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An overview on mirrors for Cherenkov telescopes manufactured by glass cold-shaping technology

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ABSTRACT

The cold glass-slumping technique is a low cost processing developed at INAF-Osservatorio Astronomico di Brera for the manufacturing of mirrors for Cherenkov telescopes. This technology is based on the shaping of thin glass foils by means of bending at room temperature. The glass foils are thus assembled into a sandwich structure for retaining the imposed shape by the use of a honeycomb core. The mirrors so manufactured employ commercial off-the-shelf materials thus allowing a competitive cost and production time. They show very low weight, rigidity and environmental robustness.

In this contribution we give an overview on the most recent results achieved from the adoption of the cold-shaping technology to different projects of Cherenkov telescopes. We show the variety of optical shapes implemented ranging from those spherical with long radius of curvature up to the most curved free form ones.

Keywords: Imaging Atmospheric Cherenkov Telescope, segmented optics, glass slumping, glass, technology, optical fabrication, mirrors, free form

1. INTRODUCTION

Imaging Atmospheric Cherenkov Technique has made ground-based γ-ray astronomy possible. Scientific discoveries have been pioneered starting from the late 1980's by instruments such Whipple and HEGRA. Those experiments have shown, for instance, that TeV emission takes place in the Crab Nebula as well as in extragalactic sources such as Mkr 421. Ground-based very-high energy astronomy have shown that the GeV–TeV energy band is crucial to investigate the physics found in remote cosmic objects as well as to testing fundamental physics. Since early 2000's a new generation of instruments has begun operations and the number of sources in the gamma-ray sky started to rapidly increase. As today, more than 150 objects have been catalogued [1]. Now VERITAS [2], HESS [3] and MAGIC [4] represent the state of the art; these instruments also growth in complexity and dimensions. Consequently, the associated technologies for their deployment need to be specifically developed. For instance, since they are arrays composed by some telescopes, the technologies adopted for the production of the mirrors have to be somehow different from those adopted so far. In fact, these instruments require about 500-1000 m^2 of reflecting surface divided into several hundreds of individual mirror segments. Suitable technologies that guarantee a mass production of mirrors within the requirements are mandatory.

Furthermore, the international TeV astrophysics community is moving towards a newer generation of Cherenkov telescopes. Both in Europe, USA, South America, South Africa and Japan a number of Agencies and a large consortium of Institutes support the implementation of the Cherenkov Telescope Array (CTA) observatory [5]. CTA is the largest instrument for γ-ray astronomy ever conceived. It consists of an extended array of about hundred of telescopes of

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different sizes deployed over two sites. It provides global coverage of the sky: from the Southern site a detailed exploration of the Galactic plane and of the extragalactic sky will be possible; while the Northern site will be mainly devoted to the study of extragalactic sources. CTA will be implemented with a small number of Large Size Telescopes (LST) of 23 m in diameter (4+4 units for the North and the South) and a larger number of Medium Size Telescopes (MST) of 12 m in diameter (15+25 units for the North and the South). Moreover the Southern site will include also 70 units of Small Size Telescopes (SST) of 4 m in diameter and up to 36 Schwarzschild-Couder Telescopes (SCT) of 9.5 m diameter. Hence, the quest for the manufacturing of the mirrors is unprecedented. Several thousands of pieces are required. However, the requirement in terms of angular resolution is more relaxed compared to those for optical telescopes, but the mirrors are permanently exposed to the environment because domes do not protect the Cherenkov telescopes. The goal is to design and develop lightweight, robust, reliable and low-cost mirrors of 1-2 m size with adequate reflectivity and focusing performance, but demanding limited maintenance. Typically, a point spread function below some arc-minutes is acceptable.

In the framework of Cherenkov telescope, INAF-Osservatorio Astronomico di Brera (INAF-OAB) has jointly developed with the Media Lario Technologies company (www.media-lario.com) a manufacturing technology for mirrors. It is applied to a number of use cases of both present and future projects. In particular for MAGIC I and II, MST, SCT, SST-1M and ASTRI SST-2M. In the following sections some of these are briefly described.

2. THE COLD-SHAPING TECHNOLOGY

The cold-shaping (CS) technology is a replication-based technique, capable of mass production, for the manufacturing of mirrors for astronomical application. This process is very effective in reducing both cost and production time, but keeping the quality of the products within the requirement. The CS technique has been developed by the Media Lario Technologies company in collaboration with the INAF-OAB [7]. Both subjects, with the goal of addressing specific cases, have later conducted further studies and developments independently.

The main steps of the technology are conceptually sketched in Figure 1 and described hereafter. The mold is machined to the negative profile of that desired for the mirror. Then, a thin glass foil is bent over it by means of a vacuum suction until it adheres to the mold surface. A sandwich-like structural configuration is implemented using aluminum honeycomb as reinforcing core and a second glass skin. Epoxy glue, cured with proper temperature and timing, is used to keep the sandwich together. As soon as the polymerization of the glue finishes the vacuum suction is released. After the coating of the optical surface, the mirror is finished by sealing its edges and by the application of the mechanical interfaces. The mold can be reused to produce hundreds replicas without suffering evident surface deterioration.

Since this process occurs at room temperature without softening the glass, some limitations on the surface profiles of the mirrors are present. In fact, the elasticity of glass is the working principle of this technique and the glass retains the tensile stresses resulting from the bending. However, this mechanical structure is characterized by high rigidity and low areal density. Details on this aspect and other effects given by the operative loads on the mirrors are presented in [8].

For the case of the mirrors for the Cherenkov telescopes all the materials used are off-the-shelf, including both the glass foils and the honeycomb sheets. This was possible because of the relaxed optical requirements of the Cherenkov telescopes thus we have given priority to the cost and production time with respect to the best optical shape achievable; however, despite the quite simple approach, the CS technology can be used also for higher quality mirrors as shown in [9]. The replication mold is the sole component specifically manufactured to the design required by the optical layout of the mirrors to be produced. But since the CS process is not going to replicate the micro-roughness, the mold can be made out of metal (*e.g.*, aluminum or steel) through conventional turning/milling machining.

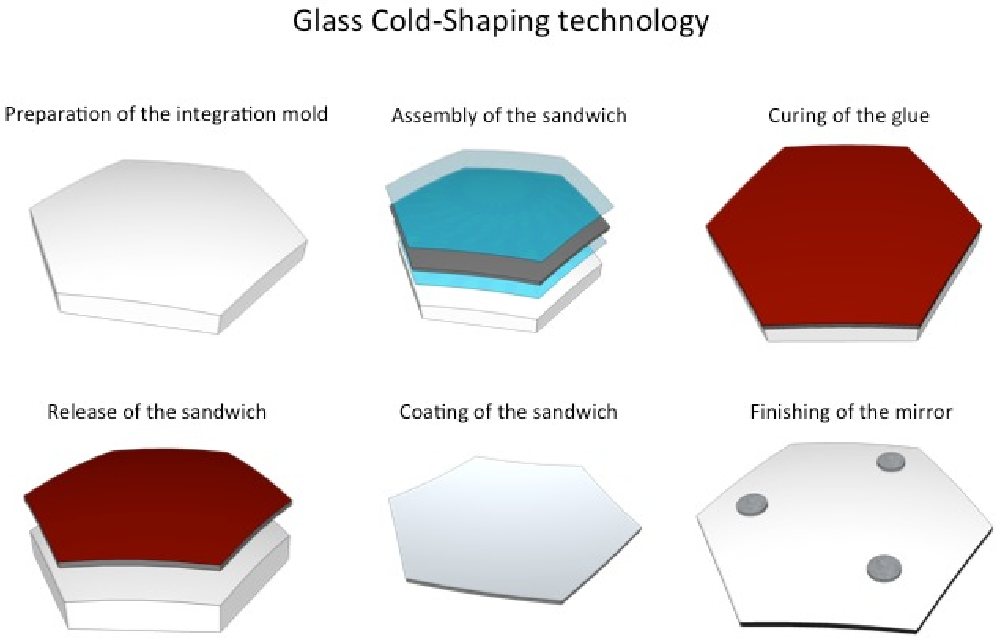

Figure 1 Main steps for the cold-shaping technology. The sandwich structural configuration is implemented with a honeycomb core a few cm thick and skins made by glass foils kept together with epoxy resin.

3. SPHERICAL MIRRORS FOR CHERENKOV TELESCOPES – LONG AND SHORT RADII OF CURVATURE

The reflectors of the Cherenkov telescopes are usually segmented into individual mirrors. Spherical mirrors are the most used type. This is due to the optical layouts generally adopted (in fact most current instruments use either a parabolic layout or Davies-Cotton one) and because of the modest angular resolution requirement; up to now the Cherenkov telescopes are single-reflection instruments with angular dimension of the pixels on the sky of the order of 2-4 mrad. The typical figure of merit used to evaluate the angular resolution is the diameter containing the 80% of the focused energy of the point spread function (D80). As a rule of thumb the D80 has to be maintained below 1-1.5 mrad (depending on the optical parameter of each telescope). In the following we present some examples of the application of the CS technology.

MAGIC is a very-high-energy experiment sited at the Observatory of the Roque de Los Muchachos in La Palma, Canary Island. MAGIC is composed of two telescopes of 17 meters aperture and f/D = 1. The optical layout implemented by the MAGIC telescopes is a single dish with a parabolic profile. This ensures to keep isochronous the arrival time of the photons emitted by the Cherenkov shower (despite the large aperture) while maintaining within an acceptable level the off-axis point spread function. Each telescope has 236 mirror segments mounted on a dish made of a lattice frame of carbon fiber beams. The mirrors have an active control to keep them properly aligned and all together they form the parabolic shape. Each mirror, 1 meter in side and square in shape, has a spherical profile that ranges from 33.8 m to 36.3 m, which varies with the radial position in the dish to approximate the parabolic shape of the global reflector. The MAGIC experiment is run by a collaboration of research institutes in several Countries, such as Germany, Spain, Italy, Switzerland, Japan and others.

Late in 2008 a first batch of 112 mirrors were manufactured to complete the reflecting surface of the MAGIC-II telescope [10]. In particular 104 mirrors were mounted on the telescope dish and 8 more were spares. More recently, in 2014, 72 additional mirrors have been manufactured in order to replace degraded mirrors on both the telescopes. In particular 62 were mounted on MAGIC-I and the remaining 10 on MAGIC-II. The manufacturing and optical characterization activities were carried out in synergy between Media Lario Technologies and INAF-OAB; while INAF-OAB has taken the full responsibility for the installation.

From a technical point of view, once the technology has been set, the manufacturing of the mirrors within the requirements was not a major problem. However, to minimize the number of different molds needed to cope with the different radii of curvature of the mirrors, we decided to take advantage of an aspect of the technology itself. When the vacuum suction is stopped the spring back effect is expected because the glass foils and the honeycomb are elastically deformed. The spring back phenomenon can be tuned by a careful distribution of the glue between the two glass skins. In this way, we have obtained a controlled spread in the radius of curvature of the mirrors at the expense of a slightly worse shape accuracy. Figure 2 shows the results achieved with the two manufacturing campaigns conducted respectively in 2008 and 2014. From the top raw it is possible to appreciate the large spread in the radii of curvature achieved simply using a total of three different molds having radii of 35 m, 36.3 m and 36.6 m. From the histograms in the bottom raw it is possible to see that the optical requirement of D80 < 1 mrad was largely met by the entire set of 184 mirrors. Typical errors maps for the molds and of the replicated mirrors are shown in Figure 3. The measurements have been taken with a coordinate measuring machine sampling the entire surface with steps of 5 cm. The molds show errors from the best fitting sphere of the order of 4-6 µm rms; while the mirrors have about 10-15 µm rms.

From a management point of view, we had to establish a well-controlled pipeline between different industrial providers to ensure the best production yield and quality standards. In particular, the coating of the mirrors was done by the ZAOT s.r.l. company while the manufacturing of the mechanical interfaces and of the replication molds were provided by Dell'Oro Romano s.r.l. and LT Ultra-Precision Technology GmbH. The global yield has reached the 97%.

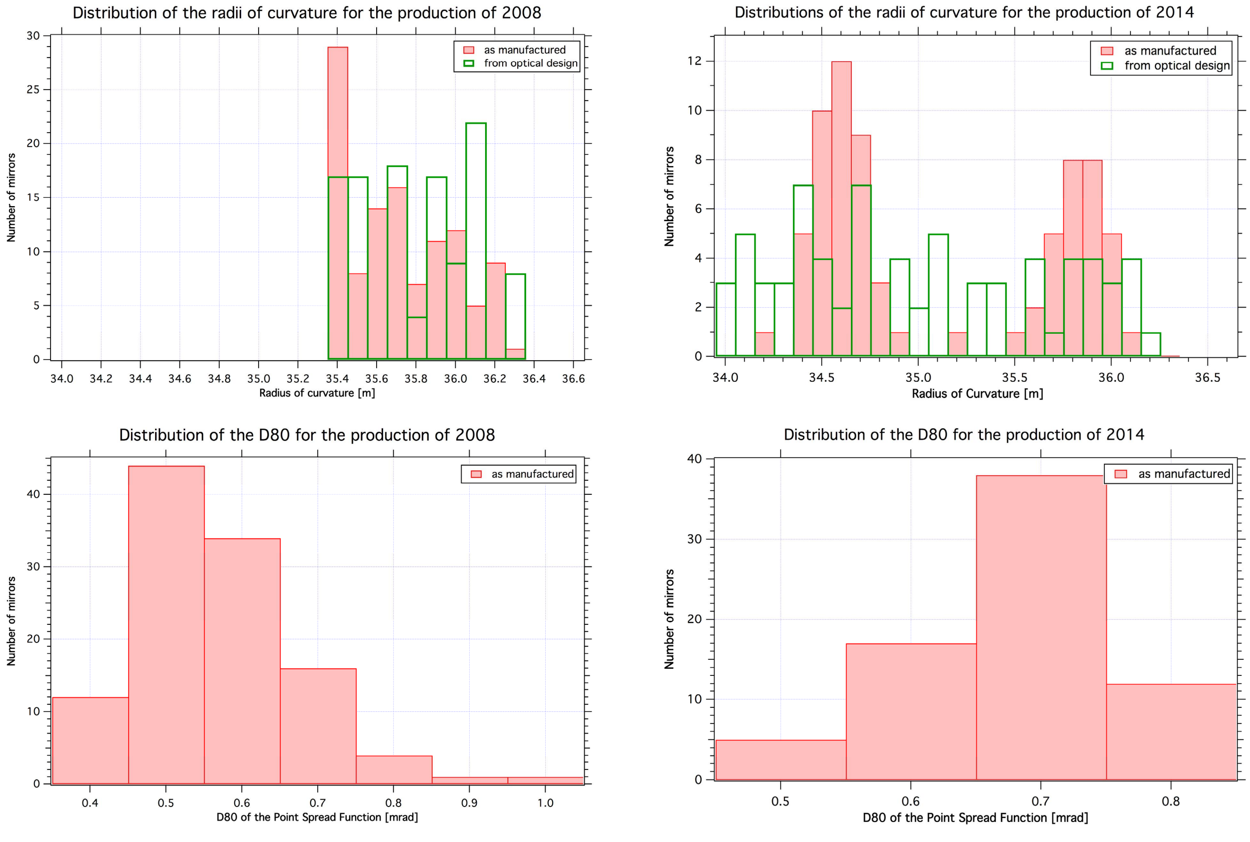

Figure 2 Top raw: statistical distribution of the radii of curvature of the mirrors manufactured during the campaign of 2008 and 2014, left and right respectively. Bottom raw: statistical distribution of the diameter containing the 80% of the focused energy (D80) of the point spread function of the mirrors manufactured during the campaign of 2008 and 2014, left and right respectively.

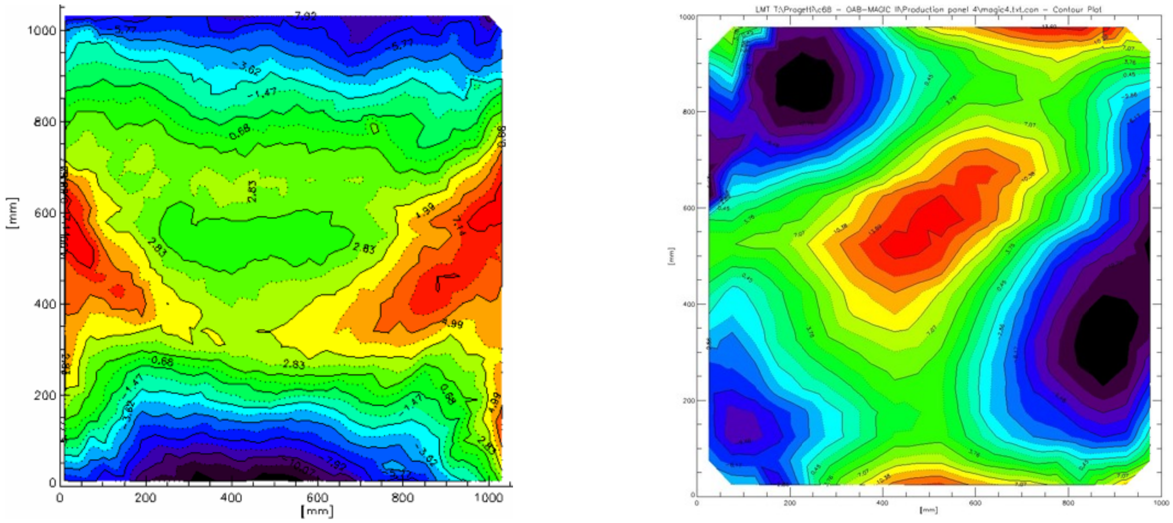

Figure 3 Typical errors maps of the replication molds (left) and mirrors (right). The measurements, acquired with a coordinate measuring machine, have about 400 sampling points.

MST and SST-1M are two classes of telescopes that will populate the array of the CTA Observatory. These telescopes will be replicated in several tens of units. Both types implement the Davies-Cotton optical layout [11]. Several identical spherical mirror segments of focal length *f* (and hence radius of curvature *2f*) are arranged on a dish of spherical shape of radius *f* (see Figure 4). This solution, even if it delivers a discontinuous optical surface, provides improved off-axis point spread function with respect to the parabolic solution and keeps the photon arrival time isochronous within about 1 nm. This optical solution is particularly suited for telescope aperture below 15 m.

MST is a telescope of 12 meters aperture and f/D = 1.33. Each telescope will have 88 mirrors segments mounted on a dish made of steel beams. The mirrors have an active control to properly align them to the Davies-Cotton prescription. Each mirror has a spherical profile with 32 m radius of curvature. It is hexagonal in shape with a dimension of 1.2 m face-to-face. The MST prototype development is led by DESY but several research institutes actively collaborates, such as INAF, CEA, Tübingen University and others. The central panel of Figure 4 shows the prototype installed in Berlin. For this telescope we applied the CS technology with the goal to have all the mirrors within the requirement at the predetermined radius of curvature, the same for all. In 2011 a small batch of 26 mirrors has been manufactured to tune the process in view of a larger production of mirrors. All the mirrors were replicated from one mold. Despite the small statistic, it is possible to identify a cluster of mirrors in the distribution of the radii of curvature shown in the left panel of Figure 5. The panel on the right, instead, shows the distribution of the D80.

Figure 4 Left: Scheme of the Davies-Cotton optical design. Mirrors with radius of curvature *2f* are arranged on a mechanical structure with radius *f*. Center: the MST prototype with the mirrors manufactured by the authors. Right: the SST-1M prototype with dummies.

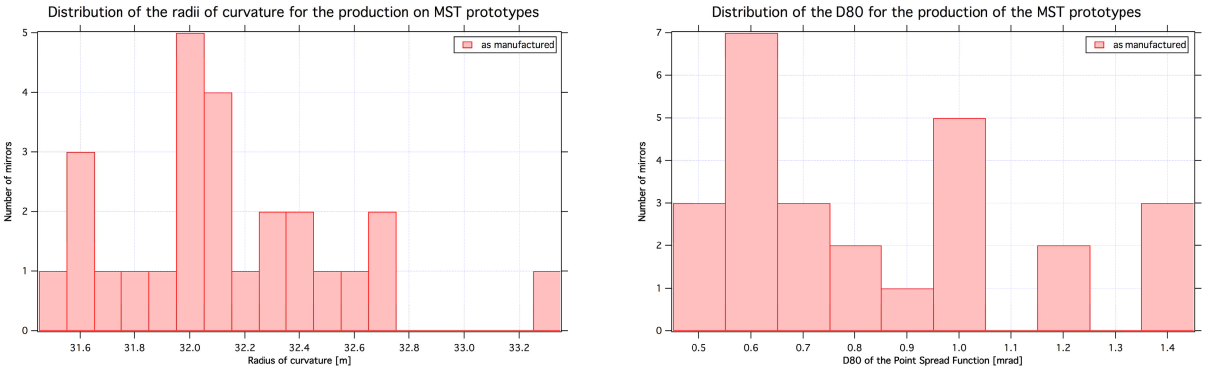

Figure 5 Left: statistical distribution of the radii of curvature of the prototype manufactured for the MST prototype. Right: statistical distribution of the D80 of the mirrors.

SST-1M is a telescope of 4 meters aperture and f/D = 1.4. Each telescope will have 18 mirrors segments mounted on a dish made of radial steel beams. Also in this case the mirrors have an active control to properly align them to the Davies-Cotton prescription. Each mirror has a hexagonal tile's shape of 78 cm face-to-face with a spherical profile with 11.2 m radius of curvature. The University of Genève in collaboration with others Swiss and Polish research institutes leads the SST-1M prototype development. The mechanical assembly prototype has been manufactured by IFJ-PAN and it is now installed in Cracow, see the right panel of Figure 4. In this case, we have pushed the technology toward very short radii of curvature: the most difficult to be realized. In fact, during the manufacturing, the glass is undergone to a high level of tensile stress, which can break the glass foil if it overcomes the threshold. For this kind of mirrors the stress can reach values up to about 15 MPa. Two mirrors prototypes have been successfully realized, both perfectly matching the required radius of curvature. From left to right, in Figure 6 are shown: the errors map of one of the replicated mirrors as measured by a deflectometry setup installed in INAF-OAB; the simulation of the expected point spread function at the radius of curvature; the measurement of the point spread function taken by illuminating the mirror from its radius of curvature. The surface shape measurement returns an error of 2.5 mm in the radius of curvature (only the 0.02% with respect to the nominal value) and a deviation of 8.5 μm rms. Moreover, the simulation and the measurement show an excellent agreement in terms of point spread function shape and D80 value. The D80 is 0.9 mrad.

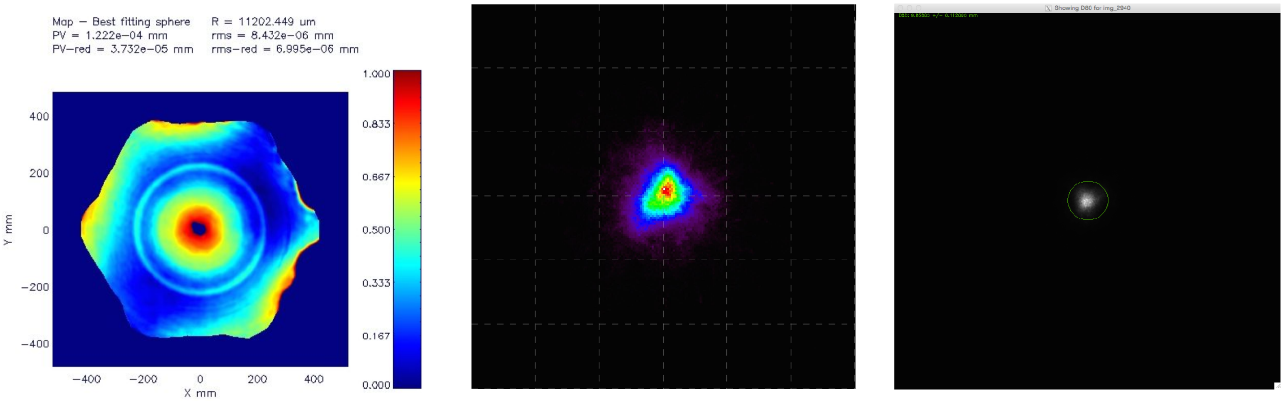

Figure 6 Left: Typical errors map of the replicated mirror. Center: Simulation of the expected point spread function. Right: measured point spread function.

4. POLYNOMIAL MIRRORS

A peculiar need comes from the Cherenkov telescopes devoted to the furthermost tail of the very-high-energy range. These kinds of telescopes need a very large field of view in order to imaging high-energy and distant impact point Cherenkov showers. Single-mirror designs suffer from significant optical aberrations with a resulting increase in the point spread function, unless they adopt long focal lengths. Dual-mirror designs can provide significantly improved imaging quality, at the expense of a more complex telescope design. One solution is the Schwarzschild-Couder optical design adopted, for instance, by the ASTRI SST-2M telescope within the CTA observatory. This design was studied in 1905 by Schwarzschild [12] and refined by Couder in 1926 [13], then firstly proposed for Cherenkov Telescope in 2007 by Vassiliev [14].

ASTRI SST-2M is a telescope of 4.3 meters aperture and f/D = 0.5. The primary mirror is composed by 18 mirrors segments of three different surface profiles; while the secondary mirror is a monolithic piece of 1.8 m in diameter. The mirrors have an active control to properly align them to the optical prescription. The ASTRI SST-2M development for CTA is led by INAF in collaboration with the University of Perugia, the University of Sao Paolo (Brazil) and The Northwestern University (South Africa). The telescope end-to-end prototype, whose development is led by INAF, is now installed in Serra la Nave on the Etna Volcano (Sicily, Italy); details about the latest results on the prototype are presented in [15].

Concerning the primary mirror segments, each one of them has an off-axis aspherical profile with about 10 m radius of curvature in the radial direction and about 20 m in the tangential one. They are hexagonal in shape with a dimension of 0.85 m face-to-face. Each segment is essentially a freeform mirror whose asphericity can reach about 900 μm rms. Details on the optical characterization of these mirrors are presented in [16]. Also in this case we applied the CS process for the manufacturing of the mirrors. The challenges faced were both on the short radii of curvature and of the strong aspherical profile to be imparted. Some modifications to the standard process has been developed, tested and applied.

The results are shown in Figure 7. On the left panel, the low spatial frequency errors of the shape of the mirrors in terms of deviation from the best focus position are shown. The histogram shows three different clusters. Each one corresponds to each class of mirror. Clearly visible is the different amount of the spring back effect. As expected, it is more pronounced for the mirrors that have a shorter radius of curvature (green, blue and yellow clusters respectively). However, the deviation of each cluster is typically contained within 1-2 mm with the exception of two outliers. This result suggests a very good reproducibility achievable by the CS process. The panel on the right in Figure 7 shows the rms slope errors measured on the mirrors. Independently from the radius of curvature all the mirrors have an error of about 1 mrad or less. This result is in line with the typical error shown by the mirrors manufactured with the CS process.

Two sets of mirrors have been produced with different reflecting coating solution: aluminum plus quartz and a dielectric multilayer. Moreover, the dielectric coating has given us the possibility to test an additional variation in the CS process. In fact, due to the high temperature usually reached by the mirror substrate during this kind of coating, we were forced to proceed with the coating of the bare glass foils prior the shaping phase. This introduces an economical risk in the manufacturing. The eventual failure of the shaping process (or of any subsequent phase) translates not simply in the waste of the bare materials (glass foils, honeycomb and the glue) but also in the expense of the coating. Results in terms of deviation from the best focus position and slope errors are compatible with those shown in Figure 7.

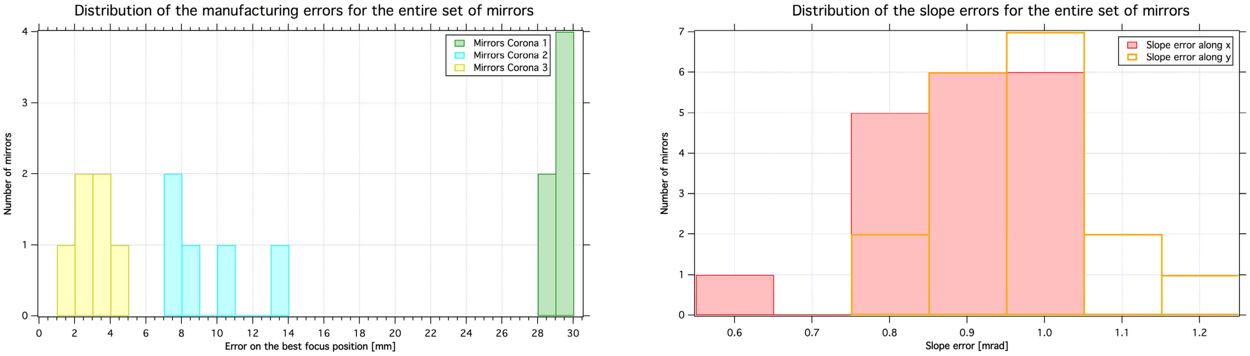

Figure 7 Mirrors of the ASTRI SST-2M telescope prototype. Left: deviations from the nominal focus position. Right: slope errors of the mirrors.

5. CONCLUSIONS

This paper presents an overview of the glass Cold Shaping technique developed and used over the past years by the INAF-OAB in collaboration with the Media Lario Technologies company. The CS process is a proven technology specifically developed for the manufacturing of the mirrors for Cherenkov telescopes. The mirrors are typically very lightweight, robust against strong environmental conditions and cheap. Cold Shaping has also proved to be a process easily tunable to match the needs coming from the optical prescriptions. Indeed, it is applicable for a variety of optical solutions. Spherical mirrors can be easily replicated over a wide range of radii of curvature ranging from below 10 m up to several tens; residual errors are at most of 15 μm rms. Free form surfaces can also be manufactured. A further characteristic of this manufacturing process, although not discussed in the paper, is that a big number of mirrors can be produced and delivered in short time frame.

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