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Appendix B

SEASA: The Stockholm Educational Air Shower Array

Introduction

Cosmic rays offer outstanding educational value – nature has provided us with a free source of high energy subatomic particles! Already at SCFAB there is a student laboratory exercise in which cosmic ray muons are brought to rest and their lifetime measured*. This laboratory demonstrates how a fundamental property of a seemingly abstract subatomic particle can be measured as well as exposing students to particle detection techniques, modern electronics and data analysis.

This proposal details a project which has several educational possibilities:

- A laboratory exercise for undergraduate students.
- An Outreach activity for local schools.
- Research opportunities for diploma students / postgraduate students.

The basic idea is to create an array of distributed cosmic ray detectors in order to study showers of particles produced when high energy primary cosmic rays interact at the top of the earth's atmosphere. The size of the shower footprint at the earth's surface depends on the energy of the primary cosmic ray. At first the array would be of modest size and it is proposed to place a few scintillator detectors on the roof of the main SCFAB building and then on top of some of the satellite buildings. Signals from the Global Positioning Satellite (GPS) network will be used to allow time coincidences to be identified between the detector units. As the most physically interesting ultra-high energy cosmic rays will have very large footprints (in excess of 10 km²) it is beneficial to have as large a detecting area as possible. A second phase is therefore proposed whereby schools in the Stockholm region (and further afield) will be invited to host a detector system. This follows closely existing schemes operational in the USA, Canada[†] and Europe. As well as hosting the detecting apparatus, it is easy to envisage an exciting schools Outreach program where students participate in the construction, testing, maintenance and operation of the detectors as well as the data analysis.

* <http://www.particle.kth.se/~pearce/muonlab>

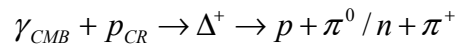
[†] For example, see: <http://csr.phys.ualberta.ca/nalta/> and links therewithin.

Cosmic Rays

Cosmic rays are particles originating from space which bombard the Earth's atmosphere. They are probably the only samples of extragalactic matter which we can detect directly. The energy spectrum of cosmic rays extends from less than 10^6 eV to greater than 10^{19} eV. Between 10^6 eV and about 3×10^{15} eV the spectrum can be represented by the power law $dN/dE \sim E^{-2.65}$ and from 10^{16} eV to 10^{19} eV, the spectrum steepens to $dN/dE \sim E^{-3.1}$, as shown in figure 1. Around 10^{15} eV, there is a so-called knee in the spectrum. It is generally thought that particles produced above the knee are confined to our galaxy whereas those below the knee are too energetic to be trapped by our galactic magnetic field. At the knee it is therefore likely that at least some of the acceleration mechanisms within our galaxy have reached their maximum energy. The energy spectrum appears to flatten from 10^{19} eV up to the highest energy cosmic ray measured at $\sim 3 \times 10^{20}$ eV – this region is often referred to as the ankle.

At energies below 10^{14} eV, where the flux is high, the spectrum has been measured directly by balloon- and satellite-borne experiments. These experiments generally have a collecting area of less than 1 m^2 . Above this energy, the flux is generally too small to make direct measurements realistic. Ground-based experiments are therefore used, where the energy of the primary cosmic ray must be inferred from its interaction with the Earth's atmosphere.

Data indicates that the high energy primary cosmic rays are protons. These protons must move through a bath of cosmic microwave background (CMB) photons on their way to the earth. Above a threshold energy, the following photoproduction interaction is allowed:



Above the energy threshold for this interaction, the number of protons should dramatically decrease. This energy is referred to as the Greisen-Zapsepkin-Kuzmin (GZK) cut-off and corresponds to a proton energy of $\sim 4 \times 10^{19}$ eV. Protons above this energy will interact with the CMB photons and have their energy degraded. Figure 2 shows the mean energy of the proton as a function of the distance travelled from the source for initial proton energies of $10^{20}, 10^{21}$ and 10^{22} eV. Once the proton has traversed ~ 100 Mpc through the CMB bath the resulting proton energy is essentially independent of the initial energy. So, if a proton is observed with an energy greater than 10^{20} eV the source must lie within ~ 100 Mpc of the earth[‡]. This distance is large compared to the size of our galactic halo (~ 100 kpc) but comparable to the size of the local galactic cluster (~ 100 Mpc). There is no known acceleration mechanism which can accelerate cosmic rays to such high energies. The most powerful acceleration mechanism known is accredited to supernovae shock waves but this cannot exceed $\sim 10^{19}$ eV – the first enigma.

Cosmic rays with energies above the GZK cut-off will not be significantly deflected by galactic magnetic fields ($O(\mu\text{G})$) and so their arrival direction can be used to identify the location of the source. The direction of these cosmic rays are not aligned with nearby potential acceleration sites, such as M87 (a giant elliptical galaxy, 60 million light years away) and Centaurus A (the nearest active galaxy, 11 million light years away) – another enigma.

It appears that either these cosmic rays somehow evade the GZK cut-off (this would require that special relativity does not apply at high energies) or their source is not a normal astronomical object. To fill this role, unstable topological defects in the universe's fabric have been proposed but often the expected cosmic ray flux is too low though. A particular class of topological defects called Cosmic Necklaces may be an exception though.

[‡] If the primary cosmic rays are nuclei, similar conclusions can be reached since the nuclei start to disintegrate after collisions with CMB photons at energies similar to the GZK cut-off.

These arguments do not hold if the primary cosmic ray is a photon, however this primary particle hypothesis is not well supported by the characteristics of the particle showers produced when the cosmic rays slam into the atmosphere. Another possibility is neutrinos. This is unlikely for massless neutrinos as the interaction path length in the atmosphere is too small considering that all of the ultra-high energy candidates have been observed at angles less than 40° from zenith. If neutrinos have a mass around 0.1 eV then electroweak interactions with the relic neutrino background – so-called Z-bursts – are a possible source of high energy hadrons. Other possibilities are that the cosmic rays originate from the decay of particles left over from the Big Bang (known as ‘cryptons’ and ‘vortons’) and predicted by exotic Grand Unified Theories.

A further problem is that current experiments either sample the air shower on the ground using scintillators and / or water Cerenkov detectors (for example, AGASA)[§] or look for fluorescence produced by the excitation of nitrogen in the earth’s atmosphere (for example, HiRes^{**}). The two types of experiment do not agree on the flux of cosmic rays observed above the GZK cut-off – with the bulk originating from AGASA^{††}. The different detection techniques as shown schematically in figure 3.

The number of models certainly exceeds the number of data points. Several large experiments are planned to address this. Some plan to observe the fluorescence in the atmosphere from space using free flying satellites (OWL^{‡‡}) or from the International Space Station (EUSO^{§§}). The first of the next generation of air shower experiments to be ready will be ground-based - The Pierre Auger Observatory^{***}. A 3000 km² array of 1600 water Cerenkov detectors with a 1.5 km pitch are interspersed with 30 air fluorescence detectors to allow systematic studies of air showers. Installation is due to be complete by the end of 2004.

Air Showers

A primary cosmic ray interacting with an nucleus at the top of the atmosphere (on average about 20 km above the Earth’s surface) will produce a cascade mostly charged and neutral pions. These particles will subsequently decay or interact with other nuclei. The number of particles in the shower is therefore multiplied. After reaching a maximum, the number of photons, electrons, muons and hadrons starts to fall as more and more particles fall below the threshold for further particle production. A disk of relativistic particles hits the earth’s surface and has a diameter of some 10’s of metres (ie: building sized) for a primary energy of 10^{14} eV and several kilometres (ie: village sized) for primary energies of 10^{20} eV. By measuring a small number of these particles on the ground, the properties of the primary particle (e.g. energy and mass) can be reconstructed. The air shower has three components: electromagnetic, muonic and hadronic. For a 10^{15} eV shower, approximately one million particles reach the ground comprising approximately 80% photons, 18% electrons, 1.7% muons and 0.3% hadrons. Neutrinos are not counted, although they are copiously produced in weak decays. Relativistic charged particles will produce Cerenkov light as they propagate through the atmosphere. Finally, excitations of nitrogen molecules in the atmosphere will generate fluorescence light. Contemporary experiments generally use the fluorescence and / or detect ground particles.

By measuring the multiplicity of muons and electrons at each detector site, the energy and mass of the primary cosmic ray (ie: proton or iron nucleus) can be determined on a statistical basis. However, this is not a straight-forward process since the air shower observables tend

§ <http://www-akeno.icrr.u-tokyo.ac.jp/AGASA/>

** <http://www.cosmic-ray.org/>

†† For a (hopefully clear) summary, try: http://www.particle.kth.se/~pearce/jclub/mark_030902.ppt

‡‡ <http://owl.gsfc.nasa.gov/>

§§ <http://euso-mission.org/>

*** <http://www.auger.org/>

to suffer large fluctuations and are sensitive to both the mass and energy of the primary. A detailed simulation of the detector array is needed. A number of Monte Carlo codes exist to simulate the properties of air showers for experimental design. The 'Aires' package^{†††} (as used by Auger) has been investigated and is well suited. Software has been installed and initial simulation work has started. It is hoped to be able to attract an 'exjobb' student to this work in the near future.

Experimental Concept

The detection of air fluorescence is costly and not well suited to bright inner-city locations. However, the particles reaching the ground from an air shower can easily be detected.

The simplest and cheapest way to detect particles reaching the Earth's surface from a cosmic ray shower is to use plastic scintillators read out by photomultiplier tubes (PMT). A single detector unit could consist of three scintillator units arranged in a triangular configuration, as shown in figure 4. In order to reduce the false trigger rate due to noise and uninteresting single particle events, the three scintillators are operated in a triple coincidence mode, ie: each of the units must indicate the passage of a particle within a certain time window to qualify the event for storage. Although not yet studied in detail, it is expected that the scintillators will be separated by ~ 10 m. One of the scintillator units acts as a 'master' and contains all the electronics and power supplies within its housing. The simplest way to distinguish between muons and electrons will be to place lead above some of the scintillators, thus absorbing the electrons but letting the muons through. This feature is not shown in the figure and the implementation is being optimised with simulation studies.

A fundamental design concept is to reduce costs as much as possible by using commercial 'off-the-shelf' electronics as opposed to specialist (e.g. VME) electronics designed for particle physics experiments.

Scintillator Detectors

To save money during the initial stages of this project, plastic scintillator recovered from the CPLEAR experiment at CERN can be used. There are 15 pieces of scintillator which are 1.5 cm thick \times 13 cm wide \times 140 cm long available. Each piece can be cut into three pieces and reassembled into a rectangle of dimensions ~ 47 cm \times 52 cm. Again to save money, the scintillators will be read-out by compact Hamamatsu R5900 PMTs left over from development work for the PAMELA satellite experiment.

A bar of wavelength shifter is wrapped around the scintillator edges, as shown in figure 5. This allows light to be directed towards the PMT. All exposed surfaces are covered in reflective and then light-proof material. Although more expensive than a simple light-guide, the superior light collection efficiency and uniformity simplifies the front-end electronics.

In-situ calibration with flashing LEDs could also be foreseen.

Front-end Electronics

The signals from the PMTs have a small amplitude (10's mV) and are very fast (10's ns). The front-end electronics has two purposes. Firstly, the signal from the PMT must be discriminated to remove the effects of noise and converted into a signal compatible with digital electronics, so that the threefold coincidence can be formed. The part of the design will strongly follow electronics already built and tested for the anticoincidence system of the PAMELA satellite experiment, as shown in figure 6. The second task is to determine the charge measured by the PMT. This allows the number of particles passing through the scintillator to be estimated, once the charge deposited by a single particle is known from

^{†††} <http://www.fisica.unlp.edu.ar/auger/aires/>

laboratory calibrations. Different methods are under study but as a baseline it is proposed to adopt the charge-to-time (QTC) technique used for the PAMELA Time-of-flight system. A capacitor is charged with a constant current for a time depending on how long the integrated PMT signal is above a threshold voltage. The capacitor is then discharged and a digital pulse produced which also has a length proportional to the area under the PMT signal (ie: the collected charge). The length of the digital pulse can be sampled using a suitably fast clock, as shown in figure 7. Both parts of the electronics makes use of commercial off-the-shelf electronics.

Timing using GPS Satellites

Signals from the GPS navigation satellite network will be used to provide a precise timestamp for each threefold coincidence recorded by a given detecting unit. By comparing timestamps between detector units offline, temporal coincidences between widely separated detectors can be looked for and showers identified.

Once the detector array is large enough (~1 km spacing between detector sites), the direction of the incoming shower wavefront can be estimated by comparing the arrival time of signals for different detectors in the array. In figure 8, a shower front inclined at 45° to the zenith impinges on two detector stations separated by 1 km. The time difference of the signal between the two detectors is $2.36\mu\text{s}$. The error in angular determination is shown as a function of zenith angle and the GPS timing error. For a timing error less than 65ns, the angular error is less than 2° .

The GPS constellation consists of 17 satellites (there are also 3 spares) which house highly accurate and stable atomic clocks. The satellites orbits and clocks are monitor from earth and corrections applied to keep all the clocks well synchronised. On the ground, a user must lock onto at least 4 satellites to determine the latitude, longitude and height. If the position is already known only one satellite is required to determine the time precisely. This works because the satellite regularly broadcasts its orbital position, so the receiver can easily calculate the distance to the satellite at a given time. The propagation delay due to the finite speed of light can then be calculated and the receiver clock synchronised to that onboard the satellite. The receiver position can, of course, be determined using the same GPS receiver. In order to determine the position with sufficiency accuracy, the average of many readings can be taken during an initialisation phase.

The GPS timing system can be easily implemented using a receiver boards such as the Oncore range manufactured by Motorola. These boards can be controlled and read out using a standard RS232 link. Precise timing data cannot be registered in this way since there is a 50 ms variance for data sent through the serial port. Instead a dedicated Pulse Per Second (PPS) output which is synchronised to GPS time is provided. An external 100 MHz crystal oscillator is used to start a counter when a cosmic ray trigger is asserted, as shown in figure 9. The PPS signal stops the counter and the recorded time can be added as an offset to the GPS time, which is requested via the serial link when the trigger is received. The accuracy of this system for tagging coincidental events is readily testable using two scintillators viewing the back-to-back gamma rays from a ^{60}Co source or two overlapping scintillators placed in coincidence to measure cosmic ray muons.

Data Acquisition

The data acquisition system should be cheap, reliable and scaleable – so that additional sites can be added easily. The approach suggested is shown in figure 10. Off-the-shelf commercial components are used through-out.

The discriminated and QTC pulses are fed into a programmable logic chip ('FPGA') which is used to identify coincidences, measure the length of the QTC pulse and record counting

rates. The PPS output from the GPS board is also fed to the FPGA, so that a precise timestamp can be generated using the approach outlined in figure 9.

A 'PIC' chip with onboard analog to digital converters takes care of 'slow controls' – external and internal temperatures are logged along with humidity and any other environmental parameters needed. The internal temperature is used to decide whether or not a heater needs to be activated⁺⁺⁺.

The FPGA and PIC boards are connected via data buses to the 'Linux on a chip' (LOC) board. This is a small circuit board with a custom CPU running Linux. An RS232 port allows the GPS board to be read out. Interfacing to the FPGA and PIC is not yet finalised. The LOC board has a built in Ethernet adapter, allowing communication with the outside world.

For each trigger, the charge from each PMT, the GPS timestamp, the PPS counter offset, and environmental measurements will be stored as an event. Events are made available over Ethernet from the http server running on the LOC board. This approach makes a scaleable system very straight-forward to implement.

Power Supplies

Each detector unit will be fed by a single 240 V supply. The low voltage power supplies for the electronics can be provided by cheap commercial battery eliminators. The high voltage supply for the PMTs (~1000 V) can be obtained from miniature DC/DC converters.

Environmental Considerations

The detector units must be weatherproof as they will be placed outdoors!

Project Plan

The first phase of SEASA is to installed a set of three cosmic ray detectors in the grounds of SCFAB. There will be two sets of detectors on opposite ends of the roof of the main building. Another set of detectors will be placed on top of one of the outlying building – 'Vetenskapshuset' is an excellent candidate. See figure 11 for an overview. This set-up will be use as a 'proof-of-principle' before expanding the array into local schools. The proof-of-principle array can also be used as a laboratory exercise by KTH students. The steps needed to build-up the proof-of-principle system are as follows and the financing needed to reach this stage is presented in the next section.

The electronics proof-of-principle system,

The steps needed to :

- Build and test a single detector. Then produce a set of three. Initially, only muons will be detected by placing a layer of lead above each scintillator. When simulations are complete, the detector arrays will be optimised for the detection of both muons and electrons. This may require more scintillators at each detector site.
- Build prototype electronics set-up. Commercial evaluation boards will be used for the GPS, FPGA and LOC functions. A dedicated circuit board will be needed for the front-end electronics.
- Operate a single set of three detectors and understand trigger rate, multiplicity measurements etc. Debug electronics. Time coincidence can be debugged using back-to-back emissions from ⁶⁰Co in the laboratory.
- Freeze electronics design and produce custom-made PCBs.
- Produce an additional two sets of detectors and three new sets of supporting electronics. Debug time coincidence functionality across all systems.

⁺⁺⁺ Maybe some form of cooling will also be required during the summer?!

- Pilot run for the proof-of-principle array in the grounds of SCFAB.
- Debug distributed system, including central server software.
- System available for KTH student laboratory.
- Apply for additional funding. Additional nodes can then be added as required – hopefully at schools. Debug shower angle reconstruction etc.

Cost Estimates

Detectors

| Item | Supplier | Cost (SEK) |
|------------------------|---|--|
| Scintillator sheet | Recovered from CPLEAR | 0. |
| Scintillator cutting | SCFAB Workshop | 2 hours ⇒ 500. |
| Scintillator polishing | Volunteers! | 0. |
| Wrapping material | Spares from PAMELA | 0. |
| Wavelength shifter | Bicron BC-482A. (2 pieces, 15mm x 15mm x 60cm, required for each detector, so 18 in total). | 40 000. |
| Plastic optical glue | Bicron BC-600 (250 g) | 2500. |
| PMT | Spares from PAMELA (9 needed) | 0. NB: 32 x R5900U PMTs for PAMELA cost approximately 290 kSEK. Cheaper PMTs may be selected for further units. |
| HV divider | PAMELA design (9 needed). | 0. (1000. for components) |
| Cables + connectors | Spares from PAMELA and CPLEAR etc. | 0. |
| HV supply | Farnell (3 needed) | 3 x 500 = 1500. |
| Housing (9 needed) | SCFAB Workshop (parts and labour) | 5000. |
| Total | | 50 500 |

Electronics for First ‘Proof-of-Principle’ System

The design of the read-out and data acquisition electronics will first be developed by connecting together commercial evaluation boards. This reduces development costs when the design may need to be changed often. For mass production, it will be cheaper to house the front-end electronics, FPGA and LOC chip on a single board. Since the GPS receiver contains non-trivial high-speed electronics, this will be purchased as a module and plugged into the main circuit board.

| Item | Supplier | Cost (SEK) |
|--|--|--|
| Analog front-end | Schematics: MP PCB design: in-house Production and mounting: CTM Components: Farnell, RS etc. | Similar board made for PAMELA cost 3000 SEK to produce and mount. Assumes design done in-house for free. |
| FPGA board + software | ALTERA University Program | 0. |
| LOC board + software | AXIS (ETRAX 100LX). | 0. (supplied by Fysikum) |
| GPS receiver board + antenna | Motorola | 2000. |
| Low voltage power supplies (12V and 5V from 240 V input) | ELFA (3 sets needed) | 500. |
| Miscellaneous components, connectors and cables | ELFA | 1000. |
| Total | | 6500 |

Production Electronics

Once the design of the electronics is tested and finalised, a single PCB design can be made.

| Item | Supplier | Cost (SEK) |
|------|----------|------------|
|------|----------|------------|

| | | |
|---|-----------------------------|---|
| Circuit board production and mounting. Layout done for free in-house. | CTM (> 3 needed) | 5000. |
| Analogue front-end | In-house design (3 needed) | 3 x 1000 = 3000. |
| FPGA | Altera. (3 needed) | 3 x 500 = 1500. |
| GPS receiver module + antenna | Motorola (2 needed) | 2 x 2000 = 4000. |
| Etrax 100LX 'LOC' multichip module and supporting components | Axis (3 needed) | 1000 x 3 = 3000. |
| PIC-based temperature (etc.) monitoring | Not yet decided | Low! 1000 to equip all boards is estimated. |
| Low voltage power supplies (12V and 5V from 240 V input) | ELFA (2 needed) | 2 x 500 = 1000. |
| Miscellaneous components, connectors and cables | Various. ELFA, Farnell etc. | 2000. |
| Total | | 20 500 |

Total cost is therefore: 50 500 SEK + 6500 SEK + 20 500 SEK = 77 500 SEK

Cost Sharing with Vetenskapshuset

The possibility of sharing some of these costs with Vetenskapshuset should be explored. Initial contact has been made with Christer Nilsson with the aim of involving Gynasium students in the construction and testing of the scintillator detectors.

Time Schedule

It is hoped that the proof-of-principle system can be constructed within 6 months to one year from now depending on the manpower and level of funding secured.

Other Infrastructure Required

As the project progresses, it will be necessary to purchase or borrow a modern PC with sufficient disk space to act as the hub of a distributed array and allow data analysis. This is not included in the price estimated as it is hoped that an old PC can be 'recycled' from a research group.

Possible Student Activities

The following list details ideas for student projects and laboratory exercises.

Student projects:

- Building detectors: polishing scintillator, attaching wavelength shifter, wrapping, attaching PMTs.
- Assembling PMTs: building HV dividers and testing.
- Testing complete detectors with cosmic rays and radioactive sources ^{137}Cs etc. Setting discriminator levels and HV.
- Investigating detector calibration using the LED technique.
- Development of physics simulation using the Aires framework (excellent exjobb!).
- Firmware for electronics. Graphical FPGA programming, firmware for http server. PIC programming for environmental monitoring.
- Control electronics and algorithms for temperature control.
- Software for event display and analysis.
- Server software for a distributed array.
- GPS timing resolution studies with ^{60}Co etc.
- The planned distributed nature of the system will, in principle, allow quantities other than

cosmic ray fluxes to be measured. Any sensor with an electrical output can be included! For example, a distributed system for monitoring environmental quantities (e.g.: air quality or radon levels) could be established.

Laboratory exercises:

- Investigation of the coincidence rate with detector spacing and clustering.
- Time profile of triggers.
- Trigger rates as a function of environmental variables, such as: temperature, humidity, rainfall, etc.
- Studying the energy information from detectors.
- Identifying variables which can be used to determine the primary cosmic ray energy and composition.
- Direction of showers (requires an additional detector station, as least 1 km from SCFAB).

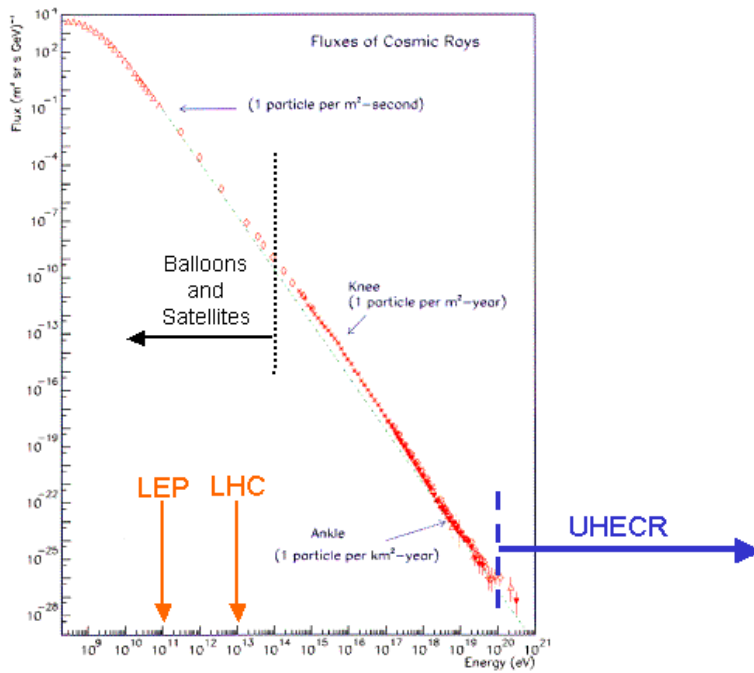


Figure 1: The cosmic ray energy spectrum.

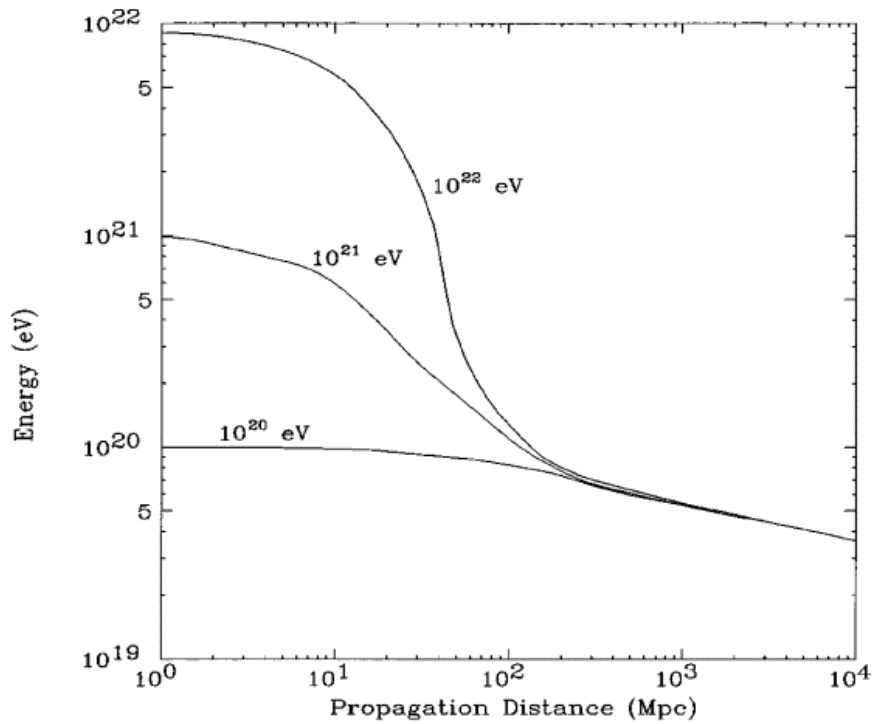


Figure 2: The propagation distance for protons of several energies above 10^{20} eV. The effect of the GZK cut off is clearly seen. Showers with reconstructed energies exceeding approximately 10^{20} eV must originate from acceleration sites close to the Earth – however, no such sites exist!

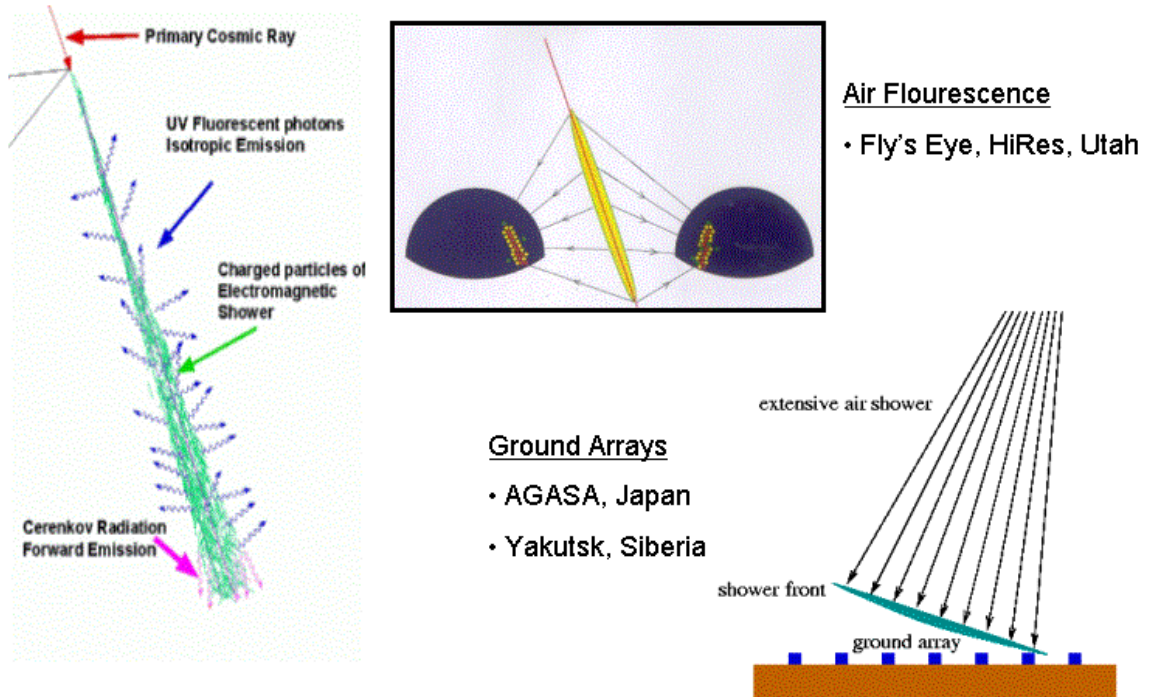


Figure 3: Detecting cosmic ray air showers.

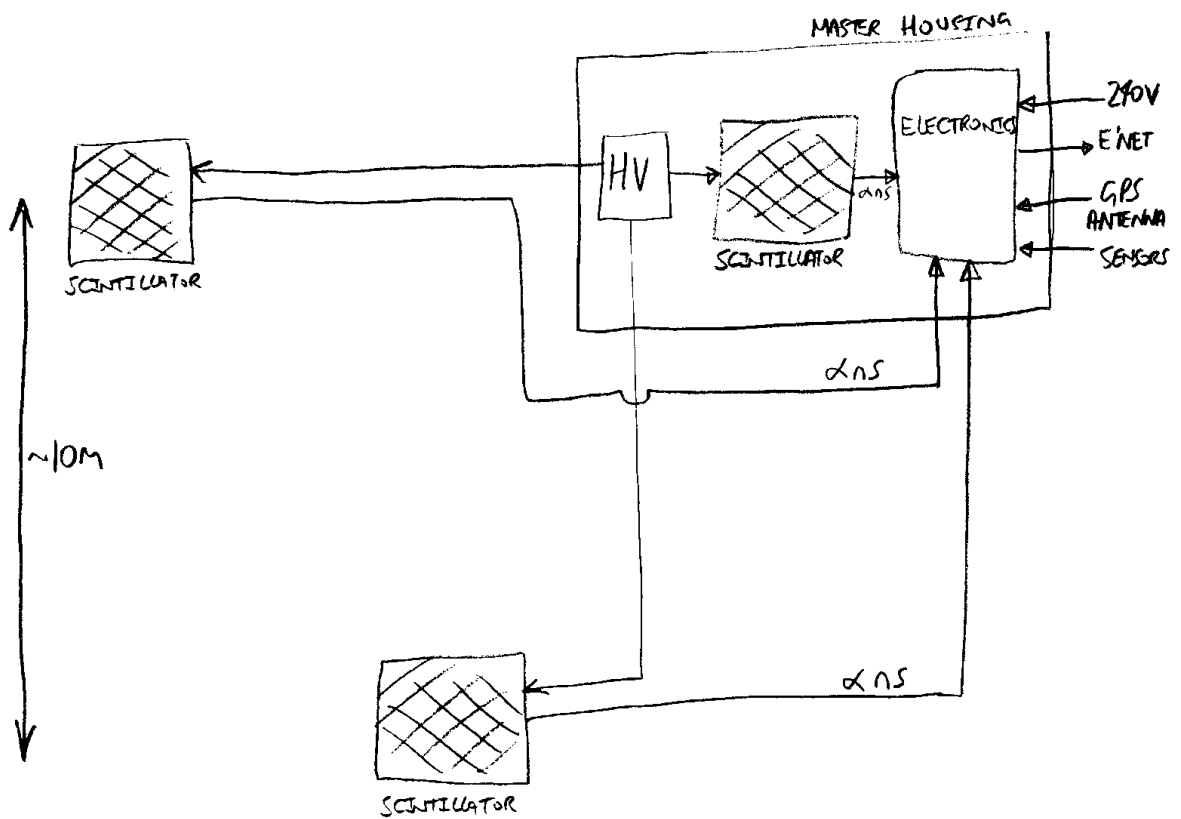


Figure 4: Proposed detector set-up.

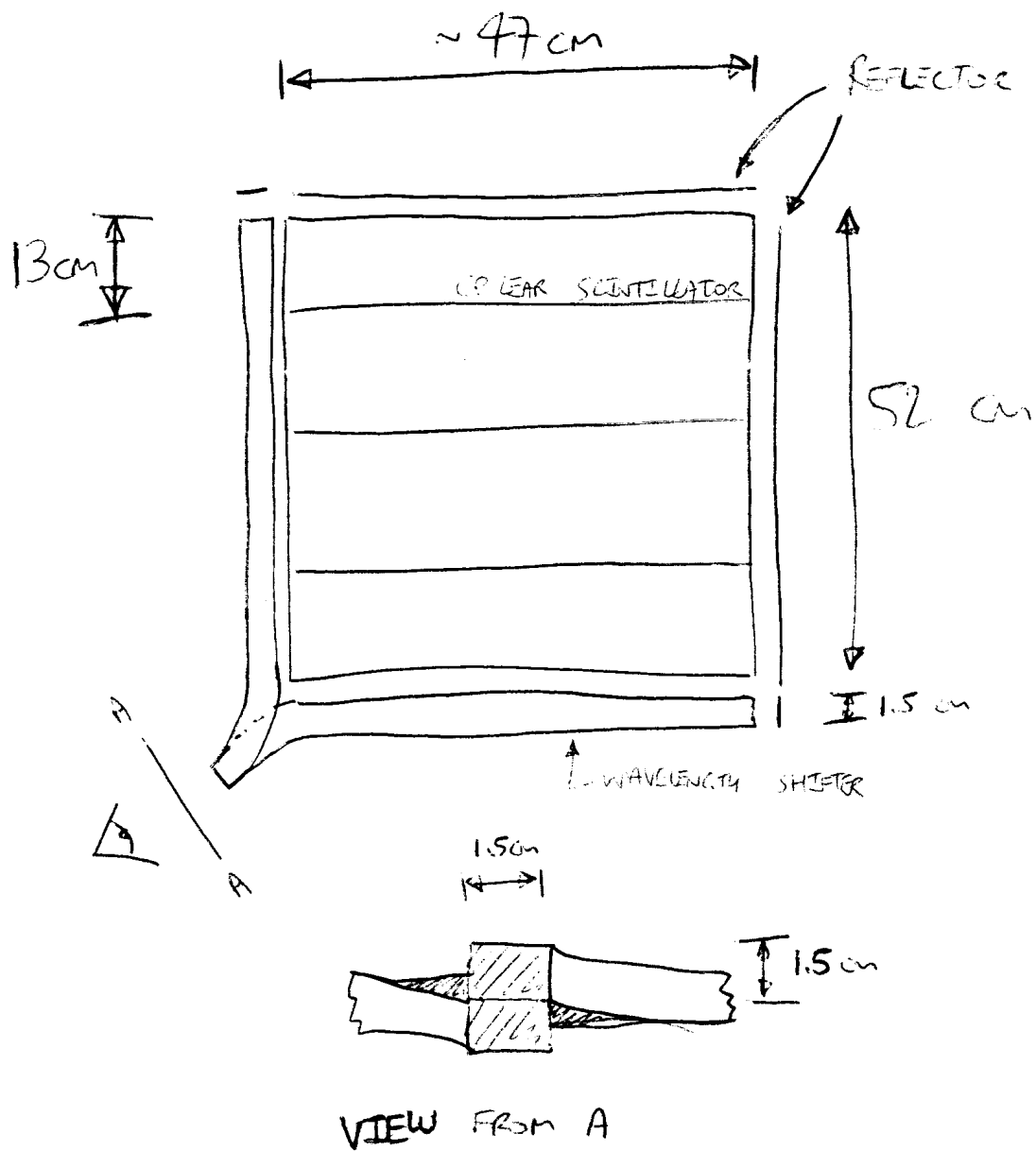


Figure 5: Proposed scintillator detector design

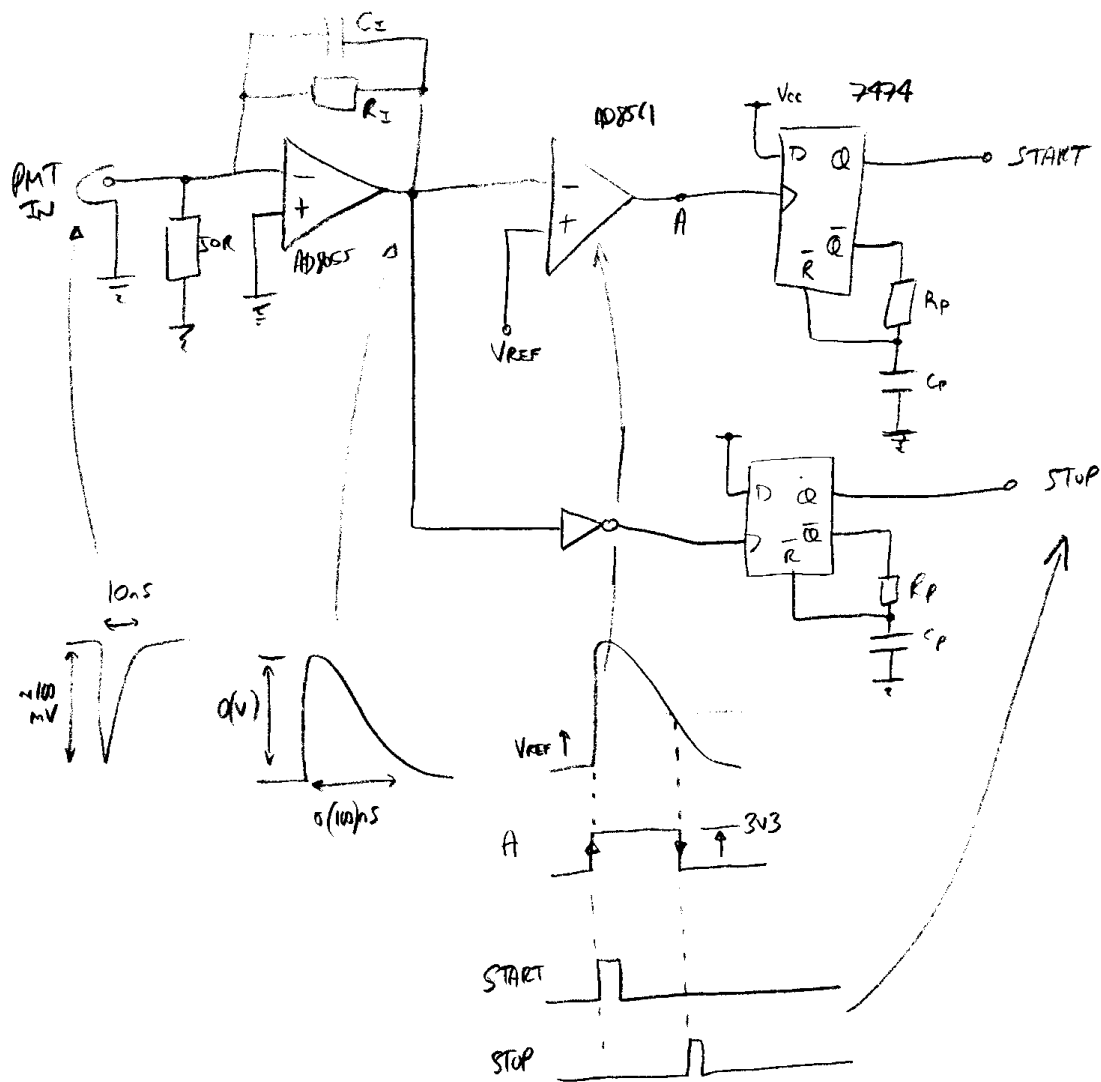


Figure 6: Front-end electronics scheme.

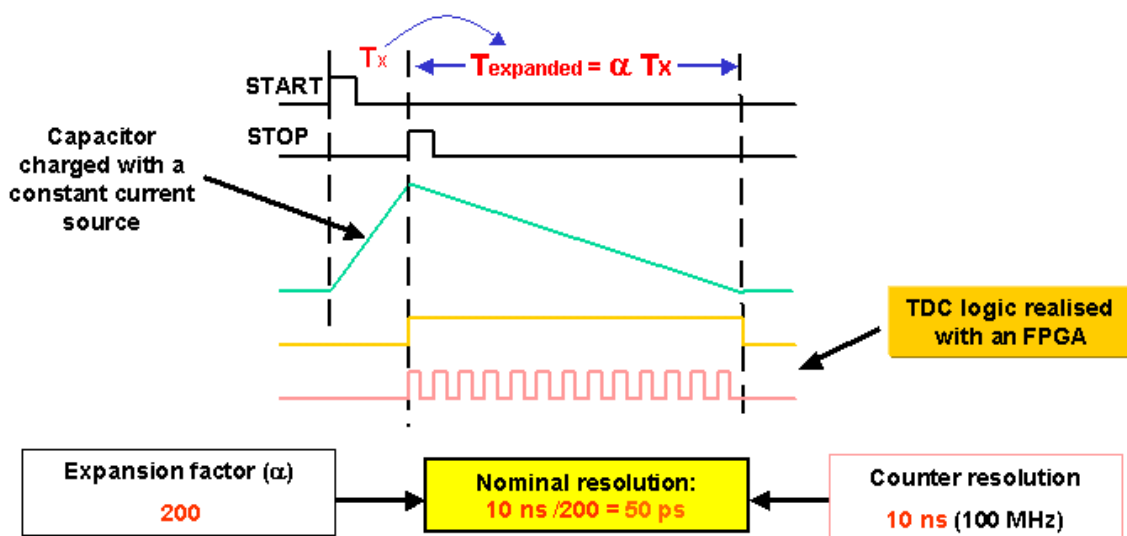
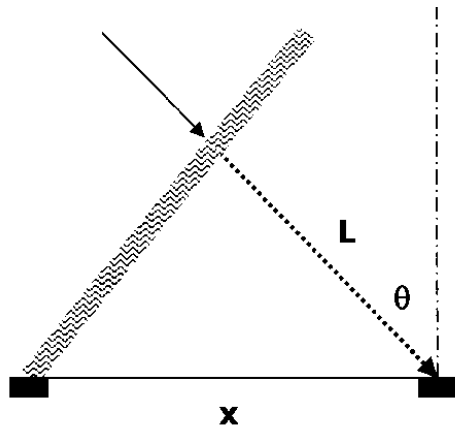


Figure 7: Scheme for energy (multiplicity) measurement using charge to time conversion.



Zenith angle $\theta=45.00$ deg
 $X=1000\text{m}$,
 $L=707\text{m}$
 $\Delta t=L/c=2.36 \mu\text{sec}$
With timing error:
 $\Delta t+65 \text{ nsec}=2.42 \mu\text{sec}$

- **apparent $L = 727 \text{ m}$**
- **apparent $\theta = 43.4 \text{ deg}$**
- **$\Delta\theta = 1.6 \text{ deg}$**

angular error vs zenith angle for $\delta t=65 \text{ nsec}$

Angular error vs timing error, zenith angle = 45 deg

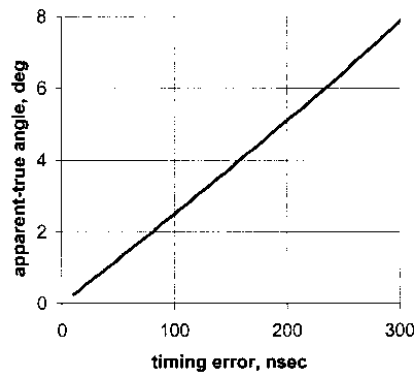
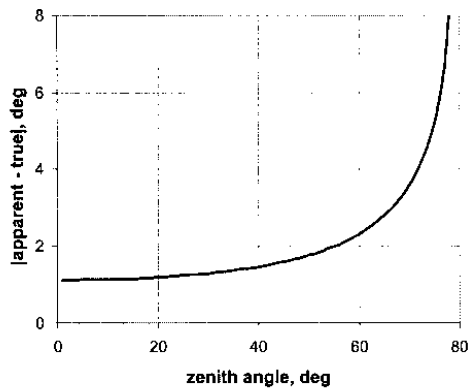


Figure 8: The dependence of the angular resolution for a shower front on the shower angle and GPS timing error..

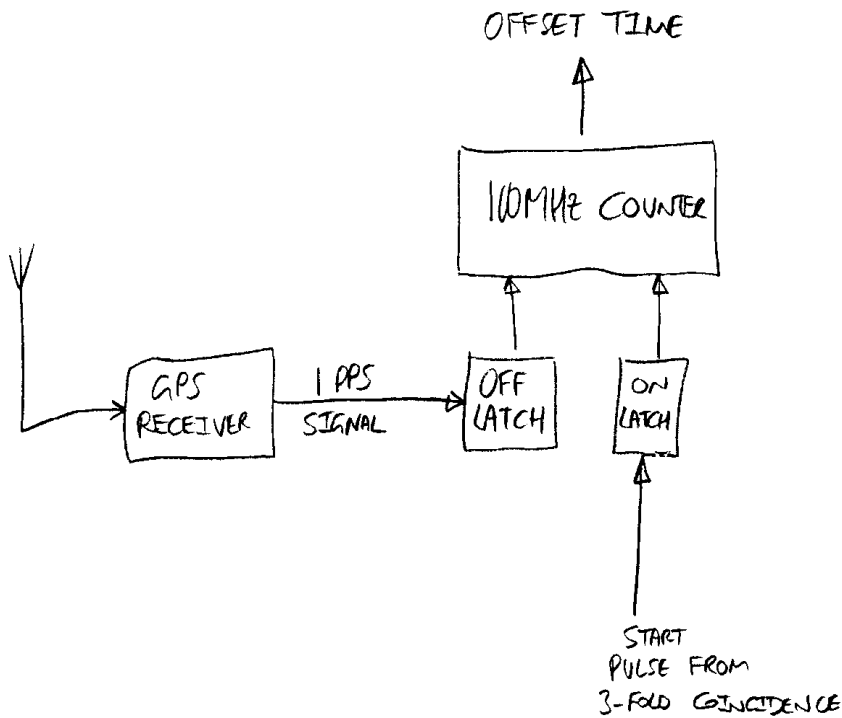


Figure 9: Scheme for precision timing using the GPS PPS output and a fast clock.

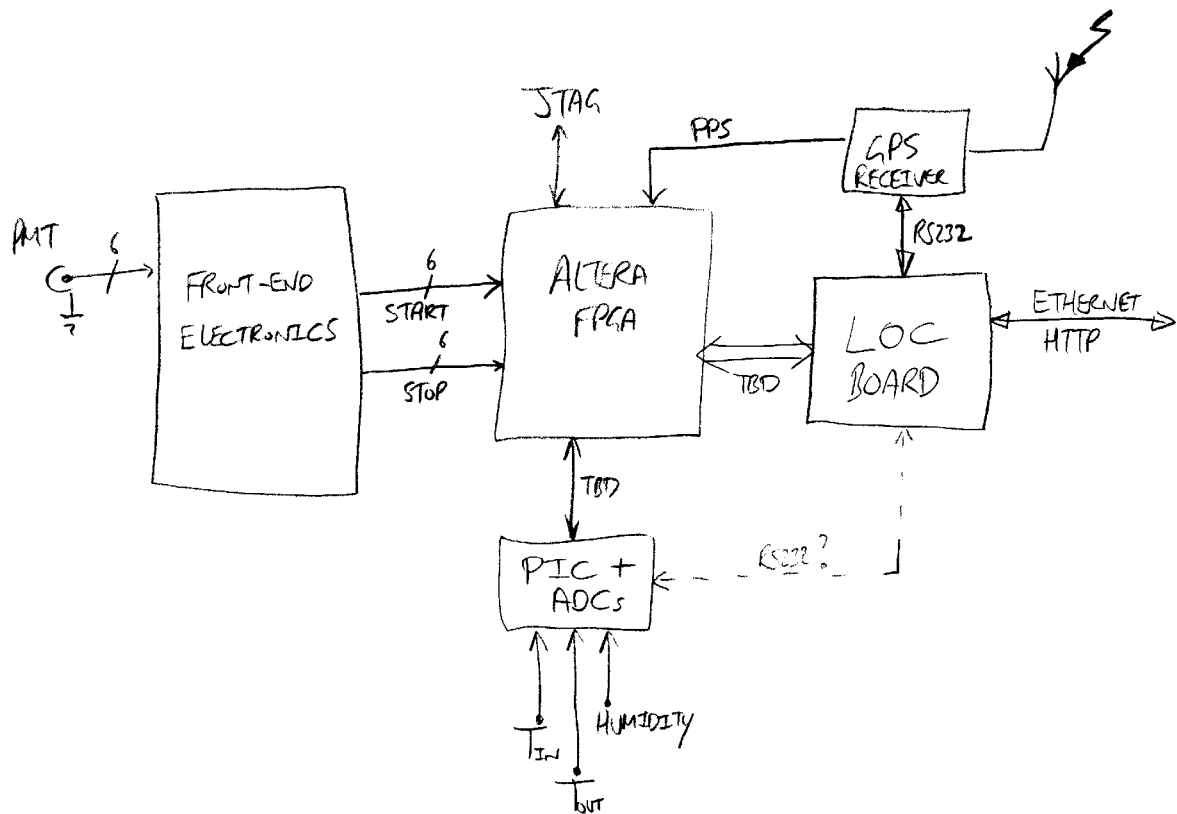


Figure 10: Overview of the overall DAQ system.

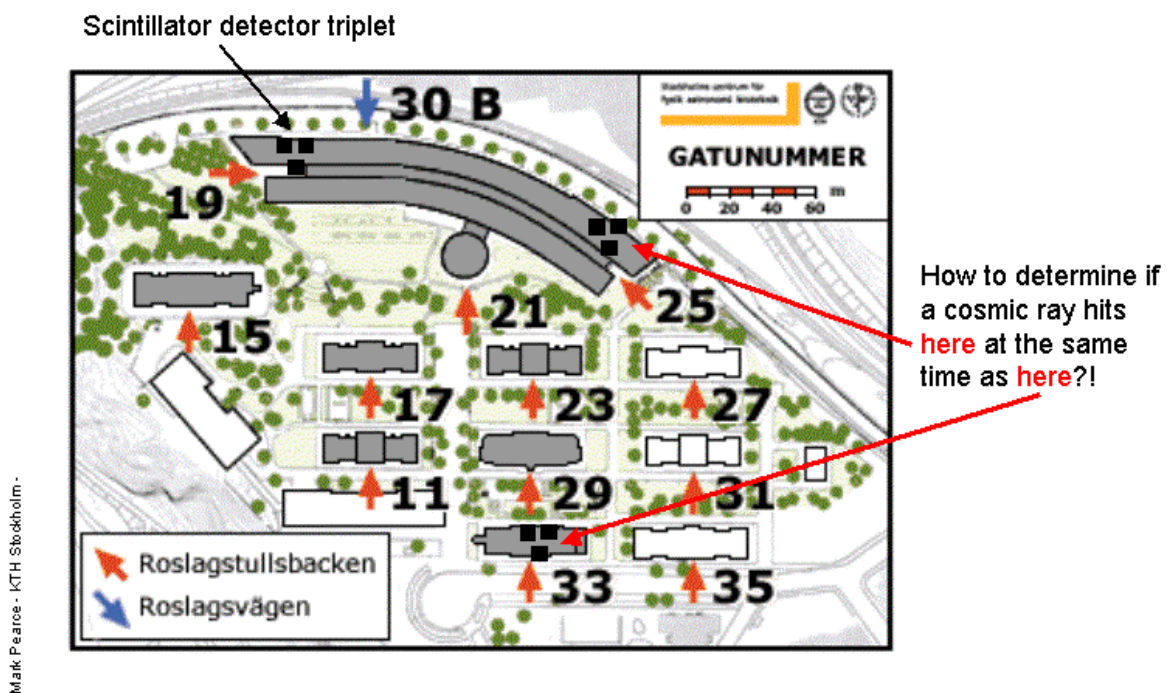


Figure 11: A possible detector layout in the SCFAB area.

