Cosmic Ray Detection from Electromagnetic Wave Reflection Using a Matched Filter

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***Abstract*—A new technique for detecting high-energy cosmic rays by using the front scattering of electromagnetic waves has been introduced recently. The reflected signals are captured by antennas and demodulated. The present work makes use of optimal filtering for detecting cosmic rays and removing the huge background noise. The detecting system achieves 98% of the detection efficiency for a false alarm probability as low as 1%.**

I. Introduction

In modern High Energy Physics (HEP) laboratories, like the European Organization for Nuclear Research (CERN, Switzerland) [1] and Brookhaven National Laboratory (BNL, EUA) [2], complex experiments have been assembled to detect and study elementary particles generated by collision of highly energetic subatomic particles [3]. Typically, in HEP huge detectors with hundred of thousand of high-rate readout channels are used, operating simultaneously. The collisions can be performed either in a controlled environment, by using big machines (particle colliders) [4] or by means of natural collisions that happen when cosmic rays interact with atmospheric particles [5]. In the last case, difficulty increases, because of the low signal-to-noise characteristic and rarity of interesting events. However, this natural acceleration process became one of the main issues in physical research, given rise to the construction of modern instruments to detect and study cosmic rays [6].

Recently [7], for detecting ultra high-energy cosmic rays, a new detection technique has been introduced, which uses the front scattering of electromagnetic waves [8]. A goal of this technique is the possibility to use, as electromagnetic wave source, commercial TV transmitters located far from the receptor antenna. This method has extensively been used for meteor detection [9] and it can be adapted to cosmic ray detection requirements. As meteors, high-energy cosmic rays are able to ionize atoms from the atmosphere. This ionization process reflects the electromagnetic waves which then may be captured by antennas and demodulated.

Due to the rarity of target events, raw data captured by the receptor antenna are mostly background noise. In order to avoid storing data when no reflective wave is present, a trigger system should be developed. Because of the weak intensity of the reflected wave, signal detection has to be performed in low signal-to-noise ratio conditions. Hence, stochastic signal processing techniques look attractive for extracting signals from noise [10]. In this work, the optimal filtering technique [11] is applied to online detection of cosmic rays from electromagnetic wave reflection. The model assumes that the received signal is masked by additive noise and both signal and noise statistics are used to design a matched-filter [12]. Thus, cosmic ray detection is performed by correlating the incoming signal with replicas of the target signal components in the receiver end. This linear filtering approach is optimal in terms of signal-to-noise ration, provides simple implementation and short processing time. The detection performance of the proposed online detection system is evaluated using experimental digitized data. As an optimal signal detection technique, the matched filter should perform reasonably better than a simpler threshold detection system, which is being used today for offline triggering.

The paper is organized as it follows. An overview of the detection technique is presented in Section II. The data acquisition setup is then described in Section III. The detection theory is summarized in Section IV and a free-running algorithm for signal detection is developed in Section V. Results of the matched filter based cosmic ray detection are shown in Section VI. Finally, conclusions are derived in Section VII.

II. Overview

Figure 1 shows the cosmic ray detection principle. Primary cosmic rays generate a shower of particles in the atmosphere and charged particles from this shower ionize the atmospheric gas. The free electrons from this ionized gas may reflect on electromagnetic waves coming from a parasitic transmitter antenna. A receptor antenna, tuned to the transmitter carrier, captures waves reflected by the atmosphere when a cosmic shower arrives. Thus, the cosmic shower detection is obtained indirectly. In order to get only reflected waves and to avoid signals coming directly from the transmitter, the receptor antenna is positioned far away from the transmitter. This technique allows to detect not only cosmic rays but any kind of physical phenomenon that is able to ionize the atmospheric gas, as meteors, lightning and even airplanes. Eventually, scintilators can be used to detect cosmic rays in a small area. This is useful for the calibration and test of the detector setup [13].

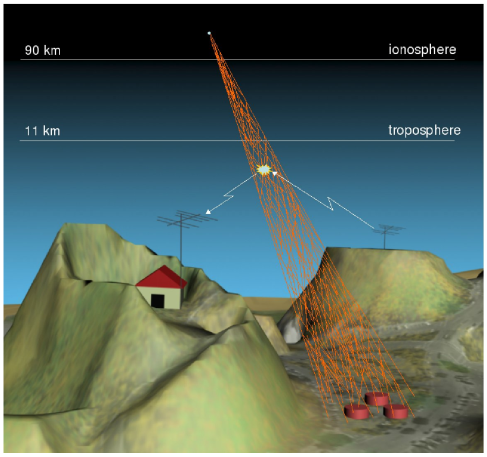

Fig. 1. Cosmic ray detection for scattering of electromagnetic waves.

The forward scattering of radio waves by ionized gas is a well known physical phenomenon described by classical electromagnetism [8]. According to this theory, the wave frequency range should be between 30 to 300 MHz in order to be reflected by atmospheric gas ionization. As it was mentioned, receptor antenna should be positioned far away from the transmitter station. With this approach the direct signal from the transmitter does not reach the receptor, since the antenna is bellow the horizon line and also there is no reflection in the ionosphere for this frequency range.

III. Data Acquisition System

For the proposed technique, data acquisition is still in an initial phase. A prototype assembled with off-the shelf parts is being used. Figure 2 shows the system used for the first experimental data acquisition. The radio receivers are tunned to the TV commercial channels 55.25 and 67.25 MHz, the distance from the transmitters being enough to get only reflected waves. The signal coming from the scintilators are acquired using standard NIM crate [14]. A GPS (Global Positioning System) is used in order to synchronize the information when there is more than one receptor antenna. All analog signals are digitized in a 24-bit word by an 8-channel commercial sound board. The sampling frequency can be performed in the range 8 to 96 kHz. The sound board is connected to a PC (Personal Computer), which runs the software that acquires and stores data in huge volumes.

Figure 3 shows a typical cosmic shower signal candidate recorded by this acquisition system. Up to now, raw data are stored in permanent media, feeding dozens of GBytes of information by week, where most of it is noise. The proposal of the present work is to implement a free-running algorithm to detect cosmic rays using the matched-filter technique. This algorithm should be able to run online in the next versions of the setup, in order to store only interesting events for further offline analysis, removing the huge background noise.

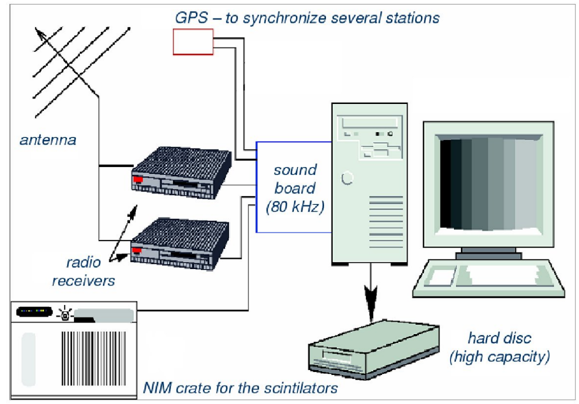

Fig. 2. Data Acquisition System.

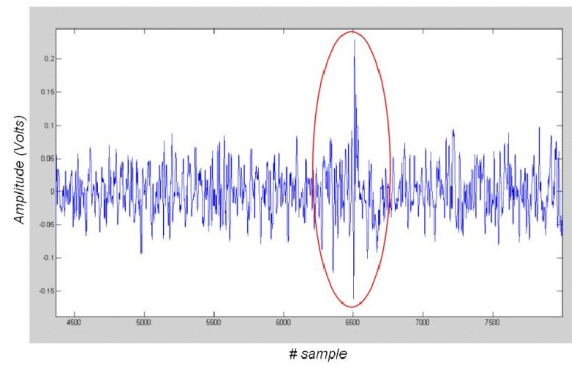

Fig. 3. Typical signal possibly generated by a cosmic shower.

IV. Matched Filter

Although cosmic signal candidates are better modeled as a stochastic process, as a first approach and to keep the algorithm as fast as possible, a matched-filter for deterministic signal was implemented using the average of cosmic ray signal candidates as the target signal. This corresponds to consider small fluctuations on cosmic signal candidate distribution. This approximation avoids the highly computational cost procedure of representing the stochastic processing by the principal components of the Karhunen-Löeve expansion of the original process, which would be required by the standard design [11].

Using this approximation and supposing additive white Gaussian noise, the likelihood ratio between the probability density functions of the Hypothesis 1 (H_1 - signal is present) and Hypothesis 0 (H_0 - only noise is present), for a given received signal $\mathbf{l}$, reduces to

$$\mathbf{l}^T\mathbf{s} \underset{H_0}{\overset{H_1}{\gtrless}} \gamma \tag{1}$$

where the decision rule is given by the inner product between $\mathbf{l}$ and a copy of the target signal $\mathbf{s}$ [11]. This is known as the matched-filter. The determination of the detection threshold γ depends on the detection efficiency and the amount of the false alarm probability that can be handled.

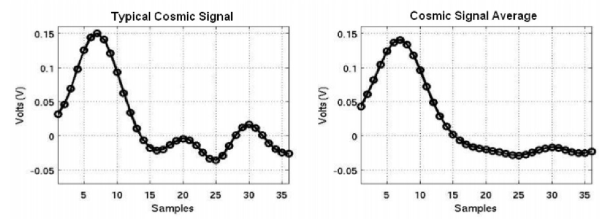

Fig. 4. Typical and averaged pulses for cosmic ray signal candidates.

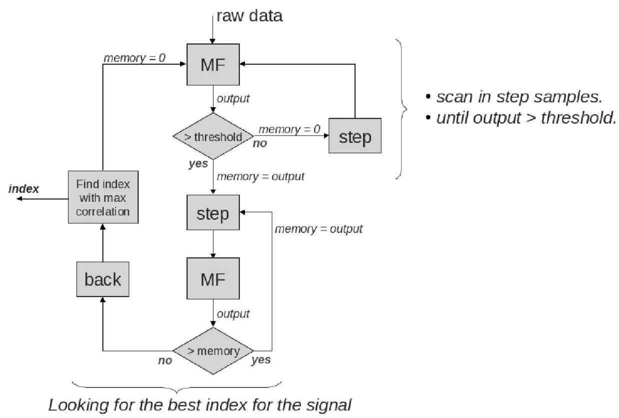

Fig. 5. Free-running algorithm block diagram.

V. Free-running Algorithm

Figure 4 shows typical and averaged pulse shapes for the cosmic signal candidates. The signal window was obtained by applying pulses with 20 μs width to the acquisition system input, using a pulse generator. This is a typical cosmic shower time interval [13]. The output time window response of the system is about 450 μs (36 samples long at 80 kHz). Such averaged signal is used as the target detection signal.

In order to use the matched-filter technique for incoming data selection, a free-running algorithm was developed (Figure 5). This algorithm comprises two decision stages, both based on a single matched-filter design. The first stage applies the matched-filter over a 36 sample data window. That window is moved along incoming data by controlling the *step* parameter, which defines a gap between data windows. This stage eliminates most of the noise and selects the cosmics candidates, which are further analyzed by the second stage. One should select optimal values for both the *step* and the *threshold* parameters depending on the required detection efficiency and false alarm probability. In the second stage a more detailed analysis, using a matched-filter applied at each incoming sample, is performed.

VI. Results

Preselected cosmic signal candidates and noise samples were concatenated in a data vector where the actual indexes of the cosmic signal candidates were known. Thus, the detection probability with respect to *threshold* and *step* parameters could be evaluated. Results are discussed below.

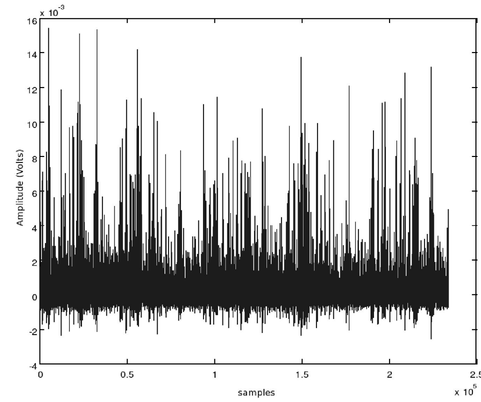

Fig. 6. Noise data.

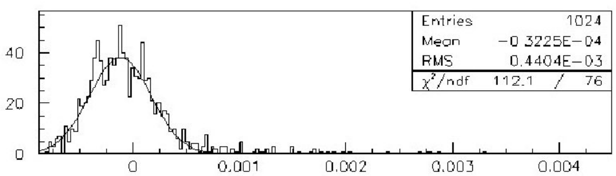

Fig. 7. Gaussian fit applied to the noise distribution.

A. Noise Analysis

Figure 6 shows digitized noise data. The corresponding Gaussian fit to the distribution of the noise samples is shown in Figure 7, which indicates that, as a first approximation, noise can be considered Gaussian.

This is also pointed out by the noise covariance matrix (see Figure 8), which exhibits small crosstalk. This indicates a small deviation from a fully white noise process.

B. Free-running parameter estimation

The *step* parameter should be as high as possible, in order to get the minimal computational cost without loosing signals. Similarly, the highest *threshold* value where no signal is missed avoids that a lot of noise passes to the next trigger stage. An algorithm to scan several combinations of these two parameters was performed and it turned out that, for a

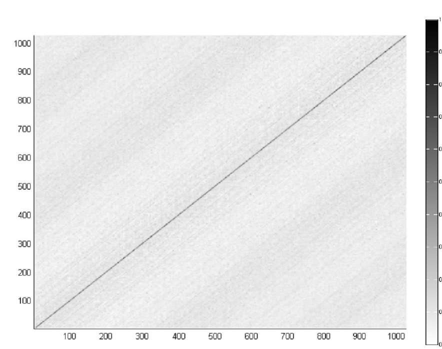

Fig. 8. Noise covariance matrix in gray scale

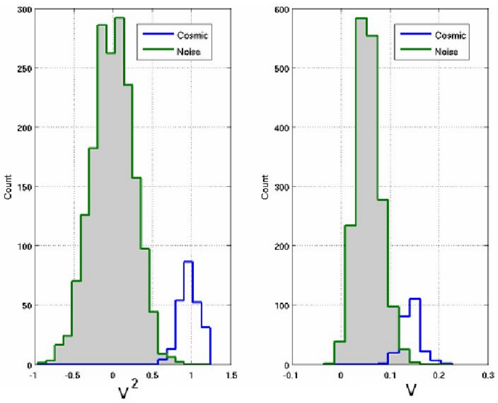

Fig. 9. The matched-filter (left) and threshold detection (right) distributions.

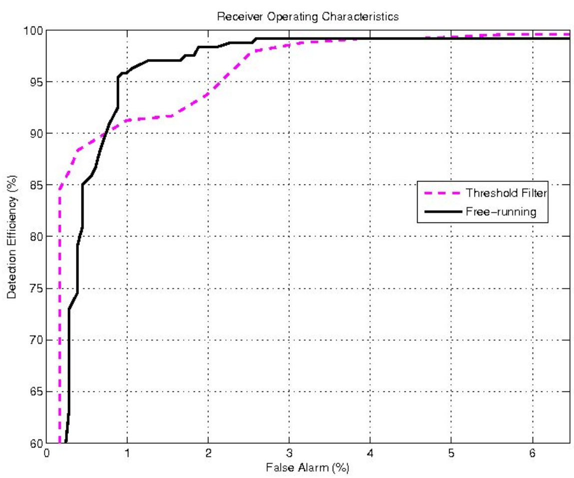

Fig. 10. ROCs for free-running and threshold detection algorithms.

step value higher than 6 samples, interesting signals start to be missed. Thus, fixing the *step* parameter in 6 samples, the optimal value for the first matched-filter threshold become 0.5 V^2.

C. Detection efficiency

In order to determine the detection efficiency, 480 preselected cosmic signal candidates and 3,600 noise segments were organized in two data sets of the same size: development and test sets. The development set is used for design parameter estimation and filter development, whereas the testing set evaluates the detection system generalization and operation performance.

The matched-filter output distribution for the testing set is shown in Figure 9, which also displays the threshold detection distribution for comparison. One can notice a better separation between noise and signal distributions for the matched-filter approach. Figure 10 shows the Receive Operating Characteristics (ROC) [11] for the free-running and the threshold detection algorithm.

VII. Conclusion

To improve the cosmic shower detection from the front scattering of electromagnetic waves, a simplified matched-filter design has been realized. This filter achieves detection efficiency of 98% for a false alarm as low as 1%, reducing drastically the amount of stored data for offline analysis.

Since the first stage of the free-running algorithm eliminates most of the background noise and the second stage can run at a lower rate, a more accurate detection process can be performed by the last stage, which increases the detection efficiency. Further improvements on signal detection efficiency may be achieved by applying a whitening filter to incoming data and adapting the matched filter design for stochastic process detection. Also, nonlinear discriminant techniques, as neural networks [15], may be used for exploring higher order correlations. These are ongoing activities.

Acknowledgment

The authors would like to thanks CAPES, CNPq and FAPERJ (Brazil). Special thanks to Helio Takai from BNL (USA) for providing the data used in this paper and for fruitful discussions concerning this work.

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