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Status and performance of the ASTRI-Horn dual mirror air-Cherenkov telescope after a major maintenance and refurbishment intervention

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The ASTRI-Horn telescope has been developed under the leadership of the Italian National Institute for Astrophysics (INAF) as a prototype of a compact aplanatic dual-mirror (4 m diameter) Imaging Atmospheric Cherenkov Telescope (IACT) with a large FoV (8°). It is the pathfinder of the small-size telescopes adopted for both the ASTRI Mini-Array (Tenerife, Canary Islands) and the SST/CTA array (Paranal, Chile) to perform 1-200 TeV gamma-ray astronomy with an unprecedented combination of high angular/energy resolution and flux sensitivity across a large Field of View. ASTRI-Horn is a complete end-to-end system; since 2014 it is installed in Italy at the INAF "M.G. Fracastoro" observing station (Mt. Etna, Sicily). The telescope already successfully demonstrated, first time ever, the optical behavior of a dual-mirror Schwarzschild-Couder telescope as a Cherenkov system, and also obtained the first gamma-ray source detection, the Crab Nebula. During 2020-2022, ASTRI-Horn - which operates in a harsh environment on an active volcano - has been subject to significant maintenance and refurbishment to restore systems and improve performance. Mirrors have been substituted, adopting high-performance new-recipe coatings, and the camera electronics has been further optimized. Now the telescope is extensively used for cosmic rays, gamma rays, and muon-radiography of the Etna volcano investigations.

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Figure 1: ASTRI-Horn telescope installed on Mt.Etna (Italy) at the INAF “M.G. Fracastoro" observing station.

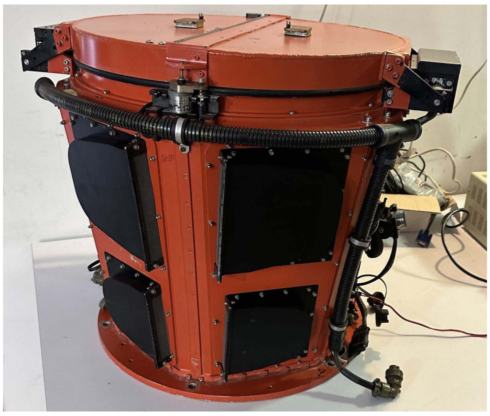

Figure 2: The ASTRI-Horn Cherenkov camera during pre-loading testing phase at the site.

1. Introduction

ASTRI-Horn is a Cherenkov dual mirror telescope studied and built by the Italian National Institute for Astrophysics (INAF) as an end-to-end prototype for the 4 meter class telescopes of the Cherenkov Telescope Array (CTA) Project [1] that are specifically designed to investigate the energy range between a few TeV and 200 TeV and more. ASTRI-Horn is based on a Schwarzschild Couder (SC) design adapted to be compliant with the CTA Small Sized Telescopes (SSTs) requirements; it’s primary mirror (M1) is 4.3 meters mirror in diameter and is composed of 18 segments that can be actuated to reach the correct positions and alignment; the secondary mirror (M2), instead, is a 1.8 meter monolithic mirror also equipped with actuators. ASTRI-Horn primary mirror segments were developed by INAF to fit both budget and optical requirements [2]. All reflecting surfaces were made by an Al layer and a protecting coating with the purpose to slow down the ageing of the surfaces and to reduce the reflecting efficiency loss over time. The SC design make the telescope very compact with a small plate scale that enabled the development of a compact Silicon PhotoMultiplier (SiPM) based camera with a Field of View (FoV) that can reach 10.5° in the current configuration. The camera has been developed and mainly built inside INAF laboratories and takes advantage of a number of innovative solutions [3].

The telescope has been installed at the INAF "M.G. Fracastoro" observing station also known as Serra La Nave (SLN for short), Italy, see fig. 1 [4]. After the needed commissioning, ASTRI-Horn was optically validated in 2017 [5]. Eventually during the observing season 2018-2019 ASTRI-Horn was able to make the detection of the reference γ ray source Crab Nebula with a statistical significance of 5.4 σ above an energy threshold of ~3 TeV in 12.4 h of on-axis observations [6].

2. ASTRI 2020-22 major intervention

Since the successful detection of the Crab Nebula, the telescope, after extensive tests, has proven to fulfil all technical objectives. One of these tests was the evaluation of the ageing on the

Figure 3: ASTRI-Horn at the INAF SLN station after the installation of the new 18 segments of M1.

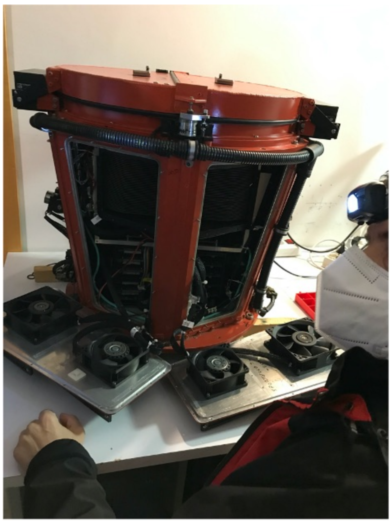

Figure 4: A moment during refurbishment of the ASTRI-Horn Cherenkov camera.

reflecting surfaces and over the entire telescope. In particular, the aim was to test the lifetime of the telescope subsystems that will be built within the ASTRI Mini-Array and CTAO projects in the search for solutions to increase the reliability and time durability. The fact that the telescope operates in harsh environment, close by the active craters on Etna, worked as an ageing accelerator. During 2020-2022 the telescope has undergone an extensive verification and refurbishment. Both mirrors were replaced with new ones and a new receipt was used for the primary mirror reflecting coating that allowed us to limit the transmission in the energy range where the diffuse night sky background flux is higher than the Cherenkov signal [7]. Fig. 3 shows ASTRI-Horn after the installation of the new tassels: a bluish reflection characterizes the new M1.

Relevant refurbishments involved also the Cherenkov camera (Fig. 4) together with a deep review of the camera and telescope control software [8].

3. Post refurbishing verification tests and results

After the M1 mirror alignment, the Point Spread Function (PSF) was measured and the radius that includes 80% of the detected light (R_{80}) turned out to be 3.89 mm, stable along all the FoV. Fig. 5 shows an example of the measured PSF. These results are in line with the ones relative to the previous configuration [5]. That results was not apriori granted being the coating receipt completely new and also the production process different from the the one used for the previous M1 segments.

After the measurements for the new pointing model, the telescope pointing capability was evaluated. We found that the pointing error does not exceed 6 arcmin before any additional correction using the Pointing Monitoring Camera (PMC). Since the Cherenkov camera pixel is 11.4 arcmin, it follows that the pointing of any source is assured within one pixel.

The Cherenkov camera underwent major refurbishment in laboratory; that led to a new set of calibrations both in laboratory and at the SLN site [9].

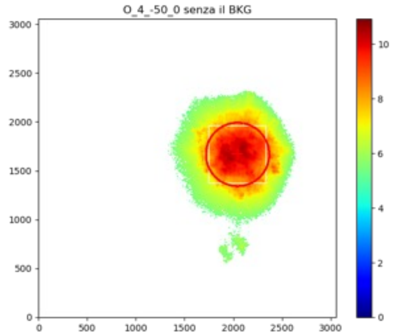

Figure 5: ASTRI-Horn example of PSF obtained after M1 and M2 substitution, alignment and collimation.

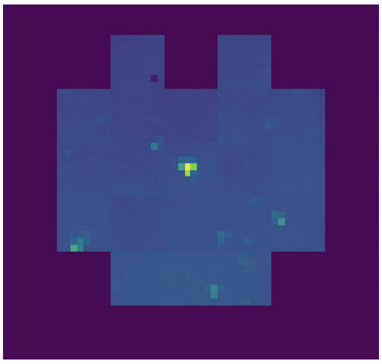

Figure 6: Example of $Variance$ image from the ASTRI-Horn Cherenkov camera at the end of refurbishment operations.

After the completion of the camera refurbishment, the new improved calibration procedure also includes the measure of the cross talk for each pixel see [10]. The stability of the pixels gain over time was measured and it turned out to be better than 1%. As a result of the reached stability, the $Variance$ image [11], that is also routinely produced during scientific acquisition, was so well calibrated that we were able to produce a reliable flat fielding procedure [9] enabling astrometrical measurements. That could be possible thank to the improved image quality, camera sensitivity, and to the large FoV (~8 deg) within which it is possible to find stars with magnitude up to 7.2, whose position can be easily traced on the image. We measured that, using a single image, the mean astrometry error does not exceed 4 arcmin. Fig. 6 shows one example of $Variance$, the image is also available to the on-duty operator within the camera Graphical User Interface (GUI) giving him/her the chance to monitor the observations with a glance.

$Variance$ images enabled us to evaluate also the tracking stability during observations; we found that, in a 30 minutes run, the tracking error remains within 4 arcmin. See [9] [12] (same conference papers) for further details.

3.1 Telescope performances from scientific data analysis

Scientific data, gathered during observations, together with Cherenkov showers contain also muon rings, see fig. 8 for a typical example of muon ring detection. From the analysis of the geometrical characteristics of the rings and of the light distribution along it, we derived relevant information about the telescope Optical Throughput (OT), that is the overall telescope efficiency. Analysing data from the observations performed after the telescope refurbishing, we find a significant improvement. In fact in 2022 data $OT_{2022} = (12.9 \pm 2.8)\,\%$ to be compared to $OT_{2018} = (8.5 \pm 2.4)\,\%$ in 2018 observations. The full method and details can be found in [13]. An independent analysis conducted with a different method (Catalano O., private communication), gave $OT_{2022} = 12.5\,\%$ and $OT_{2018} = 8.9\,\%$ confirming the previous figures.

Moreover, from the muon ring it is possible to estimate the Cherenkov telescope PSF. Since this method can be applied to all observing nights and being the amount of observed muons high, it has the advantage to give a measure of the PSF from a statistically significant sample. It can be

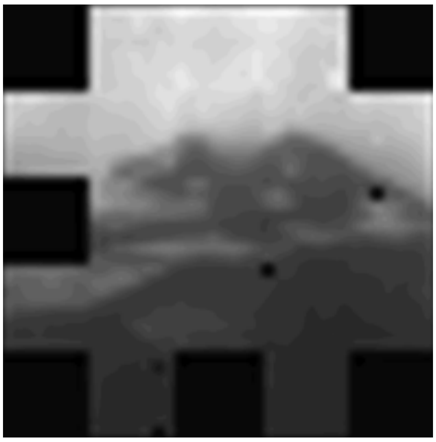

Figure 7: An image of the Etna South-East crater taken with the ASTRI-Horn Cherenkov camera. The crater profile and orography features are clearly visible together with clouds in the sky.

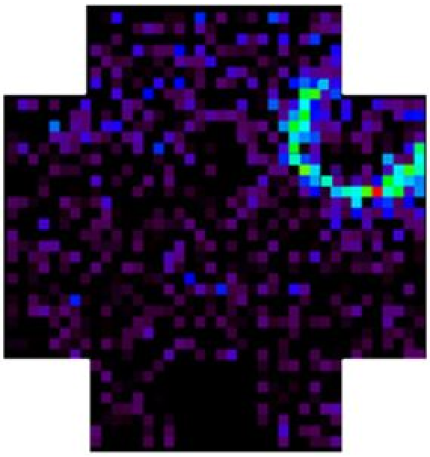

Figure 8: Example of image of a Muon ring.

also easily used to check the evolution of the PSF value over time. We compared data provided by both the previous ASTRI-Horn configuration and data after the recent refurbishment. Being the pixel of the Cherenkov camera 7x7 mm about 5.4 times the maximum pixel dimension allowed by Nyquist theorem to resolve the PSF, we do not expect to be able to obtain the same value obtained with optical camera whose pixel size is 0.07 mm well beyond the needed Nyquist condition. The value of R_{80} from muon rings detected in 2022 was R_{80}^{2022} =(6.0 ± 1.3) mm, the value obtained with a data set taken in 2018 was R_{80}^{2018} =(6.0 ± 0.9) mm, almost the same result.

Along with the other measurements, we obtain the width of the Pedestal (SP) in photoelectrons (pe) on images including muon rings. That measure is a direct estimation of the image background. Also in this case it was possible to compare data for the two different ASTRI-Horn configurations in 2022 and 2018 obtaining the following figures SP_{2022} =(2.35 ± 0.13) pe and SP_{2018} =(3.51 ± 0.24) pe. The results indicate that the mirror coating used in the new setup together with the optimized calibrations increased the efficiency of ASTRI-Horn.

4. Summary and conclusions

The recent refurbishment of the INAF ASTRI-Horn telescope was primarily meant to perform additional test on new M1 mirror coating and to learn how to reduce the ageing effects on the mirror having in mind the many telescopes that will be built for both ASTRI Mini-Array in Tenerife Canary Island and for CTA in Chile.

The results are very encouraging. In fact, after the refurbishment, the PSF measured on the images obtained with the Optical Camera confirms an R_{80} =3.89 mm that is quite similar to the first measurements done in 2017 when the primary mirror was coated with aluminum. Pointing and tracking were also checked and turned to be in line with previous results.

The overall reliability of the ASTRI-Horn in operation has also been increased thanks to the many improvements on camera and telescope hardware, and to the software debug that have reduced observing downtime.

The camera performance has been drastically increased due to hardware improvement and calibration measurement. The camera stability over time is improved so that the measured gain fluctuations are less than 1%. The improved performances enabled a multiple use of the $Variance$ data, previously impossible, that impact on both real time observing consciousness and data quality. As an example of the reached image quality in fig. 7 one $Variance$ image registered during a pointing toward the Etna South-Est crater is shown. Many orographical features are clearly recognizable together with smoke and clouds in the sky.

Using muon analysis we were also able to measure the R_{80} using the Cherenkov camera images for both configurations before and after the refurbishment. We found that they are equal within errors.

More important, we were able to estimate both Optical Throughput and the Pedestal width that gives us the background noise. The new configuration results to be more effective in OT by $\backsim$ 50% and also with lower background noise by $\backsim$ 35%, that is, we obtained an increase in gathering efficiency and, at the same time, a noise reduction.

All improvement here described are being also studied to be applied to the incoming ASTRI-MA and in the future CTA-SSTs. Details on the work in progress can be found in [14], [9], [10] at this conference.

Since October 2022 ASTRI-Horn has entered a new operation phase that is still in progress. Together with technical observations oriented to verify and develop the hardware and the software a few science cases have been identified. From ten to fifteen nights monthly, around the new moon, telescope observations are now aimed also to explore ASTRI-Horn effectiveness in studies on: cosmic rays, gamma rays, muon-radiography.

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