Ultra High Energy Cosmic Ray Extensive Air Shower simulations using CORSIKA

Date: April 2006
Author: Jochem D. Haverhoek ©
Contents

1 Abstract 4

2 History 5

3 Cosmic Rays 7
   3.1 Fundamental Forces .......................... 7
   3.2 EM- or soft component ........................... 8
   3.3 Meson- or hard component ........................ 10
   3.4 Nucleonic component ............................. 11
   3.5 Origin .................................. 13

4 Detecting EAS on the ground 15
   4.1 Volcano Ranch ................................ 15
   4.2 Haverah Park Array ............................... 15
   4.3 Yakutsk Array .................................. 15
   4.4 Fly’s Eye .................................... 15
   4.5 AGASA ...................................... 15
   4.6 Auger ....................................... 16
   4.7 HiSPARC ..................................... 16
   4.8 Detection with HiSPARC ............................ 16

5 Simulation program CORSIKA 18
   5.1 Use of the program .............................. 18
      5.1.1 Interaction models .......................... 18
      5.1.2 Thinning algorithm and Energy cuts ............ 19
      5.1.3 Energy cuts ................................ 20

6 Air Shower Simulations 22
   6.1 Height of first interaction ....................... 22
   6.2 Longitudinal shower development .................. 24
      6.2.1 Longitudinal particle distribution ............... 24
      6.2.2 Longitudinal energy deposition ................. 24
   6.3 Particle densities ................................ 24
   6.4 Particle energies ................................ 27
   6.5 Shower front structure ............................ 31
   6.6 Inclined showers ................................ 33

7 Concluding remarks 35

8 Future study 37

9 Acknowledgements 38

10 APPENDIX A: CORSIKA 39
   10.1 Main output ................................ 42
11 APPENDIX B: FIGURES

11.1 Longitudinal particle distributions ........................................ 45
11.2 Longitudinal energy deposition .............................................. 48
11.3 Particle densities at sealevel ............................................... 51
11.4 Energy per particle .............................................................. 55
11.5 Shower front structure .......................................................... 58
1 Abstract

Cosmic Rays have been a topic of interest ever since their discovery in 1912. These exotic particles of astounding energies are detected but it turns out they should not even exist\(^1\). It proves that we know much and yet so little of the Universe.

In this thesis I will take you on a journey from the discovery of cosmic rays to the present day means of detecting cosmic rays and determining their primary energy.

To try to answer the question about their energies and origin we need to know more about the Extensive Air Showers they produce and the trace they leave on the ground. In order to do this, I have used the Simulation program CORSIKA\[^{[1]}\] to investigate particle densities and energies at ground level and the time structure of the shower front.

\(^1\)More on this exciting phenomenon in section 3.5
2 History

Theodor Wulf, a Jesuit priest and physics teacher at the Jesuit University of Valkenburg built a device to detect energetic charged particles (or electro-magnetic waves): the electrometer. With his electrometer he detected natural sources of radiation on the ground. He predicted that if he moved further away from these sources, the detected radiation would decrease. In his article, published in 1909[3], he describes various radiation measurements in the open air, in a room and in the chalk caves near Valkenburg. He registered (a little bit) more radiation in the room than outside and a reduction of up to 42% inside the chalk mines. It is a pity that he does not draw any essential conclusions from his important measurements. Because only a few years later, someone else did...

Cosmic Rays is a term first introduced by the American physicist Robert Millikan in 1936, but it is Victor F. Hess who is considered to be the father of Cosmic Ray physics. This Austrian physicist was the first to formulate a hypothesis as to why an isolated electroscope still recorded radiation. It was first considered that this radiation had its origin in the earth. This was rejected when, in 1912, Hess took an electroscope on a balloon flight to an altitude of 5350 meters and recorded an increase in radiation from an altitude of 2000 meters and up. He thus had to conclude that the detected radiation was extraterrestrial in origin. On a second flight during a solar eclipse he noticed there was not a significant decrease in radiation, so the sun could not be the main source of this radiation. In 1936, Victor Hess received the Nobelprize for his discovery\(^3\) of Cosmic Rays.

The American physicist Robert A. Millikan was one of the first to formulate a hypothesis as to what the origin is of Cosmic Rays. He proposed it was gamma radiation due to the formation of complex nuclei from protons and electrons\(^2\). If this was the case, cosmic radiation was not charged and therefore would not be influenced by the earth magnetic field. However, in 1932, Carl Anderson discovered antimatter while watching the tracks of charged cosmic ray particles passing through his cloud chamber. It was the anti-electron, later called the positron. Consequently, as with everything new in physics, a debate raged over the nature of cosmic rays which even made the front page of The New York Times.

A worldwide survey initiated by Compton conclusively demonstrated that the intensity of cosmic radiation did indeed depend on magnetic latitude and therefore had to consist mainly of charged particles.

Pierre Auger and Roland Maze where the first to measure time coincidence of Cosmic Rays in their Paris laboratory in 1938. Their detectors stood 20 meters apart, indicating that the observed particles where secondaries originating from a common source. Further experiments in the Alps led to time coincidences of detections as much as 200 meters apart. The resulting primary energies were extreme:

\(^2\)We know now that radioactive decay inside the walls is responsible for some of the measured radiation.

\(^3\)One can question who really discovered cosmic rays. But that is a different story. The interested reader is referred to [4].
In a time when the highest energies achieved in laboratory experiments were of the order of magnitude of several MeV\(^4\), the detection of particles with an energy of one billion times higher, \(10^{15}\) eV, was astounding. It was unthinkable that only one process was responsible for the acceleration of the primary particle to such energies. Auger proposed that

\[\text{\ldots it seems much more likely that the charged particles which constitute the primary cosmic radiation acquire their energy along electric fields of a very great extension...}\]

(Auger et al.,1939)

And it even gets better...

John Linsley and collaborators detected the first \(10^{20}\) eV primary\(^5\) in 1962 at the Volcano Ranch Array in New Mexico. This surpassed all imagination and seemed to be chewing at the existing laws of physics themselves\(^6\).

\(^{4}\)1 MeV is \(10^6\) eV, or one million electron Volt. This is the energy that an electron gains when traversing a potential of one million Volts. \(1\text{eV} \approx 1.6 \times 10^{-19}\text{Joule}\).

\(^{5}\)This is enough energy in one particle to lift 1.6kg one meter into the air.

\(^{6}\)See section 3.5.
3 Cosmic Rays

As mentioned earlier, it was Robert Millikan who suggested that these high energetic particles where in fact not particles, but gamma rays. He was proven wrong in the sense that they turned out to be mostly charged particles. But, as is often the case in physics, because Cosmic Particles sounds too down-to-earth and Cosmic Rays sounds much better, the latter made it through...

When a cosmic ray enters the earth’s atmosphere (with a speed comparable to the speed of light) it is called a primary. These are predominately atomic nuclei ranging in species from protons to iron nuclei, with some traces of heavier elements. Soon after its entrance in the atmosphere it will interact with an air particle and new particles are produced, which in turn produce more particles. All the particles that are produced after the first interaction are called secondaries.

Sections 3.1 to 3.4 are quite theoretical and can be skipped on first reading. They are included to give a more complete view of the interactions taking place in an EAS. There is a short summary at the end of section 3.4.

3.1 Fundamental Forces

All the known forces in the universe are manifestations of four fundamental forces, the strong, electromagnetic, weak, and gravitational forces.

<table>
<thead>
<tr>
<th>Force</th>
<th>Description</th>
<th>Strength</th>
<th>Range (m)</th>
<th>Particle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong</td>
<td>Force which holds nucleus together</td>
<td>$10^{-15}$</td>
<td>(nucleus sized)</td>
<td>Gluons</td>
</tr>
<tr>
<td></td>
<td>&quot;quark colour force&quot;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>Charge repulsion and attraction</td>
<td>$\frac{1}{137}$</td>
<td>Infinite</td>
<td>Photon</td>
</tr>
<tr>
<td>Weak</td>
<td>Essential for buildup of heavy nuclei</td>
<td>$10^{-6}$</td>
<td>$10^{-18}$ (proton size)</td>
<td>Intermediate vector bosons $(W^+, W^-, Z_0)$</td>
</tr>
<tr>
<td></td>
<td>&quot;quark flavour force&quot;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gravity</td>
<td>Between masses</td>
<td>$6 \cdot 10^{-39}$</td>
<td>Infinite</td>
<td>Graviton?</td>
</tr>
</tbody>
</table>

Table 1: Fundamental forces of the universe.

But why four? Why not one? There is not yet an answer to this question and discussion would be beyond the scope of this thesis. But what I can say about this fascinating subject is that it is believed that these four forces are manifestations of one and the same force and that in the early universe (when everything was really hot and dense) there was only one force that ruled. Unification to one Theory Of Everything is about to make its first step though: The weak and electromagnetic forces are on the verge of being unified into the Electroweak

---

7There is no SF-movie which does not use the word "Ray" or "Rays".
8read: "cooler".
9If the cosmic ray is a proton with an energy of 10 GeV its velocity is 99.6% of the speed of light. Note that the highest energies observed are ten billion times higher!
10Hot as in really HOT, $\approx 10^{32}$ Kelvin. The universe was only $10^{-50}$ seconds old. Particle energies corresponded to $10^{28}$ eV!
3.2 EM- or soft component

This is the component of the Air Shower in which photons and electrons (and positrons\textsuperscript{12}) are formed. The number of photons and electrons are very closely linked.

- Pair production, figure 1, is most dominant at the highest energies. This is where a high-energy photon is converted to an electron-positron pair\textsuperscript{13}. Which on its turn can annihilate to produce two photons. See figure 2.

- The Compton effect takes over at lower energies as the interaction cross section of pair production decreases\textsuperscript{14}. In this process a photon looses energy as it is scattered off an atomic electron. See figure 3.

- In the photoelectric effect a photon is absorbed by an atom and consequently an electron is ejected from one of the shells. At lower energies than 1 MeV this process dominates. See figure 4.

\textit{Unification}. However, this requires the existence of a new boson, the Higgs boson which has not been found as of yet\textsuperscript{11}.

These Fundamental Forces play a very important role in the reactions taking place after a primary particle hits Earth’s atmosphere. These reactions can be categorized into three components.

\section*{3.2 EM- or soft component}

Figure 1: Pair-production: Feynman-diagram of how an electron-positron pair can be produced from one photon. The direction of time is to the right. It might strike the reader as odd, that the positron is moving backwards in time. In fact: the positron is nothing else than an electron moving back in time. The interested reader is referred to [5].

Figure 2: Pair-annihilation: Feynman-representation of how an electron and its anti-particle, the positron annihilate to form 2 single photons (2 photons, in order to conserve momentum).

\textsuperscript{11}Since the discovery of the top quark, there is evidence that the Higgs boson may have energies in the range of a few hundred GeV and therefore within the range of present day accelerators, such as ATLAS (CERN, Switzerland), scheduled to be finished in 2007. Proof of the existence of the Higgs particle would surely result in a Nobel Prize (as would the proof of its non-existence result in a Nobel Prize, for then the Standard Model of elementary particles would crumble like a stack of cards and all we thought we knew would be nothing more than an illusion: an elaborate, frantic means to discover the Truth).

\textsuperscript{12}from now on, unless stated otherwise, when I talk about electrons I mean both electrons and their anti-particles: positrons.

\textsuperscript{13}Einstein showed us that energy and matter are interchangeable.

\textsuperscript{14}The interaction cross section is the probability that an interaction occurs. So in this case, the probability that electron-positron pairs are produced decreases with decreasing energy.
3.2 EM- or soft component

- Bremsstrahlung is radiation emitted as an electron is deflected from its path by the strong pull of an atomic nucleus (see figure 5). If a charged particle is accelerated (or decelerated) it emits radiation. The energy the charged particle loses is proportional to \((\frac{E}{m_c})^4\) so the process is very important for low mass charged particles (such as electrons and positrons) but not for muons, pions or protons.

- Čerenkov radiation is a second process which results in the production of photons. When a particle moves faster than the local speed of light, it emits a photon\(^{15}\). The cone of light is emitted at an angle \(\theta\) (see figure 6) \(\cos \theta = \frac{c}{nv}\), where \(c\) is the speed of light, \(v\) is the velocity of the charged particle and \(n\) the refractive index of the medium (in this case, the medium is the atmosphere).

- There is another process which causes electrons to lose energy. At electron energies below \(\sim \frac{600}{Z}\) MeV, ionization losses take over (here is \(Z\) the atomic number). In this process the electron loses energy because it ionizes an atom (i.e. it kicks one electron from the outer shells of the atom). See figure 7.

\(^{15}\)Analogously, a sound wave is produced when an airplane moves faster than the local speed of sound.
3.3 Meson- or hard component

This is the second category of reactions taking place in an extensive air shower. Mesons\(^{16}\) are intermediate mass particles which are made up of a quark-antiquark pair. There are a lot of exotic mesons which do not have long lifetimes; they quickly decay into the lightest of them all: \(K^+, K^-, K^0\) (light) and \(\pi^+, \pi^-, \pi^0\) (lighter still). These then decay through[6]:

\[
egin{align*}
K^+ & \rightarrow \mu^+ + \nu_\mu \quad (1, 24 \cdot 10^{-8}) \\
K^+ & \rightarrow \pi^+ + \pi^0 \quad (1, 24 \cdot 10^{-8}) \\
K^- & \rightarrow \mu^- + \bar{\nu}_\mu \quad (1, 24 \cdot 10^{-8}) \\
K^- & \rightarrow \pi^- + \pi^0 \quad (1, 24 \cdot 10^{-8}) \\
K^- & \rightarrow \pi^0 + \mu^- + \bar{\nu}_\mu \quad (1, 24 \cdot 10^{-8})
\end{align*}
\]

Table 2: Decay modes of the charged K-mesons into lighter components with its lifetime in seconds

And for the neutral Kaons:

\[
egin{align*}
K^0 & \rightarrow \pi^+ + \pi^- \quad (0, 89 \cdot 10^{-10}) \\
K^0 & \rightarrow \pi^0 + \pi^0 \quad (0, 89 \cdot 10^{-10}) \\
K^0 & \rightarrow \pi^+ + \pi^- + \pi^0 \quad (5, 2 \cdot 10^{-8}) \\
K^0 & \rightarrow \pi^0 + \pi^0 + \pi^0 \quad (5, 2 \cdot 10^{-8})
\end{align*}
\]

Table 3: Decay modes of the neutral K-meson into lighter components with its lifetime in seconds. Note the difference in lifetimes. The first two are called K-zero-short and the last two are called K-zero-long decay modes.

And for the pions:

\(^{16}\)Mesons are \textit{bosons}, which means that they have integer spin and are not constrained by the Pauli exclusion principle. In short this means that there can be an unlimited number of particles in the same energy state; they can condensate. At low energies, this process is called \textit{Bose-Einstein condensation} and is responsible for superfluidity.
3.4 Nucleonic component

\[
\begin{align*}
\pi^+ & \rightarrow \mu^+ + \nu_\mu \quad (2,60 \cdot 10^{-8}) \\
\pi^- & \rightarrow \mu^- + \bar{\nu}_\mu \quad (2,60 \cdot 10^{-8}) \\
\pi^0 & \rightarrow \gamma + \gamma \quad (0,83 \cdot 10^{-16}) 
\end{align*}
\]

Table 4: Decay modes of the \(\pi\)-meson into lighter components with its lifetime in seconds.

The photons\(^{17}\) produced in the neutral pion decay start the EM-component of the Extensive Air Shower (EAS). The muons have no strong interaction, so they have a relatively long lifespan so they have a fairly good chance to reach the ground. They are like electrons, but only heavier. They decay through:

\[
\begin{align*}
\mu^- & \rightarrow e^- + \bar{\nu}_e + \nu_\mu \quad (2,20 \cdot 10^{-6}) \\
\mu^+ & \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \quad (2,20 \cdot 10^{-6})
\end{align*}
\]

Table 5: Decay modes of the \(\mu\)-lepton into lighter components with its lifetime in seconds.

We shall see in due course that these muons are of great importance for the detection of EAS.

3.4 Nucleonic component

Nuclei are composed of protons and neutrons. These particles belong to the group of baryons\(^{18}\). The most important baryons are the proton and the neutron. The proton is really stable: it has a half-life of the order of \(10^{32}\) years. A free neutron however, has a half-life of approximately 10.3 minutes\(^{19}\).

There are a lot more exotic baryons\(^{20}\) and excited states of the proton and neutron, but they quickly decay to the most stable ones (protons and neutrons) and/or pions through the strong interaction which is typically of the order of \(10^{-23}\) seconds\(^{21}\).

The particles reaching the ground are mainly nuclear fragments, protons and neutrons. The protons lose energy due to electromagnetic interaction. The neutrons, however, are electrically neutral and therefore pass through the atmosphere almost unhindered to reach the ground\(^{22}\).

\(^{17}\)Photons are bosons too.
\(^{18}\)Unlike mesons, baryons are composed of three instead of two quarks. Baryons are fermions (half-integer spin) which implies they (unlike bosons) obey the Pauli-exclusion principle. Baryons and mesons together belong to the overall class of hadrons, the particles that interact by the Strong Force.
\(^{19}\)A neutron is stable if combined into a nucleus.
\(^{20}\)And even a class of five-quark combinations, called pentaquarks.
\(^{21}\)It should be noted that some of these decay modes are forbidden due to violation of certain conservation laws. These modes then decay through the weak force instead of the strong. These modes have a typical half-life of the order of \(10^{-10}\) seconds.
\(^{22}\)Because they are neutral, it is also very difficult to detect neutrons on the ground.
A short summary of the important discussion in the last few subsections is:

An Extensive Air Shower is a "shower" of secondary particles due to one primary particle with very high energy. This shower can be categorized into three groups of particles:

**Electromagnetic component:** consists of photons and electrons. We shall see that the vast majority of the particles arriving at ground level are photons, followed closely by electrons.

**Meson component:** consist of a wide variety of exotic particles, but the most important ones are the muons which are the third to most abundant particles arriving at the ground. This component induces the electromagnetic component.

**Nucleonic component:** consists of debris of shattered air molecules and atoms, protons and neutrons. Apart from neutrons, these are the least abundant particles reaching the ground.
3.5 Origin

We have seen that cosmic rays are predominantly atomic nuclei ranging from protons to iron. The relative abundances are similar to those found in the sun. This means that approximately 89% are protons, 10% helium and about 1% heavier elements.

The energies range from less than $10^6$ eV to more than $10^{20}$ eV. The differential flux of
these particles is described by a power law:

\[
\frac{dN}{dE} \sim E^{-\alpha}
\]

(1)

with the spectral index \( \alpha \) roughly 3. The flux of cosmic rays is about \( 1 cm^{-2} s^{-1} \) at 100 MeV and \( 1 km^{-2} century^{-1} \) at an energy of \( 10^{20} \) eV\(^2\). The origin of cosmic rays is largely unknown, but it is believed that most cosmic rays of energies below \( 10^{15} \) eV find their origin within the Galaxy. A popular explanation is that shock waves of super nova explosions accelerate the interstellar medium. These shock waves can accelerate protons to energies as high as \( 10^{17} \) eV, but the galactic magnetic field is not strong enough to contain these particles. Its limit lies at approximately \( 10^{15} \) eV. Thus for particles with energies exceeding \( 10^{15} \) eV, the origin has to be extra galactic. This is thought to be the cause of the small change in slope in figure 8 referred to as the \textit{knee}. The change in slope at an energy of \( 10^{18.5} \) eV, the \textit{ankle}, is due to the transition of heavy nuclei cosmic rays to protons\(^7\).

Because particles with energies as high as \( 10^{20} \) eV are very little deflected by the galactic magnetic field (and even less by the extra-galactic magnetic field), we should be able to backtrack such an observation to its origin. But so far, no likely source has been identified that is close enough. Close enough, because, particles above an energy of \( 5 \cdot 10^{19} \) eV (the so-called GZK-cutoff energy\(^2\)) are likely to interact with the cosmic background radiation: From the proton’s perspective, the low-frequency background radiation photon appears to be a gamma ray which, upon collision with the proton results in the production of pions. Each time such a collision occurs, the energy of the proton is reduced by approximately 20% until its energy is again below the GZK-cutoff. This process translates itself into a relatively close source of ultra-high energy cosmic rays, say within a distance of \( 10^8 \) lightyears, 30 Mpc, of the Earth.

Cosmologists offer a possible explanation for the mysterious source of the highest energy cosmic rays. They postulate a universe filled with relics left over from the Big Bang. These hypothetical objects, called topological defects\(^{25}\), can, if they really exist, create particles with ultra-high energies when they collapse. This, however, has not been verified as of yet with experimental evidence.

\(^{25}\)This has implications for the detection of these rare particles. To cover as large an area as possible, one needs very large detector arrays. This is where projects as HiSPARC come into view. See section 4.7.

\(^{24}\)named after its discoverers: Greisen, Zatsepin and Kuzmin

\(^{25}\)such as cosmic strings, domain walls and monopoles.
4 Detecting EAS on the ground

As the quest for detecting Cosmic Rays was initiated by Victor Hess, this was only the beginning. An almost frantic search for the ray of highest energy was set in motion and on various places on Earth detector arrays sprouted from the ground as flowers in the rain\(^\text{26}\).

4.1 Volcano Ranch

In 1961 the first big particle detector array was built in Volcano Ranch (New Mexico) by J.Linsley, L.Scarsi and B.Rossi\(^\text{15}\). The array consisted of 19 plastic scintillator detectors of an area of 3.3m\(^2\) each. As an energetic particle passes through the scintillator, particles in the detector are excited. When they fall back into their ground state they emit a photon. These photons are led through a photomultiplier and consequently converted to an electric signal. Originally the distance between the detectors was 442m but for a period of approximately 650 days this distance was increased to 884m to an area of in total 8.1km\(^2\).

4.2 Haverah Park Array

The Haverah Park Array in the United Kingdom was in use from 1967 to 1987 with a total area of 12km\(^2\). It consisted of water-filled Čerenkov detectors.

4.3 Yakutsk Array

In Yakutsk (Siberia) at the Institute of Cosmophysical Research and Astronomy in 1970 an array was built covering an area of 18km\(^2\). In 1995 the Yakutsk group condensed the array to an area of 10km\(^2\) to obtain more detailed measurements.

4.4 Fly’s Eye

The Fly’s Eye project, situated in the deserts of Utah (US), was founded by the University of Utah in 1981. The name is attributed to the way a fly sees the world; the total sky is observed where each of the 67 mirrors covered a 5.5\(^o\)-diameter hexagonal area of the sky.

The technique is based on the concept that shower particles excite air molecules which emit ultraviolet fluorescent light when they fall back to their ground state. The drawback, however, is that detection can only be done during the night.

A second Fly’s Eye was built, situated on a 3.4km distance. When this second site was taken into use, stereo analysis resulted in far better measurement accuracy. At this site the highest-energy event so far (3 \times 10^{20} \text{ eV}) has been measured [17]. In 1997, a new project was founded at the same location, named HiRes. The sensitivity of these two detectors (12.5km apart) is 10 times higher than that of Fly’s Eye.

4.5 AGASA

AGASA (the Akeno Giant Air Shower Array) in Japan is the biggest array at this moment and covers an area of 100km\(^2\). It consists of 4 detector arrays which were combined in 1995 to one array of in total 111 scintillators of 2.2m\(^2\) each [16]. At 27 of the 111 scintillators were also muon detectors of varying sizes (2.4-10m\(^2\)) installed.

\(^{26}\)or, in this case, as flowers in a shower.
4.6 Auger

This detection array is sited in western Argentina and consists of two systems. The first is a Čerenkov detector array of 1600 tanks of 11000 liters of pure water each. These detectors are situated 1.5 km apart and will cover a total area of about 3000 km². Each of these stations will be self-contained and will operate on solar power. A second detection system is based on the Fly’s Eye method of detection. The combination of these two methods is very promising and will result in a very powerful tool to detect the rarest cosmic rays.

This list of Cosmic Ray sites is far from complete and a more accurate listing is available at the web site[8].

4.7 HiSPARC

Apart from these sites, wholly initiated and maintained by research groups, new arrays have been set up. The last few years more and more research institutes in countries all over the world support so called high school projects in which high school students come in contact with the world of research as they build their own scintillator detector with the help and expertise of a nearby research center. Participating schools thus form a cluster where the data of each individual detector is sent to a server at the research facility. The more schools participating (taking into account a certain distance from each other) the higher the chance of detecting a ”big hit”.

One of these projects is HiSPARC (High School Project on Astrophysics Research with Cosmics) in the Netherlands. The first cluster was set up in the city of Nijmegen under the name of NAHSA (Nijmegen Area High School Array). Now also Amsterdam, Utrecht, Groningen and Leiden have fully operational clusters. These five clusters contain a total of 39 detectors27, of which 32 are placed on high-schools.

4.8 Detection with HiSPARC

In the HiSPARC project, each detector consists of two scintillator plates of 0.5m² each, placed a few meters apart from each other. To exclude counts caused by natural radiation, a hit is only registered if a particle passes through both detectors in a small time interval28.

To detect an Air Shower, particles from that Air Shower need to leave a trace in the detector. But not every particle passing through the detector has enough energy to leave a trace and more importantly: there have to be time coincidences from detectors in one cluster to be able to say something about the radius of the Air Shower and thus, of its primary energy and direction. In an article by Nagano and Watson [9] the particle density as a function of

---

\(^{27}\)Last year, a delegation of students from Leiden University went to Khartoum, Sudan to help build a detector there.

\(^{28}\)this is not the same particle of course, but secondaries originating from the same primary. (the probability of two secondaries from different primaries in the time window is nihil)
distance to the core of the shower is calculated using the Extensive Air Shower simulation program CORSIKA [11].

![Particle density graph](image)

Figure 10: Particle density at 900m above sea level as a function of radial distance to the core of a $10^{19}$ eV primary proton induced shower. Nagano and Watson [9].

At least one particle has to pass through the detector. In the case of a 0.5m$^2$ detector this means a lower limit of 2 particles per square meter. And then we have not taken into account the detector response to that particle$^{29}$. As can be seen in figure 10, for a $10^{19}$ eV shower this is at a radius of $\approx 750$ m for muons with a minimal energy of 1.0 GeV. In section 6.3 our own simulations using CORSIKA will be done to check the results of Nagano and Watson.

---

$^{29}$this would be a good subject for further studies.
5 Simulation program CORSIKA

CORSIKA (COsmic Ray SImulation for KAscade) is a program for detailed simulation of extensive air showers initiated by high energy cosmic ray particles. It was developed for simulations for the KASCADE experiment at Karlsruhe, Germany.

Various particles such as protons, light nuclei up to iron and photons may be treated as primary particles up to an energy of some $10^{20}$ eV. These particles are tracked through the atmosphere until they undergo interactions with air nuclei or - in the case of instable secondaries - decay. The program gives type, energy, location, direction and arrival times for each particle at up to 10 observation levels.

5.1 Use of the program

The main program source is kept as a CMZ-file. This has the advantage that several versions of one program can be kept with optional code. The program is a merger of three programs. The first was developed in 1970 and describes the basic hadronic interactions. These hadronic processes all have their own probability so we need some sort of chance-die to determine which process does occur.

As most simulation programs, CORSIKA makes use of the Monte Carlo-theory. This is a theory for the generation of random numbers and it was developed in 1944 and named after the city Monte Carlo in Monaco due to the comparison with the roulettes in this city’s casinos. To achieve randomness from a deterministic machine as the computer, uniformly distributed numbers have to be generated. For statistical reasons a lot of numbers are needed. CORSIKA uses the random number generator RANMAR of the CERN program library. This generator can generate simultaneously up to $9 \cdot 10^8$ independent sequences with a length of $\approx 2 \cdot 10^{44}$ each.

5.1.1 Interaction models

This section can be skipped upon first reading. Section 5.1.2 is important to read, however.

Hadronic interactions are simulated within CORSIKA by several models depending on energy. If the energy is high enough, the interaction is treated by one of the models VENUS [26], QGSJET [21], DPMJET [19], SIBYLL [24] or HDPM. The high energy models reach their limit when the energy available for generation of secondary particles drops below a certain value. One of the low-energy models GHEISHA [27] or ISOBAR then takes over. For GHEISHA, this transition energy is 12 GeV corresponding to a laboratory energy of 80 GeV. For ISOBAR this value is $E_{cm} = 10$ GeV respectively $E_{lab} = 50$ GeV.

The GHEISHA routines as implemented in CORSIKA are taken from the detector simulation program GEANT3 [35]. This program is used by many high-energy experimental groups and thus much experience on the validity of the GHEISHA routines exists. It is important to note that the bulk of the interactions in the CORSIKA routine fall in this low-energy region.

In the article by Nagano and Watson the two models QGSJET and SIBYLL are compared. Both interaction models give almost the same results, but QGSJET is shown to be superior in proton-induced showers. In articles [33] and [34] the QGSJET (Quark Gluon String model with JETs) also prevails over the SIBYLL hadron interaction model. Therefore all calculations in this paper will be done with this model. This choice automatically forces
the GHEISHA option, as the baryons with strangeness \( \pm 2 \) and \( \pm 3 \) generated by this model cannot be treated by the ISOBAR model.

To go into details of the physical properties of the QGSJET model is beyond the scope of this text, but the interested reader is referred to articles [21], [22] and [23].

5.1.2 Thinning algorithm and Energy cuts

In Monte Carlo simulations for extensive air showers the computing time roughly scales with the energy of the primary particle.

For showers initiated by particles with primary energies \( E_0 > 10^{16} \text{ eV} \), these computing times become excessively large. See table 6.

In 1997, M. Hillas, the developer of the program MOCCA, proposed a way out of this problem: ‘thin sampling’ or ‘variance reduction’[37].

All secondary particles with energies \( E \) below a certain fraction of the primary energy \( E_0 \) (the so-called thinning level \( \varepsilon_{th} = E/E_0 \)) are subject to this procedure. All particles with energies greater than \( \varepsilon_{th} \) are followed in detail, but if the energy sum of all \( j \) particles produced in a certain interaction falls below the thinning energy

\[
\sum_j E_j < \varepsilon_{th} E_0
\]  

(2)

only one particle is followed. This surviving particle is selected at random according to its energy \( E_i \) with the probability

\[
p_i = E_i/\sum_j E_j.
\]  

(3)

All the other particles are discarded. In order to conserve energy, an appropriate weight \( w_i = 1/p_i \) is assigned to the surviving particle. If the energy-sum of the secondary particles exceeds the thinning level, more than one particle will survive.

Table 6 gives an overview of the relative computation times for various thinning levels.

<table>
<thead>
<tr>
<th>( \varepsilon_{th} )</th>
<th>( 10^{-3} )</th>
<th>( 10^{-4} )</th>
<th>( 10^{-5} )</th>
<th>( 10^{-6} )</th>
<th>none</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time</td>
<td>1</td>
<td>7.5</td>
<td>45</td>
<td>300</td>
<td>600</td>
</tr>
</tbody>
</table>

Table 6: Relative computation times for various thinning levels. (Primary energy \( 10^{15} \text{ eV} \))

The thin sampling method thus reduces computation times considerably. There is a drawback however:

Only one particle (or more, depending on the sum of the energies of the secondaries) is followed of the bunch of particles produced in the interaction. Although secondaries with higher energies are more probable to survive, there are still secondaries of the bunch (with likely comparable energies) which are discarded completely. Possible reactions caused by secondaries which are not followed in detail are not taken into account in CORSIKA. Conservation of momentum dictates that not every particle will travel in the same direction and
5.1 Use of the program

5.1.3 Energy cuts

In all simulations a compromise has to be made between simulation time (and perhaps the manageability of the output files) and the accuracy of the simulations.

<table>
<thead>
<tr>
<th>E-cuts (GeV)</th>
<th>hadrons</th>
<th>$\mu^\pm$</th>
<th>$e^\pm$</th>
<th>$\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>customized</td>
<td>0.05</td>
<td>0.05</td>
<td>0.005</td>
<td>0.005</td>
</tr>
</tbody>
</table>

Table 7: Energy cuts used in this thesis

On top of the thinning algorithm, which becomes active when the thinning level is reached,
another process in the CORSIKA program ensures that computation times remain manageable. Particles with energies falling below a certain value, the *cut-off energy*, are dropped from the simulation altogether.

More on energy cuts in section 6.4.
6 Air Shower Simulations

In this section, results of simulations done with CORSIKA are discussed.

In section 6.1 the most probable height of first interaction is determined with its effects on the particle distributions. In section 6.2 longitudinal distributions of particles and distribution of energy deposition is determined for primary protons ranging in energy from $10^{17}$ eV to $10^{20}$ eV. Particle densities, energies and shower front structures are discussed in sections 6.3 to 6.5 to conclude with inclined showers in section 6.6.

6.1 Height of first interaction

![Graph: Muon densities for different heights of first interaction of a $10^{19}$ eV proton primary; Inclination, $\Theta = 0$; The error bars are the root mean square due to averaging over 100 showers. See table 8 for the bins that are used.]

Figure 13: Muon densities for different heights of first interaction of a $10^{19}$ eV proton primary; Inclination, $\Theta = 0$; The error bars are the root mean square due to averaging over 100 showers. See table 8 for the bins that are used.

The height of first interaction can be selected in CORSIKA to be varied at random according to the appropriate mean free path. In a 500 shower simulation this height has proven to be approximately 25.0 km above sea level with a standard deviation of 8.9 km. At this altitude, the primary particle collides with an air particle for the first time. The target of this first interaction is randomly selected according to atmospheric abundances.

As can be seen from figure 13 the height of the first interaction has little effect as to how
many muons per square meter arrive at sealevel for large distances to the core. The points lie reasonably within each others error-bar.

For 75km, 50km and 25km the difference is even less than for 20km, 15km and 10km. A possible explanation is the following: If the first interaction occurs at 75km altitude (though the probability is very small), the most probable altitude at which the second interaction takes place is still 25km. And because of the zero inclination of the shower and high $\gamma$-factor of these particles created at 75km, the deviation of their path is negligible; they go straight down.

In adverse, however, primaries penetrating very deep into the atmosphere generate more muons which survive till they reach the ground. These deep-penetrating showers in the simulations are responsible for the high amount of particles close to the shower core. Close to the shower core, because, the deeper the primary penetrates into the atmosphere, the smaller the chance of getting scattered far away from the core.

Figure 14: Comparison between fixed first interaction height at 25km and random interaction height determined by CORSIKA as the local mean free path (with an average of 25km). Values are averaged over 100 showers with root mean square as error bars.

A look at figure 14 shows an important fact:

The particle densities are independent of the height of first interaction of the primary. This eliminates one degree of freedom of determining the primary energy by means of a
6.2 Longitudinal shower development

When a primary hits Earth’s atmosphere, the number of secondaries grows exponentially as the shower penetrates Earth’s atmosphere and diminishes again as it reaches sealevel. Section 6.2.1 discusses the longitudinal particle distribution and section 6.2.2 discusses the energy that is lost to the shower development.

6.2.1 Longitudinal particle distribution

If we would cut the atmosphere into horizontal slices of 20g/cm$^2$ thick and we would count all particles in that bin we would get a distribution like that of Figure 15. Most particle species, with the exception of muons, have an optimum abundance at a depth of 600 to 700 g/cm$^2$. The muon distribution falls less rapidly than that of the other particles because the muons are fairly stable and have a high chance to survive until reaching the ground. In appendix B, section 11, figures 25 to 28, longitudinal distributions are given for different primary energies. It can be seen that the optimum of longitudinal particle densities of the shower shifts closer to the ground for increasing primary energies. Which will result in higher particle densities at ground level. This will be discussed in section 6.3.

6.2.2 Longitudinal energy deposition

As an EAS develops through the atmosphere, various processes cause energy to be lost to the shower. This lost energy cannot be used create new particles that sustain the shower development.

One of these processes is the drop below the energy cuts. But energy is also carried away through the production of neutrino’s and the ionization of air particles, see figure 16 (and analogous figures 29 to 32 of other primary energies in Appendix B, section 11).

Most energy is lost to the shower due to ionization by electrons and in a lesser degree due to them falling beneath the energy cuts. Less than one tenth of the energy loss is due to photons falling beneath the energy cut and one hundredth part is due to muons ionizing the air. As expected, at high altitudes, almost all of the energy that is lost is due to the production of neutrinos. At these high altitudes almost all mesons (especially kaons and pions) decay and consequently result in the production of a lot of neutrinos.

6.3 Particle densities

To determine what the energy of the primary particle is, one needs to determine the radius of the shower. This means that the particle density at sealevel has to be calculated. This has been done by counting the amount of particles$^{30}$ arriving in a radial bin of certain width and divide this number by the area covered by the bin.

$^{30}$Because we have implemented the thinning algorithm, we need to multiply each particle with its appropriate weight to get the number of particles which that particle represents.
Figure 15: Longitudinal particle distribution as a function of atmospheric depth (g/cm\(^2\)). Primary energy of 10\(^{17}\) eV, zero inclination. Bins of 20 g/cm\(^2\) have been used.

Table 8: Bin widths for various distances to the core of the shower. These bins have been used throughout this thesis.

<table>
<thead>
<tr>
<th>radius (m)</th>
<th>bin width (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 &lt; r &lt; 100</td>
<td>5</td>
</tr>
<tr>
<td>100 &lt; r &lt; 200</td>
<td>10</td>
</tr>
<tr>
<td>200 &lt; r &lt; 500</td>
<td>25</td>
</tr>
<tr>
<td>500 &lt; r &lt; 1000</td>
<td>50</td>
</tr>
<tr>
<td>1000 &lt; r &lt; 2000</td>
<td>100</td>
</tr>
<tr>
<td>2000 &lt; r &lt; 4000</td>
<td>250</td>
</tr>
</tbody>
</table>

In figure 17 we have done a simulation of 100 showers for each of the energies 10\(^{17}\) eV, 10\(^{18}\) eV, 10\(^{19}\) eV, 10\(^{20}\) eV. It is important to note that the height of first interaction has not been fixed at a certain altitude, but left at random.

Pay close attention to the error bars of the muon density distribution at large distances from the core. We shall see that those error bars are larger for photon and electron densities. In fact, for photons and electrons there are only upper limits to the densities at large distances from the core of the shower. The densities of electrons, photons but also of protons and pions are given in figures 33 to 37 of Appendix B in section 11. An explanation as to why the error
bars of muons are still relatively small at large distances is that muons are fairly stable (see figure 15 in section 6.2.1). Most muons that are headed for large distances from the core, actually get there which is not necessarily the case for electrons and photons.

Throughout this thesis, we keep 2 particles (for all particles, not just muons) per square meter as a reference for the radius of the shower\(^{31}\). The following table gives an overview of the shower radii for different particles and energies with errors deduced from figures 33 to 35. That is to say, I have taken the radius (a) from the lower-limit error bar at which there were still 2 particles per square meter and the radius from the upper-limit error bar at which there were still 2 particles per square meter and I have averaged those radii (which are the numbers in table 9, c). The errors (given in parentheses in table 9) are the difference between the average and the lower or upper limit (c-a).

<table>
<thead>
<tr>
<th></th>
<th>10^17</th>
<th>10^18</th>
<th>10^19</th>
<th>10^20</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\mu^+)</td>
<td>120(15)m</td>
<td>400(30)m</td>
<td>925(50)m</td>
<td>1650(100)m</td>
</tr>
<tr>
<td>(\gamma)</td>
<td>575(25)m</td>
<td>1010(40)m</td>
<td>1650(150)m</td>
<td>2275(250)m</td>
</tr>
<tr>
<td>(e^+)</td>
<td>270(20)m</td>
<td>530(45)m</td>
<td>920(130)m</td>
<td>1625(425)m</td>
</tr>
</tbody>
</table>

Table 9: Radii at which there are approximately 2 particles per square meter

What can be seen from table 9 is that although the radius of the muon shower at 10^{20} eV is smaller than that of photons (and of the same order of magnitude for electrons), it is more sharply defined. This gives our first clue that muons are promising particles from which to

\(^{31}\)This equals to one particle per detector in the case of HiSPARC.
Figure 17: Average number of muons per square meter as a function of radial distance to the core of the shower. Averaged over 100 showers with one sigma as error bars. Zero inclination. Bins used as stated in table 8.

deduce the shower radius and thus the primary energy.

### 6.4 Particle energies

Until we know whether a particle has enough energy to leave a trace in the detector, particle densities alone are not enough.

To get the average energy per particle (per bin), the total energy of all *weighted*-particles is multiplied by their weights and hence divided by the sum of weights of all particles (of one specie, of course) in the bin, see equation 4.

\[
E_{\text{averaged}} = \frac{\sum w_i p_i}{\sum w_i}
\]  

The result is given for muons and photons in figures 18 and 19. These figures including the one for electrons can be found in appendix B.

What should strike the reader first is that from a few hundred meters and more from the core of the shower, there is an increase in electron and photon energy. The radius at which this increase occurs depends slightly on the primary energy and lies further out for showers...
induced by $10^{20}$ eV than $10^{17}$ eV. This can be explained by the following[38]:

As we have seen in section 3 there are various processes involving the equilibrium between photons and electrons. We have also seen that these processes have interaction cross sections depending on the energy.

It turns out that the dying away of a shower starts at the low end of the energy spectrum of the shower:

At large distances, the low energy electrons are dying away due to ionization losses while the more energetic ones scattered sideways survive. Eventually, the electron has lost so much energy that it falls beneath the energy-cut and is lost. The net-effect is a re-increase in the average energy per electron. The distance of the minimum energy depends somewhat on the primary energy because this determines from which altitude these sideways scattered electrons come from. For low energy photons, the ionization cross section becomes dominant over the Compton effect (and pair production). These low energy photons are lost to the shower development.

If we look at the error bars of muons compared to those of electrons and photons we see that for large radii the muon energies are more well defined.

On closer inspection of figure 18 we see that the average energy per muon (and in a lesser
degree for electrons and photons) is higher for 10\textsuperscript{17} eV than for 10\textsuperscript{20} eV induced showers.

A possible explanation is that the 10\textsuperscript{17} eV shower has died out more than the 10\textsuperscript{20} eV shower, as can be seen in the longitudinal particle distributions figures 25 to 28 in Appendix B. This would result in the dying away of the low energy end of the particles first. And consequently result in a higher average energy per muon for 10\textsuperscript{17} eV induced showers than for 10\textsuperscript{20} eV showers.

However, as mentioned earlier, the muons are fairly stable and although there is a small bend visible in figure 18 which would suggest the starting of a re-increase of the muon energy, this would not be enough to have caused this effect. Further research is needed on this problem.

In combination with table 9 and figures 38 to 40 we can now give an overview of the average energy per particle at the radius where there are approximately two particles per square meter, see table 10.

It can be seen from table 10 that the average energy per muon\textsuperscript{32} is approximately 2 orders of magnitude higher than that of photons and electrons. The errors for muons decrease with increasing primary energy whereas the errors for photons and electrons increase up to 80%.

\textsuperscript{32}at radii at which there are 2 particles per square meter.
6.4 Particle energies

<table>
<thead>
<tr>
<th></th>
<th>$10^{17}$</th>
<th>$10^{18}$</th>
<th>$10^{19}$</th>
<th>$10^{20}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu^+$</td>
<td>8.65(2.15)</td>
<td>3.10(0.6)</td>
<td>1.75(0.25)</td>
<td>1.40(0.20)</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>0.020(0.001)</td>
<td>0.019(0.004)</td>
<td>0.027(0.011)</td>
<td>0.034(0.021)</td>
</tr>
<tr>
<td>$e^\pm$</td>
<td>0.031(0.001)</td>
<td>0.046(0.009)</td>
<td>0.051(0.026)</td>
<td>0.094(0.076)</td>
</tr>
</tbody>
</table>

Table 10: Average energy per particle (in units GeV) at radii at which there are approximately 2 particles per square meter.

Figure 20: Average energy per photon at ground level as a function of distance to the core of the shower for different energy cuts. This is a one-shower simulation. Zero inclination. Bins used as stated in table 8.

It should be stressed that the average energies of the particles are closely related to what energy cuts are implemented.

As can be seen in figure 20, if the energy cuts are lowered, the average energies at ground level converge. The energy cuts used in this thesis (0.005 for photons) result in a factor $\sim 2$ too high energy, see figure 20.

\[\text{33} \] Which is, of course, what we expect. Lower energy cuts means particles are tracked for a longer period of time.
6.5 Shower front structure

If a shower hits the surface of the Earth, we would like to measure it. We would like to know what the shower front of an EAS looks like for the following reasons:

- The shower front determines with what accuracy the primary can be traced back to its origin. For the simple reason that the determination of the inclination of the primary particle depends on the observed time difference at three (or more) points on the ground\textsuperscript{34}.
- The shower front also gives us an idea of the integration time required for the electronic equipment on the ground.
- How fast need our electronics be in order to measure individual particles originating from one shower? What is the sample rate?

The arrival times of each particle at the ground is calculated. It is assumed that in each radial bin, the arrival times are uniformly distributed. Figure 21 shows a schematic view as to

\begin{center}
\includegraphics[width=0.5\textwidth]{shower_front_structure.png}
\end{center}

Figure 21: Schematic view of the shower front structure.

why a shower front becomes wider with increasing distance to the core of the shower: particle 2 will arrive later in the bin than particle 1 (assuming they have the same speed). The $\sigma$ in the figure is the root mean square of the arrival times of all the particles (of the same specie) in each bin and is calculated using equation 5.

\textsuperscript{34}This is called triangulation.
\[ \sigma = \sqrt{\frac{\sum (w_i(t_i - \mu)^2)}{\sum w_i}} \]  

Here \( t_i \) is the arrival time and \( w_i \) the weight of particle \( i \). \( \mu \) is the averaged arrival time of the particles in the bin, calculated with equation 6.

\[ \mu = \frac{\sum (t_i w_i)}{\sum w_i} \]  

If we multiply the found sigma with the speed of light we obtain a width in meters of the shower front. At these energies all particles travel nearly at the speed of light, so this is legitimate.

Figure 22: Thickness of muon wavefront averaged over 100 showers. Zero inclination, \( \Theta = 0^\circ \). Radial binning as stated in table 8. To get the thickness of the wavefront in seconds, simply divide by the speed of light, \( c \).

The thickness of the muon wavefront has been calculated in figure 22. Again, the error bars are due to averaging over 100 showers. In figures 41 to 43 in Appendix B, the results are given for muons, photons, and electrons. Note that I have defined one root mean square to be the thickness of the shower front. One can also define a wavefront thickness to be 4 sigma. Then we get 95% of all the particles in each bin. Depending on what the demanded specifics of the recording electronics are and how many particles of one shower one wants to detect, the wavefront thickness can be redefined.
6.6 Inclined showers

Until now we have only discussed showers with zero inclination. In practice, however, most primaries will have some inclination. An air shower experiment in Turku, Finland [39] has shown that the arrival distribution at sealevel for detected showers is \( \Theta \) dependent (Zenith angle) and \( \Phi \) independent (Azimuth angle) as equations 7 and 8 show:

\[
\frac{dN}{d\Theta} \propto \sin \Theta (\cos \Theta)^{8.9 \pm 0.2} \tag{7}
\]

\[
\frac{dN}{d\Phi} \propto \text{constant} \tag{8}
\]

Formula 7 is plotted in figure 23. The average zenith angle is 22.4\(^\circ\), and the most probable angle is 18.5\(^\circ\).

What is the difference between non-inclined and inclined air showers? Figure 14 shows that the average height of first interaction of the primary remains unchanged because the air density remains 0\(g/cm^2\) at an averaged altitude of 25 km. But the time travelled for the wavefront to reach sealevel is extended. A result of this is that the effective distance travelled through the atmosphere is longer. Due to this longer effective length, the shower has more time to develop and hence will look older when it hits ground. As we have seen in section 6.2.1, from a certain altitude the longitudinal particle multiplicity of an EAS decreases with distance travelled. Thus we expect less particles to arrive at sealevel if the shower is inclined opposed to non-inclined. Figure 24 shows the longitudinal muon distribution for a shower simulation where \( \Theta \) is the only variable that has been varied.

It appears that the "age" of the shower, i.e. the number of particles arriving at ground level, is approximately the same for showers with inclination of \( \Theta < 30^\circ \). The number particles rapidly diminishes for increasing values of \( \Theta \).

Inclined showers are suspected to result in a different particle density distribution. It is important for primary energy determination by particle densities and for triangulation.
Figure 24: Longitudinal muon distribution for various shower inclinations, $\Theta$. Averaging is over 30 showers with one sigma as error bars. Binning is in $20\text{g/cm}^2$. The number of particles arriving at the ground is approximately constant for $\Theta < 30^\circ$.

purposes to know more about these inclined showers. This is a good subject for further studies.
7 Concluding remarks

In our quest to explore the properties of Extensive Air Showers, caused by ultrahigh energy cosmic rays, we have come to know a few important things. Here follows a list of the most important ones:

- In a simulation of 100 showers we have seen that the altitude of first interaction lies well around the average of 25.0 km. This means that, in a simulation of 100 showers, the height of first interaction is eliminated as degree of freedom in determining the particle densities at ground level and thus determining the primary energy of the cosmic ray. It should be noted however, that the $\sigma$ of the first interaction altitude distribution is $\sim 9$ km and that primaries penetrating deep into the atmosphere generate more particles that reach ground level than high-altitude ones. Assuming a normal distribution, 95% of all cosmic rays have their first interaction between an altitude of 42.8 km and 7.2 km.

- Extensive Air Showers have their optimum rather close to the ground. Closer for a $10^{20}$ eV primary than for a $10^{17}$ eV primary; all particle numbers (in a lesser degree for muons) decrease eventually as they reach the ground. This gave our first hint that muons are very important in determining the primary energy: because their particle densities are fairly stable even at large distances from the core compared to photons and electrons.

- Most of the energy that is lost to the shower development is lost due to electrons ionizing the air. Electrons falling beneath the energy cut is the second loss of energy. This should be very troublesome, because this energy would in real life be available for shower development. This is true but, more importantly, we are only interested in the particles arriving at ground level so that we can detect them. Only the most energetic ones will survive the long traverse through the atmosphere and frankly, we don’t care what happens to particles which, in practice, we were unable to detect anyway.

- We have seen that particle densities are dependent on primary energy and that, for large distances from the core of the shower, the muon densities are still well defined whereas the photon and electron densities vary significantly. This is what we expected from the longitudinal development of the shower and seems to confirm our hunch that muons are very promising particles.

- The particle energies that have been calculated show us a nice, well defined energy for muons and a re-increase in photon- and electron energies beyond a certain distance from the core. This is due to the fact that the dying away of an EAS starts at the low

\footnote{This energy cannot be used to create high energy secondary particles.}
\footnote{Note that this is only a loss in the simulation. Not in practice.}
energy end of the energy spectrum.

<table>
<thead>
<tr>
<th></th>
<th>$10^7$</th>
<th>$10^8$</th>
<th>$10^9$</th>
<th>$10^{10}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu^-$</td>
<td>8.65(2.15)</td>
<td>3.10(0.6)</td>
<td>1.75(0.25)</td>
<td>1.40(0.20)</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>0.020(0.001)</td>
<td>0.019(0.004)</td>
<td>0.027(0.011)</td>
<td>0.034(0.021)</td>
</tr>
<tr>
<td>$e^\pm$</td>
<td>0.031(0.001)</td>
<td>0.046(0.009)</td>
<td>0.051(0.026)</td>
<td>0.094(0.076)</td>
</tr>
</tbody>
</table>

Table 11: Average energy per particle (in units GeV) at radii at which there are approximately 2 particles per square meter.

- Again, muons prevail above photons and electrons. This gave our second hint that muons are important in determining the energy of the primary particle: because they have relatively high and well-defined energies even at large distances from the core compared to photons and electrons. The energy cuts that have been used are of influence to the resulting average energy per particle, but only up to an order of 0.5 Mev (for photons). New simulations should be done in future with as low energy cuts as possible.

- Time front structure calculations have been done for muons, photons and electrons which will be of use to determine the accuracy of triangulations and integration times for recording electronics.

- Primary cosmic rays should be isotropic, but reaching ground is a different story. We have seen that primaries with an inclination of less than 30 degrees differ not that much from each other. That is to say, they appear approximately equally old. What the exact density- and energy distributions will be, is a good subject for further studies.
8 Future study

- Detector response and energy deposition in the detectors of HiSparc;
- Inclined shower simulations, especially the particle density distributions;
- Triangulation and primary direction accuracy determinations;
- Generic reconstruction of direction from uniform particle densities based on the available detector array;
- LOFAR meets HiSPARC?
9 Acknowledgements

This work has been made possible by various people, including Prof. Dr. Bob van Eijk, Dr. Henkjan Bulten, Prof. Dr. Pierre van Baal and Dr. Dieter Heck.

I want to express my gratitude to all the people who inspired me and kept me going[40].
10 APPENDIX A: CORSIKA

The handling of the program CORSIKA isn’t as straightforward as the manual lets you think. Even though the main part of the program is reasonably well explained, there are some things that are not and can result in a lot of irritation and time consuming debugging.

To get the program, send an email to Dieter Heck dieter.heck@ik.fzk.de. He will ask for your host-name (that is the name of the computer) from where you want to go to the anonymous ftp server ftp-ik3.fzk.de to get the CORSIKA code and all other files you need. Once you followed all instructions to download at the ftp server. Read the README file and print the CORSIKA_GUIDE6031 (in postscript format or DVI). Before proceeding, read the first two chapter of the guide. The next part gives an overview of how the program works:

The corsika6031.car file is a CMZ-file. This makes it possible to extract several versions of the program, depending on the computer system you are using, the compiler you are going to use to compile the fortran files, but also the hadron interaction model you want to use and much more.

Now read section 2.1.1 CMZ-commands of the user’s guide;

This is a part where things might go wrong. While extracting the CMZ-file, some selected options may be conflicting. (Read footnote 8 on page 10). This are the options I have selected for my simulations:

UNIX
BYTEECL
QGSJET
QGSSIG
QGSJETOLD
QGS01C
GHEISHA
THIN

The obtained corsika_compilefile.f must be edited for convenience in future:

Open the file with a text-editor and search for the word ‘MONIIN’. After a few hits, you will see a ”5” behind the word ‘MONIIN’. Change this logical unit number of ’MONIIN’ (standard input is from keyboard) from 5 to another logical unit number which is not yet in use (see page 18 of the user’s guide). This will ensure that the input to steer the simulation is read from a file called ’INPUTS’ in the local directory of the CORSIKA program instead of (laboriously) typing it in by hand.

Now the program has to be compiled and linked with the proper routines:
g77 corsika_compilefile.f qgsjet01c.f gheisha2002.f -o corsika.

What needs to be done now is generate an 'INPUTS' file to steer the simulation. Chapter 3 of the user’s guide deals with these steering words. See chapter 5 on page 66 of the user’s guide for an input example.

The steering words I have used on my simulations are the following:
The boldface steering words are often changed for each simulation. These steering words need to be in accordance with the version of the program you have extracted from the CMZ-file. The THIN steering word, for example is only available if the THINNING option is selected in the extraction. Sometimes certain options exclude or demand certain other options. It is recommended to read chapter 4 of the user’s guide extensively.

Just a few problems I have encountered:
If you want to split a simulation of, say, 100 showers into 10 simulations of 10 showers it is important to note the following. The SEED steering words ensure that, when a simulation has gone awry, it can be simulated again, bit for bit and particle for particle. When splitting a simulation into multiple ones, the seeds thus have to be different for each simulation. The RUNNR and EVTNR also have to be different:

Simulation 1: first 10 showers

RUNNR 1
EVTNR 1
NSHOW 10
SEED  1  0  0  hadronic part
SEED  2  0  0  EGS4 part
SEED  3  0  0  Čerenkov part
. . . EXIT

Simulation 2: showers 11 to 20

RUNNR  2
EVTNR  11
NSHOW  10
SEED  4  0  0  hadronic part
SEED  5  0  0  EGS4 part
SEED  6  0  0  Čerenkov part
. . . EXIT

Simulation : showers 21 to 30

RUNNR  3
EVTNR  21
NSHOW  10
SEED  7  0  0  hadronic part
SEED  8  0  0  EGS4 part
SEED  9  0  0  Čerenkov part
. . . EXIT

Etcetera.

Notice that above steering words have an additional seed. This seed is for the Čerenkov part of the simulation. But since investigation in the Čerenkov photons have not been part of this theses, I have not included them in table 10.

After executing the simulation, several output files are generated (depending on your steering words).

\textbf{DATnnnnnn.LONG} where \( n \) is the run number is generated because of the \texttt{LONGI}-steering word is set to \textit{true}. This file contains a table of longitudinal distributions for various particles and a table of longitudinal energy deposits (in GeV) by various particle species as a function of optical depth in atmosphere (in grams/cm\(^2\)) (see chapter 10.5 on page 82 of the user’s guide)

\textbf{DATnnnnnn.DBASE} is generated because of the \texttt{DATBAS}-steering word is set to \textit{true}. This file contains an overview of the options selected as is given in the ’INPUTS’ file of this simulation and is very handy for quick reference when you are wondering what again you were doing in this world.\textsuperscript{37} (see table 14 on page 84 of the user’s guide)

\textsuperscript{37} Of course the only thing we live for is learning more about high energy particle physics, what else?
CERnnnnnn is generated if the CERFIL-steering word is set to true and the CERENKOV option has to be selected when extracting the CMZ-file. This file contains the Čerenkov output and has not been used in this thesis.

10.1 Main output

DATnnnnnn is the main output file generated by CORSIKA. Depending on energy and number of showers, this file can become as large as several Gigabytes. It is recommended to run no more than a few tens of showers in each simulation run, because it turned out that some versions of Linux cannot handle files exceeding 2 Gb.

Details on the structure of this file can be found in table 6 to 12 in section 10.2 on page 74 of the user’s guide. The file is binary and can be converted to text with the fortran executable obtained by the files corsikaread.f or corsikaread.thin.f, depending on whether the thinning option is selected or not. This output file had the standard name fort.8.

As discussed in section 5.1.2, thinning is strongly advised when dealing with high energies.

If thinning is selected, the DATnnnnnn file contains 8 columns and numerous lines and has the following structure:

RUN HEADER
This block is made up of 39 rows of 8 columns each. This block starts with the word 'RUNH' (or, as a real number: 1.11111E+07) and each further entry has information stored as given in table 7 on page 75 in the user’s guide.

EVENT HEADER
Next comes for each event (i.e. for each shower) a block which contains an EVENT HEADER of 39 lines. This block starts with the word 'EVTH' (or, as a real number: 3.33333E+07). See table 8 on page 76 in the user’s guide.

DATA BLOCKS
The next lines grouping in blocks of 39 lines each contain the particles arriving at ground, just the information which we want to have. For each particle, the particle type, px, py, pz, x, y, t and the weight is written down. See table 9 on page 78 of the user’s guide.

If the last data block is not filled completely, trailing zeroes are added.

EVENT END
As the shower data is written to files, the event end sub-block of 39 lines is written out. This block starts with the word 'EVTE' (or, as a real number: 7.77777E+07). Table 12 on page 80 of the user’s guide handles the contents of this block.

If there are more showers in one simulation run, then the whole thing starts again at a

---

This is not mentioned in the guide
new event header.

**RUN END**

After all the showers, the DATnnnnnn file is closed with a last block of 39 lines beginning with the word 'RUNE' (or as a real number: 9.99999E+07).
11 APPENDIX B: FIGURES
11.1 Longitudinal particle distributions
11.1 Longitudinal particle distributions

Figure 25: Longitudinal particle distribution. Averaged over 100 showers

Figure 26: Longitudinal particle distribution. Averaged over 100 showers
11.1 Longitudinal particle distributions

Figure 27: Longitudinal particle distribution. Averaged over 100 showers

Figure 28: Longitudinal particle distribution. Averaged over 100 showers
11.2 Longitudinal energy deposition
11.2 Longitudinal energy deposition

Figure 29: Longitudinal energy deposition. Averaged over 100 showers.

Figure 30: Longitudinal energy deposition. Averaged over 100 showers.
11.2 Longitudinal energy deposition

Figure 31: Longitudinal energy deposition. Averaged over 100 showers

Figure 32: Longitudinal energy deposition. Averaged over 100 showers
11.3 Particle densities at sealevel
11.3 Particle densities at sea level

APPENDIX B: FIGURES

Figure 33: Muon density. Averaged over 100 showers.

Figure 34: Photon density. Averaged over 100 showers.
11.3 Particle densities at sea level

Figure 35: electron density. Averaged over 100 showers

Figure 36: proton density. Averaged over 100 showers

53
Figure 37: Pion density. Averaged over 100 showers.
11.4 Energy per particle
11.4 Energy per particle

Figure 38: Average energy per muon. Averaged over 100 showers

Figure 39: Average energy per photon. Averaged over 100 showers
Figure 40: Average energy per electron. Averaged over 100 showers.
11.5 Shower front structure
11.5 Shower front structure

APPENDIX B: FIGURES

Figure 41: Thickness of muon wavefront. Averaged over 100 showers.

Figure 42: Thickness of photon wavefront. Averaged over 100 showers.
Figure 43: Thickness of electron wavefront. Averaged over 100 showers.
References


[16] 'Akeno Giant Air Shower Array (AGASA) covering 100km² area’, N.Chiba et al, Nucl. Instr. and Meth A311 (1992) 338


REFERENCES


[38] J.D. Haverhoek, private email-communications with Dieter Heck, Forschungszentrum Karlsruhe GmbH, Karlsruhe, August and September 2005


[40] William Ernest Henley, Sir Thomas Wyatt, John Keats, William Butler Yeats, Walter de la Mare, and many, many more.