Production via thermal slumping of large glass monolithic secondary mirrors (1.8 m diameter) for Schwarzschild-Couder air-Cherenkov gamma-ray telescopes

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ABSTRACT

The standard design for 4-meter diameter class Imaging Atmospheric Cherenkov Telescopes (IACTs) used in ground-based gamma-ray astronomy is the dual-mirror Schwarzschild-Couder-like configuration. This design has been adopted for the telescopes in the ASTRI-Horn and ASTRI Mini-Array experiments (1 + 9 telescopes) and the construction of the 37 telescopes in the Small Size Telescope (SST) sub-array of the Cherenkov Telescope Array Observatory (CTAO) in Chile. The design provides an aplanatic optical response across a field of view wider than 10 degrees and is suitable for compact cameras using small pixels such as SiPM sensors. The telescopes feature secondary mirrors with a diameter of 1.8 meters, made of monolithic glass using a hot-slumping replication process. The paper discusses the manufacturing and characterization results of the prototype mirrors.

Keywords: Imaging Atmospheric Cherenkov Technique (IACT), Cherenkov telescopes, ASTRI, CTAO, SST, Schwarzschild-Couder dual-mirror telescopes, thermal slumping, hot replication process, sizeable monolithic glass substrates

1. INTRODUCTION

The standard design for 4-meter diameter class Imaging Atmospheric Cherenkov Telescopes (IACTs) (see e.g. [1]) used in ground-based gamma-ray astronomy is now the dual-mirror Schwarzschild-Couder-like configuration [2]. The Italian Institute for Astrophysics (INAF) successfully developed and realized the 4 m diameter ASTRI-Horn telescope prototype [3], which is now working perfectly in Sicily [4]. This represents a significant advancement in Cherenkov Telescope design as the first example of an implemented Schwarzschild-Couder (SC) dual-mirror aplanatic telescope [5,6].

This design uses two aspheric mirrors to compensate for optical aberrations, offering better angular resolution across a large field of view with minimal vignetting and a more convenient plate scale than single-mirror Cherenkov telescopes [7,8]. Telescopes like the ASTRI-Horn are now being replicated for the ASTRI-Mini Array (9 telescopes) [9,10,11] and the CTA Observatory south-site [12] as SST (37 telescopes) [13, 14].

The introduction of the secondary mirror in IACTs marks a significant milestone, not only in terms of design but also in overcoming technological challenges. The aspherical secondary mirrors for telescopes like ASTRI [15] have a diameter of 1.8 m and a small radius of curvature (about 2 meters), resulting in a concavity of about 200 mm peak-to-valley (see Table 1).

The INAF Astronomical Observatory of Brera is taking the lead in developing the ASTRI Mini-Array (9 telescopes) and SST telescopes (37 telescopes), including implementing their optics system. The primary 4-meter-diameter mirror is segmented into 18 hexagonal tiles, produced using the "cold replication" technique. The secondary 1.8 m diameter mirror of the ASTRI and SST telescopes is monolithic, which simplifies the alignment procedures.

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It should be noted that another Schwarzschild-Couder dual-mirror telescope prototype for gamma-ray astronomy IACT applications has been developed in the US, called pSCT, 9 m diameter [16]. This effort was carried out to demonstrate the possibility of using the dual mirror solution also for the CTAO telescope of mid-class size (9-12 m diameters). In this case, the secondary mirror is huge (6 m), and the substrate is not monolithic but made of 6 petals.

The cold-slumping method is a popular technology for creating the reflecting tiles of the primary mirrors of IACT Telescopes [17,18,19,20]. This process involves replicating the stress of thin glass foils to create a compound sandwiched panel. It is a time-effective and cost-effective method suitable for mass production (with a typical cost of a few KEuro per square meter). However, this method cannot make the large monolithic secondary mirrors of ASTRI and SSTs because of their excessive concavity and large size. Cold-shaped mirrors are intrinsically stressed and can only be produced within specific parameters. The preferred manufacturing process for making large M2 monolithic substrates is the hot slumping of monolithic glass substrates. The hot slumping technique retains the advantages of the replica concept but allows the production of highly concave substrates due to the high temperature applied to the glass.

Table 1: characteristics of the monolithic mirror M2 in ASTRI-like dual-mirror telescope

Characteristic	***Value***
Dimension	1.8 m diameter, circular shape with 50 mm diameter central hole
Concavity/Sag.	~200 mm
Thickness	19 mm, chamfered edges (for safe handling)
Weight	~ 120 kg
Shape	Aspherical shape, radial profile difference from sphere ~1 mm
Accuracy	The angular resolution requirement for the dual-mirror telescopes that the 80% PSF focal spots stay within a diameter of 0.19 deg; this translates in a rms error of 20 µm rms and 100 µm PtV for the secondary mirror.
Reflecting layer	Al + protective layer
Mechanical Interfaces	12 stainless steel Pads glued on the back side + pad around central hole

Up until now, these substrates (including the one installed on the ASTRI-Horn telescope prototype in Sicily) have been produced by the German FLABEG Gmbh company (https://www.flabeg.com/en.html), which produced several substrates within (but sometimes at the limit for such regarding the surface accuracy requirement) of the specs. Moreover, an unsuspected problem of oxidation of the Aluminum coating deposited on the produced substrates happened, which obliged INAF to perform, in collaboration with the Marcon Telescopes Italian company (http://www.marcontelescopes.comscopes), a lapping process of the substrate to remove the oxidate layer prior of the coating deposition. On the other hand, due to a change in the FLABEG company's business plan, producing the substrates using this supply chain is no longer possible.

INAF, as part of the ASTRI Mini-Array, CTAO-SST, and CTA+/PNRR programs, is consolidating the technologies for the large production of Cherenkov telescopes. In such a context, a proactive decision was made to establish a new supply chain for the substrates of the secondary mirrors. This was achieved through a specific development program carried out by INAF in collaboration with Italian companies Media Lario srl (https://www.medialario.com) and Vetrolamp srl (https://www.vetrolamp.net).

Prototypes were created to evaluate this new and optimized supply chain, including all the necessary manufacturing, handling, and metrology tools for producing such large mirrors. This paper overviews the program's activities over the past year and shares some preliminary results.

2. REVIEW OF THE HOT SLUMPING TECHNOLOGY

The hot slumping technology involves a few main steps, as shown in Figure 1 and listed hereafter:

1. First, a flat glass is placed inside an oven on a mold with the desired shape for the mirror.
2. Then, a thermal cycle is initiated. When the oven reaches high temperatures, the glass starts to bend under its weight, being in contact with the mold and taking on its shape.

3. Once the glass has cooled, it is removed from the mold and is prepared for coating.

The process also involves attaching structural interface pads to the back of the glass. This indirect slumping method ensures that the optical surface never touches the mold, which helps preserve the glass's original micro-roughness.

INAF-OAB has a long heritage in the hot slumping method for producing mirror substrates for astronomical applications [21,22]. Given the replication philosophy, the technology is well suited for several mirrors' fast and cheap realization. It offers several advantages for enhancing the production yield, e.g.:

- A very low surface roughness of glass is maintained during the process, with no need for mirror polishing.
- The aspheric shape is obtained efficiently by replicating the mold.
- The approach is cost and time-effective for mass-production.

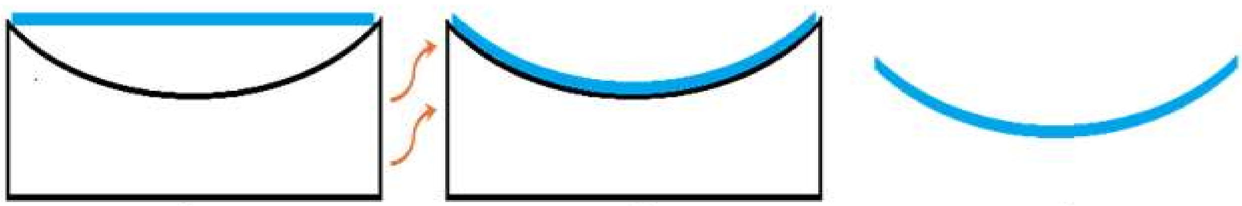

Figure 1 - Schematic steps of the hot-slumping technology for manufacturing large monolithic mirrors: 1. A flat glass substrate is placed on a pre-shaped mold (left). 2. The mold and glass substrate are heated until the glass reaches a plastic deformation state and flows onto the mold (center). 3. After cooling, the substrate is detached (right).

One potential issue with the indirect slumping replication method is the known transmission of mid-spatial frequency errors from the original glass foils. This is especially true when there are differences in thickness among the initial glass slabs [23,24].

Hot Slumping Technology is an advanced innovation for producing the 2 m sized M2 mirrors. As a result, initial development efforts have been necessary to evaluate a new production line capable of making such large mirrors. For the specific application under consideration, the materials and tools considered are:

1. **GLASS**
   Pilkington Optiwhite, 19 mm thick. Before slumping, the glass is cut to the final circular shape, and the edges are chamfered for safety reasons. A hole 50 mm in diameter is realized in the center to allow for the positioning of a calibration flasher for the Cherenkov camera once the mirror is mounted in the telescope. The hole is also helpful since it provides the substrate for air escape during the hot slumping and helps water flow during the wet cleaning phases. This activity is being carried out by Vetrolamp srl under INAF's supervision.

2. **MOULD**
   A steel mold with the negative shape of M2 (indirect slumping) is produced. The mold is thermally stabilized before slumping to remove the impurities. A separation layer (e.g., Boron Nitride) is applied to avoid sticking of the glass during the forming process. The RoC (Radius of Curvature) is in the range of the ASTRI telescope, i.e., about 2.3 m. Media Lario srl and Vetrolamp srl carried out this activity in cooperation under INAF's supervision.

3. **OVEN**
   Electrical oven: 4000 x 2500 x h1200 mm internal dimensions were procured. The electrical elements are positioned on top and bottom of the oven and divided into eight separated areas controlled by dedicated K-type thermocouples to allow for better thermal uniformity. The maximum reachable temperature allowed by the oven is 850°C. The oven has been purchased by INAF and installed at Vetrolamp srl.

4. **HANDLING TOOLS**
Media Lario srl, in agreement with INAF, developed suction cups for glass handling, belts, and a crane to remove the glass from the mold; a holding structure for coating application; and a specific container for shipment and storage.

3. PROTOTYPE REALIZATION

To achieve high-quality results using the hot slumping technique, it is crucial to ensure that the oven is calibrated correctly for uniform thermal load application. Variations in thermal cycles can lead to stresses in the glass substrate, which may result in shape errors on the surface. Due to the specific dimensions of the oven's cavity in the ASTRI-M2 manufacturing process, maintaining thermal uniformity is especially important. Our first step was to conduct a shape accuracy test for the hot-slumping manufacturing process. The accuracy of the process was evaluated by calculating the root mean square (rms) difference between the mold shape and the slumped substrate shape. The adopted slumping forming process foresees a long duration, more than 45 hours, with a maximum reached temperature of about 600 ºC. Some pictures of the different steps of the slumping process applied to produce the prototypes are reported in Figure 2.

a) ASTRI M2 metallic mould + flat glass sheet

b) ASTRI M2 mould + slumped glass sheet

c) ASTRI M2 with I/Fs to the telescope

d) ASTRI M2 metal mould measurement

Figure 2 - Pictures of 4 phases of the hot-slumping manufacturing process of the large secondary mirror substrates.

Figure 2 *a)* shows the glass positioned on the mold at the start of the process. The central hole is visible in this picture. Figure 2 *b)* shows the slumped glass still on the mold at the opening of the oven; the glass appears in excellent contact with the mold, as also verified with a test performed with a shim 80 µm thick (it was not possible to insert it between the glass and the mold, demonstrating the excellent contact between the two). *Figure 2 c)* shows the supports and the holding jig to be used during coating, handling, and integration activities. Figure 2 *d)* shows the mold during the metrological step; it should be noted that the same 3D CMM TCX machine has been used for the metrology of slumped glass to quantify the slumping process accuracy, the shape error of the mold was compared with the profile of the replicated substrates.

4. PRELIMINARY RESULTS

To determine the shape accuracy achievable with the hot-slumping process, we compared the shape measurements of the steel mold and the replicated glass substrate. The measurements were taken using the 3D CMM TCX 3D contact machine operated by Media Lario srl, with lateral sampling steps of 5 cm. We analysed the acquired data to calculate the residual errors compared to the desired polynomial aspherical design of the mirror, allowing free roto-translations to minimize the residuals. We repeated the fitting process while coupling the measurements to the theoretical design and the theoretical design setting the RoC as a free parameter of the fit, as a difference in RoC is inherent to replica processes and must at least compensate the substrate thickness when using inverse hot slumping as the manufacturing process.

In Figure 3, Figure 4, and Table 2, we report the shape error measured on the metallic mold and the replicated glass substrate. The shape error is given in peak-to-valley and standard deviation compared to the theoretical mirror design (fixing and leaving the RoC parameter free, respectively).

The shape of the mold is noticeably affected by a significant astigmatism error, which is accurately reproduced on the slumped glass substrate. Considering that the initial step in our manufacturing chain development was to verify the accuracy of the hot-slumping process, this result should be viewed positively. The next step involves obtaining a mold that meets specifications, with a shape capable of compensating for some low-frequency systematic errors (specifically, the difference in the correct RoC) inherent in the replication process.

The mold has a shape error of 1.5 mm root mean square (rms) compared to the theoretical shape, assuming the radius of curvature (RoC) is fixed at the nominal value. It also has a shape error of 454 µm rms compared to the best-fitting RoC of 2231 mm, when the RoC is allowed to change as a fit parameter.

The replicated glass substrate has a sag error of 1.0 mm rms compared to the theoretical shape (when the RoC is fixed to the nominal value) and a shape error of 488 µm rms compared to the best-fitting RoC of 2212 mm. The expected difference between the RoC of the replicated glass substrate and the mold is 19 mm, corresponding to the substrate thickness, albeit the observed RoC difference is 20 mm. Therefore, an offset of 1 mm RoC needs to be added to the mold for its final refurbishment.

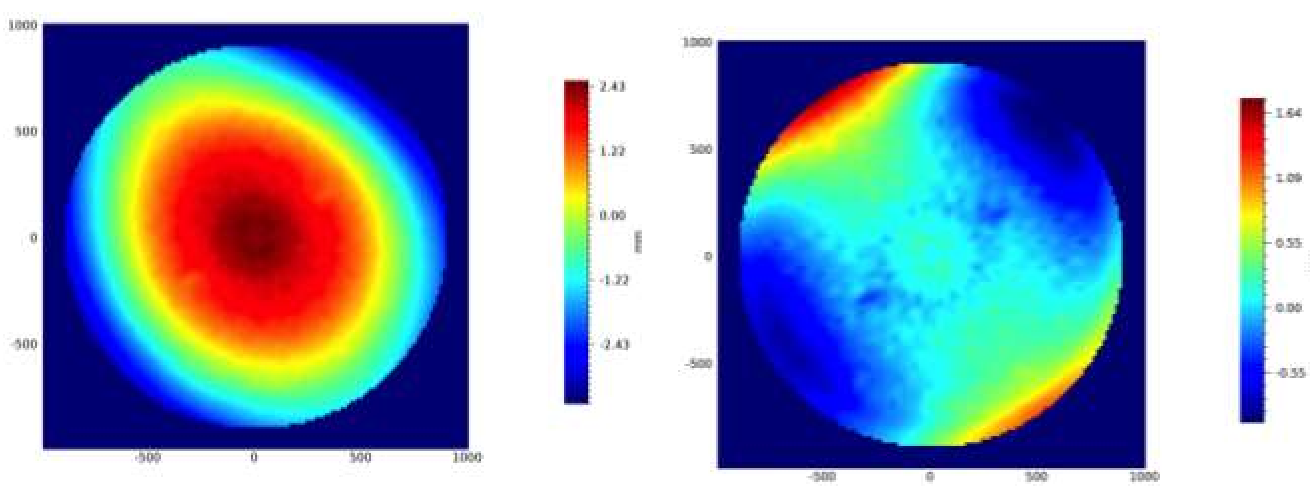

Figure 3 – Mould shape error residuals compared to the theoretical mirror design (left) and the theoretical design, leaving the RoC as a free parameter (right).

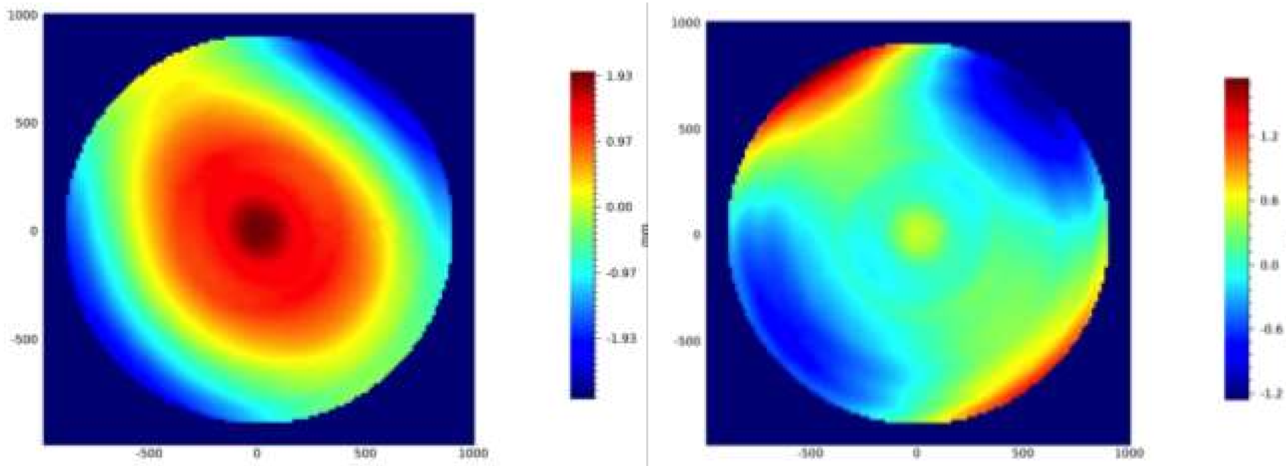

Figure 4 – Replicated glass substrate shape error residuals compared to the theoretical design (left) and the theoretical mirror shape, leaving the RoC as a free parameter (right).

Table 2: Shape error measured on the metallic mould and the replicated glass substrate. The shape error is given in terms of peak-to-valley and standard deviations compared to the theoretical mirror design (Fixed RoC) and the theoretical mirror design, leaving the RoC as a free parameter (Free Roc).

	Fixed RoC		**Free RoC**		
Error (mm)	**PV**	**rms**	**RoC**	**PV**	**rms**
Mould	6.086	1.467	2231	2.731	0.454
Replica	4.827	1.016	2212	3.026	0.488

Figure 5 presents the difference in shape error measured on the metallic mold and the replicated glass substrate compared to the theoretical mirror design with the RoC left free to fit the respective shapes. The map displays the typical annular distribution of the mold backing structure reinforcement. The shape error was evaluated to be 104 µm rms, which aligns with the accuracy of our hot-slumping manufacturing process and is suitable for ensuring the necessary optical resolution of 0.19 degrees for the ASTRI and SST telescopes.

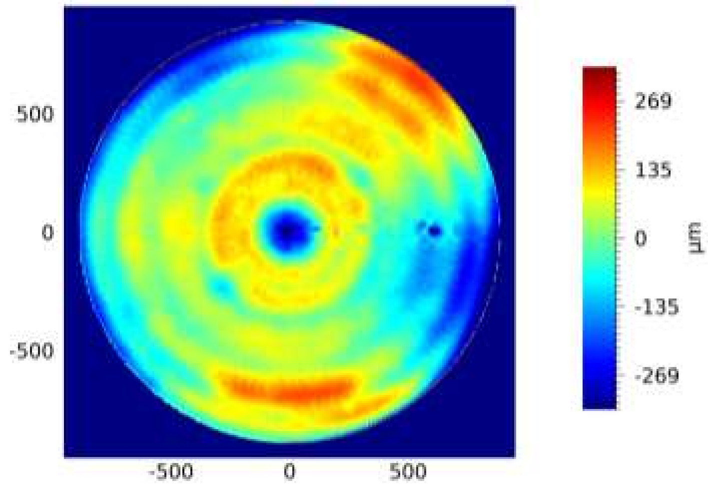

Figure 5 - The difference between the shape error measured on the metallic mold and the replicated glass substrate compared to the theoretical mirror design, having left the RoC free to fit the respective shapes.

5. CONCLUDING REMARKS

The INAF-Brera Astronomical Observatory is currently involved in developing the ASTRI-Mini Array and CTAO, and it is responsible for producing the CTAO SST telescopes (similar to the ASTRI telescopes). The simultaneous development of telescopes for these observatories requires consolidating the optics procurement chain. The optics of ASTRI-like telescopes are different from existing IACTs due to the presence of a large aspheric secondary mirror. This mirror is characterized by its large dimensions (1.8 m in diameter), strong concavity (~200 mm sag), and moderate shape accuracy. To meet the required angular resolution of 0.19°, the hot-slumping technique was chosen as the most suitable manufacturing process for these large substrates.

In this paper, we presented the initial findings from establishing a new manufacturing process developed by INAF in partnership with Media Lario srl and Vetrolamp srl companies. The first step of assessing the new manufacturing process involves producing prototype substrates to establish an effective hot-slumping replication process that ensures the necessary level of precision. The experimental data obtained so far indicate that the process is nearing achieving the required optical quality.

To meet the requirements for the final production, the next steps in the development process involve refurbishing the mold used for testing (or creating a new one) with a surface that can accurately replicate the polynomial mirror shape via a hot replication process. The new mold profile should be designed to compensate for the inherent low-frequency errors of the replication process, particularly the error in RoC. Subsequent activities will focus on verifying the replication process. Finally, a reflective coating will be applied to the mirror surface to assess scattering effects, coating adhesion, and potential oxidation issues.

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