Investigation of a novel slumping technique for the manufacturing of stiff and lightweight optical mirrors

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ABSTRACT

The Astronomical Observatory of Brera (INAF-OAB) is investigating a novel slumping technique for the manufacturing of stiff and lightweight optical segments. We propose a 2-steps technique: initially the procedure foresees to manufacture a mirror segment using the hot slumping technique. This step produces a thin and floppy Borofloat™ glass shell using the slumping of a glass sheet onto a ceramic mould that has a surface with a high optical quality. After this step, this curved shell is assembled and glued to a stiff substrate made in foamed and pre-shaped material. On the back of the substrate it is also glued a flat sheet of the same glass. This procedure combine the good optical performances achievable on optics produced by means of the hot slumping technique with the lightweight and stiffness of the foamed material and, finally, the good structural properties achievable in sandwich-like structures.
This approach could be in principle used for the production of mirrors for a number of applications, from the primary segmented mirror for large telescopes to the mirrors for the future Cherenkov telescopes nowadays under development.
This paper describes the process of production of a prototype optical segment and the status of the investigation.

Keywords: Segmented Optics, Glass Slumping, E-ELT, Cherenkov telescopes, lightweight optics

1. INTRODUCTION

The Cherenkov telescopes are large collectors for very quick flashes (duration of few nsec) of UV light generated into the Earth atmosphere from high energy particles or photons emitting Cherenkov light. The typical optical design of this telescopes is the Davies-Cotton[1] and it foresees a large primary mirror disk, of the order of some tens of meters in diameter, and composed by a number of segments to achieve a very large collecting area (few hundreds of m^2). Due to the large field of view and the single optical surface, the focal spot for these types of telescopes is not aberration-free and hence the angular resolution requirement is quite relaxed, some arcmin. Another important issue is the production time needed for the whole set of mirror segments, some hundreds, that must be kept short. Last but not least, the weight of the mirror panels must be kept low (about 10 kg/m^2) so to avoid the necessity of a heavyweight support structure.
Summarizing, the technological goal to be achieved with these telescopes is a very large collecting area, similar to that for the next generation of large optical telescopes, keeping the overall costs of the instrument very low and with a fast production time. For a comparison, the costs budget in terms of €/m^2 of collecting area is of about 2-5 kEuro, while for an optical telescope like E-ELT the same parameter reaches some hundreds kEuro.
In Fig. 1 are shown the two MAGIC Cherenkov telescopes[2] sited at the Canary Islands, near the NOT and TNG optical telescopes. The MAGIC telescopes have a primary segmented mirror of 17 m in diameter with a focal length of 17.5 m. The mirrors are composed by several spherical segments aligned to approximate a parabolic optical surface. Each segment is 1 m^2 wide and hosts a laser used for its alignment. With this configuration it is achieved a total collecting area of about 240 m^2, a field of view of 3 deg with an angular resolution (in terms of D90) of about 3 arcmin.
This last generation of Cherenkov Telescopes (H.E.S.S.[3], MAGIC[2], VERITAS[4])is now allowing imaging, photometry and spectroscopy of sources of high-energy radiation with good sensitivity and good angular resolution. Nevertheless, in the next decade Gamma Ray Astronomy will improve greatly with two gamma ray dedicated satellites (AGILE[5] and GLAST[6]). Moreover, the presence of other X-ray experiments in orbit (e.g. Swift, Chandra, Newton-XMM, etc.) will make possible for the first time to imagine the Universe all over the whole electromagnetic spectrum at

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almost same time. In such a scenario a new generation of ground-based very high energy gamma-ray instruments are needed in order to significantly improve, the sensitivity, the observed energy band, the field of view and the observing time.

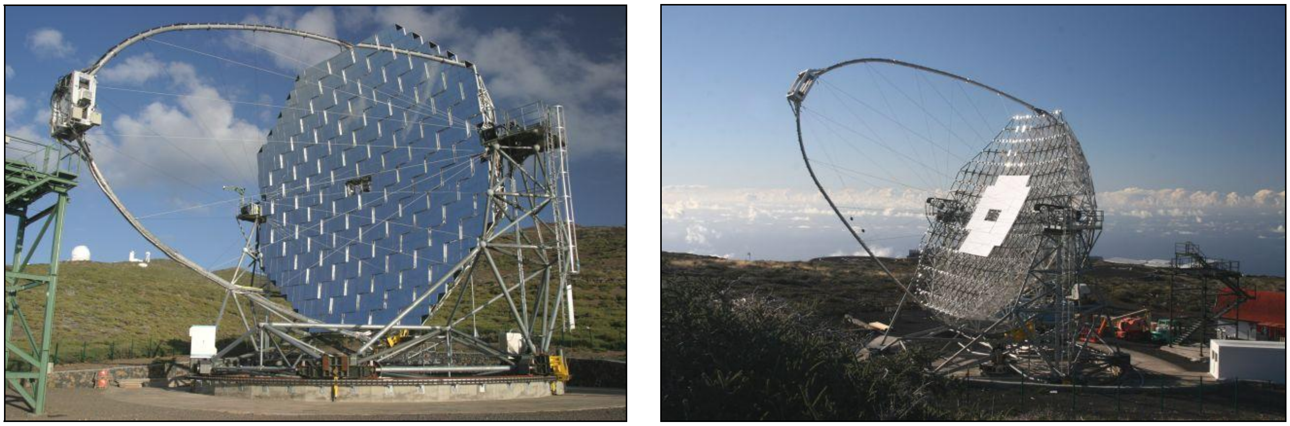

Fig. 1: MAGIC I and II telescopes at the Canary Islands. The two MAGIC telescopes having an F/1 optical configuration with a mirror diameter of about 17 m. The mirror panels of the MAGIC II telescopes are made with two different technologies: the panels in the inner part have been developed by INFN-Padova, while the outer ring panels by INAF-OAB and Media Lario Techn.

A consortium of European scientists is thus now thinking to the design of a new research infrastructure: the Cherenkov Telescope Array (CTA) [7]. The aims of the CTA observatory are to increase sensitivity in the core energy range from about 100 GeV to about 10 TeV by roughly one order of magnitude, and at the same time to expand the energy range for very high energy gamma astronomy towards both lower and higher energies, effectively increasing the usable energy coverage by a factor of 10. In addition, CTA would provide both significant improvements in angular resolution, revealing finer details in the sources, and unprecedented detection rates, enabling researchers to track transient phenomena on very short time scales. CTA can achieve this performance by a large-scale deployment of proven techniques. CTA will - for the first time in this field - be operated as an observatory, raising issues such as remote operation of the facility, observation scheduling, and data dissemination.

The basic concept for this kind of telescopes array if shown in Fig. 1 (left), where are visible three different rings. The central part of this area will be composed by few large telescopes of the same kind of the actual ones (MAGIC, H.E.S.S., VERITAS), these telescopes will monitor the sky in the lower energy band. An outer ring of some hundreds meters radius will be composed of medium size telescopes for the medium energy band. The last external ring, having a diameter of about 1 km, will be filled with smaller telescopes. The optical configuration must be able to gather data from the high energy band (up to few TeV) with a better angular resolution than that of the inner rings telescopes and with a wider field of view. An example proposed by Vasiliev et al.[8] for this type of telescopes is shown in Fig. 2 (right). In this case, the optical configuration foresees a double reflection; the main mirror is composed by a number of panels so to create an optical surface of about 10 meters in diameter with a radius of curvature of about 30 m, while the secondary mirror has a diameter of about 5 meters. Also this last mirrors is segmented and has a radius of curvature of about 7 m. For these panels the weight should be kept in the order of 15 kg/m^2. The optical system is optimized to maintain a constant angular resolution of about 1-3 arcmin over a wide field of view (about 10 deg).

In the present paper we propose a new manufacturing concept which could be used for the production of the panels for the secondary mirrors of the wide-field planar Cherenkov telescopes of the kind proposed by Vasiliev et al. Depending from the limits of this technology, that will be investigated in the future, this approach could be useful also for the production of higher precision optical segments like those necessary for optical telescopes. Also some very preliminary results are shown.

In the next section are presented two key technologies developed by our institute: one for the manufacturing of the segments for the mirror of the MAGIC 2 telescope, the other for the manufacturing of thin glass shells for adaptive optics.

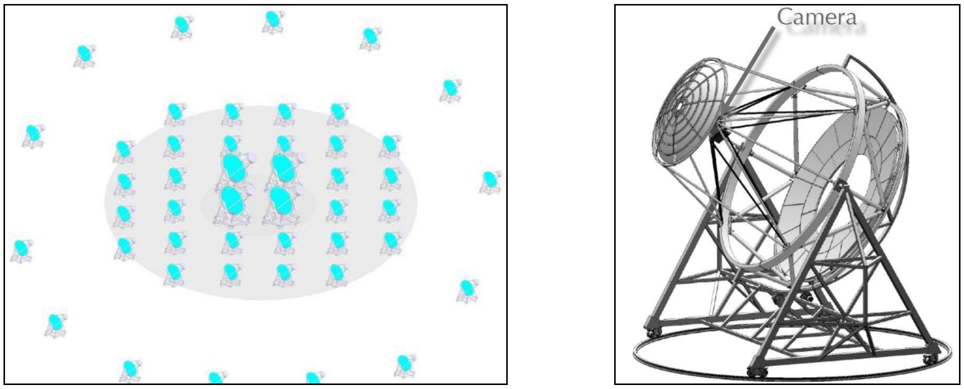

Fig. 2: **(left)** Cerenkov Telescope Array concept. **(right)** Proposed telescope (AGIS) for the outer ring (wide field of view, high energy).

2. PRESENT TECHNOLOGIES

The INAF-OAB has developed a new technique for the production of segmented optics. This is based on the so called "cold slumping"[9][10], a technology that works at room temperature and it is specifically addressed to the realization of segmented primary mirrors of Cherenkov telescopes. This technique uses a convex Aluminum master mould (see Fig. 3 left) figured by fly cutting to impart to a thin (1-2 mm thick) sheet of glass a concave shape. By means of a vacuum suction the initially flat glass is placed in contact with the mould. The glass is then fixed with glue to a honeycomb structure and sandwiched using another glass sheet applied to the back of the panel. This technique is possible when using long radius of curvature: in this case, in fact, the sag of a single panel of 1 meter side is of few millimeters. This concept works in the regime in which the glass is elastic and it accepts small deformations without introduce other distortions.

This approach is very attractive since massive production with short manufacturing times is possible (e.g. 5 mirrors per day if 5 masters are available) maintaining very low costs and weights. The cost of a single panel is in the order of 2 kEuro and its weight is of 9-10 kg.

This technique has been developed by INAF-OAB in collaboration with the Media Lario company (see Fig. 3) and in close contact with the INFN group at the University of Padova. Based on this development, 100 of the 240 square segments with spherical shape of the MAGIC 2 primary mirror have already been produced (and shipped to the telescope site) under the INAF-OAB responsibility. The whole set of panels has been produced in only 6 months. In view of the CTA this technology could be improved aiming at achieving imaging performances even better and with the possibility of using also aspherical profiles (e.g. parabolic shapes).

Fig. 3: Production of glass panels with spherical shape for MAGIC II using the process described. **(left)** Aluminum mould (1 x 1 m) with spherical shape (34.9 m radius of curvature) obtained with a diamond milling facility. **(right)** Final glass panel look ready to be mounted in the structure of the MAGIC II telescope.

Another study we are performing concerns the development of a technique for the hot slumping of thin glass optical segments[11] for adaptive optics under a study financed in the frame of OPTICON-FP6. This technology employs a mould made in ceramic to change the shape of an initially flat sheet of glass having thickness less than 2 mm. So far the technology has been investigated for the segmented adaptive secondary mirrors of future extremely large optical telescopes like E-ELT. When sufficiently heated the glass will soften enough to slump onto the mould surface (in this case made of ceramic material) and to adapt to its shape. At the end of the procedure, after the cooling down of the glass and mould, the glass sheet will be separated from the mould. At this point the surface of the glass sheet will have the requested optical shape and will be (ideally) ready to be coated with a reflective layer and used as an optical thin shell in an adaptive system. The advantage of this approach is that, once the mould has been manufactured, it is possible to replicate very quickly a number of segments with a low cost of production and with a very good precision. In Fig. 4 are shown the two ovens installed at INAF-OAB and used for the slumping.
Till now the tests has been made on a 150 mm diameter ZERODUR K20 mould to slump 130 mm diameter thin glass shells[12]. This mould has a spherical convex shape with radius of curvature of 4 m. A good copy capability was observed in the slumped segments with thermal cycles of about 15 hours. Recently it has been started a scaled-up study aimed to produce a 500 mm diameter glass shell having thickness of 1.7 mm (see Fig. 5)[13].

Fig. 4: Hot slumping facility available at INAF-OAB. The facility is composed by two ovens, a small one **(left)** and a big one **(right)** able to host moulds up to 1.1 m in diameter, a clean room environment for the preparation of the samples and a crane for the handling of weights up to 500 kg.

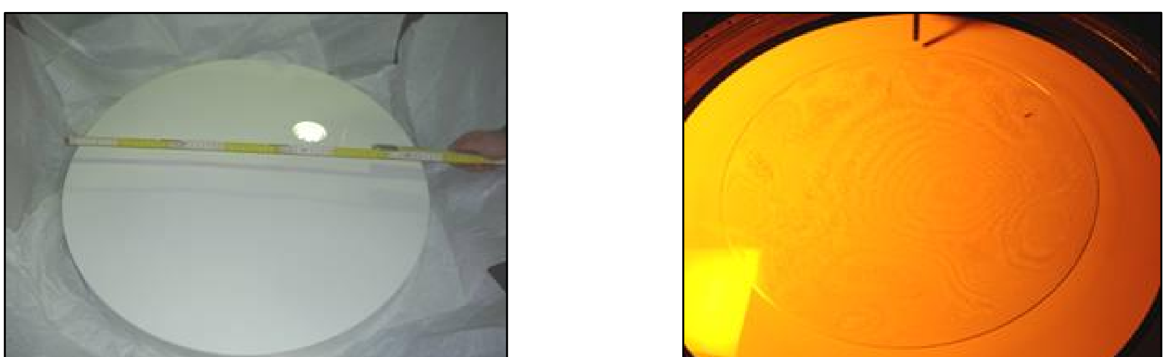

Fig. 5: **(left)** 700 mm ZERODUR K20 mould used for scaling-up the slumping process. **(right)** 500 mm diam. Borofloat^{TM} 33 glass segment after a slumping cycle and till placed on the mould.

3. DESCRIPTION OF THE 2-STEPS MANUFACTURING PROCESS

The process here proposed for the production of a lightweight optical mirrors can be divided into two separate steps. The first one uses the slumping to obtain an optically good thin glass shell. This, due to its low thickness, is obviously very floppy. The second step is necessary to froze the optical shape of the shell using a stiff substrate structure having low weight. The final optical mirror panel will shows a low weight maintaining the good optical quality as obtained from the slumping process. In addition, with this approach the cost of a finished segment can be maintained quite low.

3.1 Step 1: Hot Press Direct Slumping phase

A thin and flat sheet of glass, that typically is 1-2 mm thick, is precisely shaped following the approach of the "Hot Press Direct Slumping" as widely discussed in a previous paper[13]. Using an optically figured and polished mould and applying a suitable thermal cycle, it is possible to precisely impart to the initially flat glass sheet the (negative) shape of the mould. The process foresees to reach a uniform temperature distribution of about 650 °C, depending on the glass type and sag of the mould.

This approach for the production of the slumped segments is shown in Fig. 6 (left) and it consists of a number of phases.

A mould having the complementary shape desired for the optical segment is manufactured in a suitable material to minimize the eventual CTE mismatch between it and glass to be slumped. Another important request to the mould is its microroughness surface finishing, that must be similar to that necessary for the slumped segment. This requirement is necessary because the procedure foresees to copy not only the geometry of the mould but also its higher spatial frequencies and in particular a part of its microroughness.

Initially it was made a comparison of the theoretical thermo-mechanical parameters of suitable materials for the mould and some practical tests to check the response with different glass types. It was decided that a good trade-off for the material of the mould was the ZERODUR K20[14] paired with the Borofloat™ 33 glass for the mirror shell. This decision is supported using the considerations discussed in a previous paper[13] and here summarized:

- The ZERODUR K20 has a CTE near to the Borofloat™ 33, the Schott glass that will be used for the slumped segments.
- The CTE homogeneity of the ZERODUR K20 is the highest of all the other materials investigated. This is an important parameter to minimize local shape deviation at high temperature.
- The ZERODUR K20 has not shown sticking attitude to the glass within the thermal cycles presently used (up to 660 °C) and hence doesn't need any anti-sticking coating. The sticking of the glass on the mould is an event that very likely can create a heavy damage to the mould, requiring a re-figuring.
- The dimensions of ZERODUR K20 blank can be easily scaled-up to several meters in diameter (if necessary).
- The characterization of a non transparent mould using a 3D machine for the measurement of the geometry (long spatial frequencies) and of a 25-30 cm spherical master to control the higher spatial frequencies on patches of the mould is a well known and trusted technique.
- The cost of the finished mould in ZERODUR K20 is not far from that of the other moulds made in the other materials.

After the cleaning of the mould and the flat Borofloat™ glass sheet, in a cleanroom environment, they are placed in a muffle, the glass placed above the mould. The use of a muffle is useful to reach a better temperature distribution during the slumping process. It permits also to remove the air reducing the convection so to use only the irradiation, with obvious advantages in terms of homogeneous heat distribution. The dust contamination is a well known problem in many industrial processes. The use of the muffle helps to maintain a control of this parameter, because it protects the mould and the glass from the dusty ambient of the oven.

The muffle is placed inside the oven and a thermal cycle tailored to the specific experiment is then applied with predetermined warming-up, holding times and cooling rates. An example of thermal cycle is visible in Fig. 6 (right). During the slumping an homogeneous pressure is applied on the glass so to force it against the mould surface. This approach ensures the full contact of the glass against the mould. Since the optical surface is in direct contact with the mould surface, it is necessary to manufacture the mould surface with a good microroughness so to avoid to degrade the surface finishing of the glass.

The mirror shell produced following this approach is floppy enough to change its shape under its own weight. The next step is to freeze its shape so to use the shell as a freestanding mirror segment.

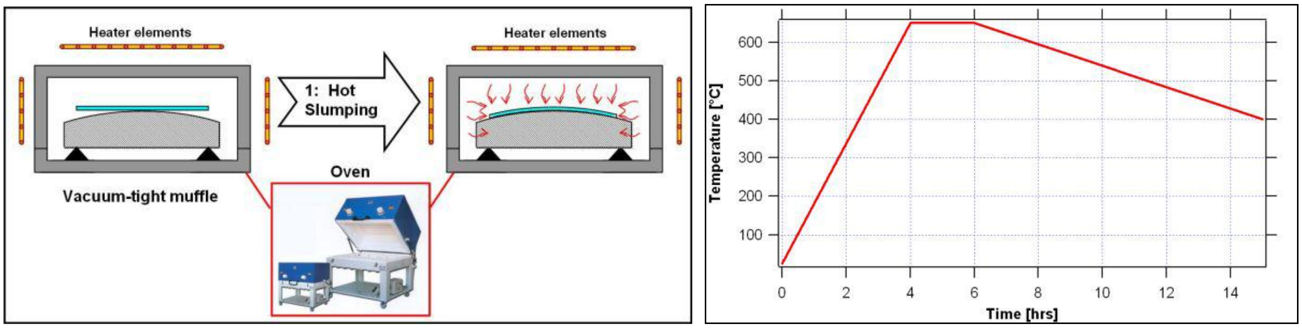

Fig. 6: **(left)** Hot slumping concept developed for the manufacturing of thin mirror shells for adaptive optics. A thin glass sheet is placed above the mould having convex shape, mould and glass are hosted inside a vacuum-seal muffle as described in the text. The process foresee to reach a temperature of about 650 °C and to apply a uniform pressure. **(right)** Example of a possible thermal cycle.

3.2 Step 2: Stiffening phase

At the end of the slumping the glass sheet will have copied the shape of the mould. Even if the thermal gradients have been minimized, the shell could contain some shape errors, due to small deformations arising mainly during the cooling-down and also due to the difference in CTEs between glass and mould. These shape errors, if any, will be easily visible as interference fringes under Sodium light with the glass still placed above the mould (an example is visible in Fig. 6 right). The pattern of fringes shows the difference in shape between mould and glass. This difference is in the worse cases of some tens of microns. Since it is assumed a mould having the desired shape (ideally perfect) it is necessary to force the curved segment completely against the mould itself, so to obtain essentially no fringes. The difference in shape to be removed is so small that in practice no stresses will be introduced and hence, after the freezing, no spring back will be appreciable.

The second step is performed at the end of the thermal cycle, but before removing the shell from the mould. The curved glass is forced to stay in full contact with the mould trough an air suction. When in full contact, it is glued above it a foamed substrate and again a flat glass sheet so to form a sandwich. The Fig. 7 shows these steps.

The air suction allows to strongly reduce the small potential shape differences arising from the little CTE mismatch between glass and mould at the slumping temperature. Avoiding to remove the slumped glass helps to maintain dust-free the interface between glass and mould.

To permanently freeze the glass shape a suitable reinforcing substrate is glued to the mirror shell. Similarly to the MAGIC II mirror panels it is foreseen to adopt a sandwiched structure due to its good mechanical property in terms of stiffness. This configuration has also a good structural stability when exposed to temperature variations, due to the symmetry of the system. In this case the middle layer of the panel is constituted by a foamed material. The foams typically shows good performances in stiffness and weight when compared with bulk materials of the same density. Moreover, it is possible to pre-work this foam on one side and shape it to allocate the curvature of the slumped glass segment. This further step helps in maintaining as constant as possible the thickness of glue when the foam is forced against the curved glass shell. This avoids differential shrinkages (from point to point) of the glue and hence it helps in maintain the optical quality reached with the hot shaping step.

A particular attention must be addressed in the choice of the foam substrate and of the glue used to put together the sandwich. In particular, it is important to minimize the CTE mismatch between the foam and the glass sheet to avoid optical distortions due to possible environmental thermal gradients. For what concern the glue, a very low percentage shrinkage is mandatory to minimize overall stresses during the curing phase, as well the application of a thin layer with a uniform thickness to avoid local stresses. Ideally, the curing of the glue should be done near the working temperature of the telescope that will mount the mirror panel.

For the authors, these considerations are the key points to obtain the optical quality requested (assuming no errors in the mould figure), even if the implementation of the sandwich structure helps in limiting those sources of deformations.

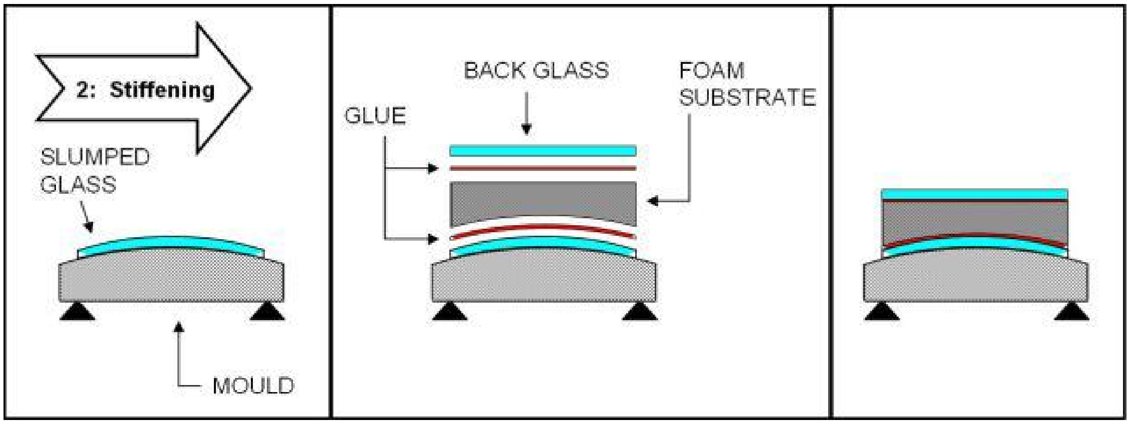

Fig. 7: Proposed concept for the stiffening step. Once the glass has been hot slumped, it will be added a pre-shaped foam substrate and a second flat glass on the back. The foam substrate give stiffness and lightweight to the final mirror panel, while the sandwich structure assure a good structural stability.

4. PRELIMINARY RESULTS OF THE INVESTIGATION

After having developed a suitable procedure and technology for the hot slumping of thin glass shells it has been started the slumping of a number of circular Borofloat™ 33 disks having diameters of 130 mm and 2 mm thickness. The mould has a spherical convex shape with about 4000 mm radius of curvature. To verify the repeatability of the hot slumping step in shaping the glass, the first slumped shells have been measured with a ZYGO GPI-XP interferometer without gluing the foamed substrate. In all the measured segments it is visible a pattern of features that repeat itself with a good approximation. It is very likely hence that these features are present on the mould and they are simply replicated onto the segment surface. This is an indication that the process has a very good copy capability.
In Fig. 8 and Fig. 9 are shown the optical shapes of a typical slumped segment in a central diameter of 80 mm and on the overall surface. The figure errors are respectively of 100 nm rms (~ $\lambda/6$) and 290 nm rms (~ $\lambda/2$) @632.8 nm. In the following , these measurements will be used as reference when compared with the final mirror panel.

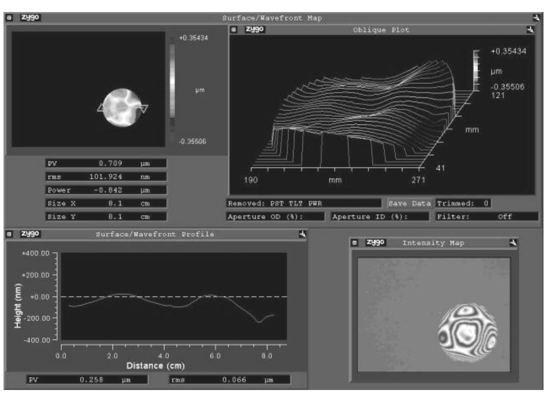

Fig. 8: Glass slumping on 80 mm (~ $\lambda/6$)

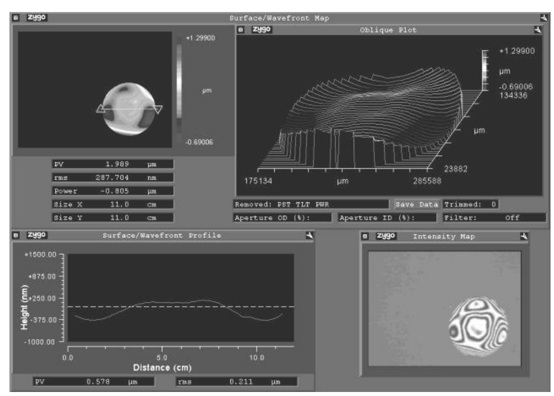

Fig. 9: Glass slumping on 120 mm (~ $\lambda/2$)

The foam that as been used for this exercise is made of the same glass type of the slumped shell (Borofloat™). Even if the materials are the same, the CTE of the foam is different from that of the glass. This is due to the production process of the foam that create a closed cell structure with gas trapped inside. This gas influence the mechanical behavior of the foam altering the CTE of the bulk glass since it expands or contracts more than the glass. To minimize the effect of the CTEs mismatch either the curing of the glue and the interferometric measurement were made at the same temperature. It is clear that the use of a foam with a better match in CTE (respect to the glass) is a necessary step that will be implemented in the next tests. A good candidate could be a Silicon Carbide foam substrate that has a CTE very near to that of the Borofloat™ glass. Typically the SiC CTE range from 2-4 µm/°K·m respect to 3.3 µm/°K·m of the Borofloat™ glass.

It has been also tested the capability of the foam to resist in a vacuum environment. It has been found that the glass structure is able to withstand to the vacuum without break and this permits to coat the panel ones finished.
A side of the foam has been per-worked to fit the curvature radius of the slumped segment. This has been done by means of an *ad hoc* tool mounted on a drill.
The glue used is a two components epoxy product that has a very low percentage shrinkage in the order of 0.037% and the same quantity of epoxy was used for both the foam sides.
In the left side of Fig. 10 is shown the stack during the curing of the glue. It is visible the K20 mould with the slumped glass kept in full contact by the vacuum suction. The foam substrate having a thickness of 40 mm is placed above the slumped glass with the glue in between. On the foam, then, was putted a second glass sheet to create the sandwich. At the end of the stack is visible a weight used to spread the glue all over the surfaces.
The right side of Fig. 10 is a picture of the final mirror panel after the aluminization of the optical surface.
With this configuration of glass and foam thicknesses the test mirror panel produced has a total weight of about 200 gr. This means that the areal density, when scaled up to 1 m^2, is of about 16 kg. This is already very near to the requirement for the Cherenkov telescopes application.

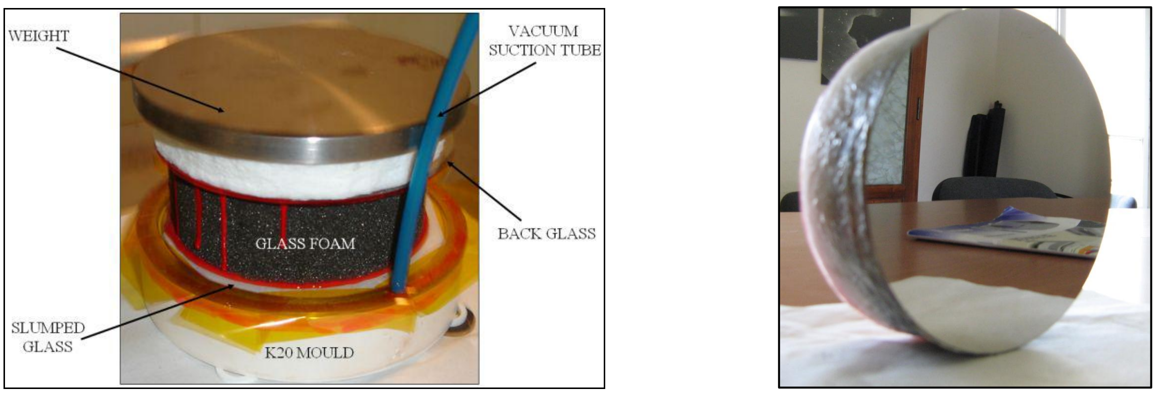

Fig. 10: **(left)** Mirror panel stack during the final phase of the production: the curing of the glue. They are visible the vacuum suction tube, the slumped glass above the K20 mould and the foam substrate with the back glass. **(right)** The mirror panel after the aluminization. The total weight is of only 200 gr.

After the curing, the mirror panel has been measured interferometrically using the same set-up previously arranged. In Fig. 11 and Fig. 12 are shown the results. When compared with the reference (Fig. 8 and Fig. 9) measurements it is possible to note a slight decrease in the optical quality on the 80 mm diameter in the order of about 25 nm rms (from λ/6 to λ/5). On the overall surface, instead, the measurement gave essentially the same value as before, λ/2 for both. This seems to confirm that the implementation of the sandwich structure do not degrade appreciably the overall optical quality.

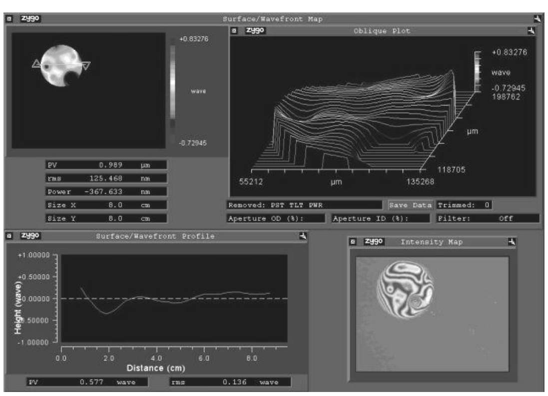

Fig. 11: Final mirror panel on 80 mm (~ λ/5)

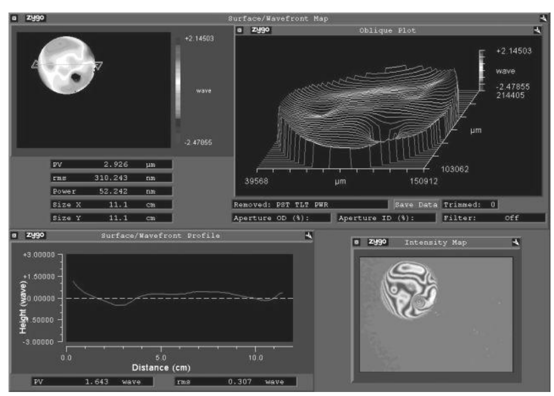

Fig. 12: Final mirror panel on 110 mm (~ λ/2)

Using the interferometric measurements shown in Fig. 12 it has been performed a ray tracing simulation with the ZEMAX code. The aim was to obtain a focal spot to have an estimation of the encircle energy, then used to compute the angular resolution in terms of D80. The resulting focal spot is shown in Fig. 13 where the square box contain the 80% of the ray traced. The angular resolution obtained is of about 3 arcmin, a value already in spec for a Cherenkov telescope application.
It is clear that the dimension of the panel here produced are not fully representative of a mirror segment to be used in a telescope. Anyway, the results obtained so far seem very encouraging and this experiment has been useful to probe the concept with the related technological problems.

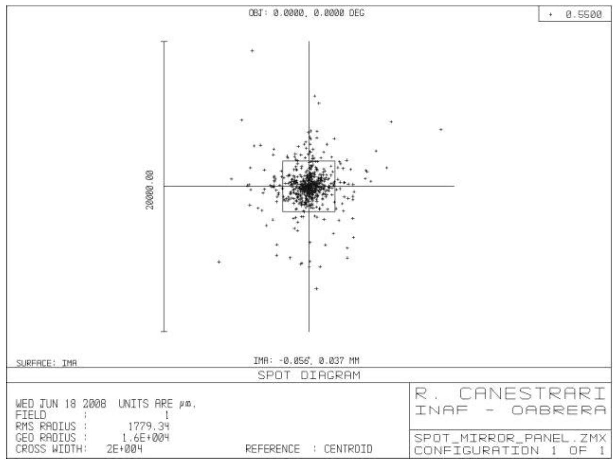

Fig. 13: Focal spot obtained by a ZEMAX simulation

5. CONCLUSIONS

The initial tests performed so far, and here presented, have the only intent to show the potentiality that can be achieved with this technology if adequately investigated. Substantial improvements could be obtained with a complete study and if an optimization of the various parameters is performed, in particular from the thermo-mechanical point of view.
The total weight of the test panel produced is of 16 kg/m^2 and this value can be probably reduced below the requirement for the Cherenkov application. This can be achieved performing a trade-off study between the thickness of the glass sheets, the thickness of the foam substrate and its density, but preserving a reasonable stiffness of the final mirror panel.
From the thermal side of the problem, it is very important to use a foam substrate that minimize the CTE mismatch with the glass sheet. A number of solutions can be investigated to find the best couple glass-foam. In the next months, an attractive material that will be tested consists in a foam substrate made of Silicon Carbide coupled with the Borofloat^{TM} glass. This solution shows a CTE difference of about 0.8 μm/°K·m depending of the SiC type used. Another possible alternative could be the use of cellular glass as substrate with D263 glass sheets.
Concerning the main application for the segmented secondary mirrors of the next generation aplanatic wide-field Cherenkov telescopes it seems that this technique has the potential to permit the manufacturing of the segments.
The limits of this approach will be investigated in a follow-up study that will use larger moulds to produce more representative optical segments.
We are confident that, considering the relatively low effort needed to obtain the present results, it will be possible to improve the optical quality of the panels. In this case, other possible applications could be: Solar collectors for energy production, primary mirrors for optical telescopes and lightweight optics for space missions.

REFERENCES

[1] J.M. Davies, E.S. Cotton, “Design of the Quartermaster Solar Furnace”, Solar Energy Sci. Eng. 1 (1957) 16–22.

[2] E. Lorenz, “Status of the 17 m diameter Magic telescope”, in: M. Simon, E. Lorenz, M. Pohl (Eds.), Proceedings of the 27th International Cosmic Ray Conference, Hamburg, 2001, pp. 2789–2792.

[3] W. Hofmann, “Status of the H.E.S.S. project”, in: M. Simon, E. Lorenz, M. Pohl (Eds.), Proceedings of the 27th International Cosmic Ray Conference, Hamburg, 2001, pp. 2785–2788.

[4] T.C. Weekes, et al., “VERITAS: the very energetic radiation imaging telescope array system”, in: M. Potgieter, C. Raubenheimer, D.J. van der Walt (Eds.), Proceedings of the 25th International Cosmic Ray Conference, Durban, 1997, p. 173.

[5] M. Tavani, “The AGILE Gamma-Ray Mission”, American Astronomical Society, 2008, vol. 10, p. 28.

[6] N. Gehrels, P. Michelson, “GLAST: the next-generation high energy gamma-ray astronomy mission”, Astropart. Phys. 11 (1999) 277–282.

[7] G. Hermann, “The ground-based gamma-ray observatory CTA”, Astronomische Nachrichten, 2007, vol.328, issue7.

[8] V. V. Vassiliev, S. J. Fegan, P. F. Brousseau, "Wide field aplanatic two-mirror telescopes for ground-based gamma-ray astronomy", Astropart. Phys, 2007, vol. 28, issue 1, p. 10-27

[9] D. Vernani, R. Banham, et al., “Development of cold-slumping glass mirrors for imaging Cherenkov telescopes”, Proc. SPIE 7018-32, Present Conf.

[10] G. Pareschi, R. Canestrari, et al., “Glass panels by cold slumping to cover 100 m^2 of the MAGIC II Cherenkov telescope reflecting surface”, Proc. SPIE 7018-33, Present Conf.

[11] M. Ghigo, R. Canestrari, S. Basso, D. Spiga, “Development of lightweight optical segments for adaptive optics”, Proc. SPIE 6691, 2007

[12] M. Ghigo, S. Basso, et al., “Manufacturing of lightweight glass segments for adaptive optics”, Proc. SPIE 6272, 2006

[13] R. Canestrari, M. Ghigo, et al., “Lightweight optical segment prototype for adaptive optics manufactured by hot slumping”, Proc. SPIE 7015-137, Present Conf.

[14] T. Doring, R. Jedamzik, et al., “Forming mandrels for X-ray telescopes made of modified Zerodur”, Proc. SPIE 5168, p. 148, 2004