Operation and performance of the Cosmic Ray Tracking (CRT) detector system

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Abstract

The Cosmic Ray Tracking (CRT) detectors consist of two drift chambers of the TPC type and an iron plate as a muon filter between the two chambers. CRT detectors are designed to detect and identify secondary cosmic ray particles in extensive air showers. Each detector has a local electronics box with a readout, trigger, and monitoring system. The local computers at the detector stations are used for hit and track finding in parallel to the detector readout. Detector stations are permanently calibrated online, using the cosmic ray data. The online software, including data processing and calibration procedures, are presented in this paper.

Ten detectors are in operation at the site of the HEGRA air shower array. The detector performance has been evaluated using data from these detectors and the HEGRA array as well as by Monte Carlo simulations. The spatial resolution has been found to be about 1 mm both in drift and in wire direction. The corresponding angular resolution is about 0.4° in each projection for a single track. Muons are usually identified if scattered by less than 2.5° in the iron plate, corresponding to energies above about 1 GeV. In HEGRA-triggered showers an overall muon identification efficiency of 87% is achieved, with a fraction of only 0.07% of the electrons being misidentified as muons.

1 Introduction

Cosmic rays of *very high energies* (VHE) – of the order of TeV and above – give rise to *extensive air showers* (EAS) where secondary particles may reach ground-level. The traditional detection technique for EAS is that of scintillator arrays which reconstruct the shower direction from the differences of arrival times of secondary particles in counters separated by tens to hundreds of meters (timing method). In the *Cosmic Ray Tracking* (CRT) project, detectors have been developed to reconstruct shower directions from the arrival directions of the secondaries (tracking method).

The CRT project has been initiated in 1988 by proposing an array of almost 400 tracking detectors with muon identification [1, 2, 3]. Such a CRT array would achieve a lower energy threshold than any existing particle detector array (about 3 TeV at an altitude near 4000 m). Its main purpose would be to search for γ-ray sources.

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The detectors, that have been developed, use two circular drift chambers of the *time projection chamber* (TPC) type and a 10 cm thick iron plate as muon filter between the two chambers. Drift chambers and iron plate have a diameter of 1.8 m. Each detector has a local computer for readout of the FADC system, for track reconstruction, and detector calibration. Ten CRT detectors are in operation at the site of the HEGRA experiment [4] on La Palma, Canary Islands, for about two years. Detector hardware and the custom-designed electronics are described in detail in another paper [5] (in the following referred to as Paper I). The main purposes of this installation have been long-term operation tests at mountain-altitude conditions and the evaluation of the detector performance under such conditions. The angular resolution and the hadron rejection of this mini-array of 10 detectors are not considered to be sufficient to search for steady γ-ray sources but are appropriate to check for VHE γ-rays from known *gamma-ray bursts* (GRB) [6].

In the following section the online software including local data processing at the detector stations is described. A detailed Monte Carlo simulation of the CRT detectors is used to check our understanding of the detector and to evaluate performance parameters which cannot be easily measured. Finally, the performance of the detectors on La Palma is presented.

2 The online software

2.1 Design goals

In the design of the CRT online software, several requirements had to be met. With as many detectors as proposed for a full-sized CRT array, the local detector stations have to be independent, requiring little central control, and, in particular, very little control by personal during regular operation. Dead-time caused by calibration tasks should be small.

The Motorola 68040 processor provides enough computing power for local data processing at each detector station. This processing includes hit finding and track reconstruction. During regular operation, only track data should be transmitted to the central computer. For offline testing and optimizing of the processing algorithms the data from preceding processing stages can be transmitted as well. Since different kinds of computers are used for offline data analysis, a hardware-independent data format is used. The whole online software has been ported to different kinds of realtime operating systems, like OS-9 and Lynx-OS. An array of CRT stations could even be operated in a mixed operating system environment.

The main tasks for central online computers in the array remain network communication, event building, shower reconstruction from the particle tracks reconstructed at the detector stations, and tape backup.

2.2 Data readout of the detectors

A multi-buffer scheme is used for the *Flash ADC* (FADC) readout of the detectors. A readout interrupt is initiated either by the FADC system or by the *Event Grader Slave* (EGS, see paper I), depending on the trigger conditions. When the CRT detectors are operated as part of an array ('array mode'), the CPU interrupts are generated by the EGS. When a CRT detector is operated independent of others ('stand-alone mode'), the trigger module uses only wire signals to provide a trigger to the FADC.

The interrupt service function fills raw data buffers in the computer main memory, as long as a free buffer is available. With each 32-bit VME-bus access, data from four different FADC channels are read. A fast scan (zero-suppression) is done to look for data sections of interest [7]. The raw data buffers are processed and released later by the main online task. Typically, buffers for 15 events are used. Therefore, the online data processing causes essentially no additional dead-time, as long as the average trigger rate is below the average rate at which events can be processed.

2.3 Hit finding

At first, the main online task searches for hits in the wire raw data (see fig. 1). For a charge-division wire the average of both ends is used. The *difference-of-samples* (DOS) method is applied for finding hits. The difference of the contents in consecutive bins is required to exceed a given threshold. The signal itself also has to exceed a threshold above the nominal baseline value for several bins in sequence, in order to reject noise. The start time of a pulse is defined by a weighted centre of the difference signal in the rising part of the pulse.

Figure 1: FADC raw data and two identified hits shown for both sides of a charge-division wire and the corresponding four cathode pads. The data corresponds to a time interval of about $9\,\mu$s. Positions and sizes of crosses indicate the reconstructed start times and pulse areas, respectively.

For the reconstruction of coordinates along the wires, ratios of charges on the two ends of charge-division wires or on the four pad channels, respectively, are required. These are determined from the corresponding *pulse areas* and the calibration of the *relative gains* of relevant channels. If a bin is in overflow for one channel, it is discarded also for the other side of a charge-division wire or the other three pad channels. In overlapping pulses, the tails of the earlier pulses are subtracted from the later pulses (for details see [7]).

2.4 Track finding and reconstruction

The drift times are available for hits on all six wires of a drift chamber – except for a common trigger offset t_0 – whereas the positions in wire direction can be reconstructed only on two charge-division wires without ambiguities. Therefore, the track finding is based entirely on the drift times. The x (drift) coordinates of the hits are evaluated for both sides with respect to the wire chamber, given the measured time $t - t_0$, the drift velocity v_d, and the wire staggering (alternating offsets) x_w:

$$x_\pm = x_\mathrm{w} \pm v_d\,(t - t_0).$$

Track candidates are searched along straight lines through suitable pairs of hits on two *seed wires*. Projected zenith angles of less than 60° are required. On the other four wires, hits less than 8 mm from that line are accepted. This search is done under both assumptions that the track is on either side of the wires. If suitable hits are found on enough wires, least squares fits are applied, which resolve the $x_\pm$ ambiguity by using the side with the smaller χ^2 per *number of degrees of freedom* (ndf). Track candidates with a bad χ^2/ndf are discarded. Tracks are required to have hits on at least four wires.

Most tracks are found from more than one pair of seed wires and different tracks may have one or more common hits. A hit common to two tracks is removed from the track with the larger residual for this hit, if the difference is significant, or from the track with the worse χ^2/ndf. Tracks with too few remaining hits are discarded, otherwise the least squares fit is repeated. In the end, no hit is assigned to more than one track.

For the remaining tracks, the y (wire) coordinates and slopes are evaluated, provided that the tracks have at least hits on both charge-division wires or on one charge-division wire and one other wire with cathode pads. The charge-division coordinates y_cd are obtained from the charges q_r and q_l measured on the right and left sides of the wires (see section 2.6). The y_cd coordinates are required to resolve the 22-fold ambiguity of the more precise pad coordinates y_{pad}. The pad coordinates are derived from the centre-of-gravity of the pad with the largest charge and its two neighbours and then corrected for remaining systematic errors via a lookup table.

If hits on both charge-division wires are available, a straight line through the combined y positions is extrapolated to the other wire(s) with pads. There, the extrapolated positions y_ext are used to resolve the pad ambiguity. A least squares track fit is applied to the set of all available y coordinates from charge-division and non-charge-division wires with pads. If on the non-charge-division wire(s) the y_ext (modulo the pad period length) are not in reasonable agreement with the derived pad coordinates, one or both of the charge-division coordinates may be wrong. In such a case, the wire causing the problem is usually identified, e.g. by an overflow, a very small signal, or overlapping pulses, and the correct s_y track slope is derived without the signals of this wire. If only hits on one charge-division wire and on one other wire with pads are available, some ambiguity of the track slope remains.

Finally, corrections for small angular and spatial misalignments of the two drift chambers of a detector are applied before muons can be identified.

2.5 Muon identification

The identification of muons was an important aspect in the design of the CRT detectors. After the track reconstruction, muon identification is a further step of the data processing which can be done online at individual detector stations. For this purpose, all pairs of one track in the upper chamber and one in the lower chamber are compared. Both slope components should be consistent. Due to the 90° rotation angle between upper and lower chambers this can be written as

$$s_{x,\mathrm{u}} \approx s_{y,\mathrm{l}} \tag{1}$$
$$s_{y,\mathrm{u}} \approx -s_{x,\mathrm{l}} \tag{2}$$

for the slope components in x and y projection of the tracks in the upper and lower chamber (u, l), respectively, with x always being measured in drift direction of a drift chamber, y in wire direction.

Pairs of muons tracks in the upper and lower chambers should match when they are extrapolated to the middle of the iron plate: $x_\mathrm{u} \approx y_\mathrm{l}$, $y_\mathrm{u} \approx -x_\mathrm{l}$. However, the delay between the particle arrival time and the FADC stop signal is not well known, i.e. the x coordinates have a common but event-dependent offset. There is one linear combination of the intersection coordinates, $\rho_1 = (x_\mathrm{u} \pm y_\mathrm{l}) \pm (x_\mathrm{l} \pm y_\mathrm{u})$, which is independent of this offset, with signs depending on the 'quadrant' (the combination of upper and lower tracks being to the left or right side of the wires in the corresponding drift chamber). If the offset is known, the orthogonal linear combination ρ_2 can be used to check that a muon candidate arrived at the proper time:

$$\rho_1 \approx 0 \tag{3}$$
$$\rho_2 - v_\mathrm{d} t_0 \approx 0. \tag{4}$$

Indeed, muons unrelated with the showers triggering the array of CRT detectors are expected to be the most severe background to muons of the showers, if the trigger delay is not known. It is usually not known during online pattern recognition at a detector station but can be determined in the case of a CRT array triggered by CRT detectors only, after combining data from many detectors at the central station. In the case of the detectors triggered by the HEGRA scintillator array, the trigger delay is well known.

Other possible sources of muon background are hadrons and punch-through electrons. Charged high-energy hadrons are likely to be misidentified as muons because the iron plate has a thickness of only 0.6 interaction lengths. For a search for γ-ray sources, misidentified hadrons are of no concern because they, like muons, are indicators of nucleon-induced air showers. In addition, charged high-energy hadrons are only found very close to the shower axis. Electrons of more than about 1 GeV energy, also found only close to the shower axis, may give rise to electromagnetic showers in the iron plate, with opening angles of secondaries in the lower drift chamber of several ten degrees. Such muon background can be easily rejected by applying isolation criteria to the 'muon' track in the lower chamber. Real 'punch-through' electrons with a single track in the lower chamber within a 2° cone of the upper track are very unlikely and not a severe muon background (see sects. 3 and 4.4).

2.6 Online detector calibration

The online calibration procedure consists of four stages which are carried out continuously during regular data acquisition: FADC baseline (pedestals) calibration, gain calibration, pad and charge-division coordinate calibration, and drift velocity calibration. Except for the FADC baseline calibration, all calibration stages use regular event data. Therefore, periodic updating of all relevant parameters on a short time-scale is achieved essentially without interrupting the data acquisition. Only the baseline calibration, which is repeated every few hundred events, gives rise to short dead-time intervals. The later stages can also be performed offline if raw data or hit data are recorded.

The coordinate and drift velocity calibrations require that the preceding stages have been passed at least once. Apart from that, data for the different stages are collected independently and in parallel. When enough data are accumulated for a stage, the corresponding parameters are determined and updated. The calibration status can be saved when a run is terminated and restored before the next run is started. Otherwise, after starting with an uncalibrated detector, some 30000 self-triggered events are required for a complete pass through all stages, which takes about 10 minutes.

In the FADC baseline calibration all FADC channels are read without trigger and checked that there are no random pulses in the data. If the measured baseline of any channel deviates by more than 1.0 count from the nominal value, the baseline is adjusted by changing the DAC setting of that FADC channel and measuring the baseline again. This is important for the fast zero-suppression by software. For the reconstruction of pulse areas the measured baseline is used, not the nominal value.

The track reconstruction with CRT detectors requires to know the ratios of the overall gains of both sides of a charge-division wire and of all four channels of a pad board. The absolute values of the gains, on the other hand, are of minor importance. Test pulses from the fast DAC of the monitor module are not required during regular detector operation [8]. Instead, the gain calibration is done with cosmic-ray data, using pulse-area histograms of isolated hits.

For the pad coordinates a lookup table is required to correct for the systematic imaging errors of up to 0.9 mm of the simple *centre-of-gravity* (c.o.g.) method. This method derives a coordinate $y_{\mathrm{c.o.g.}}$ from the charges on the pad with the largest signal and its two neighbours without knowing the pad response function. Lookup tables for $y_{\mathrm{pad}}(y_{\mathrm{c.o.g.}})$ are derived from the histograms of uncorrected pad coordinates during the regular online calibration. For deriving the lookup tables we use the fact that the correct pad coordinates y_{pad} should be homogeneously distributed, averaged over all 88 pads, while the raw $y_{\mathrm{c.o.g.}}$ is found preferentially near the centre of a pad.

The charge-division calibration takes advantage of the 22-fold ambiguity of the pad coordinates. This ambiguity results in 22 peaks in histograms of $y_{\mathrm{cd}} - y_{\mathrm{pad}}$ (see fig. 2). The positions of these peaks are used to update the calibration constants a_0,

Figure 2: Histogram of $y_{\rm cd} - y_{\rm pad}$ as used for the calibration of the charge-division.

a_1, and a_2 for the charge-division coordinate

$$y_{\rm cd} = a_0 + a_1 r_{\rm cd} + a_2 r_{\rm cd}^2, \tag{5}$$

with

$$r_{\rm cd} = \frac{q_{\rm r} - q_{\rm l}}{q_{\rm r} + q_{\rm l}} \tag{6}$$

depending on the charges $q_{\rm r}$ and $q_{\rm l}$ on the right and left sides of a wire. The widths of the peaks are dominated by the charge-division resolution. They are smallest near the middle of the wire ($\sigma_{\rm cd} \approx 9\,{\rm mm}$) and increase as expected by about a factor of $\sqrt{2}$ towards the ends.

The final calibration step for the drift velocity and the alignment of upper and lower drift chambers is done with cosmic-ray muons penetrating the iron plate. Due to the $90°$ angle between the drift directions in upper and lower chamber a geometric slope in one chamber as derived from pad and charge-division coordinates corresponds to a slope in time multiplied by the drift velocity in the other chamber:

$$s_{x,{\rm u}} = v_{\rm u} s_{t,{\rm u}} \approx s_{y,{\rm l}} \tag{7}$$

$$s_{x,{\rm l}} = v_{\rm l} s_{t,{\rm l}} \approx -s_{y,{\rm u}}. \tag{8}$$

Drift velocity and alignment constants are derived by a robust fit procedure from typically 1000 pairs of a single track in the upper chamber and a single track in the lower chamber, after discarding obvious random pairs. Figure 3 shows that the drift velocity correlates well with the temperature in the detector container but with a few hours delay. Remaining water vapour and perhaps other contaminations of the counting gas are the reason for this behaviour.

2.7 Tasks of the central VME system

Two computers are used at the central station: a VME system for the control of common triggers and common event numbers in array mode and an UNIX worksta-

Figure 3: Drift velocities in upper and lower drift chambers and the average temperature in a CRT detector as functions of time.

tion for collecting event data, event building, online shower reconstruction, and data backup. For the central VME system a Motorola 68040 CPU is currently used.

The central VME system is used to control the central trigger electronics and the Event Grader Master (EGM). In the setup on La Palma, additional interfaces to the HEGRA array (see paper I) are also included in this central system. The EGM sends the trigger plus the event number for each accepted central trigger and generates an interrupt. The central trigger is also used to store the precise time in the Clock Module latch registers.

2.8 Communication and event building

The event numbers are used for event building in the central computer when the asynchronously processed data from all detector modules are collected there. In the initial test phase with CRT detectors, the data from each detector was written to a separate file and the event building was done offline.

Remote detector control and data transfer are implemented on top of the connectionless *User Datagram Protocol* (UDP) to achieve high transfer rates via Ethernet. Remote control of the data acquisition program at the detector modules, of the run control program at the central VME system, and of the event builder and I/O server program at the UNIX workstation is possible from different types of UNIX workstations and also from VMS or OS-9 systems connected to the local network.

Data are collected by the detector computers until a given block limit (typically 64 kbytes) is reached, the data are requested by the central station, or a run is stopped.

3 Monte-Carlo detector simulation

A detailed detector simulation by the Monte Carlo method has been implemented and used to check our understanding of the detectors and the main limitations for the angular resolution. The GEANT detector description and simulation tool [10] is used to trace the incident and any secondary particles through the detector, including scattering and interaction processes.

For all the charged particles crossing a *sensitive volume*, i.e. the 1 cm high cylindrical slices from where electrons can drift to the proportional wires, the various effects relevant to measured signals are simulated [11]. First of all, the fluctuations of the ionization along the track segments in the sensitive volumes are taken into account. This effect is responsible for the deterioration of the detector resolution with increasing zenith angle (see sect. 4.5). The longitudinal and transverse diffusion of the ionisation electrons on their way to the wires are included as well. At the sense wires the gas amplification is simulated, including the statistical fluctuations of the gain for each sample of electrons arriving at the wire and the $1/t$ time dependence of the signal.

The signals induced on the cathode pads in each time interval are based on an analytical approximation to the measured response function. The charge-division wire signals are also simulated. Because the wires are capacitively coupled to the preamplifiers, the charge-division signals consist of a fast and a slow exponential component that influences the tails of the pulses. The slow component causes a slight undershoot on the 'near' side, where the fast component is larger, and a corresponding overshoot on the 'far' side. These effects are included in the simulation.

In order to obtain the proper frequency-dependent response function of the electronics chain of preamplifiers and shapers, the electronics was simulated with SPICE [12]. The resulting response function is folded with the charge at each preamplifier as a function of time. The electronics gains are chosen to have average pulse areas comparable to those measured with CRT detectors. The resulting signals are then digitized in 25 ns intervals as in the real FADCs. Because the noise resulting from many different sources is very difficult to simulate, we decided to use measured noise signals and add them to the digitized simulated signals instead of adding simulated noise before the digitization.

Figure 4: Simulated and measured resolutions in drift direction (top) and wire direction (pad resolution, bottom) for tracks with less than about 20° zenith angle.

The resulting 'raw' data are then processed by the same hit and track reconstruction software as used for the real data, and the same muon selection criteria are applied. In order to check the simulation procedure we compared pulse shapes, pulse-area histograms, and, in particular, the resolution with experimental data. Indeed, simulated data behaves very much like real data, although the resolutions in drift as well as in wire direction are slightly (10–20%) better than in reality (see fig. 4). Due to the better charge-division resolution there are also less tracks with a bad reconstruction in the y–z plane as observed experimentally (see sect. 4.4).

Understanding the resolution raises confidence in the simulations to attack questions which cannot be measured easily, like track reconstruction efficiencies as functions of particle types and momentum (see fig. 5 and 6) and the probabilities to misidentify electrons or hadrons as muons. The threshold for electron reconstruction is about 10 MeV/c. This can be explained by the energy loss in the detector container (about 4 MeV) and the scattering of low-energy electrons in the counting gas which prevents reconstruction of straight tracks. Photons can also lead to reconstructed tracks if they suffer pair-production or Compton-scattering in the detector container or the drift cage.

Figure 5: Simulated efficiency of reconstructing a track in the upper drift chamber as a function of the momenta of electrons and of gammas converting to e^+/e^- in the detector container. The dashed curves represent fits to the simulated efficiencies (points).

Figure 6: Simulated efficiency of reconstructing and identifying vertical muons. The dashed line is not a fit but a simple approximation accounting for losses due to multiple scattering in the iron plate, energy loss, and an internal resolution of 0.3° per chamber.

The punch-through fraction of electrons misidentified as muons rises from 0.1% at 200 MeV/c to 0.6% at 500 MeV/c and 1.5% at 1 GeV/c, after applying the isolation criterium for tracks in the lower chamber. Without isolation criterium about three times more electrons would be identified as muons.

4 Detector operation and performance

4.1 Operating CRTs with scintillator arrays

Operating CRT detectors together with a scintillator array was important to evaluate the performance of individual CRT detectors and of a small CRT array. CRTs have been operated at two scintillator arrays: the 25-station array on the Heidelberg institute campus at an altitude of 300 m [13] and the larger HEGRA array [4] on La Palma (Canary Islands) at an altitude of 2200 m. With the scintillator arrays, the secondary particle density in the shower can be sampled at more positions than with only 10 CRT detectors. Therefore, the shower core position can be better evaluated with scintillator data. Also the shower direction obtained from scintillator data can be used as a reference although the angular resolution of the HEGRA scintillator array is just of the same order as the resolution of a CRT detector for a single particle track. With the smaller Heidelberg scintillator array the array resolution is a severe limitation for observing the angular distribution of muons in air showers.

Simultaneous observations with a scintillator array and CRT detectors were used to check the particle angular distributions predicted by numerical air shower simulation programs, in particular by CORSIKA [14][15]. For measurements with the Heidelberg scintillator array and a first CRT prototype see [13]. Only data obtained with the HEGRA array and the 10 CRT modules on La Palma were used for the present paper. The HEGRA-plus-CRT observations were used to evaluate track reconstruction and muon identification efficiencies.

4.2 Operational conditions on La Palma

During most of the time since the first CRT detectors were installed on La Palma, the detectors were remotely operated from Heidelberg. The 8 mm data tape cartridges were exchanged by HEGRA operators about once per week. The online UNIX workstation was set up to reboot in case of power failures while all other online computers could be booted from the workstation, if necessary. Starting and controlling the data acquisition for individual CRT detectors or the whole CRT array was done from the UNIX workstation, a DECstation 5000/200.

A very slow deterioration of the gas quality was seen and the gas of the first four detectors was exchanged in November, 1993 – up to 11 months after the initial filling. Five detectors have been opened on-site for repair of a particular badly soldered cable. The cause of this problem was identified and can be avoided in future detectors. Once a defective preamplifier had to be exchanged. Both types of defects caused only a slight deterioration of the angular resolution and the muon identification efficiency. In all cases the detectors remained fully operational. Except for these minor repairs the detectors performed without any problems, by now up to 28 months after installation on La Palma.

4.3 Trigger and event rates

The trigger rate, event rates, and also the data rates of standalone CRT detectors as well as of the small CRT array on La Palma have been studied in detail. The peak event rate per detector is currently mainly limited by the CPU performance of the 25 MHz Motorola 68040 processors. For a 1 kHz single-detector trigger rate and full online pattern recognition and calibration an event rate of about 50 Hz is achieved with typically one track per event.

This rate is perfectly adequate for the proposed large CRT array [2] where typically only 30–40 detectors out of almost 400 would be hit by charged secondaries from an air shower and, therefore, have a local trigger together with the common array trigger. At an array rate of about 100 Hz the relevant detector rates would be between 20 Hz in the dense central part and less than 5 Hz in the outer part of the array. Including calibration, monitoring, and auxiliary information a total data rate of some 700 kbytes of data per second is expected for such a large array. With the present setup of 10 detectors and a 8 Hz detector trigger (for a 17 Hz trigger from HEGRA) about 10 kbytes are recorded per second.

Internal trigger rates with CRT detectors were found to be significantly higher than expected from [16], which is based on [17]. At the institute campus in Heidelberg (300 m a.s.l.), instead of the expected rate of some 450 Hz the observed rate for 3 out of 4 wires of the upper chamber is about 790$\pm$40 Hz with 0.94$\pm$0.03 tracks reconstructed per event. The reason for this discrepancy seems to be the low threshold of CRT detectors for the soft $e^{\pm}$ component of secondary cosmic rays.

When looking for muons, no obvious discrepancy is found. The expected rate, including the geometric detector acceptance, is about 250 Hz. A CRT muon trigger rate of 330 Hz is observed. With this trigger 0.55 muons were reconstructed per event (corresponding to a 182 Hz muon rate), if the same muon identification criteria as for shower muons are applied. If less strict criteria are applied, which are more appropriate for the softer non-shower muons, 0.65 muons per event (corresponding to 215 Hz) are found. Even with the less strict muon cuts about 10–20% of the soft non-shower muons are expected to fail the cuts. Expected and measured muon rates are, therefore, consistent. For a CRT detector in Heidelberg only 35% instead of the quoted 75% [16] of the observed particle flux is due to the muon component.

At mountain altitude (La Palma, 2200 m a.s.l.), the fraction of the soft component is even larger. For the same detector and the same operating conditions the trigger rates of single wires in the upper drift chamber and of coincidences rise by 37% with respect to the values measured at Heidelberg. Rates in the lower chamber increase by only 20%. Muon trigger rates increase by 32%.

For a CRT array triggered on coincidences between CRT detectors, coincidence gate widths of at least the maximum drift time – some 14 μs – are required. With these widths and an ordinary majority trigger logic, random array triggers can be a serious problem. Assume that in an array with n detectors used for the trigger logic all detectors have the same (independent) single-detector rate ν_1. If at least k out of the n detectors are required for a coincidence of width τ, the random array trigger rate is

$$\nu^{\star}_{k,n} = k \binom{n}{k} \nu_1 (\nu_1 \tau)^{k-1}, \tag{9}$$

without taking into account that the trigger gate causes a dead-time τ after each trigger. Correcting for that, the random rate is

$$\nu_{k,n} = \nu^{\star}_{k,n} \exp(-\tau \nu^{\star}_{k,n}). \tag{10}$$

Measured trigger rates and expected random rates for the small array on La Palma are shown in table 1. With the small array a trigger of at least four out of eight detectors is required to have the random rate well below the measured rate.

Table 1: Trigger rates for the small CRT array at La Palma with eight detectors connected to the central trigger logic. In addition to measured trigger rates the expected random trigger rates for the average single-rate of 1019±8 Hz and a gate width of 15 μs are shown. The CRT detectors were triggered with a coincidence of at least 3 out of 4 wires in the upper chambers.

trigger multiplicity (k of n)	Measured trigger rate [Hz]	Expected random rate [Hz]
$\geq$ 1 of 8	7280±8	7215±50
$\geq$ 2 of 8	848±5	861±13
$\geq$ 3 of 8	56.5±0.8	40.0±0.9
$\geq$ 4 of 8	8.1±0.4	1.02±0.03
$\geq$ 5 of 8	3.8±0.2	0.016±0.001
$\geq$ 6 of 8	2.3±0.15	10^{-4}
$\geq$ 7 of 8	1.23±0.06	10^{-6}
all 8	0.84±0.06	10^{-9}

4.4 Track reconstruction and muon identification efficiencies

The track reconstruction efficiencies for data taken with the HEGRA trigger on La Palma has been evaluated. Unless otherwise stated, the mentioned efficiencies apply to detectors with four cathode-pads boards per drift chamber triggered by the HEGRA array. Note that the efficiencies depend on particle energy and type, track multiplicities, on the position in a chamber, and on the zenith angle. Muons and other high-energetic particles penetrate the gas in a drift chamber with very little scattering. On the other hand, low-energy particles – mainly electrons – may scatter quite significantly or even stop within a drift chamber. In addition, the detector response deteriorates if the detector is hit by many particles in the same event.

The overall detector efficiency can be expressed by the *effective area*, which is the measured rate divided by the flux of particles from a given direction. In a simplified way the effective area of a CRT for reconstructing a track from a charged particle of zenith angle θ can be expressed as

$$A_{\mathrm{eff}} = A_{\mathrm{geo}} \epsilon_{\mathrm{hit}} \epsilon_x \epsilon_y \cos\theta. \tag{11}$$

Various efficiency factors have to be taken into account: ϵ_{hit} for finding enough hits, ϵ_x of finding a track from these hits, and ϵ_y that the track is also reconstructed in the y–z plane. For muons, where tracks in both chambers are required, the geometrical area $A_{\text{geo},\mu}$ is different from that for tracks in a single chamber. Including the muon selection cuts a simple expression for the effective muon reconstruction area is

$$A_{\text{eff},\mu} = A_{\text{geo},\mu} (\epsilon_{\text{hit}} \epsilon_x \epsilon_y)^2 \epsilon_{\text{angle}} \epsilon_{\text{pos}} \epsilon_{\text{iso}} \cos\theta. \tag{12}$$

Here, ϵ_{angle} is the efficiency that the angles of the two tracks match, ϵ_{pos} that the extrapolated positions at the middle of the iron plate match, and ϵ_{iso} that the muon track in the lower chamber is isolated.

Figure 7: Histograms of muon track positions in the upper drift chamber, for tracks with four hits and with six hits. Four-hit tracks are predominantly found for particles crossing the wire plane or the outer edge. The outer detector border is indicated by dashed circles.

While geometrical areas are easily calculated (see table 2) the efficiency factors are derived from the cosmic ray data. Efficiencies for high-energetic secondaries with little scattering in a drift chamber can be obtained from muon tracks. The hit efficiency ϵ_{hit} is evaluated from muon tracks in a fiducial volume of the drift chambers away from the edges and wire plane, where in the ideal case only 6-hit tracks are expected. Hit losses can be due to ionization fluctuations or due to overlapping multiple pulses.

Table 2: Sensitive horizontal geometrical detector areas A_{geo} (in m^2) as a function of zenith angle θ after applying the geometrical acceptance for tracks in the upper chamber (with at least 4, 5, or 6 hits) and for muons.

track type	$\theta = 0°$	30°	45°	60°
≥ 4 hits	2.54	2.44	2.35	2.21
≥ 5 hits	2.54	2.34	2.13	1.94
6 hits	2.54	2.21	1.97	1.57
muons	2.54	1.95	1.53	0.89

Observed fractions of single muon tracks with 6, 5, and 4 hits in the fiducial regions are 95%, 5%, and 0.2%, respectively. The corresponding single hit efficiency is 99.1%. Losses of tracks due to ionization fluctuations, i.e. having only three hits or less, are negligible. However, the track finding may be disturbed by additional tracks. The fraction of 4-hit muon tracks rises to 1.4% with one other track, 3.2% with two, and 4% with three other tracks. The average of all events is 1.4%. Muon tracks actually lost due to other tracks are estimated to be, on average, less than 0.5% per chamber. Only near the cores of large showers is the muon identification considerably hampered by additional tracks in the detector.

For high-energetic particles like the muons no significant losses due to scattering in the drift chamber gas are expected ($\epsilon_{\mathrm{x}} \approx 1$). However, a low-energy particle scattering in the gas may be reconstructed e.g. as a 4-hit track because the hits on two wires are not on a sufficiently straight line with the four others. Due to such low-energy particles, the overall fraction of 4-hit tracks is much larger than for muons. With only one track in a drift chamber, the fractions of 6-, 5-, and 4-hit tracks are 70%, 16%, and 14% for the upper chamber and 54%, 21%, and 25% in the lower chamber. With more than one track, the fractions of 4-hit and 5-hit tracks are even larger.

Some of the tracks cannot be properly reconstructed in the y–z projection, e.g. because they have no or too small hits on the two charge-division wires. Averaged over all track multiplicities and angles, ϵ_y was found to be 99.5%, 98%, and 90% for tracks with 6, 5, and 4 hits, respectively. With no or few other tracks in a chamber, the efficiencies are much better: with three or less tracks in a chamber ϵ_y is 99.9%, 99.8%, and 91.4% for tracks with 6, 5, and 4 hits. The performance of detectors with only three cathode-pads boards per chamber is slightly worse.

The muon-specific efficiency factors $\epsilon_{\mathrm{angle}}$, ϵ_{pos}, and ϵ_{iso} are calculated by releasing one cut and looking at the distribution in the corresponding variable. Because the trigger delay is not known online, the position cut is done with linear combinations of the two coordinates: ρ_1 which is independent of the delay and ρ_2 which is only available offline after subtraction of the average delay (see sect. 2.5). All muons should have $\rho_1 \approx 0$, shower muons also $\rho_2 \approx 0$.

See fig. 12 for the observed angular match and fig. 8 for the distribution of the position parameters ρ_1 and ρ_2. For a $2.5° \times 2.5°$ angular cut $\epsilon_{\mathrm{angle}}$ is $93.5 \pm 1.2\%$ for CRTs placed inside the HEGRA array and triggered by HEGRA showers. The losses are consistent with the multiple scattering of the muons in the iron plate. Muons lost in the angular cut essentially all have momenta less than 2 GeV/c.

Figure 8: Histogram of the muon cut parameters ρ_1 and ρ_2 for the separation between extrapolated upper and lower track in the iron plate. Note the logarithmic grey-scale to enhance faint details. The central peak is from correctly reconstructed shower muons, the other peaks from muon tracks reconstructed with the correct angle but offset by one or more pad periods. The vertical strip in the middle is from accidental muons not originating from the shower.

In fig. 8 it turns out that in a fraction of the events, the charge-division coordinates were wrong by one or even more pad periods. Most such events have additional tracks in the detector which disturbed the track reconstruction. On average, 87.5% of all shower muons are found in the central peak ($|\rho_1| < 30$ mm and $|\rho_2| < 50$ mm), 10% in the four peaks corresponding to an offset of one pad period, and 2.5% in further peaks (97.2%, 2.6%, and 0.2% in events with no other tracks than the muon). For this reason, track pairs in the one-period-offset peaks are, generally, also accepted as muons ($\epsilon_{\rm pos}$=97.5%).

In a final cut, candidates for punch-through electrons are discarded. From showers of high-energy electrons in the iron plate sometimes one or several tracks may leak into the lower drift chamber, resulting in fake muons. Hadrons interacting in the iron plate could also cause more than one track in the lower chamber. For 7.7% of all shower-muon candidates a second track is found within an extrapolated intersection in the iron plate less than 60 mm in drift projection from the muon track (8.3% if the one-period-offset peaks are included). Of these 1.6% (1.9%) are expected to be real shower muons with an accidental second track, i.e. $\epsilon_{\rm iso} = 98.4\%$ (98.1%). The other 6.1% (6.4%) are punch-through electrons or interacting hadrons. According to detector simulations, about 68% of the punch-through electrons are recognized as such. Thus, about 3% of the muon candidates with HEGRA trigger should be unidentified punch-through electrons with just one track in the lower chamber, assuming that all identified punch-through particles are electrons. That corresponds to about $7 \cdot 10^{-4}$

of the total number of registered electrons. According to shower simulations, most of these high-energy electrons are very close ($< 25\,\mathrm{m}$) to the shower core. Beyond 50 m from the core the punch-through electrons and hadrons should be insignificant. In the HEGRA-triggered data, the ratio of identified punch-throughs to muons drops from 9% at 20 m core distance to 3% at 250 m.

Apart from the geometrical acceptance, the overall efficiency for muons in HEGRA-triggered showers is $87 \pm 3\%$ if the one-period-offset peaks in the ρ_1–ρ_2 plot are included, $78 \pm 4\%$ if only the central peak is used. The remaining background among the shower muon candidates is estimated as up to 3% single-track punch-through electrons, 1.2% non-shower muons and 0.2% random combinations of tracks in upper and lower chamber (0.08% with the central ρ_1–ρ_2 peak only). Very close to the shower axis several percent are expected to be hadrons.

4.5 Track resolution

The angular resolution of the CRT detectors for particle tracks has been measured in several different ways. Each method has its advantages and its drawbacks. Three methods are shown here in detail. They are based on the track fit residuals in both drift and wire directions (method 1), the angles between the corresponding tracks of muons in upper and lower chamber (method 2), and the angles between CRT muon tracks and the corresponding shower axis as reconstructed from the HEGRA scintillator data.

Method 1 gives only a first estimate of the angular resolution that can be expected and does not take possible drift field distortions into account. Method 2 requires to use muons from air showers which have typical momenta above $10\,\mathrm{GeV}/c$. Muons recorded with standalone CRT detectors, having typical momenta of the order of $2\,\mathrm{GeV}/c$ [16], scatter too much in the iron plate. By method 3 systematic deviations of CRT tracks with respect to the reconstructed shower axis can be measured. Due to the large intrinsic scatter of the *radial* angles, only the *tangential* component (angle difference in a plane parallel to the shower axis and perpendicular to the shortest line from the CRT detector to the shower axis, see fig. 9) with an intrinsic width of only some 0.2° should be used. For this decomposition the shower core position from the scintillator data is needed.

By method 1 the dependence of the hit resolution on various parameters has been evaluated, in drift (x) as well as in wire (y) direction. The hit resolutions in both directions show a linear dependence on the drift length (fig. 4). The resolution in x also depends on the track angle in the x-z plane and that in y on the angle in the y-z plane (fig. 10) but not vice-versa. In addition, the pad and charge-division resolutions but not the drift resolution have been found to deteriorate with an increasing number of tracks in the drift chambers (see fig. 11). This deterioration is mainly due to the slow signal components which slightly offset the FADC pedestals for subsequent hits. The hit resolutions averaged over all angles, drift distances, and track multiplicities are about 0.9 mm in x and 1.1 mm in y, corresponding to track angle resolutions of 0.31° and 0.43° with unweighted track fits. The weighted fits, as implemented, it should be 10–15% better.

The projected angles between the upper and lower tracks of shower muons (fig. 12) include the resolution in x of one chamber, in y of the other, and the multiple scattering in the iron plate. The observed Gaussian σ of 0.57° is consistent with the

Figure 9: The geometry of radial and tangential angles between the shower axis, e.g. as reconstructed from scintillator data, and the track of a particle measured by a CRT detector.

resolution derived from the fit residuals, if the average multiple scattering of muons with a typical momentum of the order of 10 GeV/c is taken into account. Therefore, irregular drift field distortions do not pose a significant limitation on the resolution of the CRT detectors. For muons observed with standalone CRT detectors the average angles between the two tracks are 40% larger due to the lower muon momentum and the larger scattering in the iron.

The expected angular resolution for a single shower muon is expected to be of the order of 0.4° in both projections if systematic field distortions are also insignificant or can be fully corrected afterwards.

By comparison with the HEGRA shower axis, the muon angular resolution has been checked. For this comparison the inclinations of the detectors and scaling factors for the track slopes have been evaluated by comparison with HEGRA data. A small systematic mismatch of a few tenths of a degree between these inclinations and those determined with standalone CRT detectors could be either due to HEGRA or to the east-west effect caused by the earth's magnetic field. The track-slope scales generally deviate by less than 1% from the nominal value.

The resolution achieved for the tangential angle difference between single muon

Figure 10: Hit resolution in x as a function of the angle in the x-z plane and the resolution in y as a function of the angle in the y-z plane, averaged over all drift distances and multiplicities.

tracks and the HEGRA shower axis of $0.79°$ is mainly due to the HEGRA resolution. The HEGRA resolution improves with increasing shower size while the CRT muon resolution is essentially independent of the shower size. Due to an increasing number of other tracks in addition to the muon, the CRT muon resolution could only deteriorate with increasing shower size. Indeed, the tangential angle difference resolution improves with increasing shower size (see fig. 13) to about 0.4–0.5° for very large showers. We conclude that CRT detectors have a resolution of about 0.4° for single muons, when systematic offsets from the HEGRA reference system are corrected for.

The angular resolution has also been checked using the angles between two muons in the same detector as well as in separate detectors and by data obtained with a trigger from an Atmospheric Cherenkov Telescope on the HEGRA site. Results from these methods are consistent with those of the methods explained in detail.

5 Conclusions

The operational experience of about two years with the 10 CRT detectors on La Palma at an altitude of 2200 m has shown that CRT detectors are very robust devices. With these detectors the TPC technique has been adopted to outdoor mountain-altitude conditions. The detectors have been operated with full online data processing and detector calibration at the local detector stations. Processing speeds with the current Motorola 68040 CPUs are fully sufficient for the 10 CRT detectors operated either with triggers from the HEGRA array or as a small array on its own. Processing speeds would also be adequate for a large CRT array as proposed by [2].

Using CRT detectors, tracks from electrons above about 10 MeV energy can be reconstructed and muons above about 1 GeV can be identified very well. Punch-through electrons are efficiently suppressed and occasional random muons not related

Figure 11: The cathode-pad resolution as a function of the number of tracks in the drift chamber.

Figure 12: The projected angles between upper and lower tracks of muons in HEGRA-triggered showers.

with the measured showers are recognized. Muons are very rare in γ-ray initiated air showers. Therefore, a single shower muon would be sufficient to reject a hadron shower with a large CRT array searching for sources of cosmic γ-rays above a few TeV energy.

The achieved angular resolution is about 0.4° for muons. For high-energy electrons the resolution is comparable to that while for low-energy electrons (below about 100 MeV) the resolution is somewhat deteriorated by multiple scattering in the detector container. The good overall angular correlation of the shower secondaries with

Figure 13: The resolution of tangential angles between CRT muons and HEGRA showers as a function of shower size N_s. The dashed line is a fit, assuming a size-independent CRT resolution and a HEGRA resolution proportional to a power of N_s.

the direction of the primary cosmic rays is conserved. We estimate that with a large CRT array the direction of the primaries can be determined with an accuracy of about $(3°–4°)/\sqrt{N}$ where N is the number of recorded secondaries in the CRT detectors. A detailed study of the resolution to be achieved with a CRT array is still in progress.

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