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From the Horn d'Arturo segmented telescope to the ASTRI-HORN end-to-end system: cutting-edge technologies and industrial involvement in astronomical instrumentation

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1. Introduction

The ASTRI telescope Pareschi (2016),Scuderi (2018), dedicated to Guido Horn d'Arturo, has been developed by INAF (the Italian National Institute of Astrophysics) with the support of the Italian Government as a prototype. It has been realized in the context of the research and development activities in view of the implementation of the Cherenkov Telescope Array Observatory Acharya et al. (2013) (CTAO, *https://www.cta-observatory.org*), the large observatory for ground gamma rays under construction with two sites in both the northern and southern hemispheres (in La Palma, Canary Islands, an Paranal, Chile, respectively). In particular, the ASTRI-HORN telescope represents a pathfinder for the array of up to 70 Small Size Telescopes (SSTs) of 4 meters that will be implemented at the Southern size of CTAO, whose realization realization represents a real technological challenge. Moreover, INAF will implement a mini-array of 9 ASTRI telescopes at the site of the Observatorio del Teide (Tenerife, Canary Islands) to make observations with unprecedented flux sensitivity and angular resolution in the northern hemisphere in the 10 - 100 TeV gamma-ray energy range (http://www.brera.inaf.it/ astri/wordpress/). It should be reminded that Guido Horn d'Arturo succeeded, after many years of from the initial conception Horn-D'Arturo (1936),Jacchia (1978), to build an innovative telescope based on a segmented primary mirror (in this respect, it should be noted unfortunately he was turned away from his research activity by the events of the second world war and, in particular, because of the racial laws imposed in Italy by the fascist government that directly struck him). The innovative segmented 1.8 m telescope was implemented by Horn d'Arturo in the fifties years of the past century at the Observatory of Bologna also thanks to the introduction a series of technological developments and advanced solutions for that time. In particular, Horn and his collaborators were able not only to fabricate reflecting segments using very advanced with modern super-polishing techniques but, in addition, they were able to found a correct mount with the use of actuators in order to optimize the reflective surface of the primary mirror and to mimic very well a continuous mirror surface.

The ASTRI-HORN telescope now represents the largest telescope on Italian soil and it is based upon a segmented (18 faced) primary mirror of 4 m diameter. Also in the case of the ASTRI-HORN telescope, a number of innovative solutions have been introduced to realize the structure, the mirrors and the detection camera, having in mind from the beginning of the project the need of optimizing the scientific return and costs. Moreover, for this prototype it has been followed a realization approach that will allow us to pursue in future an industrial production of many telescopes, since the system would be replicated in a large number of units to implement the ASTRI mini-array and the CTAO SST array. On the other hand, the telescope design is innovative in itself, being its configuration based on the idea of the great German astrophysicist Karl Schwarzschild (1873 - 1916), then consolidated by the French astronomer and opto-mechanical engineer André Couder (1897 -1979) for obtaining an "aplanatic" optical system (i.e. with constant angular resolution within the field of view) and a small platescale system. The configuration was proposed for the use in future Chrenkov telescope programs a few years ago Vassiliev (2007),Sironi (2017) because it allows to implement an aplanatic wide field focal plane with a small plate scale.

Furthermore, ASTRI-HORN also represents the first example of a two-mirror telescope used for astronomy with Cherenkov technique (so far only single-telescope have been used) not only completely developed but also fully proven with optical tests Giro (2017) and real gamma ray observations performed (with also the gamma-ray detection of the Crab nebula in the TeV energy region Lombardi et al. (2019)). For this purpose, an ad hoc Cherenkov camera has been developed by INAF based on SiPM sensors (Silicon Photo-multipliers) and adopting state-of-theart front-end electronics. To this end, INAF closely co-worked with private companies, in the tradition of developing large astronomical projects in very close collaboration with private industries. In addition to the scientific importance and the success of the realized instrumentation, this type of approach has brought important benefits in terms of economic development, has stimulated technological innovations (with spin-offs also in areas different than astronomy (for example in the field of biomedical devices o micro-electronics), also allowing the Italian astronomical community to play a leading role at international level. Among the examples of past highly successful projects (some of them also carried out the support of the Italian Space Agency), based on a close union with the industry one should certainly mention the Beppo-SAX satellite for X-ray astronomy (and the contributions given by Italy to the payload of the XMM and Swift space projects), the INTEGRAL and AGILE satellites for gamma-rays and, as far as the Earth projects are concerned, the development of adaptive optical technologies then adopted in LBT and VLT.

Hereafter it is given a short description of the various sub-systems implemented in the ASTRI-HORN telescope, also briefly reporting on the innovative aspects implemented with the support of to the different industries involved in the ASTRI project.

2. ASTRI-HORN telescope structure

The structure of the ASTRI-HORN telescope was designed in order to meet the scientific requirements and specifications of both the CTA and ASTRI mini-array projects Canestrari (2015). In this respect, a particularly demanding parameter was the need for the telescope structure to resist and remain operational even in the event of an intense earthquake (as expected in Chile) but still preserving the features of a good reliability, low costs and to be suited to perform easy preventive maintenance. Furthermore, it was very important to adopt highly reliable and precise electro-mechanical technologies and components, possibly already used in previous experiences. For this reasons, for making the structure we considered subsystems already used in former projects with the involvement of INAF and European industries, like e.g. the ESO ALMA and VLT projects such as or other international projects such as e.g. LBT.

The SST prototype development took place along two different phases. When the project started (2009), the Tomelleri srl of Verona and BCV Projects Italian companies were involved for pursuing the phase A study and to produce the preliminary design and analysis. Subsequently, the project was refined and consolidated up to an executive level and implementation by the GEC industrial consortium (formed by the two Italian companies Galbiati Group and EIE). The GEC consortium also oversaw the implementation of the prototype under the supervision of INAF, while BCV Progetti designed the foundations of the telescopes at the Serra La Nave site on the Etna Mount slope. An important collaboration with the local authorities in the area around Mount Etna (municipalities of Nicolosi and Ragalna, State Forestry Corp, Etna Regional Park) allowed us to perform a rapid installation of the telescope that was inaugurated in September 2014. By means of the prototype it was possible to better study the system in view of a finalization of the definitive design of the telescopes for ASTRI mini-array and CTAO-SST programs.

The telescope structure can be separated into two main elements: the Base and the Azimuthal Fork. The Base, thanks to its conical shape, allows the foundation to be adequately connected to the Azimuth bearing used for the azimuthal rotation of the telescope, guaranteeing the best compromise between structural weight and performance. It also provides access, through a specific door, to the delicate subsystems contained within the telescope. The Azimuth fork, is one of the most important structural elements and is also fundamental to provide support to most of the other sub-systems.

The support structure for the optics (consisting of the primary and secondary mirrors) rotates entirely around the elevation axis. The concept adopted for the design of the structure originates from the idea that all the optical elements are sufficiently stable to allow observations within the requirements of both the ASTRI mini-array and CTA SST array. In particular, since the Schwarzschild-Couder optical layout includes a primary and a secondary mirror for conveying the optical beam into the Cherenkov camera, the interfaces for each of these elements must be stable in every configuration of the elevation angle.

The result is a very robust structure, which allows us to rely on a remarkable pointing stability (with a reconstructed accuracy <7 arc seconds), a rapid repositioning (within one minute all the positions in the sky are reachable independently of the previous position of the telescope). Moreover, the high rigidity ensures a high reliability and, for example, the mirrors, once aligned with the actuators, remain in the correct position for months without the need for re-alignment.

2.1. The Primary Mirror

The primary mirror of ASTRI-HORN Canestrari (2015) consists of 18 pseudo-hexagonal tiles - similar to the configuration of the tessellated mirror of the first Horn telescope - with a maximum linear dimension of 80 cm and an areal density of about 10 kg/m^2. These segments are divided into three coronas, each based on 6 identical segments, which allow us to mimic a highly aspheric monolithic surface of about 4 m in diameter. The mirrors have a sandwich structure, with an aluminium honeycomb central part (“core”) that separates two sheets of glass (the outer part of one of the two sheets represents the reflective surface). Thanks to their low weight, the mirror tiles are particularly easy to handle, while maintaining an angular resolution of a few minutes of arc (i.e. within the requirements of both astir mini-array and CTAO). The realization technique, based on the "cold" replication of the mirror surface starting from a convex master, was developed within a joint development activity carried out in close collaboration by INAF and the Italian company Media Lario (Lecco), a partner with a long heritage programs developed together with INAF and ASI (many scientific projects have been carried out starting from the replicated grazing incidence mirrors for the BEPPO-SAX, XMM and Swift X-ray satellites up to the panels for the ALMA antennas for astronomy at millimetric wavelengths). The reflective coating (a two-layer film of Aluminium + Quartz, the latter applied for protective purposes) were deposited by Joule effect evaporation at the company ZAOT (Milano, Italy), that was also previously involved several times in the implementation of past INAF projects (for example for the realization of the bi-reflective mirror used from the REM robotic telescope and for the mirrors of the MAGIC Cherenkov telescopes).

2.2. The Secondary Mirror

The secondary mirror Rodighiero (2016) of about two meters in diameter is monolithic and highly aspheric. The mirror profile was therefore obtained by hot forming at the Flabeg German company, while the application of the reflective coating and of the supporting structures were carried out by ZAOT and Media Lario respectively.

3. The ASTRI Camera

Also the ASTRI camera Catalano (2018) presents a number of innovative aspects. Thanks to the optical design of the telescope, it is very compact and, in particular, the curved focal plane is covered with small (7 mm x 7 mm pixels) SiPM (Silicon Photo Multiplier) sensors Bonanno et al. (2016), new devices that are going to rapidly replace the large size photomultipliers used so far. The camera also makes use of last generation electronic front-end devices, including the Citiroc ASIC "peak-finder" chip developed by the French company Weeroc in collaboration with INAF Impiombato et al. (2015). The ASTRI camera is very compact camera, with an aperture of 60 cm and a mass of just 70 kg. It is much smaller an lighter compared to the much larger (up tp a couple of meters) and more massive cameras (up to a couple of tons) based on photomultipliers used so far for single-reflection Cherenkov telescopes. It has been specifically studied and designed to fit the curved focal plan of the ASTRI double-mirror telescope, covering a wide field of view, equal to about 100 square degrees, that is about 400 times the apparent surface of the full moon. The signals are read at very high speed, some tens of nonoseconds, in order to reconstruct the structure and follow - observing the Cherenkov light - the rapid evolution of the shower of particles generated at about 10 km from the soil. The prototype camera was developed entirely by INAF, especially in the INAF Institutes of Palermo and Catania, but also with the support by a series of Italian companies including Novasis Ingegneria (Limbiate, Milan, that designed and produced the "Voltage Distribution Box", VDB), and the Mindway Design company (Settimo Milanese, Italy) which contributed to the development and implementation of the front-end and back-end electronic boards. Moreover, Hamamatsu Italia supplied the SiPM sensors while Thermacore Italia developed the thermal control system.

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