The HEGRA stereoscopic System of Imaging Cherenkov Telescopes

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Abstract

The HEGRA collaboration is operating 6 IACTs at the Canary island of La Palma. Four of these telescopes, CT3-CT6, are operating as a stereoscopic system since December 1996. This overview presentation summarizes the status and performance of the HEGRA IACT System as well as the results of observations performed so far with the CT-system.

1. Introduction

The key feature of a stereoscopic system of telescopes is the ability to observe individual air showers with several telescopes. The stereoscopic views provide enough information for the full geometrical reconstruction of air showers in space by the stereoscopic imaging technique (Akerlof, 1991) (Kohnle,1996) (Daum, 1997a). The precise knowledge of shower parameters on an event by event basis yields an improved energy determination (Hofmann, 1997). The use of a system trigger scheme effectively suppresses nightsky background and background from local muons while enriching γ-ray initiated air showers. The partly uncorrelated image information in the several cameras enable for a strong hadron suppression, which results in the capability of measuring TeV γ-ray sources (in the flux level range of Crab Nebula) almost background free. Thus high sensitivity to weak γ-ray sources can be obtained.

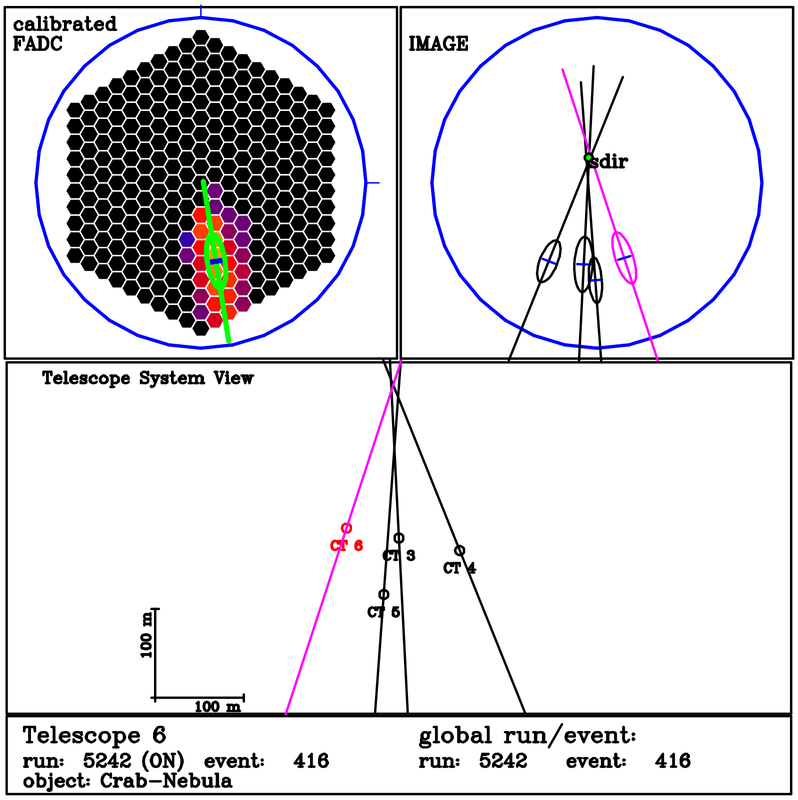

Fig. 1: View of a system event shown by the online display. Upper left: image recorded by CT6. Upper right: overlay of all images recorded by the 4 telescopes. The intersection point of the image axis define the apparent source direction of the air shower. Lower part: reconstruction of the shower impact point. Note the over determined reconstruction.

The rich information of an air shower event recorded by a system of telescopes enables for systematic studies on an event by event basis by redundant experimental data (see Fig. 1). This feature is of special importance in the context of recent measurements of energy spectra (Hermann, 1997a)(Bradbury, 1997), which show up by errors clearly dominated by systematic uncertainties.

2. Technical Description of the IACT System

The HEGRA Cherenkov telescopes are located at the HEGRA experimental site on the Canary Island of La Palma (28.75° N, 17.89° W, 2200m a.s.l.). Figure 2 gives an overview of the HEGRA Cherenkov Telescopes. The spacing between the central CT3 and the outer telescopes of 70-80m is adapted to a typical Cherenkov light pool area of radius ≈100m created by a 1TeV gamma-ray initiated air shower, and results in a significant amount of light recorded in several telescopes, which is essential for the stereoscopic technique.

The telescopes CT1,2 are prototype telescopes which are operational since several years. The first system telescope CT3 became operational in late 1995. In 1996 CT4-6 were installed and came into operation. Since August 1996 a telescope system is running with a hardware coincidence trigger requiring at least 2 coincident telescopes. Now CT3-6 form a system of 4 identical telescopes which are taking data in coincidence mode. Table 1 summarizes the technical characteristics

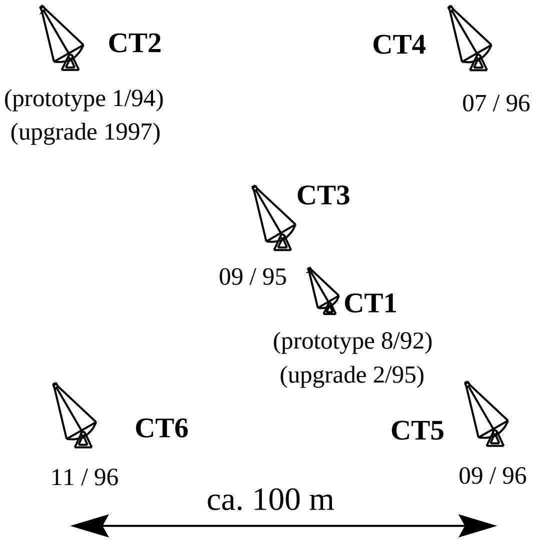

Fig. 2: The HEGRA Telescopes.

Table 1: Overview of the Technical Characteristics of the HEGRA Telescopes

Telescope	mount	mirror[m^2]	field of view[°]	Camera pixels	Pixel size[°]	readout
CT1	equatorial	5.0	3.2	127	0.25	CAMAC
CT2	alt-az	8.5	3.6	61	0.43	CAMAC
CT3-6	alt-az	4 x 8.5	4.3	4 x 271	0.25	VME

of the telescopes. The prototype CT2 telescope, which has a quite similar mount and reflector but carries a 61 pixel camera, will be upgraded by a system type camera and readout electronics, thus completing the 5 IACT system. This readout electronics of the system telescopes is based on VME standard and designed to allow for fully computer controlled experimental setup. The main component is a 120MHz Flash ADC system recording the history of the pixel signals and buffering it in a hardware ringbuffer of 34μsecs depth. This is enough to wait for a system trigger decision, i.e. 2 out of 271 neighboring pixels in 2 out of 4 telescopes triggered in coincidence, which needs in the order of μsec due to the spacing of the telescopes. When a system trigger occurs, all telescopes are read out by the local readout electronics controlled by a CPU located inside the VME crates. The CPUs of all telescopes forward their one-telescope event packages to a main computer via Ethernet. The main computer subsequently performs an online event building, enabling for online reconstruction of the air showers based on the stereoscopic imaging technique. Elsewhere the readout electronics and DAQ (Daum, 1997b), the telescope system trigger (Daum, 1997c) and pre-analysis procedures of FADC signals (Heß, 1997a) are described in more detail.

3. Performance of the IACT System

3.1. Trigger Rates

The trigger rates of several trigger conditions were measured as a function of single pixel trigger threshold. Fig. 3 demonstrates the improvement in lowering trigger thresholds by using a pattern recognition of next-neighbored pixels and a telescope coincidence trigger scheme. Even at the very low end there is no rise in the system trigger rate due to background triggers observed. Thus a further decrease of trigger threshold seems feasible after increasing the bandwidth of the DAQ, which will be done soon by exchanging our 2.5 years old main DAQ computer by a modern one. The operating point of the system was already lowered in July from 8p.e. to ≈7 p.e. in July 1997, but all following studies refer to previously taken data.

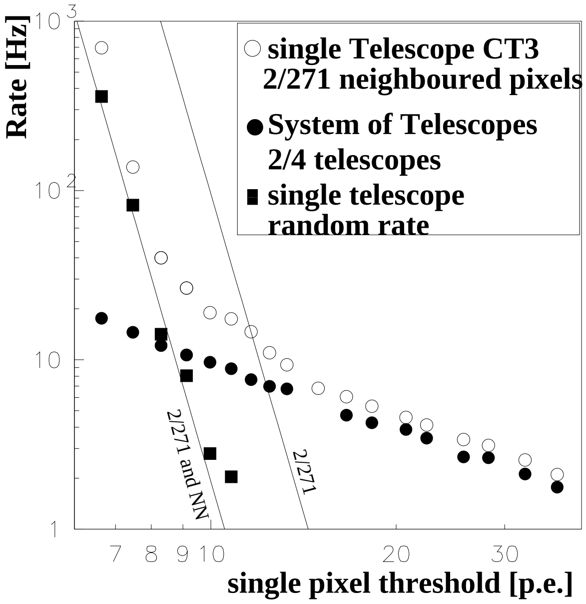

Fig. 3: Trigger rates of CT3 and System. The coincidence requirements are ≈12ns (pixels in one camera) and ≈70ns (inter telescope). The single telescope random rate is derived from the single pixel rates. The line 2/271 and NN is put by hand through the random rate to guide the eye. The line 2/271 takes into account the combinatorial factor of the NN pattern.

3.2. Sensitivity to the Crab Nebula and the Angular Resolution

In order to study the performance of the telescopes the "standard candle" Crab Nebula was observed. Fig. 4 illustrates the measured angular resolution on an event by event basis. Calibration runs on selected bright stars serve as a database for offline pointing modelling, leading to an absolute pointing accuracy of each telescope at the level of 0.01°. This pointing accuracy is not only a prerequisite for stereoscopic reconstruction but enables to locate γ-ray sources with a precision of 0.01° (Panter, 1997).

Table 2 summarizes the achieved Crab detection of the telescopes CT1,2,3 and the 4 telescope system. Due to the ≈ 0.1° resolution in the stereoscopic reconstruction of the shower direction and an efficient reduction of background on trigger level, a highly significant Crab signal is already revealed without applying any image shape cuts (Daum, 1997a). By applying loose cuts on the width of the images one obtains the high γ count rate from the Crab which is quoted in Table 2 and supplies high statistics for the study of bright TeV γ-ray sources, i.e. flux and energy spectra determination. The ability of full reconstruction of air showers in space, especially localization of the shower core, allows to efficiently relate the light yield of the telescopes to energy (Aharonian, 1997), leading to an energy resolution of ≈20%.

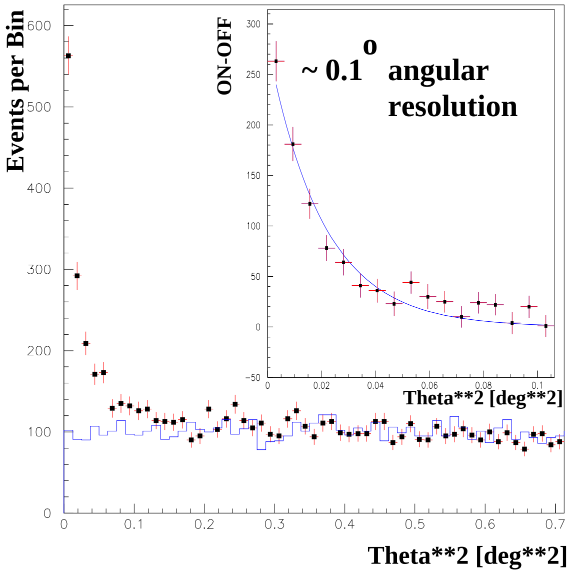

Fig. 4: Angular resolution derived from 11.7 hours on source data of Crab Nebula.

Table 2: Performance ot the HEGRA Telescopes based on Crab Nebula Observations

Telescope	CT1	CT2	CT3	CT3-6
Trigger rate [Hz]	1	3	5	12
Energy threshold [TeV]	≈1.5	≈1.0	≈0.8	≈0.5
Crab detection rate [mHz]	2.2	3.9	6.4	19
Crab signal σ in 1 hour	1.5	1.1	2.3	>6

3.3. Gamma/Hadron Separation Power and Flux Sensitivities

Based on the good angular resolution and the precise localization of the shower impact point with σ ≈15m (Ulrich, 1997), a strong Gamma/Hadron separation is obtained by applying cuts on the image parameters depending on shower zenith angle, distance of the telescope to the shower impact point and the image amplitude, see Fig. 5. By applying tight cuts one obtains a hadron suppression of a factor ≈100 whereas 40% of the γ-signal survives the cuts (Daum, 1997a). A drawback of these tight cuts are the expected large systematic errors. Alternatively one can define another variable $Scaled = (MeasuredValue)/(MeanMC)$ and apply loose cuts on the mean scaled width. The resulting γ efficiency of ≈95% with a ≈30% hadron efficiency can be used for "bias free" analysis of energy spectra of strong sources.

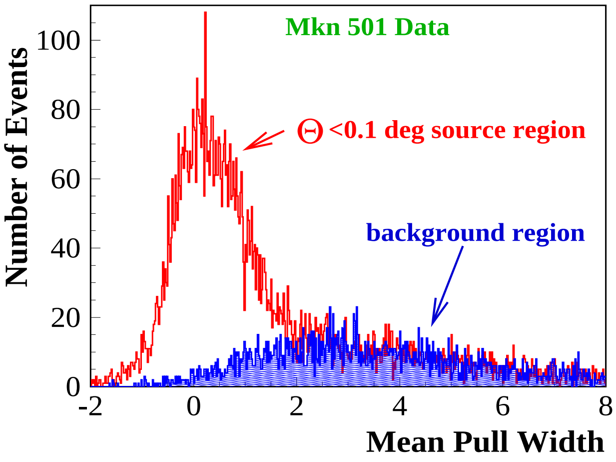

Fig. 5: Gamma/Hadron Separation power illustrated by Mkn 501 data using the width of the images. From simulations the Mean and RMS of the width of the images are calculated depending on the image amplitudes and the distance between the telescope and the shower impact point. The Pull is defined as Pull=(Measured Value - Mean MC)/(RMS MC). The mean pull is the average over all triggered telescopes with good images.

A quantitative study of the properties achieved in experiment was carried out by applying tight cuts to the Crab Nebula data sample. One obtains a nearly background free detection of the Crab, 23 γ/h^{-1} versus 1.2 background events $/h^{-1}$ in a circle of radius 0.13° around the position of the Crab Nebula (Daum, 1997a). From these numbers one can derive a sensitivity on the 5σ level after 100 hours of observation of a point source with a flux at the level of 3% of the Crab. Due to the measured isotropic background one can extrapolate to the sensitivity to spatial extended gamma ray sources by scaling the Crab numbers with the angular phase space. A extended source with 15% Crab flux within a 1° diameter area should be observable at a 5σ level after 100 hours of observation. The background "free" detection of Crab Nebula and the large field of view of the cameras imply that sky surveys by Cherenkov telescopes become feasible. Asking for 10 γ's in 1 hour of observation with 1 background event results in a minimum detectable flux of a point source of ≈50% of the Crabflux within an effective field of view of 2°x2°.

4. Overview of Observations

The IACT system was already used for various observations of potential galactic and extragalactic TeV γ-ray sources. This was done partly in parallel to the commissioning of the telescope system. Table 3 summarizes the observations.

Table 3: Overview of the Observations performed with the HEGRA CT System. All results are based on preliminary (partly online) analysis of the data. Upper limits correspond to 0.99865 (3σ) confidence level and are calculated using the method described in (Helene, 1983). For all observed objects, except G78, exist the same amount of off source data, either due to appropriate ON-OFF pairs or due to the so called wobble mode, where the source is displaced by 0.5° in respect to the camera center and the displacement is changed every 20 minutes.

Object	Observation Period	On source	# CTs	TeV γ detection
Crab Nebula	Sept. 96 - Febr. 97	>30 hours	3/4	yes , constant
Mkn 501	March 97 onwards	>60 hours	4	yes , highly variable
Mkn 421	March 97 onwards	>50 hours	4	yes , sporadic
1ES2344+514	Oct. - Nov. 96	25 hours	3	< 0.15 Crab
GRS1915+105	Apr. - July. 97	34 hours	4	< 0.07 Crab
BL Lacertae	2./3.+3./4. July 97	4 hours	4	< 0.21 Crab
G78.2+2.1[a]	Sep. - Nov. 96	47 hours	3	< 0.19 Crab in 1°
IC443[a]	Dec. 96 - Apr. 97	11 hours	4	< 0.32 Crab in 0.75°

[a] Results from (Heß, 1997b)

Apart from the Crab Nebula two other highly significant TeV γ-ray sources, Mkn 421 and Mkn 501, were detected. From Mkn 421 sporadic activity on the timescale of days was observed (Hermann, 1997b). The analysis of Mkn 501 data revealed a high flux variability on the timescale of days (Aharonian, 1996) with maximum fluxlevels in the order of ≈9 times Crab. The high flux levels allow for the investigation of variability on timescales of few minutes. However so far no significant deviations from a constant flux within a view hours of consecutive observations was observed (Aharonian, 1996)(Hermann, 1997a).

Due to the consecutive commissioning of the telescopes several interim stages of the system occured. In order to derive reliable numbers from data analysis of the different setups, observations of the Crab Nebula were used as an experimental measure of the sensitivity. After accounting for zenith angle dependencies in the analysis upper limits could be derived in terms of Crab flux levels. In addition comprehensive Monte Carlo studies are underway.

Triggered by the detection of 1ES2344 in December 1995 reported by the Whipple group (Weekes, 1996), observations were carried out by an interim 3CT System, resulting in an upper limit of a constant flux during the observation period.

In order to confirm the hint of a signal from GRS1915 obtained by the HEGRA CT2+3 in 1996 data and also triggered by the active state report of the all-sky monitor of the Rossi X-ray Timing Explorer (RXTE), 34 hours of observation in wobble mode were carried out. Although the much higher sensitivity of the CT system compared to the single telescopes CT2+3, no signal showed up in the 1997 data.

Triggered by strong activity in the optical and given the positive detection of the BL Lacs Mkn 421 and 501, the BL Lacertae itself was observed, resulting in an upper limit of the flux level like the measurements performed by the Whipple group in 1995 (Catanese, 1997). Further observations of the BL Lac, not yet included in this analysis overview, are already performed.

An important goal of the CT system is to derive constraints on the cosmic ray content of supernova remnants by measuring the (spatial) TeV γ ray flux from those objects. Extended observation periods were dedicated to G78.2+2.1 and IC443. A more detailed presentation of the SNRs analysis is published elsewhere (Heß, 1997b).

The capability of the CT system to perform sky surveys was used from June 1997 onwards for a still ongoing survey of the galactic plane ($-1^\circ <$longitude$<54^\circ$) with a 1° spacing between the scan points and $\geq$1 hour of observation per point. In addition the local arm of the galaxy is scanned. Unfortunately so far no outstanding source was observed.

5. Conclusions

The HEGRA-collaboration succeeded in building a stereoscopic system of Cherenkov telescopes. Analysis of Crab Nebula data shows that the performance of the system fully comes up to the predictions of previous Monte Carlo simulations (Aharonian, 1993) carried out for design studies. The performance parameters derived from experiment imply that already the currently operating 4CT-System is one of the most powerful instruments currently available for TeV γ-ray astronomy. This stereoscpic system can be considered as the first (scaled-down) operating model of the next generation detectors like HESS and VERITAS.

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