

## Mirror Development for the Cherenkov Telescope Array

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**Abstract:** The Cherenkov Telescope Array (CTA) is a planned observatory for very-high energy gamma-ray astronomy. It will consist of several tens of telescopes of different sizes, with a total mirror area of up to 10,000 square meters. Most mirrors of current installations are either polished glass mirrors or diamond-turned aluminium mirrors, both labour intensive technologies. For CTA, several new technologies for a fast and cost-efficient production of light-weight and reliable mirror substrates have been developed and industrial pre-production has started for most of them. In addition, new or improved aluminium-based and dielectric surface coatings have been developed to increase the reflectance over the lifetime of the mirrors compared to those of current Cherenkov telescope instruments.

**Keywords:** CTA, imaging atmospheric Cherenkov telescope, gamma rays, optics, mirrors

### 1 Introduction

In recent years, ground-based very-high energy gamma-ray astronomy has experienced a major breakthrough demonstrated by the impressive astrophysical results obtained with experiments like H.E.S.S., MAGIC, and VERITAS [1]. The Cherenkov Telescope Array (CTA) project is being designed to provide an increase in sensitivity of at least a factor ten compared to current installations, along with a significant extension of the observable energy range down to a few tens of GeV and up to  $> 100$  TeV [2]. To reach the required sensitivity, several tens of telescopes will be needed with a combined mirror area of up to 10,000 m<sup>2</sup>. Current design studies investigate three telescope sizes: small-sized telescopes with a diameter of approximately

4 m, medium-sized telescopes (12 m) and large-sized telescopes (23 m). In addition, telescopes with dual mirror optics (Schwarzschild-Couder configuration) are under investigation.

The individual telescopes will have reflectors of up to 400 m<sup>2</sup> in area. The requirements for the point spread function (PSF) are more relaxed compared to those for optical telescopes. Typically, a PSF below a few arcmin is acceptable which makes the use of a segmented reflector consisting of small individual mirror facets (called mirrors hereafter) possible. Usually, the telescopes are not protected by domes and the mirrors are permanently exposed to the environment. The design goal is to develop low-cost, light-weight, robust and reliable mirrors of 1 – 2 m<sup>2</sup> size with adequate reflectance and focusing qualities but demanding

very little maintenance. Current installations mostly use polished glass or diamond-milled aluminium mirrors, entailing high cost, considerable time and labour-intensive machining. Most technologies currently under investigation for CTA are based on a sandwich concept with cold-slumped surfaces made of thin float glass. In most cases, aluminium honeycomb is used as core material, but an implementation with v-shaped aluminium spacers exists as well. In addition, there are sandwich structures made entirely from aluminium and prototypes made from composite material using a moulding technique from the car manufacturing industry.

## 2 Basic specifications

The mirrors for the single-reflector CTA telescopes will be hexagonal in shape, with sizes of 1 – 2 m<sup>2</sup>, well beyond the common size of 0.3 – 1 m<sup>2</sup> of current instruments. IACTs are normally placed at altitudes of 1,000 – 3,000 m a.s.l. where significant temperature changes between day and night as well as rapid temperature drops are quite frequent. All optical properties should stay within specifications within the range –15° C to +25° C and the mirrors should resist temperature changes from –25° C to +40° C, with all possible changes of their properties being reversible.

Intrinsic aberrations in the Cherenkov light emitted by atmospheric showers limit the angular resolution to around 30 arcsec [3]. However, the final requirements for the resolution of the reflectors of future CTA telescopes, i.e. the spot size of the reflected light in the focal plane (camera), depend on the pixel size of the camera and the final design of the telescope reflector. There is no real need to produce mirrors with a PSF well below the half of the camera pixel size, which is ordinarily not smaller than 5 arcmin. A diffuse reflected component is not critical as long as it is spread out over a large solid angle. The reflectance into the focal spot should exceed 85% for all wavelengths in the range from 300 to 550 nm, ideally close to (or even above) 90%. The Cherenkov light intensity peaks between 300 and 450 nm, therefore the reflectance of the coating should be optimized for this range.

## 3 Test facilities

The standard way to determine the PSF of such mirrors is a so-called  $2f$ -setup: the mirror is placed twice the focal distance  $f$  away from a pointlike light-source and the return image is recorded using CCDs or photodiodes. Using waveband filters or narrowband LEDs, measurements at different wavelengths are possible. Normalizing for the intensity of the light-source, the total directed reflectance into the focal spot can be estimated as well. Comparable setups currently exist in several institutes involved in the development and characterization of CTA mirrors.

While being a reliable method,  $2f$ -measurements need a lot of space (several 10s of meters) and are rather time-intensive. An alternative approach with a compact setup, especially for testing large numbers of mirrors, is being pursued at the University of Erlangen: Phase Measuring Deflectometry (PMD) [4, 5]. The basic idea of PMD is to observe the distortions of a defined pattern after it has been reflected by the examined surface and from them to calculate the exact shape of the surface. For this, sinusoidal patterns are projected on a screen and cameras take pictures of the distortions of these patterns. The primary measurement

of PMD is the slope of the mirror surface in two perpendicular directions. A map of the mirror's curvature can be calculated by differentiating the slope data. Using a ray-tracing script in which the normal and slope data from the PMD measurements are the input parameters, it is possible to calculate the PSF at arbitrary distances from the mirror.

Cherenkov telescopes usually operate without domes and the mirrors are exposed to the environment for many years. Therefore, an extensive programme of long-term durability tests is being performed at the University of Durham and the Max-Planck-Institut für Kernphysik in Heidelberg, trying to use ISO standards wherever applicable. Apart from classical temperature and humidity cycling for accelerated ageing the test series involves abrasion tests and sand blasting of mirror surfaces, pull tests with sticky tape to check the adhesion of the coating, tests of the influence of bird faeces on the reflective coating, and detailed tests of the water tightness of the sandwich structures as well as of their resistance to mechanical impact from, e.g., hail.

## 4 Technologies under investigation for CTA mirrors

Several institutes within the CTA consortium have developed or improved different technologies to build mirrors, most of which are in a pre-production phase at the moment.

### 4.1 Glass replica mirrors

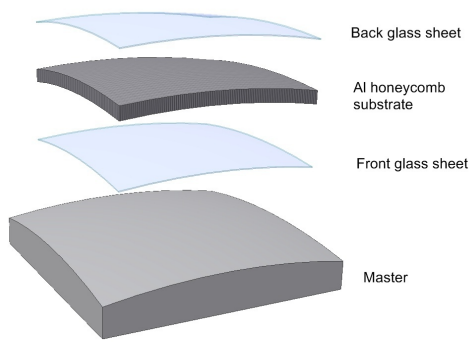
The basic concept of this method, originally developed by INAF Brera, is to form a thin sheet of glass on a high precision mould to the required shape of the mirror and to glue a structural material and a second glass sheet to its back to form a rigid sandwich structure. This concept is being applied by four institutes (INAF Brera, Italy; CEA Saclay, France; ICRR, Tokyo, Japan; IFJ-PAN, Krakow, Poland) together with industrial partners. A sketch of the basic layout of this technology is shown in Fig. 1.

#### *INAF Brera, Italy*

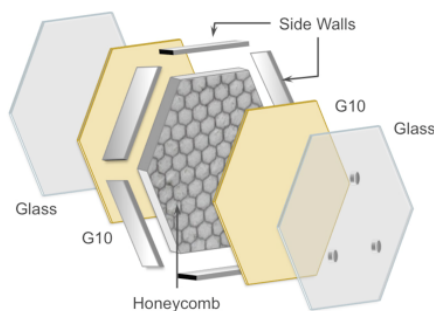
Almost half of the mirror facets of MAGIC II are cold-slumped glass-aluminium sandwich mirrors [6, 7, 8]. A thin sheet of glass is cold-slumped on a high precision spherical mould. This glass sheet, an aluminium honeycomb and a back sheet are then glued together with aeronautical glue. The shaped substrates are coated in the same way as traditional glass mirrors. A sketch of the design is shown in Fig. 1. For CTA the main development goal was to improve the process and to reduce the costs. A first series of 20 mirrors has been produced for the prototype of the medium size CTA telescope, and these have gone through an extensive testing programme.

#### *CEA Saclay, France*

A similar method is being pursued by the Irfu group at CEA (Saclay) [9], i.e. a sandwich structure is formed by 2 glass sheets and an aluminium honeycomb core, and the spherical shape of the front surface is created by cold-slumping the front sheet on a high-precision mould. Intermediate layers of G10 are inserted between the glass and the honeycomb, improving the shape and the stiffness of the structure. Rigid side walls are used to maintain the correct curvature at the periphery of the mirror. A sketch of the mirror is shown in Fig. 2. A series of 30 hexagonal mirrors of 1.2 m flat-to-flat (the planned size for the medium-size



**Fig. 1:** Cold-slumped glass mirrors (INAF Brera).



**Fig. 2:** Cold-slumped glass mirrors with G10 layers (CEA Saclay).

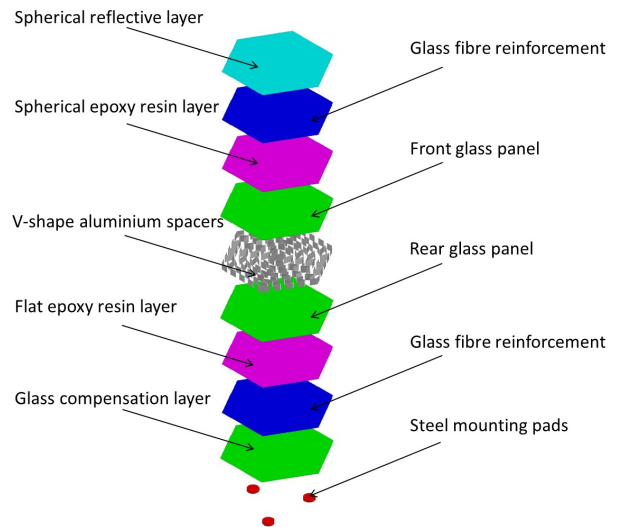
telescopes of CTA) with 16.07 m focal length have been produced this way.

*ICRR, Japan*

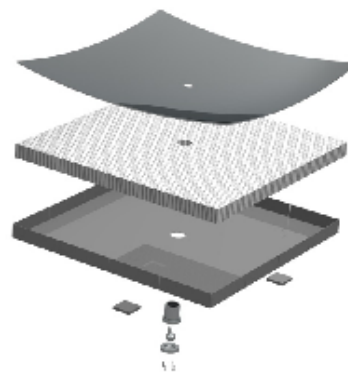
Slumping technology is also being pursued by the ICRR in Tokyo, Japan, concentrating on hexagonal mirrors with a size of 1.5 m flat-to-flat as planned for the large-sized telescopes of CTA. The mirrors have a sandwich structure consisting of a glass sheet of 2.7 mm thickness, an aluminum honeycomb of 60 mm thickness, and another glass sheet. The reflective layer of the mirror is coated with Cr and Al on the surface of the glass sheet with a protective multicoat layer of SiO<sub>2</sub>, HfO<sub>2</sub>, and SiO<sub>2</sub>. A first pre-series mirror production is ongoing.

*IFJ-PAN, Krakow, Poland*

The open, cold slumped structure under investigation is a rigid sandwich, which consists of two flat glass panels separated by v-shaped aluminium spacers, which are glued using epoxy resin. In a second step an additional, spherical layer of epoxy resin is formed on the front panel using a master mould. Then, a reflective layer made of Borofloat 33 glass sheet, coated with Al and SiO<sub>2</sub>, is glued to the support structure using the same mould. There are also two glass fibre reinforcements in between the spherical reflective layer/glass compensation layer and the spherical/flat layer of the epoxy resin to improve resistance to mechanical impact. The open sandwich structure enables good cooling and ventilation of the mirror panels and avoids trapping water inside the structure. A stainless steel mesh is attached to the side walls to protect the mirror structure against contamination by insects or bird waste. A sketch of the



**Fig. 3:** Cold-slumped open structure glass mirrors (IFJ-PAN Krakow).



**Fig. 4:** Aluminium sandwich mirror (INFN Padova).

principal design is shown in Fig. 3 and a detailed description is given in [10].

**4.2 All-aluminium mirrors**

*INFN, Padova, Italy*

The entire reflector of MAGIC I and more than half of the MAGIC II mirrors are made of a sandwich of two thin aluminium layers interspaced by an aluminium honeycomb structure that ensures rigidity, high temperature conductivity and low weight, as shown in Fig. 4 and described in [11]. The assembly is then sandwiched between spherical moulds and put in an autoclave, where a cycle of high temperature and pressure cures the structural glue. The reflective surface is then generated by precision diamond milling. The final roughness of the surface is around 4 nm and the average reflectance is 85%. The aluminium surface is protected by a thin layer of quartz (with some admixture of carbon) of around 100 nm thickness. This technology is being further developed for CTA, particularly by the use of either a thin, coated glass sheet or a reflective foil as front layer to reduce the cost imposed by the diamond milling of the front surface.

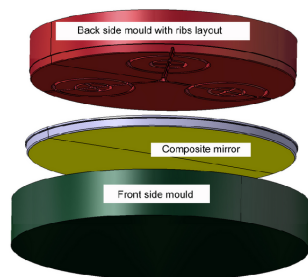


Fig. 5: Composite mirror (SRC-PAS Warsaw).

### 4.3 Composite mirrors

*SRC-PAS, Warsaw, Poland*

Carbon fibre/epoxy based substrates have good mechanical properties and show the potential for fast and economical production in large quantities. The challenge is to produce mirrors with good surface qualities without labour-intensive polishing.

Currently, at SRC PAS, the sheet moulding compound (SMC) technology for composite mirrors is being developed. This technique has two major features: a) the structure is composed of one isotropic, thermally conductive material, b) there is no glass in the structure. The mirror substrate is formed compressing the SMC material in a mould (see Fig. 5). The material is a low-cost, widespread and semi-fabricated product. SMC is a proven technology in the automotive industry and some of its advantages include: only a one-step process is needed to produce the substrate, it is a fast process which takes 3 minutes only and the material shows no shrinkage. The top surface of the composite mirror does not require polishing, as its smooth surface is obtained using a mould with a highly polished surface.

### 5 Reflective and protective coating

Cherenkov telescope mirrors need to have a good reflectance between 300 and 550 nm which makes aluminium the natural choice as reflective material. The mirrors are exposed to the environment all year round, therefore this aluminium coating is usually protected by vacuum deposited  $\text{SiO}_2$  (in the case of H.E.S.S.),  $\text{SiO}_2$  with carbon admixtures (for MAGIC) or  $\text{Al}_2\text{O}_3$  obtained by anodizing the reflective Al layer (in the case of VERITAS). Nevertheless, a slow but constant degradation of the reflectance is observed.

The Max-Planck-Institut für Kernphysik, Heidelberg, together with an industrial partner, has performed studies to enhance both the reflectance and the long-term durability of mirror surfaces [12]. Coatings under investigation include: a) Multilayer dielectric coatings of alternating layers of materials with low and high refractive index (e.g.  $\text{SiO}_2/\text{HfO}_2$ ) on top of the aluminization. Simple 3-layer designs are already able to increase the reflectance between 300 and 600 nm by 5%. b) Purely dielectric coatings without any metallic layer, which avoids the rather low adhesion of aluminium on glass. These show a reflectance greater than 95% in the wavelength region of interest and very low reflectance of only a few percent elsewhere. With this the night-sky background above 550 nm can be significantly suppressed, which is of special interest if silicon detectors rather than the standard photomultipliers are used, since they have a higher sensitivity at these wavelengths. Extensive tempera-

ture and humidity cycling as well as abrasion tests indicate a more stable long-term behaviour of these purely dielectric coatings. The disadvantage is that mirror with these coatings are more likely to form condensation [13]. Modifications to improve this are currently under investigation.

In addition, the University of Tübingen is working on simulations to improve the design of the multi-layer coatings and operates a coating chamber for the production of small mirror samples to study systematically various coating options and their production techniques [14]. Furthermore, the University of Sao Paulo is working to improve the classical Al +  $\text{SiO}_2$  coating.

### 6 Summary

Many of the challenges induced by the demand for a few thousand mirrors with a total reflective area of up to 10,000  $\text{m}^2$  for CTA have been technically solved on the prototyping level, such as the production of large-sized facets of up to 2  $\text{m}^2$  in area with low weight and high optical quality. Currently pre-production series have been or are being produced for the different technologies to prove that an easy and rapid series production at reasonable costs is possible. For the mirror coatings, alternatives to the standard solution have been developed that show improved durability in laboratory tests. For quality control, extensive test facilities have been set up, for testing both the optical performance of the mirrors and the durability of substrates and of coatings.

### Acknowledgements

We gratefully acknowledge support from the agencies and organisations listed in this page: <http://www.cta-observatory.org/?q=node/22>.

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