Studies for High Energy air shower identification using RF measurements with the ASTRONEU array

S.Nonis[1], G.Bourlis[2], I.Gkialas[1], A.Leisos[2], I.Manthos[1], K.Papageorgiou[1], A.G.Tsirigotis[2] and S.E.Tzamarias[2,3]

[1]Department of Financial and Management Engineering, University of the Aegean, Chios, Greece
[2]Physics Laboratory, School of Science and Technology, Hellenic Open University, Patras, Greece
[3]Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece

Introduction

The Hellenic Open University (HOU) Cosmic Ray Telescope (ASTRONEU) comprises 9 charged particle detectors and 3 RF antennas arranged in three autonomous stations operating at the University Campus of HOU in the city of Patra. In this work, we extend the analysis of very high energy showers that are detected by more than one station and in coincidence with the RF antennas of the Telescope. We present the angular distributions as well as the energy distribution of the selected showers in comparison to the Monte Carlo (MC) simulations expectations. Special attention is given to the transfer functions of the antennas which are strongly frequency and angular dependent. We find that the RF spectra (at frequencies 30-80 MHz) of the detected showers are exhibiting features of the antenna response predicted by detailed MC simulation suggesting thus, that a single antenna spectrum might give access to the Cosmic Ray arrival direction.

Air Shower Development - Radio Frequency (RF) emission

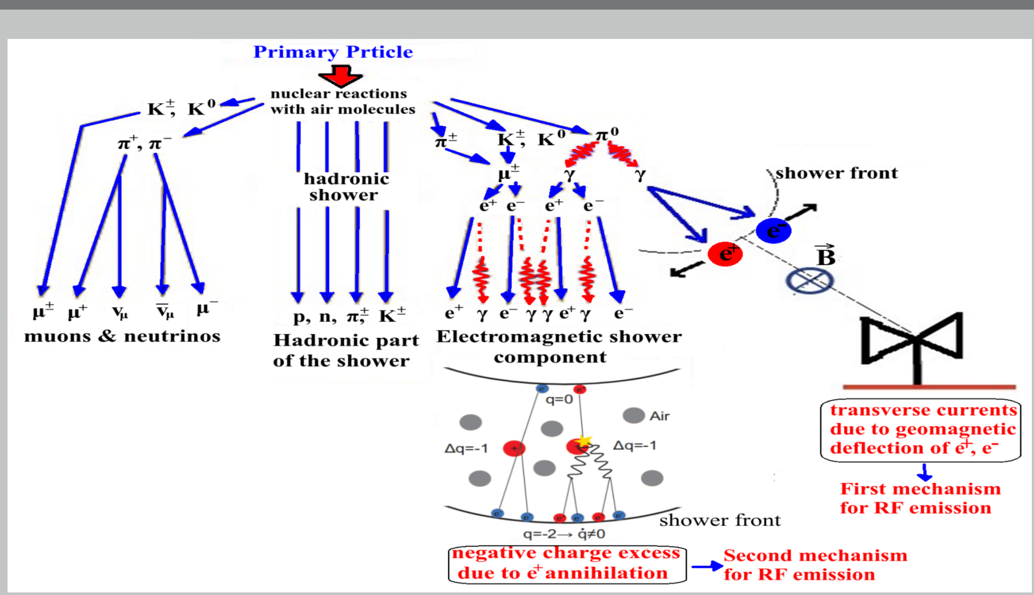

Figure 1: Schematic representation of the shower development and the main contributions to the RF emission from air-showers: (a) Geomagnetic effect: a current produced by deflection of electrons and positrons emits a radio signal (b) Askaryan effect: negative charge excess leads to a time-varying electrical potential which contributes to the RF signal.

The ASTRONEU array - Installation and Operation

- ASTRONEU is a combined scintillator detector and RF antenna array (3 stations) which was developed in the campus of the HOU in the outskirts of the city of Patras, Greece (Figure 2).
- Each station includes 3 HELYCON Detector Modules (HDM) [1] and 1 Codalema type RF butterfly antenna [2] (Figure 3).
- HDM is $1m^2$ plastic scintillator counter, made of 160 scintillating tiles.The light, which is generated by the interaction of particles with the scintillation material, is collected by optical fibers and is driven to photomultiplier (PMT). The signals of the three HDM were readout with the use of the Quarknet [3] electronics which implement the Time over Threshold (ToT) technique and measures the time of the crossings of the waveforms with predefined voltage thresholds (1.25 ns accuracy).
- The RF antenna is a "Butterfly" bowtie antenna with dimension $2x2x1m^3$ constructed with two electrically short dipole aligned in East-West (EW) and North-South (NS) directions. The dipole signals are fed directly into the input of the Low Noise Amplifier (LNA) at the center of the antenna.

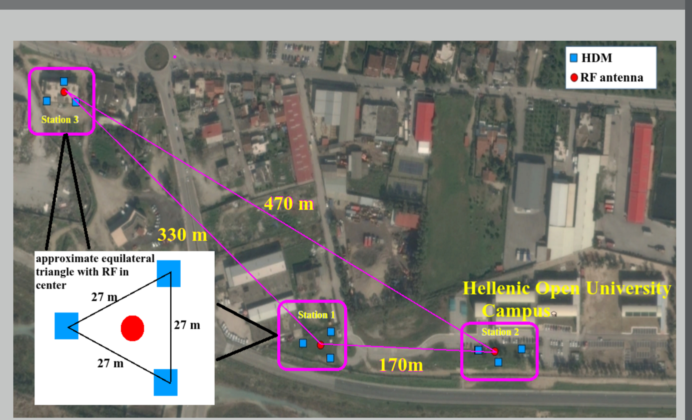

Figure 2: The outline of the ASTRONEU array installed in HOU campus, consisting of 3 stations. Each station includes three HELYCON Detector Modules (HDM) and a CODALEMA type RF antenna.

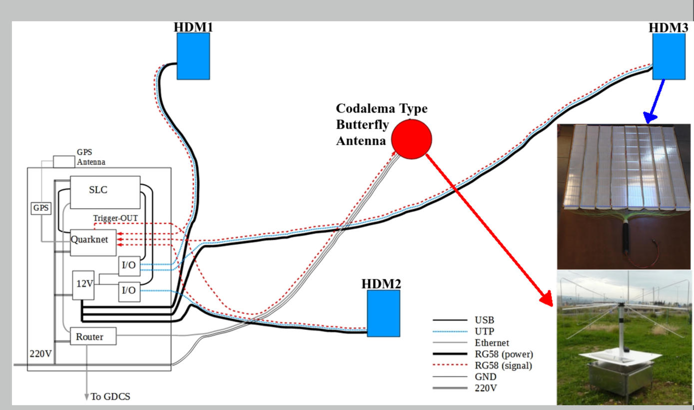

Figure 3: Schematic representation of the connections between the central Electronics Box and the station's detectors.

- The station trigger is created when all three HDM of the station acquire signal above the $\mathbf{9.7}mV$ threshold (in a trigger time window of 120 ns). This trigger signal is driven into the antenna external trigger input which activates the recording of the full **2560** buffer signal samples.
- ASTRONEU cosmic ray telescope operates in an urban environment with a lot of man made RF signals.

Event Selection - RF Analysis

RF Signal criteria for characterizing an event as of cosmic origin [4]

- It presents an intense peak localized in a narrow time interval ($\sim\mathbf{30}ns$) (Figure 4).
- Signal to Noise Ratio (SNR) criterion. The expected position of the signal in the buffer is well known (around 1100ns). Separating the hole 2560ns buffer in 11 windows (1 is the signal and 10 the noise) we calculate the SNR

$$SNR = \sum_{signal} E^2_{field} / \frac{1}{10} \sum_{noise} E^2_{field}$$

which was set > 8 for RF noisy environment.

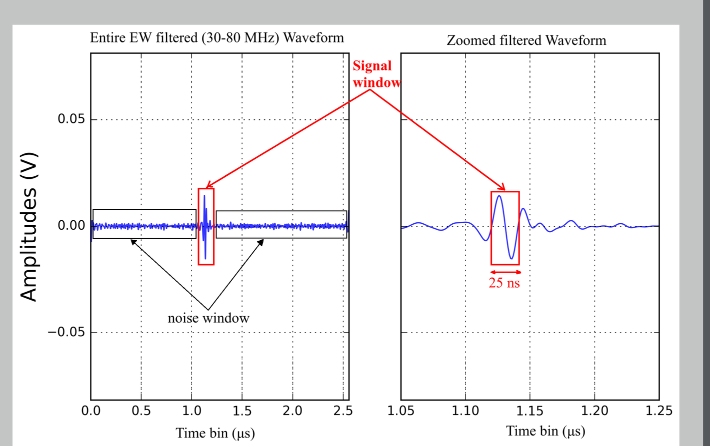

Figure 4: Filtered signal, for EW antenna pole for a cosmic event.

- It exhibits short signal rise time. Signal rise time can be defined as the time required for the normalized cumulative function

$$C(i) = \sum_{k-128}^{k+128+i} E^2_{field} / \sum_{k-128}^{k+128} E^2_{field}$$

(k is the buffer bin of signal's maximum) to switch from a low value (10% of C_{max}) to a high value (70% of C_{max}). For cosmic events signal rise time is $\leq 28ns$ (Figure 5, left).

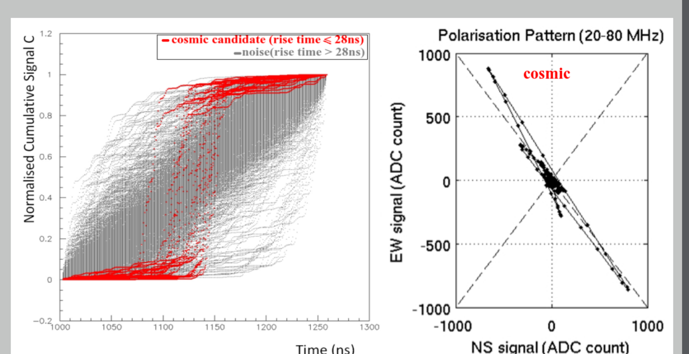

Figure 5: Left: Cumulative signal in a $\pm\mathbf{128}ns$ window around the peak voltage for antenna. Right: Polarization pattern for cosmic event

- Its polarization is approximately linear (EW vs NS) (Figure 5 right). Transverse current and charge excess have different polarization patterns (both linear). Different ellipse's inclination (with respect to x-axis) correspond to different position of antennas with respect to the shower core.

Correlation Study and Combined Performance

- Double station coincidence events select EAS with energy $> \mathbf{5 \cdot 10^3}$TeV. The timing of the EW-RF signals are examined if they are compatible with the plane particle front approximation. In Figure 7 (a) is shown the expected arrival time of the RF signal (histogram) with respect to the latest pulse of the particle detectors within the station, in comparison with the data. Including the RF signal, the zenith and azimuth distribution of the reconstructed showers is shown in Figure 7 (b) and (c). The asymmetry in the azimuth direction is expected since the EW component of the RF signal is used.
- The electric field at the antenna position can be used for the estimation of the EAS energy. This is depicted in Figure 6 (a) where the energy of the EAS that are reconstructed by stations A and B in coincidence is plotted versus the electric field at the antennas position. Taking into account the response of the RF antennas we transform the RF signals to electric field and compare with the MC prediction (Figure 6 (b)).

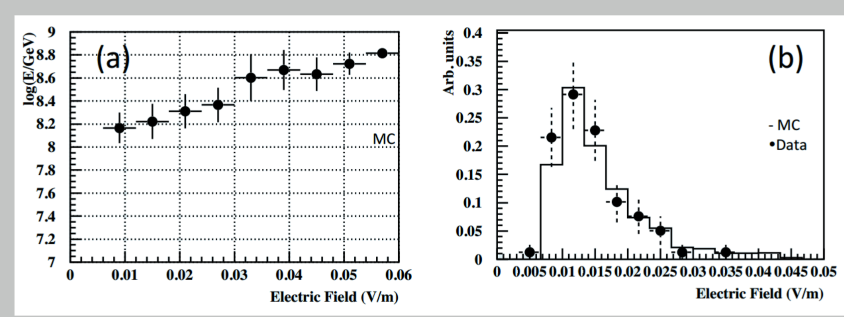

Figure 6: (a) The energy of the EAS versus the electric field (b) RF signals compare with the MC prediction

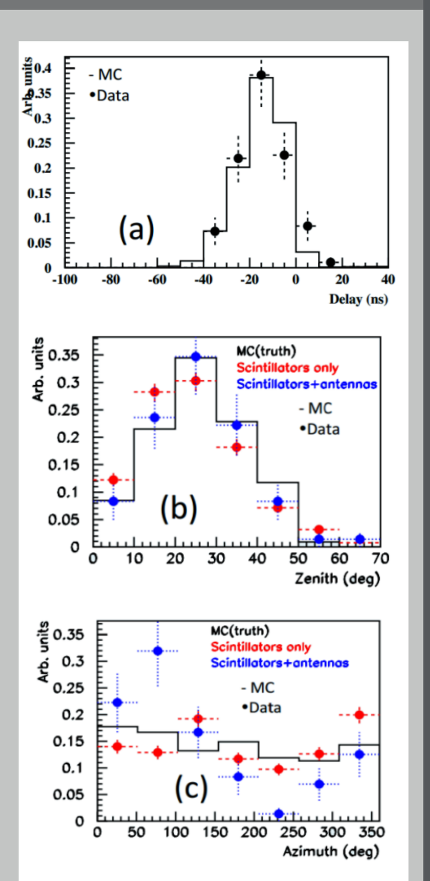

Figure 7: (a) The expected arrival time of the RF signal with respect to the latest pulse of the particle detectors, (b) the zenith and (c) azimuth distribution of the reconstructed showers

Cosmic Ray Arrival Reconstruction from Single RF Antenna Spectrum

- Detailed description of the directional and frequency dependencies of the set-up (antenna+LNA) can be achieved through Vector Effective Length (VEL) $L = \frac{V}{E}$ which can be expressed in terms of the gain and structural features of the system. We computed RF antenna's VEL with NEC simulations [2,5] (Figure 8). SELFAS is a MC autonomous code (no need for shower creator) which calculates the RF signal during shower development [6].
- The voltage response model of the system (antenna+LNA) to an incident electric field arrives from direction (θ, ϕ) is the multiplication of the field and the VEL for both polarizations (in frequency domain)

$$V_{EW/NS}(\theta,\phi,\omega) = L_{EW/NS}(\theta,\phi,\omega) \cdot E_{EW/NS}(\theta,\phi,\omega)$$

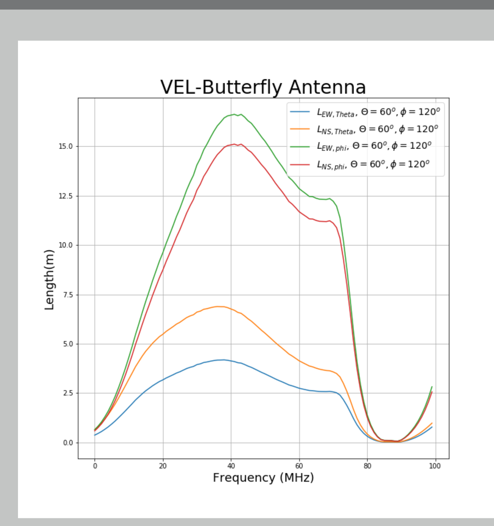

Figure 8: Butterfly Antenna VEL 30-80 MHz for EW/NS poles

- Combining NEC's simulations for the VEL in the frequency domain 30-80 MHz with the electric field generated by SELFAS 2 for various directions (fixed core, Energy, primary) we calculate a voltage response model for the RF system $V_{response} = f(\theta, \phi, \omega)$ (Figure 9)

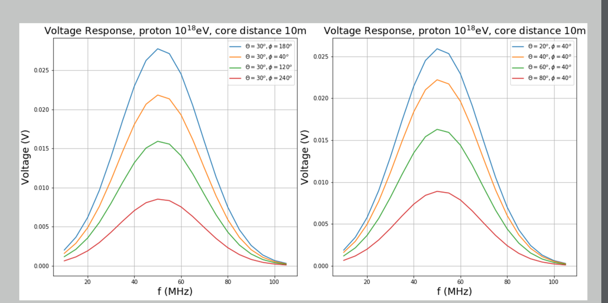

Figure 9: Butterfly Antenna voltage response model for EW pole

- We can achieve an estimation of the CR arrival direction by fitting the spectrum of a real cosmic event and the response which is calculated for different (θ, ϕ) (Figure 10) by minimizing

$$\chi^2 = \sum_{30-80MHz} (\alpha \cdot V_{response}(\theta,\phi,\omega) - V_{realevent}(\theta,\phi,\omega))^2$$

where α is a scale factror due to different energy and shower core between simulations and real event.

- We plot χ^2 as a function of θ, ϕ and fit to these data points a surface. In the total minimum of this surface we have the event arrival direction $(\theta_{event}, \phi_{event})$ (Figure 11).
- Analyzing 92 events (from both Stations 1,2) and comparing with scintillator's arrival reconstruction we found a deviation of about $\mathbf{\Delta\theta = 6.2^o}$ predicting θ and $\mathbf{\Delta\phi = 11.5^o}$ predicting ϕ (Figure 12).

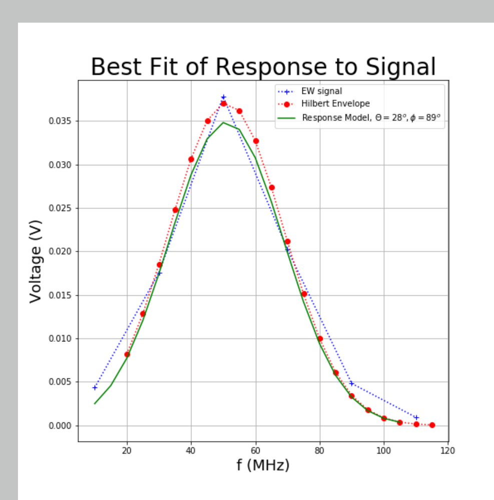

Figure 10: Example of best fit between response model and real event EW spectrum.

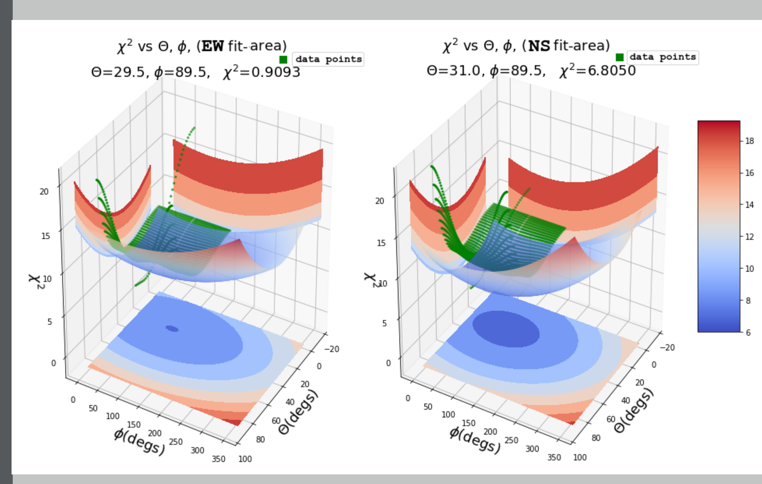

Figure 11: χ^2 plot as a function of θ, ϕ for EW and NS polariation

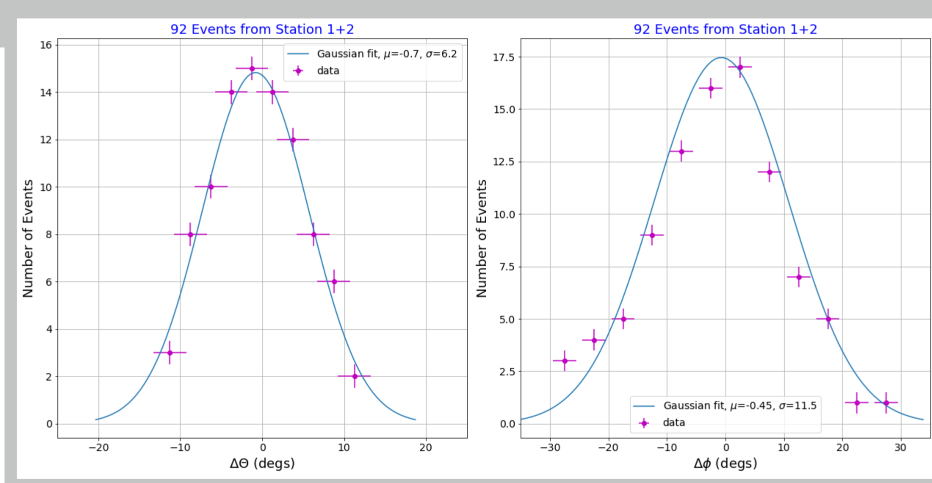

Figure 12: The distributions of $\mathbf{\Delta\theta}$ (left), $\mathbf{\Delta\phi}$ (right) for the analyzing events compared with scintillator's predictions.

Conclusions

- Using a trigger signal from particle detectors, the RF components of the showers was detected in a noisy city environment.
- Were found evidence that RF antenna's spectrum is directional depended in 30-80 MHz frequency range. This can be applied in the reconstruction of the arrival direction from single antenna's spectrum.

Acknowledgments

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References

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S. Nonis (snonis@aegean.gr)