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Research Paper

Directional Dependence of the Angular Resolution of a Radio Antenna Array due to the Earth's Magnetic Field

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Abstract. Recent years have seen a growing interest in radio detection of Cosmic Rays. We investigated the incident direction of Cosmic Rays for an array of 11 radio antennas through a series of simulations using the CoREAS toolkit. We have determined that utilizing the east-west component of the electric field yields improved angular resolution for our array compared to the north-south and vertical components. Our findings reveal a significant correlation between the error in direction estimation of cosmic rays and the angle between the earth's magnetic field and the cosmic ray's trajectory. Specifically, for 10^{17} eV proton showers, we observe that the angular resolution is poorer for showers originating from the south (0.91°±0.06°) compared to those from the east (0.48±0.07), north (0.33°±0.08°), and west (0.30°±0.10°) directions. Additionally, a slight decrease (less than 0.1°) in angular resolution is noted for 10^{18} eV showers. This research sheds light on the impact of Earth's magnetic field on cosmic ray detection using radio antenna arrays.

Keywords: Cosmic rays, CoREAS, Radio antenna array, Earth's magnetic field

1 Introduction

Radio antenna arrays have garnered increased interest in recent years due to their ability to operate continuously and provide accurate resolution in determining the direction of cosmic rays and the location of the shower maximum [1–3]. Successful operation of LOPES and CODALEMA [4,5] have inspired other research groups to consider developing radio arrays as extensions to existing experiments or as independent endeavors, exemplified by projects like LOFAR [6].

Several radio antenna arrays began their operations with a limited number of antennas, such as MSU, which utilized 11 antennas, Yakutsk with 20 antennas, and LOPES, which initially deployed ten antennas and later expanded to 30 antennas [7–10]. These arrays operate in conjunction with particle detector arrays, which play a crucial role in providing trigger signals to the radio arrays.

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Meanwhile, there are two active cosmic ray experiments in Iran. The Alborz-1 experiment, located at the Sharif University of Technology, commenced operation with five central detectors in 2016 and is set to scale up to 20 scintillation detectors in the future [11,12]. On the other hand, the Semnan University Radio Array (SURA) [13] began operations in 2020 with four log periodic antennas and one inverted-V dipole antenna. Both experiments face significant challenges: Alborz-1's moderate altitude location at 1200 meters above sea level hinders its performance, while SURA, located within Semnan city, is exposed to high levels of environmental noise and requires a particle detector array for improved triggering capabilities. Recent simulations [14] indicate that the Alborz-1 experiment reaches an average count rate of less than one gamma ray per year from the Crab Nebula, which is difficult to distinguish from background cosmic rays.

There is a proposal to construct a new cosmic ray experiment, incorporating both a particle detector array and a radio antenna array, at a fresh location. Bilindi Mountain, home to the Khaje Nasir Observatory (KNO) of Tabriz University, presents a promising option. KNO boasts several advantages, including its high altitude of 2650 meters above sea level, pristine environment, existing infrastructure, and convenient 30-kilometer road access from Tabriz City. A particle detector array at the location of the KNO can investigate gamma rays and cosmic rays within the energy range near the spectral knee. Additionally, it can provide a trigger signal to the radio array, benefiting from improved performance away from urban noise. Our study focused on assessing the angular resolution of an 11-antenna radio array deployed at the Khaje Nasir Observatory.

2 Array Configuration and simulation procedure

The configuration of our radio array is tailored to the unique geometry of the KNO site, as illustrated in (Figure 1). This setup includes one central antenna, six antennas positioned at the vertices of a hexagon within the flat area of the observatory, and four additional antennas situated at the corners of a square along the road approximately 85 meters away from the central point.

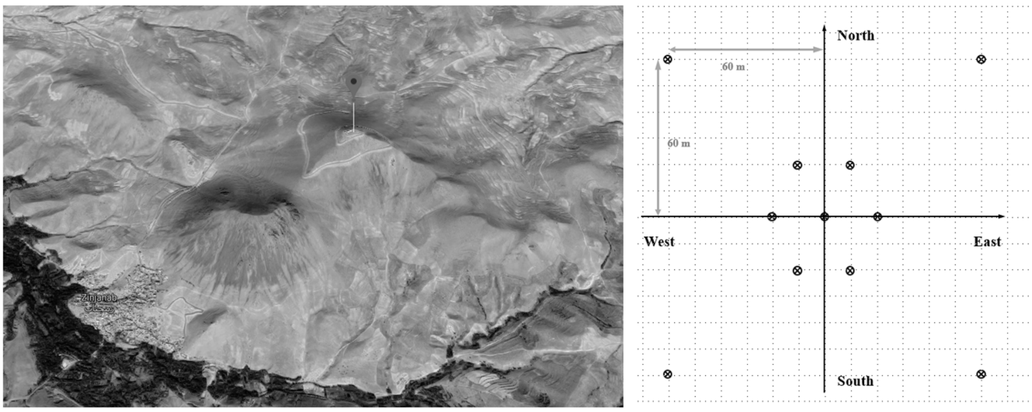

Figure 1: Khaje Nasir Observatory 1.5 km from Zinjanab Town (left); Our radio antenna array configuration, with 11 antennas, grids scale is 10 m (right).

In our simulations, we employed CORSIKA-76400 with QGSJETII and GHEISHA as the high and low-energy interaction models with CoREAS and thinning as additional options.

CoREAS is a code to simulate the radio emission of Extensive Air Showers (showers for short) [15,16]. We simulated extensive air showers initiated by protons at energy levels of 10^{17} and 10^{18} eV, with a zenith angle of 30 degrees and azimuth angles of 0, 90, 180 and 270 corresponding to cosmic rays coming from the south, east, north and west. Each simulation run requires approximately 7 hours to complete. The magnetic field parameters in the simulation input files were adjusted to match the specific location of KNO, with values set as follows: (B_{North}=26.29μT, B_{East}=-6.12μT, $B_{Vertical}$=40.74μT [1]). Because of the strong radio frequency interference at the lower frequencies and the proximity of the FM band at the upper part, most CR radio experiments use a bandwidth between 30 and 90 MHz [6]. In this study, we have limited ourselves to the 40 to 80 MHz frequency band to reduce the noise level. Estimating the direction of a shower, which closely aligns with the direction of primary cosmic rays (CR), follows a standard procedure in particle detector array experiments, as described in the literature (see [17] for example). This procedure can also be applied to radio antenna arrays. The shower front can be approximated as a flat plane. The line perpendicular to this plane indicates the direction of the shower. Therefore, the problem is reduced to finding the equation of the shower plane. To do this, we need coordinates from at least three points in the plane. Since we know the ground locations (x and y) of the antennas, and we can measure the time difference of received signals relative to a reference time, each antenna provides coordinates for a point in the plane. In CoREAS simulations, each antenna generates an output text file with four columns: absolute time stamp, and the north-, west-, and vertical components of the electric field (as shown in the upper-left side of Figure 2). We extract the time at which the electric field intensity reaches its maximum and use it in our Direction Estimation Python Code (DEP Code).

In practice, the radiated electric field can often be indistinguishable from environmental noise. Therefore, we employ a Python code called the Filter Noisy Frequencies (FNF Code) to address this issue. Here's how it works:

1- Data Extraction: The FNF code retrieves the electric field values from the CoREAS output file (depicted in the upper-left plot).

2- Frequency Domain Transformation: It then performs a fast Fourier transform (FFT) to convert the electric field from the time domain to the frequency domain (as shown in the lower-right plot of Figure 2).

3- Frequency Filtering: Unwanted frequencies—those below 40 MHz and above 80 MHz—are filtered out by setting their values to zero.

4- Time Domain Reconstruction: Finally, a second FFT is applied to convert the filtered electric field back to the time domain (illustrated in the lower-left plot of Figure 2).

This process enhances the accuracy of our analysis by mitigating noise interference. In Figure 2, we employed the FNF code to evaluate an example output file from CoREAS for one of the antennas.

3 East-West component of Radiated Electric filed

Particles of a shower radiate electromagnetic waves with several mechanisms. Transverse currents due to the earth's magnetic field have the major contribution to the total radio emission of a shower [8]. Since the electrons and positrons in a shower, sense the Lorentz

[1] We used the magnetic field calculator of National Center for Environmental Information website: https://www.ngdc.noaa.gov/geomag/magfield.shtml

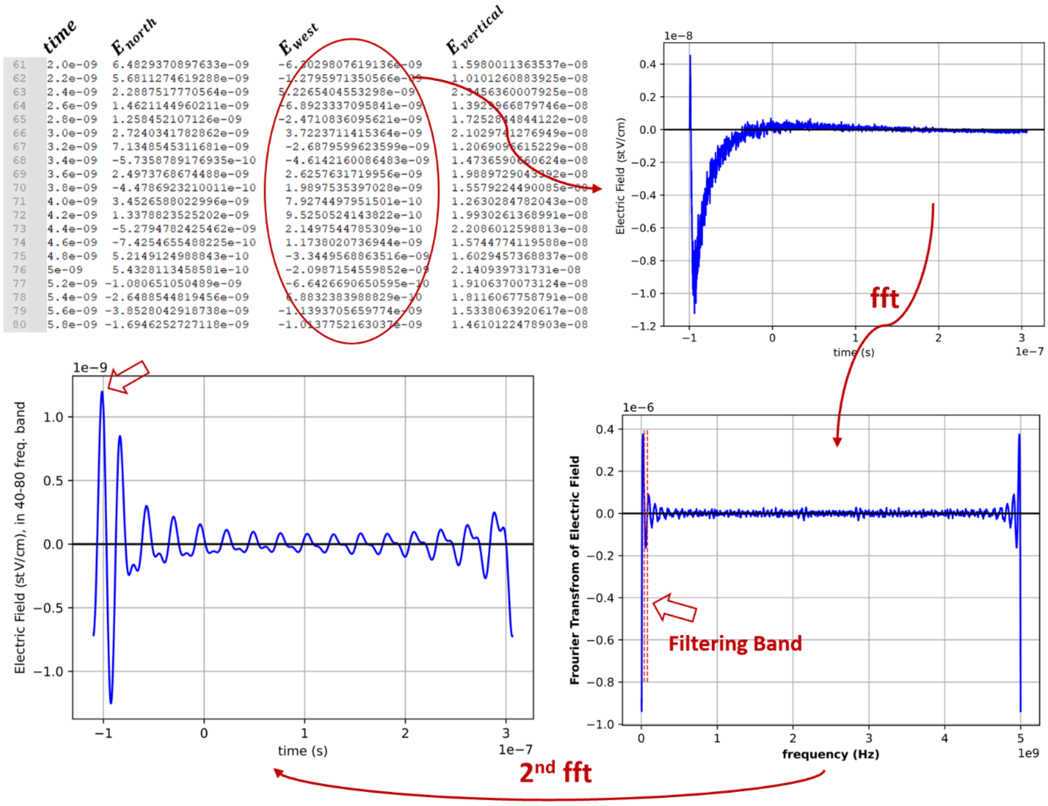

Figure 2: The Filter Noisy Frequencies (FNF) code extracts electric field values from the CoREAS output file (depicted in the upper-left). The electric field, plotted as a function of time, appears on the upper-right side of the figure. Next, the code computes the electric field in the frequency domain using a fast Fourier transformation (FFT) (shown in the lower-right). Finally, a second FFT is applied to convert the filtered electric field back to the time domain (illustrated in the lower-left plot).

force, due to the earth's magnetic field, in the east-west direction, the transverse current will have an east-west orientation. Consequently, the east-west component of the radiated electric field will be stronger. COREAS output files confirm that the east-west component of the electric field is about 1-2 orders of magnitude larger than the vertical and north-south components. We simulated five CR by COREAS, with an energy of 10^{17} eV at the zenith and azimuth angles of 30 and 180 degrees, respectively. The average error of zenith θ and azimuth ϕ angles is given in the second and the third columns of the Table 1. The average discrepancy of the estimated direction γ and its standard deviation σ_γ is given in the 4th and 5th columns of Table 1. Different rows are simulation results obtained by using different components of electric field (indicated in the first column). The average discrepancy of the estimated direction reaches above 1.5°for the vertical and north-south components, and 0.33°for the east-west component. This means that the east-west component of the electric field gives a better estimation for the direction of CR.

From the experimental point of view, we can use antennas sensitive to the dominant component of the electric field.

Table 1: Deviation of estimate direction obtained by simulation, when zenith and azimuth angles are 30 and 180 degrees, energy of CR is 10^{17} eV and, a band-pass filter (40-80 MHz) is applied.

Electric field component	Zenith angle average error $\Delta\theta$(degrees)	Azimuth angle average error $\Delta\phi$(degrees)	γ (degrees)	Standard deviation of γ σ_γ(degrees)
$E_{north-south}$	1.51	0.42	1.52	0.10
$E_{east-west}$	0.29	0.36	0.33	0.08
E_z	1.70	0.19	1.70	0.10
E_{Total}	0.26	0.35	0.30	0.07

4 Direction estimation as a function of the azimuth angle of CR

By using only the east-west component of the electric field, we investigated the relationship between azimuth direction of CR and the error in the direction estimation. For cosmic ray energies of 10^{17} and 10^{18} eV, we simulated showers in four directions: north, south, east, and west (5 showers in each direction).

We estimated the direction of showers by using the antennas information, and found the angle between this estimated direction and the real direction. The second and the third rows in the Table 2 show the angle (γ) between the estimated directions and the real direction of cosmic rays with energies of 10^{17} and 10^{18} eV respectively.

Results of Table 2 show that for the showers coming from the north, the angle between the estimated direction and the real direction reaches its maximum value of 0.9. There is a correlation between two angles: 1- the angle between real and estimated direction of CR (γ) and 2- the angle between the magnetic field and the real direction of CR (β): a smaller value of β leads to a larger value of γ.

Table 2: Average difference between the estimated direction and the real direction (θ) and its stochastic error for cosmic rays with primary energy of 10^{17} eV (2nd row) and 10^{18} eV (3rd row).In the 4th row, β is the angle between primary cosmic ray and the magnetic field of the earth

	east	**north**	**west**	**south**
γ **(at 10^{17} eV)** (degrees)	0.48±0.07	0.33±0.08	0.30±0.10	0.91±0.06
γ **(at 10^{18} eV)**	0.56±0.13	0.42±0.09	0.40±0.08	0.95±0.03
β **(angle between CR and B)**	38	63	49	8

all values are in degrees

Electrons and positrons of a shower feel the Lorentz force which is proportional to the sine of the angle between particles velocity (direction of primary CR) and the earth's magnetic field. For the smaller β angles, the Lorentz force and, consequently the transverse current will be smaller. In our case, since the Khaje Nasir Observatory locates in the northern hemisphere, the angle between particles speed and the magnetic field is lower for cosmic rays coming from the south (8 degrees, Table 2). Smaller angle between particles speed and magnetic field results in smaller Lorentz force. Lower Lorentz force consequently results in a smaller transverse current. Small transverse current has weaker radiation. Weaker radiation is accompanied with more significant fluctuations. Finally, the more significant fluctuations of emitted radiation can explain the excess error of the estimated direction of showers coming from the south in Table 2.

Even in the worse case of cosmic rays coming from the north, the angular resolution of our small radio array is better than 1 degree.

5 Conclusions

We designed a small radio antenna array with 11 antennas at the site of KNO. Simulations showed that this array can estimate the direction of a cosmic ray with a resolution better than 1 degree. We showed that the estimated direction is more accurate if we use the east-west component of electric field. Since the east-west component is more robust, we can conclude that the estimated direction is better when the electric field at antennas locations is more potent. By the same way, losing the accuracy of the estimated direction for showers coming from the south can be explained by the fact that the electric field of showers coming from the north is weaker.

Authors' Contributions

All authors have the same contribution.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no potential conflicts of interest.

Ethical Considerations

The authors have diligently addressed ethical concerns, such as informed consent, plagiarism, data fabrication, misconduct, falsification, double publication, redundancy, submission, and other related matters.

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