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Dependence of normalized phase angle of cosmic ray radio signals on core location of an extensive air shower

M Sabouhi and G Rastegarzadeh
Physics Faculty, Semnan University, Semnan, Iran

E-mail: grastegar@semnan.ac.ir

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Abstract
High energy cosmic rays hitting the earth atmosphere induce extensive air showers propagating downward with a high gamma factor. Determining the core location of such air shower is a necessary step to measure other important characteristics of a cosmic ray such as the lateral distribution function. In this study and based on computer simulations and radio signal analyses we investigate the relation between normalized radio signal phase angle emitted from particles in an air shower to the position of a shower core. We perform a series of simulations based on CORSIKA and COREAS code for cosmic rays with different types of primary particles with an energy range from 0.1 to 1 EeV. The results show a direct relationship between the average slope of normalized radio signal phase angle as a function of frequency to the absolute distance from extensive air shower core location. We have calculated the normalized radio signal phase angle to have the absolute minimum value at close distances to a shower core location. We discuss a possible approach to estimate core location with different types of virtual radio arrays.

Keywords: Semnan University Radio Array (SURA), Cosmic Rays, Radio Detection

1. Introduction

There are different approaches to detect cosmic rays and to determine their key properties either by direct measurements or by investigating air showers created as a result of a primary particle interacting with the earth atmosphere [1]. These researches are carried out to answer unsolved question about cosmic rays and their possible sources [2]. Other cosmic ray characteristics including mass composition has also been investigated to provide a better understanding of the cosmic ray spectrum [3].

Over the past decade, the radio detection of cosmic ray air showers with its advantages including a nearly 100 percent duty cycle, an inexpensive setup and the complementary features has been used in many different experiments to determine key parameters of cosmic rays either in a self-trigger setup or as a complementary element with other detection techniques such as particle detectors and fluorescence light detectors [4], [5]. These techniques have been used in different experiments to determine a cosmic ray property such as energy, type and mass determination [6], [7] through an investigation on the properties of an extensive air shower.

Early measurements showed possibility of detecting radio signals from cosmic rays to be coherent in the frequencies below 100 MHz [8], [9]. Because of the progress made in this field, it is now possible to determine some of the most important characteristics of a cosmic ray like energy, direction and type of primary particle from radio measurements only [10], [11]. Previous studies have also shown the possibility of determining an air shower propagation direction based on the lateral distribution analyses [12]. The other important parameter is a place where the extensive air shower axis hits the ground, the shower core. Determining the position of this point may lead to specifying other important properties of a cosmic ray.

Radio signals can be interpreted in different ways in order to obtain various types of information. The phase value of radio signals in one of such elements which we investigate in this paper. Based on previous studies we know that the shower front of a cosmic ray extensive air shower is not a totally flat surface and even the radio signals propagating toward the ground forms a hyperbolical shape [13]. As a result of that, a study on the phase of radio signals and more specifically on the “Slope of the Normalized Phase Angle (which we call

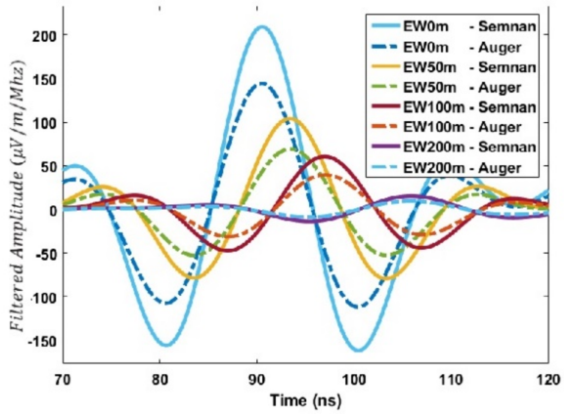

Fig.1. Filtered radio signals at the location of PAO and SURA for a vertical proton cosmic ray with 10^{17} eV energy. A small delay between the recorded radio signals is visible in different distances from shower core at the location of PAO and SURA.

SNPA in this study) can be useful to extract even more information from radio signals.

2. Semnan University Radio Array (SURA)

The first porotype of the Semnan University Radio Array [14] has started its operation on the roof of the physics faculty of the Semnan university. This prototype includes 4 custom build LPDA antennas placed in a rectangular layout. The stations are connected to the central receiver unit with a 30m meter coaxial cable. In order to amplify and filter unwanted radio emission outside 40-80 MHz frequency band each station is equipped with a low noise amplifier and a band pass filter. The central receiver unit includes a 160 MSPS analog to digital converter connected to a field programable gate array which receives and analyses the radio signals in real time. A custom build program investigates the data and records possible cosmic ray candidates on a PC for further analyses.

It is planned to add three particle detectors in near future to the radio array which will work as an external trigger for the radio setup which will improve the efficiency of the experiment in capturing cosmic ray candidates.

It is also planned to add few more radio antennas to the radio array. 10 dipole antennas are designed and build and are ready to the added to the array once the required electronic are in place.

3. Calculating SNPA from Simulated Radio Signals

After simulating cosmic ray radio signals various types of analyses can be carried out to extract the desired values. The raw data in both simulation and experiment are in a time-domain regime which shows the electric field values as a function of time. Using Fast Fourier Transform (FFT) it is possible to move to the frequency-domain which contains information about both magnitude and phase of the signal. Using a custom developed program, we normalized the phase angle value of the signal with π after taking an FFT, considering the length of the samples and the sampling frequency of the simulated radio signals to derive the normalized phase angle and extracted the normalized phase values for each individual frequency of interest. SNPA is the Slope of the Normalized Phase Angle diagram in terms of frequency.

4. Received Radio Signals

As we discussed in the previous section and because of the front shape of radio signals, theoretically, we expect radio antennas close to the shower axis to record the first set of radio signals for a vertical cosmic ray. Although radio signals are coming almost instantly in all directions, it is possible to distinguish the received radio signals at different points with a fine measurement. In such situation, the time of the recorded radio signals is in proportion to their distance from a shower core. This will create a small but important delay between the recorded signals by the antennas. This is visible in Fig.1 where we simulate the radio signals for two vertical proton cosmic rays with 10^{17} eV energy propagating in the location of the Pierre Auger Observatory (PAO) and the location of the Semnan University Radio Array (SURA). One important difference between these two sites is the intensity of the Earth magnetic field which is an important factor in creatin and propagation of radio signals from an extensive air shower [15]. In order to calculate the radio signal phase angles, we use a specific computer code developed for this study. This code is capable of calculating various types of information from CoREAS output data like peak radio amplitude at any desired frequency. Using this code, we calculate the slope of the phase angle of radio signals from cosmic ray air showers normalized by π. comparing the value of this parameter for different cosmic rays and finding the relation to the distance from a shower core, shapes the basis of our study.

5. Computer Simulations

For this study, a series of computer simulations were performed using CORSIKA 7.5 [16] and CoREAS 1.1 [17]. The simulated cosmic rays produce vertical and inclined extensive air showers with different initial energy from 10^{17} to 10^{18} eV with Proton, Iron and Gamma as primary particles. QGSJETII-04 [18] and Gheisha 2002d has been selected as hadronic interaction

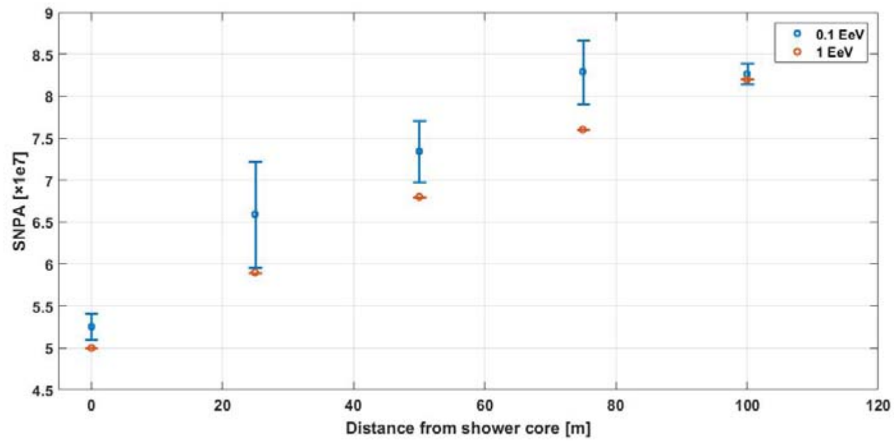

Fig 2. The SNPA values for two sets of vertical proton cosmic rays with 10^{17} and 10^{18} eV energy at the location of SURA in different distances from shower core. Each set contains 10 simulated cosmic rays. We calculated the SNPA for 1 EeV cosmic rays to be exactly the same in 3 out of 5 places and almost identical in other distance from shower core.

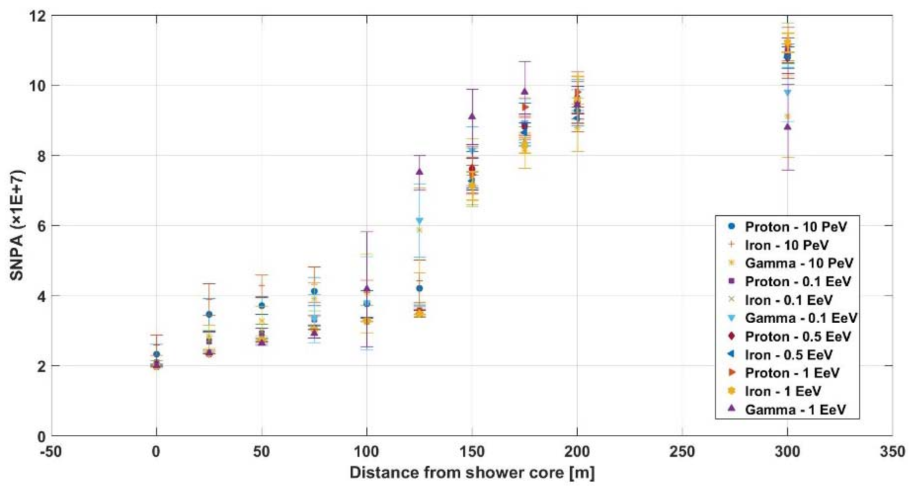

Fig 3. SNPA as a function of distance from shower core in the North direction for 93 simulated cosmic rays with 10^{16}, 10^{17}, 5.10^{17} and 10^{18} eV energies. For all simulated vertical cosmic rays regardless of initial energy and type of primary particle, the lowest SNPA is recorded by an antenna at shower core.

models for high and low energies in our simulations with the Thinning set to 10^{-6}.

As we mentioned earlier this technique requires a very fine measurement of radio signals. For this reason, simulated cosmic rays sampled with 5 and 0.2 ns time resolutions at the location of SURA and PAO respectively. SURA currently samples the radio signals with a time resolution of 6.25 ns. Using software-based technique it is possible to up sample the recorded data to reconstruct the initial radio signal with higher accuracy.

6. SNPA & distance from shower core

The first step is to show the dependency of SNPA to the distance from a shower core. For this reason, we calculated this parameter for a series of vertical proton cosmic rays with 10^{17} and 10^{18} eV initial energy. The core location of these cosmic rays is set to be at (0m,0m). As it is clear from Fig.2 the lowest SNPA were calculated from the received radio signals by an antenna at the shower core. The highest SNPA is calculated for the antenna located at 100 meters from shower core. It is clear that the SNPA increases by an increase in the distance from the shower core. The simulations are performed for two series of vertical proton cosmic rays each contain 10 simulated air showers with 0.1 and 1 EeV initial energy respectively. For cosmic rays with 10^{18} eV energy, the SNPA is almost identical for all 10 air showers in different distances from shower core (exactly the same in 3 out of 5 distances) and hence the error bars are not visible in Fig.2

As the energy of a cosmic ray increases, we calculate a better relationship between the SNPA and the distance from shower core with fewer fluctuations. In any case, the lowest SNPA is calculated by an antenna at the shower center in this setup.

Next, we expand our study on 93 cosmic rays with a much broader range of energies including 10^{16}, 10^{17}, 5.10^{17} and 10^{18} eV. We also increased the observation distance to 400m from shower core and included Gamma cosmic rays in our new study. This comprehensive set of simulations which can be seen in Fig.3 once again shows the dependence of SNPA to distance from shower core.

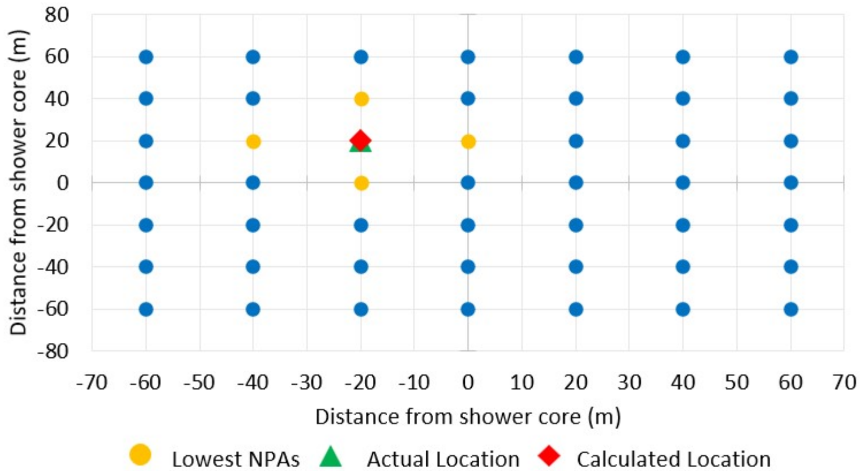

Fig 4. A virtual radio array and the location of actual and calculated core location based on the lowest recorded SNPAs for a vertical proton cosmic ray with 10^{17} eV energy. Using the average technique, we estimated the shower core location at (-20m,20m).

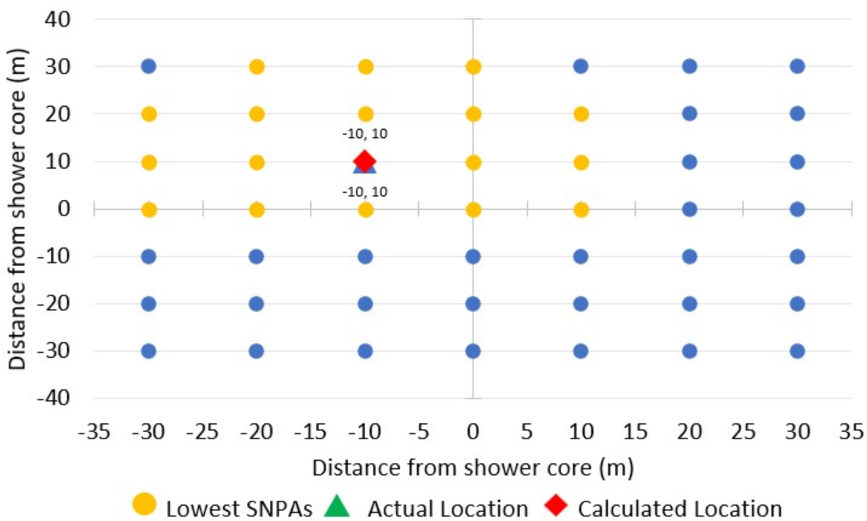

Fig 5. Another virtual radio array and the location of actual and estimated core location based on the lowest recorded SNPAs for a vertical proton cosmic ray with 10^{17} eV energy. By making an average on the location of proper antennas, we estimated the core location in this setup.

In all simulations, the actual core location is positioned at (0m,0m). Although there are some differences in the value of error bars and the SNPA numbers for different types of primary particles and initial energies, the important point is an increase in the SNPA values in proportion to the distance from shower core.

7. Estimating the core location

In this section, we investigate a possible approach to estimate the position of a cosmic ray core location. As we discussed in the previous section and since the SNPA is minimum at close distances to a core location and increases as we move further for vertical cosmic rays, it is possible to use different techniques to locate the position of that point.

A very simple case is when we have a dense radio array and the shower impact falls inside that setup. In best case scenario there would be an antenna where the shower axis hits the ground and thus that specific radio antenna would record the lowest SNPA and other antennas will record higher values compared to that station. An example of such situation is depicted in Fig.4 and Fig.5. Otherwise, since the SNPA values change in accordance to distance from shower core we would notice a quick jump in values as we get distance from the position of a shower center. Considering this important note, we can make an average on the position of the antennas where we have recorded the lowest SNPAs to estimate the position of a shower core.

Fig.4 shows a virtual setup where we have an array of 49 antennas. Here, the actual location of the shower core is at (-20m,20m). As we discussed earlier the adjacent antennas to the position of the shower core (Yellow marks in Fig.4) have recorded the lowest SNPAs and for the rest of antennas, we have a noticeable jump in the values of calculated SNPAs. the smallest values recorded by the antennas in Fig.4 is presented in Table.1. The four intended antennas surrounding the core location have very similar SNPA values.

Table 1. Smallest recorded SNPAs for a vertical proton cosmic ray with 10^{17} eV energy at the location of SURA dedicated to Fig.4

Antenna Location (North-South) (m)	60	-20	-20	-40	0	-20
Antenna Location (East-West) (m)	-40	40	20	20	20	0
SNPA ($\times 10^{[illegible]}$)	5.081	5.01	5	4.99	4.99	4.984
Subtracted SNPA ($\times 10^{[illegible]}$)	0.097	0.026	0.016	0.006	0.006	0

Table 2. Part of calculated SNPAs for a vertical proton cosmic ray with 10^{17} eV energy at the location of SURA dedicated to Fig.5

Antenna Location (North-South) (m)	30	-10	-10	0	-20	0
Antenna Location (East-West) (m)	30	30	20	30	30	20
SNPA ($\times 10^{[illegible]}$)	5.1	5.01	5.01	5.005	5.004	5.002
Subtracted SNPA ($\times 10^{[illegible]}$)	0.118	0.028	0.028	0.023	0.022	0.02

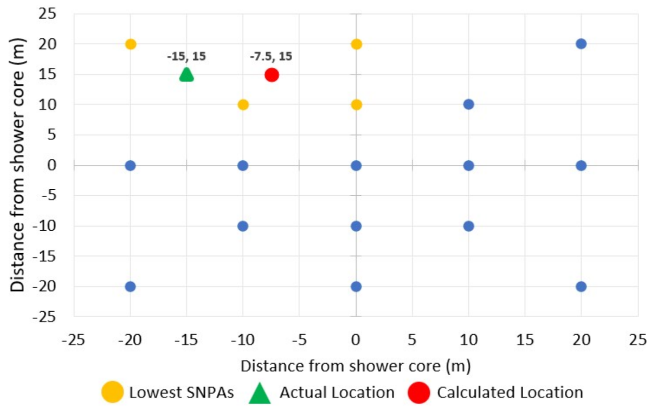

Fig 6. The lowest recorded SNPAs for a vertical proton cosmic ray with 10^{17} eV energy in much smaller virtual radio array compared to Fig.4 and Fig.5. Even in this case, it is possible to estimate the location of this shower core using the same average approach.

Since the SNPA values calculated by the antennas are very close to each other there needs to be a clear approach which would make it possible to choose the correct antennas for estimating the core location based of their calculated SNPA values. Our method includes finding the lowest SNPA among all calculated values where in this case is from an antenna at (-20m,0m), subtracting the calculated SNPA value of this antenna from all individual SNPA values from all antennas and finding antenna locations with subtracted SNPA value smaller than 0.1. The antennas with SNPA values less than 0.1 are what we choose to make an average of their locations. All SNAPs were calculated with up to 3 decimals and in case of using just two or one decimal in the tables which follows, we calculated the third or the second decimal number to be zero. In all tables we will show the first antenna with the SNAP value higher than 0.1 or close to that value for comparison purposes.

In this setup and by applying the above procedures, we find 4 antennas to have these conditions and therefore by making an average on their locations it is possible to estimate the core position at x=20m, y=20m.

Here we need to explain one important point. If there be an antenna right in the location of a vertical air shower core position, it will record the lowest SNPA as we discussed in [19]. The reason that we see a difference here where the lowest SNPA is calculated by an antenna close to the shower core is because of the fact that we adjusted our program to calculate the slope of the phase angle on a much wider range of frequencies. As a result of that and because of the behavior of cosmic ray radio signals above 100 MHz frequency range where radio signals from cosmic ray air showers lose their coherence, we may calculate the SNPA to have a minimum value in a close distance to a shower core in a proper dense array.

In the second setup, we have the same radio array with 49 antennas as in Fig.4 with narrower spacing between the stations as shown in Fig.5. Using the same method, it is possible to estimate the location of the shower core. In this setup, the actual core location was set at (-10m,10m). Using the same technique as described in the previous section makes it possible to estimate the core location.

In this case, 20 antennas have subtracted SNPA values less than 0.1 and we have to make an average of their locations. Even by doing that we estimated the shower core with good accuracy. Since there are too many antennas with less than 0.1 subtracted SNPA values in this setup we show part of calculated SNPA values in Table.2.

Next, we have a virtual radio array with much fewer radio antennas compared to Fig.4 and Fig.5. In this case, the actual core location is at (-15m,15m). Here we do not have a radio antenna where the shower axis hits the ground, yet using the same procedure it is possible to find the eligible antennas to make an average on their coordinates and estimate the core location of this cosmic ray. Fig.6 shows the location of the antennas where we calculated lowest SNPAs. Subtracting the lowest SNPA value from all quantities and choosing the antennas with a subtracted value less than 0.1 (as can be seen in Table.3) will help us to find the right antennas for making an average on their positions. The estimated core location of this cosmic ray is at (-7.5m,15m) which is a

Table 3. Smallest recorded SNPAs and subtracted values for a vertical proton cosmic ray with 10^{17} eV energy at the location of SURA dedicated to Fig.6

Antenna Location (North-South) (m)	20	-20	0	-10	0
Antenna Location (East-West) (m)	-20	20	20	10	10
SNPA (× 10[illegible])	5.104	5.003	4.997	4.995	4.992
Subtracted SNPA (× 10[illegible])	0.112	0.011	0.005	0.003	0

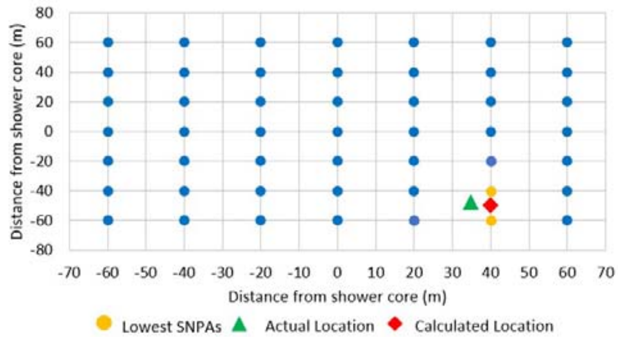

Fig.7. The same radio array as in Fig.4 and 5 recording radio signals from a vertical proton cosmic rays with 10^{17} eV energy. Here the actual core location falls between our radio antennas but by finding the location of proper antennas with less than 0.1 subtracted SNPA values, we estimate the shower core at (40m, -50m).

Table.4. Smallest recorded SNPAs and subtracted values for a vertical proton cosmic ray with 10^{17} eV energy at the location of SURA dedicated to Fig.7

Antenna Location (North-South) (m)	20	40	40
Antenna Location (East-West) (m)	-60	-60	-40
SNPA (× 10[illegible])	5.676	5.475	5.397
Subtracted SNPA (× 10[illegible])	0.279	0.078	0

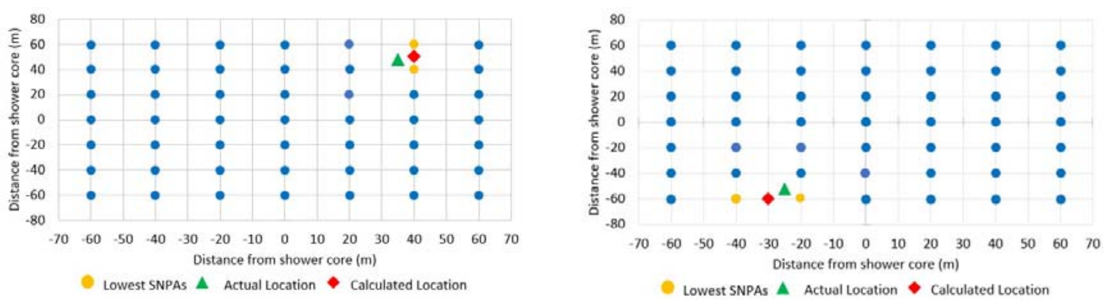

Fig.8. Two more vertical proton cosmic ray simulations with 10^{17} eV energy where the actual core location falls between radio antennas. From left to right the actual core location is at (35m,48m) and (-28m, -52m) and the estimated location of that point is (40m,50m) and (-30m, -60m) respectively.

Table.5. From left to right, lowest calculated SNPA values for two vertical proton cosmic ray with 10^{17} eV energy as described in Fig.8.

Antenna Location (North-South) (m)	20	40	40	-20	0	-20	-40
Antenna Location (East-West) (m)	60	60	40	-20	-40	-60	-60
SNPA (× 10[illegible])	5.678	5.48	5.393	2.47	2.433	2.321	2.243
Subtracted SNPA (× 10[illegible])	0.285	0.087	0	0.227	0.19	0.078	0

good estimation considering the number of antennas in this array.

We also investigate a similar situation where the actual core location of a vertical proton cosmic ray with 10^{17} eV energy falls inside a much denser radio array. Fig.7 shows the same array as in Fig.4 and Fig.5 where the actual core location is at (35m, -48m). The calculated SNPA values are presented in Table.4 where only two antennas have subtracted SNPA values less than 0.1. Making an average on their locations yields the estimated core location at (40m, -50m).

Two more setups for a vertical proton cosmic rays with 10^{17} eV energies are also depicted in Fig.8. In both cases, the actual core location falls between virtual radio antennas where we do not have a radio antenna at the location of shower cores. From left to right the actual core locations are at (35m,48m) and (-28m, -52m). In both setups, only two antennas have subtracted SNPA value less than 0.1. Using the same approach, we estimated the core locations at (40m,50m) and (-30m, -60m) respectively. The calculated SNPA values smaller and equal to 0.1 are also presented in Table.5.

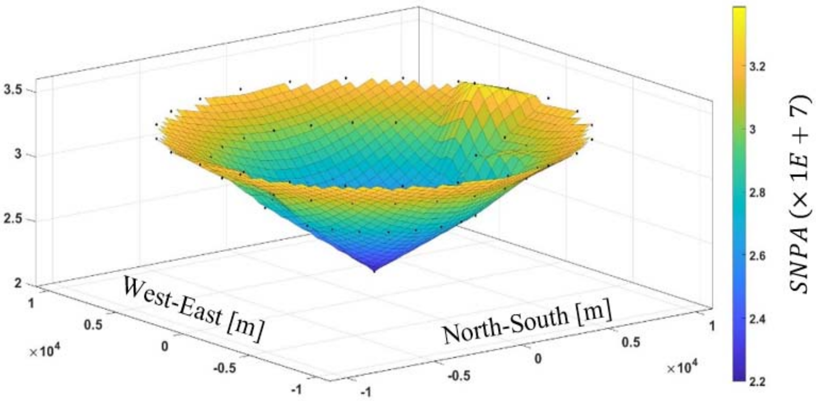

Fig.9. A contour plot for the cosmic ray described in Fig.6. Since we record the lowest SNPA in close distances to a shower core, it is possible to determine the core location zone by applying a proper level step on this graph.

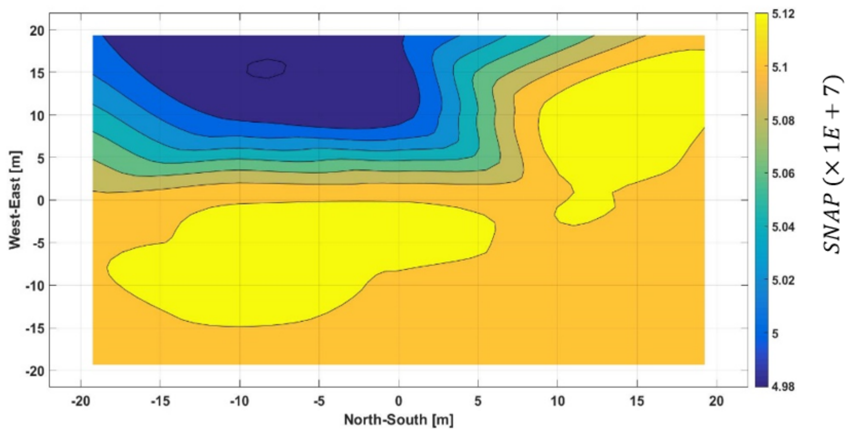

Fig.10. 3D graph of the SNPA values for a vertical proton cosmic ray with 10^{17} eV energy. the lowest SNPA value is recorded by an antenna at the shower core located at (0m,0m). The black dots represent our virtual radio array in this setup.

Table.6. Smallest recorded SNPAs and subtracted values for a vertical proton cosmic ray with 10^{17} eV energy at the location of SURA dedicated to Fig.10

Antenna Location (North-South) (m)	50	0
Antenna Location (East-West) (m)	0	0
SNPA (× 10[illegible])	2.721	2.199
Subtracted SNPA (× 10[illegible])	0.522	0

It is possible to demonstrate the relationship between SNPA values and distance from a shower core in different styles. Fig.9 shows the contour plot of the same cosmic ray described in Fig.6. By applying a proper level step for this contour plot, it is possible to locate the core location zone. Further analyses may estimate the location of that point with higher accuracy but just by looking at this plot we can have a rough estimation of the core location for this specific cosmic ray.

Another way to demonstrate the relationship between SNPA and distance from shower core is by using a 3D graph. Fig.10 shows a 3D graph of SNPA values for a vertical proton cosmic ray with 10^{17} eV energy. In this simulation, the actual core location is at (0m,0m). This new array is consisting of 72 radio antennas expanding radially from the center to 100 meters at 15 degrees intervals. It is clear that the SNPA increases radially as we move from the position of this shower core. It is also obvious that the lowest SNPA value is recorded by the antenna at (0m,0m). Here we can see how the SNPA value increases radially as we get distance from shower core.

Table 6 shows the SNPA values for Fig.10. The black dots are the location of our virtual radio antennas. As expected only one antenna has a subtracted SNPA value less than 0.1 which is the antenna located at the shower core.

Previous studies showed that an inclined air showers might be easier to be detectable in radio detection techniques due to their much larger radio footprint on the ground [20]. Fig.11 shows a 3D plot of calculated SNPA values for an inclined proton cosmic ray with $\theta=30^{\circ}$ and 10^{17} eV energy propagating to the south. Although the lowest SNPA is calculated from radio signals of an antenna at shower center (0m,0m), applying the same approach as we did for vertical cosmic rays, leads us to

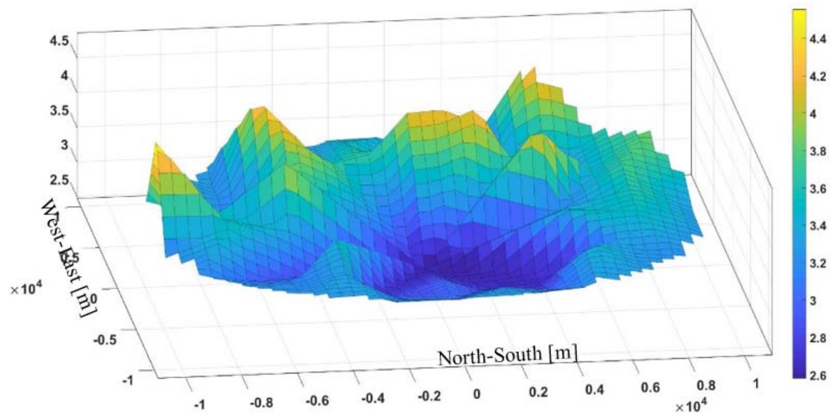

Fig.11. 3D graph of the SNPA values for inclined proton cosmic ray with $\theta = 30^\circ$ and 10^{17} eV energy. The lowest SNPA value is recorded by an antenna at the shower core located at (0m,0m). However, by applying the same method that we used for vertical cosmic ray, we estimated the core location at (17.63m, -17.72m).

Table.7. Smallest recorded SNPAs and subtracted values for an inclined proton cosmic ray with $\theta = 30^\circ$ and 10^{17} eV energy at the location of SURA dedicated to Fig.11.

Antenna Location (North-South) (m)	25.64	0	43.31	-43.35	-50.00	-24.95	-86.54
Antenna Location (East-West) (m)	-96.66	0	24.99	-24.92	0	43.33	50.11
SNPA ($\times 10^{7}$)	3.359	2.812	4.334	4.324	4.296	4.267	4.226
Subtracted SNPA ($\times 10^{7}$)	0.547	0	0.108	0.098	0.07	0.041	0

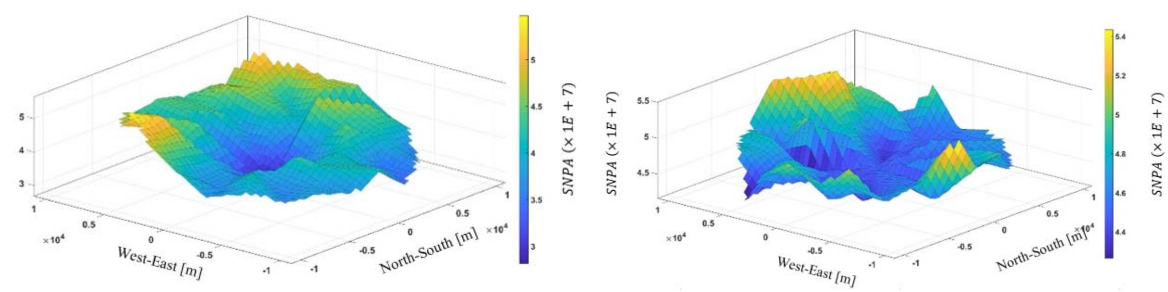

Fig.12. From left to right: 3D graphs of the SNPA values for inclined proton with $\theta = 45^\circ$ and $\theta = 60^\circ$ and 10^{17} eV energy propagating to the South. For the cosmic ray with $\theta = 45^\circ$ the lowest SNPA value is recorded by an antenna at the shower core located at (0m,0m). However, for a fully inclined cosmic ray with $\theta = 60^\circ$ that is not the case anymore. Even in this case and by applying the same procedure we can estimate the core location at (-51.21m,17.13).

Table.8. From left to right: Smallest recorded SNPAs and subtracted values for an inclined proton cosmic ray with $\theta = 45^\circ$ and $\theta = 60^\circ$ and 10^{17} eV energy propagating to the south at the location of SURA dedicated to Fig.12

Antenna Location (North-South) (m)	24.88	35.26	0
Antenna Location (East-West) (m)	-43.37	-35.45	0
SNPA ($\times 10^{7}$)	2.711	3.674	2.58
Subtracted SNPA ($\times 10^{7}$)	0.131	0.094	0

find that two antennas have subtracted SNPA values less than 0.1. By making an average of their location we can estimate the core location at (17.63m, -17.72m).

We also perform two more simulations for inclined proton cosmic rays with θ=45° and θ=60° and 10^{17} eV energies propagating to the South. The 3D plots of these simulations are depicted in Fig12 from left to right respectively. Table 8 shows calculated SNPA values for Fig.12. As it can be seen even for an inclined cosmic ray with θ=45° the lowest SNPA is recorded by an antenna at shower core and that antenna is the only one with subtracted SNPA value less than 0.1. This will help up to estimate the location of that inclined cosmic ray with good accuracy. However, for a fully inclined cosmic ray, the lowest SNPA is not calculated by an antenna at shower core (0m,0m) anymore. Regardless of this fact and by applying the same approach we can estimate the core location based on the SNPA values of the antennas which have subtracted SNPA value with less than 0.1 at (-51.21m,17.13m).

Conclusion

In this study and based on computer simulations and radio signal analyses, we investigated the relationship between the slope of the normalized phase angle of radio signals from a cosmic ray air shower to the position of a shower core.

For this purpose, a series of simulations were performed using CORSIKA and CoREAS code. The simulated cosmic rays had 10^{15} to 10^{18} eV initial energies with Proton, Iron, and Gamma as primary particles. We used an exclusive computer code to analyze the radio signals which was developed specifically for this study. Using this code, we calculated the slope of normalized phase angle (SNPA) for the received radio signals. We found that the lowest value of the SNPA is recorded at the shower core or in very close distances to that location.

In order to show the relationship between the calculated SNPAs and the location of a shower core, we calculated the SNPA for a series of vertical cosmic rays with 10^{16}, 10^{17}, 5.10^{17} and 10^{18}eV energies. In all simulations, we found the SNPA to have the minimum value at shower center. Using a series of virtual radio arrays, we showed that it would be possible to estimate the location of a shower core by making an average on the location of specific radio antennas. In order to find the location of intended radio antennas, we presented a possible approach where we need to subtract the lowest calculated SNPA value from all quantities and select the antennas with subtracted SNPA less than 0.1. Few setups were demonstrated to show the functionality of this approach. We investigated both cases where we have or have not a radio antenna at the location of a shower core for vertical cosmic rays. We also showed that it would be possible to estimate the core zone by deriving a contour plot of SNPA values with a proper level step. Furthermore, we also calculated the SNPA for inclined cosmic rays with $\theta=30^\circ$, $\theta=45^\circ$ and $\theta=60^\circ$. The results in finding the core location for such events showed that that this method is not suitable for inclined air showers as we found the core location with low accuracy. For a fully inclined cosmic ray with $\theta=60^\circ$ the lowest SNPA were not calculated by the antenna at shower core.

References

1. K H Kampert and A A Watson, *Extensive air showers and ultra high-energy cosmic rays: a historical review. The European Physical Journal H*, 37 (**3**), (2012) 359.
2. G Rastegarzadeh and H Fallahnejad, *Effects of different source characteristics on the propagated CR and secondary neutrino spectra: A CRPropa3 simulation. Advances in Space Research*, 63 (**12**), (2019) 4058.
3. G Rastegarzadeh and M Nemati, *Dependence of the muon pseudorapidity on the cosmic ray mass composition around the knee. International Journal of Modern Physics* D 24 (**01**), (2015) 1550010.
4. Pierre Auger Collaboration, The Pierre Auger cosmic ray observatory. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, **798** (2015) 172.
5. H Kawai, S Yoshida and H Yoshii, *et al*., *Telescope array experiment. Nuclear Physics B (Proceedings Supplements)*, (175-176), (2008) 221.
6. G Rastegarzadeh and M Nemati, *Study of the extensive air shower mass sensitive parameters in prototype of ALBORZ array. Advances in Space Research*, 55 (**6**) (2015) 1734.
7. G Rastegaarzadeh and J Samimi, *A wavelet-based multifractal separation technique for extensive air showers. Journal of Physics G: Nuclear and Particle Physics*, 27 (**10**) (2001) 2065.
8. J V Jelley, J H Fruin, and N A Porter, *et al*, *Radio pulses from extensive cosmic-ray air showers. Nature*, 205 (**4969**) (1965) 327.
9. Wilson, J.G., Wouthuysen, S.A. and Sard, R.D., 1959. Progress in Elementary Particle and Cosmic Ray Physics. PhT, 12(11), p.46.
10. D Ardouin, A Belletoile, and D Charrier, *et al*,. *Radioelectric field features of extensive air showers observed with CODALEMA. Astroparticle Physics*, 26 (4-5) (2006) 341.
11. T Huege, *May. Theory and simulations of air shower radio emission. In AIP Conference Proceedings, American Institute of Physics* 1535, No. **1** (2013) 121.
12. M Sabouhi and G Rastegarzadeh, *August. A new method to determine air shower propagation direction based on radio signal patterns. In The 34th International Cosmic Ray Conference*, SISSA Medialab, Vol. **236** (2016) 474.
13. A Corstanje, P Schellart, and A Nelles, *et al*,. *The shape of the radio wavefront of extensive air showers as measured with LOFAR. Astroparticle Physics*, 61 (2015) 22.
14. G Rastegarzadeh and M Sabouhi, *SURA: Semnan University Radio Array. Experimental Astronomy*, 49(1) (2020) 21.
15. M Sabouhi and G Rastegarzadeh, *January. The effect of geomagnetic field on radio signal patterns from cosmic ray air showers. In 35th Int. Cosmic Ray Conf.(ICRC)* Vol. **301**, (2017**)** 568.
16. D Heck, J Knapp, J.N Capdevielle, *et al*,. *CORSIKA: A Monte Carlo code to simulate extensive air showers. Report fzka*, 6019 (11) (1998).
17. T Huege, M Ludwig,. and C W James, *May. Simulating radio emission from air showers with CoREAS. In AIP Conference Proceedings, American Institute of Physics*. 1535 No **1** (2013) 128.
18. S Ostapchenko, *QGSJET-II: towards reliable description of very high energy hadronic interactions. Nuclear Physics B-Proceedings Supplements*, 151(1) (2006)143.
19. M Sabouhi and G Rastegarzadeh, *January. An investigation on the phase angle of radio signals from cosmic ray air showers. In ICRC* 301 (2017) 567.
20. M Sabouhi, and G Rastegarzadeh. "*Are inclined air showers from cosmic rays the most suitable to radio detection?." The 34th International Cosmic Ray Conference*. **236**. SISSA Medialab (2016)