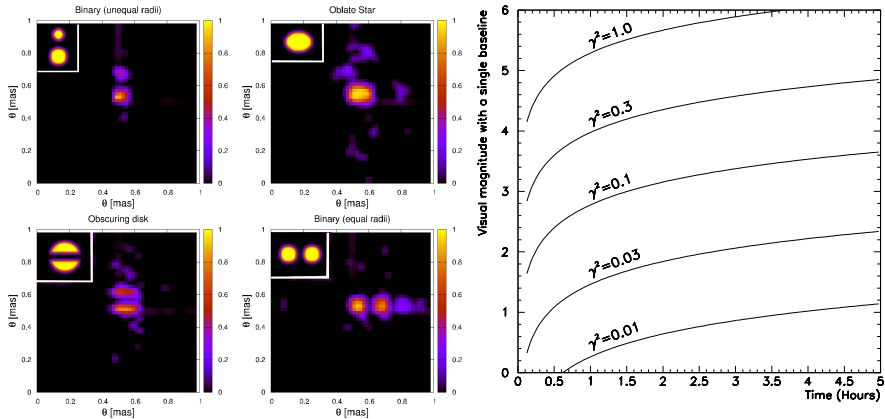


Figure 4: On the left, four examples of reconstructed images from a simulated SII observation using an IACT telescope array. The simulation uses a wavelength of ~ 400 nm with one hundred CTA-like telescopes and a inter-telescope separation of ~ 100 m. The pristine image is shown at the top left in each example. The images were produced [28] using an algorithm based on the Cauchy-Riemann equations [19]. The analysis does not yet include a realistic noise component, which is still actively being investigated. On the right, for a range of degrees of coherence $|\gamma|^2$, the visual magnitude for which a five standard deviation measurement is possible with a single baseline is indicated as a function of the observing time. We assumed $A = 100\text{ m}^2$ light collectors with quantum efficiency $\alpha = 30\%$ and a signal bandwidth of 100 MHz. Baseline multiplicities of 10, 30, 100 and 300 improve the sensitivity by 1.25, 1.85, 2.51 and 3.11 magnitudes respectively. This is for model independent imaging only. Model fitting would allow the study of objects with fainter visual magnitudes.

2.3 Capabilities of an SII implemented within the CTA/AGIS IACT arrays

Next generation IACT arrays such as CTA [2] and AGIS [1] are planned for construction and operation during the decade 2010-2020. These square kilometer arrays will use up to 100 telescopes (Figure 3) providing up to 5000 base-lines ranging from ~ 50 m to ~ 1.4 km. Calculations indicate that a CTA-type IACT array used as an SII observatory would allow direct imaging on angular scales between several mas to less than 0.1 mas.

The SII technique provides a measurement of the magnitude of the Fourier transform of the image, but does not directly measure the phase information of the Fourier transform. Several phase reconstruction techniques have been proposed which employ higher order intensity correlations to recover the phase information [9, 8, 24, 37]. The exploitation of higher order correlations has implication on the design of the Intensity Interferometer. Signals from telescope triplets, quadruplets and more have to be brought together to be combined. A possibly more promising method exploits the analyticity properties of the Fourier transform to establish a relation between finite differences in the magnitude and in the phase of the Fourier transform [19]. A typical implementation used to recover high resolution source images with a CTA-like array is illustrated on the left of Figure 4. This method has been demonstrated to be very robust against potential noise contamination [18].

The sensitivity of the SII is determined by the shot noise in the incoming photon stream from each telescope. In the measurement of the degree of correlation of intensity fluctuations between two telescopes, the signal to noise ratio (S/N) is

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

where A is the light collection area of one telescope, α is the quantum efficiency, $|\gamma(d)|^2$ the square

of the magnitude of the degree of coherence for a given baseline d . The right side of Figure 4 shows the expected S/N ratio as a function of the exposure time for conservative telescope parameters ($A = 100 \text{ m}^2$, $\alpha = 30\%$ and $\Delta f = 100 \text{ MHz}$). With five hours of observation, a single baseline can provide measurements of $|\gamma|^2 = 0.3$ and $|\gamma|^2 = 0.03$ for stars of visual magnitude 4.8 and 2.4 respectively, with a 5σ statistical significance.

The statistical sensitivity of these observations can be further improved by 1 to 3 magnitudes (depending of number of baselines used and specific array design) by exploiting the redundancy of the baseline measurements in the full array. This could be further improved if additional optical channels are available at each telescope. Finally, when the information sought does not require a model independent reconstruction of the image (as in the case of a binary, a fast rotating oblate star, a star with an obstructing disk, etc), all the baselines can be simultaneously exploited to push SII sensitivity to objects approaching $m_v = 9$.

For typical Cherenkov telescope quality ($\text{PSF} = 0.05^\circ$, $\text{area} = 100 \text{ m}^2$), the ultimate sensitivity ($m_v = 9$) is dominated by the integrated night sky background in the PSF, and not by the SII signal statistics. The observation of objects fainter than $m_v = 9$ requires both higher telescope optical quality as well as extended observation time. For each additional visual magnitude, the required observation times increases by a factor > 6 . This does not preclude the utilization of larger telescopes ($\text{Area} > 100 \text{ m}^2$) as long as the source remains unresolved across the diameter of the mirror. In particular, a five hour observation by a single pair of CTA 600 m^2 telescopes will provide $|\gamma|^2 = 0.3$ and $|\gamma|^2 = 0.03$ measurements for visual magnitude 6.7 and 4.3 stars, respectively.

3 Technology drivers

The currently envisioned SII implementation does not depend on the development of any critical technological capability. There are technology developments, however, that can benefit the capabilities of future large scale Intensity Interferometer arrays. These technological developments may extend SII to higher sensitivities, thereby extending the imaging capabilities to dimmer visual magnitudes. In this section, we describe the potential impact of two technological drivers.

3.1 High speed data recording and handling

A major improvement in the ultimate sensitivity of a large SII array can be accomplished by continuously recording each telescope's stream of intensity fluctuations with minimal signal processing, and calculating the inter-telescope correlation functions post-observation. This capability can allow studying the degree of correlation as a function of time-lag between the two photon streams. Ofir and Ribak [30] have recently proposed that the time-lag dependence of the correlation carries detailed information regarding the source emission process. The availability of the full data stream from each telescope can also allow analysis techniques based on higher order intensity correlations (i.e. 2, 3 and more points). These higher order correlations are employed for both phase reconstruction analysis and also for absolute source distance measurements based on light wave front curvature [32, 30].

The ability to handle such large data rates has only recently become technically feasible. A continuous 200 MHz digitization of the photo-detector signal with 4 bit accuracy generates 360 Gb per hour of operation of a single CTA telescope, and about 280 Tb per observation night for the full array. Using existing technology such as off the shelf 1.5 Tb SATA disks (2009 price : \$150 each) in a distributed, parallel RAID array, it is feasible to archive the data in real time for next-day processing. The next day analysis pipeline would employ a farm of distributed processors to generate the intensity correlations and invert the Fourier plane to generate the source image for

each observation. The data storage requirements are minimal once the SII data has been correlated and inverted (10-100 Gbyte/night maximum), and so after analysis, the RAID data storage farm would be overwritten by the next night's data. As hard-disk technology continues to advance, it may eventually be possible to archive the entire raw data set each night for longer term study and re-analysis.

Technological challenges associated with a 1-day turnaround pipeline analysis are of similar magnitude to other state-of-the-art telescope systems such as LOFAR, ALMA, and SKA. The most significant technological challenge to a large SII array is probably in establishment of sufficient bandwidth across the widely distributed array that will allow efficient transport all data to localized data storage nodes for collection and correlation. The data collection and processing scheme must be designed to provide sufficient redundancy and robust operation so that it may continue to perform its analysis task even when one or more telescope systems in the array have failed.

3.2 High speed & high quantum efficiency photo-detectors

As described previously, the S/N ratio for SII is proportional to the photo-detector quantum efficiency α and also to the square root of the combined photo-detector/optical bandwidth Δf . For a fixed stellar magnitude, improvements in the S/N ratio (and therefore visual magnitude sensitivity) can therefore be achieved through technological improvements to the photo-detector quantum efficiency and speed (Figure 5).

A standard bialkali photomultiplier tube will provide quantum efficiency $\alpha = 25\%$ at optical wavelength $\lambda = 350$ nm and signal bandwidth $\Delta f = 200$ MHz. Super-bialkali photomultiplier tubes have recently become available with $\alpha = 35\%$, and Ultra-bialkali with $\alpha = 43\%$. Consequently, one may improve the S/N ratio by a factor of two for a minimal cost per telescope. The sensitivity improvement is equivalent to doubling the mirror area with a standard bialkali photomultiplier tube. The application of ultra-bialkali photomultipliers to SII is fairly straightforward and relatively inexpensive. This technology has yet to be deployed on a current SII instrument; The SII observation environment poses special challenges due to the strong optical intensity at the focal plane. Issues regarding temperature stability, saturation, and photomultiplier tube lifetime have yet to be explored. This technological development is underway and should proceed rapidly over the next few years.

The highest quantum efficiency photo-detectors commercially available are based upon semiconductor technology; these devices (e.g. avalanche photodiodes) may approach $\alpha = 95\%$ at $\lambda = 330$ nm. Large area silicon devices suffer from substantial inherent electronic noise related to the silicon bulk resistivity and the depth of the depletion layer at the PN junction. In order to achieve single photon sensitivity, recent technology has focused on the development of large arrays of very small area Single Photon Avalanche Photodiodes (SPADs). By minimizing the SPAD area (and hence the capacitance), each SPAD achieves sufficiently low inherent electrical noise to allow detection of single photons with $\alpha > 50\%$. The reduced capacitance also allows these devices to be extremely fast; typical photo-detector bandwidth is improved by a factor of 5-10 over conventional photomultiplier tube. The combination of these two improvements can allow an increase in S/N of a factor of 3-6 over conventional photomultiplier tubes, and 2-4 over ultra-bialkali photomultiplier technology.

Present technology SPADs are relatively inexpensive, and are stable with respect to intense light exposure, but suffer from comparatively large (80 nsec) dead-time after observation of a light pulse. At the present time, a first implementation of a high speed, high quantum efficiency camera using SPAD technology has been constructed and tested. This device, called AquEYE [27], is a first generation implementation the ESO QuantEYE concept[26]. AquEYE employs four independent

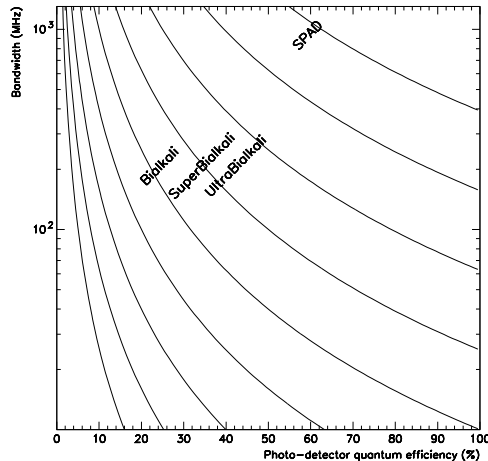


Figure 5: Sensitivity contour lines are separated by one visual magnitude in the signal bandwidth versus quantum efficiency plane characterizing photo-detectors. SPADs could give a 4 magnitude improvement compared to regular bialkali photomultipliers. However, the effective signal bandwidth is limited to 100 MHz for 10 m Davis-Cotton f/1 Cherenkov telescopes. Larger Cherenkov telescopes (MAGIC, H.E.S.S. II) are parabolic and provide a signal bandwidth close to 1 GHz.

50 μm diameter SPAD pixels, with pixel timing better than 50 psec and $\alpha > 50\%$ for λ between 500 nm and 600 nm. AquEYE was first successfully tested in June 2007 on the 182 cm Asagio Cima Ekar Telescope. Future technological development of SPAD type photo-detector technology will need to focus on reducing detector dead-time and overall system cost.

4 Activity, Organization, Partnerships and current status

The main organizational body overseeing the development of Intensity Interferometry as a modern astronomic technique is the SII Working Group within IAU commission 54 on optical and infrared interferometry. The SII Working Group, commissioned in 2008, held its initial meeting at the August 2008 SPIE meeting in Marseilles, France. At this meeting, it was decided to organize an SII workshop in January 2009 at the University of Utah³ in order to review the scientific and technical status of international SII development activities, and to coordinate research efforts. Members of the SII working group are independently pursuing science topics and technical developments related to SII. Some of these activities include:

- Correlators, optical fibers, and photo-detectors are being developed and tested by independent research groups in the US and Europe.
- The University of Utah is deploying a pair of 3 m telescopes on a 20 m East-West baseline⁴ in order to provide a realistic SII test environment for the SII working group.
- SII Working Group Members of the VERITAS collaboration, in collaboration with Dravins, have performed inter-telescope correlation feasibility studies in October 2008 at the VERITAS Observatory. Correlations between fast intensity fluctuations between two VERITAS 12 m

³2009 workshop on Stellar Intensity Interferometry: <http://www.physics.utah.edu/~lebohec/SIIWGWS/>

⁴StarBase Utah: <http://www.physics.utah.edu/starbase/>

diameter telescopes were studied using the central photomultiplier tube of the VERITAS gamma-ray cameras.

- Close contacts are maintained with the CTA and AGIS collaboration regarding SII science topics and integration of SII specific electronics and secondary optics with the IACT gamma-ray cameras.
- A working group focused specifically on SII science and SII camera integration, led by Dravins, has been established with the CTA collaboration. The CTA SII group has recently submitted a CTA Phase A design study for implementation of SII capability onto the CTA Observatory.
- Theoretical studies of optimal image and phase reconstruction techniques are underway, with significant efforts in Israel, Utah, and Europe.

Ongoing progress in all of these various directions necessitates frequent meetings to discuss results, ideas, and to plan new initiatives. The SII Working Group also serves as the main organization for development of the research collaboration that will develop the SII instrumentation and science research programs for the CTA and/or AGIS Observatories. We intend to coordinate these various efforts through yearly meetings of the SII Working Group.

5 Activity schedule

The SII working Group envisions the development of the SII in four distinct Phases

1. Initial Prototype Phase (2008-2010)
2. IACT Array ‘Piggyback’ Phase (2011-2013)
3. CTA/AGIS Science Program Phase (2013-2020)
4. Dedicated SII facility phase (2020-2030)

During the Initial Prototype Phase (2008-2010), the SII working group is working on parallel and complementary developments of experimental and computational tools and facilities that will allow initial observations using a modern SII system. Part of this work will involve using the Grantsville SII 3 m telescopes to test out system components and reproduce measurements of stellar diameters and binaries. This phase will generate initial experience and validation of the SII technique which will prepare the SII Working Group to deploy a multiple telescope (> 2) SII system.

Experience and technology developed during Phase 1 will be refined and standardized during Phase 2 which will likely include the installation and testing of a SII system at a Current IACT array. The SII working group will work with the VERITAS and HESS collaborations to develop a fully instrumented SII system that can be deployed on either or both IACT arrays. The SII group will submit science and development proposals to these observatories to deploy and operate a full four telescope SII system. We anticipate performing 2 years of science observations with the SII system during moonlight conditions, accumulating up to 1600 hours of source observations during this time. During Phase 2, an emphasis will also be placed on developing a reliable SII system that can be fabricated and deployed on the larger CTA/AGIS arrays, which should then be under construction.

In 2013, we will enter Phase 3 which includes operating a 50-100 telescope SII system. When the first CTA/AGIS telescopes are deployed, a small subset will be equipped with SII hardware for further testing (2013-2015) while the full scale implementation will be under preparation. By 2016,

the entire CTA array will have been equipped with SII hardware and the observation program will be carried until 2020. The large number of redundant baselines sampled will substantially extend the capabilities of the SII technique. It should be possible to establish a strong science program with excellent image reconstruction and angular resolution in the sub micro-arcsecond range.

Phase 4 would include the construction and operation of a dedicated SII km² area array of high signal bandwidth (\sim GHz) telescopes. This would allow a substantial increase in the number of available observation hours especially in dark sky (no moonlight) conditions. This should result in increased sensitivity for observing more distant (fainter) objects. This stage would take advantage of experience gained with CTA/AGIS in the operation of large arrays of large light collectors. This project is beyond the current decadal survey.

6 Cost estimate

As the proposed SII observations can be carried out using existing technology, the cost of many of the key items for the SII project can already be reliably estimated. However, the basic design of the AGIS and CTA telescopes is still under discussion, including the number of telescopes, separations, diameters, etc. Consequently, the cost of the presently envisioned full SII implementation on CTA/AGIS inherits cost estimate uncertainties from uncertainties in the design of these observatories. We can make a representative estimate of the SII implementation based upon a strawman CTA Observatory. The strawman CTA Observatory employs 97 telescopes which will generate 4656 baselines. Each CTA telescope will be equipped with secondary SII optics (\sim \$5,000) and at least two SII photo-detectors and associated power supply and slow control (\sim \$3,000). SII signals will have to be communicated to the central station to be processed. This communication will have to ensure synchronization to a fraction of nanosecond in order to maintain 100 MHz bandwidth. This can be achieved by optical fibers running to each telescope (\$2,000). The total cost for measuring the optical signal at each telescope and transporting the signals to a central correlation/recording station is approximately \$970,000. The two point correlation for each of the 4656 baselines can be achieved with various techniques. Several correlator designs are under study and all are available for less than \$200 to which one would need to add the price of the computing facility to centralize and record the data (\$50,000). The full recording of the raw data at each telescope for off-line processing might be possible for a similar or smaller cost. This brings the total hardware cost of the entire SII add-on system to \$1,951,200.

Additional costs for construction and operation of the SII facility at CTA/AGIS include on-site manpower, travel, and infrastructure. We estimate The SII construction phase will require at least two or three full time engineers/technicians on site over the three years construction phase. Typical Cost for on-site personnel is estimated at \$600k for this construction phase. Infrastructure costs cannot realistically be estimated at this stage but can be expected to remain a relatively small fraction of the above mentioned costs. Additional costs for student and faculty personnel have not been included above. We have not included costs for travel by off-site collaborators to the site to perform observations. Including a rough estimate of these costs, we estimate a Total project cost (hardware, engineering, construction and operation over six year of Phase 3 operations) for an SII implementation at a single CTA (or AGIS) IACT array observatory of approximately \$5 million, including overhead. This is less than 5% of the projected CTA (or AGIS) construction budget.

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