5 A Cherenkov Telescope Array for Very High Energy Astronomy (CTA)

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The full CTA collaboration consists of 115 institutes from 23 countries.

(CTA)

For electromagnetic radiation starting with the ultraviolet, the Earth's atmosphere becomes increasingly more opaque with increasing photon energy. As a result, astronomical observations in these regimes must be made from very high elevation, or from space. Telescopes such as FERMI (1) and Chandra (2) are thus deployed as satellites. However, as the photon energy increases further, through the tens of GeV range, telescopes are unable to contain the particles produced by the photon's impact with absorber materials, and direct observations are again not possible. Because of this, the energy range of several tens of GeV and above, Very High Energy (VHE) gamma radiation, is sometimes referred to as the "last electromagnetic window".

Where atmospheric attenuation of photons generally hinders ground-based telescopes, this effect is actually employed in order to observe the VHE window. A VHE gamma ray will enter the atmosphere and produce an electron-positron pair. This pair, together sharing the energy of the initial gamma ray, will induce an electromagnetic shower in the upper atmosphere of many highly energetic, charged particles. Though these charged components of the shower may not reach the ground, they produce a cone of Cherenkov light that does reach the ground, and typically covers a circular area of roughly 250 m in diameter. The currently running MAGIC (3), H.E.S.S. (4), and VERITAS (5) observatories, which are Imaging Atmospheric Cherenkov Telescopes, operate by detecting this Cherenkov light and are able to reconstruct the energy and direction of the initial gamma ray. Figure 5.1 shows the sensitivities of MAGIC, H.E.S.S., and FERMI. The next generation of VHE telescopes, the Cherenkov Telescope Array (CTA), will improve upon these works by using optimized optical designs, improved light readout and electronics, and deploying a large array of such IACTs.

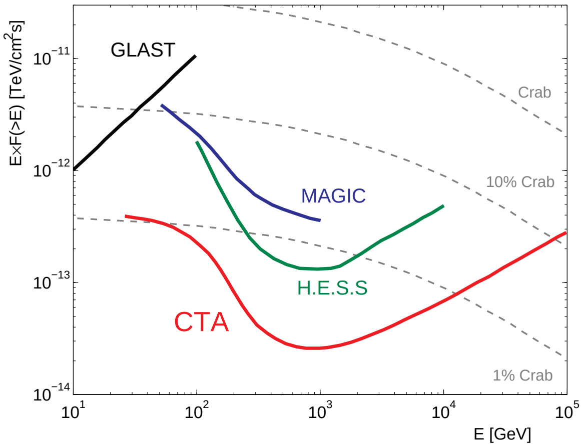

Figure 5.1: The sensitivity of several gamma ray observatories as a function of energy. The flux from the Crab nebula is shown as a reference.

5.1 Active Mirror Control

CTA will consist of three complementary arrays of IACTs, differing in mirror size and number and distribution of telescopes. The Large Size Telescope (LST) array will use 20-30 m primary mirrors, the Medium Size Telescope (MST) array 10-12 m primary mirrors, and the Small Size Telescope (SST) array 5-8 m primary mirrors. Constructing single mirrors to precision shape and uniformity becomes increasingly difficult as the size of the mirror increases. Instead, the primary mirrors will be constructed from a collection of "mirror segments", which are smaller mirrors of 1-2 m^2 area, placed together to form a larger mirror. With such a segmented primary mirror, each segment can be individually oriented, correcting for any irregularities on large scales. The segmented nature of the MAGIC primary mirror can be seen in Fig. 5.2. H.E.S.S. and VERITAS likewise use segmented primary mirrors.

Throughout the lifetime of the telescope, it can become necessary to readjust the orientation of the mirror segments. This can occur because of varying weather conditions, or because the telescope frame flexes and bends when placed in different zenith positions. In order to accomplish this task in a systematic way, the CTA group at UZH is developing an Active Mirror Control (AMC) system. In this system, each mirror segment is attached to the main telescope frame at three positions. One attachment is a fixed point, while the other two attachments are movable actuators.

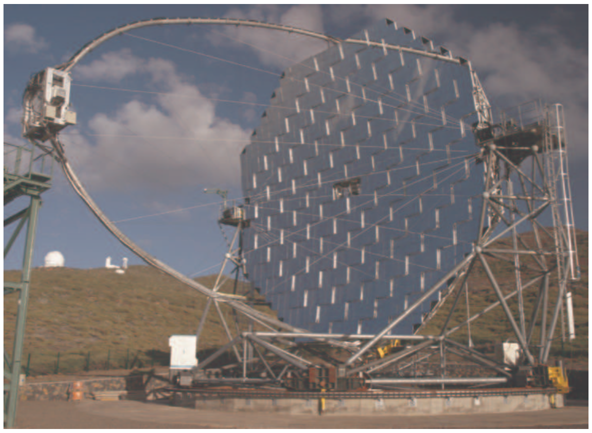

Figure 5.2: The MAGIC telescope.

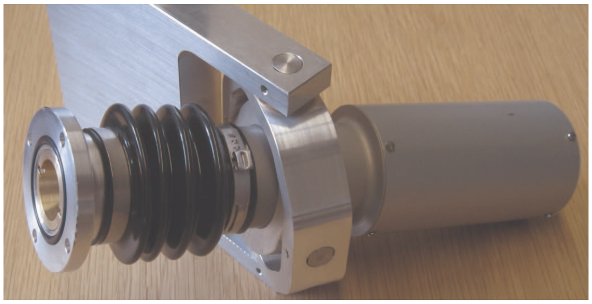

Figure 5.3: The AMC actuator.

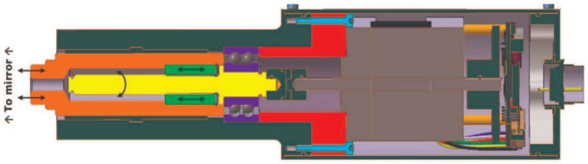

Figure 5.4: A cross sectional schematic diagram of the actuator, exposing the inner components.

The two attachments that provide the motion, seen in Figs. 5.3 and 5.4, contain a step motor drive in the rear section, connected to a M8×1 spindle (1 turn = 1 mm later motion), with a maximum range of 36 mm. The connection between the step motor and the spindle is such that it is able to make accurate changes in elevation as small as 15 μm.

The actuators provide a moving force of 400 N. The maximum applied forces, in case of hurricane-force winds, would not exceed 6000-7000 N, and the devices shown here have been tested and confirmed to hold more than 9000 N of extended applied force. The lifetime of CTA could be decades, exposing the hardware to varying weather conditions including rain, snow, wind, extremes of temperature, and extended use. The long term durability of these devices is therefore paramount.

An outdoor test stand has been constructed to test this long term durability of the AMC actuators. The test stand supports a "dummy mirror" of similar size and shape as a mirror segment, supported in three positions by a fixed point and two actuators. Figure 5.5 shows this test, with both actuators visible.

The actuators have been continuously cycled over 3 mm over the course of more than one year. This process has completed over 1.2 million cycles, an equivalent of roughly 30 years of telescope usage. Control of the actuators is performed wirelessly, over a ZigBee industry standard wireless protocol. Soon, the actuators will be removed from the test stand, disassembled, and inspected for mechanical wear.

5.2 Light Concentrators

The light that reflects from the telescope's primary mirror will be concentrated at the mirror's focal point, and is therefore the location of the camera. In order to allow for a field of view of 5°, the camera must cover an area 1-2 m in diameter. Obtaining 100% coverage of such an area with photodetectors alone is costly and impractical. Instead, the effective coverage of each single photodetector is enhanced by a Light Concentrator (LC), which focuses the flux of photons incident upon a large area onto a smaller area. Typical LC designs consist of a set of mirrors arranged in a hollow cone shape. The shape of the cone can be parabolic, or they can take the shape of a tilted parabola, often called a Winston Cone. In addition to a hollow cone, a solid LC can be constructed which relies on total internal reflection to accomplish the concentration, seen in Fig. 5.6. A solid LC has the advantage that, due to refraction at the entrance, larger entrance area to exit area ratios are allowed than for a hollow cone of similar size.

A test station has been constructed at UZH to measure the performance of various LC

Figure 5.5: The test stand of the AMC actuators. The actuators have been cycled over 1.2 million times, equivalent to roughly 30 years of use.

Figure 5.6: A collection of solid, refracting light concentrators constructed at UZH.

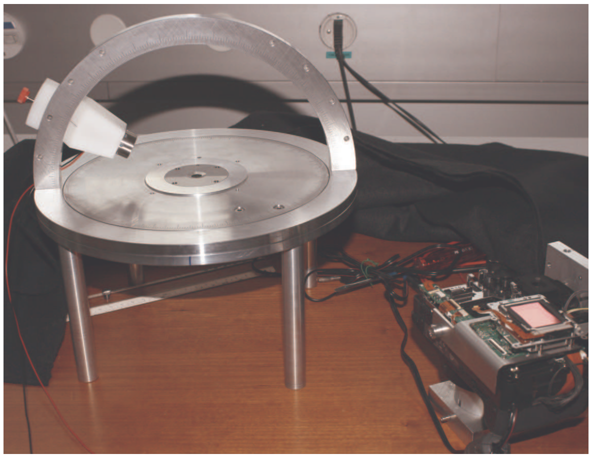

Figure 5.7: The test station for measuring the transmission properties of the LC array.

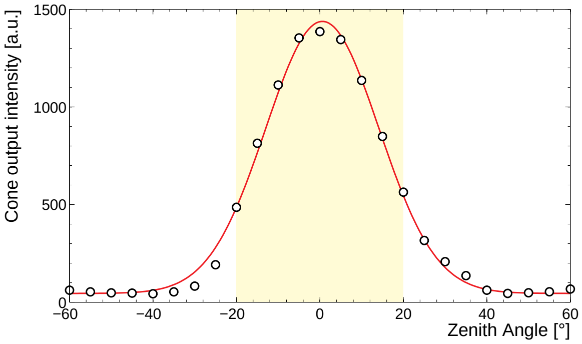

Figure 5.8: The response of the parabolic light concentrators as a function of zenith angle of the light source, relative to the intensity at 0°. The angle subtended by the primary mirror, ±20°, is indicated by the shaded yellow region.

designs, seen in Fig. 5.7. The test stand holds an array of five LCs, the entrance of one cone is exposed to light, while the entrances of the remaining four LCs are blocked. This is done to study possible cross-talk effects between neighboring LCs. The exit faces of all five cones are optically coupled to a Complementary Metal-Oxide-Semiconductor (CMOS) photo sensor. This sensor is most commonly used in digital cameras. The test stand has a mounting device for a light source that can be adjusted to illuminate the LC from any direction within the hemisphere that lies above the entrance face of the LC.

The ability of the LCs to collect and concentrate the light that crosses the cone entrance is an important feature, but also the behavior of this feature as a function of the incoming angle of the light. Two competing effects demand attention to this behavior. First, the LC will collect light from all segments of the primary mirror, which subtends $\pm\sim20°$ at the position of the camera. The LC must allow light from all mirror segments or else the field of view is compromised. Second, extraneous light not coming from the primary mirror might also be incident on the LC. Naturally, this light is of no scientific importance and presents only background. This feature demands a high attenuation of light at zenith angles larger than ±20°. Figure 5.8 shows the light acceptance as a function of the zenith angle of our prototypes measured with the test setup described above.

5.3 FlashCam

The CTA group at UZH also contributes to the development of a fully digital photon sensor readout called FlashCam, together with the University of Geneva, EPFL Lausanne, ETH Zürich, Jagiellonian University Cracow, MPI für Kernphysik Heidelberg, University of Leeds, and University of Tübingen. A fast ADC will allow the storage of data continuously in a digital ring buffer, replacing the classical analog ring buffer electronics. Such a digital camera will make it possible to use all information of the full precision data for triggering purposes. The implementation in Field-Programmable Gate Array (FPGA) devices will allow for reliable and flexible calibration and other online calculations.

Each analog channel is sampled by two ADCs. A 250 MS/s high gain channel is used to determine accurate timing and low threshold trigger information, while a 80 MS/s low gain channel allows for accurate measurement of large signal amplitudes. Monte Carlo (MC) simulation studies, together with an ADC hardware evaluation, have shown that with such a system the full VHE gamma ray shower information can be determined, while the prices for the ADCs are still affordable, assuming a total of about 100’000 readout channels to be equipped in the final CTA MST system.

This requires a sampling clock with a very good phase stability over the whole CTA system. The clock generation and distribution possibilities are studied presently by the electronics workshop.

One of the critical items of the telescope simulation consists of the electronic coupling from the photon sensor to the ADC. Therefore a laboratory system has been set up to record a photomultiplier signal from a fast pulsed laser diode with a selection of different anti-aliasing filters, different sampling frequencies, and realistic cabling. A preamplifier, which fits to the signal specifications and allows for gain adjustment has been developed by the electronics workshop. The measured data was compared to the simulation and found to be in good agreement.

The group is also looking into trigger options and their implementations in an FPGA. Standard triggering ideas for such telescopes use the summed amplitude of all pixels to form the trigger. At high gamma ray energies, this technique is adequate, but signals from low gamma ray energies are inundated with ambient light hitting the camera, called Night Sky Background (NSB). In order to deal with this, triggering schemes involving clustering algorithms that are able to distinguish a valid Cherenkov pulse (which is highly clustered) from NSB (which is uniformly distributed) are being studied and characterized. Such triggering algorithms are feasible only in the context of a fully digital system.

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