Hybrid Detection of High Energy Extensive Air Showers

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Hellenic Open University

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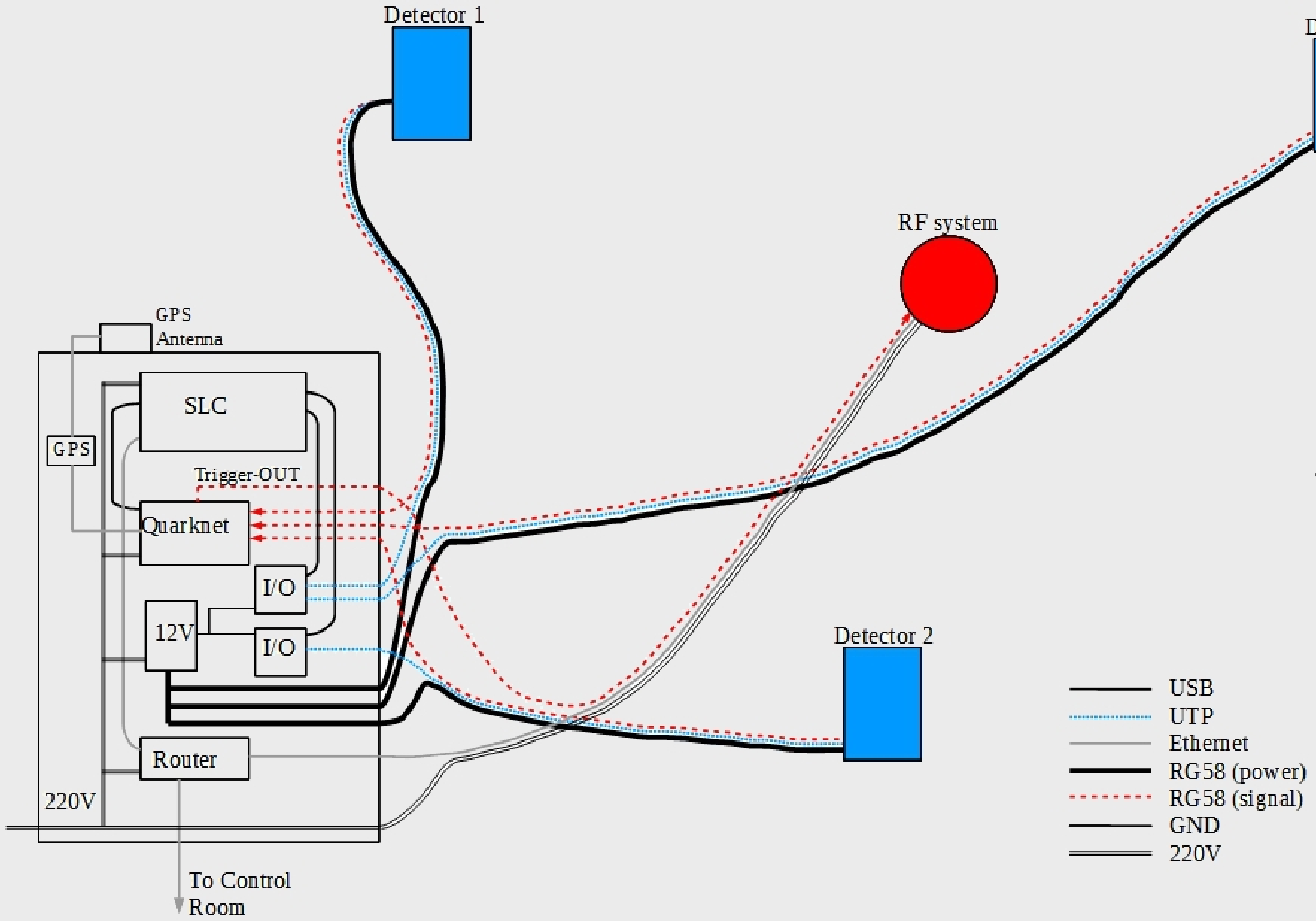
ΠΕΝΕΡ ΕΑΠ
ΦΚ-228

Outline

- Description of the Hellenic Open University (HOU) Cosmic Ray detector array
  - Station and array layout
  - Operation and DAQ system
- Previous results
  - Calibration of the detectors, stations and the DAQ system
  - Analysis of data from autonomous stations and double station coincidence data
  - Detection of the RF signal of EAS
- Hybrid detection of EAS
  - Timing of detectors and antennas
  - Analysis of double station coincidence data
  - Performance and comparison with the simulation predictions
- Next steps

HOU detector array layout

Detector array station layout



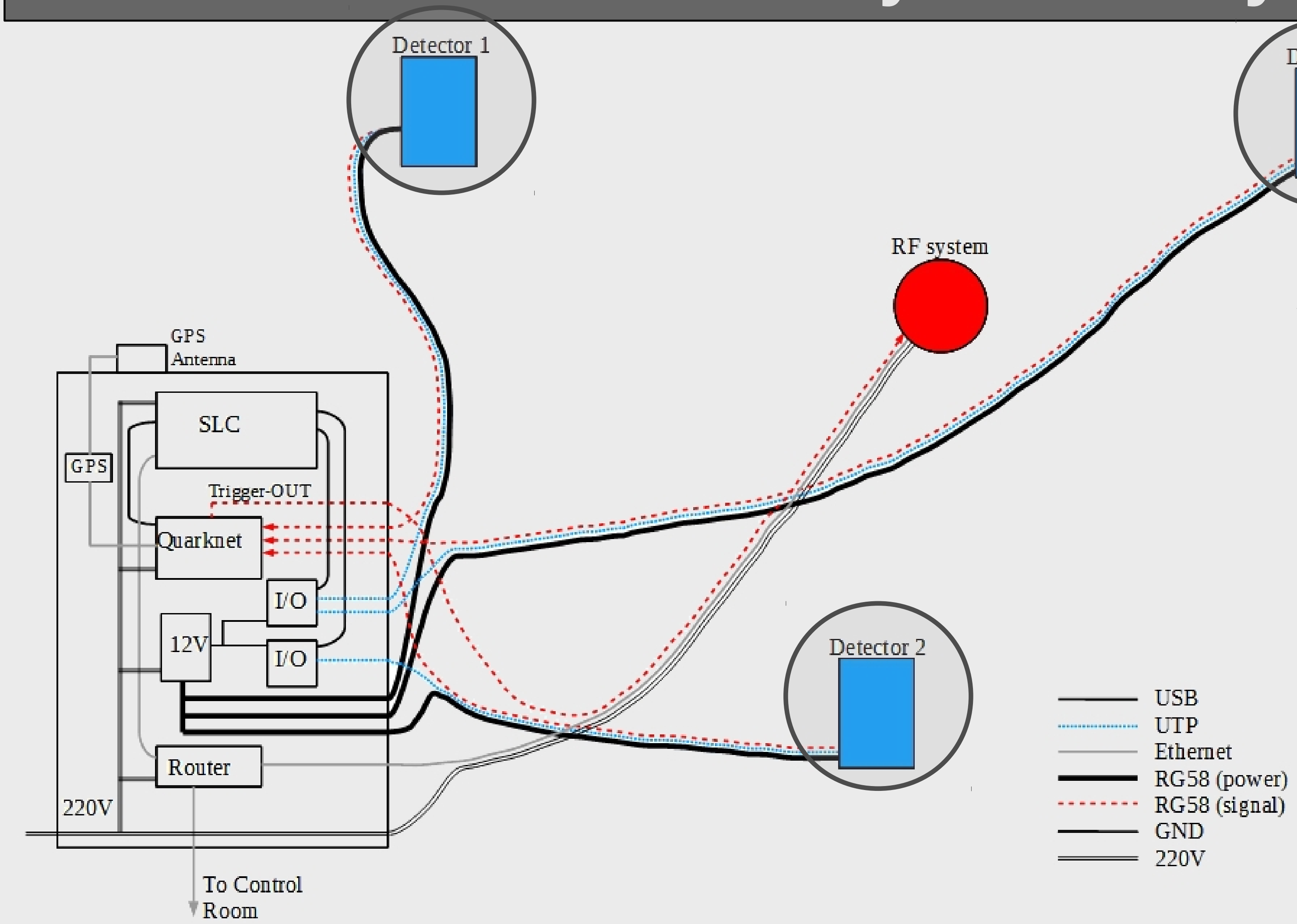
3 scintillator detectors

1 CODALEMA antenna for EAS RF detection

The control – DAQ box

- powering of the detectors
- electronics for control and monitor of the station
- the detector DAQ system
- the station hosting computer

Detector array station layout

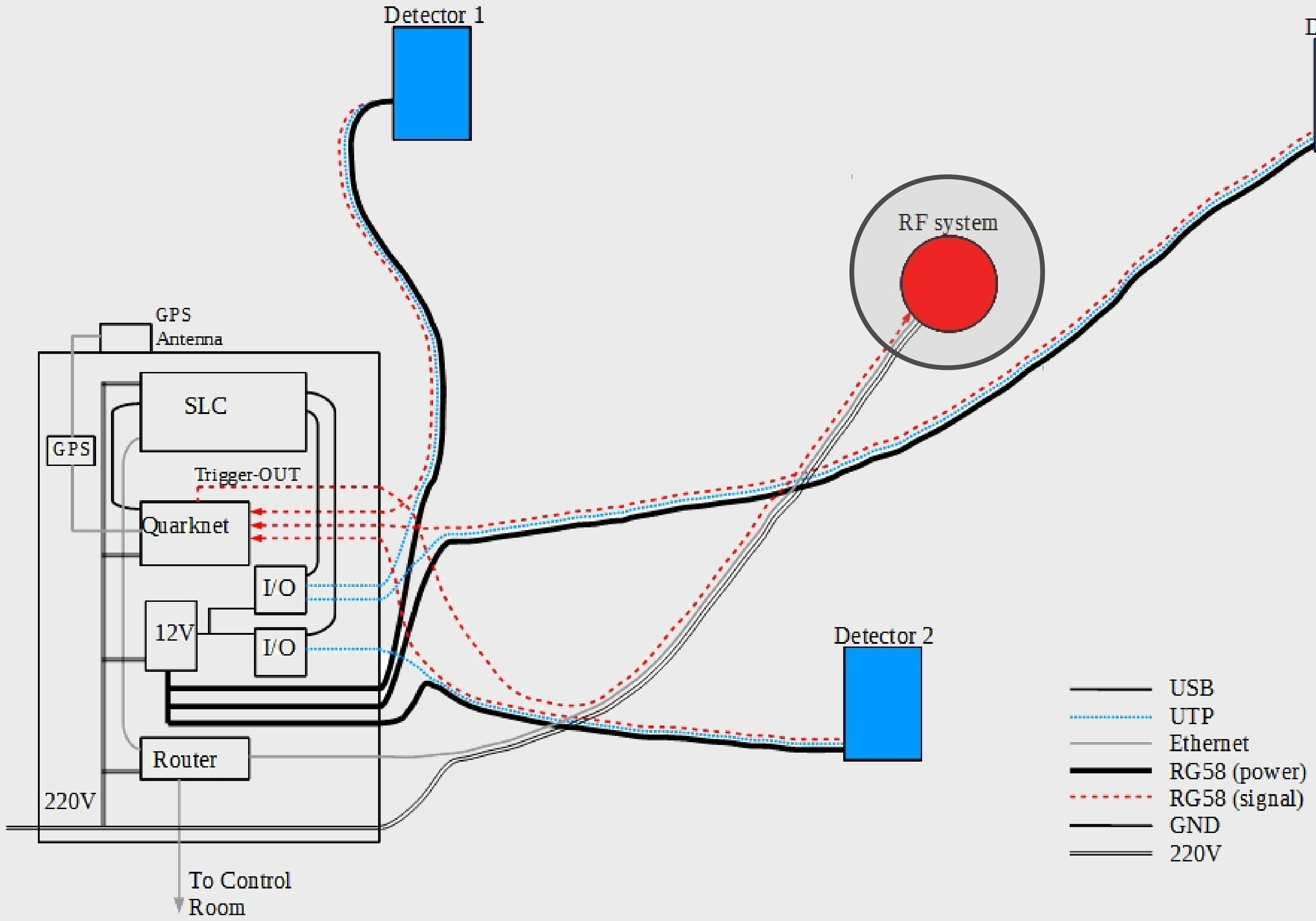


3 scintillator detectors

- Protvino SC-301
- Bicron BCF91-A WLS fibers
- Photonis XP1912 PMT
- EMCO CA20N high voltage dc-dc converter

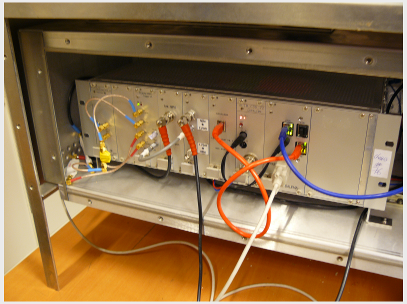
~30m between detectors

Detector array station layout

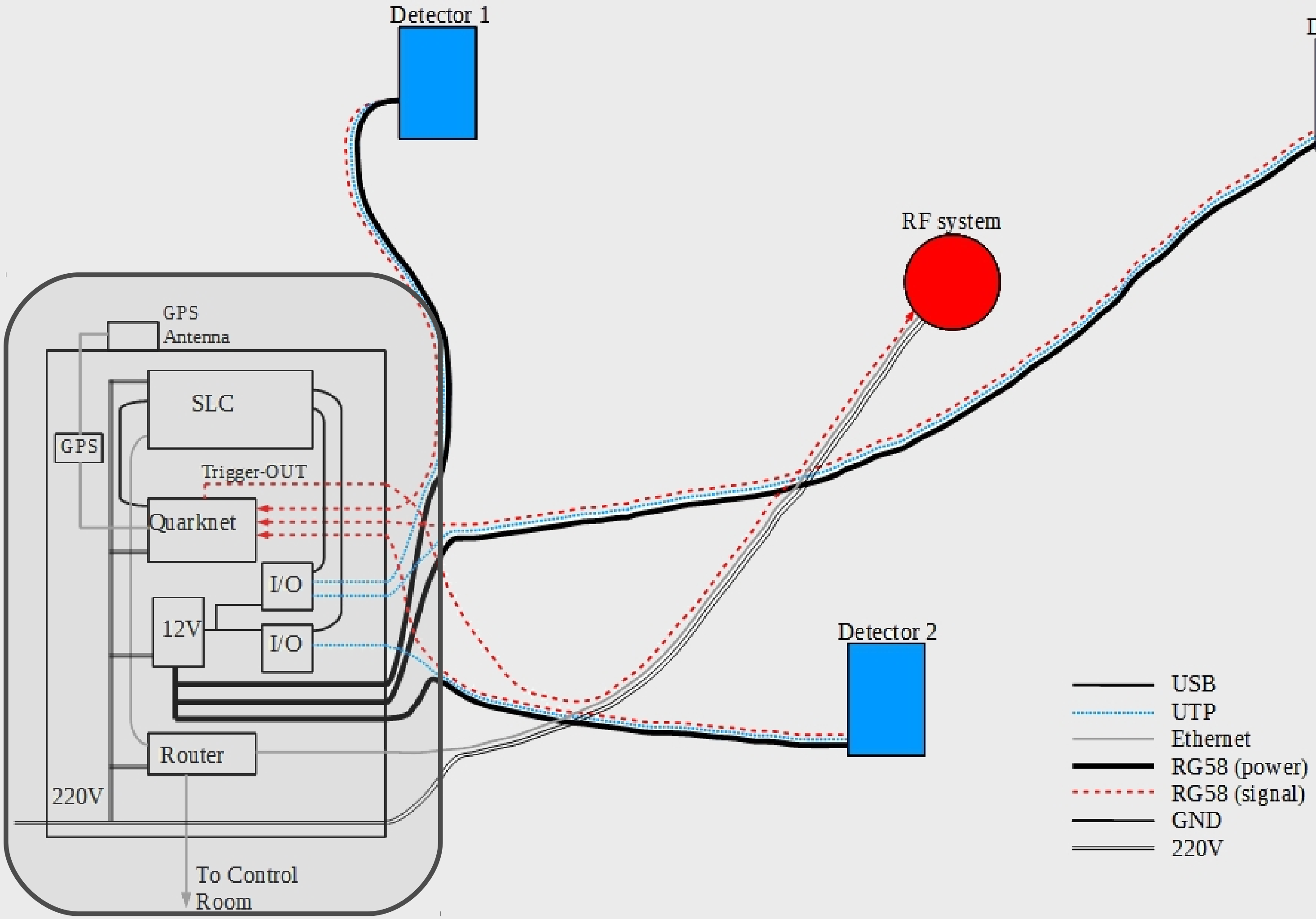


1 RF detection antenna (CODALEMA)

- Filters
- ADC board
- Trigger board
- Control & power supply board
- Linuc PC board
- GPS module

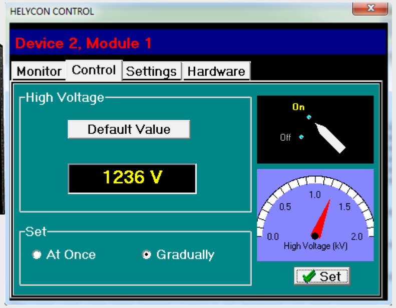


Detector array station layout

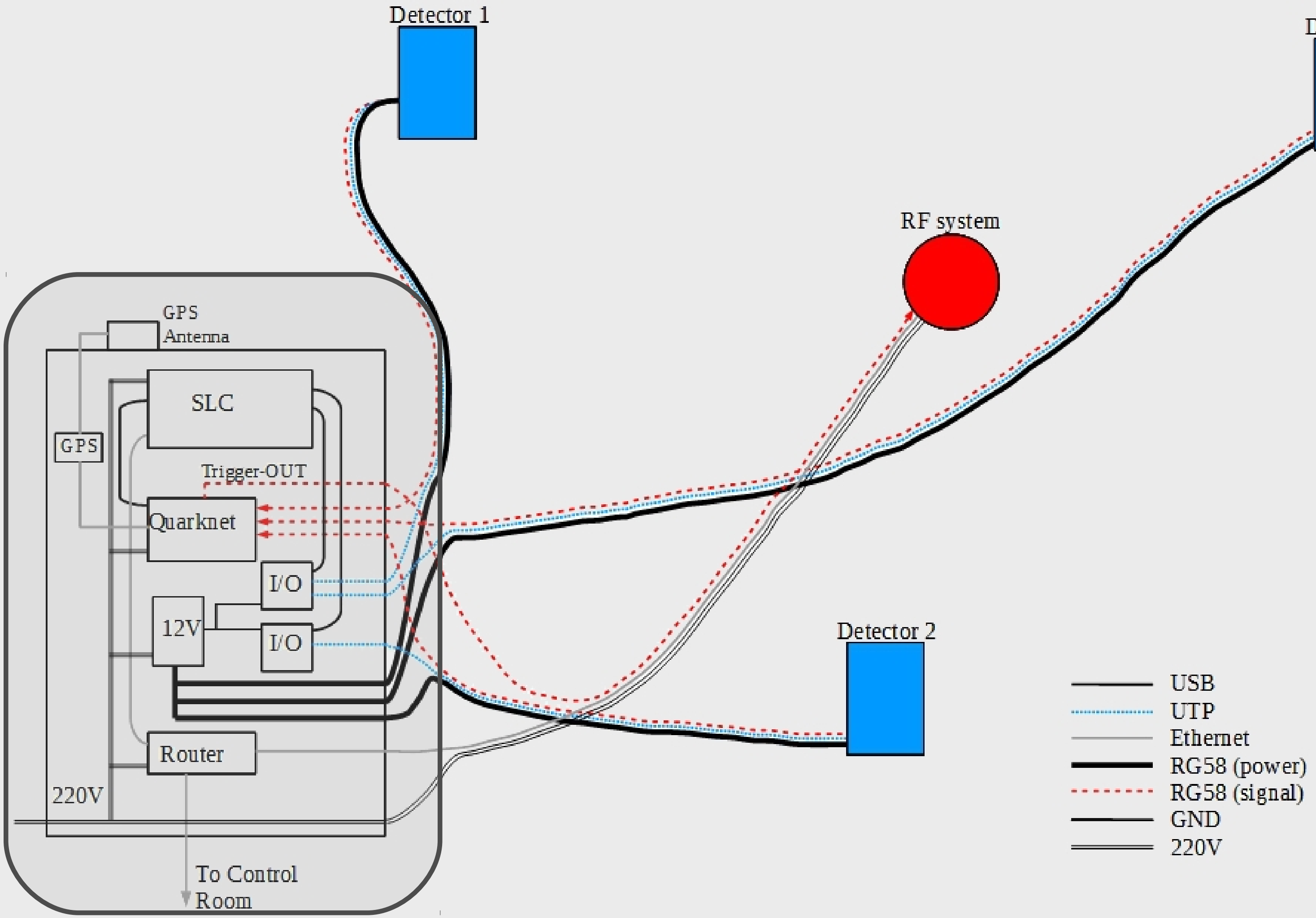


Control and DAQ Box

- Low voltage power supply
- Control and monitor of detector's high voltage and temp (2 x NI-USB 6008)
- DAQ system (Quarknet board)



Detector array station layout

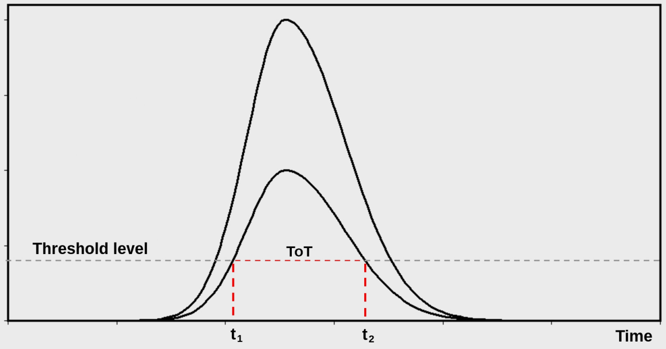


Control and DAQ Box

Station DAQ system

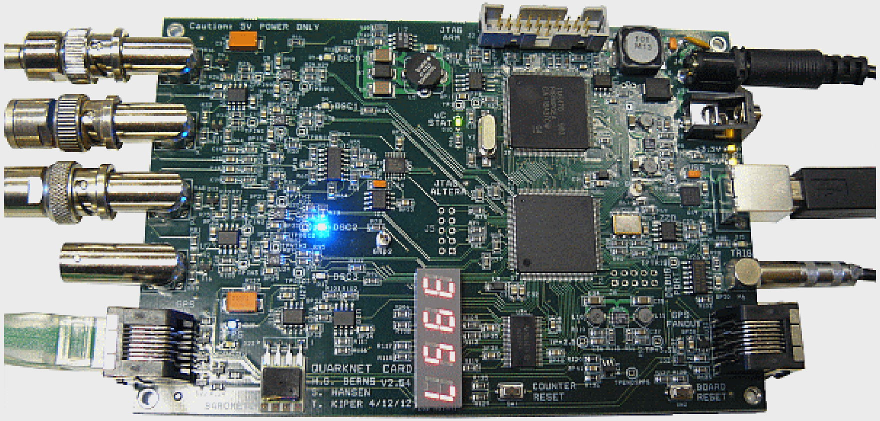
Scintillator detectors DAQ System based on the Fermilab Quarknet board

- 4 signal inputs
- Time tagging of the crossings of the pulses with adjustable thresholds (allows timing of the pulses and estimation of their size using the ToT values)
- 1.25ns time resolution
- Adjustable trigger criteria (majority, thresholds, time window)
- Trigger out signal (employed for triggering of the station's RF antenna)
- GPS module to provide the absolute time of the event
- USB connection to the station computer



RF antenna DAQ

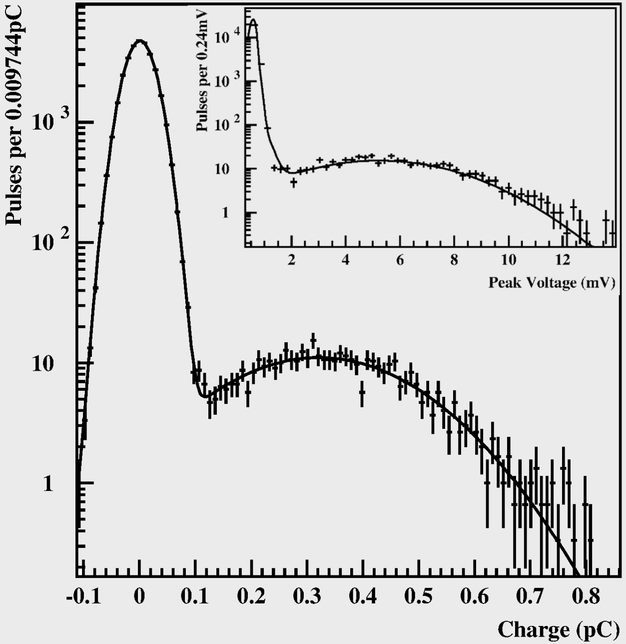
- Self trigger, external trigger, automatic trigger
- Recorded buffer of 2560ns with 1ns resolution
- Adjustable trigger position within the buffer



Detectors and station calibration

Extensive testing and calibration of the detectors and stations before commissioning

- PMT Calibration (gain, single pe characteristics, dark current rate)
- Detector calibration (response to MIPs)
- Signal cables effect (50m RG58)
- DAQ boards calibration (fine tuning of the set thresholds relation to the actual thresholds)
- Station calibration and simulation fine tuning



PMT spe characteristics @ operating high volatge:
- mean pulse height ~2mV
- mean charge ~0.12pC
- dark current rate <40Hz (25°C)
- gain $7.5 \cdot 10^5$
- $G_V = G_{V_0}(V/V_0)^\alpha$ with gain slope α~7.05

S.E. Tzamarias, HELYCON: towards a sea-top infrastructure, in: IDM 2006, World Scientific (2007), p. 464 (ISBN-13978-981-270-852-6)
George Bourlis, Ph.D. Thesis, "Development of instrumentation and methodology for the detection of atmospheric cosmic ray showers and applications in calibrating an underwater neutrino telescope"

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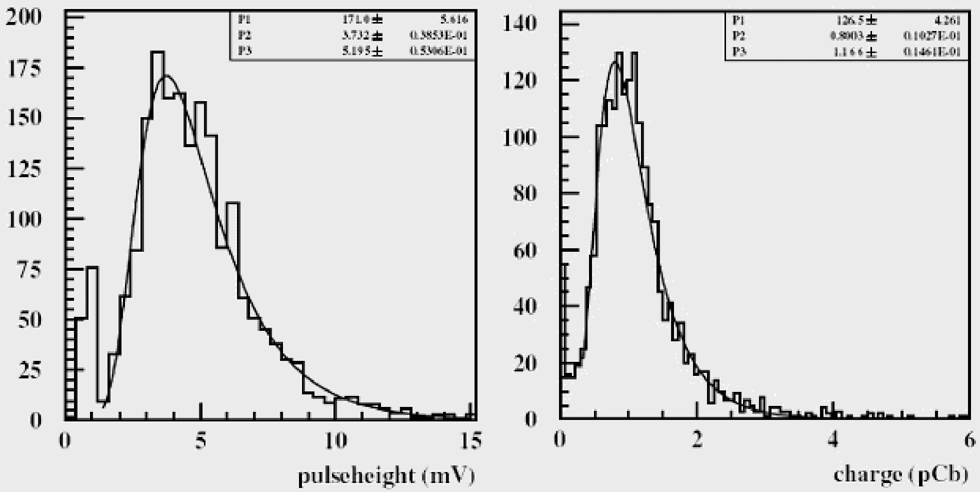

MIP response characteristics @ operating high volatge:
- mean pulse height ~5mV
- mean charge ~1.2pC
- corresponding to ~21pe
- variation of detector response <15%

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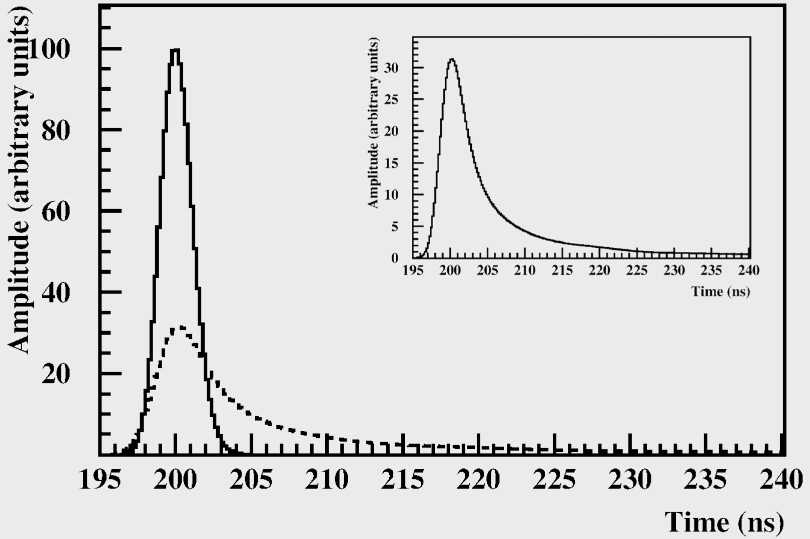

Pulse charge conserved but peak voltage reduced to around 30%

Theodore Avgitas, Master Thesis, "Atmospheric Showers of Energetic Cosmic Particles: Detection and Reconstruction", http://nemertes.lis.upatras.gr/jspui/handle/10889/7903

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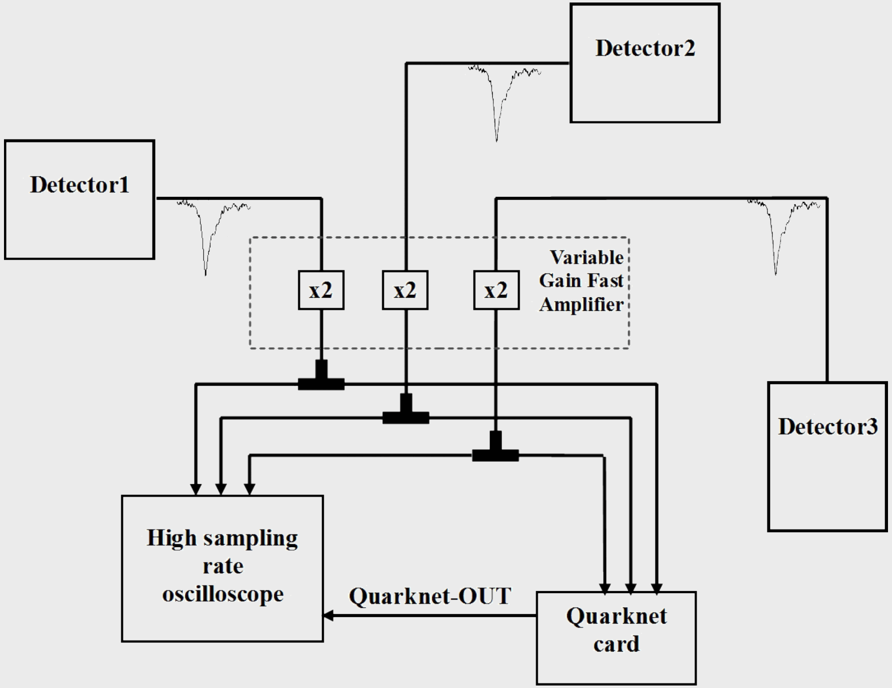

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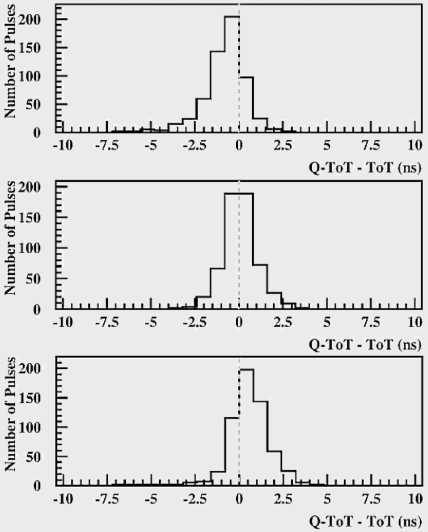

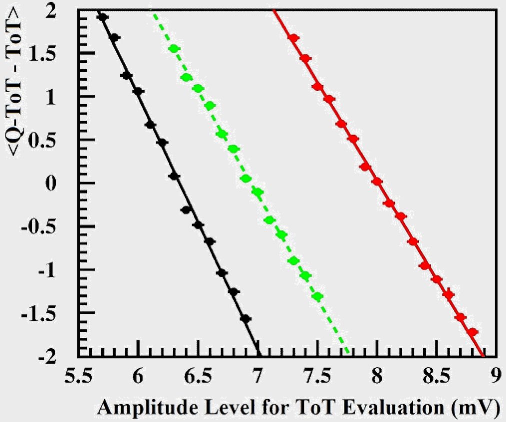

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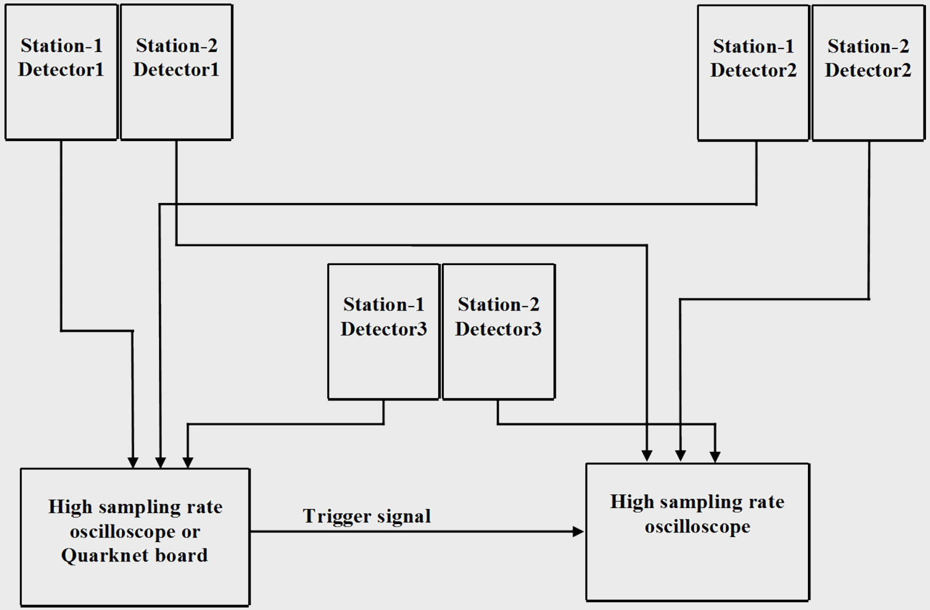

- Station calibration and simulation fine tuning
  - Estimate relation between ToT and size of the pulses (pulse height and charge)
  - Estimate the timing error due to the size of the pulses (slewing) for the employed thresholds
  - Fine tuning of the simulation parameters
  - Evaluation of the stations' performance in reconstructing the EAS direction

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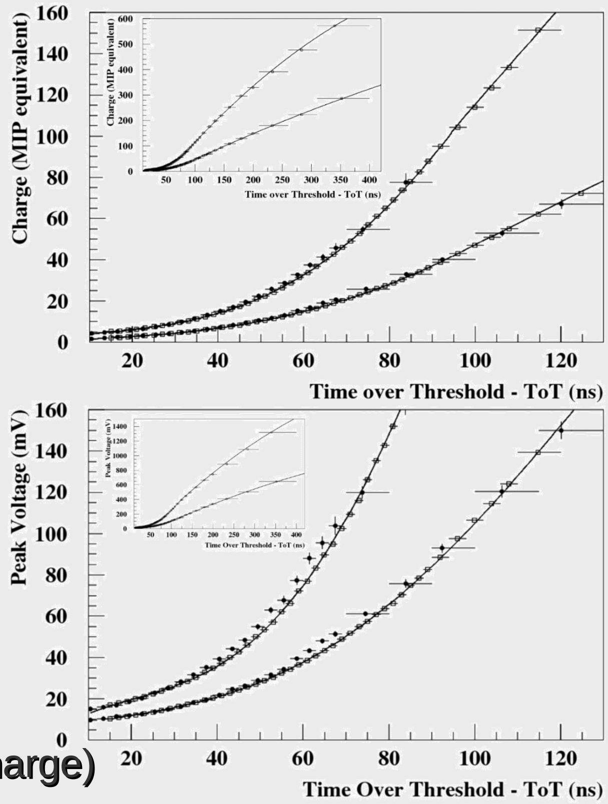

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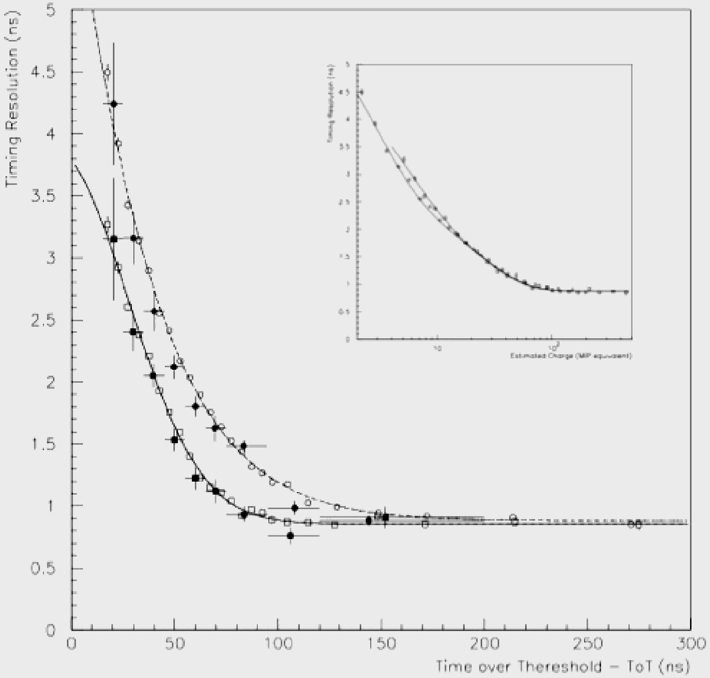

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Simulation of the detector array

- CORSIKA for the simulation of the cascade development
  - 200 million events with energy 10^{13}eV – $5 \cdot 10^{15}$eV
  - 50000 events with energy $5 \cdot 10^{15}$eV – 10^{18}eV
  - 100 events with energy 10^{18}eV – 10^{19}eV
- HOURS (HOU Reconstruction and Simulation) package for
  - Interaction of each particle of the EAS with the scintillator detector
  - Production of the photoelectrons at the PMT photocathode
  - Production of the scintillator detector's waveform
  - Simulation of the electronics (digitization, triggering, etc.)
- Antennas simulation
  - SELFAS (for the electric field generation)
  - 4NEC2 (for the conversion of the electric filed to signal)

QGSJET-II-04 package for high energy hadronic interactions

GEISHA package for low energy hadronic interactions

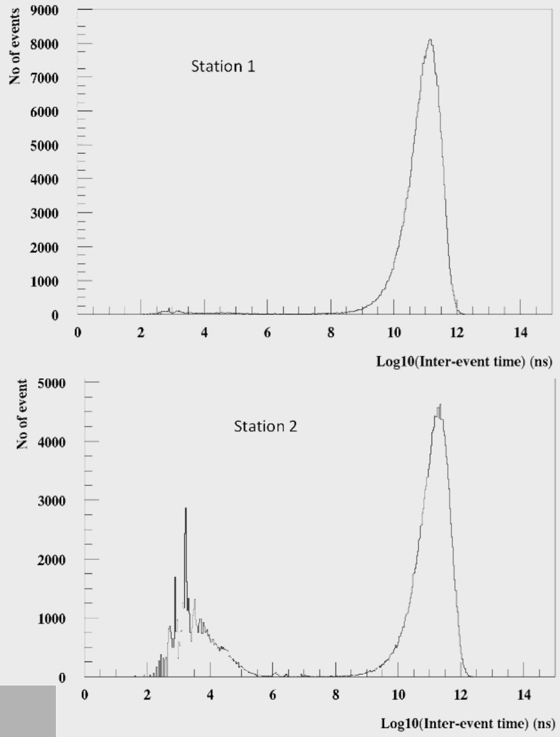
EGS4 for electromagnetic interactions

A.G. Tsirigotis A. Leisos S.E. Tzamarias. HOU reconstruction & simulation (HOURS): A complete simulation and reconstruction package for very large volume underwater neutrino telescopes. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 626627:185-187, 2011

Detecting EAS (event selection)

- 3-fold coincidence trigger within a 150ns window, threshold of 9.7mV (~2 times the MIP mean pulse height)
- Rejection of events caused by noise
- Selection criteria based on the rising and falling edges of the events
  - At least one rising and one falling edge
  - Alternating rising – falling edges
- Merging or disregarding of pulses for each detector waveform
- Application of timing corrections as a function of ToT values

Following data are from a period of around 20 months



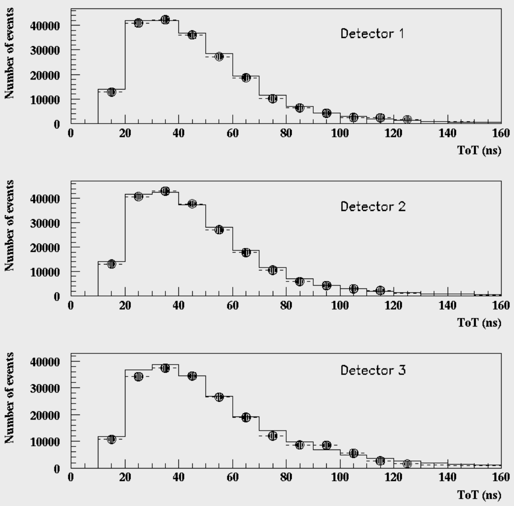
Station	A	B	C
Number of events	338658	245275	368804
Number of events selected after criteria	226269	116850	249570
Operating period (h)	12946	10123	13222

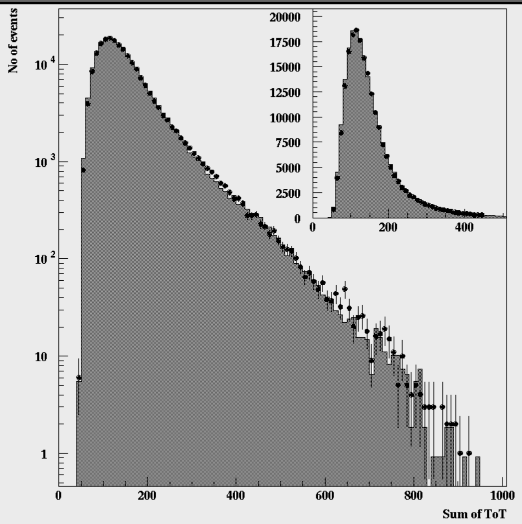
Detecting EAS (data – MC comparison)

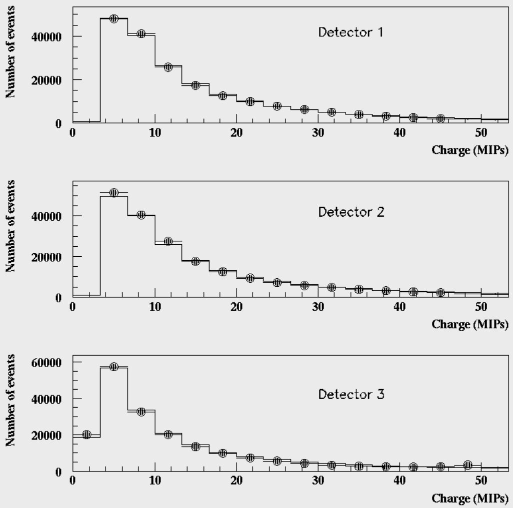
ToT distribution

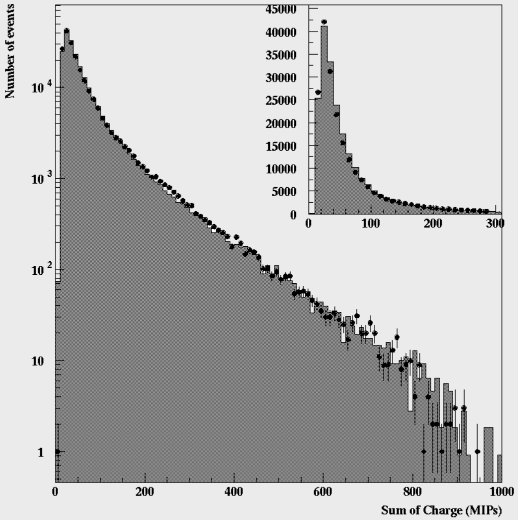
Charge distribution

● data
— simulation









- charge calculated from the full waveforms for the MC events, from the charge versus ToT parameterizations for the data
- MC distributions normalized to station operating time
- very good agreement between data and simulation predictions

T. Avgitas, G. Bourlis, G.K. Fanourakis, I. Gkialas, A. Leisos, I. Manthos, A. Stamelakis, A.G. Tsirigotis and S.E. Tzamarias. Operation and performance of a pilot HELYCON cosmic ray telescope with 3 stations. e-print: arXiv:1801.04768 [physics.ins-det]

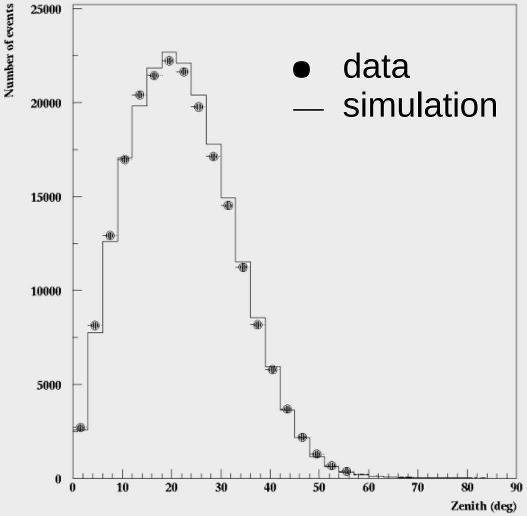
EAS direction reconstruction

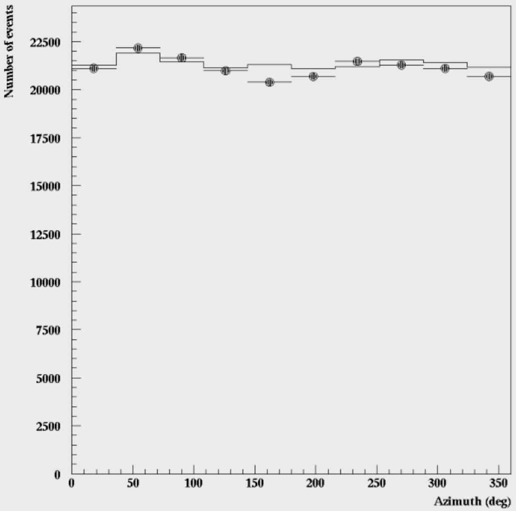
Reconstruction of EAS direction (theta and phi) using the triangulation method

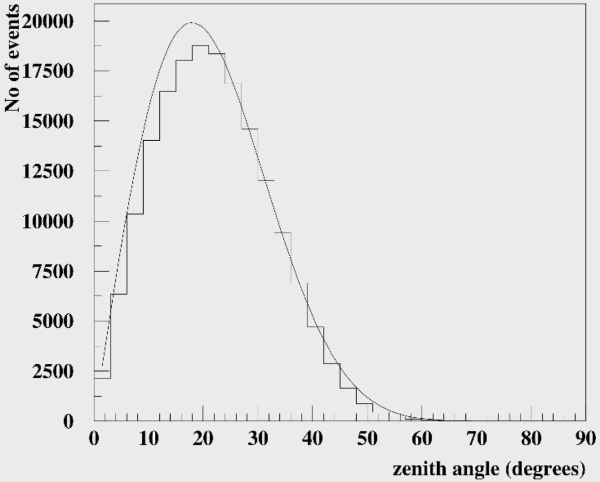
- arrival time of the pulse on each detector is the first crossing of the waveform with the threshold
- corrections for systematic errors (slewing)
- corrections taking into account signal cable lengths
- Azimuth angle equal-probably distributed
- Zenith angle follows a model flux

$$\frac{dN}{d\cos\theta} \sim \cos\theta^{\alpha}$$

- Fit gives a spectral index of α=9.55±0.02







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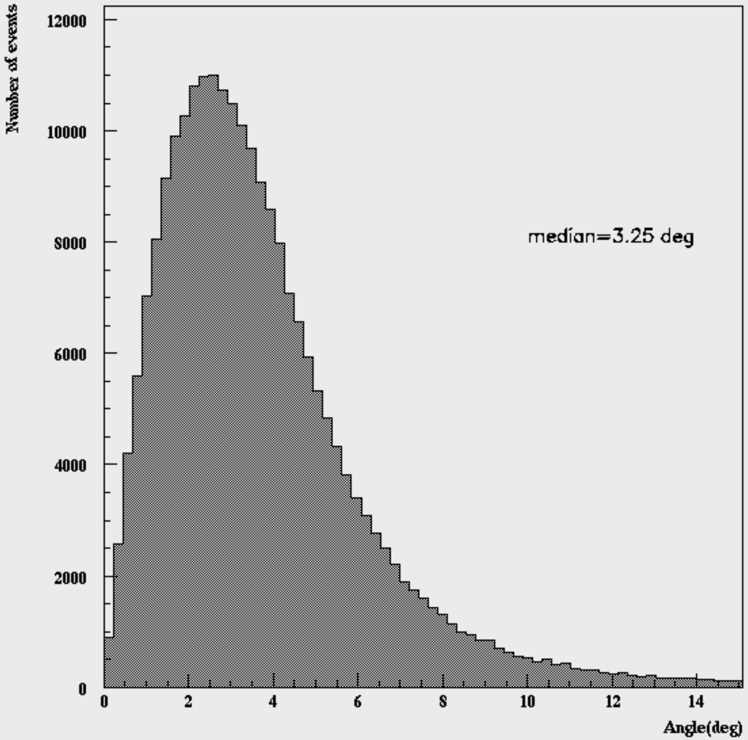
EAS direction reconstruction

Angular difference between true primary particle direction and EAS local shower front direction, employing the triangulation method (for the MC events)

- station A: median = 3.25 deg
- station B: median = 5.3 deg
- station C: median = 3.5 deg



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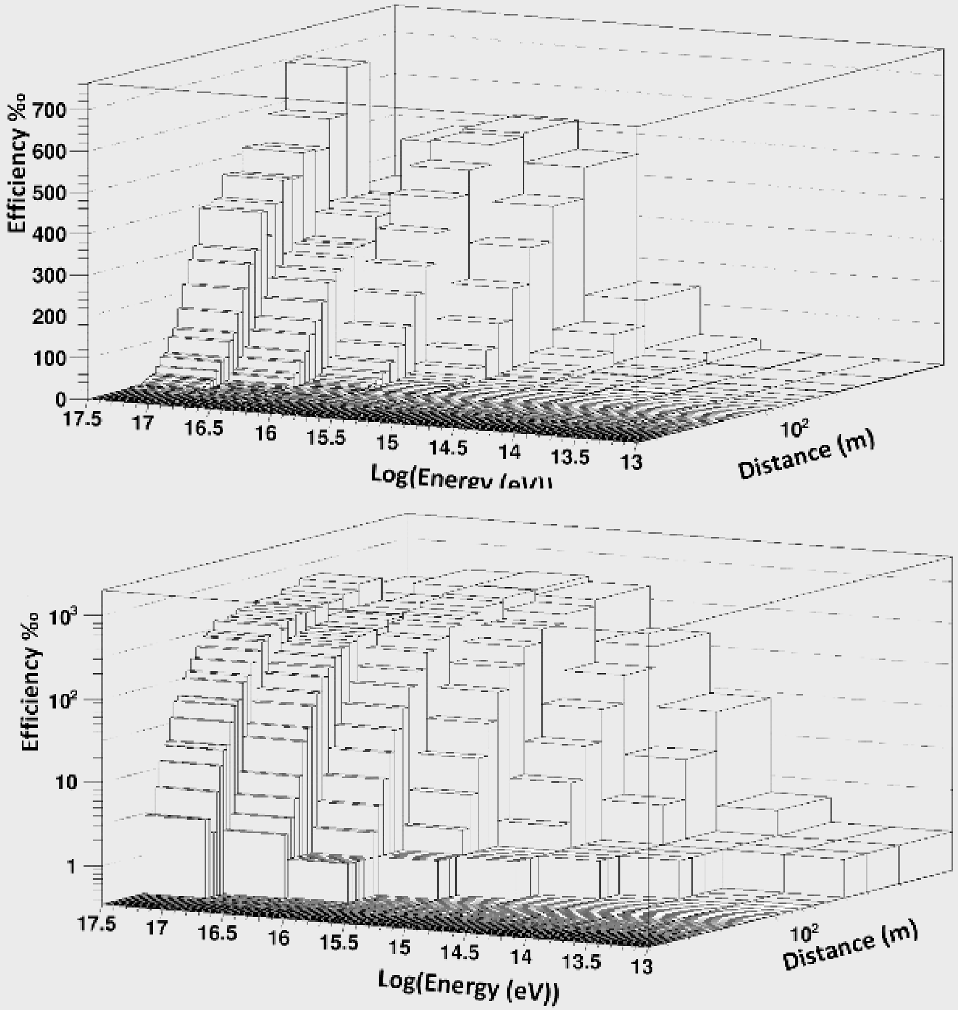
EAS direction reconstruction

Efficiency of station A in detecting EAS depends on

- the EAS impact point distance from the station center and
- the EAS primary particle energy

Maximum efficiency is 60% for station A

It drops to zero close to the borders of the simulation area



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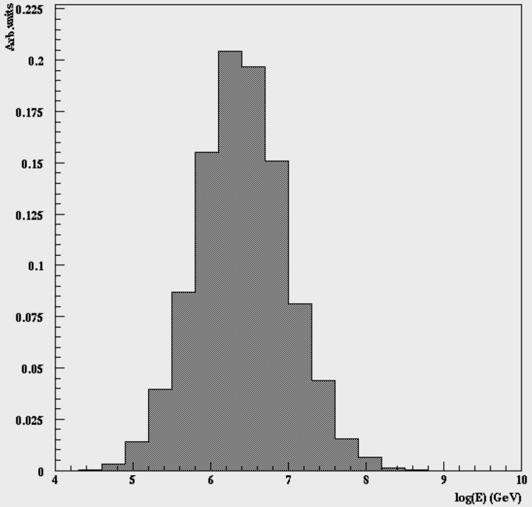
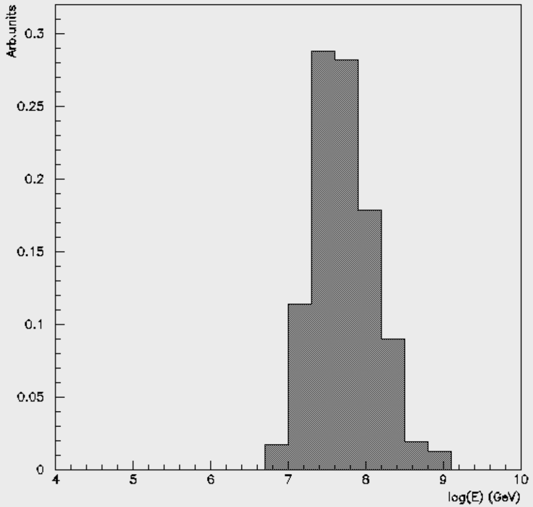
Detecting EAS (multiple station coincidence)

Multiple station coincidence is checked through the absolute GPS times of the events

- Only higher energy EAS can trigger more than one station





Stations	Distance	Detected events	Expected events	Operating time (h)
A-B	164	1395	1410	9402
A-C	328	33	30	12288
B-C	467	12	12	9450
A-B-C	-	6	8	8904

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Detecting EAS (multiple station coincidence)

Multiple station coincidence is checked through the absolute GPS times of the events

- Only higher energy EAS can trigger more than one station
- More statistics for A-B station pair
- EAS impact point between stations
- Earliest signal on det closer to the center of the interstation distance

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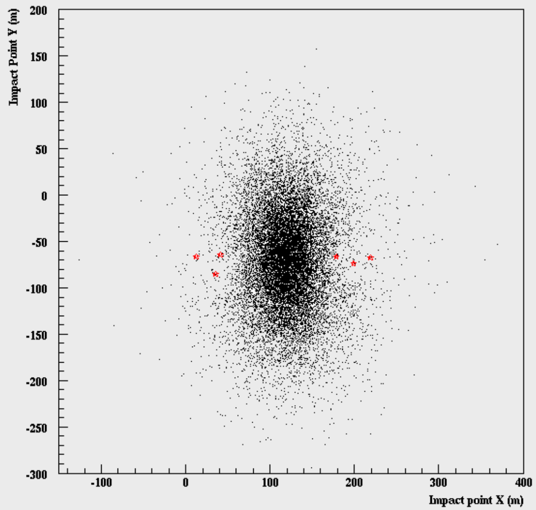
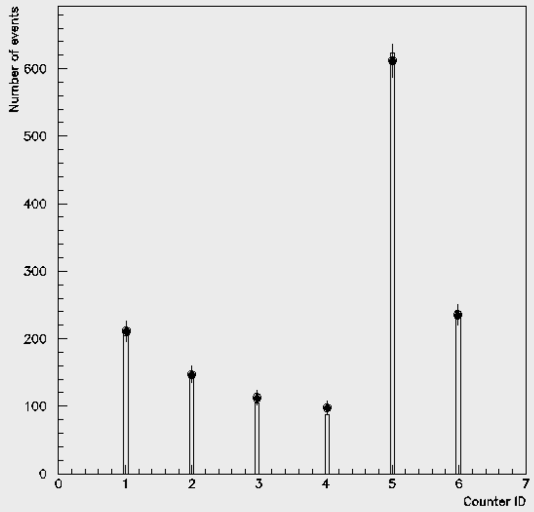




Reconstructing EAS (double station coincidence)

For reconstruction of the direction of EAS triggering 2 stations the curvature of the shower front has to be taken into account

- Small effect of the EAS carvature for single stations EAS
- Deviation of the shower arrival time on the stations up to 15-20ns for more distant showers with the plane shower front approximation
- Negligible effect for showers axis at the same distance from stations, larger as distances become different

To categorize showers we use the ratio

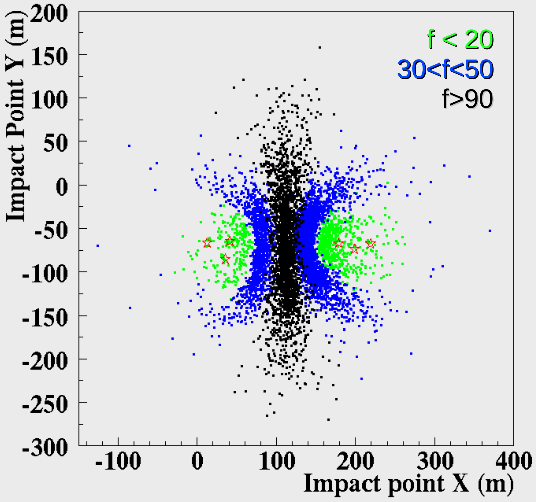
$$f = 100 \cdot min(dA_{max}, dB_{max}) / max(dA_{max}, dB_{max})$$

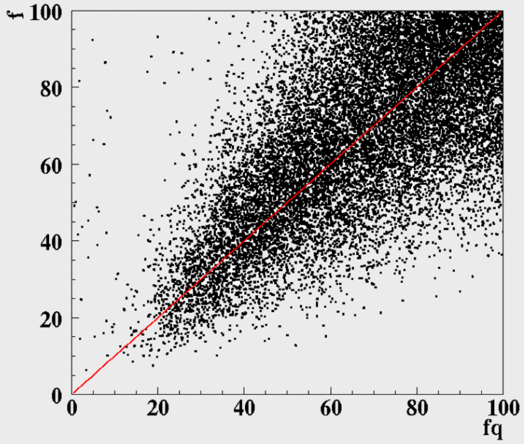
with dA_{max}, dB_{max} the distances of the most energetic detectors of each station from the shower axis.

To estimate the ratio f from the experimental data, we used the ratio

$$fq = 100 \cdot min(qA_{max}, qB_{max}) / max(qA_{max}, qB_{max})$$

with qA_{max}, qB_{max} the largest charge collected on each station





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Reconstructing EAS (double station coincidence)

To categorize showers we use the ratio

$$f = 100 \cdot min(dA_{max}, dB_{max}) / max(dA_{max}, dB_{max})$$

with dA_{max}, dB_{max} the distances of the most energetic detectors of each station from the shower axis.

To estimate the ratio f from the experimental data, we used the ratio

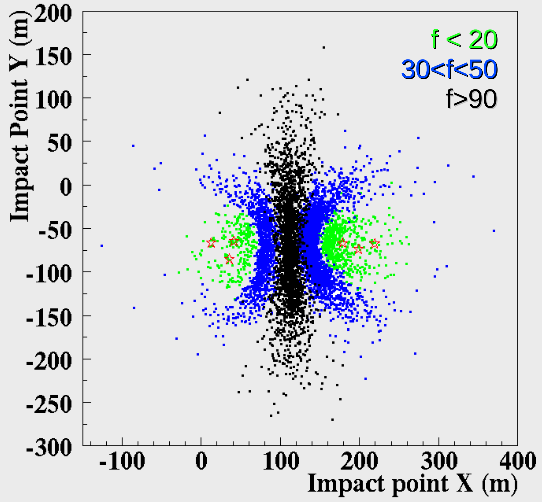
$$fq = 100 \cdot min(qA_{max}, qB_{max}) / max(qA_{max}, qB_{max})$$

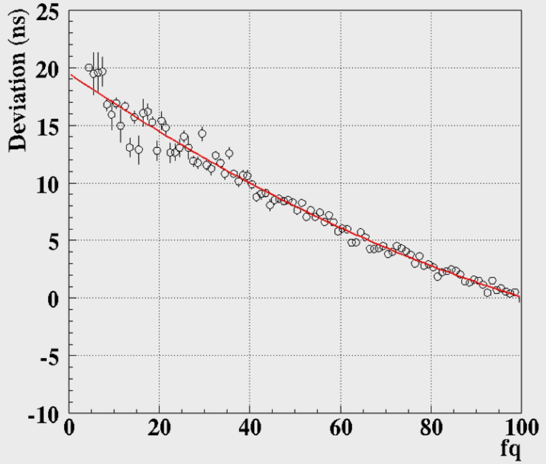
with qA_{max}, qB_{max} the largest charge collected on each station

Then, the deviation

$$\Delta(fq) = dt_{true} - dt_{plane}$$

can be parameterized versus the ratio fq, which can be calculated from the charge versus ToT parameterizations.





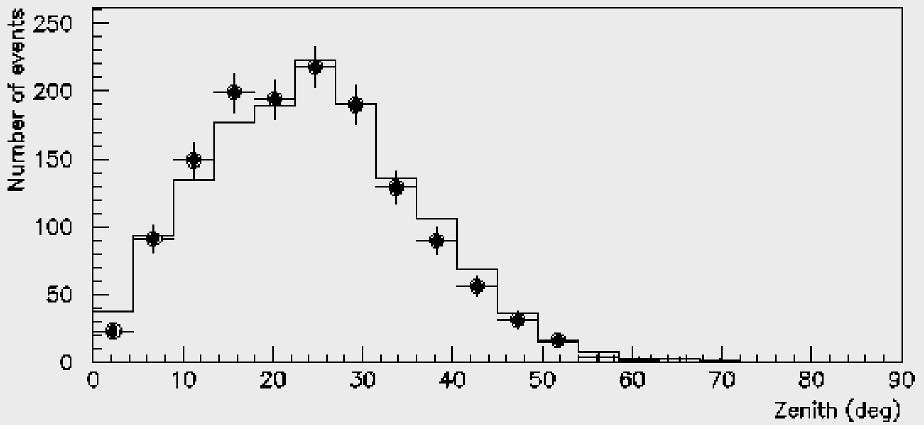
T. Avgitas, G. Bourlis, G.K. Fanourakis, I. Gkialas, A. Leisos, I. Manthos, A. Stamelakis, A.G. Tsirigotis and S.E. Tzamarias. Operation and performance of a pilot HELYCON cosmic ray telescope with 3 stations. e-print: arXiv:1801.04768 [physics.ins-det]

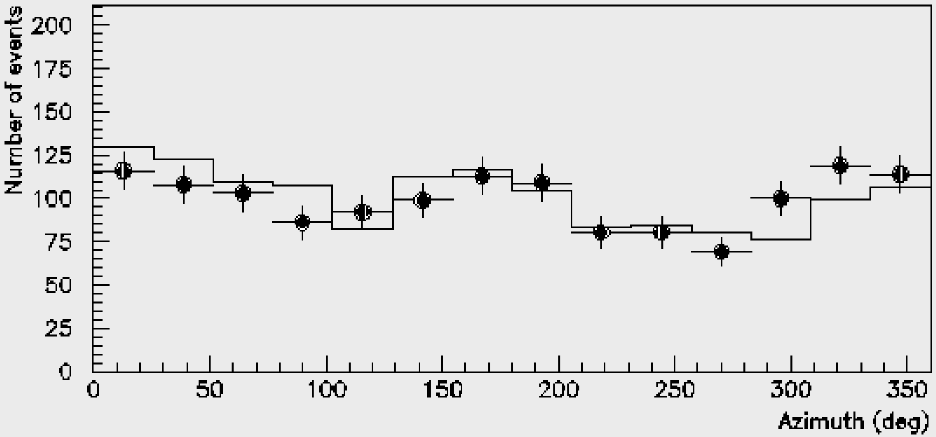
Reconstructing EAS (double station coincidence)

The EAS direction reconstruction is performed via a χ^2 minimization

$$\chi^2 = \sum_{iA=1}^{2} \left(\frac{dt^{\exp}_{iA,A_{max}} - dt^{meas}_{iA,A_{max}}}{\sigma_{iA}} \right)^2 + \sum_{iB=1}^{2} \left(\frac{dt^{\exp}_{iB,B_{max}} - dt^{meas}_{iB,B_{max}}}{\sigma_{iB}} \right)^2 + \left(\frac{dt^{\exp}_{A_{max},B_{max}} - \Delta(fq) - dt^{meas}_{A_{max},B_{max}}}{\sigma_{AB}} \right)^2$$

where the errors σ_{iA}, σ_{iB} and σ_{AB} include both the experimental timing resolution (incl. slewing) and the statistical fluctuation due to the shower front thickness.





T. Avgitas, G. Bourlis, G.K. Fanourakis, I. Gkialas, A. Leisos, I. Manthos, A. Stamelakis, A.G. Tsirigotis and S.E. Tzamarias. Operation and performance of a pilot HELYCON cosmic ray telescope with 3 stations. e-print: arXiv:1801.04768 [physics.ins-det]

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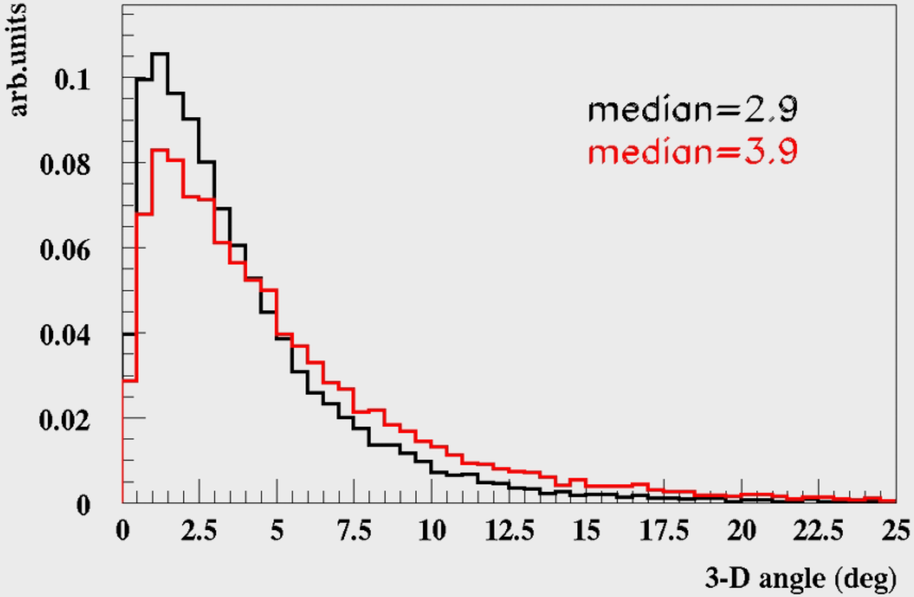


Angular difference between true primary particle direction and EAS local shower front direction

median=3.9 with the plane shower front approximation

median=2.9 when taking into account the carvature and applying the derived correction

T. Avgitas, G. Bourlis, G.K. Fanourakis, I. Gkialas, A. Leisos, I. Manthos, A. Stamelakis, A.G. Tsirigotis and S.E. Tzamarias. Operation and performance of a pilot HELYCON cosmic ray telescope with 3 stations. e-print: arXiv:1801.04768 [physics.ins-det]

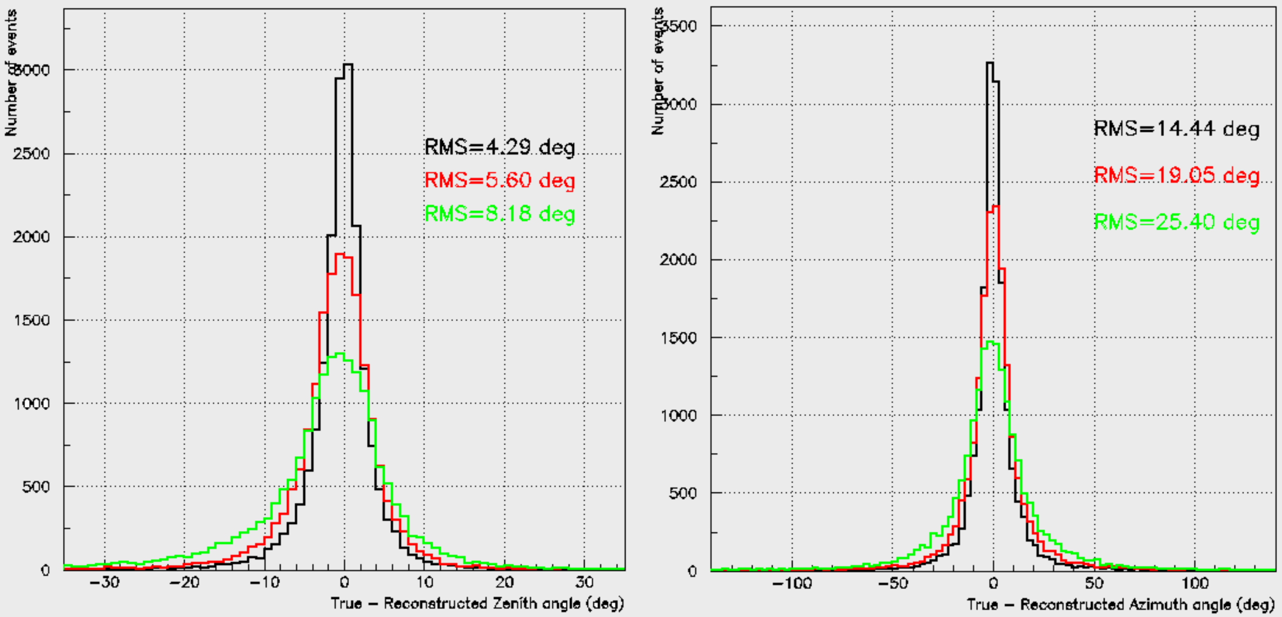
Reconstructing EAS (double station coincidence)

Distributions of the difference between true and reconstructed zentih and azimuth angles

- calculated using all 6 detectors timing information

- employing the triangulation method (station A)

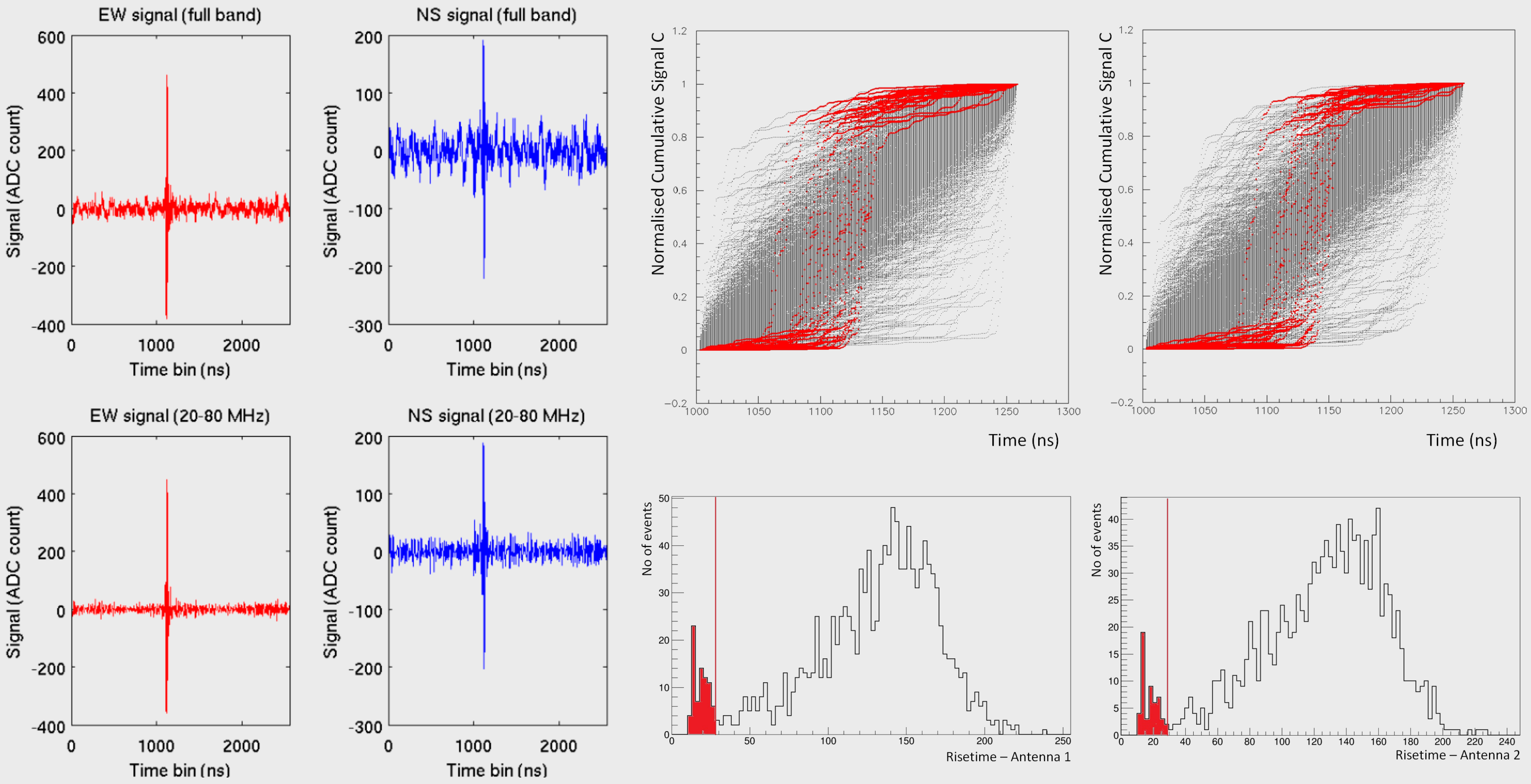
- employing the triangulation method (station B)



T. Avgitas, G. Bourlis, G.K. Fanourakis, I. Gkialas, A. Leisos, I. Manthos, A. Stamelakis, A.G. Tsirigotis and S.E. Tzamarias. Operation and performance of a pilot HELYCON cosmic ray telescope with 3 stations. e-print: arXiv:1801.04768 [physics.ins-det]

Detection of RF signal of EAS

- RF signals detected for higher energy EAS (double station coincidence)
- They fulfill a number of criteria
  - small rise time
  - high SNR
  - good polarization
- Such RF signals are used for the following analysis

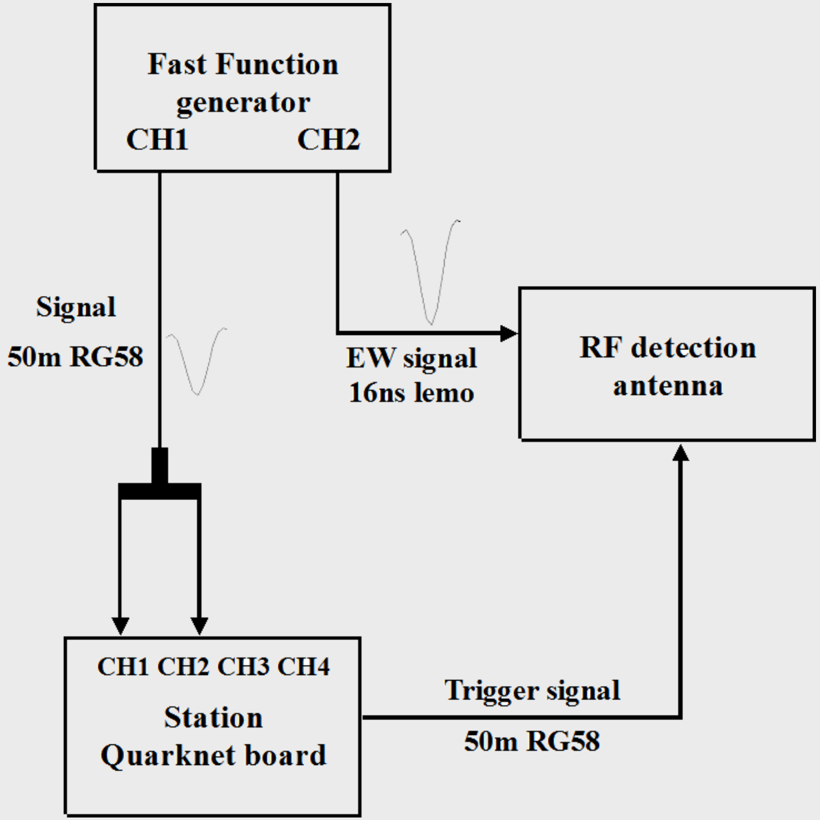


I. Manthos, I. Gkialas, G. Bourlis, A. Leisos, A. Papaikonomou, A.G. Tsirigotis and S.E. Tzamarias. Cosmic Ray RF detection with the ASTRONEU array. e-print: arXiv:1702.05794 [physics.ins-det]

Hybrid EAS reconstruction

Timing of the detector with the RF antenna signals

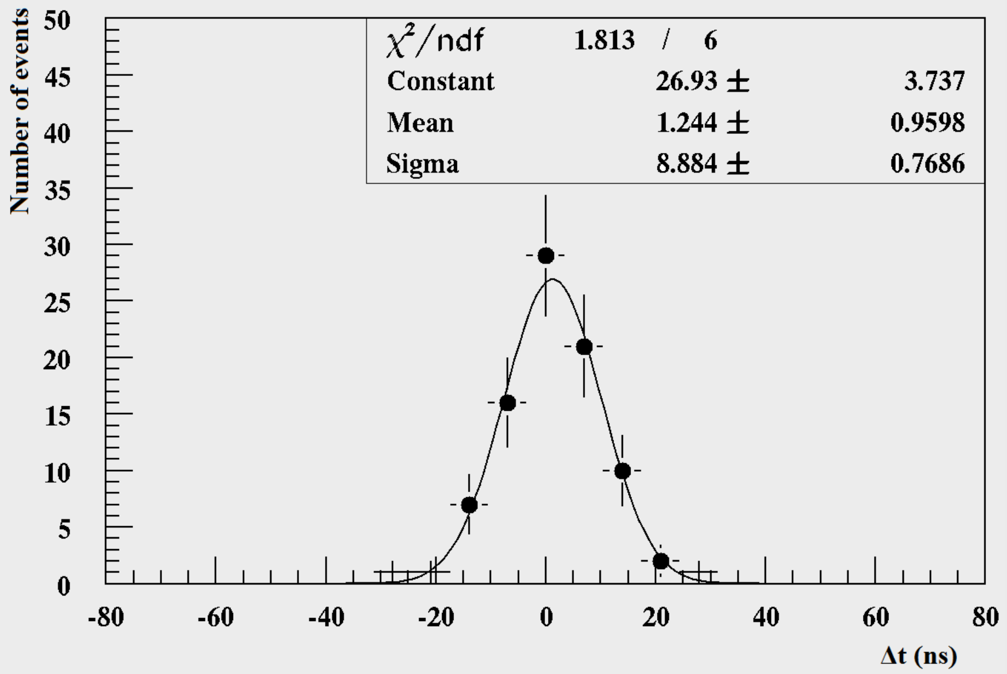
- Function generator to provide a fast pulse imitating the response of the detectors to the shower
- Signal driven to Quarknet which is triggered and the trigger out signal of the Qnet is employed to trigger the RF antenna as in normal operation
- Acquisition of 4000 events
- Timing of the pulses on the antenna with repect to the pulse on the Quarknet (that defines the trigger)



Hybrid EAS reconstruction

Check of the antennas and detectors timing employing the double station coincidence events (stations A and B)

- Select the events with antenna pulses that exhibit a maximum of more than 10 times the rms of the baseline (not constant for the antenna waveforms)
- Use of zenith and azimuth angles from the EAS direction reconstruction from each station to calculate the expected time of the pulse on the antenna.
- Calculate the difference between the time of the antenna pulse (peak position) from the calibration and the expected time calculated above
- 37 events from station A antenna and 51 events from station B antenna (difference due to increased noise on station A)
- The error is due to both the direction reconstruction error and the antenna pulse timing error (approximately 3-5ns)



Hybrid EAS reconstruction

Distribution of the difference of the antenna pulse time and the later pulse of the station (that determines the trigger signal)

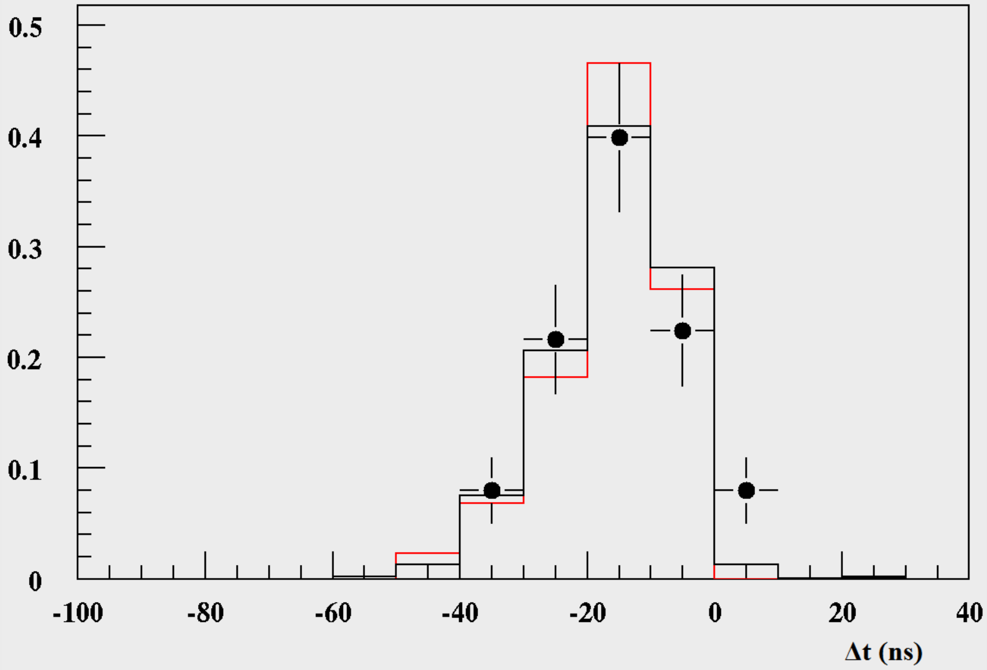
- Red: the expected antenna time is employed for the difference

  (negative difference as the antenna lays close to the station center)

- Black: smearing the expected antenna pulse time using the zenith – azimuth resolution

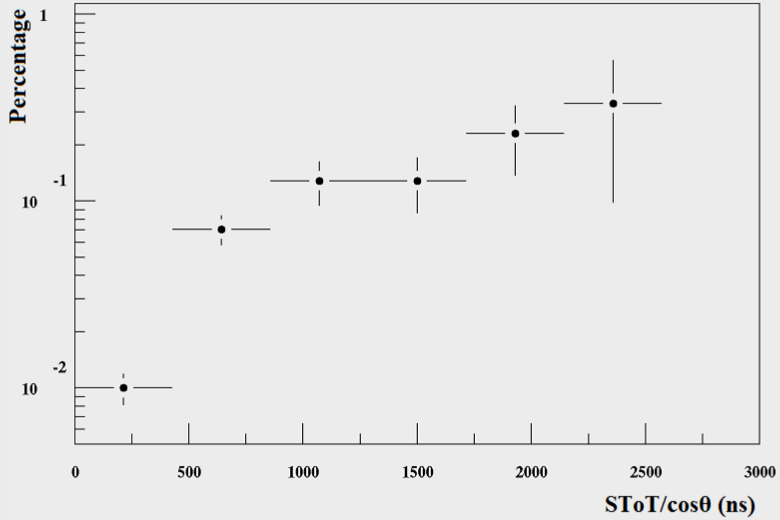
- ● Points: the distribution of the difference employing the experimental antenna pulse times

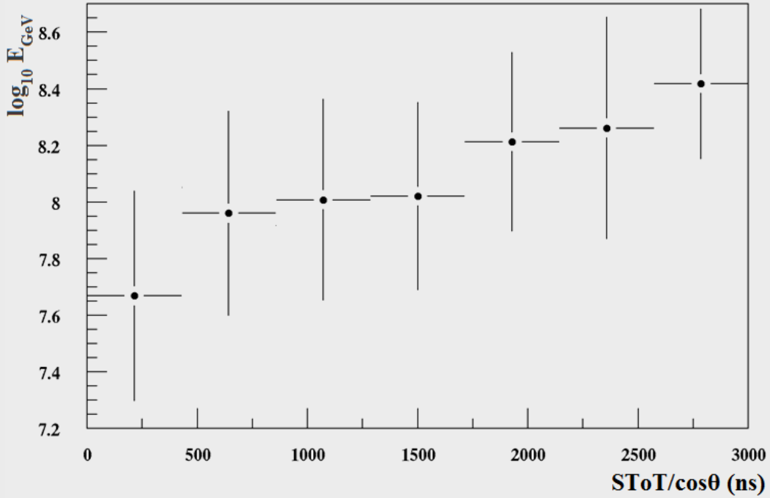
  The same 37 + 51 events are included (for stations A and B)



Hybrid EAS reconstruction (efficiency)

- Percentage of the data with a detected signal (according to the criteria set) on the antenna as a function of the sum of the ToT values divided by cosθ, SToT/cosθ
  - $SToT = \sum_{i=1}^{3} ToT_i$
  - data from both station are included
  - SToT/cosθ is a measure of the total charge per square meter perpendicular to the EAS direction
- Energy ($\log_{10} E_{GeV}$) of the EAS primary particle as a function of the sum of the ToT values divided by cosθ, SToT/cosθ





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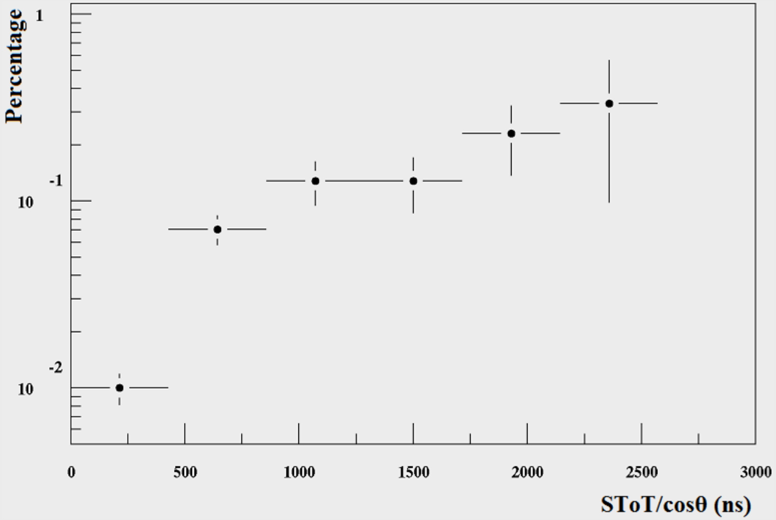

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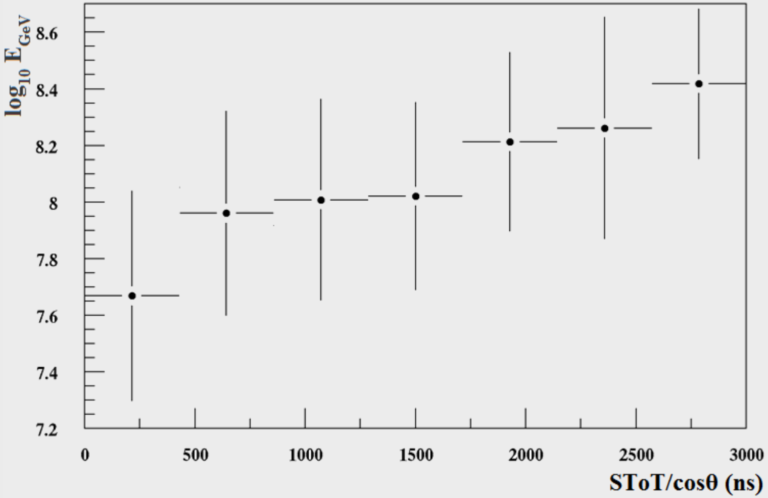
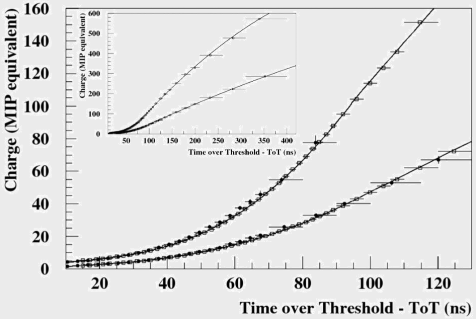
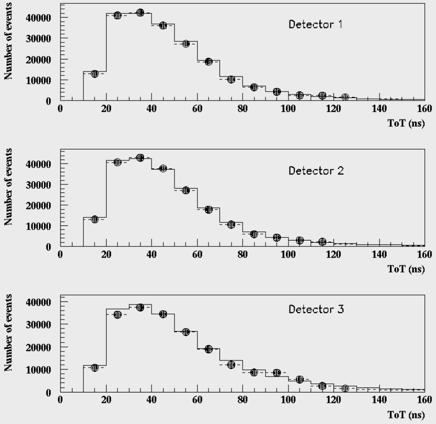




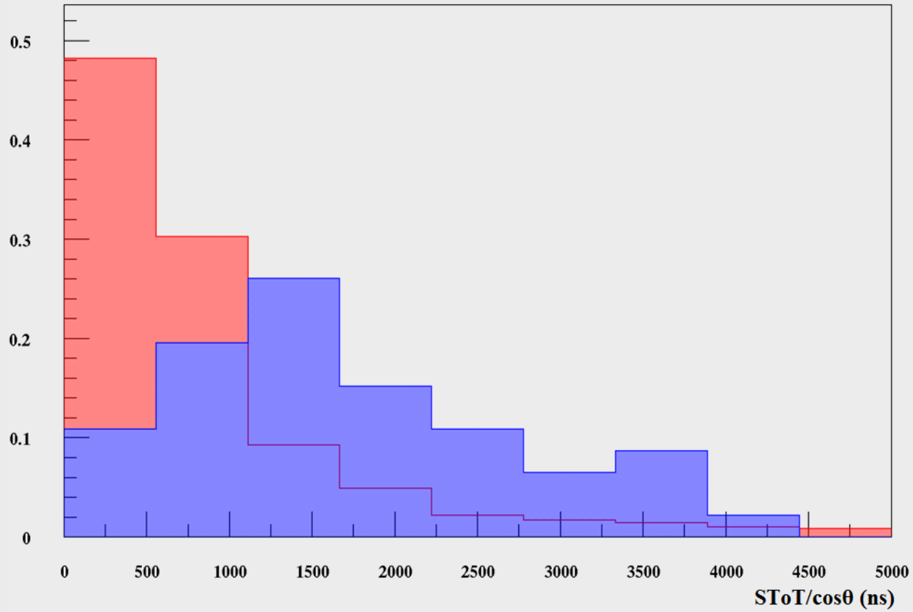


Hybrid EAS reconstruction

Normalized distribution of the sum of the ToT values for all six detectors of stations A and B for the double station coincidence events, divided by cosθ

- Red: for all double station coincidence events
- Blue: for the events with a detected antenna signal fulfilling the selection criteria

On the following analysis we apply a cut of SToT/cosθ > 500, for the selection of higher energy events

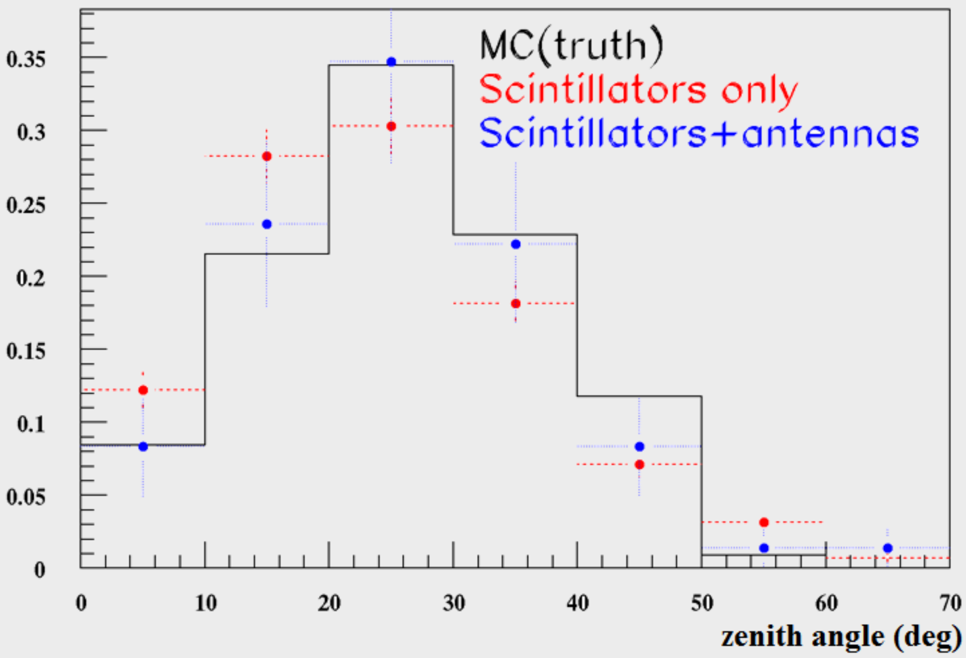


Hybrid EAS reconstruction

Applying SToT/cosθ > 500 and reconstructing the EAS direction:

Zenith angle distribution

- Black: true primary particle zenith angle for the MC events that trigger both stations and fulfill SToT/cosθ > 500
- Red: the reconstructed zenith angle employing the timing info from all six detectors (data)
- Blue: the reconstructed zenith angle employing the timing info from all six detectors and the antennas (data)

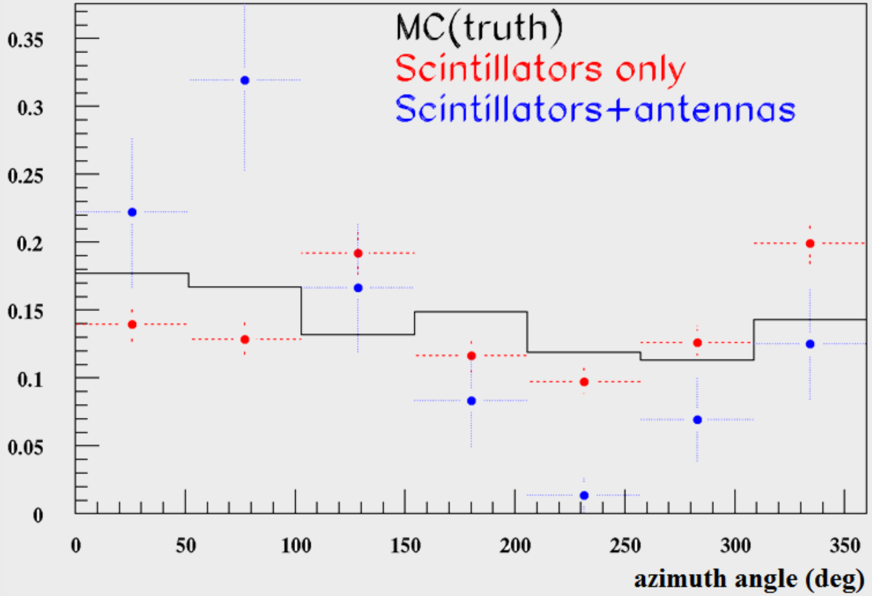


Hybrid EAS reconstruction

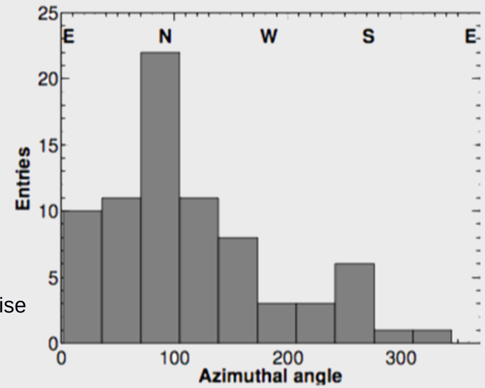
Applying SToT/cosθ > 500 and reconstructing the EAS direction:

Azimuth angle distribution

- Black: true primary particle zenith angle for the MC events that trigger both stations and fulfill SToT/cosθ > 500
- Red: the reconstructed zenith angle employing the timing info from all six detectors (data)
- Blue: the reconstructed zenith angle employing the timing info from all six detectors and the antennas (data)



The asymmetry in the direction seems to be in agreement with similar results from the CODALEMA experiment.

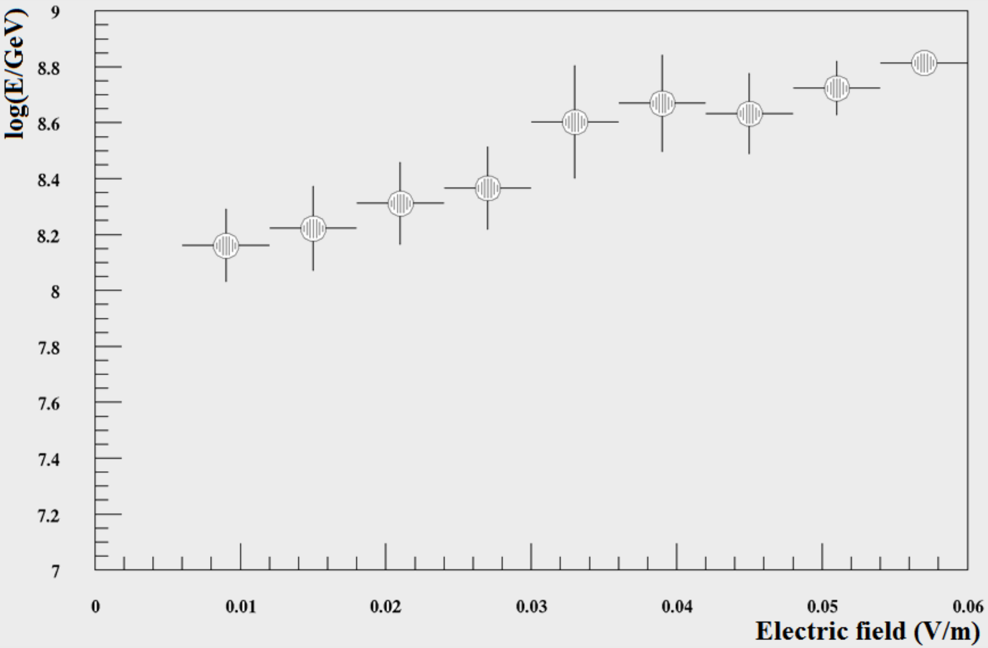


Diego Torres Machado. Radio detection des rayons cosmiques d'ultra-haute energie: mise en oeuvre et analyse des donnees d'un reseau de stations autonomes. Phenomenes cosmiques de haute energie [astro-ph.HE]. Universite de Nantes, 2013. Francais.

Radio emission simulation

Using the SELFAS simulation package to predict the electric field at the antenna positions for MC events that trigger both stations A and B and fulfill SToT/cosθ > 500, we get the electric field as a function of the energy of the EAS primary particle.

The convertion to the antenna response will be based on the 4NEC2* code package.

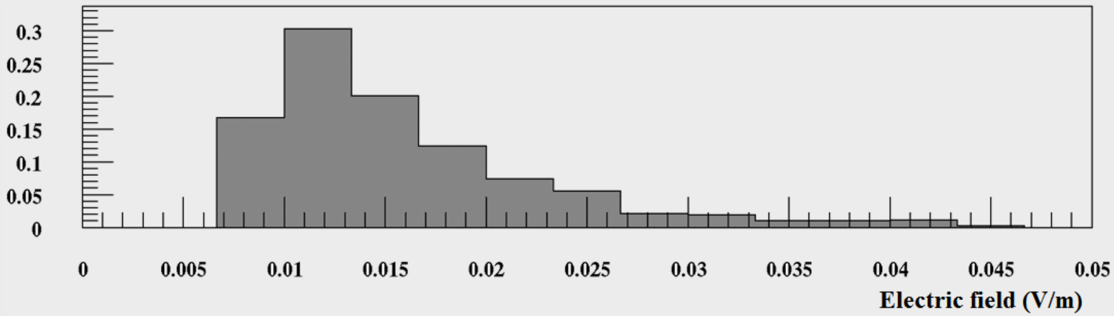


Stavros Nonis, Phd student (Aegean University)

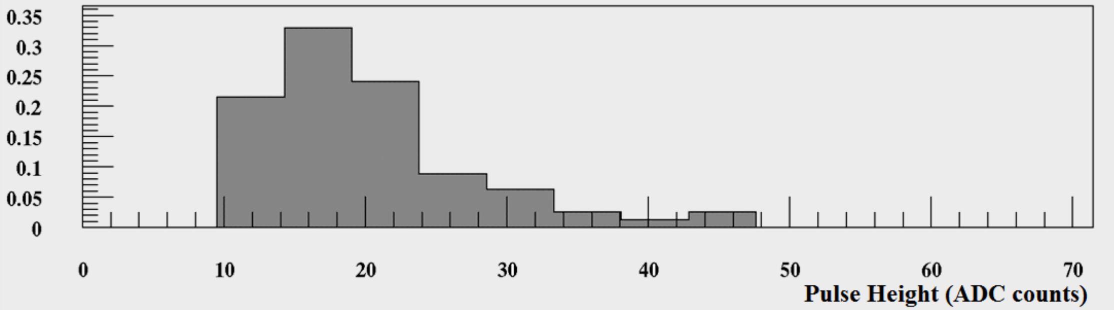
* D. Charrier for the CODALEMA Collaboration, Antenna development for astroparticle and radioastronomy experiments, Nucl. Instrum. Methods Phys. Res., Sect. A 662 (2012) 142–145

Hybrid EAS reconstruction

Distribution of the predicted electric field at the antennas position for the events that trigger both stations A and B (MC) and fulfill SToT/cosθ > 500.



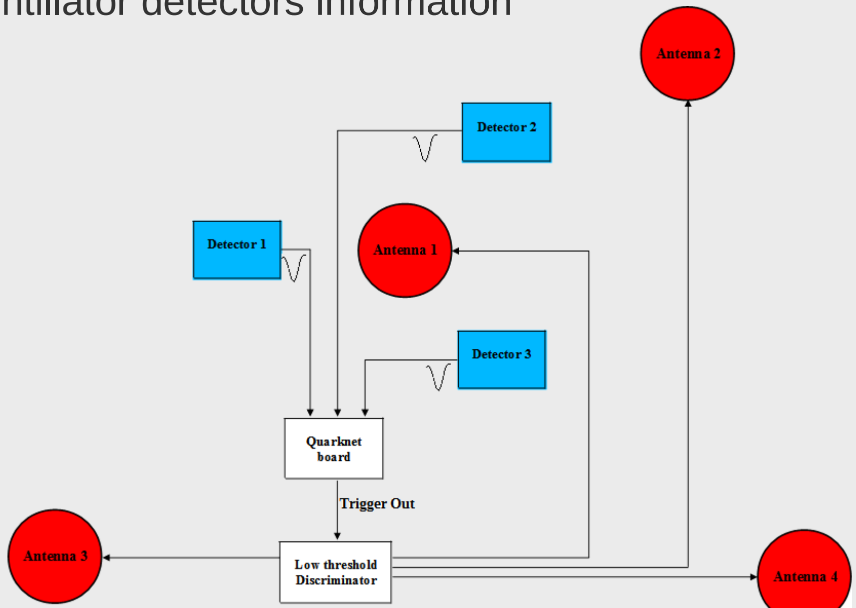
Distribution of the antennas' response (ADC counts) for data that trigger both stations A and B and fulfill SToT > 500 (data).



Stavros Nonis, Phd student (Aegean University)

Future plans

- Analyze events from single stations (full dataset)
- Analyze station coincidence events (full dataset)
- Analyzing data from the current configuration of station A with 4 antennas
  - Reconstruction of the showers direction employing information from the 4 RF antennas only
  - Reconstruction employing all (4+1) RF antennas and (3+3) scintillator detectors information
- A proposal has been submitted for the installation of 24 stations and 6 antennas at the HOU campus
  - More studies can be performed (shower core, energy, Xmax, sudden death, etc.)



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Hybrid EAS reconstruction

Timing of the

- Function gen
  response of t
- Signal driven
  trigger out sig
  RF antenna a
- Acquisition o
- Timing of the
  pulse on the