Mirror Development for CTA

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Abstract: CTA will be an array of Imaging Atmospheric Cherenkov Telescopes (IACTs) for VHE gamma-ray astronomy with a proposed total mirror area of approximately 10000 square meters. The challenge is to develop lightweight and cost-efficient mirrors with high production rates and good long-term durability. Several technologies are currently under rapid development: sandwich structures based on carbon/glassfibre-epoxy composite materials and monolythic carbon fibre structures, either with glass or epoxy surfaces; cold-slumped glass sheets with aluminium honeycomb or glass foam as structural material; all-Aluminium mirrors. New surface coatings are under investigation with the aim of increasing the reflectance and long-term durability. In addition, new methods for a fast and reliable testing of thousands of mirrors are being developed.

Keywords: CTA, Imaging Atmospheric Cherenkov Telescope, Gamma-rays, Optics

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 IACT arrays 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 10000 m^2. Current design studies investigate three telescope sizes: small-sized telescopes with a diameter of approximately 6 m, several 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^2 area. The requirements for the focal 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 in the following) possible. IACTs are usually not protected by domes, the mirrors are permanently exposed to the environment. The design goal is to develop low-cost, lightweight, robust and reliable mirrors of $1-2$ m^2 size with adequate reflectance and focusing qualities but demanding very little maintenance. Current IACTs mostly use polished glass or diamond-milled aluminium mirrors, entailing high cost, considerable time and labour intensive machining. The technologies currently under investigation for CTA pursue different methods such as sandwich concepts with cold-slumped surfaces made of thin float glass and different core materials like aluminium honeycomb, glass foams or aluminium foams, constructions based on carbon fiber/epoxy or glass fibre substrates, as well as sandwich structures made entirely from aluminium.

2 Basic specifications

The mirrors for the CTA telescopes will be hexagonal in shape, with an anticipated size between $1-2$ m^2, well beyond the common size of $0.3-1$ m^2 of the currently operational 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 $-10°$C to $+30°$C and the mirrors should resist to temperature changes from $-25°$C to $+60°$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), will 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 80% for all wavelengths in the range from 300 to 600 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 pointlight light-source and the return image is recorded using a CCD 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 huge numbers of mirror 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 the patterns due to the reflection on the mirror surface. The primary measurement of PMD is the slope of the mirror 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.

IACTs usually operate without domes and the mirrors are exposed to the environment for many years. Therefore, an extensive set of long-term durability tests is being defined by the University of Durham, trying to use ISO standards wherever applicable. Apart of classical temperature and humidity cycling for accelerated aging the intended test series involve corrosion tests in salt fog atmospheres, abrasion tests by sand blasting, pull tests with sticky tape to check the adhesion of the coating, or tests of the influence of bird faeces on the reflective coating.

4 Technologies under investigation for CTA mirrors

Several institutes within the CTA consortium are developing or improving different technologies to build mirrors, most of which are in a prototyping phase at moment:

4.1 All-aluminium mirrors

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. 1a [6]. 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. For CTA, this technology is being further developed especially by the use of either a thin coated glass sheet as the front layer or a reflective foil to reduce the cost imposed by the diamond milling of the front surface.

4.2 Glass replica mirrors

The basic concept of this method, originaly 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 glue a structural material and a second glass sheet or other material to its back to form a rigid sandwich structure. This concept is being pursued by three institutes (INAF Brera, Italy, CEA Saclay, France, and Sanko, Japan). A sketch of the basic layout of these mirrors is shown in fig. 1b.

INAF Brera, Italy

Almost half of the reflector facets of MAGIC II are cold-slumped glass-aluminium sandwich mirrors [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 aeronautic glue. The shaped substrates are coated in the same way as traditional glass mirrors. For CTA R&D activities are going on to improve the process and to reduce the costs. While Al honeycomb is the baseline design, in addition the use of FoamGlass® as structural material is being investigated. This material has a low weight, ($0.1-0.165$ g/cm^3), a very low thermal expansion coefficient (CTE $\simeq$ 9 μm K/m), is water tight, can easily be machined, has high strength and is very competitively priced.

CEA Saclay, France

A similar method is being pursued by the IRFU group at CEA (Saclay) [9]. Here as well 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-prescision mould. First hexagonal mirrors of 1.2 m flat-to-flat (the planned size for the medium-size telescopes of CTA) with 16.7 m focal length have been produced this way.

Sanko, Japan

The same technology is also being pursued by Sanko in Japan, concentrating on hexagonal mirrors with a size of 1.5 m flat-to-flat as planned for the large-sized telescopes of CTA. First prototypes have been produced and a closed-cell aluminium foam as alternative core material is being investigated.

4.3 Composite mirrors

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. In addition, variations of the same designs using glass fibre and/or aluminium as structural material are being studied. These types of composite mirrors are under development at CEA Saclay, France, SRC-PAS, Warsaw, Poland, and IFJ-PAS, Krakow, Poland.

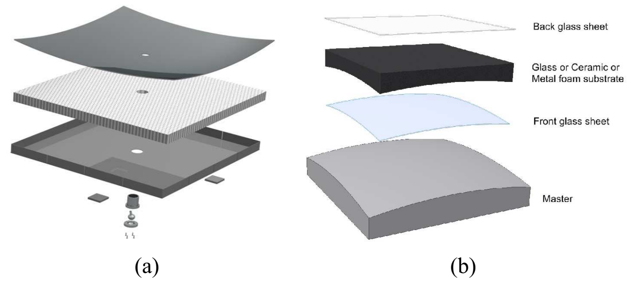


Figure 1: (a) All-aluminium mirrors (INFN Padova). (b) Cold-slumped glass mirrors (INAF Brera, CEA Saclay, Sanko)

CEA, Saclay, France

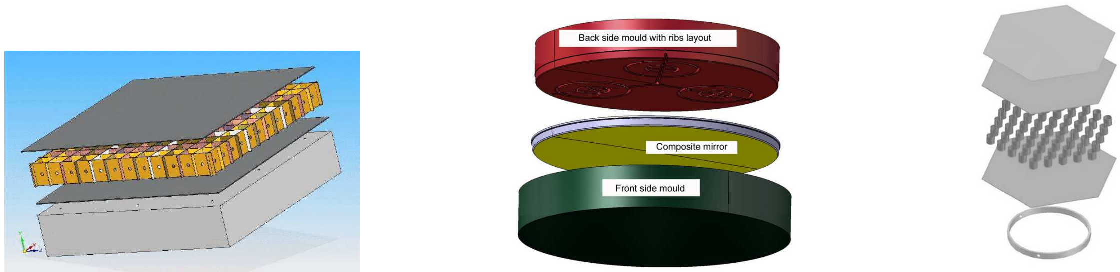
The CEA composite mirror design [9] has a core of rectangular strips of either carbon fibre, glass fibre or aluminium. On one side they are machined to the radius of curvature. To this core a front and a back sheet of the same material are glued, the front having been shaped on a mould with the appropriate radius of curvature. In a second step a thin glass sheet is glued to the front side, again using the mould, that is coated with a reflective coating. Several hexagonal mirrors of 1.2 m have been produced and are being tested. A principal sketch is shown in fig. 2a

SRC-PAS, Warsaw, Poland

The SRC is investigating the sheet moulding compound (SMC) technology, in which a composite material (Menzolit®) is formed in a spherical steel mould at high pressures (60 bar) and high temperatures (150°C). Menzolit has a carbon fibre content of 60%, a Young's modulus of $20-50$ GPa (depending on fibre direction) and 0% shrinkage. The moulding process takes approximately 10 min. The whole mirror structure is made as a single part and of one material, with ribs formed on the rear to increase mechanical stability. The spherical surface is formed by an in-mould coating process (IMC) during the forming process of the structure itself which is later coated or by using a reflective aluminium material called Alanod® . A sketch of such a composite mirror and the respective mould is shown in fig. 2b.

IFJ-PAN, Krakow, Poland

The composite structure under investigation is a rigid sandwich which consists of two flat panels of either carbon fibre, glass fibre or aluminium separated by perforated aluminium tubes of equal length. In a second step a spherical epoxy layer is formed on the front panel using a master surface. Alternatively front surfaces made of a cold-slumped glass sheet or of Alanod® are under investigation. The open sandwich structure enables good cooling and ventilation of the mirror panels and avoids trapping water inside the structure. The flatness and uniform thickness of the sandwich structure facilitates production, while the robustness of the structure ensures easy handling of the mirror. A sketch of the principal design is shown in Figure 2c.



(a) (b) (c)

Figure 2: (a) Sandwich design with rectangular hoeneycomb (CEA Saclay). (b) Monolythic composite mirror (SRC-PAS Warsaw). (c) Open structure composite mirror (IFJ-PAN Krakow).

5 Reflective and protective coating

IACTs need to have a good reflectance between 300 and 600 nm wavelength 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 SiO_2 (in the case of H.E.S.S.), SiO_2 with carbon admixtures (for MAGIC) or Al_2O_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 industrial partners, is performing studies to enhance both the reflectance and the long-term durability of mirror surfaces [10]. Coatings under investigation include: a) Multilayer dielectric coatings of alternating layers of materials with low and high refractive index (e.g. SiO_2/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 avoiding 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. Extensive temperature and humidity cycling as well as corrosion tests in salt-fog atmospheres show a very stable long-term behaviour of these purely dielectric coatings. More extensive durability testing is ongoing at the moment. In addition, the H.E.S.S. experiment is re-coating the mirrors of its telescopes at the moment. 99 of these mirrors have been re-coated with a purely dielectric coating, several hundred with a three-layer protective coating on top of the aluminium layer, so that durability data from a real application in the field will become available.

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 systematically study various coating options [11]. Furthermore, groups from Argentina and Brasil with experience in the field of mirror coating have joint the efforts recently.

6 Summary

The demand for a few thousand mirrors with a total reflective area of up to 10,000 m^2 for CTA is a challenge in quite a few aspects such as the production of large size facets of up to 2 m^2 in area, low weight ($\simeq 20$ kg/m^2), high optical quality, easy and rapid series production and especially low costs. One of the major constraints is the requirement for a very slow degradation of the reflectance allowing at least 10 years of operation without re-coating. Currently, quite a few mirror technologies are under study with the goal to improve the performances substantially and to minimize the production and maintenance costs.

Acknowledgements

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

References

[1] Aharonian, F. et al, Rept. Prog. Phys., 71, 2008, 096901
[2] W. Hofmann et al. arXive:1008.3702, August 2010
[3] W. Hofmann, arXiv:astro-ph/0603076.
[4] M. C. Knauer, PhD Thesis, Universität Erlangen-Nürnberg, 2006
[5] A. Schulz et al., these proceedings, 2011
[6] Doro, M. et al., NIM A, 595, 2008, 200-203
[7] Pareschi, G. et al., SPIE Proc., 7018, p. 70180W (2008)
[8] Vernani, D. et al., SPIE Proc., 7018, p. 70180V (2008)
[9] C. M. Medina et al., these proceedings, 2011
[10] A. Förster, R. Canestrari, P. Chadwick and A. Knappy, these proceedings, 2011
[11] A. Bonardi et al., these proceedings, 2011