Licentiate Thesis

Imaging the High Energy Cosmic Ray Sky

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Cover illustration: The sky coverage of cosmic rays for the SEASA array in galactic coordinates
Image by Petter Hofverberg

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Abstract

The Stockholm Educational Air Shower Array (SEASA) project is deploying an array of plastic scintillator detector stations on school roofs in the Stockholm area. Signals from GPS satellites are used to time synchronise signals from the widely separated detector stations, allowing cosmic ray air showers to be identified and studied. A low-cost and highly scalable data acquisition system has been produced using embedded Linux processors which communicate station data to a central server. Air shower data can be visualised in real-time using a Java-applet client.

The design and performance of the first three detector stations located at the AlbaNova University Centre are presented. The detectors have been running since the beginning of October 2005 and the data from this period is analysed to assess the stability and performance of the detector array. A total of 503 showers with a primary particle energy above $10^{16}$ eV, hitting all three detector stations simultaneously, have been detected during this period. The read out and data-base system used to collect the data are described together with a quicklook tool for ensuring the integrity of the data.

A preliminary study of the acceptance of the detector array as a function of weather conditions, to be used in future studies of cosmic ray anisotropy, is presented. The acceptance of the single detector stations is found to decrease with increasing atmospheric pressure and to stay constant over a large range of temperatures. The acceptance of the entire array of detector stations is found to have a stronger continuous dependence on temperature than single stations. The dependence of the array acceptance on pressure is inconclusive.

The ability of the array to reconstruct the primary cosmic ray direction is assessed with simulations. A critical feature for the reconstruction is the time resolution of the system. The performance of the GPS system is therefore tested, and the time resolution is found to be better than 15 ns for all tested GPS units. The angular resolution of the array for this time resolution is found to be $(7.0 \pm 0.3)^\circ$. As the time resolution is expected to decrease for a larger array of detectors, the dependency of the time resolution on the angular resolution is derived.

The measured distribution of the primary cosmic ray arrival direction is derived and compared to the expected distribution to check the performance of the system. The agreement between the distributions is good and the GPS timing system can
therefore be concluded to work well. The simulations also show that the energy threshold of the array is slightly above $10^{16} \text{ eV}$.

A preliminary study of the cosmic ray anisotropy is presented. The hypothesis of an isotropic flux of cosmic rays was tested using a two point correlation function. The probability that the observed flux is a random sampling from an isotropic flux was checked with a Kolmogorov test and it was found to be $82\%$. The hypothesis of an isotropic flux is therefore supported.
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Introduction

Outline of the Thesis

This thesis describes the construction and performance of the three first detector stations in the Stockholm Educational Air Shower Array (SEASA). The emphasis of the thesis is on studies of the reconstruction of the direction of the primary cosmic ray. The direction reconstruction is then used to map the celestial sky in cosmic rays.

Chapter 1 provides an overview of the field of cosmic rays with an emphasis on air shower detection techniques. The field is put in context with a historical overview, starting with the discovery of the cosmic rays. The physics of air showers is presented and followed by a discussion of the origin and arrival distribution of cosmic rays.

The construction of the SEASA experiment is described in chapter 2. All the major parts are described in detail: the detectors, the GPS system, the electronics and the server.

Chapter 3 presents general features of the data collected with the array from October 2005 to April 2006. This data set is then used in subsequent chapters for data analysis. A study of the influence of weather on the array acceptance is presented. Lastly, a monitoring tool used during the data collection is described.

The angular resolution of the detector array is analysed in detail in chapter 4. Algorithms for deriving the incident direction of the cosmic ray air shower are presented. The measured distributions of arrival directions are presented and used to check the performance of the array. Simulations are performed to estimate the angular resolution of the array and this is compared to data.

The measured arrival distribution of cosmic rays, the sky map, are analysed in chapter 5. Methods to perform point source and anisotropy searches are presented and the hypothesis that the cosmic ray sky is isotropic are checked with data collected by SEASA.

Chapter 6 summarises the most important conclusions in the thesis and gives an outlook of future work for SEASA.
The Author’s Contribution

My work at the Particle and Astroparticle Physics group at KTH began in July 2003 when I started my diploma work for SEASA [1]. This work finished in December the same year and shortly afterwards I started a PhD position in the same group. The first year as a PhD student was mainly dedicated to the space experiment PAMELA [2], scheduled for launch in mid June 2006. My work consisted partly of designing the software for the DSP on the electronic read-out board for the anticounter (AC) detectors, but also concerned integration tests of the AC detectors with the final flight configuration in the INFN laboratories in Rome.

After my first year of employment I have devoted increasingly more time to the SEASA experiment as the integration tests of the PAMELA experiment finished. The scale of the SEASA experiment has allowed me to be involved in practically all aspects of it. I have been responsible for the software development for the embedded Linux computer that controls the GPS system, the Altera board and the data handling to the SEASA server. I have worked on integrating and testing the GPS system. I have designed a data acquisition and databasing system based on ROOT, and coupled to that, a monitoring tool to check the performance of the detector stations. I have worked in close collaboration with engineer Stefan Rydström with hands-on work to get the detector stations up and running. And more over, I have been solely responsible for the data analysis.
Publications


- P. Hofverberg et al., 'First Results from the Stockholm Educational Air Shower Array (SEASA)', Proc. International Cosmic Ray Conference, Pune, India, August 2005


Internal notes

- P. Hofverberg, 'The data format and operating modes for the AC system: two board configuration', Internal note for the PAMELA collaboration

- P. Hofverberg, 'The Anticounter Quicklook Software', Internal note for the PAMELA collaboration

- P. Hofverberg, 'Calibration procedure for the two board AC configuration', Internal note for the PAMELA collaboration
Chapter 1

Cosmic rays

Nature has provided us with a source of particles having energies greatly surpassing what can be achieved in man-made accelerators. Although these ‘cosmic rays’ have been known for over ninety years many basic questions regarding their nature and origin remain to be answered. The history and present status of this field with a focus on ground based detection techniques are described in this chapter.

1.1 A Brief History of Cosmic Rays

After the discovery of radioactivity it was noticed that the air was constantly being ionised no matter how well the detectors were shielded. The scientists first thought that the ionisation was due to radioactive material in the bed rock, but measurements at for example the Eiffel tower showed that the ionisation increased with height. The question was finally solved by the physicist and balloon pioneer Victor Hess when he performed a series of balloon flights and measured the rate of ionisation during the ascent. What he measured was that the ionisation steadily increased as the balloon went higher and Hess’ conclusion was that - “a radiation of a very high penetrating power enters the atmosphere from above” [3]. This marked the discovery of cosmic rays for which Victor Hess received the Nobel prize in 1936 together with C. Andersson. The term ‘cosmic rays’ was however first coined by another physicist, Robert Millikan. Although first sceptical of Hess’ work, he performed his own measurements and was soon convinced that the particles indeed were extra-terrestrial. Millikan was also the first to show that the cosmic rays observed at earth were secondary particles - results of interactions of the primary cosmic ray particles at the top of the atmosphere.

During the following years cosmic ray research concentrated on the high energy part of the particles - the only source of such particles at that time. A plethora of new particles and phenomena were discovered with the aid of this abundant source. In 1932 C. Andersson discovered the first evidence for antimatter. By using a cloud chamber separated by a lead foil he saw a particle with the mass of
Chapter 1. Cosmic rays

an electron bending in the wrong direction in a magnetic field. He realised that he had discovered the antiparticle of the electron - the positron. Andersson continued looking for new particles in the cosmic rays and in 1936 he, and his colleague S. Neddermeyer, believed that they had found the pi-meson predicted by H. Yukawa in 1935 as the carrier of the strong force. The particle they had discovered was however the muon, a particle similar to the electron but much heavier. The pi-meson was not discovered until 1947, when C. Powell brought a detector up in the stratosphere with the aim to detect primary cosmic ray particles.

In 1934, when Bruno Rossi performed a series of experiments aimed to investigate the east-west effect he noticed that the Geiger counters, that were separated with tens of meter horizontally, occasionally discharged exactly simultaneously. He didn’t have time to investigate the matter further but concluded that “...it seems that once in a while the recording equipment is struck by very extensive showers of particles, which causes coincidences between the counters, even placed at large distances from one another.” Pierre Auger independently reported on the same phenomena shortly after Rossi’s discovery. He investigated the subject further and concluded that the particle showers must be initiated by extremely high energy primary particles which interact with air nuclei at the top of the atmosphere and initiate a shower of secondary particles that ultimately reach the ground in the form of photons, electrons and muons.

The energies and arrival directions of the high energy primary particles were first studied by a group at the Massachusetts Institute of Technology in USA [4]. They measured the particle density and structure of the shower using 11 ‘fast-timing’ scintillator detectors within a circle with a diameter of 460 m. This basic detection method has been widely used by air shower experiments since then. From that pioneering work at M.I.T, and from the many following experiments in Japan, England, US and Russia, the energy spectra of the cosmic rays is now known to extend to beyond $10^{20}$eV.

1.2 Cosmic Ray Air Showers

Cosmic ray air showers are initiated by extremely high energy particles hitting the top of the earth’s atmosphere. Depending on the nature of the primary cosmic ray, the particle cascade develop differently. The shower profiles of three air showers with the same primary energy initiated by a photon, a proton and a iron nuclei are shown from left to right in Fig. 1.1. The hadronic induced showers are clearly broader than the photon induced shower, and especially the shower induced by a iron nuclei. The reason for this is that hadronic interactions transfer more energy laterally than electromagnetic interactions. Also, according to the ‘superposition principle’ heavier nuclei can be regarded as a superposition of its constituent nucleons. For the same energy of the primary particle, heavier particles transfer more energy laterally than single nucleons. Air showers induced by heavier particles also develop earlier.

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1The effect that low energy cosmic rays from the east are suppressed compared to those from the west because of the influence of the terrestrial magnetic field.
in the atmosphere. This is partly because a heavy nucleus has a larger cross section for interacting with an air molecule. Most importantly however, an air shower's depth of maximum ($X_{\text{max}}$), the point in the atmosphere where the air shower has developed the largest number of particles, for a proton shower increases with energy. For the same energy, a heavy primary particle shears the energy among its constituent nucleons thus reducing $X_{\text{max}}$ compared to a proton shower.

![Figure 1.1](image.png)

**Figure 1.1.** The structure of an air shower induced by a $10^{15}$eV photon (left), proton (middle) and iron-nuclei (right). The showers are shown from the point of the first interaction, at the top of the atmosphere, to the point where the shower hits the earth. The black part close to the shower axis is the hadronic component of the shower, and the grey part the electromagnetic component. The lateral width is larger for hadronic showers and it also increase with atomic number. The average depth of first interaction and the depth of shower maximum instead decrease with atomic number. Notice that the shower maximum, the point in the shower development where the shower has developed the largest number of particles, are well above ground level for showers of this energy. This has implications on the detection methods used for different energy regimes, described in section 1.2.2.

The shower development can be divided into the different *cascades* that are generated and fed throughout the passage in the atmosphere: the hadronic, pionic and electromagnetic cascade. In the first interaction a large amount of the energy is transferred to secondary mesons, primarily pions. Approximately twice as many charged pions than neutral pions are produced. The rest of the energy goes to the secondary nucleon which travels on average one interaction length and then interacts again, producing a second *hadronic cascade*. Charged pions have a relatively large interaction length and can either decay or interact. Low energy charged
pions most probably decay into muons and muon neutrinos - feeding the electromagnetic cascade. High energy charged pions almost exclusively interact because of the large interaction length boosted by the time dilatation, again generating two-thirds charged pions, thus feeding the pionic cascade, and one-third neutral pions. Secondary neutral pions almost immediately decay into two $\gamma$-rays. The daughter $\gamma$-rays most likely interact by pair production and are the major contributor to the electromagnetic cascade. These cascade processes are schematically displayed in Fig. 1.2.

**Figure 1.2.** A simplified picture of the shower development. The cosmic ray starts a hadronic cascade with primarily charged and neutral pions. Neutral pions almost exclusively decay to two high energy photons, while the charged pions either decay, producing a muon, or interact creating more pions. The result at ground is a electromagnetic and muonic component spread over a large area, and a small component of hadrons close to the shower core. Figure taken from [5]
1.2.1 Structure of the shower front

The air shower spreads out far from the shower axis during the passage through the atmosphere due to Coulomb scattering and transverse momentum in interactions and decays. As the shower hits the earth it has the form of a thin, slightly curved cone. The thickness of the cone ranges from a few nanoseconds at the core up to several microseconds far from the core for the highest energy showers. The time spread at a point in the shower disc is roughly proportional to the distance from the shower core.

For a $10^{15}$ eV shower, approximately one million particles reach the ground comprising approximately of 80% photons, 18% electrons, 1.5% muons and 0.5% hadrons. The hadrons are distributed very close to the shower axis, while the photons, electrons and especially the muons are distributed over large areas. Photons out-number all other types of particles close to the core. The electron density is one to two orders of magnitude smaller than the photon density and the muon density a couple of orders magnitude smaller than that. However, the lateral distribution of muons is flatter than for all other particles and for large distances from the shower core muons dominate the ground density. The muons also carry significantly more energy than electrons and photons ($\mathcal{O}$(GeV) compared to $\mathcal{O}$(MeV)) because of their low number of interactions during the passage through the atmosphere. The density of particles is symmetric around the shower axis outside the shower core for a vertically incident shower. The measured lateral distribution can therefore be used as a tool for determining the properties of the primary cosmic ray.

The lateral distributions for electrons and muons for primary energies between $5 \times 10^{14}$ eV and $10^{17}$ eV measured by KASCADE [6] are shown in Fig. 1.3. The sensitivity for photons are low with the thin plastic scintillators used by SEASA because of the low atomic number and density of the material, and electrons and muons are therefore the two main contributors to the detected signal. The particle density corresponding to a probability of 50% to trigger a station in SEASA is marked with a horizontal line. The probability have been calculated as

$$P_{\text{trigg}} = (1 - e^{-\rho A})^3$$

(1.1)

where $\rho$ is the particle density and $A$ the detector area (0.5 m$^2$). The electron density are about two orders of magnitude greater than the muon density close to the shower core, and the muon density can therefore be disregarded in a first order approximation of the trigger probability. Showers at the low end of the energy regime ($5 \times 10^{14}$ eV) are just dense enough to be detectable by one station, if the shower hit close to the station, while the largest shower, with an energy of $10^{17}$ eV, can be detected at a distance over 200 m.

1.2.2 Detecting air showers

The observation of air showers are to date only done with ground based detectors. Three different techniques are widely used:
Figure 1.3. The lateral distribution of electrons (top) and muons (bottom) for showers with a zenith angle below 18° measured by KASCADE. $N_e$ and $N_{\mu}$ are measures on the shower energy which ranges from $5 \times 10^{14}$ eV to $10^{17}$ eV in the plot. The horizontal lines show the density of particles corresponding to a 50% probability to trigger a station in SEASA. Figure adopted from [7].
1.2. Cosmic Ray Air Showers

- **Cherenkov telescopes**
  Air shower particles travel faster than light in the atmosphere and a cone of Cherenkov radiation is therefore beamed in the forward direction of the shower. The Cherenkov light can be collected with a telescope and shower parameters derived through the properties of this light. This method allows for the detection of the shower as it traverses the atmosphere and the shower maximum can therefore be accurately determined. This is a great benefit compared to particle detector arrays. The Cherenkov cone is very narrow because of the small reflective index of the atmosphere and the light is therefore quite intense close to the shower axis. The energy threshold for this technique is therefore low, about 1 TeV. This detection method is therefore mostly used for the detection of primary gamma rays. An experiment currently using this technique is HESS [8].

- **Fluorescence detectors**
  Air showers can also be detected by the fluorescence light that is emitted from nitrogen molecules excited by shower particles. This gives the same benefits as the Cherenkov method. The fluorescence light is however emitted isotropically, and not in the forward direction as for the Cherenkov light. The energy threshold for this technique is therefore large ($> 1 \, E_{eV}$). A drawback with both Cherenkov telescopes and fluorescence detectors is that both detection methods require clean and dry atmospheric conditions, no cloud coverage and moonless nights. The Fly’s Eye experiment [9] is a fluorescence experiment located in the desert in Utah. It consists of two separate telescopes (HiRes I and HiRes II) located on small mountains 13 km apart. This allows for a stereoscopic view of the air showers thereby improving the shower reconstruction.

- **Particle detectors**
  In this method, the shower particles are detected as they reach the ground. The detectors are usually plastic scintillators or tanks of water. Scintillation or Cherenkov light is generated as the shower particles cross the detectors and this light can be read out using photo-multipliers. The drawback with detector arrays is that they only sample the shower at the ground, at a late stage of the shower development well past the shower maximum for air showers with energies above the ankle. This is somewhat compensated by the large exposure of detector arrays - ideally 24 hours a day.

Experiments that detect air showers from space are also planned. EUSO [10] is a future experiment that will measure the fluorescence and Cherenkov light generated by UHE air showers from space. An optical detector in space will have a large collection area compared to ground based experiment and it is believed that this method would increase the world statistics in UHE shower with orders of magnitude. One question that still needs to be answered is what the energy threshold for these kind of experiments will be.
1.3 The Origin of Cosmic Rays

Our present knowledge is that the cosmic ray spectrum spans the range from below $10^6\text{eV}$ to above $10^{20}\text{eV}$, and follows a rather featureless power law $dN/dE \sim E^{-\gamma}$. However, two 'kinks' occur in the spectrum, as shown in Fig. 1.4. The first at about $4 \times 10^{15}\text{eV}$, called 'the knee', and the second at $5 \times 10^{18}\text{eV}$ naturally then called 'the ankle'. The origin of these changes in the spectrum is unknown, but it is believed that they represent changes between different classes of acceleration mechanisms.

![Fluxes of Cosmic Rays](image)

**Figure 1.4.** The cosmic ray energy spectrum at the top of the atmosphere.

While the low energy part of Fig. 1.4 is well understood, the origin of ultra high energy (UHE) cosmic rays remains one of the greatest mysteries in contemporary astroparticle physics. The particles below the knee are believed to be produced in our galaxy as they are contained by the galactic magnetic field. The origin of the particles between the knee and the ankle are subject to debate, while the highest energy particles, above the ankle, are likely to be extra-galactic. It is believed
that particles can be accelerated to energies close to the knee in shock fronts of supernova remnants (SNR). In this model, particles are scattered across the shock fronts of the SNR, gaining energy at every crossing. Recent calculations [11] derive the maximal energy achievable in this process to be

\[ E_{\text{max}} = Z \times 5 \times 10^{14} \text{ eV} \] (1.2)

where \( Z \) is the proton number. The maximal energy could even be higher if more efficient acceleration mechanisms are present and it is not ruled out that SNR can account for particle energies up to the ankle. A consequence of equation 1.2 is that the cosmic ray composition would change toward heavier elements close to the knee, the end for this acceleration mechanism, as higher \( Z \) particles can be accelerated to higher energies. Experimental evidence for this is not completely clear. While air shower array experiments support this theory, Cherenkov experiments instead shows a significant tendency towards lighter particles at the knee [12].

The places in the universe where particles with energies above \( 10^{18} \text{ eV} \) are produced must either be extremely large or have extreme magnetic fields. To date, no such sources have been seen in our galaxy. Also, if they did, an excess of events from the galactic plane would have been expected as these particles retain some of their directional information. No experiment has detected an excess from the galactic plane implying that particles with such energies are produced outside our galaxy.

However, cosmic rays above a threshold energy can not travel further than about \( \sim 100 \text{ Mpc} \), approximately the distance to our closest neighbouring galaxies. The reason for this is that the cosmic rays occasionally interact with a photon in the Cosmic Microwave Background - the bath of 2.7 K photons that permeate the universe. For a proton above an energy of \( \sim 5 \times 10^{19} \text{ eV} \), the following reaction is allowed

\[ \gamma_{\text{CMB}} + p \to \Delta^{+} \to p + \pi^{0}/n + \pi^{+} \] (1.3)

For every collision with the CMB bath the cosmic ray looses energy and after travelling approximately 100 Mpc the energy of the UHE cosmic ray is totally independent of its primary energy, as illustrated in Fig. 1.5. If particles with energies higher than the GZK-cutoff are observed at the earth their sources must consequently be closer than \( \sim 100 \text{ Mpc} \) or they must somehow evade the GZK-cutoff, implying new physics.

A number of experiments have looked for the GZK-cutoff, with varying results. The AGASA experiment has claimed evidence for an excess of super-GZK particles [13] whereas the Hi-Res experiment refutes this [14]. The situation is complicated since these experiments use different techniques for detecting air showers. The AUGER project, which is under construction, is hoped to resolve this issue by using both observational techniques simultaneously.
Chapter 1. Cosmic rays

Figure 1.5. The particle energy versus propagation distance for protons of several different primary energies above $10^{20}$ eV. Due to the GZK-effect, described in the text, the energy of the protons are independent of the primary energy after travelling $\sim 100$ Mpc. Taken from [15].

1.3.1 Possible sources of UHE cosmic rays

A naive, but possible, way of identifying sources capable of accelerating particles to ultra high energies is to look for the largest and most luminous objects in the universe. An additional requirement if they should be able to account for super-GZK particles is the proximity to the earth (within $\sim 100$ Mpc) if particles from the source should be able to avoid the GZK-cutoff. Acceleration mechanisms aside, the minimum requirement for an acceleration site is the containment of the accelerated cosmic ray at the site. The maximum energy achievable is then $E_{\text{max}} = \gamma e Z B R$, where $\gamma$ accounts for the Lorentz factor of the medium where the acceleration proceeds, $e$ is the electron charge, $Z$ the proton number, $B$ the magnetic field at the site and $R$ its linear dimension. Fig. 1.6 illustrates this requirement. Sites that can accelerate protons to energies above $10^{20}$ eV, above the GZK-cutoff, are on the upper right corner above the dotted line. The two other lines parallel to this corresponds to proton-energies above $10^{21}$ eV (above) and iron with energies of $10^{20}$ eV (below). There are only four known types of sites that can accelerate particles above $10^{20}$ eV: high magnetic field neutron stars, active galactic nuclei, lobes of giant radio galaxies and gigaparsec shocks in the interstellar medium.

Maybe the most attractive object for accelerating particles above $10^{20} eV$ are radio galaxies. FR II type galaxies are giant radio galaxies with two jets emanating in opposite directions. With an efficient acceleration, the termination shock in
1.4. The Arrival Distribution of Cosmic Rays

The arrival distribution of cosmic rays is remarkable isotropic for energies ranging from TeV to the highest energy cosmic ray measured to date. The high degree of isotropy for particles with energies up to the ankle is believed to be the result of the propagation of the particles through the magnetic field which permeate the galaxy. It is generally accepted that the magnetic field within the galaxy has a large scale (1 kpc) component along the spiral arm with a strength of a few micro Gauss and a
smaller ($\sim 100$ pc) random component with an equal strength. Low energy charged particles diffuse along the magnetic field lines with the exact motion determined by the rigidity of the particle ($pc/Ze$). As a result, low energy cosmic rays have no memory of their original direction. However, the arrival distribution is still of interest as it is related to the local magnetic field.

The transition energies between the energies of diffusive behaviour ($\sim 10^{14}$ eV) and the regime of small deflections ($\sim 10^{19}$ eV) may be very rich in new phenomena. A sketch of the different CR propagation regimes is shown in Fig. 1.8 as proposed by [17]. According to this theory, particle diffusion abates around the knee and particles instead start to drift along the magnetic field lines. For even higher energy particles some information about the original direction is retained. The scintillation regime marks the energies around the ankle where cosmic rays take different but correlated paths between the source and the earth. The result is that a large number of images of the same source are detected. For slightly higher energies, in the lensing
1.4. The Arrival Distribution of Cosmic Rays

regime, the number of images is reduced and effects similar to gravitational lensing occurs. The magnetic field can also lead to focusing effects for these energies which magnify or demagnify the source.

As the energy of the cosmic rays increase they retain more and more of their original direction. At energies of about $5 \times 10^{19}$ eV the regime of small deflections begins. The deflections here may be so small that 'cosmic ray astronomy' may be performed. However, as these particles are extra-galactic, the degree of deflection depends heavily on the properties of the extra-galactic magnetic field, which is poorly known. For example, for a $10^{20}$ eV cosmic ray source of a distance of 20 Mpc and a uniform intergalactic field with a strength of 1 nG the deflection angle should be about $10^\circ$ [16]. On the other hand, an equally strong random field with a length scale equal to the average distance between galaxies would cause a deflection angle less than $2^\circ$ [16]. The use of UHE cosmic rays for astronomy is thus not completely clear.

1.4.1 Neutral particles

Neutral particles are not affected by the galactic and interstellar magnetic fields and thus travel to the earth unscattered. Neutral particles could therefore be used for cosmic ray astronomy. The two candidates for this, excluding neutrinos, are photons and neutrons. Air shower arrays are however not the optimal method for detecting photon induced showers. High energy photons are heavily suppressed by interactions with the CMB background which begins at relatively low energies compared to cosmic rays. The energy spectra for photons therefore falls very steeply demanding an energy threshold well below $10^{15}$ eV which is difficult with air shower arrays. A huge background of hadronic showers also cloud the gamma ray induced showers. Still, the Tibet air shower array have successfully detected large and small scale anisotropies of TeV gamma rays [18].

A better candidate for cosmic ray astronomy with air shower experiments are neutrons which also can reach the earth unscattered. However, free neutrons decay, and this limits the maximal distance to the neutron source. The decay length of the neutron, which depend on the energy, must be comparable to the distance to the source. An energy of $10^{17}$ eV corresponds to a distance of 1 kpc, and for a
neutron to reach the earth from the galactic centre an energy of about $10^{18}$ eV is required.

### 1.4.2 Recent results

A number of air shower arrays have measured the arrival distribution of cosmic rays with various results. Buckland Park [19], located in Adelaide, Australia and KASCADE, in Karlsruhe, Germany, are two experiments focusing on cosmic ray energies around the knee. While the Buckland Park air shower array, located 35°S, measured a small anisotropy with an amplitude of 0.84% at about $10^{16}$ eV [20], KASCADE, located in the Northern hemisphere, have not measured any deviations from isotropy [21] [22].

AGASA and SUGAR, both studying UHE cosmic rays, has reported on an excess of events from the region around the galactic centre. While AGASA claims evidence for an extended source near the galactic centre [23], shown in the bottom picture in Fig. 1.9, SUGAR claims a more point like source [24], shown in the top in the same figure. To date, AUGER have not seen signs of an excess from this region [25]. A model has been suggested [26] that could accommodate both claims. In this model, the anisotropy is explained by neutrons created in the Galactic centre by proton-proton collisions. The neutron part appear as a point like source while the protons appear as an extended source.
Figure 1.9. Top: The extended anisotropy near the galactic centre and anti-centre measured by AGASA. The lines show the galactic plane. Bottom: SUGAR measured a more point source structure at the galactic centre and anti-centre. Notice the inverted colour schemes.
Chapter 2

The SEASA Experiment

This chapter describes the Stockholm Educational Air Shower Array (SEASA), an air shower array operating in Stockholm, Sweden, primarily meant for outreach to high school students. The first section gives a conceptual view of the experiment. The following sections describe the hardware and software that have been developed for the experiment in detail.

2.1 Introduction

The 'Stockholm Educational Air Shower Array' (SEASA) [27] project is establishing a network of cosmic ray air shower detector stations over the Stockholm region. Each station consists of 3 large plastic scintillator detectors arranged in a triangular formation (see Fig. 2.1 for an example of the detector set-up). Air showers are identified by coincidental signals from the three scintillator detectors within a predefined time window ("triggers"). The primary energy threshold for triggering a station is approximately $10^{14}$ eV to $10^{15}$ eV depending on the separation of the scintillator detectors. Cosmic ray activity at stations separated by arbitrary distances is correlated using timing signals from GPS navigation satellites.

A compact data acquisition system has been developed based on a programmable logic array (PLA), an embedded Linux processor and a GPS receiver system. The Linux system is connected to a server located at the AlbaNova University Centre through the internet. Through this, trigger and housekeeping data are sent and station maintenance performed. The server also runs a MySQL database where the information from the detector nodes is stored. The database is accessible offline for data analysis but also through the "viewer" - an on-line java-applet client where information about the detector nodes as well as trigger statistics and housekeeping can be displayed "on demand".

1 by a TCP/IP socket
2 web address: http://cosmic.particle.kth.se:8080
Figure 2.1. One of the two detector stations on the roof of the main AlbaNova University Centre building. The scintillators are housed in car roof boxes for weather protection, and are separated by approximately 15 m. The GPS antenna can be seen as a white triangle close to the leftmost car roof box. The white object in the centre of the image is a skylight.

A primary aim of the project is to give high-school students, aged between 16 and 18 years, the possibility to gain insight and work on a modern research project and so the detector stations are located at high-schools (on roofs or in attics) in the Stockholm area. The students themselves participate in the construction, testing, installation, commissioning and running of their detector station. During the first phase of the project in 2006, the network will consist of 7 detector stations located at AlbaNova University Centre and four high-schools. Additional stations are expected to be installed at other high-schools both within and outside of Stockholm in subsequent years.

2.2 Array Geometry

The detector array consists of 7 detector stations, 6 located in the inner city area and one in Nacka, just outside Stockholm (see Fig. 2.2). Three of the stations are placed in the AlbaNova area, two at the far ends of the main building and one on one of the satellite buildings. The other four stations has been delivered but not
installed at the time of writing. The distance between the stations at the AlbaNova area ranges from 140 m to 230 m. A denser grid of stations allows studies of air showers with lower energies than the complete grid which is beneficial, not only because of the extended energy range which can be measured, but also of the large increase in statistics which is expected for air showers with lower energies.

Figure 2.2. The SEASA air shower array (in May 2006). The stations at the AlbaNova area are shown in greater detail in the inset picture in the upper right corner. The dotted station is a fourth station planned for installation at the AlbaNova area. The stations are henceforth labelled after their school: Thorildsplan, Enskilda, Nacka and Norra Real. The compass direction is added as a suffix to the names of the AlbaNova stations: AlbaNova W, E and S. The black dot at the entrance of the main building marks the centre of the coordinate system for SEASA.

The position of the detector stations are determined by the GPS system (see section 2.3.3), which sets the position in geodetic coordinates; longitude and latitude and height (over the GPS reference ellipsoid). In order to reconstruct air shower properties the detector coordinates must be converted to a Cartesian coordinate system. A representation of the coordinate system of the Earth on a flat surface is therefore needed. The UTM (Universal Transverse Mercator) coordinate system is a widely used projection scheme that is often used for maps. This system is suitable for the SEASA array because of its conformal properties, meaning that small shapes and angles on the globe project as the same angles and shapes on the projection. The drawback with a conformal projection is the great variation of
scale away from the equator. For example, Sweden looks larger than Madagascar on maps but in reality it's the other way around (see Fig. 2.3)

The earth is divided in 60 longitude zones, labelled 1 at 180° west to 60 at 180° east, and 20 latitude zones, labelled from C at 90° south to X at 90°.

The conversion between geodetic and UTM coordinates is shown in Appendix A.1. The coordinates for the detector stations in the SEASA project are shown in Table 2.1 for geodetic and SEASA coordinates (the latter UTM coordinates relative to the chosen origin of the SEASA grid: the entrance of the AlbaNova main building, see Fig. 2.2).

2.3 The SEASA System

The three key parts of the detector stations are the data acquisition unit, based on an embedded Linux computer and an Altera programmable array, a GPS unit for time tagging of the triggers and the three plastic scintillator detectors read out by photomultipliers. Each of these three parts are described in detail in this section, starting with a description of the hardware and software of the data acquisition system.
2.3. The SEASA System

<table>
<thead>
<tr>
<th>Station</th>
<th>Longitude</th>
<th>Latitude</th>
<th>Northing [m]</th>
<th>Easting [m]</th>
<th>Height [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>AlbaNova W</td>
<td>59.35396 N</td>
<td>18.05629 E</td>
<td>40.6 N</td>
<td>-53.6 E</td>
<td>71.5 H</td>
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<tr>
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<td>59.35351 N</td>
<td>18.05944 E</td>
<td>-17.6 N</td>
<td>123.4 E</td>
<td>70.6 H</td>
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<tr>
<td>AlbaNova S</td>
<td>59.35239 N</td>
<td>18.05850 E</td>
<td>-139.9 N</td>
<td>64.5 E</td>
<td>80.5 H</td>
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</table>

<table>
<thead>
<tr>
<th>Station</th>
<th>Detector</th>
<th>North [m]</th>
<th>East [m]</th>
<th>Height [m]</th>
</tr>
</thead>
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</tr>
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<td></td>
<td>2</td>
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<td>3</td>
<td>40.9</td>
<td>-53.3</td>
<td>71.3</td>
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<tr>
<td>AlbaNova E</td>
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<tr>
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<td></td>
<td>3</td>
<td>-136.0</td>
<td>55.9</td>
<td>77.5</td>
</tr>
</tbody>
</table>

Table 2.1. The coordinates of the GPS antennas and the scintillator detectors. The GPS antenna coordinates are given in geodetic and UTM coordinates, the latter relative to the origin of the SEASA coordinate system: the entrance of the main building of the AlbaNova University Centre. The height is relative to the GPS reference ellipsoid. Absolute detector coordinates are given in the SEASA coordinate system.

2.3.1 The data acquisition system

The design of the data acquisition system has been motivated by the need to produce a compact, configurable, scalable and low cost system. The system has four main components: an analogue front-end, a Programmable Logic Array (PLA), a GPS receiver and an embedded Linux processor, shown in Fig. 2.4. A high voltage unit is also part of the system and is seen in the top right corner of the picture. Each station is also equipped with a temperature and pressure sensor, read out by the data acquisition system.

The analogue front-end follows the design used for the anti-coincidence system of the PAMELA satellite experiment [28], which is based on off-the-shelf components. The photomultiplier (PMT) pulses are sent to an inverting integrator with a constant decay time. The output from the integrator is then sent to a discriminator where it is compared to a reference voltage set by a Digital-to-Analog Converter (DAC). This is described in Fig. 2.5. The discriminator signals an event when the integrator output exceeds the reference voltage. This allows photomultiplier pulses arising from cosmic ray interactions in the scintillators to be distinguished from noise. The reference voltage from each channel is measured by an ADC and reported in the data string.
An Altera Cyclone EP1C6T144C6 Programmable Logic Array [30] is the key digital component. It processes data arriving from the detectors (to identify coincidences, for example) and environmental sensors forming events which are sent to the Linux system. In the present design, a simple coincidence is formed between the discriminated PMT pulses. The relative time between the leading edges of the discriminated pulses is also recorded, which allows a crude estimation of the local shower angle. The length of the discriminator pulse is sampled at both edges of a 100 MHz clock which allows the energy deposited in the scintillator to be estimated with a ‘time-over-threshold’ approach.

A GPS system is used to set the position of the detector station and to provide the time tag for each coincidence event. This is covered in section 2.3.3.

The PLA is controlled and read out through a RS232 link which connects to an embedded Linux system (Axis 82 developer board [31]). The Linux system provides cold start configuration of the GPS receiver through a second RS232 link as well as configuring the PLA by an Altera Passive Serial Loader (APSL). This interface uses the General Purpose IO Pins (GPIO) on the Linux chip, and provides a very simple
2.3. The SEASA System

Figure 2.5. A schematic overview of the front-end electronics which processes the photomultiplier pulses before they are sent to PLA. The inset picture is a screen dump from an oscilloscope showing the pulses at three different locations of the front-end circuit. Taken from [29].

way to configure Altera FPGA chips. A Joint Test Action Group (JTAG)-based configuration scheme is also under development.

During the operation of a detector station the Linux processor has three tasks: read out data from the PLA, send trigger information to the server and receive and execute commands sent from the viewers. Data is sent once per second from the PLA and so does not represent a major load on the system. However, when commands are sent from a viewer to the Linux system an event pile-up could occur and information from the PLA could be lost. To ensure that data from the PLA is always read, even in the case of an event pile-up, the data acquisition software is multi-threaded. The highest priority thread reads out the PLA through one of the serial ports and pushes the data to an event queue. A second thread performs commands issued by the viewers and pushes the response from these actions to the event queue. A third thread pulls events from the event queue and sends them to the server. This software scheme makes it easy to add functionality to the system in the future without compromising the read out of the PLA. A collaboration diagram
modelling the thread interactions is displayed in Fig. 2.6.

![Collaboration Diagram for the Data Acquisition System](image)

**Figure 2.6.** A collaboration diagram for the data acquisition system. Three threads control the acquisition on the Linux processor: The **Server Handler**, performing tasks sent from the viewers, the **PLA Handler**, responsible for the read out of the PLA and the **Queue Handler**, pushing events from the event queue to the server. Events in the event queue can either be trigger events or information about commands performed by the Server Handler.

### 2.3.2 The detectors

The detector design has undergone many changes and upgrades since the start of the project. All the designs have been based on a plastic scintillator read out by a PMT. In the old detector design, henceforth called *design I*, the light from the scintillators was collected with a wavelength shifting bar (WSB) and read out by a small PMT connected to the far end of the bar. This is the design for the two oldest detectors still operational, AlbaNova W and E [32] and is illustrated in the top picture in Fig. 2.8. The use of a WSB was essential as the scintillators consisted of many small pieces (20 cm x 30 cm) glued together. Even though light transparent glue was used to glue the scintillators together, light is inevitable lost at the edges of the scintillators. A WSB then made it possible to collect light from each scintillator plate separately.

The current detector design, referred to as *design II*, was chosen in such a way that it is easy to built, to let high school students participate in the building, robust and cheap. This has been achieved by using an extremely simple design using as few parts as possible: a single sheet of plastic scintillator read out by a large area photomultiplier mounted directly on top of the scintillator. This detector design is
2.3 The SEASA System

illustrated in the bottom picture in Fig. 2.8. The AlbaNova S station, constructed in August 2005, was the first station that was build following this new design. There has been very few problems with this station and so all four new detectors adopted this design. This will probably be the standard design in the future.

A plastic scintillator from Bicron, BC-408 [33], approximately 1.5 cm x 30 cm x 100 cm, serves as the detection material. The decay time of this scintillator is 2.1 ns and the light attenuation length 210 cm. This type of scintillator is therefore suitable for this application where a quick response time is crucial and a large light collection efficiency beneficial. The wavelength distribution of the emitted photons is shown to the left in Fig. 2.7 and peaks around 425 nm. The light from the scintillator is read out by a large diameter (76 mm) photomultiplier (Photonis XP3314B [34]) glued to the centre of the scintillator’s largest surface. The Sylgard 184 optical glue [35] has been used. The quantum efficiency of the PMT is shown to the right in Fig. 2.7 and matches the wavelength distribution of the photons created in the scintillator. The photomultipliers operate at a high voltage of −1100 V.

The scintillator assemblies are wrapped in two layers of reflective Dupont Tyvek, covered in a layer of black paper and put in a car roof box which prevents it from being directly exposed to rain and snow.

Figure 2.7. Left: The wavelength distribution of the photons emitted from the Bicron BC-408 plastic scintillator [33]. Right: The quantum efficiency of the Photonis XP3314B PMT [34].
Figure 2.8. Top: A detector built with the old detector design (design I). It consists of eight plastic scintillators with a wavelength shifting bar in the middle. A photomultiplier is located at the far end of the bar (not visible in the picture). The bottom picture shows a detector built with the new design (design II). A single sheet of plastic scintillator is used, read out by a large area photomultiplier glued directly on top of the scintillator.
2.3.3 The GPS system

The primary tasks for the GPS system is to accurately measure the position of the detector station and most importantly, to time tag triggers received by the station. This sets very stringent demands on the timing capabilities of the GPS system. To reconstruct shower parameters from the thin shower front moving almost with the speed of light a time resolution of tens of nanoseconds is needed. The performance of the GPS system chosen for the SEASA experiment is shown in this section.

A GPS receiver card (Motorola M12+) and antenna (Motorola Timing 2000) [36] constitutes the GPS system. The basic time tag is provided by the time-of-day information (hh,mm,ss) from the GPS unit. It is realised by the PPS (Pulse Per Second) signal which is issued every second by the receiver. This signal is synchronised to the atomic clocks on board the GPS satellites which are tracked by the GPS receiver. Thus, the GPS systems produces highly synchronised PPS signals which can be used for the time tagging. The precision of the tag is increased by using a 100 MHz counter implemented in the PLA to measure the offset between the PPS signal and the coincidence trigger. A self calibrating system for the 100 MHz crystals is used to compensate for differences in the crystal frequencies and variations in the crystal frequency. To be self calibrating, the system counts the number of oscillations between PPS’s, and uses this value to calibrate the number of oscillations from the trigger to the PPS. Fig. 2.9 illustrates this schematically. By using both falling and rising edges of the counter pulse, a timing resolution of 5 ns is achieved. This approach follows that pioneered by the Leeds group [37]. The GPS receiver also provides a so-called sawtooth correction which compensates for the granularity of the internal GPS clock used to produce the PPS signal. With this correction the PPS should be accurate to within 5 ns. The calculation of the event time from the GPS information is shown in appendix A.2.

Figure 2.9. A 27 bit counter increments at the arrival of a pulse from the 100 MHz crystal. At the arrival of a PPS the value of the counter is transferred to a parallel shift register. At the arrival of the next PPS the value stored in the first shift register is transferred to another shift register, and the new value are stored in the first. The system thus stores the two latest counter values. A third shift register is used to store the counter value when a trigger arrives. The difference between the counter values in the first and second shift registers then forms the calibration value, and the difference between the second and third shift register corresponds to the event time.
Before producing reliable timing information, the GPS receiver must be initialised by setting the receiver coordinates (latitude, longitude and height). The receiver is then put into position-hold mode where it no longer solves for position. With the position known the time is the only remaining unknown. In order to compute the time, the GPS receiver only requires one satellite. If multiple satellites are tracked the time solution is based on an average of the satellite measurements. The receiver position is set at installation of the station by averaging approximately 60 000 valid position fixes which takes approximately 24 h. The motivation for this is to average out observed fluctuations in the position fix due to changes in the satellite constellation. Initialisation of the GPS is performed by the Linux system during normal operations.

2.4 Detector Calibration

Setting the discriminator (DAC) levels is a trade-off between lowering the efficiency of the detector and increasing the detection rate of uncorrelated signals. A large count rate also increases the probability for accidental coincident triggers. The coincidence window is 1 ms, and is set considering the distance between the detectors and the shower front thickness. An accidental hit in all three detectors then have a probability of $p = 10^{-12} f^3$, where $f$ is the singles rate. A pragmatic approach for determining the DAC values has been used: The DAC value that gives a singles rate of 100 Hz is chosen. This singles rate was chosen considering the muon flux at ground, which the PDG review [38] quotes as $70 s^{-1} m^{-2} sr^{-1}$. The detectors have an area of about 3000 cm$^2$ which gives a singles rate of 130 Hz assuming a 2π acceptance.

A singles rate of 100 Hz gives an accidental trigger every 12th day, which is acceptable. The DAC levels are set with the aid of 'calibration curves' - plots of the singles rate as a function of the DAC level. Calibration curves are made at the installation of a detector station to allow the DAC values to be set to achieve the correct singles rate. Calibration curves are also made at regular intervals to make sure that the characteristics of the detector does not change. An example of a calibration curve is shown in the top picture in Fig. 2.10. The differences between the curves are due to the different PMT quantum efficiencies. The trigger rate as a function of the singles rate for each detector station are shown in the bottom picture in the same figure. The trigger rate increases rapidly for values of the singles rate up to approximately 100 Hz and then saturates, indicating that a higher singles rate only increases the detection rate of uncorrelated particles. This further strengthens the choice of a DAC value corresponding to a singles rate of 100 Hz.
2.4. Detector Calibration

Figure 2.10. Top: An example of the result of a detector calibration. The rate of detected particles (singles rate) is plotted versus discriminator value (DAC). Bottom: Trigger rate as a function of singles rate. The big difference between AlbaNova S and AlbaNova W,E is due to the difference in detector design. The W and E stations reach the noise level already below 200 Hz. The performance of the newer detector design is manifestly more stable.
2.5 Timing Accuracy and calibration of the time stamps

The time measured by the GPS system, $\sigma_{\text{meas}}$, is the sum of the true time $\sigma_{\text{true}}$, offsets induced in cables and GPS receiver card ($\delta_{\text{cables}}, \delta_{\text{rec}}$) and a Gaussian fluctuation from the true time inherent in the system, $\sigma_{\text{GPS}}$ - the time resolution of the system. This is illustrated by equation 2.1.

$$\sigma_{\text{meas}} = \sigma_{\text{true}} + \sigma_{\text{GPS}} + \delta_{\text{cables}} + \delta_{\text{rec}} \quad (2.1)$$

The offsets can easily be measured and corrected for, which is done in section 2.5.1. A measurement of the time resolution is performed in section 2.5.2. Two components that also contribute to the total timing bias are not included here: the error of the detector position measurement, $\delta_{\text{pos}}$, and $\sigma_{\text{shower}}$, the difference between the real shower front and the plane front approximation (see chapter 4). These will be studied in detail in the future.

2.5.1 Calibrating for offsets in the timing

The timing resolution needed for this experiment is so high that signal delays in cables may cause significant distortions to data. This is especially true for the dense array at AlbaNova where the time differences between the stations are small. The cable lengths thus have to be measured to allow the time tags to be calibrated.

Two sets of cables cause delays in the time tag: the GPS antenna cable and the signal cables between the detectors and the electronics. The delay caused by the GPS cable is calibrated for by the GPS system. The receiver is programmed to output the PPS signal earlier to compensate for the antenna cable delay. This can be done in one nanosecond increments up to a maximum of one millisecond. The calibration for the delays caused by the signal cables is done offline in software.

The measurements of the cable lengths were performed in the following way. A pulse was sent through the cable via an oscilloscope. The time from this pulse, the start time, to the time of its echo, the stop time, was then registered. The start and stop time were defined at the point where the pulse reached half of its maximum value. The accuracy of this determination is $\sim 2 \, \text{ns}$. The cable delay used for the calibrations is then simply half of this value. The result of these measurements are included in Table 2.2.

2.5.2 Measuring the time offset and resolution of the GPS system

To test the performance of the GPS system, the offset between the time-tags produced by the GPS system and a reference system (AlbaNova W) fed with accurately synchronised trigger signals was investigated.

The principle of the test is as follows. For every trigger, a time stamp from each GPS card is retrieved. These time stamps should be identical in a perfect system.
### Timing Accuracy and calibration of the time stamps

#### Table 2.2. The result of the measurement of the cable delays.

<table>
<thead>
<tr>
<th>Station</th>
<th>Cable</th>
<th>Cable Length ($\delta_{cables}$) [ns]</th>
</tr>
</thead>
<tbody>
<tr>
<td>AlbaNova W</td>
<td>GPS</td>
<td>67</td>
</tr>
<tr>
<td>AlbaNova W</td>
<td>Signal 1</td>
<td>113</td>
</tr>
<tr>
<td>AlbaNova W</td>
<td>Signal 2</td>
<td>114</td>
</tr>
<tr>
<td>AlbaNova W</td>
<td>Signal 3</td>
<td>114</td>
</tr>
<tr>
<td>AlbaNova E</td>
<td>GPS</td>
<td>67</td>
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<tr>
<td>AlbaNova E</td>
<td>Signal 1</td>
<td>156</td>
</tr>
<tr>
<td>AlbaNova E</td>
<td>Signal 2</td>
<td>156</td>
</tr>
<tr>
<td>AlbaNova E</td>
<td>Signal 3</td>
<td>156</td>
</tr>
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<td>AlbaNova S</td>
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<td>AlbaNova S</td>
<td>Signal 1</td>
<td>139</td>
</tr>
<tr>
<td>AlbaNova S</td>
<td>Signal 2</td>
<td>139</td>
</tr>
<tr>
<td>AlbaNova S</td>
<td>Signal 3</td>
<td>140</td>
</tr>
</tbody>
</table>

The time stamp is provided by the sawtooth corrected PPS and the 100 MHz oscillator implemented in the PLA. All measurements in the test were done with a satellite mask angle of ten degrees to exclude unreliable time measurements from satellites close to the horizon.

This measurement was done for the GPS setups from all detector stations. The results from the measurements of the AlbaNova E and S stations are plotted in Fig. 2.11.

The offset of the mean value seen in Fig. 2.11 changes sign when the GPS cards are exchanged, indicating a systematic error between these two. This effect can be reduced by calibrating each card against a “standard card”, and then correcting the time stamps from each card accordingly. In this test, the GPS cards mostly tracked the same satellites. It is inevitable that detector stations spread out over a larger area will have different sets of satellites visible to them. A test was therefore conducted where the GPS cards were configured to use independent sets of satellites. The standard deviation increased by about 50% [39]. It should be noted that when the antennae are separated by longer distances the standard deviation may increase due to the effect of atmospheric corrections.

The results from all measurements are included in Table 2.3. The RMS and mean value quoted in the table is obtained from the histograms of the time difference. The RMS quoted for each station in the third column is the summed RMS from two stations: the reference station and the station subject for the measurement. The RMS for one single board, i.e. its time resolution, is then $\sigma_{GPS} = RMS_{meas}/\sqrt{2}$ if the errors are regarded as independent. This is included in the fourth column in Table 2.3.
Figure 2.11. The distribution of the time tag difference between AlbaNova W and E (top) respectively AlbaNova W and S (bottom) when fed with synchronised trigger signals.
2.6 Data Processing and Monitoring

The most primitive form of data in the SEASA project is the 67 bytes long data string that is formed by the PLA and the Linux system when a trigger is issued. A detailed description of all bytes can be found in appendix B. The trigger string is saved locally in ASCII format on the flash memory of the embedded Linux chip and also sent to the server located at AlbaNova where it is stored in a MySQL database. The ASCII trigger file is downloaded every night by the server and saved for backup. Before data analysis can begin the raw data string is refined to a higher level format - the 'Level1' format. This is performed once a day on bunches of data. A ROOT script transforms the raw data to physically meaningful parameters and searches the data for coincidences between detector stations. When a so-called ‘super-trigger’ is found, a simultaneous trigger between multiple detector stations, data from all involved detector stations are added in a ROOT data base. This data base is then used for subsequent data analysis.

The SEASA project has developed multiple ways of checking the status of the detector stations and ensuring the integrity of the data. The first, and most thorough check, is the daily quicklook which is e-mailed out every night. It plots the most significant parameters for each station and is a good check that the stations work as expected. A web page has also been developed which can be used to check the status of the detectors in real-time. This page is also used as a tool for high school students to do basic data analysis. A history of quicklook PDF-sheets is available on the web page for backward checks. The web page structure is described in section 2.6.1 below, while the quicklook is described in chapter 3.

2.6.1 The server and viewer

The SEASA server ties all detector nodes together into a single huge detector. Data is collected from each detector node by the server and stored in the local MySQL database. This database is accessible through a web portal - the connecting point for students and researchers in the SEASA experiment. The primary functions of the web portal are:

<table>
<thead>
<tr>
<th>Station</th>
<th>Mean [ns]</th>
<th>RMS$_{\text{meas}}$ [ns]</th>
<th>$\sigma_{\text{GPS}}$ [ns]</th>
</tr>
</thead>
<tbody>
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<td>AlbaNova E</td>
<td>-18.5</td>
<td>13.6</td>
<td>9.6</td>
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<tr>
<td>AlbaNova S</td>
<td>-18.4</td>
<td>16.5</td>
<td>11.7</td>
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<td>7.4</td>
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<td>-18.7</td>
<td>11.4</td>
<td>8.1</td>
</tr>
</tbody>
</table>

Table 2.3. The result of the measurement of the GPS timing accuracy. The numbers 6B906X are the serial numbers of the Linux processors. The mapping serial number - school was not known at the time of writing. The seventh GPS system has not yet been tested.
• Project information
  To give general information about the project and other relevant areas such as cosmic rays.

• The Event viewer
  A tool to visualise cosmic ray activity at the detector stations 'live'. This display is designed to run permanently at schools and institutes.

• Mission Control
  An interface to check the performance of the detectors, current and past. Operational parameters of the detectors can also be changed.

• Data analysis
  A java applet (part of the Event viewer) allowing the students to download data from the server and to make simple analysis.
Figure 2.12. The SEASA viewer, allowing the students to follow the cosmic ray activity at their detector station in real time. The page in the background is the start page of the SEASA web portal. The front page shows the java applet: a map of the Stockholm area where the detector stations are marked with a triangle. A dark triangle corresponds to an active station while a bright to a station that is currently down. Activity at a station (a trigger) is shown with a flashing circle enclosing the station. Information about the latest trigger is shown to the right in the applet: which station that received the trigger, time of the event and environmental information.
Figure 2.13. The 'mission control' page where the performance of the detector array can be monitored.
Chapter 3

Performance of the Detector Array

The first steps towards an air shower array began during the summer of 2003 when the development of the detector design and the GPS timing system started [39]. In parallel the first Monte Carlo simulations were performed for the project [1]. The first prototype detector station, following design I (see section 2.3.2), was constructed in spring 2004 [40] and operated for a test period of 55 days on the west side of the AlbaNova main building - the current site for the AlbaNova W station. Although the test was successful, many lessons were learnt, especially on how unforgiving the weather in Sweden can be. After a few improvements of the detector design another station was built, now called AlbaNova E, and placed on the other side of the AlbaNova building. With this stereo setup, the GPS time stamp technique could be proved and the first air showers hitting multiple stations simultaneously were detected [32]. After this second test period it was decided to adopt a simpler, more robust and cheaper design for the detectors (design II, see section 2.3.2). A third detector station was built during the summer of 2005 [41] following this final design. This station was installed in the attic of one of the satellite buildings in the AlbaNova area in late September the same year, and the third, and final, test data period officially started September 27th 2005. The array then consisted of three detector stations: the two stations with the old design, AlbaNova W and E and the first station following the final detector design, AlbaNova S. The last test data period ended the third of April. The data presented in this thesis is the result of this third data taking period.

The performance of the detector array is presented in this chapter. The first sections present data collected by the three stations during the third data taking period. The number of triggers and supertriggers collected during this period is shown below in table 3.1. The last section presents the 'quicklook', a tool heavily used during the data taking to regularly check the status of the detectors and the integrity of the collected data.
3.1 Detected Trigger Rates

The trigger rates for the stations in the AlbaNova area has been quite stable during the last period of data taking, with the possible exception for the AlbaNova W station. This station has been subject to numerous tests and this is visible as fluctuations in the trigger rate, shown in Fig. 3.1 for each station.

The discriminator thresholds were finally set October 27th 2005, therefore the increase in trigger rate seen in Fig. 3.1 for especially AlbaNova W and E at this moment. The drop in trigger rate during parts of November and December for AlbaNova W was caused by a test that increased the dead time after each trigger to about 50 s. AlbaNova S suffers a higher trigger rate than the rest of the stations even though the singles rate is the same. Simulations of this effect are on-going but the cause is clear: the density of particles is increased approximately by a factor two by the roof and walls that surround this detector. This lowers the energy threshold for this detector station and thereby increases the trigger rate.

The supertrigger rate suffers the same drop as the AlbaNova W station during November and December for the same reason. The overall trigger rate, displayed in Fig. 3.2, is 3.9 supertriggers per day. This is a quite low rate compared to other experiments with the same node separation. The IceTop array for example has a node separation of 125 m and detects air showers with a frequency of 0.7 Hz [42]. This gives a rate of over 60 000 showers a day compared to ∼ 5 (during normal conditions) for SEASA. The vastly higher trigger rate for IceTop can be explained by the differences in energy threshold for the two arrays. While IceTop has an energy threshold of about $10^{15}$ eV [42], the threshold for SEASA is almost two orders of magnitude larger. As the rate of air showers decreases with approximately a factor of 100 per decade of energy below the knee, SEASA should detect about 10 000 times less events, which is the case. The difference in energy threshold originates primary in the large difference in effective area of the detectors between the experiments, but also in the more strict trigger criterion for SEASA.

<table>
<thead>
<tr>
<th>Station</th>
<th>Number of Triggers</th>
<th>Up-time</th>
</tr>
</thead>
<tbody>
<tr>
<td>AlbaNova W</td>
<td>$1.7 \times 10^5$</td>
<td>79.4%</td>
</tr>
<tr>
<td>AlbaNova E</td>
<td>$2.7 \times 10^5$</td>
<td>93.2%</td>
</tr>
<tr>
<td>AlbaNova S</td>
<td>$1.7 \times 10^5$</td>
<td>83.2%</td>
</tr>
<tr>
<td>SuperTriggers</td>
<td>503</td>
<td>72.0%</td>
</tr>
</tbody>
</table>

Table 3.1. The number of triggers and supertriggers collected from the 27th of September 2005 to the third of April 2006, and the up-time during that period. The up-time for the supertriggers is the time when all three stations are operational simultaneously.
Figure 3.1. The trigger rate distribution (left) and over time (right) for the three stations at AlbaNova. The scatter plots in the right column and the solid line histograms in the left column are normalised for pressure variations according to equation 3.1, described in section 3.2. The dotted histograms in the left column shows the unnormalised trigger rate distribution for comparison.
Figure 3.2. The supertrigger rate distribution (top) and over time (bottom). The dotted distribution in the top figure shows the super trigger rate excluding the period between the 24th of November and the 28th of December as a test was performed during that period that lowered the super trigger rate. A Poisson curve, which is the expected distribution of supertriggers, is fitted to the dotted dataset and the fit is reasonably good with the Poisson parameter $\mu = 4.66$. 
3.2 The Influence of Weather on the Array Acceptance

An empirical study of the influence of the weather conditions on the acceptance is presented in this section. In the single station case this is only used for checking the performance of the stations. For the three station setup, this will constitute an important part of the calculation of the total acceptance in the future, but is omitted at present due to lack of statistics. A derivation of the acceptance of the array is presented in section 5.2.1.

Weather conditions can change the acceptance of the experiment in two different ways; either by effecting the detectors and PMTs (the electronics are kept indoors and so are not affected) or by changing the properties of the air showers. A scenario where the detector acceptance is influenced by the temperature could be if the properties of the coupling media between the PMT and the scintillator changes with temperature. The PMT-scintillator coupling directly determines the efficiency of the detector so this phenomena would then give a significant effect on the acceptance of the station.

If the lateral profile of an air shower changes with atmospheric parameters, the acceptance of the array could dramatically change as the weather varies. Exactly how the lateral behaviour of an air shower depends on atmospheric conditions is unknown, but it is likely that the shower size depends on column density along the shower. The atmospheric pressure is therefore a likely relevant parameter for this study. Also, the Molière radius is directly determined by the temperature and it has been shown that the density of particles at ground increases with this radius [43]. The temperature is therefore also considered in this study.

The acceptance variation as a function of temperature or pressure is derived by comparing the “event data”, the temperature or pressure values at each trigger, with weather data sampled continuously - called “weather data” henceforth. Deviations between these two distributions are signs of variations of the acceptance with weather conditions.

A histogram is filled with weather data (temperature or pressure) sampled every hour by the considered station. This is normalised and compared to another histogram with the “event data”. The correlation between acceptance and temperature or pressure is derived by dividing the event values with the weather values. A linear fit to each of these histograms shows the correlation between acceptance and temperature and pressure.

3.2.1 Single station

The distribution of the atmospheric pressure and the event pressure is shown to the left in Fig. 3.3 for the three stations AlbaNova W, E and S. The right column shows
the relative acceptance as a function of the pressure. The resultant linear fits are

\[ a_W(P) = 10.4 - 0.0092P \]  \hspace{1cm} (3.1)
\[ a_E(P) = 10.1 - 0.0088P \]  \hspace{1cm} (3.2)
\[ a_S(P) = 5.4 - 0.0043P \]  \hspace{1cm} (3.3)

The trend is that the acceptance reduces with pressure, which is natural considering that the air showers travels a greater distance through the atmosphere and therefore have a lower particle density when they reach the ground. The AlbaNova W and E stations shows a very similar dependence. The trigger rate for AlbaNova S however has a slightly lower dependence on pressure. This could either be an effect of the differences in the detector design between AlbaNova W, E and S, or an effect of that AlbaNova S is located indoors.

The distribution of the temperature is shown in a similar fashion as for the pressure in Fig. 3.4. AlbaNova S is not equipped with a thermometer so this station is not included below. The acceptance is not strictly linear in this case why the linear fit is excluded. As the figure shows, the acceptance is almost constant up to a temperature of about 288 K where it suddenly drops almost 40\% and then stays constant again. Such a discrete behaviour could be a sign of a problem with the detectors, for example with the PMT-scintillator coupling. The lack of temperature data from the new detector design is unfortunate, it is important to see if this effect is present for these detectors as well.

### 3.2.2 Three station setup

The energy threshold for the three station setup is \( \sim 100 \) times larger than for a single station. The acceptance variation for air showers with these energies is not necessarily the same as for the single station case as the shower properties are different. The measured pressure and temperature distribution and the corresponding event pressure and temperature is shown in Fig. 3.5, and the resultant linear fits to the acceptance are shown in equation 3.4. The temperature and pressure values are taken from AlbaNova E, the most stable station.

The acceptance dependency of the pressure for super triggers is of the same order of magnitude as for the acceptance for single stations, but the error of the fit is large. Equation 3.4 also shows that the dependency of temperature is one order of magnitude larger than the dependency of pressure for super triggers. If this is a detector or shower effect remains to be explained, but it is clear that the acceptance changes significantly with temperature and that this will have to be taken into account in the derivation of the acceptance in the future. Also, as expected, the drop in acceptance that was seen slightly below 290 K is seen for super triggers as well.

\[ a_{\text{super}}(P) = 4.2 - 0.0032P \]  \hspace{1cm} (3.4)
\[ a_{\text{super}}(T) = 10.5 - 0.034T \]  \hspace{1cm} (3.5)
3.2. The Influence of Weather on the Array Acceptance

Figure 3.3. Left: The event pressure compared to pressure sampled continuously for the three stations at AlbaNova. The peak for the event pressure at 1010 HPa is probably due to a test with a large number of artificial triggers conducted at that atmospheric pressure. Right: Correlation between acceptance and pressure obtained by dividing the event pressure with weather data.
Figure 3.4. Left: The event temperatures compared to temperature sampled continuously for AlbaNova W and E. The thermometer for the AlbaNova W station seems not to have worked properly as the temperature distribution is shifted to higher values. Right: Correlation between acceptance and temperature obtained by dividing the event temperature with weather data. The large peak at 272 K for event data for the AlbaNova W station is due to tests with artificial triggers that were conducted during the spring. A drop in the acceptance occurs at approximately 288 K for both detector stations but most significantly in the data for the AlbaNova E station. The cause of this phenomena is unclear but will be investigated.
3.2. The Influence of Weather on the Array Acceptance

Figure 3.5. Top Left: The event temperatures compared to temperature sampled continuously for super triggers. Top Right: Correlation between acceptance and temperature obtained by dividing the event temperature with weather data. Bottom Left: The event temperatures compared to temperature sampled continuously for super triggers. Bottom Right: Correlation between acceptance and temperature obtained by dividing the event temperature with weather data.
3.3 The Quicklook

A quicklook has been developed to have a tool to regularly check the status of the detector stations and limit the dead time of the detectors caused by hardware problems and software bugs. This has been especially important during the initial phase of the project when problems occur frequently because of the many software and hardware updates. The quicklook script runs every night and performs an analysis on the data collected the previous day. The resultant histograms are converted to PDF-format and mailed out to the administrators. The PDFs consists of five sheets, each containing a specific type of information:

**Figure 3.6. Pulse page:** This sheet plots the two parameters that was intended to give information about the density of particles at each detector but it has been shown that the information is of poor quality. The top row shows the pulse length (explained in section 2.3.1), and the bottom row the pulses in gate, the number of PMT pulses within the coincidence gate. These parameters cannot be used to extract physically meaningful information, but the shape of the distributions should stay constant for a properly working detector. The mapping to the new names of the detector stations is: AlbaNova W - Mensch, AlbaNova E - Robot, AlbaNova S - Android.
Figure 3.7. Environmental page: Here is weather information plotted together with the number of tracked GPS satellites. A slight difference in the number of tracked satellites can be seen which reflects the sky coverage for each GPS antenna. The mapping of the detectors follows the old style, explained in the Pulse sheet.
Figure 3.8. Timing page: This sheet displays more detailed information about the GPS timing. The first picture shows the distribution of trigger times within the second and should be flat if the GPS works as expected. The second picture shows the GPS calibration value and is a narrow peak if the crystal frequency is constant (see section 2.3.3). The sawtooth values are plotted in the last picture (the forth should be empty) and should show a peak around zero. The mapping of the detectors follows the old style, explained in the Pulse sheet.
3.3. The Quicklook

Figure 3.9. Trigger page: This sheet shows the singles-, trigger- and supertrigger-rates which all are good indicators for a multitude of problems, from light leaks to GPS problems. The top row shows the singles rate and should be peaked around 100 Hz for every detector. The bottom picture to the left shows the time between triggers and should be an exponentially decreasing function for each station. The middle, bottom picture shows the trigger- and supertrigger-rate. AlbaNova W and E normally detects around 1000 triggers per day, and AlbaNova S slightly higher. The number of super triggers for each configuration of the three stations should reflect the distance between the stations. For example, the number of supertriggers between AlbaNova E and S should be largest as these stations are closest to each other. The bottom, right picture shows the trigger- and super-rate over time and is a good tool for discovering periods where the stations have been down. The mapping of the detectors follows the old style, explained in the Pulse sheet.
Figure 3.10. Hardware sheet: The last sheet shows the current hardware settings. The DAC values for each detector are plotted in the top row for each station. The bottom, left image shows the high voltage gain. This is different for the old and new detector design as they are using different PMT’s. The AlbaNova W station is powered externally so the high voltage gain of 2000 V is not correct. The trigger criterion is shown in the bottom, middle picture (“Excluded detectors”). This day, all detectors were working and the trigger criterion was set to require a hit in all three detectors within the coincidence window. The length of this window is shown in the last image, and is 1µs for all stations. The mapping of the detectors follows the old style, explained in the Pulse sheet.
Chapter 4

Reconstruction of The Shower Angle

The shower angle is one of the most important parameters to determine accurately for an air shower experiment. Not only for directional studies of air showers but also because the shower angle must be known when determining other shower parameters like the primary particle energy. The major scientific objectives for SEASA are anisotropy and point source searches and also the study of large scale correlations of air showers if multiple arrays are constructed in the future, all of which require accurate determination of the shower angle. The study of methods for angle reconstruction and the accuracy with which SEASA can determine the shower angle using them is therefore of crucial importance.

4.1 Method

The basic assumption when reconstructing the shower angle is that the shower front is a thin disc travelling with the speed of light through the atmosphere. The time delay between hit stations then determines the shower direction. The detector with the smallest time stamp marks the general direction of the shower, and with three or more detectors the shower direction can be reconstructed. This is illustrated in the one dimensional case in Fig. 4.1. The time difference between the two hit detectors would be $\Delta t = l \cdot \tan \theta / c$ where $\theta$ is the zenith angle, $c$ the speed of light and $l$ the distance between the detectors. As the length between the detectors is known and the hit times are measured, the angle $\theta$ can be derived unambiguously.

In practice, the shower angle is determined by fitting the measured arrival times to the shower plane. The shower angle that minimises the fit is the choice for the direction of the shower. The fitting procedure is complicated by the thickness and curvature of the shower front and possible coincident hits of unrelated particles. The curvature can be accounted for if the location of the shower core can be determined. However, this requires that the particle density at each station can be measured.
Chapter 4. Reconstruction of The Shower Angle

Figure 4.1. A one dimensional simplification of how the shower direction is determined. The shower front is approximated as a thin disc and from the differences of the measured arrival times the direction of the disc can be calculated. The approximation of the shower front as a thin disc worsens far from the shower core as the thickness and curvature of the front increases.

which unfortunately not is the case for the SEASA experiment at present. This worsens the performance of the shower reconstruction for SEASA, but the effect is limited by the fact that SEASA requires a relatively high particle density to trigger and therefore mostly detects showers that hit close to the array.

The thickness of the shower front induces large fluctuations in the measured arrival times, especially far from the shower core where the thickness increases rapidly. The fit of the arrival times to the shower plane is therefore iterated and arrival times with large deviations from the shower plane are eliminated in each step. The iteration continues until the solution is stable.

4.2 Reconstruction Algorithm

The angle reconstruction algorithm solves for the zenith ($\theta$) and azimuthal ($\phi$) angle of the shower direction\(^1\) defined in Fig. 4.2. The zenith angle is defined in the interval $0^\circ \rightarrow 90^\circ$, where $0^\circ$ points in the vertical direction, i.e towards zenith. The azimuthal angle is the angle around the vertical axis and is defined between $0^\circ \rightarrow 360^\circ$ where $0^\circ$ points east and the angles are measured clockwise around the vertical axis. The direction cosines are often used in the calculations instead of the

\(^1\) $\theta$ and $\phi$ are defined in the opposite direction, but the notion of $\theta$ and $\phi$ as the shower direction are kept.
shower angles and are defined as $u = \sin \theta \cos \phi$ and $v = \sin \theta \sin \phi$. The coordinates $(x,y,z)$ of the detectors are the UTM coordinates discussed in section 2.2.

Figure 4.2. The definition of the angles that defines the arrival direction of an air shower. The angle towards the vertical line is the zenith angle, labelled $\theta$. The angle around the vertical axis is the azimuthal angle, labelled $\phi$.

If we assume that the shower front is a perfectly thin plane, the arrival time at each detector $i$ is $t_{i,\text{plane}}$

$$t_{i,\text{plane}} = T_0 - \frac{ux_i + vy_i}{c} \quad (4.1)$$

where $T_0$ is the arrival time of the front, $c$ the speed of light and $x_i$ and $y_i$ the coordinates for detector $i$. To fit the parameters $u,v$ and $T_0$ to a set of arrival times $t_{i,\text{meas}}$ the chi-square of the fit of the measured arrival times to a plane front is minimised using Minuit [44].

$$\chi^2 = \sum_i w_i \left( t_{i,\text{meas}} - t_{i,\text{plane}} \right)^2 \quad (4.2)$$

with $w_i = 1/\sigma_i^2$, where $\sigma_i$ is the measurement error on $t_{i,\text{meas}}$.

The height difference between the detector stations can be accounted for through an iterative method after the initial values of $u,v$ and $T_0$ have been calculated. The value of $t_{i,\text{meas}}$ is replaced with $t_{i,\text{meas}} + \delta_{i,\text{alt}}$, where $\delta_{i,\text{alt}}$ is defined as:

$$\delta_{i,\text{alt}} = \frac{(z_i - Z_{\text{ref}})}{c} \cos \theta = \frac{(z_i - Z_{\text{ref}})}{c} \sqrt{1 - u^2 - v^2} \quad (4.3)$$
where \( z_i \) is the height of detector \( i \) and \( Z_{\text{ref}} \) a reference altitude (70 m for SEASA, see table 2.1). This procedure is iterated and converges very rapidly, usually after one or two iterations.

After this step, the iterative procedure to remove bad time stamps is performed. A time stamp is removed from the fitting of the shower plane if it deviates with more than 100 ns from the arrival time of the point of the reconstructed shower plane projected to by the particle. An acceptance window of 100 ns was found to be optimal in simulations and increased the angular resolution of the direction reconstruction with \( \sim 1^\circ \).

### 4.3 Shower Data

Data has been collected with the three station setup at AlbaNova between September 2005 and April 2006, with a few stops for detector maintenance and tests (see chapter 3 for details of the performance of the array). A total of 503 supertriggers were collected during this period. The distributions of arrival directions for this data is presented in this section. First the distributions of the reconstructed angles by the entire detector array and then a comparison between these and the “local angles” - the shower angles reconstructed by the three detectors at a given detector station.

The cosmic ray arrival distribution is roughly isotropic above the earth’s atmosphere. The directional distribution of air showers reaching ground is however not isotropic because of the influence of the atmosphere. While the azimuthal angle distribution is retained, the zenith angle distribution rapidly diminishes as the zenith angle increases because of the increased atmospheric absorption as the air shower has to travel a greater distance before it strikes ground. This atmospheric absorption more than compensates for the growing solid angle when the zenith angle increases. With a full detector acceptance, disregarding the atmospheric absorption, the arrival distributions should be proportional to:

\[
\frac{dN}{d\theta} \sim \cos \theta d\theta (cos \theta) = \cos \theta \sin \theta d\theta \quad (4.4)
\]

\[
\frac{dN}{d\phi} \sim \text{constant} \quad (4.5)
\]

where \( \sin \theta \) is the surface term of the sphere where the primary cosmic ray originate from, and \( \cos \theta \) is the effective surface of the detector for various angles. The atmospheric absorption can be taken into account by adding a Fermi-Dirac term \( 1/(1 + \exp(\frac{\theta - \theta_0}{\Delta \theta})) \) to the zenith angle distribution. Deviations from these distributions for shower data can be seen as signs of malfunction of the experimental setup and is therefore a good integrity check of the array. Especially the distribution of the azimuthal angle is sensitive to biases in the timing and the shape of the distribution can be used to determine the erroneous detector [45].
4.3.1 Super triggers

A super trigger is defined as a simultaneous hit in all three detectors. The acceptance window is currently 1 µs which was set considering the shower thickness and the distance between the detector stations. The reconstructed angles for all such events are shown in Fig. 4.3. The distribution of the azimuthal and zenith angle is fitted by equations 4.4 and 4.5, with the Fermi-Dirac term added to the zenith angle distribution. The distribution of the zenith angle follows the expected \( \cos \theta \sin \theta \)-distribution. The distribution of the azimuthal angle is not flat as would be expected if the trigger times are correctly measured. As the AlbaNova W station has undergone a large number of tests this station is the most likely cause of the erroneous time measurements. During January and February the signal cables of this station were extended with another set of approximately 20 ns long cables. The azimuthal distribution of events during that period is shown in the top picture in Fig. 4.4. Even though the length of the extra signal cables were known a suitable time correction for this period have not been found and it is likely that other tests has influenced the time measurements as well, complicating the time bias.

![Figure 4.3](image-url) The measured distribution of the azimuthal (\( \phi \)) and zenith (\( \theta \)) angle. The theta distribution is well fitted by the expected function. The azimuthal distribution is not completely flat as expected indicating a bias in the timing measurement.
The complete data set for the azimuthal distribution excluding January and February is plotted in the bottom picture in Fig. 4.4. The inhomogeneous feature is gone, and apparently it is restricted to the Jan-Feb period. To test the compatibility of the distributions of the azimuthal angle with a flat distribution a Kolmogorov test was performed of which the result is shown in Table 4.1.

<table>
<thead>
<tr>
<th>Distribution</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Phi_{\text{All}}$</td>
<td>18.1%</td>
</tr>
<tr>
<td>$\Phi_{\text{Jan/Feb}}$</td>
<td>3.7%</td>
</tr>
<tr>
<td>$\Phi_{\text{Jan/Feb excl}}$</td>
<td>98.5%</td>
</tr>
</tbody>
</table>

Table 4.1. The result of a Kolmogorov test to check the compatibility of the azimuthal distributions with a flat distribution. The agreement for the data set excluding Jan-Feb ($\Phi_{\text{Jan/Feb excl}}$) is good.

4.3.2 Local triggers

The relative time between signals making up a trigger in a detector station are measured which allows the local shower angle to be reconstructed. The accuracy of this reconstruction is poor but it can still be of importance. Showers that trigger all nine detectors allows the reconstruction not only by the entire array, but also with the single stations. The local angles should then ideally point in the same direction as the angle reconstructed by the entire array. The distance between the detectors within a station is only between ten and fifteen meters so the fluctuations of the arrival time of the shower front are large in comparison. The angular resolution using a single station is therefore too poor to allow for comparisons between the reconstructed local and global angles for single events. However, the distributions of the differences between local angles and global angles are useful in the limit of large statistics. The shape of these distributions can be used to check the properties of the stations: that the detectors are mapped correctly and that the geometry of the station is accurately measured. Another benefit of this comparison is that it makes it possible to compare real data to simulations, which is done in section 4.4.

The distribution of the difference between the reconstructed local and global angle for real data for each station is shown in Fig. 4.5. The agreement between local and global angle is surprisingly good bearing in mind the small distance between the detectors within the stations. The reason for the large base of the histograms is not completely known, but could be an effect of the parabolic form of the air shower front. A station measures the angle pointing perpendicular to the tangent of the shower front at a point in the front, while the entire array determines the angle from information over a larger area. This induces a bias in the angle reconstruction of the stations. The distribution of the azimuthal angle for the AlbaNova S station is significantly broader than for the other stations, while the distribution of the zenith angle is similar. The reason for this effect is most likely that this station is inside a building. Simulations have shown that small sub showers are created when the shower particles hit the walls and roof that surround the detectors. Apparently,
4.3. Shower Data

**Figure 4.4.** The distribution of the azimuthal angle during January-February 2006 (*top*) and for the data set excluding January-February (*bottom*). The distribution is clearly not flat in the top picture indicating a timing bias in one or more of the detectors.
this decreases the accuracy of the azimuthal angle reconstruction but has negligible effect on the zenith angle reconstruction.

4.4 Simulation of the Angular Resolution

The simulation engine used in this work is AIRES 2.6.0, developed by S.J. Sciutto [46]. AIRES is a 3D Monte-Carlo simulation program which propagates particles in a realistic environment, where the characteristics of the atmosphere, the
4.4. Simulation of the Angular Resolution

geomagnetic field and the Earth’s curvature are taken into account. AIRES is used by many of the present large air shower experiments and has been refined many times since its release.

AIRES is used in this work to determine the accuracy of the angle reconstruction, presented in section 4.4, and also to study more general properties of the array like the trigger efficiency presented in section 4.4.2.

4.4.1 The simulation model

Air showers are sampled with a primary energy following the probability distribution:

$$p(E)dE = \frac{\gamma E^{-(\gamma+1)}}{E_{\text{min}}^{-\gamma} - E_{\text{max}}^{-\gamma}}$$ (4.6)

where $E_{\text{min}}$ and $E_{\text{max}}$ is set to $10^{16}\text{eV}$ and $10^{19}\text{eV}$ respectively. The former value is chosen with the energy threshold for SEASA in mind (see Fig 4.7 for details). This means that SEASA only detects air showers above the knee, which is located at $\sim 10^{15.5}\text{eV}$. A value of $\gamma$ of 2.0 is therefore used, the measured spectral index of cosmic rays above the knee. The latter value, $E_{\text{max}}$, was chosen considering the steep energy spectrum and the relatively small number of air showers generated in the simulations. The chemical composition of cosmic rays is set to p(42%), He(13%), O(14%), Si(15%) and Fe(16%). This is the so called ‘normal composition’ measured around the knee. The injection direction is sampled uniformly between 0° and 360° for the azimuthal angle and between 0° and 60° for the zenith angle. The cut angle at 60° is used for real data as well and is used to discriminate against air showers with very different lateral profiles.

A total of 2000 cosmic rays with the above properties were generated and injected at the top of the atmosphere. The ground particles from each shower were repeatedly used to hit the ground at different locations relative to the detector array. The impact coordinates of the core of the air shower was set to follow a 9×9 grid with a node separation of 50 m and the origin placed in the centre of the detector array. The number of detected showers with the impact point outside this area is negligible and can thus be excluded. The detector locations overlaid with the grid nodes are plotted in Fig. 4.6.

A detector is triggered if it is hit by an electron/positron, muon or heavier charged particle. If a photon hits the detector it is triggered with a 1% probability. This value corresponds to the probability that a photon leaves at least 1 MeV in a 1 cm thick scintillator. To simulate imperfections in the data acquisition and GPS time tagging a time jitter $\sigma_t$ sampled from a Gaussian with a standard deviation of 15 ns is added to the time of the hit. This value is based on the time resolution measurements presented in section 2.5. The influence of the time resolution on the angular resolution is investigated in section 4.4.3.
Figure 4.6. The simulation grid. The squares represent the detectors (not to scale) on the AlbaNova area. The grid of dots is the set of impact points of the shower core in the simulations. Each shower is thus used 49 times. The dotted circles represent the ground coverage of air showers of energies $10^{15}$ eV, $10^{16}$ eV and $10^{17}$ eV. The coverage is defined as the area where the particle density corresponds to a 50% probability to trigger a detector station (3/3 scintillators hit).

4.4.2 Trigger efficiency

The trigger efficiency of the air shower array has been determined from the simulations simply by dividing the number of detected showers to the number of incident cosmic rays for bins of energy. Fig. 4.7 shows the result of the simulation for the two different trigger criteria: 3/3 detectors hit or at least 2/3 detectors hit. The energy threshold is consequently around $10^{16.5}$ eV and the most probable energy slightly higher, $\sim 10^{17}$ eV. Thus, SEASA mainly detects cosmic rays with energies below the knee with this setup. It would be beneficial to lower the energy threshold above the knee to get access to the large amount of interesting studies at energies around the knee, for example the study of the anisotropy in energy intervals around the knee. Models have been proposed that predict changes in the anisotropy due to changes in propagation around the knee [17]. The trigger efficiency is slightly underestimated in Fig. 4.7 as the simulation program doesn’t propagate particles close to the core and a detector station is thus not triggered if an air shower strikes
4.4. Simulation of the Angular Resolution

The angular resolution of the detector array is derived by comparing the shower direction reconstructed from the timing information of the hit detectors with the direction of the primary particle inputted in the simulation. The precision of the reconstruction is measured as the angular distance between the two shower directions, characterised by the parameters \((\theta_1, \phi_1)\) and \((\theta_2, \phi_2)\). The concept of angular distance is illustrated in Fig 4.8, and can be calculated as

\[
\Psi = \cos^{-1}(\cos \theta_1 \cos \theta_2 + \sin \theta_1 \sin \theta_2 \cos(\phi_1 - \phi_2)) \tag{4.7}
\]

The simulated showers are distributed according to the grid in Fig. 4.6 and for every shower that triggers the array the shower direction is reconstructed. The simulation has been done for two trigger criterion’s: i) at least two out of three detectors in each station are hit, and ii) all three detectors in each station are hit. The derived distribution of the differences of the reconstructed azimuthal and zenith angle and the true angle using the latter trigger criterion are shown in Fig. 4.9. The

**Figure 4.7.** The trigger efficiency for the SEASA array for two different trigger criteria.

**Table 4.1**

<table>
<thead>
<tr>
<th>Trigger Efficiency</th>
<th>% Detected</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Trigger Efficiency</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>0.0</td>
</tr>
<tr>
<td>log(GeV)</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>1.0</td>
</tr>
<tr>
<td>7.5</td>
<td>0.8</td>
</tr>
<tr>
<td>8</td>
<td>0.6</td>
</tr>
<tr>
<td>8.5</td>
<td>0.4</td>
</tr>
<tr>
<td>9</td>
<td>0.2</td>
</tr>
<tr>
<td>9.5</td>
<td>0.0</td>
</tr>
<tr>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>
distribution of the azimuthal angle have been multiplied by \( \sin(\theta) \) to account for the zenith angle dependence. Both distributions are well characterised by a sum of two Gaussian functions

\[
f(\theta/\phi) = A_1 G(m_1, \sigma_1) + A_2 G(m_2, \sigma_2)
\]

which might imply two different sub-classes of events. The results of the fits are summarised in Table 4.2.

<table>
<thead>
<tr>
<th>Dist.</th>
<th>( A_1 )</th>
<th>( m_1 )</th>
<th>( \sigma_1 )</th>
<th>( A_2 )</th>
<th>( m_2 )</th>
<th>( \sigma_2 )</th>
<th>( \chi^2/\text{ndf} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \theta )</td>
<td>196.9</td>
<td>0.34</td>
<td>3.26</td>
<td>30.9</td>
<td>1.55</td>
<td>9.31</td>
<td>21/32</td>
</tr>
<tr>
<td>( \phi )</td>
<td>15.9</td>
<td>-3.7</td>
<td>29.5</td>
<td>131.1</td>
<td>0.07</td>
<td>8.1</td>
<td>101/56</td>
</tr>
</tbody>
</table>

Table 4.2. The result of the fit of the sum of two Gaussian functions \( G(m_1, \sigma_1) \) and \( G(m_2, \sigma_2) \) to the distributions of the zenith and azimuthal angles.

The angular resolution of the detector array is defined as the angular distance which contains 68% of the reconstructed angles. This is the most common way to define the angular resolution and therefore makes it straight-forward to compare the result from SEASA to other air shower arrays. Some experiments use the 50% level
4.4. Simulation of the Angular Resolution

Figure 4.9. Simulated accuracy of the zenith and azimuthal reconstruction

as the angular resolution and this is therefore included in the results below. The
distribution of the angular distance is plotted in Fig. 4.10 below for both trigger
criterions. On top of the distributions are the integral of the angular distance
histogram shown with the corresponding axis to the right in the plots. The vertical
dotted line marks the 68% level of the integral.

The angular accuracy of the three station setup is summarised in Table 4.3 for
the two trigger criterions. The errors have been calculated by randomly regener-
ating the histogram of the angular distance a large number of times from the true
distribution. The RMS of the derived distribution of the angular resolution is then
used as the error for the true angular resolution. The angular accuracy, as shown in
Table 4.3, is the same within statistical fluctuations for both trigger modes. This
is an important conclusion and makes it possible to increase the trigger rate by
loosening the trigger criterion without compromising the angular accuracy of the
array.
Figure 4.10. The histograms show the angular distance between the reconstructed angle and the true angle of the primary particle for two trigger criteria. The axis to the right in each plot corresponds to the integral of the angular distance, overlaid on the histogram. The dotted vertical line marks the 68% level of the integral and is the definition of the accuracy of the angle reconstruction for the three station setup for SEASA.
4.4. Simulation of the Angular Resolution

<table>
<thead>
<tr>
<th>Trigg. Crit.</th>
<th>Resolution 68%</th>
<th>Resolution 50%</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Psi_{2/3}$</td>
<td>$6.5 \pm 0.25$</td>
<td>$4.5 \pm 0.15$</td>
</tr>
<tr>
<td>$\Psi_{3/3}$</td>
<td>$7.0 \pm 0.26$</td>
<td>$4.5 \pm 0.18$</td>
</tr>
</tbody>
</table>

Table 4.3. The angular resolution of the detector array for two different trigger criterion’s and levels. The 68% level is used for the definition of the angular resolution for SEASA.

The angular resolution is expected to be constant as a function of the azimuthal angle. Small changes can appear due to the asymmetry of the array. The dependency of the zenith angle is more pronounced. The resolution should increase as the zenith angle increases as the time difference between detector stations becomes larger. The increase in resolution from this effect is more than compensated by the changes in shower structure for large zenith angles. These effects can be seen in Fig. 4.11 where the angular resolution for SEASA as a function of the zenith angle is plotted. The resolution clearly decreases for zenith angles close to 60° strengthening the choice for the cut angle at this value.

Figure 4.11. The angular resolution as a function of the primary zenith angle. The horizontal error bars corresponds to the bin size. The vertical error bars are calculated in the same way as in Table 4.3.
The time resolution of 15 ns used in the simulations are only valid for the AlbaNova array. The accuracy of the GPS time stamps decreases when the distance between the stations is larger because of differences in the atmosphere along the path lengths between the two GPS systems. The GPS systems can also use completely different satellites if the stations are separated by distances comparable with the earth’s curvature. The effect of the time resolution on the angular resolution has been investigated by varying the Gaussian time jitter $\sigma_t$, introduced in the last section, and the result is presented below in Fig. 4.12.

![Figure 4.12](Image)

**Figure 4.12.** The angular resolution as a function of the time resolution in the system. For the array at AlbaNova, a time resolution of 15 ns is used, but this is expected to increase with a larger array as described in the text.

**Validation of the simulations**

To confirm the validity of the shower simulations the difference between super angles and local angles are derived for real and simulated data. These are compared below in Fig. 4.13 and the agreement is relatively good for AlbaNova W and E. The shift in the histograms between simulated and real data for the azimuthal distributions are likely caused by the crude measurement of the local coordinate system for the detectors in each station. The agreement is however poor for AlbaNova S.

This is most likely due to the effect of the roof and walls that surround this station. Simulations that takes this into account will be performed in the future. However, the results in Fig. 4.13 are a good indicator that the simulations are correct. The difference between the reconstructed angles are in fact smaller for real data indicating that the performance of the array may be better than the simulations show.

The characteristic shape of the histograms of the difference between reconstructed and real angle, displayed in Fig. 4.9, with a two-component Gaussian comprised of a sharp peak and a broader base is also seen here but the effect is more pronounced. The effect was first thought to be caused by the asymmetry of the detectors but simulations with a detector station comprised of four detectors in a quadratic geometry showed the same type of results. It now seems that it is a shower-induced and not a detector-induced effect, but the exact cause is unknown.
Figure 4.13. A comparison between real data and simulations of the difference between super angles and local angles. The agreement between data and simulations are good except for the azimuthal distribution for AlbaNova S which most likely is caused by the fact that this station is located inside a building. Notice that the difference between super angles and station angles are somewhat smaller for real data than for the simulations.
Chapter 5

Anisotropy Searches

The galactic magnetic field randomises the arrival direction of cosmic rays to our solar system, with the exception of the very highest energy cosmic rays. Solar modulation distorts the arrival distribution of cosmic rays to the earth for energies up to approximately $10^{12}$ eV. The arrival distribution for higher energy cosmic rays are however not significantly affected by the solar wind and thus arrives from a largely random direction. However, small anisotropies are predicted and these reflect the general propagation of cosmic rays through the galaxy which depends on the strength and structure of the galactic magnetic field. A recent model [48] predicts an amplitude of the anisotropy between $10^{-1}$ to $10^{-4}$ depending on the energy and mass of the cosmic rays and the characteristics of the magnetic field.

Studies of the anisotropy could in principle solve the mystery of the knee in the cosmic ray power spectrum. Models exist [48] that explain the knee as a result of the change in the escape mechanism from the galaxy, and not as a change in the acceleration efficiency of the source which is the traditional explanation. A unique feature of this theory is that it predicts a change in the anisotropy at the knee. This could be the subject for a future study for the SEASA experiment.

This chapter presents a preliminary study of the methods that can be used by the SEASA experiment to search for large scale anisotropies. To date, the collected statistics are poor due to the short period of data taking, the low rate of triggers, and of the numerous tests that have been performed during the initial phase of the project. SEASA aims to lower the energy threshold in the future, by adding more stations and loosening the trigger criterion, thereby increasing the rate of detected showers. More accurate studies of small and large scale anisotropies will then be feasible.

The first section describes the methods and tools that are commonly used to perform anisotropy analysis. In the following sections, the exposure and acceptance of SEASA are derived and maps of the expected number of cosmic rays are derived. Finally, an estimation of the cosmic ray anisotropy measured by SEASA is derived. The coordinate systems used in these studies are explained in detail in appendix C.
5.1 Method

Studies of cosmic ray anisotropy with air shower arrays have until recently mostly been conducted with the Rayleigh formalism [49]. This consists of reducing the two dimensional arrival distribution to one dimension, the right ascension, and computing the Fourier first harmonic amplitude of the data set. The benefit with this projection is the large statistics that is achieved when going from two to one dimension. The major drawback is that it only allows a one dimensional projection of the anisotropy to be recovered. A more advanced technique is to expand the observed cosmic ray distribution on the spherical harmonic basis. The angular power spectrum, $C_l$, can then be estimated similarly to the procedure followed in CMB studies. Unfortunately, the sky coverage of SEASA is too small to adopt this method. Instead a two point correlation function is used to characterise the cosmic ray distribution.

The search for anisotropies and point sources relies heavily on the estimation of the number of cosmic rays expected from each direction in the sky. Such an estimation is henceforth called a coverage map. An unbiased coverage map is crucial in order to separate true anisotropies from acceptance effects. This is relatively straightforward for ultra high energy cosmic rays ($E > 10^{18}$ eV) where the total acceptance almost exclusively depends on the geometrical acceptance of the experiment. For lower energies the influence of atmospheric variations plays a significant role on the detector acceptance and complicates the derivation of the coverage map. This is balanced somewhat by the large number of low energy events.

A method commonly used to derive the coverage map is the so called shuffling method. It consists of redistributing the arrival times (UTC\(^1\)) of the detected events randomly. The shuffled data set has the same declination distribution as the original data sample but an ‘averaged’ distribution in right ascension as the UTC and right ascension are directly coupled. The benefit of this method is that it conserves the UTC distribution which is important for experiments running only parts of the day, like fluorescent detectors which only operate on nights with excellent weather conditions. The drawback is that a true large scale anisotropy will show up partly in the coverage map because right ascension and UTC is not independent.

Another method to estimate the coverage map, proposed by the Auger experiment [50] is used here. It is based on a fit of the zenith angle distribution obtained from real data. The coverage map is obtained by filling all values of right ascension with the declination distribution, which is obtained by a simple transformation from the zenith angle distribution. It has been shown [50] that the zenith angle distribution is essentially unchanged in the presence of a large scale anisotropy and this is therefore an unbiased method to estimate the coverage map.

---

\(^1\)Coordinated Universal Time (UTC), also sometimes referred to as Zulu time (Z) or less accurately as Greenwich Mean Time (GMT).
5.2 The Coverage Map

As mentioned above, the coverage map is essentially the arrival distribution of cosmic rays in celestial space assuming an isotropic flux. The coverage map can be obtained by integrating the acceptance of the experiment over the data taking period. The acceptance generally depends on the direction in the sky, characterised by the coordinates declination and right ascension \((\delta, \alpha)\), which corresponds at UTC \(t\) to \((\theta(t), \phi(t))\) in horizontal coordinates. The acceptance can also change because of daily and seasonal modulations due to temperature and pressure effects on the trigger rate, as discussed in section 3.2. The total acceptance thus depends on time \((t)\), sky direction \((\theta, \phi)\), temperature \((T)\) and pressure \((P)\) and can be written as \(a_{\text{tot}} = a(t, \theta, \phi, T, P)\). The coverage map \(W\) is then

\[
W = \int_{t_{\text{start}}}^{t_{\text{stop}}} a_{\text{tot}} \, dt \quad (5.1)
\]

The acceptance can be regarded as independent of the azimuthal angle for a well constructed experiment. Simulations will be performed for the SEASA experiment to confirm this. To a first approximation, the acceptance can also be regarded as independent of temperature and pressure. A consequence of this is that the acceptance is independent of time as the exposure is independent of right ascension (and therefore time) and weather effects is thus the only parameter that changes over time. With these simplifications, the acceptance is only a function of the zenith angle. The zenith angle can be related to the equatorial coordinates through the expression [51]

\[
\cos(\theta - A(t)) = \sin \delta \sin \lambda + \cos \delta \cos \lambda \cos(\alpha - A(t)) \quad (5.2)
\]

In this formula, \(\lambda\) is the latitude of the array and \(A(t)\) is the right ascension of the zenith of the location of the array at the time \(t\). By integrating the simplified expression for the acceptance over one day a coverage map which only depends on declination is obtained.

\[
W(\delta) = \int_{0}^{24h} a[\theta - A(t), \delta] \, dt \quad (5.3)
\]

This simplified approach of deriving the coverage map described above is used here as the statistics are too low to make any precise estimations of the influence of temperature and pressure on the acceptance. Thus, an accurate determination of the acceptance of the experiment, which in this case only depends on the declination, is needed to calculate the coverage map.
5.2.1 Derivation of the acceptance

The acceptance of the array is calculated using a semi-analytical approach. As mentioned in section 5.1 the zenith angle distribution has been shown to be almost unaffected by anisotropies. This distribution is therefore used as a basis when calculating the acceptance in celestial space - the expected declination distribution. To derive this, a function \( P(\theta) \) is fitted to the measured zenith angle distribution and then transformed to a declination distribution \( a(\theta) \) by simple geometrical methods. Assuming an isotropic flux of cosmic rays, the normalised declination distribution then corresponds to the acceptance of the experiment.

The fit to the zenith angle distribution is performed in section 4.3 and the result is used here (but with a data set excluding January and February). Function 5.4 fitted the distribution with the variables \( A, \theta_0 \) and \( \Delta \theta \).

\[
P(\theta) = A \cdot \cos \theta \sin \theta \cdot \frac{1}{1 + \exp\left(\frac{\theta - \theta_0}{\Delta \theta}\right)} \quad (5.4)
\]

\[
A = 131.6 \pm 27.2 \quad (5.5)
\]

\[
\theta_0 = 23.4 \pm 4.2 \quad (5.6)
\]

\[
\Delta \theta = 8.9 \pm 1.2 \quad (5.7)
\]

The declination acceptance \( a(\theta) \) is related to \( P(\theta) \) through the formula

\[
a(\theta) = \frac{1}{\sin(\theta)} \cdot P(\theta) \quad (5.9)
\]

(solid angle effect). The resulting declination acceptance is plotted in the top part of Fig. 5.1. Integrating the acceptance over the celestial sphere gives a total coverage of

\[
\text{Coverage}_{\text{tot}} = \int_{\text{Celestial Sphere}} a(\theta) = 21\% \quad (5.10)
\]

This is lower than for example AUGER south (\( \sim 40\% \)) and is due to the north location of the SEASA array. An array located closer to the equator have access to a larger band in declination space as the solid angle goes as \( \cos(\delta) \). On the other hand, an array close to one of the poles have a large acceptance for events close to the respective celestial pole. The acceptance can be compared to the exposure, shown in the bottom part of Fig. 5.1. The exposure is the effective collecting area for a flux from each position in the sky; detector and atmospheric effects are thus disregarded.

The relative exposure for an air shower array operating full time, meaning that there is no exposure variation over time and therefore constant exposure in right
5.2. The Coverage Map

Figure 5.1. Top: The relative acceptance in sidereal coordinates. Bottom: The calculated relative exposure for the SEASA experiment from each point on the celestial sky. Because the exposure is uniform in right ascension this is just a function of the declination. The exposure is largest near the north celestial pole as this area always is visible from the latitude of Stockholm. The acceptance peaks before this, at a declination of about 70° as the effective surface of the array goes as \( \cos(\theta) \).
ascension, and that is fully efficient for particles arriving with an zenith angle up to $\theta_m = 90^\circ$ can be calculated as [52]

$$w(\delta) \propto \cos(\lambda)\cos(\delta)\sin(\alpha_m) + \alpha_m\sin(\lambda)\sin(\delta) \quad (5.11)$$

where $\alpha_m$ is given by

$$\alpha_m = \begin{cases} 
0 & \text{if } \xi > 1, \\
\pi & \text{if } \xi < -1, \\
\cos^{-1}(\xi) & \text{otherwise.} 
\end{cases}$$

and

$$\xi = \frac{\cos(\theta_m) - \sin(\lambda)\sin(\delta)}{\cos(\lambda)\cos(\delta)}$$

where $\lambda$ is the latitude of the detector array.

The declination acceptance can be compared to the measured declination distribution as a cross-check. As the measured distribution is over the whole celestial sphere, the acceptance is integrated over right ascension. The result is shown in Fig. 5.2 and the calculated distribution can be seen to match the measured distribution well.

---

**Figure 5.2.** The integral of the calculated acceptance (solid line) compared to the measured declination-distribution. Coverage in arbitrary units.
5.2.2 Realisation of the coverage map

A coverage map can be realised by building the declination distribution, obtained from equation 5.3, for all values of right ascension. The coverage maps in galactic (Fig. 5.3) and equatorial coordinates (Fig. 5.4) are shown below. The plots are made with the Healpix [53] tool, and use equal area pixels with a size of $\sim 3.5^\circ$ (chosen only for esthetic reasons).

As shown in Fig. 5.3 the galactic centre, located in the centre of the coordinate-system by definition, is not within the detectable window of SEASA. The galactic anti-centre, located at the left and right corners of the map, are within the window of SEASA, but with a low acceptance. These are areas that have shown anisotropies in the cosmic ray distribution when measured by other experiments (see section 1.4) and are therefore of interest.

5.3 Measuring the Anisotropy Using a Two Point Correlation Function

The hypothesis that the flux of cosmic rays is isotropic can be tested using data from the SEASA experiment. A simple approach is to derive the angular two point correlation function $w(\Phi)$. In its angular form it is defined by the expression

\[ \delta P = N[1 + w(\Phi)]\delta \Omega \]  \hspace{1cm} (5.12)

where $\delta P$ is the probability to find a second object within an angular distance of $\Phi$ from the primary object within an area $\delta \Omega$ if the mean object density is $N$. The two point correlation function thus represents an “excess probability” above what is expected from an isotropic distribution.

The measured sky-plot of cosmic rays is plotted in equatorial coordinates in Fig. 5.5. A total of 287 good events have been detected. The two-point correlation distribution is derived by calculating the distance between all possible pair of events for this data set. To compare this to the hypothesis that the arrival distribution is isotropic a second two-point correlation distribution is derived from a randomly generated isotropic distribution convoluted with the coverage map derived in section 5.2.2. Possible deviations of the first distribution from the second then reveals anisotropies of the cosmic ray arrival distribution. Both correlation distributions mentioned above are plotted in Fig. 5.6. The probability that the observed flux is a random sampling from an isotropic flux is checked with a Kolmogorov test and it is found to be 82%. The hypothesis of an isotropic flux is therefore supported.

The ratio of the ‘measured’ two-point correlation distribution and the isotropic distribution is plotted in Fig. 5.7. This corresponds to the expression $1 + w(\Phi)$ in equation 5.12. A straight line is plotted to guide the eye for $w(\theta) = 0$, which corresponds to complete isotropy. The error bars increase dramatically for large angular distances because of low statistics. The structure shows small irregularities, an excess before 1.0 radians followed by a deficit at approximately 1.2 radians,
Chapter 5. Anisotropy Searches

Figure 5.3. The coverage map in galactic coordinates. The galactic centre is unfortunately not detectable with the SEASA experiment which can be seen in the map. The exposure is largest “west” of the galactic centre. The map has a resolution nside=316 corresponding to \(\sim 3.6^\circ\) pixels. The map is generated with 10 000 events following the declination distribution 5.2 randomly distributed over right ascension. The units in the bar below the map are in events per pixel.

Figure 5.4. The coverage map in equatorial coordinates. The map has a resolution nside=16 corresponding to \(\sim 3.6^\circ\) pixels. The map is generated with 10 000 events following the declination distribution 5.2 randomly distributed over right ascension. The units in the bar below the map are in events per pixel.
5.3. Measuring the Anisotropy Using a Two Point Correlation Function

but the significance is low. However, deviations from isotropy can originate from errors in the trigger time measurements or from a biased coverage map. A small bias of the coverage map is expected because of the acceptance variation versus temperature and pressure which is neglected in this study, but exactly how this would be revealed in the two point correlation function has not been studied. To conclude, the measured distribution of cosmic rays with the SEASA experiment is compatible with an isotropic sky.
Figure 5.6. The distributions of the two point distance for measured events and randomly generated isotropic events.

Figure 5.7. The ratio of the distributions of the angular two point distance for measured events and isotropic events. A line is drawn for a value of one which indicates isotropy.
Chapter 6

Summary

6.1 Conclusions

The work presented in this thesis concerns the construction and performance of the SEASA experiment, an experiment investigating high energy cosmic rays.

The design of a detector system for measuring cosmic ray air showers has been described, with a focus on the parts the author has been part of developing: the data acquisition and GPS system. The performance of the GPS system has been tested and the time resolution was found to be \( \sim 15 \) ns for a small cluster of stations. The performance of the detector stations has been evaluated from the data collected during the last seven months. The resilience of the detectors to the harsh weather is a key consideration as many of the detectors are located outside. The detectors have been found to perform well over a large range of temperatures and weather conditions, and the detector design presented in this thesis is considered a final design.

A study of the influence of weather on the acceptance of the stations and on the array, to be used in future studies of the cosmic ray anisotropy, has been presented. The statistics were too low to make any final predictions, but it was found that the acceptance of the detector array significantly changes with weather conditions, and primarily with temperature. This affects the derivation of the coverage map and must therefore be investigated further in the future to derive the exact relations between acceptance, temperature and pressure.

A detailed study of the ability of the SEASA array to reconstruct the direction of the primary cosmic ray have been performed. A method for converting the geodetic coordinates measured by the GPS systems to a Cartesian coordinate system have been implemented. An algorithm for determining the direction of the primary cosmic ray from the position information and the measured time stamps from each detector is presented. The measured distributions of the shower angles have been compared to the expected ones to assess the performance of the time-tagging. The
time-tagging have worked well and so the shower direction reconstruction have been successful.

Simulations have been performed to derive the angular resolution of the array and it was found to be $(7.0 \pm 0.3) ^\circ$. The resolution has been found to be independent of the trigger mode, i.e the requirement of $(2/3)$ or $(3/3)$ hit detectors to trigger a station. The simulations have been qualified by the comparison of the distributions of the difference between the angles reconstructed by the stations and the angles reconstructed by the entire array. It has been shown that such simulated data matches real data well.

The simulations have also been used to assess the energy threshold and trigger efficiency of the array, for both trigger modes. The energy threshold was found to be slightly above $10^{16}$ eV for both trigger modes. The trigger efficiency was, not unexpectedly, found to be higher for the $(2/3)$ trigger criterion. This trigger mode will therefore be adopted in the future.

A preliminary study of the cosmic ray anisotropy has been presented. A method for deriving the expected number of cosmic rays in each direction in the sky - a coverage map, was developed. As a part of this, the acceptance and coverage of the experiment was derived. The coverage was found to be 21% of the celestial sphere. A consequence of this is that a spherical harmonics analyses of the cosmic ray anisotropy not is possible to perform as it requires a higher coverage. The hypothesis of an isotropic flux of cosmic rays was instead tested using a two point correlation function. The probability that the observed flux is a random sampling from an isotropic flux was checked with a Kolmogorov test and it was found to be 82%. The hypothesis of an isotropic flux is therefore supported.

### 6.2 Outlook

This work concludes the development phase of the SEASA project. The detector design has converged to a system that has proven to be stable over a long time. A data acquisition and data basing system has been developed and successfully used and the experiment is now ready to expand. A fourth station will soon be installed in the AlbaNova area, thereby improving the capabilities of anisotropy studies around the knee. The additional four detector stations to be placed at high-schools in the Stockholm area are being installed at the time of writing. This marks the start of the search for ultra high energy showers. An additional aim of the project is to establish clusters of stations in towns outside Stockholm. This would make long range correlations between air showers possible to detect, a study which is complementary to what professional arrays can do.

A critical feature, still missing in the SEASA system, is the ability to measure particle density at each station. If this would be possible, it would greatly improve the analysis presented in this thesis and also make more types of analyses possible. The development of this feature will therefore be pursued in the future.
Appendix A

Calculations

A.1 Conversion of Geodetic to UTM Coordinates

The Easting (E) and Northing (N) can be calculated in a UTM zone from the latitude $\lambda$ and longitude $\phi$ as

$$E = k_0 N \left( A + (1 - T + C) \frac{A^3}{6} + (5 - 18T + T^2 + 72C - 58e^2) \frac{A^5}{120} \right)$$  \hfill (A.1)

$$N = k_0 (M - M_0 + N \cdot \tan \phi \cdot S)$$  \hfill (A.2)

where

$$S = \left( \frac{A^2}{2} + (5 - T + 9C + 4C^2) \frac{A^4}{24} + (61 - 58T + T^2 + 600C - 330e^2) \frac{A^6}{720} \right)$$  \hfill (A.3)

$$M = a \left( 1 - \frac{1}{4} e^2 - \frac{3}{64} e^4 - \frac{5}{256} e^6 - \frac{175}{16384} e^8 + \ldots \right)$$  \hfill (A.4)

$$- a \left( \frac{3}{8} T^2 + \frac{3}{32} T^4 + \frac{45}{1024} e^6 + \frac{105}{4096} e^8 + \ldots \right) \sin 2\phi$$  \hfill (A.5)

$$+ a \left( \frac{15}{256} e^4 + \frac{45}{1024} e^6 + \frac{525}{16384} e^8 + \ldots \right) \sin 4\phi$$  \hfill (A.6)

$$- a \left( \frac{35}{3072} e^6 + \frac{175}{12288} e^8 + \ldots \right) \sin 6\phi$$  \hfill (A.7)

$$+ \left( \frac{315}{131072} e^8 + \ldots \right) \sin 8\phi + \ldots$$  \hfill (A.8)

$$T = \tan^2 \phi, C = \frac{e^2}{1 - e^2 \cos^2 \phi} = e^2 \cos^2 \phi, A = (\lambda - \lambda_0) \cdot \cos \phi$$  \hfill (A.9)

$$e' = \frac{e^2}{1 - e^2}$$  \hfill (A.10)
and $a$ is the semi-major axis, $\epsilon$ the eccentricity of the ellipsoid. $M_0$ and $\lambda_0$ is the values of $M$ and $\lambda$ at the origin of the UTM zone and $k_0$ the scale along longitude ($= 0.9996$).

**A.2 Calculation of The Event Time**

The time line in Fig. A.1 shows a trigger event arriving between two GPS PPS pulses. A 100 MHz oscillator in the Altera determines the trigger time within the second by measuring the number of oscillations from the trigger event to the next PPS. This information is saved in the data string as 'trigcount'. As the oscillation frequency varies slightly it is calibrated by measuring the number of oscillations between successive PPS's. The value of this calibration is stored in the data string as 'calcount'. An additional correction, the sawtooth correction, accounts for the granularity of the GPS internal clock as explained in section 2.3.3. There is one sawtooth value for each PPS, so in total two values are saved in the data string. The trigger time can then be calculated as:

$$Triggtime = yy:mm:dd:ss(PPS1) + offset$$

(A.11)

$$offset = \left(1 - \frac{trigcount}{calcount}\right) \times (10^9 + sawtooth1) + sawtooth2$$

(A.12)
A.2. Calculation of The Event Time

Figure A.1. The derivation of the trigger time from the trigger information. The trigger time is determined within the GPS second by measuring the number of 100 MHz oscillations from the trigger event to the next PPS (trigcount). The length of the second is calibrated by counting the number of oscillations between the two PPS’s next to the trigger event.
## Appendix B

### The Data Format

### Raw data format

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</tr>
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</tr>
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<td>9</td>
<td>GPS hour</td>
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</tr>
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<td>10</td>
<td>GPS second</td>
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Raw data format

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<td>V(ADC) Ch3</td>
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<td>photomultiplier high voltage setting</td>
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<td></td>
</tr>
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<td>27</td>
<td>Ch1 trigger time 1</td>
<td></td>
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<tr>
<td>28</td>
<td>Ch1 trigger time 2</td>
<td></td>
</tr>
<tr>
<td>29</td>
<td>Ch1 trigger time 3</td>
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</tr>
<tr>
<td>30</td>
<td>Ch1 trigger time 4</td>
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</tr>
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<td>counter is stored when a trigger signal is</td>
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<tr>
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<td>51</td>
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## Raw data format

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<td>60</td>
<td>Coincidence choice</td>
<td>Defines what combination of detector signals needed for a trigger.</td>
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<td>61</td>
<td>Coincidence gate length 1</td>
<td>The length of the time window (also called 'gate') during which coincidences are allowed.</td>
</tr>
<tr>
<td>62</td>
<td>Coincidence gate length 2</td>
<td></td>
</tr>
</tbody>
</table>

**Event-type block**

| 63          | Event type                | Only kept for historical reasons                                      |

**emLinux block**

| 64          | Preceding sawtooth        | sawtooth 1. A value of 128 indicates that no sawtooth correction could be recovered. |
| 65          | Station ID                | A unique identifier for each station                                   |
| 66          | Not used                  |                                                                       |
Appendix C

Astronomical Coordinate Systems

The direction of a detected air shower is reconstructed in spherical coordinates - also called horizontal coordinates. This coordinate system moves together with the observer, the earth. To be able to study the distribution of arrival directions the coordinates are transferred to a celestial coordinate system - the Equatorial coordinate system. A second celestial coordinate system, the galactic coordinate system, is used for studies of arrival distributions in relation to our own galaxy. These three coordinate systems are described in this section together with the mathematical relations that connects them.

C.1 Horizontal Coordinates

The most natural and fundamental way of describing a point in the sky, or on the celestial sphere, is with the horizontal coordinate system. This coordinate system is based on the observers position. The origin is located at the observer. The observers horizon is the reference plane and the local vertical axis the reference axis. An object in the celestial sphere is then described by the zenith ($\theta$) and azimuthal ($\phi$) angle. The zenith angle is the angle to an object measured from the zenith. The azimuthal angle is the angle around the plane, usually measured clockwise from the north axis.

The horizontal coordinate system is fixed to the earth and the coordinates ($\theta, \phi$) of objects on the celestial sphere therefor changes with time. This coordinate system is thus not adequate for describing points in the sky.
As the name suggests, the *Equatorial coordinate system* is referenced to the plane of the equator of the earth. Imagine this plane stretched out to a sphere at infinite distance on to all the sky is projected. This is the celestial sphere. The north pole on this sphere is located exactly above the north pole of the earth and is called the *North Celestial Pole*. The south pole is then consequently called the *South Celestial Pole* and lies below the earths south pole. The celestial sphere is fixed in space so a star on the sphere will describe a circle during one day as the earth rotates, according to an observer at earth.

A point on the celestial sphere is described by the coordinates *declination* ($\delta$) and *Right Ascension* ($RA$). Declination is the hight above the equator plane and ranges from $-90^\circ$ at the celestial south pole and $+90^\circ$ at the celestial north pole. Right ascension corresponds to longitude in geodetic coordinates and is measured from $0^\circ$ to $360^\circ$ beginning at the Vernal Equinox. However, it is more common that right ascension is measured in hours, minutes and seconds. $0h$ then corresponds to $0^\circ$ and $24h$ to $360^\circ$.

### C.3 Galactic Coordinates

The *Galactic coordinate system* is used to describe relations between objects in our own galaxy. Origin is the position of the sun, and the fundamental line is the line that connects the sun and the centre of the galaxy. The plane of reference is then

---

*Figure C.1. The horizontal coordinate system.*
the plane of the galaxy. This is illustrated in Fig. C.3 where S marks the sun, G
the centre of the galaxy and X the position of a star.

The galactic coordinates for the star X are defined by the *galactic longitude* \( l \),
alogous to right ascension, and the *galactic latitude* \( b \), analogous to declination.
The galactic latitude is the height above the galactic plane and ranges from ±90
at the galactic poles. The galactic longitude is the angular distance between the
projection of X onto the galactic plane \((X')\) and the line SG. This is measured
clockwise from the centre of the galaxy.

### C.4 Conversion Between Coordinate Systems

To convert between horizontal and equatorial coordinates the time of day is needed
in addition to the horizontal coordinates \((\theta, \phi)\). The declination can be obtained in
the following way

\[
sin \delta = \sin \theta \sin \lambda + \cos \theta \cos \phi \cos \lambda \tag{C.1}
\]

where \( \lambda \) is the latitude of the array. To calculate the right ascension \((RA)\) the hour
angle \( H \) and the Greenwich Mean Sidereal Time \((GMST)\) are needed. The hour
angle can be calculated as

\[
tan H = \frac{-\sin \theta \sin \phi}{\cos \theta \cos \lambda - \sin \theta \cos \phi \sin \lambda} \tag{C.2}
\]

Right ascension can then be calculated as

\[
RA = GMST + Longitude - H/15. \tag{C.3}
\]
Longitude refers to the array. RA is then given in hours.

The conversion from equatorial to galactic coordinates is easily done by the following equations:

\[
\sin b = \cos \delta \cos(27.4) \cos(\alpha - 192.25) + \sin \delta \sin(27.4) \quad (C.4)
\]

\[
\tan l = 33.0 + \frac{\sin \delta - \sin(b) \sin(27.4)}{\cos \delta \sin(\alpha - 192.25) \cos(27.4)} \quad (C.5)
\]
Acknowledgements

I should probably start by thanking the person who gave me the job, so thanks Mark! I especially want to thank you for inspiring me to choose astroparticle physics and also for being one of the few persons that still keeps me inspired.

There is so much more to work than work, if you are employed at Partikelfysik, KTH. This is of course due to my colleagues who have made the time here really great. I want to give a big hug to all the “old guys”: Jens, Janina, Sara, Tore, Silvio and Hank, whom most of now have left or is leaving for the real world. You have all been a great support and always a source of enjoyment from my first day as a PhD student. Work will not be the same without you, thats for sure. I guess its up to you and me now Pelle to get this institution running!

I also want to thank the rest of the astro- and particle-physics group for making this such a great place to work. A special thanks to Stefan Rydström for all the invaluable help in the lab, and to Jan Conrad for late input to the thesis. It should also be mentioned that this thesis is in debt to all the diploma workers that have worked in SEASA over the years. I therefore would like to thank Magnus, Anton, Henrik, Maurizio, Christian and Lisa for your work that formed the foundation of this thesis.

A warm thought goes to my family: Anna-Carin, Bertil, Lotta, Jakob, Tobias and Kjell. You are an endless source of love and support and nothing I have accomplished this far would have been possible without you. Hopefully, we will see each other more often in the future than during these last months.

And, finally, a thought goes to a lost friend who I miss dearly.
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