HiSPARC: A Scintillating Experiment

KASPER VAN DAM

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UNIVERSITY
OF TWENTE.

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HiSPARC

A SCINTILLATING EXPERIMENT

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Intellectual freedom is essential – freedom to obtain and distribute information, freedom for open-minded and unfearing debate and freedom from pressure by officialdom and prejudices. Such freedom of thought is the only guarantee against an infection of people by mass myths, which, in the hands of treacherous hypocrites and demagogues, can be transformed into bloody dictatorship.

Dr. Andrei D. Sakharov

Progress, coexistence, and intellectual freedom, 1968

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Chapter 1

Introduction

1.1 Cosmic rays

In addition to photons from the Sun and stars also charged particles come from space. These particles are known as cosmic rays and consist of protons (90%), Helium nuclei (9%) and heavier nuclei (1%) [1]. The majority of these particles are relativistic. Some of them have extremely high energies. The origin of those very energetic particles is unknown. The flux of cosmic rays decreases rapidly with energy. Figure 1.1 shows the cosmic ray energy spectrum in particles per energy-per-nucleus as function of kinetic energy-per-nucleus. The fluxes of nuclei other than H are scaled. The inset shows the H/He ratio at constant rigidity, i.e. at energies chosen such that both particles have the same dynamics in a magnetic field. The cosmic ray energy spectrum can be described by a power law. The flux as function of energy in the range from 10^9 eV to 10^{14} eV is approximately given by [2]:

$$I(E) \approx 1.8 \cdot 10^4 (E/1 \text{ GeV})^{-\alpha} \left[\frac{\# \text{ of nucleons}}{\text{m}^2 \text{ s sr GeV}} \right] \quad (1.1)$$

with $\alpha \approx 2.7$. The fluxes at these energies are measured using balloons and spacecraft.

For higher energies this approach becomes unfeasible because of the low cosmic ray flux, the limited collection area and lifetime of space based instruments. Above 10^{14} eV cosmic rays are studied using the Earth's atmosphere. When a cosmic ray enters the atmosphere it will most likely interact with a nitrogen or oxygen nucleus. In this interaction new particles are produced which, in turn, will interact with other atmospheric particles. The particle generation continues until there is insufficient energy left for the creation of additional particles. This phenomenon is known as an Extensive Air Shower (EAS). The particle footprint of an EAS on the ground is sampled using detector arrays. The direction and energy of the cosmic ray can be reconstructed from the arrival times and sampled particle densities. This reconstruction is less precise than space based measurements. For high energy cosmic rays it is especially hard to determine the mass of the particle. The cosmic ray energy spectrum with energies above 10^{14} eV is expressed in particles per energy-per-nucleus since the difference between kinetic and total energy is negligible. Also a total cosmic ray energy spectrum

Figure 1.1: Fluxes of cosmic ray nuclei in particles per energy-per-nucleus plotted versus kinetic energy-per-nucleus. The fluxes of He nuclei and beyond are scaled. The inset shows the H/He ratio at constant rigidity, i.e. at energies chosen such that both particles have the same dynamics in a magnetic field. Reprinted from [3].

Figure 1.2: The all-particle spectrum as a function of energy-per-nucleus from air shower measurements. The spectrum is scaled with $E^{2.6}$ to emphasize the knee, second knee and ankle. Reprinted from [3].

instead of individual components is shown since it is difficult to identify the primary particles. Figure 1.2 shows the all-particle cosmic ray energy spectrum multiplied with a factor of $E^{2.6}$ to emphasise the structure in the spectrum. Several features exist. First, there is the steepening of the spectrum between 10^{15} and 10^{16} eV, known as the ‘knee’. A ‘second knee’ occurs around 10^{17} eV. Next, there is a change in the spectrum at $10^{18.5}$ eV. This is known as the ‘ankle’. Finally, there is the drop at the highest energies. The features in the spectrum are interpreted in terms of different cosmic ray origins.

1.1.1 Solar system

Cosmic rays with energies below 10^{10} eV are either produced by the Sun or modulated by the heliospheric magnetic field [4]. Cosmic rays produced by the Sun are referred to as solar energetic particles (SEP) [5]. They consist of electrons, protons and heavier nuclei, and are produced in solar flares and coronal mass ejections. The latter are able to produce the highest energy SEPs with energies up to several GeV. The scientific field of ‘space weather’ concerns the production and propagation of SEPs in the heliosphere.

The Sun produces a plasma consisting of electrons, protons and Helium nuclei with energies in the order of several keV. This stream of charged particles is known as the solar wind [6]. Embedded within this solar wind is the heliospheric magnetic field. The conduction fluid, i.e. solar wind, in the magnetic field of the Sun induces electrical currents which generates magnetic fields. The heliosphere is the cavity formed by the solar wind within the interstellar medium. The solar wind is turbulent and changes in position and time. When cosmic rays encounter the heliospheric magnetic field their flux may be altered. This results

in time-, space-, energy- and particle-dependent variations of the galactic cosmic ray flux. For higher energy cosmic rays ($> 10^{10}$ eV) the heliospheric magnetic field does not affect the particles significantly. The two Voyager spacecraft have left the heliosphere and entered the interstellar medium [7, 8]. Their measurements confirmed the existence of transitions of the solar wind; the termination shock phase in which the plasma is dominated by the supersonic solar wind, the heliosheath in which the solar wind slows from supersonic to subsonic speed and the heliopause, i.e. the beginning of interstellar space.

Also the Earth has its own magnetic field. Charged particles mainly originating from the solar wind but also from cosmic rays are captured by this magnetic field and get trapped in one of the two Van Allen radiation belts [9]. The inner belt mainly consists of electrons with energies in the range of hundreds of keV and of energetic protons with energies in the MeV range. Protons with energies < 50 MeV are trapped SEPs. Higher energy protons originate from the decay of neutrons produced by cosmic rays interacting with the upper atmosphere. The outer belt mainly consists of energetic electrons (0.1-10 MeV).

1.1.2 Galactic cosmic rays

Cosmic rays with energies between 10^{10} eV and 10^{18} eV are considered to be of galactic origin [10]. Below 10^{14} eV the composition of the cosmic rays is measured by balloons and spacecraft (fig. 1.1). Figure 1.3 shows the elemental abundances of cosmic rays (160 MeV per nucleon) [11] compared to solar system abundances as determined from the Sun's photosphere and meteorites [12]. The nuclei with an even charge are more tightly bound and thus more abundant. The elements below carbon (Li, Be and B) and below iron (Sc, Ti, V, Cr and Mn) are only sparsely produced in stellar nucleosynthesis. Their abundance in cosmic rays is because these elements are produced as spallation products of higher mass elements interacting with interstellar matter. The ratio of these spallation products to the original cosmic rays, for example B to C, carries information on the amount of interstellar matter traversed during propagation. Analogously, the ratio of radioactive cosmic rays to their decayed counterparts, e.g. ^{10}Be to ^9Be , can be used to probe the escape time of cosmic rays in the galaxy. This is further described in [1].

Due to the randomly oriented magnetic fields in the galaxy ($\sim 3 \mu\text{G}$ [1]) the paths of cosmic rays are very stochastic in nature. Cosmic ray measurements such as spallation and radioactive decay ratios as well as features in the cosmic ray energy spectrum are interpreted in terms of propagation models (e.g. the leaky-box model [1] or the diffusion model [15]). The GALPROP computer program [16] is the current standard to describe cosmic ray propagation in the Galaxy. The study of cosmic ray propagation in the Galaxy is reviewed in [16].

Sources for galactic cosmic rays are astrophysical objects in which particles are accelerated. The first suggestion for cosmic ray acceleration was given by Enrico Fermi in 1949 [17]. The Fermi acceleration mechanism is based on particles moving through magnetic clouds. On average, per encounter some macroscopic kinetic energy of moving magnetised plasma is transferred into the particle. The energy gain is proportional to the initial energy $\Delta E = \epsilon E$. The probability to escape from the acceleration region is P_e . Then, after N encounters, this

Figure 1.3: Relative abundance of elements in the Solar system and cosmic rays. The relative abundances are normalized (Si = 1000). The nuclei with an even charge are more tightly bound and thus more abundant. The cosmic ray nuclei below carbon (Li, Be and B) and below iron (Sc, Ti, V, Cr and Mn) are produced as spallation products of higher mass elements interacting with interstellar matter. Data from [11, 12, 13, 14].

becomes $E_n = E_0(1 + \epsilon)^n$. The number of encounters needed to reach energy E is

$$n = \frac{\ln(\frac{E}{E_0})}{\ln(1 + \epsilon)} \quad (1.2)$$

The number of particles that gain more energy than E is then given by

$$N(> E) \propto \sum_{m=n}^{\infty} (1 - P_e)^m = \frac{(1 - P_e)^n}{P_e} \quad (1.3)$$

Substitution with equation 1.2 gives

$$N(> E) \propto \frac{1}{P_e} \left(\frac{E}{E_0} \right)^{-\gamma} \quad (1.4)$$

with

$$\gamma = \frac{\ln(\frac{1}{1 - P_e})}{\ln(1 + \epsilon)} \approx \frac{P_e}{\epsilon} = \frac{1}{\epsilon} \times \frac{T_c}{T_e} \quad (1.5)$$

here a characteristic time for an acceleration cycle T_c is introduced as well as the characteristic time to escape from the acceleration region T_e (the division is interpreted as a probability). This mechanism produces a power law spectrum of energies. However, as Fermi already pointed out [17], the energy gain ϵ is proportional to the square of the cloud's velocity $\beta^2 = v^2/c^2$. This means that the acceleration takes a long time and is inefficient.

Figure 1.4: Hillas plot (1984) showing potential cosmic ray acceleration sites. Objects beneath the lines cannot accelerate protons (solid) or iron nuclei (dashed) to 10^{20} eV. β refers to the velocity of the shock front. Depending on their size and magnetic field strength astrophysical objects occupy different places in the diagram. Reprinted from [19].

Although Fermi was not able to explain the high cosmic ray energies, he was the conceptual father of the general idea of acceleration mechanisms. In the 1970s, his mechanism was modified for astrophysical shock fronts (e.g. [18]). In this ‘diffusive shock acceleration’ (also known as ‘first order Fermi acceleration’) the particle gains energy not on average, but in every encounter. The energy gain ϵ is now proportional to the shock’s velocity $\beta = v/c$. The strong shocks present in supernova remnants are thought to be good candidates for the sources of galactic cosmic rays.

The maximum energy from diffuse shock acceleration is [1]

$$E_{\max} \propto ZBR \quad (1.6)$$

with the magnetic field strength B , source radius R and nuclear charge of the particle Z . Anthony Hillas used this relation to arrange potential cosmic ray acceleration sites according to their maximum acceleration energy [19]. Figure 1.4 shows the ‘Hillas plot’. Objects beneath the diagonal lines cannot accelerate protons (solid) or iron nuclei (dashed) to 10^{20} eV. A lower $E_{\max}$ corresponds to a lower diagonal line. Also the particle charge (e.g. proton or iron nucleus) affects the position of the line. Depending on their size and magnetic field strength astrophysical objects occupy different positions in the diagram.

The knee in figure 1.2 could be interpreted as being caused by most galactic accelerators having reached their maximum energy for protons. In this scenario heavier cosmic rays reach

their maximum at higher energies leading to a steepening of the cosmic ray energy spectrum [20]. This interpretation is supported by findings of the KASCADE-Grande experiment [21]. It measured a transition of the cosmic ray composition towards heavier elements [22] and a second steepening of the spectrum (second knee). The knee could also indicate a reduced efficiency of the galactic magnetic field to confine the higher energy cosmic rays within the Galaxy [23].

1.1.3 Extra-galactic cosmic rays

Particles with energies beyond 8×10^{18} eV stem from extra-galactic sources [24]. The cosmic ray energy spectrum slightly below this energy shows a change in power law (ankle). It is often interpreted as the transition to extra-galactic cosmic rays [1]. As super nova remnants can accelerate protons to a maximum of $\sim 10^{15}$ eV and iron nuclei to $\sim 3 \times 10^{16}$ eV [1], a second Galactic source is needed to explain the region from the second knee to the ankle [25]. Alternatively, extra-galactic cosmic rays may already occur at $\lesssim 10^{17}$ eV. In this case the ankle could be explained as a pileup effect: at energies above $\sim 3 \times 10^{18}$ eV (start of the ankle) cosmic rays may start to lose energy due to pair production by cosmic ray protons with the cosmic microwave background (CMB) [26].

The apparent end of the spectrum at $\sim 5 \times 10^{19}$ eV is caused by the energy losses of high energy cosmic rays by photo-pion production and photo-disintegration during propagation in the CMB. This limit was first introduced by Greisen, Zatsepin and Kuzmin [27, 28] and is known as the GZK cut-off. Alternatively, the end of the cosmic ray energy spectrum can be interpreted as the maximum energy of astrophysical accelerators.

1.2 Cosmic rays in the atmosphere

An extensive air shower can be subdivided into an electromagnetic, hadronic and muonic component. A large fraction of the particles produced after the first interaction are pions. A neutral π^0 decays into gammas which will interact with matter via pair production. The subsequent electron and positron emit gamma radiation due to Bremsstrahlung. The two processes (pair production and Bremsstrahlung) generate the electromagnetic component. The other particles produced in the first interaction proceed in the hadronic component of the shower. Also pions that interact before decaying will most likely remain part of this component. Non-interacting charged pions and charged K mesons decay into muons and neutrinos. Because of their larger mass, the energy loss due to Bremsstrahlung is small compared to electrons. The muons reach sea level relatively unhindered and form the muonic component.

1.2.1 Atmospheric cascade theory

The majority of particles in an air shower are electrons and gammas. Electromagnetic shower theory was developed in the 1930s. Approximations were needed to create an analytical description of the shower phenomenon. Initially, only pair creation and Bremsstrahlung

were considered and ionization losses were neglected. Also complete screening was assumed. This is now known as Approximation A [29, 30, 31]. Later on, also constant ionization losses were included. This theory is known as Approximation B [32, 33]. In both cases Compton scattering is disregarded. Both Approximation A and B are one-dimensional descriptions of the shower phenomenon. After this, numerous physicists (e.g. [34]) worked on the creation of a three dimensional model since pair creation, Bremsstrahlung and Coulomb scattering introduce a lateral spread in the shower particles. In this analytical three dimensional treatment Coulomb scattering was identified as the main source for the lateral spread. The development of the three dimensional description led to NKG (Nishimura, Kamata and Greisen) theory [35, 36, 37, 38] which currently is the standard analytical description of electromagnetic showers.

1.2.2 Monte Carlo cascade simulation

The analytical shower theory is limited by the necessary approximations since a full description involves great mathematical complexity. Using computers and Monte Carlo methods it is possible to overcome these limitations. The first efforts to describe electromagnetic air showers using computers were done in the 1960s [39, 40, 41, 42]. This eventually led to the EGS4 code [43], which is the now widely accepted standard for three dimensional cascade simulations.

A limiting factor of the Monte Carlo method is the quickly rising number of particles for higher energy cascades. This implies that both the computation time and the storage size of the shower grow beyond what is feasible with current computing facilities at universities. In order to reduce the computation time and storage space, but still be able to process high energy showers, so-called thinning or sampling methods are introduced [44]. These methods result in a less precise description of air showers. No such method is used in this thesis.

The hadronic component of the air shower is also simulated with the Monte Carlo method. Hadrons are made of quarks carrying colour charge. Their strong interaction is described by quantum chromodynamics (QCD) whereas quantum electrodynamics (QED) describes the electromagnetic interactions. Hadronic interactions with high momentum transfer (hard interactions) are described by perturbative QCD (pQCD) in combination with the DGLAP (Dokshitzer Gribov Lipatov Altarelli Parisi) framework [45, 46, 47]. Soft interactions are harder to describe. For this, the phenomenological Gribov-Regge theory [48, 49, 50] is applied. Soft interactions are treated by the exchange of one or more Pomerons, representing multi-gluon Feynman diagrams. Inelastic processes (kinetic energy not conserved) are handled by cutting Pomerons. This produces two colour strings per Pomeron which subsequently fragment into hadrons. Hadronisation is handled via Lund strings [51]. Nucleus-nucleus interactions are treated by tracking the participating partons. These phenomenological descriptions are tuned to Large Hadron Collider (LHC) data. This is a difficult exercise since most energetic secondaries escape detection in colliders as the forward cones in which the secondary particles move are not well instrumented. Beyond LHC energies (i.e. cosmic rays with energies beyond $\sim 10^{17}$ eV) extrapolations are used.

Various hadronic interaction models exist for air shower simulations. A short history and some important models are discussed in [52]. For high energy hadronic interactions the QGSJET-II [53] model is selected. Interactions of hadrons with energies below 80 GeV are

simulated using GHEISHA [54]. Electromagnetic interactions are described by the EGS4 [43] model. The models are incorporated as plug-in sub-packages in the COsmic Ray Simulations for KAscade (CORSIKA) program [55].

1.2.3 Atmospheric Muons

If a low energy cosmic ray (e.g. 10^{11} eV) hits the Earth's atmosphere, the air shower dies out before reaching the ground. The majority of EAS particles are absorbed at high altitude. Only energetic remnants, mainly muons, are able to reach ground level. Cosmic rays with energies below $\sim 10^{11}$ eV only result in single muons reaching ground level and no electromagnetic component is left. Because of the large flux of these low energy cosmic rays, there is a large number of isolated muons that reach ground level. The energy and zenith dependence of the muon flux can be derived from the primary cosmic ray flux [1]. Throughout this thesis a parametrisation for the muon flux from [56] is used:

$$I(p, \theta) = \cos^3 \theta \times I_V(p \cos \theta) \quad (1.7)$$

Here p and θ are the muon momentum and zenith angle respectively. The equation relates the flux per zenith angle to the perpendicularly incident muon flux $I_V(p)$ [$\text{cm}^{-2} \text{sr}^{-1} \text{s}^{-1} \text{GeV}^{-1}$]:

$$I_V(p) = c_1 p^{-(c_2 + c_3 \log p + c_4 \log^2 p + c_5 \log^3 p)} \quad (1.8)$$

with $\log$ the base 10 logarithm, $c_1 = 0.00253$, $c_2 = 0.2455$, $c_3 = 1.288$, $c_4 = -0.2555$ and $c_5 = 0.0209$. In the remainder of this thesis the muon energy instead of momentum is used. The rate of energetic muons (energy larger 1 GeV) per surface area is calculated as follows. First, the flux is integrated over all energies above 1 GeV:

$$I_E(\theta) = \int_{1 \text{ GeV}}^{\infty} I(E, \theta) dE \quad (1.9)$$

The flux of perpendicularly incident muons at sea level is $\sim 70 \text{ m}^{-2} \text{s}^{-1} \text{sr}^{-1}$ above an energy of 1 GeV [2]. Next, the flux is integrated over the solid angle:

$$R = \int_0^{2\pi} \int_0^{\pi/2} I_E(\theta) \sin(\theta) d\theta d\phi \quad (1.10)$$

Resulting in a rate of $R = 162 \text{ m}^{-2} \text{s}^{-1}$, or approximately 1 muon per square centimetre per minute.

The total flux of perpendicular incident electrons and positrons above 10, 100 and 1000 MeV is approximately 30, 6 and $0.2 \text{ m}^{-2} \text{s}^{-1} \text{sr}^{-1}$ resp. [2]. The angular dependence is complex because of the different sources of electrons which have different altitude dependencies (e.g. cascades from neutral pion decay at higher altitudes and muon decay or knock-on electrons at lower altitudes). Muon decay is the dominant source of electrons at sea level. The ratio of photons to electrons plus positrons is approximately 1.7 (below ~ 81 MeV, the critical energy at which ionization and Bremsstrahlung energy losses are equal) [2].

The absorption of EAS particles in the atmosphere depends on the atmospheric pressure since it is a measure for the amount of atmosphere the particles have to traverse [57, 58].

The first interaction height is related to the temperature at high altitude as for higher temperatures the atmosphere extends further into space [59]. Also the muon production is related to the temperature since it describes the density at high altitudes. Secondary particles (especially pions) produced in the first interactions can either decay into muons or participate in further interactions. The density steers the decay versus interaction ratio [60, 61]. The pressure and temperature effects are extensively described in [62]. The variation in the muon rate due to the pressure and temperature effects are at the percent and sub-percent level resp. (see e.g. [63]).

1.3 Extensive Air Showers

1.3.1 Longitudinal density profile

Since the density of atmospheric nuclei is not homogeneous (air pressure decreases with altitude) EAS development is not expressed in height above sea level but in the vertical column density of the atmosphere, also known as the atmospheric depth. The atmospheric depth at altitude z is defined as

$$X(z) = \int_z^\infty \rho(r) dr \quad (1.11)$$

with ρ the density of air. The standard atmosphere is defined as 101,325 Pa, i.e. the mass of a column of air from sea level to the top of the atmosphere exerts a ‘weight’ resulting in a pressure of 101,325 N m⁻². Division by the gravitational acceleration (9.81 m s⁻²) gives an atmospheric depth at sea level of 1033 g cm⁻².

The development of an air shower as function of atmospheric depth is known as the longitudinal density profile. The depth at which the shower is at its maximum, i.e. when the number of shower particles is largest, is known as $X_{\max}$. In the electromagnetic ‘approximation B’ description the longitudinal density profile is given by [35]

$$N_e(E_0, E_{\text{crit}}, t) = \left(\frac{0.31}{\sqrt{\ln(E_0/E_{\text{crit}})}} \right) \exp \left(t \left(1 - \frac{3}{2} \ln(s) \right) \right) \quad (1.12)$$

here N_e is the number of electrons and $E_{\text{crit}} = 81$ MeV, i.e. the critical energy at which ionization and Bremsstrahlung energy losses are equal [2]. The age parameter s is given by

$$s = 3t \left(t + 2 \ln \left(\frac{E_0}{E_{\text{crit}}} \right) \right)^{-1} \quad (1.13)$$

with $t = X/\chi_0$ where X is the atmospheric depth and $\chi_0 = 36.66$ g cm⁻² the radiation length in air [52]. In one unit of radiation length an electron loses $(1 - e^{-1})$ of its energy by radiation (Bremsstrahlung). Figure 1.5 shows the longitudinal density profiles for energies from 10¹¹ eV to 10¹⁹ eV (blue lines). The shower maxima occur at $s = 1$. The red dotted lines connect the equal stages of shower development. The shower maximum shifts to larger atmospheric depths for increasing energy.

Figure 1.5: Longitudinal density profiles for energies from 10^{11} eV to 10^{19} eV (blue lines) obtained under approximation B (eq. 1.12). The red dotted lines connect the equal stages of shower development characterized by the age parameters s . At $s = 1.0$ the shower is at its maximum development. The shower maximum shifts to larger atmospheric depths for increasing energy. Recreated from [52].

1.3.2 Lateral density profile

The lateral density profile describes the electron density ρ as function of the perpendicular radial distance from the shower axis. For electromagnetic air showers an analytical expression exists known as the NKG function:

$$\rho(r, N_e, s) = \frac{N_e}{2\pi r_M^2} \left(\frac{r}{r_M} \right)^{(s-2)} \left(1 + \frac{r}{r_M} \right)^{(s-4.5)} \left(\frac{\Gamma(4.5-s)}{\Gamma(s)\Gamma(4.5-2s)} \right) \quad (1.14)$$

with $r_M = 79$ m the Molière radius at sea level [52]. It is the lateral distance an electron of critical energy, E_{crit} , is scattered in traversing a longitudinal distance of one unit of radiation length (height dependent).

Figure 1.6 shows the lateral density profiles at an atmospheric depth of 1033 g cm^{-2} for energies from 10^{14} eV to 10^{19} eV (blue lines). The N_e and s needed in equation 1.14 are obtained from equation 1.12. The highest energy air showers have sizes up to several km. The red dashed lines show the lateral density profiles for 10^{12} eV (bottom) and 10^{13} eV (top) evaluated at an atmospheric depth of 600 g cm^{-2} . At these low energies air showers cannot penetrate deeply into the atmosphere. They can only be detected at high altitude.

1.3.3 Shower front

The EAS shower front is approximately a very thin disc. The thickness of the disc is due to time dispersion of the particles caused by different Lorentz factors and, more importantly,

Figure 1.6: NKG lateral density profiles (eq. 1.14) at an atmospheric depth of 1033 g cm^{-2} for energies from 10^{14} eV to 10^{19} eV (blue lines). The highest energy air showers have sizes up to several km. The red dashed lines show the lateral density profiles for 10^{12} eV (bottom) and 10^{13} eV (top) evaluated at an atmospheric depth of 600 g cm^{-2} . These low energy air showers have died out at large atmospheric depths. They can only be detected at high altitude or if the first interaction height is low.

Figure 1.7: Arrival time distributions of muons (red) and electrons (blue) as function of distance to the shower core obtained from a perpendicular incident 10^{15} eV proton induced EAS simulation (CORSIKA). The arrival time of the first particle at ground level is set to 0 ns. There is an increasingly large delay for particles at larger core distances. Most muons are in the front of the disc whereas the bulk of the electrons arrives later.

different path lengths caused by numerous scattering and decay processes. The latter also causes an increasing thickness of the shower front away from the shower axis (i.e. the extension of the initial momentum vector of the primary cosmic ray). The average energy of the particles decreases with radial distance. The front of the particle disk is curved. At larger distances to the shower core (i.e. the central region) the particles arriving on a plane perpendicular to the shower axis experience an increasingly large time delay with respect to the first particles arriving at the plane (in the shower core).

Figure 1.7 shows the arrival time distributions of muons (red) and electrons (blue) as function of distance to the shower core obtained from a perpendicular incident 10^{15} eV proton induced EAS simulation (CORSIKA). The first arrival time is set to 0 ns. Most muons are in the front of the disc whereas the bulk of the electrons are located further in the arrival time distributions. The shower front is trailed by low energy muons and locally produced scattered electrons.

1.3.4 Detection and reconstruction of EASs

Since it is difficult to cover large footprints with a single detector, EASs are usually sampled by relatively small particle detectors arranged in arrays. Other EAS measuring techniques involving optical Cherenkov, radio or fluorescence detectors are not discussed in this thesis. By reconstructing the EAS, properties of the original cosmic ray can be derived. Examples of sampling experiments are KASCADE (13 m detector separation, $200 \times 200 \text{ m}^2$) [64],

KASCADE-Grande (137 m detector separation, $700 \times 700 \text{ m}^2$) [21], AGASA (1 km detector separation, 100 km^2) [65], Telescope array (1.2 km detector separation, 762 km^2) [66] and the Pierre Auger Observatory (1.5 km detector separation, 3000 km^2) [67].

To obtain the energy and mass of the primary cosmic ray from direct observables such as particle densities and particle arrival times of EAS footprints, a realistic simulation of the entire air shower process, including the detector response, is indispensable. The most reliable reconstruction methods compare and match the simulation results with measured experimental data. The accuracy and completeness of the simulations is thus equally important as the experimental data. Unfortunately, many of the fundamental processes and their energy dependence are not well known. At the highest energies, uncertainty on the EAS reconstruction is currently dominated by the accuracy of the hadronic interaction models.

A straightforward approach to obtain the EAS energy, and therefore the primary cosmic ray energy, is to fit a lateral density profile to the particle densities sampled by the detector array. The particle density at several hundred meters from the shower core is almost independent (within about 20%) of the particle production mechanisms and the cosmic ray mass at fixed energy [52]. Because of this, the particle density at some radial distance (i.e. 600 m) can be used to probe the energy of the EAS. For example, at the Akeno Giant Air Shower Array (AGASA) a NKG-like lateral density profile was used [68]:

$$S(r) \propto \left(\frac{r}{r_M}\right)^{-1.2} \left(1 + \frac{r}{r_M}\right)^{-(\eta-1.2)} \left[1 + \left(\frac{r}{1000}\right)^2\right]^{-0.6} \quad (1.15)$$

with distance to the shower core r in meter, $\eta = 3.84$ and Molière radius $r_M = 91.6 \text{ m}$. The determination of the particle densities is, however, not trivial and comes with uncertainties due to random sampling (Poisson). The energy associated with a lateral density profile is given by [69]:

$$E = a \cdot 10^{17} \cdot (S(600))^b \quad [\text{eV}] \quad (1.16)$$

with $a = 2.03$ and $b = 1.0$.

Reconstruction of the primary mass is more complicated. As the binding energy per nucleon of cosmic ray nuclei is much smaller than their typical interaction energies, a nucleus of mass A can be considered as A independent nucleons. This ‘superposition model’ leads to two predictions. At the same primary energy, more muons are generated by heavier cosmic ray nuclei than by protons. Secondly, heavier cosmic ray EASs develop faster than proton induced showers, leading to a shallower depth of the shower maximum (higher X_{max}) [52]. The primary mass composition can thus be probed by measuring the muon to electron number ratio. Additionally, measurements of curvature of the shower front can be used as interactions at high altitude yield flatter shower fronts.

1.4 Aims of this thesis

This thesis is about the scientific exploitation of a widespread, irregular EAS detection array called HiSPARC. It is a collaboration of universities, scientific institutes and high schools each hosting their own detection station(s). The majority of the stations is located at high schools. The primary goal of HiSPARC is to engage high school students with modern

physics and let them contribute to real scientific research. In 2001, the Nijmegen Area High School Array (NAHSA [70]) was founded. In 2003 Nikhef initiated the expansion of NAHSA into a nationwide network: HiSPARC. The geometry of the array is determined by the location of the collaborating institutions. This has lead to an irregular grid of detection stations. Irregular arrays of cosmic ray detectors are not new, e.g. LAAS [71], SEASA [72], CHICOS [73], and more recently, EEE [74]. The latter three projects have a strong education component involving high schools as well.

The scientific goal of HiSPARC is to investigate the use of small EAS detection stations for cosmic ray research. Multiple of these independently operating HiSPARC stations are combined and function as traditional EAS detection arrays. Also the research possibilities of a single station are examined in this thesis. The HiSPARC experiment is first introduced in chapter 2. The next two chapters involve the description of the HiSPARC detectors and stations. The direction and energy reconstruction capabilities of a station are discussed in chapter 4. Chapter 5 introduces a new method to probe the cosmic ray energy flux at energies previously inaccessible from sea level using a single station. Multiple HiSPARC station are combined in chapter 6. Here the energy reconstruction based on lateral density profiles is discussed. In chapter 7 the entire HiSPARC array is shown to detect meteorological phenomena. Finally, in chapter 8, a HiSPARC station is used to probe the interior of a steel blast furnace using muon tomography.

Chapter 2

The HiSPARC experiment

The High School Project on Astrophysics Research with Cosmics (HiSPARC) [75] has approximately 140 detection stations distributed throughout the Netherlands, United Kingdom and Denmark (figure 2.1), and Namibia. HiSPARC is a collaboration of universities, scientific institutes and high schools each hosting their own detection station(s). The majority of the stations is located at high schools. HiSPARC has a strong outreach component. Stations are maintained by high school teachers, their students and university staff. Data are stored at Nikhef, the Dutch National Institute for Subatomic Physics [76]. A number of HiSPARC stations also employs a weather station. Their data are stored in the central database at Nikhef as well. Weather stations are used to analyse atmospheric conditions affecting EAS development.

HiSPARC detection stations are relatively robust, cheap, small and straightforward to assemble. Single (remote) stations are mainly used for educational purposes and to provide local measurements of the single muon flux, EAS flux and EAS directions. Clusters of stations can be used for more advanced EAS reconstruction.

2.1 Scintillation detector

The detection philosophy of HiSPARC is to sample EAS footprints using scintillation detectors. The light output of a scintillator is proportional to the number of charged EAS particles traversing the detector.

A scintillator (100 cm x 50 cm x 2 cm), see A in Figure 2.2, is glued to a slightly thicker triangular light-guide (base 50 cm, top 2.5 cm, height 67.3 cm, B) which is connected to a photomultiplier tube (PMT, D) via a small adapter light-guide (C). Both light-guide (polymethylmethacrylate or PMMA) and scintillator have comparable refractive indices (1.49 and 1.58 resp.). The scintillation material [77] has a light attenuation length of 380 cm. The wavelength of maximum emission is 425 nm. The surfaces of the scintillator and light-guides are diamond polished to achieve a high surface reflectivity. The detector is wrapped in aluminium foil (thickness 30 μm) and is made light-tight with black pond liner (thickness 0.45

Figure 2.1: Layout (early 2019) of the HiSPARC array. Each red dot represents one or more stations.

Figure 2.2: Sketch of the HiSPARC detector. The scintillator and light-guide are denoted by the letters A and B resp. The light-guide adapter piece (C) enables the cylindrical PMT (D) to be mounted to the square end of the light-guide.

mm). The assembly is placed inside a roof box (fig. 2.3).

2.1.1 PMT

When a charged particle traverses the scintillator, it loses energy. Apart from radiative energy loss, the particle primarily loses energy due to inelastic collisions with the atomic electrons of the scintillation material. Multiple molecules will be excited. These molecules will quickly return to their ground state and emit photons. The wavelength of the scintillation photons matches the wavelength characteristics of the PMT [78, 79]. The photons may scatter several times inside the detector and only a fraction will reach the PMT. Figure 2.4 shows a typical PMT output signal. The analogue signal is sampled by an ADC in 2.5 ns bins. The area under the curve, or pulse integral, is a measure for the number of scintillation photons that have reached the PMT. The pulse integral is then calculated by summing the ADC values for each bin exceeding -10 mV (dotted line in fig. 2.4).

Figure 2.3: The HiSPARC detector inside a roof box.

HiSPARC deploys PMTs with a cathode diameter of 25 mm. The 12 cm long glass tube is enclosed by mu-metal, providing shielding against external magnetic fields. The PMT-base is supplied with a DC voltage of -12 V which is converted into a DC voltage ranging from -300 to -1500 V. The quantum efficiency at 425 nm is typically 25%. Two different types of PMT bases are used. A commercial one [80] and an in-house developed version [81]. The Nikhef base provides a highly linear response over a large dynamic range, allowing to generate signals well in excess of -5 V (fig. 2.5, red crosses). The rise-time is almost independent of the output signal amplitude. The impedance of the line driver, cable and subsequent readout electronics have been matched. The dynamic range of the commercial base is limited (fig. 2.5, blue dots). The response curves were measured with a device containing 24 LEDs (light-emitting diodes) [82]. The LEDs were connected to the PMT using optical fibres. The pulsed light-output of each single LED was measured with the same PMT. Higher light intensities were obtained by bundling optical fibres. Figure 2.5 shows that for small intensities both PMT assemblies behave linearly but at higher intensities the output flattens for the commercial base. The response of the PMT assemblies can be parametrised with a single function:

$$f(x) = \frac{ax}{(x^b + c)^{\frac{1}{b}}} + dx \quad (2.1)$$

with $a = 0.237$, $b = 13.5$, $c = 9.34 \cdot 10^4$, $d = 0.918$ for the Nikhef base and $a = 1.42$, $b = 2.74$, $c = 4.13$, $d = 0.150$ for the commercial base. For $x < c^{\frac{1}{b}}$ the left term is approximately $(a/c^{\frac{1}{b}})x$ whereas for $x > c^{\frac{1}{b}}$ the left term approaches a (constant).

As atmospheric conditions change, the temperature of the PMT assembly can vary between -30°C on cold winter nights and $+60^\circ\text{C}$ when the Sun heats the air in the roof box. Temperature differences affect the height of the signal pulse. For the commercial base a higher temperature results in a lower gain. The Nikhef base shows a higher gain at higher temperatures. To arrive at a proper measure for the pulse height, temperature variations need to be taken into account.

The value of the pulse height corresponding to 1 MIP is derived from EAS data as a function

Figure 2.4: Example of a typical signal with a pulse height of 150 mV. The FWHM is ~ 25 ns. The pulse integral is calculated by summing all values in the bins where the signal exceeds -10 mV (dotted grey line). The default trigger thresholds are -30 and -70 mV (dashed grey lines).

Figure 2.5: Response of two HiSPARC PMT assemblies with different bases. On the horizontal axis the emulated pulse height (the combined pulse intensity of multiple LEDs) is shown. The vertical axis shows the measured pulse height (mV). The blue dots indicate the response for the commercial base whereas the red crosses show the pulse heights for the Nikhef base. Both response curves can be well described by the expression in eq. 2.1. The black line indicates an ideal linear response. Up to about -0.7 V both assemblies give a linear response.

Figure 2.6: Correlation between temperature and MIP-peak value for a PMT with a commercial base. The temperature was measured inside the roof box with a scale uncertainty of 0.5°C . The temperature and MIP-peak value were determined by averaging over 4-hour periods. There is a clear trend between the MIP-peak value and the local temperature.

of temperature. The height of the MIP peak is averaged over short periods in time (4 hours) and is used to calibrate the PMT output signal. Figure 2.6 gives an example of the correlation between temperature and MIP-peak value for a commercial assembly. Of order 1000 events are collected within 4 hours. A smaller time window results in a less accurate determination of the MIP-peak value. Alternatively, a method can be applied using a running average.

2.1.2 PMT calibration using experimental data

The response curves of a set of PMTs have been determined using the LED device. The PMT behaviour, however, can also be deduced from experimental data. Figure 2.7 shows three PMT pulses; one generated by a PMT with a Nikhef base (red dots) and two generated by a PMT with a commercial base (black dots and stars). Their pulse integrals (see fig. 2.4) are 70 Vns and 100 Vns. Because of the different amplifier in the commercial base with respect to the Nikhef base, the signals get spread out in time, decreasing the pulse height. This is also shown by the 100 Vns pulse; the height only increases marginally whereas the width of the pulse changes significantly. If the current coming from the PMT's anodes is assumed to be constant irrespective of PMT base, the pulse integral is an accurate measure for the amount of scintillation light arrived at the PMT.

The pulses can be described by a log-normal equation [83]:

$$U(t) = g \cdot \exp\left(-\frac{1}{2} \left(\frac{\ln(t/\tau)}{\sigma}\right)^2\right) \quad (2.2)$$

Figure 2.7: Log-normal parametrisation (solid lines) fitted to PMT pulses generated by a commercial base (black dots and stars) and a Nikhef base (red dots). Because of the different amplifiers in both bases, pulses with the same pulse integral (70 Vns) have different pulse heights and widths. Increasing the pulse integral for the commercial base (e.g. 100 Vns, black stars) only yields a slightly larger pulse height whereas the width of the pulse increases significantly.

with g the gain in V, τ a measure for the rise time in ns and σ a measure for the width of the pulse. The fits are shown by the solid lines in figure 2.7. The fit parameters are used to describe the behaviour of the PMT base. Figure 2.8 shows the fit parameters as function of the pulse integral for four PMT assemblies. Two have a Nikhef base (red and green dots) and two have a commercial base (black and blue dots). For the Nikhef bases, the parameters stay constant or perform linearly. For the commercial bases, however, the behaviour is somewhat chaotic. The pulse integral can be estimated from the fit parameters:

$$\text{PI} = \int_0^\infty U(t) dt = \sqrt{2\pi} g \sigma \tau \exp\left(\frac{\sigma^2}{2}\right) \quad (2.3)$$

The g parameter scales with the pulse height. By using the MIP-peak (see chapter 3.1) to relate the pulse integral to an inferred pulse height, the PMT response curve can be derived. Figure 2.9 shows the pulse height as function of inferred pulse height for the four PMT assemblies. The parametrisation in equation 2.1 has been fitted to the curves with the commercial bases (solid blue and black lines). The Nikhef base response curves are linear. If the pulse is larger than the dynamic range of the ADCs (dash-dotted line), the fit quality of equation 2.2 to the pulse deteriorates. This is reflected by the change of the slope above ~ 2.4 V. The deviation from perfect linear behaviour (dashed line) may be due to uncertainty in the conversion from pulse integral into inferred pulse height using the MIP-peak.

Figure 2.8: Fit parameters of the log-normal parametrisation as function of pulse integral. Four PMTs are shown: two with a Nikhef base (red and green dots) and two with a commercial base (black and blue dots). For the Nikhef bases, the parameters stay constant or behave linearly. For the commercial bases, however, the behaviour is somewhat chaotic. The dashed line in the upper left plot indicates the dynamic range of the read-out electronics (ADC). If the g value is larger than this line, the fit is less constrained since a large fraction of the pulse lies outside the dynamic range.

Figure 2.9: The g parameter as function of the inferred pulse height. The MIP-peak in pulse integral values is related to the MIP-peak in pulse height values. Using this relation a pulse height can be inferred from a pulse integral. For four PMT assemblies the response curves are shown. The parametrisation in equation 2.1 has been fitted to the curves with the commercial bases (solid blue and black lines). The Nikhef base response curves are linear. If the pulse is larger than the dynamic range of the read-out electronics (dash-dotted line), the fit quality of equation 2.2 to the pulse deteriorates. This is reflected by the change of the slope above ~ 2.4 V. The deviation from perfect linear behaviour (dashed line) might be due to uncertainty in the conversion from pulse integral into inferred pulse height using the MIP-peak.

Figure 2.10: Typical configuration of a two-detector station. A GPS antenna is located between the two detectors and provides a signal to timestamp the arrival time of the EAS particles.

2.2 HiSPARC station

A HiSPARC station combines two or four detectors with the aim to distinguish EASs from single background muons. Since the arrival times of particles in an EAS are highly correlated, this is achieved by demanding a response in two or more detectors within a small time window.

The layout of a HiSPARC station with two detectors is shown in Figure 2.10. The majority of high schools deploy a two-detector station. Four-detector stations come in two different layouts; a diamond formation (figure 2.11) and an equilateral triangle with one detector at the centroid of the triangle (figure 2.12). When at least three detectors in a four-detector station observe one or more particles of an EAS, the direction of the EAS (and thus the direction of the primary cosmic ray) can be obtained by triangulation. When only two detectors are hit, as for a two-detector station, the time difference between the two detectors only allows for the reconstruction of the arrival direction in the vertical plane perpendicular to the axis that connects the two detector centres.

Changes in atmospheric pressure are of importance; the higher the pressure, the higher the probability for a (low energy) shower particle to be absorbed before reaching the ground. Consequently, this will affect the size of the footprint. The pressure also influences at which height the first interaction occurs. Currently, 19 HiSPARC stations are equipped with a weather station [84]. The weather station data is timestamped with the GPS.

2.2.1 Read-out electronics

Detectors are connected to read-out electronics by cables with a standard length of 30 m. The custom designed electronics control and read out two PMTs (figure 2.13). One electronics unit facilitates two detectors. For a four-detector station two units are connected in Master-Slave configuration. All four detectors are treated exactly the same. Their signals can be used to construct a matrix of trigger conditions.

The digitisation of the analogue input signal is carried out by two 12 bits, 200 MHz analogue-to-digital converters (ADCs). One ADC is triggered at the rising edge of the clock, the other

Figure 2.11: Four detectors placed in a diamond formation.

Figure 2.12: Four detectors placed in a triangle formation with the fourth detector at the centroid.

Figure 2.13: Front (top) and back (bottom) of the HiSPARC readout unit. Two PMTs are connected to the front of the unit and supplied with +12 V DC and a reference voltage. In the PMT-base, this reference voltage (+0.3 to +1.5 V) is converted into a high voltage (-300 to -1500 V). An orange LED next to the signal input flashes when the input signal (-10.3 to $+0.3$ V) exceeds the lower threshold. A white LED behind the air outlet (centre) flashes when a trigger condition is met. At the back of the unit there are connectors for the 1.5 A 12 V DC power supply, GPS antenna cable and USB port for monitor and control of the GPS unit. At the far left there is a USB connector for data output. Two UTP ports facilitate the communication between Master and Slave units. There is also an input for an (+3 V) external trigger. The ADCs are set to a dynamic range of -2.2 V to $+0.1$ V. The maximum trigger rate is in excess of 30 events per second.

ADC at the falling edge, thus doubling the sampling frequency to 400 MHz, i.e. at 2.5 ns intervals. A calibration procedure (ADC ‘alignment’) ensures that both ADCs yield the same baseline, gain and dynamic range ($\sim +0.1$ V to ~ -2.2 V or 0 - ~ 15 MIPs). For larger signals two comparators with adjustable threshold (default at -2.5 V (~ 17 MIPs) and -3 V (~ 20 MIPs) resp.) are added. The comparator data significantly improve the offline reconstruction of large signals that exceed the dynamic range of the ADCs [85].

The output of the ADCs is transferred into embedded memory in a field-programmable gate array (FPGA). The FPGA is clocked at 200 MHz as well. Per channel two thresholds can be defined: a low threshold and a high threshold. The FPGA raises flags when a signal exceeds a threshold. Combining flags (AND/OR) for up to four detector channels provides an extensive matrix of trigger conditions. For test purposes the unit has a separate external trigger input that can be combined with this trigger matrix. Figure 2.14 gives an example of how a trigger condition for a two-detector station is generated and how an event is composed.

Assume the trigger condition is defined such that both detectors have to generate a signal that exceeds the low threshold within a limited amount of time. The time window has to be large enough to be fully efficient for detecting particles belonging to the same EAS (with different arrival times, covering all possible angles of incidence of the shower), while it has to be small enough to minimize the random number of coincidences between background muons. In the figure a first flag is raised when detector 1 generates a signal that exceeds the low threshold (channel 1) – the signal may also be large enough to raise the flag for exceeding the high threshold –. At the same time a ‘coincidence’ time window is opened. The length of this time window is typically of order $1.5\text{ }\mu\text{s}$. If during the $1.5\text{ }\mu\text{s}$ the second detector also generates a signal that exceeds the low threshold, the trigger condition is met and an event is generated. An event consists of data taken just before the coincidence window was opened (the pre-trigger time window, typical length $1\text{ }\mu\text{s}$), the coincidence time frame ($1.5\text{ }\mu\text{s}$) and post-trigger period; the post-trigger time window ($3.5\text{ }\mu\text{s}$).

The maximum length of an event window is $10\text{ }\mu\text{s}$ ($= 2000$ 12 bit ADC samples = 3kB memory). Per detector channel, the maximum event size becomes 6 kB. The (embedded) memory may contain multiple events (maximum 3 for the time windows defined above) and acts as a de-randomizing buffer. Events are transferred from the FPGA’s embedded memory into a USB buffer from where they are read by the DAQ PC. If the internal memory is full and the USB buffer is not read out fast enough, new events are discarded until an event is transferred to the DAQ PC. In practice, the trigger rate remains below 1 Hz for all three station layouts. The probability that a fourth event immediately occurs after three consequent triggers ($18\text{ }\mu\text{s}$) is negligible.

A small GPS module [86] is mounted on top of the electronics mother board. It generates one second ‘tick marks’ that are sent to the FPGA that generates a separate message for the DAQ software. Each second a counter is started that counts until the trigger flag is raised or the next one second information arrives. In addition to the one second information (in ns) and value of the counter, the message also includes the number of GPS satellites and their signal strength. The DAQ software combines three one second messages, the counter values for the intervals and GPS quantisation error to calculate the precise time stamp of an event. In a four-detector station a ‘Slave unit’ is connected to the ‘Master’. Both Master and Slave contain the same electronics and FPGA firmware. However, the Slave unit has a motherboard without GPS module. By connecting the two units (figure 2.13), the trigger

Figure 2.14: A schematic representation of an event in a two-detector station. Dashed vertical lines: the pre-trigger ($1\text{ }\mu\text{s}$), coincidence ($1.5\text{ }\mu\text{s}$) and post-trigger ($3.5\text{ }\mu\text{s}$) windows. Shaded area: the data-reduction window. Data outside this window will not be stored. The dotted lines indicate the low and high threshold values.

matrix is extended to four channels. The individual Master and Slave messages are combined by the DAQ software to produce the full event. Each second and for all channels, also the number of times a signal exceeds the high and/or low threshold is recorded. This is referred to as the 'singles rate'.

There exist two versions of the electronics. They have the same functionality. The HiSPARC II unit has an on-board memory chip that contains firmware that is loaded into the FPGA at power-up. The HiSPARC III box has an additional USB channel via which the DAQ software transfers the firmware to the FPGA at start-up / reset.

2.2.2 DAQ software

To control the electronics unit and to monitor the data, software with a graphical user interface based on LabVIEWTM[87] has been developed that executes on a WindowsTMPC. A screenshot of one of the interface panels is shown in figure 2.15. Typical pulse height distributions for a four-detector station are shown in the central graph. On the right the pulse integral distributions are displayed. With a typical pulse length of 30 to 50 ns (fig. 2.4) a zero-suppression algorithm is applied to reduce the event size.

The DAQ software also performs a preliminary analysis of the data. The baseline (which is also used by the zero suppression algorithm) and the fluctuation of the baseline are recorded. Subsequently, the pulse height and pulse integral are calculated. The software also keeps track of the number of accessible GPS satellites and their signal strength over time.

The DAQ software stores the raw data from the electronics unit(s) combined with the first analysis results into a local MySQL [88] database. A Python [89] program monitors the number of written events and uploads the data at regular intervals to the data-store server at Nikhef.

The Nagios [90] software package is used to monitor the status of both hardware (electronics and PC) and DAQ software for each station. In case a service fails an e-mail is generated and automatically forwarded to the person responsible for the station with the request to intervene. To avoid down time during weekends and (long) high school (summer) breaks, Nikhef operates an OpenVPN [91] network that provides remote access to each station (TightVNC [92]). This network is also used to install software updates.

2.2.3 Timing offsets

Assuming that the distribution of the angle of incidence of EASs is isotropic, each detector of a two-detector station has about equal probability to be hit first. Figure 2.16 shows the (arrival) time differences between two detectors in a two-detector station (station #4). About 8×10^5 events were collected between the 5th of March and the 2nd of April 2018. The shift of the peak with respect to the dashed line at 0 ns shows an average timing offset between the two detectors of 12 ns. A plateau (blue horizontal line) is reached for offsets large than ~ 300 ns. This is the result of random coincidences, i.e. two uncorrelated particles, a particle and a spontaneous emission in the PMT etc. The height of the plateau is obtained by making a fit for offsets between 300 ns and $1.5 \mu\text{s}$ (default coincidence time window). The expected number of random coincidences per second (N) can be calculated with $N = 2\tau r_1 r_2$. τ is the coincidence time window and r_1 and r_2 are the recorded singles rates in the detectors. Integration over the full length of the plateau region yields 3.21×10^5 events. This is well in agreement with the estimated number of random coincidences: 3.17×10^5 . Note that the number of random coincidences within a time difference of 300 ns (blue crossed region) is small.

The arrival time differences between detectors of a four-detector station are shown in figure 2.17. Station #501 (diamond formation, fig. 2.11), recorded 3.1×10^5 events from the 1st of January till the 1st of March 2018. Only time differences in events for which all four detectors generated a signal exceeding the low threshold are considered. The random coincidence plateau is absent. The probability that four random signals coincide within $1.5 \mu\text{s}$ is thus very small. The timing offset in detector combinations 1-2 (blue) and 1-4 (green) show almost identical distributions. The distance between the detectors in the two pairs is the same. The distance between detectors 1 and 3 is larger as they lie along the diagonal of the diamond. The time offset distribution for this combination (in red) is therefore slightly broader.

For each station the timing offsets are calculated and stored on a daily basis. They are important parameters in for instance the direction reconstruction of an EAS.

2.3 Clusters of stations

A HiSPARC cluster is a collection of stations. The surface that the cluster covers often depends on the number of stations that a high school hosts and/or how many high schools there are in the neighbourhood. For extensive research a dense cluster at the Amsterdam Science Park is created (fig. 2.18). The Science Park cluster contains thirteen four-detector stations. The distance between the stations varies from ~ 1 m up to 280 m. Several stations

Figure 2.15: Screenshot of a panel in the HiSPARC DAQ control and monitor user interface. The top three histograms show (from left to right) the number of signals above threshold in an event for each detector, the pulse heights and the pulse integral distributions resp. The bottom control panels set the PMT high voltage for Master (left) and Slave (2nd from right). The other panels display singles rates for signals exceeding low and high thresholds. Additional tabs (visible at the top of the screenshot) include event settings, status and error messages, and display GPS data.

Figure 2.16: Timing offset between two detectors in a two-detector station (in red). The plateau (blue horizontal line) is due to random coincidences (uncorrelated particles, PMT noise etc.). For time differences smaller than 300 ns (blue crossed region) the random coincidences are indistinguishable from air shower coincidences. Their contribution is however small.

Figure 2.17: Timing offsets between detectors in a four-detector ‘diamond’ station. Only events in which all detectors generated a signal exceeding the low threshold are taken into account. There is no plateau due to the small probability that a random coincidence occurs between all four detectors. The distance between detectors 1 and 2, and detectors 1 and 4, are equal and show an almost identical time offset distribution (in blue and green resp.). The distance between detectors 1 and 3 is larger; they lie along the diagonal of the diamond. The time difference distribution (in red) is therefore slightly broader.

Figure 2.18: Location of stations at the Amsterdam Science Park cluster. One of the stations is located inside the Nikhef building and is not on the map. Each red dot represents a detector and each combination of four dots forms a station. There are diamond and triangle shaped station configurations. At one location, four ‘diamond’ stations are essentially positioned ‘on top of each other’ (stations shifted ~ 1 m with respect to each other) and only a single station is displayed (blue stars).

may sample the same (large) EAS while each station generates its own GPS time stamp. To reconstruct the angle of incidence of the primary cosmic ray the arrival time of EAS particles in each station has to be precisely known. This implies that it is crucial to account for time offsets between GPS modules.

2.3.1 GPS timing

Each GPS is operated in ‘overdetermined clock mode’ and is at a fixed location. Upon installation, the GPS receiver performs a 24 hour self-survey to accurately determine its position which, in turn, also provides the absolute coordinates for the detectors of that station. The precision of the self-survey is investigated by performing multiple self-surveys using various combinations of GPS antennas, cables and GPS modules (of same type and make). These systematic studies show that 50% of the longitudinal differences stay within 0.73 m, 75% within 1.8 m and 95% within 4.1 m while for the latitude differences are 50% within 0.48 m, 75% within 1.1 m and 95% within 2.6 m. Analysis of the altitude data shows that 50% of the combinations stay within 1.5 m, 75% within 2.8 m and 95% within 6.1 m. The manufacturer of the GPS electronics quotes a 1σ timing accuracy of 15 ns [86]. When combining data from multiple stations in reconstructing an EAS, the precise timing offsets between all stations in a cluster have to be known. By replacing the detectors by stations, the same method can be applied with which the timing offsets between individual detectors

within one station were obtained. Again, the angle of incidence of EASs is assumed to be isotropically distributed; each station has an equal probability to be hit first. The timing offsets between ~ 100 station pairs have been examined. Combining their offsets, a Gaussian distribution with $\mu = 2.7$ ns and $\sigma = 18.9$ ns is obtained. As the distance between the majority of the stations is (much) larger than the distance between the detectors within a station, the rate at which coincidences between stations occur is much smaller than the event rate in a station. Consequently, GPS offsets can usually not be derived on a day-to-day basis due to lack of statistics.

2.4 Data processing

All stations (~ 140) send their data to Nikhef where they are stored in HDF5 [93] format. Each night, a Django [94] web application preprocesses the raw data and generates an event summary database (ESD). The ESD contains information such as the pulse heights and timestamp of an event, detector position and timing offsets, etc. The same application supports direct web access to the ESD. It also provides an application programming interface (API) through which also raw data are publicly accessible.

For data manipulation a Python based module has been developed. The SAPPHiRE (Simulation and Analysis Program Package for HiSPARC Research and Education) [95] facilitates downloading HiSPARC data and performing analyses. It contains an extensive set of EAS reconstruction tools. In addition to the Python module a JavaScript library is developed called jSparc [96]. With jSparc students can work with (or create their own) web applications to explore the HiSPARC data.

The SAPPHiRE (Python) library also forms the basis for a set of Jupyter Notebooks [97]. These notebooks are developed for use in the classroom and for (high school) student research projects.

Chapter 3

Scintillation detector

The HiSPARC detection network is a sparse array of two-detector and four-detector stations. With the limited number of data points the HiSPARC array offers, it is not straightforward to accurately derive air shower properties such as the energy or arrival direction. A highly precise understanding of the HiSPARC equipment is required. For this, extensive simulations have been performed which are compared to experimental data. First, a theoretical description of the energy loss of charged particles in a HiSPARC scintillator is given.

3.1 Energy loss of charged particles

When a charged particle traverses the scintillator it loses energy. Apart from radiative energy loss, the particle primarily loses energy due to inelastic collisions with the atomic electrons of the scintillation material. The inelastic collisions are grouped into soft and hard collisions. The soft collisions only result in excitation of the material. Hard collisions also cause ionization. These ionized electrons are known as δ -rays or knock-on electrons. Just like the original particle, the δ -rays lose energy due to excitation. Multiple molecules will be excited. These molecules will quickly return to their ground state and emit photons. The wavelength of the scintillation photons matches the wavelength characteristics of the PMT. The photons may scatter several times inside the detector and only a fraction will reach the PMT.

Other processes such as elastic scattering from nuclei or Bremsstrahlung will be ignored in the following treatment. Bremsstrahlung, although responsible for a significant part of the total energy loss, creates photons which will leave the detector unhindered and cannot be detected by the PMT because of their incompatible wavelengths. Emission of Cherenkov radiation, albeit a small contribution, is treated separately.

The average energy loss per unit path length due to collisions with atomic electrons is defined as the stopping power. This measure includes excitation, ionization and Cherenkov radiation but does not take radiative energy loss, such as Bremsstrahlung, or nuclear energy loss into account. For heavy particles (i.e. heavy with respect to an electron), in this case

a muon, it is given by the Bethe-Bloch formula [98]:

$$-\frac{dE}{dx} = 2\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A} \frac{z^2}{\beta^2} \left[\ln \left(\frac{2m_e \gamma^2 c^2 \beta^2 W_{\max}}{I^2} \right) - 2\beta^2 - \delta - 2\frac{C}{Z} \right], \quad (3.1)$$

with N_a Avogadro's number, r_e the classical electron radius, m_e the electron mass, c the speed of light, ρ the density of the absorbing material, Z the atomic number of the absorbing material, A the atomic weight of the absorbing material, z the charge of the incident particle in units of e , $\beta = \frac{v}{c}$ of the incident particle, $\gamma = 1/\sqrt{1-\beta^2}$, $W_{\max}$ the maximum energy transfer in a single collision, I the mean excitation potential, δ the density correction and C the shell correction. In the case of HiSPARC $I = 64.7$ eV and $\frac{Z}{A} = 0.54141$ [99]. The maximum energy transfer, $W_{\max}$ is given by:

$$W_{\max} = \frac{2m_e c^2 \beta^2 \gamma^2}{1 + 2\gamma m_e/m_\mu + (m_e/m_\mu)^2}, \quad (3.2)$$

with m_μ the muon mass. The logarithm in the Bethe-Bloch formula has its origin in a non relativistic, non quantum-mechanical approximation known as Bohr's calculation [100]. The $1/\beta^2$ behaviour also follows from this classical calculation and can be interpreted as slower particles feeling the electric force of the atomic electrons for a longer time. The $2\beta^2$ term was later introduced in Bohr's relativistic but still non quantum-mechanical calculation [101]. Bethe [102], Møller [103] and Bloch [104] obtained the correct relativistic and quantum-mechanical formula listed above in equation 3.1.

The δ term denotes the correction for the density effect, first calculated by Fermi [105]. Depending on the density of the detector material, the electric field of the particle polarizes the atoms along its path. Due to this polarization, electrons far from the particle get shielded from the field of the moving particle. Because of this shielding, outer lying electrons will contribute less to the total energy loss. The density correction becomes more important for high energetic particles. The transversal electric field increases because of the Lorentz transform. This makes that the interaction cross section increases. The correction for the density effect is given by:

$$\delta = \begin{cases} 2\ln(\hbar\omega_p/I) + 2\ln(\beta\gamma) - 1 & \text{for } \beta\gamma \geq 100, \\ 2\ln(\hbar\omega_p/I) + 2\ln(\beta\gamma) - 1 + \delta^* & \text{for } 1 < \beta\gamma < 100, \\ 0 & \text{for } \beta\gamma \leq 1, \end{cases} \quad (3.3)$$

With $\hbar\omega_p$ the plasma energy. This equation is analogous to Sternheimer's parametrisation [106]. The δ^* term is described by [99, 107]:

$$\delta^* = 0.46(2 - \log(\beta\gamma))^{2.8} \quad (3.4)$$

The plasma energy is given by [99]

$$\hbar\omega_p = 28.816 \sqrt{\rho \langle Z/A \rangle}. \quad (3.5)$$

The Sternheimer parametrisation is an empirical expression for the density correction, adequate for this treatment. Using a quantum description of the density effect [108] it can be shown that it is responsible for Cherenkov radiation [109]. This means that the Cherenkov contribution is already included in the energy loss calculation.

Finally, the C term stands for the shell correction. If the velocity of the particle is comparable to that of the orbital velocity of the bound electrons, the assumption that the electron is stationary with respect to the incident particle is invalid. The shell correction preserves the validity of the Bethe-Bloch formula for very low energy incoming particles. In the case of HiSPARC, the shell correction is of negligible order [99] and is not taken into account.

For electrons and positrons the Bethe-Bloch formula must be modified. The assumption that the particles are undeflected as they travel through matter is invalid, i.e. large angle multiple scattering does occur. Also, the assumption that each energy loss event is a small fraction of the incident energy is invalid. Finally, with electrons there is scattering of identical particles. Now, also the indistinguishability must be taken into account. This gives the following equation [98]:

$$-\frac{dE}{dx} = 2\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A} \frac{1}{\beta^2} \left[\ln \left(\frac{\tau(\tau+2)W_{\max}}{I^2} \right) + F(\gamma) - \delta - 2\frac{C}{Z} \right]. \quad (3.6)$$

Here τ is the kinetic energy of the incoming electron in units of $m_e c^2$. Note that for electrons, since they are indistinguishable, $W_{\max} = E_{\text{kin}}/2$ whereas for positrons $W_{\max} = E_{\text{kin}}$. The $F(\gamma)$ term is given by [110]:

$$F(\gamma) = \begin{cases} \frac{1}{\gamma^2} (1 - (2\gamma - 1) \ln 2 + \frac{(\gamma-1)^2}{8}) & \text{for } e^-, \\ 2 \ln 2 - \frac{\beta^2}{12} \left(23 + \frac{14}{\gamma+1} + \frac{10}{(\gamma+1)^2} + \frac{4}{(\gamma+1)^3} \right) & \text{for } e^+. \end{cases} \quad (3.7)$$

This term differs for electrons and positrons since their scattering cross section is different for scattering by a nuclear Coulomb field or scattering by another electron.

The Bethe-Bloch formula describes the mean energy loss per unit path length. However, the energy lost by a particle travelling through the detector will in general not be equal to the this mean value. Since large, single-collision energy deposits are possible, this makes that the mean energy loss is weighted with these very rare events. The most probable energy loss is a more useful parameter. For this the energy loss distribution must be examined. Landau was the first to calculate this distribution using three assumptions [111, 112]:

1. The maximum energy transfer permitted is infinite.
2. The electrons are treated as free, i.e. the individual energy transfers are large and small energy transfers from distant collisions (large impact parameters) are ignored.
3. The particle maintains a constant velocity.

Later, Vavilov generalized Landau's calculation by taking the correct expressions for the maximum allowable energy transfer into account. Essentially, fixing the first assumption. This general case will be treated here [113].

The function describing the probability density of depositing energy Δ when traversing a detector with thickness x is given by:

$$f(x, \Delta) = \phi_V(\lambda_V, \kappa) / \xi. \quad (3.8)$$

Following Landau and Vavilov, ξ is an approximate measure for the Bethe-Bloch mean energy loss

$$\xi = 2\pi N_a r_e^2 m_e c^2 \rho \frac{Z}{A} \left(\frac{z}{\beta} \right)^2 x. \quad (3.9)$$

The function $\phi_V(\lambda_V, \kappa)$ is known as the Vavilov distribution. It depends on Vavilov's adaption (λ_V) of the original Landau parameter (λ_L) and on a parameter κ which takes the maximum energy transfer allowable in a collision into account. This parameter is the ratio between the mean energy loss and the maximum energy transfer:

$$\kappa = \xi/W_{\max}. \quad (3.10)$$

The Vavilov distribution is given by:

$$\phi_V(\lambda_V, \kappa) = \frac{1}{2\pi i} \int_{c-i\infty}^{c+i\infty} \psi(s, \kappa) e^{\lambda_V s} ds, \quad (3.11)$$

$$\psi(s, \kappa) = e^{\kappa(1+\beta^2\gamma)} e^{\rho(s, \kappa)}, \quad (3.12)$$

$$\rho(s, \kappa) = s \ln \kappa + (s + \beta^2 \kappa) \cdot \left(\int_0^1 \frac{1 - e^{-st/\kappa}}{t} dt - \gamma \right) - \kappa e^{-s/\kappa}. \quad (3.13)$$

The parameter λ_V is related to the Landau parameter by:

$$\lambda_V = \kappa(\lambda_L + \ln \kappa), \quad (3.14)$$

with

$$\lambda_L = \frac{1}{\xi} [\Delta - \xi(\ln \xi - \ln \epsilon + 1 - C_E)], \quad (3.15)$$

$$\ln \epsilon = \ln \frac{(1 - \beta^2)I^2}{2m_e c^2 \beta^2} + \beta^2. \quad (3.16)$$

Here C_E is Euler's constant, $C_E \approx 0.577$ and the quantity ϵ represents the minimum energy transfer allowed by Landau's second assumption.

For $\kappa \rightarrow 0$, i.e. for very energetic particles or very thin absorbers, the Vavilov distribution tends to the Landau distribution:

$$\phi_L(\lambda_L) = \frac{1}{2\pi i} \int_{c-i\infty}^{c+i\infty} e^{s \ln s + \lambda_L s} ds. \quad (3.17)$$

This distribution does not depend on κ . The most probable energy loss is found to be

$$\Delta_{mp} = \xi[\ln(\xi/\epsilon) + 0.198 - \delta] \quad (3.18)$$

In the case of a 5 GeV muon traversing the HiSPARC detector this comes down to 3.51 MeV.

If κ becomes large the Vavilov distribution approaches a Gaussian distribution with $\mu = C - 1 - \beta^2 - \ln \kappa$ and $\sigma^2 = (2 - \beta^2)/2\kappa$ [114]. Note that for very low energetic particles or thick absorbers Landau's third assumption is invalid. For these small energies it is likely that the particle does not leave the scintillator.

A computer program has been used to evaluate the Vavilov distribution [115]. For $\kappa < 0.01$ the Landau distribution is used and for $\kappa > 10.0$ the Gaussian distribution is used. Figure 3.1 shows the energy loss distribution of a 5 MeV electron and a 5 GeV muon for 2 cm scintillation material. The muon follows the Landau distribution with a large tail whereas

Figure 3.1: Expected energy loss for a particle travelling through a HiSPARC detector. The most probable energy loss of the 5 MeV electron does not differ much from that of a 5 GeV muon. The muon follows the Landau distribution with a large tail whereas the electron follows the Vavilov distribution due to its low energy. The difference between the most probable energy loss and the mean energy loss shows that the Bethe-Bloch parameter is not an ideal measure for the energy lost in a detector.

the electron follows the Vavilov distribution due to its low energy. The difference between the most probable energy loss and the mean energy loss shows that the Bethe-Bloch parameter is not an ideal measure for the energy lost in a detector. Vavilov's description provides the tools to accurately describe the energy loss for particles with different energies.

With Bethe-Bloch and Landau-Vavilov theory it is possible to describe the creation of photons in the scintillator. For the light-guide however, only the Cherenkov effect is of importance. When the particle exceeds the speed of light in the light-guide, an electromagnetic shock wave is generated. This light is emitted spherically for each atom and travels with the phase velocity of the medium. Since the particle moves faster than this phase velocity, the emitted waves add up constructively and coherent radiation is generated which travels at an angle θ_C with respect to the direction of the moving particle. This coherent radiation is known as Cherenkov radiation. The emission of this light is due to the fact that the incident particle polarizes the atom along its path. These atoms become electric dipoles and emit electromagnetic dipole radiation.

The angle θ_C with which the conical electromagnetic shock wave is created is given by [98]

$$\cos \theta_C = \frac{1}{\beta n(\nu)}. \quad (3.19)$$

Here $n(\nu)$ denotes the refractive index which is a function of the frequency ν of the photon.

In the case of a particle passing through the perspex light-guide, the effect creates photons within a wavelength regime that the PMT will detect. Therefore, the Cherenkov effect needs to be taken into account. The energy loss due to the Cherenkov effect is [98]

$$-\frac{dE}{dx} = z^2 \frac{\alpha \hbar}{c} \int \nu \left(1 - \frac{1}{\beta^2 n^2(\nu)} \right) d\nu. \quad (3.20)$$

Here z and α are the charge of the particle and the fine structure constant. This amounts to an energy loss in the order of only $10^{-3} \text{ MeV cm}^{-1}$. However, the small number of photons created by the Cherenkov effect are more likely to reach the PMT because they are generated closer to the PMT.

3.2 Detector simulation

Despite the straightforward design of a HiSPARC detector, there are numerous processes that need to be taken into account when simulating the detector. Processes such as the scattering and attenuation of scintillation light or the capture and subsequent decay of low energy muons. In order to incorporate all these effects GEANT4 has been used [116].

In the simulation program the geometry of the detector is defined. It consists of the scintillator, a glue layer, light-guide, aluminium foil, plastic foil and the roof box lid. The glue layer and plastic foil are estimated to have a thickness of 0.5 mm. The aluminium foil has a thickness of 30 μm . The light-guides (triangle and adapter piece) have a thickness of 2.4 cm and the roof box lid is assumed to have a thickness of 2.5 mm. The further geometry of the detector is equal to the sizes discussed in chapter 2.1. Both the plastic foil and roof box lid are assumed to be made of polycarbonate. The number ratio of the atoms in the glue are

assumed to be 6:3:1 for H:C:O respectively. The refractive index of the glue is assumed to be the same as that of the scintillator. The refractive indices of the light-guide (poly(methyl methacrylate), PMMA) and scintillator are 1.49 and 1.58 resp. The attenuation length of the light-guide is assumed to be equal to that of the scintillator, i.e. 380 cm. The atomic compositions of the light-guide and scintillator, as calculated from their chemical formulas, are taken into account. Also, the emission spectrum of the scintillator has been implemented in the simulation [77]. Finally, the appropriate physics modules have been implemented.

The simulation program accounts for all aspects of the detector except for the PMT. The output consists of the number of photons that reach the PMT and the arrival time of each photon. The simulation assumes that the aluminium foil tightly encloses the detector. In reality, air pockets between scintillator and aluminium foil result in internal reflections. These reflections generate a higher yield of photons at the PMT than for a scintillator with a perfectly fitting aluminium envelope. In the simulation program this lack of air pockets is accounted for by increasing the aluminium reflectivity from 0.88 to a value of 0.93. This only scales the number of photons.

3.2.1 Transmission of scintillation light

The yield of scintillation photons has been analysed by exposing the detector simulation (scintillator and light-guides) to perpendicular incident minimum ionizing muons. The photons have a different probability to reach the PMT depending on the location at which they are released in the scintillator. The plot on the right in figure 3.2 shows the distribution of the number of scintillation photons arriving at the PMT as a function of position. The muon flux was kept constant over the full area of the detector. The left hand figures show the distribution of the number of photons that reach the PMT from locations A (top) and B (bottom) in the scintillator. The distribution of photons follows Landau theory (black curves). The discrepancy between simulation and Landau curves is believed to be due to local differences in attenuation and reflection. Figure 3.3 shows the total distribution of the number of photons reaching the PMT for all locations. Also a scaled Landau distribution (peaks aligned) is shown.

Figure 3.2 also shows that the maximum light output is obtained when the muon hits a corner of the scintillator near the light-guide (top). Surprisingly, within the area that is represented by the mirror image of the light-guide in the scintillator, the photon yield is relatively small.

To verify the simulation a table-top experiment was designed [75]. A $1.5\text{ cm} \times 1.5\text{ cm}$ scintillator is connected to a small PMT. This small scintillator is positioned on top of the HiSPARC detector. A 3×5 grid (figure 3.4, positions 1-15) defines the locations. In the vicinity of for instance point 10, the simulation predicts a large light yield gradient. In this region four additional measurements (16-19) were carried out. The readout is triggered when both scintillators signal a MIP. In figure 3.5 the pulse integral distributions obtained at positions 16 and 17 are compared. Although the locations are very near, there is a sizeable difference in the photon yield reflected in the shift of the peak value. Position 17 has the peak at ~ 4400 mVns whereas the yield at position 16 (~ 3600 mVns) is by $\sim 20\%$ smaller. Both distributions can accurately be described by a Landau distribution convoluted with a Gaussian. PMT response characteristics are not included in this simulation. Moreover,

Figure 3.2: Spatial distribution of the number of muon induced scintillation photons arriving at the PMT. In this simulation a large number of relativistic muons was shot at the detector from the zenith. The impact positions were chosen from a uniform distribution. The right graph shows the spatial distribution of the number of arriving photons. The position of the light-guide is at the top. The two histograms on the left show the distribution of photons within the small white squares. In both cases the expected Landau distribution is compared to the histogram.

Figure 3.3: Distribution of muon induced scintillation photons arriving at the PMT. In this simulation a large number relativistic muons was shot at the detector from the zenith. The impact positions were chosen from a uniform distribution. The dashed line shows a scaled Landau distribution.

simulations only account for perpendicular incident muons whereas the experiment is susceptible to muons from all directions where both scintillators generate a sufficiently large signal. This results in Gaussian smearing.

Figure 3.6 shows the comparison between the light-output of the table-top experiment and detector simulation (scintillator and light-guide). Both experimentally measured and simulated MIP-peak values have comparable statistical uncertainties. The simulation reproduces the experimental data rather well.

3.2.2 Light-guide

Using GEANT4 the consequences of the Cherenkov effect are investigated. In this simulation a large number of relativistic muons was directed at the light-guide from the zenith. The impact positions were chosen from a uniform distribution. Figure 3.7 shows the spatial distribution of the number of photons that reach the PMT. As expected, the number of photons that reach the PMT decreases for increasing distance to the PMT. Due to the small number of photons a large part of the light-guide does not result in detectable Cherenkov signals. Figure 3.8 shows the total distribution of Cherenkov photons reaching the PMT. The large likelihood of finding a small number of photons is because of the decreasing probability to measure Cherenkov photons for increasing distance to the PMT.

The light-guide reduces the scintillator light yield as demonstrated in figure 3.2. However, the light-guide also may generate detectable Cherenkov photons when a charged particle penetrates. Using GEANT4 the production and propagation of these Cherenkov photons have been investigated. The light-guide was exposed to perpendicular incident relativistic

Figure 3.4: The scintillator (including light-guide) light transmission is measured at 19 locations in the detector. The dotted lines show the position at which the largest gradients are observed (figure 3.2). The circles indicate the positions at which the efficiency is measured. Fifteen positions are defined on a grid, with four additional measurements performed around point 10.

Figure 3.5: Pulse integral distributions for events collected at position 16 and 17. Despite the small distance between the two positions there is a large difference in photon yield. Both distributions can accurately be described by a Landau convoluted with a Gaussian. The lower end of the spectrum results from gammas, low energy particles, and PMT noise.

Figure 3.6: Comparison between measured and simulated light yield of a HiSPARC detector (scintillator and light-guide). The numbers in the plot correspond to the locations indicated in figure 3.4.

muons. Again, the muon flux was kept uniform over the full surface of the light-guide. Figure 3.7 shows the spatial distribution at which the Cherenkov photons are released scaled with the number of photons that reach the PMT. The further away from the PMT the Cherenkov photons are generated, the smaller the probability they reach the PMT. Even for large Cherenkov photon yields close to the PMT, the number of photons is small compared to the number of photons generated in the scintillator.

Figures 3.5 and 3.6 show the measured signal yield and transmission at selected grid points in the scintillator. To obtain the muon response over the full surface of the detector (scintillator and light-guide) taking into account the proper energy spectrum and angle of incidence of the muon, a second experiment was conducted. Two stacks of each two detectors are placed parallel at a distance of 6 m. Figure 3.9 shows this configuration. When three or more detectors generate a signal exceeding the noise cut-off at -15 mV (fig. 2.4), the event is recorded. In the analysis, events containing signals with a time difference between both stacks of less than 300 ns are discarded. This excludes the contribution from EASs in which particles arrive in a relatively small time window. If the time difference is larger than 300 ns, the event most likely stems from a random coincidence. These random coincidences are due to single muon background and ‘noise pulses’ (PMT dark pulses, low energy electrons, gamma rays, etc.). When two detectors in the same stack generate a signal exceeding -15 mV, a MIP traversed both detectors. If only one detector of a stack generates a pulse, it is most likely caused by ‘background noise’. This noise generates a pulse-spectrum that peaks at ~ 50 mV. The high rate of noise pulses in detectors of the same stack causes only a small number of random background coincidences. By choosing those events in which two detectors in one stack are triggered by a MIP (time difference with a signal in the other stack is larger than 300 ns), single muons are selected. The result is shown in figure 3.10 (red histogram). All four detectors generate a similar pulse height spectrum.

Figure 3.7: Cherenkov light yield as function of position in the light-guide for photons reaching the PMT. In the GEANT4 simulation the light-guide was exposed to perpendicular incident relativistic muons. The muon flux was kept constant over the full area. The probability of measuring Cherenkov photons strongly decreases with increasing distance to the PMT.

Figure 3.8: Distribution of muon induced Cherenkov photons arriving at the PMT. In this simulation a large number relativistic muons was shot at the light-guide from the zenith. The impact positions were chosen from a uniform distribution. The large likelihood of finding a small number of photons is because of the decreasing probability to measure Cherenkov photons for increasing distance to the PMT.

Figure 3.9: Two stacks of each two detectors are used to differentiate single muon events from other signals. When three or more detectors detect a signal (indicated by a star), the event is recorded. Events with a time difference larger than 300 ns between both stacks are due to random coincidences. If the time difference is large and both detectors of one stack simultaneously detect a particle, a single muon traversed the stack. Events that generate a signal in only one detector are due to gamma rays (see chapter 7).

Figure 3.10: Comparison between single muon pulse height distributions of simulated and experimental data. Below -100 mV the simulation represents the experimental data rather well. The small peak at ~ -50 mV is due to a small number of randomly coinciding background noise pulses. The contribution below -50 mV is dominated by Cherenkov radiation and is slightly overestimated in the simulation.

Next, the single muon response in a detector is investigated using the simulation procedure described before. In addition to the propagation of the photons in the scintillator and the light-guide an analytical description of a single photo-electron PMT response is added [117]. Muon direction and energy follow the distributions presented in chapter 1.2.3. The energy and zenith-angle are sampled using the Metropolis-Hastings algorithm [118]. The muons are uniformly distributed across the detector surface. Below -100 mV, the simulation (blue histogram) in figure 3.10 compares well with the experimental data. The small peak at ~ -50 mV is due to the small number of randomly coinciding background pulses in two detectors of the same stack. The small pulse heights stem from Cherenkov radiation in the light-guide. The simulation tends to slightly overestimate the contribution from the Cherenkov photons.

3.2.3 Detection efficiency

The detector simulation describes the experimental data rather well and is used to investigate the detection efficiency for electrons, muons and gamma rays. The efficiency does not only depend on a combination of gain (i.e. precise value of the MIP-peak) and applied signal threshold (defined in terms of the fraction of the MIP-peak value), but also on the energy of the particle and its angle of incidence. A lower limit on the efficiency is obtained when perpendicular incident particles are considered. The detection efficiency is then defined as the fraction of the pulse height distribution exceeding the threshold divided by the full range of pulse heights. Only the area covered by the scintillator is considered; the contribution from Cherenkov photons in the light-guide is ignored.

Figure 3.11: Detection efficiency of a detector (only the area covered by the scintillator is considered) as a function of threshold (fraction of the MIP-peak value) for muons, electrons and gamma rays. The MIP-peak is defined as the most probable signal response for a single minimum ionizing particle. For high energy electrons (50 MeV, blue, dotted line) and energetic muons (5 GeV, red dashed line) the efficiency curves coincide. For low energy electrons (3 MeV, green dash-dotted line) the efficiency drops significantly. For gamma rays, the full energy range is considered. The energy spectrum is obtained from air shower simulations [55]. The gamma detection efficiency is small (black solid line).

Figure 3.11 shows the detection efficiency curves for muons, electrons and gammas. The majority of muons is considered to be minimum ionizing as they are produced at high altitudes. Electrons however, are also generated in electromagnetic showers closer to ground. Low energy electrons are therefore more abundant than low energy muons. For high energy muons (5 GeV) and high energy electrons (50 MeV) the detection efficiencies are the same (dashed red and dotted blue lines coincide). This is to be expected since at these energies both particles are minimum ionizing. For thresholds up to 0.5 MIP their detection efficiency is very close to 100%. For low energy electrons (e.g. 3 MeV), the detection efficiency is very different (green dashed-dotted line) and stays well below 100% over the full range of threshold values. Low energy particles have a high chance to be absorbed in the scintillator and will therefore produce only a limited number of excitation photons.

Gamma rays are abundant in EASs. The majority of gamma rays do not interact in the scintillator; their detection efficiency will therefore be small. For perpendicular incident gamma rays, a lower limit on their detection efficiency as function of threshold is also depicted in figure 3.11 (solid black line). Only a fraction (less than 10%) of the gamma rays will be detected.

3.3 Gamma ray detections

Next to electrons, positrons and muons the vast majority of detectable particles in a cosmic ray air shower are gamma rays. These photons interact with the detector mainly via three mechanisms: the photoelectric effect, Compton scattering and pair production. In all mechanisms an electron is ejected or an electron positron pair is created. These moving particles behave according to Bethe-Bloch and Landau-Vavilov theory. It is via these particles that the gamma ray is detected. In the case of the photoelectric effect only one low energetic electron is ejected which cannot excite enough atoms to subsequently create enough scintillation photons to be detected by the PMT. The two mechanisms of importance are Compton scattering and pair production.

Contrary to charged particles, where the energy loss is mainly due to many inelastic collisions with atomic electrons, an incoming photon which undergoes an interaction stops to exist. The probability to travel without interacting decreases exponentially with respect to the distance travelled. It is thus possible to define a distance λ for which the probability of a photon not to have interacted is $1/e$. This distance λ is known as the attenuation length. The probability to find a photon at depth x is then given by:

$$P_{\text{travel}}(x) = \exp\left(\frac{-x}{\lambda}\right). \quad (3.21)$$

The attenuation length is material and energy dependent. Figure 3.12 shows the attenuation length of a HiSPARC scintillator as function of energy. It also shows the probability for a gamma ray to interact within the detector as a function of energy. For Compton scattering and pair creation the interaction probability is small. However, due to the large number of photons in an air shower, gamma ray interactions may not be ignored.

The first of the two mechanisms, Compton scattering, involves the scattering of photons on free electrons. In practice, these electrons are bound but if the photon energy is large

Figure 3.12: Attenuation length as function of energy for photons travelling through scintillation material (left) and the probability to interact within the HiSPARC detector as function of energy (right). The three interaction mechanisms are shown by different line styles. Data from NIST [119].

compared to the binding energy, the electrons can be considered free. The scattering process is shown in figure 3.13. The energy of the scattered photons depends on the scattering angle θ via [98]:

$$h\nu' = \frac{h\nu}{1 + \gamma(1 - \cos \theta)}, \quad (3.22)$$

with $\gamma = \frac{h\nu}{m_e c^2}$, h Planck's constant and ν the frequency of the original gamma ray. The kinetic energy and scattering angle of the outgoing electron are given by:

$$T = h\nu - h\nu' = h\nu \frac{\gamma(1 - \cos \theta)}{1 + \gamma(1 - \cos \theta)} \quad (3.23)$$

and

$$\cot \phi = (1 + \gamma) \tan \frac{\theta}{2} \quad (3.24)$$

respectively. The scattered electron will excite and possibly ionize the atoms in the scintillator medium. Equation 3.23 shows that for large scattering angles (i.e. $\theta = 180^\circ$) there is a maximum energy for the electron. This is known as the Compton edge:

$$T_{\max} = h\nu \frac{2\gamma}{1 + 2\gamma}. \quad (3.25)$$

Using GEANT4 the effects of Compton scattering are investigated by shooting numerous gamma rays at the scintillator from the zenith. The impact positions were chosen uniformly. Three different energies, i.e. 3, 5 and 10 MeV, for which Compton scattering is the main interaction mechanism were chosen. The first three distributions in figure 3.14 shows the

Figure 3.13: Kinematics of Compton scattering. The incoming photon with energy $h\nu$ scatters with an electron. The outgoing photon has an energy $h\nu'$ and scattering angle θ . The scattered electron has kinetic energy T and scattering angle ϕ . Adapted from [98].

distribution of the number of scintillation photons reaching the PMT for these three energies. The maximum energy of the scattered electron (eq. 3.25) results in a maximum number of scintillation photons that can be produced. This Compton edge shifts to larger number of photons arriving at the PMT for increasing gamma ray energy. The energy loss of the scattered electrons follows Vavilov theory and creates the tails in the distributions. Another clear feature is the approximately linear decrease in how often large numbers of photons reach the PMT. This is due to the differential cross section for Compton scattering, given by the Klein-Nishina formula [120]. The probability to scatter with scattering angle θ decreases for larger scattering angles. Given that the kinetic energy of the electron is a function of θ , more energetic electrons and thus more scintillation photons, are less likely.

The second interaction mechanism is electron positron pair production. In this process the gamma ray photon is transformed into an electron and positron. The process can only occur if energy and momentum are conserved. This means that pair production can only happen if the gamma ray has enough energy and in the presence of a third body. The most probable opening angle between the electron and positron depends on the energy of the incoming gamma ray and is given by [121]:

$$\theta_{\text{open}} = \frac{0.8}{E_{\gamma}}. \quad (3.26)$$

with θ the opening angle in radians and E_{γ} the energy of the gamma ray in MeV. For the energy regime in which pair production starts to become important (~ 50 MeV) this opening angle is already smaller than 1 degree. This means that both the electron and positron can be assumed to travel in the same direction as the original gamma ray. The resulting electron follows Vavilov theory.

The positron will also behave according the description in section 3.1 until annihilation with an electron from the medium. The subsequent photons created by the annihilation may or may not undergo Compton scattering in the detector. Annihilation occurs if the positron has almost stopped. The continuous slowing down approximation (CSDA) range of the positron exceeds the 2 cm detector thickness if the new positron has an energy above 4 MeV [122]. Given that pair production most probably generates positrons which are much more energetic, it is safe to assume that the positron will travel all the way through the detector and thus create a similar number of photons as the generated electron.

Figure 3.14: Distribution of the number of gamma ray induced photons arriving at the PMT for four different gamma energies. In all simulations 100,000 gammas were shot at the detector from the zenith. The impact position was chosen uniformly. The energy of the incoming gammas is denoted by E_γ . Compton scattering is the dominant mechanism for 3, 5 and 10 MeV interactions. The Compton edge increases for higher gamma ray energy. The energy loss of the scattered electrons follows Landau theory and creates the tails in the distributions. The linearly decreasing probability to find more photons at the PMT is due to the Klein-Nishina formula. Pair production starts to become of importance at 50 MeV interactions resulting in a somewhat different distribution.

Using GEANT4 the expected distribution of the number of photons that arrive at the PMT is simulated. The last distribution in figure 3.14 shows the spectrum of arriving scintillation photons for 50 MeV gamma rays. For this energy both Compton scattering and pair production may occur. Given that for pair production two charged particles, i.e. the electron and positron, can generate scintillation photons the number of photons that reach the PMT is even larger than the single particle peak shown in figure 3.3.

Finally, the distribution of the number of gamma ray induced scintillation photons that reach the PMT can be simulated for an air shower. In this simulation the gamma ray energies were sampled from a simulated air shower (see chapter 4). The impact positions were chosen uniformly. Figure 3.15 shows the obtained distribution. The larger interaction probability of low energy gamma rays in combination with the large number of low energy gamma rays in air showers explains why often a small number of scintillation photons is detected at the PMT. The distribution can be interpreted as a combination of single energy distributions shown in figure 3.14. Because of the absence of a MIP peak, it is impossible to estimate the number of interacting gamma rays from the number of photons reaching the PMT.

Figure 3.15: Distribution of the number of gamma ray induced photons arriving at the PMT for an air shower. In this simulation a large number of gamma rays was shot at the detector from the zenith. The energies of the gamma rays were sampled from a simulated 10^{15} eV proton induced air shower. The impact positions were chosen uniformly. The larger interaction probability of low energy gamma rays in combination with the large number of low energy gamma rays in air showers explains why the number of gamma ray induced scintillation photons arriving at the PMT is often small (typically less than 50 photons).

3.4 PMT simulation

The GEANT4 simulation program propagates each scintillation photon until it is either absorbed or reaches the PMT. Next to the number of photons that arrives at the PMT also the arrival times of these photons are recorded. The simulated photon arrival time distributions change for different impact positions on the scintillator. These different arrival time distributions affect the PMT pulse shape. In order to compare these simulations to experimental data, the PMT pulses at the 19 positions in the table top experiment (figure 3.4) are further examined.

For each position, a large number of vertically incident minimum ionizing muons was directed at the scintillator in the simulation. The muons were homogeneously distributed within a $1.5\text{ cm} \times 1.5\text{ cm}$ square centred at each position. The average arrival time distributions of the photons was determined to correct for quantum fluctuations. Only the events in which the number of photons that arrive at the PMT is close to the Landau peak (see left hand plots in figure 3.2) are taken into account. Events in which the photon yield was large (tail of the Landau distribution) are disregarded because they disproportionately affect the average. A bin size of 2.5 ns was chosen which corresponds to the sample frequency of the PMT signal. Figure 3.16 shows the simulated arrival time distributions for each position in the scintillator. The figures are ordered such that they correspond to the positions in figure 3.4. The four additional points around grid point 10 are shown in the most right column. A black line connecting the bin middles was added to emphasise the recurring peaks in the distributions. At 0 ns the particle entered the scintillator. The distributions for positions in the back of the scintillator show that some time is needed for the first photons to reach the PMT. The arrival time distributions are clearly different. For horizontal mirror positions (e.g. positions 1 and 3) the distributions are identical. This is to be expected because of mirror symmetry in the detector.

Similarly to the simulated arrival time distributions, also the average experimental PMT pulses are determined to remove quantum fluctuations. Only pulses with pulse heights close to the Landau peak are considered. This makes that all pulses have similar pulse heights. Contrary to the perpendicular incident muons in the simulation, the experiment is susceptible to muons from all directions where both scintillators generate a sufficiently large signal (-30 mV). Although the atmospheric muon flux is highest for perpendicular incidence, particles which traversed more than 2 cm of scintillator are included in the sample. Also no distinct zero time exists. The pulses are shifted in order to calculate the average pulse. The time step at which a pulse first exceeds -40 mV is used to align all pulses. Figure 3.17 shows the average pulses for all 19 positions. The differences in pulse height are related to the different photon yields displayed in figure 3.2. Also the width of the pulses is different. Further from the PMT the pulse becomes smaller and a kink arises at around 40 ns .

3.4.1 Single photo-electron response

The differences in pulse shape of the 19 average pulses (figure 3.17) are due to the different photon arrival time distributions at the 19 positions (figure 3.16). Per photo-electron the PMT starts an electronic cascade process which results in a signal. When disregarding

Figure 3.16: Simulated average arrival time distributions of scintillation photons generated by minimum ionizing muons traversing the detector at the 19 positions as displayed in figure 3.4. The bin width matches the sampling frequency of the HiSPARC electronics (2.5 ns). At time 0 the particle impacts the scintillator. For positions far away from the PMT (i.e. positions 1, 2 and 3) several nanoseconds are needed for the first scintillation photons to reach the PMT. All distributions show multiple peaks due to reflections in the detector.

Figure 3.17: Average pulses for minimum ionizing (atmospheric) muons traversing the detector at the 19 positions as displayed in fig. 3.4. The time step at which a pulse first exceeds -40 mV is used to align all pulses in time before calculating the average. The pulses are shifted somewhat (~ 15 ns) with respect to time 0. The pulses at different positions (e.g. 1 and 15) differ significantly in both shape and amplitude.

fluctuations and noise, this single photo-electron response convoluted with the arrival time distribution of the scintillation photons results in the signal pulse. Deconvolution of the simulated photon arrival time distribution from the average pulse thus results in the single photon-electron response. Note that the quantum efficiency of the PMT is not taken into account. If simulations and measurements agree, this single-photon response should be similar for all 19 positions.

Figure 3.18 shows the single photo-electron responses for all 19 positions. The simulated photon arrival time distributions are deconvoluted from the average pulses using Wiener deconvolution. There is considerable similarity between all single photo-electron responses (grey lines). Only the amplitude of the response differs substantially whereas the width and rise time of the single photo-electron pulse is constant. This is reflected in figure 3.19 which shows the single photo-electron responses normalised to -1.0 mV.

The single photo-electron response can be well parametrised by equation 2.2 (reprinted):

$$U(t) = g \cdot \exp\left(-\frac{1}{2} \left(\frac{\ln(t/\tau)}{\sigma}\right)^2\right) \quad (3.27)$$

The red line in figures 3.18 and 3.19 shows the parametrisation fitted to the data points of all 19 positions. The obtained fit parameters are: $g = -1.07$ mV, $\tau = 9.05$ ns and $\sigma = 0.72$.

The variety in amplitude of all deconvoluted single photo-electron PMT responses has to do with the amplitude of the average pulse and the total number of photons arriving at the PMT. It unclear why the simulated number of photons that arrives at the PMT does not totally agree with measurements. Possibly the reflectivity settings in the GEANT4 simulation program differently affect the photon yield for each position. Nevertheless, the agreement of all 19 normalised photo-electron responses indicate that the simulated photon arrival time distributions agree with data and that the obtained parametrisation can be used as a measure for the single photo-electron response.

With the analytical expression for the single photo-electron pulse, the measured photon arrival time distribution can be obtained by deconvolution of the single photo-electron response from the average pulses. Figure 3.20 shows the deconvoluted photon arrival time distributions of all 19 positions (red line) compared to the simulated distributions (black line). The deconvoluted curves have been shifted in time to match the simulated arrival times. The recurring peaks in the simulated distributions are clearly retrieved in the experimental data.

3.4.2 PMT pulse generation

The arrival time distribution of scintillation photons at the PMT, generated by the GEANT4 simulation program, is used in combination with the analytical expression for the single photo-electron response to simulate the PMT pulse. The arrival times are binned in 2.5 ns bins. The number of photons in the first bin is taken and for each photon a 25% PMT quantum efficiency is simulated. Next, the photo-electron response for that bin is calculated by scaling the single photo-electron response (eq. 3.27). This procedure is repeated for all bins in the photon arrival time distribution. The responses are summed taking the time delay with respect to the first bin into account. The bottom plot in figure 3.21 shows an

Figure 3.18: The single photo-electron responses obtained by deconvolution of the simulated arrival time distribution from the average pulse for all 19 positions. The signals are horizontally aligned at the time step at which the signals first exceed -0.57 mV. The analytical model fitted to the responses is displayed in red. Except for variations in the amplitude there is ample similarity between all single photo-electron responses.

Figure 3.19: The single photo-electron responses normalized to -1 mV. The signals are horizontally aligned at the time step at which the signals first exceed -0.57 mV. The analytical model fitted to the responses is displayed in red. The similarity between all 19 normalized single photo-electron responses is striking, only at ~ 45 ns there are some irregularities between the responses.

Figure 3.20: Arrival time distributions obtained by deconvolution of the analytical single photo-electron response from the average pulses (red) compared to simulations (black) for all positions. The measured arrival times have been shifted to match the simulated arrival time distributions. For all positions there is great similarity between simulated and measured distributions.

example of a simulated PMT pulse (blue line) compared to an experimentally detected pulse (red line). The upper plot shows the corresponding simulated arrival time distribution of the scintillation photons. At time step 0 a muon entered the scintillator at position 2 in figure 3.4. The experimentally detected pulse was also generated by a particle traversing the scintillator at position 2. There is good agreement in the rise time and width of both pulses.

3.4.3 Estimating the impact position from the PMT pulse shape

As the arrival time distribution of the scintillation photons reaching the PMT, and thus the PMT pulse shape, depends on the impact position on the scintillator, an attempt was made to generate an artificial intelligence (AI) algorithm to predict the impact position from the arrival time distribution. For this, a neural network has been developed [123] which uses the simulated arrival time distributions (e.g. figure 3.16) as input to predict the position (x,y) at which a simulated MIP traversed the scintillator. The x-axis is measured along the length of the scintillator with 0 cm being the furthest away from the PMT and 100 cm the closest (figure 2.2). The y-axis is measured along the width of the scintillator. Since the detector can be mirrored along the x-axis, absolute values for the y-axis are taken. This means that the maximum width is 25 cm. The mirror axis through the detector is at $y = 0$ cm. To prevent the algorithm to use the latency between the moment of impact (0 ns) and the moment at which the first scintillation photons reach the PMT as a measure for the distance to the PMT (e.g. positions 1, 2 and 3 versus positions 13, 14, and 15 in figure 3.16), the times at which the arrival time distributions peak were aligned. A neural network with three layers of dimensions 50 (input layer), 50 (hidden layer) and 2 (output layer) was trained on a subset (17,000 elements) of the simulated data. Figure 3.22 shows the predictions made by the trained algorithm on a separate subset of the data (3,000 elements). The impact positions of most simulated particles could be predicted well. The algorithm has some difficulties predicting the x positions furthest from the PMT ($x = 0$). At these positions the arrival time distributions are very similar (figure 3.16). The same is true for the central y axis through the scintillator ($y = 0$ cm) and near the edges ($y = 25$ cm).

It was investigated whether these results could be reproduced with experimental data. Unfortunately, the large spread in PMT pulse shapes obtained at the same impact position means that deconvolution of the single photo-electron response yields widely differing arrival time distributions of the scintillation photons. Several noise reduction techniques (e.g. low-pass filter) were tried without success. Similar neural networks were trained on simulated and experimentally obtained PMT pulses (instead of arrival time distributions) but also these were not able to predict the impact positions. The deviation of single PMT pulses from the average PMT signals (figure 3.17) is simply too large. More research is needed to assess whether this approach could still be viable with other equipment (e.g. higher sampling frequency) or settings (e.g. higher gain).

Figure 3.21: Generation of a simulated PMT pulse (blue line, bottom plot) from the arrival time distribution of scintillation photons at the PMT (upper plot). The scintillation photons are simulated using GEANT4. At time step 0 a simulated muon entered the scintillator at position 2 in figure 3.4. The arrival time distribution of scintillation photons is used in combination with the analytical expression for the single photo-electron response (eq. 3.27) to simulate the PMT pulse. An experimentally detected signal, also generated by a particle traversing the scintillator at position 2, is shown for comparison (red line). There is good agreement in the rise time and width of both pulses. The dotted lines indicate the 30 mV and 70 mV thresholds.

Figure 3.22: Predicted impact positions on the scintillator made by a neural network versus the true impact position. Simulated arrival time distributions of the scintillation photons reaching the PMT (e.g. figure 3.16) were used as input for the AI algorithm. Each dot denotes one simulated arrival time distribution. The times at which the distributions peak were aligned to prevent the algorithm to use the latency between the moment of impact (0 ns) and the moment at which the first scintillation photons reach the PMT as a measure for the distance to the PMT (e.g. positions 1, 2 and 3 versus positions 13, 14, and 15 in figure 3.16). The left plot shows the position in the length of the scintillator (x-axis) with 0 cm being the furthest away from the PMT. The right plot shows the positions in the width of the scintillator (y-axis). Since the detector can be mirrored along the x-axis, absolute values for the y-axis are taken. This means that the maximum width is 25 cm. The mirror axis through the detector is at $y = 0$ cm. The red lines indicate a perfect prediction. The algorithm has some difficulties predicting the x positions furthest from the PMT. At these positions the arrival time distributions are very similar (figure 3.16). The same is true for the central y axis through the scintillator ($y = 0$ cm) and near the edges ($y = 25$ cm).

Chapter 4

HiSPARC station

4.1 Trigger efficiency

The default trigger condition for a two-detector station is straightforward. An event is selected if the signals in the two detectors exceed the low threshold within the coincidence time window (1.5 μ s). The default trigger conditions for a four-detector station are: the signals of at least two detectors pass the high threshold or at least three detectors generate a signal that exceeds the low threshold.

Figure 3.11 demonstrated that the detection efficiency for perpendicular incident MIPs traversing a detector is $T_L = 0.999$ for the low threshold (0.2 MIP) and $T_H = 0.997$ for the high threshold (~ 0.5 MIP). For a two-detector station this leads to a trigger efficiency of $T_L^2 > 0.99$. For a four-detector station the trigger efficiency depends on the number of detectors that are hit. For two MIP events the trigger probability depends on the high threshold: $T_H^2 > 0.99$. For three MIP events, for which it is unknown which three detectors are hit, the station will still trigger even if one of the particles is not detected ('1 non'). If one of the MIPs does generate a signal that goes over the low threshold, the two other MIPs may still generate a signal that goes over the high threshold (2 high). This combination occurs three times:

$$\begin{aligned} P_{3\text{mip}}^{\text{four}} &= P(3 \text{ low}) \\ &\quad + 3 \cdot P(2 \text{ high} | 1 \text{ non}) P(1 \text{ non}) \\ &= T_L^3 + 3 \cdot T_H^2 \cdot (1 - T_L) \\ &\gg 0.99 \end{aligned} \tag{4.1}$$

Finally, for four MIPs crossing four different detectors the station is also very efficient:

$$\begin{aligned}
 P_{4\text{mip}}^{\text{four}} &= P(4 \text{ low}) \\
 &\quad + 4 \cdot P(3 \text{ low} | 1 \text{ non})P(1 \text{ non}) \\
 &\quad + 6 \cdot P(2 \text{ high} | 2 \text{ non})P(2 \text{ non}) \\
 &= T_L^4 + 4 \cdot T_L^3 \cdot (1 - T_L) \\
 &\quad + 6 \cdot T_H^2 \cdot (1 - T_L)^2 \\
 &\gg 0.99
 \end{aligned} \tag{4.2}$$

In all cases the trigger efficiency of HiSPARC stations for MIPs is well above 99%. In practice not only MIPs will be detected. Also gamma rays, low energy electrons and low energy muons are part of the EAS. The detection efficiency then strongly depends on their energy and nature.

4.2 EAS direction reconstruction

In section 2.1 a detailed simulation of the single particle response of a HiSPARC detector was presented. Using this detector simulation, the response of a four-detector HiSPARC station to EASs can be investigated. With CORSIKA, proton initiated EASs are generated with energies ranging from 10^{13} to $10^{16.5}$ eV. Their relative abundance follows the cosmic ray energy spectrum. ‘Thinning’ [44] was not applied. The interactions are described by the models listed in chapter 1.2.2. While the location of the station in the simulations remains fixed, the position of the EAS core is randomly chosen within a circle with a radius of 100 m centred at the station. Arrival directions are chosen isotropically. When one or more EAS particles hit a detector the full detector simulation is applied. For events satisfying the trigger conditions and having at least two MIPs in each detector, the direction of the shower is reconstructed assuming a flat shower front using the (triangulation) algorithm described in [124, Chapter 5].

Figure 4.1 gives the 1σ uncertainty in the shower direction reconstruction for a four-detector triangle shaped station (fig. 2.12) as a function of zenith angle (blue dots). The distribution is obtained by comparing the direction of the primary cosmic ray as set in the CORSIKA Monte Carlo program and the reconstructed direction after detector simulation. The average uncertainty ($\theta < 40^\circ$) is 7.7° .

The shower direction can be decomposed in terms of zenith angle and azimuth. Figure 4.2 shows the 1σ uncertainty in the azimuthal angle (blue dots) and zenith angle (blue crosses) as a function of zenith angle. Again, the distribution is obtained by comparing the direction in which the shower developed as set in the CORSIKA Monte Carlo program and the reconstructed direction after detector simulation. With increasing zenith angle, the 1σ uncertainty on the reconstructed zenith angle slightly increases. The uncertainty on the reconstructed azimuth however, rapidly increases for smaller zenith angles; in the limit where the zenith angle goes to zero the azimuth becomes undefined.

In 2008 a four-detector HiSPARC station (triangle configuration) was integrated in the KASCADE experiment [64]. When KASCADE detected an EAS in the area where the

Figure 4.1: The 1σ uncertainty in the shower direction reconstruction as a function of zenith angle (blue dots) is calculated by comparing the direction of CORSIKA generated showers and the direction reconstructed after full detector simulation in a four-detector, triangle shaped, HiSPARC station. A station with the same configuration was integrated in the KASCADE experiment. The reconstruction algorithm that was applied to the simulated EASs was used to obtain the shower directions from the HiSPARC data in the KASCADE setup. The algorithm only used events (satisfying the trigger conditions) with at least 2 MIPs in each detector. The comparison between the shower direction reconstructed by KASCADE (0.3° accuracy) and measured by the HiSPARC station is shown as a function of zenith angle (red dots).

Figure 4.2: The 1σ uncertainty in the reconstruction of azimuth (blue dots) and zenith (blue crosses) as a function of zenith angle are calculated by comparing the direction of CORSIKA generated showers and the direction reconstructed after full detector simulation in a four-detector, triangle shaped, HiSPARC station. A station with the same configuration was integrated in the KASCADE experiment. The reconstruction algorithm that was applied to the simulated EASs was used to obtain the shower directions from the HiSPARC data in the KASCADE setup. The reconstruction algorithm only used events (satisfying the trigger conditions) with at least 2 MIPs in each detector. The comparison between the shower direction reconstructed by KASCADE (0.3° accuracy) and measured by the HiSPARC station, is shown for azimuth (red dots) and zenith (red crosses) as a function of the zenith angle.

Stations	Difference [°]
501-510	6.02 ± 0.04
501-512	6.14 ± 0.04
501-513	6.06 ± 0.04
510-512	6.35 ± 0.04
510-513	6.37 ± 0.04
512-513	5.93 ± 0.04

Table 4.1: The first column lists the pairs of stations for which the reconstruction of the shower direction was compared. The second column gives the 1σ difference between the two angles. For details see [125].

HiSPARC station was located, the experiment generated a signal that triggered the DAQ of the HiSPARC station. Between July 1 and August 6 2008 more than 5×10^5 events were recorded [75]. The direction of these showers was reconstructed by applying the same algorithm as used in the reconstruction of the simulated EASs (again demanding at least 2 MIPs in each detector). KASCADE reconstructed the direction of these EASs with zenith angles between 0° and 40° with 0.3° accuracy [64]. Figure 4.1 shows the 1σ uncertainty on the HiSPARC direction reconstruction (red dots). The average uncertainty ($\theta < 40^\circ$) is 6.1° . Figure 4.2 gives the decomposition into the azimuth (red dots) and zenith (red crosses) angles as a function of the zenith angle.

When compared to KASCADE data it appears that the uncertainty obtained from the simulations (7.7°) slightly underestimates the real direction reconstruction performance of the HiSPARC station (6.1°). However, the simulated data only contain proton initiated showers with energies starting at 10^{13} eV. The KASCADE data contain all primary cosmic ray compositions while only showers with an energy in excess of 10^{14} eV are reconstructed. This results in a higher contribution from events with slightly higher particle densities. Moreover, in the simulations the shower core positions were evenly distributed in all directions up to a distance of 100 m from the station centre. The nearest boundaries of the (square) KASCADE array are in two directions only ~ 55 m and ~ 70 m away from the HiSPARC station [75]. The contribution from showers with their core position close to or beyond these boundaries are therefore suppressed. This will also reduce the number of lower multiplicity events observed by the HiSPARC station.

Finally, one month of data (April 2019) from four closely spaced four-detector diamond shaped stations (#501, #510, #512 and #513) was analysed [125]. The relative distance between the centres of the stations ranges from ~ 1.5 m to ~ 5 m. The direction of showers was reconstructed provided all four stations triggered at the same time and all 16 detectors observed a signal corresponding to at least 2 MIPs. These conditions favour the high multiplicity region in air showers and resulted in 123800 events. In each station the direction of the shower was reconstructed. By pairwise comparing the directions 6 distributions were obtained. For each distribution the 1σ difference between the two measurements was calculated. The results are listed in Table 4.1. They agree well with the outcome of the KASCADE data analysis.

4.3 EAS energy reconstruction

Despite the evident limitations of a single HiSPARC station, i.e. the limited number of detectors, the relatively small distance between the detectors and the limited precision in the determination of the number of particles traversing a detector, it is possible to reconstruct the energy of the primary cosmic ray using a single four-detector station. The energy is determined by fitting a lateral density function (LDF), i.e. an analytical description of the particle densities in EAS footprints, to the measured particle densities. The number of particles traversing a detector is determined by dividing the measured pulse integral by the MIP-peak value. Since only the particle numbers at four detector positions can be determined, the maximum number of free parameters in the LDF is three; two for the core position and one for the energy. The core positions of low energy showers ($\sim 10^{14.5}$ eV to $\sim 10^{15.5}$ eV) are expected to lie within the station since EASs with their core outside the station are not likely to result in a trigger. For large showers there are two solutions to the LDF fitting procedure; one with the core inside and one outside the station area. Also, if all four detectors measure a similar number of particles, the data contain no information that can be used to accurately reconstruct the core position and thus the energy. Finally, in order to determine the energy flux, the effective surface area of an EAS footprint as function of energy needs to be known. Proton induced CORSIKA simulations in the energy range from $10^{14.5}$ eV to $10^{16.5}$ eV have been used to determine the effective surface area and to define the LDF.

Figure 4.3 shows the simulated particle numbers as a function of distance to the shower core for multiple energies. For each shower the number of particles that traverse a 1 m by 0.5 m detector has been determined for various core positions. The markers display the averages of these particle numbers. For each energy a different marker is used. Only perpendicular incident proton simulations are shown. The fluctuation in the number of particles within showers of the same energy is large. The shaded regions show the 1σ spread. The lines show the LDF used for the energy reconstruction. Despite the limited number of free parameters, the particle numbers are still well described by the function. A modification of the Nishimura-Kamata-Greisen formula [1, and references therein] has been used as LDF. The number of free parameters in the original NKG formula has been reduced. The age parameter which is related to the shower maximum is effectively taken as a constant. In the simplified NKG formula the number of particles N at distance r is given by:

$$N(r) = A \left(\frac{r}{r_o} \right)^a \left(1 + \frac{r}{r_o} \right)^b \quad (4.3)$$

with $r_o = 29.6$ m, $a = -0.566$, $b = -2.57$ and A the fit parameter related to the energy. For inclined showers the particle numbers are reduced due to the increase in path length through the atmosphere. This is corrected for by using:

$$A_{\perp} = A \cdot \exp \left(p \left(\frac{1}{\cos \theta} - 1 \right) \right) \quad (4.4)$$

with θ the zenith angle and $p = 6.937$. The energy (eV) of the primary cosmic ray is then calculated with:

$$\log(E) = c \cdot (\log(A_{\perp}) + d) \quad (4.5)$$

Figure 4.3: The simulated average number of particles that fall inside a 0.5×1 m rectangle as a function of distance to the shower core at different energies. The markers show the average particle numbers. The shaded regions show the 1σ fluctuations. The lines show the modified NKG formula for each energy.

here $c = 0.797$ and $d = 17.62$. The modified NKG formula is circle symmetric and two parameters are required to determine the core position.

Three months of coincidences between stations 501 and 510 have been used to investigate the energy resolution obtained using the modified NKG method. Only events in which all 8 detectors of both stations measured a signal above 2 MIPs are considered. Furthermore, only events for which both directions deviate less than 15° are used. Also, the average zenith angle has to be less than 35° . Finally, if the spread in the number of MIPs in the four detectors is less than 2, the event is discarded. This selection avoids events with similar particle numbers that contain no information about the core position. Coincident events between station 501 and 510 provide two independent energy measurements. Per reconstruction two initial guesses for the parameters are used. One with the core position inside the four detectors and another one outside. The fit parameters of the solution with the lowest χ^2 value are used. If the best χ^2 value of one of the two stations is below 5, the event is discarded. Figure 4.4 shows the distributions of reconstructed EAS energy differences between station 501 and 510. Four distributions are displayed each containing a selection of energies as determined by station 501 (within a $\log(E) = 0.5$ bin width). At higher energies a bimodal distribution appears reflecting the two solutions for the core position. Multiple stations at sufficiently large distance are required to resolve this problem.

The cosmic ray energy spectrum is obtained by dividing the distribution of energy measurements by the solid angle (zenith angle of 35°), the time span (3 months) and the effective surface area of an EAS footprint. CORSIKA simulations have been used to obtain the radius at which the particle number drops below 2 (fig. 4.3). The effective surface area at an energy is determined as the area of a circle with that radius. The radii at intermediate energies have been estimated by fitting a second order polynomial to the radii of the simulated

Figure 4.4: Distributions of reconstructed EAS energy differences between station 501 and 510 (colour online). Four distributions are displayed each containing a selection of energies as determined by station 501 (within a $\log(E) = 0.5$ bin width). At higher energies a bimodal distribution appears reflecting the two solutions for the core position (inside and outside the station).

energies. Figure 4.5 shows the energy spectrum obtained using stations 501 (red stars) and 510 (blue dots). Both stations yield very similar results. For energies between $10^{14.8}$ eV and $10^{15.5}$ eV (dotted lines) a slope (α) has been fitted to both distributions (solid lines). The values of these slopes (2.85 and 2.86) are similar and do not deviate much from the known value of 2.7 [1]. For higher energies the measured energy spectrum starts to soften whereas a steepening is expected. This follows from the bimodal distribution at higher energies (fig. 4.4). If only solutions to the energy reconstruction problem with the core position inside the four detectors are taken into account, the spectrum steepens rapidly and no energies larger than 10^{16} are measured. The black dashed line shows the known energy spectrum with a steepening to a slope of 3.1 at 3×10^{15} eV. The large offset between the HiSPARC measurements and the spectrum is due to the detection efficiency and because of the numerous analysis cuts that are applied (e.g. all detectors have at least 2 MIPs). This leads to an overestimation of the effective surface area and effective solid angle, affecting the vertical scaling of the measured flux. More simulations are needed to include the detection efficiency and analysis cuts in the determination of the effective surface area and solid angle.

A similar analysis using KASCADE data has been carried out. Unfortunately the number of KASCADE reconstructions was too limited for a decisive analysis. The uncertainty in the $\sim 10^{15}$ eV region seems to agree with the analysis using stations 501 and 510. For two-detector stations it is not possible to reconstruct the energy of individual EASs. However, by investigating the pulse height distribution it is possible to probe the cosmic ray energy spectrum. This is discussed in chapter 5. In several regions stations are positioned close enough that a combination of stations can be used for energy reconstruction. A preliminary study with the Science Park Cluster [124, chapter 7] has been carried out. A more elaborate

Figure 4.5: The energy spectrum obtained using stations 501 (red stars) and 510 (blue dots). For energies between $10^{14.8}$ eV and $10^{15.5}$ eV (dotted lines) a slope (α) has been fitted to both distributions (solid lines). For higher energies the measured energy spectrum starts to soften whereas steepening is expected. This is due to the bimodal energy reconstruction for higher energies. The black dashed line shows the known energy spectrum. The large offset between the HiSPARC measurement and the spectrum is due to the detection efficiency and because of the numerous analysis cuts that are applied. These affect the vertical scaling of the measured flux.

study is presented in chapter 6.

4.4 Shower detection

To derive the EAS detection efficiency of a station a detailed comparison has to be made between the measured detector response curve and the pulse height distribution obtained in the simulation. Showers are again generated in an energy range from 10^{13} to $10^{16.5}$ eV following the cosmic ray energy spectrum with randomly chosen directions and EAS core positions.

4.4.1 Pulse height distribution

Figure 4.6 shows the pulse height distribution of a detector in a two-detector station compared to simulations. For pulses in excess of -400 mV the simulation (blue) agrees reasonably well with the data (red). Note that EASs with higher energies than $10^{16.5}$ eV are not included. For small pulses however, there appears to be a clear discrepancy. In the simulation however, an important contribution is absent. Only EASs with energies larger than 10^{13} eV are considered. Lower energy showers responsible for the single muon background are not taken into account. When an energetic muon decays prior to reaching the Earth it will produce an energetic electron. This electron initiates an electromagnetic ‘mini-shower’. These muon-induced mini-showers are indeed present in for instance 10^{10} eV proton induced CORSIKA showers. Adding this contribution resolves the discrepancy.

Alternatively, contributions from muon-induced mini-showers can also be rejected. As the number density of these mini-showers is low, the probability of detecting a mini-shower rapidly decreases when three or more detectors are required to produce a signal in excess of -30 mV. Figure 4.7 shows the simulated pulse height distribution for a detector in a four-detector station (blue) and the measured pulse height spectrum (red). All four detectors generated a signal in excess of -30 mV. The discrepancy for small pulse heights completely disappears; demanding a signal in all four detectors completely removes contributions from single muon induced mini-showers. Contrary to what is observed in figure 4.6, the experimental data now show a pronounced excess for large pulses. Since EAS energies beyond $10^{16.5}$ eV are not included, the simulations underestimate the contribution from EASs with higher particle densities.

The pulse height distributions in figures 4.6 and 4.7 receive contributions from electrons, muons and gamma rays. This is demonstrated in figure 4.8 where the contribution from a number of particles (and their combinations) to the simulated spectrum in figure 4.6 (blue) is shown. The contributions from one electron (black), one gamma (red), one muon (light blue), two electrons (green) and electron plus gamma (purple) are shown separately. Small pulses are predominantly generated by single gamma rays and single low energy electrons. The blue histogram is the sum of all these contributions and also includes higher multiplicity combinations; it matches the simulated pulse height distribution in figure 4.6. Figure 4.8 also demonstrates that the pulse height is a measure for the number of particles that traverses a detector.

Figure 4.6: Pulse height distribution of a detector in a two-detector station (red, solid) compared to simulations (blue, dashed). The contribution from random coincidences has been removed from the data while the MIP-peak value has been corrected for temperature fluctuations. For large pulses, data and simulations agree rather well. The discrepancy for small pulses is caused by the absence of muon induced ‘mini-showers’ (muons decaying into single electrons which in turn generate an electromagnetic shower) in the simulations. These events are caused by the large number of showers for which the primary particle carries an energy less than $\sim 10^{12.5}$ eV.

Figure 4.7: Pulse height distribution of a detector in a four-detector station (red, solid) compared to simulations (blue, dashed). Only events that contain a signal in excess of -30 mV in each of the four detectors are selected. In contrast to figure 4.6, there is no discrepancy between data and simulation for small pulse heights as the size of the shower footprint has to be as large as or larger than the size of the station (i.e. EASs with an energy larger than $\sim 10^{13}$ eV). The discrepancy at large pulse heights becomes apparent; the simulations do not include EASs with energies larger than $10^{16.5}$ eV.

Figure 4.8: Simulated response (blue histogram) of a detector in a two-detector station (colour online). The distribution receives contributions from electrons (single electrons: black, 2 electrons: green), single muons (light blue), single gamma rays (red), single electron plus single gamma (purple) and higher multiplicities of various combinations (not shown separately). This simulation can be used to attribute a likelihood to finding the particle multiplicity in a detector at a specific pulse height.

Figure 4.9: EAS detection efficiency of 10^{15} eV showers as function of distance between the shower core and station centre for zenith angles of 7.5° (dots), 30° (crosses) and 45° (stars). At 7.5° and for small core distances the efficiency is close to 1. For larger core distances the EAS detection efficiency decreases rapidly. The lines display the parametrisation in eq. 4.6.

4.4.2 EAS detection efficiency

The probability for detecting an EAS with a single two-detector station as function of distance between the shower core and station centre and zenith angle is investigated with CORSIKA shower simulations. The station was exposed to EASs with an energy of 10^{15} eV. The direction of primary cosmic rays is chosen uniformly between 0° and 60° . The positions of the shower core with respect to the station centre were homogeneously distributed within a circle with a radius of 150 m. Note that for increasing zenith angle the size of the shower footprint augments, while at the same time the chance of particle absorption in the atmosphere significantly increases. Both effects result in a lower particle density in the footprint. Also, the number of EASs that arrive at large core distances is larger than at small core distances because of the homogeneous exposure and the increasing effective area at larger (ring shaped) core distance bins. The same goes for the zenith angle. The solid angle Ω of the circular field of view subtended by a rotated zenith angle θ is given by $\Omega = 2\pi(1 - \cos(\theta))$. This implies that larger zenith angles result in larger solid angles.

Figure 4.9 shows the EAS detection efficiency as function of core distance for zenith angles of 7.5° (blue dots), 30° (blue crosses) and 45° (blue stars). At 7.5° and for small core distances the efficiency is close to 100%. With increasing core distance the EAS detection efficiency rapidly decreases. Figure 4.10 shows the detection efficiency as function of zenith angle for core distances of 10 (blue dots), 25 (blue crosses) and 50 m (blue stars). If the shower core is close to the centre of the station (e.g. 10 m in the figure) the EAS detection efficiency remains close to 100% for even relatively large zenith angles. If the shower core is further away from the station centre the efficiency becomes much lower.

Figure 4.10: EAS detection efficiency of 10^{15} eV showers as function of zenith angle for core distances of 10 (dots), 25 (crosses) and 50 m (stars). If the shower core is close to the centre of the station (e.g. 10 m in the figure) the EAS detection efficiency stays close to 1 up to relatively large zenith angles. The lines display the parametrisation in eq. 4.6.

A 2D parametrisation (combining the fits in figures 4.9 and 4.10) is derived that describes the detection efficiency as a function of the distance between station and shower core, and zenith angle. For small core distances, because of the high number density near the shower core, the EAS detection efficiency as function of core distance is expected to be 100%. At a distance r_m , at which the probability for EAS particles to miss a detector becomes substantial (e.g. for the 7.5° EAS detection efficiency in fig. 4.9 the value of r_m is ~ 20 m), the efficiency decreases. For core distances larger than r_m the radial dependency of the EAS detection efficiency can accurately be described by the formula of an exponentially modified Gaussian distribution. The zenith angle dependence is obtained by shifting r_m to smaller and eventually negative values depending on the zenith angle. This leads to the following parametrisation:

$$p(\mathbf{r}, \boldsymbol{\theta}) = \begin{cases} f(r_m, \alpha, \mu(\boldsymbol{\theta}, \chi, \rho), \sigma, \lambda) & \text{for } r < r_m \\ f(\mathbf{r}, \alpha, \mu(\boldsymbol{\theta}, \chi, \rho), \sigma, \lambda) & \text{for } r \geq r_m \end{cases} \quad (4.6)$$

with α , χ and ρ fit parameters. The exponentially modified Gaussian distribution $f(r, \alpha, \mu, \sigma, \lambda)$ is given by:

$$f(r, \alpha, \mu, \sigma, \lambda) = \alpha \exp \left[\frac{\lambda}{2} (2\mu + \lambda\sigma^2 - 2r) \right] \times \operatorname{erfc} \left(\frac{\mu + \lambda\sigma^2 - r}{\sqrt{2}\sigma} \right) \quad (4.7)$$

μ and σ are the mean and standard deviation of the Gaussian part of the distribution and λ is the rate of the exponential distribution. The $\operatorname{erfc}(x)$ factor is the complementary error

Figure 4.11: A 3D display of the parametrised EAS detection efficiency of 10^{15} eV proton induced showers. For small zenith angles and core distances the efficiency is close to 1. For larger angles and distances the efficiency decreases but the surface area and solid angle increase substantially.

function and is given by:

$$\operatorname{erfc}(x) = \frac{2}{\sqrt{\pi}} \int_x^{\infty} e^{-y^2} dy \quad (4.8)$$

The value of r_m is the mode of $f(r, \alpha, \mu, \sigma, \lambda)$ and depends on μ , σ and λ . The function $f(r)$ is thus continuous at r_m . The shift of r_m as function of the zenith angle depends on μ . The zenith angle dependency is thus absorbed in μ :

$$\mu(\theta, \chi, \rho) = (\chi + \rho) \exp[-(\sec \theta - 1)] - \chi \quad (4.9)$$

The exponential decrease of μ (and thus r_m) with the secant of the zenith angle can be thought of as an exponential diminishing of the shower particle density for larger travel distances through the atmosphere.

The lines in figures 4.9 and 4.10 show the parametrisations obtained by fitting α , σ , λ , ρ and χ to the simulated EAS detection efficiency. The obtained fit parameters are 2.15, 20.9, $7.22 \cdot 10^{-2}$, 7.84 and 129 resp. Figure 4.11 shows a 3D plot of the parametrised EAS detection efficiency. With increasing EAS energy the ‘plateau’ at ~ 1 for small zenith angles and core distances increases. The shower detection efficiencies at other primary energies are discussed in chapter 5.

Chapter 5

Probing the cosmic ray energy spectrum using two scintillators

If a low energy cosmic ray (e.g. 10^{11} eV) hits the Earth's atmosphere, the air shower dies out before reaching the ground. The majority of shower particles are absorbed at high altitude. Only energetic remnants, of which mainly muons (and neutrinos), are able to reach ground level. The flux of perpendicularly incident muons at sea level is $\sim 70 \text{ m}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ above 1 GeV [2]. If an energetic muon decays before reaching the ground, the decay electron (positron) emits gamma radiation due to Bremsstrahlung. Energetic gamma rays will interact with matter via pair production. The two processes (Bremsstrahlung and pair production) generate an electromagnetic shower. Figure 5.1 shows an example of such a shower in a 10^{11} eV proton CORSIKA [55] simulation. The upper right figure shows the longitudinal profile, i.e. the number of particles per type as function of atmospheric depth. The original shower dies out and, at a depth $\sim 900 \text{ g cm}^{-2}$, a second, electromagnetic (e.m.), shower appears. The bottom right plot shows the energy per particle type as function of the atmospheric depth. In one of the first interactions, ~ 40 GeV of the 100 GeV proton is forwarded to a single muon. At a height of 1.6 km (855 g cm^{-2}) this muon decays and a large fraction of its energy is transferred to the electron (positron) which initiates an e.m. shower. The left figure shows the footprint created by the shower at the ground. The particle density is very small. The position of the secondary shower core is shifted with respect to the original direction of the cosmic ray proton due to absorption of the shower particles other than the muon, and neutrino(s) escaping detection. Muon decay is the dominant source for electrons at sea level. The total flux of perpendicular incident electrons and positrons above 10 MeV is $\sim 30 \text{ m}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ [2].

5.1 Pulse integral distribution (PID)

The value of the PMT pulse integral, i.e. the area under the pulse, is directly proportional to the number of scintillation photons that reach the PMT, and thus to the number of particles traversing the detector (MIPs). The energy loss of a MIP follows Landau's theory [111].

Figure 5.1: Example of a muon decay induced shower in a 10^{11} eV proton CORSIKA [55] simulation. The upper right figure shows the longitudinal profile, i.e. the number of particles per particle type as function of atmospheric depth. The original shower dies out and, at a depth ~ 900 g cm⁻², a second (very large) shower emerges. The bottom right plot shows the energy per particle type as function of the atmospheric depth. In one of the first interactions, ~ 40 GeV of the available 100 GeV is transferred to a single muon. At a height of 1.6 km (855 g cm⁻²) this muon decays and a large part of its energy is passed on to an electron (positron) which ignites an e.m. shower. The left figure shows the e.m. shower footprint at the ground. The position of the shower core is slightly shifted from the direction of the primary proton as particles are absorbed and neutrino(s) remain undetected.

The Landau distribution has a peak at the most probable energy loss with a pronounced tail towards higher energies. If multiple particles simultaneously traverse a detector, the energy loss in the detector is described by a sum of Landau distributions. The shape of the pulse integral distribution is then determined by the number of MIPs that traverse the detector within the trigger time window (1.5 μ s). The energy of the primary cosmic ray is directly proportional to the number of EAS particles in the footprint at the ground.

5.1.1 Analysing the PID

In a first approach all cosmic rays are assumed to stem from the zenith. The particle densities can be approximated by the lateral density profile from AGASA [68]:

$$S(r) \propto \left(\frac{r}{r_M}\right)^{-1.2} \left(1 + \frac{r}{r_M}\right)^{-(\eta-1.2)} \times \left[1 + \left(\frac{r}{1000}\right)^2\right]^{-0.6} \quad (5.1)$$

with distance to the shower core r in meter, $\eta = 3.84$ and Molière radius $r_M = 91.6$ m. The energy associated with this lateral density profile is given by [69]:

$$E = a \cdot 10^{17} \cdot (S(600))^b \quad [\text{eV}] \quad (5.2)$$

with $a = 2.03$ and $b = 1.0$. The dashed lines in figure 5.2 show EAS particle densities as function of distance to the shower core for primary energies of 10^{13} (blue), 10^{14} (red), 10^{15} (green) and 10^{16} eV (orange). Obviously, as the EAS energy increases, the size of the footprint increases as well. Next, the particle density per unit area is rounded to an integer. This is illustrated by the solid lines in figure 5.2. As an example a 10^{13} eV EAS footprint with a regular pattern is shown in figure 5.3. Within each ring the particle density is constant. Each dot represents a single particle.

If a detector with a size of 1 m^2 is randomly projected at the density map, the probability to detect x number of particles scales with the surface area of each ring. For $x = 1$ the probability is equal to the surface area of the outermost ring divided by the surface area of the entire disc. This is illustrated in figure 5.4 which displays the probability density to find a number of particles as a function of EAS energy. Each probability density represents a single energy PID. When many particles simultaneously traverse the detector, a large pulse integral is generated. If only one particle traverses the scintillator, the value of the pulse integral follows a single Landau distribution.

In order to predict the PIDs more accurately, a Monte Carlo simulation is constructed that includes multiple EAS zenith angles and accurate EAS evolution and detector description.

5.1.2 Detector separation

The small particle densities at low energy EASs ($\lesssim 10^{13}$ eV) generate a steeply falling PID, i.e. there is a relatively high probability to detect just 1 or 2 particles; higher multiplicities at this energy become rare. Increasing the distance between the detectors then translates

Figure 5.2: The dashed lines show the lateral density profiles at sea level for 10^{13} (blue), 10^{14} (red), 10^{15} (green) and 10^{16} eV (orange) showers described by eq. 5.1. The solid lines show the multiplicity rounded to the nearest integer. In the calculation only EASs from the zenith are considered.

into an energy cut. Since the size and shape of the PID directly depends on the number of particles that ‘simultaneously’ traverse the detector, it provides an indirect measure for the energy of the primary cosmic ray. Figure 5.2 shows that for 10^{13} eV showers (blue curve) the probability to detect particles beyond 20 m from the shower core becomes extremely small. Thus, if two HiSPARC detectors are placed 40 m apart, the EAS detection probability at this energy vanishes. Since it is impossible to select single energy EASs, a PID obtained by a station can be thought of as a sum of single energy PIDs. Introducing an energy cut by increasing the detector separation will affect the shape of the station’s PID as single low energy PIDs are excluded from the collection.

Figure 2.16 shows the measured distribution of arrival time differences for particles in the two detectors. The times at which the PMT pulses exceed the threshold are taken as arrival times. The plateau of random coincidences (green striped region) extends to small time differences (blue horizontal line). The peak is caused by particles belonging to EASs. For time differences smaller than 300 ns the random coincidences are obviously indistinguishable from EASs. However, the PID distribution obtained by selecting random coincidences can be subtracted (proportional to the number of background events - blue crossed region) from the PID for time differences smaller than 300 ns.

A small experiment has been carried out in which the PID is measured for different detector separations (5, 15 and 35 m). The result is shown in figure 5.5. The number of single MIP events decreases with increasing detector separation. The number of large pulse integrals stays approximately constant since these events are caused by high energy showers.

Figure 5.3: Example of a 10^{13} eV perpendicular incident EAS footprint. Each dot represents a single particle. Within each ring the particle density is taken constant. When a detector with a size of $1 \times 1 \text{ m}^2$ is randomly projected on the density map, the probability to detect x number of particles scales with the surface area of each ring. For $x = 1$ the probability is equal to the surface area of the outermost ring divided by the surface area of the entire disc.

Figure 5.4: The probability to detect a number of particles in the footprint at a fixed energy. For low energy EASs the probability to detect a single MIP is relatively large compared to higher multiplicities. With increasing energy the slope of the distributions changes significantly.

Figure 5.5: PID for different detector separations. By increasing the distance between the detectors, the station will not trigger on low energy EAS footprints due to their small particle density (fig. 5.4). The number of single MIP detections decreases proportionally to the increasing detector separation. The number of large pulse integrals (multiple simultaneous particles) traversing the detector stays approximately constant since these events are caused by high energy showers which are still detected at large detector separations.

Figure 5.6: PIDs of ten detector combinations in a four-detector (diamond shaped configuration) station. Each colour represents one detector. Per detector two or three PIDs are displayed. The detector separation for each combination is 10 m. Combinations with the same detector (e.g. red lines) are very similar. The difference between the detectors is larger, especially at large pulse integrals (see orange and green lines).

5.1.3 Systematic uncertainties

The relation between the shape of the PID and the energy of the primary cosmic ray can then be used to probe the cosmic ray flux at a certain energy range. To quantify systematic differences between detectors, the PIDs of detector combinations in a four-detector station (diamond shaped configuration) [126] have been compared. Each detector in this station can be paired with three other detectors. The four sides of the diamond are 10 m. The long diagonal combination is discarded. This results in ten PID distributions. Figure 5.6 shows the ten distributions of the four detectors. All combinations with ‘detector one’ are displayed in blue, all combinations with detector two are displayed in red, etc. The PIDs obtained with the same detector are very similar. The difference between detectors is larger and becomes more visible at large pulse integrals (see orange and green lines). This indicates that there are instrumental differences caused by variations in the number of scintillation photons reaching the PMT, large pulse PMT response, etc. After closer inspection, systematic differences between the PIDs up to ~ 35 Vns (~ 12 MIPs) are small.

5.2 EAS Simulations

A large sample of EASs for primary cosmic rays with an energy of 10^{12} , 10^{13} , 10^{14} , 10^{15} and 10^{16} eV has been generated with CORSIKA. Only proton initiated showers are considered. The showers have been generated with zenith angles ranging from 0° to 60° in steps of 3.75° .

Figure 5.7: Simulated PIDs at five different energies. As expected from figure 5.4 the PID depends on the energy of the EASs. Contrary to the model, a full detector simulation is carried out with isotropically selected EASs and uniformly chosen core distances. Only proton induced EASs are considered. The difference becomes evident at large pulse integrals.

The interactions are described by the models listed in chapter 1.2.2. The full particle shower was simulated (no ‘thinning’). The location of the EAS shower cores were randomly chosen within a circle with a radius of 150 m. The two-detector station is at the centre of the circle. The arrival direction (azimuth and zenith) was chosen isotropically (random points on the surface of a unit sphere). The response of the scintillator and light-guide to particles traversing the detector was simulated using GEANT4 in combination with the parametrised PMT response (chapter 3.4.2). Finally, the HiSPARC trigger conditions were applied.

Figure 5.7 shows the normalized, simulated PIDs for the five different energies. At higher energies the relative abundance of large pulses increases considerably. By fitting a linear combination of the simulated distributions to the experimentally observed spectrum, the cosmic ray flux at a fixed energy interval can be estimated.

5.2.1 Effective surface area and solid angle

EASs at large zenith angles result in lower particle densities at ground level because of increased absorption due to the larger path length through the atmosphere. Moreover, the particle density observed in the detection station strongly depends on the distance to the shower core. These two effects need to be quantified in order to calculate the cosmic ray flux. For this an effective surface area and effective solid angle are introduced. The fraction of events that results in a trigger is defined as the ‘EAS detection efficiency’ (ε). The left plot in figure 5.8 shows ε for 10^{15} eV air showers as function of the zenith angle and distance to the shower core. The maximum efficiency occurs at small r and small zenith angle θ .

Integrating over the solid angle yields the effective solid angle as a function of core distance (upper right plot):

$$\Omega(r) = \int_0^{2\pi} \int_0^{\pi/2} \varepsilon(\theta, r) \sin \theta d\theta d\phi \quad (5.3)$$

The effective solid angle can accurately be parametrised using the exponentially modified Gaussian distribution (earlier used in chapter 4.4.2):

$$\begin{aligned} \Omega(r; \alpha, \mu, \sigma, \lambda) = & \alpha \exp \left[\frac{\lambda}{2} (2\mu + \lambda\sigma^2 - 2r) \right] \\ & \times \operatorname{erfc} \left(\frac{\mu + \lambda\sigma^2 - r}{\sqrt{2}\sigma} \right) \end{aligned} \quad (5.4)$$

with α a scaling parameter, μ and σ the mean and standard deviation of the Gaussian part of the distribution and λ the rate of the exponential part. The complementary error function, $\operatorname{erfc}(x)$, is given by:

$$\operatorname{erfc}(x) = \frac{2}{\sqrt{\pi}} \int_x^\infty e^{-y^2} dy \quad (5.5)$$

Integrating the detection efficiency over the surface area (polar coordinates r and ζ) yields the effective surface area as a function of zenith angle (bottom right plot in figure 5.8):

$$A(\theta) = \int_0^{2\pi} \int_0^\infty \varepsilon(\theta, r) r dr d\zeta \quad (5.6)$$

The effective surface area can be parametrised using the following formula:

$$A(\theta) = a \exp \left(-b \left(\frac{1}{\cos \theta} - 1 \right) \right) \quad (5.7)$$

with a and b fit parameters. Since, in order to obtain the flux, the number of events needs to be divided by both the effective solid angle and the effective surface area, there is no need to evaluate them separately. Instead, the two are combined:

$$A\Omega = \int_0^{2\pi} \int_0^\infty \Omega(r) r dr d\zeta \quad (5.8)$$

$$= \int_0^{2\pi} \int_0^{\pi/2} A(\theta) \sin \theta d\theta d\phi \quad (5.9)$$

Table 5.1 shows the fit parameters that describe the effective solid angle and surface area for the simulated energies (for 10^{15} eV proton showers $A\Omega$ is $8.58 \cdot 10^3 \text{ m}^2 \text{ sr}$). The $A\Omega$ values can be calculated from eqs. 5.8 or 5.9, or by direct summation of the two-dimensional histogram in figure 5.8. The last column in table 5.1 lists the averages and standard deviations of these three methods.

Figure 5.9 shows the five $A\Omega$ values. The interpolation is defined by the following equation:

$$\log_{10}(A\Omega) = ax^2 + bx + c \quad (5.10)$$

Table 5.1: The parameters in eq. 5.4 (effective solid angle $\Omega(r)$) and eq. 5.7 (effective surface area $A(\theta)$) are listed as a function of energy. The last column gives the value of the combination $A\Omega$ (eq. 5.8 or 5.9).

E [eV]	$\Omega(r)$				$A(\theta)$		$A\Omega$ [m ² sr]
	α	μ	σ	λ	a	b	
10^{12}	$1.73 \cdot 10^{-5}$	-2.3	1.0	$8.00 \cdot 10^{-2}$	$4.86 \cdot 10^{-2}$	9.66	$(2.75 \pm 0.09) \cdot 10^{-2}$
10^{13}	$8.71 \cdot 10^{-3}$	-3.1	3.6	$1.22 \cdot 10^{-1}$	7.85	6.89	5.50 ± 0.14
10^{14}	$5.44 \cdot 10^{-1}$	-10.4	8.1	$8.78 \cdot 10^{-2}$	$6.30 \cdot 10^2$	7.90	$(4.23 \pm 0.21) \cdot 10^2$
10^{15}	4.40	-14.2	24.5	$7.25 \cdot 10^{-2}$	$9.21 \cdot 10^3$	4.76	$(8.58 \pm 0.28) \cdot 10^3$
10^{16}	6.92	-50.7	63.3	$2.71 \cdot 10^{-2}$	$6.33 \cdot 10^4$	3.62	$(7.33 \pm 0.13) \cdot 10^4$

with $x = \log_{10}(E)$, $a = -0.239$, $b = 8.31$, $c = -66.8$. Extrapolation leads to an estimate at 10^{11} eV of $A\Omega = 4.2 \cdot 10^{-5}$ (red circle). A precise direct estimate at this energy from simulation is difficult because it is computationally expensive to collect a sufficiently large data set; the number of EASs that satisfy the selection criteria is extremely small. The number of triggers at an EAS energy of 10^{11} eV is approximately 400 times smaller than at 10^{12} eV. This is consistent with the estimate obtained by extrapolation of eq. 5.10.

5.3 Fitting single energy PIDs to experimental data

The data set used for figure 2.16 was used to obtain a PID. The contribution to the PID from random coincidences was subtracted (see section 5.1.2). A Bayesian method was used to fit a combination of simulated single energy PIDs in the range 10^{12} – 10^{16} eV to the experimental data. Only pulse integrals smaller than 35 Vns are considered to limit systematic differences between the detectors (figure 5.6). Signals are affected by gamma rays, and Cherenkov light generated in the light-guide [126]. Especially at lower multiplicities this contribution becomes apparent. Pulse integrals below 6 Vns (2 MIPs) are therefore discarded as well.

As shown in figure 5.9, the probability that a 10^{11} eV shower results in a footprint that triggers the station is negligible. The slope of PIDs with energies 10^{17} eV and beyond becomes rather similar to that of 10^{16} eV in the pulse integral range between 6 to 35 Vns whereas the flux at those energies rapidly decreases. The experimentally observed PID will therefore be restricted to the sum of five single energy contributions (10^{12} – 10^{16} eV):

$$\begin{aligned}
 z(n_i, \vec{x}) = & x_1 \cdot \text{PID}_{12}(n_i) + x_2 \cdot \text{PID}_{13}(n_i) \\
 & + x_3 \cdot \text{PID}_{14}(n_i) + x_4 \cdot \text{PID}_{15}(n_i) \\
 & + x_5 \cdot \text{PID}_{16}(n_i)
 \end{aligned} \tag{5.11}$$

Here $\vec{x} \equiv (x_1, x_2, x_3, x_4, x_5)$, n_i is the bin value, $z(n_i)$ is the expected number of events in each bin and each $\text{PID}(n_i)$ is a single energy model (fig. 5.7). The uncertainty in the number of entries in the bins of the experimentally observed PID is described by a Poisson distribution. The probability to obtain a number of counts y_i in bin n_i given $\vec{x}$ is given by:

$$p(y_i, n_i | \vec{x}) = P(y_i, z(n_i, \vec{x})) \tag{5.12}$$

Figure 5.8: Left: The detection efficiency (ε) for 10^{15} eV proton induced showers as function of core distance (r) and zenith angle (θ). Top right: the detection efficiency integrated over the zenith angle yields the effective solid angle as function of core distance ($\Omega(r)$, blue points) which can accurately be described using the parametrisation in eq. 5.4 (black line). Bottom right: the detection efficiency integrated over the core distance yields the effective surface area as function of zenith angle ($A(\theta)$, blue points) and can be described by the parametrisation in eq. 5.7 (black line).

Figure 5.9: The blue curve (eq. 5.10) shows the interpolation of the $A\Omega$ values (blue dots) listed in in table 5.1. $A\Omega$ at 10^{11} eV (red circle, $A\Omega = 4.2 \cdot 10^{-5} \text{ m}^2 \text{ sr}$) is obtained by extrapolation.

with the Poisson distribution:

$$P(y, z) = \frac{z^y}{y!} e^{-z} \quad (5.13)$$

Bayes' rule can be exploited to define a probability to obtain the fit parameters $\vec{x}$.

$$p(\vec{x}|N, Y) = \frac{p(N, Y|\vec{x})p(\vec{x})}{p(N, Y)} \quad (5.14)$$

Here N and Y are the combined collection of elements n_i and y_i . The denominator $p(N, Y)$ is a normalization constant. The $p(\vec{x})$ is known as the prior probability distribution. The prior states that the parameters x_1, x_2, x_3, x_4 and x_5 cannot become negative. The function $p(\vec{x}|N, Y)$ is the posterior probability distribution. The $p(N, Y|\vec{x})$ function is the likelihood (the product of conditional probabilities):

$$p(N, Y|\vec{x}) = \prod_{i=1}^M p(y_i, n_i|\vec{x}) = \mathcal{L} \quad (5.15)$$

Since the slope differences between the PIDs occur at higher multiplicities, a gradually larger weight is assigned with increasing multiplicity. This leads to a weighted likelihood:

$$\hat{\mathcal{L}} = \prod_{i=1}^M p(y_i, n_i|\vec{x})^{w(n_i)} \quad (5.16)$$

with $w(n_i)$ the weight function:

$$w(n_i) = 1.161^{n_i} \quad (5.17)$$

Table 5.2: Best fit for the number of events with their uncertainties.

Energy [eV]	Number of events
10^{12}	$(4.09 \pm 1.76) \cdot 10^4$
10^{13}	$(2.04 \pm 0.23) \cdot 10^5$
10^{14}	$(1.25 \pm 0.20) \cdot 10^5$
10^{15}	$(5.65 \pm 1.32) \cdot 10^4$
10^{16}	$(2.43 \pm 1.04) \cdot 10^4$

which corrects for the number of entries in the lower ($1.7 \cdot 10^4$ at 6 Vns) and higher bins (231 at 35 Vns). By taking the logarithm of this weighted likelihood, the product converts into:

$$\log(\hat{\mathcal{L}}) = \sum_{i=1}^M w(n_i) \cdot \log \left(\frac{z_i^{y_i}}{y_i!} e^{-z_i} \right) \quad (5.18)$$

$$= \sum_{i=1}^M w(n_i) \cdot (y_i \log(z_i) - z_i - \log(y_i!)) \quad (5.19)$$

$$= \sum_{i=1}^M w(n_i) \cdot (y_i \log(z_i) - z_i - C) \quad (5.20)$$

with $z_i = z(n_i, \vec{x})$ and C is a constant.

Instead of directly maximizing the posterior probability distribution, a range of parameters ($\vec{x}$) are explored. This is done using a Markov Chain Monte Carlo (MCMC) algorithm [127]. Figure 5.10 shows (lower dimensional) subsets of the sampled (five dimensional) posterior probability distribution. The upper (on the diagonal) Gaussian shaped histograms show the sample selection in the dimension of the fit parameters. The median of the histogram (red lines) is taken as the best fit. The uncertainty is shown by the standard deviation (green lines). The best fit values are $(3.01 \pm 0.35) \cdot 10^4$, $(2.32 \pm 0.05) \cdot 10^5$, $(1.09 \pm 0.03) \cdot 10^5$, $(5.63 \pm 0.20) \cdot 10^4$, $(2.63 \pm 0.16) \cdot 10^4$ for 10^{12} to 10^{16} eV resp. The other subplots display the relation between two fit parameters. There is some interdependence between the fit parameters of neighbouring energies. This is especially pronounced at fit parameters x_4 and x_5 (fourth sub-plot in bottom row) due to the relatively small slope differences between the 10^{15} and 10^{16} eV PIDs (figure 5.7). The resulting fit to the experimental data is shown in figure 5.11.

In addition to the statistical uncertainty in the experimental data, the single energy models also have an intrinsic statistical uncertainty. Creating larger data sets for the single energy PIDs is currently limited by the generation of simulated EASs which is computationally expensive. The uncertainty has been estimated by resampling the single energy PIDs. The number of events in each bin was randomly resampled following Poisson statistics. A combination of these new PIDs was fitted to the experimental data as well. This procedure was carried out multiple times. The mean and standard deviation of the best fit parameters are listed in table 5.2.

Figure 5.10: Subsets of the sampled posterior probability distributions. The upper Gaussian shaped histograms show the sample selection in the dimension of the fit parameters ($\vec{x}$). The median of the histogram (red lines) is taken as the best fit. The uncertainty in the fit is shown by the standard deviation (green lines). The other subplots display the relation between two fit parameters. There is some interdependence between the fit parameters of neighbouring energies. This is more pronounced for x_4 and x_5 (fourth sub-plot in bottom row). See also figure 5.7.

Figure 5.11: A linear combination of five simulated PIDs (coloured lines, see figure 5.7) fitted to the experimentally obtained PID (thick grey line). The black line shows the best fit. The bottom plot gives the ratio of the experimental data and the fit.

Table 5.3: Cosmic ray flux values obtained using a two-detector HiSPARC station.

Energy [eV]	Flux [$\text{m}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{GeV}^{-1}$]
10^{12}	$(2.08 \pm 0.93) \cdot 10^{-4}$
10^{13}	$(5.19 \pm 0.60) \cdot 10^{-7}$
10^{14}	$(4.14 \pm 0.70) \cdot 10^{-10}$
10^{15}	$(9.22 \pm 2.20) \cdot 10^{-13}$
10^{16}	$(4.64 \pm 2.01) \cdot 10^{-15}$

5.4 Cosmic ray flux

The estimated number of events per energy decade derived from the fit can be used in combination with the effective surface area and solid angle to obtain the cosmic ray flux as a function of energy. The fluxes are calculated using:

$$F = \frac{N_{\text{events}}}{A\Omega \cdot t \cdot \Delta E} \quad (5.21)$$

with t the duration of the experiment ($t = 29 \text{ days} = 2.506 \cdot 10^6 \text{ s}$) and ΔE the width of the energy bin (e.g. $10^{15.5} - 10^{14.5} \approx 2.85 \cdot 10^{15} \text{ eV}$). The flux values are listed in table 5.3. Figure 5.12 shows the cosmic ray energy spectrum (circles) from several experiments [128, 129, and references therein] together with the flux values derived from HiSPARC data (red dots). The uncertainties are smaller than the dot size. The grey line represents the function in equation 1.1. The HiSPARC values agree well with the other measurements. Note that the reference flux values below 10^{14} eV are measured using spacecraft (e.g. Proton satellite [130]).

Figure 5.12: Cosmic ray fluxes at 10^{12} – 10^{16} eV from HiSPARC data (red dots) compared to results from other experiments [128, 129, and references therein] (circles). The uncertainties are smaller than the dot size. The fluxes obtained by HiSPARC agree well with the other measurements. The grey line represents eq. 1.1.

5.5 Discussion and conclusion

A HiSPARC station (at sea-level) with only two 0.5 m^2 scintillator detectors was used to probe the cosmic ray energy spectrum in the range 10^{12} – 10^{16} eV (five energy decades). One month of data shows to be sufficient to obtain flux values that are in good agreement with the results from dedicated (space-based) experiments.

The presented analysis is very different from those applied by other ground-based cosmic ray observatories. The method does not require the reconstruction of the shower core and/or shower size of individual EASs but relies on deriving the energy dependent particle multiplicity distributions in a single scintillator detector. PMT pulse integrals are used as a proxy to estimate the number of particles simultaneously traversing the detector. In comparing simulated PIDs at 10^{15} and 10^{16} eV (and beyond 10^{16} eV) with experimental data, the simulation starts to suffer from lack of statistics; showers become very large exceeding the presently available CPU power and data storage facilities. Re-doing the analysis with simulations in which ‘thinning’ is applied has not been explored but may offer an alternative. On the other hand, as becomes apparent from figure 5.7, the difference in slope of the PIDs towards higher particle multiplicities decreases with increasing energy. Moreover, at these large multiplicities, the dynamical range of the readout electronics and non-linearities in detector response require careful evaluation. By extending the distance between the detectors, the contribution from small, low energy (10^{12} – 10^{13} eV) EASs can be reduced, improving the sensitivity of the analysis towards higher energy EASs.

Since the HiSPARC network consists of more than 120 stations in which the separation between the scintillators varies between 5 and 17 m while for several stations more than 10

years of data are stored, statistics can easily be increased and systematic uncertainties can be investigated in detail.

Finally, the cosmic ray flux below 10^{12} eV could possibly be derived by increasing the altitude of the HiSPARC station and thereby compensating for the shift of the shower maximum towards higher altitudes. The two-detector station in Windhoek (Namibia), at an altitude of almost 2 km, could be used to further investigate this.

Chapter 6

Science Park cluster

6.1 Science Park stations

In chapters 4 and 5 the energy and flux reconstructions using a single HiSPARC station were discussed. With a two-detector station only the flux can be probed. With a four-detector station the energy can be determined but the reconstruction method becomes ambiguous above $10^{15.5}$ eV (figure 4.5). A combination of stations enables a more accurate EAS energy reconstruction. At the Amsterdam Science Park a collection of 12 HiSPARC stations is placed on the roofs of Nikhef and other scientific institutions. A thirteenth station is placed inside the Nikhef building. Figure 6.1 shows the locations of the 12 roof stations since late 2018. The station numbers are also denoted. At one location, four ‘diamond’ stations are essentially positioned ‘on top of each other’ (equivalent detectors are ~ 1 m apart) and only a single station is displayed (blue stars). The roof – and station – heights differ substantially. Table 6.1 lists the roof heights obtained from a technical map provided by Nikhef (cm precision). The height of station 509 is obtained from GPS measurements and is somewhat less precise. In this chapter the EAS energy and flux reconstruction using the Science Park cluster will be discussed.

6.2 Data selection and quality

Station coincidences between stations 501, 502, 503, 504, 505, 508, 509, 511 and 514 are searched for in the database from November 2018 to September 2020. During this period the stations are located as displayed in figure 6.1. Station coincidences are events in which multiple stations detect the same EAS and trigger within 10 μ s. The trigger time is the moment at which the trigger conditions are met (e.g. three signals over low threshold). The probability that a station coincidence is caused by two uncorrelated EASs is negligible. The detection rate (r) for EASs beyond 10^{14} eV in a single station is approximately 0.2 Hz. This rate rapidly decreases for higher energy showers. A HiSPARC station detects two EASs within a 10 μ s time window (τ) every $1/(2\tau r^2) = 1.25 \cdot 10^6$ s or every 2 weeks.

Figure 6.1: Location of stations at the Amsterdam Science Park cluster since late 2018. Each red dot represents a detector and each combination of four dots forms a station. The station numbers are also denoted. At one location, four ‘diamond’ stations are essentially positioned ‘on top of each other’ (stations are shifted ~ 1 m with respect to each other) and only a single station is displayed (blue stars). As can be seen from comparison with figure 2.18, one station has been relocated since its building has been demolished (former 506, now 514).

Table 6.1: Station roof heights with respect to station 501. The height of station 509 is obtained from GPS measurements (less precise), other heights come from a technical map provided by Nikhef (cm precision).

Station	Height [m]
501	0
502	0
503	-6.00
504	-0.94
505	-7.29
508	-5.33
509	0.7
510	0
511	-0.77
512	0
513	0
514	3.60

Figure 6.2 shows the data availability per station. During red periods the stations did not provide (useful) data. Only two of the four detectors were operational during the orange periods. The stations were fully operational most of the time (green). Unfortunately, problems with the absolute timing of station 508 rendered a large part of that data useless for comparison with other stations. Issues with the computer of station 511 result in quite some red periods. Station 509 was fully operational the entire period.

Only station coincidences in which stations 501, 502, 503 and 514 have triggered are considered. Requiring all Science Park stations to have detected the EAS results in a small selection of very high energy EASs. On the other hand, if only two or three stations are required to have sampled the shower, the number of EAS samples is rather limited for the LDF fit. A minimum of four stations was deemed the best trade-off between including low energy EASs ($\sim 10^{16}$ eV) and having a sufficient number of samples to reconstruct the EASs. Stations 501, 502, 503 and 514 were chosen because of their central location and proximity to each other. Station 508, despite its central location, is not included in this selection criterion because of the large period of missing data. Additionally, as the size of the EAS is typically much larger than the distance between these four stations, the core positions of the detected EASs lie approximately within a disk around these central stations. This simplifies the determination of the effective surface area of the Science Park cluster from experimental data. A more loose requirement of, for example, at least four stations (and it does not matter which ones) results in a distribution of core positions that does not approximate a disk and subsequently complicates the calculation of the effective surface area. Only one station (501) of the four stations ‘on top of each other’ is considered to avoid oversampling one part of the shower footprint.

Each day the MIP peak is determined from the pulse integrals for each detector. The pulse integrals are calculated as discussed in the caption of figure 2.4. The number of particles traversing the detector is obtained by dividing the pulse integral by the MIP peak value of that day. This way, large scale fluctuations in signal strength due to PMT temperature fluctuations or changes to the gain settings, are corrected for. Detections with a particle count smaller than 0.5 MIP are discarded. This way random coincidences caused by gamma rays from nearby radioactive decays or other small signals are excluded. Random coincident muons typically generate signals above 0.5 MIP and may still be included as it is impossible to distinguish a late shower particle from an uncorrelated muon. The probability for this to occur is small (1.5 μ s trigger window per station with a muon rate of ~ 81 Hz, see chapter 1.2.3). Moreover, as the uncertainty of the particle count measured by a detector is typically several MIPs, one extra muon does not significantly affect that EAS footprint sample. Other non-EAS signals (e.g. electromagnetic radiation from nearby telecommunication antennas picked up by the cables, etc.) with a pulse height above 0.5 MIP are not excluded either. However, as the rate for these kinds of events is extremely small, the probability that such a signal coincides with an EAS is negligible. Distortion of the signal, for example due to incorrect alignment of the HiSPARC electronics, also may occur. The pulse integral is in these cases expected to still represent the number of particles traversing the detector as the distortion does not modify the underlying signal.

Figure 6.3 shows the pulse integral distribution (PID) obtained by station 508 in July 2018. Only events in which all four detectors triggered are considered, this way random coincidences are excluded. Detectors 1 and 4 use a commercial PMT base whereas the PMTs of detectors 2 and 3 have a Nikhef base. The PIDs of the other stations and periods are

Figure 6.2: Data availability per station. During red periods the stations did not provide (useful) data. Only two of the four detector were operational during the orange periods. The stations were fully operational most of the time (green). Unfortunately, problems with the absolute timing of station 508 rendered a large part of that data useless for comparison with other stations.

Figure 6.3: Pulse integral distribution obtained by station 508 in July 2018. Only events in which all four detectors triggered are considered to exclude random coincidences. Detectors 1 and 4 use a commercial PMT base whereas the PMTs of detectors 2 and 3 have a Nikhef base. The determination of the pulse integral does not account for values exceeding the ADC range. Therefore, the number of large pulse integrals detected by detectors 1 and 4 is underestimated. Especially above 30 MIP this effect becomes apparent.

similar. The shape of the PID depends on the PMT base (red and green versus blue and light blue lines). For PMT assemblies in which the Nikhef base is used, the PMT pulses start to exceed the ADC range (~ 2.2 V) if more than ~ 15 MIP ($\sim 150 \text{ mV} \times 15 = 2.25$ V) traverse the scintillator. For assemblies with a commercial base the PMT pulses get spread out in time; inadvertently keeping the pulse heights within ADC range (see chapter 2.1.1). The determination of the pulse integral does not account for values exceeding the ADC range. Therefore, the number of large pulse integrals detected by detectors 1 and 4 in figure 6.3 is underestimated. Especially above 30 MIP this effect becomes apparent. The determination of the pulse integral value could possibly be improved by fitting eq. 2.2 to the parts of the pulse that are within ADC range. In this analysis, the underestimation of the pulse integral by PMTs with Nikhef base is limited by clipping the particle counts to 30 MIP. Only 7 of the 36 PMTs in the 9 stations employ a Nikhef PMT base. For all detectors, no pulse integrals over 100 MIP are detected whereas, as the shower core sometimes falls on a detector, the number of particles traversing the detector could be well over 1000. This indicates that for very large particle numbers the determination of the number of particles traversing the scintillator is inaccurate, irrespective of the PMT base used.

Only events with a zenith angle smaller than 30° are considered. This way the difference in particle densities in EAS footprints due to extra attenuation because of larger path lengths through the atmosphere is limited. Furthermore, the energy reconstruction method is based on the LDF earlier used in chapter 4.3 for which the attenuation correction becomes invalid for large zenith angles.

6.2.1 Timing offsets

In order to reconstruct the direction of the EAS the timing offsets between the stations and the detectors within a station need to be corrected for. As explained in chapter 2.2.3, the timing offsets are calculated from the distribution of arrival time differences. Also the height difference (in light-time) between the stations is taken into account. Figure 6.4 shows the change of the timing offsets of the Science Park stations over time with respect to station 501. The time period required to determine the offset depends on the distance to station 501 as only high energy EASs (rarer) have sufficiently large footprints to cause coincidences. This makes that the time step at which the offsets can be determined differs per station (e.g. one measurement every 8 days for station 509). For most stations the timing offsets are reasonably constant and only significantly change if there was a station reconfiguration (GPS reinitialization, hardware change, etc.). These moments are indicated with green vertical lines. The red lines show the mean timing offsets. These mean values are used to correct for the offsets. Stations 510, 512 and 513 are placed ‘on top of’ station 501 (blue stars in figure 6.1). Because of their proximity the offsets can be determined more frequently. Especially station 510 shows that the timing offset is not constant but varies slightly within ~ 10 ns. These small GPS timing offsets do not affect the direction reconstruction as stations typically have a separation of ~ 100 m. Moreover, only station 501 of the four station ‘on top of each other’ is considered.

The timing offsets of the detectors within a station are also determined. Figure 6.5 shows the change of the detector timing offsets with respect to detector 2 for station 503 over time. The offsets are determined every 24 hours with a 2.5 ns precision. The gradual change during the summer months could be due to temperature changes of the PMT. Contrary to the station timing offset, no mean values are calculated. Instead, for each coincidence, the determined timing offset that is closest in time, is used.

6.3 Direction reconstruction

The direction of the shower is reconstructed assuming a flat shower front using the (triangulation) algorithm described in [124, chapter 5]. Only events having at least two MIPs in the detector are considered. This way, random coincidences caused by muons, gamma rays from nearby radioactive decays or other signals are excluded. The precision of the direction reconstruction is investigated by comparing the reconstructed direction of the cluster to that of individual stations in the coincidence. Also for the station reconstructions only events with two MIPs in all detectors are considered. Figure 6.6 shows the distribution of angles between the reconstructed direction from station 501 alone and the direction as reconstructed from the entire Science Park cluster (blue interpolated dots). The increasing solid angle for larger angles has been corrected for (division by $\sin \theta$). The differences do not follow a Gaussian or Lorentzian distribution. The width at half maximum (WHM) is 7.4° . This roughly agrees with the uncertainties found in chapter 4.2 (figure 4.1). Similar values are found for the other stations indicating that the station timing offsets are correctly taken into account. Further away from the shower core the uncertainty increases. The red crosses show the same distribution for events with the shower core at least 100 m away from station 501 (see next section for core determination). A Gaussian is fitted to the distribution (red

Figure 6.4: Timing offsets per station with respect to station 501 over time. The time period required to determine the offset depends on the distance to station 501 and thus differs per station (e.g. one measurement every 8 days for station 509). For most stations the timing offsets are constant and only significantly change if there was a station reconfiguration (GPS reinitialization, hardware change, etc.). These moments are indicated with green vertical lines. The red lines show the mean timing offsets.

Figure 6.5: Detector timing offsets with respect to detector 2 for station 503 over time. The offsets are determined every 24 hours with a 2.5 ns precision. The gradual change during the summer months could be due to temperature changes of the PMT.

line) with a σ of 13.3° . The lower precision could be caused by the larger spread in the arrival time of the EAS particles further away from the shower core.

6.4 Energy reconstruction

From the reconstructed zenith and azimuth a vector is defined pointing towards the arrival direction of the cosmic ray. Two unit vectors, $\vec{e}_1$ and $\vec{e}_2$ are defined perpendicular to the direction vector and to each other. The detector positions are projected to the plane spanned by $\vec{e}_1$ and $\vec{e}_2$. The distances from the detector positions to their projected positions on the plane are calculated and used to adjust the arrival times (speed of light). The left plot in figure 6.7 shows an example of the projected detector positions (dots) on the $(\vec{e}_1, \vec{e}_2)$ plane. The size of the dots scales with the number of particles traversing the detector. The colour of the dots indicate the arrival time with respect to the first projected arrival time.

A lateral density function (LDF) is fitted to the projected particle numbers to find the position of the shower core and energy of the EAS. If stations were fully operational but did not trigger within the 10 μ s trigger window, a particle count of 0 (with an uncertainty of 1) at those projected detector positions is included in the fit. Stations located at the edge of the shower where the particle density is low but non-zero may not trigger because of Poisson statistics (e.g. no or only 1 detector was hit). For these events the true particle density is underestimated as a particle count of 0 is assumed. However, this approach was deemed the best way to treat the non-trigger stations. Excluding the non-trigger stations in the fit results in unconstrained best fit solutions with core positions far away from the triggered stations (i.e. the problem in chapter 4.3). Assuming a non-zero particle count (e.g. 1) would

Figure 6.6: Distribution of angles between the reconstructed direction from station 501 alone and the direction as reconstructed from the entire Science Park cluster (blue interpolated dots). The increasing solid angle for larger angles has been corrected for (division by $\sin \theta$). The differences do not follow a Gaussian or Lorentzian distribution. The width at half maximum (WHM) is 7.4° . This roughly agrees with the uncertainties found in chapter 4.2 (figure 4.1). Further away from the shower core the uncertainty increases. The red crosses shows the same distribution for events with the shower core at least 100 m away from station 501. A Gaussian is fitted to the distribution (red line) resulting in a σ of 13.3° . Similar values are found for the other stations.

also affect the fit as stations far away from the shower would then be assumed to still have detected the EAS footprint. The same LDF is used as in chapter 4 for a single four-detector station. For completeness eqs. 4.3–4.5 are repeated here: The number of particles N at distance r is given by:

$$N(r) = A \left(\frac{r}{r_0} \right)^a \left(1 + \frac{r}{r_0} \right)^b \quad (6.1)$$

with $r_0 = 29.6$, $a = -0.566$, $b = -2.57$ and A the fit parameter related to the energy. Because of the particle counts being cut off at 30 MIP, also the LDF is clipped:

$$N_{\text{fit}}(r) = \min(N(r), 30) \quad (6.2)$$

For inclined showers the particle numbers are reduced due to the increase in path length through the atmosphere. This is corrected for by using:

$$A_{\perp} = A \cdot \exp \left(p \left(\frac{1}{\cos \theta} - 1 \right) \right) \quad (6.3)$$

with θ the zenith angle and $p = 6.937$. The energy (in eV) of the primary cosmic ray is then calculated with:

$$\log(E) = c \cdot (\log(A_{\perp}) + d) \quad (6.4)$$

here $c = 0.797$ and $d = 17.62$. The cross in the left plot of figure 6.7 indicates the best fit core position. The upper right plot shows the particle counts as a function of distance to the core position (dots) together with the fitted LDF (red line).

In first approximation the EAS shower front is a thin disk. However, at larger core distances there is an increasingly large delay on the first arrival time. The average energy of the particles decreases with increasing radial distance. Because of larger scattering angles and lower Lorentz factors, this also leads to a larger thickness of the shower front further from the core. The shower front can be approximated by a catenary [131], i.e. a curve that an idealized hanging chain or cable assumes under its own weight when supported only at its ends:

$$t = \frac{a}{2c} \left(e^{\frac{r}{a}} + e^{-\frac{r}{a}} \right) \quad (6.5)$$

with r the core distance, c the speed of light and a a fit parameter. The bottom right plot in figure 6.7 shows the projected arrival times as a function of distance to the shower core (dots). The red line displays the catenary function fitted to the data points.

6.5 Results

The direction of $\sim 91\%$ of the station coincidences that include stations 501, 502, 503 and 514 could be reconstructed. For the remaining events the arrival time data was inconclusive, for example due to a too limited number of signals above 2 MIP. Of the reconstructed EASs $\sim 28\%$ had a zenith angle larger than 30° and were discarded. In over 99.9% of the cases the energy could also be determined once the direction reconstruction was successful and the zenith angle was below 30° .

Figure 6.8 shows the distribution of the reconstructed EAS energies detected by the Science Park cluster between November 2018 and September 2020. Below $\sim 10^{16}$ eV the detection

Figure 6.7: The sampled particle footprint of a $10^{16.6}$ eV EAS on the $(\vec{e}_1, \vec{e}_2)$ plane perpendicular to the arrival direction of the shower (left) combined with the lateral density function (top right) and shower front arrival times (bottom right). The dots indicate the detector positions on the $(\vec{e}_1, \vec{e}_2)$ plane. The size of the dots scales with the number of particles traversing the detector. The colour of the dots indicate the arrival time with respect to the first particle. The core position (black cross) is obtained by fitting the 2D LDF (eq. 6.2) to the particle counts. Also the energy is derived from this fit (eq. 6.4). The particle counts and the arrival times as function of the distance to the shower core are shown in the upper and lower right figures resp. Also the LDF and catenary fits are shown (red lines).

Figure 6.8: Histogram of the reconstructed EAS energies. The condition that stations 501, 502, 503 and 514 have triggered imposes a lower limit on the EAS energies of $\sim 10^{16}$ eV. The non smooth decrease of events with lower energies (‘bump’ at $\sim 10^{15.2}$ eV) is believed to be caused by the trigger conditions. A trigger caused by two signals over the high threshold typically detects a lower particle density than a trigger caused by three signals over the low threshold.

efficiency starts to decrease as the particles densities in shower footprints of lower energy EASs are often too low to trigger stations 501, 502, 503 and 514. The non smooth decrease of events with lower energies (bump at $\sim 10^{15.2}$ eV) is believed to be caused by the trigger conditions. A trigger caused by two signals over the high threshold typically detects a lower particle density than a trigger caused by three signals over the low threshold. In the 22 month time period only one EAS above 10^{19} eV was detected.

6.5.1 Effective solid angle

In order to calculate the cosmic ray energy flux from the distribution of reconstructed EAS energies, the effective surface area and effective solid angle of the Science Park cluster are needed. The development and attenuation of an EAS is affected by its path length through the atmosphere. With increasing zenith angle, the path length and thus attenuation increases. Because of this, the acceptance of the Science Park cluster decreases for larger zenith angles. Since only zenith angles between 0° and 30° are considered, this effect is reasonably limited (path length increases with $1/\cos(30^\circ) \approx 1.15$). Figure 6.9 shows the distribution of reconstructed zenith angles for six energy bins (width $\log_{10}(E/\text{eV}) = 0.25$). For most energies, the distributions start to flatten at zenith angles approaching 30° . The EAS attenuation rises approximately exponentially with increasing path length. This makes that the EAS detection efficiency as function of zenith angle can be described with:

$$I(\theta, a, b) = a \cdot \exp[-b \cdot (\sec \theta - 1)] \quad (6.6)$$

with θ the zenith angle and a and b fit parameters. A zenith angle bin in figure 6.9 spans a ‘ring’ with a solid angle that depends on the zenith angle. This effect ($\sin \theta$) needs to be taken into account in order to fit eq. 6.6 to the distributions:

$$I_{\text{fit}}(\theta, a, b) = \sin \theta \times I(\theta, a, b) \quad (6.7)$$

The red lines in figure 6.9 show the best fits to the data. At 10^{16} eV the fit does not correctly describe the data. It is not clear why this is the case. For high energy EASs (beyond 10^{17} eV) the shower energy is sufficient for the footprint to reach the Earth’s surface irrespective of zenith angle. Because of this the lines for the two bottom plots are approximately linear.

The effective surface area is obtained by integrating the detection efficiency (eq. 6.6) over the solid angle of the circular field of view subtended by a rotated zenith angle:

$$\Omega = \int_0^{2\pi} \int_0^{\pi/6} \sin \theta \frac{I(\theta)}{I(0)} d\theta d\phi \quad (6.8)$$

with ϕ the azimuthal angle. The detection efficiency is set to 1 at $\theta = 0^\circ$. Figure 6.10 shows the effective solid angles as a function of EAS energy. The dashed line indicates the maximum solid angle at 30° ($\Omega = 2\pi(1 - \cos 30^\circ) = 0.84$ sr). Above 10^{17} eV the efficiency is 100%. The red line shows a linear fit excluding the point at 10^{16} eV at which the efficiency fit was inadequate (figure 6.9). This linear fit is used for the effective surface area with a maximum of 0.84 sr.

6.5.2 Effective surface area

The effective surface area of the Science Park array is obtained by investigating the spatial distribution of reconstructed core positions. Figure 6.11 shows the two dimensional distribution of core positions for six energy bins (width $\log_{10}(E/\text{eV}) = 0.25$). The red dots indicate the station positions. As expected, the maximum distance of the detected EAS shower cores to the central stations increases with energy. For lower energies (e.g. 10^{16} eV) there seems to be an overdensity of core positions somewhat right below station 501. As the four stations in the selection criterion (501, 502, 503 and 514) do not form a regular array, some areas are preferred in the fitting procedure as no data points constrain the fit at those positions. For higher energies the core positions lie reasonably homogeneous in a disk around the central stations.

By determining the centre of mass of the two dimensional distributions, the distribution of core distances r can be investigated. Figure 6.12 shows these distributions for the six energies. To correct for the geometrical effect of increasing surface area at larger r , the counts in each bin are divided by the surface area of each bin (rings of $2\pi r$). The peaks in the two upper plots at ~ 50 m are the overdensities in figure 6.11 at 10^{16} and $10^{16.25}$ eV. This representation in terms of core distance shows that the detection efficiency is approximately constant up to a certain radius at which it starts to decrease (e.g. see the fourth plot in figure 6.12). The distributions can be described reasonably well with the parametrisation earlier used in chapters 4.4.2 and 5.2.1:

$$g(r) = \begin{cases} f(r_m, \alpha, \mu, \sigma, \lambda) & \text{for } r < r_m \\ f(r; \alpha, \mu, \sigma, \lambda) & \text{for } r \geq r_m \end{cases} \quad (6.9)$$

Figure 6.9: Zenith angle distributions for six EAS energies. The uncertainty is given by the square root of the number of events in each bin. The red lines show the fits of eq. 6.7. Because of the small solid angles subtended by bins (rings) at small zenith angles, the number of events in these bins is limited.

Figure 6.10: Effective solid angle as a function of EAS energy. The effective solid angles are obtained by integrating the detection efficiency (eq. 6.6, fits in figure 6.9) over the circular field of view subtended by a rotated zenith angle. The dashed line indicates the maximum solid angle at 30° . Above 10^{17} eV the efficiency is 100%. The red line shows a linear fit excluding the point at 10^{16} eV at which the efficiency fit was inadequate (figure 6.9).

Here, all values below r_m have a constant value which is equal to the function $f(r; \alpha, \mu, \sigma, \lambda)$ evaluated at that r_m . All other values follow the exponentially modified Gaussian distribution:

$$f(r, \alpha, \mu, \sigma, \lambda) = \alpha \exp \left[\frac{\lambda}{2} (2\mu + \lambda\sigma^2 - 2r) \right] \times \text{erfc} \left(\frac{\mu + \lambda\sigma^2 - r}{\sqrt{2}\sigma} \right) \quad (6.10)$$

Here α is a scaling parameter, μ and σ are the mean and standard deviation of the Gaussian part of the distribution and λ is the rate of the exponential distribution. The $\text{erfc}(x)$ factor is the complementary error function and is given by:

$$\text{erfc}(x) = \frac{2}{\sqrt{\pi}} \int_x^\infty e^{-t^2} dt \quad (6.11)$$

Unlike in the case of a Gaussian distribution, the mode is not equal to μ . For the exponentially modified Gaussian distribution the mode is given by:

$$r_m = \mu - \text{sgn}(1/\lambda) \sqrt{2}\sigma \text{erfcxinv} \left(\frac{|1/\lambda|}{\sigma} \sqrt{\frac{2}{\pi}} \right) + \lambda\sigma^2 \quad (6.12)$$

Here $\text{erfcxinv}(x)$ is the inverse of the scaled complementary error function which is given by:

$$\text{erfcx}(x) = e^{x^2} \frac{2}{\sqrt{\pi}} \int_x^\infty e^{-t^2} dt. \quad (6.13)$$

Figure 6.11: Two dimensional distribution of core positions for six EAS energies. The red dots indicate the station positions. The maximum distance of the detected EAS shower cores to the central stations increases with energy.

At $10^{17.25}$ eV (bottom right plot) the number of events is too low for an adequate fit.

With the detection efficiency as function of core distance, the effective surface area can be calculated by integrating the circumference at r :

$$A = \int_0^\infty 2\pi r \frac{g(r)}{g(0)} dr \quad (6.14)$$

Similar to eq. 6.8, the detection efficiency is set to 1 at $r = 0$ m. Figure 6.13 shows the effective surface areas as function of EAS energy. As the radius of the shower footprint is typically much larger than the distance between the four stations in the selection criterion (501, 502, 503 and 514), the effective surface area of the array is approximately the effective surface area of the shower. The shower radius increases linearly with the logarithm of the shower energy. Because of this, the effective surface area increases quadratically with the logarithm of the energy (πr^2 with $r \propto \log(E)$). The red line shows a quadratic function:

$$A(\log(E)) = a(\log(E) - \log(E_0))^2 \quad (6.15)$$

fitted to the data points excluding the point at 10^{16} eV. Here A is the effective surface area, a a fit parameter and E and E_0 the energy in eV and a fit parameter resp. At 10^{16} eV the quadratic parametrisation is not valid since the shower footprint is not much larger than the distance between the four stations. The effective surface area below $10^{16.25}$ eV is described linearly (straight line versus dotted quadratic line).

6.5.3 Energy spectrum

The cosmic ray energy spectrum can now be obtained from the reconstructed energies (figure 6.8), effective solid angle, effective surface area and the detection time period ($t = 22$ months):

$$F = \frac{N_{\text{events}}}{A \cdot \Omega \cdot t \cdot \Delta E} \quad (6.16)$$

with ΔE the width of the energy bin. Figure 6.14 shows the HiSPARC cosmic ray energy spectrum obtained with the Science Park cluster. There is good agreement between HiSPARC measurements and data from other experiments (open circles, see figure 5.12 to distinguish the different experiments). The black line shows a power law fitted to the data in log space with a slope of -3.08 . This is consistent with the reference value of -3.1 [1]. A change of the slope near the ankle ($\sim 10^{18.5}$ eV) cannot be identified because of the limited number of events in that energy region.

6.6 Conclusion and outlook

A combination of HiSPARC stations placed at the Amsterdam Science Park was used to measure the (all-particle) cosmic ray energy spectrum. EASs up to an energy of $\sim 10^{19}$ eV were detected within a 22 month data taking period. Below $\sim 10^{16}$ eV the particle densities in the shower footprints are typically insufficient to meet the selection criterion of stations 501, 502, 503 and 514 having triggered. Because of this, the knee region of the cosmic ray

Figure 6.12: Distribution of the radial distances of the reconstructed core positions to the centre of mass of the core positions (figure 6.11) divided by the surface area of each radial bin (rings of $2\pi r$) for six energies. The uncertainty is given by the square root of the number of events in each bin. The red lines show the fits of eq. 6.9 to the distributions. At $10^{17.25}$ eV the number of events is too low for an adequate fit of eq. 6.9.

Figure 6.13: Effective surface areas as function of EAS energy. The effective surface areas are obtained by integrating the detection efficiency (eq. 6.14, fits in figure 6.12) over the surface area of a disk with radius of 1000 m. The red line shows a quadratic function (eq. 6.15) which is used to parametrise the effective surface area as function of energy. Below $10^{16.25}$ eV this parametrisation is not valid and the effective surface area is described linearly (straight line versus dotted quadratic line).

Figure 6.14: The HiSPARC cosmic ray energy spectrum obtained with the Science Park cluster. The black line shows a power law fitted to the data in log space with a slope of -3.08 . There is good agreement between HiSPARC measurements and data from other experiments (open circles, see figure 5.12 to distinguish the different experiments).

spectrum ($\sim 10^{15.5}$ eV) was not probed. The cosmic ray flux values obtained by HiSPARC agree well with data from other experiments. Also the slope of a power law fitted to the data matches the literature value.

The timing offsets between the detectors within a station and between stations are corrected for using air shower data. From the detector trigger times the direction of the EASs is reconstructed by planar approximation of the shower front. The uncertainty in the arrival direction roughly agrees to that of a single station.

The position of the shower core and energy of the EASs are reconstructed by fitting a LDF to the particle densities sampled by the detectors projected on the arrival plane. As the LDF that is used (eq. 4.3) is invalid for large zenith angles, only events with $\theta < 30^\circ$ are considered. The particle density near the shower core cannot accurately be determined since the PMT pulse generated by these large particle numbers ($> \sim 30$) is largely outside the ADC range. Because of this the LDF is clipped to 30 MIP.

The cosmic ray energy flux is finally obtained by determining the effective solid angle and effective surface area from the experimental data. For this, parametrisations for the zenith angle distribution and the two-dimensional distribution of core positions are used.

The agreement between the HiSPARC spectrum and the data from other experiments shows that the discussed energy and flux reconstruction methods are correct. However, more research is needed to investigate the uncertainty in the energy estimation. For this, CORSIKA simulations at higher energies than used in chapter 4 are required; these are computationally very expensive. With simulations also a more advanced LDF could be acquired that is specifically tailored to the Science Park array. Additionally, new reconstruction algorithms based on artificial intelligence¹ or Bayesian methods (e.g. chapter 5.3) could be developed which process the arrival times and particle densities in the same fit procedure as opposed to the current division between the direction and subsequent energy reconstruction. More advanced methods could possibly even allow for estimating the primary mass as it is related to the curvature of the shower front.

HiSPARC stations provide the means to create cheap and scalable air shower arrays. They could be applied in situations where large arrays are too expensive or too difficult to locate. For example, at the Cubic Kilometer Neutrino Telescope (KM3NeT, [133]) which, in addition to neutrinos, also detects high energy cosmic ray muons. Placing an air shower array above KM3NeT would enable investigating new research topics (e.g. for high energy EASs the predicted muon distributions differ per hadronic interaction model). This is, however, impractical as the experiment is located deep in the Mediterranean Sea. By placing a limited number of HiSPARC stations in boats above the telescope, EASs can be detected and reconstructed with limited resources. The array can easily be expanded by increasing the number of stations. Moreover, as the high energy muons that reach KM3NeT (~ 2.5 km depth) are generated in the shower core, the direction and core position of the EAS can accurately be derived. This improves the precision of the EAS energy estimation. For such applications, the gain settings of the PMT should be adjusted such that particle numbers above ~ 30 MIP can accurately be determined.

¹Two students have worked on this [132, 85].

Chapter 7

Precipitation and radiation

7.1 Terrestrial radiation

In addition to radiation from cosmic origin, there are also terrestrial radiation sources due to radioactive decay. Uranium-238, thorium-232, potassium-40 and their decay products are the dominant telluric radionuclides and have been present since the formation of the Earth. The concentrations of these elements and their progenies in building materials used in the Netherlands are typically 10–100 Bq kg⁻¹ [134].

In the uranium and thorium decay chains the noble gas radon is produced. Radon emanates naturally from the ground and can migrate freely through faults in rocks and through fragmented soils. The thorium decay chain produces ²²⁰Rn whereas the uranium chain generates ²²²Rn. The half-life of ²²⁰Rn is 55.6 seconds and therefore it does not travel far in air. The half-life of ²²²Rn is 3.8 days. This means that ²²²Rn appears in the air at a significant concentration. In the Netherlands this is ~ 3 Bq m⁻³ [135].

Alpha particles produced in the decay chains of uranium or thorium will not pass the roof box, plastic foil and aluminium foil. Electrons produced in beta decay are able to penetrate the detector but are not expected to have sufficient energy to produce a signal above threshold. The range (continuously slowing down approximation) of a 1 MeV electron through air is 3.9 m [136]. Energetic beta particles will thus only be detected when produced very close to the scintillator.

The attenuation length of a 1 MeV gamma ray in air is approximately 120 m [136]. When a gamma ray interacts with an atmospheric nucleus, a new gamma ray is produced via Compton interaction. Only the decays of a selected set of radionuclides within the uranium and thorium decay chains, and in potassium decay, produce gamma rays with an energy of 0.9 MeV and above. A list of decays is given in table 7.1. To shorten the list only decays with an emission probability larger than 3% are shown. There are numerous decays that result in lower energy gamma rays that will not be seen by HiSPARC.

Table 7.1: Gamma ray energies and emission probabilities for naturally occurring isotopes. Only decays with a gamma energy larger than 0.9 MeV and probabilities larger than 3% are listed. Their origin is also indicated. Data from [137].

Isotope	Energy [keV]	Probability [%]	Series
⁴⁰ K	1460.8	10.72	n.a.
²²⁸ Ac	911.2	25.8	Thorium-232
²²⁸ Ac	969.0	15.8	Thorium-232
²²⁸ Ac	964.8	4.99	Thorium-232
²²⁸ Ac	1588.2	3.22	Thorium-232
²⁰⁸ Tl	2614.5	99	Thorium-232
²¹⁴ Bi	1764.5	15.4	Uranium-238
²¹⁴ Bi	1120.3	15.1	Uranium-238
²¹⁴ Bi	1238.1	5.79	Uranium-238
²¹⁴ Bi	2204.2	5.08	Uranium-238
²¹⁴ Bi	1377.7	4.00	Uranium-238
²¹⁴ Bi	934.1	3.03	Uranium-238

7.1.1 Pulse height distributions

The coincidence method ensures that the majority of events are caused by EASs. It is, on the other hand, still possible to investigate the pulses caused by background radiation or by cosmic ray particles that are not part of an EAS. This can be done by selecting random coincidences. Figure 7.1 shows the pulse height distributions of random coincidences (i.e. the time differences between both detectors in the station was larger than 300 ns) detected in detector 1 of two different stations. Random coincident MIPs generate pulse heights that follow the Landau distribution and peak at 150 mV. Since the muon and electron (positron) fluxes that provide the MIPs are the same at the two station locations, the number of events is selected such that both peaks overlap. The PMTs of both stations are of the same type and have similar gain settings (adjusted such that the MIP peak lies at 150 mV). The threshold of 30 mV is sufficiently high to remove PMT noise. There is a large difference in the number of detections with pulse heights smaller than 100 mV. This difference can be explained by the two different detector environments. Pulses with an amplitude below 100 mV are primarily caused by gamma rays from environmental radionuclides. The blue solid line in figure 7.1 shows the spectrum of a station hosted by a high school. This distribution is typical for most high school stations. The green dashed line shows the spectrum of a station on top of a building at the physics department of Leiden University. The much lower number of small pulses indicates that this station has less environmental radioactivity. This is likely since the university station has less concrete in its environment. Most detectors are mounted on the roof with 8 concrete bricks of 16.5 kg (total 132 kg) as displayed in figure 2.3. The roofs of Dutch high schools are often made of concrete as well. The detectors of the Leiden station are mounted using less concrete. Also the roof and walls of the building are not made of concrete (steel, aluminium, glass).

Figure 7.1: The pulse height distribution of random coincidences (i.e. the time differences between both detectors in the station was larger than 300 ns) measured in detector 1 of two different stations. The peak at 150 mV is due to minimum ionizing particles (mainly atmospheric muons) whereas pulses smaller than ~ 100 mV are caused by gamma rays from the decays of radioactive nuclides.

7.2 Singles rate fluctuations

Although HiSPARC has been running for over 15 years, only recently a new software version has been released which also sends the singles rates to the central database at Nikhef (Dutch National Institute for Subatomic Physics). Between 2017 and 2020 this software update has been gradually deployed, most recently at the HiSPARC stations in the United Kingdom.

The singles rates are typically in the order of several hundred Hz. A large contribution comes from atmospheric particles. The muon flux (beyond 1 GeV) integrated over the full sky gives a rate of $\sim 160 \text{ m}^{-2} \text{ s}^{-1}$ [2]. For a HiSPARC detector the muon rate is thus ~ 80 Hz. Because of the complex angular dependence of electrons and positrons it is difficult to calculate the number of singles due to this electromagnetic component. A rough estimate of the singles rate due to cosmic ray initiated muons and electrons (positrons) is in the order of ~ 120 Hz.

The other contribution comes from gamma rays from nearby radioactive decay. This number is harder to quantify as it depends on the local environment. Moreover, a different calibration of the PMT strongly affects the singles rate. For example, if the MIP peak of the pulse height distribution in figure 7.1 is shifted to a larger value (by changing the gain settings of the PMT), gamma ray induced PMT pulses that normally would result in a signal below 30 mV can now pass the threshold.

The singles rate measurements are not constant in time but distinct patterns appear. These temporary singles rate increases are correlated with passing weather fronts. Figure 7.2 shows an example of such singles rate increases passing over England and The Netherlands on 22

and 23 September 2019. The circles show the locations of a selected set of stations and the colours indicate the time of the first singles rate increases with dark red indicating 0 hr (22nd 00:00) and dark blue indicating 30 hr (23rd 06:00). The fronts move from west (dark red) to east (dark blue). On these dates a convergence zone was followed by a cold front. For eight stations the singles rates (averages of 2 minute bins) in all detectors for those stations are shown. The rates between detectors of the same station differ substantially. This is because of varying sensitivities due to different gain settings of the PMTs.

Temperature fluctuations of the PMT affect its sensitivity and thus the number of pulses that pass the threshold. These effects are understood [126, section 2] and do not cause the singles rate increases. Various hypotheses to explain the patterns have been considered. Given the correlation with passing weather fronts, an atmospheric origin for the singles patterns is expected. Although both pressure and temperature influence the number of particles measured at the ground, the singles rate increases are of such high amplitude that a cosmic ray origin is unlikely.

7.3 Gamma rays and precipitation

With a large fraction of the singles rates coming from nearby radioactivity, the temporary increases could have similar origin. It is known that precipitation contains radionuclides (e.g. [138]). When it rains (or snows) an increase in gamma rays is observed. The mechanisms leading to this increase are known as the rain-out and wash-out of daughter nuclei of ^{222}Rn in the air [139]. As radon is a noble gas it is highly unreactive. Its daughter nuclei, however, are easily attached to matter suspended in the atmosphere. These aerosols are subsequently scavenged by raindrops in the cloud (rain-out) or below the cloud during the fall of the raindrop (wash-out). The mechanisms of rain-out and wash-out are complex and depend on many factors. Some authors suggest that rain-out is the dominant process [140].

An order of magnitude estimate of the expected number of gamma ray detections due to radon progenies in the air (when it is not raining) can be made as follows. Only in the decay of ^{214}Bi , gamma rays with an energy higher than 0.9 MeV are produced. This happens $\sim 50\%$ of the decays. The other radionuclides listed in table 7.1 are not part of the ^{222}Rn decay chain and are therefore not present in rain. The gamma rays are isotropically emitted. The probability p to hit the 0.5 m^2 detector surface area at a distance r is approximated by

$$p = \frac{0.5 \text{ m}^2}{4\pi r^2} \quad (7.1)$$

This calculation assumes that all gamma rays arrive perpendicularly at the detector, i.e. the projected surface area of the detector is not taken into account. Gamma rays within a half spherical volume with a radius of the attenuation length (120 m) are able to reach the detector. Integrating over this volume, while taking the probability to hit the detector into account, gives the effective volume:

$$V_{\text{eff}} = \int_0^{120 \text{ m}} p \cdot 2\pi r^2 dr = \int_0^{120 \text{ m}} 0.25 \text{ m}^2 dr = 30 \text{ m}^3 \quad (7.2)$$

With 3 Bq m^{-3} and a gamma ray detection efficiency of $\sim 10\%$ this gives an expected number of hits in the order of 5 Hz.

Figure 7.2: Singles rate increases passing over England and The Netherlands on 22 and 23 September 2019. The circles show the locations of a selected set of stations and the colours indicate the time of the first singles rate increases with dark red indicating 0 hr (22nd 00:00) and dark blue indicating 30 hr (23rd 06:00). The fronts move from west (dark red) to east (dark blue). On these dates a convergence zone was followed by a cold front. For eight stations the singles rates in all detectors of those stations are shown.

When it rains the radon progeny concentration in the air increases. The radon progeny concentration in rainwater is $\sim 1 \text{ Bq mL}^{-1}$ [141]. The raindrop size depends on the rain intensity. The average raindrop size is described by [142, 143]:

$$\langle d \rangle^{-1} = 4.1 R^{-0.21} \quad (7.3)$$

with $\langle d \rangle$ the average diameter in mm and R the rain rate in mm h^{-1} . A regular Dutch rain shower amounts to 5 mm h^{-1} or $5 \text{ L h}^{-1} \text{ m}^{-2}$. The average raindrop size $\langle d \rangle$ is then 0.34 mm. The velocity of raindrops depends on their size and is given by [144]:

$$V = 9.65 - 10.30 e^{-0.6d} \quad (7.4)$$

with V the velocity in m s^{-1} and d the raindrop size in mm. The velocity of a 0.34 mm raindrop is 1.26 m s^{-1} . Dividing the rain intensity ($5 \text{ L h}^{-1} \text{ m}^{-2}$ or $1.39 \text{ mL s}^{-1} \text{ m}^{-2}$) by the raindrop velocity gives the concentration of rainwater in the air during a shower: 1.1 mL m^{-3} . Multiplication by the ^{214}Bi concentration in rainwater is ($\sim 1 \text{ Bq mL}^{-1}$) gives an increase of the ^{214}Bi concentration in the air of 1.1 Bq m^{-3} during rain. This is a $\sim 2 \text{ Hz}$ increase in the singles rate. The contribution of gamma ray detections due to ^{214}Bi decay in mid-air raindrops is thus small compared to the number of uncorrelated muons, electrons and positrons, irrespective of the weather conditions.

7.4 Rain measurements

Despite the previous calculation, a striking correlation between the singles rate and rain is shown in figure 7.3. The singles rate (averages of 2 minute bins) of detector 1 of station 501 in Amsterdam is displayed together the rain rate and the spread in the wind direction measured by the directly adjacent HiSPARC weather station. The data are taken from 3 to 8 September 2018. On the 5th of September there was a thunderstorm above Amsterdam. Most singles rate increases coincide with rain events. A small peak on the 4th of September is not caused by rain. The singles rate increase during that time is expected to be caused by ^{222}Rn (and their subsequent progenies) being transferred from the ground into the air by upward winds. The weather station measures the wind direction every 5 seconds. The standard deviation of the wind direction (σ_{wind}), as measured in 2 minute bins, can be thought of as a measure for this upward wind. During the small singles rate increase on the 4th of September, there was also a large increase in σ_{wind} . The amount of rain and the peak intensities of the singles rate are not strictly correlated. This is because the amount of radon differs for each rain cloud. The so called ‘activity density of rain’ depends on a variety of factors of which their precise influence is not well understood [145]. For example the cloud trajectory is of importance. Clouds coming from sea have lower radon concentrations than clouds coming from land [146].

Contrary to the expected number of gamma rays due to mid-air bismuth decay ($\sim 2 \text{ Hz}$), the singles rate increases in figures 7.2 and 7.3 are in the order of tens to hundreds Hz. The extra detections are expected to be caused by ^{214}Bi in the rainwater still present on the rooftop. This hypothesis is corroborated by the observation that the increase in the singles rate persists after the rain has stopped, as can be seen in figure 7.4. This figure shows the singles rate increase compared to the rain rate at 13 and 19 June 2019.

Figure 7.3: Singles rate of detector 1 of station 501 in Amsterdam combined with the rain rate and the spread in the wind direction measured by the directly adjacent HiSPARC weather station. The data are taken from 3 till 8 September 2018. On the 5th of September there was a thunderstorm above Amsterdam. Most singles rate increases coincide with rain events. A small peak on the 4th of September is highly correlated with a period in which there is a large spread in the wind direction. The singles rate increase during that period is interpreted as to be caused by ^{222}Rn (and their subsequent progenies) being transferred from the ground into the air by upward winds. The weather station measures the wind direction every 5 seconds. The standard deviation of the wind direction (σ_{wind}), as measured in 2 minute bins, can be thought of as a measure for upward wind.

Since during rain, only an excess of gamma rays from ^{214}Bi is measured, the expected decay of the radiation can be modelled [145]. The half-life of ^{214}Bi is $\tau_{\text{Bi}} = 19.9$ minutes, this gives a decay rate of $\lambda_{\text{Bi}} = \frac{\ln(2)}{\tau_{\text{Bi}}}$. The rate of the ^{214}Bi decays ($a_1(t)$) is then given by:

$$a_1(t) = c_0 e^{-\lambda_{\text{Bi}} \cdot t} \quad (7.5)$$

with t the time, c_0 the amount of bismuth at time 0. The bismuth is generated from its parent nuclide ^{214}Pb with a half-life of $\tau_{\text{Pb}} = 26.8$ minutes or $\lambda_{\text{Pb}} = \frac{\ln(2)}{\tau_{\text{Pb}}}$. The amount of bismuth c_0 thus does not only decrease due to its decay but is also replenished by the decaying lead. This means that also a source term needs to be taken into account in the model:

$$a_2(t) = d_0 \frac{\lambda_{\text{Pb}}}{\lambda_{\text{Bi}} - \lambda_{\text{Pb}}} (e^{-\lambda_{\text{Pb}} \cdot t} - e^{-\lambda_{\text{Bi}} \cdot t}) \quad (7.6)$$

with d_0 the amount of ^{214}Pb at time 0 and $a_2(t)$ the rate of ^{214}Bi decays due to ^{214}Pb in rainwater. The total rate of bismuth decays ($A(t)$) is then given by:

$$A(t) = a_1(t) + a_2(t) \quad (7.7)$$

Taking the convolution of this model with the rain rate, as measured by the weather station, should yield the increase in the singles rate. The red dashed lines in figure 7.4 show the modelled singles rates compared to the measured singles rates (blue solid line) during two rain events. The amount of bismuth directly from the rain c_0 and the amount of lead d_0 generating more bismuth are unknown as they differ per rain cloud. These values have been fitted to match the singles rates. Also a constant baseline has been added in the model. The event displayed in the upper plot shows that there is good agreement between the model and the singles rate peak. The singles rate increase in the bottom plot starts approximately 10 minutes earlier than the first rain measurements. The reason for this is unclear. A possible explanation for this is the evaporation of the first raindrops given that within those first 10 minutes the temperature decreases rapidly from 16.8°C to 15.3°C. Also a small peak at ~15:00 h is measured. This peak is not caused by a single outlier. Instead, multiple high values are measured within the 2 minute bin. The reason for the peak is unclear. It does not show up in detector 2 of the station.

Finally, the pulse height distribution of the random coincidences during a rain period has been investigated. Figure 7.5 shows a large singles rate peak (solid blue line) and rain measurements (dashed green line) on the left combined with the pulse height distribution of the random coincidences during the rain period (solid red line) and a dry period (dashed black line) on the right. The grey regions in the left plot indicate the rain and dry periods. Both periods have the same duration. However, because the rate of random coincidences depends on the singles rates of both detectors ($N = 2\tau r_1 r_2$), the number of random coincidences is larger for the rain period. Since the uncorrelated muon and electron (positron) fluxes are the same during both periods, the number of events is selected such that both peaks overlap (MIP peak at ~175 mV). The gamma rays emitted by ^{214}Bi decay have a maximum energy of 2.2 MeV (table 7.1). The pulses generated by these gamma rays are thus expected to have amplitudes below the MIP peak. Figure 7.5 shows that all extra signals during the rain period (red line) have small pulse heights well below the MIP peak.

Figure 7.4: Singles rate increases (solid blue line, left axis) compared to the rain rate (dashed green line, right axis) and to the rain based model (dashed red line, left axis) fitted to the singles rate data for two separate events. The event displayed in the upper plot shows that the model very accurately describes the singles rate increases. The singles rate increase in the bottom plot starts approximately 10 minutes earlier than the first rain measurements. A possible explanation for this is the evaporation of the first raindrops given that within those first 10 minutes the temperature decreases rapidly from 16.8°C to 15.3°C. It is unclear what causes the small peak at ~15:00 h.

Figure 7.5: A large singles rate peak (solid blue line) and rain measurements (dashed green line) on the left combined with the pulse height distribution of the random coincidences during the rain period (solid red line) and a dry period (dashed black line) on the right. The grey regions in the left plot indicate the peak and dry periods. All extra signals during the rain period have small pulse heights well below the MIP peak (~ 175 mV).

7.5 Conclusion

Significant increases in the singles rate are observed in multiple stations and appear to have a strong correlation with passing weather fronts. Atmospheric effects that influence the number of particles measured at the ground cannot explain the large singles rate increases.

Radioactivity in rainwater on the rooftop in the vicinity of the detector was identified to cause the temporary singles rate increases. In the uranium and thorium decay chains the noble gas radon is produced. Only ^{222}Rn appears at significant concentrations in the air. During rain an excess of ^{222}Rn daughter nuclei, scavenged by raindrops, falls to the ground. This results in an increase of gamma rays. Since only ^{214}Bi decays result in gamma rays that can be detected, the expected singles rate increase can be described by a simple decay model taking fluctuations of the rain intensity into account. Finally, it was shown that the pulse height distribution of random coincidences during rain has an excess at low pulse heights, as is expected from gamma rays emitted by ^{214}Bi decay.

The increased radioactivity during precipitation measured by HiSPARC shows that the detector signals are well understood and that a large, irregular array of cosmic ray detection stations can also be used for measuring the radioactivity in the atmosphere. Since HiSPARC has a strong educational component, the phenomenon of radioactive rain and the possibility to measure this with HiSPARC can also be used to explain (and interactively work with) radioactivity in the classroom.

Chapter 8

HiSPARC at a blast furnace

8.1 Muon tomography

Most cosmic rays have insufficient energy to generate air showers of which a significant fraction of particles can reach the ground. The majority of particles is absorbed in the atmosphere and only remnants of the air shower are able to reach the ground. Among these remnants are many muons. As stated in chapter 1.2.3 the flux of perpendicularly incident muons at sea level is $\sim 70 \text{ m}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ above an energy of 1 GeV. Its energy and zenith dependence is given by eq. 1.7. Muons have a relatively long life time compared to other unstable shower particles. This, in combination with their high energies, makes that they have a long mean decay length due to time dilation. Furthermore, because of the large mass of the muon with respect to the electron, the radiation energy loss due to Bremsstrahlung is relatively small; ionization and excitation energy losses dominate the energy loss. This means that muons can penetrate deeply into the atmosphere and other materials.

The stable, naturally occurring flux of deeply penetrating muons can be used for imaging purposes. This is known as muon tomography or muography. Either the energy loss or the change of direction due to multiple scattering can be used to derive the density of the traversed material. For muon scattering tomography the direction of the muon needs to be obtained before and after traversing the imaged object. The change in direction of the muons is determined by the density of the material. Transmission muon tomography exploits the broad energy distribution of cosmic ray muons. The number of muons that have high enough energies to traverse the imaged object along a line-of-sight is compared to the muon flux. By estimating the number of muons that do not make it through, the energy loss and thus the object's density along that line-of-sight can be derived.

A pilot study has been carried out to investigate whether transmission muon tomography can be applied to image the interior of a blast furnace. A HiSPARC station has been placed at a blast furnace (Hoogoven 7) located at Tata Steel Europe in IJmuiden on the 24th of September 2018. The furnace is a large reactor ($\sim 40 \text{ m}$ high and $\sim 15 \text{ m}$ wide) in which iron oxides (in the form of pellets or lump ore) and coke (hard, porous fuel with a high carbon content) are loaded in layers from the top. Oxygen enriched hot air is blown into

the furnace from the bottom. The oxygen reacts with the carbon generating heat, carbon monoxide and subsequently (higher in the furnace) carbon dioxide. The cokes and iron ore descend through the furnace and slowly heat up. At a temperature of ~ 1100 °C the ore starts to soften and melt. The zone in which this occurs is known as the cohesive zone. Below the cohesive zone only (solid) coke is present as the molten iron ore and non-ferrous materials (slag) trickle down to the bottom of the furnace where they are tapped.

The cohesive zone largely determines the performance of the blast furnace [147]. The upward going gas has to make its way through the descending bed of iron ore and cokes. The balance of these two streams greatly affects the efficiency and stability of the steel-making process. The oxygen rich gas is distributed into the upper parts of the furnace through the cohesive zone. The permeability of the cohesive zone affects the gas flow towards the untouched coke layers. Reduced permeability generates an upward force working against the descending ore and cokes. At the same time, the softening and melting of the iron and slag in the cohesive zone influences the downward movement of the solids. The trickling down of the iron in the cohesive zone generates room for other solids, driving the descend of the ore and cokes layers above the cohesive zone. The softening and melting could potentially create an uneven flow or hanging of the material. Because of the high temperatures, the process can only be monitored indirectly by measuring the properties of the outgoing material flows (e.g. hot metal temperature and composition). If cosmic ray muons could enable (near) real-time monitoring of the cohesive zone, the performance of the blast furnace could be improved.

The interior of a blast furnace can be thought of to consist of three zones or rings. Inside there is the cokes heart with a density of ~ 500 kg m⁻³ consisting mainly of carbon. The outermost ring contains the iron ore and cokes layers. The ore predominantly consists of Fe₂O₃, SiO₂ and CaO and has a bulk density of ~ 1900 kg m⁻³. This decreases to ~ 1700 kg m⁻³ when the iron oxides reduce to Fe₃O₄, FeO and Fe. The average density of the alternating ore and cokes layers amounts to ~ 1350 kg m⁻³. Between the cokes heart and the layered ore is the cohesive zone. Here the iron oxides reduce to liquid iron with a density of ~ 6600 kg m⁻³. Because of this, the average density of the cohesive zone greatly increases to ~ 4500 kg m⁻³. The densities of the three zones differ significantly (i.e. from inner to outer ring: ~ 500 , ~ 4500 and ~ 1350 kg m⁻³). The goal of the pilot study is to locate the cohesive zone using muon tomography. In this chapter the setup, methods and results are discussed.

8.2 Setup and method

Four HiSPARC detectors are placed around the blast furnace. They are positioned such that combinations of two detectors form four lines-of-sight crossing the centre of the furnace, as displayed in figure 8.1. The detectors are placed on furnace levels 2, 3, 4 and 5 (contrary to what is shown in the artist's impression). The height difference of the lowest and highest detectors is approximately 20 m. The exact position and orientation of the detectors is measured with respect to the wall of the blast furnace, of which the position is accurately known. The uncertainty on this measurement is approximately 5 cm. The height of the furnace levels, and thus of the detectors, is well known.

No roof boxes are used for this HiSPARC setup. A stainless steel case has been designed

Figure 8.1: An artist's impression of the setup with detectors and blast furnace to scale. Created by Marco Kraan.

to protect the detectors for use in the industrial environment. The cases are fitted on an adjustable solar panel mounting rack at a 45° angle. For additional durability a plastic PMT holder has been developed. The high voltage settings of the PMTs are chosen during a calibration period of the detectors (placed horizontally) at Nikhef. The trigger settings of the setup are chosen such that the station stores data when two detectors measured a signal passing the low threshold.

Figure 8.2 shows the time difference distributions of the six detector combinations obtained over a 58 days period (25 September – 22 November 2018) of data taking. The detectors of the purple and light blue lines are located one above the other. A large number of muons (and electrons) traverse these detectors relatively unhindered resulting in many coincidences. For the four lines crossing the furnace, two peaks can be identified. The right, small peak corresponds to muons traversing the furnace. The left, broad peak is caused by air showers coincidences. If two different particles from a perpendicular incident air shower trigger both detectors, the time difference corresponds to the vertical projection of the distance between both detectors. Because of these multi-particle detections, time differences are detected that seem to cross the distance between the detectors faster than the speed of light. The measured time differences do not correspond to the (time-)distance between both detectors since cables of different length have been used. This also explains the negative time difference for detector combination 2–4 (blue line).

Figure 8.2: Time difference distributions of the six detector combinations. The detectors of the purple and light blue lines are located one above the other. A large number of muons (and electrons) traverse these detectors relatively unhindered resulting in many coincidences. For the four lines crossing the furnace, two peaks can be identified. The right, small peak corresponds to muons traversing the furnace. The left, broad peak is caused by air showers coincidences. The measured time differences do not correspond to the (time)distance between both detectors since cables of different length have been used. This also explains the negative time difference for detector combination 2-4 (blue line).

Figure 8.3: The muon flux as a function of momentum evaluated at the zenith-angles of the four lines through the oven.

8.2.1 Expected rate

The number of muons traversing both detectors of a line per time period is to be compared to the expected rate. For this the muon flux is used. Because of the increasing atmospheric mass with larger zenith angles, the muon flux depends on the zenith angle. Figure 8.3 shows the muon flux as a function of momentum evaluated at the zenith angles of the four lines through the furnace.

In order to calculate the expected rate, the fluxes need to be integrated over the time period, solid angle and surface area. Time periods of 12 hours are chosen. This period is large enough to have a sufficient number of muons to calculate accurate statistics but shorter than the expected density fluctuations in the blast furnace. The surface area of the bottom detector and solid angle subtended by the upper detector are more difficult to determine. Because of the orientation of the detectors, the projected surface area and solid angle need to be calculated. This is done by making a three-dimensional model of the detectors. The plane perpendicular to the line between the centres of the detectors is determined. The positions of the eight corners of the scintillator slab (rectangular cuboid) are projected on this plane. A subset of these points form a polygon. Depending on the orientation of the detector, other points may lie inside the polygon. In order to calculate the area of the polygon, these inner points have to be identified. All 336 permutations of triangles one can make with 8 points are checked to see if another point lies inside such a triangle and thus inside the polygon.¹ After removal of the inner points, the projected surface area is calculated. The same procedure is used to calculate the surface area of the other detector. The solid angle Ω is obtained by dividing the projected surface area A by the squared distance r between both detector centres: $\Omega = \frac{A}{r^2}$. This calculation is strictly different from a projection of the detector on the unit sphere but for the distances between both detectors, the difference is

¹This is known as the point-in-polygon problem in computational geometry.

negligible (less than 0.1%).

The expected rate also depends on the threshold energy: the muon energy needed to traverse the furnace. This is calculated by integrating over the energy from the threshold value to infinity (1 TeV in practice). The rate as function of this threshold energy is shown in figure 8.8. The slopes of the lines differ because the flux depends on the zenith-angle (figure 8.3). The amplitude differences are caused by the zenith-angles but also by different distances between the detectors (i.e. solid angles). By evaluating the plot at the measured rates, the energy loss through the furnace along the line-of-sight can be estimated.

Finally, the energy losses need to be divided by path lengths through the furnace. These are calculated using the three-dimensional model of the setup. The intersection points of the line with the cone shaped blast furnace are calculated analytically. The energy loss through the air between the detector and furnace wall is thus not taken into account. This way the measured rate can be converted in an energy loss per meter, which can be compared along the different lines.

8.2.2 Determination of the rate

The upper left plot in figure 8.4 shows the time difference distribution of coincidences between the detectors in line 5–3. To further constrain the contribution from air shower coincidences, only the events are selected for which there are no detections in the other two detectors. The upper right plot shows the pulse height distribution of events with a time difference near the muon peak value (grey region in the upper left plot). As is to be expected from single muons (MIPs), a Landau-like distribution is found. The same has been done for the air showers (grey region in the bottom left plot). This distribution (bottom right plot) is slightly more complicated since it is composed of a multiplicity of particles. The figure is similar to the pulse height distribution discussed in chapter 4.4.1.

The number of muons traversing both detectors is determined by fitting a Gaussian to the single muon peak in the time difference distribution as shown by the red line in the upper left plot of figure 8.4. For all detector combinations through the furnace the fitted Gaussians have a standard deviation of about 5 ns. This corresponds to the spread in travel time of the scintillation photons from the impact position of the muon to the PMT. A vertical offset is included in the Gaussian fit to also include random coincidences, which are uniformly distributed in time, caused by uncorrelated particles or PMT noise pulses.

8.2.3 Atmospheric pressure

The two lines that do not cross the furnace (lines 5–4 and 3–2) do not generate easily identifiable muon and air shower contributions in the time difference distribution (figure 8.2). As the detectors are located one above of the other, perpendicular incident showers cause the same time difference as single muons or electrons. Additionally, as there is mainly air between the detectors, also low energy muons are also detected. The flux of these low energy muons is affected by the atmospheric pressure effect (see chapter 1.2.3). Figure 8.5 shows the total number of coincident events (i.e. not only muons but all particles) of the two ‘air lines’ detected in three hour periods compared to the atmospheric pressure measured

Figure 8.4: Time difference and pulse height distributions of the coincidences between the detectors on level 5 and 3. Upper left (a): The distribution of time differences with two peaks. Time differences in grey region are caused by individual muons. A Gaussian (red line) is fitted to determine the number of muons. Upper right (b): The pulse height distribution of the muons (grey region in a). Bottom left (c): Selection of time differences caused by air showers in grey. Bottom right (d): The pulse height distribution of air showers coincidences (grey region in c). Small pulse heights are caused by gamma rays. The figure is similar to the pulse height distribution discussed in chapter 4.4.1.

Figure 8.5: Correlation of the rates (per 3 hours) of lines 5–4 and 3–2 with the atmospheric pressure measured at Nikhef. The number of events is not obtained from a Gaussian fit but all coincidences (including muons and electrons) are included in the rate.

at Nikhef (27 km away, but similar air pressure). The figure clearly shows the correlation between the rate and atmospheric pressure. For high energy muons that can penetrate the blast furnace, however, this pressure effect, and earlier described temperature effects (chapter 1.2.3) do not significantly affect the muon flux.

8.3 Results

The total number of muons traversing both detectors in a 12-hour time period (N) is calculated from the Gaussian fit. During the 58 day period a total of $M = 116$ measurements have been made of N . Figure 8.6 shows these measured rates for the four lines through the blast furnace. The number of muons arriving within the time period is a Poisson process, i.e. the number is not constant but varies according to the Poisson distribution. On the right the histograms are shown together with the expected Poisson distributions (no fit). The mean of the measurements ($\bar{N}$) is taken for Poisson parameter λ . Given that for large N the Poisson distribution approaches the Gaussian distribution, the uncertainty of N can be calculated by:

$$\sigma_{\bar{N}} = \frac{\hat{\sigma}}{\sqrt{M}} \quad (8.1)$$

with $\hat{\sigma}$ the sample standard deviation:

$$\hat{\sigma} = \sqrt{\frac{\sum_{i=1}^M (N_i - \bar{N})^2}{M - 1}} \quad (8.2)$$

Figure 8.6: Measured rates per 12 hours for the four lines through the blast furnace. From top to bottom: line 5-3 (red), line 4-3 (blue), line 5-2 (green) and line 4-2 (black). On the right the histograms are shown together with the expected Poisson distributions.

This results in a $\sigma_{\bar{N}}$ of about 0.6%. The obtained average rates and uncertainties are listed in table 8.1.

It takes approximately 8 hours for the deposited iron ore to make it through to the bottom of furnace. A Fourier transform of the rates has been made to see whether this 8 hour turnover time could be seen in the data. For this 3-hour time windows instead of 12-hour windows have been used. Figure 8.7 shows the Fourier spectrum of the rates for the four lines through the furnace. There is no sign of any increase at the turnover frequency of the blast furnace (i.e. 35 μHz or every 8 hours).

Figure 8.8 shows the expected rates as function of the threshold energy for the four lines through the furnace. The measured rates are indicated by the coloured dots. The energy loss through the blast furnace can be read of (dashed coloured lines); only muons with an energy higher than the threshold energy make it through the oven. The uncertainty of the energy threshold ($\sigma_{E_{\text{thr}}}$) is obtained by taking the mean of the upper ($\bar{N} + \sigma_{\bar{N}}$) and lower ($\bar{N} - \sigma_{\bar{N}}$) deviations from the energy threshold. The obtained energy thresholds are listed in table 8.1.

Division of the energy threshold by the distance of the line through the furnace yields the energy loss per meter. The obtained energy losses per meter are listed in table 8.1. Figure 8.9 shows the top and side views of the setup with the energy loss values shown in GeV m^{-1} . The coloured rings indicate the cokes-heart, cohesive zone and cokes/ore layers. The obtained energy losses are similar. Line 4-3 (blue) has the largest zenith-angle and the lowest energy loss. This could be due to its path through the furnace. It traverses relatively more through the cokes heart and ore layers than through the cohesive zone. The more oblique lines (red and green) run through more of the cohesive zone; their energy losses per meter are also

Figure 8.7: Fourier transform of the rate measurements (every 3 hours) for the four lines through the furnace. There is no sign of any increase at the turnaround frequency of the blast furnace (i.e. $35 \mu\text{Hz}$ or every 8 hours).

Figure 8.8: The expected rate as function of the threshold energy for the four lines. The slopes of the lines differ because the flux depends on the zenith-angle (figure 8.3). The amplitude differences are also caused by the zenith-angles but also by different distances between the detectors (i.e. solid angles). The measured rates are indicated with dots. The energy loss through the furnace is found on the x-axis (also shown in the legend).

Figure 8.9: Top and side view of the setup. The coloured rings indicate the cokes-heart, cohesive zone and cokes/ore layers. In the right figure the energy loss values in GeV m^{-1} are indicated for the four lines.

Table 8.1: Measurements of the four lines through the center of the furnace.

	N	E_{thr} [GeV]	d [m]	E_{loss} [GeV m^{-1}]
Line 5 – 3	382.9 ± 2.1	3.72 ± 0.03	16.55 ± 0.05	0.225 ± 0.002
Line 5 – 2	275.1 ± 1.8	4.44 ± 0.03	20.17 ± 0.05	0.220 ± 0.002
Line 4 – 3	247.2 ± 1.6	2.65 ± 0.05	15.24 ± 0.05	0.174 ± 0.003
Line 4 – 2	322.0 ± 2.0	3.57 ± 0.03	18.06 ± 0.05	0.198 ± 0.002

higher.

8.3.1 Measurements encircling the furnace

In order to locate the high density cohesive zone the upper detector at level 4 has been periodically moved to encircle the furnace. The detector at level 5 was moved to level 4 to obtain measurements twice as quickly. Per position the rate is measured during a one or two week period. The rates and energy losses for lines 4–2 and 4–3 are listed in tables 8.2 and 8.3 resp.

The upper two plots in figure 8.10 show a top view of the setup with the directions of lines 4–2 (left) and 4–3 (right). The bottom two plots show the energy losses (Q) as a function of the angle (α) that the line makes with the centre line through the furnace (dashed lines in upper plots). The detector position at 25° and 30° for levels 4–2 and 4–3 respectively, is measured twice during different periods. The mirrored points are light-coloured. The energy loss near the wall of the furnace increases. This could possibly be due to the refractories (heat resistant bricks) encapsulating the furnace in combination with a solid iron wall. The radial measurements seem to show an increase in the energy loss between 15° and 30° , especially for line 4–3 (bottom plot).

The measurements indicated with an asterisk (*) deviate significantly from the neighbouring data points. To investigate this, the energy loss at this position has been monitored for a much longer time period. Figure 8.11 shows the energy loss along this line for the time

Table 8.2: Measurements of the radial lines from level 4 to level 2.

α [°]	Period [days]	N	E_{thr} [GeV]	d [m]	E_{loss} [GeV/m]
35.2	6 (5 Jul - 11 Jul)	440.1 ± 7.7	3.60 ± 0.08	10.79 ± 0.05	0.334 ± 0.008
32.1	16 (13 Jun - 29 Jun)	398.6 ± 4.7	3.51 ± 0.06	12.40 ± 0.05	0.283 ± 0.005
28.3	6 (5 Jul - 11 Jul)	379.4 ± 8.3	3.37 ± 0.10	13.91 ± 0.05	0.242 ± 0.007
24.7	16 (13 Jun - 29 Jun)	356.5 ± 4.8	3.44 ± 0.06	15.00 ± 0.05	0.229 ± 0.004
24.6	9 (5 Feb - 14 Feb)	377.7 ± 5.0	3.40 ± 0.06	15.00 ± 0.05	0.227 ± 0.004
21.2	7 (12 Jul - 19 Jul)	316.7 ± 7.8	3.85 ± 0.14	15.85 ± 0.05	0.243 ± 0.009
17.3	30 (20 Jul - 19 Aug)	301.5 ± 3.0	3.96 ± 0.06	16.63 ± 0.05	0.238 ± 0.004
14.0	7 (12 Jul - 19 Jul)	305.8 ± 5.6	3.82 ± 0.10	17.13 ± 0.05	0.223 ± 0.006
11.8	14 (21 Feb - 7 Mar)	302.0 ± 4.2	3.84 ± 0.08	17.41 ± 0.05	0.221 ± 0.005
10.4	30 (20 Jul - 19 Aug)	285.8 ± 2.4	4.14 ± 0.05	17.56 ± 0.05	0.236 ± 0.003
-20.8	7 (8 Mar - 15 Mar)	380.8 ± 7.7	3.68 ± 0.11	15.99 ± 0.05	0.230 ± 0.007

Table 8.3: Measurements of the radial lines from level 4 to level 3.

α [°]	Period [days]	N	E_{thr} [GeV]	d [m]	E_{loss} [GeV/m]
40.8	6 (5 Jul - 11 Jul)	631.6 ± 10.5	2.07 ± 0.09	6.66 ± 0.05	0.311 ± 0.014
37.5	16 (13 Jun - 29 Jun)	505.5 ± 4.7	2.02 ± 0.05	8.48 ± 0.05	0.238 ± 0.006
33.5	6 (5 Jul - 11 Jul)	413.1 ± 6.3	2.21 ± 0.10	10.15 ± 0.05	0.218 ± 0.010
29.7	16 (13 Jun - 29 Jun)	374.3 ± 3.9	2.14 ± 0.07	11.36 ± 0.05	0.188 ± 0.006
29.6	9 (5 Feb - 14 Feb)	398.0 ± 5.3	2.19 ± 0.09	11.36 ± 0.05	0.193 ± 0.008
26.1	7 (12 Jul - 19 Jul)	300.6 ± 4.0	2.95 ± 0.09	12.33 ± 0.05	0.239 ± 0.007
21.9	30 (20 Jul - 19 Aug)	268.7 ± 2.4	3.15 ± 0.06	13.23 ± 0.05	0.238 ± 0.005
18.5	7 (12 Jul - 19 Jul)	257.2 ± 5.5	3.12 ± 0.16	13.83 ± 0.05	0.226 ± 0.012
16.2	14 (21 Feb - 7 Mar)	255.9 ± 3.6	2.92 ± 0.11	14.19 ± 0.05	0.206 ± 0.008
14.7	30 (20 Jul - 19 Aug)	237.5 ± 2.2	3.39 ± 0.07	14.37 ± 0.05	0.236 ± 0.005
-18.2	7 (8 Mar - 15 Mar)	295.2 ± 6.1	2.62 ± 0.15	13.90 ± 0.05	0.188 ± 0.011

period between 19 July 2019 to 10 July 2020. Significant variations occur over a timescale of weeks and months. For example, in September 2019 the energy loss was much lower. This indicates that the deviating points in figure 8.10 are just an instantaneous measurement. In April 2020 technical problems rendered the setup non-operational. In June 2020 the station was functioning for a while until it definitively failed. In May and June 2020 the station was working correctly for only some periods of time. The 12-hour periods in which the station was functioning are indicated with dots.

8.4 Conclusion and outlook

A pilot study has been carried out to investigate whether transmission muon tomography can be applied to image the interior of a blast furnace. A HiSPARC station has been placed at a blast furnace (Hoogoven 7) located at Tata Steel Europe in IJmuiden. Four detectors are positioned around the reactor such that combinations of two detectors form four lines-of-sight crossing the blast furnace. The goal was to locate the cohesive zone as it largely

Figure 8.10: Top view with the orientations of the lines 4-2 (upper left) and 4-3 (upper right) through the furnace. The detector at level 4 is moved every few weeks. The measured energy losses (Q) are indicated in the bottom two plots. The angle between the line and the centre line (dashed) is on the x-axis. The detector position at 25° and 30° for levels 4-2 and 4-3 respectively, is measured twice during different periods. The mirrored points are light-coloured. Two deviant measurements are indicated with a *. The change of the energy loss with time of these measurements is shown in figure 8.11.

Figure 8.11: Change of the energy loss with time of the two lines through the blast furnace indicated with a * in figure 8.10. Significant variations occur over a timescale of weeks and months. In April 2020 technical problems rendered the setup non-operational. In June 2020 the station was functioning for a while until it definitively failed. In May and June 2020 the station was working correctly for only some periods of time. The 12-hour periods in which the station was functioning are indicated with dots.

determines the performance of the blast furnace.

Qualitative interpretation of the results indicates that the cohesive zone can be located using muon tomography. The clear increase of the energy loss at an α between 25° and 12° for line 4–2 and between 30° and 15° for line 4–3, points to a volume inside the furnace with a higher density: the cohesive zone. The deviation of the neighbouring data point (annotated with an asterisk) was shown to be not indicative for the energy loss along that line since the measurements change significantly with time. That same time dependent change of the energy loss suggests that the position of the cohesive zone is not constant but slowly moves. The periods in September 2019 and June/July 2020 (figure 8.11) show a much lower energy loss, possibly indicating that the muons traversed less of the cohesive zone and more of the cokes heart. Other interpretations such as an temporary increase of the muon flux or the muon rate being greatly affected by atmospheric effects are extremely unlikely.

In order to quantitatively interpret the measured energy losses along the lines through the furnace precise simulations of the blast furnace are needed (e.g. using GEANT4). A rough estimate of the density can, however, be made. For the lines crossing mainly the iron ore and cokes layers, the material along those lines is approximately constant. By dividing the energy loss along such a line by the stopping power of muons in the ore/cokes layers, an estimate of the density can be obtained. For Fe, O, Si, Ca and C the stopping power is 1.451, 1.788, 1.664, 1.655 and 1.753 MeV cm² g⁻¹ resp. [148]. The number ratios of these elements in the ore/cokes layers is unknown. As a rough estimate a value of 1.65 MeV cm² g⁻¹ is taken. The energy loss along a line piercing through mainly ore and cokes is approximately 0.23 GeV m⁻¹. This results in a density of very roughly 1400 kg m⁻³ which seems to be in good agreement with the expected density of ~ 1350 kg m⁻³.

A precise, quantitative interpretation of the measurements is beyond the scope of this pilot study. However, the qualitative interpretation of the data already shows that the application of muon tomography to monitor the insides of a blast furnace is viable. Increasing the number of lines through the oven would enable the creation of a three-dimensional image (or movie) of the steel-making process. More studies are needed to investigate what kind of setup would yield the best performance. The current approach using multiple detectors surrounding the furnace involves a lot of cabling and detector maintenance. Possibly, the use of hodoscopes provides a better alternative.

Chapter 9

Summary and conclusions

9.1 The HiSPARC experiment

The High School Project on Astrophysics Research with Cosmics (HiSPARC) is a widespread, irregular EAS detector array (chapter 2). It is a collaboration of universities, scientific institutes and high schools each hosting their own detection station(s). The majority of the stations is located at high schools. The primary goal of HiSPARC is to engage high school students with modern physics and let them contribute to real scientific research. The scientific goal of HiSPARC is to investigate the use of small EAS detection stations for cosmic ray research. In this thesis the research possibilities of the HiSPARC detector and station are extensively reviewed (chapters 3, 4 and 5). If multiple independently operating HiSPARC stations sample the same EAS, their data can be combined for more detailed analyses (chapter 6). Unexpected, transient fluctuations in the detection rates of all detectors in a station were found in many, often distant, stations. These could be linked to passing weather fronts (chapter 7). Finally, HiSPARC detectors have been used to investigate whether cosmic ray muon tomography can be used to monitor the insides of a blast furnace (chapter 8).

9.1.1 Detector

A HiSPARC detector consists of a scintillator glued to a light-guide which is connected to a photomultiplier tube. The detector is wrapped in aluminium foil and is made light-tight with black pond liner. The assembly is placed inside a roof box and mounted on the rooftop of a building.

The detector is simulated using GEANT4. The simulation program accounts for all aspects of the detector except for the PMT. It was found that the scintillation photons have a different probability to reach the PMT depending on the location at which they are released in the scintillator. This was verified by a table-top experiment. The light-guide generates photons via the Cherenkov effect, which may be detected by the PMT. The further away from the PMT the Cherenkov photons are generated, the smaller the probability they reach the PMT. Even for large Cherenkov photon yields close to the PMT, the number of photons is

small compared to the number of photons generated in the scintillator. A second experiment was conducted to verify the simulated particle response over the full surface of the detector (scintillator and light-guide). The response measured in this experiment was used to obtain the detection efficiency. For thresholds up to 0.5 MIP the detection efficiency is very close to 100%.

For 19 impact positions on the scintillator, PMT pulses were obtained in the table-top experiment. The arrival time distributions of scintillation photons that reach the PMT were also simulated at these positions. By comparing the experimental data to the simulations the single photo-electron response of the PMT could be determined. This response in combination with the GEANT4 simulation provides the means to fully simulate a HiSPARC detector.

9.1.2 Station

A HiSPARC station combines two or four detectors with the aim to distinguish EASs from single background muons. Since the arrival times of particles in an EAS are highly correlated, this is achieved by demanding a response in two or more detectors within a small time window. Custom designed electronics control and read out two PMTs. One electronics unit facilitates two detectors. For a four-detector station two units are connected in Master-Slave configuration. All four detectors are treated exactly the same. A GPS antenna provides accurate, absolute timing information.

For a two-detector station, an event is selected if the signals in the two detectors exceed the low threshold within the coincidence time window (1.5 μ s). The default trigger conditions for a four-detector station are such that the signals of at least two detectors must pass the high threshold or that at least three detectors must generate a signal that exceeds the low threshold. The detection efficiency for perpendicular incident MIPs traversing a detector is 0.999 for the low threshold (0.2 MIP) and 0.997 for the high threshold ($\sim$ 0.5 MIP). For a four-detector station the trigger efficiency depends on the number of detectors that are hit. In all cases the trigger efficiency of HiSPARC stations for MIPs is well above 99%.

The response of a HiSPARC station to EASs was investigated using the detector simulation in combination with simulated EAS footprints generated with the CORSIKA Monte Carlo program. This way, the pulse height distribution of two- and four-detector stations could be reproduced with simulations, enabling the identification of the different particle multiplicities (e.g. 2 electrons, 1 electron + 1 gamma ray, etc.) contributing to the total pulse height distribution. The EAS detection efficiency as function of distance between the shower core and station centre and zenith angle was also determined using simulations.

When at least three detectors in a four-detector station observe one or more particles of an EAS, the direction of the EAS (and thus the direction of the primary cosmic ray) can be obtained by triangulation. The uncertainty of the direction reconstruction was estimated with simulations, by comparison of data from four different stations sampling (almost) the same part of the same EAS, and by comparison of data from the KASCADE experiment with that of a HiSPARC station (integrated in the KASCADE array). All three methods yield similar uncertainties of about 6°. When only two detectors are hit, as for a two-detector station, the time difference between the two detectors only allows for the reconstruction of

the arrival direction along the axis that connects the two detector centres.

9.1.3 Cluster

A HiSPARC cluster is a collection of stations. The surface that the cluster covers often depends on the number of stations that a high school hosts and/or how many high schools there are in the neighbourhood. At the Amsterdam Science Park thirteen four-detector stations are placed on the roofs of Nikhef and other scientific institutions. The stations are located close enough to each other to be able to sample the same (large) EASs.

The station's GPS receivers operate in 'overdetermined clock mode' (fixed location). Upon installation, the GPS receiver performs a 24 hour self-survey to accurately determine its position. Systematic studies show that 50% of the longitudinal differences stay within 0.73 m, 75% within 1.8 m and 95% within 4.1 m while for the latitude differences are 50% within 0.48 m, 75% within 1.1 m and 95% within 2.6 m. Analysis of the altitude data shows that 50% of the combinations stay within 1.5 m, 75% within 2.8 m and 95% within 6.1 m. Timing offsets between stations are determined from EAS station coincidences. The timing offsets of ~ 100 station pairs have been examined. Combining their offsets, a Gaussian distribution with $\mu = 2.7$ ns and $\sigma = 18.9$ ns is obtained.

9.2 Cosmic ray energy and flux reconstruction

9.2.1 Two-detector station

As a two-detector station only provides two samples of an air shower footprint, it cannot be used to reconstruct single EASs. However, with a two-detector HiSPARC station it is possible to probe the cosmic ray energy spectrum directly. A new method has been presented which is very different from those applied by other ground-based cosmic ray observatories. The analysis does not require the reconstruction of the shower core and/or shower size of individual EASs but relies on deriving the energy dependent particle multiplicity distributions in a single scintillation detector. If a detector detects a large number of shower particles simultaneously traversing the scintillator (i.e. a large pulse integral), they could be part of a relatively low energy EAS with its shower core close to the detector, or originate from a high energy EAS with its core further removed from the detector. The probability for both possibilities differs. By accurately modelling the pulse integral distribution as a function of energy (Monte Carlo simulations), these probability characteristics can be exploited to determine the cosmic ray energy flux.

One month of data is sufficient to obtain flux values in the range 10^{12} – 10^{16} eV (five energy decades) that are in good agreement with the results from dedicated (space-based) experiments. For the first time, the cosmic ray flux at 10^{12} and 10^{13} eV is derived at sea level. The blue dots in figure 9.1 show the flux values obtained with a two-detector station. The open circles denote the flux values obtained by other experiments. The blue line shows a power law fitted to the data point in log-space. The slope of -2.71 ± 0.07 agrees with the literature value of -2.7 [1].

9.2.2 Four-detector station

With a four-detector station it is possible to reconstruct the energy of the primary cosmic ray. The energy is determined by fitting a LDF to the measured particle densities. Proton induced CORSIKA simulations in the energy range from $10^{14.5}$ eV to $10^{16.5}$ eV have been used to define the LDF. Since only the particle numbers at four detector positions can be determined, the maximum number of free parameters in the LDF is three; two for the core position and one for the energy. The core positions of low energy showers ($\sim 10^{14.5}$ eV to $\sim 10^{15.5}$ eV) are expected to lie within the station since EASs with their core outside the station are not likely to result in a trigger. For large showers there are two solutions to the LDF fitting procedure; one with the core inside and one outside the station area.

The uncertainty in the energy reconstruction has been investigated by comparing two stations placed ‘on top of each other’ (detectors are ~ 1 m apart). The two solutions for the LDF fit complicate a clear determination of the uncertainty, especially at higher EAS energies. The uncertainty in the $\sim 10^{15}$ eV region is in the order of $\log_{10}(\Delta E/\text{eV}) = 0.2$. A similar analysis using KASCADE data has been carried out. Unfortunately, the number of KASCADE reconstructions was too limited for a decisive analysis. The uncertainty in the $\sim 10^{15}$ eV region seems to agree with the analysis using the two stations.

By estimating the sensitive detection area from EAS footprint simulations (CORSIKA) and assuming the effective solid angle to be constant with energy, the cosmic ray energy spectrum (scaled with the detection efficiency) was obtained. Both stations yield very similar results. For energies between $10^{14.8}$ eV and $10^{15.5}$ eV a slope has been fitted to both distributions. The values of these slopes (-2.85 and -2.86) are similar and do not deviate much from the reference value of -2.7 . For higher energies the measured energy spectrum starts to soften whereas a steepening is expected. This follows from the two solutions for the LDF fit.

9.2.3 Science Park cluster

With a cluster of stations the two solution problem for the LDF fit in a four-detector station can be overcome. Data from 9 stations in the Science Park cluster have been combined to determine the cosmic ray energy spectrum. The direction of the EASs was reconstructed from the detector trigger times by planar approximation of the shower front. The uncertainty in the arrival direction roughly agrees to that of a single station. The position of the shower core and energy of the EASs were reconstructed by fitting the LDF (same as used for a four-detector station) to the sampled particle densities projected on the arrival plane. The effective solid angle and effective surface area were determined from the experimental data.

EASs up to an energy of $\sim 10^{19}$ eV were detected within a 22 month data taking period. Below $\sim 10^{16}$ eV the particle densities in the shower footprints are typically too low to be detected by multiple stations. The cosmic ray flux values obtained by the Science Park cluster agree well with data from other experiments. The red dots in figure 9.1 show the flux values. A power law has been fitted to the data in log-space. The slope of -3.08 ± 0.02 agrees well with the literature value of -3.1 [1].

The agreement between the HiSPARC spectrum and the data from other experiments shows that the discussed energy and flux reconstruction methods are correct. However, more re-

Figure 9.1: Cosmic ray energy spectrum obtained with a two-detector station (blue dots) and the Science Park cluster (red dots). There is good agreement between HiSPARC measurements and data from other experiments (open circles). Two power laws have been fitted to the separate data sets. The blue line shows the best fit to the two-detector measurements. Its slope of -2.71 ± 0.07 agrees well with the reference value of -2.7 below the knee. The red line shows the best fit to the flux values obtained by the Science Park cluster. The slope of -3.08 ± 0.02 agrees well with the reference value of -3.1 at energies beyond the knee.

search is needed to investigate the uncertainty in the energy estimation. For this, CORSIKA simulations at energies beyond 10^{16} eV are required which are computationally very expensive. With such simulated EAS footprints, a more advanced LDF could be acquired that is specifically tailored to the Science Park array. Additionally, new reconstruction algorithms based on artificial intelligence or Bayesian methods could be developed.

9.3 Radioactive rain

It was found that, unexpected, transient patterns appear in the the singles rates (i.e. the number of PMT signals exceeding the threshold per second) of all detectors in a station. Significant singles rates increases are observed in multiple stations that appear to have a strong correlation with passing weather fronts. Atmospheric effects that influence the number of air shower particles measured at the ground cannot explain the large singles rate increases.

Radioactivity in rainwater on the rooftop in the vicinity of the detector was identified to cause the temporary singles rate increases. In the uranium and thorium decay chains the noble gas radon is produced. Only ^{222}Rn appears at significant concentrations in the air. During rain an excess of ^{222}Rn daughter nuclei, scavenged by raindrops, falls to the ground. This results in an increase of gamma rays. Since only ^{214}Bi decays result in gamma rays

that can be detected, the expected singles rate increase can be described by a simple decay model taking fluctuations of the rain intensity into account. Furthermore, the pulse height distribution of random coincidences during rain has an excess at low pulse heights, as is expected from gamma rays emitted by ^{214}Bi decay.

The increased radioactivity during precipitation measured by HiSPARC shows that a large, irregular array of cosmic ray detection stations can be used for measuring the radioactivity in the atmosphere. Since HiSPARC has a strong educational component, the phenomenon of radioactive rain and the possibility to measure this with HiSPARC can also be used to explain (and interactively work with) radioactivity in the classroom.

9.4 Muon tomography

A pilot study has been carried out to investigate whether transmission muon tomography can be applied to image the interior of a blast furnace. A HiSPARC station has been placed at a blast furnace (Hoogoven 7) located at Tata Steel Europe in IJmuiden. Four detectors are positioned around the reactor such that combinations of two detectors form four lines-of-sight crossing the blast furnace. By comparing the number of coincident muons with the muon flux (literature), the energy loss along these lines-of-sight can be estimated. The goal was to locate the high density ‘cohesive zone’ as it largely determines the performance of the blast furnace.

Qualitative interpretation of the results indicates that the cohesive zone can indeed be located using muon tomography. Change of the energy loss along a line through the cohesive zone suggests that its position is not constant but slowly moves. In order to quantitatively interpret the measured energy losses precise simulations of the blast furnace are needed. A rough estimate of the density seems to be in good agreement with the expected density.

The pilot study shows that the application of muon tomography to monitor the insides of a blast furnace is viable. Increasing the number of lines through the oven would enable the creation of a three-dimensional image (or movie) of the steel-making process. More studies are needed to investigate what kind of setup would yield the best performance.

9.5 Concluding remarks

Contrary to most high energy physics experiments which often could be characterized as ‘big science’, HiSPARC is, despite the numerous stations and the large community of teachers and students, a typical ‘small science’ experiment. This allows for great versatility (e.g. the muon tomography project) and requires an all-round, generalists approach. Resources (especially manpower) were limited and often rightfully, and very successfully, devoted to the primary purpose of HiSPARC: to engage high school students with modern physics. Nevertheless, as this thesis shows, the research possibilities of HiSPARC are plentiful. Some of the results merit further investigation. These are outlined below.

In chapter 3 it has been shown that the impact position of a MIP on the scintillator affects the arrival time distribution of scintillation photons at the PMT, and subsequently the PMT

pulse shape. An attempt was made to exploit this feature to estimate the impact position from the PMT pulse shape. In order to definitively state whether this is possible, a new experiment has to be carried out with hardware optimized for this purpose (e.g. higher sampling frequency).

The new method presented in chapter 5 enables probing the cosmic ray energy spectrum with very limited resources. More research is needed to investigate the systematic uncertainties of the method. For this, simulations have to be carried out that include other hadronic interaction models and other cosmic ray primaries (e.g. iron nuclei instead of protons). Also, the research possibilities of a dedicated instrument that can distinguish the particle types and energies of simultaneously traversing EAS particle multiplicities, could be further investigated.

Using a collection of HiSPARC stations the cosmic ray energy spectrum can be measured (chapter 6). As HiSPARC provides the means to create cheap and scalable air shower arrays, it could be considered to place HiSPARC stations in boats above the KM3NeT neutrino telescope. By doing this the science goals of the KM3NeT collaboration can be extended.

In chapter 7 it was shown that the decay of radon daughters in precipitation can be detected by HiSPARC. A widespread array, similar to HiSPARC, with dedicated gamma ray detectors can be used to determine the amount of radioactivity in the rain. Together with weather models, such measurements could be used to research the emanation of radon from the ground. Possibly, the weather station sites of the Royal Netherlands Meteorological Institute (KNMI) could be suitable for this.

Finally, as was already discussed in chapter 8, the application of muon tomography to monitor the insides of a blast furnace should be further researched.

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Nederlandse samenvatting

Het HiSPARC experiment

Toen ik op zeventienjarige leeftijd (2008) door mijn natuurkundedocente werd gewezen op HiSPARC als onderwerp voor het profielwerkstuk kon ik niet vermoeden dat ik er dertien jaar later op zou promoveren. Sterker nog, ik wist niets van ‘supernova’s’, ‘kosmische straling’ of ‘deeltjeslawines’. Toch was ik direct geboeid door deze wondere wereld van elementaire deeltjes en heftige kosmische explosies op vele lichtjaren afstand. Het feit dat we dat soort ingewikkelde zaken gewoon konden detecteren op het dak van de school verraste me. Achteraf bleek dit nou precies het doel van het ‘High School Project for Astrophysics Research with Cosmics’: het brengen van 21^e eeuwse natuurkunde in de klas en leerlingen laten deelnemen aan echt onderzoek. Tegenwoordig zouden we het ‘citizen science’ noemen maar die term was nog niet in zwang toen HiSPARC (naar Nijmeegs voorbeeld) in 2003 door mijn promotor werd co-opgericht. Na een studie sterrenkunde in Leiden ging ik in 2016 de uitdaging aan om de wetenschappelijke potentie van HiSPARC zo goed mogelijk te benutten.

Naast het licht van de zon en sterren komen er ook andere deeltjes uit de ruimte, deze worden kosmische stralen (of straling) genoemd. Kosmische straling bestaat uit verschillende soorten atoomkernen. Ze worden onder andere gemaakt in supernova’s: sterren die aan het einde van hun leven exploderen. Deeltjes met een hoge energie zijn zeldzamer dan die met een lagere energie. Sommige kosmische stralen hebben gigantisch hoge energieën; hiervan is het nog onduidelijk wat voor kosmisch proces deze deeltjes produceert. Als een kosmische straal de aarde bereikt, botst hij op een atoomkern van de dampkring (bijvoorbeeld stikstof of zuurstof). Bij deze interactie worden nieuwe deeltjes gemaakt uit de hoge energie van de kosmische straal (Einstein’s $E = mc^2$). Op hun beurt botsen de nieuwe deeltjes weer met andere atmosferische atoomkernen waardoor er nog meer nieuwe deeltjes worden gemaakt. Deze kettingreactie gaat door totdat er niet genoeg energie meer is om nieuwe deeltjes te maken. Dit proces heet een deeltjeslawine. Zodra de energie op is, sterft de lawine langzaam weer uit en worden de deeltjes ‘opgenomen’ in de atmosfeer. Als de energie van de oorspronkelijke kosmische straal hoog genoeg is, kan de deeltjeslawine het aardoppervlak bereiken. Een deeltjeslawine kan worden beschouwd als een soort pannenkoek van deeltjes reizend met de lichtsnelheid. De grootte van de pannenkoek kan oplopen tot vele honderden meters. Door op verschillende plekken de lokale hoeveelheid deeltjes en hun aankomsttijden te meten, kan de richting en energie van de oorspronkelijke kosmische straal worden gereconstrueerd. Dit wordt gedaan met een combinatie van speciale deeltjesdetectoren. Als

Figuur 1: De HiSPARC detector in een skibox.

meerdere detectoren vrijwel tegelijk deeltjes meten dan is er zeer waarschijnlijk sprake van een deeltjeslawine.

In het HiSPARC experiment worden deeltjeslawines gedetecteerd op het dak van middelbare scholen en wetenschappelijke instellingen met detectiestations bestaande uit twee of vier detectoren. Een HiSPARC deeltjesdetector is robuust, goedkoop en relatief eenvoudig te assembleren omdat ze worden betaald door scholen en gebouwd door scholieren. De detectoren worden in een skibox op het dak gemonteerd. Inmiddels staan er zo'n 400 skiboxen op daken door Nederland en het Verenigd Koninkrijk; ze zijn dan ook kenmerkend geworden voor het HiSPARC project. De detector zelf bestaat uit een scintillator en een hypergevoelige lichtdetector. Een scintillator is een speciaal soort plastic plaat die een heel klein beetje licht uitzendt als een geladen deeltje door de plaat reist. Dit licht wordt door de lichtdetector omgezet in een elektrisch signaal en vervolgens door een computer uitgelezen. Figuur 1 laat een detector in de skibox zien. In een HiSPARC station worden twee of vier detectoren gecombineerd (figuur 2). Alleen als meerdere detectoren vrijwel tegelijkertijd een deeltje meten, worden de meetgegevens door de computer opgeslagen. Dit noemen we een coïncidentie. Enkel van coïncidenties kunnen we stellen dat ze veroorzaakt zijn door passerende deeltjeslawines. Als een enkele detector een deeltje meet, zou dat ook kunnen komen door bijvoorbeeld een radioactief verval vlakbij de detector. In de loop der tijd zijn er een hoop HiSPARC stations gebouwd. Inmiddels staan er zo'n 140 stations door Nederland en het Verenigd Koninkrijk maar ook in Denemarken en Namibië (figuur 3).

Energie- en fluxreconstructie

Het hoofddoel van dit proefschrift is om te onderzoeken in hoeverre het mogelijk is om met HiSPARC de eigenschappen te bepalen van de kosmische stralen die ten grondslag liggen aan de gedetecteerde deeltjeslawines. Dit is een lastige opgave omdat met een HiSPARC station slechts twee of vier monsters worden genomen van de deeltjeslawine. Bovendien

Figuur 2: Typische configuratie van een twee-detector station. De GPS antenne in het midden van detectoren wordt gebruikt voor precieze tijdinformatie.

Figuur 3: Layout (begin 2019) van het HiSPARC netwerk. Elke rode stip geeft de locatie van een of meerdere stations weer.

zijn die monsters ook erg lokaal: binnen 10 m van elkaar. Met een vier-detector station is het mogelijk om de richting van de lawine, en dus van de oorspronkelijke kosmische straal, te reconstrueren. Met twee detectoren is dat onmogelijk, er blijft namelijk altijd een as waarop er geen informatie is. Het reconstrueren van de energie van de kosmische straal is nog lastiger, daarvoor wil je het liefst de volledige voetafdruk van de deeltjeslawine op de grond bemonsteren. Het lijkt er dus op dat er maar weinig mogelijk is met een twee-detector station. Toch blijkt dat niet het geval. In hoofdstuk 5 van dit proefschrift beschrijf ik een nieuwe methode waarmee het mogelijk is om het energiespectrum van kosmische straling (de mate van zeldzaamheid voor deeltjes met steeds hogere energie) af te tasten met slechts twee HiSPARC detectoren. Deze methode berust op een statistische benadering. Individuele deeltjeslawines kunnen niet worden gereconstrueerd maar van een grote verzameling van lawines is het wel mogelijk een uitspraak te doen over hoeveel lage, middel en hoge energieën er tussen zitten.

Als een detector een lawine detecteert, kunnen er 1, 2, 3, ..., tot soms wel honderden deeltjes tegelijk door de plaat reizen. Uit de elektrische puls van de hypergevoelige lichtdetector kan worden afgeschat hoeveel deeltjes het waren. Dit noemen we de pulsintegraal. Als we nu alleen kijken naar lawines met een redelijke lage energie (maar hoog genoeg om de grond te bereiken), dan zullen dat vaak 1, 2 of 3 deeltjes zijn, maar tientallen tegelijk is onwaarschijnlijk. Andersom is het bij een energetische lawine een stuk waarschijnlijker dat juist veel deeltjes tegelijk door de HiSPARC detector gaan. De kans op het meten van een aantal gelijktijdige deeltjes kan worden weergegeven in een verdeling. Op de x-as zie je het aantal gelijktijdige deeltjes, en op de y-as hoe vaak dat voorkomt. Per energie van de kosmische straling is deze verdeling een beetje anders. Omdat het met de HiSPARC apparatuur niet mogelijk is het aantal deeltjes te tellen, maar slechts het aantal deeltjes af te schatten van de pulsintegraal, staat er nu de pulsintegraal op de x-as. Met computersimulaties zijn deze ‘pulsintegraalverdelingen’ zo goed mogelijk bepaald. In figuur 4 geven de gekleurde lijnen de verdelingen weer bij verschillende energieën (in eV ofwel electronvolt). De wat dikkere, grijze lijn geeft de verdeling weer zoals gemeten met een HiSPARC station. Door de juiste hoogtes van de gekleurde lijnen te kiezen (ofwel te ‘fitten’) kunnen de gemeten data worden benaderd met de gesimuleerde data. De beste fit is weergegeven met de zwarte lijn. Uit de verschillende hoogtes van de gekleurde lijnen kan nu het aantal 10^{12} eV, 10^{13} eV, etc worden berekend. Je kunt zien dat er veel 10^{13} eV lawines (blauwe lijn) gemeten zijn. Langs deze weg blijkt het dus toch mogelijk om een uitspraak te doen over het energiespectrum van kosmische straling zonder individuele lawines te reconstrueren.

Met een combinatie van meerdere stations is het wel mogelijk om de voetafdruk van de deeltjeslawine op aarde zo goed mogelijk te bemonsteren. Dit is onderzocht in hoofdstuk 6. In figuur 5 is een plattegrond weergegeven van het Amsterdam Science Park met daarop de locaties van de vier-detector stations beheerd door de HiSPARC groep op Nikhef. Bij de blauwe sterren staan vier stations (16 detectoren) zeer dicht bij elkaar maar is ervoor gekozen geen 16 rode punten te tekenen. Als een grote deeltjeslawine op het Science Park neerslaat dan zullen alle detectoren de lokale deeltjesdichtheid en aankomsttijd meten. Door de aankomsttijden op zoveel plekken te combineren, kan de richting van de ‘deeltjespannenkoek’ goed worden bepaald. Hiervoor moeten de detectoren in alle stations wel eerst goed op elkaar worden gekalibreerd. Zodra het aankomstvlak bepaald is, worden de gemeten deeltjesdichtheden op dit vlak geprojecteerd. Dat wil zeggen dat het coördinatensysteem zo wordt gedraaid, dat het lijkt alsof de lawine direct van boven komt. In de linker plot

Figuur 4: Een combinatie van vijf gesimuleerde pulsintegraalverdelingen (gekleurde lijnen) gefit aan de experimentele data (dikke, grijze lijn). De zwarte lijn geeft de beste fit weer. In de onderste plot is de ratio van de fit en experimentele data weergegeven.

van figuur 6 is zo'n geprojecteerde deeltjeslawine weergegeven. De stippen corresponderen met de (geprojecteerde) locaties van de detectoren en de grootte van de stippen geeft de deeltjesdichtheid weer. De kleur van de stippen is een maat voor de aankomsttijd op het geprojecteerde vlak. De kleuren hebben vrijwel dezelfde tint, dat is een goed teken want dat betekent dat de lawine in eerste benadering een vrijwel platte schijf is (pannenkoek). Als je preciezer kijkt, zie je dat verder uit het midden de kleuren donkerder worden. Dit geeft aan dat de lawine een klein beetje gekromd is. Door een wiskundig model op de geprojecteerde deeltjesdichtheden te 'fitten', kan de kern van de lawine worden bepaald. Deze is aangegeven met een kruis. Het wiskundige model wordt weergegeven met de rode lijn in de plot rechtsboven in figuur 6. De afstanden van de stippen tot het kruis staan op de x-as en de deeltjesdichtheden (grootte van de stippen) staan op de y-as. De detectoren kunnen de deeltjesdichtheid meten tot een bepaald maximum. Hierboven wordt het model afgekapt. Dit is te zien aan het horizontale stukje rode lijn. In de plot rechtsonder in figuur 6 staan de (geprojecteerde) aankomsttijden weergegeven met opnieuw de afstand tussen het kruis en de punten op de x-as. Ook hierin is duidelijk te zien dat de lawine gekromd is. De rode lijn in deze plot betreft een ander wiskundig model. Uit de fit op de (geprojecteerde) deeltjesdichtheden (plot rechtsboven) kan de energie van de lawine, en dus van de oorspronkelijke kosmische straal, worden bepaald. Door een zeer groot aantal deeltjeslawines te detecteren en op deze manier te reconstrueren, kan het energiespectrum van kosmische straling worden bepaald. Omdat deze methode alleen werkt als meerdere stations worden geraakt, kunnen alleen grote deeltjeslawines met een energie van 10^{16} eV of hoger worden gebruikt.

De twee hierboven besproken methodes zijn zeer verschillend maar complementair. Met een twee-detector station kan met behulp van een statistische methode het energiespectrum van kosmische straling worden afgetast. Dat wil zeggen, er kunnen enkele datapun-

Figuur 5: Locaties van de stations op het Amsterdam Science Park. Elke rode stip geeft een detector weer en elke combinatie van vier stippen vormt een station. Op één locatie zijn de detectoren van vier stations zeer dicht naast elkaar geplaatst en is daarom één station weergegeven (blauwe sterren).

ten worden bepaald. Met het Science Park cluster kan het energiespectrum nauwkeuriger worden bepaald maar dan enkel bij hoge energie. De resultaten van beide methodes zijn weergegeven in figuur 7. De blauwe en rode datapunten tonen de metingen van de respectievelijk twee-detector en Science Park cluster methodes. De open datapunten zijn van andere experimenten. De overeenkomst tussen de HiSPARC en externe metingen geeft aan dat de beschreven methodes en toepassing daarvan correct zijn. De twee dunne lijnen geven machtsfuncties weer die zijn gefit aan de datapunten van de twee-detector (blauw) en Science Park cluster (rood) methodes. De hellingen van deze machtsfuncties komen ook goed overeen met de literatuurwaarden. Het is dus mogelijk om met HiSPARC het energiespectrum van kosmische straling over een groot bereik (10^{13} – $10^{18.5}$ eV) te bepalen!

Radioactieve regen

Alleen bij een coïncidentie van twee of meer detectoren worden alle meetgegevens opgeslagen. Op deze manier worden enkel de deeltjeslawines geselecteerd uit een grote hoeveelheid andere detecties. Het opslaan van alle gegevens zou teveel opslagruimte kosten. Het totaal aantal detecties per seconde wordt wel opgeslagen voor elke detector; deze noemen we de ‘singles rates’. Hierin zitten detecties veroorzaakt door deeltjeslawines, door muonen die zijn overgebleven uit uitgestorven deeltjeslawines of bijvoorbeeld door radioactieve vervallen in de omgeving. Gezien het aantal deeltjeslawines en muonen vrijwel constant is, was de verwachting dat de singles rates ook constant zouden moeten zijn. Er bleken echter plotselinge toenames voor te komen in de singles rates van alle detectoren binnen een station. In hoofdstuk 7 zijn deze toenames verder onderzocht. Hierbij bleek HiSPARC’s geografische

Figuur 6: De gedetecteerde voetafdruk van een $10^{16.6}$ eV deeltjeslawine geprojecteerd op het aankomstvlak (links) samen met de deeltjesdichtheid (rechtsboven) en aankomsttijd (rechtsonder) als functie van de afstand tot de kern van de lawine (aangegeven met een kruis). De stippen corresponderen met de (geprojecteerde) locaties van de detectoren en de grootte van de stippen geeft de deeltjesdichtheid weer. De kleur van de stippen is een maat voor de aankomsttijd op het geprojecteerde vlak. De rode lijnen geven wiskundige modellen weer die de deeltjesdichtheid (rechtsboven) en aankomsttijd (rechtsonder) beschrijven als functie van afstand tot de lawinekern.

Figuur 7: Het energiespectrum van kosmische straling zoals gemeten met een twee-detector station (blauwe punten) en het Science Park cluster (rode punten). Er is goede overeenkomst tussen de HiSPARC metingen en die van andere experimenten (open cirkels). Twee machtsfuncties zijn gefit aan de twee separate data sets. De blauwe lijn toont de beste fit aan de twee-detector metingen en de rode lijn aan die verkregen met het Science Park cluster. De gevonden hellingen van -2.71 ± 0.07 en -3.08 ± 0.02 komen goed overeen met de literatuurwaarden.

opzet van groot belang. De afstanden tussen de verschillende stations zijn groot, soms honderden kilometers. Bij dicht bij elkaar gelegen stations waren de toenames in alle detectoren vrijwel tegelijkertijd te zien. Bij verder van elkaar gelegen stations kwamen de toenames op verschillende tijdstippen. Bovendien was er enige verandering in de vorm van de toename. De onderste plots in figuur 8 laat de singles rates van acht HiSPARC stations zien in het geval van zo'n plotselinge toename. Afhankelijk van of het een twee- of vier-detector station betrof, zijn er twee of vier lijnen te zien. Het tijdstip van het begin van de toenames verschilt. In de bovenste plot zijn de locaties van meerdere stations weergegeven waarbij de kleur van de punten het tijdstip van het begin van de toename aangeeft. Zoals te zien betreft het in dit geval een tijdelijke toename die van Bristol naar Enschede beweegt.

Gezien deze toenames onverwacht waren, was het aanvankelijk gissen naar de oorzaak van de extra detecties. De snelheid van de verplaatsing duidt op een verband met atmosferische zaken. Kon er hoog in de atmosfeer iets aan de hand zijn dat extra muonen veroorzaakt? Na consultatie bij het KNMI (Koninklijk Nederlands Meteorologisch Instituut) werd een relatie met regen gevonden. Figuur 9 geeft de singles rate weer van het HiSPARC station van de Universiteit Leiden (blauwe lijn) samen met de hoeveelheid regenwater (groene stippellijn) gemeten met het daar aangesloten HiSPARC weerstation. Vooral in de bovenste plot is de overeenkomst overduidelijk; zodra het begint te regenen, begint de singles rate toename. In de onderste plot is er om onbekende reden een kleine vertraging. Na verder onderzoek blijkt dat regenwater een klein beetje radioactief is, en dat deze radioactiviteit wordt opgepikt door de HiSPARC detectoren. In de natuur is het element radon aanwezig. Het ontstaat bij het verval van natuurlijk uranium of thorium en komt als gas uit de grond. Het kan enkele dagen in de lucht verblijven tot het uiteindelijk vervalt tot andere elementen. Radon is een edelgas, dat betekent dat het met niks een reactie aangaat. De vervalproducten van radon zijn dat niet. Als radon in de lucht vervalt, dan zal het nieuw ontstane vervalproduct zich gemakkelijk hechten aan materiedeeltjes in de lucht, aerosolen genaamd. Zodra het gaat regenen worden al die aerosolen, met hun aangehechte radioactieve deeltjes, naar beneden gespoeld. In de plas water op de grond vervallen die radioactieve deeltjes verder tot hun volledige vervalketen is doorlopen en er een stabiel (niet radioactief) element is ontstaan. Van al die vervalproducten is de HiSPARC detector gevoelig voor bismuth (een van de vele tussenstappen in de vervalreeks). De singles rates toenames worden dus veroorzaakt door het verval van bismuth in de directe omgeving van de detectoren. Al dit bismuth belandt daar door de regen. Als de hoeveelheid regen bekend is, kan met behulp van een wiskundig model worden bepaald hoeveel bismuth detecties er moeten zijn. De rode, gestreepte lijn in figuur 9 geeft dit model weer. Het komt zeer goed overeen met de gemeten singles rates (blauwe lijn). Ook als de regen gestopt is (groene gestippelde lijn weer op 0) zal de plas regenwater nog even een heel klein beetje radioactief blijven.

Conclusie

HiSPARC is een project waarbij middelbare scholen samen met wetenschappelijke instellingen een groot netwerk vormen om kosmische straling te kunnen meten. In dit proefschrift is de HiSPARC hardware uitgebreid beschreven, zijn methodes geïntroduceerd voor de behandeling van de HiSPARC meetgegevens en zijn de wetenschappelijke resultaten die hieruit voortkomen vergeleken met andere experimenten. In het bijzonder is er een nieuwe analyse

Figuur 8: Singles rate toenames trekkend over Engeland en Nederland op 22 en 23 september 2019. De cirkels markeren de locaties van een geselecteerd aantal stations en de kleuren geven de momenten weer waarop de toenames beginnen. De toenames bewegen van het westen (donker rood) naar het oosten (donker blauw). Op deze dagen trok er een koufront over met veel regen. Voor acht stations zijn de singles rates van de detectoren weergegeven.

Figuur 9: Singles rate toenames (blauwe lijn, linker y-as) vergeleken met de hoeveelheid regen (groene stippellijn, rechter y-as) voor twee gebeurtenissen. De toenames in de singles rates zijn goed te beschrijven met een wiskundig model (rode, gestreepte lijn) waarbij de hoeveelheid regenwater als input wordt gebruikt. In het onderste figuur is er om onbekende reden een vertraging tussen de start van de singles rate toename en van de regen.

methode ontwikkeld waarmee het mogelijk is om het energiespectrum van kosmische straling te bepalen met slechts twee HiSPARC detectoren. Daarnaast is een combinatie van HiSPARC stations op het Amsterdam Science Park gebruikt om een nauwkeurigere bepaling van het energiespectrum te doen in een hoger energiegebied. Voor beide methodes komen de resultaten zeer goed overeen met literatuurwaarden.

Een parallel onderzoek richtte zich op een onverwacht signaal in de HiSPARC singles rates. In één geval leek zo'n plotselinge, tijdelijke toename zich te verplaatsen over het Verenigd Koninkrijk en Nederland. De oorzaak van de singles rate toenames bleek radioactief verval van bismuth in regenwater in de nabijheid van HiSPARC detectoren. De op het eerste gezicht grillige toenames in de singles rates zijn goed te beschrijven met een wiskundig model waarbij de hoeveelheid regenwater als input wordt gebruikt.

Al sinds 2003 brengt HiSPARC moderne, 21^e eeuwse natuurkunde in de klas en laat het leerlingen deelnemen aan echt wetenschappelijk onderzoek. Dit proefschrift laat zien dat HiSPARC een breed scala van onderzoeksmogelijkheden biedt en dat er in samenwerking met middelbare scholen op grote schaal en over langdurige periode waardevolle data over kosmische straling kunnen worden verzameld.

Ten slotte is er in hoofdstuk 8 een industriële toepassing van HiSPARC besproken waarbij met behulp van kosmische straling het binnenste van een hoogoven wordt onderzocht. Dit onderzoek is niet beschreven in deze Nederlandse samenvatting maar kan worden teruggevonden in het Nederlands Tijdschrift voor Natuurkunde (NTvN) waarin een Nederlandstalig artikel over dit onderzoek is gepubliceerd (zie publicaties).

Publications

- van Dam, Kasper, et al., The HiSPARC experiment, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 959 (2020) 163577
- van Dam, Kasper, Increased radioactivity during precipitation measured by the HiSPARC experiment, Physica Scripta 95 (2020) 074011.
- I was (co)author of 8 pieces published in the Nederlands Tijdschrift voor Natuurkunde (Dutch Journal of Physics). Two relevant publications are:
 - Kooij, Tom, et al. HiSPARC: big data voor scholieren, Nederlands Tijdschrift voor Natuurkunde 82(12) (2016) 12–15
 - van Dam, Kasper, Koffeman, Els, Kijken in het binnenste van een hoogoven met muonen, Nederlands Tijdschrift voor Natuurkunde 85(12) (2019) 58–63

Curriculum vitae

I grew up in Alphen aan den Rijn and went to the Groene Hart Lyceum where the main subjects I studied were Ancient Greek, Latin, chemistry, mathematics and physics. As a teenager I had multiple side jobs. The one I enjoyed most was being a correspondent for a local newspaper (Witte Weekblad, circulation of 30,000). My physics teacher suggested me to write the ‘profielwerkstuk’ about HiSPARC. Together with a friend we made a documentary about cosmic rays for which we won a trip to CERN at the HiSPARC Symposium. Nobel prize winner professor Gerard ‘t Hooft was part of the jury and I remember him asking a question about statistics (for which we luckily knew the answer). The profielwerkstuk was very inspiring to me and it was when I met my later promotor professor Bob van Eijk. In 2008 I attended astronomy courses at Leiden University as part of the Leiden Advanced Pre-University Programme for Top students (LAPP-Top). This eventually led me to study astronomy in Leiden.

During my freshman year in Leiden I got involved with HiSPARC as a student assistant for dr. Henk Buisman. From 2012 to 2013 I worked several days per month at Nikhef to assist HiSPARC PhD student Arne de Laat. During the bachelor’s programme (2009–2014) I did multiple extra-curricular activities. Together with a friend we started a software company specialised in (iPhone) app development. As we were more skilled in creating than actually selling the apps, we closed the company down in 2014. In that same period I worked part-time as a mobile application developer for another software company. As a co-founder I was also involved in ‘Stichting Steun de Wetenschap’ (Support Science Foundation) which aimed to enable the use of crowdfunding to finance scientific research projects. During the master’s programme (2014–2016) my focus shifted towards my studies. In that period I was the website administrator of the Leiden Institute of Physics and teaching assistant for two courses: an introductory Python course and ‘astronomy lab and observing project’. The latter included an excursion to Roque de los Muchachos Observatory, La Palma.

The last years as a PhD student (2016–2020) I had many opportunities. I participated in two PhD schools, four international conferences / symposia and numerous national conventions of which I particularly enjoyed the annual conference for physics teachers (WND). At the Royal Netherlands Meteorological Institute (KNMI) I was given the opportunity to give a colloquium about my work. During the PhD programme I have co-supervised ten high school teachers as part of the ‘Leraar-in-onderzoek’ programme and six students. I also helped numerous high school students building and installing HiSPARC stations. Within the HiSPARC group I was responsible for the data infrastructure and data reduction and simulation pipelines. For this I oversaw five servers running numerous applications. Together

with SURFsara I initiated the creation of an online programming environment (JupyterHub) for high school students to work with HiSPARC data. Finally, at Nikhef I got involved in a project researching the use of muon tomography to study the interior of a steel blast furnace (chapter 8), became an editor of the ‘Nederlands Tijdschrift voor Natuurkunde’ (Dutch Journal of Physics) and joined as a board member of the Energy and Climate section of the ‘Nederlandse Natuurkundige Vereniging’ (Dutch Physical Society).

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Daarnaast wil ik Niek Schultheiss, Tom Kooij, dr. Reno Beekman en dr. Jan Oldenziel bedanken voor hun onmisbare bijdragen in het reilen en zeilen van het HiSPARC project. Vooral Toms inspanningen omtrent de HiSPARC servers hebben mij veel tijd opgeleverd voor onderzoek. Ik wil Niek graag bedanken voor zijn scherpzinnige analyses en creatieve inslag bij het oplossen van allerlei fysische problemen. Reno's bijdragen als zelfbenoemd 'oliemannetje' zijn cruciaal geweest in het in de lucht houden van vele stations. Daarnaast wil ik Jan bedanken voor zijn adviezen en het amicale kamergenootschap op de dins- en donderdagen.

Tijdens mij promotie heb ik (co-)begeleider mogen zijn van 10 'leraren in onderzoek', 6 studenten en vele scholieren. Zonder een ieder bij naam te noemen wil ik allen bedanken voor hun inspanningen, gezelligheid en inhoudelijke discussies die in veel gevallen ook tot interessante onderzoeksresultaten hebben geleid.

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Tenslotte ben ik de Nikhef ondersteuningsafdelingen (computer technologie, elektronica technologie, mechanische technologie, facilities en helpdesk) zeer dankbaar voor hun bereidwilligheid bij allerlei aangelegenheden. Zo was toegang tot apparatuur, tot geavanceerde digitale infrastructuur of tot moeilijk bereikbare detectoropstellingen nooit een probleem ondanks de beperkte financiële mogelijkheden van HiSPARC. Langs deze weg wil ik ook SURFsara bedanken voor het kostenvrij herbergen van de online JupyterHub omgeving voor HiSPARC waar veel scholieren gebruik van hebben gemaakt.