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A Stellar Intensity Interferometry Instrument for the ASTRI Mini-Array telescopes

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ABSTRACT

The ASTRI Mini-Array is an International collaboration, led by the Italian National Institute for Astrophysics, that is constructing and operating an array of nine Imaging Atmospheric Cherenkov Telescopes to study gamma-ray sources at very high energy and perform optical stellar intensity interferometry (SII) observations. Angular resolutions below 100 microarcsec are achievable with stellar intensity interferometry, using telescopes separated by hundreds to thousands of meters baselines. At this level of resolution it turns out to be possible to reveal details on the surface and of the environment surrounding bright stars on the sky. The ASTRI Mini-Array will provide a suitable infrastructure for performing these measurements thanks to the capabilities offered by its 9 telescopes, which provide 36 simultaneous baselines over distances between 100 m and 700 m. After providing an overview of the scientific context and motivations for performing SII science with the ASTRI Mini-Array telescopes, we present the baseline design for the ASTRI Stellar Intensity Interferometry Instrument, a fast single photon counting instrument that will be mounted on the ASTRI telescopes and dedicated to performing SII observations of bright stars.

Keywords: instrumentation: interferometers, techniques: interferometric, stars: fundamental parameters, stars: imaging

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1. INTRODUCTION

Nowadays, we are in a position to image bright stars in the visible light waveband at very high angular resolution using a technique known as Stellar Intensity Interferometry (SII), which is based on the measurement of the second order coherence of light [1]. Angular resolutions below 100 micro-arcsecond (μas) are achievable with this technique, using large collecting area telescopes separated by hundreds to thousands of meters baselines. At this level of resolution it turns out to be possible to reveal details on the surface and of the environment surrounding bright stars on the sky, that typically have angular diameters of 1-10 milli-arcsecond (mas) [2].

Stellar intensity interferometry is based on the correlation of the light intensity fluctuations of a star detected at two or more telescopes, at variance with ordinary amplitude interferometry which measures the fringes generated by the direct interference of the telescopes light beams (e.g. the Michelson interferometer). SII was pioneered by Robert Hanbury Brown and Richard Q. Twiss between the 50s and the 70s [3–7]. They built the Narrabri Stellar Intensity Interferometer using twin 6.5 m diameter telescopes movable along a circular track at Narrabri, New South Wales, Australia, and performed the first direct astronomical measurements of stellar radii via SII. After the successful Narrabri experiment, SII was shelved for about 40 years. The possibility to operate simultaneously an array of large area telescopes and to connect them electronically, with no need to directly combine the photons they detect, has recently renewed interest for SII as a tool for performing imaging observations in the optical band using a detection method similar to long-baseline radio interferometric arrays [e.g. 8, 9]. Indeed, this possibility is offered by the sparsely distributed arrays of Imaging Air Cherenkov Telescopes (IACTs), such as the ASTRI Mini-Array, which have adequate optical properties, sufficiently large mirror areas, and telescope time available during the full Moon. SII also requires the measurement of photon arrival times with a precision of the order of one ns or better at each telescope, over baselines extending to km distances. This accuracy corresponds to tenths of meter light-travel distance, and thus any instrumental or atmospheric delay smaller than a fraction of one meter can be tolerated. New implementations of SII technology to astronomy have then been recently pursued by several groups, either simulating thermal sources in the laboratory [e.g. 10], or performing pilot experiments or observations with 1-3 meter class telescopes [e.g. 11–15]. Eventually, the capability of performing SII measurements with the MAGIC and VERITAS IACTs has been convincingly demonstrated by [16] and [17], respectively.

Since the beginning of 2019 also the INAF ASTRI (Astrophysics with Italian Replicating Technology Mirrors) Collaboration recognizes the scientific value of SII and endorses the development of a SII observing mode. The ASTRI project was approved in 2010 to support the development of technologies within the Cherenkov Telescope Array project. In this framework INAF will build an independent Mini-Array of 9 Cherenkov 4m-class telescopes in Schwarzschild-Couder optical configuration in Tenerife (Spain) (Figure 1; [18]). Despite being limited to bright targets because of the limited collecting area, the ASTRI Mini-Array will provide an ideal SII imaging installation thanks to the capabilities offered by its 9 telescopes, that provide 36 simultaneous baselines over distances between 100 m and 700 m [19]. This will be rivalled only by the full deployment of the CTA observatory.

The ASTRI Mini-Array equipped with a SII instrument will provide the first images of bright Galactic stars with sub-mas angular resolution. This capability will open up unprecedented frontiers in some of the major topics in stellar astrophysics. Measuring the angular shape of a selected number of stars (including main sequence stars) with a resolution of $\sim 100\,\mu$as will provide their oblateness and enable direct measurements of the stellar rotation, extending in the visible band the still limited sample of infrared images collected with the Center for High Angular Resolution Astronomy (CHARA) interferometer [20, 21]. Imaging with this resolution can also allow the detection of dark/bright spots or other surface features [22]. An example of a low-resolution measurement of this type is provided by the visible light image of the extended red supergiant Betelgeuse, taken with VLTI/SPHERE during its recent pronounced dimming [23], that clearly revealed a substantial asymmetry in the surface brightness distribution of the star. Furthermore, observing stars with circumstellar discs/eruptions will reveal details of the disc structure, density gradients, and scale height, and will show how these systems evolve and dynamically interact [24]. In this respect, the ASTRI Mini-array operated in SII mode will leave an extraordinary legacy of sub-mas images of the brightest nearby stars and their environments.

For SII observations the optimal targets are stars with high brightness temperature, that have both a significant photon flux and structures small enough to produce coherence over long baselines (e.g. [2]). Therefore, O-thorough-G type stars of adequate brightness are all suitable and potential targets, which makes the B band

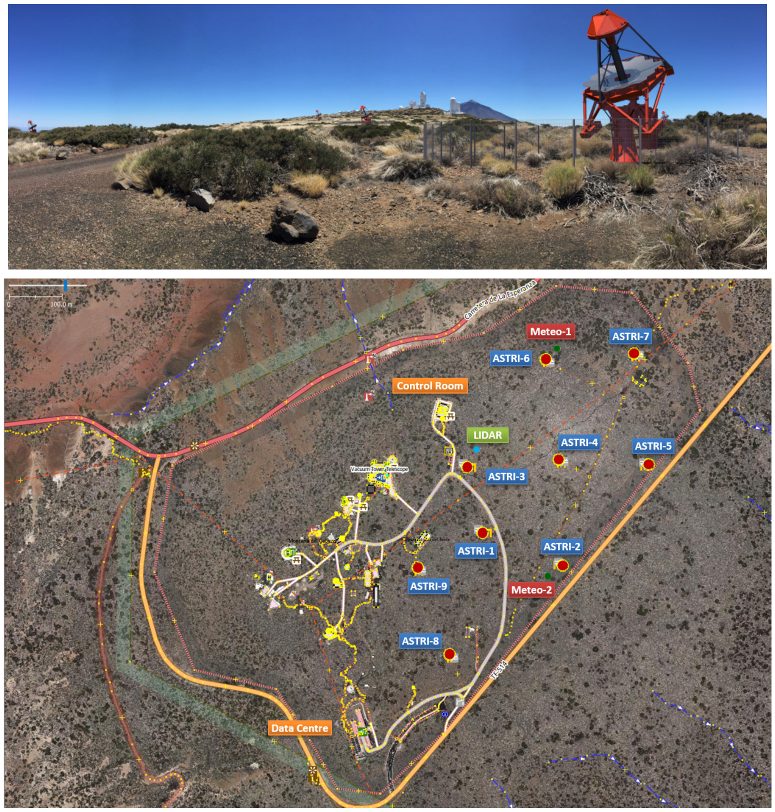


Figure 1. *Top*: Artist impression of the ASTRI Mini-Array site. *Bottom*: Final layout of the 9 ASTRI Mini-Array telescopes at the site of El Teide in Tenerife, Spain [18].

(between 420 nm and 500 nm) the appropriate working wavelength window. In this respect, SII observations can be considered complementary to conventional interferometric observations (such as those performed with CHARA), that are carried out in the infrared band.

2. MEASUREMENT OF THE DEGREE OF COHERENCE

We aim at measuring the spatial correlation of the radiation intensity emitted from a star. Hanbury Brown and Twiss showed that this measurement conveys information on the source size and successfully applied it to Astronomy deriving the angular diameter of a number of stars [6]. The measurement of the correlation can be performed using the continuous intensity fluctuations ('analog SII', as in the Narrabri interferometer; [7]), the discrete intensity fluctuations ('digital SII', as in the MAGIC and VERITAS interferometers; [16, 17]), or the photon arrival times ('photon counting SII'; as in the Asiago interferometer experiment; [12]). We adopt the latter approach, which is based on counting coincidences in photon arrival times measured at two telescopes and exploits entirely the quantum properties of the light emitted from a star. As discussed in the next Section, we consider this approach as appropriate for performing SII observations and measurements with the ASTRI Mini-Array telescopes.

In photon counting mode the second order discrete degree of coherence of a star is calculated using the expression (e.g. [12]):

$$g^{(2)}(\tau, d) = N_{XY} N / N_X N_Y \,, \tag{1}$$

where d is the separation between two telescopes X and Y, τ is their relative time delay, N_X and N_Y are the number of photons they detect in an observation of duration T_s, N_{XY} is the number of simultaneous photon detections (coincidences) in small time bins dt, and $N = T_s/dt$ is the total number of bins in time T_s. The major contribution to N_{XY} comes from random uncorrelated coincidences. The signal is a tiny excess of coincidences related to the quantum nature of light (bosons giving a joint detection probability greater than that for two independent events). The discrete degree of coherence at zero delay is shown in Figure 2 as a function of the telescope separation for stars of different angular sizes.

The theoretical resolving capability achievable with telescopes separated by 100-700 m is impressive, potentially reaching an angular resolution below 100 μas. An array of telescopes would clearly offer many different baselines for performing simultaneous measurements of the degree of coherence over a range of distances and along various directions. 2-D measurements of this type would finally lead to image reconstruction through classical interferometric techniques.

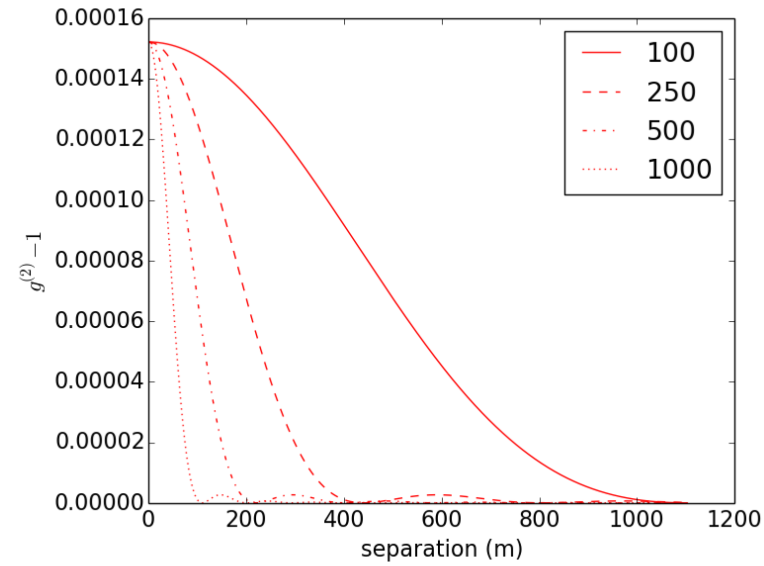


Figure 2. Discrete degree of coherence at zero delay ($g^{(2)}(0, d)$) as a function of telescope separation for stars (approximated as discs with uniform brightness) with different angular sizes (in μas). The sampling time $dt = 1$ ns.

3. INSTRUMENT CAPABILITIES

As discussed in the previous Section, the main scientific goals of an SII instrument on the ASTRI Mini-Array are: performing observations of bright O-thorough-G type Galactic stars in photon counting mode; measuring the discrete degree of coherence of the stars light among two (or, in principle, even more) telescopes of the array; obtaining the first images of these stars and their environment with sub-mas angular resolution. In this Section we discuss the main scientific requirements that a SII instrument mounted on the ASTRI Mini-Array shall have to achieve these goals.

3.1 Implementing SII on the ASTRI Mini-array

The quality of a SII measurement between two telescopes is dictated by the signal-to-noise (S/N) ratio of the degree of coherence at zero delay $g^{(2)}(0, d)$. For polarized light, the expected theoretical signal-to-noise ratio of such a measurement is (e.g. [12]):

$$S/N = n(\lambda/c)(\lambda/\Delta\lambda)\alpha|\gamma(0, d)|^2(T/dt)^{1/2}\,, \tag{2}$$

where n is the geometric average of the source count rate over the two telescopes in photons per second in the optical bandpass $\Delta\lambda$, λ is the central wavelength of the bandpass, and α is the detector efficiency. The squared visibility $|\gamma(0, d)|^2$ is strictly related to the second order discrete degree of coherence $g^{(2)}(0, d)$, being (for polarized light): $g^{(2)} = 1 + |\gamma|^2 t_c/dt$, where $t_c = \lambda^2/(c\Delta\lambda)$ is the light coherence time.

For the photon flux of a very bright ($V = 0$) star, a successful detection with $S/N \sim 4$ can be obtained already with 2-m class telescopes equipped with fast photon counters (with $\alpha \sim 0.5$), with an observation of 30-minute duration, and a sampling time/frequency of 400 ps/2.5 GHz [12]. An ASTRI telescope has a significantly larger collecting area (hence photon flux). If equipped with instrumentation having a comparable detector efficiency, sampling time and relative time accuracy ($\sim$1 ns), a measurement with a high S/N (> 10) is achievable within a reasonable observing time ($\sim$few hours). As mentioned above, this accuracy corresponds to a 30-cm light-travel distance, consistent with any conceivable instrumental tolerance.

Equation (2) shows that S/N depends on the ratio $n/\Delta\lambda$. As the photon rate n depends on the width of the optical bandpass $\Delta\lambda$, it follows that S/N does not depend on the bandpass. Therefore, in order to limit the photon rates to values affordable with present technologies, while maintaining at the same time a significantly high coherence, it is convenient to adopt very narrow band filters.

Figure 3 shows the S/N for a measurement with two ASTRI Mini-Array telescopes as a function of stellar magnitude (for a B-type star) calculated using equation (2) and assuming to correlate the photon arrival times with a bin time of 1 ns. For very bright targets the rate exceeds 100 Mcounts/s even in a 3 nm bandpass, and we assumed to limit it to this value. Stars with magnitude $V < 3$ are observable with the ASTRI Mini-Array telescopes with a $S/N > 5$, for an exposure time $\sim$ 8 hours.

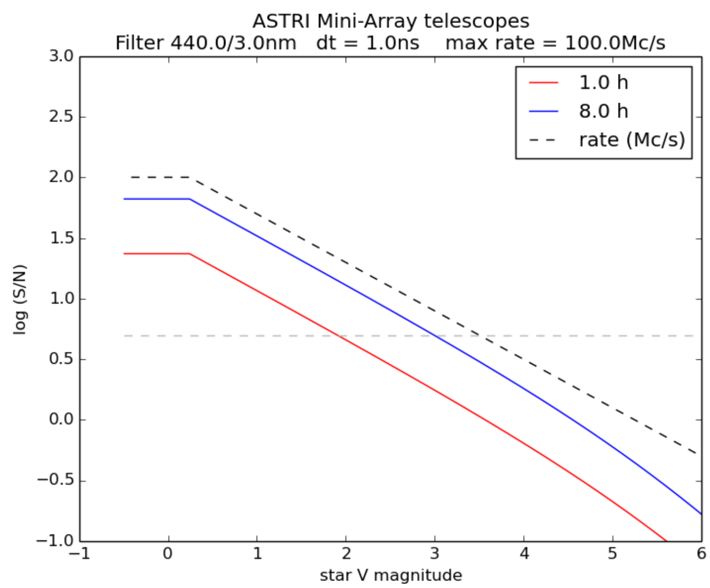


Figure 3. S/N ratio for a SII measurement with two ASTRI Mini-Array telescopes as a function of stellar magnitude. The source photon flux is limited in order to give a maximum rate of 100 Mcounts/s. The simulation is done using a narrow-band filter centered at 440 nm and with a FWHM of 3 nm (+ a polarizer). The bin time is 1 ns and the observing time is 1 hr (red line) and 8 hrs (blue line). The gray dashed line corresponds to $S/N = 5$.

Therefore, in order to carry out SII observations with the ASTRI Mini-Array, the telescopes shall be equipped with suitable instrumentation capable of performing fast single photon counting with a resolution and a relative time accuracy below the ns. Clearly, telescopes need to be synchronized at this level with a dedicated time synchronization system. At the same time, the optics shall be capable of effectively filtering photons in an optical window of a few nm. This requirement implies the insertion of suitable focal plane optics. In fact, if the filter were simply inserted in the optical path of the telescope, for example in close proximity to its focus, the angle of incidence of the light rays would range from zero up to tens of degrees. As the spectral bandwidth of a filter is a function of the angle of incidence (it shifts with changing angle of incidence), the transmitted marginal rays would have lower wavelengths than the rays coming at normal incidence. This effective broadening of the transmitted bandpass results in a degradation of the S/N ratio, as it is not associated to an increase of the photon rate. Placing a (removable) optical module at the telescope focal plane, suitably designed to reduce the angle of incidence, will narrow the filter bandpass while maintaining a good transmission efficiency. The same module should guarantee that the entire point spread function of the star falls on the detector. An implementation of this type will also allow to perform multi-narrow-band observations of the continuum and/or of specific spectral lines, by inserting a collection of filters centred at different wavelengths.

An alternative possibility for performing the same measurement without such a stringent requirement on the filter bandwidth is correlating the photon fluxes (currents) of two telescopes, using photon counters in integration mode ('digital SII'). If sampling frequencies up to 500 MHz (or even 1 GHz) can be achieved, the photon rates need not to be severely limited. In fact, the rate should be sufficiently high to reach an adequate statistics per time bin. For a 4-m class telescope such as the ASTRI Mini-Array telescope, this approach is adequate for bright targets ($V = 0$), but not for weak targets ($V = 2 - 3$) because, at a sampling frequency of 1 GHz, the photon statistics per bin becomes inadequate. Therefore, the full photon counting approach outlined above is the appropriate solution for performing SII observations and measurements with the ASTRI Mini-Array telescopes. In principle, it could also enable the computation of the correlation among three or more telescopes, or of higher order.

An important additional capability of a SII instrument is having the possibility of at least one simultaneous measurement of the degree of coherence at zero baseline, that permits to calibrate the measurement and to reduce the uncertainty on the parameters estimation (e.g. [12]). For this reason we envisage the implementation of this capability on the ASTRI Mini-Array. The expected S/N ratio achievable with an instrument of this type is shown in Figure 4 as a function of filter width and for two stars of different brightness.

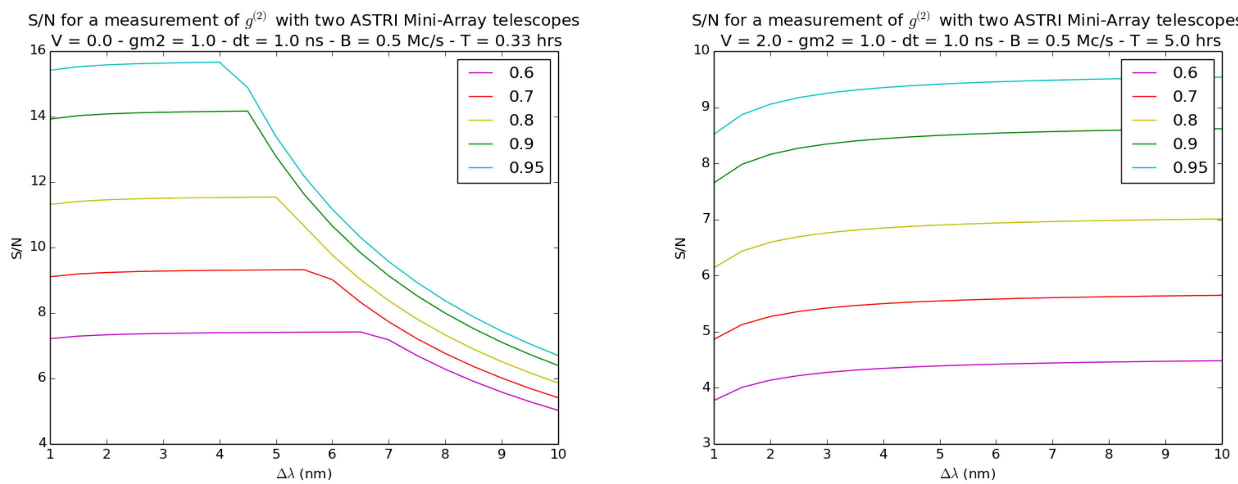


Figure 4. S/N ratio for a measurement of $g^{(2)}(0, d)$ with two ASTRI telescopes as a function of the narrow band filter width and for different values of the efficiency of the focal plane optics (from 0.6 to 0.95). *Left*: The star magnitude is $V = 0$ and the exposure time is 1 hour. *Right*: The star magnitude is $V = 2$ and the exposure time is 16 hours.

3.2 The ASTRI Mini-Array as a SII observatory

Assuming that the time allocated for SII observations is that unusable for Cherenkov observations (3 nights/month around Full Moon) and that the time lost for unfavourable weather conditions is 20%, the total effective observing time of the ASTRI Mini-array that can be devoted to SII observations is 240 hrs/year. We estimate that for, a bright ($V < 1$) star, 8-24 hrs are needed to perform 100-300 measurements of the correlation using all the baselines of the ASTRI Mini-Array, each with a $SN > 10$ (see Figure 4). An average ($V \sim 2$) star needs 16 hrs for 36 measurements using all the baselines of the ASTRI Mini-Array, each with a $SN > 10$. For bright stars we expect to be able to perform accurate image reconstruction. For average targets, we will perform image reconstruction, but the number of baselines will in any case allow well-constraining high angular resolution measurements of surface features.

Figure 5 shows a simulation for an average target, the star epsilon Orionis, a B-type supergiant (V=1.7) with an estimated angular diameter of 460 μas. For illustrative purposes, we assume three different surface brightness distributions for the star: a uniform brightness disc of 460 μas (solid line in Figure 5); a dark spot with a radius 68% that of the star and with a temperature 5% lower, superimposed on a uniform stellar disc (dashed line); a bright spot with a radius 46% that of the star and with a temperature 40% higher, superimposed on a uniform stellar disc (dotted line).

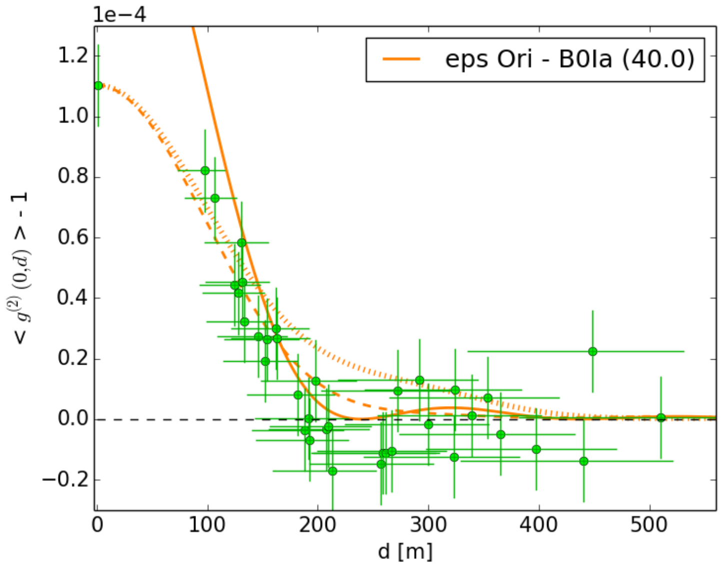


Figure 5. ASTRI Mini-Array simulated measurements of the discrete degree of coherence for the star epsilon Orionis ($V = 1.7$, B0Ia), at a distance of 600 pc. The star has an estimated angular diameter of 460 μas. All the 36 baselines of the array (plus the zero baseline measurement) are shown and the total exposure time is 12 hours per telescope (Zenith angle 40 degrees). The *solid line* represents the theoretical $g^{(2)}$ for a uniform brightness disc of 460 μas. The *dashed line* shows the theoretical $g^{(2)}$ for a spot with a radius 68% that of the star and with a temperature 5% lower, superimposed on a uniform stellar disc. The *dotted line* represents a spot with a radius 46% that of the star and with a temperature 40% higher, superimposed on a uniform stellar disc.

The simulated data are drawn from the expected theoretical value of the degree of coherence $g^{(2)}$ for the dark spot superimposed on the uniform stellar disc. The best match is obtained for the same theoretical curve (reduced $\chi^2 = 0.8$ for 35 degrees of freedom). The other curves are not consistent with the simulated data (reduced $\chi^2 > 1.9$ for 35 degrees of freedom). Thanks to the long baselines and the zero baseline measurements available at the ASTRI Mini-Array, we would then be able to clearly identify surface features and measure their size.

4. INSTRUMENT PERFORMANCE

The Stellar Intensity Interferometry Instrument (SI3 or SI^3) is designed to perform accurate measurements of single photon arrival times (1 ns) in a narrow optical window (3-8 nm) centered at a wavelength in the range 420-500 nm. Measurements with the SI3 instruments mounted on the telescopes of the array will be used to determine the second order degree of spatial and temporal coherence of a star. A simultaneous measurement of the degree of coherence at zero baseline will also be done by placing a beam splitter and two detector arrays on the focal plane of one telescope and correlating the signal among them. All measurements of the coherence will be performed counting photon coincidences in post-processing by means of a single photon software correlator. Processing data off-line has the advantage that the data reduction chain can be repeated more times, enabling the possibility to check for systematics, tune the parameters of the analysis, optimize the procedure, and increase the accuracy of the results. As mentioned above, it could also enable the computation of correlations among three or more telescopes.

Simultaneous measurements with the 36 available baselines will allow to carry out image reconstruction through the same techniques used in classical phase interferometry.

The expected photon rate of the ASTRI telescopes in the wavelength range of a narrow band (3 nm + polarizer) filter centered at 440 nm is reported as a function of star V magnitude in Figure 6. The telescope optical transfer function (mirror reflectivity+transmission of the optics and filter) is 0.17 and the detector efficiency is 0.5. The count rate is around 100 Mcounts/s and exceeds this value only for an A-though-O type star with magnitude $V < 0.5$. Changing the telescope optical transfer function between 0.14 and 0.2 and the detector efficiency between 0.45 and 0.55 causes a variation of the maximum rate between ∼75 and ∼130 Mcounts/s for the limiting case of a $V = 0.5$ mag O-type star.

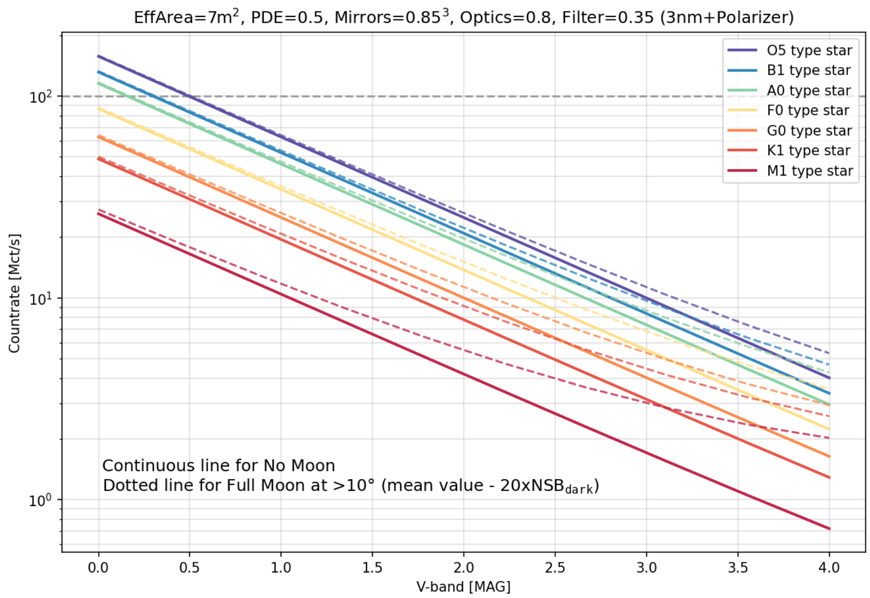


Figure 6. Expected ASTRI telescopes photon rate in a narrow band (3 nm + polarizer) filter centered at 440 nm as a function of V band magnitude for stars of different spectral types, including sky and Moon background.

The quality of a SII measurement is dictated by the signal-to-noise ratio of the degree of coherence, the main SII observable, that depends linearly on the photon rate, as shown in Figure 3.

5. INSTRUMENT DESIGN

The baseline design of SI3 was selected after careful consideration of different options. The criteria adopted to guide the final choice are:

- minimizing the impact on the ASTRI telescopes, limiting the instrument size, weight, and number of interfaces;
- adopting all the network standards and the timing and communication protocols used by the ASTRI Mini-Array;
- realizing a compact and independent instrument, with no impact on the development, operations and maintenance of the Cherenkov camera;
- requiring no on-site intervention (apart from maintenance operations);

- focusing on truly application-specific aspects of the instrumentation, that have a crucial impact on the performance;
- adopting a fully photon counting, post-processing approach for the calculation of the correlation.

Figure 7. ASTRI telescope during factory assembly (*left*) and schematic view of ASTRI SI3 (*right*), with the Focal Plane Module (FPM) deployed in front of the Cherenkov camera by the moveable positioning Arm and the box containing the Front End Electronics (FEE). The Back End Electronics (BEE) is located in the telescope cabinet and is not shown.

The design comprises three separate modules:

- the first containing the focal plane optics, the detectors and the read-out electronics, all mounted on a moveable arm that places them and removes them from axis;
- the second containing the front end electronics that performs signal conditioning;
- the third containing the back end electronics that tags the detected photons with the required timing accuracy. A schematic view of SI3 is shown in Figure 7.

The optical module of SI3, containing the focal plane optics, is positioned in front of the telescope Cherenkov focal plane. The system is completely detached and independent of the ASTRI Cherenkov camera, and is deployed (and withdrawn) through a dedicated mechanical arm during the intensity interferometry observations (Figure 8).

The design of the optical module of SI3 is based on a prefocal system, as shown in Figure 9 (top panel). The beam is reflected off M3 and collimated by L1 to cross an Interference Filter (IF) and then refocused by L2 onto the intensity interferometry focal plane. The module is a catadioptric system composed of one spherical convex mirror (M3, 180 mm diameter), two spherical lenses (L1, L2, 40-60 mm diameter), and one interference filter (IF, 40 mm diameter). A detailed analysis of the opto-mechanical tolerances shows that the worst offender is the relative tilt of the entire SI3 optical module with respect to a reference frame attached to the telescope. A

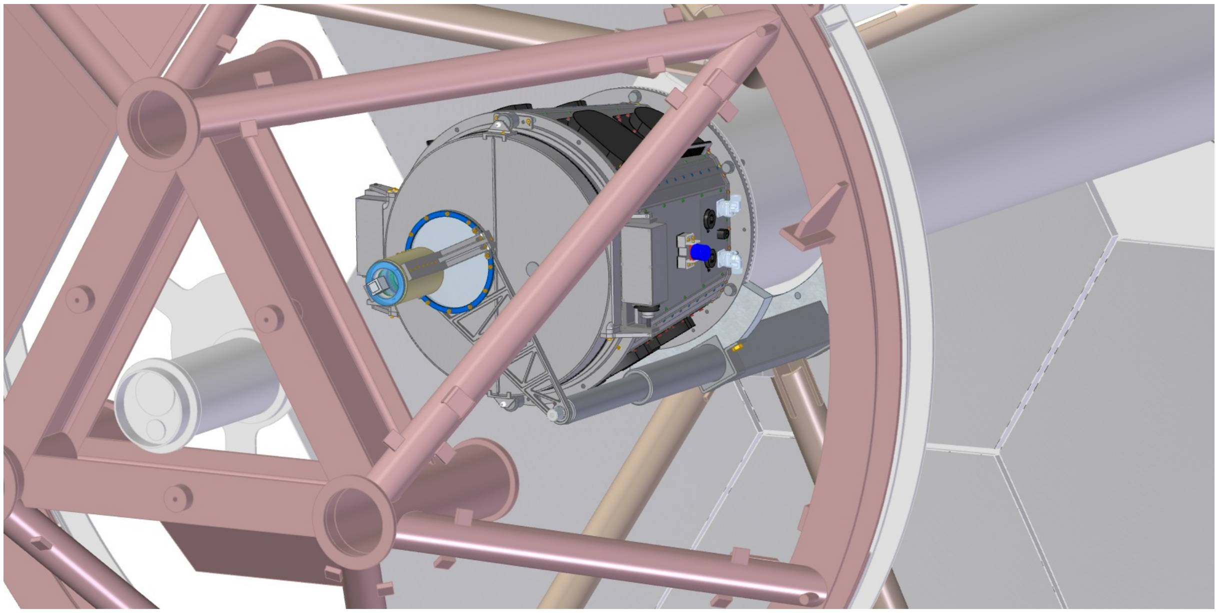


Figure 8. Close-up view of the SI3 positioning arm holding the focal plane optics, desployed above the Cherenkov camera.

large relative tilt (±0.07 deg) between the ASTRI M2 mirror and the SI3 module makes the PSF marginally fall out the focal plane array. One telescope of the ASTRI Mini-Array will host a slightly modified SI3 camera that contains, in addition to the aforementioned optics, a cubic beam splitter (CBS) to split the light beam into two channels and providing the zero baseline measurement (Figure 9, bottom panel).

A 2x2 SiPM (3 mm each) focal plane array of detectors is placed at the SI3 focus. The detectors have a spectral response range from 270 to 900 nm, with peak sensitivity at 450 nm, and are cooled with a single Peltier cell so as to maintain them at a few degrees Celsius and reduce the dark noise. The signal from the detectors is read by a commercial evaluation board and amplified with four broadband amplifiers. All these components (PRE-FEE) are enclosed in the focal plane module. Another separate module performs signal conditioning and is located on the telescope mast (FEE; orange box in Figure 7). In this module the signal is input to two high speed comparators (with ∼300 ps response time). By selecting the appropriate threshold, the comparators generate PECL digital pulses. A dedicated circuitry is incorporated for powering on and controlling the detectors and electronics (Voltage Distribution Box and Command Control Unit). A scheme of the entire FEE and an image of its prototype version are shown in Figure 10. For a more detailed description of the FEE and its components we refer to a companion paper in these Proceedings [25].

The digital signal from the FEE is sent to the Back End Electronics for time-tagging at a rate up to 100 Mcounts/s. The data stream is then transferred immediately to the Array Data Acquisition System (ADAS) of the telescope for acquisition. The core of the BEE is a fast Time-to-Digital-Converter (TDC) board, mounted on an Industrial PC (IPC) and disciplined with a Pulse-Per-Second (PPS) and a 10 MHz reference signal from a Time Distribution Unit (TDU). The reference and PPS signals are used to reconstruct the absolute (UTC) time in post-processing. The TDU has a time synchronization system based on the White Rabbit technology. A schematic view of the BEE of the ASTRI SI3 is shown in Figure 11. The TDC acquires the actual signal from the four channels of the FEE, with a resolution better than 100 ps, and streams them continuously to a solid state disc onboard the IPC and then from it to the ADAS. The data output stream is compressed with a format of 5 Bytes per event. The maximum data transfer rate to ADAS is then 500 MB/s or 4 Gbit/s. The physical link between the IPC and the ADAS system is provided by a dedicated optical fiber with a 10 Gbit/s SFP+ (Small Form-factor Pluggable) transceiver. The system will acquire ∼100 TB of raw data each month that will be transferred and analyzed off-site before the start of the following observing run. Assuming an average data transfer rate of ∼125 MB/s, all the data are transferred in ∼10 days.

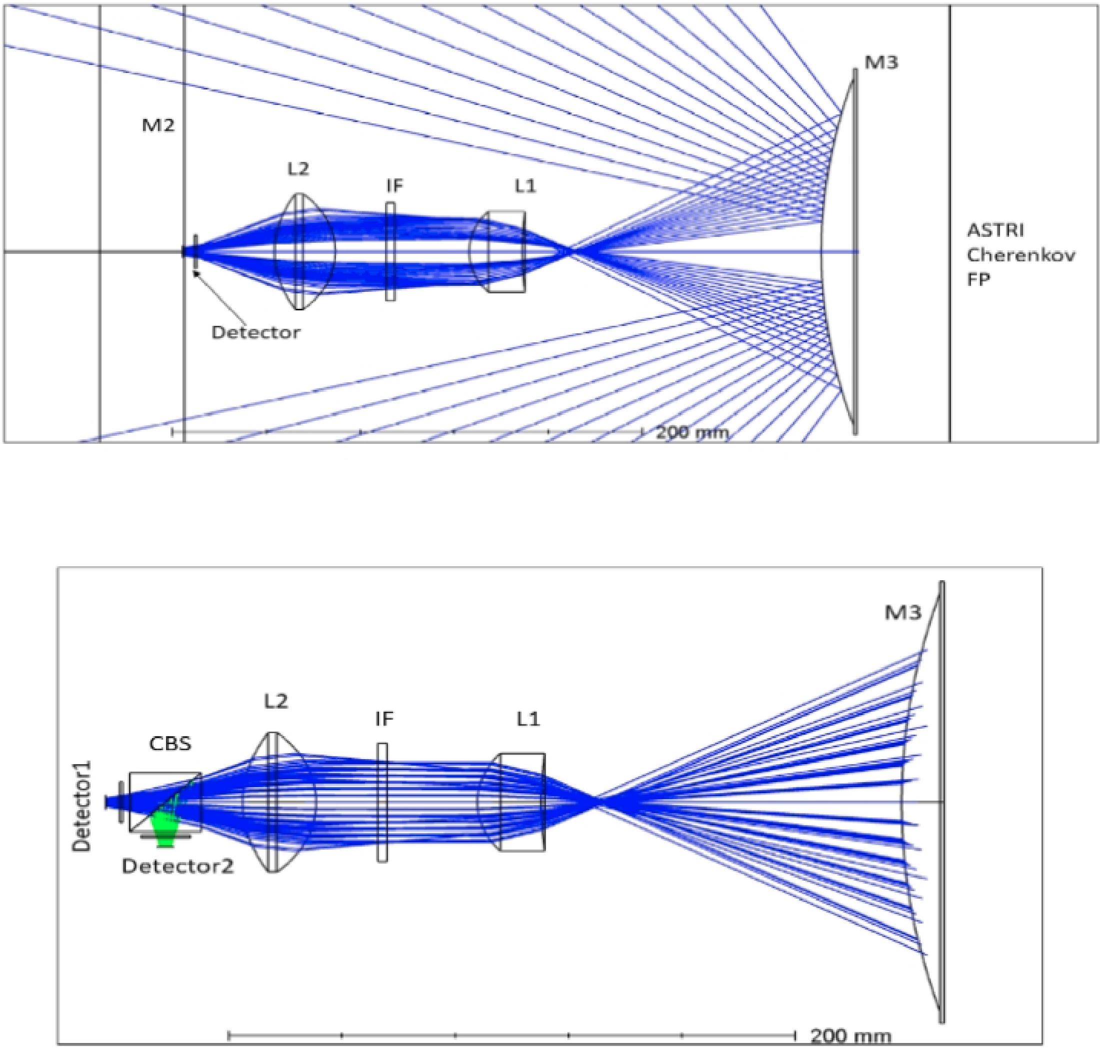


Figure 9. Design of the SI3 catadioptric module deployed above the Cherenkov camera. *Top*: base 1-beam design. *Bottom*: 2-beams design for the zero baseline measurement.

6. DATA PROCESSING

The TDC raw data will be processed to produce reconstructed and calibrated event lists using the time reference signals from the TDU. The final photon time tags are referred to UTC. After removing unusable/low quality data by filtering them through suitable quality checks, the event lists are ready for the scientific analysis. They are then segmented in chunks of size adequate for being efficiently handled in the following steps. Then, coincidences are searched for in the arrival times at different telescopes varying the time delay between them. An efficient implementation of the entire procedure has been already developed and tested in the Asiago intensity interferometry experiment [12]. For the data volume of ASTRI SI3 and scaling from the processing time required for the data of the Asiago experiment, we need to organize the threads and run them in parallel on machines with a suitable number ($\sim$1000) of cores and/or adapt the processing software for running on machines that perform hardware acceleration (GPUs). The final output will be the diagram of the temporal and spatial correlation of a star for any two telescopes of the array. Image reconstruction can eventually be performed from these data.

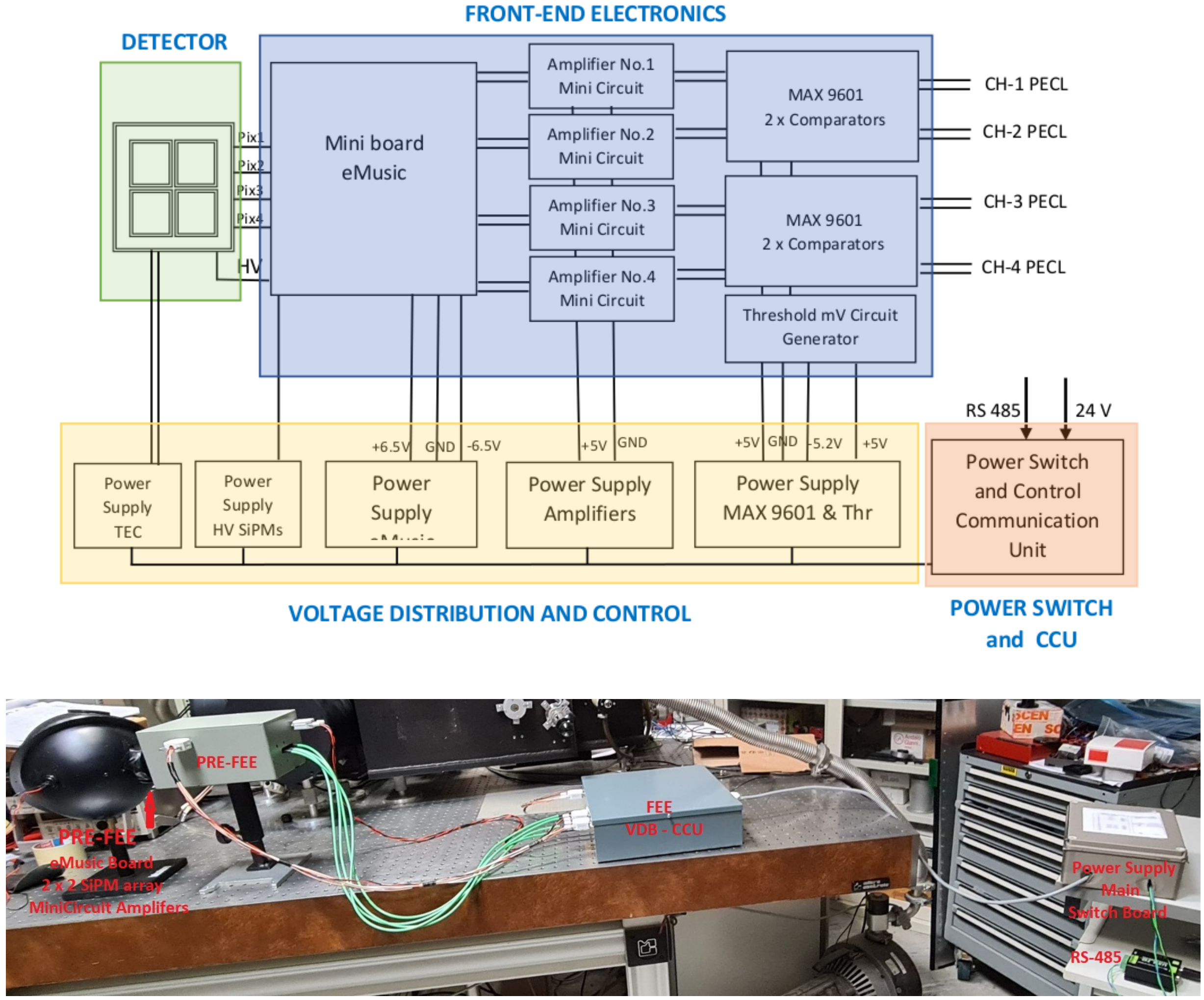
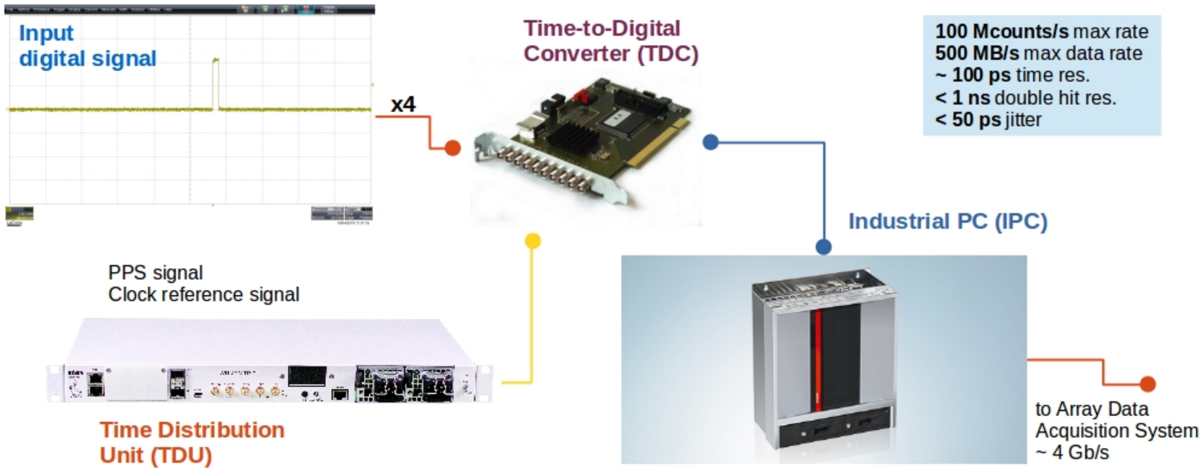


Figure 10. *Top*: Schematic representation of the components and internal connections of the FEE of ASTRI SI3. *Bottom*: Prototype version of the FEE mounted in the laboratory [25].

7. CONCLUSIONS

We aim at measuring the spatial correlation of the radiation intensity emitted from a star using the ASTRI Mini-Array. Our scientific goals are measuring the discrete degree of coherence of the stars light among two (or, in principle, even more) telescopes of the array, performing well-constraining high angular resolution measurements of surface features of bright O-thorough-G type Galactic stars, and obtaining the first images of these stars and their environment with sub-mas angular resolution.

To carry out these measurements we are designing and realizing a fast photon counting instrument, called Stellar Intensity Interferometry Instrument (SI3), that will be positioned above the Cherenkov camera through a dedicated arm in the nights around Full Moon. This paper describes the expected instrument capabilities, performance and design. The instrument is conceived to make accurate measurements of the arrival time of a single photon (1 ns) in a narrow wavelength window (3-8 nm), centered in the 420-500 nm wavelength range. The ASTRI Mini-Array will offer many different baselines to perform simultaneous correlation measurements in photon counting mode over an extended range of distances (100-700m) and along various directions. Indeed, 2-D measurements of this type will pave the way to image reconstruction using classical interferometric techniques.



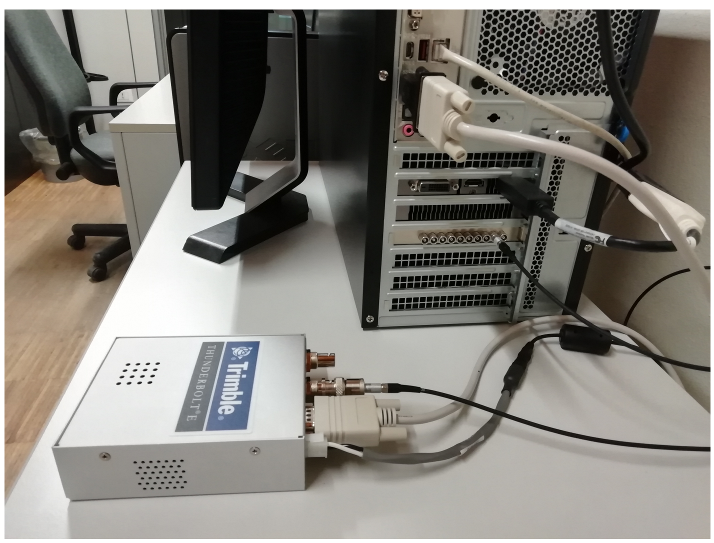


Figure 11. *Top*: Schematic representation of the components and internal connections of the BEE of ASTRI SI3. *Bottom*: Prototype version of the BEE mounted in the laboratory, tested with a PPS input signal from a GPS receiver.

The theoretical resolution capability achievable with these baselines is impressive, potentially enabling angular resolution of less than 100 μas.

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