Glass Mirrors by cold slumping to cover 100 m^2 of the MAGIC II Cherenkov telescope reflecting surface

G. Pareschi[*a], E. Giro[b,d], R. Banham[c], S. Basso[c], D. Bastieri[d], R. Canestrari[a], G. Ceppatelli[e], O. Citterio[c], M. Doro[d], E. Giro, M. Ghigo[a], F. Marioni[c], M. Mariotti[d], M. Salvati[f], F. Sanvito[c], D. Vernani[a,c]

[a]INAF – Osservatorio Astronomico di Brera, Via Brera 28, Milano, ITALY, 20121-I
[b]INAF – Osservatorio Astronomico di Padova, Vicolo Osservatorio 5, Padova, ITALY, 35122-I
[c] Media Lario Technologies S.r.l., Località Pascolo, Bosisio Parini (LC), ITALY 23842-I
[d]INFN Sezione di Padova, Via Marzolo 8, Padova, ITALY, 35131-I
[e]Fundación Galileo Galilei – INAF, Rambla José Ana Fernández Pérez, 7, Breña Baja – Tenerife – España 38712-E
[e] INAF – Osservatorio Astrofisico di Arcetri - L.go E. Fermi, 5, Firenze, ITALY 50125-I

ABSTRACT

We report on the production and implementation of 100 square panels 1 m x 1 m, based on the innovative approach of cold slumping of thin glass sheets. The more than 100 segments will cover around one half of the 240 m-square reflecting surface of the MAGIC II, a clone of the atmospheric Cherenkov telescope MAGIC I (with a single-dish 17 m diameter mirror) which is already operating since late 2003 at La Palma. The MAGIC II telescope will be completed by the end of 2008 and will operate in stereoscopic mode with MAGIC I. While the central part of the of the reflector is composed of by diamond milled Aluminum of 1m^2 area panels (following a design similar to that already used for MAGIC I), the outer coronas will be made of sandwiched glass segments. The glass panel production foresees the following steps: a) a thin glass sheet (1-2mm) is elastically deformed so as to retain the shape imparted by a master with convex profile - the radius of curvature is large, the sheet can be pressed against the master using vacuum suction -; b) on the deformed glass sheet a honeycomb structure that provides the needed rigidity is glued ; c) then a second glass sheet is glued on the top in order to obtain a sandwich; d) after on the concave side a reflecting coating (Aluminum) and a thin protective coating (Quartz) are deposited. The typical weight of each panel is about 12 kg and its resolution is better than 1 mrad at a level of diameter that contains the 90% of the energy reflected by the mirror; the areal cost of glass panels is ~2 k€ per 1m^2. The technology based on cold slumping is a good candidate for the production of the primary mirrors of the telescopes forming the Cherenkov Telescope Array (CTA), the future large TeV observatory currently being studied in Europe. Details on the realization of MAGIC II new mirrors based on cold slumping glass will be presented.

Keywords: Cherenkov telescopes, mirror production, glass cold slumping

1. INTRODUCTION

The field of Very High Energy (VHE) ground-based γ-ray astronomy, pioneered by the Whipple 10m Atmospheric Cherenkov Telescope (ACT) [1], is coming to age by the second generation observatories, H.E.S.S. [2], MAGIC [3], and VERITAS [4]. More than 30 new γ-ray sources, some representing new classes of VHE (50 GeV – 100 TeV) emitters, have been discovered during the last years [5]. In the next decade Gamma Ray Astronomy will improve greatly also due to of the two gamma ray dedicated satellites (AGILE [6] and GLAST [7]), already successfully launched, with operational range in the band 10 MeV – 50 GeV band, that will allows us to perform simultaneous observations with ground-based ACTs. Moreover, the presence of other X-ray experiments already in orbit (e.g. Swift, Integral, Chandra, Newton-XMM, etc.) and ground-based optical and IR telescopes will make possible for the first time to imagine the Universe all over the whole electromagnetic spectrum at almost same time; example of such large band observations of BL-Lac objects have been already successfully performed (see e.g. Tagliaferri et al, 2008, ref. [8]) .

[*]E-mail: giovanni.pareschi@brera.inaf.it; phone +39 039 9991169; fax +39 039 5971000; www.brera.inaf.it

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Ground based Gamma Astronomy with ACTs is concerned with gamma photons that typically interact within the first radiation length of the atmosphere with atoms and generate electromagnetic showers. The showers extend over many kilometers in length and few tens to hundreds of meters in width and have their maximum located around an air mass of 0.2 to 0.3, i.e. around 8-12 km altitude in case of vertical incidence. Below ≈ 100 TeV shower particles stop high up in the atmosphere and cannot be directly detected at ground. A sizeable fraction of the charged secondary shower particles, mostly electrons and positrons in the shower core, moves with ultra-relativistic speed and emits Cherenkov light. This radiation is mainly concentrated in the near UV and optical band and can therefore pass mostly un-attenuated to ground and detected by appropriate instruments. A typical Cherenkov light flux density between 300 and 600 nm from a 1 TeV gamma shower is around 100 photons/m^2, nearly uniformly spread over an area of 50 000 m^2 at ground. The faint light flashes must be detected against a substantial night sky light background. Light flashes from showers have a very short duration, typically 2-3 ns in case of a γ shower. For these reasons ACTs must obviously have large collecting surface.

MAGIC I and II (see Fig 1) are two telescopes with 17 m primary mirror surfaces built at a distance of 85 meters from each-other and located at the Canary Island of La Palma [9,10,11]. They have been built by a collaboration of several institutes, mainly German, Italian, and Spanish. The telescopes will work in stereoscopic mode in detecting Cherenkov showers. MAGIC I is operated since 2003, while the first light of MAGIC II is foreseen for September 2008. Whereas the mechanical structure of the telescopes is the same, different solutions have been proposed for the reflecting surfaces. MAGIC I mirror is composed by 964 square aluminum diamond milled mirrors 0.5 m x 0.5 m large [12,13,14], MAGIC II is composed by 247 square mirrors [15,16,17], of 1 m^2 area, with 104 glass mirrors realized with an innovative technique called *cold-slumping* [18], while the remaining 143 have been realized in Aluminum, upgrading the diamond-milling approach used for MAGIC I. The technology based on cold slumping is also a good candidate for the production of the primary mirrors of the telescopes forming the Cherenkov Telescope Array (CTA) [19], the future large TeV observatory currently being studied in Europe. This paper describes the production of these glass panels. The paper is organized as follows: section 2 will describe the reflector characteristics of MAGIC II, section 3 the design, the realization technique and the productions of these > 100 glass mirrors, section 4 discusses the optical properties and the achieved quality.

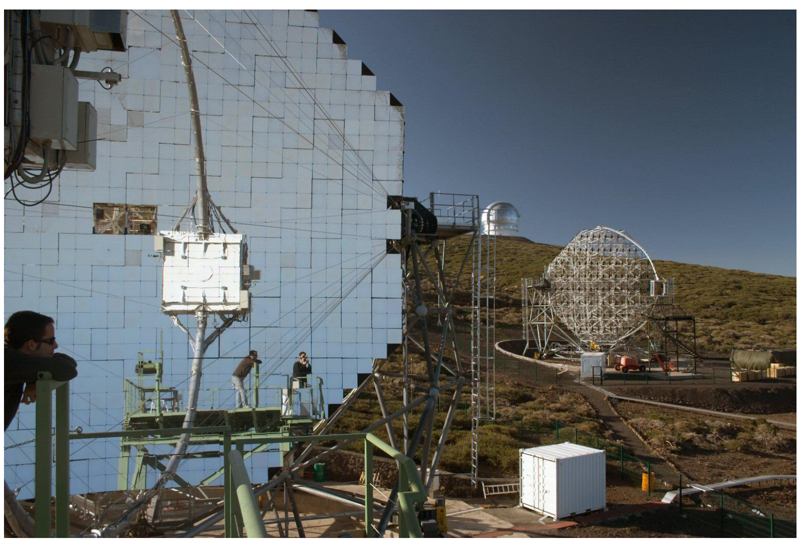

Figure 1: The two MAGIC telescopes. MAGIC I with its reflecting surface in foreground and the mechanical structure of MAGIC II in background (CREDITS: MAGIC Collaboration).

2. THE REFLECTOR OF MAGIC II

In order to maintain the temporal structure of the few nanosecond signal from a Cherenkov flash of the electro-magnetic shower, the overall profile of the reflector is an almost parabolic configuration, with a focal length of 17 m and focal ratio f/D=1. Davies-Cotton reflector [20,21], the most commonly used configuration for TeV telescopes, is therefore adopted also for the configuration of the MAGIC telescope dishes (Fig. 2). Originally, the Davies-Cotton telescope was developed as a solar concentrator and, as such, it does not satisfy the rigorous requirements of astronomy in the visible wavelength range. However a large reflector composed of many small, identical, spherical facets is relatively inexpensive to build, while the alignment of the optical system is easy [22]. A Davies-Cotton telescope indeed consists of a primary mirror with parabolic approximated configuration, formed by several coronas of spherical mirrors each at different radii; the half radius of central panels coincides with the nominal focal length of the primary. The parabolic profile of MAGIC telescopes is fitted by 247 spherical mirrors with different focal lengths, to match the local curvature of the parabola. The curvature radius of the mirrors varies from 34 meters in the centre to 36.4 meters in the outermost ring. In principle mirrors of various rings are different and must be produced with different curvature radii. Constraints on the Point Spread Function of the telescope are, at the end, given by the dimension of the photomultipliers (PMTs) mounted on the prime focus camera. The single PMT represents the camera pixel and has a size of one inch. The PSF results very affordable for the image quality of the typical mirrors. While in the inner part facets of the reflector have been produced with the well known diamond milling technique used for MAGIC I, and improved for the realization of mirrors with a collecting area of 1 m^2 each [23], the outermost 104 mirrors, with curvature radii between 35.4 and 36.4 meters have been realized in glass using the so called *cold-slumping.*

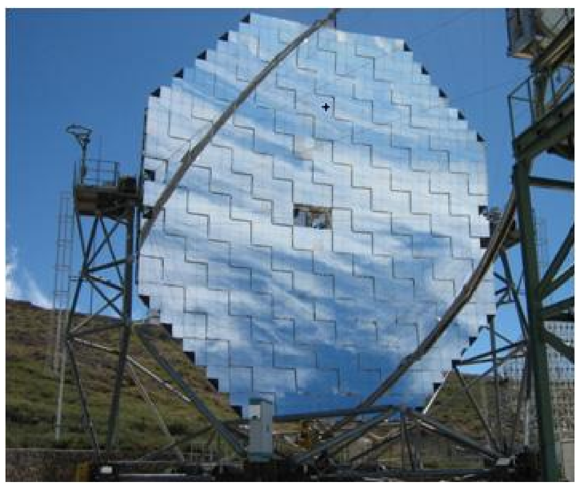

Figure 2: The primary-mirror dish of the MAGIC I telescope, based on the Davies-Cotton configuration.

3. DESIGN AND PRODUCTION OF GLASS PANELS

For Cherenkov Telescopes high collecting area is needed, achievable by the use of a large diameter primary, made of a mosaic of many (possibly light-weight) reflecting facets, like the ones needed for future next generation ground based optical telescopes as e.g. the 42 m E-ELT [24] telescope studied by ESO. While in both cases a high volume production has to be achieved for making the reflecting panels, for Cherenkov telescopes the angular resolution is not an issue (each panel should present a PSF with a radius at 90% focusing better than 3 arcmin, compared to the 0.1 arcsec value requested for each E-ELT panel). However the areal cost and areal density needed for Cherenkov telescopes are quite challenging, since they should maintained <1000-3000 Euros / m^2 and 20 kg / m^2 respectively; for comparison, the same target parameters for E-ELT are 300 kEuro /m^2 and 70 kg/ m^2 respectively.

The *cold glass slumping* is a new method derived from a similar technique proposed for the manufacturing of X-Ray optics of the XEUS mission [25], that fits the requirements of Cherenkov telescopes. It has been developed by the Media

Lario Technologies (MLT) company in collaboration with INAF - Brera Astronomical observatory; MLT has been also in charge of the glass panel production and quality control for MAGIC II. A thin glass sheet, about 2 mm of thickness, is elastically deformed so as to retain the shape imparted by a master with a convex profile. The master has to be worked with the same optical precision needed for the mirrors, because every defect on its surface will be reproduced on the glass. The master typically is in Aluminum and its surface is diamond milled in the same way of the MAGIC I mirrors. In Fig. 3 (A) one of the master used in Media Lario Techn. production is shown; the master has been produced by the LT-Ultra company (Germany); Fig. 3 (B) is a picture of a mirror replicated from the master.

(A) (B)

Figure 3: (A) An aluminum master used for the cold slumping technique and a mirror prototype; (B) a mirror produced using the master.

With large curvature radii the glass sheets can be pressed against the master using vacuum suction. In order to provide the necessary rigidity a honeycomb structure is glued on the deformed sheet under the vacuum forces. At last a second glass sheet is glued on the top of the honeycomb structure, in order to obtain a sandwich. The gluing process is realized by heating the Aluminum mould up to around 80^{o} C. After this stage the panel is aluminized and coated with quartz to protect the reflecting surface. In Fig. 4 the various steps of the process are shown. In principle from a single master one could think that only one radius of curvature for the mirror could be obtained. Nevertheless, by a careful control of the spring-back effect during the gluing process, one can obtain several mirrors with curvature different than the master's one. Using this feature in the case of the MAGIC II production to obtain 12 different curvatures within the angular resolution specifications only two masters have been used.

To assure that the optical characteristics required by the telescope design are maintained during operations the mechanical structure of the single panel has been evaluated with FEM analysis. The final design for the panel is the following:

- Dimensions 985 x 985 mm
- Sandwich structure with the following characteristics:
    - reflecting skin 1.7 mm thick (glass)
    - bonding 0.2 mm thick
    - Aluminum honeycomb 20 mm thick
    - bonding 0.2 mm thick
    - backing skin 1.7 mm thick
- Panel total mass: 12 kg
- Three rigid supports glued in the back part of the panel (stainless steel plates 80x80 mm).

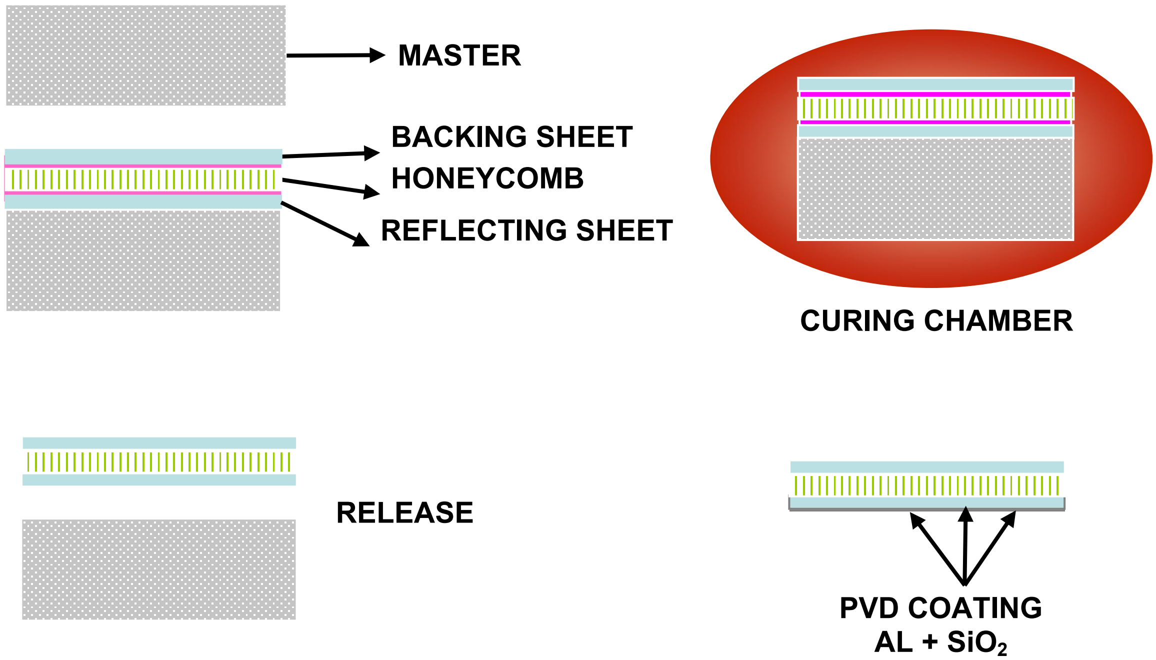

Figure 4: The cold glass slumping process for the mirror production

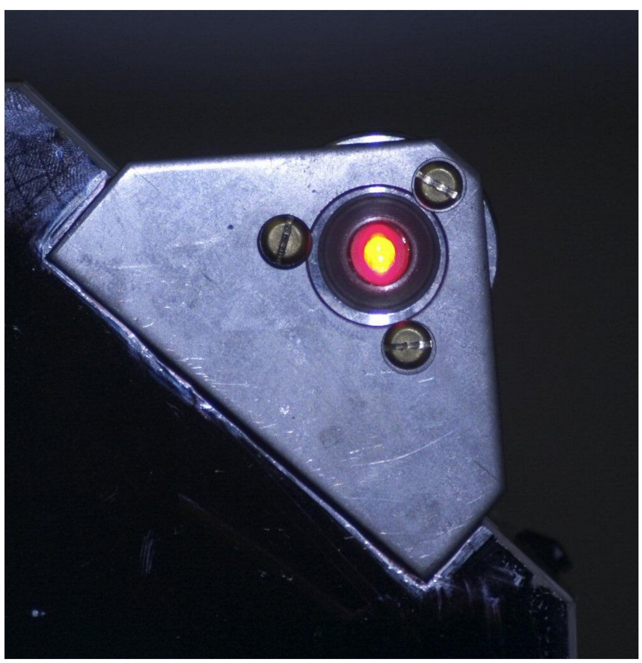

Figure 5: the laser with its older applied to panel

After the productions of the mirrors on a corner of each panel has been installed a plate designed as holder for a laser. This laser is used to align the mirror during Active Motion Control (AMC) operations [26]. In Fig. 5 an image of the laser installed on a prototype is shown.

4. QUALITY TESTS

Mirrors produced via cold glass slumping have been qualified following a rigid quality control process, in order to assure that specifications required by the MAGIC II telescope design have been fulfilled. In particular, curvature radius measurement and PSF spot size has been tested on the full batch of the production. In table 1 a summary of the qualification tests is reported. In the next subsections the main results coming from the tests are discussed.

Table 1: summary of the qualification

Qualification test	on each mirror	on sample	on prototype
Curvature radius	X	X	X
PSF spot size	X	X	X
Glass microroughness			X
Reflectivity		X	X
Reflectivity before and after weathering test		X	
Reflectivity before and after Salt and fog test		X	
Coating adhesion test		X	X
Sealing test		X	X

4.1 Curvature radii distribution

The curvature radii of the panels have been measured illuminating the mirror with a point light source at about 35 m and searching for best the image position on a screen with respect to the panel position (see Fig 6). The distance between the mirror and the point source (and between the mirror and the screen) is equal to the nominal curvature radius (or twice the focal length) of the mirror itself, in such a way that a point image is reflected again into a point image. The image obtained on a screen with a CCD camera has been used for the PSF evaluation test. The distribution obtained using two masters with curvature radii of 36.3 m and 36.5 m is shown in Fig 7. The maximum difference between the required radius and the produced one is of 18 cm, with a mean value of 5 cm and a standard deviation of 6 cm. Considering that the typical error in estimating the curvature radius is between 5 and 10 cm, depending by the quality of the PSF, the distribution fully matches the requirements.

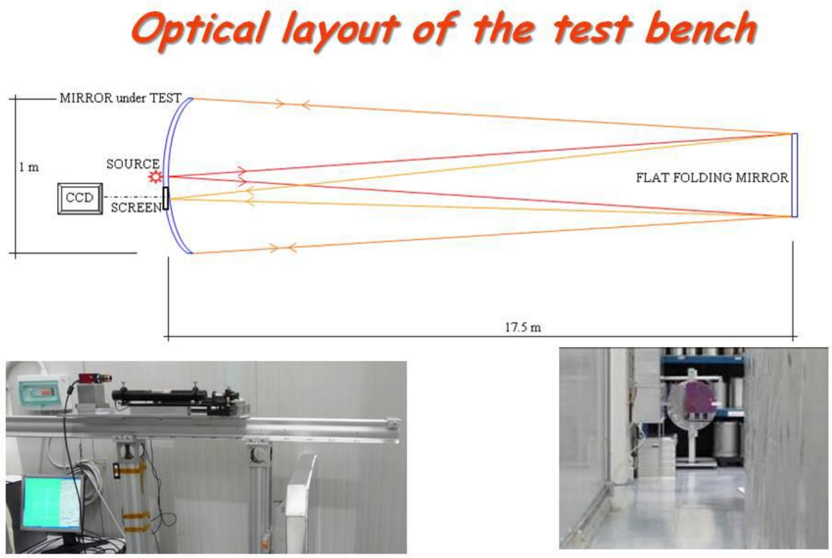

Figure 6: Top: layout of the optical bench used for the measurement of the curvature radius and of the PSF; it is based on a flat folding mirror (see the picture in the right bottom corner) for achieving the right distance from mirror and source. In the left bottom corner it is shown the jig hosting the mirror to be tested, the light source and the detection system, mounted onto a tunable translational stage. In the right bottom corner a picture of the flat folding mirror is shown.

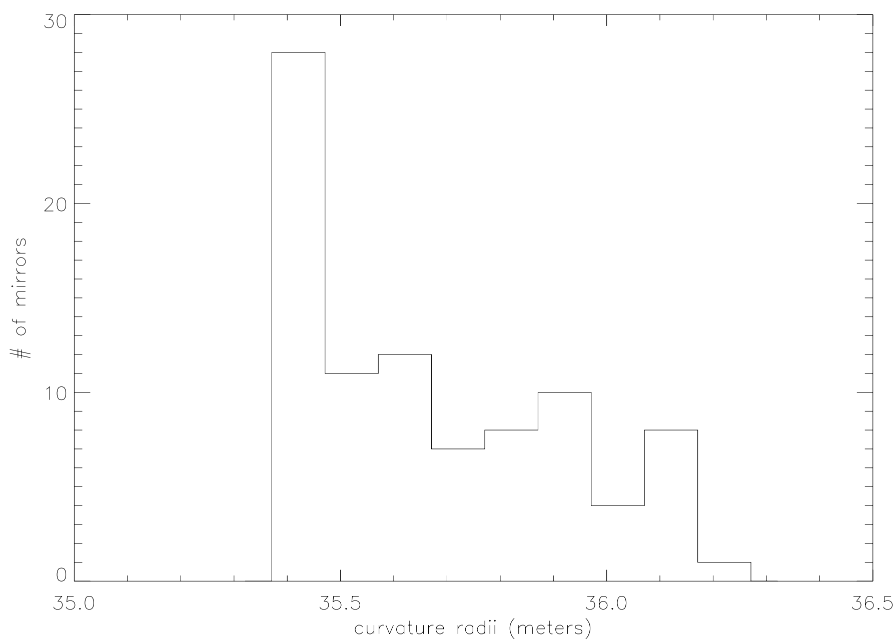

Figure 7: radii distribution for the panel, in the statistics also rejected mirrors are taken into account. This is the reason for the strong left wing of the distribution.

4.1 Surface quality and PSF

The optical quality of the mirrors has been qualified into two way:

- Estimating the size of the radius which contain 90% of the light reflected by the mirror (r_90);
- Estimation of the microroughness of the glass.

In the first case the same setup described in the previous subsection has been used for all the mirrors produced. The typical image taken with a CCD camera is shown in Fig. 8, with over plotted its r_90.

Distribution of the measured r_90 is shown in Fig. 9. The mean of r_90 at 35 meters is about 12.5 mm (0.7 millirad) with a standard deviation about 2.5 mm. Except for some border line mirror in the wings of the distribution all the PSF are well inside optical requirements of the telescope.

During prototyping the angular resolution has been tested also before and after thermal cycling (five cycles between -20 C and +20C, plateau of 12 hours, and then between +20C and +40C , plateau of 4 hours). No changes in PSF occurred before and after test.

About microroughness of the glass, profiles taken with a WYKO TOPO 2D interferometer system have been taken on a glass sample used for prototypization. Results are shown in Fig. 10 (lower profile). A comparison with a surface sample of the aluminum mirrors used for MAGIC I (upper profile). As expected glass roughness is an order of magnitude less than Aluminum case, the latter being affected by the typical grooves structure due to the diamond milling.

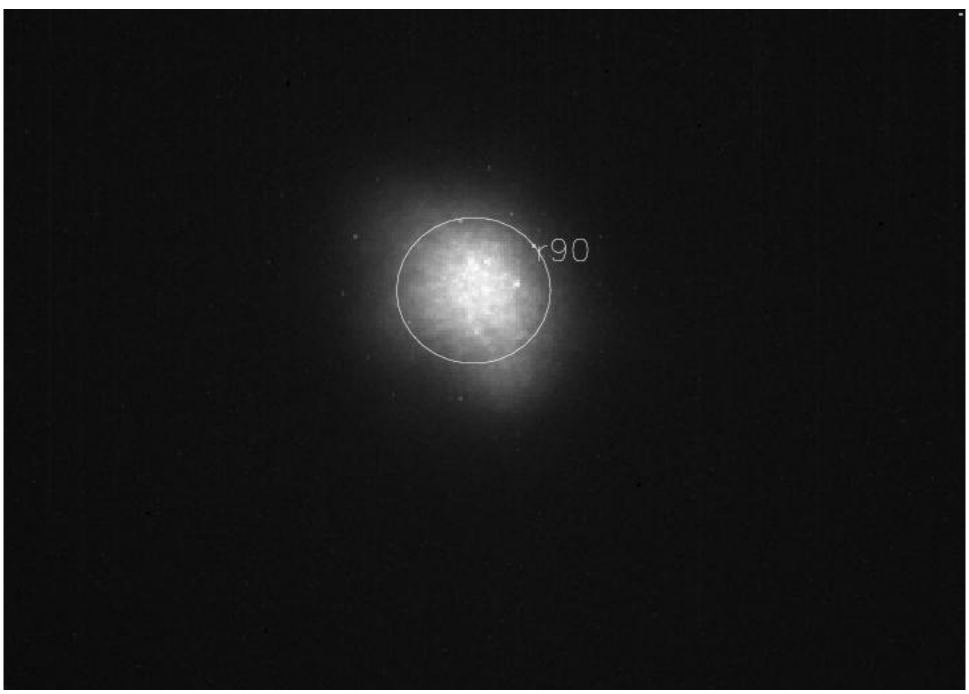

Figure 8: PSF image taken with the setup described in section 4.1 with over-plotted the circle with radius r_90.

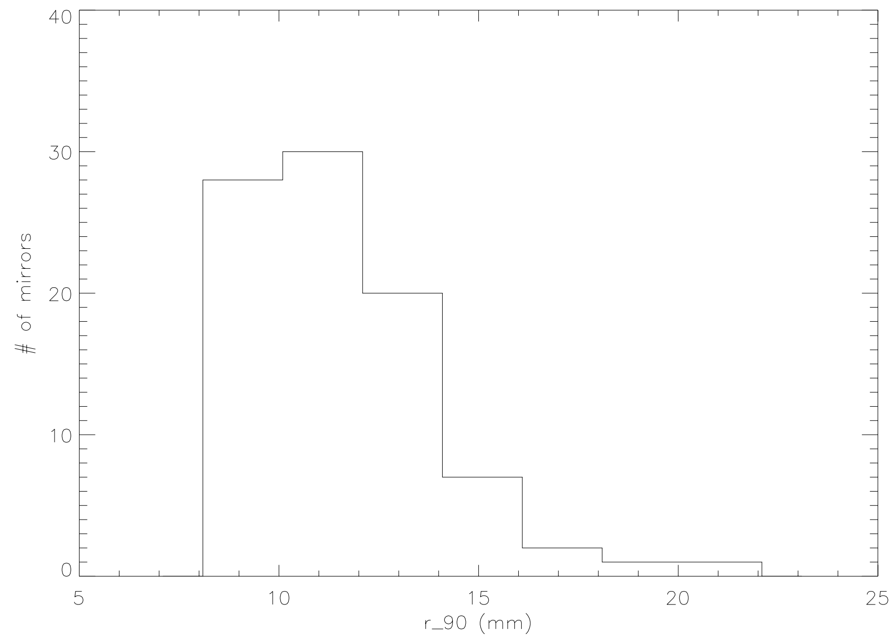

Figure 9: distribution of the measured r_90 spot sizes.

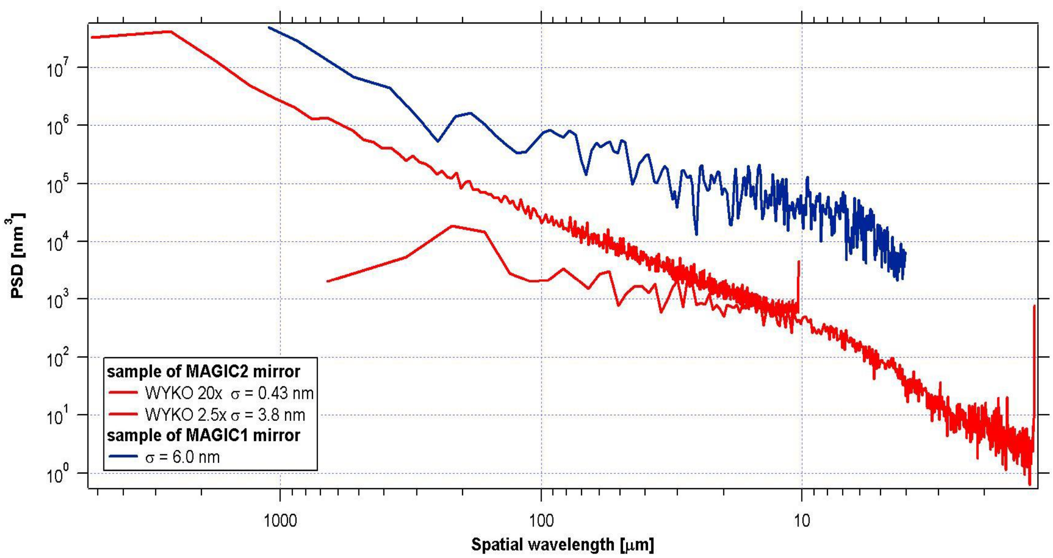

Figure 10: glass microrougness PSD in comparison with the MAGIC I mirror one obtained with a WYKO microscope

4.2 Reflectivity and aging tests

Reflectivity of the panels has been measured on samples, before and after salt-fog test and weathering test. Moreover the same measurement has been performed on a prototype installed at the telescope site as in operational situation, after six months. For the measurements various instruments have been used giving very similar values, among them an Ocean Optics USB2000 equipped with integrating sphere and reflectance standard, an IRIS 908RS2 and a Minolta spectrophotometer. All measurements were on small portion of the reflecting surface. The mean value in the B band (470 nm) just after coating was about 88%. Difference before and after aging tests are below 1

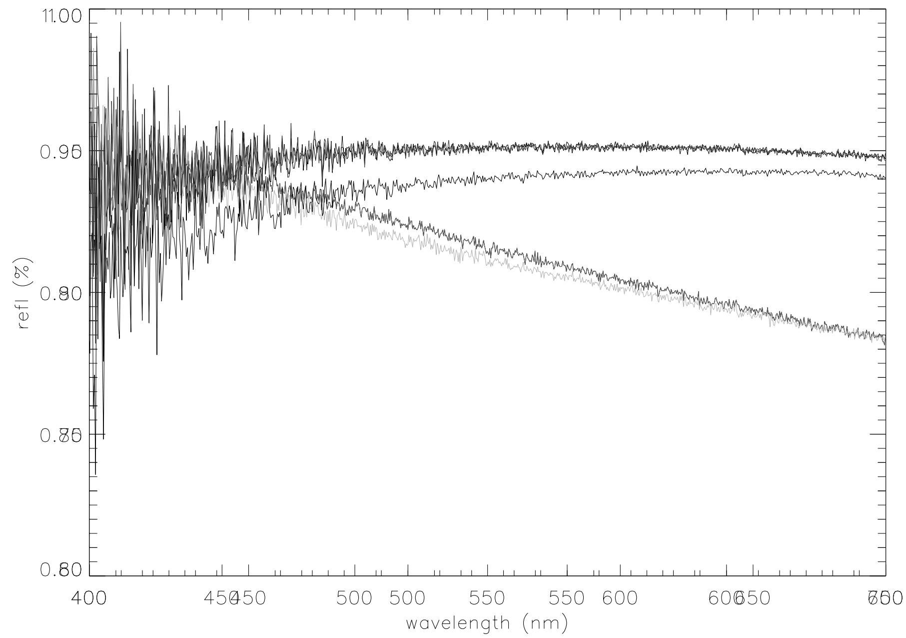

Figure 11: reflectivity in the spectral range between 400 and 700 nm. Different gray tone curves are relative to different portion of the mirror.

In Fig. 11 the spectrum obtained with Oceans optics USB2000 is shown. Good uniformity of the coating on the surface of the mirror is quite evident. Salt-fog test has been executed on a dedicated chamber on two glass samples coated as the panels. Weathering test has been realized on coated samples with 10 fluorescent lamps and filters to realized the pass-band and irradiation needed for the test. During irradiation the humidity of the climatic chamber has been changed between 25 to 95%, temperature is changed between -40C and 70C. The test has been performed during 42 days. No change in reflectivity has been measured.

5. CONCLUSIONS

The reflecting surface of MAGIC II, composed by aluminum and glass panels, is almost ready to be installed on the telescope (foreseen installation date July 2008). One hundred glass panels commissioned by INAF have been realized and qualified in the time schedule needed to the experiment. The test realized on their optical performances demonstrated that the cold glass slumping is a very promising technique to be applied in the production of the reflecting surfaces of next generation Cherenkov telescopes like CTA.

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