Prospects of Measuring High Energy Cosmic Rays and Neutrinos Using Radio Antenna Arrays

K. Papageorgiou[a] and I. Gkialas[a]

[a]*University of the Aegean, Department of Financial and Management Engineering, 41 Kountouriotou Str., 82100, Chios, Greece*

Abstract. The earth is continuously bombarded by highly energetic particles, the cosmic radiation. The origin and the acceleration mechanism of the highest energy particles are still remain unknown. Understanding the origin of the ultra-high energy cosmic rays (UHECR), the highest energy particles observed in nature, is of great importance as it may impact our understanding of particle physics, fundamental cosmology, and extremely energetic phenomena in the Universe. We explore the possibilities of detecting the radio emission from cosmic ray air showers using a digital radio telescope in a form of an array of low-frequency antennas operating at 10-90 MHz. We discuss the system design requirements, calculated sensitivities and count rates.

Additionally we review several detection strategies including co-operation with particle detectors arrays consisting of large plastic scintillation counters and equipped with GPS, trigger, digitization and slow control electronics and a computer based data acquisition system, in order to provide a unique tool for the study of the energy spectrum and composition of cosmic rays and the determination of their nature and origin.

Combination of the non-ionizing electromagnetic radiation measurements in the environment with the ionization caused in the scintillation counters can lead to the calculation of the cosmic rays flux and shed some light in the study of their relation with several climatic factors like nebulosity. Finally we report on the operation status of a single low frequency radio antenna installed on Chios Island and we address the scientific perspectives of such an undertaking and effort.

Keywords: Air showers radio emission, Low frequency antennas, Radio frequency arrays, Cosmic rays
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INTRODUCTION

Charged particles that continuously impinge on the earth's atmosphere are called "cosmic rays" and constitute an important astronomical window. They mainly consist of protons and ionized atomic nuclei of elements in the range from hydrogen to iron. The origin of cosmic rays is still a matter of scientific debate and many fundamental questions are remaining unanswered. Possible sources are supernova remnants, pulsars, quasars, active galactic nuclei, or other exotic particles. Due to their wide range in energy spectrum, different emission mechanisms are also possible. Since these charged particles are deflected in the interstellar magnetic fields, important information about their origin can be extracted from their energy and mass.

High energy cosmic rays hitting the earth's atmosphere undergo nuclear reactions with atmospheric nuclei, producing elementary secondary particles in an extensive air shower propagating towards the ground with almost the speed of light. This interaction processes fall into the realm of particle physics and consequently cosmic rays form one of the most important links between the two fields and their study is at the centre of the "astroparticle" physics. Furthermore, the secondary electrons and positrons in the particle cascade are then deflected by the earth's magnetic field producing dipole radiation in the frame of the shower as in synchrotron radiation. This radio emission from cosmic ray air showers can be detected using an array of low-frequency antennas. Because a significant fraction of the natural radioactivity on earth is caused by the fragments of cosmic ray induced extensive air showers, cosmic ray related effects have significance in our every day life. Additionally, strong evidence for a direct link between the cosmic ray flux reaching the earth and several climate factors like nebulosity have also been reported [1].

Direct measurements of cosmic rays are only possible above the earth. Due to their low flux, cosmic rays at energies above 1 PeV cannot be effectively measured by direct measurements. A standard method to observe these cosmic rays is to measure the secondary particles of an extensive air shower with an array of particle detectors on the ground. As the state of an air shower at the ground level depends on many factors, like primary particle energy and type, atmospheric conditions and statistical fluctuations, the determination of primary particle energy and type from the measured particles is not straightforward. Very useful information for the determination of primary particle energy and type can be obtained by additionally observing the air shower as it evolves.

Measuring radio emission from air showers might be an alternative method for such observations, providing a much better efficiency. This becomes particularly relevant since a new generation of digital radio telescopes – designed primarily for astronomical purposes – promises a new way of measuring air showers.

EMISSION PROCESS

Experiments have clearly established that cosmic ray air showers produce radio pulses. Two main emission mechanisms have been proposed in the past for radio emission from Extensive Air Showers (EAS). The original motivation suggested by Askaryan [2] was that the annihilation of positrons would lead to a negative charge excess in the shower and therefore can produce Cherenkov radiation as it moves through the atmosphere with a velocity higher than the speed of light in that traversed medium.

At radio frequencies the wavelength of the emission is larger than the size of the emitting region and the emission should be coherent. The radio flux would then grow quadratically with the number of particles rather than linearly and thus would be greatly enhanced. This effect is important in dense media where it was already experimentally verified [3] and is important for detecting radio emission from neutrino showers in ice or on the moon.

However, the dependence of the emission on the geomagnetic field detected in several later experiments indicates that another process may be important. The basic view according to the other proposed mechanism by Kahn and Lerche [4] was that the continuously created electron–positron pairs were then separated by the Lorentz force in the geomagnetic field which led to a transverse current in the shower. If one considers a frame moving along with the shower, one would observe electrons and positrons drifting in opposite directions impelled by the transverse electric field induced by the changing geomagnetic flux swept out by the shower front. This transverse current then produces dipole (or Larmor) radiation in the frame of the shower. When such radiation is Lorentz-transformed to the lab frame, the boost then produces strongly forward beamed radiation, compressed in time into an electro-magnetic pulse.

An equivalent scenario to that of the transverse currents is the coherent geosynchrotron emission [5] from highly relativistic electron-positron pairs gyrating in the earth's magnetic field. Coherence is achieved since the shower in its densest regions is not wider than a wavelength around 100 MHz and at a few kilometer height the phase shift due to the lateral extent of the shower for an observer on the ground is similarly less than a wavelength even out to some 100 m from the core. The proposed coherent geosynchrotron process is derived from the basic formula for dipole radiation but does not require a consideration of charge separation. The different sign of the charges of electrons and positrons in the shower is almost completely canceled by the opposite signs of the Lorentz force acting on electrons and pairs. Hence both populations will contribute in roughly the same way to the total flux and will not interfere destructively.

To an observer at the ground the acceleration vectors of electrons and positrons projected on the sky point in opposite directions and hence the systems resembles a radiating dipole, with electrons going in one direction and holes going in the other direction.

RADIO PROPERTIES OF EXTENSIVE AIR SHOWERS

Radio emission from cosmic ray Extensive Air Showers (EAS) was discovered for the first time by Jelley [6] in 1965 at a frequency of 44 MHz, using an array of dipole antennas in coincidence with Geiger counters. The results were soon verified and emission from 2 up to 520 MHz was found in the late 1960s. Due to the difficulty with radio interference, the uncertainty about the interpretation of experimental results and the success of other cheaper experimental techniques for air shower measurements, these activities almost completely ceased in the subsequent years.

The radio properties of air showers are summarized in an extensive review by Allan [7]. The main result of this analysis led to the following approximate formula relating the received time-integrated voltage of air shower radio pulses with other various parameters,

$$\varepsilon_v = 13\,\mu V\ m^{-1}\ MHz^{-1}\left(\frac{E_p}{10^{17}\ eV}\right)\left(\frac{\sin a.\cos\theta}{\sin 45^\circ.\cos 30^\circ}\right)\exp\left(\frac{-R}{R_0(\nu,\theta)}\right)\left(\frac{\nu}{50\,MHz}\right)^{-1}$$

where E_p is the primary particle energy, R is the offset from the shower center and R_0 is around 110 m at 50 MHz, θ is the zenith angle, a is the angle of the shower axis with respect to the geomagnetic field, and ν is the observing frequency. Some discrepancies in the frequency scaling factor may be due to the systematic errors in the determination of the primary particle energy E_p which was used to normalize the results.

DETECTING EXTENSIVE AIR SHOWER RADIO EMISSION

Conceptual Design of a Cosmic Rays Radio Detector

The basic idea is to build an array of four quasi-omnidirectional low frequency dipole antennas (RF Station) distributed at the site of the HELYCON (Hellenic Lyceum Cosmic Observatories Network) experiment in Chios Island, Greece, in order to investigate the properties of the radio component of an extensive air shower. Upon global trigger arrival from a pre-defined number of particle detector stations, the received waves from the low frequency antennas are then digitized and sent to a central cluster of computers, taking advantage from an interesting feature of the experimental design to store the entire data stream for a certain period of time.

HELYCON [8] consists of four detector stations, each one equipped with three large plastic Scintillation Counters for Extensive Air Shower detection. It also includes a Global Positioning System (GPS) device, trigger and digitization electronics, slow control electronics and a computer based data acquisition system. The time synchronization between the detector stations rely on the timing signals from the GPS navigation satellites. The first installed RF antenna was designed and developed by ASTRON [9] as prototype for the HELYCON experiment and it is very similar to those used in LOFAR experiment [10], a large array for astronomical purposes. At low frequencies the RF station has the ability to monitor a large fraction of the sky at once. This can be used to look for astrophysical transients, such a gamma ray bursts, X-ray binary flares and other interesting phenomena, opening a completely new window for radio astronomy.

From a scientific point of view the aim of such a prototype station of cosmic rays radio detector is to correlate the observables of the radio emission measurements with the shower properties provided by the array of the particle detectors of HELYCON experiment. Due to the fact that the prototype cosmic rays radio detector is triggered by the HELYCON particle detectors, the reconstructed shower data can be used initially as starting values in the development of a standalone reconstruction algorithm of the radio signals in a self-triggering antennas scheme. Therefore the unique combination of an established and well understood air shower together with a new detection technique offers the best opportunity to study the radio emission in extensive air showers.

THE HARDWARE OF THE COSMIC RAYS RADIO DETECTOR

Scintillation Counters

The HELYCON charged particle detector is a scintillation counter of 1 m^2 active area. It is made of two layers of polystyrene scintillation tiles, adjusted on a wooden frame. Each layer consists of 25 tiles (tile dimensions: 200x200x5 mm^3) wrapped in reflective paper. The scintillation light is collected by 40 in total wavelength shifting optical fibers (Bicron BCF-91A), embedded inside the grooves of the scintillating tiles and it is detected by an FEU-115M [11] photomultiplier tube (PMT). The efficiency of the scintillation counters is better than 99% for minimum ionizing particles. A Cocroft-Walton voltage multiplier mounted on the wooden frame of the detector, supplies high voltage (HV) to the photomultiplier tube with low voltage external feeding of 18 V. Finally, the whole construction is enclosed inside a water resistant wooden box. A Scintillation Counter of the HELYCON experiment is shown in figure 1.

The electrical pulses of each PMT are curried to the digitization electronics by a long (~200 m) RG58 cable. The control and monitor signals are transmitted through standard UTP cables. The Readout system is based on a High Precision Time to Digital Converter (HPTDC) chip, designed at CERN, whilst a 12-bit multifunction USB data acquisition card (National Instruments USB-6008) is used for the slow controls. The synchronization between the HELYCON stations relies on the GPS (Motorola M12+) time signal.

The Readout card for HELYCON was designed and developed in the Detector Instrumentation Laboratory of the Nuclear Physics Institute at “DEMOKRITOS” [12] and offers up to 5 analogue inputs, each one for a scintillation detector. The input signals are amplified and compared to six predefined and remotely adjustable thresholds. The corresponding times of the PMT waveform-threshold crossings are digitized with an accuracy of 100 ps by the HPTDC, along with the 1 PPS output of the GPS receiver. A first level trigger is formed as the fast hardware coincidence between two of the PMT inputs. Second level triggers are realized in the Field Programmable Gate Array (FPGA) of the Readout card, requiring a certain time relation between the input signals. Both the first and the second level triggers are provided as NIM and as TTL card outputs. The FPGA is also responsible for formatting the data and for communicating with the station (local) PC through the USB or/and the Ethernet ports of the card. The data are saved on the hard disk of the local computer and transmitted on request, via the Internet, to the central server of the HELYCON telescope.

FIGURE 1. A Scintillation Counter of the HELYCON experiment

The RF Station

The RF station operates in the frequency range of (10–90) MHz. This is a band where there are few strong man made radio transmitters, as it lies between the short-wave- and the FM-band. Also the frequency is low enough, that the emission from air showers is strong, while it is still high enough, so that the background emission from the galactic plane is still low.

The basic element of the RF station is a Low Band antenna (LBA) originally developed by ASTRON for HELYCON experiment in Chios Island. It consists of two perpendicular inverted-V shaped dipole antennas and two active baluns, integrated on a single board, to provide amplification and impedance transformation. Mechanically, the antenna consists of a centre pole that is kept upright by four wires. The top part of each wire is made of copper and these wires form the four dipole arms. The lower parts of two (perpendicular) wires consist of rubber springs. The height of the antenna feed point is governed by the radiation pattern at the highest frequency and the sensitivity at the lowest frequency. A higher antenna will increase the sensitivity at lower frequencies, but will degrade the pattern (the sensitivity towards zenith) for the highest frequencies (optimum height ~3/8 of the shortest wavelength). A photograph of the LBA antenna is depicted in figure 2.

FIGURE 2. The Low Frequency Antenna used in the Cosmic Rays Radio Detector experiment.

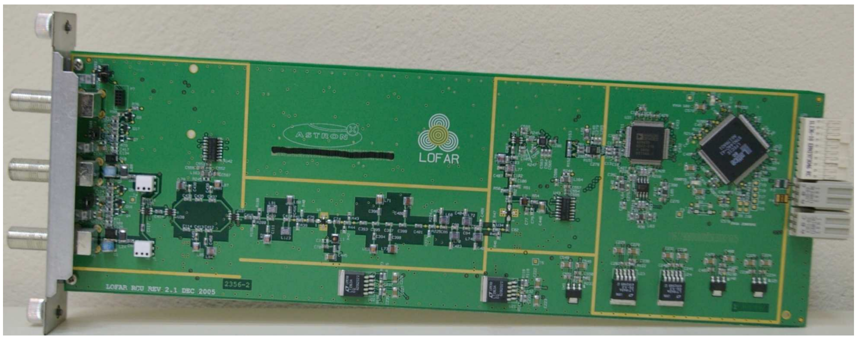
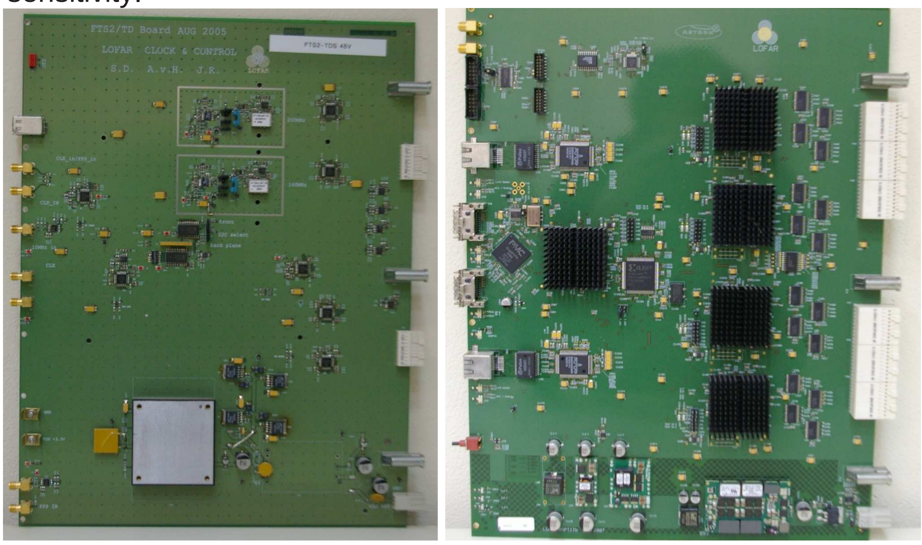


FIGURE 3. The Receiver Unit (RCU)

Received radiation is converted into electrical signals. The analogue signals are then transported over coaxial cables toward the Receiver Unit (see figure 3). The receiver converts the signals into the digital domain and once digital, the filter block takes care of representing the broad band signal at the input of the filter. The radio frequency signal is sampled without the use of a local oscillator inside the receiver module. The necessary dynamic range to detect weak pulses while not saturating the ADC with radio interference is achieved by using 12-bit ADCs. The sampling rate is 200 MHz. The sample clock for the ADC's is generated on a central clock module, the Time Distribution board (TDS) shown in figure 4a and is then distributed to all boards. This allows us to combine the data from all antennas as a phased array and thus enhance the sensitivity.



(a) (b)

FIGURE 4. (a) The Time Distribution Board (TDS) and (b) The Remote Station Processing (RSP) board

From the Receiver Modules (RCU's) the signals are fed to the Remote Station Processing (RSP) board, shown in figure 4b, where they are filtered and beam formed. After a trigger signal is received, the data is read out and sent to a central DAQ-PC, the Local Control Unit (LCU), where it can be analyzed online or stored on hard disk. The LCU is a 19 inch rack PC with Redhat Linux operating system. This system can be accessed locally via keyboard and mouse and remotely via the switch with an SSH link. The LCU controls all the boards in the sub-racks, it receives the timing signal and can be also used to monitor the temperature inside the station or read alarm contacts. All the specialized hardware for the RF station in Chios Island was developed at ASTRON in Dwingeloo, Netherlands in the frame of INTERREG IIIA program.

CURRENT STATUS AND FIRST RESULTS

The first stage of the Cosmic Rays Radio Detector located in Chios Island is nearly complete. The sub-rack for the RF system (see figure 5) and one antenna is set up at the HELYCON experiment site, where all the twelve scintillation counters have already been deployed. At the time of writing the low frequency antenna is taking air shower data.

FIGURE 5. The Receiver Unit (RCU)

A preliminary analysis of the first data has already been performed. A power spectrum received from the single operating low frequency antenna during a data taking phase is reconstructed using an offline reconstruction algorithm, running on the data set stored in the hard disc of the DAQ-PC and the results are depicted in figures 6a and 6b for X and Y polarity respectively.

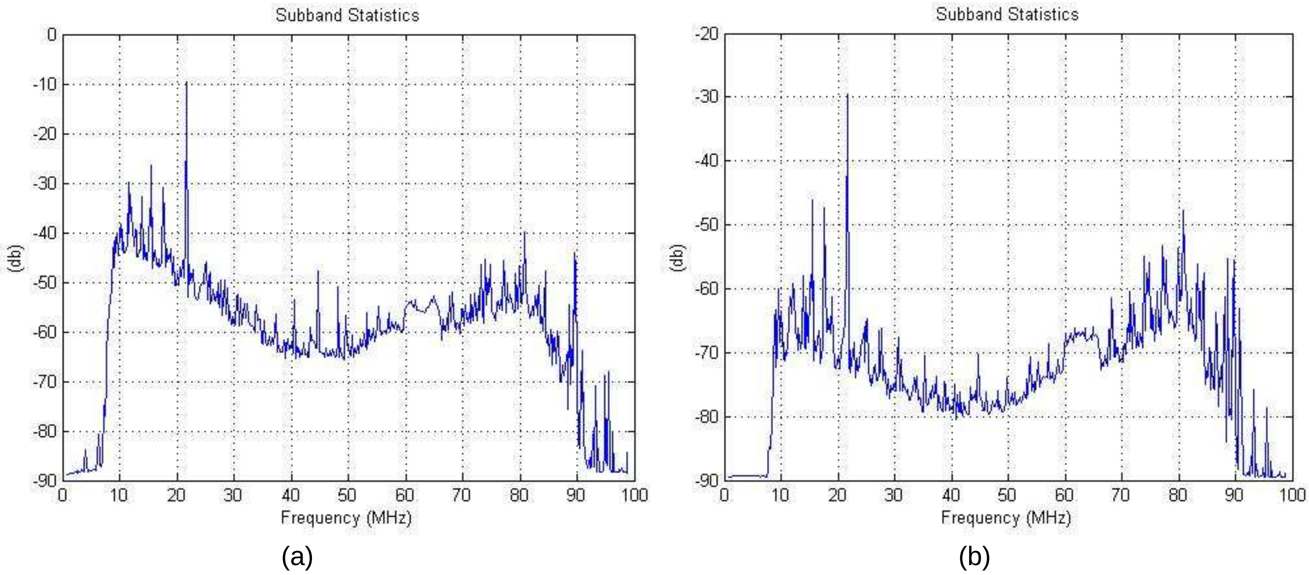


FIGURE 6. (a) Left Panel: Offline reconstruction of a power spectrum received from the single RF antenna during an online data taking phase, (b) Right Panel: Offline reconstruction for Y-polarity and for the same data set

OUTLOOK AND DETECTION STRATEGIES

Currently we are working on the development of reconstruction algorithms for data analysis and for the improvement of the system for the second stage. As it is already pointing out the detection of astrophysical transient events could benefits from the current design (using an external trigger from particle detectors) of the Cosmic Rays Radio Detector, although the development of a standalone piece of software to detect radio emission from extensive air showers is mandatory for self-triggering antennas scheme. The basic idea behind is to correctly combine the signals from all the different dipoles of the telescope array by beam forming, thus taking into the account the appropriate time delay in signal reception due to the distances between the antennas. This technique is expected to increase the sensitivity and to further suppress the radio frequency interference.

By applying different shifts to the many antenna signals, someone can point the telescope virtually anywhere, because the individual elements don't need to be pointed. One data set for a certain period of time contains data of the entire sky.

In conclusion state of the art electronics and information technology can be used to digitally form multiple beams in almost any desired direction. With such a technology one can adaptively form beams in any shape and even look back in time using buffered data and taking advantage from this interesting feature of the telescope design.

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