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Memorie della

The ASTRI project

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1. Introduction

The ASTRI project was born as one of the so called "flagship" projects, funded by the Italian Ministry for the University and the Scientific Research. The program is led by the Italian National Institute for Astrophysics (INAF) and is finalized to the technological development of the next generation of Imaging Atmospheric Cherenkov Telescopes (IACT) for ground-based gamma ray astronomy. In this framework ASTRI is part of the Cherenkov Telescope Array (CTA) project, an international program to build a ground-based observatory for gamma rays open to the worldwide physics and astrophysics community.

CTA will improve by an order of magnitude the flux sensitivity of the current Cherenkov telescopes (HESS, MAGIC and VERITAS), while having a very broad energy coverage from few tens of Gev to beyond 100 TeV. To reach these performances more than a hundred telescopes will be built in two different sites, the first one in Chile in the southern hemisphere and the second one in the northern hemisphere in the Canary Islands. To cover its wide energy range CTA will need three classes of telescopes, the Large Size Telescope (LST - 23 meters in diameter and four units in each site, covering the low energy range) the Medium Size Telescope (MST - 12 m in diameter and 24 units in the south site and 15 in the north, covering the medium energy range) and the Small Size Telescope (SST - 4m in diameter, 70 units in the south site only, covering the high energy range). More than 1400 scientists and engineers from 32 countries and 210 research institutes and universities are participating in the development of the CTA project.

INAF interest in high energy astrophysics and then in gamma ray studies has always been high and has its recent roots in the realization and exploitation of the FERMI and AGILE space-based satellites and of the MAGIC telescope.

Since the beginning INAF takes part to the development of the CTA project through ASTRI. The acronym ASTRI stands for "Astronomia a Specchi a Tecnologia Replicante Italiana" which means Astronomy with mirrors built through Italian replica technology. The term was coined by Nanni Bignami at that time INAF president that till the end was an enthusiastic supporter of the project.

2. The ASTRI project in a nutshell

The aim of the MIUR "flagship" project was to design, realize and install a prototype (ASTRI-Horn) telescope of the SST class for CTA to be tested under operative conditions at the mountain station of the INAF - Catania Astrophysical Observatory on the slopes of Etna volcano. Final aim of the ASTRI project

Fig. 1. A picture of ASTRI group in front the ASTRI-Horn prototype telescope during the inauguration ceremony on the 24th of September 2014.

is to contribute to the construction of the 70 telescopes of the SST class for the CTA south site.

The project involves more than 100 researchers of the INAF institutes in Milan, Padua, Bologna, Palermo and Catania. The universities of Perugia, Padova, Catania, Genova and the Milano Polytechnic together with the INFN sections of Roma Tor Vergata and Perugia also participate to the project. The university of Sao Paulo in Brazil and the North Western University in South Africa are the international partners of the project. Finally, several italian and foreign companies actively participate to the project. In particular, the electromechanical structure has been realized by a consortium of Italian companies (Galbiati and EIE), the mirrors have been realized with the contribution of Media Lario, ZAOT and the German company Flabeg SE, finally, the Cherenkov camera has been produced with the participation of the French company Weeroc, the British one Thermacore, the Japanese Hamamatsu and the Italian companies Mindway and Novasys.

The prototype telescope ASTRI-Horn was born essentially as technological demonstrator. Indeed, ASTRI-Horn is the first Cherenkov telescope to adopt a two mirrors optical configuration and among the first to use Silicon PhotoMultipliers (SiPM) as detectors.

The telescope has been designed and realized with an end-to-end approach. This implies that its functionality has been proven not just through technical tests but using astrophysical observations of a sample of selected sources. To do this it was necessary to realize the full chain from the “photon capture” to its analysis which comprehend not only the telescope and the Cherenkov camera but also the internal and external calibration system, the hardware and control software, the data reduction and data analysis software and the archive system. This is the reason why the telescope has been installed at an astronomical site, the M.G. Fracastoro station of the INAF - Catania

Fig. 2. The ASTRI-Horn prototype telescope during a night technical observation.

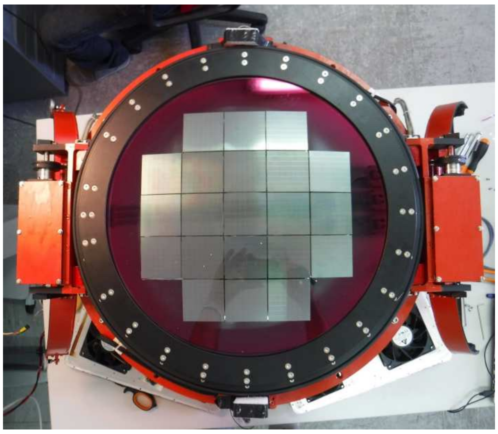

Fig. 3. The first glass foil is positioned, bent and fixed over the mould; then it is forced to adhere to the mould surface by vacuum suction. In this way, the shape of the mould is replicated.

Astrophysical Observatory, placed at an altitude of 1725 meters above the sea level inside the Etna regional park.

The construction of the prototype telescope ASTRI-Horn started in the spring of 2014 and its installation occurred during the summer. The official inauguration was held the 24^{th} of September of 2014 during the CTA Consortium Meeting (Fig.1).

3. Characteristics of the ASTRI - Horn prototype

Compared to the existing Cherenkov telescopes the ASTRI-Horn prototype implemented two innovative solutions: the optical configuration and the camera to detect the atmospheric showers.

The ASTRI-Horn prototype telescope is the first Cherenkov telescope that adopted a dual mirror design based on a modified Schwarzschild - Couder configuration. The optical designer is Paolo Conconi former astronomer of the Brera Astronomical Observatory. This design considers a double reflection on mirrors with polynomial profile and radially symmetric. The advantage of this design is to be aplanatic allowing the simultaneous correction of spherical aberration, astigmatism and coma yielding a uniform optical quality on a large field of view together with a good angular resolution. Furthermore, the use of a secondary mirror allows to reduce the equivalent focal length which translates in a compact telescope. Eventually, the distance between primary and secondary mirror is 3 meters while the distance of the latter by the Cherenkov camera, containing the focal plane, is 0.52 meters only (Fig.2).

The mechanical mount is alto-azimuthal, and its design allows to rotate 270 degree in the azimuth direction. The the primary mirror cell is mounted on a fork that allows the elevation axis to rotate between -1 and 90 degrees. The weight of the telescope is around 19 tons and its height varies between 7.5 and 8.5 meters depending on the telescope orientation (at the horizon, when in parking position, or at the zenith). The stiff structure allows the telescope to have outstanding performance in pointing and tracking celestial objects.

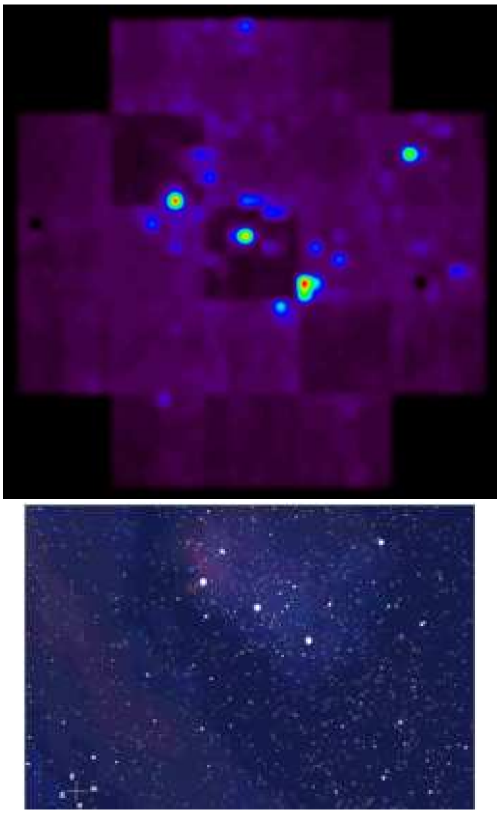

Fig. 4. 4a: An image of the Orion belt obtained with the ASTRI Cherenkov camera using the variance method. 4b: An optical image of the Orion belt.

Fig. 5. The segmented primary mirror of the ASTRI-Horn prototype telescope.

The primary mirror is segmented and has a diameter of 4.3 meters while the diameter of the secondary mirror, which is monolithic, is 1.8 meters only.

Another “side effect” of having a Schwarzschild - Couder optical design is having a Cherenkov camera that is light and compact (70 kg with dimension just above half a meter). The Cherenkov camera of the ASTRI-Horn prototype telescope has designed in the INAF institutes In Palermo and Catania and then integrated in Palermo. The innovative elements that characterize the camera are the detectors and the read-out electronics.

The detectors used in the Cherenkov camera are called Silicon Photomultiplier (SiPM). They are very sensitive and extremely fast, able to catch the flash of Cherenkov light produced by the interaction of gamma rays with the Earth’s atmosphere. Every SiPM is a pixel of 7x7 mm. The focal plane of the prototype Cherenkov camera can hold up to 2400 SiPM even if, being a demonstrator, it hosts only 1344 arranged in 21 matrices of 8x8 pixels (Fig.3).

The dimensions of the single pixels match perfectly the linear resolution of the telescope and coupled with the dimensions of the camera allows to cover an area in the sky, the camera field of view, up to 10.4 degrees in diameter (8.4 in the prototype camera). Just for reference the full moon has a projected angular diameter on sky of 0.5 degrees.

The other original element of the camera is the way the Cherenkov signal produced by the interaction of a gamma ray with the atmosphere is detected and elaborated through the read-out electronics. This electronics is based on an integrated circuit (ASIC) that has been designed and realized specifically for this purpose through a collaboration between INAF and the French company Weeroc. The characteristics and the operating modes of the read-out electronics are thoroughly here described in the next paper by O. Catalano so here it will be enough to remind that acquisition of the pulse generated by the Cherenkov signal uses a method of signal integration rather the method of signal sampling generally used in this kind of applications. The method guarantees the same performance, but it has sev-

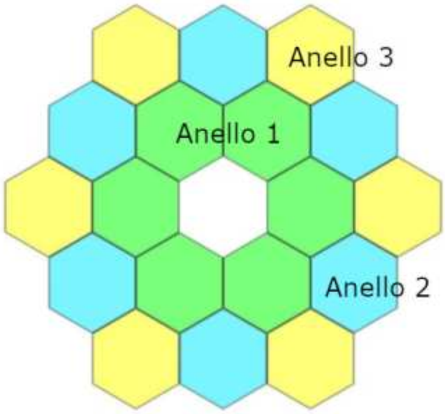

Fig. 6. The ring diagram for the primary mirror. The mirrors of the first ring are shown in green, second ring in light blue and third ring in yellow.

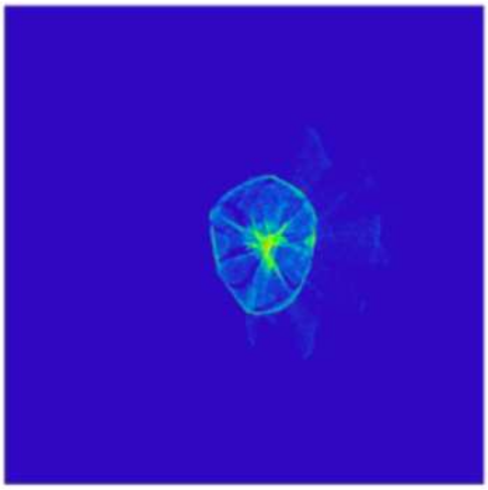

Fig. 7. Image of a point-like source obtained when all the primary mirror panels are aligned.

eral useful side effects in terms of data volume produced or electronics power needed by the camera. To conclude the short description of the Cherenkov camera characteristics we have to mention a particular operating mode called variance method. This operating mode allows the camera to obtain sky images as a normal digital photographic camera (Fig.4).

The images obtained using this method allow to measure the night sky background level but also to monitor the alignment of the mirrors and the pointing performance of the telescope.

4. The segmented mirror

The primary mirror (Fig.5) is segmented. In particular, it is made up by 18 panels arranged in three rings (Fig.6) each containing 6 panels/mirrors. The mirrors that make up the ring have identical optical characteristics that, in turn, differ from those of the mirrors of the other rings. Each panel is mounted on the structure of the telescope through triangular supports. One the vertex of these triangles is fixed while motors are mounted on the other two. These motors, called actuators, allows to tip/tilt the mirror. Moving appropriately the actuators it is possible to align among them the various mirrors so that the primary mirror will assume the shape requested by the optical design actually behaving like a monolithic mirror. Actuators allows also to keep the mirrors aligned and the shape of the primary mirror unchanged when environmental conditions (temperature or wind) or the mechanical characteristics of the telescope (flexures due to gravity) change.

When all mirrors are aligned the image produced by a point-like source as a star on a detector, also called Point Spread Function, has a very precise appearance (Fig.7). The reason for this is that each mirror produces a very specific image. For example, the mirror of the first ring, the inner one, produce six arcs to create a full circle (Fig.8).

The mirrors of the other rings produce geometrical images more complex but in the end each of them will contribute with its characteristics image to produce the final image (see again 8). It shall be noted that the shape of the image of a point-like source depends on its position on the telescope focal plane but, as we said before, the adopted optical design ensures that the total dimensions of the image do not vary going from the center to the edge of the field of view. As the image produced by each mirror has its characteristics signature, to align the mirrors will be enough to observe a star, recognize the images produces by the various

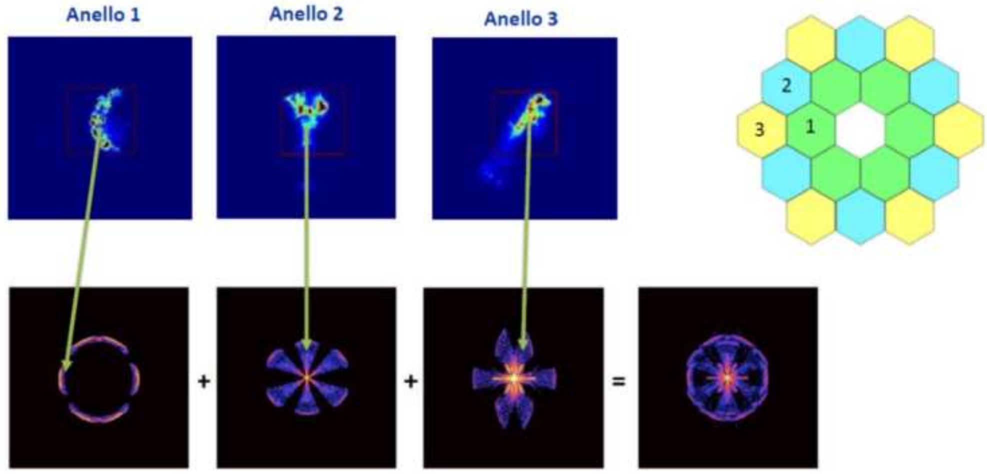

Fig. 8. Images of a point-like source produced by the mirrors belonging to the different rings. Top row, from left to right the image produced by a panel of ring 1, 2, 3 respectively. Bottom row, the combined images produced by the mirrors in the various rings and the final image. The images on the top raw are real images while those on the bottom are simulations.

mirrors (Fig.9), that is the mirrors themselves, and then move them through the actuators to produce the expected image (Fig.7).

The production technique of the panels of the ASTRI primary mirror is called cold slumping process and it is the one that has given the name to the project. The technology has been developed in sinergy by a group at the Brera Astronomical Observatory lead by Oberto Citterio and by an Italian company (Media Lario srl). The construction phases of the panels consists of the following steps:

1. An aluminum mould is machined until its shape reproduces the negative of the theoretical mirror design within the tolerances. For ASTRI-Horn, three different moulds were produced, one for each corona.

2. A pair of thin glass foils, typically 2 mm thick, and one honeycomb buffer layer made of aluminum are prepared by cutting them out from larger foils. The cutting operations can easily be done by using shape templates and cutters. The glass tiles are then carefully cleaned. heating caused by the coating process under vacuum.

3. The first glass foil is positioned, bent and fixed over the mould; then it is forced to adhere to the mould surface by vacuum suction. In this way, the shape of the mould is replicated.

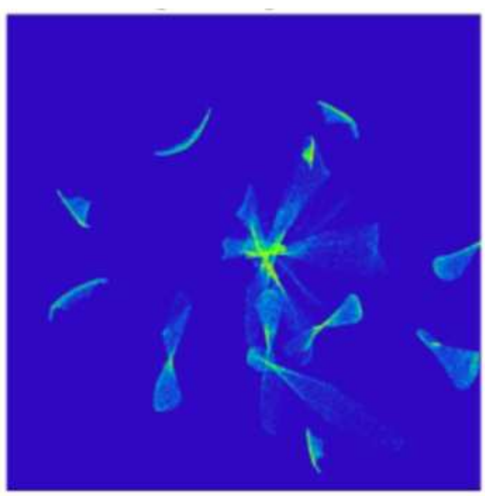

Fig. 9. Image of a point-like source obtained when the panels of the primary mirror are misaligned.

4. Afterwards the sandwich is assembled. The connection between the honeycomb sheet and the glass foils is achieved by bonding the three parts together with epoxy resin. The resin is made to polymerize through the use of a

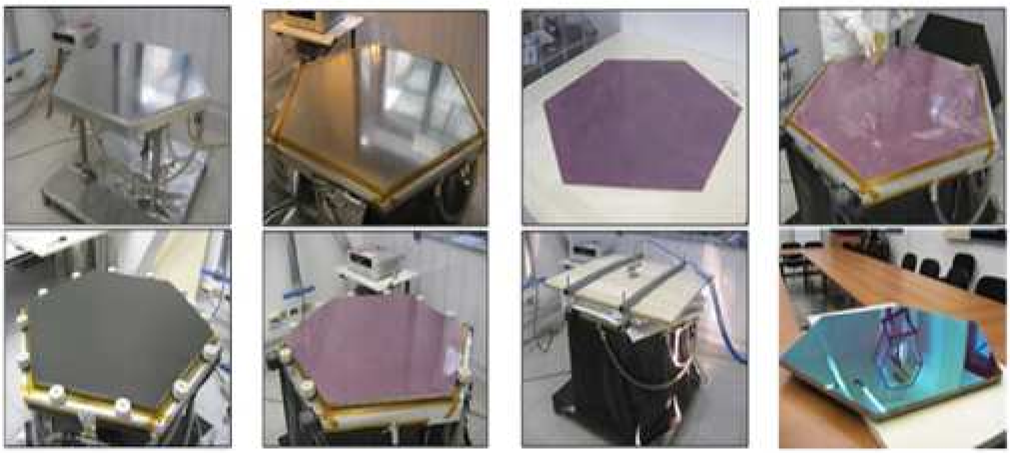

Fig. 10. The production process of the panels of the primary mirror.

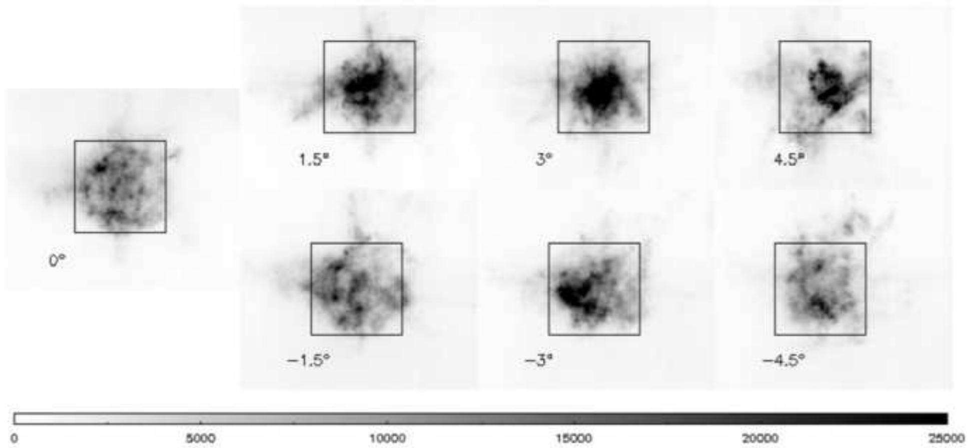

Fig. 11. Images (PSF) of a point-like source (Polaris star) obtained moving a CCD camera along the field of view of the ASTRI-Horn telescope.

proper curing cycle. Temperatures and timing play a key role in the resulting shape of the mirror, as well as the amount of glue.

5. Once the polymerization has taken place, the vacuum suction is stopped, and the sandwich is carefully released from the mould.

6. After a thorough cleaning of the front glass, the reflective coating is applied via an evaporation process (PVD, Physical Vapor Deposition). Methods and layers are chosen in accordance with the final use of the mirror. It is also worth mentioning that, since the glue keeps the sandwich together, attention must be paid to the

7. Finally, the interfaces with the supporting structure are fixed and the edges of the mirror are sealed. This solution also ensures high rigidity and mechanical protection of the mirror edges/corners.

Figure 10 10 shows the entire production process. The mould can be used several times making this technique very efficient for mirrors mass production. Furthermore, the mirror produced through this technique are very light (density is 15 kg/m2) with clear advantages for the mounting operations.

5. Characterization of the ASTRI-Horn Telescope

To conclude the description of the prototype telescope we show some of the results of the test accomplished to demonstrate its functionalities and to measure its performances

After the inauguration the telescope went through several technical tests to obtain the first optical light on May 2015 using a CCD camera placed at the telescope focal plane instead of the Cherenkov camera. In October 2016 the optical design was validated through a dedicated observational campaign. To do that it was necessary to measure the PSF produced by the mirrors as a function of its position on the field of view using a CCD camera that could be moved in various positions along the field of view. The results (Fig.11) showed that, as expected, the PSF does not change when moving in the field of view covered by the Cherenkov camera.

In December of 2016 the tests with the Cherenkov started and in May 2017 we had the first Cherenkov light that is the direct observation of a Cherenkov signal produced by the interaction of an energetic particle with the Earth's atmosphere. Currently, telescope and camera are busy with the observation of a gamma-ray source (Crab nebula).

6. Conclusion

We can conclude affirming that the ASTRI-Horn prototype telescope ended the first phase of its path, that of technological demonstrator, entering in the next phase where its scientific performance will be verified. The telescope will also be used as a training center for maintenance and operations and, beyond the science verification phase, as a test bench for the development of new hardware and software.

References

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