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Technical Performance of the MAGIC Telescope

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The 17m diameter MAGIC Cherenkov telescope was completed in its nominal configuration and started commissioning in summer 2004. MAGIC has emphasized technical innovation in its design. Standard operation regularly involves the largest reflector in the world, active mirror control, analog optical transport of the signal, a fully programmable two-level trigger and 300 MHz signal digitizers. We describe the general performance during the first months of datataking.

1. Introduction

The MAGIC (Major Atmospheric Gamma Imaging Cherenkov) Telescope was designed in 1998 [6, 1] with the main goal of being the Imaging Cherenkov Telescope with the lowest possible gamma energy threshold. It was based on the experience acquired with the first generation of Cherenkov telescopes and intended to incorporate a large number of technological improvements. In this paper we present a first review of the performance of the telescope elements.

2. Frame and drive system

The 17 m diameter $f/D = 1$ telescope frame is made of light weight carbon fiber tubes (the frame itself weighs < 20 tons while the whole structure plus the undercarriage amounts to about 60 ton). The assembly of the whole frame took only one month thanks to a construction based on the so-called tube and knot system of the company MERO.

The azimuth axis of the telescope is equipped with two 11 kW motors, while the elevation axis has a single motor of the same power. The position of the telescope is measured in the mechanical telescope frame by three absolute 14-bit shaft encoders. With this configuration it is possible to measure the telescope position with an accuracy of about 0.02°. The maximum repositioning time of the telescope is 22 seconds, below the 30 seconds that were set as a target for gamma ray burst follow-ups. By using a CCD camera mounted on the reflector frame we have established that the telescope tracks to better than a 1/10 of a pixel size (see [10] in these proceedings for more details).

3. Reflector and Active Mirror Control

The overall reflector shape is parabolic in order to minimize the time spread of the Cherenkov light flashes in the camera plane. The preservation of the time structure of the Cherenkov pulses is important for increasing the signal to noise ratio with respect to the night-sky background light (NSB). The dish is tessellated by 956 0.495 × 0.495 m^2 mirrors covering a total surface of 236 m^2. Each mirror is a sandwich of alluminum honeycomb on which a 5 mm plate of AlMgSi1.0 alloy is glued. The alluminum plate is diamond-milled to achieve a spherical reflecting surface with the radius of curvature that is more adequate for its position in the paraboloid. A thin quartz layer protects the mirror surface from aging.

In order to check the light collection efficiency of the reflector we use a direct method based on light measurements with a high-resolution large dynamic range CCD camera. The camera is mounted on the mirror frame in a position that permits simultaneous measurements of part of the focal plane of the camera and of the corresponding portion of the sky. For a measurement, the camera is covered with a diffusely reflective disk [9], of 17 cm diameter. The telescope is directed at a point-like source (star or distant lamp), and the CCD simultaneously records the direct light spot and its reflection from the disk in the focal plane. For strong sources, saturation of the CCD pixels is avoided by defocussing the CCD camera.

The camera used was an STL-1001E from SBIG. The reflectity of the disk is specified to be 99%. The active mirror area at time of measuring (including mirror imperfections, temporary defocussing, and all effects of shadowing) was estimated to be $212m^2$. From several sources with a wavelength spectrum peaking at 500 nm, the average specular reflectivity is measured to be 0.77 ± 0.04. This value has been confirmed by independent measurements using PIN diodes. Future measurements at regular intervals are being planned, and will determine the reflectivity with an improved precision of ± 0.01.

A large diameter telescope makes strong requirements on the stiffness of the reflector frame. When directing the telescope to different elevation angles the reflector's surface deviates from its ideal shape under gravitational load. In order to correct these deformations in a light-weight material frame, we equipped the reflector with an "Active Mirror Control" system. Every four mirror facettes are mounted on a single panel. Two of the three mounting points of the panel are equipped with actuators which can be used to adjust its position on the frame. The main elements of each actuator are a two-phase stepping motor (full step 1.8°, holding torque 50 N cm) and a ballspindle (pitch 2 mm, maximum range 37 mm). In the center of the panel a laser module is pointed towards the common focus of the four mirrors. The panels are aligned using the artificial light source, the positions of all the laser spots are recorded and can be used as a reference to re-align them for each elevation angle.

The PSF of the reflector can be extracted from the analysis of the width of muon rings (see [4]) and from the comparison of Hillas parameters in real and MC data. The reflector is focused at a distance of 10 km because this is the typical distance to the shower maximum of low zenith angle 100 GeV γ-ray showers. After AMC reflector adjustment, a point-like light source at this distance produces a gaussian image at the camera plane with σ=10.5 mm, which corresponds to 0.035°.

4. Camera, signal transmission and readout

The MAGIC camera has 3.5-3.8° FOV. The inner hexagonal area is composed of 397 0.1° FOV hemispherical photomultipliers of 1 inch diameter (Electron Tubes 9116A[7]) surrounded by 180 0.2° FOV PMTs of 1.5 inch diameter (ET 9117A). The time response FWHM is below 1 ns. The photocathode quantum efficiency is enhanced up to 30% and extended to the UV by a special coating of the surface using a wavelength shifter [8]. Each PMT is connected to an ultrafast low-noise transimpedance pre-amplifier, the 6-dynode high voltage system is stabilized with an active load. Dedicated light collectors have been designed to let the photon double-cross the PMT photocathode for large acceptance angles.

The PMT signals are transmitted over 162 m long optical fibers using Vertical Cavity Emitting Laser Drivers

(VCSELs, 850 nm wavelength). Transmission over optical links drastically reduces the weight and size of the cables and protects the Cherenkov signal from ambient electromagnetic noise in the line. In the receiver boards located at the electronics room the signal is amplified and split. One branch goes to a software adjustable threshold discriminator that generates a digital signal for the trigger system. The signal in the second branch is stretched to 6 ns FWHM and again split into a high gain line where it is further amplified by a factor $\sim$10 while the low gain line is only delayed by 55 ns. If the signal is above a preset threshold around 50 photoelectrons both lines are combined and digitized by the same FADC channel.

8 bit 300 MHz Flash ADCs continuously digitize the analog signals. If a trigger signal arrives within less than 100 μs the position of the signal in the ring buffer for each pixel is determined and for each pixel 15 high gain plus 15 low gain samples are written to a FIFO buffer at a maximum rate of 80 Mbyte/s. The readout of the ring buffer results in a dead time $\sim$20 μs. This corresponds to about 2% dead time at the design trigger rate of 1 kHz. The data are saved to a RAID0 disk system at a rate up to 20 MByte/s which results in up to 800 GByte raw data per night.

The charge in the high gain is intercalibrated for each individual channel with the charge in the low gain by using pulses of about 70 phe that do not saturate the high gain yet but already give a measurable signal at the low gain.

The main source of noise is found to be light of night sky. In average the inner pixels record 0.13 NSB phe/ns. This corresponds to a pedestal RMS of about 4.5 ADC counts in each FADC 3.3 ns time slice, which is more than a factor 2 larger than the pedestal RMS due to electronic noise. The current in the anodes of the PMTs is also proportional to the rate of NSB, so the pedestal RMS is also found out to be proportional to the square root of the anode current. For an average pixel the pedestal RMS in a FADC time slice is 6.5 ADC counts/$\sqrt{\mu A}$.

About 3% of the channels are in average defective during standard operation due to problems in the PMT, electronic base, optical transmission or FADC.

5. Trigger

For each channel the above mentioned discriminator issues a digital signal whenever a pulse is above $\sim$10 phe ($\sim$12 phe for galactic sources with an increased light background). The individual pixel rates of the channels included in the trigger are monitored using 100 MHz scalers and used to dynamically regulate the discriminator thresholds. This "Individual Pixel Rate Control" acts only on pixels that are affected by stars brighter than $\sim 4^m$.

The output of the discriminators goes to a second-level trigger system with programmable logic [2]. The first level (L1T) applies tight time coincidence and simple next neighbour logic on the output of the discriminators. The trigger is active in 19 hexagonal overlapping regions of 36 pixels each, to cover 325 of the inner pixels of the camera. The second level (L2T) can be used to perform a rough analysis and apply topological constraints on the event images. Using for instance a fast evaluation of the size of the Cherenkov image it is possible to significantly reduce the NSB, thus allowing a reduction of the discrimination level and the gamma ray threshold.

The global trigger rate is about 250 Hz for extragalactic sources (standard pixel threshold) and about 200 Hz for galactic sources (increased pixel threshold). According to the full MC simulation[5] this rate corresponds to a trigger threshold around 60 GeV.

6. Calibration

The calibration system (see [3] for a detailed description) consists of a light pulser and a continuous light source (both situated in the center of the mirror dish), a darkened, single photoelectron counting PMT ("blind pixel"), located in the camera plane and a calibrated PIN-diode 1.5 meter above the light pulser. The pulsed light is emitted by very fast (3-4 ns FWHM) and powerful (10^8-10^{10} photons/sr) light emitting diodes in three different wavelenghts (370 nm, 460 nm and 520 nm) and different intensities (up to 2000-3000 photoelectrons per pixel and pulse). It is therefore possible to calibrate the whole readout chain in wavelength and linearity.

The conversion factor from phe to ADC counts is obtained by means of the so-called F-Factor method that estimates the number of photoelectrons from the width of the charge distribution of calibration events. The conversion factor in an individual pixel is known to drift by at most 10% in time scales of several minutes due to instabilites in the optical transmission, and coherently for all pixels in the camera by at most 20% in time scales of hours to days due to thermal effects in the HV regulation and the optical transmission. These fluctuations can be corrected out using "interleaved calibration events": during standard datataking, calibration events with a fixed color (370 nm) and intensity (around 35 phe in the inner pixels) are taken together with cosmic events at a 50 Hz fixed rate. The final precision in the determination of the charge in phe for the individual pixels is about 3%.

7. Observation duty cycle

The commissioning phase of the telescope ended in Fall 2004 and MAGIC started regular observations. December 2004, February and March 2005 were practically lost for data taking due to bad weather. During the rest of the months since January 2005 the telescope has recorded an average of 90 h per month. This corresponds to a duty cycle of 13%. On average about 10 hours were taken with moonlight every month.

8. Conclusions

The commissioning of MAGIC was successfully completed at the end of 2004. All of the technical innovations have been put to work without major problems. Most of the telescope parameters are within the design specifications. MAGIC is at present taking γ-ray data regularly.

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