4m Davies-Cotton telescope for the Cherenkov Telescope Array

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Abstract: The Cherenkov Telescope Array (CTA) is the next generation very high energy gamma-ray observatory. It will consist of three classes of telescopes, of large, medium and small sizes. The small telescopes, of 4 m diameter, will be dedicated to the observations of the highest energy gamma-rays, above several TeV. We present the technical characteristics of a single mirror, 4 m diameter, Davies-Cotton telescope for the CTA and the performance of the sub-array consisting of the telescopes of this type. The telescope will be equipped with a fully digital camera based on custom made, hexagonal Geiger-mode avalanche photodiodes. The development of cameras based on such devices is an RnD since traditionally photomultipliers are used. The photodiodes are now being characterized at various institutions of the CTA Consortium. Glass mirrors will be used, although an alternative is being considered: composite mirrors that could be adopted if they meet the project requirements.

We present a design of the telescope structure, its components and results of the numerical simulations of the telescope performance.

Keywords: imaging atmospheric Cherenkov telescope, CTA

1 Introduction

The Cherenkov Telescope Array (CTA) will be the next generation observatory of the very high energy (VHE; > 10 GeV) gamma rays. It will provide unprecedented sensitivity in the energy range 10 GeV-300 TeV. To achieve its goals the array will consist of at least three types of telescopes. The sensitivity in the highest energy range, above several TeV, will be provided by the sub-array of telescopes. The sensitivity in the energy range 10 GeV-300 TeV, will be provided by the sub-array of telescopes. The telescope will be equipped with a fully digital camera based on custom made, hexagonal Geiger-mode avalanche photodiodes.

A prototype of an SST is currently being developed by a consortium of Polish and Swiss institutions. The prototype will be based on the proven Davies-Cotton (DC) design, used in the currently operated VHE gamma-ray observatories like H.E.S.S. or VERITAS. A new idea is to equip the telescope with a fully digital camera based on silicon photodetectors. The overall view of the telescope is presented in Fig. 1.

2 4m Davies-Cotton Small Size Telescope

2.1 Structure

The telescope frame and the drive system has been designed at the Institute of Nuclear Physics, Polish Academy of Sciences (INP) in Kraków, Poland. The frame is made of steel. A camera is placed in front of the mirror dish on a quadripod. The dish is fixed to the dish support structure, that contains the counterweights, and is mounted on the telescope support. The quadripod is connected to the dish support in order not to deliver any direct stress on the mirror.

The telescope support consists of a tower fitted with an azimuth drive system, and a special head with an elevation drive. Both the azimuth and the elevation drive systems are based on a set of a roller-bearing and an IMO slew transmission equipped with two servo-motors. When in horizontal position the overall dimensions of the telescope are roughly 5 m height × 9 m long × 3.5 m wide. The weight of the telescope is around 9 t. For a transportation from a production site to the assembly point three telescope structures can be packed in a standard, open-top 12 m container.

The telescope structure design has been optimized and
checked for conformance with the CTA specifications through the Finite Element Method (FEM) analysis. Such analysis delivers information on the telescope deformation and mechanical stresses, camera displacement, and structure eigenfrequencies for various loads, including the gravity, earthquake, snow and ice, and the wind conditions expected at a future CTA site. For the regular observing conditions the maximum camera displacement with respect to the mirror dish is about 8 mm, which is 1/3 of the physical pixel size. The structure is also strong enough to sustain all extreme load cases – the mechanical stresses in the structure are well below the plasticity of the materials used. Finally, the lowest eigenfrequencies of the structure are 3.8 Hz, 4.5 Hz, and 11.41 Hz. For more details on the telescope structure see [2].

2.2 Mirror

The main telescope mirror has a spherical shape and the focal length of \( f = 5.6 \) m. It consists of 18 hexagonal facets of 78 cm dimension (flat-to-flat). The facets are also spherical with a radius of curvature \( R = 2f = 11.2 \) m. Such a number of facets and the facet size has been chosen to maximize the mirror area, while keeping the point spread function (PSF) of the mirror within the required 0.25°. The total mirror area corrected for facets inclination is 9.42 m², while the PSF, determined through ray-tracing, is 0.21° for the rays at an off-axis angle of 4°. A camera housing together with a quadrupod causes a shadowing of 20% of the light, thus the final collecting area of the mirror is 7.6 m². The mirror is not isochronous, but the optical time spread is less than 0.84 ns (rms).

Glass mirror facets are foreseen for the telescope. Glass will be coated with Al+SiO₂+HfO₂ coating to maximize the reflectance and provide weatherability. The expected average reflectance is of the order of 94% in the wavelength range 300 – 550 nm. Alternative coatings may be considered for the mirror, which include simple Al+SiO₂, or multilayer dielectric coating.

2.2.1 Alternatives to glass mirrors

Two alternatives for the glass mirrors are currently being developed at the Space Research Centre of the Polish Academy of Sciences, Warsaw (SRC) and INP. Both technologies use composite materials instead of glass to speed up the production process and reduce the mirror mass. SRC technology is based on sheet moulding compound (SMC) – a fiber reinforced thermoset material, formed in a high temperature, high pressure steel mold. The coating is applied directly on the composite surface (see Fig. 2). In the technology developed by INP an aluminum V-shaped honeycomb structure is used to support two glass panels and additional 1 mm thick glass sheet is cold slumped on the spherical layer of epoxy resin. Deposition of resin layer and cold slumping is performed on the mould. Both technologies are now intensively tested to prove the fulfillment of the requirements.

2.2.2 Mirror adjustment system

Each mirror facet is going to be equipped with the justification system to allow focusing of the whole mirror. For each facet the system consists of tree actuators: one fixed, one movable with one degree of freedom, and one movable with two degrees of freedom. Control electronics completes the system. To reduce the number of cables the movable actuators are going to be controlled wirelessly. The focusing is performed by observing the image of stars on the lid of the main telescope camera with a dedicated CCD camera. Three versions of the system are currently being developed by Universität Zürich, SRC (see Fig. 3), and Universität Tübingen. The system will be able to position the mirror facets with 2 \( \mu \)m accuracy.

2.3 Camera

The main telescope camera is based on the FlashCam concept [3] and bears the working name DigiCam. The design separates the photon detection plane (PDP) from the camera electronics thus allowing these two parts to be physically placed in different locations, e.g. PDP in the focal plane of the telescope and camera electronics in a box outside of the telescope structure. In the camera the signal coming from the photodetectors, after amplification and possibly shaping, is digitized and both trigger decisions and readout is done on digital signal. Such a scheme allows for a great flexibility in trigger algorithms and readout organization.

Contrary to the original FlashCam design DigiCam will use the Geiger avalanche photodiodes (G-APD) instead of the vacuum tube photomultipliers (PMT) [6]. These are new
Figure 3: Two prototype actuators build at the Space Research Centre.

Figure 4: Hamamatsu S12516 Geiger-mode avalanche photodiode.

Figure 5: Single motherboard with two FADC cards under tests at the Max-Planck Institut für Kernphysik, Heidelberg.

The concept of digitization and data transmission has been extensively tested with demonstrator setups. It was shown that 2150 MB/s sustained data transfer is possible without packet loss using raw Ethernet protocol for up to 84 simulated FADC boards resulting in the estimated maximal event rate after central trigger of 22 kHz. The performance
of standard CAT5/6 cables to transfer analog signals has been verified.

3 Telescope performance

The expected telescope performance has been estimated through a number of numerical simulations of signal processing, of a single telescope and of an array of the telescopes. All simulations have been performed for a Hamamatsu S10985 chip as at the time of the data generation no measurements for the newest S12516 photodetector were available. The present measurements (see [5]), however, show that the real performance of the device is compatible with the assumed PDE spectrum used in the simulation. Light concentrators transmission curve was calculated using ZEMAX ray-tracing software (see [8]). The altitude of 2000m is assumed for the simulations.

Signal reconstruction procedure has been investigated to verify the accuracy of the estimation of the intensity of the Cherenkov light. The simulation procedure involves generation of signal in photodetector, change of the signal shape by preamplifiers and filters, signal digitization, and signal reconstruction using convolution of smoothed signal with its derivative. It was shown that for sampling rate of 250MS/s, electronic noise rms corresponding to 15% of single photoelectron (PE) signal, and thermal noise of 0.6 MHz the systematic error on the absolute intensity of the Cherenkov light is less than 8.5% for a signal amplitudes above 20PE. This is less than required value of 10% for SST. For amplitudes larger than 50PE the error is less than 5%. The estimated error of the photon arrival time is less than 0.6ns.

For a single telescope one of the important parameter is the level of the night sky background (NSB). It is the detection rate of background photons in a single pixel of the camera. The NSB level strongly depends on the optical properties of the mirror and the quantum efficiency of the photon detector. For our telescope the nominal (dark sky) NSB level has been estimated to be 85 MHz, and 32 MHz for Al+SiO$_2$+HfO$_2$ and dielectric coating, respectively. The low NSB level for dielectric coating is caused by negligible reflectance of this coating beyond 550 nm, where the NSB intensity increases significantly. The same effect can be achieved for Al+SiO$_2$+HfO$_2$ coating by introduction of a filter in the optical path of the telescope. The expected NSB level for partial moonlight conditions is five times higher than the nominal level.

To estimate the performance of the array of the telescopes we use a concept of “telescope cell” [7]. In this approach the cell is a set of four telescopes and only events detected inside the cell are considered. The results of the analysis are then extrapolated to any size of the array. In such a way lower limits on the estimated parameters of the array are obtained since events detected outside of the cell are not taken into account. The relative error is smaller if the number of cells becomes larger. It is worth noting that to achieve the required 7km$^2$ effective area of the array with less than 70 telescopes the telescopes need to be separated by at least 360m. In our analysis we simulated different cell sizes, from 120m up to 1000m. Here we present the results for 120m, 200m, 300m, and 400m separations, since the results for larger distances are significantly worse. The obtained differential sensitivity of the 64-telescope array is presented in Fig. 6. The results below 10 TeV are quite uncertain due to low proton statistic. The angular resolution of the sub-array is below 0.2°, but will improve once the photon arrival time is used in the analysis. The details of the analysis are provided in [8]. It is clear that such an array is able to fulfill the requirements for a telescope separation larger than 300m.

![Figure 6](http://www.cta-observatory.org/fig.png)

**Figure 6**: The expected point source differential sensitivity of the 64-telescope array for four different telescope separations: 120m, 200m, 300m, and 400m. 50h observation time and 5σ detection significance is assumed. The solid, black line indicates the required sensitivity of the array as defined by the CTA project.

The full simulation of the whole 70-telescope array has been recently performed with the use of the European grid infrastructure (see [9]). The results of these simulations are currently under investigation.

4 Conclusion

The 4m Davies-Cotton telescope equipped with a fully digital camera meets all requirements of the CTA project. This telescope has many advantages: it is lightweight, easy to transport and install, easy to operate. Moreover, the estimated cost of 600kEUR of the prototype indicates that by mass production technique the target cost of 420kEUR can be reached.

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