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Radio Ground Footprints of Extensive Air Showers at the Location of the SURA Experiment

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Abstract. Radio stations can record different values of the electric field strength from an extensive air shower induced by a cosmic ray. It is possible to derive the ground footprint of a cosmic ray using the calculated electric field strength recorded by a proper set of radio antennas in a specific frequency range. In this study and based on computer simulations, we investigate the properties of the ground foot-prints of vertical and inclined cosmic rays propagating in a location of a new cosmic ray radio experiment in the Middle East. Semnan University Radio Array is a new radio detection site that aims to detect ultra-high energy cosmic rays. We investigate the effect of the zenith angle of a cosmic ray on the illuminated area as a result of radio emission from an extensive air shower development. We also discussed the maximum possible spacing between radio antennas in order to be able to detect coincident events for both vertical and inclined cosmic rays at the location of this new experiment.

Keywords: Cosmic Rays, Radio detection, SURA, Extensive Air Showers

1 Introduction

Investigating the properties of ultra-high energy cosmic rays is still one of the most important topics in high energy physics. There still exist a lot of unsolved questions about cosmic rays including their possible sources [1],[2], and the way they are accelerated to such high energies [3]. One of such questions is the mass composition [5]of cosmic rays in the cosmic ray spectrum. Many different techniques including particle and fluorescence light detectors have been used over the years to answer these questions [4]. These techniques have been used to derive the most important cosmic ray properties including arrival direction, and mass determination [6]of a cosmic ray based on a study of an extensive air shower which has been induced as a result of a primary particle interacting with the earth atmosphere. However, the drawbacks of these techniques caused scientists to search for new approaches. It is already known that extensive air showers from a primary particle entering the earth atmosphere emit radio emission in the range of MHz as the shower develops through the atmosphere [7],[8]. In recent years, a new approach has emerged with possible advantages over existing techniques. Radio detection of cosmic rays has evolved over the past decade with high expectations [9]. As a result of the progress in both technical and theoretical aspects of radio signal interpretation, this new technique has been used in many different experiments to detect cosmic rays and to determine their key properties either as a self-trigger experiment or as a complementary setup alongside other detection methods. Following promising results from LOPES[10] and CODALEMA [11] experiments, a new generation of radio detection sites including AREA [12], LOFAR [13] and Tunka-Rex [14] started their operation to showcase the potential of this new technique.

This approach has many advantages including a high duty cycle, inexpensive hardware, and the ability to work alongside other detection methods.

Semnan Univesity Radio Array (SURA)[1] is a first cosmic ray radio experiment in the Middle East [15]. The ultimate goal of this new site is to detect ultra-high energy cosmic rays with an investigation on their radio signal properties. In its first phase of operation, this new site will work as a self-trigger radio array. In the first prototype of the SURA experiment (SURA-4), four Log Periodic Dipole (LPDA) antennas and the required electronics are recording radio signals on the roof of physics faculty at Semnan University in Semnan, Iran. However, it is planned to add three particle detectors in the near future as an external trigger to this experiment which also provides hybrid cosmic ray detection.

It is also planned to increase the number of antennas and the particle detectors over time. Currently, ten more dipole antennas have also been designed and built for the SURA experiment and are ready to be deployed in the near future.

In this study, we investigate the ground footprints of cosmic rays in the location where the first phase of SURA has started its operation. The location of this new array and the specification of the environment including low industrial noise and high active sun hours makes it an ideal location to establish a new cosmic ray experiment. The details about the scientific aspects of this new array will be discussed in a separate study.

The values of the electric field strength that we obtain in this study to derive the ground footprint of a cosmic ray can be used to extract some important information about a cosmic ray. Using these values, it is possible to investigate the lateral distribution function of a cosmic ray which in turn can be used to identify both the energy and type of primary particle [16]. Furthermore, it is possible to estimate the propagating direction of a cosmic ray based on the shape and orientation of these patterns [18]. The optimal spacing between radio antennas to be able to detect coincident events is also an important subject that we discuss in this study.

2 Simulation Specifications

The computer simulations for this study are based on CORSIKA 7.6 [19] and CoREAS 1.3 [17]. These are the latest available releases of this simulation package which have been used in many different cosmic ray experiments and have shown great agreement with experimental results [20].

We used QGSJETII-04 [21] and Gheshia2002-d as high and low interaction models. The thinning is set to 10^{-6} for all simulations. We investigate Proton and Iron induced air showers with 10^{17} and 10^{18} primary energies. A virtual radio array consists of of259 radio antennas has been used in this study. The radio array is located at 1135m above sea level to simulate the current location of SURA antennas. The observation level of simulations is however set to a much lower altitude (sea level) in the CORSIKA steering file to fully simulate the extensive air showers.

The magnetic field values in the CORSIKA input file are set to 28.09, 39.43 according to the data from the National Centers for Environmental Information which corresponds to the current location of the SURA experiment in Semnan Province. This parameter includes two values dedicated to horizontal and vertical component parts of the Earth's magnetic field respectively.

[1] sura.semnan.ac.ir

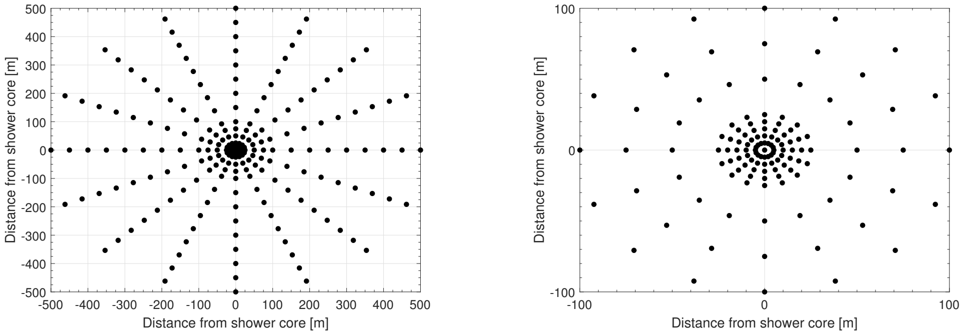

Figure 1: The radio array which has been used for this study. This virtual radio array consists of 259 radio antennas which expand from shower core to 500m. The right figure shows the location of radio antennas around the core location.

In all simulations, the core location of the air shower is set to (0,0) and CORSIKA coordinates were used in all figures. As a result, the positive X-axis represents the North, and the positive Y-axis points towards the East orientation.

We have used a virtual radio array consists of 259 antennas to make a deep investigation on the ground footprints of a cosmic ray. As it can be seen in the left panel of the Fig.1, this array starts from the radio core location and expands to 500m in 22.5-degree intervals. Antennas are located at 5,10,15,20,25,50,75,100,150,200,250,300,350,400,450,500m from shower core. The array is denser around shower core (Right image in Fig.1) since radio signals get weak quickly as we move from the core location especially for the chosen energies [23].

In order to calculate the peak radio amplitude in the 30-50 MHz frequency range which is the operative band of SURA experiment, we used a specific computer code developed for radio studies at Semnan University cosmic ray group. CoREAS Analyze Program for Semnan radio experiment is capable of doing a wide range of radio signal analyses including calculating the electric field strength in any desired frequency band.

In this program, we apply a nearly idealized rectangular bandpass filter on CoREAS output data to obtain peak radio amplitudes in the 30-50 MHz range. The COREAS output data provides North-South, East-West, and vertical components of the electric field strength. For this study, we analyze the ground footprints arising from the value of these components.

3 Results

The calculated electric field strength values in the specified frequency range for all radio antennas can be used to drive the radio signal patterns of a cosmic ray. The plot in Fig.2 shows the shape of such a pattern for the North-South (E_x) polarization of a vertical proton-induced air shower with 10^{17} eV energy. This figure is very similar to previous studies of the same component at locations with similar magnetic field values [12]. In Fig.2 The highest electric field strength values were recorded by the radio antennas around the core location and signals get weak rapidly in distances away from that point. For a cosmic ray with this energy which is the minimum possible threshold of SURA experiment, the radio signals have negligible changes for distances larger than 200m from shower core for a vertical proton-induced air shower. The right image in Fig.2 shows the same pattern around the

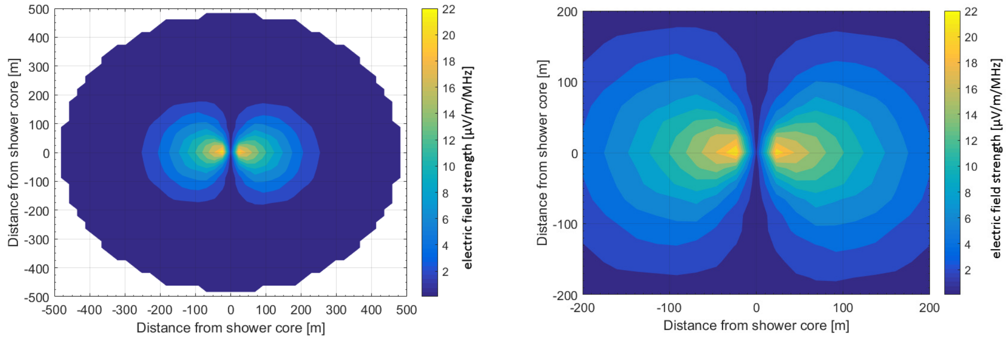

Figure 2: The ground footprint of the E_x component for a vertical proton-induced air shower with 10^{17} eV energy. For this energy, we have calculated noteworthy field strength values around the core location. The figure shows E_x component behavior in close distances to shower core.

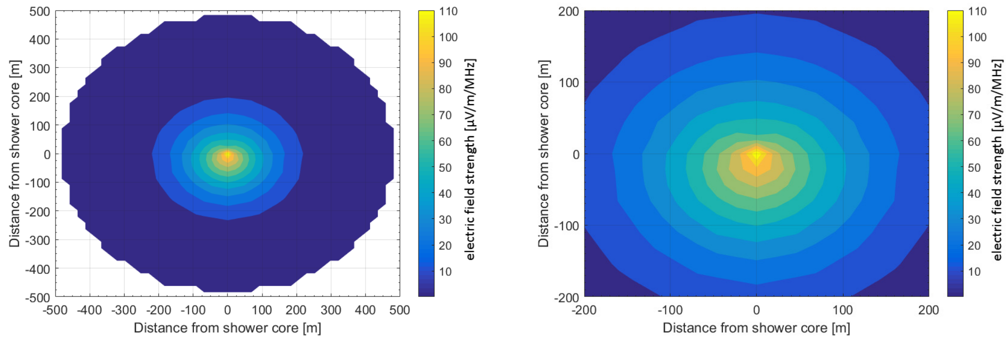

Figure 3: The ground footprint of the E_y component for a vertical proton cosmic ray with 10^{17} eV energy. The left image shows the recorded electric field strength from all antennas while the right figure shows the same footprint around the core location.

core location. The high amount of radio antennas around that point makes it possible to have a fine measurement.

The E_y component does have an orientation to the East due to the Earth's magnetic field effect. This situation also arises from contributions from different emission mechanisms especially the charge excess [17]. The left pattern in Fig.3 shows the expected ground footprint of the E_y component for a vertical proton cosmic ray with 10^{17} eV at the location of SURA experiment.

It is visible that the radio signals have different values from shower core to 200m. The rest of the antennas have recorded negligible electric field strength values. Also, the right panel of Fig.3 shows the same pattern around the shower core.

In practical situations where the radio antennas only cover a single polarization direction, this component is of great importance. As can be seen in Fig.3 the maximum distance for radio antennas in order to detect coincident events is around 200m for a proton-induced cosmic ray with 10^{17} eV energy under extremely low environmental noise.

We also provide the shape of the vertical electric field component pattern. The footprint of this component has much smaller electric field strength values compared to other polarizations. Also, we do not observe a specific shape for this pattern. Fig.4 shows this

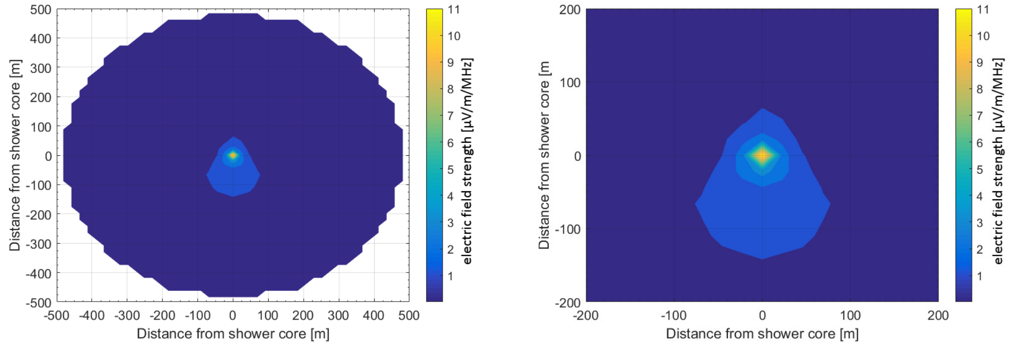

Figure 4: The ground footprint of the E_z component. This component has much weaker PRA values and does not provide a specific shape compared to other elements.

pattern calculated from all antennas and its shape around the core location from left to right respectively.

It is also possible to derive the total field pattern based on different electric field components of radio signals. Previously we showed that the overall shape of this pattern is very similar to E_y [23].

It should also be mentioned that the small differences in the overall shape and values of the calculated patterns in this study (as compared to previously published results) [23], [17] is possibly due to the different frequency band and the specification of the applied digital bandpass filter.

In Fig.5 we see the footprints of a vertical Iron induced air shower with 10^{17} eV energy. From top left to bottom right, these figures show the E_x, E_y, E_z, and E_{total} patterns. Although proton-induced air showers have deeper shower maximum compared to shallower shower maximum from heavier primary particles like Iron, we observe similar ground footprint for both primary particles. It has already been noted that shower to shower fluctuations may wash out the effect of primary particle type on its ground footprint [23].

For practical purposes and since the SURA radio antennas operate in one polarization direction and because of the fact that the E_y component of radio signals from cosmic rays has much stinger field strength compared to other elements, we only investigate the E_y patterns for the rest of this study.

The next pattern in Fig.6 dedicates to a slightly inclined cosmic ray with $\theta = 15^0$ and $\phi = 0^0$ & $\phi = 90^0$ from left to right respectively. In this situation, the overall shape of the E_y pattern is very similar to a vertical one as we saw in Fig.3; but the important point is the bigger footprint on the ground which increases the possibility of detecting a radio event with a less dense array. The area where we have calculated significant electric field strength values has slightly increased for an inclined cosmic ray.

The effect of the cosmic ray zenith angle on the expansion of a cosmic ray footprint on the ground is more visible in Fig.7 where we see the entire area of the array is illuminated by the footprint of an inclined proton-induced air shower with $\theta = 45^0$ at the same energy as in Fig.6. From left to right, the air shower is propagating to the North and West respectively.

The last footprint in Fig.8 shows the electric field strength for an inclined proton-induced air shower with $\theta = 60^0$ propagating to the North. In this case, we have recorded a much broader range of signal strength in the entire area of the array.

It is clear that the zenith angle plays an important role in the size of the air shower footprint on the ground. For a vertical air shower, the space between the radio antennas should

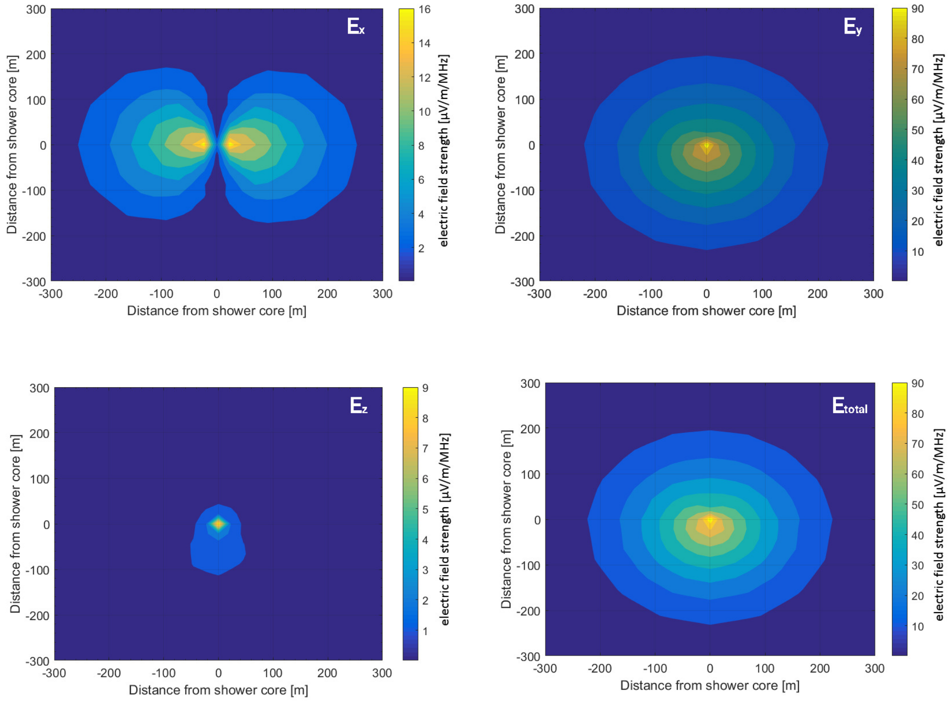

Figure 5: From top left to bottom right: The ground footprint of E_x , E_y , E_z , E_{total} components for a vertical Iron induced cosmic ray with 10^{17} eV energy.

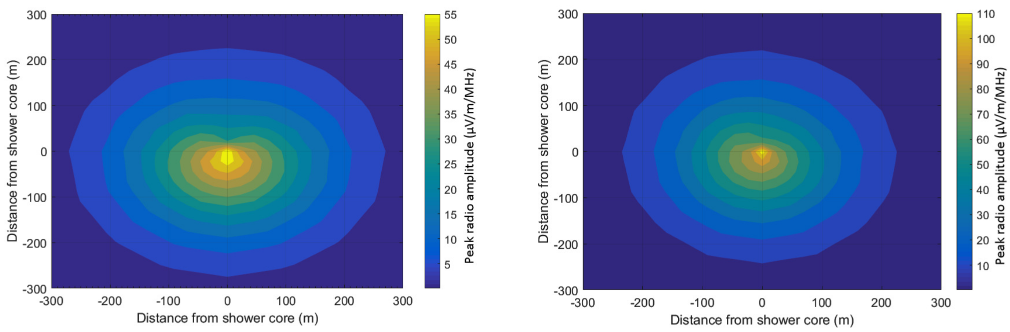

Figure 6: From left to right: The ground footprint of the (E_y) component for an inclined Iron cosmic ray with θ= 15^0 and 10^{17} eV energy propagating to the North and West respectively. The footprint is slightly larger compared to Fig.3.

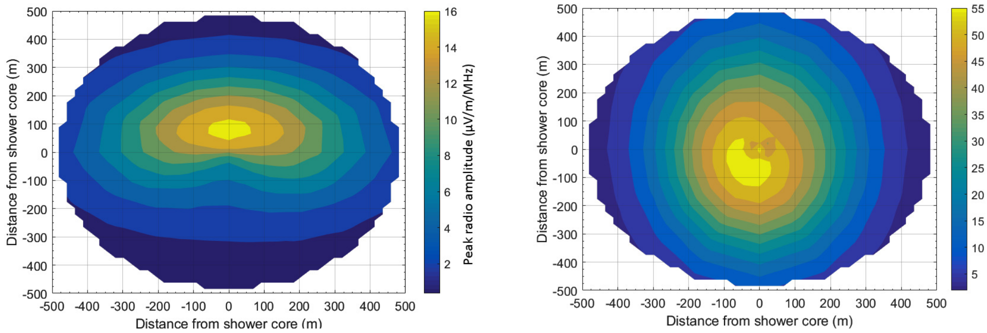

Figure 7: From left to right: The ground footprint of the (E_y) component for an inclined proton cosmic ray with $\theta = 45^0$ and 10^{17} eV energy propagating to the North and West respectively.

not be more than 300m for coincident detection which requires a high-quality instrument, fine radio signal interpretation, and extremely low noise in the detection site. However, as the shower becomes more inclined, it is possible to make a coincident detection of an air shower with the spacing of about 500m or more depending on its zenith angle.

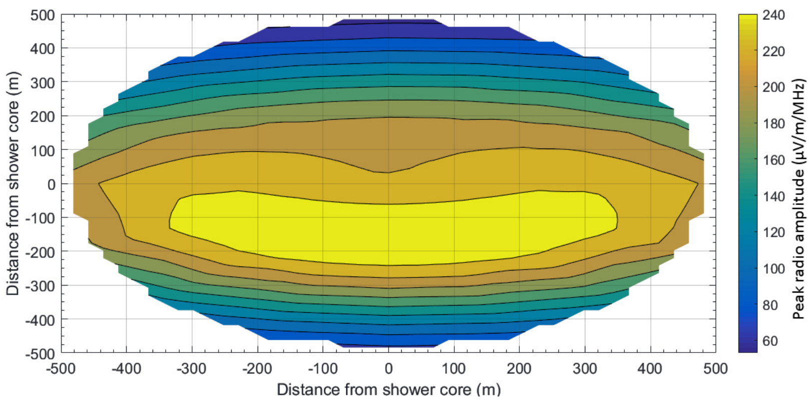

Figure 8: The ground footprint of E_y component for an inclined proton-induced cosmic ray with $\theta = 60^0$,$\phi = 0^0$ with 10^{17} eV primary energy at the location of SURA experiment.

4 Discussion

In this study, we used CORSIKA and CoREAS code alongside an exclusive program developed at Semnan University for radio signal analyses to derive the ground footprints of cosmic rays at the location of a new SURA experiment.

Semnan University Radio Array (SURA) is a new radio detection site in the Middle East which aims to detect ultra-high energy cosmic rays. In order to better understand the radio signal properties in this new location, we performed a series of computer simulations and calculated the signal strength in the location of the SURA experiment considering the Earth's magnetic field specifications in this new location. Furthermore, for all simulations, we used a very dense radio array consists of 259 radio antennas which covers an area of about $2km^2$. This array is denser around shower core, so we could make fine measurements around that location. Using the calculated signal strength, it is possible to investigate the various type of cosmic ray properties including the energy and type of primary particle.

The results show strong similarities for the ground footprints of a vertical proton-induced air shower with 10^{17} eV energy at the location of the SURA experiment compared with previous studies in other locations with similar magnetic field values. Small differences are possibly due to the specification of the digital filter applied on radio signals.

We investigated the effect of the cosmic ray zenith angle on the extent of its footprint. For inclined cosmic rays, we observed a much bigger footprint on the ground. This was obvious in the ground footprint of a fully inclined cosmic ray with 10^{17} energy and $\theta = 60^0$ where the entire space of the radio array was illuminated by the cosmic ray.

The result shows that the maximum spacing of the antennas for detecting a coincident vertical proton-induced air shower with 10^{17} energy can be up to 200m where this space can be increased to 500m for an inclined cosmic ray with $\theta = 45^0$ at the same energy.

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