Techniques for the manufacturing of stiff and lightweight optical mirror panels based on slumping of glass sheets: concepts and results

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ABSTRACT

In the last decade Very High Energy (VHE) gamma-ray astronomy has improved rapidly opening a new window for ground-based astronomy with surprising implications in the theoretical models. Nowadays, it is possible to make imaging, photometry and spectroscopy of sources with good sensitivity and angular resolution using new facilities as MAGIC, HESS and VERITAS. The latest results of astronomy in the TeV band obtained using such facilities demonstrate the essential role of this window for high energy astrophysics. For this reason new projects (e.g. CTA and AGIS) have been started with the aim to increase the sensitivity and expand the energy band coverage.

For such telescopes arrays probably tens of thousands of optical mirror panels must be manufactured with an adequate industrial process, then tested and mounted into the telescopes. Because of the high number of mirrors it is mandatory to perform feasibility studies to test various techniques to meet the technical and cost-effectiveness requirements for the next generation TeV telescopes as CTA and AGIS.

In this context at the Astronomical Observatory of Brera (INAF-OAB) we have started the investigation of different techniques for the manufacturing of stiff and lightweight optical glass mirror panels. These panels show a sandwich-like structure with two thin glass skins on both sides, the reflective one being optically shaped using an ad-hoc slumping procedure. The technologies here presented can be addressed both for primary or secondary mirrors for the next generation of Cherenkov telescopes. In this paper we present and discuss the different techniques we are investigating with some preliminary results obtained from test panels realized.

Keywords: Segmented Optics, Glass Slumping, lightweight optics, Cherenkov telescopes, CTA, AGIS

1. INTRODUCTION

The astronomy in the TeV band has achieved exceptional results since the discovery of TeV emission from the Crab Nebula by Whipple in 1989 to the most recent sources (about 100) detected thanks to the high sensitivity of the present days Cherenkov telescopes. Both galactic and extragalactic sources has been detected using very large mirror areas such for the two MAGIC telescopes in La Palma (Canary Islands) and the high performance of the telescope arrays such as H.E.S.S. in Namibia or VERITAS in Arizona (USA).

The international communities working in the TeV astronomy both in Europe and USA are now involved in the study of huge arrays of Cherenkov telescopes such as the Cherenkov Telescope Array (CTA) [1] and the Advanced Gamma-ray Imaging System (AGIS) [2]. The ambitious goal is to reach sensitivity above one order of magnitude greater than the current instruments in the very wide energy range from 10 GeV to more than 100 TeV. These new, complex and very large facilities need, among other things, a substantial technological development of many telescope subsystems. From the installation, operational and maintenance procedures of each single telescope to the efficient coordination of the complete array in a structure organized as an observatory, from the data handling and archiving to the huge power supply need and management.

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Figure 1 shows the two concepts of the telescopes array distribution for both the projects under studies, respectively CTA and AGIS, while in the right panel is visible the double reflection telescope that will be adopted by AGIS. In fact the two projects adopt a different layout. In CTA it is foresee a number of telescopes divided in three different classes: small, medium and large size of respectively about 6, 12 and 23 meters in diameter. All the telescopes will probably adopt a more conservative, but proven, single reflection Davies-Cotton [3] (D-C in the following) optical design. Meanwhile the AGIS collaboration is intensively studying an array with a 36 telescopes layout exploiting a more innovative Schwarschild-Coude' [4] (S-C in the following) optical design. The S-C telescope takes advantage of a double reflection mirrors configuration on strong aspherical surfaces showing a wide aplanatic field of view with almost constant angular resolution. In particular the secondary mirror of such instruments seems quite challenging from the manufacturing point of view because it has a pronounced concave surface, with sags of 30-50 mm on a single 1 m^2 mirror panel.

The final layout of these arrays is still under investigation through Monte Carlo simulations, but it is foresee, as order of magnitude, to have about 10000 m^2 of total reflecting area with single telescopes reflectors reaching up to 400 m^2. Each reflector composed by a number of 1-2 m^2 sized mirror panels. Typical angular resolution requirement is of the order of a mrad (below a few arcmin for each mirror panel), a relaxed value compared to PSF for optical telescopes. Another peculiarity of Cherenkov telescopes is that mirrors are exposed to the environment because the absence of a protecting dome. For such and others reasons the technological goal is to manufacture mirrors with a number of challenging characteristics as low-cost, light-weight, robust, showing an adequate reflectance and focusing qualities and demanding limited maintenance [5].

In this paper we concentrate on these aspects, in particular we suggest two technologies under development in Italy at the Astronomical Observatory of Brera. Both are based on the manufacturing of glass mirror panels with a sandwich-like structure. The following sections 2 and 3 are divided in two sub-sections each. They describe respectively the technologies proposed and related results obtained on mirror prototypes realized so far. Section 4 reports some conclusions and future steps of our work.

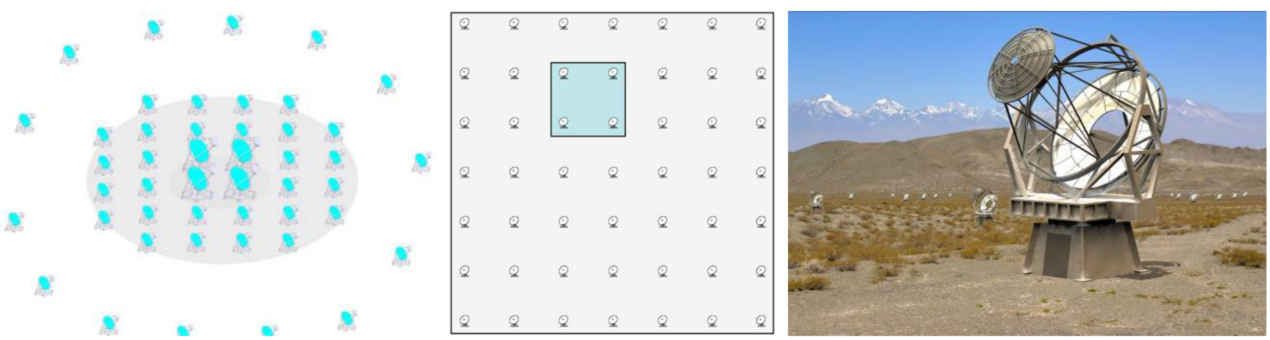

Fig. 1. (left) Concept for the telescopes array of the CTA project. (center) Concept for the telescopes array of the AGIS project. (right) Artistic impression of the S-C telescopes adopted by AGIS (credit: AGIS web pages).

2. TECHNOLOGICAL APPROACHES UNDER INVESTIGATION

The two processes here described produce composite glass mirror panels with a symmetric sandwich-like structure as shown in the left side of figure 2. Each panel is composed by two thin glass sheets glued as skins of a suitable material being the core of the panel itself. The front glass sheet is conformed to the desired optical shape using a process based on the replication of a master, while the rear one is used to increase both the stiffness and the thermal stability of the panel when exposed to temperature variations.

The choice of the material for the core plays a very important role in the design of the panel. To obtain an overall panel with low weight (areal density in the order of 20 kg/m^2), but high stiffness we use materials with a foam structure. In fact, they show good performances in stiffness and weight if compared with bulk materials of the same density. Also, milling (or turn on a lathe) these foam boards on the front side it is possible to shape them and match the curvature of the glass sheet in contact with the master. This step helps in maintaining as constant as possible the thickness of glue between core board and front glass sheet when the sandwich is assembled. This avoids differential shrinkages (from point to point) of the glue and hence it allows a better copy of the master's shape.

In both the approaches hereafter presented the production can be easily transferred to an industrial process as already proven with the glass mirror panels of the MAGIC II telescope manufactured by the Italian company Media Lario Technologies [6]. In addition, the production time can be relatively fast with a final cost per panel maintained quite low, in the range of few thousands of Euros depending from the approach.

The following sub-sections contain a description of the two approaches, while the scheme in figure 2-right summarize the main features of them.

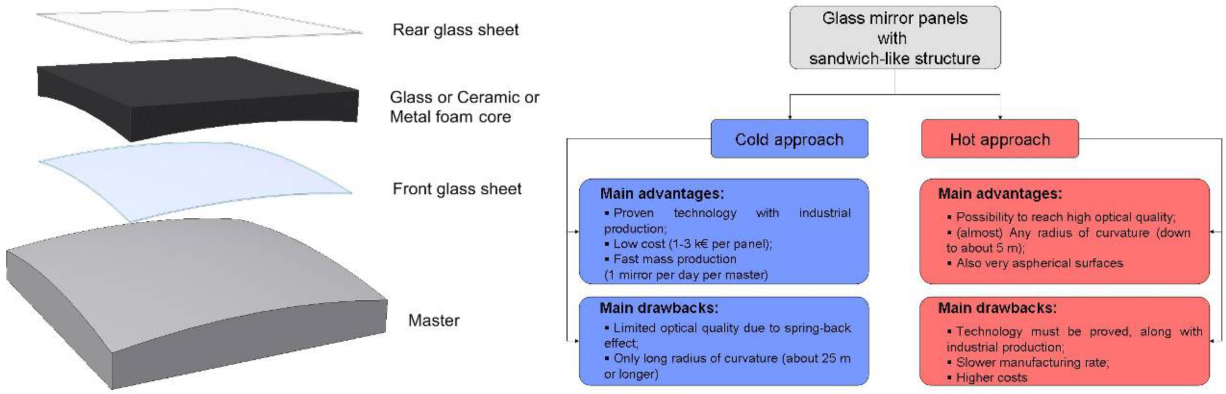

Fig. 2. (left) Blow-up sketch showing the principal components of the mirror panels described in this paper. The master is used to shape either with cold or hot approach the front glass sheet. The mirror panel is then assembled gluing the foam board as core and another glass sheet so to realize a sandwich-like structure. (right) Summary of the main pros and cons for the described technologies.

2.1 Cold slumping approach

As already successfully experimented for almost half of the mirror facets installed on the MAGIC II Cherenkov telescope we propose a similar technology for the manufacturing of mirror panels. As described in past papers [6][7] the process foresees to copy the shape of a master taking advantage of the elastic deformation regime of thin glass sheets.

Following the scheme in figure 3, a glass sheet with thickness in the range of 1-2 mm is uniformly pushed against a master using a vacuum suction. The geometrical shape of the master has to be worked so to have the same precision needed for the final mirror, while the surface of the master should be smooth because every defect on it will be reproduced on the glass.

If the curvature of the master is large enough, the glass will bend without broke it. In general, thinner the glass sheet is, better the copy of the master geometry will be. However, the sheet thickness can not be took as thin as possible, but must be carefully evaluated during the mirror panel design in order to ensure adequate robustness of the optical surface. In fact, Cherenkov telescopes don not have a protective dome and their mirrors must survive to strong environmental conditions: night-day thermal gradient, wind, snow, frost, etc.

In order to provide the necessary rigidity and to maintain the glass sheet in the deformed shape a reinforcing structure is glued and at last, a second glass sheet is added to form the sandwich. The gluing process is one of the most critical phases of the procedure. In fact, both the choice of the glue type and the capability to apply a uniform bonding layer are very important points to get a good replica of the master's shape. Low percentage shrinkage, in the order of 0.1 % or less, UV resistant and a wide range of operational temperature are all parameters that must fit in the glue characteristics.

After the curing of the glue, the vacuum force can be eliminated and the panel released from the master. At last, the front side of the sandwich panel can be coated with a suitable reflecting layer and a protective one, typically Al and SiO_2 respectively. Repeating these steps it is possible to manufacture a number of equal mirror panels with a short production time, as for MAGIC II in the order of one panel per day per master.

As discussed in the introduction of the paper, the next generation of Cherenkov telescopes will have optical designs in some cases very different from the classical D-C one, widely used up to now. This implies the use of mirror dishes having increased performances both from the mechanical and optical point of view. As mentioned, the geometrical area of each mirror panel is foresee to be increased up to 1-2 m^2 with a PSF not worse than about 1 mrad.

The way we are pursuing is to substitute the Aluminum honeycomb core, used in the mirror panels produced for the MAGIC II telescope, with a more performing material. We are investigating foams, in particular a glass one called Foamglas® [8] from Pittsburg Corning company: it is an all-glass closed-cell structure material composed of millions of completely sealed glass cells. It shows a number of interesting characteristics that made it particularly attractive for our application. It comes in lightweight boards produced in several thicknesses, from 40 to 120 mm, and density ranging from 120 kg/m^3 to 165 kg/m^3, it is stiff and easy to work. Moreover, it is waterproof, stable in time with a low CTE of about 9 μm/K · m and, last but not least, the cost is below hundred of Euro per square meter.

Due to the stiffness of the Foamglas® boards, into the process described before must be added few steps. A number of boards will be assembled together so to form the tile shape needed. At this point we have a plano-plano panel, this will be worked on the front side so to obtain a plano-concave shape fitting the curvature of the master and then used as core of the sandwich (see figure 2-left). The machining of this blank panel has been done in the labs of INAF-OAB using a dedicated facility, a CNC milling machine similar to a pantograph capable to work on pieces up to 1500x1700 mm.

We think that using Foamglas® instead of Aluminum honeycomb it will be possible to produce mirror panels with better characteristics respect to the present ones. Some expected improvements are here summarized.

As before mentioned, being the core worked to match the shape of the curved glass sheet, the final mirror panel results to be in a more stable condition, with spring-back effect limited just to the front glass sheet and not to the whole sandwich.

An increase of the tile area of each panel will require also an increase of the thickness of the panel itself in order to maintain the rigidity. This could translate in a more difficult handling during the on-site assembly and/or maintenance of the telescope mirror dish, something that should be avoided especially for projects that foresee a large number of telescopes such as CTA and AGIS.

Also, the linear dimensions of the cells are typically smaller than the hexagons of the honeycomb and this imply a wider surface of contact between the glass skin and the core board. So, the glass sheets are glued to a more uniform supporting structure and probably the thickness of the skins can be reduced with benefits both in the master's shape copy capability (thinner sheets are more flexible) and overall panel's weight.

Using glass also for the core of the panel we realize essentially an all-glass mirror panel in which it is reduced of about a factor 3 the CTE mismatch between the principal components of the panel itself (skin-core-skin), respect to the MAGIC II glass mirror panels. This will have a net improvement in the stability of the focal spot produced by the mirror when exposed to environmental thermal gradients, with no differential expansion/contraction between skins and core.

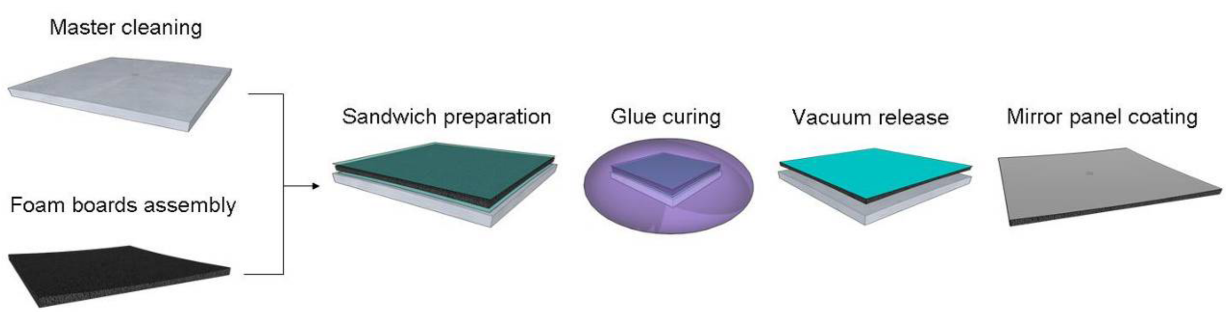

Fig. 3. Main steps of the cold slumping approach proposed for the production of mirror panels for D-C Cherenkov telescopes. A thin glass sheet is elastically deformed so to copy the shape of a master, then is glued a pre-worked foam board and a second glass sheet so to form a sandwich-like panel. After the glue curing the panel is released and the coating is applied.

2.2 Hot slumping approach

The process we are proposing has been already partially discussed in previous paper [9] and it is herein summarized for completeness. It can be divided into two separate steps shown in figure 4: the first one uses a thermal forming procedure to conform the shape of a thin glass sheet to a mould. This sheet having low thickness is obviously very floppy and needs to be stiffed up. In the second step, with the glass still placed in contact with the mould, the sandwich-like structure is assembled gluing on its back a reinforcing material and a second glass sheet.

In fact, unlike the cold approach above described, it is also possible to shape the glass sheet applying a thermal cycle up to temperatures above the glass transition temperature T_g, where the glass viscosity becomes low enough to permit to the glass sheet to slump and retain permanently the new geometry when cooled down. The use of a hot glass forming step can be unavoidable if it is foresee to manufacture a mirror panel having short radius of curvature or strong aspherical geometry. Moreover, it is possible to copy with better accuracy the structures of the mould also in the high spatial frequency domain. This last characteristic translates in an overall better copy of the mould and hence in a higher optical quality of the mirror panel. On the other hand, it is important to have a very good figured and polished mould, with a microroughness surface finishing being at a level similar to the requirement for the mirror segment.

The first step is derived from an ongoing R&D program started for an ESO FP6 activity for the development of a technique based on hot slumping of thin glass sheets to manufacture floppy glass shells for adaptive optics [10][11][12]. A mould, having as a shape the negative of the desired optical profile, is manufactured in a suitable material; it has to withstand high temperature with no major shape changes during the thermal cycle and after repeated ones. In addition, the CTE of the mould should be as similar as possible to the glass to be slumped to have a close replica.

After a deep cleaning of the two components (mould and glass sheet), they are placed onto a muffle with vacuum capability. Roughly, the muffle is a stainless steel box that permits to remove the air convection, with advantages in terms of homogeneous heat distribution, and it protects from the dusty ambient of the oven.

The muffle is placed inside the oven. A suitable thermal cycle is applied up to 650 °C (depending from the glass type); during the slumping a uniform pressure of about 150 g/cm^2 is applied on the glass so to force it against the mould surface. This ensures the full contact of the glass against the mould. At the end, the glass sheet will have copied the shape of the mould. The process is able to replicate the features at high spatial frequencies, and this explains why a superpolishing of the mould is needed.

Based on the experiments we have already done and using our facilities it is possible to reach the maximum temperature with limited (< 5 °C) thermal gradients inside the muffle in less then one day on an oven volume of 1.3 x 1.3 x 0.6 m^3. The total thermal cycle has duration of about 3 days before the cool down to room temperature and this gives a time scale for the production of such a mirror panel.

After thermal shaping of the glass sheet we force it completely against the mould itself trough an air suction, in a similar way as in the cold approach above described, so to eliminate any difference between mould and glass due to CTE mismatch. If the choice of material has been done following a good trade off, the difference in shape to be removed is so small (tens of microns at most) that in practice no stresses will be introduced and no spring back force will be present in the finished mirror panel, contrary to the cold approach.

The next steps follow the same philosophy of the ones described in the sub-section 2.1: to freeze permanently its shape increasing the stiffness of the glass sheet. A thin layer of glue (0.2-0.3 mm) is uniformly distributed on the glass sheet and the reinforcing low-density foamed board is glued to form the sandwich-like structure. Also in this case the core board is pre-shaped on one side to allocate the curvature of the slumped shell. The glue is cured following the proper thermal cycle, if needed, and then the sandwich is released from the mould.

Also in this case we are experimenting the use of Foamglas® boards as core of the mirror panel and for this reason all the consideration mentioned in the previous sub-section are still valid: very low weight of each panel, high thermal stability due to good match in CTE, use of low cost materials and fast production rate. Nevertheless, using the hot approach here described it is possible to get high optical quality mirror panel, well beyond the real needed for a classical D-C Cherenkov telescope. Instead, a more interesting application can be in instruments with a more complex optical design such as the S-C telescopes of AGIS that requires mirror panels of higher quality with a pronounced curvature.

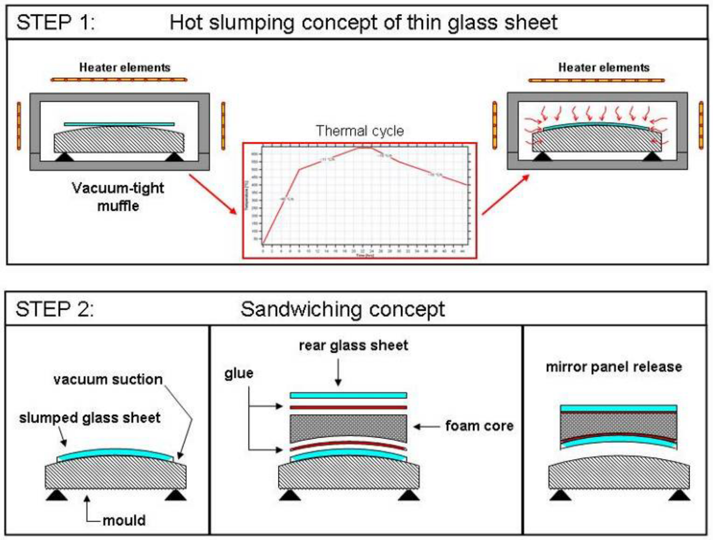

Fig. 4. (top) Hot slumping concept: a thin glass sheet is placed above the mould having convex shape; mould and glass are hosted inside a vacuum-seal muffle. The process foresees to reach a temperature of about 650 °C and to apply a uniform pressure to copy the shape of the mould. (bottom) Sandwiching concept: once the glass has been hot slumped the sandwich is assembled. A pre-shaped foam board and a second glass sheet are glued on the back of the front glass sheet.

3. TESTS AND RESULTS ON MIRROR PANELS PROTOTYPES

In the present section are reported a number of results obtained measuring and testing some mirror panel prototypes realized by the authors. These prototypes have been realized using both the approaches presented in this paper, but mainly for reasons of simplicity in the procedure, costs and production time we focused on panels realized by cold approach. For similarity in the use of materials and linear dimensions of the mirror panels some of the results presented can be totally transferred to panels manufactured with the hot approach.

All the measurements and tests here reported have been done using equipments (fig. 5) installed in the labs of INAF-OAB, mainly aimed to the focusing capability of the mirrors. This has been done using a long horizontal optical bench equipped with a laser source, an optical layout for the generation of the spherical wavefront (lens and pinhole) and a CCD camera for the acquisition of the focal spot image. The bench works in a so called “2-f configuration” where a spherical wavefront is reflected and concentrated by the mirror under test, located at a distance equal to the radius of curvature (double of the focal length, 2-f) so that each light ray strikes the mirror surface perpendicularly. In this case, due to the very long radius of curvature, the bench is composed of two stages: one with the laser source, the camera and the mirror to be tested, while the second one at a distance equal to the focal length hosts a flat folding mirror. In addition, some mirror panels have been tested also after undergoing thermal cycling. For the prototype realized with the hot approach we have also measured the optical quality with an interferometer.

Fig. 5. Instrumentations used for the measurements of the mirror panel prototypes. From left to right: horizontal optical bench for focal spot measurement (laser source, lens and pinhole for spherical wavefront generation, CCD camera for image acquisition), 100 mm ZYGO GPI-XP interferometer and chamber for thermal cycling.

3.1 Cold slumping

The prototypes realized and presented hereby have been replicated from one of the aluminum master used for the manufacturing of the glass mirror panels of MAGIC II. The master has a squared tile shape of 1000 mm side, while the surface is a convex sphere of about 36300 mm radius of curvature. The figuring of the master has been done with a fly cutting milling technology using a diamond tool, by LT-Ultra company (Germany). The measured figure P-V is of about 21 μm and the RMS of 4.5 μm. The glass sheets used are Borofloat 33 type from Schott with a thickness of 1.1 mm.

A number of mirror panels with dimensions of 300x300 mm have been realized and tested. The choice to start with these small dimensions was done for practical reasons: very easy handling for most of the tests and measures and easy preparation of the Foamglas® boards used for the core of the panels and to take practice and set-up a working procedure.

The left picture in figure 6 shows one panel still on the master and during the curing of the glue. The light coming from the bottom is to heat the master and cure the glue at the right temperature, while in the central picture it is possible to see an aluminized mirror panel. As visible, there is a clear edge effect coming from the replication process. In fact, to protect the soft surface of the master from possible damages from the edges of glass sheet, we use a thin foil of breathing material. This foil prevents the complete contact of glass with the master's surface and hence, approaching the edges, the shape of the glass sheet deviates from the master's one. On the right photo is visible, projected on a building wall, a typical image of the Sun generated by the panel. The spot is round and sharp, meaning that the edges are not affecting in a significant way the focusing quality of the mirror.

Fig. 6. (left) Mirror panel prototype 300x300 mm and master during the curing phase. (center) Panel as it is after the aluminum coating. (right) Image of the Sun generated by the mirror panel.

Being these mirrors well different from what it is classically considered having an optical shape, their focusing capability is obviously limited. On the other hand a high focusing capability is not necessary for this kind of application due to the nature of the observed light source and a parameter as the FWHM is not the optimal one to describe such mirrors. In general it is more convenient define the disk containing the 90% of the reflected energy. In the following, the diameter related to this disk is reported and indicated as D90.

In figure 7 left side is shown as an example the focal spot generated by a prototype into the radius of curvature. The right panel reports its measurement, where the D90 is of about 0.5 mrad, being the radius of curvature about 32000 mm. The difference in the radius of curvature from the one of the master can be ascribed to a local shape deviation of the maser itself form a perfect sphere of 36 m radius of curvature. However, the reported value of the D90 is already well below 1 mrad, the typical specification for a Cherenkov telescope.

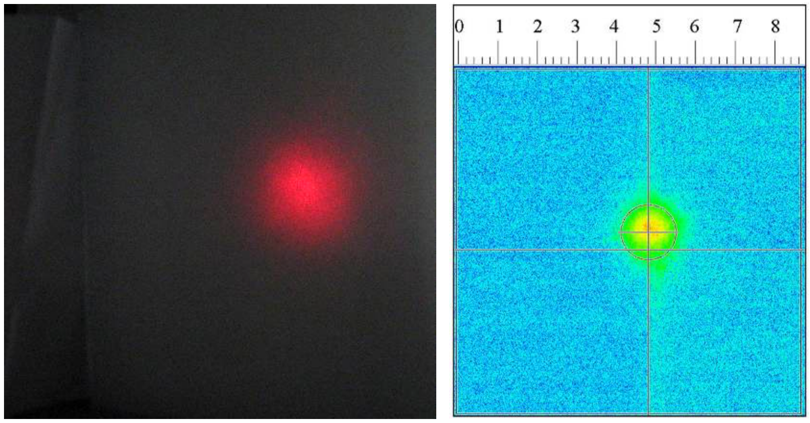

Fig. 7. (left) Focal spot generated into the radius of curvature by a spherical wavefront. (right) Measure of the focal spot, the small circle superimposed to the image contains the 90% of the energy.

To observe Cherenkov light limiting the atmospheric absorption, telescopes are placed on top of mountains, above 2000 m a.s.l. The mirrors are continuously exposed to atmospheric conditions variations that could be very strong, with day-night temperature variation of 30 °C and mirrors heated up to 50 °C on sunny days.

Mirror panels must be intensively tested for survival. A few of them have undergone a rapid thermal cycle after which a measure of the focal spot has been taken. This has been repeated for a number of times and the results compared to check any degradation of the focusing quality of the mirrors. The different types of thermal cycles applied are shown in the graph of figure 8 and spans from -20 °C to 60 °C in few hours, while in the right part of the figure a set of focal spots are presented. Till now the mirrors tested have shown no appreciable degradation of the D90. However, this result must be carefully considered due to very small dimensions of the prototypes tested with respect to a full scale mirror panel. Nevertheless, it is an encouraging preliminary result that must be repeated on full scale mirrors.

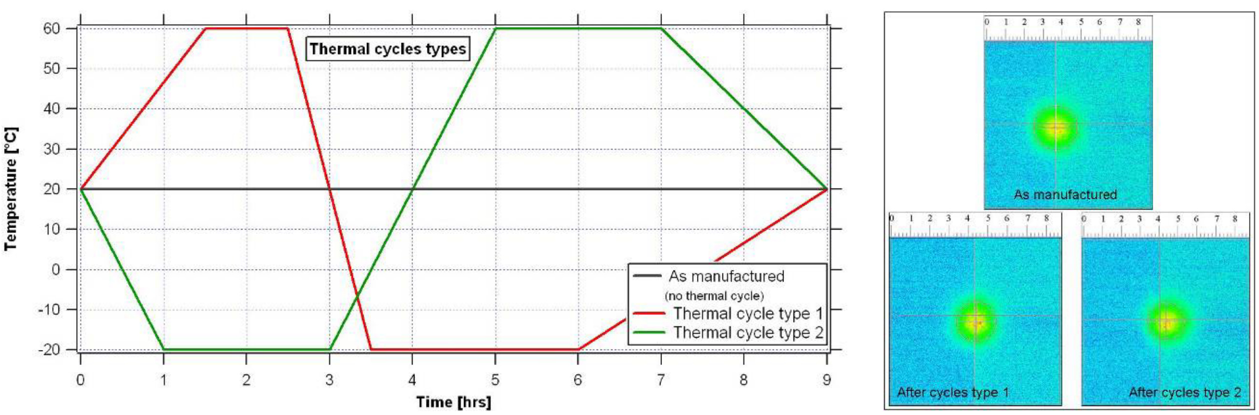

Fig. 8. (left) Thermal cycles used for testing the survival of prototypes. (right) A set of focal spot images showing a not appreciable degradation of the D90 after thermal cycling.

Recently, has been realized a scaled up mirror panel prototype using Foamglas® boards as core, the geometrical area has been increased by a factor of 4. The pictures in figure 9 shown some moments during the manufacturing. From left to right: the assembly of Foamglas® boards to realize the blank panel to be machines as described in sub-section 2.1, the spread of the thin and uniform layer of glue being one of the most crucial step of all the procedure, and last the 600x600 mm mirror panel after the vacuum release. Still yet with a not optimized design, this panel has a weight of just 4.5 kg that scales to about 12 kg/m^2, a value of areal density already into the specification for the next generation of Cherenkov telescopes.

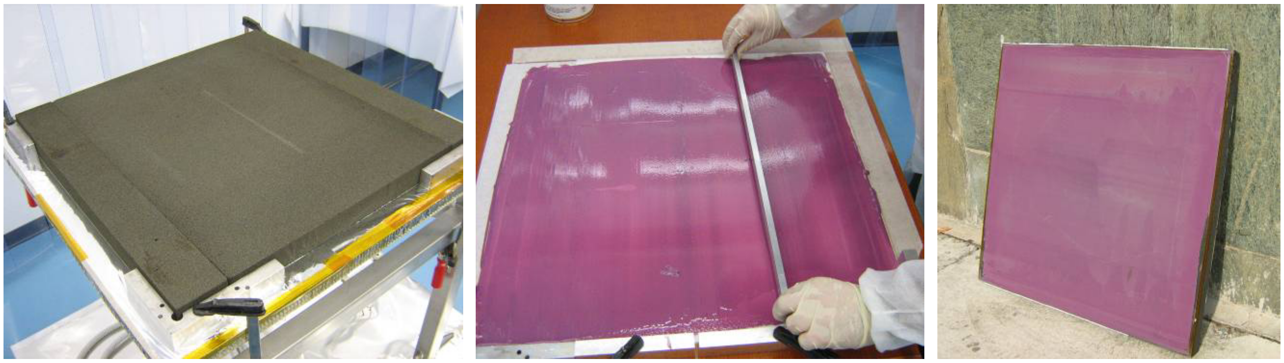

Fig. 9. Some steps of the manufacturing of the 600x600 mm mirror panel prototype. Foamglas® boards assembly, glue spread onto the glass sheet and the panel after the vacuum release.

Also for this larger mirror panel we have measured the focal spot dimension using the horizontal optical bench available in INAF-OAB. In figure 10 are shown on the left a photograph of the spot, while on the center its measure. The reported value for the D90 is of about 1.2 mrad, not yet in specification for a Cherenkov telescope but still very close to it. Meanwhile, masking the mirror to light just its central part the value drops to about 0.7 mrad, a value very similar to that reported for the 300x300 mm panels. At contrary, the measured radius of curvature is of 35800 mm, a difference from the master's radius of only 1.5%. As before, the picture on the right of figure 10 is the image of the Sun as generated by this larger mirror panel prototype.

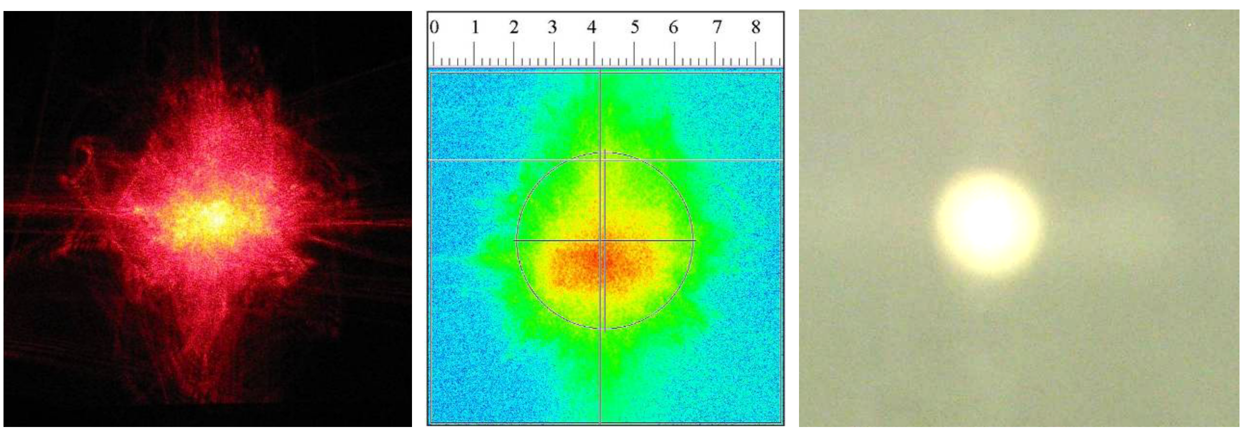

Fig. 10. (left) Picture of the spot generated on the radius of curvature. (center) Measure of the focal spot, the D90 is of about 1.2 mrad. (right) Projected image of the Sun generated by the 600x600 mm panel.

3.2 Hot slumping

In analogy with the previous sub-section, the prototypes presented in the following have been replicated from a mould already available in INAF-OAB. It is made in Zerodur K20, a ceramic material from Schott with a circular tile shape of 700 mm in diameter. Its surface geometry has been figured with a classical optical polishing process to be a convex sphere of approximately 9700 mm radius of curvature with a figure RMS error of about 1 or 2 λ at 632.8 nm, while the microroughness finishing level is of about 3-5 nm RMS. The glass sheets used for the hot slumping process are disks of Borofloat 33 type from Schott, 500 mm in diameter and thickness of 1.7 mm.

A number of mirror panels of a smaller dimension of 150 mm diameter have been realized and tested as reported in a past paper [9]. Hereby we report the results of a scale-up prototype of 500 mm in diameter obtained using a previously hot slumped glass shell. This choice partially influenced in a negative way the results, but hollow us a very fast response on the problematic. A next prototype will be realized and tested starting from a virgin glass sheet.

In figure 11 are shown some phases of the prototype manufacturing. In particular, from left to right it is visible the preparation of the blank with Foamglas® boards, the slumped shell placed on the mould and the finished mirror panel after the vacuum release. In the central image the curved glass sheet is in contact with the mould through an air suction distributed all around the glass circumference. In this condition a number of interference fringes should be visible. These are generated by the shape difference between mould and slumped shell, if no difference is present no fringes is visible and hence the glass matches exactly the mould shape. The present situation returns an almost complete match on a wide central area covering more the 80% of the total, with just some islands due to not perfect cleaning of the glass surface. On the contrary, along the glass perimeter a corona of dense fringes is visible; it comes once again from a lack of adequate cleaning of the shell edge.

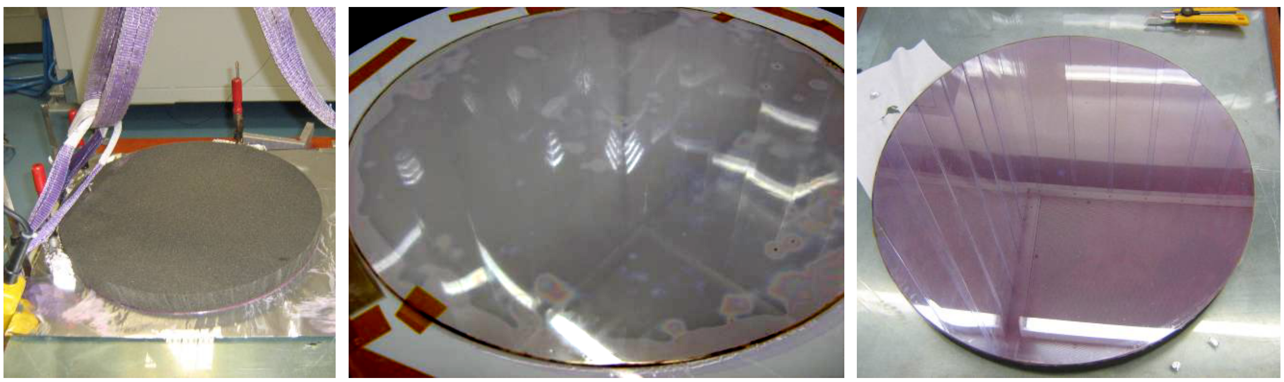

Fig. 11. (left) Foamglas® boards assembled to form the panel core. (center) Hot slumped glass shell in contact with its forming mandrel. Only a narrow corona along the glass circumference deviates from the mould shape. (right) Mirror panel after the curing of the glue and the vacuum release.

A preliminary evaluation of the optical performance of the mirror panel has been done through its capability to form images; in figure 12 are presented few of them. On the left panel it is shown a small, sharp and very intense disk of light generated pointing the mirror onto the Sun. The central photo is the focal spot derived from the concentration of a spherical laser wavefront placed on the radius of curvature. The bulge of the spot is contained in about 3 mm, while the measured radius of curvature is 9850 mm. At last, in the right panel there is the image of a filament lamp as generated by the mirror. As visible it is possible to recognize some features as the incandescent filament itself and the glass bulb.

Fig. 12. Images generated by the prototype mirror panel realized: (left) an image of the Sun disk, (center) the focal spot on the radius of curvature and (right) a filament lamp.

The mirror has also been measured with a ZYGO GPI XP interferometer equipped with an optical reference sphere for the generation of the laser wavefront. Due to the long focal length of the mirror it was not possible to measure it using a vibration dumped optical bench. The result of the measure is reported in figure 13. Almost the whole surface generates interference fringes with the reference laser beam, while the dark areas have a tilt respect to it. The overall figure error of the mirror is of about 1.5 λ, in complete agreement with the figure manufacturing specification of the mould. Hence, in the low spatial frequencies domain the procedure here adopted permits to copy with good fidelity the overall geometry of the forming mandrel. Superimposed to this shape, at higher frequencies there is an irregular set of fringes that degrades the surface quality of the mirror. In our understanding this contribution can be strongly attributed to the glue layer that bonds the Foamglas® core to the front glass sheet. In fact, we were not able to apply a uniform layer of glue due to the pronounced curvature of the slumped glass. To overcome this problem we have designed a proper tool that will be used for future prototypes. In this way we think to be able to improve significantly the coping of the mould.

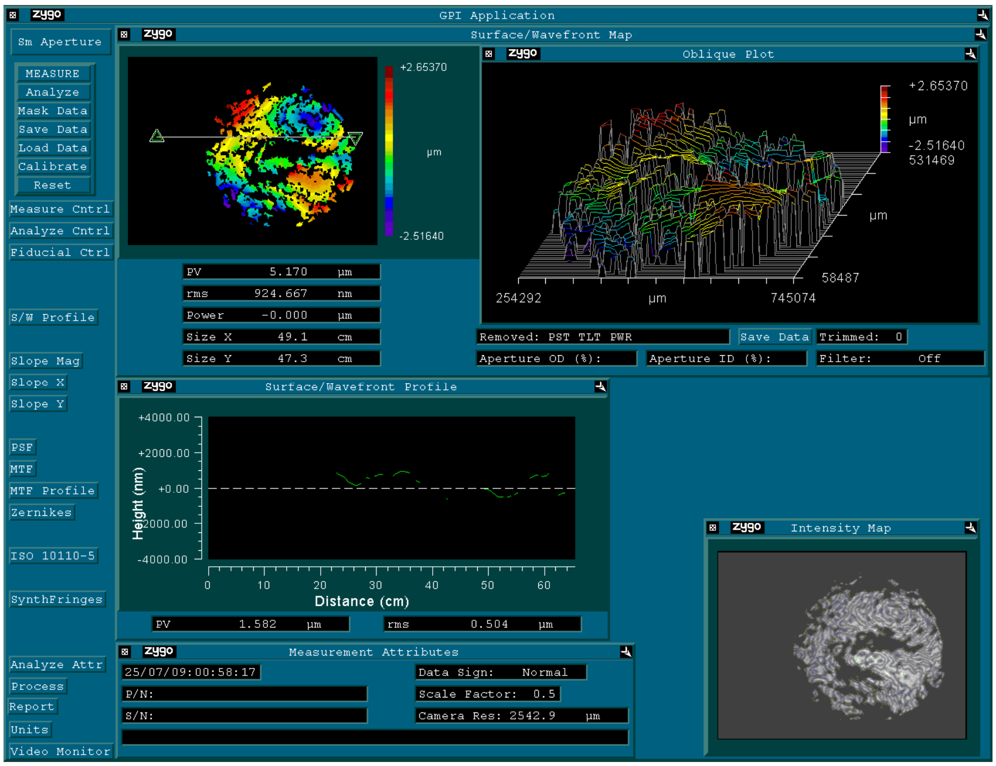

Fig. 13. Interferometric measure of the mirror panel prototype realized from a previously hot slumped thin glass sheet. The overall figure error is of about 1.5 λ RMS respect to a perfect sphere. The higher frequencies contribution is attributed to a not optimized gluing procedure.

4. CONCLUSIONS

Following the structure used all along the paper we split also the conclusions into two parts.

Concerning the cold approach, we have realized and tested with success a number of 300x300 mm mirror panels. These panels have measured focusing performances typically below 1 mrad as needed for Cherenkov telescopes. They have been able to be aluminized, meaning that the closed cell structure foam core withstands the vacuum; they survived to a number of rapid thermal cycles from -20 °C to 60 °C with no appreciable deformation of the focal spot. All these results are very promising in view of using foams, in particular Foamglas®, as core material for sandwich panels. Also, it is realized and tested a larger size prototype showing a focusing quality not far from 1 mrad and with areal density below

15 kg/m^2. In the next months we foresee to realize a full scale 1 m^2 MAGIC II like mirror panel with Foamglas® core. It will be intensively tested for focusing performances, survival and operational temperature, ageing and reflectivity. In the intention of the authors, one or more of these full scale mirrors will be shipped to the MAGIC site for on-site testing.

Concerning the hot approach, we have realized and tested one mirror panel prototype with diameter of 500 mm. The interferometric measure returns a good copy of the mould for the overall geometry, while a worsening in the higher spatial frequencies domain. This last effect is mostly attributable to a not correct spreading of the glue, problem that will be solved with an ad hoc tool. Nevertheless, it seems possible to reach very accurate coping of the mould at levels well beyond the real needed for S-C Cherenkov telescopes. The use of this technique for the manufacturing of mirror segments for high quality optical telescopes primary mirror should be considered and carefully investigated, as it is in the future plans of the authors. The very low areal density, the fast and cost effective production of such panels are all noticeable characteristics. However, for high performance optical telescopes it is mandatory to use different materials as well as higher optical quality moulds. In particular, concerning the core material we want to concentrate both on very low CTE open cell structure fused silica foam and on Silicon Carbide foam. Also the use of different glues will be investigated.

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