ASTRI Mini-Array
Stellar Intensity Interferometry Instrument
Science Requirements

Prepare by: L. Zampieri
Verified by: G. Tosti
Approved by: S. Scuderi
Released by: G. Pareschi

Date: 14/03/21
Main Authors: L. Zampieri

Contributing Authors:
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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 stellar intensity interferometry observations of bright stars.

1.1 Purpose

This is the science requirement document of the ASTRI Stellar Intensity Interferometry Instrument (SI\textsuperscript{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\textsuperscript{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\textsuperscript{3}, a fast single photon counting instrument for performing stellar intensity interferometry (SII) observations of bright stars with the ASTRI Mini-Array.

1.3 Content

After providing an overview of the scientific context and motivations for performing SII observations with the ASTRI Mini-Array, the document gives a detailed list of the high-level scientific requirements for the ASTRI SI\textsuperscript{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\textsuperscript{3}: Stellar Intensity Interferometry Instrument

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1.4.2 Definitions

1.4.2.1 System Related Definitions

The specific definitions for the SI\textsuperscript{3} adopted in this document are:

- **Degree of coherence.** Measurement of the spatial or temporal correlation between the photons fluxes of a star received at two telescopes.

- **Time Synchronization System.** A system designed to keep clocks synchronized to sub-ns accuracy for SI\textsuperscript{3} event time tagging at each ASTRI telescope.
2 Related Documents

2.1 Reference Documents

[RD1] ASTRI Mini-Array
3 Scientific Motivations and Instrumental Capabilities

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 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).

SII was pioneered by Robert Hanbury Brown and Richard Q. Twiss between the '50s and the '70s (see e.g. Hanbury Brown 1974 and references therein). 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 better than one ns at each telescope, over baselines extending to km distances. This accuracy corresponds to a 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) (...). 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 1000 m (Figure 1; Vercellone et al. 2021). This will be rivalled only by the full deployment of the CTA observatory.

![Figure 1](image)

**Figure 1**: *Left*: Artist impression of the ASTRI Mini-Array site. *Right*: 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 IR stellar 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.
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.
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 Instrument capabilities for implementing SII on the ASTRI Mini-array

The quality of a SII measurement between two telescopes separated by a distance $d$ is dictated by the signal-to-noise $(S/N)$ ratio of the main SII observable, the degree of coherence at zero delay $|\gamma(0,d)|$ (e.g. Zampieri et al. 2021). For polarized light, the expected theoretical signal-to-noise ratio of such a measurement is:

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

(1)

where $T$ is the duration of the observation, $dt$ the sampling time, $n$ is the geometric average of the source count rate over the two telescopes in photons per second in the optical bandpass $\Delta\lambda$, $\lambda$ is the central wavelength of the bandpass, and $\alpha$ is the detector efficiency. 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 of 400 ps (sampling frequency 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 ($\sim 1$ 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.

Clearly, the photon rates must be limited to affordable values without reducing the coherence (i.e. without significantly attenuating the photon flux). For this reason, narrow band filters are usually adopted, with the goal of limiting the photon flux leaving $n/\Delta\lambda$ unchanged.

Figure 4 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 (1) 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 SSTs with a $S/N>5$, for an exposure time $<8$ hours.

Therefore, in order to carry out SII observations on the ASTRI Mini-Array, the telescopes shall be equipped with suitable instrumentation capable of performing fast
single photon counting with a resolution and absolute time accuracy below the ns. At the same time, the optical system of the telescope 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, for the very small f/numbers (i.e. $\sim f/1$) of the Cherenkov telescopes, the angle of incidence of the rays coming on the narrow band filter from the outer portion of the mirror is very large (tens of degrees). Consequently, the transmitted wavelength of such rays is significantly smaller than that of the rays coming at normal incidence. This broadening of the transmitted bandpass $\Delta \lambda$ for a given photon rate reduces the S/N ratio of a measurement. 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 (10 arcmin for the ASTRI telescopes) falls on the detector.

![Figure 4: 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.](image)

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 (à la Hanbury-Brown and Twiss). 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 too scanty.

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 the following Section, we summarize all the scientific requirements that must be fulfilled by an instrument working in this mode. The S/N ratio achievable with an instrument mounted on the ASTRI Mini-Array and fulfilling these requirements is shown in Figure 5 as a function of filter width and for two stars of different brightness.

Figure 5: S/N ratio for a measurement of the (discrete) degree of coherence 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 2 hours. Right: The star magnitude is V=2 and the exposure time is 24 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 \( \sim 20\% \), the total effective observing time of the ASTRI Mini-array that can be devoted to SII observations is \( \sim 240 \text{ hrs/year} \).

We estimate that for a bright (0 < V < 1) star, 12 hrs are needed to perform 200 measurements of the correlation using all the baselines of the ASTRI Mini-Array, each
with a $S/N = 14$. An average $(1 < V < 2.5)$ star needs 24 hrs for 36 measurements using all the baselines of the ASTRI Mini-Array, each with a $S/N = 8$. Figure 6 shows a simulation of these measurements and, for illustrative purposes, the corresponding fit to determine the star radius.

With 240 hrs/year we then expect to be able to observe 2 bright and 9 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 compromise significantly the scientific outcome of the program.

Figure 6: ...
4 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.

<table>
<thead>
<tr>
<th>Code</th>
<th>Name</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>2200</td>
<td>SII telescope effective area</td>
<td>The telescope shall have a total mirror Effective Area not smaller than $7, \text{m}^2$ in the wavelength range 420-500 nm.</td>
</tr>
<tr>
<td>2210</td>
<td>SII average detection efficiency</td>
<td>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 effective area of the telescope, the detector photon detection efficiency and dead space, the efficiency of the telescope and focal plane optics, and the transmission of the narrow band filter.</td>
</tr>
<tr>
<td>2220</td>
<td>SII instrument field of view</td>
<td>The intensity interferometry instrument mounted on each telescope shall have a Field of View comparable to the telescope optical Point Spread Function.</td>
</tr>
<tr>
<td>2230</td>
<td>Signal-to-noise ratio of a SII measurement</td>
<td>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 3.5 for stars with magnitude $V=0$ and $V=2$, respectively.</td>
</tr>
<tr>
<td>2240</td>
<td>SII timing accuracy</td>
<td>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 time accuracy not larger than 0.5 ns.</td>
</tr>
<tr>
<td>2250</td>
<td>SII telescope(s) deadtime</td>
<td>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.</td>
</tr>
<tr>
<td>2260</td>
<td>SII observing deadtime</td>
<td>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.</td>
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</table>
5 References