ASTRI Mini-Array

Stellar Intensity Interferometry Instrument

Science Requirements

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TABLE OF CONTENTS

INDEX OF FIGURES & TABLES

DOCUMENT HISTORY		
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1.0	14/03/2021	First release
1.1	26/03/2021	First release (revised)
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1 Introduction

The ASTRI (Astrofisica con Specchi a Tecnologia Replicante Italiana) Mini-Array is an INAF project finalized to the construction of nine identical dual-mirrors Cherenkov gamma-ray telescopes that will be installed at the site of the Teide Observatory in Tenerife (Spain) to study astronomical sources emitting in the TeV spectral band. Besides carrying out a scientific program in the Very High Energy Gamma-ray band, the ASTRI Mini-Array will also perform intensity interferometry observations of bright stars.

1.1 Purpose

This is the science requirement document of the ASTRI Stellar Intensity Interferometry Instrument (SI^3) and is part of the top level documentation describing the requirements specifications of the ASTRI Mini-Array. It is directed to ASTRI members involved in the construction and development of the SI^3 and to external scientists.

1.2 Scope

This document aims at providing a reference framework for the development, construction and commissioning of the ASTRI SI^3, a fast single photon counting instrument for performing intensity interferometry observations of bright stars with the ASTRI Mini-Array.

1.3 Content

After providing an overview of the scientific context and motivations for performing stellar intensity interferometry observations with the ASTRI Mini-Array, the document gives a detailed list of the high-level scientific requirements for the ASTRI SI^3.

1.4 Definitions and Conventions

1.4.1 Abbreviations and acronyms

The following abbreviations and acronyms are used in this document:

ASTRI	Astrofisica con Specchi a Tecnologia Replicante Italiana
INAF	Istituto Nazionale di Astrofisica
MIUR	Ministero dell’Istruzione, dell’Università e della Ricerca
SII	Stellar Intensity Interferometry
SI^3	Stellar Intensity Interferometry Instrument

1.4.2 Definitions

1.4.2.1 System Related Definitions

The specific definitions for the SI^3 adopted in this document are:

- **Degree of coherence.** Measurement of the spatial and/or temporal correlation between the photons fluxes of a star received at two telescopes
- **Time synchronization system**. A system designed to maintain clocks at each ASTRI telescope synchronized to sub-ns accuracy for photon time tagging

2 Related Documents

2.1 Applicable Documents

[AD1] ASTRI Mini Array Optical design description: ASTRI-INAF-DES-7200-001

[AD2] ASTRI Mini Array Telescope Mechanical Structure Design Requirements Specification: ASTRI-INAF-SPE-7100-001

2.2 Reference Documents

[RD1] ASTRI Mini-Array Operation Concept: ASTRI-INAF-SPE-1000-001

[RD2] ASTRI Mini-Array Stellar Intensity Interferometry Conceptual Design document: ASTRI-DES-7400-001

[RD3] ASTRI Mini-Array Stellar Intensity Interferometry Instrument Requirements: Specifications document: ASTRI-INAF-SPE-7400-002

3 Scientific Motivations

Imaging a celestial object has always been a primary goal in Astronomy, since much of our understanding depends on our ability to resolve it, measure its size, and determine its spatial structure. For the first time, 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 (Glauber 1963). Angular resolutions below 100 microarcsec (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) (Kieda et al. 2019).

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 (Hanbury Brown 1956; Brown & Twiss 1957, 1958; Hanbury Brown et al. 1974; Hanbury Brown 1974). 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. Le_Bohec et al. 2006, Dravins et al. 2013). 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. Dravins et al. 2015), or performing pilot experiments or observations with 1-3 meter class telescopes (e.g. Zampieri et al. 2016, 2021; Guerin et al. 2017; Matthews et al. 2018; Rivet et al. 2020). Eventually, the capability of performing SII measurements with the MAGIC and VERITAS IACTs has been convincingly demonstrated by Acciari et al. (2020) and Abeysekara et al. (2020), 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) [RD1]. 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 (Figure 1; Vercellone et al. 2021). This will be rivalled only by the full deployment of the CTA observatory.

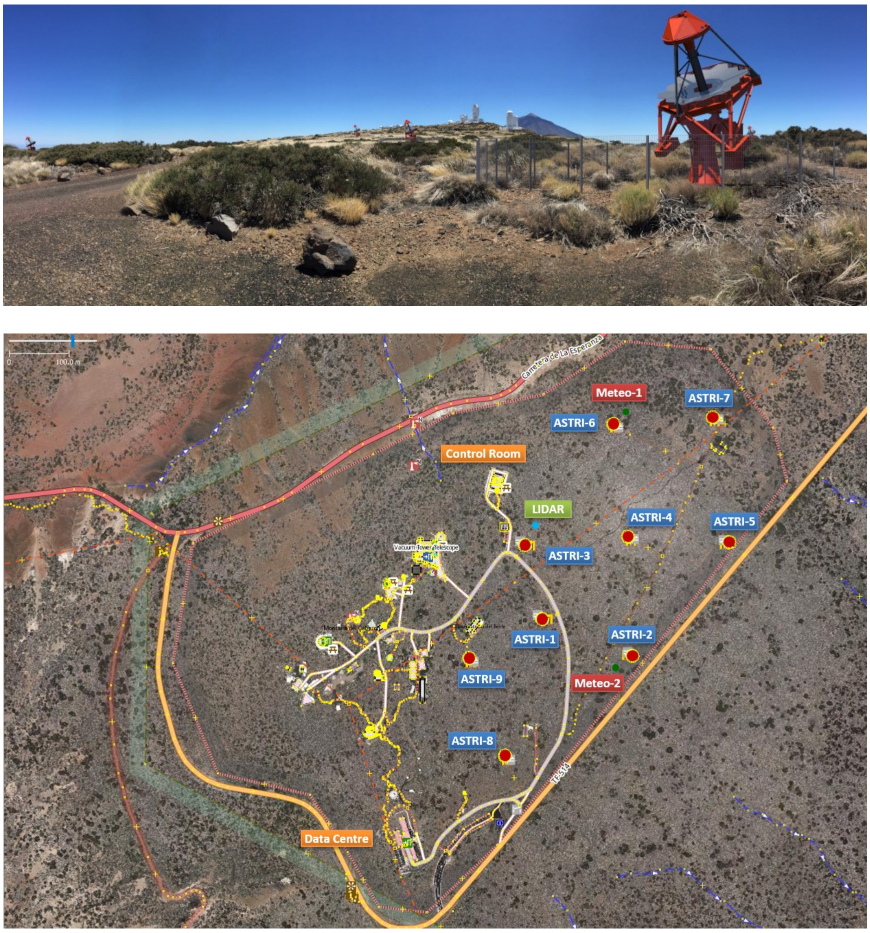

Figure 1: *Top*: Artist impression of the ASTRI Mini-Array site. *Bottom*: Final layout of the 9 ASTRI Mini-Array telescopes at the site of El Teide in Tenerife, Spain (Vercellone et al. 2021).

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 ~ 100μas 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 (see Figure 2, left panel; Che et al. 2011, Monnier et al. 2014). Imaging with this resolution can also allow the detection of dark/bright spots or other surface features (see Figure 2, right panel; Nunez et al. 2012). 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 (Montargès et al. 2020), that clearly revealed a substantial asymmetry in the surface brightness distribution of the star (Dupree et al. 2020). 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 (see Figure 3; Kloppenborg et al. 2010). In this respect, the ASTRI Mini-array operated in SII mode will leave an extraordinary legacy of sub-marcsec 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. Kieda et al. 2019). Therefore, O-thorough-G type stars of adequate brightness are all suitable and potential targets, which makes the B band (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.

3.1 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 (Hanbury Brown et al. 1974). The measurement of the correlation can be performed using the continuous intensity fluctuations ('analog SII', as in the Narrabri interferometer; Hanbury Brown 1974), the discrete intensity fluctuations ('digital SII', as in the VERITAS and MAGIC interferometers; Abeysekara et al. 2020, Acciari et al. 2020), or the photon arrival times ('photon counting SII'; as in the Asiago interferometer experiment; Zampieri et al. 2021). 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.

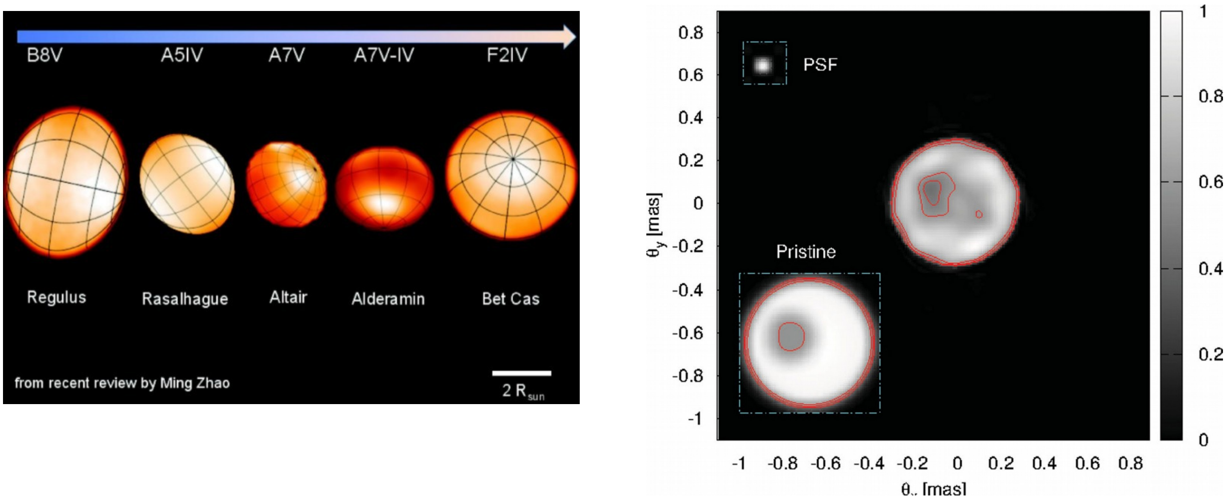

Figure 2: *Left*: CHARA Infrared observations of B-through-F main or post-main sequence stars, showing significant oblateness and/or gravity darkening at the equator (Monnier et al. 2014). *Right*: Simulated reconstruction of a dark spot on a star with V=3. The star temperature is 6000 K, while the spot temperature is 5500 K (Nunez at al. 2012).

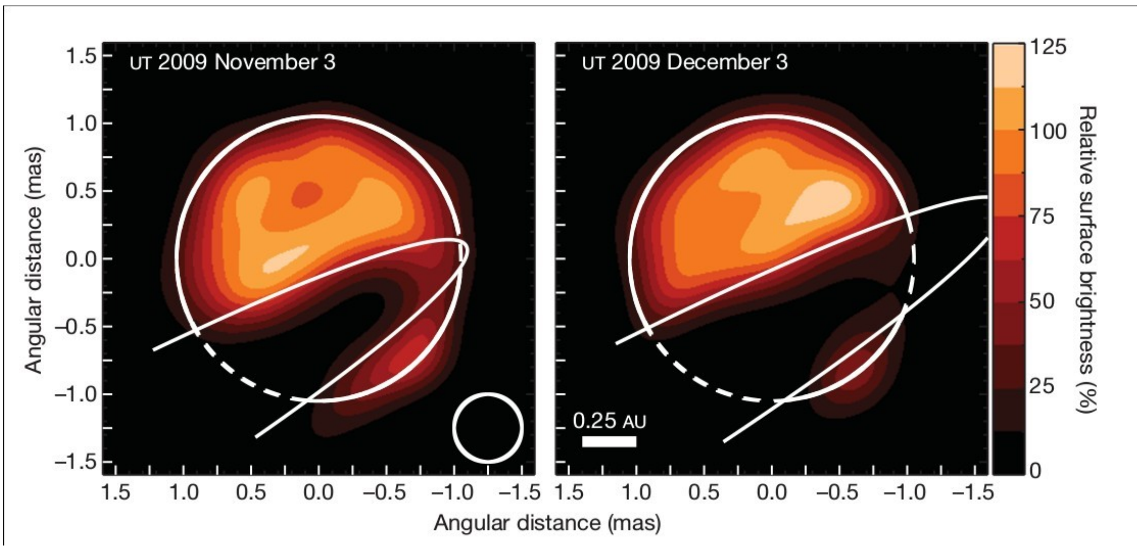

Figure 3: CHARA H-band synthetized images of eps Aur taken one month apart (Kloppenborg et al. 2010). The images show that the 18-month long partial eclipse of the star eps Aur is produced by a disc orbiting the companion.

In photon counting mode the second order discrete degree of coherence of a star is calculated using the expression (e.g. Zampieri et al. 2021):

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

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 4 as a function of the telescope separation for stars of different angular sizes.

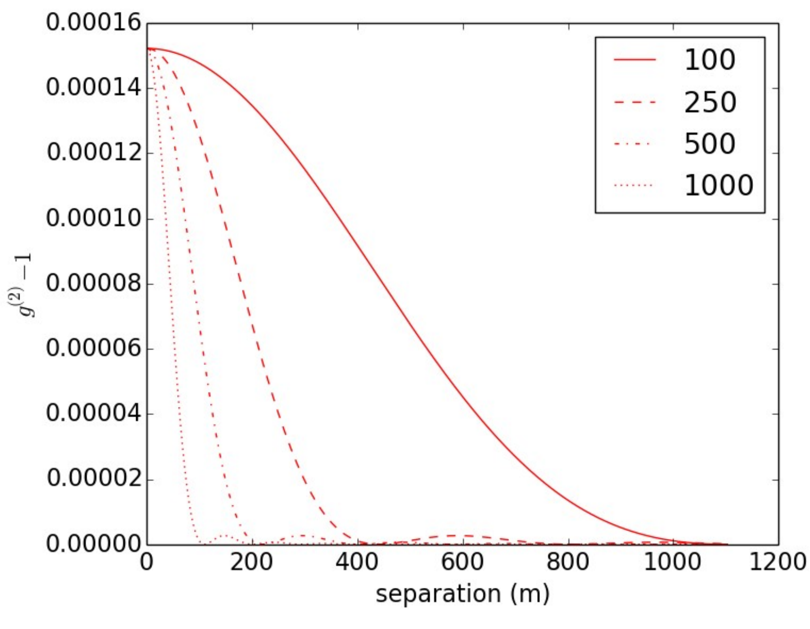

Figure 4: Discrete degree of coherence at zero delay ($g^{(2)}(0, d)$) as a function of telescope separation for stars (approximated as discs with uniform brightness) with different angular sizes (in microarcsec). The sampling time dt = 1 ns.

The theoretical resolving capability achievable with telescopes separated by 100-700 m is impressive, potentially reaching an angular resolution below 100 microarcsec. 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 allow to carry out image reconstruction through classical interferometric techniques.

4 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.

4.1 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. Zampieri et al. 2021):

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

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): $g^{(2)} = 1+ |\gamma|^2\,\tau_c/dt$, where $\tau_c = \lambda^2/(c\Delta\lambda)$ is the light coherence time.

For the photon flux of a very bright (V=0) star, a successful detection with S/N ~ 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 (Zampieri et al. 2021). 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 (~ 1 ns), a measurement with a high S/N (> 10) is achievable within a reasonable observing time (~ 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 5 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 then 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 <8 hours.

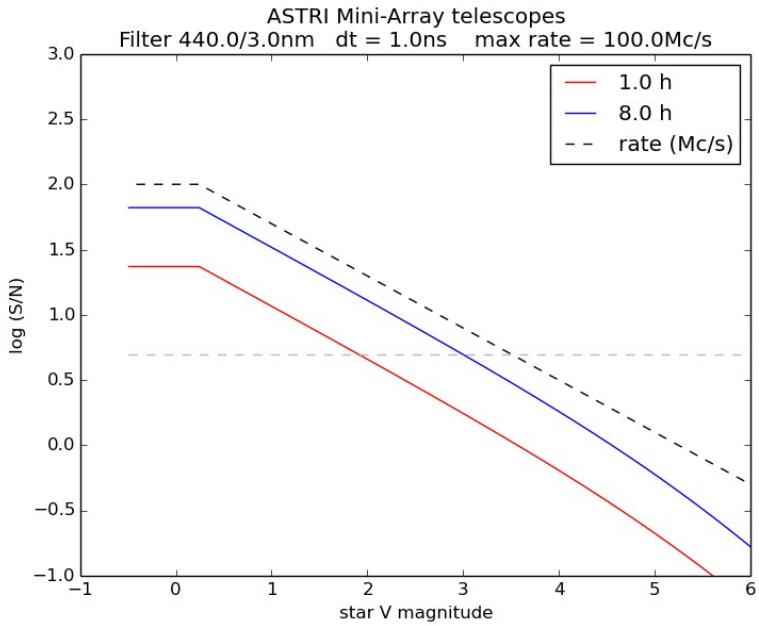

Figure 5: S/N ratio for a SII measurement with two ASTRI Mini-Array telescopes as a function of stellar magnitude. The source photon flux is limited in order to give a maximum rate of 100 Mcounts/s. The simulation is done using a narrow-band filter centered at 440 nm and with a FWHM of 3 nm (+ a polarizer). 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, allows narrowing 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. Zampieri et al. 2021). For this reason we envisage the implementation of this capability on the ASTRI Mini-Array.

In the following Section, we summarize all the scientific requirements that must be fulfilled by a SII instrument working in photon counting on the ASTRI Mini-Array telescopes. The expected S/N ratio achievable with an instrument of this type and fulfilling all requirements is shown in Figure 6 as a function of filter width and for two stars of different brightness.

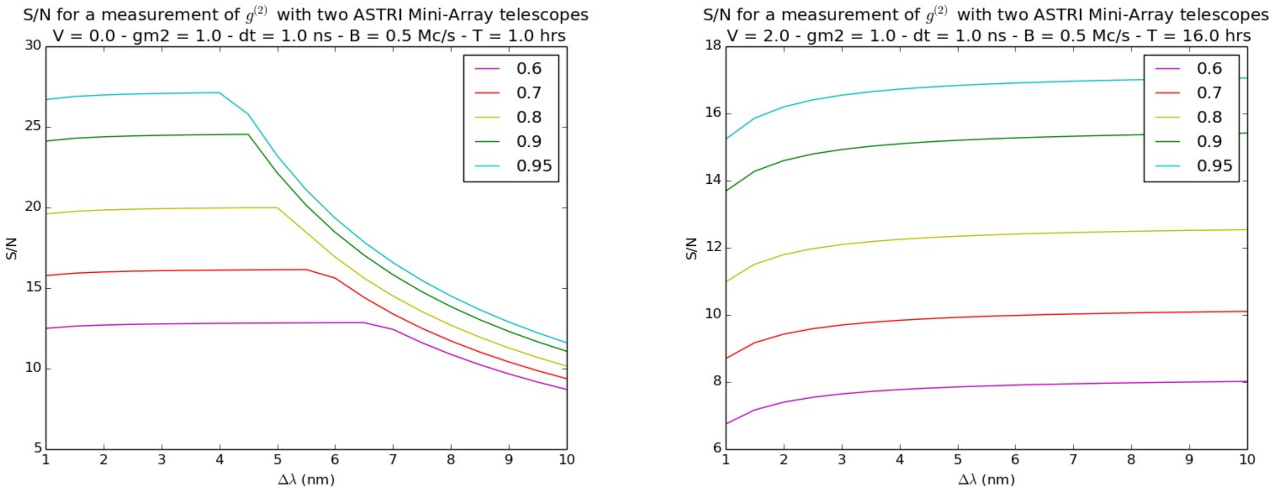

Figure 6: S/N ratio for a measurement of g$^{(2)}$ (0, d) with two ASTRI telescopes as a function of the narrow band filter width and for different values of the efficiency of the focal plane optics (from 0.6 to 0.95). *Left*: The star magnitude is V=0 and the exposure time is 1 hour. *Right*: The star magnitude is V=2 and the exposure time is 16 hours.

4.2 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 S/N > 10 (see Figure 6). An average (V ~ 2) star needs 16 hrs for 36 measurements using all the baselines of the ASTRI Mini-Array, each with a S/N > 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 7 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 microarcseconds. For illustrative purposes, we assume three different surface brightness distributions for the star: a uniform brightness disc of 460 microarcseconds; a dark spot with a radius 68% that of the star and with a temperature 5% lower, superimposed on a uniform stellar disc; a bright 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 chi2 = 0.8 for 35 degrees of freedom). The other curves are not consistent with the simulated data (reduced chi2 > 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.

With 240 hrs/year we expect to be able to observe 3-8 bright and 14 average stars per year. Reducing by 10% the useful observing time because of the deadtime of individual telescopes (each subtracting 8 baselines) and/or inefficiency in data collection, transfer and/or storage would not impact significantly on the expected scientific performance of the SII observatory and is then acceptable. Larger dead times would start to impact on the scheduling of the scientific program.

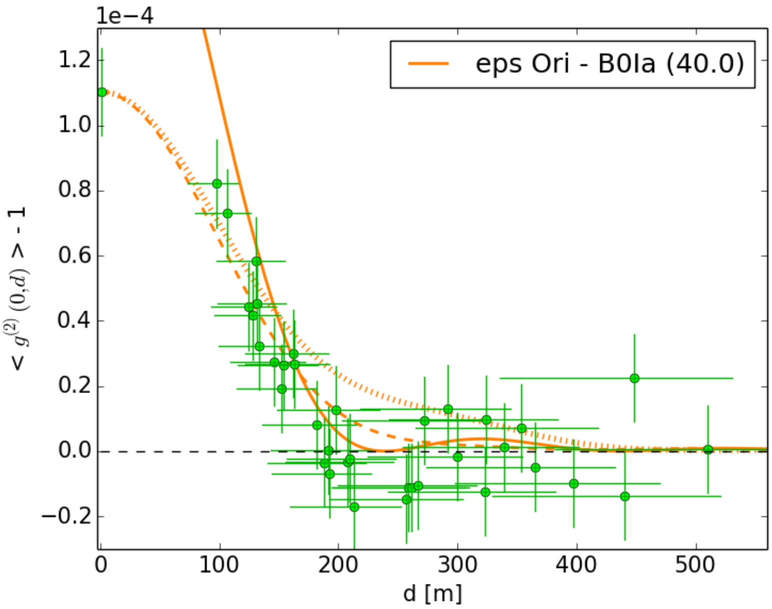

Figure 7: ASTRI Mini-Array simulated measurements of the discrete degree of coherence for the star epsilon Orionis (V=1.7, B0Ia), at a distance of 600 pc. The star has an estimated angular diameter of 460 microarcseconds. All the 36 baselines of the array (plus the zero baseline measurement) are shown 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 microarcseconds. 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.

5 Science Requirements for Stellar Intensity Interferometry with the ASTRI Mini-array

The scientific requirements reported in the previous Section are summarized below. They are valid in the elevation range 30-90 degrees, and for the whole lifetime of the ASTRI MA project. For what not explicitly referenced in this Section and related to the optical and mechanical requirements of the ASTRI Mini-array telescopes (point spread function, tracking, pointing, etc.), we refer to the corresponding top-level requirement documents (ASTRI Mini Array Optical design description: ASTRI-INAF-DES-7200-001 [AD1]; ASTRI Mini Array Telescope Mechanical Structure Design Requirements Specification: ASTRI-INAF-SPE-7100-001 [AD2]).

Code	Name	Description	M
2200	SII telescope effective area	The telescope shall have a total mirror effective area not smaller than 7 m^2 in the wavelength range 420-500 nm.	
2205	Accuracy of telescopes positions	The position of the telescopes, referred to the intersection of the telescope azimuth and elevation axes in the WGS84 reference frame, shall be known with an accuracy of 10 cm.	
2210	SII average detection efficiency	The average photon detection efficiency, weighted with a reference spectrum of an O-through-G star in a narrow optical band (3-8 nm) and centered around a wavelength in the range 420-500 nm, shall be larger than 8.5%. This value includes the detector photon detection efficiency and dead space, the efficiency of the telescope and focal plane optics, and the transmission efficiency of the narrow band filter.	
2220	SII instrument field of view	The instrument shall deliver a sensed field of view between 1.2 and 1.4 times larger (in area) than the instrument point spread function (90% containment radius) to cope with the telescope tracking errors and to minimize sky background contamination.	
2225	SII instrument zero baseline measurement	The instrument shall be capable of performing a zero baseline measurement of the correlation.	
2230	Signal-to-noise ratio of a SII measurement	The acquisition and timing system of the instruments mounted on the Mini-array shall guarantee to achieve measurements of the correlation between any two telescopes with the signal-to-noise ratio and the exposure time reported (as a function of filter width) in Figure 6 for stars with magnitude V=0 and V=2, respectively.	
2240	SII timing accuracy	The acquisition and timing system of the instruments mounted on the Mini-array shall have the capability to sample the photon flux with a time bin of 1 ns and shall be able to detect each single photon event with a relative (among telescopes) time accuracy	

		less than 0.5 ns over the whole duration of an observing run.	
2250	SII telescope(s) deadtime	The fraction of the time that it is not possible to acquire or process data from an individual telescope whilst in the observing state shall be smaller than 10% per night.	
2260	SII observing deadtime	The fraction of data lost during an observation (with telescopes on target) because of inefficiency in data collection, transfer and/or storage, shall be smaller than 10% per night.	

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