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The Italian ASTRI program: an end-to-end dual-mirror telescope prototype for Cherenkov light imaging above few TeV.

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Abstract: ASTRI (Astrofisica con Specchi a Tecnologia Replicante Italiana) is a flagship project of the Italian Ministry of Education, University and Research related to the next generation IACT (Imaging Atmospheric Cherenkov Telescope), within the framework of the CTA International Observatory. In this context, INAF (Italian National Institute of Astrophysics) is currently developing a scientific and technological breakthrough to allow the study of the uppermost end of the VHE domain (a few TeV - hundreds of TeV). The ASTRI project timeframe is of about 3 years, and foresees the full development, installation and calibration of a Small Size class Telescope prototype compliant with the requirements of the High Energy array of CTA. The ASTRI prototype will adopt an aplanatic, wide field, double reflection optical layout in a Schwarzschild-Couder configuration. Moreover, the focal plane instrument will explore small pixelated detector sensors such as multi-anode PMTs or Silicon PM. Among the number of technological challenges, this telescope will be the very first instrument implementing both the Schwarzschild-Couder optical configuration and the double reflection for air Cherenkov imaging. In this paper we describe the status of the project, and we present the results obtained so far among the different technological developments.

Keywords: Imaging Atmospheric Cherenkov Telescope, CTA, gamma-rays, wide field aplanatic telescope.

1 The ASTRI program

ASTRI (Astrofisica con Specchi a Tecnologia Replicante Italiana) is a Italian *flag* project financed by the Ministry of Education, University and Research (MIUR) to develop special technologies suitable for the CTA project. ASTRI was submitted in Spring 2010 by INAF for a three-year Research and Development period almost simultaneous with the CTA Preparatory Phase (2011−2013), and selected in Fall 2010 by MIUR for a 8 MEuro total budget. The technologies, studies, and components produced within the ASTRI program will be carried out to address the problematics for the CTA implementation [1]. The ASTRI first-year allocated budget (3 MEuro) will cover:
− the realization of a small-size, dual-mirror telescope end-to-end prototype (SST-2M);
− the design of the mechanical structure and the prototyping of the critical components of a single-mirror small-size telescope (SST-1M);
− the design, development and manufacturing of part of the mirror facets for the SST-1M;
− the design, development and manufacturing of part of the mirror facets for a Medium Size Telescope developed within the CTA Preparatory Phase;
− the support to all the INAF CTA activities necessary for the finalization of the technological aspects, such as the completion of the scientific requirements, the Monte Carlo simulation, and the data handling.
As far as the dual-mirror prototype is concerned, ASTRI will cover studies on the telescope mirrors based on the replica technique, the mechanical mount for the telescope, and the sensors and electronics for the camera.

2 The dual-mirror prototype

The main goal of the ASTRI Program is the design, realization and operation of a 4-m class, dual-mirror, small-size telescope end-to-end prototype, with a wide field of view, and with a camera based on monolithic MPPC array. The dual-mirror end-to-end prototype will have a wide energy range, from a few TeV up to > 100 TeV.
The Schwarzschild-Couder (SC) optical design is a novelty in the Cherenkov telescope for very high-energy physics [2]. The aspherical primary and secondary mirrors designs present challenging aspects with respect to currently available technologies, in particular concerning the tight cost requirements imposed by the CTA project. The camera, based on innovative silicon photo-multiplier ar-

rays, can open a new path for wide field of view Cherenkov telescopes .

A detailed and on-site end-to-end calibration and operation of the prototype, acquiring and managing data from celestial sources, is the final step of the ASTRI program.

2.1 The optical layout

The proposed layout [3] intends to be fully compliant with the requirements of the telescopes composing the SST array of the CTA Observatory. In particular, the pixel size ($\approx 0.2°$), the large field of view ($8°-10°$) and the effective area (enough to trigger at $1 - 3\,\mathrm{TeV}$) as suggested by preliminary Monte Carlo simulations. Moreover, this design has been optimized taking into account also a realistic way to implement the telescope, such as the segmentation of the primary mirror M1 and the arrangement of detection units into the detector.

The SC optical system is shown in Figure 1 (top panel). It has a focal ratio F# of 0.5, a plate scale of 37.5 mm/°, a pixel size of approximately 0.16° and an equivalent focal length of 2150 mm. This setup delivers an usable field of view up to 9.6° in diameter as shown by the enclosed energy curves plotted in Figure 1 (bottom panel).

Concerning the throughput we achieve a mean value of the effective area of about 6.5 m^2, taking into account: the segmentation of the primary mirror, the obscuration of the secondary mirror, the obscuration of the detector, the reflectivity of the optical surfaces as function of the energy and incident angle, the losses due to the detector's protection window and finally the efficiency of the detector as function of the incident angles (ranging from 25° to 72°). In Table 1 we summarize the geometry of the optical system: the telescope results compact having M1 of 4 m and the primary-to-secondary distance of 3 m.

Surface	Dimension	Radius of Curvature	Distance to...
M1	$4306\,mm$	$-8223\,mm$	M2: $3108\,mm$
M2	$1800\,mm$	$2180\,mm$	DET: $520\,mm$
DET	$360\,mm$	$1000\,mm$	–

Table 1: Geometry of the optical system.

2.2 Telescope structure and drive system: preliminary design

The optical layout described in section 2.1 will be implemented by means of a telescope structure composed by primary and secondary mirrors cells, a pillar and counterweights, the drives systems and a suitable detector interface. The telescope mount exploits the classical alt-azimuthal configuration, as shown in Figure 2. The pillar is composed by two coaxial and concentric stainless steel pipes with proper wall thickness. The inner one is directly connected with two ball bearings axially preloaded (one on top and the other on the bottom) that sustain the total weight of the telescope. The azimuthal drive system is composed by two torque motors with pinions coupled to the rim gear directly applied to the inner pipe. The backlash is reduced by differential torque preloading. Finally, angular encoder with suitable accuracy and resolution are directly coupled to the axis.

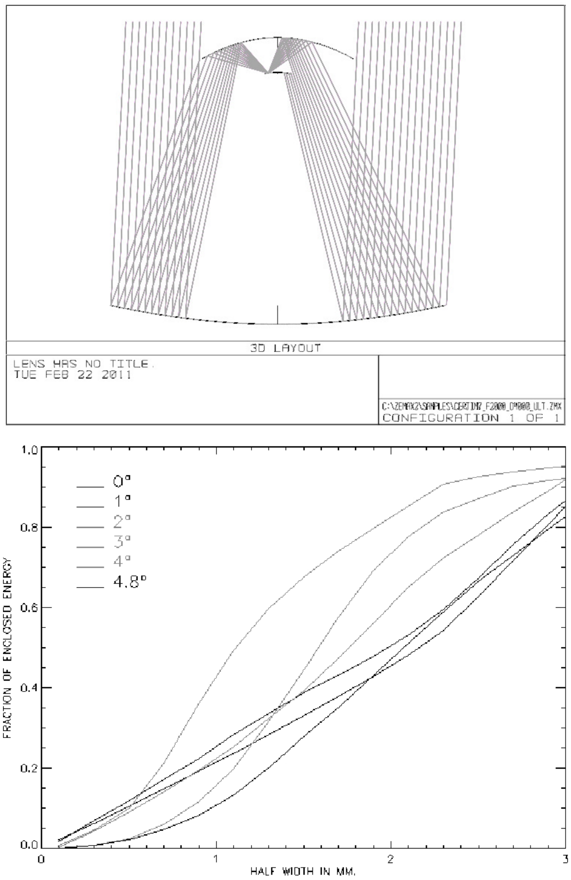

Figure 1: (top panel) The Schwarzschild-Couder optical layout adopted for the ASTRI end-to-end prototype. (bottom panel) Fraction of the enclosed energy for various field angles.

The pillar and the primary mirror cell joint in three points in order to have an isostatic support. One point is the connection with the drive system: an axial actuator made of a ball screw with double preloaded bushings and moved by means of a low-backlash motorized gearbox. The joint is done with preloaded tapered roller bearings. The remaining two joints form the elevation bearing system. It is composed of two lateral shafts supported by two couples of radial tapered roller bearings. The angular encoders are directly coupled to the elevation axes so to increase the accuracy in the pointing.

The secondary mirror cell and detector interface will be sustained by a mast structure designed to confer the requested rigidity to the structure because it is not foreseen the use of an active control of the mirror panels misalignment with the pointing orientation.

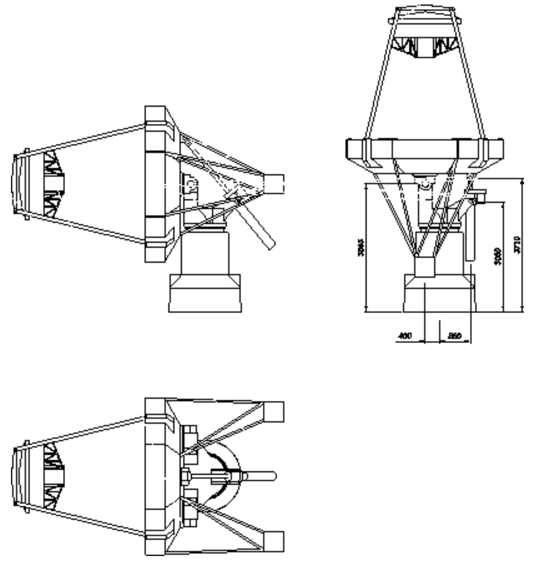

Figure 2: Preliminary mechanical layout of the ASTRI dual-mirror end-to-end prototype.

2.3 The challenge of the reflecting surfaces

The mirror surfaces are aspherical and can be described with the classical polynomial equation used in optics:

$$z = \frac{cr^2}{1+\sqrt{1-(1+k)c^2r^2}} + \sum \alpha_i r^{2i}$$

where z is the surface profile, c the curvature, r the radial coordinate, k the conical constant and α_i are the coefficients of the asphere. Both the reflecting surfaces, even if tasseled, have strong built-in deviations from the classical spherical profile usually adopted by the mirror facets of the Davies-Cotton configuration. Figure 3 shows for M1 (top panel) and M2 (bottom panel) the profiles of the two mirrors surfaces, their best spheres and related residuals.

2.3.1 The primary mirror, M1

The primary mirror is segmented into 18 tiles; the central one is not used because completely obstructed by the secondary mirror. The segmentation requires three types of segments having different surface profiles. The segments have hexagonal shape with an aperture of 849 mm face-to-face. There is a gap of 9 mm between a panel and the next one for mounting and alignment purposes. Each segment will be equipped with two actuators plus one fixed point for alignment. Only tilt misplacements will be corrected; piston correction will not be available for the primary mirror segments.

2.3.2 The secondary mirror, M2

The secondary mirror is monolithic and equipped with three actuators. The implementation of the third actuator makes available also the piston/focus adjustment for the entire optical system. Despite known technical difficulties in manufacturing of large aspherical mirrors we intend to pursue this way because of a number of clear advantages. As an example, it will be possible to implement a simpler and lighter mechanical structure, the use of less actuators and avoiding a non-trivial alignment system for double-segmented surfaces. These should lead also to a reduction of the costs. Moreover, it is important to remind that it is not requested to follow the design prescriptions with optics precision.

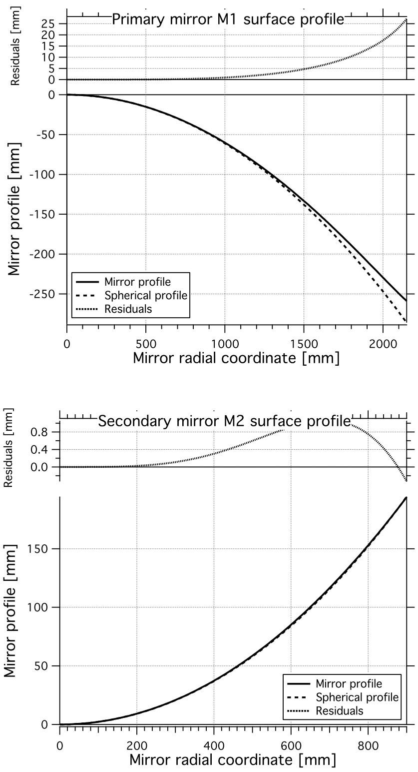

Figure 3: Radial profiles of the primary M1 (top panel) and secondary M2 (bottom panel) mirrors, and deviations from sphere.

2.3.3 The mirror manufacturing technology

The manufacturing technology should be able to provide mirrors compliant with the desired optical performance together with lightweightness, robustness and economicity. These characteristics are particularly important when a project, such as CTA, foresees the implementation of a large number of identical telescopes and where reliability is essential to increase the duty cycle of the array. For such reasons we think that manufacturing technologies that exploit the concept of replication of a master shape are best suited.

A recent project at the INAF-Osservatorio Astronomico di Brera was dedicated to a manufacturing process optimized for large spherical mirror facets for IACT. The process is called cold-glass slumping [4]. It has been adopted at the worlds largest Cherenkov telescope: the 17 m MAGIC II telescope [5].

The chosen substrate has a sandwich-type mechanical structure that confers stiffness and low areal density. A thin glass sheet is bent and is made to adhere to a mold having a highly precise shape. The complete panel is assembled by gluing a reinforcing core structure and a second thin glass sheet. After the glue is polymerized, the panel can be released and properly coated. The coating provides adequate reflectivity and protection against reflectivity losses and scratches.

Limitations in the surface profiles achievable, particularly the short radii of curvature needed for the SC layout presented above, are emerging. To overcome them, we are implementing a thermal shaping of the glass sheets before the cold-glass slumping process. Heating the glass can become soft enough to easily accept modeling. This makes it possible to impose the required surface profile, even a very curved one.

Some preliminary mirrors have been realized as we look mainly for a reduction in the radius of curvature. A segment having a spherical concave profile of 5 m has been produced and tested in our labs, achieving promising results and demonstrating the feasibility of this approach [6]. The next step will be to add the aspherical contribution to the main spherical profile. If this test is successful, it could prove that this modification of the cold-glass slumping technology can be adopted for SC Cherenkov telescopes.

2.4 The focal surface instrument

The advantage of adopting a SC optical configuration consists in shrinking the focal surface, that in the current design is of about 360 mm × 360 mm, maintaining the optical properties within the requirements imposed by the CTA project. Such small detection surface, in turn, requires a spatial segmentation of a few square millimeters to be compliant with the imaging resolving angular size (pixel size). Among the commercially available light sensors that offer photon detection sensitivity in the $300 - 700$ nm band, a fast temporal response and a suitable pixel size, the Silicon Photomultipliers (SiPM) Hamamatsu S11828-3344M [7], was selected as the baseline focal surface detector. The Hamamatsu MAPMT H10966 [8] provides the backup solution. About 1984 channels (pixel size of about 6 mm) are foreseen for covering the full field of view. The large number of channels imposes a compact and modular design of the focal surface in order to make minimum the distance between SiPM modules as well as the distance from the front-end electronics. The focal surface will be tiled into 31 independent Photon Detection Modules (PDM) (see Figure 4). Each PDM is formed by 16 SiPM modules (8×8 pixels) electrically interfaced to the front-end electronics and mechanically interfaced to the supporting focal surface structure. Each one is tilted in a suitable way with respect to the optical axis in order to fit the curvature of the focal surface. An intensive work is in progress to model the camera in all its relevant aspects. A 3D mechanical model will be soon available. Implementation of simulation tools aiming to assess the telescope design end-to-end are in advanced phase. In parallel SiPM characterization is also started.

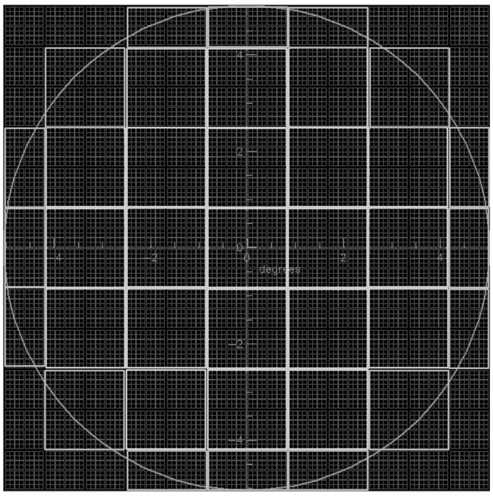

Figure 4: The detector assembly layout. The circle encloses 9.6° of corrected field of view.

3 Conclusions

We introduced the ASTRI project, the main activities, its funding and timeframe. A particular attention has been posed on the development, construction and operations of an end-to-end prototype compliant with the needs and requirements of the future CTA Observatory. Fully designed and developed in Italy by INAF, this telescope will be a pioneering instrument for the VHE γ-astronomy, exploiting a very wide field of view, innovative SiPM detectors and optical layout. The scientific impact of an array composed by a number of such instruments promise to be significant.

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