Methods for the characterization of mirror facets for Imaging Atmospheric Cherenkov Telescopes

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Abstract: To achieve a total mirror surface of about 10000 m^2 for the upcoming Cherenkov Telescope Array (CTA), individual mirror facets with a size of 1 to 2.5 m^2 each will be used. The production and testing of these mirror facets bears a particular organizational and logistical challenge. Here we compare two methods to determine the optical quality of mirror facets, namely the commonly used $2f$-method and a new approach, called Phase Measuring Deflectometry (PMD). PMD was developed by the OSMIN group in Erlangen. It offers a variety of advantages compared to the $2f$-method: the result of the PMD measurement is a precise map of the shape of the mirror (on a micrometer level) and of its curvature (with an accuracy up to 0.001 D). Hence it yields detailed information of the mirror surface, which is not possible with the standard $2f$-method. The PMD setup is compact, the characterization of a mirror facet is fast and the method is applicable for a variety of mirror sizes. We will present PMD, describe the different setups, and show first results for CTA mirror prototypes.

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

1 Introduction

The great potential of γ-ray astronomy has been shown by the existing Imaging Atmospheric Cherenkov Telecopes (IACTs), leading to an initiative to build a next generation instrument, namely the Cherenkov Telescope Array (CTA). A detailed description can be found in the CTA design report [1]. The projected sensitivity of CTA exceeds that of any existing IACT by one order of magnitude. CTA aims to extend the photon energy range from some tens of GeV to beyond 100 TeV. Studies of the morphology of TeV-sources will benefit from the array's enhanced angular resolution. The increased detection area will boost the detection rates and open possibilities to investigate transient phenomena. CTA aims to enhance the all sky survey capability, the monitoring capability, and the flexibility of operation.

To achieve this performance 50 – 70 telescopes of three different types will be integrated in the array. The inner part of the array will consist of few Large Size Telescopes (LSTs), with a diameter of 23 m mainly dedicated to the detection of low energy photons. These will be surrounded by several tens of Medium Size Telescopes (MSTs) covering $\sim 1\,\mathrm{km}^2$. These telescopes will have a diameter of 9 – 12 m and be optimized for the energy range from 100 Gev to 10 TeV. A sparse array of Small Size Telescopes (SSTs) will cover the large detection area needed for the highest energies. The mirror area of the telescopes, in total about 10000 m^2, will be composed of mirror facets with a size of 1 – 2.5 m^2. The current baseline for the mirrors for the MSTs is to use hexagonal mirrors with a flat-to-flat size of 1.20 m. The total number of mirrors will be around 10000.

Currently two different types of mirrors are used in Cherenkov telescopes: glass mirrors, which are heavy and not durable and aluminium machined mirrors, which are lighter and more robust, but twice as expensive as glass mirrors. Various solutions are under study to obtain light-weight, robust, and cost-effective mirrors with the required reflectivity and focussing quality. The latter is described by the point spread function (PSF), characterized here by d_{80}, the diameter containing 80% of the reflected light. The PSF of the mirrors has to be < 1 mrad as stated in the design report [1]. Currently, different technologies to construct mirrors are under investigation at different institutes, ranging from cold slumped glass mirrors to diamond milled aluminium mirrors (see [1], [2], and [3] for details). Most methods are sandwich techniques, based on a honeycomb core structure to ensure rigidity and sheets made of different materials on top. To ensure the spherical shape of the mirror, all groups use moulds with the required radius of curvature ($R = 2f$) to form the shape of the sheet. The sheet is in most cases coated afterwards, and different coatings are under investigation.

Mirror development and mass production of CTA mirrors requires a fast and reliable test procedure. Commonly,

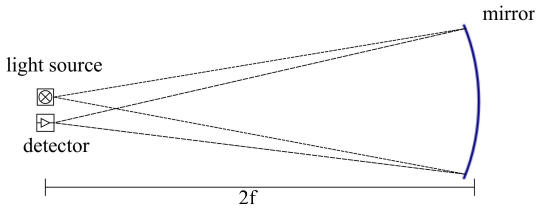

Figure 1: Sketch of the $2f$ measurement setup. The distance between the light source and the detector is extremely exaggerated to demonstrate the light rays more clearly.

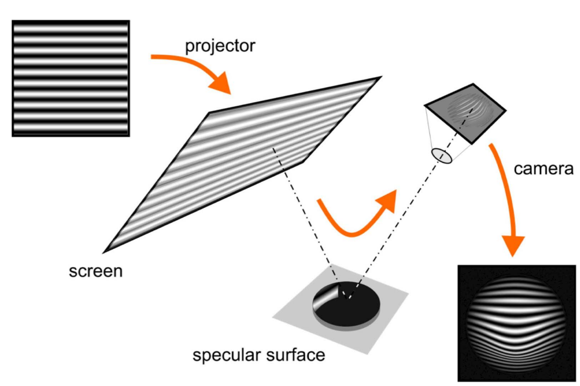

Figure 2: Sketch of the measurement principle of PMD. The sinusoidal pattern is projected on a screen or a ground glass. The camera takes pictures of the distortions of the pattern after the reflection on the object; picture from [5].

the so-called $2f$-method is used to characterize mirrors of IACTs. Phase measuring deflectometry is a new method to characterize mirrors yielding superior information compared to the $2f$-method, making this a good candidate for the standard test method for IACT mirrors as will be shown in the following.

2 Measurement at $2f$

For a $2f$ measurement a light source is placed at a distance of $2f = R$ from the mirror and the reflected picture of the light source is detected at the same distance. The size and shape of the PSF can be tested with this kind of setup. A sketch of the $2f$-setup can be seen in Fig. 1.

This test setup is rather simple to implement, but has several disadvantages: the need of a sufficiently large room ($R = 34$ m for the MST mirrors), as well as the rather difficult alignment of the mirror, and the absence of information about the surface parameters of the mirror. The surface parameters are crucial to understand possible problems concerning the focussing quality of a mirror. Another disadvantage of the $2f$-method is that the testing conditions differ from the operation conditions on a telescope: the testing is done with an on-axis light source at ~ 30 m while the mirrors on the telescope are mainly operated off-axis and the light source, in this case the air-shower, is at a height of ~ 10 km.

3 Phase measuring deflectometry (PMD)

A method avoiding the disadvantages of the $2f$-method is Phase Measuring Deflectometry (PMD). This metrology is used to measure the properties of specular surfaces. It has been developed by the OSMIN group at the University of Erlangen[1] and is described in detail in [5]. PMD is, among others, used to check the quality of progressive eyeglass lenses, windscreens, and painted car bodies. A very successful project is the precise measurement of the local refractive power of progressive power eyeglasses. Solutions based on this development are now being used by all major European eyeglass manufacturing companies. The basic idea of PMD is to observe the distortions of a defined pattern after it has been reflected by the examined surface (see Fig. 2). From these distortions one can calculate the exact local slope and by numerical differentiation and integration the corresponding curvature and shape of the surface, respectively.

Specular Reflection is guided by the normal of the surface, that is the reason why the slope of the object is the primary quantity measured by of deflectometric systems. Since specular surfaces reflect light monodirectionally, care has to be taken that the reflected rays are visible to the camera. Therefore, the light source has to cover a large solid angle. One way to ensure this is to use a big screen, which is diffusely emitting. An alternative for concave mirrors is to place the screen and the observing cameras at a distance of $2f$, trading in the advantage of a short working distance for a smaller size of the required screen. An important part of the technique is to code the position on the screen by the projected pattern. PMD uses a sinusoidal pattern, which has the advantage that the phase of the sinus does not change if the pattern is observed out of focus [4]. It is not possible to observe the object and the pattern in focus at the same time. In order to obtain a high lateral resolution we focus on the object, so that the structured illumination pattern has to be placed out of focus, resulting in a decreased contrast. To maximize angular sensitivity, the period of the sinusoidal pattern should be chosen as small as possible. On the other hand, a smaller fringe period leads to a higher loss of contrast, scaled by the aperture of the observation system. Therefore, the lateral and angular resolution are coupled and a limit for the achievable accuracy can be determined. Using the sinusoidal pattern, it is possible to assign the phase in each pixel of the camera independently. To determine the phase, known phase shift techniques like the Bruning four-shift-algorithm [6] are used, in which four sinusoidal patterns with phase shifts of $\pi/2$ are projected onto the screen. The patterns are projected

1. http://www.optik.uni-erlangen.de/osmin/

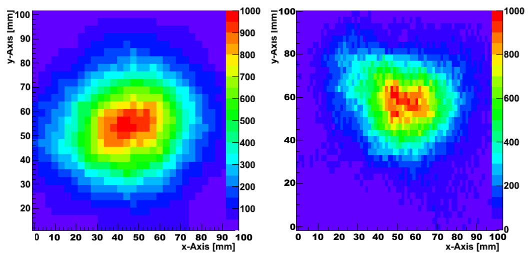

Figure 3: PSF comparison for the mirror from IRFU/CEA (50 cm), the left panel shows the $2f$-result the right panel the raytracing PSF. The color scale is identical for both panels.

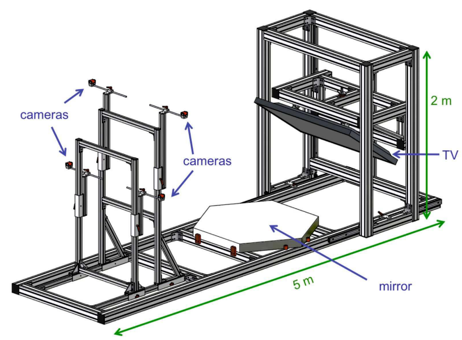

Figure 4: Sketch of the newly designed PMD setup, including four cameras and a screen.

both horizontally and vertically to determine the slope in both directions.

The primary measurand of PMD is the slope of the mirror in two perpendicular directions. The height of the mirror is obtained by integrating the slope data. A map of the mirror's curvature can be calculated by differentiating the slope data. To compare PMD results to the $2f$ data, one needs to determine the PSF of the mirror from the PMD results. We developed a ray-tracing script using the shape and slope data from PMD measurements as input parameters. This script can provide the PSF for arbitrary imaging distances and incidence angles, which is an advantage compared to the $2f$-method. The $2f$-method results in an on-axis PSF from a light source at ~ 30 m distance while the mirrors on the telescope are reflecting light from ~ 10 km distance and are used off-axis for most mirror facets.

To compare both methods the PSF calculated by the ray-tracing script is determined under the $2f$-conditions, meaning on-axis and the light source at a distance of $2f$. Fig. 3 shows a comparison of the PSF-results from both methods. This is the result for a prototype from IRFU/CEA in Saclay with a size of 50 cm. We found reasonably good agreement in size and shape of both PSFs. The size of the PSF of this mirror with the $2f$-method is 50 mm $\widehat{=}$ 1.55 mrad and thus nearly fulfils the requirements. The value for the raytracing is smaller than for the $2f$ measurement, which is due to a perfectly pointlike light source simulated for the ray tracing, while the light source in the $2f$ measurement has an extension of a few mm.

The comparison of the PSFs obtained by both methods has also been done with mirrors from H.E.S.S. and MAGIC, resulting in detailed maps of the surface demonstrating the good performance of the method.

It is possible to measure a mirror with a diameter of 1.20 m with PMD using two different approaches: the so-called Long Working Distance setup (LWD) and Short Working Distance (SWD) setup. The LWD uses a $19''$ monitor as screen and two cameras to observe the pattern after the reflection, and the mirror is placed at a distance of $2f$. This setup has the same disadvantage of the large space needed like the $2f$-method , but reveals the surface parameters of the mirror in a quick measurement. The SWD is a more compact solution using a $60''$ screen; a sketch is shown in Fig. 4. The four cameras are needed to cover the mirror completely; each camera observes a separate quarter of the specular surface while all see the mirror's center. The pictures of the cameras are then combined to get a complete image of the mirror. We have built such a setup and are currently in the commissioning phase.

4 Results of a first CTA prototype

The CTA group at IRFU, CEA in Saclay has produced first mirror prototypes for the MST using a honeycomb technique, see [7]. These mirrors are hexagonal, have a flat-to-flat size of 1.20 m, and a radius of curvature of R$= 33.4$ m. We here present first results of a PMD measurement of this mirror with the LWD setup. Fig. 5 shows the slope of the mirror in the y-direction after subtracting a best fit plane, i.e. after subtracting the basic spherical shape of the mirror approximately. Hence, in Fig. 5 the deviations from the basic shape are shown. The underlying honeycomb structure can easily be seen in this measurement. Shape and curvature can be obtained from integrating or differentiating the slope, respectively see Figs. 6 and 7. The curvature map (Fig. 7) also shows the underlying honeycomb structure. The curvature of a mirror is the inverse of the radius of curvature, the units for the curvature are dioptre $[D] = 1/\text{m}$. The average value for the mean curvature is $c_{\text{mean}} = -0.032 \pm 0.001\,\text{D}$, where the nominal value is $-0.030\,\text{D}$.

This prototype is close to fulfilling the specifications for the MST for CTA; ray-tracing and $2f$-measurements also confirm the PSF to be smaller than 2 mrad. We point out that this special mirror has gone through several ageing tests and is therefore not the mirror with the best possible performance from IRFU/CEA in Saclay.

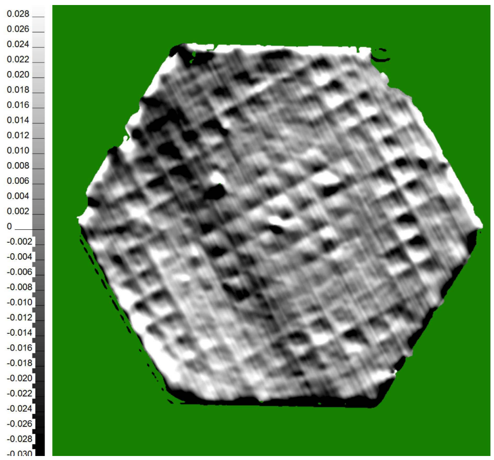

Figure 5: Slope deviation in y direction of the mirror from IRFU/CEA.

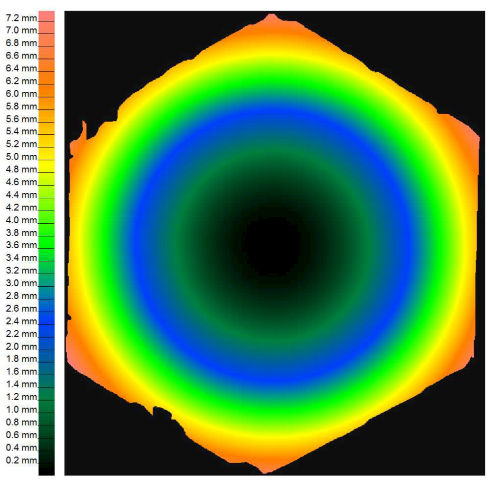

Figure 6: Surface of the mirror from IRFU/CEA.

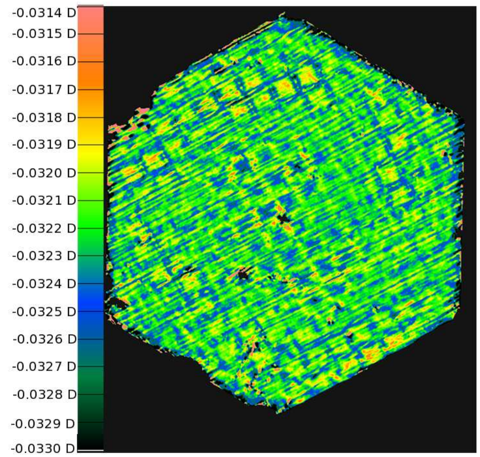

Figure 7: Mean curvature of the mirror from IRFU/CEA.

5 Summary and outlook

We have presented PMD which is a new method to measure mirrors for IACTs. It has proven to give valuable informations about the tested mirrors and the results for the PSFs are in agreement with the commonly used $2f$-method.

Using PMD to characterize mirrors will give very detailed information about the performance of the different mirrors. PMD not only allows us to gather more information on the mirror surface, but it is also quicker and more compact than the $2f$-setup. The time for a measurement is shorter since the mirror does not have to be aligned. Therefore, PMD can be used efficiently for quality control.

Following the specifications in the CTA design report [1] the mirrors have to resist temperatures between $-20°$ and $+40°$ C. Particularly, for the composite mirror technologies this can be critical due to varying thermal expansion coefficients of the different materials. One way to test the temperature behaviour of the mirrors is to heat or cool the mirror and measure the changes afterwards, but since the temperature on the site will not be stable a measurement at different temperatures is required. A climate chamber provides the needed temperature range, but it is not possible to realize a $2f$-setup inside a climate chamber. The best solution is to use the SWD PMD setup. We plan to do measurements inside a climate chamber this summer.

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