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Design and development of the reflecting panels for the Large Size Telescopes at the southern site of the Cherenkov Telescope Array Observatory (CTAO)

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ABSTRACT

In the context of the Cherenkov Telescope Array gamma-ray Observatory (CTAO), two large-size telescopes, each with a diameter of 23 m, will be installed at the southern site in Paranal, Chile. They are referred to as Large Size Telescope South, LST-S (it should be noted that 4 Large Size Telescopes, with a similar optical configuration, are already being installed at the CTAO northern side of La Palma, Canary Islands, Spain). INAF oversees the coordination of the implementation effort related to the LST-S telescopes. They will use a single mirror parabolic shape to capture images with moderate angular resolution. To achieve this shape, 198 hexagonal reflecting panels will be assembled into the telescope structure. Each panel is roughly 150 cm side-to-side in size and weighs less than 50 kg. It comprises two solid glass plates bonded to a lightweight honeycomb structure of an aluminum alloy core. The panels are spherical and distributed in three coronas with different curvature radii to achieve the desired shape. They will be exposed to the open air for several years and must withstand mechanical stresses, wind impact, and possible strong earthquake solicitations. The panels are the elements of the telescope's segmented primary mirror. The development activities for such large panels performed to optimize the mirror design and the results after the production of prototypes are summarized in this paper.

Keywords: CTAO, Cherenkov Telescope, LST, large-segmented mirror, cold shaping, glass cold slumping

1. INTRODUCTION

In the frame of the CTAO (Cherenkov Telescope Array Observatory) and the LST Consortium [1], INAF is in charge of designing, fabricating, and testing the Large-Sized Telescopes located in the southern hemisphere (LST-S) [2], [3], at an altitude of about 2150m into the valley between Paranal and Armazones. These are alt-azimuth telescopes with a 23 m diameter (28 m focal length) parabolic primary mirror.

Thanks to the large collecting area, in conjunction with a high photodetection efficiency and fast readout, these big telescopes will allow the detection of celestial gamma-rays with the IACT technique at the relatively soft gamma-ray energies in the 20 GeV to about 1 TeV range. Indeed, the IACT technique requires telescopes with more oversized mirrors as the less energetic gamma rays produce less luminous Cherenkov showers. On the contrary, the more energetic gamma rays produce very bright showers (visible even with small telescopes). Still, at the same time, they are much less numerous and, therefore, require many telescopes to be seen in sufficient numbers to conduct scientific studies. Hence, to study the sky at higher gamma-ray energies, from 1 TeV up to a few hundred TeV, it is better to build many medium-sized and small telescopes rather than a few large ones. This strategy adopted by CTAO will have many Small and Medium-sized telescopes of CTAO (SSTs and MSTs) to cover this energy band. Therefore, The LST telescopes are arranged at the array's center to lower the energy threshold and improve the sensitivity of CTAO between 20 GeV and 1 TeV.

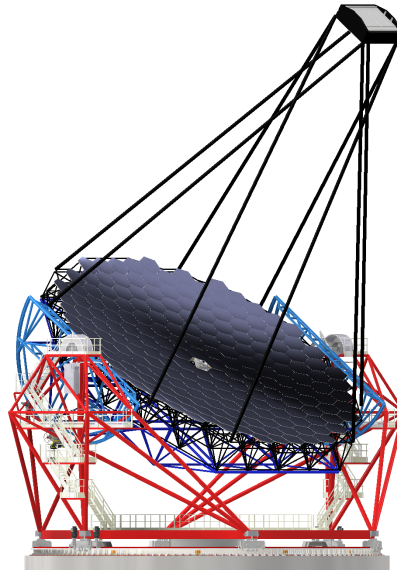


Figure 1. Schematic of the configuration that will be adopted for making the 23 m diameter LST-S telescopes (Credits: A. Busatta and A. Antonelli).

The optical design closely resembles the one developed for LST-North (LST-1) [4], [5] already implemented in La Palma (Canary Islands) at the CTAO Northern site. Still, several differences are introduced in the mechanical structure (see Figure 1) to meet the more demanding anti-seismic requirements and to handle the different loads related to the Chilean environment at Paranal. This includes accounting for powerful earthquakes.

The INAF-OAB Astronomical Observatory of Brera, in collaboration with the University of Padova and a few strategic industrial partners (Media Lario srl, BCV Progetti srl, ZAOT srl) is coordinating the effort to design the LST-S optical system and produce all the reflecting segments that will be assembled to mimic a monolithic primary mirror.

This Italian pool of Institutes and industries has a long history of using the “*cold slumping technique*” to produce the reflecting panels for Cherenkov telescopes. This approach has been successfully developed in Italy and then employed for projects such as MAGIC I and II, ASTRI-Horn and ASTRI mini array, MST/CTA, and pSCT mirrors [6], [7], [8].

On the other hand, the technology must fit into the requirements of LST-S, with its large segments to be produced due to the large size of segments. Therefore, specific prototypes for the LST-S effort have been developed to evaluate the entire production process, identify potential weaknesses for further investigation and improvement, and verify all the tools for manufacturing, handling, and measuring such large segments in mass production methods. It's worth noting that similar technology (inspired, in turn, by the previous efforts performed in Italy) has already been used to produce mirror segments for LST North by the University of Tokyo and the Sanko company in Japan [9], even if the requirements were partially different.

This paper reports on the development activities in Italy during the last months, with the aim of producing the CTAO/LST-S mirrors.

2. REMARKS ON THE COLD-SLUMPING TECHNOLOGY

The principle and main steps of the cold-slumping technology are summarized in Figure 2 using a pictorial approach. A thin glass foil is bent on an ad hoc prepared mold with the desired profile (corresponding to the negative shape of the reflecting panel to be fabricated). An Aluminum honeycomb layer and a second glass foil are glued on its back to give the segments the necessary stiffness, maintain the shape, and sustain operative loads. After properly curing the glue, the obtained lightweight yet rigid sandwich segment is removed from the mold and completed with a multilayer reflective

coating (generally based on an evaporated layer of Aluminum plus a protective layer of SiO₂ or other materials). Its perimeter is sealed to finish the mirror segment, and structural interfaces are glued on the back to allow for its integration into the telescope structure. The same pads are used for all metrological and handling activities when needed to sustain the mirror in a vertical position.

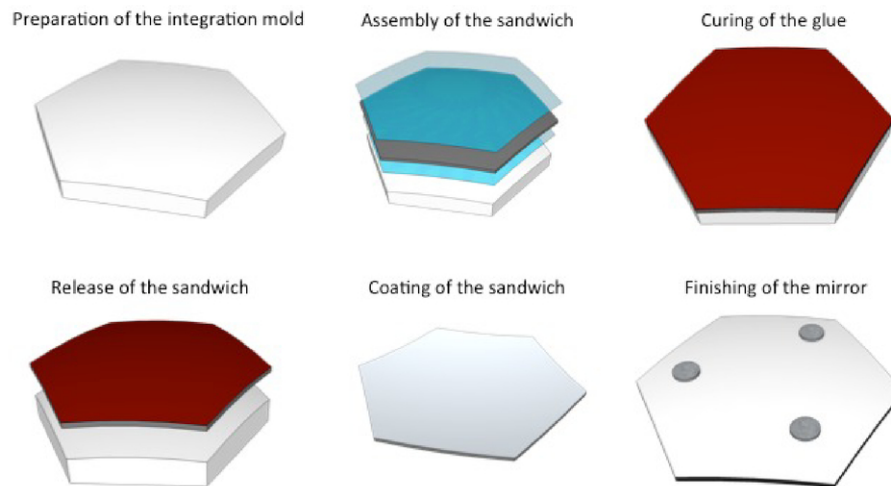


Figure 2. Schematic steps of the glass cold-slumping technology.

The technology is a cold-replication process designed explicitly for mass-producing large quantities of identical segments. This process saves time and reduces costs compared to traditional methods such as optical grinding, polishing, or thermal forming of glass substrates. Additionally, the process does not easily affect the excellent microroughness (< 2 nm rms) of the original glass foil, meeting the required optical standards.

A potential drawback is that stresses become trapped inside the thin glass sheet due to its limited elastic properties. As a result, careful selection of process parameters such as the type of glass foils and aluminum honeycomb thickness, quantity of glue, curing time, and applied force during the forming process is necessary to meet optical and environmental requirements for the mirror segments. This is accomplished through FEM simulations and process qualification at the beginning of mass production. Generally, the process is suitable for producing large curvatures that result in small sagittas of the segments, typically a few millimeters at most. This aligns well with the needs of the CTAO telescopes, making cold-slumping technology the best choice for primary mirror manufacturing.

Within CTAO, the cold slumping technology has already been adopted to produce the mirror segments for the Small-Size and Medium-Size Telescopes (SST & MST), 85cm and 1.2m large, respectively [10]. It is now being used and specifically assessed to produce large-size telescope (LST) segments of 1.5m.

3. LST-S PRIMARY MIRROR SEGMENT REQUIREMENTS

The LST-S telescopes utilize a parabolic primary mirror with a 23-meter diameter, a focal length of 28 meters, and a 1.2 focal ratio (f/D). The total effective area of the mirror is approximately 370 m². After reflecting off different mirror positions, the parabolic shape is chosen to minimize the time dispersion requirement (< 1 ns) for the focused Cherenkov light. Due to its large size, the primary mirror is produced using a segmented mirror approach, which involves assembling several optical elements to form a large monolithic mirror.

The spherical shape is adopted to optimize the large-scale production of the reflecting segments for the LST-S mirror. There are 198 segments, each with a spherical profile, grouped in three sets with different curvatures (56.3 m, 57.1 m, and 57.9 m) to mimic the illustrative parabolic-like configuration, as illustrated in Figure 3.

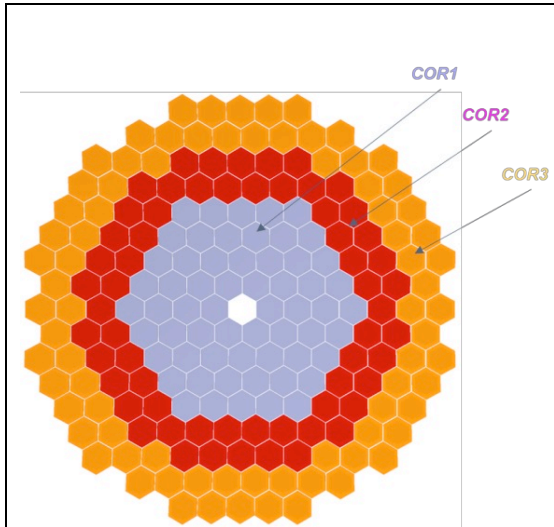


Figure 3. LST-S distribution of mirror segments in the dish.

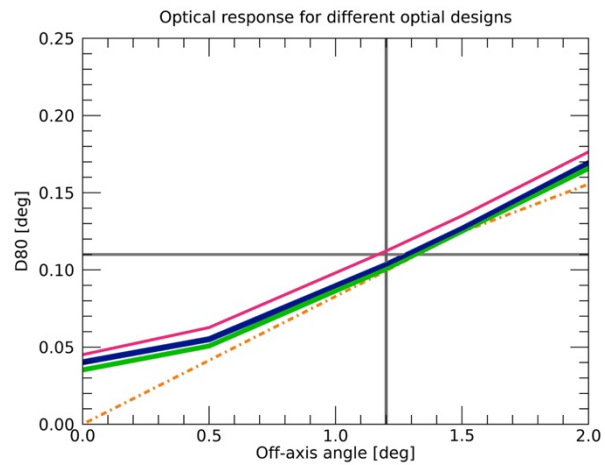


Figure 4. D80 across the FOV for the proposed solution (blue) and reference curve for parabolic telescope configuration (yellow dashed line), continuous RoC distribution (green line) and telescope mirror realized with identical segments all shaped on the mean RoC (pink line).

Table 1. Parameters for the LST-S M1 reflecting panels.

Segment characteristic	Value	Remarks
Number	198 in total, grouped in three coronas: - COR1: 60 segments - COR2: 60 segments - COR3: 78 segments	This allows a cost-effective mass production approach
Shape	hexagonal	Glass foil procured already with this shape
Dimension	- 1510 mm hexagonal flat-to-flat - 1744 mm hexagonal tip-to-tip - 872 mm hexagonal side	-2/+0 mm tolerance maximum, to avoid interfaces between segments once mounted onto the structure
Thickness	< 50 mm	Current prototypes are 46 mm thick
Weight	< 50 kg	Including supporting PADs
Watertight	Yes	The segments edges are sealed to avoid water entering in the sandwich structure
Production method	Cold slumping technology (sandwich of glass foils + Al honeycomb)	Well suited for effective mass-production
Reflective coating	Reflectivity at least 90% in the 300 - 550 nm range, non-uniformity < 8%	Al + SiO ₂ + ZrO ₂ + SiO ₂ evaporated coating to maximize reflectivity in Cherenkov wavelength range of interest and meet lifetime requ.
Optical surface shape	Spherical, three coronas with different Radii of Curvature: - COR1: RoC 56.3 ± 1.5 m - COR2: RoC 57.1 ± 1.5 m - COR3: RoC 57.9 ± 1.5 m	The design of the primary mirror is itself comatic and the theoretical optical response spread between about 0.04 deg on axis to 0.11 deg for a 1.2 deg off-axis source.
Structure I/Fs	3 Stainless steel PADs	Positioned on the back, 120° distance, on a circle of diameter 1300mm

Through intensive raytracing analyses, it has been evaluated that, considering the manufacturing process tolerances, these three radii of curvature can meet the telescope optical resolution requirement in terms of PSF on the required field of view. The D80 parameter (i.e., the diameter of the focal spot containing 80% of the focalized photons) must be < 0.1 deg for off-axis angles up to 1 deg, as shown in Figure 4.

The panels are the essential elements of the telescope's segmented primary mirror. Table 1 reports the main characteristics of LST-S M1 segments. Ultimately, the LST-S paraboloid is obtained by assembling spherical segments with a certain radius of curvature placed in a suitable position on the paraboloid to approximate the nominal shape.

As shown in Figure 4, the D80 across the FoV (Field of View) induced a degradation at the increase of the off-axis angle due to the coma aberration inherent to the parabolic configuration of the full primary mirror. The proposed solution based on three groups of spherical mirrors with different radii (blue line) to approximate a parabolic shape still meets the requirements. It's important to note that all the requirements will be thoroughly covered and verified during the production process qualification for LST-S mirrors as part of the CTA+ project [2].

Table 2. LST-S M1 segments' main environmental requirements need to be fulfilled.

<i>Requirement topic</i>	<i>Requirement Value</i>	<i>Remarks</i>
Observation temperature	$-15^{\circ} \text{ C} < T < +25^{\circ} \text{ C}$	Preliminary thermal test performed on prototypes (see chapter 4)
Survival temperature	$-20^{\circ} \text{ C} < T < +35^{\circ} \text{ C}$	
Temperature gradient	$< 7.5^{\circ} \text{ C/h}$	
Temperature shocks	$\pm 30^{\circ} \text{ C}$	
Survival air temperature gradients	$< 0.5^{\circ} \text{ C/min}$ for 20 minutes	
Observation humidity	2-90 %	Good heritage based on operative segments realized with the same technology [10]
Survival humidity	2-100 %	
Rain in 24 hours	200 mm	Heritage based on operative segments realized with the same technology [10]
Rain in 1 hour	70 mm	
Rain wind speed	$< 90 \text{ km/h}$	Survival loads have been deeply studied with FEM analyses [11]
Rain during transition	$< 2 \text{ mm/h}$	
Survival snow load	$< 20 \text{ kg/m}^2$	
Survival ice load	$< 20 \text{ mm}$	
Observation wind speed	$< 36 \text{ km/h}$	
Transition wind speed	$< 50 \text{ km/h}$	
Survival wind gust	$< 170 \text{ km/h}$	
Hailstone damage	$< 20 \text{ mm}$	Test already performed in the past for samples and/or smaller segments realized with the same technology verified this requ.
Solar radiation	$< 1200 \text{ W/m}^2$	
Aggressive atmosphere	$\text{NO}, \text{NO}_2, \text{SO}_2 < 3 \text{ ppb}$	
Water resistance	IP67	
Tape adhesion test	$> 16 \text{ N}$	Good heritage based on operative segments realized with the same technology [10]
Substrate lifetime	$> 15 \text{ yr}$	
Coating lifetime	$> 6 \text{ yr}$	

Table 2 provides a list of the main requirements. These segments must meet a comprehensive set of environmental requirements, mainly determined by the Chilean site where they will be used. In Table 2, the “Remarks” column reports the current compliance and heritage status (i.e., the same process has already been qualified in the past for other IACT) and the preliminary activities performed at the prototype level. The reflectivity and other optical performance requirements will be verified on all segments during mass production. In contrast, all other requirements will be verified at the start of production during the production process qualification.

4. PROTOTYPING ACTIVITIES

In recent months, we have carried out prototyping activities with the following objectives:

- Assess all the necessary tools and personnel needed for the manufacturing and handling of large segments
- Identify areas for potential improvements in the process
- Evaluate the repeatability of the replication process
- Understand the potential shape errors introduced by the process and their impact
- Set up the system to assess optical performance by measuring the focal spot in the 2f configuration

The PSF simulations involve ray-tracing of the mirror shape measured by a proper profilometer in both 2f configuration (for direct comparison with the optical test) and telescope configuration. The prototyping activities have been supported by an extensive FEM analysis campaign aimed at identifying the optimized mirror segment design [7]. The considered load cases include:

- ☐ gravity loads (G, for different telescope positions)
- ☐ ice loads (I, 20mm on both surfaces)
- ☐ operative wind (W, up to 36km/h)
- ☐ survival wind (W, up to 170km/h gust)
- ☐ bulk temperatures (T, range: -20°C to 35°C)
- ☐ temperature gradients (along surface and thickness) (T)
- ☐ cold shaping tensile stress frozen in the glass (CS)

Twenty-six different combinations of the above single loads have been analyzed. The specifications for the prototype activities are outlined in Table 3. These specifications were chosen as a trade-off between the FEM results and the materials and tools easily available from the market. Further refinement of these specifications will be carried out during the industrial contract to mass-produce the mirror segments.

All the hardware activities have been carried out with a pre-existing dummy mold previously developed by the University of Padova for other developments. Unfortunately, the mold suffers from some critical profile errors. Despite knowing in advance that the optical results on the mirror segments could not be inside the requirement, it was, in any case, decided to use the mold to start assessing all steps in the manufacturing, metrology, handling, and transportation and individuate possible weak points that might have required further investigation. This allowed us to save time while waiting to produce the final molds that will be employed to produce the series of LST-S reflecting panels.

The parameters of the developed prototypes are reported in Table 3.

Table 3. Parameters of the developed panel prototypes.

<i>Parameter</i>	<i>Value</i>	<i>Remarks</i>
Size	Hexagonal shape of 1500 mm flat to flat	10mm less wrt specification due to available bulk mould
Shape	Spherical with around 60 m RoC	RoC not in requirement due to available bulk mould
Thickness	46 mm in total (3mm glass foils + 40 mm Aluminum honeycomb core)	In agreement with FEM analyses and available material
Coating	Al + SiO ₂ + ZrO ₂ + SiO ₂ Reflectivity checks for value and uniformity	Confirmation of production method applicability for this size of mirrors, and check of handling procedures and test jigs. Fine-tuning of all process parameters to be carried out during the qualification phase of optics contract with industry for mass-production
PADs	3 glued on the back at 120° on a circle of 1300mm from center	I/Fs PADs applied glued on the back: Position as per requ. But PADs design slightly different (based on available material)
Optical specifications	Shape: measure with 3D CMM TCX Optical spot: PSF meas. With 2f set-up	not in requirement due to available bulk mould. Activity useful to check handling and metrological procedures and set-ups and ray-tracing analyses.
Thermal tests	Range: -20/+50 °C Rate: 30 °C/h (0.5°C/min) Dwell time: 30 min Number of cycles: 3	T range as per requ. Tests carried out at ambient pressure

5. RESULTS FROM THE FEM ANALYSIS AND PROTOTYPE METROLOGY

5.1 FEM analysis

A Finite Element Method (FEM) analysis was conducted to help select the most suitable glass and aluminum honeycomb core thicknesses. After a thorough study, it was determined that 3mm glass foils and 40mm aluminum honeycomb were the optimal choices. These dimensions ensure the glass experiences relatively low tensile stress after being subjected to cold shaping (see Figures 5 and 6). These parameters also provide the necessary stiffness to meet optical and structural requirements under operational and survival loads.

When the vacuum suction holding the glass on the mold during cold slumping is turned off, the glass returns to its original shape, causing a spring-back effect in the sandwich structure. This creates tensile stresses on the glass, which need to be considered along with other loads. The intensity of this effect depends on the glass's thickness, as illustrated in Figure 4.

A summary of the results obtained with the FEM analyses is reported in Table 4. For all load cases considered, the higher stress inside the glass has been compared with the assumed design glass strength according to the standard EN 16612, i.e.:

- $f_{gd} = 7.25$ MPa in loading combinations with permanent loads (cold slumping and gravity, i.e. CS and G).
- $f_{gd} = 18.5$ MPa in loading combinations with wind (W).
- $f_{gd} = 11.25$ MPa in loading combinations without wind (permanent loads, ice, and/or temperature loads I / T).

Utilization factor (UF) is used to quickly depict the stress status, defined as the ratio between the maximum tensile stress and the design strength f_{gd} . The computed values are always lower than one, confirming the design's ability to sustain the considered load cases.

Table 4. Utilization factors computed for the worst cases derived by FEM analyses.

Load Combination	Maximum Tensile Stress (MPa)	UF (Utilization Factor)	Load Combination	Maximum Tensile Stress (MPa)	UF (Utilization Factor)
G	4.58	0.63	G	4.81	0.66
I/T	10.1	0.90	I/T	10.5	0.93
W	12.9	0.70	W	16.2	0.87
Upper glass faceplate			Lower glass faceplate		

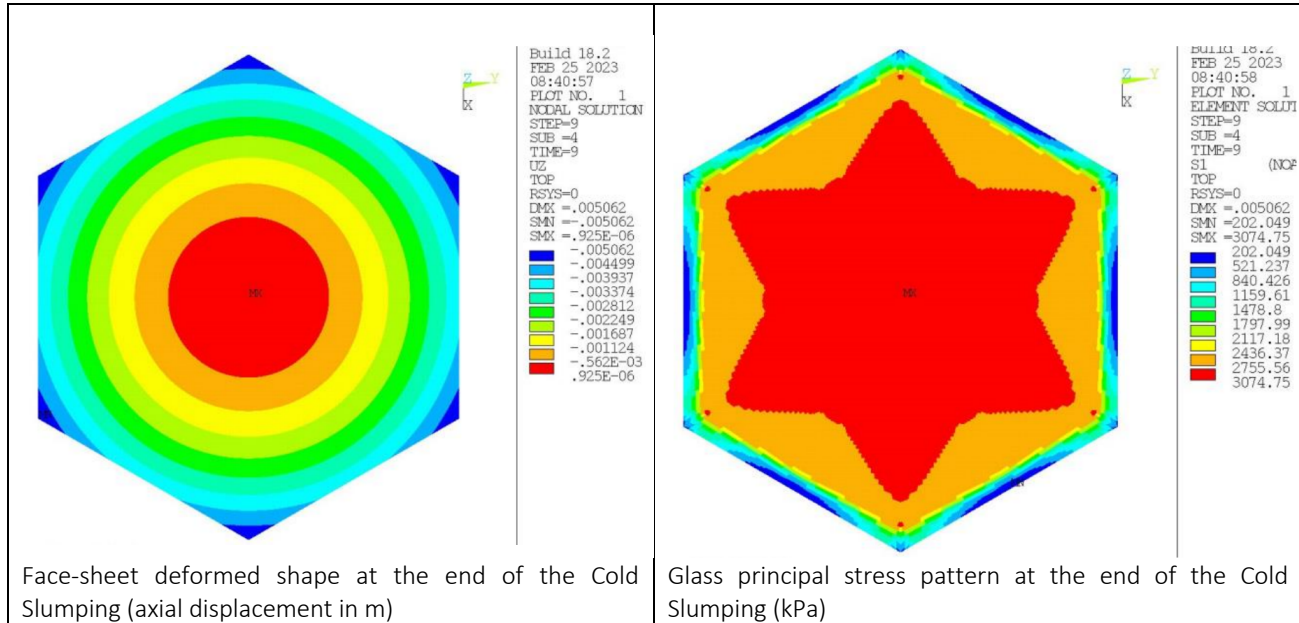


Figure 5. Shape deformation due to the spring-back effect in the glass in the cold slumping process.

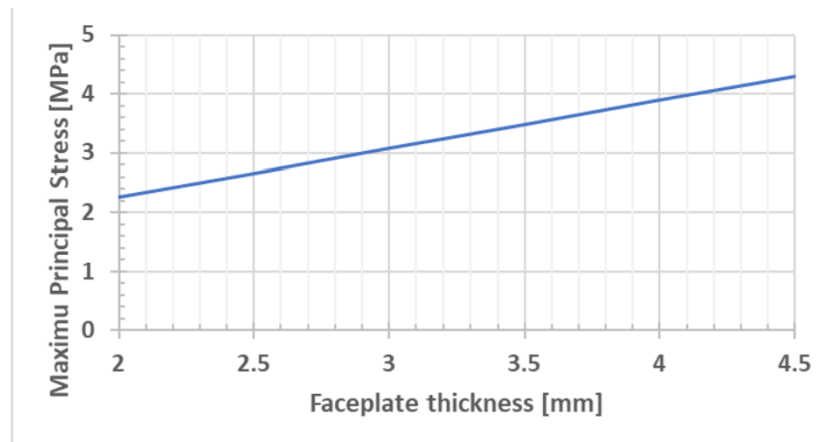
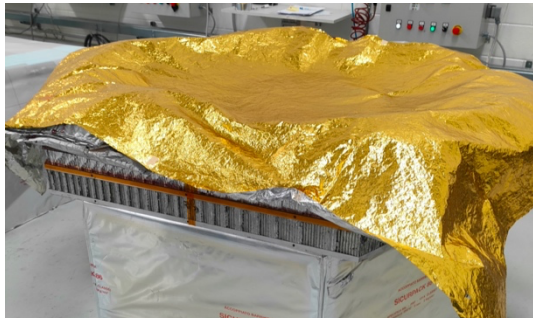


Figure 6. Maximum principal stress inside the glass due to cold slumping versus the thickness of the glass slabs, as computed in the case of $RoC = 56$ m.

5.2 Parameters inferred from the prototypes

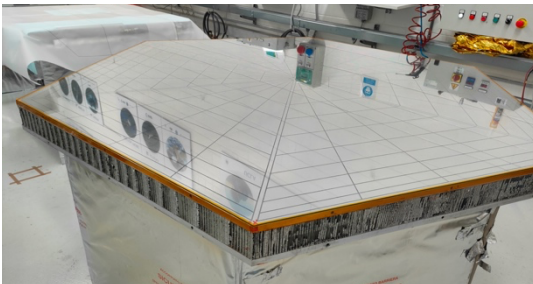
Figure 7 shows the cold-slumping technology steps adopted to produce three prototypes.



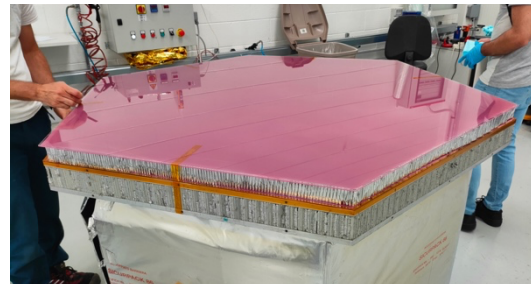
The glue is given time to properly cure.



After coating and I/Fs PADs application, one segment performed thermal test



The make-up available mould is prepared for the process



The sandwich structure of mirror segment (glued stack of glass-honeycomb-glass) is positioned on the mold

Figure 7. Cold-slumping technology steps to produce the LST-S mirror segment prototypes.

As mentioned, the dummy mold used for this process has a less-than-ideal shape. When measured using a proper contact profilometer (3D CMM TCX model), the resulting mold's Radius of Curvature (RoC) was approximately 58 m. Still, the shape was primarily characterized by a significant bump in the center of about 25 μm from peak to valley. The bump is well replicated in all the produced prototypes; therefore, as expected, the optical quality would not yet meet the LST-S reflecting panels requirements, as reported in Table 1.

On the positive side, however, the process has been demonstrated to apply to large mirror segment production, showing its repeatability in shape and focal length replication. Figure 8 shows the results obtained with a 3D CMM TCX contact profilometer. The bump is visible on the mold and then transferred to the glass after replication. The RoC obtained on the glass is around 60 m, slightly more than the mold due to the (expected) spring-back effect of the glass.

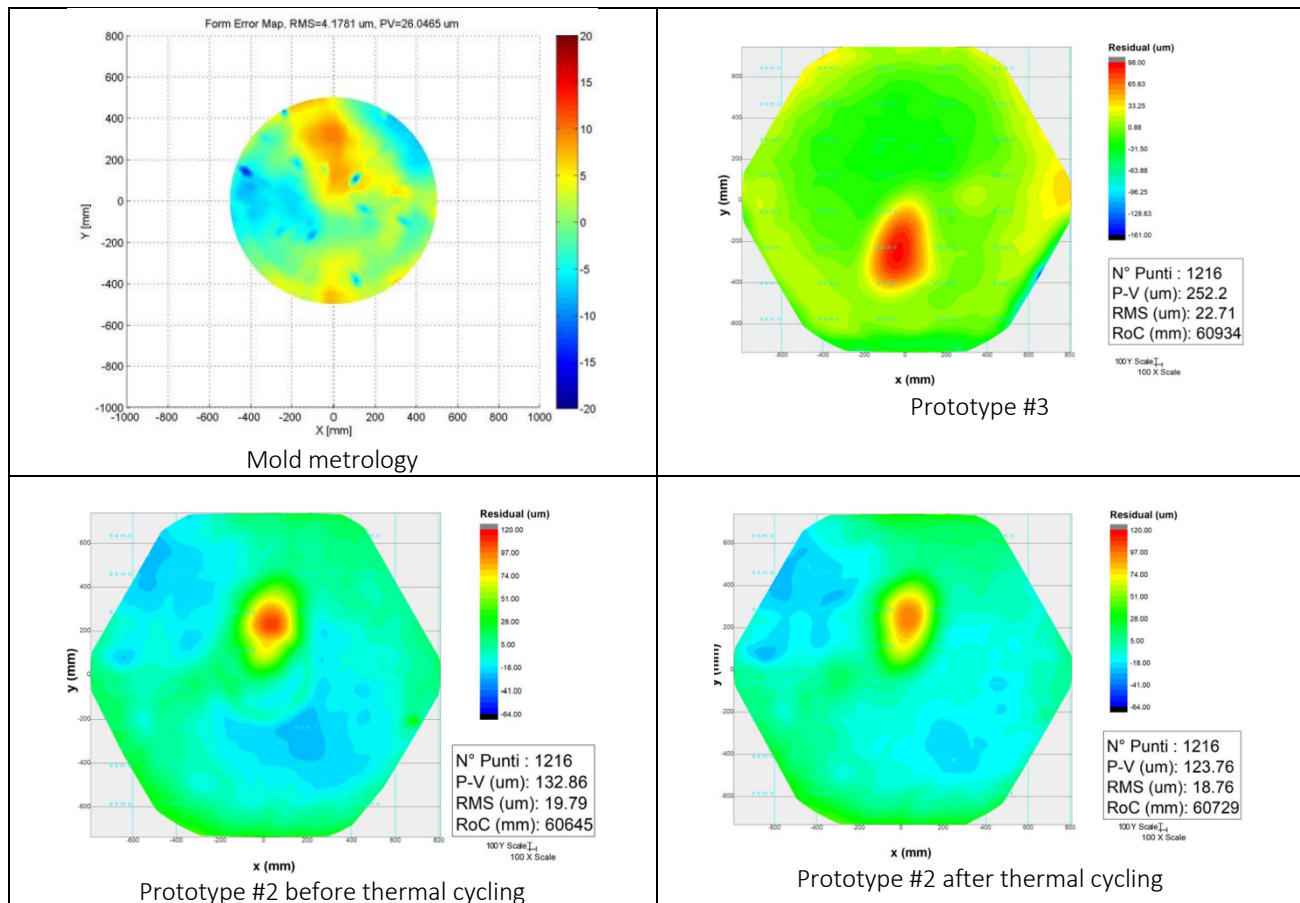


Figure 8. 3D CMM TCX contact profilometer measurement of the mold and a replicated prototype.

The results are also confirmed by the 2f optical measurement, which checks the metrological setup and the raytracing code simulations, as reported in Figure 9.

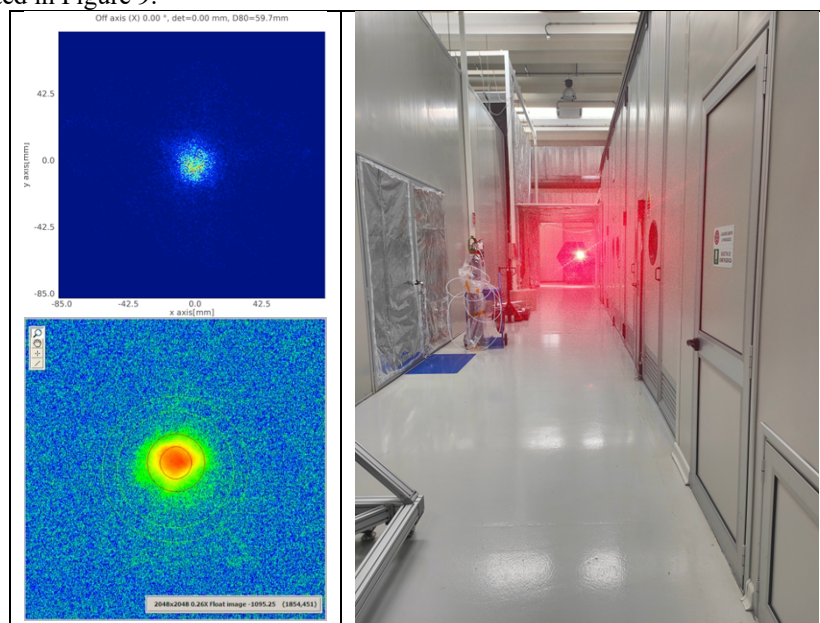


Figure 9. 2f setup for the prototype optical performance check (simulations vs. measurements).

The prototypes have been coated with an Al reflective layer plus a SiO₂ + ZrO₂ + SiO₂ protective multilayer. The reflectivity has been measured with the instrument Filmetrics LS-DT2 thin-film analyzer in 12 points distributed along three diagonals on the mirror. The collected data are reported in Figure 10. They show average values higher than 90% in the wavelength range of interest 300-550 nm, with uniformity within a few %.

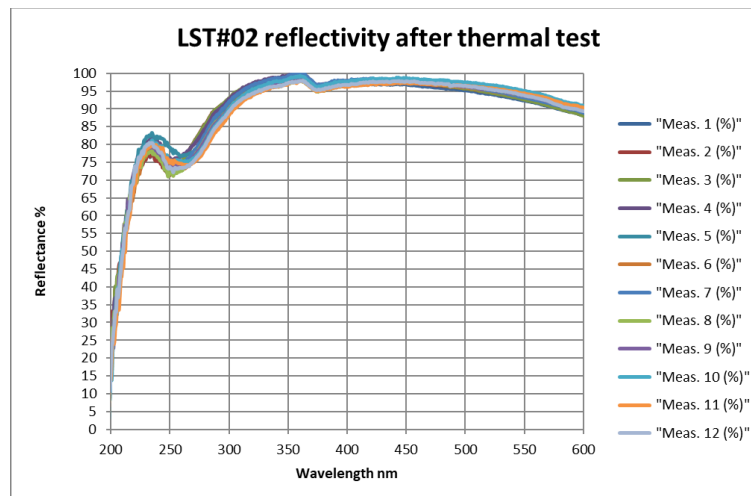


Figure 10. Reflectivity measurements versus wavelength carried out on 12 points distributed along three diagonals on the panel prototype.

Finally, one prototype was subjected to a thermal test to check process stability. The panel was supported inside the thermal chamber through the back, using the three interfaces' pads glued on it. The temperature inside the chamber was constantly monitored and recorded by two thermocouples PT100 type, one positioned on the front and one on the rear of the mirror segment. The recorded temperatures are reported in Figure 11. It should be noted that the gradient considered for cycling is relatively high, almost 30°/h. This does not represent an operative requirement; instead, it was selected as a worst-case condition to account for survivability requirements. A visual inspection was carried out on the mirror segment at the opening of the chamber, and no changes or defects have been found. The shape and reflectivity of the segments have been measured before and after the thermal cycling, and no differences have been recorded; tiny variations are present in the measurement repeatability. This confirms the survival in the thermal environmental condition and the stability of the production process.

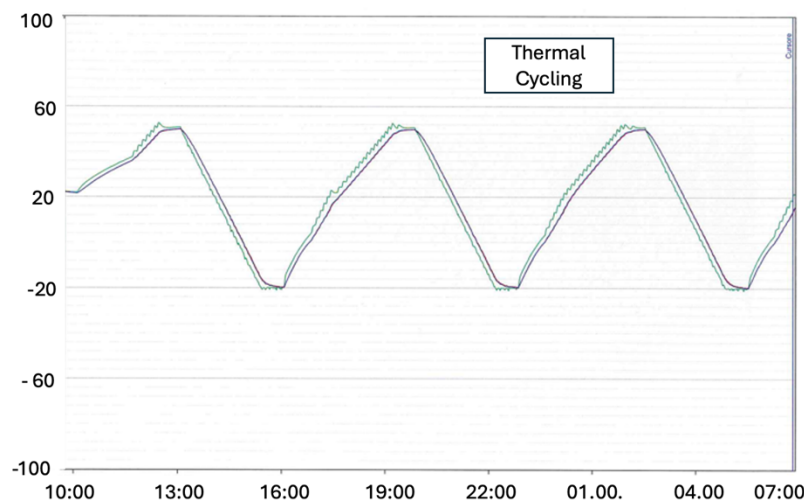


Figure 11. Thermal cycling (the temperatures reported in the y-axis are in °C, versus the time in hours in the x axis).

6. CONCLUSIONS

The design and prototyping activities carried out on the 1.5m large mirror manufactured by cold slumping technology demonstrate the applicability of the technology to produce the more than 400 mirror reflecting segments necessary for the assembly of two CTAO LST-S telescopes (including spares). Through the activities performed on prototypes, we demonstrated the applicability and stability of the cold-slumping technology for such large mirror segments, up to little more than 1.5m hexagonal shape flat-to-flat. It has been possible to check that with fine-tuning of the process parameters, the mirror's shape and Radius of Curvature are repeatable within the necessary tolerances. Unfortunately, the available mock-up mold limited the optical quality of the prototype, mainly because of a significant bump present in its shape that has been replicated in the mirror segments. Nevertheless, it was possible to check all the production, handling, and metrology procedures for such large segments to be prepared for the start of LST-S M1 mirror segments mass production envisaged to start by the end of this year. Before that, a deeper fine-tuning of all parameters will be carried out with the first 36 segments. This will serve as process and production line stability qualification in the CTAO LST-S reflecting panels procurement led by INAF-OAB and performed with the support of other institutes and industrial partners.

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