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Timing and Signal Amplitude Measurements in a Small EAS Array

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Abstract

Small detector arrays, which are designed to record relatively small EAS with energy in the ‘knee’ region, are often equipped with clocks that measure the time difference between fast signals from several detectors, as well as spectrometric channels that provide the amplitudes of these signals. When analyzing them to determine the angles of arrival and the size of the registered showers, it is important to take into account uncertainties, i.e., the dispersion of measured time differences and shower size relative to the ‘true’ values, which are unknown in the actual situation. Analyses of these spreads are essentially only possible on the basis of correctly performed simulation calculations that take into account all possible stochastic processes in the development of showers in the atmosphere. In this paper, we present a simulation-based analysis using the CORSIKA program of a small EAS array model consisting of four charged particle detectors. We demonstrate the potential offered by ideal timing and how we can infer the energy of the primary particle by analyzing signal amplitudes. The analysis shows that the costs, not only financial, of introducing timing and shower spectrometry are not worth the potential physical gains that we can achieve by using them to analyse small showers.

Keywords: cosmic rays; extensive air showers; small EAS array

1. Introduction

The domain of small Extensive Air Shower (EAS) arrays continues to thrive, and, in fact, has seen noticeable growth in recent years. These compact installations serve an important role in modern experimental physics: they function as versatile test environments in which new detection techniques, electronics, and data-acquisition methods can be designed, evaluated, and refined before being implemented in large-scale observatories or adapted for use in other scientific and technological fields.

Advances in detector technologies designed for large-scale physics experiments often arise indirectly from research carried out on smaller test installations. These compact setups provide flexible, low-cost environments where new concepts can be explored, prototypes can be constructed, and design flaws can be identified long before the technology is deployed in a full-scale facility. As a result, many of the sophisticated detection systems used in major experiments have their roots in work initially performed on much simpler arrays.

A clear illustration of this pathway is the evolution of Resistive Plate Chamber (RPC) technology used in the OPERA experiment. Before RPCs became integral components of OPERA’s muon detection system, their operating principles, materials, and electronics were refined through numerous trials in smaller experimental configurations. These early studies laid the foundation for the reliable high-precision detectors that OPERA ultimately



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used, demonstrating how small-scale research environments can significantly influence and accelerate the development of instrumentation for large, complex scientific ventures [1–3].

A significant portion of small shower = arrays are assembled from repurposed components originating from major accelerator-based experiments that have completed their operational cycles. Instead of being discarded, valuable detector modules—often still in excellent working condition—are retrieved, refurbished, and integrated into smaller research setups. This practice not only reduces costs but also ensures that sophisticated instruments continue to contribute to scientific progress long after their original projects have ended.

A notable illustration of this approach is the reuse of one-square-meter scintillation detectors originally used in the Buckland Park air-shower array [4,5]. These detectors, once part of a large shower experiment, now provide a reliable and cost-effective foundation for new small-scale cosmic-ray studies.

Of course, not all small cosmic-ray arrays originated from recycled equipment or technology-development efforts. Some were established from the outset as dedicated scientific instruments designed to address specific research questions. A notable example is the installation at the Darjeeling Campus of the Bose Institute, which was purpose-built to investigate high-energy cosmic rays under the unique atmospheric and geomagnetic conditions of the Himalayan region. This facility illustrates how small, carefully designed arrays can play an essential role in targeted studies that complement the goals of larger international experiments [6]. Another example of equipment designed for a specific scientific purpose that also plays an important role in popularizing and disseminating information about new technologies and contemporary physics is the CREDO-Maze Project, which was carried out at the University of Łódź, Poland [7,8]. Another example of a purpose-built installation is the mini-array operated by the UHE Cosmic Ray Research Laboratory at Gauhati University in Assam, India [9]. This facility was conceived specifically to study the flux and characteristics of ultra-high-energy cosmic rays in the northeastern region of the country. Despite its modest scale, it provides valuable, region-specific measurements and serves as an important training ground for students and young researchers, highlighting once again how small, well-designed arrays can make substantial contributions to both scientific inquiry and the cultivation of technical expertise.

In addition to the installations mentioned previously, several other small, purpose-built cosmic-ray arrays have been set up around the world. These include the GELATICA array in Georgia [10,11] that searches for Cosmic Ray Ensembles as part of the CREDO Collaboration [12], and the array at Sharif University of Technology in Tehran, Iran, which serves as a compact experimental setup for measuring air showers and training students in particle detection techniques [13].

These examples illustrate the diversity and global distribution of small-scale cosmic-ray experiments. Despite their modest size, these arrays provide valuable data, foster technological innovation, and serve as educational platforms for developing the next generation of experimental physicists.

Several small EAS arrays were designed with education and training as a central goal. These university-based installations allow students and young researchers to gain hands-on experience in operating particle detectors, collecting data, and performing analyzes—skills that are directly applicable to large-scale experiments in accelerator physics, space-based missions, or major cosmic-ray observatories. The EAS-UAP array at the University of Puebla in Mexico exemplifies this approach [14], providing a learning environment in which participants can directly engage with real cosmic-ray measurements while simultaneously contributing to ongoing scientific studies. Such arrays play a crucial role in the preparation of the next generation of experimental physicists for complex, high-profile research projects.

Educational initiatives such as CHICOS (California High school Cosmic ray ObServatory at Caltech, along with NATLA (North American Large-area Time-coincidence Array) including WATLA (University of Washington), ALTA (University of Alberta), SALTA (Snowmass), VICTA (Victoria), CROP (Nebraska) across the USA and Canada, and also GRAND (University of Notre Dame) and MARIACHI (BNL) also deserve mention for their role in engaging students with hands-on cosmic-ray research. Also, across Europe, a number of small-scale and educational cosmic-ray projects have been established. Notable examples include HiSPARC (High-School Project on Astrophysics Research with Cosmics) in the Netherlands and the UK, SEASA (Stockholm Educational Air Shower Array) in Sweden, ADA (Astroparticle Detectors Array) and the EEE Project (Extreme Energy Events) in Italy, CZELTA (CZEch Large-area Time coincidence Array) in the Czech Republic, and the HELYCON project (Hellenic LYceum Cosmic Observatories Network) at the Hellenic Open University in Greece. Although several of these installations are no longer operational, others continue to support both scientific research and educational initiatives.

2. CORSIKA Shower Simulations

The analysis of data from small shower arrays and the drawing of physical conclusions from observations is based on the comparison of measured EAS parameters with theoretical predictions. Although the theory of electromagnetic interactions is well understood, the strong interactions that determine the development of the hadronic component of showers are only known in part, so we must use phenomenological models to describe them.

People have been modelling strong interactions for a long time. All of the models currently on the market were developed a long time ago, but they are constantly being refined and upgraded with the release of new data. It is essential that these models be incorporated into the geometrical structure of transport through the Earth's atmosphere. Combining them with the well-understood physics of electromagnetic processes and other significant phenomena enables the simulation of the development of EAS. The extensive air showers generated by computer for this study were obtained using the CORSIKA programme [15], which was developed over three decades ago in Karlsruhe, Germany, for the KASCADE experiment [16,17]. Since then, CORSIKA has been significantly extended and developed. The most recent version, 7.78050, was released on 18 December 2025. New functions have been added over time to increase the computational capabilities and adapt to the simulation needs of new cosmic ray experiments. Even at the highest observed energies, CORSIKA is still used for simulations up to 10^{21} eV.

The CORSIKA programme offers users a variety of options. The structure of the simulation algorithm itself is important, as are the models of high- and low-energy particle interactions. These should be integrated into the basic simulation scheme. The characteristics of the simulated showers of interest to specific users are also relevant, e.g., Cherenkov radiation, radio emission and atmospheric neutrinos. Due to the sheer number of options, the most recent edition of the CORSIKA compendium extends to almost 200 pages [18], each of which must be given a minimum description.

The default set of run parameters that are already built into the program are used in typical shower simulations. If you're looking to use CORSIKA for something a little out of the ordinary, you'll need to pay close attention to the settings for a few specific parameters. This is the case if you want to use it for detailed simulations of small showers and small shower arrays.

In this work, we analyse the simulation results of CORSIKA using the EPOS LHC interaction model in the context of the high-energy interaction model [19] (v3400). Other models are available as options in CORSIKA, such as SIBYLL, QGSJET-II and VENUS.

At relatively low energies, around the knee, they produce similar results for the basic characteristics of the showers. This fact has been verified many times; (see, e.g., [20]).

We are interested in the particle energies of the ‘knee’ region of the energy spectrum, around 10^{15} – 10^{16} eV which have been studied in accelerator experiments for some time. All high-energy interaction models in CORSIKA were initially tuned to accelerator results, and similar results were found in this energy region. Discrepancies only appear when these models are extrapolated to the highest energies.

With regard to the low-energy hadronic interaction model, CORSIKA provides three choices: GHEISHA (GHe Isotope SHower) [21], FLUKA (FLUktuierende KAskade) [22] and the UrQMD (Ultrarelativistic Quantum Molecular Dynamics) model [23]. For this work, we can guess that the interaction model chosen for energies below 100 GeV is not critical. GHEISHA was used here.

The general properties of relatively small showers are said to be caused by well-known electromagnetic processes. CORSIKA describes these using the EGS4 (Electron Gamma Shower) package [24].

For the present work, we have performed simulations only for primary protons with energies from 10^{14} to 10^{17} eV. This analysis uses a minimum model EAS array consisting of four 0.5 m^2 detectors forming a square with side of 10 m.

3. Timing and Accuracy in Determining the Direction of EAS Arrival

Almost all of the small shower arrays mentioned above had active timing. Based on the measurement of time differences an attempt is made to determine the direction of the recorded EAS.

The very first shower array, used by Auger and Maze in 1938 was a significant technological achievement at that time. However, it was also extremely minimalist. Its capabilities were also minimal, consisting solely of recording the coincidence of several Geiger–Müller counters (three or four). For obvious reasons, it was impossible to determine the arrival times of the particles at the individual detectors. The discovery of Extensive Air Showers, and Auger’s demonstration of the enormous energy a particle entering the Earth’s atmosphere must possess, caused a surge of interest in cosmic radiation. Unfortunately, WWII halted the efforts of the experimenters. After the war, the study of extensive air showers progressed rapidly.

The first ‘true’ shower array was built at Echo Lake by a group of physicists from MIT, led by Rossi and Williams. The structure of the showers was investigated in detail at mountain altitudes using four fast ionisation chambers with photographic pulse height recording and electronic coincidence. Twenty-seven showers with a total energy of more than 10^{16} eV were recorded [25]. Even with ‘fast’ ionization chambers, determining directions was not and could not be very accurate.

4. Timing Measurements

4.1. First Rossi Experiments

Rossi made significant progress in the study of EAS by exploring the possibility of introducing scintillation counters. Nevertheless, more widespread regions were required. Initial MIT detectors were liquid scintillators composed of benzene with the incorporation of a modest quantity of para-terphenol to function as a wavelength shifter. In [26] they established that the particles of the shower arrived at their destination with a spread of arrival times that was sufficiently small to make it feasible to determine the directions of the shower by fast timing, using three liquid-scintillation counters, each 0.06 m^2 spaced at distances of ~ 3 to 30 m.

Rossi's findings revealed that, at a given moment, the majority of electrons with energies of approximately 20 MeV were situated in a flat disk with a thickness ranging from 1 to 2 m. Muons (particles with the potential to penetrate at least 20 cm of lead) are located on a disk with a thickness ranging from 2 to 3 m. The muon disk trails the electron disk by less than 3 m.

The measurement of the zenith angles of the shower axes was carried out by the MIT group, who used the delays between counters that had been spaced out widely. The root mean square of the sines of the projected zenith angles was found to be 0.24 ± 0.015 .

The flux of particles through the plane $z = z_0$ is given by $f(r, z_0, t)$. Thus, the probability that a particle will traverse an area of dA in the plane $z = z_0$, at a distance r from the shower axis, between times t and $t + dt$, is given by $f(r, z_0, t)dt dA$. We can define the probability of the first particle travelling through a detector of area A with the point (r, z_0) between times t and $(t + dt)$ as $F(r, z_0, t)dt$. The relationship between F and f is given by the equation

$$F(r, z_0, t)dt = \frac{A f(r, z_0, t) dt \exp\left(-A \int_{-\infty}^t f(r, z_0, t') dt'\right)}{1 - e^{-\lambda}} \quad (1)$$

where

$$\lambda = A \int_{-\infty}^{\infty} f(r, z_0, t') dt' \quad (2)$$

is the average number of particles that traverse the detector.

The definition of the shower 'front' now extends to the domain of $F(r, z, t)$, which refers to a shower that has arrived on the plane $z = z_0$ at a time t_0 , as long as t is sufficiently close to t_0 . Of course, it depends on the area of the detector.

The expected value of z at time t_0 is denoted by $z_f(r)$. This is the time of the first particle that will eventually hit the detector.

$$z_f(r) = \int_{-\infty}^{\infty} z' F(r, z_0, t) \frac{dz'}{c}, \quad \text{where } t = \frac{z' - z_0}{c} \quad (3)$$

and the surface of the points $z_f(r)$ is called the shower front.

Although the surface of a shower front may appear curved, Rossi's measurements taken close to the shower axis (within 30 m) suggest that a flat surface can also fit the data quite well. The estimated possible radius of curvature could be around 3 km.

Rossi's results suggest that the error in determining the projected zenith angle is about 15 degrees. The result encompasses two effects. Firstly, it includes the unavoidable effects associated with the thickness of the shower front. Secondly, it accounts for the uncertainty of the equipment used in the experiment, such as counters and recorders.

4.2. Results of CORSIKA Simulated Showers

Using simulation methods, we can determine when the first particle will arrive at a specific detector location in each case, without needing to know the distribution of particle delays relative to the shower front. This approach also allows us to reverse the reasoning and determine this distribution, should it have any practical significance.

When analyzing registrations made by shower detectors, we are only interested in the distribution of the times the first particle reaches the detector, $z_f(r)$, and its particular fluctuations.

To determine the direction of arrival of the Extensive Air Shower, which is defined as the direction of the primary particle that initiated it, we need to find the plane of the shower front (assuming we are only considering small showers at small distances from the center of the array) in each case. Rigorously, we should employ the maximum

likelihood method here, using the distributions of the variable $z_f(r)$ to determine the relevant probabilities. However, given the accuracy of the measured registration times, we can safely assume that these distributions are normal and use the χ^2 minimisation method instead. The normal to the shower front plane found in this way determines the direction of the EAS, which can be compared with the assumed direction of the incoming particle in the simulation calculations.

We calculated the distributions of this difference, denoted by δ , for energies ranging from 10^{14} eV to 10^{17} eV. Their examples for energies of 10^{15} eV and 10^{16} eV are shown in Figure 1. There is also shown how these distributions change depending on the number of particles recorded in all four detectors (n). A complicated relationship with the average number of hits, (λ), appearing in Equation (1), is clearly visible. For each primary energy and for showers whose axis falls near the centre of the array (i.e., for large n and λ), the distributions are clearly narrower than when the densities are small.

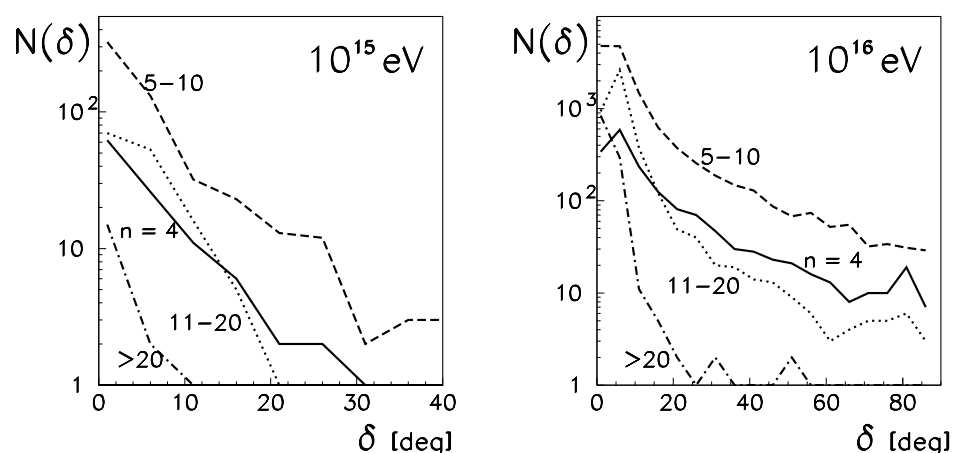


Figure 1. Examples of angular deviation distributions of the estimated direction of the shower from the true direction of the primary particle for energies of 10^{15} eV (**left**) and 10^{16} eV (**right**) for the different numbers of particles recorded in all four array detectors. The lines correspond to n equal to 4 (solid line), 5–10 (dashed line), 11–20 (dotted line), and $n > 20$ (dash-dotted line).

We calculated average value $\langle \delta \rangle$. We did not observe any significant correlation between the difference in the determined and ‘true’ directions for different particle arrival directions.

Figure 2a plots the value of $\langle \delta \rangle$ as a function of the number of particles hitting the detectors, n , for different primary particle energies.

The size of the shower we observe is, as predicted, the determining factor. This dependence is clearly visible in the form of a relationship with the number of particles detected by our small array (n). We expect to see similar results for large showers (high primary particle energy) whose axis is far from the array, as well as for smaller showers hitting near the center of the array.

As can be seen, when there are a large number of particles in the detectors, the average deviation from the ‘true’ direction approaches an asymptotic value of 5° . For small local densities, the inaccuracy in determining the direction reaches 10 – 15° . When large showers are incident far from the apparatus, the uncertainty of determination of the direction is 15° (for 10^{16} eV) and 25° (for 10^{17} eV).

In a real experiment, of course, we cannot isolate showers initiated by particles of a specific energy. Ultimately, we can only determine the average deviation of the reconstructed shower’s direction from that of the primary particle integrated over the cosmic

radiation energy spectrum at the top of the atmosphere, as a function of the number of recorded particles n .

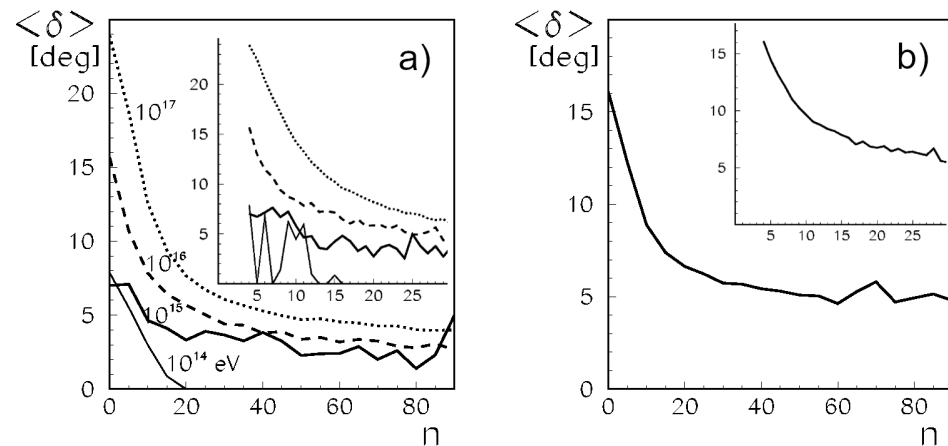


Figure 2. (a) The average angular difference of the reconstructed shower axis from its true value for energies of 10^{14} eV, 10^{15} eV, 10^{16} eV and 10^{17} eV as a function of the number of particles in the shower recorded by all four detectors (coincidence of all four detectors is required, so the minimum value of n is 4). (b) The average difference of the reconstructed shower angle from its true value, integrated with the primary cosmic ray spectrum.

These results are shown in Figure 2b.

5. EAS Size Determination

The size of a shower is defined as the number of charged particles present at the level of observation. Essentially, these are electrons (and positrons) with the addition of around 10% muons. This fraction varies with energy, especially for small showers. In simulations, we assume that all charged particles passing through the detectors of our small model array are counted. This raises the question of what conclusions we can draw about the size of the shower we are dealing with.

Since Williams' experiment [25], it has been clear that to determine the size of the EAS, the shower axis must be located. This is defined as the center of symmetry of the spatial distribution of EAS particles at the observation level. The shower axis is identified as an extension of the primary particle's arrival direction.

Shower Size with a Small EAS Array

Attempting to locate the shower axis based on measurements taken at four relatively close points by small detectors is clearly destined to fail. However, one might ask whether registering a total of n particles in all four detectors could provide information about the size of the shower and perhaps even the energy of the primary particle.

Figure 3 shows the predicted frequencies at which the four detectors in our model array would register a specific number of charged particles in all four detectors, n , for primary particles with energies of 10^{14} , 10^{15} , 10^{16} and 10^{17} eV. As before, the dominant influence is exerted by energies in the 'knee' range (10^{15} – 10^{16} eV).

Using Figure 3 to show the probability distribution densities for recording a specific number of charged particles, n , for a fixed primary particle energy, E , we can attempt to determine the probability of observing a shower initiated by a primary particle with energy E by reversing this relationship using Bayes' theorem, provided that all array detectors are hit by n charged particles.

$$p(E|n) = \frac{p(n|E)f(E)}{p(n)} ; \quad p(n) = \int p(n|E) f(E)dE \quad (4)$$

where $f(E)$ is the primary cosmic ray particle energy spectrum. We set it to be $\sim E^{-\gamma}$ with $\gamma = 2.7$.

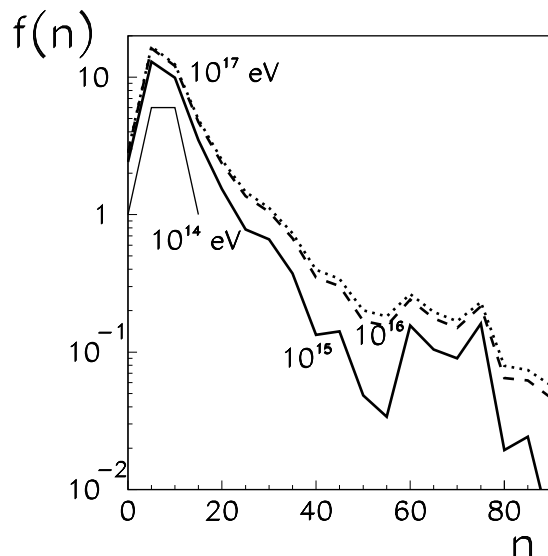


Figure 3. Distributions of the number of charged shower particle in all four detectors integrated with the energy spectrum of primary particles up to energies of 10^{14} , 10^{15} , 10^{16} , and 10^{17} eV.

We estimated Bayesian probabilities that a shower in which our array detectors observed a certain number of charged particles had a specific energy by carrying out simulations for many proton primary energies with sufficiently large statistics. The results for different numbers of recorded particles are shown in Figure 4a.

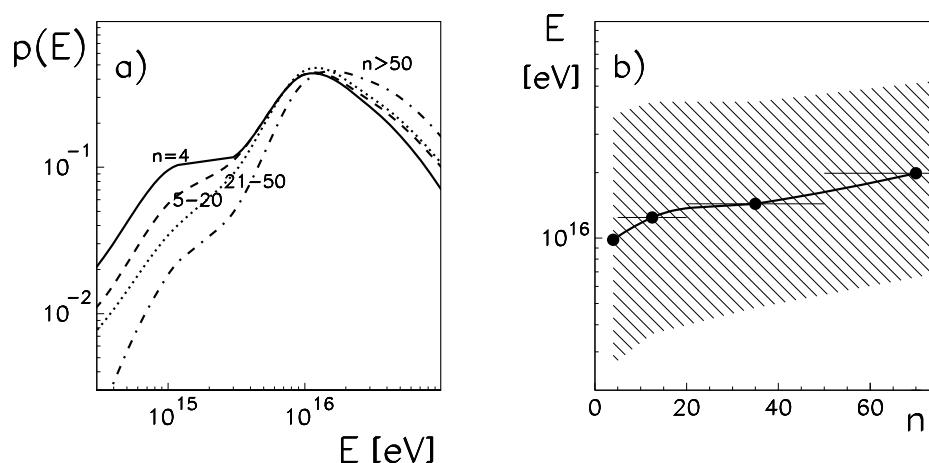


Figure 4. (a) The Bayesian probability density (on a logarithmic energy scale) of a shower initiated by an initial proton with a given energy is shown, if a specific number of charged particles was recorded in four detectors (values of n are shown next to the lines the figure). (b) Expected energies corresponding to specific numbers of particles recorded by four detectors. The hatched area shows the dispersion of this average.

Probability densities enable us to estimate both the expected (average) primary particle energy and the associated dispersion when the number of recorded particles n varies. The results are presented in Figure 4b.

As this graph shows, it is extremely difficult, if not impossible, to estimate the size of the shower—and therefore the primary energy of the cosmic ray particle—based on the total amplitude from small shower detectors. On a logarithmic scale, the accuracy of such an estimation is approximately one order of magnitude.

6. Summary

We analyzed the detection capabilities of a minimal model shower array designed to record small Extensive Air Showers. The simplest design consists of four small, and thus inexpensive, charged particle detectors. The central station that generates the trigger signal and registers the data can be equipped with timing circuits to measure the time intervals between the fast signals coming from the detectors. It can also be equipped with additional circuits to digitize the analog signal amplitudes from the detectors. However, adding these components increases the complexity of the entire array, raising its cost and making calibration and monitoring more difficult. This renders it much less suitable for constructing a large network of such arrays, particularly for educational purposes.

In this work, an attempt has been made to answer the question of what benefits are brought about by this complexity of the array and what additional physical information can be obtained in this way.

In conclusion, we should restrict our search for possible anisotropy in the directions of arrival of small showers to the study of first-order harmonic, dipole, or at most quadrupole anisotropy. The 10° precision obtained in this work is the lower limit to determine the arrival angles of showers. This demonstrates the unavoidable component of uncertainty associated with the development of cascades in the atmosphere. In real cases, all instrumental effects related to signal processing and additional electronic noise must also be considered.

We also analyzed the possibility of assessing the primary energy of the cosmic ray particles that initiated the shower, assuming that the spectrometric channels would provide information about the number of particles passing through the active surface of the detectors with absolute precision by this simple four-detector system. However, even in this ideal scenario, it would not be possible to determine the energy of the primary particles to within an order of magnitude. The steep energy spectrum significantly reduces the likelihood of identifying cases that extend beyond the knee in the primary particle energy spectrum.

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Conflicts of Interest: The author declares no conflicts of interest.

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