International Journal of Conceptions on Electrical and Electronics Engineering
Vol. 3, Issue. 2, August 2015; ISSN: 2345 - 9603

A radio detector for cosmic rays in the Northern Hemisphere

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Abstract— **Detection of cosmic rays (CR) can answer very important questions related to some extremely energetic yet unexplained astrophysical sources such as: compact binary stars, accreting black holes, supernovae etc., key elements in understanding the evolution and fate of the Universe. Moreover, these particles carry the highest energies per particle known to man, impossible to achieve in any present or foreseen man made accelerator devices thus their detection can test and probe extreme high energy physics. We concentrate our efforts in studying the possibility of building a radio observatory for cosmic rays, in the northern hemisphere. In this paper we look into the best possible locations of the new site, based on the characteristics of the radio emission from CR interactions. We also investigate its geometry and calculate the optimal number of radio detectors. The antenna spacing is determined such as the detection efficiency is as high as possible.**

Keywords- cosmic rays;radio detection;

I. Introduction

The Earth is continuously hit by cosmic rays (CR) that originate outside the atmosphere. This radiation was discovered by Victor Hess [1] during a balloon flight experiment. He observed that the intensity of the ionized radiation over 1000m is increasing with the height increase so he concluded that this radiation comes from extra-terrestrial sources.

So far there is no generally accepted theory to explain the origin of the high energy cosmic particles, their acceleration nor their reactions in the interstellar medium.

When a high energy particle enters the atmosphere and hits a nucleus, a cascade of secondary particle will appear. This secondary will interact to produce other secondary or will decay in lighter particles. The particle disk will move in the direction of the original particle and will grow up to a maximum. Together these particles form an **E**xtensive **A**ir **S**hower (EAS). At the maximum, ionization losses of electrons and positrons roughly equal their-ray production through bremsstrahlung (at a critical energy of about 80MeV in air [2]). At the end electrons lose their energy due to ionization. If the energy of the initial particle is high enough, this shower can be measured at ground level.

Particles with energies below 10^{14} eV can be measured directly with detectors on balloons or satellites. This measurements allow analysis of the energy, chemical composition etc.

Above this energy the particle flux is too small and experiments of this type become too expensive. The advantage is that they will generate EASs that can be measured with surface detectors (experiments KASCADE-Grande in Germany [3], AGASA in Japan [4], Auger surface detectors (SD) [5] etc.). The information about the primary particle is indirect.

At energies above 10^{18} eV another technique becomes useful, that is fluorescence in the visible waves emitted by excited nitrogen molecules along the shower. They have the advantage of giving information about the deposited energy in the atmosphere and allow a better reconstruction of the chemical composition and energy of the primary particle. The disadvantage is the low duty cycle (below 10%). The most popular experiment is “High Resolution Fly’s Eye” din Utah, USA [6].

The two mentioned techniques give complementary information so hybrid detectors are extremely useful [7] .

In 1965, Jelly [8] considered the possibility that EASs produce radio emission at a frequency of about 40 MHz. Radio detection technique may provide additional information which is complementary to that from surface and fluorescence detectors, as it determines directly the evolution of the electromagnetic properties of the shower in the atmosphere.

Pierre Auger Observatory (PAO), with a unique setup, allows registering air showers simultaneously with all three independent detection methods: radio waves, fluorescence light, and particle detection in water Cherenkov detectors. *Auger Engineering Radio Array (AERA)* -the radio extension of the PAO in Argentina- made a step forward in radio detection of CR [9], [10]. It records radio signals in the 30-80MHz band, sampled at 200MHz. Its deployment has started in 2010. Stable physics data-taking has begun in March 2011 and the first super-hybrid radio/particle/ fluorescence detected events have been recorded in April 2011.

After the decision in the United States not to support the construction of a new observatory in America, the PAO collaboration decided to revisit the science case, the general design and technological solution, as well as new possible sites in the next 3-5 years. This is the reason why we look into the best possible locations of the new site, based on the characteristics of the radio emission from CR interactions (Section II). We also investigate its geometry and calculate the optimal number of radio detectors. The antenna spacing is determined such as the detection efficiency is as high as possible (Section III). Last section presents the main results and conclusions.

II. RADIO EMISSION FROM EAS

Measuring the radio emission during an EAS development is a new detection technique. The radio waves can be recorded day and night, and provide a bolometric measure of the electromagnetic shower component. The quadratic dependence of the received radio power on primary energy (the energy radiated through coherent emission is expected to be proportional to the square of the number of charges within the shower [11]) will make radio detection a cost effective method for measuring the longitudinal development of air showers of the highest energy cosmic rays.

The mechanisms behind the radio emission are not completely understood. It appears that the dominant emission mechanism is due to the Earth's magnetic field that interacts with the charged particle to create both transverse currents and synchrotron radiation [12]. The Askar'yan effect should also exist for EASs [13], [14] together with effects from dipole moments.

A number of experiments for determining the polarization of the radio radiation [13] together with a set of theoretical studies confirmed that the main mechanism behind radio emission is due to geomagnetic effects.

The mechanisms behind radio emission can be derived also from the radio lateral distribution due to the fact that the latter can be related to important physical quantities such as the primary energy or the mass of the primary. More over, the lateral shape defines the optimum grid size for a radio antenna array in a stand-alone mode. Of particular interest is the scale parameter which describes the amount of the signal decrease with distance from the shower axis and the dependence of that parameter on characteristics of the primary particle.

Experimentally, Horandel [16] found that the radio emission is:

$$E = (11 \pm 1)\left((1.16 \pm 0.025) - \cos\delta\right)\cos\Theta \times$$
$$\times \exp\left(-\frac{L}{236 \pm 81\mathrm{m}}\right)\left(\frac{E_0}{10^{17}\,\mathrm{eV}}\right)^{0.95\pm0.04}\left[\frac{\mu\mathrm{V}}{\mathrm{mMHz}}\right] \quad (1)$$

where E_0 represents the energy of the primary particle, L represents the distance between the antenna and the shower axis, δ - the angle between the shower axis and the magnetic field vector and Θ - showers's zenith angle.

To avoid projection effects connected to the geometries of the cascades, the ground coordinates where back-projected in the shower coordinate system (the distance perpendicular to the shower axes). The geometry is given in figure 1. It is trivial to show that the transformation from the ground plane to the shower plane is given by:

$$L(r) = r\sqrt{1 - \cos^2(\Phi_{obs} - \Phi)\sin^2\Theta} \quad (2)$$

where (Φ, Θ) represents the azimuth and the zenith of the shower and (r, Φ_{obs}) -the distance to the shower core and azimuth of the observer.

In order to determine the radio emission at each antenna, we considered a rectangular grid, as suggested in figure 2. The number of antennas is equal on the two axis and the spacing between elements is equal in both Ox and Oy directions.

Using equations (1) and (2) we calculated the radio emission recorded by an observatory in Malague (e.g. PAO). The spacing between antennas is fixed (50m) and the number of antennas on each axis is 120 –figure 3. One can notice the geometrical projection effects for showers with higher inclination (Θ=60 deg.)

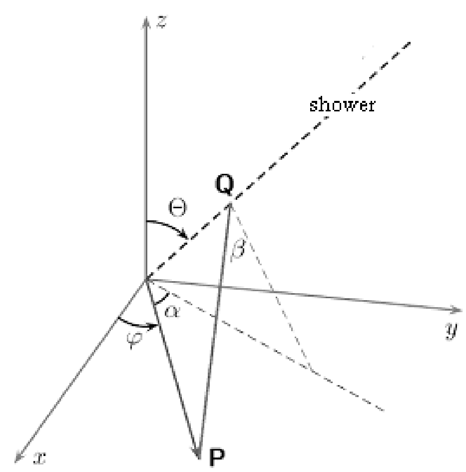

Figure 1. The polar representation of the observation point P(r,φ) on ground and in the shower plane P(r_0, β). Here α=φ-Φ, where Φ and Θ are the azimuth and the shower zenith.

Studies of radio emission are necessary because a radio detection system (antenna array) should be built with a minimum cost (that is the number of antennas should be minimal). One should investigate the dependence of the emission on the magnetic field direction in order to choose the best location of an observatory in the North hemisphere.

We spotted a number of geographical positions on the globe, based on the two criteria: a large flat surface that must be situated at a high altitude: Ufa Plateau (Russia; height 350-450m), Norrland Plateau (Sweden, 500-800m), Anatolia Plateau (Turkey, 600-1200m), Meseta Central (Spain, 610-760m), Aintab Plateau (Syria, cca. 400m), Suceava Plateau (Romania, 400-500m). Using NOOA's online magnetic field calculator [17], we determined the characteristics of the magnetic field at each location (for the city closest to the mentioned geographical position).

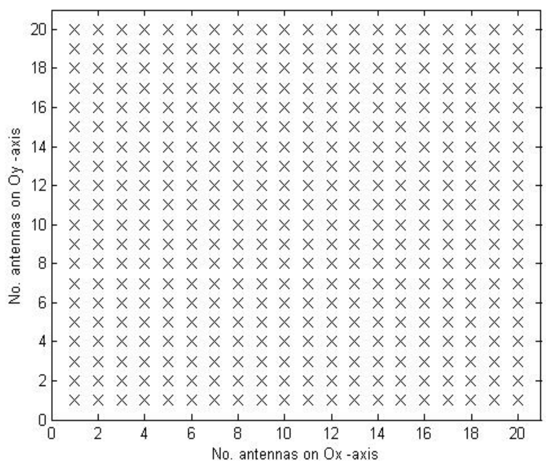

Figure 2. Antenna grid: the spacing between antennas is equal in the Ox and Oy directions

For the six locations, the maximum intensity of the EM filed was calculated. As the radio field depends on the azimuth of the shower, we presented results for different incoming directions of the cosmic radiation: 0, 45, 90 and 135 deg. (in all cases the zenith was considered 30 deg.). Results in figure 3 were obtained for an initial particle with an energy of 10^{19}eV.

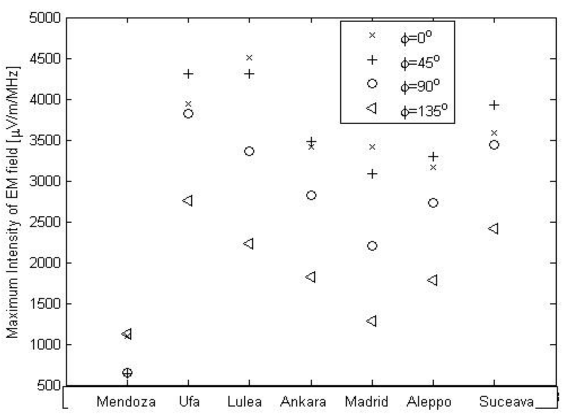

Figure 3. Maximum intensity of the EM field for seven locations. Different markers present several incoming directions of the CR

One can notice that the maximum intensity of the field is obtained if the observatory is situated in Sweden. From now on, all simulations will be performed for this location.

III. DETECTOR EFFICIENCY

In the frequency range of interest (30MHz-100MHz), the galactic noise varies between 10000K and 1000K. This corresponds to a field strength of about 3μV (that will be the threshold in the following simulations).

The array efficiency was calculated (figure 4). It was defined as the number of antennas that detect a signal higher than the threshold, divided by the total number of antennas in the array (here 400). It were considered the maximum and minimum values of the EM field strength, obtained for Φ=45 deg. and Φ=135 deg. incoming directions of the shower. The shower zenith was set to 30 deg.

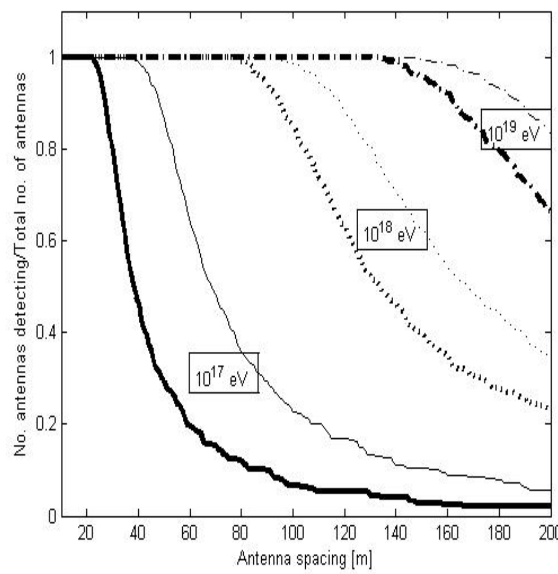

Figure 4. The thicker line presents the array efficiency for an incoming direction given by Φ =135 deg. and the thinner – the efficiency for Φ =45 deg. Continuous line marks an incoming particle with an energy of 10^{17}eV, the dotted line- an energy of 10^{18}eV and the dash-dotted line- an energy of 10^{19}eV

For a fixed incoming directions of the shower (Φ =135 deg.) -minimum EM field strength- we calculated again the array efficiency, for different shower zenith- 30 degrees and 60 degrees (figure 5). Here we imposed a minimum number of 10 antennas to record a signal higher than the galactic noise.

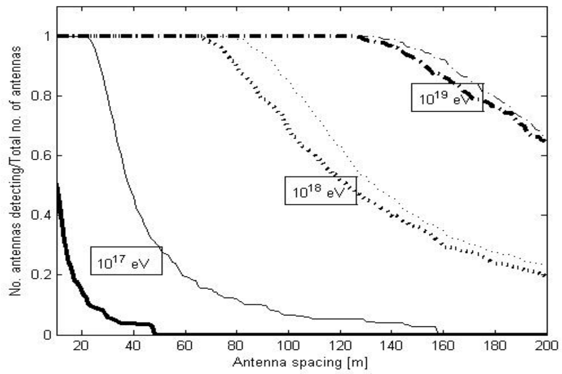

Figure 5. ction given by Θ=30 deg. and the thinner – the efficiency for Θ =60 deg. Continuous line marks an incoming particle with an energy of 10^{17}eV, the dotted line- an energy of 10^{18}eV and the dash-dotted line- an energy of 10^{19}eV

Last simulation presents the maximum permitted spacing between antennas that allows reconstruction of the primary particle characteristics. We allowed a minimum efficiency of 0.8, a threshold of 3μV detected by at least 10 antennas (figure 6). The initial energy of CR is 10^{19}eV.

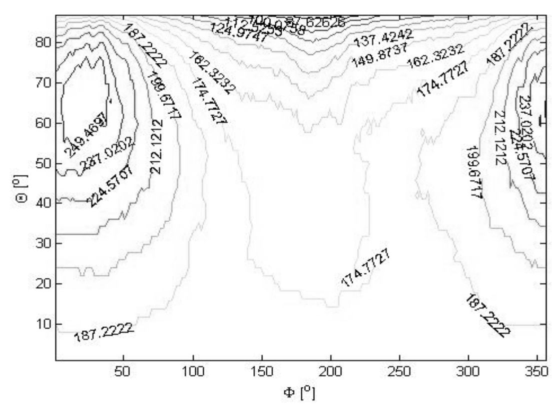

Figure 6. Maximum spacing between antennas (details are given in text)

IV. Conclusions

Based on the terrestrial magnetic field inclination we determined the best site for the construction of a new CR observatory in the North hemisphere- Lulea, Sweden. Selection was made considering the maximum intensity of the EM field that can be detected using a rectangular antenna array. Another factor to include in future simulations is the precipitation rate and its effects on the considered radio frequency band (tens of MHz).

As it can be seen, the minimum energy to be detected limits the spacing of antennas. For energies thresholds of 10^{18}eV, the maximum baseline should be of 100m.

One can notice that such an observatory will me most sensible to very inclined showers (with zenith angles of about 60 deg.). Detection of showers coming from all directions is possible if the maximum spacing between antennas is at most 100m.

References

[1] V. Hess, „Über Beobachtungen der durchdringenden Strahlung bei sieben Freiballonfahrten“, Physikalische Zeitschrift, vol. 13, 1084-1091, 1912

[2] J. Petrovic et al., “Radio emission of highly inclined cosmic ray air showers measured with LOPES”, J. Phys. Conf. Ser., 39-471, 2006

[3] A. Haungs et al., “Investigating the 2nd knee: The KASCADE-Grande experiment”, J. Phys.: Conf. Ser., 47-238, 2006

[4] T. Yamamoto, K. Mase, M. Takeda, N. Sakaki, M. Teshima, “Signatures of ultra-high energy cosmic ray composition from propagation of nuclei in intergalactic photon fields”, Astropart. Phys. 20, 405-412, 2004

[5] Abraham et al. (Pierre Auger collaboration), “Trigger and aperture of the surface detector array of the Pierre Auger Observatory”, Nucl. Instr. and Meth. in Phys. Res. A 613, 29-39, 2010

[6] P. Sokolsky et al., “Final Results from the High Resolution Fly's Eye (HiRes) Experiment”, XVI International Symposium on Very High Energy Cosmic Ray Interactions ISVHECRI 2010, Batavia, IL, USA (28 June - 2 July 2010), 2010

[7] A. M. van der Berg et al (for the Pierre Auger Collaboration), “Radio detection of cosmic rays at the southern Auger Observatory”, 2009

[8] J. V. Jelley, J. H. Fruin, N. A. Porter, T. C. Weekes, F. G. Smith, R. A. Porter, “Radio Pulses from Extensive Cosmic-Ray Air Showers”, Nature, 205-327, 1965

[9] P. Abreu et al. (Auger collaboration),”A search for ultra-high energy neutrinos in highly inclined events at the Pierre Auger Observatory”, Phys. Rev. D 84, 122005, 2011

[10] A. M. van den Berg,”Radio detection of cosmic rays at the southern Auger Observatory”, Proceedings of the 31st ICRC Lodz, 2009

[11] D. Ardouin, D. Belletoile, R. Charrier et al., “Radio-Detection Signature of High Energy Cosmic Rays by the CODALEMA Experiment”, Nucl. Instr. Meth., A 555-148, 2005

[12] K. de Vries, A. M. van den Berg, O. Scholten, K. Werner, “The Lateral Distribution Function of Coherent Radio Emission from Extensive Air Showers; Determining the Chemical Composition of Cosmic Rays”, Astropart. Phys., 34-5, 2010

[13] H. Allan, “Progress in elementary particle and cosmic ray physics”, vol 10, ed. Wilson, J. G. and Wouthuysen S. G. (North-Holland, Amsterdam, 1971), 171-304, 1971

[14] F. Kahn, I. Lerche, “Radiation from cosmic ray air showers”, Proc. Roy. Soc. A, vol.289, 1966

[15] T. Huege, R. Ulrich, R. Engel, “Dependence of geosynchrotron radio emission on the energy and depth of maximum of cosmic ray showers”, arXiv:0806.1161v2, 2008

[16] J.R. Horandel, “Experimental Efforts on Very High-Energy Cosmic Rays and their Interactions”-Conference Summary, Nucl. Phys. B (Proc. Suppl.) 196, 341–355, 2009

[17] http://www.ngdc.noaa.gov/geomag-web/#igrfwmm, accessed at 20/06/2012