PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

From the Etna volcano to the Chilean Andes: ASTRI end-to-end telescopes for the Cherenkov Telescope Array

S. Scuderi

S. Scuderi, "From the Etna volcano to the Chilean Andes: ASTRI end-to-end telescopes for the Cherenkov Telescope Array," Proc. SPIE 10700, Ground-based and Airborne Telescopes VII, 107005Z (6 July 2018); doi: 10.1117/12.2312453

Event: SPIE Astronomical Telescopes + Instrumentation, 2018, Austin, Texas, United States

From the Etna volcano to the Chilean Andes: ASTRI end-to-end telescopes for the Cherenkov Telescope Array

S. Scuderi
(*for the CTA ASTRI Project)*

INAF – IASF Milano, Via E. Bassini 15, I-20133 Milano, Italy
INAF – Osservatorio Astrofisico di Catania, Via S. Sofia 78, 95123 Catania, Italy

ABSTRACT

The Cherenkov Telescope Array (CTA) will be the largest ground-based very high-energy gamma-ray detection observatory in the world with more than one hundred telescopes located in the Northern and Southern Hemispheres (La Palma, Canary Islands and currently proposed at Paranal, Chile). The energy coverage, in the southern CTA array, will extend up to 300TeV thanks to a large number (up to 70) of small size telescopes, with their primary mirrors of about 4meters in diameter and large field of view of the order of 9 degrees. It is proposed that one of the first set of CTA small size telescopes will be represented by the ASTRI mini-array which includes (at least) nine ASTRI telescopes whose end-to-end prototype, named the ASTRI SST-2M, is installed in Italy and is now entering in its commissioning and science verification phase. During this phase, that includes scientific observations of known sources such as the Crab Nebula and a few blazars, the prototype performance will be crosschecked with the predictions of Monte Carlo simulations. ASTRI telescopes are characterized by an optical system based on a dual-mirror Schwarzschild-Couder design and by a curved focal plane covered by silicon photomultiplier (SiPM) sensors managed by a fast front-end electronics. The telescope prototype, developed by the Italian National Institute for Astrophysics, INAF, follows an end-to-end approach that includes the internal and external calibration systems, control/acquisition hardware and software, data reduction and analysis software, and the data archiving system. All these sub-systems are developed following the CTA requirements for the SSTs. A collaborative effort is ongoing, led by INAF within CTA, in synergy with the Universidade de Sao Paulo (Brazil), and the North-West University (South Africa) and the Italian National Institute for Nuclear Physics (INFN). In this contribution, we will describe the main features of the ASTRI telescopes, the latest news on the prototype activities and the ASTRI mini-array technological and scientific expectations.

Keywords: Cherenkov Telescope Array, Small Size Telescopes for CTA, ASTRI, Schwarzschild-Couder telescopes, Slumped Glass Mirrors

1 INTRODUCTION

The very-high-energy (VHE, E > 50 GeV) portion of the electromagnetic spectrum is currently being investigated by means of ground-based imaging atmospheric Cherenkov telescopes (see [1],[2] for recent reviews). Imaging Atmospheric Cherenkov Telescopes (IACT) have proven to be the most sensitive instruments for gamma-ray astronomy at VHE. Exploiting the Earth's atmosphere as the absorbing medium of a gigantic calorimeter, they detect the cascade of secondary particles produced by the absorption of incoming very high-energy gamma rays, also called the extended air shower (EAS). The method is most effective when two or more IACTs are pointing to the same sky direction and set apart by ∼100 m, observing the same shower with different parallax. This allows stereoscopic imaging and reconstruction to be performed. For a given telescope separation, the multiplicity of the telescopes drives the gamma-ray effective area of the system.

The Cherenkov Telescope Array [3] is a project to build an observatory that will detect VHE gamma rays with sensitivity, spectral coverage, angular and energy resolution and survey capabilities surpassing the current generation of IACT experiments in order to significantly expand the science possibilities in this energy range.

The observatory will operate arrays on sites in both hemispheres to provide full sky coverage, with 99 telescopes on the southern site and 19 telescopes on the northern site; flexible operation will be possible, with sub-arrays available for

Ground-based and Airborne Telescopes VII, edited by Heather K. Marshall,
Jason Spyromilio, Proc. of SPIE Vol. 10700, 107005Z · © 2018 SPIE
CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2312453

specific tasks. The northern site will be located in La Palma in the Canary Islands while the southern site is currently proposed to be in the Atacama Desert in Chile.

With an energy coverage spanning from 20 GeV to at least 300 TeV, the southern CTA array necessitates the use of three different telescope types: referred to as Large-, Medium- and Small-Sized Telescopes (LSTs, MSTs and SSTs). The LSTs provide sensitivity at the lowest energies and SSTs at the highest [4]. Three different SST prototypes [5] are currently being developed within the CTA Collaboration, namely the single mirror SST-1M [6] telescope and the dual-mirror GCT [7] and ASTRI [8] telescopes.

In this context, the Italian National Institute for Astrophysics (INAF) started a project in 2011 aiming at designing and developing, within the CTA framework, an end-to-end prototype of the SST in a dual-mirror configuration (2M). We named this telescope ASTRI SST-2M since the activities have been supported from 2011 until 2015 by the "*Astrofisica con Specchi a Tecnologia Replicante Italiana*" (ASTRI) Flagship Project of the Italian Ministry of Education, University and Research (MIUR). Now the activities are continuing, supported by the Italian government with other funds (coming from the "*Astronomia Industriale*" program). While the activities concerning the implementation of the prototype in Italy are under completion, our Institute proposed the installation of a SST ASTRI mini-array (at least 9 telescopes) at the CTA Southern site, to be operated in the early phase of the Observatory implementation in order to consolidate the technical aspects and to produce early science data [9].

2 THE ASTRI SST-2M PROTOTYPE TELESCOPE (FROM THE ETNA VOLCANO…)

The aim of the ASTRI SST-2M prototype is manifold. First, it is a demonstrator used to validate the novel technology, in particular, the optical design and the Cherenkov camera. More importantly, it has been designed and built following an end-to-end approach where the fulfilment of the CTA requirements is obtained through Cherenkov observations of a selected sample of astrophysical sources. It will also serve as training facility for telescope and maintenance operations. Finally, as it will be maintained well after the end of the verification phase it will be used as a test bench for the implementation of new HW and SW.

Keeping in mind all these aspects, we chose an astronomical site to install the prototype (see Figure 1). The prototype was inaugurated in September 2014 at the INAF "M.C. Fracastoro" observing station in Serra La Nave (Mount Etna, Sicily).

Figure 1. The ASTRI SST-2M prototype telescope installed at the INAF – Osservatorio Astrofisico di Catania "M.C Fracastoro" observing station on the Etna Volcano in Sicily. The volcano erupting can be seen in the background.

2.1 Opto-mechanical design

The ASTRI telescope is based on the modified Schwarzschild – Couder (SC) design proposed by Vassiliev et al. in 2007 [10] for the Imaging Atmospheric Cherenkov Telescopes. The advantage of the SC design is that allows to correct, at the same time, spherical, coma and astigmatism aberrations on a large field of view. In addition, the use of the secondary mirror decreases the equivalent focal length to achieve an enlargement of the plate scale that translates in the construction of compact telescopes. For these reasons, ASTRI is one of the three CTA telescope prototypes based on this dual mirror optical design [8, 14] that is being developed.

The ASTRI prototype telescope [11, 12, 13] is a compact system, with a primary mirror diameter of 4.3 m, a primary-to-secondary distance of 3 m and a distance from the camera to the secondary mirror of 0.52 m. The main telescope parameters are reported in Table 1. It adopts an altitude-azimuthal design in which the azimuth axis will permit a rotation range of ±270°. The mirror dish is mounted on the azimuth fork, which allows rotation around the elevation axis from -1° to +90°. The mast structure that supports the secondary mirror and the camera is fixed on the mirror dish.

Table 1. ASTRI Telescope prototype mechanical characteristics

Dimensions & Mass	
Height of the Telescope (pointing horizontally & vertically)	7.5 m & 8.6 m
Radius of free area for Az. Movements	5.3 m
Total Mass	19725 kg
Tracking & Pointing Parameters	
Driver Encoder Precision	2 arcsec
Tracking Precision	<0.1 degrees
Pointing Precision After Calibration	<7 arcsec

Eighteen hexagonal panels make-up the primary mirror (M1) of the ASTRI telescope. In order to reproduce the aspherical optical profile of M1, its surface is arranged in three concentric rings (see Figure 2), each built from mirror segments with different profiles (see Table 2). The result is that the M1 behaves like a monolithic mirror. The M2 mirror is instead a monolithic substrate thick glass shell of 19 mm thickness and 1.8 m diameter bent to the desired radius of curvature [14]. Table 2 lists the optical main parameters of the ASTRI prototype and details of ASTRI optical layout can be found in [8, 9, 15].

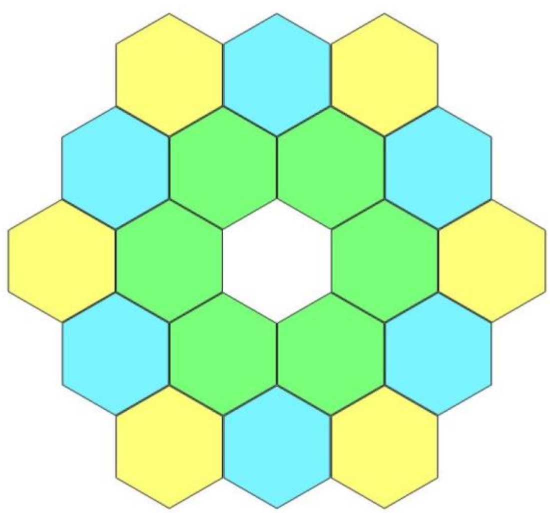

Figure 2. Schematic view of M1 mirror. Ring 1 mirrors are green, ring 2 mirrors are light blue and ring 3 are yellow

Another important characteristic of the mirror segments is the manufacturing process. The primary segments were produced using the cold slumping process in which a thin sheet of glass is formed at room temperature over a mould [16]. The mirrors have a sandwich-like structure, with an area density of about 12 kg/m^2 and this makes very light mirrors so that handling and mounting operations are easy. The technique, developed by Media Lario Technologies Company under the scientific supervision of INAF–OAB, has the advantage that, being based on a replication approach, it is well suited for mass production and is cheap.

Table 2. ASTRI main optical parameters

Optical Properties	
Optical Configuration	Schwarzschild-Couder
Average effective collecting area	5 m^2
Focal Length	2.15 m
Aperture	4.3 m
f/#	0.5
FOV	10.5^o
PSF (@ 100 % of FOV diameter)	≤ 0.19°
Primary Mirror (segmented)	
Diameter	4.306 m
Number of segments	18
Size of a segment	850 mm (face-to-face)
Nominal Radius of Curvature Ring 1	8.52 m
Nominal Radius of Curvature Ring 2	9.87 m
Nominal Radius of Curvature Ring 3	12.54 m
Profile Error (RMS)	< 30 μm
Micro-roughness (RMS, 0.1 - 200 mm spatial wavelength range)	< 2 nm
Secondary Mirror (monolithic)	
Diameter	1.8 m

2.2 The ASTRI Cherenkov Camera

Exploiting the characteristics of the SC optical design of the telescope, the ASTRI Cherenkov camera is very compact (see Table 3). Its novel design is based on two main components: the SiPM detectors and the read-out electronics.

The SiPM have linear dimensions of few millimeters that are a perfect match to the PSF generated by the telescope. Furthermore, they exhibit high quantum efficiency (see Figure 3), very fast response and excellent single photoelectron resolution.

The ASTRI camera read-out electronics [17] represents an innovative solution, being based on a custom peak-detector operation mode to acquire the SiPM pulses rather than the sampling technique usually adopted by other CTA telescopes. The SiPM read-out electronics, based on a CITIROC ASIC [18], with its signal shaper and peak detector customized for ASTRI, provides high efficiency, auto-trigger capability and very fast camera pixel read out. The ASTRI camera trigger is a topological one, activated when a given number of contiguous pixels presents a signal above a threshold equivalent to a given number of photo-electrons. A particular operating mode of the ASTRI read out electronics is the variance technique [17, 18]. Using this technique, the electric signal generated by each pixel not triggered by the first level trigger is continuously sampled. The sequence of ADC values obtained is constant with time but its variance is proportional to the photon flux falling on the pixel. The acquisition of the variance data is done in parallel with the normal Cherenkov data acquisition. The variance method has several applications going from the measurement of the telescope pointing accuracy and that of the Night Sky Background (NSB) to the monitoring of the mirrors optical alignment [17].

Table 3. ASTRI Cherenkov camera main characteristics

Camera opening Angle	70°
Sensors	SiPM
Number of Pixels	2368 (1344 protoype)
Pixel size	7x7 mm
Pixel rate	600 Hz
Dynamical range	1 – 2000 pe$^-$/pixel
Photon Detection Efficiency	> 35% @ 400nm
FoV	10.5° (7.8° prototype)
Weight	73 kg
Dimensions	0.52m x 0.66m x 0.56m
Power consumption	0.65 kW

The description of the ASTRI Cherenkov camera is given in [17]. Table 3 summarizes the main characteristics of the camera, while Figure 3 shows the camera integrated in the laboratory and in particular, the focal plane populated with 21 SiPM tiles, out of the 37 foreseen, each made-up of 64 (8x8) pixels with 7x7 mm size.

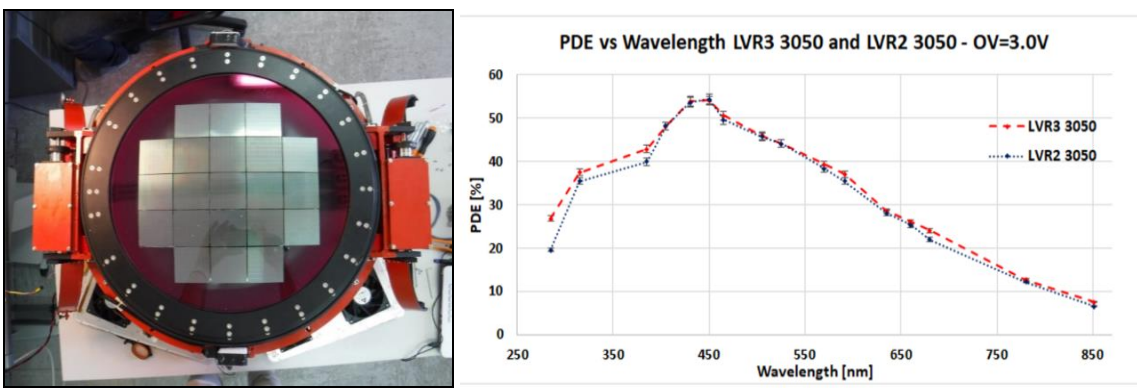

Figure 3. Left: the ASTRI prototype camera integrated in the laboratory. Right: Photo Detection Efficiency of last generation Hamamatsu LVR2 and LVR3 SiPM sensors.

3 COMMISSIONING OF THE ASTRI TELESCOPE PROTOTYPE

Since the inauguration, the prototype has gone through an extensive campaign of tests, first to characterize and then to monitor the performance of the entire telescope. In particular, this has been done for the mechanical structure and for the optics while the Cherenkov camera is still being characterized.

3.1 Monitoring pointing and tracking performances

The electro-mechanical structure has been intensively studied and its parameters optimized to get the best performance as described thoroughly in [8].

As part of regularly scheduled activity, we performed an observational campaign to monitor the pointing and tracking performances of the telescope between November 2017 and January 2018. The measurements were obtained using the Pointing Monitoring Camera (PMC), an auxiliary CCD camera placed on top of secondary mirror supporting structure [8] whose main purpose is to calibrate the position in sky of the telescope.

The pointing and tracking performance were obtained pointing the telescope at a given target in the sky with the telescope in tracking mode. The images were acquired at a maximum frequency of one every 10 seconds with exposure times typically of the order of few seconds and duration of an observational run between 10 and 20 minutes. A model to correct for flexures and misalignments of the telescope and for atmospheric refraction was applied. Finally, we computed the astrometry for each image. Figure 4 shows the results of the analysis for half an hour long data set. It is clear that the ASTRI telescope performance are well within CTA requirements on astrometric accuracy.

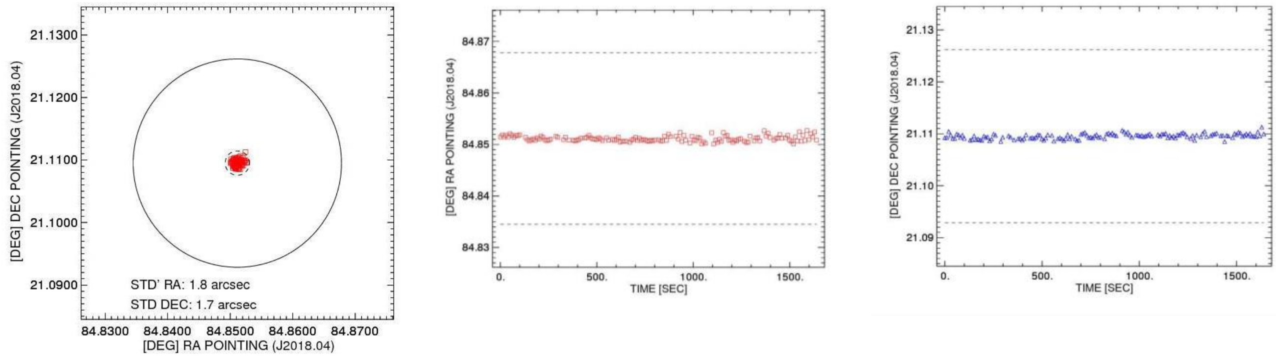

Figure 4. Pointing and tracking performance of the ASTRI telescope. Left: RA-DEC plot showing that the position of the telescope can be measured with an accuracy within the 7 arcsec (dashed circle) requested by the CTA requirement of post calibration astrometric accuracy. Center and right: RA and DEC plots versus time showing that ASTRI is well within the 1 arcmin (dashed lines) online astrometric accuracy requested by CTA.

3.2 Optical design validation

The validation of the optical design of the ASTRI prototype has been obtained during a dedicated campaign in the Autumn of 2016. The PSF produced by the optics has been measured as a function of its position along the telescope field of view [15]. In addition, we measured the PSF temporal stability and that with respect to telescope elevation [8]. The measurements were obtained with a dedicated CCD camera placed on the telescope focal plane imaging stars in different positions in the sky.

Figure 5 shows the most important result obtained, that is, the first validation ever of the SC optical design. The measurements show that the required specification of a flat PSF of ~10 arcmin along a large field of view (~10°) has been fulfilled.

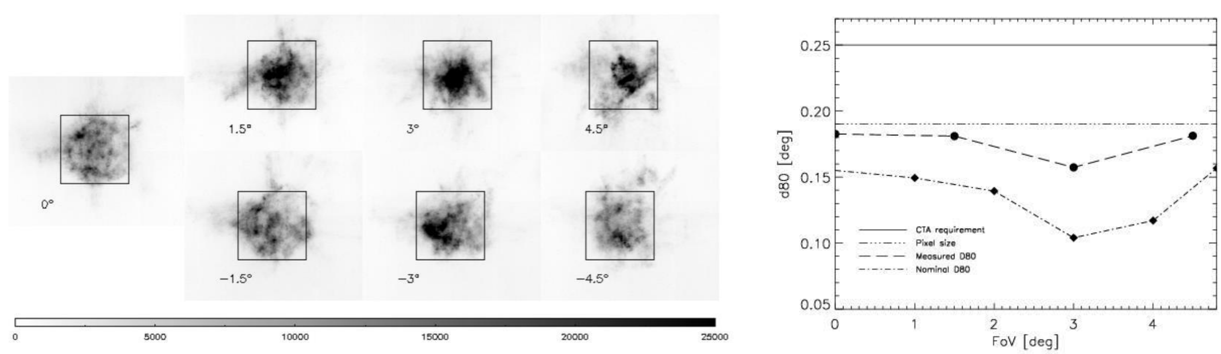

Figure 5. Left: PSF of ASTRI SST-2M telescope across the focal plane. Cherenkov camera pixel size (7x7 mm) is over-plotted for each PSF. Right: Comparison of D80 (diameter of the circle corresponding to an encircled energy of 80%) as a function of field angle (off-axis) between its ideal (dot-dashed curve) and measured at ASTRI SST-2M (dashed curve) values. SiPM pixel size (dashed horizontal line) and CTA design requirement (solid horizontal line) are also shown for reference.

The stability of the PSF with elevation and with time [13] has a huge impact on the design of the active mirror control. In fact, this subsystem has been now "downgraded" to an AIV tool that is used to align the segments of the primary mirror at the time of integration and then to realign them whenever is required (typically once per year).

3.3 Monitoring the mirror reflectivity

Monitoring the reflectivity of the mirror with time is fundamental to measure the degradation of the coating due to environment (atmosphere, dust/sand, UV light). The rate of degradation is an important parameter that has an impact on maintenance operations of the mirrors implying, for example, the necessity to have a recoating facility available at the site.

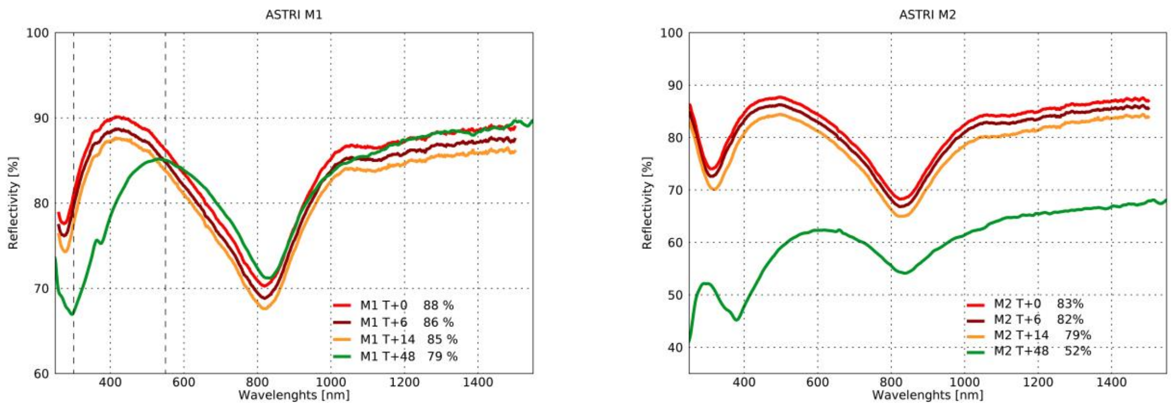

Figure 6. Reflectivity of M1 and M2 at different times. The reflectivity was measured after coating deposition and then 6, 14 and 48 months later.

For this reason, since the production we have measured the reflectivity of primary and secondary mirrors at different times. Figure 6 shows the results of such measurements. The ageing of the coating is faster than expected, especially for the secondary mirror, and this is likely due to the aggressive volcanic atmosphere with frequent emission of sulphur compounds. An identical coating was used for the MAGIC mirrors that are located on Roque the los Muchachos in La Palma (Canary Islands). In more than 8 years, the degradation of the reflectivity has been a few percent. As the site chosen for CTA in the South has no volcanos around and no aggressive atmosphere, we feel very confident that the rate of degradation will be in line with CTA requirements.

3.4 Camera On-sky performance

The Cherenkov camera current performances are described in details in [17] so we will give here just a short report on the tests performed on the sky.

The integration of the ASTRI camera at the telescope was done in May 2017 and despite the fact that the camera performance was far than optimal we were able to achieve a first Cherenkov light [19]. Since then, the camera has spent several nights at the telescope and even if most of them were devoted to engineering tests, some scientific runs were performed leading to the detection of thousands of Cherenkov events (see Figure 7).

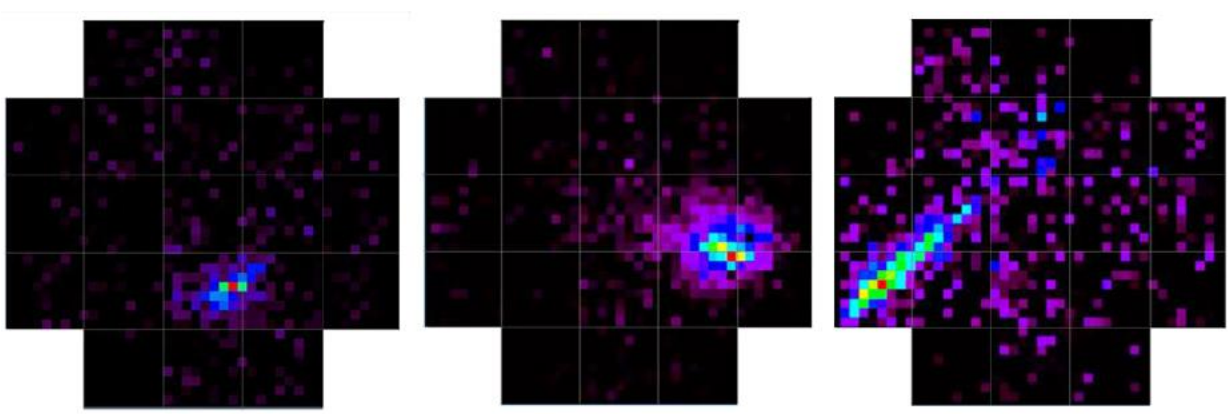

Figure 7. Images of detected Cherenkov events during on-sky observations

Figure 8 shows preliminary telescope trigger rates as a function of pixel trigger thresholds for a topological trigger of at least five contiguous pixels [17, 20] obtained during moonless nights and pointing the telescope at different sky positions. It is interesting to note how the NSB changes as a function of the telescope pointing due to illumination by the nearby city of Catania. A preliminary analysis of the curves shows that the trigger rate in the region dominated by the air shower events is lower than expected while the trigger threshold is higher [17]. A reduced efficiency of the telescope due to mirrors degradation and misalignment could be a possible cause and will be further investigated.

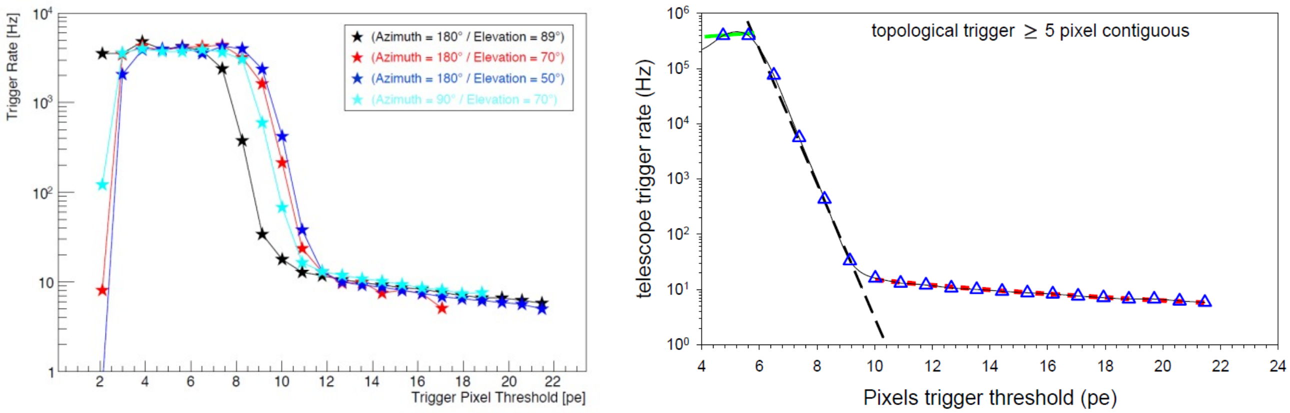

Figure 8. Trigger rate as a function of the trigger threshold in photoelectrons. Left: scans at different telescope pointing [20]. Right: trigger rate obtained pointing at zenith and corrected for dead time. Also shown are the trigger rate saturation (green line) and the random coincidence rates (black dashed line) induced by the NSB diffuse light. The red dashed line represents a power-law fit to the data points for thresholds greater than 10 pe [17].

Cherenkov shower data on the Crab Nebula were obtained in a run December 2017 when we collected ~1.7 hours of Crab Nebula and ~1.4 hours of off target data. Figure 9 shows the detection |α|-plot to search for an excess from the source (see [20] for details). Even if this is a clear non-detection, not unexpected due to the limited exposure time, the reduced efficiency of the telescope, the non-optimal tuning of the camera, and the rough calibrations used for the data reduction, however these observations allowed us to test the end-to-end concept of the prototype from the photon capture to the data analysis. A complete report of the data analysis activities is given in [20].

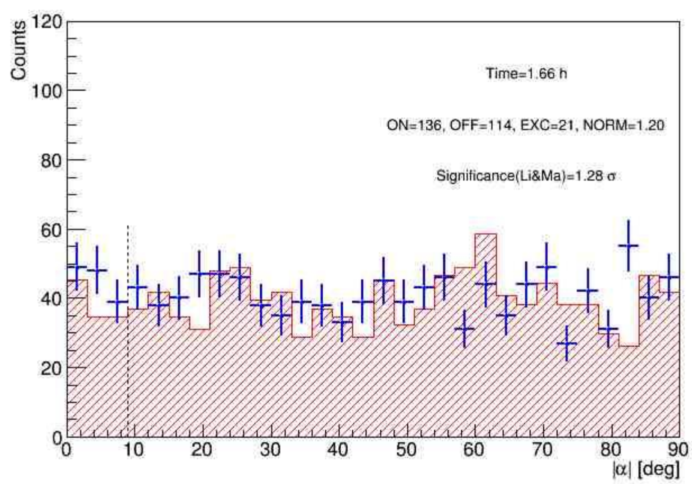

Figure 9. |α| distributions of the Crab Nebula signal and background estimation from data taken in December 2017, after an 80% efficiency-based gamma/hadron discrimination parameter cut (in the whole energy range). The region between zero and the vertical dashed line (at 9 deg) represents the fiducial signal region. See [20] for further details.

The variance mode has been tested in January and March 2018 showing its potentialities in assessing the pointing behavior of the telescope [20] and in checking the optical alignment of M1 mirrors [17]. Figure 10 shows the images of the Orion Belt taken during the January run. The images show the presence of four luminous spots in a regular pattern due to misaligned M1 mirrors. This finding was confirmed in May when during a dedicated session six mirrors were found misaligned and realigned. The two misaligned mirrors not caught by the variance technique were too close to their nominal position to be visible in the variance images. Two considerations can be deduced: first, the optical alignment is quite stable in time as this is the first time in almost two years that this needs to be adjusted and second the variance technique is an efficient method to monitor the optical alignment of the M1 mirrors.

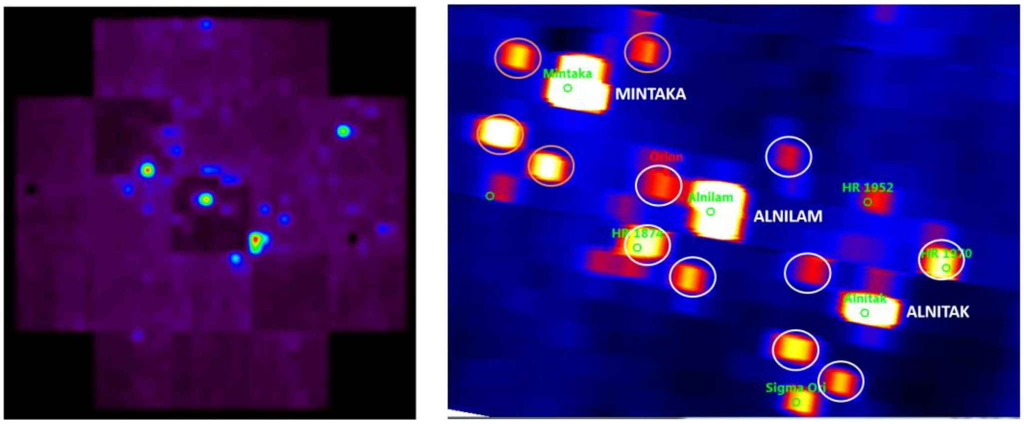

Figure 10. Variance images of the Orion belt taken in January 2018. Left: the entire variance image. Right: detail of the belt showing the spots due to misaligned M1 mirrors.

4 THE ASTRI MINI-ARRAY (…TO THE CHILEAN ANDES)

Prototypes are made to prove technology, and to test operational and maintenance procedures. This is true for a single telescope but also for an array like CTA. To test the stereoscopic imaging capabilities, the array trigger system and the array control system, it is mandatory to build an array. Within this framework we decided to develop a mini-array [9, 21, 22, 23], composed of nine SST-2M ASTRI telescopes, to be placed at the CTA southern site currently proposed to be in Chile. This effort is led, within the CTA collaboration, by INAF in synergy with the Universidade de Sao Paulo (Brazil) and the North-West University (South Africa). The ASTRI mini-array is intended to be one of the first seeds of the CTA array so its implementation will happen within the framework of CTA development. In particular, the mini-array will have to pass, before deployment, all the CTA technical reviews. The deployment of the ASTRI mini-array at the CTA south site is foreseen not before 2020.

4.1 Mini-array production activities

Going from the prototype to the mini-array means to optimize the design of all subsystems to make them suitable for mass production.

Those subsystems whose design is well consolidated were considered at low risk and so we decided to start their production. In particular, this applies to the mirrors and to the ASIC that makes the heart of the Cherenkov camera read out electronics, the CITIROC.

The optical design of the telescope has been fully validated by field tests so future ASTRI telescopes will have the same primary and secondary mirrors. The manufacture of the primary mirrors segments and that of the secondary substrates was assigned through direct contract to Media Lario Srl and to Flabeg GmbH respectively.
The production of 10 (9 + 1 spare) M2 mirrors substrates was completed at the end of 2017 (Figure 11) and the substrates will start to be coated soon.
The manufacture of segments for 9 + 1 spare primary mirrors started in September 2017 (Figure 11) after a six months long qualification phase, during which the mirrors and their coatings were tested according to CTA requirements.

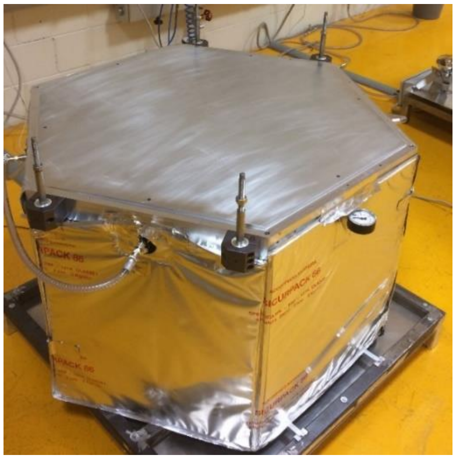
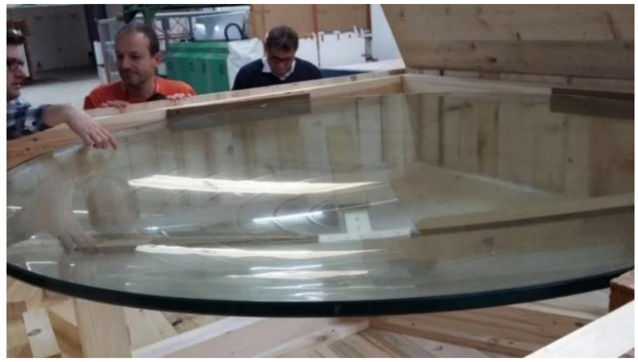

Figure 11. Mini-array mirrors production. Left: one of the primary segments being manufactured (courtesy of Media Lario srl). Right: secondary mirror substrate at Flabeg GmbH.

The only difference between the ASTRI mini-array mirrors and those of the prototype is the coating. Figure 12 shows the reflectivity curves of the two coatings. The mirrors of the ASTRI prototypes were coated with Aluminum and SiO_2 while in the new coating Zirconium Oxide (ZrO_2) is also present. The mini-array coating has the advantage of a better spectral response in the wavelength range (300-550 nm) specified by CTA requirements and a lower reflectivity (useful to reduce the contribution of the NSB) in the infrared part of the spectrum with respect to the old coating while keeping the same performance in terms of resistance and durability.

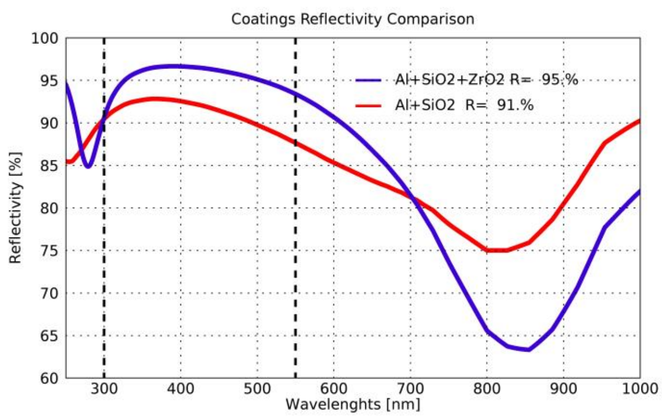

Figure 12. The reflectance of the coating of the ASTRI prototype mirrors (Al+SiO_2) compared to that of the coating chosen for the ASTRI mini-array mirrors (Al+SiO_2+ZrO_2).

The contract for the production of more than one thousand CITIROC for 11 cameras (9 cameras plus 1 engineering model and 1 spare) was assigned to Weeroc in June 2017. We started the manufacturing in March 2018, again, after a qualification phase to demonstrate the compliance with the requirements.

On the other end, the electromechanical structure and the Cherenkov camera (except the ASICs of course) are going through a phase of design consolidation and optimization. In this process, we will take advantage of the lessons learnt with the prototype after almost four years in the field, of the technology improvements (e.g. latest generation SiPM) and will consider the consolidation of CTA requirements due to the final choice of the South site.

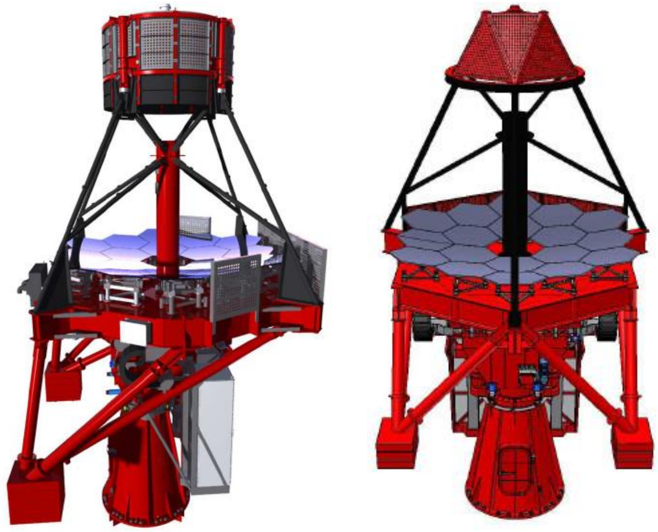

Figure 13. Design of the ASTRI Telescope mechanical structure. Left: the ASTRI prototype. Right: the consolidated design (courtesy of GEC)

The information obtained during commissioning produced several improvements in the design of the electromechanical structure, especially in terms of mass reduction and system simplification. Figure 13 shows the comparison between the consolidated design and that of the prototype. The M1 dish and the support structure of M2 have been modified, lowering the total weight while keeping the same stiffness. In addition, the excellent stability of the measured optical PSF against gravity and time allowed us to design a telescope without a permanent Active Mirror Control (AMC). The AMC will be mounted only to be used during the AIV phase and for maintenance activities with great simplification of the telescope control system and operational procedures. Once the Finite Element Analysis will be completed, the new structures will be ready to go through the CTA revision process and then manufactured.

The completion of the commissioning phase of the Cherenkov camera is foreseen for the end of this year, yielding the full characterization of the camera. The information gathered during this phase will allow to start the procurement process for mini-array Cherenkov cameras, including SiPM detectors, soon after.

4.2 Science with the ASTRI mini-array

Apart from the technological and operational aspects, the mini-array, conceived again with an end-to-end approach, can and will be used to make astrophysical observations. In fact, while the sensitivity is worse than that of the full SST array planned for CTA [3] (see Figure 14), energy and angular resolution are closer to the ones for the 70 telescopes, as only a few TeV shower events are expected to trigger more than nine units. The ASTRI mini-array will be able to perform astronomical observations with an energy resolution of about 10 – 15 %. Preliminary Monte Carlo simulations [20] of the ASTRI mini-array are shown in Figure 14 obtained using the MC pipelines used in the CTA Consortium and those obtained with the with the A-SciSoft MC analysis. The different results, below a few TeV, achieved with the ASTRI data reduction are likely due to the application of different algorithms and (low energies) analysis cuts with respect to the analysis performed with the MC pipelines currently being used in CTA (see [20] for details and the full explanation of the A-SciSoft package). Comparing the two plots it is clear that the improvement in sensitivity, for the nine telescopes of the ASTRI mini-array, could surpass the H.E.S.S. sensitivity above 10 TeV, extending up to about 100 TeV.

The ASTRI mini-array will exploit its better sensitivity and extended spectral range to investigate the emission of prominent sources such as extreme blazars (KUV 00311−1938), nearby well-known BL Lac objects (Mrk 501) and radio galaxies (M 87), galactic pulsar wind nebulae (Crab Nebula, Vela-X), supernovae remnants (Vela-junior, RX J1713.7−3946), as well as the Galactic Centre. In particular, it can help in shedding light in phenomena such as the electron acceleration and cooling, relativistic and non-relativistic shocks, the search for cosmic ray (CR) PeVatrons, the study of the CR propagation, and the impact of the extragalactic background light on the spectra of the sources.

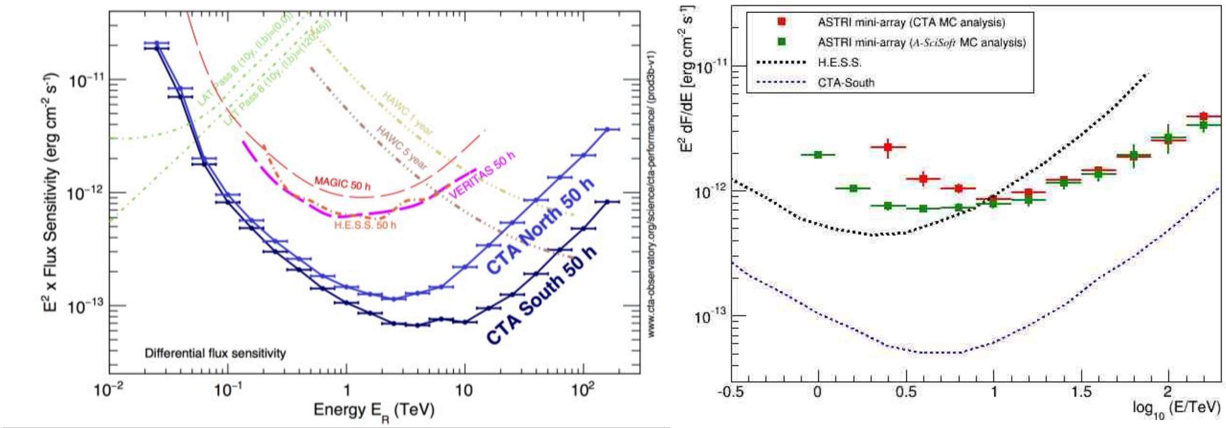

Figure 14. Left: The expected sensitivity of the CTA, achieved with cuts optimised for better low-energy response in the ASTRI case and for cuts optimised for a balanced performance in sensitivity and angular resolution for the full CTA South case, compared to existing IACT experiments, as well as the LAT instrument on board the Fermi satellite and the HAWC ground array [3]. Right: ASTRI mini-array (9 telescopes, relative distance ~250 m, square layout) differential sensitivity curves (5σ, 50 hours) achieved with the A-SciSoft MC analysis (green points) and with the CTA MC analysis. The differential sensitivities of CTA-South (blue line) and H.E.S.S (black line) are also shown for comparison.

As an example of the capabilities of the ASTRI mini-array in the search for Pevatron sources, we show the results of the work by Burtovoi et al [24] on the supernova remnant SNR RCW86. Figure 15 shows the observed gamma ray spectrum of the SNR RCW86 (Fermi-LAT [25] & HESS[26]) together with a 200 hours simulated spectrum from the source assuming leptonic or hadronic origin for the gamma rays. The results show that the ASTRI mini-array sensitivity in an extended spectral range will easily allow us to discriminate between the two scenarios and (if hadronic) to check for the presence of PeV cosmic rays.

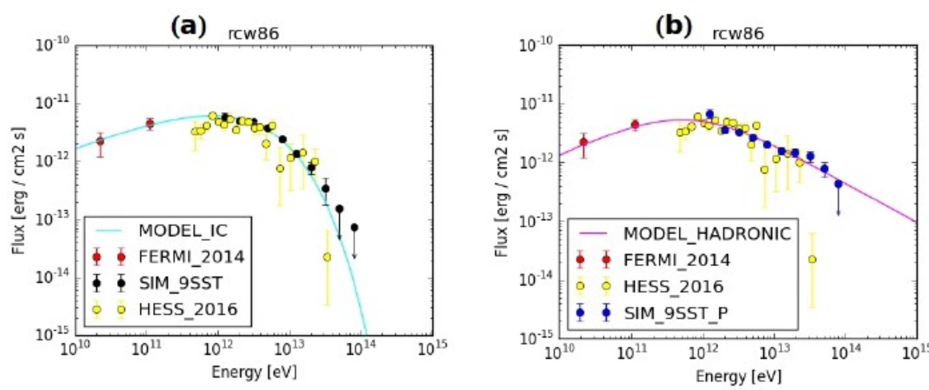

Figure 15. Simulated spectra of the SNR RCW 86 observed with the ASTRI mini-array in case of (a) leptonic (cyan line) or (b) hadronic (magenta line) mechanism of the gamma-ray origin dominates. ASTRI simulated data points are in the (a) black and (b) blue colors. For H.E.S.S. observational data points see [26] and for Fermi-LAT [25].

5 CONCLUSIONS

The Cherenkov Telescope Array (CTA) is the next generation ground-based observatory for gamma-ray astronomy at very-high energies. It will be the world's largest and most sensitive gamma-ray observatory. In the southern site CTA array will implement three different telescope types: Large, Medium and Small-Sized Telescopes (LSTs, MSTs and SSTs).

The ASTRI telescope, a prototype of the SST class of CTA, started the journey that may take it to the Chilean Andes almost 4 years ago on the slopes of the Etna volcano. Since the installation at the site, the ASTRI prototype has been extensively characterized fulfilling expectations and requirements. The science verification phase will likely be over at the end of 2018. A new phase of the journey has already started that, hopefully, will lead us to the implementation of a mini-array of nine ASTRI telescopes. This array would be one of the first building blocks of the CTA observatory and will allow early science operations extending the observation of gamma rays in an energy range previously unexplored by current IACT facilities.

ACKNOWLEDGMENTS

This work is supported by the Italian Ministry of Education, University, and Research (MIUR) with funds specifically assigned to the Italian National Institute of Astrophysics (INAF) for the Cherenkov Telescope Array (CTA), and by the Italian Ministry of Economic Development (MISE) within the "Astronomia Industriale" program. We acknowledge support from the Brazilian Funding Agency FAPESP (Grant 2013/10559-5) and from the South African Department of Science and Technology through Funding Agreement 0227/2014 for the South African Gamma-Ray Astronomy Programme. We gratefully acknowledge support from the agencies and organizations listed under Funding Agencies at this website: http://www.cta-observatory.org/.

REFERENCES

1. Hinton, J. A., and Hofmann, W., Annual Review of Astronomy & Astrophysics, "Teraelectronvolt Astronomy", 47, 523 (2009)
2. Rieger, F.M., de Ona-Wilhelmi, E., Aharonian, F.A., Frontiers of Physics, "TeV Astronomy", Volume 8, Issue 6, pp.714-747 (2013)
3. Hofmann, W., "The Cherenkov Telescope Array: Exploring the Very-high-energy Sky from ESO's Paranal Site", The Messenger, 168, 2, (2017)
4. The Cherenkov Telescope Array Consortium, "Science with the Cherenkov Telescope Array", eprint arXiv:1709.07997.
5. Montaruli, T., Pareschi, G., Greenshaw, T., "The small size telescope projects for the Cherenkov Telescope Array", Proceedings of the 34th International Cosmic Ray Conference (ICRC2015), The Hague, The Netherlands. All CTA contributions at arXiv:1508.05894 (2015).
6. Heller, M., et al., "The Single Mirror Small Size Telescope of the Cherenkov Telescope Array", AIP Conference Proceedings, Volume 1792, Issue 1, id.080003 (2017).
7. Sol, H., Greenshaw, T., Le Blanc, O., White, R., "Observing the sky at extremely high energies with the Cherenkov Telescope Array: Status of the GCT project", Proceedings of the 35th International Cosmic Ray Conference (ICRC2017), Busan, Korea, eprint arXiv:1709.09134 (2017).
8. Canestrari, R., et al., for the CTA ASTRI Project, "The ASTRI SST-2M prototype for the Cherenkov Telescope Array: status after the commissioning phase of the telescope", Proc. SPIE 10399, 1039904-1 (2017).
9. Pareschi G., et al., for the ASTRI Collaboration and the CTA Consortium, "The ASTRI SST-2M prototype and mini-array for the Cherenkov Telescope Array (CTA),"
   Proc. SPIE 9906, id. 99065T (2016)
10. Vassiliev, V., Fegan, S., Brousseau, P., "Wide field aplanatic two-mirror telescopes for ground-based γ-ray astronomy", Astroparticle Physics 28, 10 (2007)
11. Canestrari, R., et al, for the ASTRI Collaboration and the CTA Consortium, "The ASTRI SST-2M prototype for the Cherenkov Telescope Array: opto-mechanical test results", Proc. SPIE, Volume 9603, id. 960303 12 pp. (2015)
12. Marchiori, G., et al., "The ASTRI SST-2M prototype for the Cherenkov Telescope Array: prototype technologies goals and strategies for the future SST", Proceedings of the SPIE, Volume 9145, id. 91450L 9 pp. (2014)
13. Canestrari, R., et al., for the ASTRI Collaboration and the CTA Consortium, "The ASTRI SST-2M prototype for the Cherenkov Telescope Array: opto-mechanical performance", Proc. SPIE, 9906, id. 990619 (2017)
14. Rodeghiero, G., et al., "Qualification and Testing of a Large Hot Slumped Secondary Mirror for Schwarzschild-Couder Imaging Air Cherenkov Telescopes", Publications of the Astronomical Society of Pacific, Volume 128, Issue 963, pp. 055001 (2016)
15. Giro E., et al., "First optical validation of a Schwarzschild Couder telescope: the ASTRI SST-2M Cherenkov telescope," Astronomy & Astrophysics, Volume 608, A86 (2017)
16. Pareschi, G., et al., "Status of the technologies for the production of the Cherenkov Telescope Array (CTA) mirrors", Proc. SPIE, Volume 8861, id. 886103 19 pp. (2013)

17. Catalano, O., et al., for the CTA ASTRI Project, "The ASTRI camera for the Cherenkov Telescope Array", SPIE these proceedings (2018)
18. Sottile, G., et al., for the ASTRI Collaboration and the CTA Consortium, "ASTRI SST-2M Camera Electronics", Proc. SPIE , 9906-124, (2016)
19. CTA Press Release, 14 June 2017 (2017) https://www.cta-observatory.org/cta-prototype-telescope-astri-achieves-first-light/
20. Lombardi, S., et al., for the CTA ASTRI Project, "ASTRI data reduction software in the framework of the Cherenkov Telescope Array", SPIE these proceedings (2018).
21. Vercellone, S., for the ASTRI Collaboration and the CTA Consortium, "The ASTRI mini-array within the future Cherenkov Telescope Array", Proceedings of the "The Roma International Conference on Astroparticle Physics (RICAP) 2014, http://arxiv.org/abs/1508.00799 (2014)
22. Pareschi G., and Bonnoli, G., for the ASTRI Collaboration and the CTA Consortium, "The mini-array of ASTRI SST-2M telescopes, precursors for the Cherenkov Telescope Array", Proceedings of the XIV International Conference on Topics in Astroparticle and Underground Physics (TAUP2015), Journal of Physics: Conference Series Journal link tile ends , Volume 718, Issue Number Tile Start High energy astrophysics and cosmic rays (2016)
23. Bonnoli, G., et al., for the ASTRI Collaboration and the CTA Consortium, "Science with the ASTRI mini-array for the Cherenkov Telescope Array: blazars and fundamental physics", Proceedings of the XIV International Conference on Topics in Astroparticle and Underground Physics (TAUP2015), Journal of Physics: Conference Series Journal link tile ends , Volume 718, Issue Number Tile Start High energy astrophysics and cosmic rays (2016)
24. Burtovoi, A., et al., for the ASTRI Collaboration and the CTA Consortium, "Prospects for PWNe and SNRs science with the ASTRI mini-array of pre-production small-sized telescopes of the Cherenkov telescope array", AIP Conference Proceedings, Volume 1792, Issue 1, id.080007, (2017)
25. H. E. S. S. Collaboration and et al., arXiv:1601.04461, (2016).
Yuan, Q. et al., "Fermi Large Area Telescope Detection of Supernova Remnant RCW 86" ApJ Volume 785, p. L22 (2014).