Scintillator detectors and an autonomous GPS time-tagging system for the SEASA project

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Abstract

In preparation for the construction of the first detector station in the Stockholm Educational Air Shower Array (SEASA) the design of the scintillator detectors has been investigated. The design with the most position insensitive response was chosen and three detectors were constructed, enough to construct one station.

The use of GPS to supply time-stamps for events in independently operating systems was evaluated. The technique was tested in a proof-of-principle setup. By supplying a common random trigger to the two systems the difference in the resulting time-stamp can be measured. For a 3.5 days measurement, compromising 75000 events, the random error had a standard deviation of 5 ns. The mean value of all measurements turned out to have an offset of between 4 ns and 5 ns. This offset originates in the GPS part of the system and a larger system with more GPS receivers could potentially have a different offset for different GPS-cards. This would necessitate calibration of the GPS-cards. The systems sensitivity to its position fix was also investigated.
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Chapter 1

Introduction

1.1 Cosmic rays

The earth’s atmosphere is constantly bombarded by all kinds of particles. Apart from the enormous flux of neutrinos that is generally overlooked since their extremely small interaction cross-section means that they pass virtually unhindered through the atmosphere and the entire earth, there are protons, electrons and a small admixture of heavier nuclei. The highest energy photons with energies in the GeV and TeV range are also often treated like particles because their interaction with matter is very different from the way low energy photons like visible light and radio waves interact. Most of the cosmic ray particles give rise to particle showers as they interact with nuclei in the atmosphere, as shown in figure 1.1.

![Development of cosmic-ray air showers](image)

Figure 1.1: First stages of an air shower.

Only the primary particles with very low energy are able to reach the earth’s surface without giving rise to showers of secondary particles. These low energy particles originate from within the solar system, mainly from the sun, and their acceleration mechanisms are fairly well understood.

For particles with energies higher than those possible in mass ejection acceleration from stars, a new acceleration mechanism has been envisaged. Named Fermi acceleration after its discoverer, Enrico Fermi, a charged particle gyrating around a magnetic field line entering an
area where the magnetic field has a gradient will experience a force that, if the field gradient is strong enough, turns the particle back to the direction it came from with the same momentum. This is known as magnetic mirroring. Two such magnetic mirrors can trap the particle in between them. This is how a plasma is contained in a fusion reactor. A particle encountering a moving magnetic mirror will be turned back, and it will also be accelerated if the magnetic mirror and the particle move in opposite directions. If they move in the same direction the particle will instead lose energy as it is made to turn back. What Fermi did was to show that the average over many such encounters with magnetic mirrors would give an increase in energy. If the magnetic field gradient is strong enough particles can be accelerated to very high energies.

The structure in the spectrum for cosmic rays can be seen in figure 1.2.

![Flux of Cosmic Rays](image)

**Figure 1.2:** Flux of cosmic rays as a function of primary particle energy.

In our own galaxy the expanding shock waves from supernovae are places where extreme acceleration can occur. Such acceleration processes can be used to explain cosmic ray particles with energies up to \( \sim Z \cdot 10^{15} \text{ eV} \), where \( Z \) is the charge of the accelerated particle. In a plot of the number of events versus energy there is a kink at \( \sim 10^{15} \text{ eV} \), the so-called knee. This corresponds in part to the fact that the most abundant particle in the measured cosmic radiation is the proton that carries a unit charge and could therefore only be accelerated to this energy. It is also the energy where particles are thought to no longer be magnetically bound to the Milky Way, so that particles accelerated to higher energies stand a chance of escaping the galaxy. If the maximum acceleration in a supernova is \( \sim Z \cdot 10^{15} \text{ eV} \) then there should be features in the energy spectrum corresponding to the maximum attainable energies of heavier nuclei as well. A similar kink in the energy spectrum around \( \sim 10^{17} \text{ eV} \) due to iron is actively searched for. The next feature in the plot comes at \( \sim 10^{19} \text{ eV} \) where it appears to flatten. The interpretation is that there is some other mechanism responsible for acceleration of protons to energies above the knee. The most popular candidate for an even more powerful acceleration site than a supernova is the super-massive black holes in active galactic nuclei.
(AGN). This raises a new question. For protons with an energy in excess of \(\sim 5 \times 10^{10} \text{ eV}\) space becomes opaque due to interaction with the cosmic microwave background, this is known as the GZK-cut off. If these particles are indeed accelerated in AGNs their parent galaxies must lie within 50 Mpc of the Milky Way. By trying to detect the incoming direction of the primary cosmic ray one hopes to be able to link it to a possible source, preferentially an AGN since they are known to exist even though they are not fully understood. At energies less than \(10^{15} \text{ eV}\) charged particles will be deflected by the magnetic fields in space so that it will be virtually impossible to link detected particles to possible acceleration sources. Particles with higher energies will be essentially unaffected by the magnetic field and are therefore excellent to use as pointers back to their original acceleration sites.

If no candidate AGNs or other known sources can be found this means that there is a need for new physics. Several proposals for non-AGN origins have already been made. These include Topological Defects (TD) in the space-time fabric of the universe, the decay of particles in the GUT mass scale left over from the Big Bang or simply that the special theory of relativity is no longer applicable at ultra-high energies. [2], [10]

### 1.2 Detection methods

The shower of secondary particles that is created as the high energy primary particle interacts with the atoms in the atmosphere complicates the determination of the original direction and energy with a detector on the earth’s surface. Satellite borne experiments suffer from another disadvantage, the flux of the highest energy particles is too low, around the knee \((10^{15} \text{ eV})\) the flux is just one particle per square meter per year and at \(10^{20} \text{ eV}\) the flux is as low as one particle per km\(^2\) per century! To detect these rare primary particles directly seems impossible.

By analyzing the resulting air shower the properties of the primary cosmic ray can be determined. The shower characteristics will vary depending on the type and energy of the primary particle. Although the shower can contain many types of short-lived exotic particles in its initial stages, the particles that reach the surface of the earth are almost exclusively electrons, muons, neutrinos, photons and nucleons. If these secondary particles are detected as they hit the earth’s surface, it is a 'straightforward' task to reconstruct the path and energy of the primary particle. Unfortunately this is practically impossible, since already at a primary energy of \(10^{15} \text{ eV}\) the number of secondary particles hitting the earth’s surface exceeds one million. The composition of the shower is approximately 80\% photons, 18\% electrons, 1.7\% muons and 0.3\% hadrons. At this point the shower has more or less the shape of a pancake with a diameter of about 100 metres and a depth of a few metres, moving at the speed of light. For the more interesting higher energies, above \(10^{19} \text{ eV}\), the diameter of the pancake is even larger, up to several kilometres, and it contains more than \(10^{11}\) particles. The sheer size of the shower makes direct collection of all its particles impossible. Instead models of the shower development have been constructed and used in computer simulations so that detecting just a part of a shower will be enough to reconstruct the event. There are essentially two ways to detect the shower, either by detecting the particles that hit the ground or by measuring the fluorescence from the shower as it traverses the atmosphere.

#### 1.2.1 Surface particle detectors

The easiest and cheapest way to extract information from the shower is to spread out a large number of small detectors over a large area. By requiring coincidence in several detectors, small and uninteresting events will automatically be sorted out. The number of particles detected and the lateral profile of the shower will then reveal, at least statistically, the energy of the primary particle. By analyzing the exact time when the shower hits the various detectors, the direction of the shower front can be calculated. By placing some detectors in pairs close to each other and covering one of them with a thick lead plate or bury it underground will allow the muonic component to be studied. If there are no muons, the primary particle is either a photon or an electron, causing an electro-magnetic shower. Muons indicate that the
primary particle is a hadron. Two types of detectors are used for these kinds of measurements, scintillators and water Cherenkov counters. [5], [8]

1.2.2 Fluorescence detectors

As the relativistic particles in the shower traverses the atmosphere they will give rise to Cherenkov radiation. This faint light can be detected on clear, moonless nights by telescopes monitoring the atmosphere. Since the light is emitted in a narrow cone around the shower axis, the detection rate for such events is very low. The Cherenkov light is more useful for detecting cosmic rays in the form of high-energy gammas since an electro-magnetic shower does not become as spread-out as a hadronic shower. Another faint-light phenomenon that can be used to track air showers is air fluorescence. The electrons and positrons in the air shower excite atmospheric nitrogen molecules. The molecules de-excite instantaneously, emitting light in the UV region of the spectrum. Approximately 4 UV-photons will be emitted per meter of charged particle track. The advantage of air fluorescence over Cherenkov radiation is that the fluorescent light is emitted isotropically and is thus detectable up to 30 kilometers away from the line of motion of the shower. The huge number of particles in a giant shower makes this technique viable, at least for cosmic ray energies above $10^{17}$ eV. For a large shower the fluorescence signature resembles a 4 W UV light-bulb descending through the atmosphere at the speed of light. The particles in the shower move at the speed of light, so measuring the position at short time intervals gives the direction of motion of the shower and consequently the direction of the primary cosmic ray. Air fluorescence detectors and atmospheric Cherenkov detectors are both complicated and have a low duty cycle since they put severe restraints on the observatory environment. Of the few that have been operated most are Cherenkov detectors used for high-energy gamma ray observations. [9]

1.3 Present experiments

The existence of high energy particles originating from outside the earth's atmosphere has been known since 1912. Due to the difficulties imposed by the resulting showers it was not until the 1960’s that research began on the high energy part of cosmic rays. Pioneering projects like Haverah park all used arrays of surface particle detectors. Air fluorescence detectors, like the Fly’s Eye, were not built until the early 1980’s.

Today, much of the collected data about cosmic rays comes from HiRes Fly’s Eye, which is an extension of the Fly’s Eye with stereoscopic capabilities, and the AGASA array. The HiRes Fly’s Eye detected the highest energy particle ever seen when an event with an estimated energy of $3 	imes 10^{20}$ was detected. The AGASA (Akeno Giant Air Shower Array) consist of 111 detectors with a 1 km pitch placed on the ground and another 27 detectors placed under absorbers in order to filter out muons. AGASA’s detectors covers an area of about 100 km$^2$. The data from all experiments agree on the flux of cosmic rays up to the GZK-cut off. But AGASA shows an excess of events above this energy as opposed to the other experiments (figure 1.3).

The discrepancies may, in part, be explained by the fact that the two methods have never been calibrated against each other. Extrapolating known physics over eight orders of magnitude might not be possible.

The Auger Observatory is the first project in the next generation of air shower detectors. It is a hybrid design with 24 air fluorescence telescopes and 1600 water Cherenkov detectors covering an area of 3000 km$^2$ being built in the Argentinean desert. A second similar large area composite observatory is planned to be built in Utah. Together they will provide an all-sky coverage and enable a cross-calibration between surface particle detectors and air fluorescence detectors. [5], [8], [9]
1.4 The SEASA project

The Stockholm Educational Air Shower Array (SEASA) has a two-fold purpose, to do potentially valuable basic research and to serve as an outreach to local schools. In the first phase of the project three stations will be built and placed on the roof of the AlbaNova main building (2 stations) and at the roof of Vetenskipenshus (1 station) at the Fysikcentrum area. Each station consists of three scintillator detectors separated by ~10 meters, and a computer unit. When there is coincidence in all three detectors, the computer will record the event and apply a time-stamp. These time-stamps must be very accurate, on the order of 10 ns, to be usable.
This kind of accuracy can not be achieved with ordinary clocks, instead the time-stamps will be supplied by GPS technique. The event will then be sent over the Internet to a central computer that looks for coincidences between the events from different stations. Parameters like the incoming angle of the shower front, and thereby the primary particle, can be calculated if there is coincidence in at least three stations. In addition each station is capable of doing a rough calculation of the angle so that even smaller events can reveal information.

The array will eventually be expanded with local schools housing a detector unit. In densely populated areas schools are situated close enough to each other to be ideal bases for air shower detectors. Equipment for other measurements like air pollution or other environmental quantities can be attached to each station to further broaden the interest. Since each station is an autonomous unit, the array can easily be expanded to include new schools in response to interest. By letting students participate in the construction and testing of ‘their’ detector station as well as in data analysis it is an opportunity to create interest for the field of particle physics. [2]
Chapter 2

Detector Construction

A plastic scintillator was used to detect the particles in the shower. When a charged particle passes through a scintillator it will give rise to excitations in the scintillating material. As it decays to its ground state the scintillator emits photons of a characteristic wavelength. Plastic scintillators of type Bicron BC-408 that were used in these detectors de-excite by emitting a photon with a wavelength distributed around 425 nm as can be seen in figure 2.1. It has

![Wavelength distribution of emitted photons from the Bicron BC-408 plastic scintillator](image)

Figure 2.1: Wavelength distribution of the emitted photons from the Bicron BC-408 plastic scintillator.

... a quick response, the decay time is 2.1 ns, and a long light attenuation length which makes it suitable for large detectors. The scintillators were recycled from another experiment and already cut to (13×50×1) cm pieces. The plan was to use four such pieces in each detector, read out by a single photomultiplier tube (PMT).

In the PMT the photons from the scintillator generates electrons in the photosensitive cathode. These electrons are then accelerated toward a chain of dynodes. At each dynode every electron generates a number of new electrons so that in the end a single incoming photon at the cathode has produced \( \sim 10^7 \) electrons at the final dynode. The amplitude of the signal at the final dynode is proportional to the number of photons incident on the cathode, and therefore also proportional to the amount of energy dissipated in the scintillator. A plot of the quantum efficiency of the Hamamatsu R5900U that was used can be seen in figure 2.2. The quantum efficiency is a measure of the probability that a photon hitting the photo-cathode will cause it to release photoelectrons.
Figure 2.2: Quantum efficiency for the R5900U photomultiplier tube.

The window of this PMT was only 1.8×1.8 cm so if it was to be attached directly to the scintillator it would have taken several PMTs to collect even a fraction of the photons from the four scintillators. Instead a bar of wavelength shifting (WLS) material with a cross-section of 1.5×1.5 cm was used to maximize the light gathering. A WLS absorbs light of one wavelength and re-emits it at another. It is re-emitted isotropically which means that light entering the WLS from one of the scintillators has a good chance of reaching the PMT if the re-emitted photons could be made to experience total internal reflection in the WLS until it reached the photo-cathode of the PMT. Figure 2.3 shows the emission and absorption spectra of the Bicron BC-482A WLS that was used. The light entering the PMT from the WLS was no longer

Figure 2.3: Emission and absorption efficiency as function of wavelength [nm] for the BC-482A wavelength shifter.

at the optimal wavelength for the PMT (figure 2.2). But the decrease in quantum efficiency for the new wavelength was just a few percent whereas the light-gathering efficiency became several orders of magnitude larger with the addition of a WLS.

The scintillators and WLS bar were covered in reflecting material to ensure that as many as possible of the photons created in the scintillators or in the WLS are collected by the PMT. The entire detector was then wrapped in light-stopping paper to make sure that photons not originating from the cosmic-ray interaction did not reach the PMT. The PMT was fed with high voltage (800 V) from an external source and read out by connecting it to suitable electronics.
The final detector could therefore be placed in a box or some other kind of protective housing, only the two cables needed to be readily accessible. Since the final detector stations will be placed on the roofs of different schools this all weather capability will be essential. The electronics will be contained in a central unit at each station and will include discriminators to shape the signals before they will be tested for the threefolded coincidence that marks an interesting event. There will also be a time-stamp generator as well as a Linux-on-a-chip that handles all computations.

When comparing different designs, two small detectors (13×13 cm) were used to select events originating from cosmic-rays by placing one of them above and one of them beneath the detector to be tested and demanding that there should be a coincidence. When this coincidence occurred a gate was opened so that the signal from the tested detector was accepted by the Multi Channel Analyzer (MCA) in a PC. This setup gave a count rate of almost one event per second. Figure 2.4 is a drawing of this setup. The data from the MCA was analyzed by using

![Schematic diagram](image)

**Figure 2.4:** Schematic of the coincidence principle used when testing the different detector designs.

PAW to fit it to an asymmetric Gaussian. The fitting algorithm returns the position of the centroid and the $\sigma$ to the left and to the right side of the centroid. Figure 2.5 is an example of one of the MCA spectra’s.

![MCA spectra](image)

**Figure 2.5:** In this picture of the MCA spectra the horizontal axis is the channel number and the vertical axis is the number of events. The detector tests resulted in MCA spectra like this one.
2.1 Design parameters

To optimize the design the influence of several parameters were tested with a single piece of scintillator attached to the WLS. The parameters that were altered was air gap between scintillator and WLS, the type of reflecting material and the coupling between WLS and PMT. The different setups could be compared by examining the position (channel number) of the peak in the resulting spectrum. Since the muons passing through the detectors can be considered as minimum ionizing particles, they all create more or less the same number of photons in the scintillator. The higher the channel number, the more photons has been collected by the PMT, and therefore the higher the efficiency of the setup. It was also desirable to have an as narrow peak (small σ) as possible possible since this indicated a small spread in the number of detected photons.

Since the light emitted in the WLS should preferentially be subject to total internal reflection, the bar of WLS should not be mounted directly onto the scintillator. For comparison, three different air gaps were tested, 0 mm, 0.3 mm and 0.6 mm. As can be seen in table 2.1, the optimal distance was found to be 0.3 mm. Two different reflecting materials were available, Mylar (an aluminium foil) and Tyvek (a reflecting paper). Tests were done with double layers of reflecting material. With Mylar the peak was at channel 406 while for the Tyvek the peak was at channel 527. Therefore Tyvek was chosen for all future designs.

When attaching the PMT to the WLS it was desirable to have a smooth as possible transition in the refracting index to avoid that photons were reflected at the interface. For the coupling between the WLS and the PMT there was a choice between three different techniques. They could either be joined directly without any interface medium, with optical grease, or they could be coupled by means of a 3 mm thick silicon cookie. Tests with the three different methods showed that the optical grease coupling gave the best signal, evident from table 2.2 and it was therefore used in the final detectors. But the silicon cookie put less demands on the coupling so it was used for all trial versions.

Table 2.1: Peak position for different air gaps.

<table>
<thead>
<tr>
<th>Air gap [mm]</th>
<th>0</th>
<th>0.3</th>
<th>0.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak [channel]</td>
<td>292</td>
<td>401</td>
<td>329</td>
</tr>
</tbody>
</table>

2.2 Design

There are several ways to mount the four scintillator pieces to the WLS, so the best design had to be found. The detector should be planar and with an as simple as possible geometry. As before, an as strong as possible signal was desired from the design, as well as an insensitivity to where on the detector the air shower particle hit. The position sensitivity was measured by comparing the peak position when the coincidence detectors were placed close to the PMT to measurements when the coincidence detectors were placed at the other end of the detector. Three different designs were tested:

- Design 1 with the four scintillators mounted with their short-ends toward the WLS, all on the same side of the WLS.

- Design 2 where the scintillators again had their short-ends toward the WLS, but this time two scintillators on each side of the WLS so that the detector was just half the length of the detector in design 1.
Design 3 had two scintillators on each side of the WLS with their long-sides against the WLS.

![Design 1 Diagram](image1)

Figure 2.6: Design 1.

![Design 2 Diagram](image2)

Figure 2.7: Design 2.

![Design 3 Diagram](image3)

Figure 2.8: Design 3.

Design 3 turned out to give not only the strongest signal but also the narrowest peak (table 2.3). The final step was to decide whether or not to cover each scintillator in a separate reflecting package or to cover the entire assembly in a common reflecting wrapping. Tests
Table 2.3: The position sensitivity of the designs was investigated by measuring the detectors' response to cosmic rays hitting both close to the PMT and far from it by positioning the coincidence detectors at different positions relative to the PMT.

<table>
<thead>
<tr>
<th>Design</th>
<th>Position of coincidence detectors</th>
<th>Peak [channel number]</th>
<th>Amplifier gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Close</td>
<td>771</td>
<td>500</td>
</tr>
<tr>
<td>1</td>
<td>Far</td>
<td>372</td>
<td>500</td>
</tr>
<tr>
<td>2</td>
<td>Close</td>
<td>946</td>
<td>500</td>
</tr>
<tr>
<td>2</td>
<td>Far</td>
<td>596</td>
<td>500</td>
</tr>
<tr>
<td>3</td>
<td>Close</td>
<td>399</td>
<td>200</td>
</tr>
<tr>
<td>3</td>
<td>Far</td>
<td>313</td>
<td>200</td>
</tr>
</tbody>
</table>

showed that although the signal was stronger when the assembly was covered in a common reflecting wrapping, separate wrappings for each detector meant that the peak was narrower and less dependent on where the cosmic ray hit the detector. The increased position insensitivity made the alternative with separate wrappings the most favourable.

Having decided on the design, four metal spacers, each 10×15×0.3 mm, were glued to each scintillator, which in turn were glued to the WLS. To make the detector easier to handle it was placed upon a wooden support. For practical reasons the PMT could not be permanently mounted on the WLS, but it must be firmly secured to the rest of the detector. It was decided to build a small wooden frame to which the base plate of the PMT was attached with four screws. This solution should make it possible to easily change the PMT and yet keep the construction rigid. The optical grease at the interface between the PMT and the WLS made sure that there was a good coupling between the two.

![Image of scintillators with metal spacers](image)

Figure 2.9: The four scintillators have been glued to the bar of wavelength shifting material with metal spacers ensuring that the distance between them is optimal. It is about to be wrapped in reflecting paper.
Chapter 3

GPS evaluation

Not even the best detectors would produce any usable results if their data could not be compared to data from other detectors in the array. The size of the array and the intention to easily attach new nodes to it means that each node must operate in an independent way. Time-stamps must be assigned to each event at the individual nodes. The easiest and most accurate way to achieve this over arbitrary distances is to use GPS-satellites. For a short introduction to the GPS system refer to appendix A.

Computer simulations showed that an accuracy of 10 ns for the time-stamps gives good enough time resolution to allow determination of important shower parameters. The Motorola M12+ Oncore GPS unit was chosen because of the high timing accuracy promised by the manufacturer. The output from the GPS-card is a 1 PPS (Pulse Per Second) signal with an accuracy of ±25 ns. The PPS can only be emitted on the rising edge of the GPS-cards internal 100 MHz oscillator, which introduce a built in uncertainty. The output from the GPS-card also contains a negative sawtooth correction. This correction is a prediction of how early, or late, the next PPS signal will be due to the limitations of the internal 100 MHz oscillator. With the aid of this correction the PPS should be accurate to within 5 ns according to the developer of the GPS-cards.

Before integrating the GPS-cards with the detectors, their performance had to be tested to make sure they fulfilled our requirements. Therefore a special test board was built where two GPS-cards could be tested against each other to make sure that a common trigger would give identical time-stamps from both GPS-cards. [6]

3.1 Time-stamp technique

When the trigger condition was fulfilled the event was given a time-stamp from both GPS-cards so that the time-stamps could later be compared. The time-stamps from both GPS-cards should preferably be identical. The 1 PPS from the GPS gave the basic time information. To pin-point the event within the second a 100 MHz oscillator was used. The number of oscillations from the time the trigger condition was met, until the next PPS was received, were counted. As each oscillation takes 10 ns, the time elapsed was easily calculated. This time was subtracted from the time of the PPS signal and then corrected with the sawtooth correction supplied by the GPS-card. The basic principle is illustrated in figure 3.1.

3.2 Test-board construction

A test board was designed and constructed which allowed the GPS-cards to be connected both to a PC and a programmable logic array. The PC was used to configure the GPS-cards while the logic array was used to implement the 100 MHz counters. Two D-sub 9 connectors allows the board to be interfaced to the serial ports of a PC. To convert the RS232 signals from the computer to TTL levels for the GPS-cards a transceiver was needed. A multiplexer
made it possible to choose which input should control the GPS, PC or Altera. Two 100 MHz oscillators, one for each GPS-card were also mounted. The board also had a connector for a common trigger. A custom made circuit board was produced and surface mounted components were chosen to enable higher speeds. A schematic drawing of the circuit-board can be seen in figure 3.2. After mounting the components, an oscilloscope was used to make sure that command signals really ended up where they were supposed to. The multiplexer was hard-wired to pass the commands from the PC on to the GPS-cards. The photo in figure 3.3 shows the test board attached. A list with part numbers can be found in appendix B.
3.3 Basic trials

To learn more about the features of the M12+ GPS-card the WinOncore control program was used to experiment with different settings. With the antennas positioned 1 meter apart with an all sky coverage on the roof, several position fixes were made with the auto-survey tool which gives the position as an average of 10000 position fixes. During the collection of position fixes the instantaneous position drifted, as can be seen in figure 3.4. The relative positions of

Figure 3.3: The final version of the GPS test board.

Figure 3.4: A plot of the drift during position determination for GPS-card 1 (left) and 2 (right). From east to west the plots covers a distance of approximately 3 meters, north to south the distance is almost 6 meters (the circles indicates the error in the calculation of the position).
the antennas were found to be stable. However the absolute position was found to drift. In the set of eight measurements the points the furthest apart were separated with more than five meters. The simultaneity of the PPS pulses from card one and two were investigated with the aid of an oscilloscope. As they were found to be synchronous to within 30 ns of each other, (an error that could, possibly, be handled by the sawtooth correction) the basic functioning of the set-up was considered as adequate.

3.4 Communication through LabVIEW

To combine the information from the GPS-cards and the Altera-board, LabVIEW was chosen. Its intuitive graphical interface made it straight-forward to produce a simple program that communicated basic commands through the RS232 and then read the answer from the GPS-cards. Finding the right format of the message to be sent, and especially to calculate the checksum, turned out to be trickier than first expected. To find the pattern of the messages the WinOnCore program was used to send a command. The output signal was then analyzed bit by bit on an oscilloscope. These binary messages was then translated into hexadecimal and used as an output command in the LabVIEW program. When the pattern of the first message was understood it was easy to create new commands in LabVIEW.

The messages that contained time information and the prediction of the next sawtooth correction were essential. The trial routines for extracting time and sawtooth information from the GPS-cards became the building blocks for subsequent programs.

LabVIEW also had to be able to communicate with the Altera-board. All communication between the Altera and LabVIEW took place through a National Instruments Data Acquisition pad (DAQ-pad). The DAQ-pad can manage up to 96 TTL input/output channels, which is three times more than needed for this application, and was connected to the PC through an USB-port.

3.5 Programming the Altera-board

Although the LabVIEW program read out the GPS-cards, it was too slow to be used to count the oscillations of 100 MHz crystals. This counting was instead done in the Altera, which had to be programmed for this task. The Quartus software was used to build a simple counter that began counting when the trigger signal was received and incremented the counter with one for every oscillation of the 100 MHz crystal until the next PPS from the GPS arrived.

Two identical chains were built in the Altera, where one accepted its PPS from GPS-card 1 and its 100 MHz oscillations from crystal 1 and the other took its inputs from GPS-card 2 and used crystal 2 as oscillator. Both were sharing the same trigger input. The output from the counters were two 27 bit numbers that were read out by the LabVIEW program before the counters were reset and the system was made ready for another trigger.

3.6 Combining it all

With the capability for LabVIEW to gather all information, a program to combine it in the right way was needed. The sequential processing of LabVIEW put some constraints on the design. It was decided to implement a loop that was executed once every second. In every iteration of this loop time data and sawtooth correction factor was extracted and put in an array holding the information from the last four seconds. There were three cases to handle: if there had not been a trigger, if there had been a trigger but the Altera was not yet finished counting or if there had been a trigger and the Altera was ready to be read out. If there had not been a trigger then a random number generator would decide whether or not to create one in this iteration, if a trigger was to be sent, a second random number generator was used to place this trigger randomly somewhere between the PPS’s. If there had been a trigger but the Altera was not yet ready then the loop should just continue and the data would be ready.
for read-out in the next iteration. When the Altera was ready, the counters were read-out, and the sawtooth corresponding to the PPS's that terminated the counts were picked from the array. This information, together with the hours, minutes and seconds that the GPS-clock showed, was written to a separate text-file in the computer.

Calculations and plotting were then done off-line with Matlab. The sawtooth corrections were to be added to the counts and then the two counter values were simply subtracted to give the time difference between the time stamps. The initial results from Matlab were disappointing. The crystals were found to be oscillating at different frequencies, somewhat lower than 100 MHz, and the frequencies were varying as much as several tens of oscillations over a period of just a few minutes.

3.7 Self-calibrating counters

To handle the issue of different frequencies in different crystals, and especially the problem with time-varying frequencies in a single oscillator, the original design was replaced with a self-calibrating system. To be self-calibrating, the system must not only count the number of oscillations from the arrival of the trigger to the next PPS, it must also count the number of oscillations between PPS’s. Instead of starting from zero every second, the counter was made as a 27 bits counter that continuously incremented by one at the arrival of the pulse from the 100 MHz crystal. At the arrival of a PPS the value in the counter was transferred to a parallel shift register. At the arrival of the next PPS the contents of this parallel shift register was transferred to another parallel shift register and the new value of the counter was shifted into the first parallel shift register so that the system always kept the two latest counts available. A third parallel shift register was used to extract the value of the counter when the trigger pulse arrived. Figure 3.5 shows a simplified illustration of this idea. Instead of reading out all three

![Figure 3.5: The three extracted values of a self-calibrating system are the counter values at the arrival of the PPS's framing the second and the counter value when the trigger condition is met.](attachment:figure-3.5.png)

parallel shift registers to LabVIEW, some arithmetic was done in the Altera so that only two 27 bits numbers needed to be read out for chain. The difference between the two PPS values is the calibration value and the difference between latest PPS value and the trigger value is the event time.

Problems could arise if there was an attempted parallel shift at same time as the counter incremented. To prevent this, the system was designed so that shifting could only take place on the falling edge of the 100 MHz pulse. Counting always occurred on the rising edge of the 100 MHz pulse. A slight extension was made to make it possible to see whether or not shifting could have taken place half an oscillation earlier. This information increased the accuracy in the Altera to ±5 ns. Unfortunately this also meant that there were lots of information that needed to be transported around the Altera at a very high demand on more or less instantaneous delivery. Since the custom made circuit board for the GPS-cards do not take advantage of the high-frequency clock inputs that exists on the Altera, this could be a source of error. When compiling and programming the Altera there was a warning message that both chain 1 and chain 2 contained a number of devices that might not communicate fast enough.
3.8 Measurements

All measurements were done with a satellite mask angle of ten degrees, which means that only satellites that were more than ten degrees above the horizon were used in the time calculations. At this point it was decided to also include information about which satellites was used by each GPS-card at every trigger in the output file from LabVIEW.

A first data collecting run compromising 75000 events was completed. The result from this run was the basis of the analysis of the system’s performance, commented in measurement 1.

To make sure that the differences measured really reflected the true difference between the time-stamps given by GPS-cards 1 and 2, a basic test was devised. After collecting data for almost two hours, the antenna cable to GPS-card 2 was disconnected and the resulting difference between the time-stamps investigated. The result is analyzed in measurement 2.

The delay caused by the Altera was investigated by a series of measurements where the same signal was used as input for both chains in the Altera. The first one of these measurements was done using the PPS from GPS-card 2. This setup is referred to as measurement 3.

Next, 100 MHz 1 and PPS 2 were used as input to both chains. With all input parameters being the same to both chains in the Altera the difference in the output should depend entirely on conditions in the Altera. With this set-up only a short measurement time was needed to get the results for measurement 4.

Finally both chains were again fed with the same 100 MHz oscillator but this time with separate PPS’s. The analysis of this data is done in measurement 5.

After returning the circuit-board to the original setup a run over the weekend was done with GPS-card 1 was programmed to only track satellites with odd id-numbers and GPS-card 2 only tracked satellites with even id-numbers. This made it possible to see the impact, if any, of different stations using different satellites. By dividing the satellites into two groups there were always at least one satellite visible to each card. In reality an array in the Stockholm area would have most satellites common to all stations with possibly a few stations seeing additional or fewer satellites. By making this exaggerated test, any inherent discrepancies in the method with GPS timing should be revealed. The results from this study is investigated in measurement 6.

Changing the GPS-cards so that card GPS-card 1 is in the slot previously occupied by GPS-card 2 and vice-versa was done to see that the systematic errors contributed to the GPS-cards really switched with the cards as they should. That this was the fact can be seen in measurement 7.

Finally an investigation of the importance of an accurate position fix was done. Keeping the antennas fixed at their previous location, the position used by the GPS-card 2 to calculate the time was moved almost 200 meter north by entering a false latitude in the WinOnCore program. The results from a first, short run, showed interesting structure so a data collection over several days was decided. The result of this investigation of the dependence on position fix is seen in measurement 8.

3.9 Data analysis in Matlab

All the data from LabVIEW was stored as a matrix with 37 columns and a row for each event. The information stored was the time (hours minutes seconds) of the event, the difference between the timestamps with and without sawtooth correction applied. The sawtooth correction for both the start and stop PPS’s of both GPS-cards as well as the number of oscillations during the second and number of oscillations from trigger to PPS for both GPS-cards was also saved. The ID of the satellites tracked by the twelve channels of each GPS-card was also stored. Large matrices are easily analyzed with Matlab, so this program was chosen to do the off-line analysis. The first data to look at for each run is of course the time difference between the timestamps from GPS-cards one and two. This data was presented in two histograms with bin sizes of 1 ns, one for the data with the sawtooth correction applied and one for the raw
data. How the difference evolved over time was plotted for both the corrected and the raw data. This time evolution was also plotted together with the number of tracked satellites to see if any dependence could be found. The final plot showed how the difference depended on when, between the PPS’s, the trigger arrived. Matlab’s own statistical functions were used to get information about mean value of the collected differences, both the sawtooth corrected data and the raw data, as well as to calculate the standard deviation for both corrected and raw values.

3.9.1 Measurement 1
The 75726 events collected in the first run gave a result that was as close as possible to what was expected to be seen from working detector stations triggering on a simultaneous signal. With a mean value for the sawtooth corrected data of -3.7 ns, and a standard deviation of 5.1 ns (for the uncorrected data the mean value is -3.8 ns with a standard deviation of 11.1 ns) the result is a clear Gaussian peak, as seen in figure 3.6. As the figure shows, the sawtooth

![Time differences in the corrected data](image1)

![Time differences in the raw data](image2)

![Time evolution of difference for corrected data](image3)

![Time evolution of difference for raw data](image4)

Figure 3.6: Measurement 1, 75726 events.
correction did not affect the mean value noticeably, but it did greatly reduce the spread of the values. This was in perfect agreement with a histogram of the sawtooth terms which showed that they are evenly distributed around zero (figure 3.7).

![Distribution of sawtooth terms](image1)

Figure 3.7: The distribution of the sawtooth terms for measurement 1.

### 3.9.2 Measurement 2

When the antenna to GPS-card 2 was unplugged, the result was evident immediately. The difference between the time-stamps increased with almost three microseconds for each event, as seen in figure 3.8. This immediate response reassured us that we were indeed measuring differences in the time given by GPS-cards 1 and 2.

![Time evolution of error for corrected data](image2)

Figure 3.8: The effect on the time difference when the antenna for GPS-card 2 was unplugged.
3.9.3 Measurement 3

With the same PPS used in both Altera chains the mean value of the collected 19317 events was 0.4 ns with a standard deviation of 3.0 ns (figure 3.9). The increase in accuracy (lower standard deviation) when the system is independent of the individual GPS’s indicates that the inexactness of the GPS’s time signals is a limiting factor in our setup.

![Figure 3.9: With only the PPS from one GPS-card being used there is no offset.](image)

3.9.4 Measurement 4

In measurement 4 all inputs were the same to both chains in the Altera. The non-zero time difference must be due to differences in the Altera. As can be seen in figure 3.10 there were a non-negligible number of events that has produced a positive time difference. Of the 951

![Figure 3.10: With identical inputs to the Altera, differences from zero must indicate routing differences in the Altera.](image)

events, 167 had a positive time difference while only 6 had a negative time difference. The clear dependence on number of counts from trigger to PPS for the magnitude of the time difference
Figure 3.11: The time difference as a function of when in the second the trigger arrived. A clear structure can be seen.

In figure 3.11 makes it obvious that it is not a completely random error. The points with a time difference between 0 ns and 5 ns on the inclined lines and the points on the ±5 ns lines can be explained if the flip-flop that controls the shifting of the registers in one of the chains in the Altera had a slower transition time than the corresponding flip-flop in the other chain. The three points with time difference larger than 5 ns are caused by one flip-flop in each chain not flipping in time. This pseudo-systematic error in the Altera was only of the order 0.5 ns and should not be a limiting factor in the final design, it may even disappear if the I/O pins of the Altera are used in an optimal way. This was not possible in the current set-up since the Altera was already mounted on a circuit-board into which the GPS test board connected.

3.9.5 Measurement 5

With separate PPS’s for the two chains, but with the same oscillator signal, the 22514 events gave a corrected mean value of -4.9 ns with a standard deviation of 5.0 ns and a raw mean value of -4.7 ns with a standard deviation of 11.1 ns. This is plotted in figure 3.12.

Figure 3.12: Using one 100 MHz crystal as input to both Altera chains did not alter the distribution significantly compared with measurement 1. This proved the effectiveness of the self calibrating system.
3.9.6 Measurement 6

It is worth noticing that the standard deviations of the values were in very good agreement with those from measurement 1. This showed that the self calibrating system was working as planned and was removing any spread due to differences in the crystals.

With a different set of satellites for each GPS-card the standard deviation around the mean value for the 57075 events was somewhat larger, 7.8 ns, as compared with the 5.1 ns when the system was optimized. Also the offset of -5.4 ns was almost 2 ns larger than in the optimized case. Figure 3.13 illustrates this case. That problems can occur when the number of satellites visible to one or the other GPS-card changes is evident from figure 3.14.

![Figure 3.13: The resulting time differences when the two GPS-cards used different satellites.](image)

![Figure 3.14: As the number of satellites tracked changed the difference between the time-stamps could suddenly increase drastically for a short time.](image)
It is inevitable that detector stations spread out over a larger area will, at least for some time each day, have different sets of satellites visible to them. The majority of the tracked satellites will however be the same to all detector stations so this measurement studies a worst case scenario. Even so, the result is positive.

3.9.7 Measurement 7

When the GPS-cards switched places with each other the offset also switched from negative to positive as can be seen in figure 3.15. The 18 126 events had a mean difference of 6.1 ns with a standard deviation of 5.1 ns, the same as in measurement 1. This is a confirmation that there is indeed a systematic error on the order of 5 ns between these two GPS-cards. Superimposed on this GPS error is the systematic error of the Altera that was investigated in measurement 5. While the systematic error in the Altera will have a very limited impact on the final design, the systematic error of the GPS-cards should be investigated further. To reduce the effect of the offset in the GPS-cards, every GPS-card should be calibrated before it is installed into a station so that all values from that station can be corrected according to the calibration.

![Graph showing time difference in nanoseconds vs number of events](image)

Figure 3.15: Switching the two GPS-cards also switched the offset in the time difference, indicating that it was due to a systematic error in the GPS-cards.

3.9.8 Measurement 8

With one antenna given a false position fix \(\sim 200\) meters to the north, the time evolution of the difference between time-stamp 1 and 2 varied over a large time-span, as can be seen in figure 3.16. Also the periodic structure that could earlier only be inferred in the plots of the time-difference as a function of time can easily be seen in this measurement. Not only did this show the importance of getting an accurate position fix, it also made it clear that a single, fixed, position will not be sufficient if the aim is to get as high precision as possible since the average value of the position fix varies with a period of 12 hours. For a somewhat smaller antenna displacement, about five meters, the standard deviation of the sawtooth corrected data is 5.7 ns and for the uncorrected data it is 11.5 ns. Compared to the optimized setup the five meter displacement gave an increase of 10% in the standard deviation. The position fixes that were used to give these false positions were done within a few hours of each other. When using the auto-survey tool to automatically find the position, an extra error of this order should be expected.
Figure 3.16: The effect on the timing resolution when one of the cards was given a false position 200 meters away from its true location.
Chapter 4

Conclusions

4.1 Scintillator detectors

Three detectors, enough for one station, have been constructed. It was found that the PMT signal was strongest when the four pieces of plastic scintillators were arranged with the long sides toward the WLS bar. This is also the design that was the least sensitive to the position of the hit from the incoming cosmic rays.

4.2 GPS performance

The result from measurement 1, with a standard deviation of 5.1 ns (or a FWHM of just over 10 ns), shows that the Motorola M12+ GPS-card can be used in the SEASA project. In the present setup it is the Altera part that offers the best possibilities for improvement. Assuming that the pin-configuration can be reworked to more efficiently handle the signals, additional flip-flops could be added to each counter chain. These new flip-flops would then (just as the flip-flops in our current design turned the 100 MHz counters into 200 MHz counters by flagging if the parallel shift registers could have been updated half an oscillation earlier) raise the counting rate by a factor of two for each new flip-flop. With two more flip-flops this would give a counter accuracy of 1.25 ns which is on the same order as the accuracy of the sawtooth correction term.

Such an improvement will not, however, have any effect on the offset that was seen in all measurements except those where the same PPS signal was used in both chains in the Altera. It is clear that the offset originates in the GPS-cards and may therefore vary with different GPS-cards. To eliminate the risk that a new GPS-card will have its offset in the opposite direction and thereby creating a too large discrepancy in its time-stamp, every GPS-card that is to be used should be tested against a reference GPS-card in a setup like the one used in this report.

The structure visible in the plots of the time evolution of the time-difference between the time-stamps from the two GPS-cards and the fact that the position given by the auto-survey function varies with up to at least 4 meters indicates that there is another possible improvement to be considered. Instead of just using one 10000 position average of the auto-survey tool to get a position fix one can compute an average of several such position fixes made during different times of the day. This way the error in the position caused by different satellites giving slightly different positions can be minimized. A more advanced solution would be to constantly update the position of the antenna by having two GPS-cards with a common antenna at every station. This way one of the cards would be used for timing while the other card would be put in a positioning mode. The positions could then be used to calculate the average over the last 100 seconds, for example, and this average would then be fed into the first GPS-card. By updating the position of the timing card every second the risk of one station using the wrong position and therefore sending incorrect data will be eliminated. It will also make the system more
mobile since it will no longer need several hours to get a good position fix. A design with two GPS-cards at each station can however not be considered as cost efficient for the SEASA array.
Appendix A

Basic principles of the GPS system

The Global Positioning System, or GPS, relies on information obtained from satellites and processed in the users’ hardware to accurately find the 4-D position of the receiver antenna. The 29 satellites orbit the earth in circular orbits at 20200 km altitude with a period of 12 hours in six equally spaced orbital planes, inclined 55 degrees to the equator, so that at any point on earth there should always be between 5 and 8 satellites visible, this is illustrated in figure A.1.

![GPS Satellites](image)

Figure A.1: The GPS satellites in their orbits

To calculate its position, the receiver calculates the range to several GPS-satellites with known positions by measuring the time it takes for the satellites signals to reach the receiver. Each such pseudo-range gives a sphere of possible positions around the satellite. The 3-D position is then given as the intersection of three such spheres.

The signal from each satellite includes very precise orbital information for the satellites and
a PRN (Pseudo Random Number) signal that is unique for each satellite. The PRN-signal varies in time in a predetermined way and is correlated to the atomic clocks on-board the GPS-satellites. By having an identical PRN-signal in the receiver and comparing the signal from the satellite with the one in the receiver the offset between the two gives the travel time for the signal. If the receiver and the satellites do not have the exact same time the intersection points from the three spheres will not give the correct position. To make sure that the PRN-signals in the receiver is synchronized to the signals in the satellites, the 3-D position is reconstructed from four pseudo-ranges instead of three. The four spheres will not have any common intersection points unless the receiver and the satellites have a common time. By altering the time in the receiver until the four pseudo-ranges gives a well-defined position you get both an accurate position and a very precise time for the receiver antenna.

The satellites are monitored from five ground stations that measures their orbital positions and on-board clocks with great accuracy, and uploads new ephemeris and time corrections when needed. This way the satellites data is constantly kept up to date.

The GPS system is developed and maintained by the US department of defense, so the military users has the highest priority. Until June 2000 there was a time varying disturbance in the timing information that was available to civilian users. Although this Selective Availability has been turned off there is still a higher level off precision in the GPS system that is withheld from the non-US military users.
Appendix B

Parts list for the GPS test board

Evaluation board with programmable logic array:
C.A.E.N. S9007 with an Altera APEX EP20K200EBC652-2

GPS-card:
Motorola M12+ Oncore

GPS-antenna:
Oncore Timing 2000 Antenna

Multiplexer:
74LVX257 SO(16)

Transceiver:
MAX3243 SO(28)

100 MHz oscillator:
100 MHz CFPS-73B
Appendix C

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