PROCEEDINGS OF SCIENCE

Small Extensive Air Shower detector array – a tool for global cosmic-ray research

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The CREDO collaboration studies cosmic-ray related phenomena on a large scale, searching for so called Cosmic-Ray Ensembles (CRE) and other unusual correlations and anomalies of non local nature. Such studies require data on Extensive Air Showers (EAS) and flux of secondary cosmic-ray particles that covers large areas. To perform such measurements, a large network of inexpensive detectors working continuously is necessary, and this work presents a design of such a device. It comprises several small (5 cm × 5 cm × 1 cm) scintillator detectors connected in a flat coincidence circuit, which makes it a desktop-size device. This station is designed to work for months or even years without human intervention, as it can send collected data directly to the database through internet. Cost of a complete device ranges from 1000 $ to 2000 $ depending on the number of detectors used. Results of measurements performed with the use of a constructed prototype are compared with estimations based on the analysis of CORSIKA simulations of EAS with Geant4 simulation of scintillator detectors response. They indicate that the proposed device is capable to measure flux of cosmic rays with high statistics and can reliably distinguish EAS events from signals originating from various backgrounds. It is a good candidate for a component of a large-scale network that should be able to not only monitor cosmic-ray flux in real time, but also provide data for studies of CRE and other phenomena related to cosmic rays.

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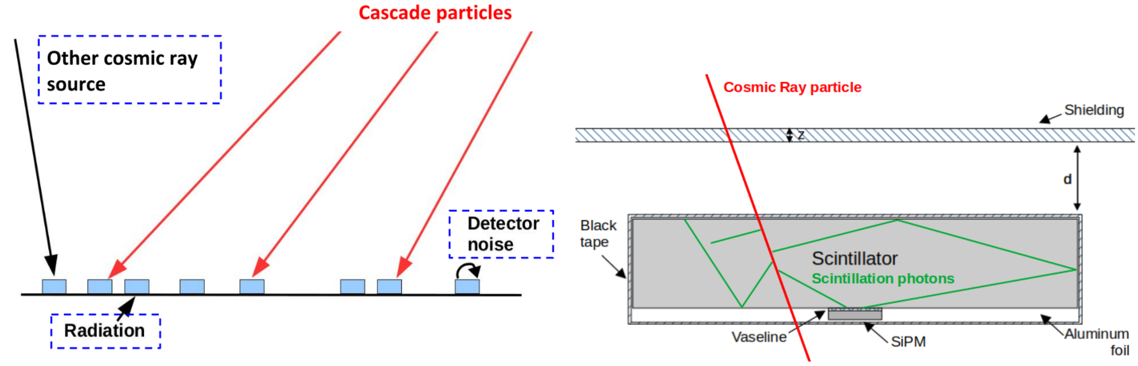

Figure 1: Sources of signals registered by an array of flat detectors (left). Principle of scintillator operation (right).

1. Introduction

One of the main goals of the Cosmic Rays Extremely Distributed Observatory (CREDO) is the search for Cosmic-Ray Ensembles (CRE) – groups of correlated Extensive Air Showers (EAS) of a common origin [1]. To confirm the existence of such phenomena large-scale observations of EAS signals and analysis of their correlations in time are necessary. For this purpose, infrastructure of low-cost detector stations should be developed, distributed over the Earth and connected in a global network. Currently, the main source of data for CREDO are smartphones in which cameras are used as particle detectors by a dedicated application [2]. However, each smartphone behaves differently and provides only information about detections of single particles with a very poor temporal resolution of about 1/30 s. This makes such data insufficient for analysis of correlations between single events. A candidate for a device with properties better suited for such purposes is an array of a few small scintillator detectors connected in a coincidence circuit. This work presents a prototype of such a station, and an exemplary method of searching for CRE that form line-like patterns using a network of such devices is presented.

2. Detector array

The EAS is a bunch of particles travelling through the atmosphere in approximately the same direction in which time between first particles arriving at some place on the ground and the last ones is of the order of one hundred nanoseconds. During this time in the area covered by the shower many secondary particles appear on the ground and can be observed as an increase in particles density over the random background (Fig. 1 (left)). The easiest method to register an EAS is to place several flat detectors next to each other and wait for signals in a few of them in a certain short time window. The key issue is the selection of the length of this coincidence time, δT. It should be equal or greater than the expected difference of arrival times between the last and the first particle from the shower which is usually less than 100 ns. Longer registration time increases probability of detection of several uncorrelated particles that form a false correlation signal. Despite its very low cost the proposed detector array works sufficiently fast for detection of EAS. It does not provide information about the direction of arrival of detected shower due to use of small detectors and short

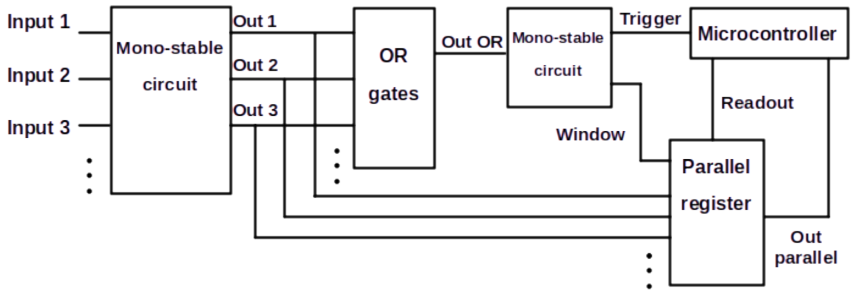

Figure 2: Diagram showing how the coincidence system works.

distances between them, but information about time and the number of detected particles are most important in the context of the global cosmic-ray research.

2.1 Scintillator detector

The proposed station's active components consist of several small scintillator detectors. The device selected for this purpose is a simplified version of the Cosmic Watch [5] even allows achieving even lower price per piece than the original (around $ 100). Each device contains a plastic scintillator with dimensions 5 cm by 5 cm by 1 cm, to which a Silicone Photo Multiplier (SiPM) is connected. When cosmic-ray particle passes through the scintillator material, photons are emitted in a very short flash as presented in Fig. 1 (right). Those photons are registered by the SiPM and turned into electric signal which is amplified and transmitted to the further part of the electronics. Disadvantages of such simple scintillator detectors are that they neither provide any information about the type of particle that produced the signal nor about their energy.

2.2 Coincidence circuit

All scintillator detectors are connected to a separate device, called master unit, that contains the rest of electronics which recognizes and registers coincidences. Its main task is to check detect signals that come from scintillators within a coincidence time, δT. Flowchart of the circuit is presented in Fig.2.

In the master unit signals from up to 8 detectors are first shaped into rectangular signals of fixed length, t_S, by a mono-stable circuit. This operation causes a small delay, Δt_1. Later they are sent through OR logic gates, which introduce another delay Δt_2, to next circuit that generates a trigger signal for a micro-controller and a time window signal for a parallel register. Both of them have length of t_W and are also delayed by Δt_1. During this time window signals from scintillators that were shaped by mono-stable circuits are read by parallel register. After short delay, Δt_{hold}, collected signals are read by the processor as a string of bits corresponding to the individual detectors. Consequently, to ensure that all signals in an EAS event arriving in the time window δT are registered as a coincidence event the following relation has to be fulfilled:

$$t_S \geq \Delta t_1 + \Delta t_2 + t_W = \delta T. \tag{1}$$

In Fig. 3 an example of time course of signals in various parts of the coincidence circuit is shown. Signals from Input 1 and Input 2 are in coincidence while signal from Input 3 occurs to late after

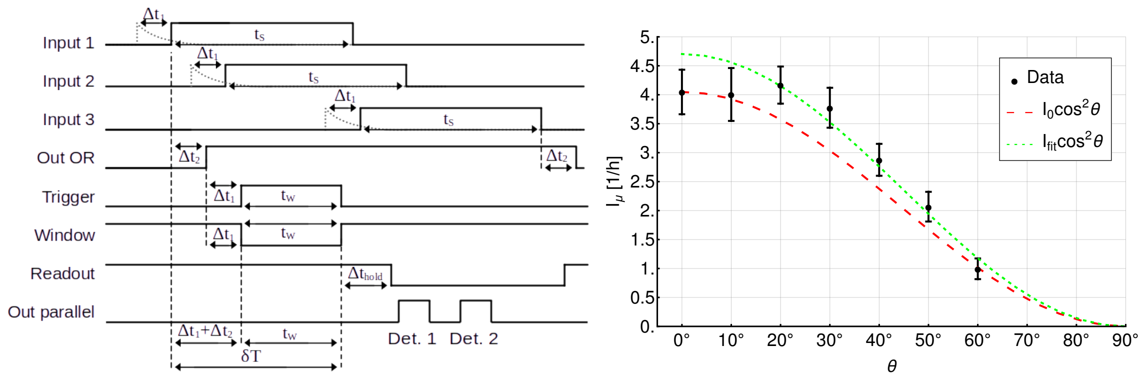

Figure 3: Time dependence of signal in different parts of the electronics (left).

first one to be caused by a particle from the same EAS. Value of $\Delta t_1 + \Delta t_2$ is determined by the electronics and for currently used parts is around 75 ns. The values of t_W and t_S are easily adjustable in a range from 50 ns to over 500 ns so achieving $\delta T \sim 100$ ns is possible. For current tests it has been set to 200 ns.

After reading the data micro-controller immediately reads the timestamp from RTC and saves both informations in a temporary buffers. Then it sets the parallel register back to the state in which the device is ready to register another signal and repeat the whole readout procedure, which is the dead time of the detector, lasts only around 40 μs. Every five minutes or when the buffer with events is full the data from barometers and thermometers are read. After that, the whole data package in a JSON format is transmitted to the server via internet and saved locally.

3. Measurements

Several measurements were conducted with the use of constructed prototype of detector array to test if it works correctly. In the first test, relationship between cosmic-ray flux and zenith angle, θ, was measured (Fig. 3). It agrees with the expected $\cos^2\theta$ dependence, but the value of $I\mu(0) \approx 70$ m^{-2}s^{-1}sr^{-1} for muons with momentum above 1 GeV/c [8] suggests, that the real efficiency of detector is between 20% to 30%. Next measurements in a flat coincidence setup, which lasted together for about a month, were performed at the rooftop of university building. Three different thicknesses of steel shielding were used: 0.5 mm, 1 mm and 1.5 mm. Results of these measurements compared to estimations based on CORSIKA simulations are presented in Fig. 4 (left).

The analysis of CORSIKA and Geant4 simulations also allows to estimate which primary cosmic-ray particles generate the registered signals. Their energy distributions are presented in Fig. 4 (right).

4. Searching for Cosmic Ray Ensembles

The main scenario of CRE that is currently considered is in the form of very long (thousands of kilometres) yet very thin (metres) line of gamma rays that reach the Earth's atmosphere []. To develop methods that could make detection of such lines possible, only their morphology on the

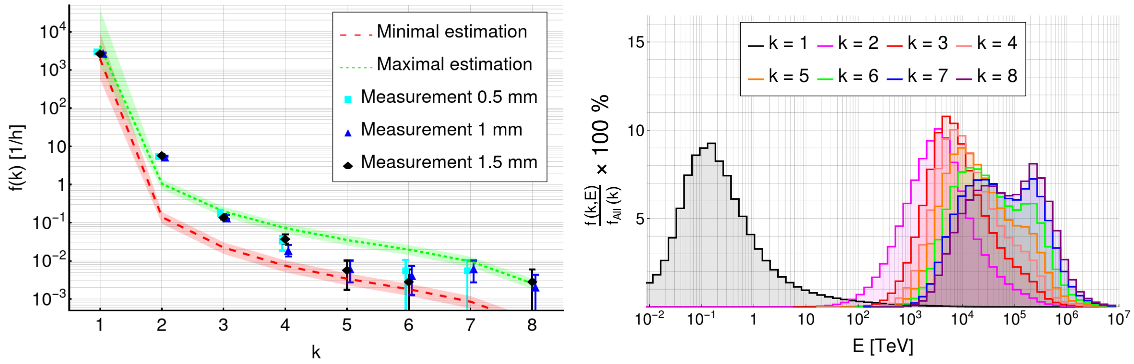

Figure 4: Frequency of coincidence events from measurements with several thicknesses of steel shielding compared to estimations based on CORSIKA [9] and Geant4 simulations (left). Percentage of signals caused by cascades initiated by primary particles of different energies (right).

top of the atmosphere is necessary. The way they form and propagate through space is irrelevant. Such CRE can be characterised with just few parameters like primary energy E_{prime}, number, M, and energy of each gamma ray, E_i, inline distance between each them r_{CRE}, and width of the line, d. Second group of important parameters are geometrical properties of such CRE relative to the analysed area covered by the detector network. Those parameters are coordinates of the centre of CRE, X_{CRE} and Y_{CRE}, and angles of incidence, θ and ϕ.

Most energy of the primary particle that produced such ensemble is carried by secondary photons that are focused around its centre which is a trajectory of the original particle. Gamma rays further away has lower energies. A simplify model of such CRE is a set of less and less energetic photons spread symmetrically further away from its centre along the line. To simulate a signal, that an ensemble with certain set of parameters, can produce in a given network a probability of detection of an EAS produced by gamma ray with energy E_i as a function of distance between the shower centre and the station, r. Since considered stations are arrays of n_j detectors, it also has to depend on the number of observed signals in coincidence, k. Such relationships can be obtained i.e. from the analysis of CORSIKA simulations.

4.1 Background

Term background in the context of search for CRE covers signals from all sources like terrestrial radiation sources, single cosmic ray particles and uncorrelated EAS. Knowing the frequency of each type of event in each array in the network it is easy to simulate data collected in such in a given period of time, t. Considered network is basically a list of N_{st} stations that have a set of properties: longitude, x, latitude, y, altitude, z, number of operating detectors at given time, n, and a list of frequencies of each type of signal, $f(k)$, where $k = 1, 2, ..., n$ is the number of detectors triggered in an event. Probability, P, of registering m number of k-fold signals in i-th station in time t is then given by the Poisson distribution:

$$P_i(x, k, t) = \frac{(f_i(k) \cdot t)^x \exp(-f_i(k) \cdot t)}{x!}. \quad (2)$$

For each station in the network, a number of each k-fold signal is drawn from this distribution. Then, a moments in time are drawn from flat distribution in a range from 0 to t for each signal.

4.2 Analysis

The problem of finding a CRE with line-like structure in a set of simple signals in discussed network is similar to the problem of finding particle tracks in a 3D space in i.e. time projection chamber [11]. In this case 3D space is replaced by a spacetime with two spacial dimensions, X and Y, and one temporal dimension, t. This spacetime contains a set of points, each one with individual coordinates (x_i, y_i, t_i) and additional information about type of registered event which are number of triggered detectors, k, and number of detectors that were operating at the time of registration, n. Analysed datasets consists of network of 10 000 stations, each one an array of $n = 8$ detectors spread unifromly on a 1000 km × 1000 km grid.

The definition of vicinity of lines depends on accuracy of spatial coordinates x_i, y_i and t_i, and the width of CRE that could produce such line, d. The temporal resolution, dt, of analysed stations is quite well defined and should be around 1 ms or better. Resolution of x_i and y_i depends on both accuracy of the geo-localisation, precision with which position of the centre of EAS can be determined, r_{max}. For stations equipped with GPS modules the first accuracy of localisation is within several meters just like width of CRE line, d. The $r_{max}(k, n)$ which depending on the type of registered event can vary from 25 to 1000 m is the only significant factor.

The first step of searching for candidates for line-like CRE is to search for all lines passing through each possible pair of points (p_i, p_j). To limit number of candidates only sufficiently long lines are considered because of limited temporal resolution of the data, relative time difference between two nearby events is not well defined. Gamma rays within ensemble travel with the speed of light, c, and maximum time differences between arrivals of subsequent EAS from ensemble on the surface of the Earth, Δt_{ij}, occurs when the ensemble comes from zenith angle $\theta = 90°$. Therefore, minimum distance between two points that could determine a potentially interesting line, Δr_{ij}, should be grater than temporal resolution divided by dt/c. For the same reason lines for which value of Δt_{ij} at distance Δr_{ij} is too big can not represent physically possible CREs as this would mean that they are travelling with lower velocities. Those criteria can be written as:

$$\Delta r = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \geq \frac{dt}{c} \quad \text{and} \quad \frac{\Delta t_{ij}}{\Delta r_{ij}} = \frac{|t_i - t_j|}{\Delta r_{ij}} \leq \frac{1}{c}, \tag{3}$$

where $x_{i/j}$, $y_{i/j}$ and $t_{i/j}$ are coordinates of points $p_{i/j}$. Line, l, that fulfil those criteria is parametrised by parameter r in the following way:

$$\begin{cases} x_l(r) = x_i + r(x_j - x_i) = a_l + r \cdot dx_l \\ y_l(r) = y_i + r(y_j - y_i) = b_l + r \cdot dy_l \\ t_l(r) = t_i + r(t_j - t_i) = c_l + r \cdot dt_l \end{cases} . \tag{4}$$

For each found line, l, a distance in XY plane, dr, and difference in time to each point $p_i = (x_i, y_i, t_i)$ is calculated. A point is considered to be close to the line if two conditions are fulfilled. First one is $dr \leq r_{max}(k_i, n_i)$ and second one is $|\delta t| \leq dt$. Every line, l, would have at least two points in their neighbourhood which are the ones used to determine its parameters. To automatically reject trivial cases with just two initial points a line is categorised as potentially interesting if there are at least 4 single detections (with $k = 1$) or 3 points from which at least one has $k > 1$. After that, a value called weight, w_l, is assigned to each ensemble to make them easy to classify. It is designed

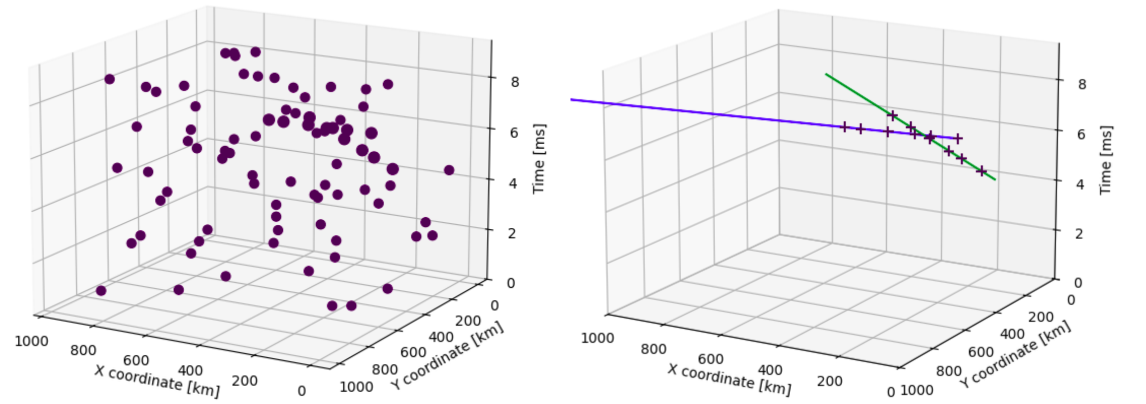

Figure 5: Algorithm input (left panel). Simulation of background and signals from two line-like CREs in a network of 10 000 devices with parameters mimicking constructed prototype. Algorithm output (right panel)

to favour lines with points of multiple coincidence events over ones containing only single events. For line with X_s single points, X_d points with $k = 2$ and X_m points with $k \geq 3$ in its neighbourhood:

$$w_l = X_s + 2\sum_{i=1}^{X_d}\left(1 + \frac{2}{n_i}\right)^2 + 3\sum_{i=1}^{X_M}\left(1 + \frac{3}{n_i}\right)^2. \tag{5}$$

To achieve better results and minimize probability that one ensemble will be described by two lines with similar parameters, a new line is found through linear regression for each group of points that reached this point of analysis. This new line then replaces the initial one used to found potential neighbouring points. The procedure is repeated as long as the weight increases. It is important to note, that once line and its points are considered an optimal ensemble candidate those points are not considered while looking for other ensembles as each EAS can be a part of only one CRE. The result of this analysis is a list of potential candidates for line-like CRE ensembles (Fig. 5).

Total complexity of the whole algorithm is proportional to N_p^3 in the first approximation, therefore to optimise the analysis, the data has to be split into smaller subsets. A whole 3D time-space of points is cut into slices in time axis and then analysed separately. Thinner slices representing shorter time periods have less events within them. To choose the shortest reasonable time period of such slice lets consider a simple example: a network that covers a 1000 km × 1000 km square and a CRE line arriving from θ close to 90° along its diagonal. If stations on the corners of that square would detect EAS from such CRE the time difference between those events, Δt_{ext}, would be ≈ 4.714 ms. To make sure that even extreme cases of CRE are analysed as a whole and to treat all periods in time equally, the shortest reasonable subsets should be of length of $2\Delta t_{ext}$. Because CRE can occur at any moment in time it can happened that the potential candidate is split and some events go to first subset and other to the second one. To make sure than no line is unfortunately split and therefore missed those slices should overlap by being shifted by half of this value.

5. Conclusions

Small detector arrays which costs should be no more than $ 1500 can monitor cosmic-ray flux in real time and efficiently observe EAS of relatively high energy with frequency of at least few per hour. However measurements are necessary to explain the excess of events with double coincidence. Significant fraction of them may be caused by a single cosmic-ray particle interacting in the enclosure and producing more particles. Improvements in the design of detectors to make their efficiency better and more uniform are still possible. Such devices, when used in a sufficiently large and dense network, should be a great tool for global cosmic-ray research that could make observation of CRE possible.

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